UNIVERSIDAD DE LAS PALMAS DE GRAN CANARIA

Tesis doctoral

Programa de Doctorado en Oceanografía y Cambio Global

Procesos biogeomorfológicos alterados por actividades antrópicas en sistemas sedimentarios eólicos costeros áridos

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Contenidos

Presentación

Este documento presenta los resultados de 4 años de mi investigación como miembro del Grupo de Investigación en Geografía Física y Medioambiente (GFyMA), adscrito al Instituto de Oceanografía y Cambio Global (IOCAG) de la Universidad de Las Palmas de Gran Canaria (ULPGC), y alumno del programa de doctorado en Oceanografía y Cambio Global (IOCAG, ULPGC). Como resultado, se presenta esta tesis doctoral que se sustenta en forma de 5 artículos publicados en revistas internacionales con impacto JCR (3 Q1, 1 Q2 y 1 Q3), más los resultados de un sexto artículo en proceso de revisión por pares (estado: under review) en la revista Geomorphology. Estos artículos son el reflejo del interés que he tenido y que tendré, sobre qué está ocurriendo con los procesos biogeomorfológicos en los sistemas sedimentarios eólicos costeros de regiones áridas, como son los canarios. Y si estos han funcionado siempre, o son el resultado del impacto ambiental que ha producido la actividad humana.

Durante este periodo he sido beneficiario de un contrato predoctoral como Personal Investigador en Formación (PIF), de 4 años de duración, mediante la convocatoria de concurrencia competitiva 2015 publicada por La Agencia Canaria de Investigación Innovación y Sociedad de la Información (ACIISI) del Gobierno de Canarias (código de la Tesis/beneficiario: TESIS2015010049) y confinanciada por el Fodo Social Europeo (Fondos Feder). Para llevar a cabo esta investigación, dentro del programa de doctorado anteriormente citado, he contado con el director y responsable de la ayuda, el Dr. Luis Hernández Calvento, del Dr. Patrick Allan Hesp como codirector, y María Emma Pérez-Chacón Espino como tutora. Asimismo, los resultados de estas investigaciones suponen una contribución al proyecto de investigación Análisis de procesos naturales y humanos asociados a los sistemas playa-duna de Canarias (cód. CSO2016-79673-R), financiado por el Plan Estatal de I+D+i (Ministerio de Economía y Competitividad, MINECO, Gobierno de España), cuyo investigador principal es Luis F. Hernández Calvento.

Presentation

This document presents the results of 4 years of my research as a member of the Physical Geography and Environment Research Group, which is affiliated to the Institute of Oceanography and Global Change (IOCAG) of the University of Las Palmas de Gran Canaria (ULPGC) in Spain, and as a student in the IOCAG doctoral programme. The results of this research are presented here in the form of an article-based doctoral thesis, comprising 5 papers published in international journals with a JCR impact factor (3 Q1, 1 Q2 and 1 Q3) and the results of a sixth work submitted to Geomorphology and which is presently under peer review. These papers reflect the interest that I have had, and will continue to have, in what is taking place in the biogeomorphological processes of coastal aeolian sedimentary systems in arid regions, as found in the case of the Canary Islands (Spain), and whether these process have always functioned as they do now, or whether they are the result of human-induced environmental impacts.

During this period, I have been supported by a 4-year Research Trainee pre-doctoral contract as a Research Trainee awarded on an open and competitive basis in 2015 by ACIISI, the Canary Government Agency for Research, Innovation and the Information Society (thesis/beneficiary code: TESIS2015010049) and co-financed by the European Social Fund. In the undertaking of this research, as part of the previously mentioned doctoral programme, I have been aided by Dr. Luis Hernández Calvento, as programme manager and in charge of assistance, Dr. Patrick Allan Hesp, as co-manager, and María Emma Pérez-Chacón Espino as supervisor. The results of the research that has been carried out also entail a contribution to the research programme headed by Luis F. Hernández Calvento titled "Analysis of natural and human processes associated with beach-dune systems of the Canary Islands" (code: CSO2016-79673-R), financed through

the R+D+i Plan drawn up by the Spanish Government's Ministry of Economy and Competitiveness (MINECO).

Resumen

El alto nivel de presión antrópica que ocurre en las áreas costeras hace que muchas de ellas estén avocadas a perder su dinámica natural. La consecuencia más inmediata es un aumento de la vulnerabilidad de los ecosistemas que se localizan en estas áreas, lo cual supone un riesgo ante procesos relacionados con el actual cambio climático. Canarias es una de las regiones del Estado español que mayor dependencia tienen del sector turístico, habiéndose especializado en el turismo de masas, de sol y playa. En este contexto, los sistemas sedimentarios eólicos costeros de Canarias han estado, en las últimas décadas, soportando actividades antrópicas, que han inducido alteraciones en el funcionamiento natural de algunos de ellos, y en algún caso, hasta el punto de su desaparición.

De lo anterior se deduce que la alteración de los sistemas dunares costeros de las islas Canarias puede tener dos consecuencias principales, una funcional y otra socioeconómica. La primera, que es tratada en esta investigación, está relacionada con los efectos sobre la biogeomorfología, es decir, sobre los cambios que se inducen en procesos en los que interactúan, de forma conjunta, especies vegetales y procesos sedimentarios eólicos (geoformas eólicas). Estos efectos se traducen en cambios en la fisonomía del espacio, en los ecosistemas y en la pérdida de servicios de ecosistema. Desde el punto de vista ambiental, es muy importante comprender que, en el caso de los sistemas de dunas de Canarias, se trata de los únicos sistemas dunares transgresivos de regiones áridas que alberga Europa. Las consecuencias socioeconómicas están relacionadas con la degradación del paisaje característico de estas zonas y, por lo tanto, con la disminución de su potencial turístico y recreativo.

Considerando estos precedentes, la presente tesis doctoral tiene como objetivo definir procesos multiescalares, naturales e inducidos por actividades humanas (especialmente por urbanizaciones, infraestructuras, servicios y usuarios), relacionados con la geomorfología y la vegetación en sistemas sedimentarios eólicos costeros de Canarias, como modelo de sistemas sedimentarios eólicos costeros de regiones áridas. La tesis, elaborada mediante el procedimiento de compendio de publicaciones, abarca seis trabajos independientes, aunque conectados por el objetivo planteado. Cada metodología y datos utilizados en estos trabajos han sido adaptados a distintas escalas espaciales y temporales. Sin embargo, en todos ellos se aplican sistemas de información geográfica (SIG), para medir variables relacionadas con la geomorfología, la vegetación y la antropización de los sistemas dunares estudiados. Las variables son analizadas espacial y estadísticamente para comprobar posibles cambios ambientales, relaciones entre ellas y conocer el origen del impacto ambiental, si es detectado.

La investigación está soportada por 5 artículos publicados y 1 artículo en proceso de revisión. Se presentan, en el contexto de esta tesis, de forma secuencial. En el primero de ellos se utiliza una escala continental/Global (Climate as a control on foredune mode in Southern Australia); en el segundo una escala regional (Urban-touristic impacts on the aeolian sedimentary systems of the Canary Islands: conflict between development and conservation); mientras que en los últimos cuatro se utilizan escalas locales (Procedure to automate the classification and mapping of the vegetation density in arid aeolian sedimentary systems; Biogeomorphological processes in an arid transgressive dunefield as indicators of human impact by urbanization; Airflow dynamics, vegetation and aeolian erosive processes in a shadow zone leeward of a resort in an arid transgressive dune system; y 2D Decadal monitoring of *Traganum moquinii*'s role in the morphometry of the foredune in an arid dunefield).

De los resultados obtenidos se deduce que los cambios ambientales y la alteración de los procesos biogeomorfológicos son más complejos a medida que la escala espacial

aumenta; sin embargo, es a escalas de detalle donde mejor se detectan cambios ambientales inducidos por actividades antrópicas.

Además de la vertiente de ciencia básica, que se aplica de forma general en todos estos trabajos, también la vertiente de ciencia aplicada tiene cambia en esta investigación: la información aportada en cada artículo es de interés para la gestión y la planificación (especialmente urbanística) en torno a sistemas dunares costeros áridos. Especialmente es interesante para aquellas regiones con sistemas sedimentarios eólicos costeros áridos que estén, en la actualidad, en proceso de desarrollo como destinos turísticos.

Abstract

The high level of anthropogenic pressure which occurs in coastal areas causes many of them to alter or lose their natural dynamics. The most immediate consequence is an increase in the vulnerability of the ecosystems that are located in these areas, and this in turn constitutes an added risk to processes potentially affected by climate change. The Canary Archipelago is one of the regions in Spain with the greatest dependence on the tourism sector, having specialized in mass *sun and beach* tourism. In this context, the coastal aeolian sedimentary systems of the Canary Islands have had to support anthropogenic activities in recent decades which in some cases have led to alterations to their natural functioning, and in others, to their disappearance.

It can be deduced from the above that these modifications to the coastal dune systems of the Canary Islands can have two main consequences, one functional and the other socioeconomic. The first, which is dealt with in this research, is related to biogeomorphological impacts, that is to changes that are induced in processes which involve the joint interactions of plant species and aeolian sedimentary processes (aeolian landforms). These effects translate into changes to the ecosystems and the physiognomy of the space, as well as to the loss of ecosystem services. From an environmental point of view, it is most important to understand that the Canary dune systems are the only transgressive dune systems in arid regions in the whole of Europe. For their part, the socioeconomic consequences are related to the degradation of the characteristic landscape of these areas and, therefore, to a decrease in their appeal as a leisure and tourism destination.

Considering this background, this doctoral thesis aims to define multiscale processes, both natural and induced by human activities (especially urbanization, infrastructure, services and users), related to geomorphology and vegetation in coastal aeolian sedimentary systems of the Canary Islands, as a model of such systems for arid regions. This article-based thesis includes six independent but thematically related works. The methodology and data used in these works have been adapted to different spatial and temporal scales. However, geographical information systems (GIS) are applied in all of them to measure variables related to the geomorphology, vegetation and anthropogenic activities of the dune systems studied. The variables are analyzed spatially and statistically to determine correlations between them, possible environmental changes and the origin of any environmental impact that is detected.

The research is supported by 5 published papers and 1 paper under review. They are presented, in the context of this thesis, sequentially. In the first, a continental/global scale is used (Climate as a control on foredune mode in Southern Australia); in the second a regional scale (Urban-touristic impacts on the aeolian sedimentary systems of the Canary Islands: conflict between development and conservation); and in the last four local scales are used (Procedure to automate the classification and mapping of the vegetation density in arid aeolian sedimentary systems; Biogeomorphological processes in an arid transgressive dunefield as indicators of human impact by urbanization; Airflow dynamics, vegetation and aeolian erosive processes in a shadow zone leeward of a resort in an arid transgressive dune system, and; 2D decadal monitoring of Traganum moquinii's role in the morphometry of the foredune in an arid dunefield).

The results show that environmental changes and the alteration of biogeomorphological processes become more complex as the spatial scale increases, but that it is at detailed scales that environmental changes induced by anthropogenic activities are best detected.

As well as the extended use of basic science throughout this thesis to understand fundamental problems, a significant contribution is also made in terms of applied science:

The results and information provided in each article are of particular relevance for management and planning (especially urban planning) decisions that have the potential to impact on arid coastal dune systems. This is particularly true for regions with arid coastal aeolian sedimentary systems that are currently being developed as tourist destinations.

Agradecimientos

Todo esto no se explicaría sin el apoyo y, sobre todo, la paciencia que han tenido conmigo en estos años, todas las personas que iré mencionando. Seguro que me dejaré a muchos y muchas, Mil disculpas por ello, pero que sepan que también forman parte de esta tesis.

A mi ejemplo a seguir, aunque no lo consiga, a mi compañera de trabajo, mi mejor amiga y pareja, antes y durante estos años. La que me ha aguantado el dejarla hablando sola, mientras yo pensaba en cómo medir o relacionar vegetación y geomorfología, y otras tantas cosas, y encima me mostraba su cariño. La verdad que ha sido una pasada, una suerte y un lujo haber podido realizar las estancias, y todo este viaje junto a tí. Carolilla, te estaré eternamente agradecido por todo esto y mucho más, pues no hay páginas para escribirlo.

A mis padres y a mi mejor amigo, mi hermano Efraín. Por todo el cariño que me han dado siempre, por estar lejos y al mismo tiempo tan cerca de mis cuestiones académicas. Porque siempre me apoyaron con el "tú estudia lo que te gusta y no lo que tiene salida, y ya se verá". Y por el esfuerzo de todos estos años, cuando he estado ausente, aunque estuviera junto a ellos (pensando y absorbido por la tesis), o cuando he estado de estancia, porque sé que para ellos es un enorme esfuerzo y sacrificio el no tenerme cerca.

A mi director Luis Hernández Calvento por darme la oportunidad de haber llegado hasta aquí, y algo que me parece todavía una locura, confiar en mí siendo como era en mi época de estudiante de geografía. Gracias por los consejos, por las ideas y por haber estado ahí para todo lo que necesitaba en cuestiones académicas.

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A todos lo miembros del grupo de Geografía Física y Medio Ambiente porque en cualquier momento me han echado una mano en discutir, facilitarme alguna información o incluso ayudarme en la parte burocrática cuando he estado lejos.

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Y por último pero muy importantes para mí, a mis abuelos y a mi madrina (Antonia), porque, aunque ya no están, se les echa de menos, y sé que hubiesen sido los primeros en haber estado sentados frente a mí, el día de la defensa de esta tesis doctoral, y quién sabe, seguramente estarán.

Asume tu nueva identidad,
una pala mecánica y a reventar,
tu memoria es ahora una ficción,
no me hables de conservación,
construyes y doblas su valor,
y tus cuentas inflas sin parar,
dónde quedó aquella realidad,
sin oxígeno que respirar,
Un mar de cemento y hormigón.

(extracto de la canción "Identidad (La isla cemento)", de Gran Banda Mandinga"

Introducción

Contexto de la investigación

La investigación que sustancia esta Tesis Doctoral, titulada “Procesos biogeomorfológicos alterados por actividades antrópicas en sistemas sedimentarios eólicos costeros áridos”, se apoya en tres ejes temáticos (Figura 1): i) la geomorfología, ii) la vegetación, iii) las actividades humanas y sus infraestructuras (Figura 1). La combinación de los dos primeros ejes se encuadra en el campo de la *biogeomorfología* (Corenblit et al., 2011), desde el que se considera que la colonización de la superficie terrestre por parte de la vegetación produjo, y produce, cambios complejos en los procesos naturales, así como en las formas de relieve (geoformas) (Murray et al., 2008; Davies y Gibling, 2009, 2010). Desde esta perspectiva, se trata de analizar tales cambios en los que la vegetación interfiere en un proceso físico natural, el transporte sedimentario eólico, dando lugar a procesos diferenciales y, con ello, a geoformas características (Hesp, 1981; Moreno-Casasola, 1986). En nuestro caso, estos dos ejes se combinan en el contexto del Antropoceno reciente, en el que las actividades humanas han dado lugar a cambios en los procesos naturales característicos del planeta Tierra, permitiendo definir un contexto de cambio global (Crutzen y Stoermer, 2000; Duarte et al., 2006). En este contexto, esta Tesis aborda también el estudio de tales cambios motivados por las actividades humanas. Dado que la investigación que se presenta trata sobre procesos y, por lo tanto, sobre dinámica, se hace necesario el uso de escalas temporales. Desde el punto de vista espacial, también esta investigación se ha tratado desde una perspectiva multiescalar. Desde esta perspectiva, entendemos que, con el aumento de la escala, también aumenta la complejidad de los análisis que deben ser abordados para entender los procesos objeto de estudio.

El ámbito de estudio de esta investigación está conformado por sistemas sedimentarios eólicos costeros áridos, habiéndose prestado especial dedicación a los localizados en las islas Canarias. Éstos están siendo objeto de estudio pormenorizado por parte de investigadores del Grupo *Geografía Física y Medio Ambiente*, del *Instituto de Oceanografía y Cambio Global* (IOCAG) de la Universidad de Las Palmas de Gran Canaria (ULPGC), centro adscrito al CSIC (Unidad *Océano y Clima*). En este Grupo se desarrollan dos líneas en las que se inserta plenamente esta investigación: i) costas de las islas volcánicas: procesos naturales e interacciones humanas; y ii) sistemas sedimentarios eólicos costeros áridos: procesos naturales e interacciones humanas.

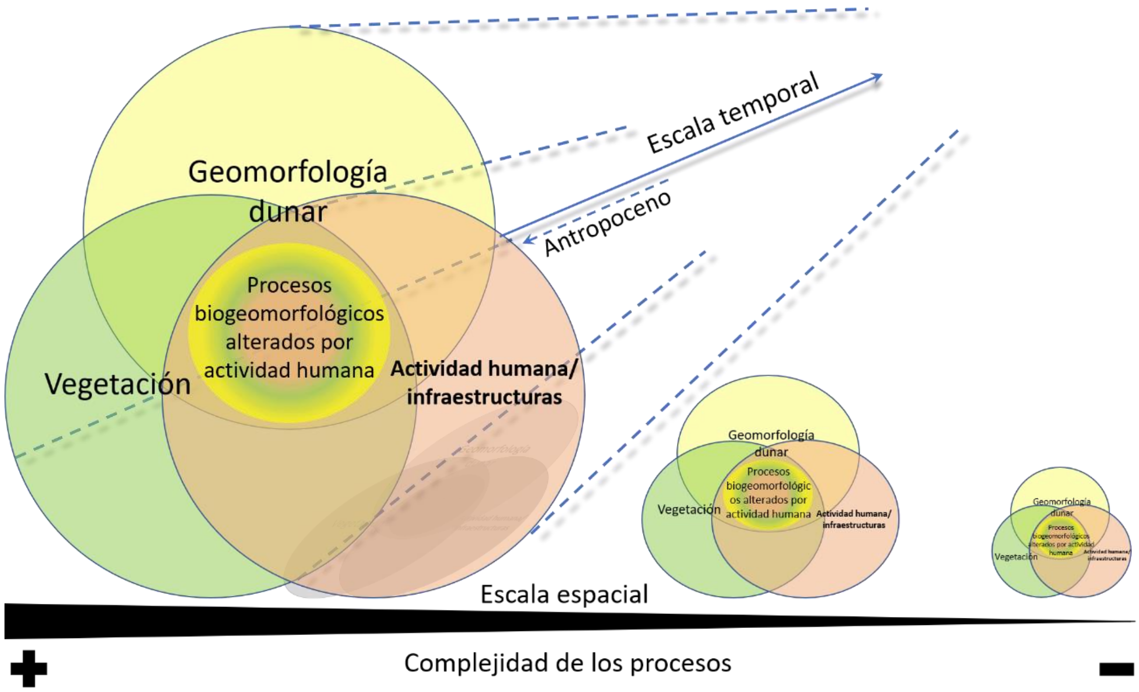

Figura 1. Ejes temáticos y escalas utilizadas en la investigación

A diferencia de lo que sucede en la mayoría de los archipiélagos de punto caliente intraplaca, las islas canarias presentan ciertas particularidades geodinámicas que se hacen palpables en la geomorfología de sus costas. Estas particularidades, conjuntamente con sus condiciones climáticas áridas, dan lugar a combinaciones de especial rareza a nivel mundial. Los resultados obtenidos en recientes estudios (Ferrer-Valero et al., 2019a, b) han observado en estas islas un claro patrón evolutivo de ambientes costeros, con incremento de la diversidad geomórfica costera y de la complejidad estructural con la edad de las islas. De esta forma, los sistemas sedimentarios eólicos, generalmente ausentes en islas oceánicas, están presentes, con cierta amplitud, en las costas de las islas canarias, especialmente en las más antiguas (Hernández-Cordero et al., 2019), lo que les otorga un alto valor, en el sentido de su exclusividad o rareza. Estos sistemas presentan la particularidad de que, debido al clima árido en el que se producen, su dinámica natural es elevada. También los efectos observables de las alteraciones que puedan sufrir se perciben más rápidamente que en los sistemas de dunas de las regiones templadas, más estudiados (Hernández Calvento et al., 2014; Hernández Cordero et al., 2018; 2019). Cabe añadir que la mayor parte de estos sistemas eólicos están protegidos por leyes de protección de la Naturaleza, como espacios naturales, tanto a nivel regional, como nacional o internacional. No obstante, la alta presión humana que soportan, induce alteraciones que, de cara a su óptima gestión, es necesario conocer, reconocer y enmendar. Los problemas detectados en estos sistemas áridos se han relacionado con alteraciones en los procesos geomorfológicos y en la vegetación (Hernández Calvento et al., 2014; Santana-Cordero et al., 2016a; Hernández Cordero et al., 2018; 2019, entre otros).

Los sistemas eólicos áridos de las islas canarias se han convertido, en las últimas décadas, en un laboratorio de investigación, a raíz del desarrollo de las líneas de investigación antes citadas. Con su desarrollo se pretenden identificar, entre otros aspectos, los procesos naturales característicos de estos sistemas, así como los alterados por las interacciones humanas. Los resultados de estos estudios están siendo publicados en revistas internacionales, así como en capítulos de libros de editoriales también internacionales. De igual forma, algunas de sus conclusiones están siendo útiles a la hora de gestionar estos sistemas, tanto como figuras de espacios protegidos, como en su vertiente de espacios de ocio. Un ejemplo de ello es el asesoramiento del Grupo de investigación anteriormente citado en el desarrollo del proyecto “MASDUNAS”, financiado por el Cabildo de Gran Canaria, que busca frenar el proceso de degradación ambiental que se ha ido produciendo durante los últimos 50 años en las Dunas de Maspalomas como consecuencia del uso desordenado de sus recursos. Es en este contexto en el que tiene cabida la perspectiva que se imprime desde esta investigación, en el que se tratan procesos en el campo de la biogeomorfología, es decir, procesos geomorfológicos y biogeográficos combinados, pero también en los que las actividades humanas son determinantes.

Es necesario aclarar en esta presentación que, debido a diferentes factores (tiempos de las revistas -revisiones, producción y publicación, financiación, campañas, estancias de investigación, etc.), el *corpus* de esta tesis se ordena de forma diferente al orden en el que han sido publicados los diferentes artículos que la conforman. Todos ellos han sido, no obstante, planteados y trabajados dentro de la fase de doctorado y, entre todos, estructuran el argumento que aquí se presenta.

Procesos geomorfológicos en sistemas dunares costeros áridos

Los principales factores que favorecen el desarrollo de los procesos geomorfológicos en sistemas dunares costeros en condiciones naturales (sin impacto humano) son: i) la disponibilidad de sedimentos susceptibles de ser movilizados por el viento; ii) la movilidad/transporte por deriva marina a lo largo de la costa; iii) la formación de acumulaciones sedimentarias en la costa (playas); y iv) condiciones topográficas y climáticas favorables para el transporte eólico (Hernández-Cordero et al., 2019). Por lo tanto, los sistemas de dunas litorales se localizan en la interfaz entre ambientes continentales y marinos, aunque el resultado de las interrelaciones entre los factores anteriormente señalados no responde a un patrón fijo. De esta forma, los sistemas de dunas presentan notables diferencias geomorfológicas, ecológicas y climáticas, lo que dificulta establecer una definición única para estos espacios (Hesp y Martínez, 2007).

Las características de los sistemas dunares, a escala global, en condiciones naturales, están directamente relacionadas con el clima que, a su vez, varía con la latitud (Figura 2, B), y con los suministros de sedimento disponibles (Hesp, 2004; Pickart and Hesp, 2019). En las regiones áridas, la escasez de precipitaciones condiciona los procesos geomorfológicos eólicos, limitando el desarrollo de la vegetación, por estrés hídrico, y favoreciendo el transporte sedimentario eólico a lo largo de todo el año (Hernández-Cordero et al., 2019).

La escasa densidad de la vegetación en estos sistemas áridos hace que en ellos predominen las "nebkhas", especialmente en las foredunes. Cuando la entrada de sedimentos es abundante y los vientos constantes, el transporte eólico tierra adentro se ve favorecido, desarrollándose sistemas de dunas transgresivos, de acuerdo con la clasificación de Hesp y Walker (2013). Estos autores diferencian dos tipos de sistemas de dunas transgresivos: i) transgressive dune sheets (cuando los aportes de sedimentos son escasos) y ii) transgressive dunefields (cuando los aportes de sedimentos son abundantes). Ambos tipos de sistemas se manifiestan en las costas de las islas canarias (Hernández-Cordero et al., 2019). También en las islas existen sistemas de dunas antiguos (fósiles) que pueden presentar puntual y localmente, procesos sedimentarios eólicos activos, debido a la erosión de eolianitas y la removilización y acumulación de sedimentos (Alonso et al., 2011).

El rol de la vegetación en la geomorfología dunar costera

La distribución de la vegetación en el planeta está determinada, en gran medida, por el clima (Von Humboldt y Bonpland, 1807; De Candolle, 1855; Woodward 1987). La vegetación, a su vez, produce cambios complejos en los procesos de la superficie de la Tierra y en las formas terrestres, hecho que sucede desde el mismo momento en que la vegetación comenzó a colonizar las superficies emergidas (Murray et al., 2008; Davies y Gibling, 2009, 2010). Desde esta perspectiva biogeomorfológica, son evidentes las relaciones que se producen entre determinados tipos de especies vegetales y determinadas geoformas. Este hecho es especialmente palpable en las foredunes de los sistemas de dunas litorales. La foredune se localiza en la playa alta de las zonas de entrada de sedimentos. Constituyen ambientes caracterizados por la formación de acumulaciones sedimentarias inducidas por la interacción de las plantas con la dinámica sedimentaria eólica. Dependiendo de las condiciones climáticas, la vegetación varía, desde plantas herbáceas hasta árboles. En consecuencia, también las foredunes presentan diferencias, pudiendo estar formadas por cordones dunares o por nebkhas (Hesp, 2002). Estas últimas se forman con un balance de arena positivo, energía eólica moderada y una escasa cubierta vegetal (Pye, 1990). Las relaciones en la foredune entre suministro de sedimento, vegetación y transporte sedimentario repercuten en las características del resto del sistema sedimentario eólico. Cosiderando estos antecedentes, se explican, a continuación, algunos ejemplos de la relación entre la morfología de especies vegetales y las geoformas que desarrollan, de acuerdo con la distancia al Ecuador. Así, en las zonas templadas, las especies de plantas que pueden formar foredunes continuas o discontinuas (alineaciones de nebkhas paralelas a la playa) son herbáceas y glicofitas perennes rizomatosas, muchas de ellas gramíneas, como *Elymus farctus*, *Ammophila spp.*, *Spinifex sericeus* o *Austrofestuca littoralis*. En general, si las dunas comienzan como nebkhas, pueden crecer en anchura y altura, fusionarse con otras nebkhas y conformar cordones continuos o barreras (Hesp, 2002; Hesp y Walker, 2013; Keijsers et al., 2015). Por ejemplo, *Desmoschoenus spiralis* muestra, en Nueva Zelanda (zona templada), tolerancia al enterramiento por arena y, dada su morfología, captura y acumula arena para la formación de una foredune continua (Holland, 1981). Sin embargo, en las zonas áridas, son normalmente especies leñosas arbustivas las que forman foredunes de tipo nebkha. Estas especies son principalmente halófilas, adaptadas a la falta de agua dulce y a la presencia de suelos con alta salinidad, como *Traganum moquinii*, *Zygophyllum spp.*, *Suaeda spp*, *Salsola spp*. (Hernández -Cordero et al., 2015, 2017). En estos casos, las dimensiones de los arbustos condicionan la morfología de las nebkhas (El-Bana et al., 2002). En las costas de islas canarias el clima es árido y *Traganum moquinii* es la especie vegetal predominante, formando nebkhas aisladas y campos de nebkhas. *Traganum moquinii,* es una especie nanofanerófita (arbustiva), que presenta compatibilidad con el enterramiento de arena (Hernández-Cordero et al., 2012), siempre que éste se produzca de forma progresiva (Viera-Pérez, 2015). Finalmente, en las costas tropicales, las foredunes normalmente se caracterizan por la presencia de dunas parabólicas o cordones continuos (Doing, 1985), siendo plantas rastreras las especies vegetales características, como *Ipomaea pes-caprae* o *Canavalia rosea* (Arun et al., 1999) o especies vegetales no leñosas rizomatosas, como *Scaveola plumieri* (Pammenter, 1983).

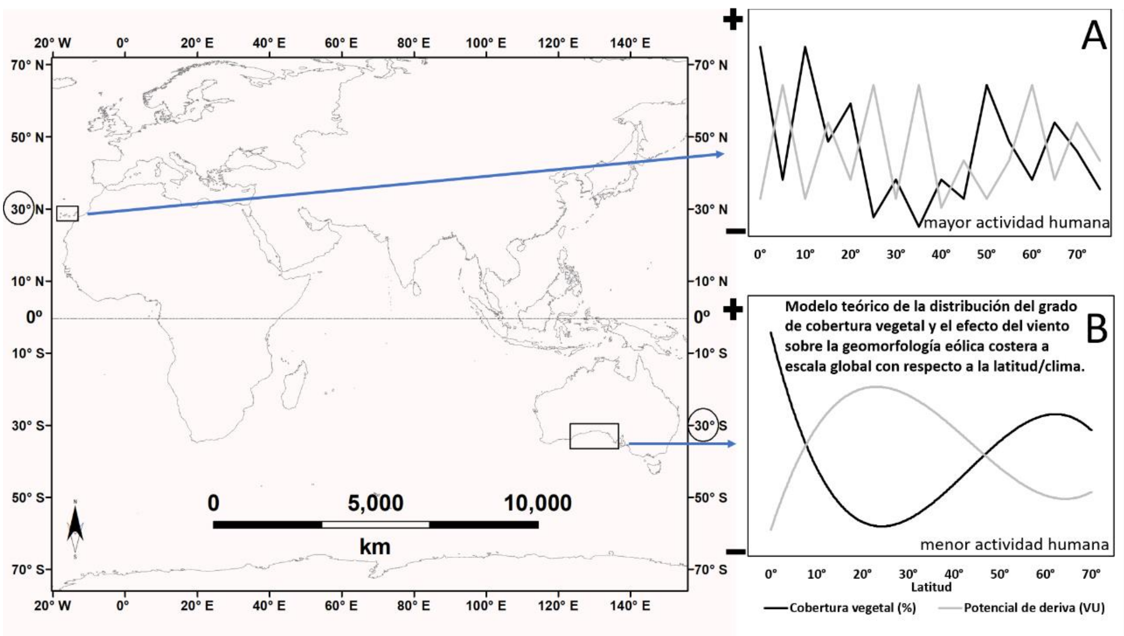

Figura 2. Distribución teórica de la cobertura vegetal y efecto del viento sobre la geomorfología éolica costera a escala global. A. Modelo con mayor impacto humano. B Modelo con menor impacto humano.

Clima y turismo: una combinación que produce impactos ambientales en sistemas costeros áridos

El clima contribuye a las condiciones ambientales que facilitan o dificultan el asentamiento humano, de modo que las personas buscan aquellos espacios que ofrecen una mayor comodidad y posibilidad de supervivencia en términos de clima (Martín, 2005). El turismo, como actividad humana, se rige por estos mismos principios. Por lo tanto, el clima es un criterio importante para el desarrollo de un destino turístico, siendo determinante a la hora de definir cómo se utiliza un área o lugar (Martín, 2005). Por este motivo, el clima delimita zonas óptimas para el turismo a escala global y regional, como lo ilustra la zona templada cálida, considerada óptima para el turismo de sol y playa (Burton, 1991; Soneiro-Callizo, 1991; Lozato Giotart, 1990; Vera et al., 1997). A niveles locales también influyen otros factores en el desarrollo del turismo (Martín, 2005).

Los sistemas de dunas ejercen, de forma natural, un papel determinante en la protección de las costas, entre otras razones por conformar una barrera protectora ante la erosión marina. Pero también por el atractivo paisajístico que supone el conjunto de los elementos que los forman, ofreciendo al mismo tiempo una gran diversidad de ecosistemas (Miththapala, 2008).

No obstante, las dunas costeras han sido históricamente objeto de explotación para la extracción de recursos. En las últimas décadas, con el desarrollo del proceso de litoralización actual, el cual implica la amplia ocupación de zonas litorales por parte de los humanos, la presión antrópica, a través de procesos urbanizadores, ha acelerado la degradación de estos sistemas y, en algunos casos, la destrucción de los ecosistemas propios de los campos de dunas, como ha sido el caso de Europa (Paskoff, 1993; European Enviromental Agency, 2006). Así, se han producido, y se producen, numerosas acciones que contribuyen a la degradación de estos ámbitos litorales. Entre ellas caben destacar la ocupación antrópica de cuencas hídricas o áreas costeras que abastecen de arena a los sistemas de dunas, la ocupación física de estos sistemas, la realización de vertidos en ellos o la extracción de áridos (De Andrés y Gracia, 2002; Del Rio y Malvárez, 2017). Esto da como resultado un funcionamiento inestable de los sistemas de dunas, así como una pérdida de bienestar, como consecuencia de los cambios ocasionados por los conflictos entre el desarrollo y la conservación (Nordstrom et al., 2000).

El turismo predominante en las islas canarias es de masas de sol y playa. Una de sus peculiaridades es que es constante a lo largo del año, debido al clima favorable, por lo que no existen periodos de reposo en el que los sistemas sedimentarios éolicos (áridos, en el caso de Canarias) puedan recuperarse de los impactos generados por los usuarios (Cabrera-Vega et al., 2013). También la mayor parte de las infraestructuras alojativas están localizadas en el entorno de las playas y las dunas. Sin embargo, los altos valores geológicos, geomorfológicos, florísticos y faunísticos que tienen los sistemas de dunas de las islas canarias determianan que la mayoría de los mismos están protegidos por figuras internacionales (UNESCO, Unión Europea), nacionales y autonómicas, como Reservas de la Biosfera, Zonas Especiales de Conservación (ZEC), Zonas de Especial Protección para las Aves (ZEPA) y distintas figuras dentro de la Red de Espacios Naturales Protegidos (Parques Naturales, Parques Rurales, Reservas Naturales, Monumentos Naturales y Sitios de Interés Científico). En este sentido, Canarias es un claro ejemplo donde se produce un importante conflicto entre el desarrollo y la conservación en torno a sus sistemas sedimentarios éolicos.

Impactos ambientales en los sistemas sedimentarios eólicos costeros

Si las dinámicas naturales que se dan en los sistemas sedimentarios eólicos son alteradas por factores naturales o antrópicos, se producen cambios en los procesos geomorfológicos y en los ecológicos (procesos biogeomorfológicos). De esta forma, pasaríamos del modelo teórico mostrado en la figura 2B al escenario mostrado en el modelo teórico de la figura 2A, en el que el funcionamiento de los sistemas playa-dunas dejan de mostrar una relación directa con variables climáticas, como plantea Tsoar (2005). En este sentido, se han podido comprobar cambios en los procesos geomorfológicos de sistemas sedimentarios eólicos por actividades tradicionales, como las relacionadas con el pastoreo, la obtención de leña o la agricultura (Tsoar & Blumberg, 2002; Kutiel et al., 2004; Levin & Ben-Dor, 2004; Santana-Cordero et al., 2016a), y por usos más recientes, acompañados de una falta de gestión y planificación ambiental, que ha posibilitado extracciones de áridos o construcciones de infraestructuras turísticas o de usos recreativos insostenibles en las inmediaciones de estos sistemas (Nordstrom & McCluskey, 1985; Nordstrom, 1994; Nordstrom, 2004; Cabrera-Vega et al., 2013; Hernández-Calvento et al., 2014; Smith et al., 2017; Delgado-Fernández et al., 2019). Los resultados se resumen en transformaciones en la geomorfología propia de los sistemas sedimentarios eólicos (Cabrera-Vega et al., 2013; Hernández-Cordero et al., 2018), el avance de las comunidades de plantas exóticas invasoras (Kim, 2005; Jørgensen & Kollmann, 2009; Kollmann et al., 2009), la reducción de las plantas pioneras en las dunas móviles y la reducción de la riqueza de especies (Kutiel et al., 1999; Curr et al., 2000; Hesp et al., 2010; Dolnik et al., 2011; Faggi & Dadon, 2011), la removilización de los sedimentos (Arens et al., 2013; Cabrera-Vega et al., 2013; Martínez et al., 2013; Santana-Cordero et al., 2016a), el incremento de los procesos de erosión (Angassa, 2014) y el cambio en la dirección y/o velocidad del flujo de viento y, por lo tanto, en el transporte sedimentario eólico (Hernández Calvento et al., 2014; Smith et al., 2017). Estos comportamientos que se han querido resumir, para el caso de las islas canarias, en el modelo mostrado de la figura 3B. Sin embargo, también se ha podido detectar sistemas sedimentarios con cambios ambientales poco significativos, coincidiendo con un desarrollo urbano-turístico prácticamente inexistente, como el sistema de Lambra (norte de la isla de La Graciosa), que presenta un comportamiento similar al modelo mostrado en la figura 3A (que se explica detalladamente en el segundo artículo de la sección "Artículos") o el sistema del Cotillo-Tostón, en la isla de Fuerteventura (Alonso et al., 2004).

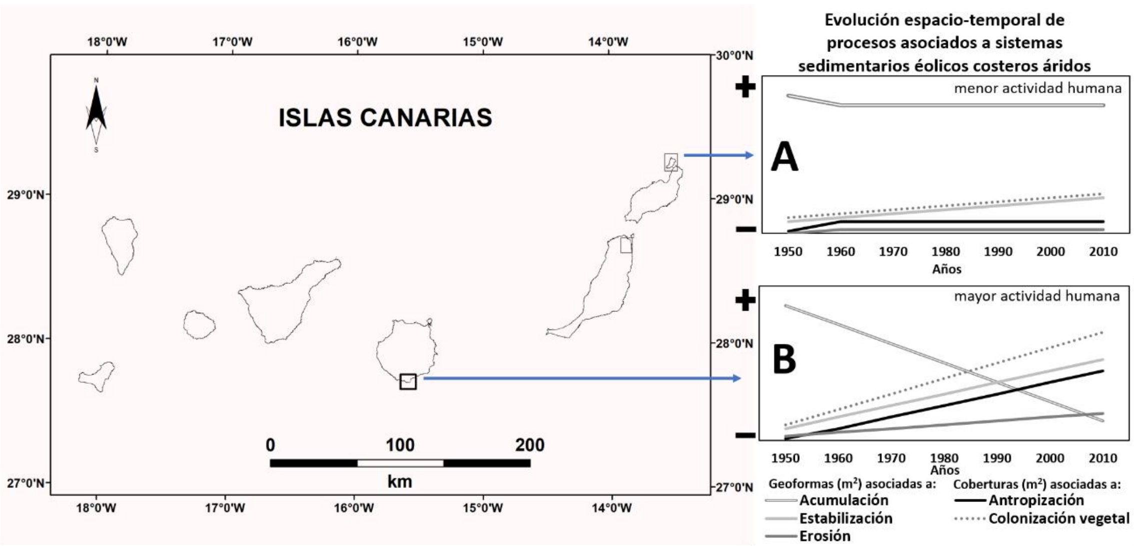

Figura 3. Evolución espacio-temporal de procesos asociados a sistemas sedimentarios eólicos costeros áridos en Canarias. A. Cambios en los procesos sedimentarios ante un escenario con menor actividad humana. B. Cambios en los procesos sedimentarios ante un escenario con mayor actividad humana.

En cuanto a los impactos debidos a la construcción de infraestructura turística o al desarrollo de usos recreativos insostenibles, la alteración de estos sistemas ha sido estudiada en relación con el tránsito de vehículos (Hernández, 2006), las extracciones de áridos (Sanjaume y Pardo, 1991), la presión causada por los visitantes o la desaparición de estos sistemas debido a su artificialización (Paskoff, 1993), así como la utilización de parcelas para desarrollar otros usos recreativos cercanos a las orillas (Fernández y Neves, 1997). Todo ello ha supuesto procesos de fragmentación paisajística y de los propios ecosistemas (Berlanga-Robles y Ruiz-Luna, 2002), la pérdida de hábitats naturales y la reducción de la diversidad biológica (Beatley, 1991). A ello se suma la pérdida del valor intrínseco, relacionado con la dinámica espacial y temporal de los sistemas de dunas (Nordstrom et al., 1990), la desaparición del valor paisajístico y recreacional con el que contaba estos sistemas anteriormente (Cruz, 1996; Demirayak y Ulas, 1996) o la pérdida de patrimonio (Nordstrom et al., 2000). La construcción de grandes urbanizaciones y equipamientos turísticos ha generado importantes impactos ambientales en los sistemas de dunas de Canarias, como en Maspalomas (Gran Canaria), Corralejo (Fuerteventura) o El Jable (Lanzarote) (Hernández Calvento, 2006; Alonso et al., 2011; Fernández-Cabrera et al., 2011; Cabrera et al., 2013; Malvárez et al., 2013; Hernández-Calvento et al., 2014). Desde esta perspectiva, se puede considerar que los sistemas de dunas suelen ser espacios en los que coexisten multitud de conflictos. El desarrollo de éstos suele conllevar la desestabilización de la foredune, geoforma que se comporta como pilar fundamental para el buen funcionamiento del resto del sistema sedimentario eólico (Bauer y Sherman, 1999). El escenario que obtenemos, por lo tanto, con el desarrollo de las actividades humanas en torno a estos sistemas, es de un aumento de inestabilidad y vulnerabilidad ante los agentes erosivos (Fernández y Neves, 1997). En la figura 4A se muestra un modelo teórico de cómo podrían comportarse las variables biogeomorfológicas a mayor escala ante una reducida actividad humana. Por su parte, en la figura 4B, se muestra un modelo basado en los resultados obtenidos en esta investigación (explicado con más detalle en los artículos cuarto, quinto y sexto de la sección “Artículos”), donde se observa un declive del estado ambiental del sistema playa-duna de Maspalomas, un sistema altamente antropizado.

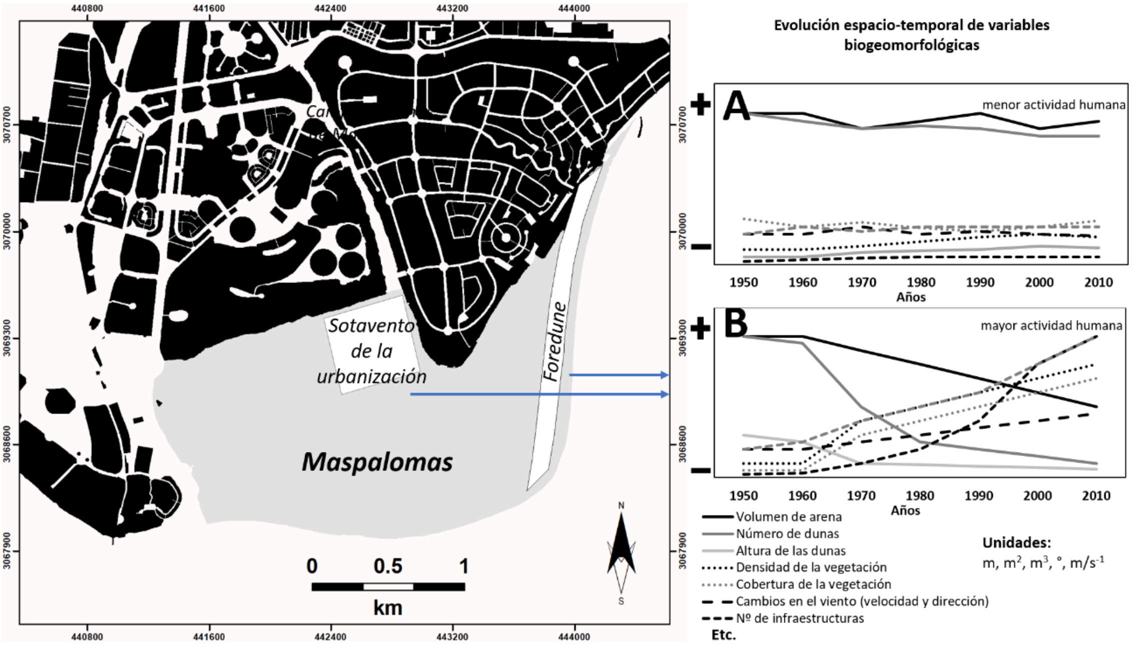

Figura 4. Cambios espacio-temporales de variables biogeomorfológicas en las dunas de Maspalomas (Gran Canaria, islas Canarias) en la foredune y a sotavento de las urbanizaciones. A. Evolución de variables biogeomorfológicas ante un escenario con menor actividad humana. B. Evolución de variables biogeomorfológicas ante un escenario con mayor actividad humana.

Para cambiar, disminuir o incluso eliminar este tipo de conflictos, es necesario conocer las dinámicas naturales, y trabajar con ciertas pautas o herramientas que permitan planificar estas zonas con criterios de sostenibilidad, posibilitando el funcionamiento de los procesos naturales. Para ello, cualquier iniciativa de gestión debe ser estudiada desde un punto de vista sostenible, entendiendo la complejidad de los procesos a partir del uso de diferentes escalas espacio-temporales y, además, teniendo en cuenta o añadiendo las posibles transformaciones inducidas por el actual cambio climático (MARM, 2008).

Hipótesis y objetivos

Hipótesis de investigación

Las hipótesis en las que se basa esta investigación son tres:

- A escala global, el clima controla la distribución espacial de los tipos de foredune en los sistemas sedimentarios eólicos costeros.
- Los procesos biogeomorfológicos en los sistemas sedimentarios eólicos costeros áridos de Canarias han experimentado, en las últimas décadas, distintos cambios, inducidos por actividades antrópicas, lo que ha afectado a la estabilidad sedimentaria de estos sistemas y ha roto patrones biogemorfológicos relacionados con el clima.
- El estudio de la distribución espacial de la cobertura vegetal, su relación con la geomorfología dunar y los cambios espacio-temporales a diferentes escalas, permitiría analizar e interpretar el estado de la dinámica sedimentaria eólica de los sistemas dunares de Canarias. Para ello se hace necesario la búsqueda de variables objetivas que se adapten a diferentes escalas de trabajo.

Objetivo general y específicos

El objetivo principal de esta investigación es **definir procesos multiescalares, naturales e inducidos por actividades humanas, relacionados con la geomorfología y la vegetación en sistemas sedimentarios eólicos costeros de Canarias, como modelo de sistemas sedimentarios eólicos costeros de regiones áridas**.

Este objetivo general se divide en seis objetivos específicos:

1. Determinar si en el actual contexto del Antropoceno, el clima y, especialmente, la lluvia, es un factor de control que determina la distribución

de tiposde foredune (i) cordones continuos o discontinuos; ii) nebkha). El desarrollo de este objetivo implica la caracterización de las foredunes a lo largo de Great Australian Bight (GAB), considerada una de las zonas costeras más remota y menos antropizada del planeta (Edyvane et al., 2004).

2. Establecer si existe una relación directa entre el desarrollo de procesos biogeomorfológicos y actuaciones humanas en sistemas sedimentarios eólicos costeros áridos. Para ello se propone analizar los cambios decadales ocurridos en cuatro sistemas sedimentarios eólicos de las islas canarias, con distinto grado de antropización: Maspalomas (Gran Canaria), Corralejo (Fuerteventura), Lambra y Jable Sur (La Graciosa).
3. Desarrollar un procedimiento automatizado simple para calcular la densidad de la vegetación en sistemas sedimentarios eólicos áridos, basado en el concepto de densidad por distancia entre individuos vegetales. Para ello se propone utilizar canales visibles de ortofotos digitales actuales, con el fin de facilitar análisis comparativos/diacrónicos con los resultados obtenidos tras la aplicación del método a fotografías aéreas históricas en blanco y negro.
4. Analizar procesos biogeomorfológicos, alterados por el desarrollo urbano-turístico, en sistemas sedimentarios eólicos costeros áridos. El área de estudio, en este caso, es una zona de sombra eólica dentro de un campo de dunas transgresivo árido (Maspalomas, Gran Canaria), donde se cortó el suministro de sedimentos tras la construcción de la urbanización Playa del Inglés.
5. Analizar y caracterizar de forma experimental procesos eólicos alterados por la acción humana. Para ello se plantea relacionar los flujos de viento locales con la topografía, la vegetación y la distancia a las edificaciones en la zona de sombra eólica inducida por el complejo Playa del Inglés.

6. Analizar, desde una perspectiva decadal, en 2 dimensiones, la relación entre las características morfológicas de una especie vegetal y cambios morfométricos en la zona de foredune de un campo de dunas transgresivo árido alterada por los usuarios y servicios de playa. El sistema elegido, en este caso, es la playa del Inglés (Maspalomas) y la especie vegetal *Traganum moquinii*.

En conjunto, el propósito de esta investigación es analizar los procesos biogeomorfológicos que ocurren en los sistemas sedimentarios eólicos costeros áridos a través de diferentes escalas espacio-temporales y situaciones con mayor o menor presencia de actividades humanas. Se presenta como una secuencia de investigación: i) a menor escala (continental/global) y con una menor actividad humana, se muestra la distribución del tipo de foredune/campos de dunas transgresivos, y su relación con el clima en una de las zonas más remotas del mundo, la Gran Bahía Australiana (GAB). Se comprueba las caraceterísitcas climáticas para la formación de sistemas dunares transgresivos y sus foredunes, atendiendo especialmente a las de tipo "nebkha". Ello permite contextualizar como este tipo de foredune, ampliamente representada en Canarias, es propia de otras regiones (incluso en el hemisferio sur) con precipitaciones similares; ii) en segundo lugar se trabaja a escala regional y a "long-term", estudiando cuatro sistemas sedimentarios eólicos costeros áridos de Canarias con distinto grado de presión antrópica en su entorno, desde espacios donde construcciones urbano-turísticas se concentran en torno a las entradas de sedimentos que los abastecen, hasta otros donde estas interacciones no se producen; iii) ante la necesidad de buscar variables que permitieran analizar el estado de los sistemas sedimentarios eólicos costeros áridos a diferentes escalas, se presenta un procedimiento para calcular la densidad de la vegetación a través del concepto de "densidad por la distancia entre individuos vegetales", debido a la importancia de la distancia entre la vegetación para el transporte sedimentario. Para su desarrollo se utilizan bandas del espectro visible de ortofotos de alta resolución para aplicar el procedimiento en fotografías aéreas históricas que se puedan utilizar para realizar estudios evolutivos.; iv) a mayor escala espacial, combinando escalas temporales "long-term" y "short-term", se tomó como ejemplo un sistema (Maspalomas) alterado por los usuarios del sistema playa-duna, como por las construcciones urbano-turísticas. A esta escala se analiza procesos biogeomofológicos inducidos por tales actividades. Las zonas de estudios concretas son la zona de sombra eólica de la terraza-urbanización Playa del Inglés indentificada por Hernández-Calvento et al. (2014) y por Smith et al. (2017). y la zona de foredune, de tipo "nebkha", del backshore de la playa del Inglés.

Metodología

La metodología se explica de forma detallada en cada uno de los artículos que componen la presente Tesis Doctoral. En este apartado se ha querido realizar un repaso por los aspectos comunes y planteamientos más importantes de la misma (Figura 5), los cuáles, en muchas ocasiones, son difíciles de tratar en el formato de un artículo.

Las escalas y complejidad para estudiar los cambios en procesos biogeomorfológicos

El concepto "espacio por tiempo" (space-for-time substitution) (Pickett, 1989) constituye una de las premisas fundamentales en la presente Tesis Doctoral. Este concepto plantea que la variación espacial es equivalente a la variación temporal a la hora de inferir cronosecuencias de largo plazo mediante la comparación de muestras de diferente edad o estado de desarrollo. Así, en esta investigación se infieren los rasgos de la evolución de los procesos biogeomorfológicos, a largo y corto plazo, mediante observación indirecta, o aproximación estática. Picket (1989) advierte sobre las limitaciones de este concepto a la hora comprender los mecanismos en escalas inferiores, pero lo recomienda por su potencial para establecer marcos conceptuales e hipótesis generales en estudios experimentales y en observaciones directas. Por otro lado, las metodologías convencionales utilizadas en la investigación geomorfológica, en general, y en la investigación sobe geomorfología eólica costera, en particular, dependen de la escala espacial (Carter y Woodroffe, 1994; Sherman, 1995; Phillips, 1999). Con base en esto, se pueden presentar problemas cuando se intentan extrapolar los hallazgos de una escala a otra (ya sea temporal o espacial) (Cooper y Pilkey, 2004). Por esta razón, dependiendo de los objetivos que se proponen en esta investigación, se han utilizado diferentes escalas espaciales y temporales y, al mismo tiempo, se han ido adaptando las metodologías en cada trabajo publicado. Las primeras cuestiones planteadas fueron saber qué y cuántas variables eran necesarias para analizar los cambios de los procesos biogeomorfológicos, y si estos cambios estaban relacionados con el grado de actividad humana.

En este sentido, a escala continental (lo que nos puede acercar a un modelo "Global"), se plantea el primer artículo. Diversos estudios proporcionan evidencias de que los cambios climáticos y la mayor presencia de actividad humana tienen un efecto sobre los cambios ambientales en sistemas sedimentarios eólicos costeros (Lancaster, 1988; Muhs and Maat, 1993; Wiggs et al., 1995; Meir and Tsoar, 1996; Stetler and Gaylord, 1996; Wolfe, 1996; Bullard et al., 1997; Lancaster, 1997; Lancaster and Helm, 2000; Muhs et al., 2003; Hugenholtz and Wolfe, 2005; Thomas et al., 2005; Yizhaq et al., 2007; Tsoar et al., 2009). Por ello, para el desarrollo del quinto trabajo publicado, se eligió una zona (la GAB, Australia) donde la actividad humana es reducida. De esta forma, se podía comprobar si el clima se relaciona con las características ecológicas, al menos, de la foredune. Dada la amplitud de la zona de estudio, las escalas espacial y temporal presentan el menor detalle. Téngase en cuenta que se trata de una zona que, no solamente se distribuye a través de varios grados de latitud y longitud, sino que es un claro ejemplo de lugar remoto y con baja presión antrópica, lo que se traduce en que sea un área que carece de fuentes de información espacial de detalle. En este sentido, es obligatorio adaptarse a variables menos precisas, pero que han ofrecido información valiosa de cara a abrir nuevas perspectivas de investigación. Por ese motivo se trabajó con datos continuos, como la longitud (m) - porcentaje (%) de línea de costa de la GAB que correspondía a cada tipo de foredune y donde se localizaban campos de dunas transgresivos (foredune mode), y superficiales (en m^2) para clasificar estos tipos de foredune. Por otro lado, se utilizaron datos discretos, como los tomados en las diferentes estaciones meteorológicas, inventarios de vegetación en parcelas de muestreo y muestras de sedimentos.

A escala regional (artículo 2) se analizaron, en primer lugar, cambios superficiales (en m^2) en geoformas y cobertura vegetal, utilizando para ello fuentes de información correspondientes a diferentes años. Los resultados permiten identificar cambios ambientales y considerar si éstos son producto del desarrollo urbano-turístico. Para ello las categorías geomorfológicas fueron clasificadas por procesos o indicadores, según su origen, es decir, si las variables se relacionan, según la bibliografía, con procesos de acumulación o erosión del sedimento, con la estabilización del sistema sedimentario eólico o con la antropización ambiental.

La predicción de las tasas de transporte de sedimentos eólicos sigue siendo un problema fundamental que dificulta los avances en múltiples disciplinas científicas, donde se incluyen la geomorfología, la geología, la agricultura, la meteorología o la climatología (Bauer et al., 1996; Baas, 2007, 2008; Kok et al., 2012; Ellis y Sherman, 2013). Los modelos, normalmente, tienen una capacidad predictiva baja, que difieren de las mediciones experimentales entre casos de estudio (Ellis y Sherman, 2013; Sherman et al., 2013, Kok et al., 2014). Esta situación ha fomentado nuevas investigaciones en un esfuerzo por mejorar la predicción a través de una mayor comprensión de la física del transporte (Anderson y Haff, 1988; Kok y Renno, 2009; Durán et al., 2011; Kok et al., 2012; Durán et al., 2012; Dupont et al., 2013; Pähtz et al., 2013). En este sentido, y con el objetivo de seguir profundizando en futuros trabajos, surge el tercer artículo, cuyo objetivo es la búsqueda de variables que puedan ser medidas de forma objetiva y remota a través del tiempo. Con ello se consegue aportar información de detalle, obteniendo variables/proxys, al obtener información directa de la vegetación y del transporte sedimentario eólico, pues este trabajo está basado en el concepto de densidad de vegetación por la distancia entre la vegetación.

A escala de detalle se plantea tres trabajos cuyo fin es medir procesos biogeomorfológicos en ámbitos afectados por actividades antrópicas (artículos 4, 5 y 6 -este último en proceso de publicación-), utilizando para ello variables específicas y mediciones *in situ*. Estas permitieron entender con más detalle los cambios experimentados en los procesos biogeomorfológicos en una zona de sombra eólica inducida por una urbanización, así como en una foredune con alta actividad humana, debido al elevado número de usuarios y servicios de playa. De esta forma, y a modo de ejemplo, en el primer artículo se plantean procesos de erosión y, a mayor detalle, se caracterizan zonas de deflación y un *trough blowout*, y se relaciona la recolonización vegetal con la proximidad del nivel freáticco a la superficie.

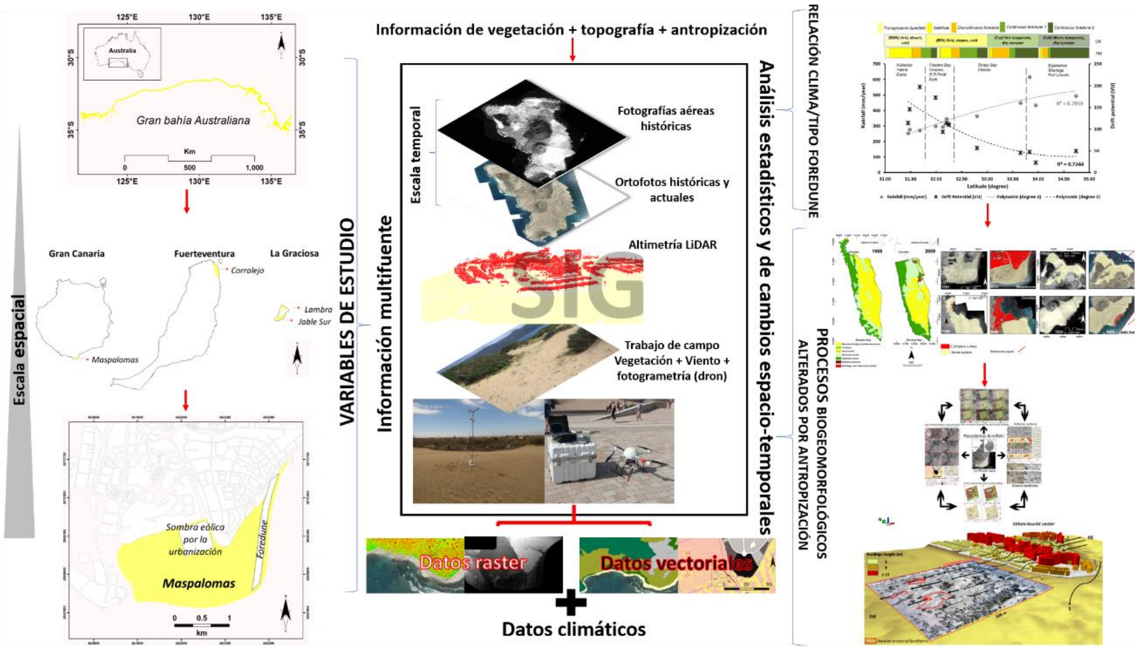

Figura 5. Flujo de trabajo y metodología general

Zonas de estudio. Justificación de la selección y características

Los estudios se realizaron en tres escalas espaciales:

Escala continental

La Gran Bahía Australiana (GAB)

En el contexto de esta Tesis Doctoral se planteó abrir nuevas perspectivas, de cara a contextualizar los sistemas sedimentarios eólicos costeros áridos de Canarias a nivel global. El objetivo era doble: i) por un lado, conocer qué procesos biogeomorfológicos tienen en común estos sistemas insulares con sus homónimos en otras regiones climáticas, incluso en el hemisferio austral; y ii) conocer qué sucede, en relación con los procesos biogeomorfológicos propios de estos sistemas sedimentarios eólios costeros áridos, cuando no se produce una importante actividad humana. Por este motivo se incluyó en la Tesis la Gran Bahía Australiana (GAB, atendiendo a sus siglas en inglés) (Figura 6). La GAB se extiende desde Esperance (Australia Occidental, 33° 51′40 ″ S 121° 53′31 ″ E) hasta Port Lincoln (Australia del Sur, 34° 43′56 ″ S 135° 51 ′31 ″ E), a lo largo de 2.668 km de costa, desde las latitudes 34° y 31° S, y las longitudes 121° y 135° E. Se trata del área más grande de sedimentación de carbonato frío en el mundo moderno (James, 1997) y de los lugares costeros que menos población por superficie tienen (Edyvane et al., 2004). Los sedimentos de la playa y las dunas del Holoceno son extensos en todo la GAB y están dominados por campos de dunas transgresivos de pequeña a gran escala, muchos de los cuales están activos. Los sistemas de calcarenitas y eolianitas se extienden hasta 80 km hacia el interior, con sistemas cada vez más complejos (Belperio et al., 1995). Estas eolianitas de Pleistoceno forman barreras relictas y acantilados marinos, islas dispersas y promontorios de rocas de minerales precámbricos que también se componen por capas de eolianitas parcialmente erosionadas.

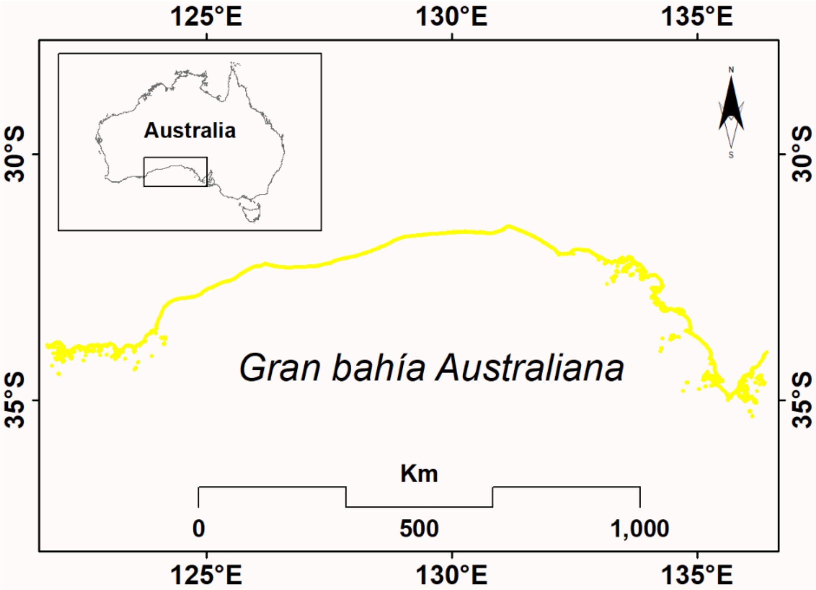

Figura 6. Localización de la Gran Bahía Australiana.

Escala regional

Esta escala se utilizó en la segunda fase de esta investigación. Para ello se tomaron 4 sistemas sedimentarios eólicos costeros de Canarias (Figura 7), con diferentes niveles de desarrollo urbano-turístico (Maspalomas, Corralejo, Lambra y Jable Sur). De ellos se extrajeron los cambios ambientales y los procesos sedimentarios eólicos (erosión, estabilización y acumulación) que mayor importancia habían tenido, dependiendo del nivel de desarrollo urbano turístico en torno a ellos (procesos de antropización).

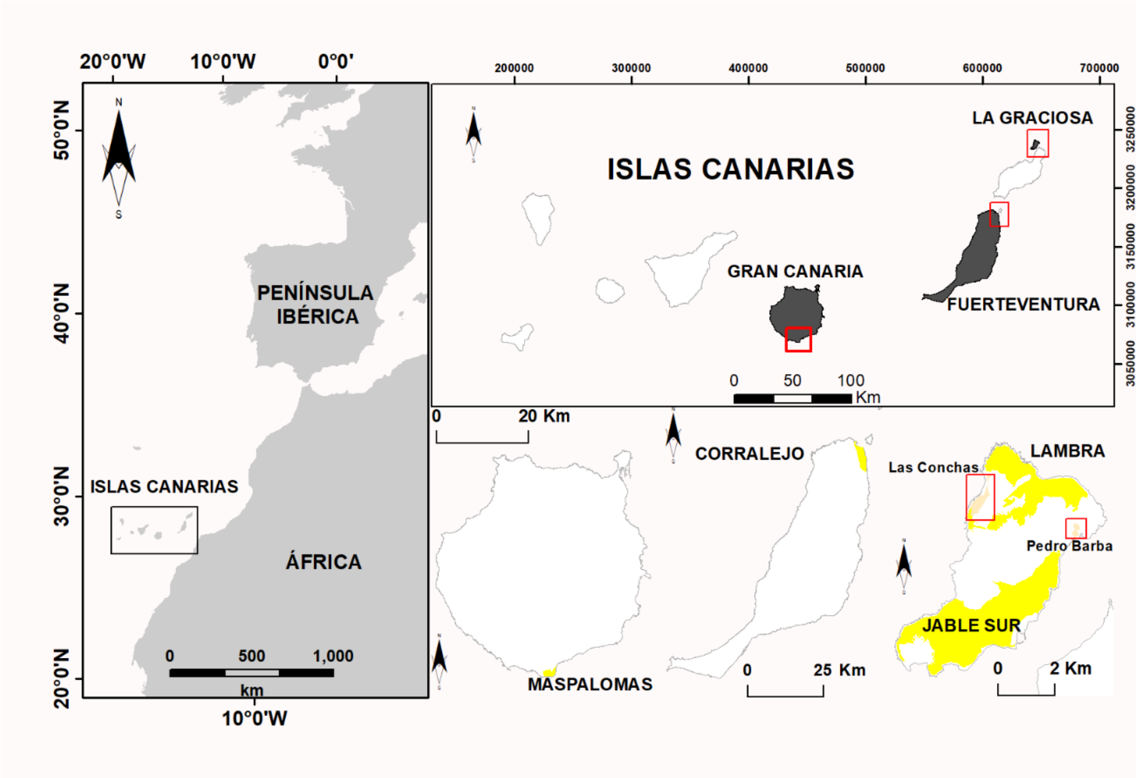

Figura 7: Zonas de estudios analizadas a escala regional. Sistemas sedimentarios eólicos costeros áridos representativos de las islas Canarias.

Maspalomas (Gran Canaria)

Esta zona de estudio, también utilizada para trabajar a escala local, tiene una superficie de 360,9 ha y se localiza en el sur de la isla de Gran Canaria. Según la clasificación de Hesp y Walker (2013), Maspalomas es un campo de dunas transgresivo. Los sedimentos acceden al sistema por su playa oriental (El Inglés) y son transportados hacia el SO por los vientos alisios, de componente E-NE (Hernández-Calvento, 2006). En este sistema se distingue tres zonas, según la actividad sedimentaria eólica asociada con formas terrestres específicas, que están condicionadas por el terreno circundante y el desarrollo turístico (Martínez, 1994; Hernández-Calvento, 2006): i) el área activa, donde las dunas libres, de hasta 14 metros de altura, predominan prácticamente desde la foredune (con nebkhas, principalmente) hasta el interior del sistema dunar y las áreas distales de la playa de

Maspalomas (con presencia de dunas barjanas, que en ocasiones se unen formando cordones barjanoides); ii) el área semi-estabilizada, formada por formas de relieve erosivas, como las superficies de deflación, y formas de relieve acumulativas, como dunas barjanas, láminas de arena y nebkhas; y iii) el área estabilizada, con presencia de dunas estabilizadas por vegetación y depresiones interdunares. La vegetación está caracterizada por 19 comunidades, siendo las de *Cyperus capitatus-Ononis serrata, Tamarix canariensis, Launaea arborescens, Suaeda mollis* y *Traganum moquinii* las que destacan por su importancia ecológica y geomorfológica (Hernández Calvento, 2006; Hernández-Cordero et al., 2015a).

Corralejo (Fuerteventura)

Localizado al norte de la isla de Fuerteventura, este sistema presenta un área de 1812.4 ha. Según la clasificación de Hesp y Walker (2013), al igual que Maspalomas, constituye un campo de dunas transgresivo, aunque solamente en su mitad sur. Dependiendo de la antigüedad de sus materiales, existen tres zonas (Fernández-Galván et al., 1982): el antiguo jable, el jable de arcilla y jable actual. Las dos primeras áreas se caracterizan por presentar dunas estabilizadas, mientras que el jable actual presenta dunas móviles (Criado, 1987). Según Criado (1987) esta última área se puede dividir en tres sectores: el de entrada de arena, el campo de dunas móvil y el de salida de arena al mar. Las dunas libres, como láminas de arena, dunas barjanas y cordones barjanoides, predominan en este jable actual, conjuntamente con nebkhas (Criado et al., 2007; Gutiérrez-Elorza et al., 2013; Malvárez et al., 2013). Las arenas acceden al sistema por el noreste y son movilizadas hacia el sur por los vientos alisios (Criado, 1987). Las principales comunidades de plantas son: la de *Traganum moquinii* (que se encuentra en la foredune y en las áreas de salida), las de *Euphorbia paralias*, *Ononis hesperia* y *Launaea* *arborescens* (en dunas móviles), y las de *Salsola vermiculata* y *Launaea arborescens* (en las dunas estabilizadas) (Fernández-Galvan et al., 1982; Fernández-Cabrera et al., 2011).

La Graciosa

Esta isla fue objeto de estudio en la segunda fase de la investigación, y también fue la zona de estudio escogida para la tercera publicación (tercera fase de la investigación) que conforma esta Tesis Doctoral. En la segunda publicación se añadieron los sistemas sedimentarios eólicos de Pedro Barba y Las Conchas, con el fin de testear el procedimiento presentado, aunque estos no fueron estudiados a escala regional, debido a que se escogieron aquellos que presentaban una mayor superficie (Lambra y Jable Sur). La isla de La Graciosa (27.05 km^2) se encuentra en el noreste del archipiélago canario (Figura 7). Se asienta sobre una plataforma marina cuaternaria, formada como resultado de la emisión de material volcánico durante el Pleistoceno superior y el Holoceno (De La Nuez et al., 1997). Procesos sedimentarios cuaternarios dieron lugar a depósitos de tierra y arena que actualmente están ligeramente cementados (eolianitas) (Ortiz et al., 2006; Meco et al., 2006). Desde el Holoceno hasta la actualidad, una parte significativa de la isla (13,96 km^2) ha sido cubierta con depósitos sedimentarios eólicos de espesor variable. Las arenas son organógenas medio-gruesas (>75% de granos bioclásticos, con abundantes fragmentos de malla de algas corallináceas, y con un contenido de carbonato >84%), según Mangas et al. (2012).

Lambra

El sistema de Lambra fue escogido al no presentar un desarrollo urbano-turístico en su entorno. Lambra está localizada en el norte de la isla de La Graciosa y presenta una superficie de 401.1 ha. Siguiendo la clasificación de Hesp y Walker (2013), Lambra es una lámina de arena transgresiva. Predominan las dunas estabilizadas y nebkhas y, en menor medida, también aparecen láminas de arena. En este sistema se identifican nueve comunidades de plantas (Pérez-Chacón et al., 2010; Hernández-Cordero et al., 2015b): las comunidades de *Salsola vermiculata*, *Traganum moquinii*, *Launaea arborescens*, *Suaeda vera*, *Polycarpaea nivea*, *Frankenia comunidad ericifolia*, *Chenoloides tomentosa*, *Astydamia latifolia* y *Mesembryanthemum nodiflorum*.

Jable Sur

Jable Sur cubre el sur de la isla de La Graciosa, con un área de 868.7 ha. De acuerdo con la clasificación de Hesp y Walker (2013), este sistema también es una lámina de arena transgresiva. Predominan las dunas estabilizadas y nebkhas. Se han identificado once comunidades de plantas (Pérez-Chacón et al., 2010; Hernández-Cordero et al., 2015b): *Salsola vermiculata, Traganum moquinii, Launaea arborescens, Ononis serrata, Euphorbia paralias, Ononis hesperia, Cakile maritima, Plantago coronopus, Euphorbia regis-jubae, Mesembryanthemum crystallinum* y *Mesembryanthemum nodiflorum*.

Escala local

Maspalomas. Otras peculiaridades

A continuación, se explica con mayor detalle la zona de estudio que se utilizó en la cuarta fase de la investigación (artículos 4, 5 y 6 -aún sin publicar-), cómo funciona y qué ha ocurrido para mostrar por qué finalmente escogimos uno de los sistemas sedimentarios más estudiados de Canarias.

Una de sus características geomorfológicas más relevantes de Maspalomas (Figura 8) es la existencia de una terraza alta (>20 m.s.n.m.) pleistocena, que se adentra en el sistema de dunas, en forma de cuña, en su límite nororiental. Desde la década de los sesenta del siglo pasado se ha venido construyendo, sobre esta terraza, uno de los mayores complejos turísticos de España (Domínguez-Mujica et al., 2011). Éste hecho ha alterado el flujo de viento y, con ello, el transporte sedimentario (Hernández-Calvento et al., 2014; Smith et al., 2017), dando lugar a tres zonas geomorfológicas diferentes: por un lado, se detecta una zona de aceleración, al sur de la terraza; por otro, se identifican dos zonas de desaceleración, con distinto grado de estabilización sedimentaria y aumento de la cobertura vegetal (Hernández-Cordero et al., 2017). En la zona de sombra eólica (a sotavento de la citada terraza), se detectó, en 2014, una geoforma erosiva, tipo cubeta de deflación (*blowout*), cuyos rasgos generales han sido descritos y comparados con otras geoformas semejantes en condiciones ambientales diferentes (Mir- Gual et al., 2015). Esta geoforma estaría explicando que la paralización de los procesos sedimentarios eólicos no es total en este sistema, debiendo existir procesos de transporte activos, cuestión que se trata en los artículos 4 y 5 de esta Tesis Doctoral.

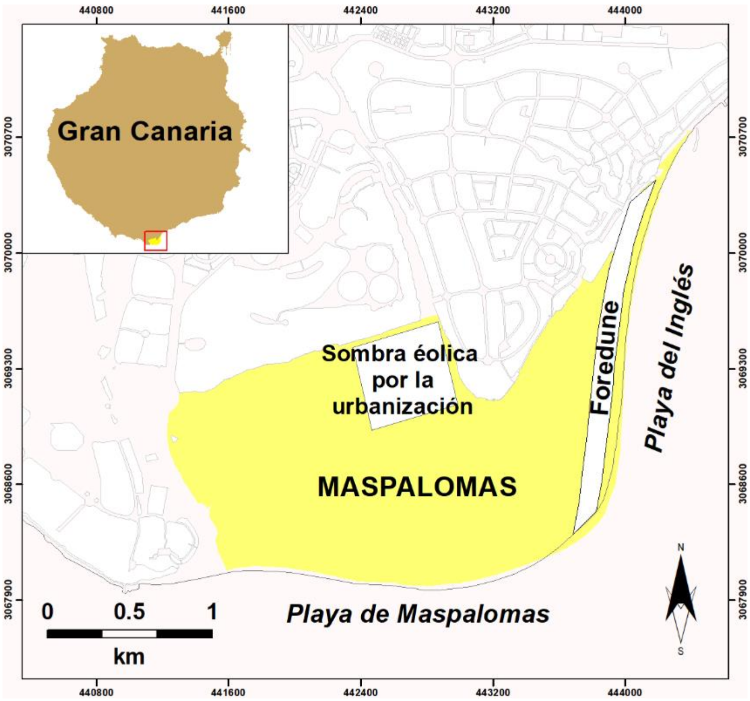

Figura 8. Sistema de dunas transgresivo árido de Maspalomas, en Gran Canaria. Áreas de estudio (sombra eólica por la urbanización y foredune).

Por otro lado, la foredune de Maspalomas se localiza en la zona activa del sistema duna y presenta una altura que varía entre 1-5 (m.s.n.m.). Está formada por nebkhas asociadas prácticamente a la única especie vegetal existente en la zona como son los ejemplares del nanofanerófito *Traganum moquinii*. Entre las dunas en montículos que integran esta zona también se generan pequeñas depresiones interdunares, que varían espacial y temporalmente en función de la dinámica de los procesos sedimentarios eólicos activos (Hernández-Cordero, 2012). Por tanto, la morfología de la foredune de Maspalomas tiene una estructura fragmentada de forma natural, lo que implica una mayor debilidad que la foredune de regiones templadas (Hernández-Cordero et al., 2019), teniendo en cuenta el papel protector que desempeñan estas unidades geomorfológicas en el sistema de dunas (Ley et al., 2007). Esta dinámica se ha podido ver alterada en las últimas décadas debido a una reducción del número de ejemplares de *Traganum moqunii* en la zona debido a la construcción urbanística, a la presión de los usuarios y servicios de la playa y también por procesos naturales como pueden ser el propio transporte sedimentario con un comportamiento inusual (Hernández-Cordero, 2012). A priori, estos cambios no han sido homogéneos espacial y temporalmente, lo que ha provocado que la función de *Traganum moquinii* sobre la foredune haya cambiado dependiendo del grado de presión antrópica.

Variables biogeomorfológicas y antropogénicas

Para cada escala espacial tratada, se plantearon variables que fueran representativas, con el fin de alcanzar los objetivos específicos de cada trabajo. Estas variables particulares se explican en cada uno de los artículos que conforman esta Tesis Dotoral. No obstante, en la tabla 1 se muestra un resumen del número de variables que se tomaron para abordar las diferentes escalas espaciales y temporales por artículo, siguiendo el orden de secuencia explicado en la sección “Objetivo general y específicos”.

Tabla 1. Resumen general de las escalas de trabajo y de las variables utilizadas en cada artículo.

Información de la investigación

	Primer artículo	Segundo artículo	Tercer artículo	Cuarto artículo	Quinto artículo	Sexto artículo
Escala Espacial						
Sistemas sedimentarios eólicos costeros	GAB (Australia)	Canarias	La Graciosa (metodológico)	Maspalomas (sombra eólica)	Maspalomas (sombra eólica)	Maspalomas (foredune)
Número de sistemas sedimentarios[1]/tramos de costa sedimentaria[2]	593[2]	4[1]	1[1]	1[1]	1[1]	1[1]
Latitud	31°-34° S	27°-29° N	29°N	27°N	27°N	27°N
Escala temporal	Actual	Histórica/actual	Actual/histórica	Histórica/actual	Actual	Histórica
Número de variables utilizadas	7	hasta 12*	2	16	9	7

* El número de variables varía de acuerdo a las geoformas detectadas en cada sistema sedimentario eólico estudiado.

En líneas generales, las variables seleccionadas, relacionadas con la vegetación, fueron las siguientes: 1) la distancia entre los ejemplares vegetales (m) en el artículo 1 como un *proxy* para determinar el tipo de foredune con respecto a los suministros de sedimento. Esta variable también es tenida en cuenta en el tercer artículo (*Procedure to automate the classification and mapping of the vegetation density in arid aeolian sedimentary systems*) y en el sexto, tanto en la primera línea de la foredune, como en el interior de las parcelas estudiadas; 2) cobertura vegetal (m^2) en el caso del segundo artículo; 3) densidad vegetal, en el tercer artículo (nº individuos/superficie × distancia entre individuos); 4) cobertura vegetal (m^2), densidad vegetal, comunidad vegetal y su altura (m), en los artículos 4 y 5. Las variables relacionadas con la geomorfología fueron: 1) superficies de arena y geomorfología (m^2) detectadas en la foredune de la GAB, en el artículo 1; 2) superficies (m^2) ocupadas por las propias geoformas detectadas en los diferentes sistemas sedimentarios éolicos, en el segundo artículo; 3) altimetría (m.s.n.m.), pendientes (º), número de frentes dunares, direcciones de los frentes de dunas (º) y volúmenes (m^3), en los artículos 4 y 5; 4) superficie de foredune en Maspalomas (m^2) y número de nebkhas, en el artículo 6. En el artículo 2 no se tuvieron en cuenta variables geomorfológicas.

Por último, las variables relacionadas con la antropización fueron: 1) diferencias en el grado de cambios ambientales analizados entre sistemas sedimentarios eólicos donde sus entradas sedimentarias fueron ocupadas por construcciones urbano-turísticas, frente a aquellas en las que no se produce este proceso, en el segundo artículo); 2) relación espacio-temporal entre el proceso urbanizador alrededor del sistema dunar de Maspalomas y los cambios ambientales que podrían suponer un deterioro ambiental en el interior del sistema sedimentario, en el artículo 4; 4) cambios en la biogeomorfología con respecto a la distancia a las urbanizaciones, en los artículos 5 y 6. En los artículos 1 y 3 no se estudiaron variables antropogénicas debido a que el primero no tenía el objetivo de estudiar cambios ambientales y procesos, y el segundo es un artículo metodológico estrictamente relacionado con la vegetación.

Datos y Análisis espacio-temporales de las variables a través de SIG

En este apartado se pretende hacer hicapié en la importancia del uso de los sistemas de información geográfica (SIG) en esta Tesis Doctoral. Los SIG en esta investigación han sido utilizados no sólo para los análisis espacio-temporales, que se explicarán a continuación, sino también para extraer datos relacionados con la vegetación, con la topografía y con la antropización de los sistemas sedimentario eólicos estudiados. De esta forma, gran parte de esta investigación está construida a partir del implemento de estos sistemas.

Las fuentes de información utilizadas para la extracción de datos fueron principalmente digitales y, en algunos casos, como las fotografías aéreas históricas, también fueron digitalizadas y georreferenciadas. En este sentido, sólo los datos recogidos en campo y los datos climáticos, obtenidos por los organismos competentes, no eran, en un principio, digitales, aunque finalmente esta información fue volcada en un entorno SIG. Se han utilizado datos ráster, obtenidos a través de reclasificaciones de fotografías aéreas históricas, ortofotos históricas y actuales, o procedentes de modelos digitales del terreno y de superficie (MDT y MDS). También datos vectoriales, obtenidos a través de la digitalización de vectores, en procesos de fotointerpretación o procedentes de formatos *shapefile* o *las* (LiDAR), almacenados en bases datos espaciales (de libre descarga), como la web del Instituto Geográfico Nacional (IGN) o de la Dirección General del Catastro en España. También han sido necesarias herramientas de conversión, para combinar datos de diferente formato (ráster y vectorial).

Para estudiar los cambios ambientales, los procesos biogeomorfológicos y explicar sus alteraciones (si las hubiera), fue imprescindible relacionar las variables, tanto espacial, como temporalmente, como se explicó en la sección anterior. Por este motivo, los SIG han sido las herramientas más utilizadas a lo largo de todo este estudio. Se han utilizado herramientas de superposición y distancia espacial, además de herramientas que permiten realizar análisis estadísticos espaciales entre datos recogidos en diferentes años (escala temporal).

Análisis estadísticos

Además del uso de los SIG, también ha sido fundamental el uso de tests estadísticos no espaciales ni análisis de series temporales, con el fin de obtener información sobre otras relaciones entre variables. De esta forma, en el artículo 1, además de diagramas de dispersión, se añadieron dos test, una tabla de contingencia que agrupó el número de tramos de costa con respecto a la latitud y longitud (también ofrecen los porcentajes), y una correlación de Pearson para relacionar los porcentajes obtenidos entre la tabla de contingencia y el tipo de foredune, clasificado por latitud y longitud (% de la línea de costa ocupada por cada tipo). En el artículo 3, fue imprescindible el cálculo de coeficientes de variación para conocer la heterogeneidad en la distribución espacial de la vegetación (relación entre la distancia entre la vegetación y la cobertura vegetal, inversamente proporcianal a la superficie obtenida a través de los muestreos por vecindad calculados), con el fin de conocer el muestreo por vecindad óptimo del procedimiento propuesto. En los artículos 4 y 5 fue necesario el desarrollo de diagramas de dispersión; también en el artículo 5 se llevó a cabo un análisis de componentes principales, para agrupar aquellas variables que mejor explicaban el comportamiento de los flujos de viento en cada transecto estudiado. Por último, quizás el artículo 6 es el que mayor complejidad presenta desde esta perspectiva. En él se aborda, por un lado, un simple análisis cluster, utilizando el método de Ward, para agrupar parcelas estudiadas con comportamientos parecidos, así como correlaciones de Pearson, para relacionar variables analizadas.También en este artículo se han diseñado modelos lineales mixtos, donde la heterocedasticidad entre parcelas de observación también se tuvo en cuenta, modelizando una varianza diferente por parcela estudiada, siguiendo a Pinheiro y Bates (2000), calculado todo ello en el software de código abierto R (R Core Team, 2016). El artículo 2 no contó con análisis estadísticos, pues los datos se agruparon en tablas que fueron descritas.

Información multifuente

Esta investigación se caracteriza por combinar datos de diferente naturaleza y fuentes de información. Se explican, a continuación, algunos rasgos de los tipos de datos y fuentes de información que fueron utilizados en cada artículo, así como su interés para abordar los diferentes objetivos específicos.

Datos climáticos (precipitaciones, temperaturas y viento)

Los datos climáticos han sido especialmente utilizados en los artículos 1, 4 y 5. En el artículo 1, fueron necesarios los datos de precipitaciones y temperaturas para comprobar si existía un gradiente, al menos latitudinal, de estas variables en la GAB. Además, se calcularon los indices de movilidad de dunas (M) propuestos por Lancaster (1988) y Tsoar (2005). En el primer índice se combinan variables relacionadas con el viento (W), las precipitaciones (P) y la temperatura (PE: evapotranspiración potencial por el método Thornthwaite (1948)), mientras que en el segundo índice se fusionan diferentes variables obtenidas por datos de viento (DP y RDP). Estos resultados permiteron comprobar si existía una tendencia en la movilidad de las dunas a través de la GAB, con respecto a la latitud y la longitud. En el cuarto artículo se utilizan las precipitaciones obtenidas en una estación cercana al campo de dunas de Maspalomas. Los análisis en esta publicación revelaron los cambios temporales en la vegetación y en la geomorfología, a medida que las construcciones rodeaban el sistema sedimentario eólico objeto de estudio. Para relacionar la casuística detectada entre la modificación y alteración de la dinámica sedimentaria de Maspalomas por la urbanización, y los cambios en los procesos biogeomorfológcios, era necesario controlar los efectos de factores naturales, como el cambio que puede darse en el clima local. Sin embargo, los resultados permitieron comprobar que este factor se descartaba, debido a que la precipitación no había variado significativamente a lo largo del período estudiado. Finalmente, en el artículo 5 se utilizan la velocidad y dirección del viento, obtenidos en un experimento llevado a cabo en el mes de marzo de 2017. El objetivo era detectar si los vientos a 0.40 m de altura, tomados en 5 transectos dentro de la zona de sombra eólica (figura 7), se aceleraban a medida que se alejaban de la urbanización del Inglés, y a qué distancia ocurría esa aceleración. Para ello se trataron por el procedimiento propuesto por Delgado-Fernández et al. (2013).

Fotografías aéreas históricas y ortofotos (históricas y actuales)

La fotointerpretación sobre fuentes de información digitales aerotransportadas, tales como fotografías aéreas históricas (escaneadas y georreferenciadas utilizando SIG), y ortofotos, tanto históricas como actuales, han servido para estudiar los cambios ambientales que se han producido en los sistemas sedimentarios eólicos costeros áridos estudiados (artículos 2, 4 y 6). También han servido para extraer información básica e imprescindible en los artículos 3 (la principal fuente de información utilizada), 1 y 5. El uso de estas fuentes de información presenta varias ventajas, recogidas en Morgan et al. (2010), además de que han sido ampliamente aceptadas, debido a que han proporcionado un espectro de información útil a gestores e investigadores para el seguimiento ecológico y cambios en el paisaje (Cohen et al., 1996; Swetnam et al. 1999; Johnston y Lowell 2000). Pero también se conocen sus desventajas, las cuáles señalaremos brevemente a continuación, especialmente relacionadas con la toma de datos, pues es importante recalcar que, aunque han sido muy útiles para el seguimiento de información relacionada con la vegetación y la geomorfología, también presentan ciertos sesgos que repercuten en la investigación. El primero de ellos es que los datos capturados por estas fuentes de información corresponden únicamente con la muestra de un instante (t) de lo que ocurre en la dinámica del ecosistema en su conjunto, y rara vez las fotografías aéreas históricas presentan repeticiones periódicas de diferentes estaciones anuales, que permitan reducir ese error. También la información (datos) extraídos suelen ser subjetivos, pues dependen de criterios de sus intérpretes (Morgan et al., 2010). Por último, la calidad de la imagen, y por tanto de los datos que serán analizados, dependen directamente del clima en el momento que la imagen fue capturada (Morgan et al., 2010).

Datos LiDAR y fotogramétricos (topografía y vegetación)

Debido a la precisión que ofrecen las altimetrías LiDAR (Light Detection and Ranging) y fotogramétrica, estas fueron utilizadas para trabajar variables que precisaban de 3 dimensiones en los artículos 4 y 5. Dado que se trataba de analizar procesos biogemorfológicos caracterizados por estas variables, era necesario disponer de registros históricos altimétricos. En estos análisis se utilizaron datos altimétricos, así como derivados de la altimetría (volúmenes, pendientes y líneas de rotura), de los años 1987 y 2003 (resolución espacial: 4 m) y deee 2017 (resolución espacial: 1 m). La fuente de datos de las primeras dos fechas fueron sendos modelos digitales de elevaciones (MDE) derivados de restitución fotogramétrica. Los datos altimétricos de 2017 se derivaron de un vuelo dron. Estos datos fueron almacenados en un fichero *las*, obteniéndose modelo digital del terreno (MDT) y un modelo digital de superficie (MDS), utilizando técnicas de oclusión (Chang et al., 2008). El MDS fue utilizado para calcular la variable “altura máxima de la vegetación” utilizada en el artículo 5 para analizar la influencia de la vegetación sobre los flujos de viento.

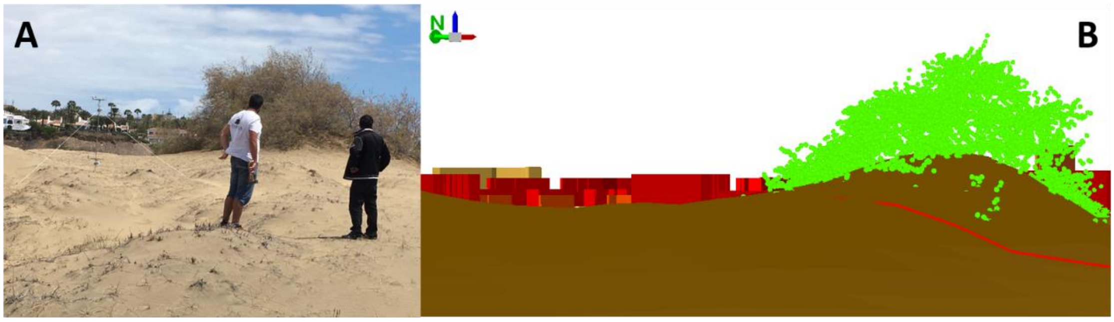

Figura 10. A. Fotografía captada el 25 de marzo de 2017 mientras se ejecutaba el experimento

explicado en el artículo 5 (dentro de la zona erosiva 3 del artículo 4). B. MDT y nube de puntos de vegetación en la misma zona de A, derivados de datos capturados por un vuelo dron fotogramétrico.

En cuanto a los datos LiDAR, los ficheros con formato "*.las*" que almacenan la nube de puntos altimétricos, fueron filtrados para generar los MDT utilizados en los años 2006, 2009, 2011 y 2015 (resolución espacial: 1 m). A través de estos MDT se calcularon cambios volumétricos y altitudinales que permitieron caracterizar las zonas de erosión y de deposición, además de caracterizar y estudiar la evolución de las geoformas eólicas erosivas detectadas en la zona de sombra eólica a sotavento de la urbanización del Inglés (Maspalomas) (Figura 7). La densidad media de puntos que recoge los ficheros *las* utilizados es de 1 pt/m^2, para los obtenidos a través de GRAFCAN, S.A.-Gobierno de Canarias (2006 y 2011), y de 0,5 pt/m^2, para los suministrados por el Instituto Geográfico Nacional, IGN-Gobierno de España (2009 y 2015).

Es necesario aclarar que los MDT generados a partir de tecnología LiDAR o fotogramétrica tienen una representación superficial incierta (que puede variar en el espacio y el tiempo), de modo que la capacidad para detectar cambios entre MDTs (en inglés DoD -DEM of Difference-) depende en gran medida de las incertidumbres de representación de la superficie inherentes a los propios MDTs (Wheaton et al., 2009, 2010). En este sentido se utilizó Geomorphic Change Detection (GCD), software que proporciona un conjunto de herramientas para cuantificar esas incertidumbres de forma independiente en cada MDT y propagarlas al DoD (Wheaton et al., 2009, 2010).

Trabajo de campo

También en esta investigación se han trabajado datos de campo, capturados a través de 3 campañas. Las dos primeras se desarrollaron en la Reserva Natural Especial de las Dunas de Maspalomas. En primer lugar, durante los días 24 y 25 de marzo de 2017 se llevó a cabo un experimento que se explica con detalle en el artículo 5 "*Airflow dynamics, vegetation and aeolian erosive processes in a shadow zone leeward of a resort in an arid transgressive dune system*". En esta ocasión fue imprescindible la toma de datos de viento a través de sistemas de sensores de vientos (anemómetro + veleta + *data logger*). Estos datos se recogieron de forma simultánea a la captura de datos por un vuelo dron fotogramétrico, lo que permitió posicionar posteriormente los resultados de flujo de viento obtenidos (*short-term*) y relacionarlos con la topografía, la vegetación y la distancia a la urbanización en sus puntos más próximos. También, durante esta campaña se llevó a cabo un levantamiento topográfico utilizando una estación total Leica TS06 con dispositivo láser para corregir la precisión de la altimetría obtenida por el dron.

La segunda campaña se realizó entre los días 8 y 12 de agosto de 2017, teniendo como objetivo chequear y corregir las comunidades vegetales del año 2017 presentadas en el artículo 3. Éstas fueron obtenidas a través de la interpretación visual de ortofotos digitales (utilizando las variables color, tamaño, densidad, textura y patrón espacial), tal y como propone Hernández-Cordero et al. (2017).

La última campaña de campo se llevó a cabo en el contexto del artículo 1 "*Climate as a control on foredune mode in Southern Australia*", entre el 12 y el 21 de noviembre de 2018, para verificar y corregir las diferentes morfologías y modos de foredune detectados desde ortofotos digitales, a través de herramientas SIG, así como para la recogida de datos de vegetación utilizados para este mismo trabajo. En total, 165.76 km de costa fueron visitados, 6.21% del área de estudio en la GAB.

Artículos

En la siguiente tabla se resumen las principales características de los artículos que se presentan, con los factores de impactos correspondientes a la fecha de aceptación, y el número de revisores que formaron parte en su proceso de revisión y evaluación.

	Primer artículo*	Segundo artículo**	Tercer artículo***	Cuarto artículo****	Quinto artículo*****	Sexto artículo******
Cuartil_JCR	Q1	Q3	Q1	Q1	Q2	_
Factor de impacto	5.589	0.897	3.375	4.61	2.346	_
Cuartil_SCImago	Q1	Q1	Q1	Q1	Q1	_
SJR	1.536	0.718	1.373	1.546	1.117	_
Fecha	dic-19	may-16	jun-18	feb-19	jun-19	_
Revisores	2	3	3	3	3	_

*__García-Romero, L.__, Hesp, P., Peña-Alonso, C., Miot da Silva, G., Hernández-Calvento, L. (2019). Climate as a control on foredune mode in Southern Australia. *Science of the Total Environment*, 694, 133768.

**__García-Romero, L.__, Hernández-Cordero, A. I., Fernández-Cabrera, E., Peña-Alonso, C., Hernández-Calvento, L., & Pérez-Chacón, E. (2016). Urban-touristic impacts on the aeolian sedimentary systems of the Canary Islands: conflict between development and conservation. *Island Studies Journal*, 11 (1), 91–112.

***__García-Romero, L.__, Hernández-Cordero, A. I., Hernández-Calvento, L., Espino, E. P. C., & López-Valcarcel, B. G. (2018). Procedure to automate the classification and mapping of the vegetation density in arid aeolian sedimentary systems. *Progress in Physical Geography: Earth and Environment*, 42(3), 330-351.

****__García-Romero, L.__, Delgado-Fernández, I., Hesp, P. A., Hernández-Calvento, L., Hernández-Cordero, A. I., & Viera-Pérez, M. (2019). Biogeomorphological processes in an arid transgressive dunefield as indicators of human impact by urbanization. *Science of the Total Environment*, 650, 73-86.

*****__García-Romero, L.__, Delgado-Fernández, I., Hesp, P. A., Hernández-Calvento, L., Viera-Pérez, M., Hernández-Cordero, A. I., ... & Domínguez-Brito, A. C. (2019). Airflow dynamics, vegetation and aeolian erosive processes in a shadow zone leeward of a resort in an arid transgressive dune system. *Aeolian Research*, 38, 48-59.

******__García-Romero, L.__, Hernández-Cordero, A. I., Hesp, P., Hernández-Calvento, L (sin publicar). 2D Decadal monitoring of *Traganum moquinii*’s role in the morphometry of the foredune in an arid dunefield -*Sin publicar*-.

Climate as a control on foredune mode in Southern Australia

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Abstract

Foredunes are formed by aeolian sand deposition in vegetation on the backshore of beaches. In this paper, the foredune mode (nebkha, discontinuous foredune, and continuous foredune), and transgressive dunefield development is studied along the Great Australian Bight (GAB), 2668 km of coastline. Orthophotos are used to classify the foredune mode, coastal landforms and the vegetation, through geographic information systems (GIS), with fieldwork support. The results show that the foredune mode is strongly controlled by rainfall and temperature with respect to latitude, and to drift potential with respect to longitude across the GAB. Between 200 and 300 mm annual rainfall, nebkha predominate. When the annual rainfall is between 300 and 400, at latitude 32°, a clear pattern is not observed in foredune mode and this is identified as a transition zone. Discontinuous foredunes and continuous foredunes are strongly represented in regions experiencing above 400 mm annual rainfall. The main contribution of this study is the identification of foredune modes which are not only related to a climatic gradient and latitude, but also related to variations in longitude, vegetation cover and diversity, and dune mobility indices. Finally, there are other environmental relationships between the wind and longitude, where the geomorphology of the bay could be playing an important role.

Keywords: climate gradient, foredune mode, nebkhas, dune vegetation, dune mobility, south Australia

1. Introduction

Studies dating back to at least the 1800s show that the world's vegetation distribution is determined largely by climate (Von Humboldt and Bonpland, 1807; De Candolle, 1855; Woodward, 1987). So climate, in combination with other environmental variables, have been extensively used to explain the main vegetation patterns around the world (Salisbury, 1926; Good, 1953; McArthur, 1972; Box, 1981; Walter, 1985; Woodward, 1987). It is recognized from the field of biogeomorphology (Corenblit et al., 2011), that since vegetation started to colonize emerged surfaces, complex changes in Earth surface processes and, consequently, in the landforms, have been produced (Murray et al., 2008; Davies and Gibling, 2009, Davies and Gibling, 2010).

Primarily in desert dune systems, but also some coastal systems, various models have been developed to explain the functioning of sand mobility and development of dunes types with respect to climatic variables, such as: wind (Fryberger and Dean, 1979; Tsoar, 2005; Miot da Silva and Hesp, 2010), a combination of wind, precipitation and temperature (Wasson, 1984; Lancaster, 1988), or wind energy and sand supply (Wasson and Hyde, 1983; Louassa et al., 2018; Lü et al., 2018). In coastal dune systems, foredunes (including nebkhas) and dunefield development and evolution has been shown to depend on a variety of regional or local factors such as wind velocity and direction (Rotnicka, 2011), wave energy and surfzone-beach type, storm intensity, scarping and overwash occurrence, and short to long term coastal dynamics (stability, progradation or retrogradation), vegetation cover and density, and sediment supply (Short and Hesp, 1982; Hesp, 1988; 2002; Davidson-Arnott, 2010; Keijsers et al., 2015; Davidson-Arnott et al., 2018).

Rainfall and temperature patterns are responsible for the different floristic regions on beach-dune systems worldwide (Doing, 1985; Takhtajan, 1986; Brunbjerg et al., 2014). The coastal vegetation, the plant species morphology and their density in the beach-dune systems reflect the local disturbance factors influencing, forming or altering aeolian landforms (Hesp and Martínez, 2007). According to the historical regime of physical disturbance, different plant morphologies facilitate the mobility pattern of the surface sediments and the abundance of species (Dangerfield et al., 1998; Stallins, 2002, Stallins, 2005; Stallins and Parker, 2003; Gumbricht et al., 2004; Nield and Baas, 2008; Corenblit et al., 2011).

There is evidence of the relationship between plant species and the formation of coastal foredunes in different coastal climatic regions, in order (greatest to least), according to the distance with respect to the Equator. In temperate zones, plant species, especially grasses, and generally rhizomatous perennial herbaceous plants and glycophytes, can form nebkhas and continuous foredunes (e.g. *Ammophila* spp., *Spinifex* spp., *Elymus farctus*, *Austrofestuca littoralis*). If the dunes begin as nebkhas, they can grow in size, merge with other nebkhas and eventually form continuous ridges (Hesp, 2002; Hesp and Walker, 2013; Keijsers et al., 2015; Hesp et al., submitted). Most of these species show variable tolerance to the burial of sand, such as *Spinifex* and *Desmoschoenus spiralis* in Australia and New Zealand (temperate zone). However, in arid zones, shrub species usually form nebkhas, but not continuous ridges. These species are mainly halophilic adapted to soils with high salinity as well as the lack of fresh water (e.g. *Traganum moquinii*, *Zygophyllum* spp., *Suaeda* spp., *Salsola* spp.) (Hernández-Cordero et al., 2015, Hernández-Cordero et al., 2017). In this case, the dimensions of the shrub strongly affect the nebkha morphology (El-Bana et al., 2002). For example, on the arid coasts of the Canary Islands, *Traganum moquinii* is the predominant plant species, which forms nebkha and nebkha fields. It is a nanophanerophyte and shrubby species that survives and thrives where burial by sand occurs (Hernández-Cordero et al., 2012; Viera-Pérez, 2015). Finally, humid tropical coast are normally characterized by continuous foredunes (Doing, 1985), where dune-building species are commonly creeping plants (e.g. *Ipomoea pes-caprae*, *Canavalia rosea*) (Arun et al., 1999), or non-rhizomatous woody species (i.e. *Scaevola plumieri*) (Pammenter, 1983). Hesp et al. (submitted) determined three typical foredune modes exist on many coasts, namely, nebkha, discontinuous foredunes, and continuous foredunes. Given the range of foredune modes present on a particular coast, and the role of climate in determining to a degree foredune development, this paper aims to determine if the climate, especially rainfall, is a controlling factor in determining the mode of foredune formation and the distribution of either continuous or discontinuous ridges or nebkhas along the Great Australian Bight (GAB), which displays a significant east to west and north to south gradient in rainfall. Vegetation data, sand mobility, climatic data and foredune modes are examined along 2668 km of coastline.

2. Study area

The Great Australian Bight (GAB) (Fig. 1) extends from Esperance (Western Australia, 33°51′40″S 121°53′31″E) to Port Lincoln (South Australia, 34°43′56″S 135°51′31″E), a total of 2668 km of coastline. This large coastal stretch traverses latitudes that range between 34°and 31°, and longitudes between 121° and 135°.

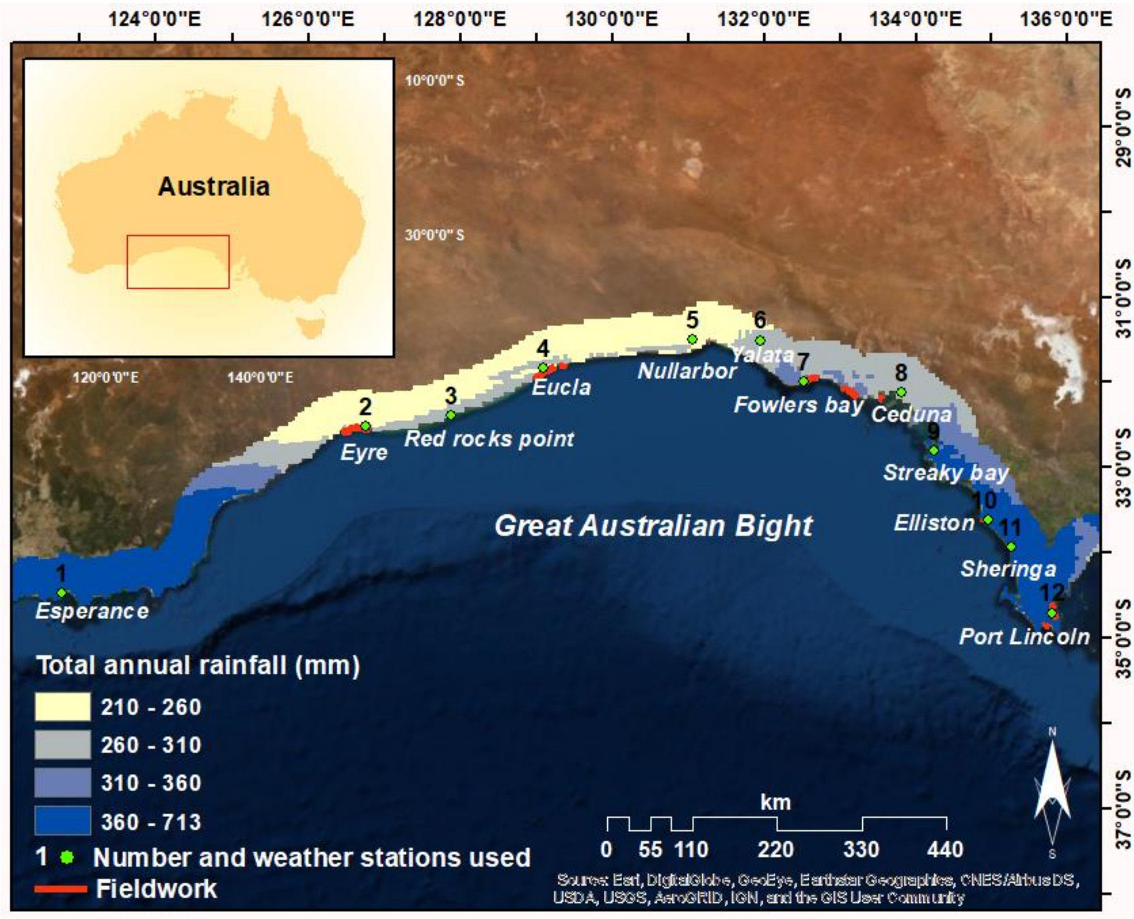

Figure 1. Study area. Total annual rainfall (mm), from Australian Bureau of Meteorology.

The GAB is part of a passive and divergent continental margin that was formed during the cretaceous separation of Australia and Antarctica, evolving during the subsequent drift to the north of the Australian continent (Veevers et al., 1991). The GAB belongs to the southern Australia platforms, and it is the largest area of cool-carbonate sedimentation in the modern world (James, 1997). While its eastern part has been well documented (Boreen et al., 1993; James et al., 1992; James et al., 1997), the central part of the platform, which is the GAB, has not been studied totally and in detail (James et al., 2001), except for some local studies (Wass et al., 1970; James et al., 1994).

The GAB has a Mediterranean climate which ranges from warm semiarid along the coast to warm arid inland (Lowry, 1970; Twidale et al., 1985). The mean annual rainfall along the coast varies from around 600 mm in Esperance to around 280 mm in Eucla, decreasing inland to approximately 150 mm. The climate pattern is interrupted every few summers by intense cyclonic depressions that bring rain. There are no rivers in this region and, therefore, no superficial fresh water (James et al., 2001). The southern Australia continent is normally storm-dominated with high modal deep-water waves (>2.5 m) (Davies, 1980; Wright et al., 1982; Short and Hesp, 1982), and the dominant wave approach is from the southwest, year-round. However, the ocean waters are affected by seasonality, since a series of low-pressure winter systems that move eastward give way to a large high-pressure summer cell with an anticyclonic wind circulation. This results in predominantly southeastern summer winds and winter western winds. The shelf currents are generally anticlockwise in summer, flowing north along the Eyre coast and westward through the GAB (Marshallsay and Radok, 1972).

With respect to the sediments that form the aeolian sedimentary systems, Holocene beach and dune sediments are extensive across the GAB, and dominated by small to large scale transgressive dunefields, many of which are still active. Aeolianite calcarenite systems extend up to 80 km into the interior as a series of beach-dune complex systems, each increasingly older inland (Belperio et al., 1995). These Pleistocene eolianites form relict barriers and marine cliffs, scattered islands, and Precambrian crystal rock promontories also occur with partially eroded eolianite caps.

1. Methodology

3.1. Climate data and mobility index

Climate data were downloaded from the national climate databank of the Australian Bureau of Meteorology. Fig. 1 shows a raster grid 50 km wide and shows total annual rainfall along the GAB coastline. 12 weather stations were selected (Fig. 1, Table 1) due to their proximity to the coast, their data record and their geographic location (latitude and longitude). Monthly mean rainfall, temperature, evapotranspiration, wind speed and wind direction were used to calculate the mobility indices. Weather stations from Fowlers Bay and Sheringa had missing data (100%) in the meteorological record, so rainfall data were obtained from the Climate Forecast System Reanalysis (CSFR product). This is a global high-resolution dataset designed to provide atmosphere, ocean, land surface and sea ice system data with the best estimate over a given period.

Table 1. Characteristics of the weather stations used in this study.

ID_SA	ID_ABM	Name	Year	Latitude	Longitude	Height (m.a.s.l.)	DC (km)
1	9789	Esperance	1969	-33.83	121.89	25	2.05
2	11019	Eyre	1885	-32.25	126.3	6	3.5

3	11053	Red Rocks point	1999	-32.2	127.53	3	1.64
4	11003	Eucla	1876	-31.7	128.84	93	4.36
5	18106	Nullabor	1888	-31.45	130.9	64	13.56
6	18161	Yalata	1968	-31.48	131.84	70	26.8
7	18030	Fowlers bay	1878	-31.99	132.44	3	1.49
8	18012	Ceduna (AMO)	1939	-32.13	133.7	15	6.78
9	18079	Streaky bay	1865	-32.8	134.21	13	1.96
10	18069	Elliston	1882	-33.65	134.89	7	5.81
11	18045	Sheringa	1877	-33.95	135.27	8	3.31
12	18217	Port Lincoln	2004	-34.74	135.86	11	0.48

ID_SA: identifier of the weather stations in the study area (Fig. 1). ID_ABM: identifier used by Australian Bureau of Meteorology. DC: distance to the coast. The year refers to the date records began.

Two mobility indices were applied to provide an estimation of dune mobility based on climate. The first mobility index (Eq. (1)) was published by Lancaster (1988):

$$M = W/(P:PE) \tag{1}$$

where *M* is the sand dune mobility, *W* is the frequency of winds exceeding the minimum threshold velocity (Table 1) which was calculated from sand samples taken by Short and Hesp (1984), Short and Fotheringham (1986) and Short et al. (1986). *P* is the daily rainfall which was used with temperature normals to predict the annual potential evapotranspiration (*PE*) (Bagnold, 1941; Thornthwaite, 1948; Thornthwaite and Mather, 1957). *M* values < 50 are considered stable regions with inactive dunes, *M* values of 50–100 indicate that only dune crests are active, *M* values of 100–200 indicate that dunes are active with vegetated interdunes and lower slopes, and *M* values >200 dunes indicate fully active dunes (Lancaster, 1988).

The second mobility index was developed by Tsoar (2005) (Eq. (2)):

$$M = \frac{DP}{1000-(750\frac{DP}{RDP})} \tag{2}$$

where *M* is the sand dunes Mobility, the *DP* is the drift potential and *RDP* is the resultant drift potential (Fryberger and Dean, 1979) and 1000 and 750 are the coefficients used by Tsoar (2005). In this index, sand dunes in areas where the annual mean rainfall is >50 mm (all meteorological stations have recorded rainfall over this value) are unvegetated and mobile, where M > 1, dunes are covered by vegetation when M < 1 (Tsoar, 2005). Note that both indices were developed primarily for deserts, not coasts.

3.2. Information sources and GIS

The coastline shapefile was created and provided by the Australian National Agency Geoscience Australia. This vectorial information was made in 2004 at a scale 1:100,000. ESRI World Imagery service was used through ArcGIS software. This service provides one meter or better satellite and aerial imagery for many parts of the world and lower resolution satellite imagery worldwide. The imagery was downloaded from SASPlanet as orthophotos. To classify the coastline, a series of criteria were measured through GIS tools (Fig. 2), such as reclassifications of the orthophotos (green band, spatial resolution: 1 m), raster data conversion to vector data and tools to calculate distances. These GIS algorithms were used in the first 200 m extending landwards from the landward edge of the backshore/toe of the foredune (Fig. 2). To classify the coastline, various variables were calculated (see Section 3.3). To detect vegetation color, the green band of the orthophotos was used because this is the region of the visible spectrum that best captures vegetation characteristics (Chuvieco, 2010). In addition, texture to detect gaps, and distance between plants to observe spatial pattern of the vegetation were considered.

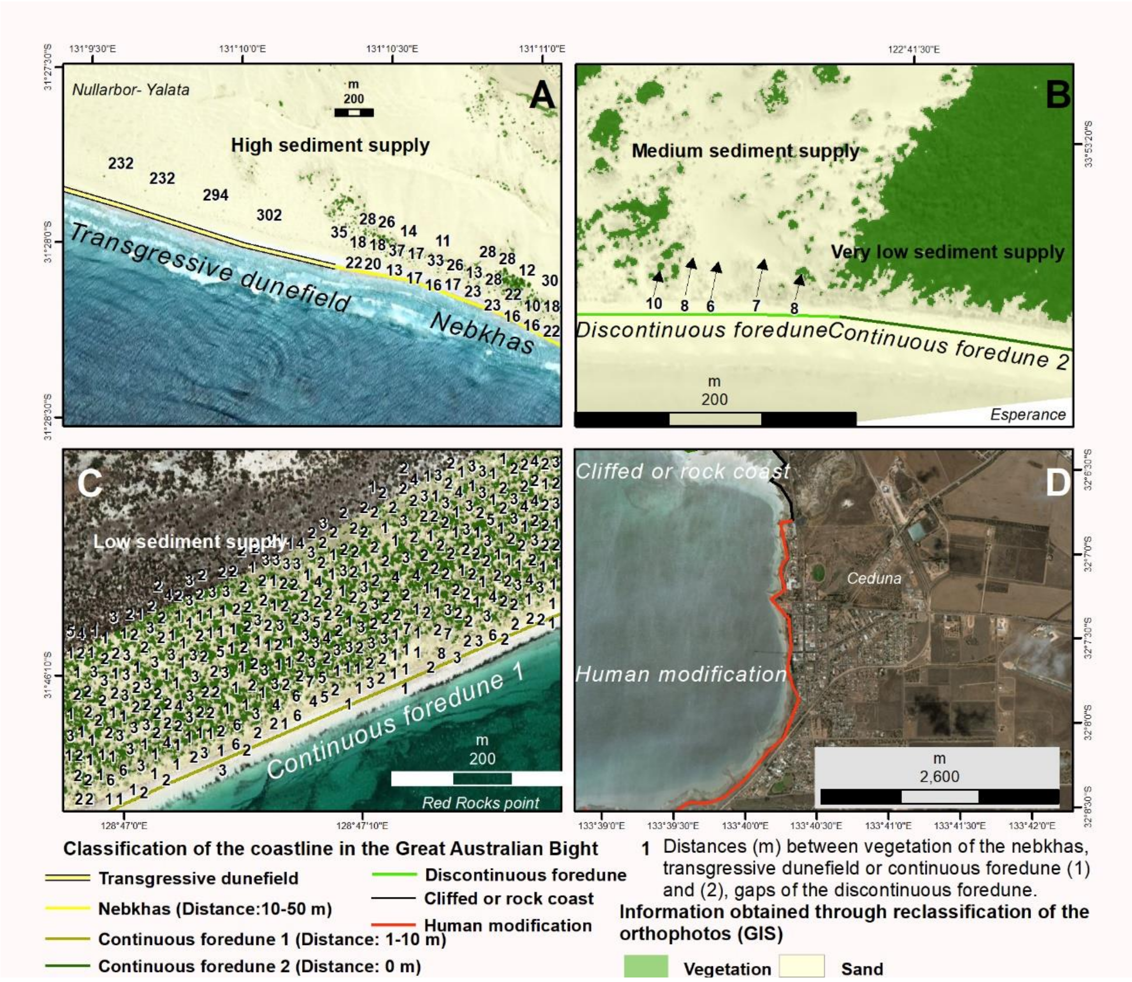

Figure 2. Criteria to classify the coastline according to the foredune mode. The numbers shown in A, B and C are the distance between plant individuals taken to classify the foredune as either nebkhas, transgressive dunefield, continuous foredune (1) and (2), and the gaps detected in the discontinuous foredunes.

The presence of estuaries was checked with the vector data (shapefile) downloaded from the Australian Estuaries Database – CAMRIS through Data Access Portal from CSIRO, in order to avoid using the coastline occupied by estuarine areas in the statistical analyses. Also the coastline occupied by cliffs and rocks and the urbanized coast were removed in the statistical analyses.

3.3. Foredune modes and coastal classification criteria

To detect the foredune modes objectively, two variables were measured in the first 200 m: i) mean distance between plant individuals, and, ii) surface occupied by sand. Then, the type of aeolian landforms behind the foredune were detected through visual analysis and this was used to determine relative sediment supply/availability due to its important for the foredune morphology (Hesp and McLachlan, 2000; El-Bana et al., 2002; El-Sheikha et al., 2010; Hesp and Smyth, 2017). Digital elevation models (DEM) or detailed topographic data was not available for the spatial scale used in this paper.

Five semi-quantitative categories were created to classify the coastline and to map the distribution of the foredune modes along the GAB (Fig. 2), as follows: i) Active transgressive dunefields with a low vegetation cover (distance between plant individuals > 50 m) and a high sediment supply, where barchanoid ridges and/or barchan dunes behind the foredune were used as indicators (if a foredune exists) (Fig. 2-A); ii) nebkhas with a medium vegetation cover (distance between plant individuals: 10–50 m). These are nebkha areas associated with a high sediment supply where shadow dunes can be seen behind each plant individual and barchan dunes can be detected inland, which are indicators of the sediment mobility and supply (Fig. 2-A); iii) discontinuous foredune: (Fig. 2-B) the foredune has clear gaps alongshore (texture detected from the orthophoto) with a distance of 5–20 m between gaps, and behind the foredune medium sediment supply can be detected with aeolian landforms such as isolated barchan dunes or parabolic dunes; iv) continuous foredune 2 (Fig. 2-B) which has a relatively high vegetation cover with no bare sand space between plant individuals and a very low sediment supply without mobile aeolian landforms behind the foredune. v) A new mode of continuous foredune was identified through fieldwork. This foredune mode appeared to be dense nebkhas on the orthophotos in the GIS, but the foredune mode shape is continuous (Fig. 2-C, continuous foredune 1). In this case, the continuous foredune has a medium vegetation cover with distances between plant individuals of 1 m and 10 m, and a low sediment supply within and behind the foredune. Also mobile landforms were not detected or there were deflation surfaces landwards of the foredune as indicators of the sediment mobility. Finally, the cliffed or rocky coast (vi), and (vii) the coast modified by human impacts/infrastructure have been classified from visual interpretation (Fig. 2-D).

3.4. Fieldwork and vegetation data

Fieldwork was carried out between 12/11/2018 and 21/11/2018 to verify the different foredune morphologies and modes detected from digital orthophotos through GIS tools. In total, 165.76 km of coast was visited, 6.21% of the study area (Fig. 1). Vegetation data were collected in a total of 17 plots (identification and number of species). 4 plots 200 × 200 m were located in each of the following beach-dune systems: Eyre (−32.25°, 126.28°), Eucla (−31.71°, 128.93°), Point Bell (Ceduna, −32.15°, 133.11°) and Sleaford (Port Lincoln −34.86°, 135.76°), and in 3 plots in Fowlers Bay (−31.99°, 132.41°), and 2 plots in Port Lincoln (−34.86°, 135.76°) due to their accessibility, geographic location and distance from each other, dimensions, and biodiversity.

3.5. Statistical analysis

A Pearson contingency test (Bortz et al., 1990) was used to relate the location of the different foredune modes with respect to latitude and longitude. Each stretch of coastline was grouped according to the latitude in 4 groups (−31° to −34°) and 15 groups of longitude (121°–135°). These classifications were related to the different categories (Fig. 2), except the cliffs and rocky coast, human modification and estuaries categories. The contingency table (Table 3) shows the number of foredune mode cases in each group (latitude and longitude) and its percentage. Second, the occupation of the coastline (%) occupied by the foredune modes (Fig. 2), are also related with the latitude and longitude through scatter diagrams adjusted in a polynomial line (degree 2). These data were obtained through summary statistical tools using GIS. Finally, to verify the robustness of both statistical analyzes, Spearman correlations between percentages obtained in the contingency table and those calculated from GIS analysis tools, were calculated (Table 5).

4. Results and discussion

4.1. Rainfall and temperature

Fig. 3 illustrates rainfall data across the GAB. The highest rainfall occurs in autumn and winter, especially between May and August, and decreases in spring and summer. The mean maximum temperature occurs in spring and summer and decreases between autumn and winter. While the annual distribution is similar for these sites, the total annual rainfall and the temperature vary. In Eucla and Nullarbor rainfall does not exceed 33 mm in the highest monthly rainfall and the minimum is around 16 mm with a total annual rainfall of 273.9 and 252.1 mm respectively. The temperatures are between a minimum of 18.5° and maximum of 27.9°. In Eyre and Streaky Bay the total annual rainfalls are 315.2 and 377.4 mm, and the temperature is between 16.5° and 29.3° respectively. In Esperance and Elliston the total annual rainfalls are 617.5 and 427.3 mm reaching 95.9 mm some months in winter, and the temperature is between 16.4° and 26.2° respectively. In general, when the latitude increases, rainfall also increases, and the temperature tends to reduce.

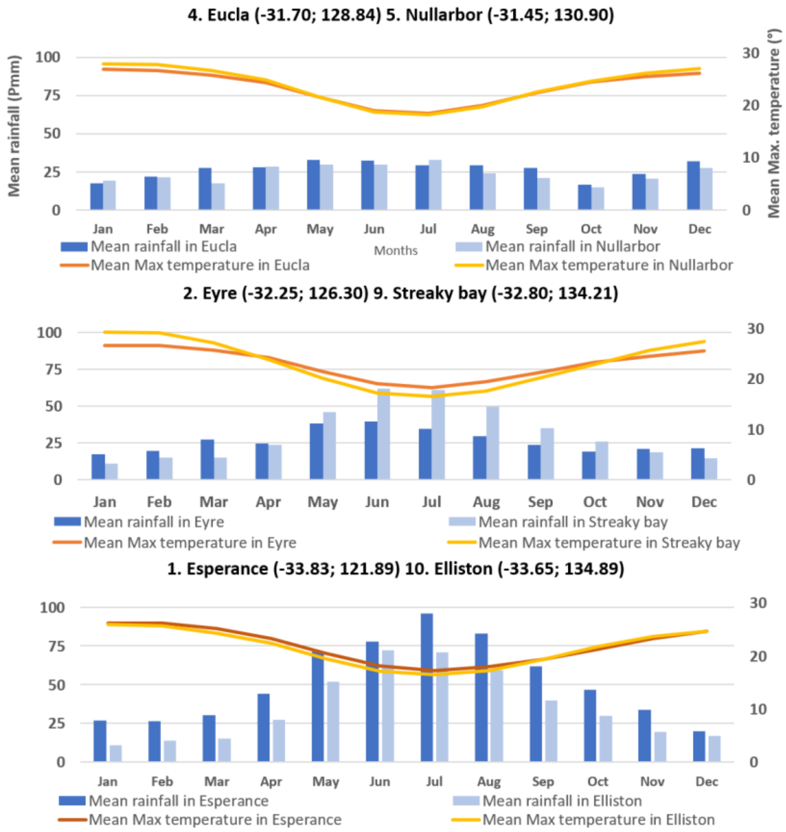

Figure 3. Differences in the mean monthly rainfall and mean maximum temperature at 6 weather stations (location in Fig. 1). There is a clear association of latitude with rainfall.

4.2. Dune mobility

Fig. 4 shows the sand dune mobility indices calculated for the study region, and in Table 2 the variables calculated and used for the mobility indices. In both cases good relationships are observed with respect to the latitude and longitude at all weather stations where the indices were calculated. Lancaster's index has a higher lineal trend ($R^2 = 0.7118$) than Tsoar's index ($R^2 = 0.6541$) when these are related to latitude. However, when both indices are related to longitude, Tsoar's index has a higher polynomial (degree 2) trend of $R^2 = 0.7608$ than Lancaster's index where $R^2 = 0.6124$. Both graphs show that the highest values of sedimentary mobility are obtained in latitudes close to latitude −31° (southern hemisphere), and between longitudes 128° and 130° of the eastern hemisphere. According to Lancaster (1988) inactive dunes (vegetation cover > 20% and when $M < 50$), can be observed from around latitude −34° to −33° to −32°. Dunes with active crestal areas only (vegetation cover 10–20% and when $M = 50$–100) are generally located in latitude −31°. According to Tsoar (2005) the dune systems are considered as “covered by vegetation” when $M < 1$. These lower values are observed around −34° to −33° to −32°, and the higher values when approaching latitude −31° (North) in the lowest rainfall zone. In no case “unvegetated and mobile” dunes are observed when $M > 1$. These results allow one to observe if there is a trend in the dune mobility across the GAB with respect to latitude and longitude, although the results are imprecise with the real mobility of the nearest beach-dune system, because currently there is a potential of error in its estimation resulting from long-term prediction of aeolian sand transport based on wind data from distant weather stations with respect to the dune system closer (Rotnicka and Dłużewski, 2019), and is being improved from methods as the one proposed by Rotnicka and Dłużewski (2019).

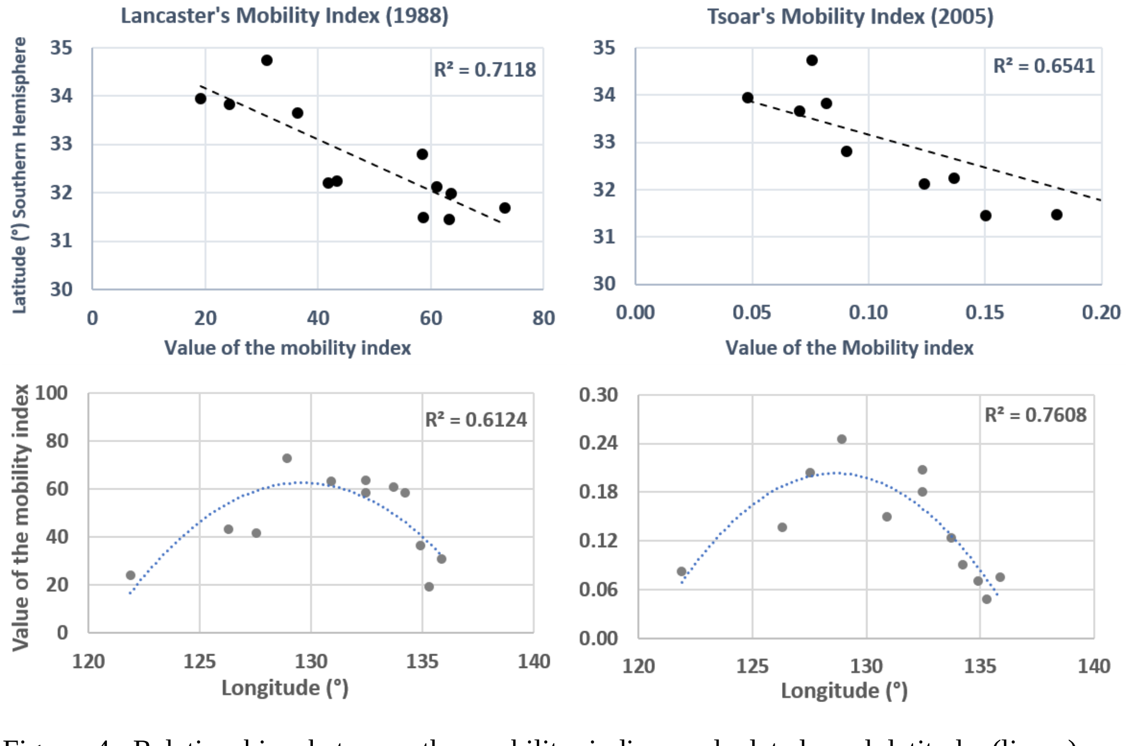

Figure 4. Relationships between the mobility indices calculated, and latitude (linear) and longitude (polynomial 2nd degree) in the GAB. The values of the mobility index related to the

latitude are showed in the x axis because the latitude is easier to understand in the y axis. However, the longitude is easier to understand in the y axis and the value of the mobility index is shown in the x axis.

Table 2. Information related to sediment size, minimum aeolian threshold velocity and variables calculated in the mobility indices.

Name	Sedim_mm	W_tv	P	EP	W	RDP	DP
Esperance	0.26	6.50	617.50	396.00	37.90	26.54	47.93
Eyre	0.13	3.25	315.20	282.00	48.44	27.98	110.80
Red Rocks point	0.17	4.25	348.50	269.00	54.22	67.23	114.38
Eucla	0.20	5.00	273.90	261.00	76.68	50.78	197.81
Nullabor	0.19	4.75	254.79	257.00	62.78	36.47	114.28
Yalata	0.21	5.25	278.90	281.00	58.20	37.35	146.17
Fowlers bay	0.28	7.00	300.20	304.00	62.81	38.78	172.93
Ceduna (AMO)	0.18	4.50	296.45	288.00	62.84	30.14	94.29
Streaky bay	0.15	3.75	366.13	369.00	58.03	28.20	56.92
Elliston	0.19	4.75	450.22	403.00	40.70	21.25	45.96
Sheringa	0.28	7.00	435.4	429.00	19.50	15.96	23.06
Port Lincoln	0.25	6.25	495.18	480.00	31.90	22.85	49.75

Sedim_mm: average diameter of the sediment (mm). W_tv: minimum aeolian threshold velocity (ms^{-1}), and drift and resultant drift potentials for the various sites.

Lancaster's (1988) mobility index combines rainfall, wind and evapotranspiration data. Fig. 3, Fig. 4 show that there is a rainfall gradient from −31° latitude (Eucla and Nullarbor) with low rainfall and a higher sediment mobility index, to −33° (Esperance, Elliston), and even on to −34° as is the case of Port Lincoln, with a higher rainfall and lower index of sand mobility. This index, which uses rainfall as a factor to explain the sedimentary mobility, has a strong relationship with latitude (reinforced with the data shown in Fig. 3). Rainfall varies across the GAB by latitude, and thus, the relationship between latitude and mobility is strong. Tsoar's (2005) index uses only wind data and has a slightly greater relationship with longitude (see further discussion below) and it performs better in arid sites with different sediment supplies.

4.3. Distribution of the foredune modes along the GAB coastline and relationship with rainfall (P) and drift potential (DP)

Between Esperance and Israelite Bay where the rainfall is around 617.50 mm and the aeolian drift potential is 47.93 DP (Fig. 5-A; Table 2) there is a mix between continuous foredune (type 1 and 2) and discontinuous foredune (high rainfall and low drift potential) modes. Between Israelite Bay and the coast of Balladonia the distribution is generally similar to that observed along the previous stretch where there are no weather stations available. However, the first nebkhas appear occasionally in some beach-dune systems especially on the Balladonia coast, where, in addition, a large cliff (to the northeast) and smaller cliffs (to the south) occur (Fig. 5-A). Between Eyre and Eucla (B), three foredune modes were identified: generally continuous foredune (1), followed by discontinuous foredune, and to a lesser degree, continuous foredune (2) and nebkhas. Finally, a large cliff occurs, located at longitude 130°. The rainfall in this area is around 273-348 mm and aeolian drift potential 110–197 DP (medium-low rainfall and high drift potential).

Between Nullarbor and Streaky Bay (C) discontinuous foredunes have the greatest presence, followed by nebkhas and finally transgressive dunefield or continuous foredune (types 1 and 2) where rainfall is between 254 and 366 mm and drift potential is 56–172 DP (medium-low rainfall and medium-high drift potential). Although estuaries/semi-enclosed bays were removed for the statistical analysis, this area has a large number of these coastal landforms. Finally, between Streaky Bay and Port Lincoln (D), there is a large area of cliffs and rocky coasts but the most common foredune mode is the discontinuous foredune, followed by continuous foredune (1) and (2) and to a lesser degree, nebkhas. In this area rainfall is 435–495 mm and drift potential is 23–49 DP (moderately high rainfall and low drift potential).

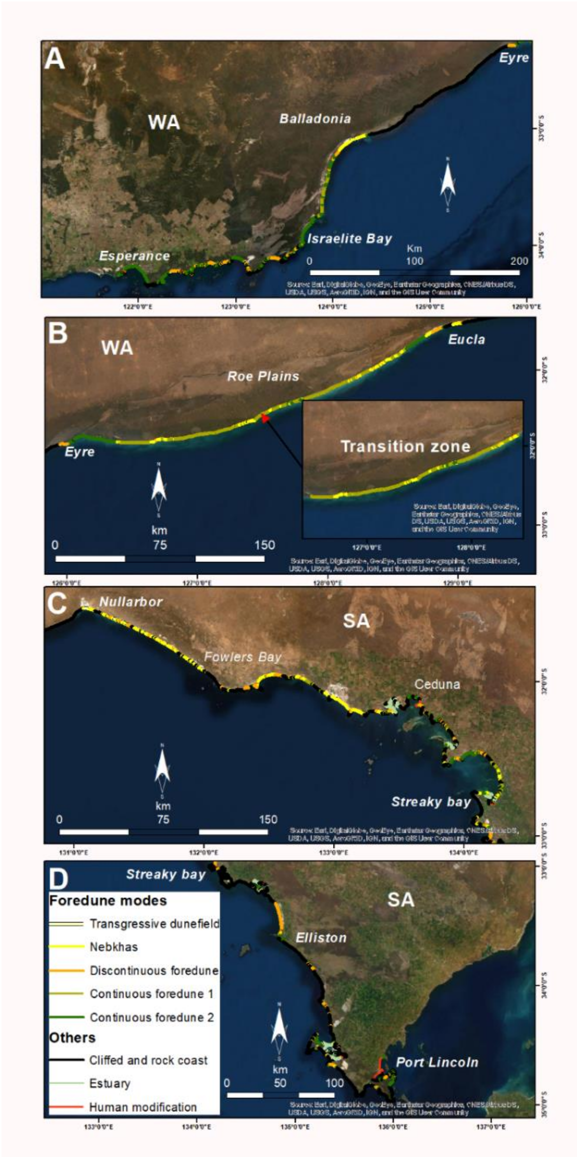

Figure 5. Coastline classified according to the foredune mode and/or coastal landform type.

In general, while there is some variability, the mapping and coastal classification shows that foredune modes with low vegetation cover and high sediment supply (e.g. nebkhas), have the highest proportion of occurrence near 31° and 32° latitudes as shown in Table 3 (254–366 mm rainfall and 56–197 DP). Discontinuous foredunes appear mainly in 33° latitude (Table 3) with 435–450 mm rainfall and 23–45 DP, and continuous foredunes in 34° latitude (Table 3) with 495–617 mm rainfall and 47–49 DP.

Table 3. Contingency table with relationships between latitude or longitude and foredune modes.

			Transgressive dunefield	Nebkhas	Discontinuous foredune	Continuous foredune 1	Continuous foredune 2
Latitude (°)	31	count	28	65	28	16	6
		% total	4.7	11	4.7	2.7	1
	32	count	9	49	46	24	46
		% total	1.5	8.3	7.8	4	7.8
	33	count	4	5	60	8	106
		% total	0.7	0.8	10.1	1.3	17.9
	34	count	3	4	32	0	54
		% total	0.5	0.7	5.4	0	9.1
	Total	count	44	123	166	48	212
		% total	7.4	20.7	28	8.1	35.8
Longitude (°)	121	Count	0	0	0	0	8
		% total	0	0	0	0	1.3
	122	Count	1	0	3	0	8
		% total	0.2	0	0.5	0	1.3
	123	Count	0	0	28	0	52
		% total	0	0	4.7	0	8.8
	124	Count	3	7	13	8	32
		% total	0.5	1.2	2.2	1.3	5.4
	125	Count	0	0	0	0	1
		% total	0	0	0	0	0.2
	126	Count	0	3	3	1	7
		% total	0	0.5	0.5	0.2	1.2
	127	Count	0	8	1	7	0
		% total	0	1.3	0.2	1.2	0
	128	Count	0	13	3	12	4
		% total	0	2.2	0.5	2	0.7
	129	Count	0	10	3	5	2
		% total	0	1.7	0.5	0.8	0.3
	130	Count	0	0	0	0	0
		% total	0	0	0	0	0
	131	Count	9	10	5	0	2
		% total	1.5	1.7	0.8	0	0.3
	132	Count	17	33	12	4	2
		% total	2.9	5.6	2	0.7	0.3
	133	Count	5	17	14	2	6
		% total	0.8	2.9	2.4	0.3	1
	134	Count	3	16	34	9	28

	% total	0.5	2.7	5.7	1.5	4.7
135	Count	6	6	47	0	60
	% total	1	1	7.9	0	10.1
Total	Count	44	123	166	48	212
	% total	7.4	20.7	28	8.1	35.8

The number of coastal stretches classified according to foredune mode and their percentage are shown in Table 3. At 31° latitude, the largest percentage of cases is represented by nebkhas (11%) and 45.45% (or 65 counts) of all coast with foredune mode were measured in this latitude. This was followed by transgressive dunefields, discontinuous foredunes, continuous foredune (type 1 and 2), (4.7%, 4.7%, 2.7% and 1% respectively). However, Continuous foredunes (type 2), with high vegetation cover and low sediment supply have a higher representation in latitudes 33° and 34°. For example, at 34° latitude, continuous foredune (type 2) has the highest percentage (9.1%) and 58.06% (54 counts) of the total coast, followed by discontinuous foredune, nebkhas and transgressive dunefield (5.4%, 0.7%, 0.5% respectively). Continuous foredunes of type 1 are not detected.

With respect to longitude, overall, foredune modes with a low vegetation cover and high sediment supply, especially nebkhas, have a high proportion to the East (131° and 135°). For example, transgressive dunefields have the highest percentage occurrence in the Eastat longitude 132° (2.9%) and 25% (17 counts). Nebkhas show a similar distribution to the East, where the highest percentage (5.6%) and 48.52% (33 counts) is also observed at 132°. Note that the lowest rainfall zones lie within the ~126° to 132° longitude range. Discontinuous foredunes show a regular distribution along the bay related to the longitude with the highest percentage in the West (123°, 4.7% and 25% of the total coast with 28 counts), and East (135°, 7.9% and 39.49% of the total stretches with 47 counts), but in the middle of the bight, they have a low proportion. Continuous foredunes (type 1) have a high percent occurrence in the middle of the Bight (128°, 2% with 12 counts or 37.5% of coast measured in this longitude) although the percentage is low. Continuous foredunes (type 2) comprise a high number of cases in the West and decrease to the East (except at 135°) with a very high percentage (10.1%) and 50.42% of the total coast in this longitude (60 counts). At 135°, an exception is found, and corresponds with the highest rainfall zone. The foredune mode with high vegetation cover and low sediment supply continuous foredunes (type 2), have a higher representation in the West (121°–126°) with 100% and 50% (8 and 7 counts) respectively of the total coast in these longitudes. Rainfall increases from 126° towards the west (121°). Lancaster's mobility index is 30.92 and therefore indicates inactive dunes, while according to Tsoar's mobility index the dunes are covered by vegetation (0.08 index).

Fig. 6 displays a regression analysis of different foredune modes and latitude and longitude in the GAB. The percentage of the occupation of the coastline classified per foredune mode in each latitude group and longitude group is used and shown in the scatter diagrams (Fig. 6). Although the results are not quite the same as those shown above, the trends are similar. With respect to latitude (Fig. 6-A), nebkhas are the dominant and most significant foredune mode in the most northerly latitude (31°) and lowest rainfall zone, and they decrease in dominance as the latitude (and rainfall) increases ($R^2 = 0.9744$). A similar trend occurs for transgressive dunefields. Continuous foredunes (type 2) show a low percentage at 31° latitude, and higher when latitude increases to 34° ($R^2 = 0.7407$), and where the relatively higher rainfall occurs.

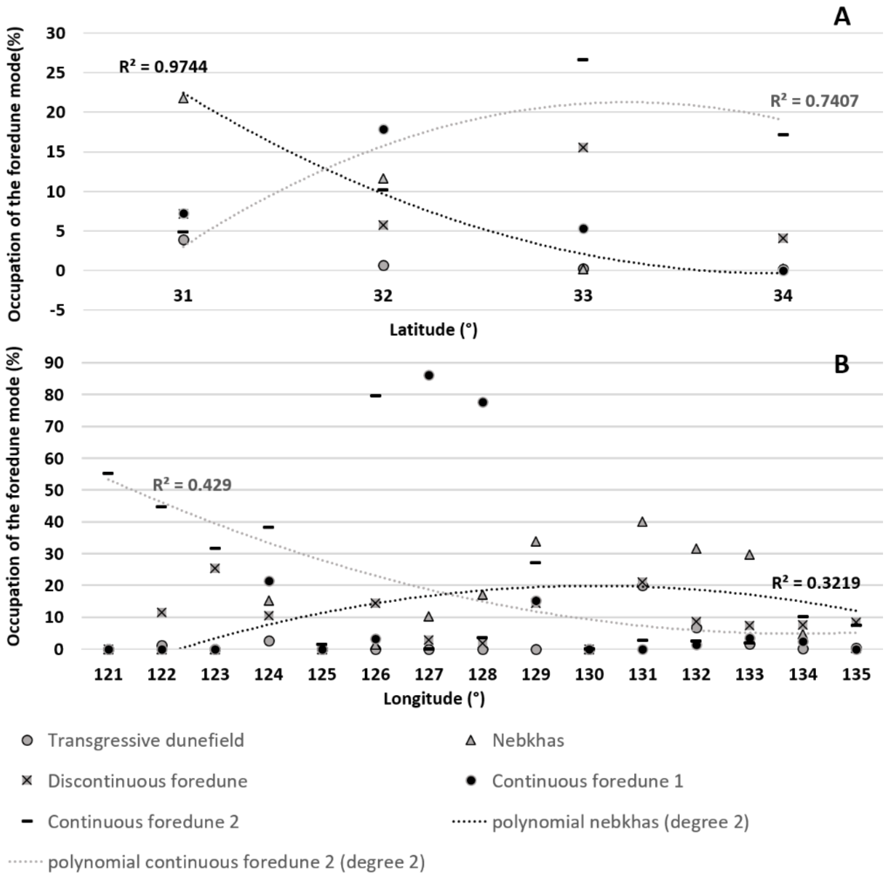

Fig. 6. Percentage occupation of the foredune modes and transgressive dunefields on the coastline per latitude and longitude. Rainfall increases as one trends from 31° to 34° latitude.

In Fig. 6-B the trend is similar to the contingency table (Table 3). Nebkhas increase in percentage occurrence to the East but with low significance ($R^2 = 0.3219$). Transgressive dunefields occur all across the Bight as demonstrated by Short and Fotheringham (1986) and our mapping. The continuous foredune mode (type 2) increases to the West with low significance ($R^2 = 0.429$) and continuous foredunes (type 1) show a regular distribution. Possibly the significances may be higher, but the region around 130° is totally occupied by cliff and rocky coast, and the percentages for the other categories are 0%.
The transition zone (indicated in Fig. 5-B), which was calculated through the crosses of the polynomial lines in Fig. 6 (32° latitude and 127° longitude), shows a similar proportion between foredune modes which have low vegetation cover and high sediment supply (e.g. nebkhas), and continuous foredunes where their characteristics are opposite (high vegetation cover and low sediment supply; Fig. 6 and Table 3. This is shown in the longitude correlation at 1.3% and 1.2% respectively, and the same occurs in the latitude data between nebkhas, discontinuous foredunes and continuous foredunes with 8.3%, 7.8% and 7.8% respectively. These results could indicate that in this section of coast the largest changes are produced in the beach-dune systems of the study area with N-S and W-E directions (see further discussion below).

4.4. Distribution of vegetation in the field plots and its role on the foredune mode

Table 4 shows the results of the vegetation samples located in the beach-dune systems of Eyre (−32.25°, 126.28°), Eucla (−31.71°, 128.93°), Fowlers Bay (−31.99°, 132.41°), Point Bell (−32.15°, 133.11°) and Sleaford (Port Lincoln, − 34.86°, 135.76°). The first level indicates the number of plant species in the beach-dune system, species that are herbaceous or sub-shrubby, and shrub species or trees. At a second level the plots are classified by the foredune mode that is detected, and from this classification the number of herbaceous or sub-shrub species is observed per type of foredune, and the number of shrub species or trees.

Results indicate that the number of species in the beach-dune system decreases as longitude and latitude increase. The same trend is identified in the number of herbaceous or sub-shrub species, and shrub or tree species. This distribution is totally opposite to the rainfall data which were explained previously such that where the rainfall is higher, normally the number of plant species is higher too, this trend is not observed in the study area. This behavior could be explained by four possibilities: i) Biodiversity depends not only on climatic factors but also on the variability of these factors (Katz and Brown, 1992; Parmesan et al., 2000). For example, the variability in rainfall can alter the key carbon cycle processes and the composition of the plant community, independently of changes in total precipitation (Knapp et al., 2002). In addition, faced with a current climate change scenario (Plummer et al., 1999; Easterling et al., 2000), rainfall regimes are increasingly variable, as well as atmospheric warming is increasing (IEA, 2001), and a distribution related only to precipitation loses its meaning. ii) Global change could be related with environmental changes in the dunefields that have undergone moderate human pressure in the past (Paton, 2010). Pastoral activities and especially the introduction of invasive species of fauna and flora, such as is the case of European rabbits (*Oryctolagus cuniculus*), have been drivers of landscape changes in South Australian dunefields (Hilton et al., 2007; Mutze et al., 2010; Paton, 2010; Saunders et al., 2010; Moulton et al., 2018). The main impact was the suppression of the regeneration of native trees and shrubs in the coast (Bird et al., 2012; Cooke, 2014; Mutze et al., 2016), as has occurred in the Younghusband Peninsula transgressive dunefields (Moulton et al., 2018). iii) The influence of the southwest Australia botanic region, considered as a biodiversity hotspot (Myers et al., 2000). Its presence might explain and contribute to the high number of plant species found in Eyre and Eucla (West Australia), where low rainfall and high temperature are the main climatic characteristics. In addition, from Nullarbor (South Australia, Fig. 1) to the Roe Plain area (West Australia), identified as a transition zone (Fig. 4), a large disjunction in the distribution of many southern Australian plants and animals is observed (Main et al., 1958; Mackerras, 1960; Green, 1964; Parsons, 1969). It may be postulated that after the "Great Arid Period", when the formation of the great dune systems and the removal of the soil from the Nullarbor occurred, a barrier preventing continuity between the flora of South-Western Australia and that of South Australia was created (Burbidge, 1960). iv) The evolutionary stage of the beach-dune system could explain the plant distribution data in Table 4. In general, if the dune system is in an early stage of development, then it is possible that foredunes have not formed yet, and sediment is directly transferred from the backshore into the dunefield (Hesp, 1989). Alternatively, still at an early stage of development, it is possible that there is only one, or a few pioneer plants present above the backshore. Once a dunefield phase has moved inland or alongshore, foredunes may form along the backshore and a larger number of plants can establish. Thus, age and stage of evolution can influence the degree of foredune development and plant diversity and density (Hesp, 2013). In this sense, the aeolianites of the dune systems to the east of the GAB belong to the Holocene (James and Bone, 2017), which could be an indicator that these are young systems.

Table 4. Vegetation and foredune modes in the plots studied along the GAB.

				EYRE (19 species)				EUCLA (17 species)				FOWLER (15			POINT BELL (15 species)				PORT LINCOLN (8)	
	Total herb or undershrub species in the plot			11 species				9 species				8 species			8 species				7 species	
		Foredune		*FD1*	*FD1*	*FD1*	*FD1*	*FD1*	*DFD*	*N*	*N*	*FD1*	*DFD*	*DFD*	*N*	*N*	*DFD*	*DFD*	*DFD*	*N*
	PLANT SPECIES	**ORIGIN**	**LIFE CICLE**	**E1**	**E2**	**E3**	**E4**	**Eu1**	**Eu2**	**Eu3**	**Eu**	**F1**	**F2**	**F3**	**P1**	**P2**	**P3**	**P4**	**PL_1**	**PL_2**
Herb or undershrub	*Arctotheca populifolia*	Alien	Perennial							x	x		x	x	x	x			x	x
	Cakile maritima	Alien	Annual	x	x	x		x	x	x	x	x	x	x	x	x	x	x	x	x
	Carpobrotus virescens	Native	Perennial	x	x	x	x	x				x	x	x		x	x	x		
	Carpobrotus edulis	Alien	Perennial																x	
	Euphorbia paralias	Alien	Perennial		x	x		x	x	x	x					x	x	x	x	x
	Ficinia nodosa	Native	Perennial	x	x	x	x	x	x			x	x	x		x	x	x		
	Salsola kali	Alien	Annual	x	x		x	x	x	x		x		x		x	x			
	Schenkia australis	Native	Annual		x															
	Senecio lautus	Native	Annual	x								x								
	Sonchus oleraceus	Alien	Annual	x																
	Spinifex hirsutus	Native	Perennial	x	x	x	x	x	x		x								x	x
	Spinifex longifolium	Native	Perennial									x	x	x		x	x	x		
	Tetragonia implexicoma	Native	Perennial	x	x	x	x	x											x	
	Threlkeldia diffusa	Native	Perennial	x	x	x		x				x	x	x	x	x	x	x	x	
	Total herb or undershrub species per foredune			***9***	***9***	***7***	***5***	***8***	***5***	***4***	***4***	***7***	***6***	***7***	***3***	***8***	***7***	***6***	***7***	***4***
	Total Shrub or tree species in the plot			**8 species**				**8 species**				**7 species**			**7 species**				**1 species**	
Shrub or tree	*Acacia cyclops*	Native	-	x	x	x	x	x												
	Acacia anceps	Native	-									x						x		
	Alyxia buxifolia	Native	-						x			x	x	x		x	x	x		
	Atriplex cinerea	Native	-	x	x	x	x	x	x	x	x	x	x	x	x	x	x		x	x
	Exocarpus syrticola	Alien	-		x															
	Leucophyta brownii	Native	-	x	x	x	x	x		x		x			x	x	x	x		
	Myoporum insulare	Native	-					x	x											
	Nitraria billardierei	Native	-	x	x	x	x	x	x	x	x	x			x	x	x	x		
	Scaevola crassifolia	Native	-	x	x	x	x	x	x					x				x		
	Spyridium globulosum	Native	-		x															
	Westringia diampieri	Native	-		x				x			x	x	x		x	x	x		
	Total shrub or tree species per foredune			***5***	***8***	***5***	***5***	***6***	***6***	***3***	***2***	***6***	***3***	***4***	***3***	***5***	***5***	***6***	***1***	***1***

E1: study plot 1 in Ecula. N: nebkhas. FD1: continuous foredune (type 1). DFD: discontinuous foredune

In the second level, dune systems such as those at Eyre have a continuous foredune (1). Practically at the same latitude but at longitude 133° (Point Bell), nebkhas and discontinuous foredunes are present together. In the north, the Eucla dune system could be the most geodiverse with respect to the rest of the dune systems studied. This system is formed by continuous foredunes (type 1), discontinuous foredunes and nebkhas. However, Fowlers Bay combines continuous foredunes (type 1) with discontinuous foredunes. Sleaford (Port Lincoln) is located further South, where discontinuous foredunes and nebkhas were observed.

In general, the largest number of herbaceous species of sub-shrubs is found in the continuous foredunes of type 1 (5–9 plants species), followed by the discontinuous foredunes (5–7 plants species). Finally, the nebkhas have a reduced number of species (3–4 plants species), except at Point Bell which has 8 of them. According to the shrub or tree vegetation, the trend is similar to the previous ones. Continuous foredunes (1) have 5 to 8 plant species, the discontinuous foredunes have between 3 and 6 plant species, except in Port Lincoln which has just one. Nebkhas have between 1 and 3 plant species. The nebkha foredune mode is dominated by rhizomatous grasses, principally *Spinifex hirsutus* or *Spinifex longifolia*, which are crucial for dune formation due to presence of the rizhomes (both are in all beach-dune systems, alternating between them). Although these are perennial species, because this factor, in addition to the availability of seeds or annual species (e.g. *Cakile maritima* is in all beach-dune systems or *Salsola kali*), are important for the vegetation cover (Davies, 1977; Maun and Lapierre, 1986; Hesp, 2002; Maun, 2009; Hesp and Walker, 2013; Goldstein et al., 2017). The vegetation role is important in foredune and nebkha formation. In the nebkhas case, the annual or biannual species such as *Salsola kali*, *Cakile maritima* tend to give rise to small nebkhas. However, if the plant species are perennial, shrub or tree, permanent nebkhas can be formed (e.g. when *Atriplex cinerea* is present) due to the plant size, shape, growth, density and shape and rooting habits. Every species associated to nebkhas or continuous or discontinuous foredune ridges have rhizomatous roots or produce new stems to replace buried ones (Holland, 1981; Hesp, 1991; Maun, 2009), as well as factors such as the wind, sediment supply and age (Hesp and McLachlan, 2000; El-Bana et al., 2002; El-Sheikha et al., 2010; Hesp and Smyth, 2017). Finally, when nebkhas are detected, in general, they are often co-located with discontinuous foredunes, as one might expect since there is often a fine line between classifying a line of nebkhas versus a discontinuous ridge. If the dunes begin as nebkhas on the backshore, they can grow in width and height, merge with other nebkhas and commonly form discontinuous or continuous ridges (with greater floristic richness as seen in Table 3) (Hesp, 2002; Hesp and Walker, 2013; Keijsers et al., 2015).

Table 5. Correlations between contingency table and occupation (%) of the foredune modes along the coastline (%).

		Latitude (N=4)				
Foredune		TD[2]	N[2]	DFD[2]	FD1[2]	FD2[2]
TD[1]	Correlation coeficient	**0.994(**)**	0.812	-0.611	0.38	-0.799
	Sig. (bilateral)	0.006	0.188	0.389	0.62	0.201
N[1]	Correlation coeficient	0.947	**0.980(*)**	-0.533	0.701	-0.856
	Sig. (bilateral)	0.053	0.02	0.467	0.299	0.144
DFD[1]	Correlation coeficient	-0.17	-0.343	**0.794**	-0.097	0.719

	Sig. (bilateral)	0.83	0.657	0.206	0.903	0.281
FD1[1]	Correlation coeficient	0.189	0.627	0.255	**0.953(*)**	-0.196
	Sig. (bilateral)	0.811	0.373	0.745	0.047	0.804
FD2[1]	Correlation coeficient	-0.79	-0.907	0.751	-0.598	**0.972(*)**
	Sig. (bilateral)	0.21	0.093	0.249	0.402	0.03
		Longitude (N=15)				
TD[1]	Correlation coeficient	**0.649(**)**	-0.185	**0.612(*)**	-0.103	-0.2
	Sig. (bilateral)	0.009	0.509	0.015	0.714	0.475
N[1]	Correlation coeficient	0.289	-0.316	0.185	0.293	0.385
	Sig. (bilateral)	0.296	0.252	0.51	0.289	0.157
DFD[1]	Correlation coeficient	-0.355	-0.257	-0.35	-0.157	0.106
	Sig. (bilateral)	0.194	0.355	0.201	0.576	0.706
FD1[1]	Correlation coeficient	**.681(**)**	0.111	**.790(**)**	0.177	-0.173
	Sig. (bilateral)	0.005	0.693	0	0.527	0.537
FD2[1]	Correlation coeficient	0.24	**.720(**)**	-0.036	0.017	-0.081
	Sig. (bilateral)	0.388	0.002	0.898	0.952	0.774

**The correlation is significant at 0.01 level (bilateral). *The correlation is significant at 0.05 level (bilateral). [1] Contigency table data (%). [2] Percent occurrence of the foredune modes and other coastal types along the GAB coastline. TD: Transgressive dunefield. N: Nebkhas. DFD: Discontinuous foredune. FD1: Continuous foredune 1. FD2: Continuous foredune 2.

4.5. General discussion

Given the strong correlation between foredune mode and latitude (and therefore rainfall) along the coast in the GAB, a general diagram of the relationship between annual precipitation, wind drift potential and coastal landform type and foredune mode is presented in Fig. 7. The Köppen-Geiger climate zones are also shown in Fig. 7. The presence of foredune modes and coastal dune/landform types (transgressive dunefield, nebkha, discontinuous foredune and continuous foredunes types 1 and 2) appears to be strongly controlled by rainfall and drift potential in the GAB. Between ~200–300 mm annual rainfall, with a high drift potential and an arid desert climate, nebkha predominate. In latitude 32°, in the ~300–400 mm annual rainfall zone, with a lower drift potential, and an arid steppe climate, a clear pattern is not observed in relation to the foredune mode. Continuous foredunes 1 and discontinuous foredunes are strongly represented in regions experiencing between ~400–500 mm annual rainfall, a low drift potential and a warm temperate climate. Above ~500 mm continuous foredunes predominate with very low drift potential and a Mediterranean climate (Fig. 7).

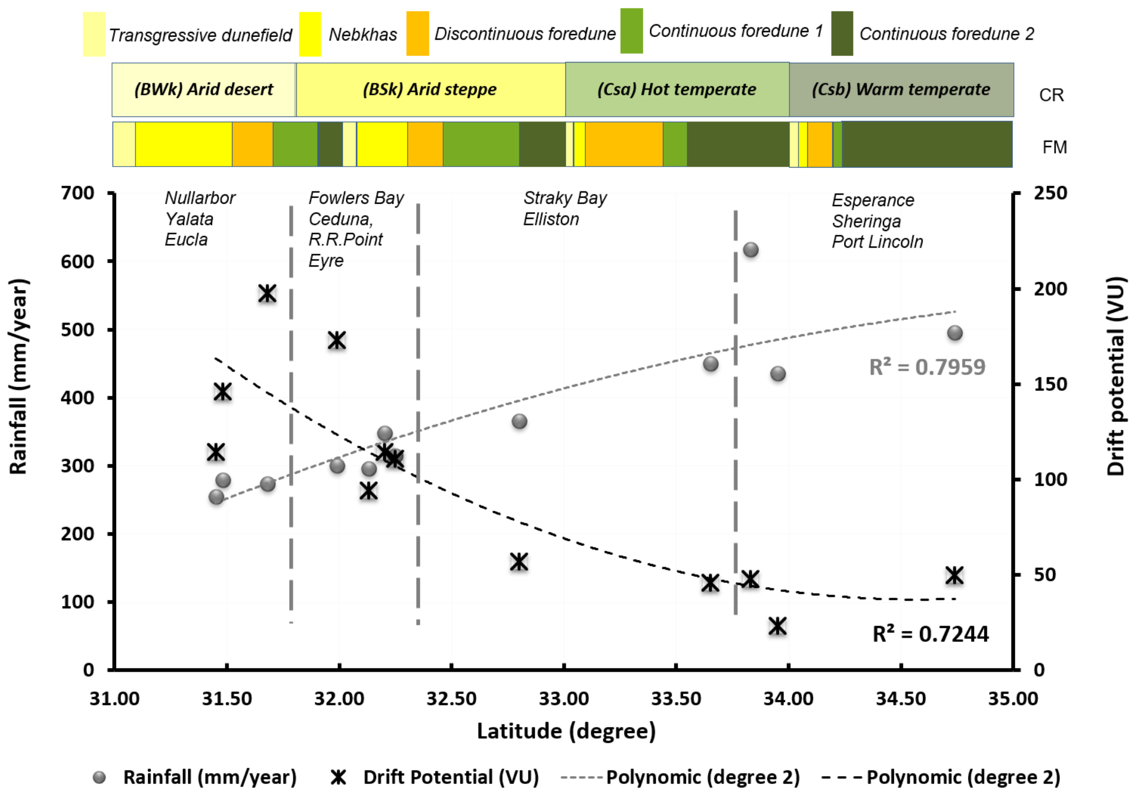

Figure 7. Relationships between annual rainfall, aeolian drift potential, latitude, Köppen-Geiger climate zones (CR), foredune modes (FM), and transgressive dunefields for the GAB. BWk: Arid, desert, cold. BSk: Arid, steppe, cold. Csa: Temperate, dry summer, hot summer. Csb: Temperate, dry summer, warm summer.

The trends identified with respect to latitude indicate that the foredune modes with low vegetation cover and high sediment supply, were directly related to the mobility indices (Fig. 4), and changes in precipitation and temperature (Fig. 3). Towards the North (around latitude 31°), the highest mobility values are related with high evapotranspiration and low total annual rainfall. In studies on arid coastal dunefields characterized by low rainfall (around 80 and 300 mm), nebkha are identified as the main landform comprising the foredune, and continuous foredunes were absent or poorly represented (Khalaf et al., 1995; Edgell, 2006; Hernández et al., 2007; Alonso-Bilbao et al., 2007; Khalaf and Al-Awadhi, 2012; Al-Awadhi and Al-Dousari, 2013; Cabrera-Vega, 2010; Hernández-Calvento et al., 2014; Hernández-Cordero et al., 2015; García-Romero et al., 2017; Hernández-Cordero et al., 2017; Hesp et al., submitted). In contrast, in some temperate to tropical regions, where climatic conditions are favorable for the development of a higher vegetation cover due to high rainfall, the foredune zones may also be formed by nebkhas (McLachlan, 1990; Wiedemann and Pickart, 1996; Hesp, 2008), but the vegetation is usually rhizomatous perennial herbaceous species and glycophytes, many of them grasses (for example, *Elymus farctus*, *Ammophila* spp., *Spinifex sericeus*, *Austrofestuca littoralis*, *Desmoschoenus spiralis*). If the dunes begin as nebkhas, they can grow in width and height, merge with other nebkhas and commonly form continuous foredunes (Holland, 1981; Hesp, 2002; Hesp and Walker, 2013; Keijsers et al., 2015). A similar case was observed in this study.

Future studies might consider a larger variety of dune formation scenarios. These could include dune fields affected by fluvial discharge and therefore be influenced by changes to sediment budgets and vegetation diversity, or subject to a range of human impacts because the GAB is considered a zone with low anthropogenic influences because it is one of the largest remote coastal areas in the world (Edyvane et al., 2004).

When the trend is studied with respect to longitude, it may be seen that there is no well-defined trend. However, it is clear that the foredune with high mobility and less vegetation cover (transgressive dunefields or nebkhas) are detected towards the East, which also coincides with the latitudes where less rainfall occurs (lat: 31°–32°, long: 131°–133°). Quite the opposite occurs with the foredunes that are characterized by low sediment supply and high vegetation cover, as they tend to increase towards the West coinciding with the latitudes where the highest rainfall occurs, except in the East (lat: 34°) also an area with high rainfall. The highest relation obtained with Tsoar's (2005) mobility index (Fig. 4) is probably due to the shape of the Great Australian Bight morphology, where the coastline orientation could be influencing incident wind (speed and direction), as it seems that DP and RDP used in this index may be the factors that might correlate better with a polynomial fit rather than linear, as is the case with Lancaster's (1988) mobility index. Due to the direct and spatially uniform tension of the winds in its interior or to the larger scale response of the adjacent platforms (Gordon and Spaulding, 1987) and which has repercussions in local and non-local winds and tides (Weisberg, 1976; Smith, 1977; Elliott, 1978; Wang, 1979).

5. Conclusions

This work presents the first study on the occurrence of foredune modes and transgressive dunefields along the Great Australian Bight (GAB) coastline (2668 km) and their relationship with climate, dune mobility and vegetation traits. A marked climatic gradient, and particularly rainfall is shown to be a critical driver of foredune mode and the occurrence of active transgressive dunefields in this paper.

A relationship between latitude and foredune mode is observed spatially and statistically in the GAB. The foredune mode with low vegetation and high sediment supply predominate (i.e. nebkhas) predominates around 31° latitude (to the North of the GAB), and the foredune mode with high vegetation and low sediment supply (i.e. continuous foredune) is significant to the South of the GAB (around 34°). With respect to the climate, between 200 and 300 mm annual rainfall, nebkha predominate. In latitude 32° a clear pattern is not apparent and all foredune modes are variably present where 300–400 mm annual rainfall occurs. Finally, discontinuous foredunes and continuous foredunes are strongly represented in regions experiencing above 400 mm annual rainfall. The dune mobility indices show statistical relationships with the latitude, and in addition, with the longitude. These results have served to check a spatial trend in the dune mobility on the GAB and the keeping of a similar relationship with the distribution of the foredune mode. Lancaster's (1988) mobility index uses climatic variables such as rainfall, temperature and wind, and this index shows a high relationship with latitude, whereas Tsoar's (2005) index which uses only wind data shows a high relationship with longitude. This differential behavior may be explained by the geomorphology of the GAB, where the Bight produces complex changes to the regional wind regimes and can alter the drift potential and the resultant drift potential.

In general, nebkhas occur where there are the least number of plants present. However, the number of plants occurring elsewhere is variable and not particularly correlated with other foredune modes. For example, the number of plants species is higher in the low rainfall zone. This may be due to the proximity of the low rainfall zone to the West Australian biodiversity hotspot, the introduction of invasive species of fauna (e.g. European rabbits, *Oryctolagus cuniculus*), and/or the age/stage of development of the present phase of dunefield development/evolution.

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Urban-touristic impacts on the aeolian sedimentary systems of the Canary Islands: conflict between development and conservation

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http://www.islandstudies.ca/sites/islandstudies.ca/files/ISJ-11-1-E-Garcia-Romero-et-al.pdf

Abstract

Aeolian sedimentary systems in the Canary Islands differ significantly from other European and African systems due to their natural characteristics (climate, vegetation and insular isolation). Consequently, their geomorphological processes are unique. In turn, they are areas under high human pressure from touristic development. The aim of this paper is to analyze the impacts of urban-touristic development in four aeolian sedimentary systems in the Canaries: Maspalomas, Corralejo, Lambra and Jable Sur. Spatial and surface changes of variables related to geomorphology and vegetation are obtained by photointerpretation of historical aerial photography and current orthophotos. The results indicate that the systems affected by urban-touristic development have experienced significant environmental changes. In contrast, the systems that have not been affected by building and construction of infrastructure show minor changes.

Keywords: Aeolian sedimentary systems, Canary Islands, urban-touristic development, conservation, environmental changes, GIS.

1. Introduction

The aeolian sedimentary systems of the Canary Islands show significant differences with respect to those in the rest of Europe. First, they have an arid climate, which affects the characteristics of the vegetation: low density, mainly consisting of plant communities and species shared with the northwest coast of Africa (from southern Morocco to Mauritania) and Macaronesia such as *Traganum moquinii*, or endemic species (Santos, 1993; Géhu & Biondi, 1998). Traganum moquinii is a shrubby species that generate foredunes with hummock-like morphologies in the Canary Islands; in European temperate areas, foredunes normally consist of continuous ridges due to greater plant cover, and also because the plants of these foredunes are herbaceous species equipped with rhizomes (Hernández-Cordero *et al*., 2012). Aridity, and the consequent lower vegetation growth together with the existence of constant and intense winds (NE trade winds) ensure that geomorphological processes and landform types of aeolian sedimentary systems also have certain characteristics in the Canaries that are different from those of other European systems. Thus, they are or have recently been transgressive systems with sediment input areas and, owing to their location on oceanic islands of small size, are also export areas after the sand has traveled (sometimes losing sediments), from hundreds of meters to several kilometers, across the interior of the islands as free dunes (transversal and barchanoid ridges, barchan dunes and sand sheets). This peculiarity of the island aeolian systems is essential to understanding how coastal domains far from input areas have received sedimentary contributions that create or maintain some beaches (Hernández-Calvento *et al*., 2009). It is these characteristics that determine the high average rates of advance of the dunes, between 8 m/year (SW trend) (Maspalomas in Gran Canaria) and 5.8 m/year (S trend) (Corralejo in Fuerteventura) (Jiménez *et al*., 2006; Pérez-Chacón *et al.*, 2007a). Moreover, in some systems such as Corralejo and La Graciosa, as a result of the transgressive nature of the dunes, the sands have been deposited on volcanic rocks, forming unique environments with mixed aeolian-volcanic characteristics. The sediment sources are mainly marine (Hernández-Calvento & Mangas, 2004; Mangas *et al.*, 2012; García-Sanjosé *et al*., 2014), although not from rivers as in continental areas, so the sands have a high proportion of organic components (forams, shells mollusks, seaweed meshes), in contrast to Europe and Africa where the composition is mainly terrigenous. Terrigenous components are also present and correspond to fragments of volcanic materials supplied by the erosion of ravines and sea cliffs.

Since the mid-sixties of the last century, the Canary Island' economy has been based primarily on the service sector, especially tourism. The predominant type of tourism is that of sun and beach, so most of the infrastructure is located on the coast, usually associated with sandy areas, such as beaches and dune systems. The construction of large touristic urbanizations and tourist facilities since the 1970s has led to an environmental perturbation of the dune systems of Maspalomas (Gran Canaria), Corralejo (Fuerteventura) and El Jable, Lanzarote (Hernández-Calvento *et al*., 2005; Hernández-Calvento, 2006; Pérez-Chacón et al., 2007b; Alonso *et al*., 2011; Fernández-Cabrera *et al*., 2011; Cabrera *et al*., 2013; Malvárez *et al*., 2013; Hernández-Calvento *et al*., 2014). These sandy systems endure constant tourist occupation throughout the year (Cabrera-Vega *et al*., 2013), such that there are no rest periods when the system can recover from the impacts of this human activity. As a result of their geological, geomorphological, floral and faunal value, the dune systems of the Canary Islands are protected as Biosphere Reserves, Special Areas of Conservation (SAC), Special Protection Areas (SPAs), National Parks and Nature Reserves by international (UNESCO, European Union), national and regional bodies.

The aim of this paper is to analyze the impact of urban-touristic development on four dune fields of the Canary Islands: Maspalomas (Gran Canaria), Corralejo (Fuerteventura), Lambra and Jable Sur (both on the island of La Graciosa) (Figure 1).

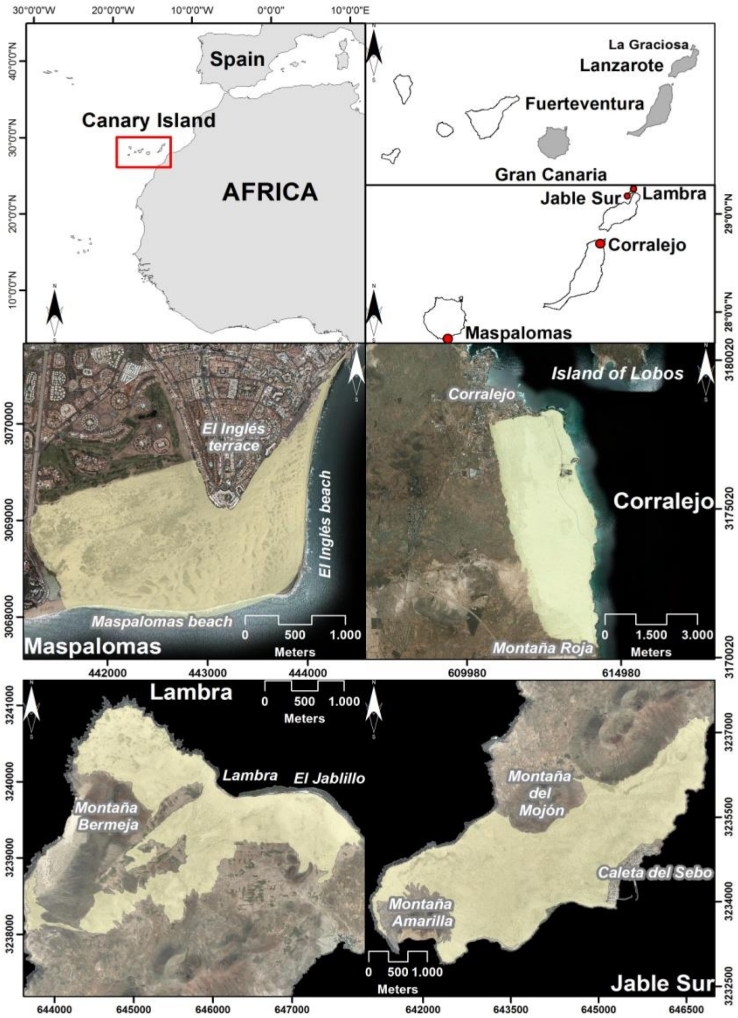

Figure 1: The four arid aeolian sedimentary systems in the Canary Islands (yellow).

1.1.Areas of study

Geomorphological diversity and degree of tourist pressure experienced by these systems in recent decades has been taken into account for the selection of the four dune fields. Thus, we intend to assess the relationship between the degree of human impact on these systems and changes in their geomorphology and vegetation. We now describe the most significant features of the four systems.

Maspalomas

With an area of 360.9 ha, this dune field is located in the south of the island of Gran Canaria. According to the classification of Hesp and Walker (2013), Maspalomas is a transgressive dune field. Sediments enter the system via El Inglés beach in the east, move inland as free dunes driven by the trade winds from E-NE, and finally return to the sea at Maspalomas beach (in the south) (Hernández-Calvento, 2006). Maspalomas has three different zones according to the aeolian sedimentary activity associated with specific landforms that are conditioned by the surrounding terrain as well as touristic development (Hernández-Cordero *et al*., 2015a): *the active area*, where free dunes up to 14 meters high predominate (from the coast inland, the following landforms are present: beach, foredune, barchan dunes and sand sheets, deflation surfaces, barchanoid ridges and interdune depressions); *the semi-stabilized area* formed by erosional landforms such as deflation surfaces, and depositional landforms such as barchan dunes, sand sheets and hummock dunes; *the stabilized area*, consisting of dunes stabilized by vegetation and interdune depressions. Vegetation consists of 19 plant communities, with the communities of *Cyperus capitatus-Ononis serrata*, *Tamarix canariensis, Launaea arborescens, Suaeda mollis* and *Traganum moquinii* (Hernández-Cordero *et al*., 2015a) standing out for their surface and ecological importance.

Corralejo

Located in the north of the island of Fuerteventura, it has an area of 1812.4 ha. According to the classification of Hesp and Walker (2013) this system, like Maspalomas, constitutes a transgressive dune field. Depending on the age of its materials, there are three zones (Fernández-Galván *et al*., 1982): *the old jable*, *the clay jable* and *the current jable*. The first two areas are characterized by stabilized dunes, whereas the current jable features mobile dunes (Criado, 1987). The old jable consists of cemented sands (organic) with calcium carbonate. The intermediate-age clay jable, consists of a mixture of clay, volcanic rocks and aeolian uncemented sands, with the stabilized dunes predominating. The current jable can be divided into three areas: sand input areas, the dune field, and areas of export of sand to the sea (Criado, 1987). Free dunes, such as sand sheets, barchanoid ridges and barchan dunes, predominate in mobile dunes, plus hummock dunes formed by plant species (Criado *et al*., 2007; Gutiérrez-Elorza *et al*., 2013; Malvárez *et al*., 2013). Sands access the land in the north and northeast of the island and are mobilized southward by the trade winds, which come from the north due to the effect of the Lobos island (Criado, 1987). Some of the sediments reach the sea along the southeast coast while others move south, and eventually reach the southern boundary of the system at the Montaña Roja volcanic cone. The main plant communities are: the *Traganum moquinii* community found in foredunes and output dunes (the dunes leading to the sea), communities of *Euphorbia paralias*, of *Ononis hesperia*, and of *Launaea arborescens* in mobile dunes, and communities of *Salsola vermiculata* and *Launaea arborescens* in the stabilized dunes (Fernández-Galvan *et al*., 1982; Fernández-Cabrera *et al*., 2011).

Lambra

This system is located in the north of the island of La Graciosa with a surface area of 401.1 ha. Following the classification of Hesp and Walker (2013), Lambra is a transgressive sand sheet. Five geomorphological units can be observed (Pérez-Chacón *et al*., 2010): coastal environment-input of sediments, mobile environment, transportation environment, detrital environment and mixed environment. Stabilized dunes and hummock dunes predominate and, to a lesser extent, sand sheets also appear. In this system nine plant communities are identified (Pérez-Chacón *et al*., 2010; Hernández-Cordero *et al*., 2015b): the *Salsola vermiculata* community, *Traganum moquinii* community, *Launaea arborescens* community, *Suaeda vera* community, *Polycarpaea nivea* community, *Frankenia ericifolia* community, *Chenoloides tomentosa* community, *Astydamia latifolia* community, and the *Mesembryanthemum nodiflorum* community.

Jable Sur

Jable Sur covers the south of the island of La Graciosa with an area of 868.7 ha. Based on the classification of Hesp and Walker (2013), this system is also a transgressive sand sheet. Fifteen geomorphological units can be observed (Pérez-Chacón *et al*., 2010): coastal environment-input of sediment, high-hillside accumulation environment, mid-hillside accumulation environment, low-hillside accumulation environment, mobile environment, climbing dune environment, heterogeneous environment, transportation environment, mixed environment, endorreic environment, aeolian terminal environment, coastal environment-output of sediment, tidal environment, accumulative environment, and high beach environment. Stabilized dunes and hummock dunes predominate. Eleven plant communities have been identified (Pérez-Chacón *et al*., 2010; Hernández-Cordero *et al*., 2015b): the *Salsola vermiculata* community, *Traganum moquinii* community, *Launaea arborescens* community, *Ononis serrata* community, *Euphorbia paralias* community, *Ononis hesperia* community, *Cakile maritima* community, *Plantago coronopus* community, *Euphorbia regis-jubae* community, *Mesembryanthemum crystallinum* community, and the *Mesembryanthemum nodiflorum* community.

2. Methodology

2.1.Information sources

The sources of information used here were historical aerial photos and digital orthophotos.
To gather information about Lambra, Jable Sur (La Graciosa) and Corralejo (Fuerteventura) in the 1950s and 1960s (before urban-touristic development began), the photos were scanned at high resolution and subsequently georeferenced through a geographic information system (GIS). In the case of Maspalomas, the WMS service by IDECanarias was used (Table 1).

Table 1. Historical information sources.

System	Date	Scale	Spatial resolution (m)	RMS (m)	Error delineation (m)
Lambra	1954	1:5,000	1	1.05- 2.01	1
Jable Sur	1954	1:5,000	1	1.05- 2.01	1
Corralejo	1969	1:7,000	1.5	0.5- 1.01	1.45
Maspalomas	1961	WMS service by IDECanarias	0.12	*	1.2

* missing data

To collect contemporary information about these aeolian sedimentary systems, recent orthophotos were used. In the case of Maspalomas, a panchromatic orthophoto with a spatial resolution of 15 cm was used. For the other three systems, color orthophotos with 10 cm spatial resolution were used (Table 2).

Table 2: Contemporary information sources.

System	Date	Scale	Spatial resolution (m)	RMS (m)	Error delineation (m)
Lambra	2009	*	0.1	*	0.1
Jable Sur	2009	*	0.1	*	0.1
Corralejo	2009	*	0.1	*	0.1
Maspalomas	2003	*	0.15	*	0.15

* missing data

The reference system for these documents is UTM (28-N) with the WGS84 datum and the delineation error was calculated according to Robinson *et al*., 1987.

2.2.Data analysis

Landforms, vegetation surfaces, bare sand surfaces, and buildings and other human infrastructure were digitized with GIS. The changes in landforms, vegetation surfaces and bare sand surfaces were used as indicators of environmental change induced by urban-touristic development. To determine the impact of urban-touristic development, these environmental changes were related to the evolution of buildings and infrastructure in systems affected to different degrees by urban-touristic development (Maspalomas, Corralejo and Jable Sur) and other unaffected systems (Lambra).

3. Results

3.2.Environmental changes in aeolian sedimentary systems

Maspalomas (1961-2003)

In the dune field of Maspalomas, landforms that have suffered a greater reduction to the point of having completely disappeared are those associated with topographic obstacles such as clifftop dunes, echo dunes, climbing dunes and falling dunes (Table 3, Figure 2). Other landforms that have suffered significant reductions are the hummock dunes, barchanoid ridges, barchan dunes and sand sheets, and the foredune. In contrast other landforms, such as the stabilized dunes and deflation surfaces, have increased their extensions. In addition, there are new landforms associated with human disturbance, including those characterized by the presence of anthropogenic deposits (Table 3). Changes in vegetation are very significant: its surface area has increased by 38.8%, while the bare sand surfaces have reduced by 61.3% in forty two years, an important amount in the smallest system that we have studied (Table 3).

Table 3: Environmental changes in Maspalomas (1961-2003).

Landform	Surface 1961 (ha)	% in the system 1961	Surface 2003 (ha)	% in the system 2003	Variation (ha)	Variation (%)
Barchanoid ridges	225.2	47.4	115.1	31.9	-110.1	-48.9
Barchan dunes and sand sheets	102.9	21.7	56.1	15.5	-46.8	-45.5

Cliff-top dunes	14.1	3.0	0.0	0.0	-14.1	-100.0
Foredune	13.2	2.8	9.5	2.6	-3.7	-28.0
Echo dunes	8.4	1.8	0.0	0.0	-8.4	-100.0
Falling dunes	6.7	1.4	0.0	0.0	-6.7	-100.0
Climbing dunes	3.3	0.7	0.0	0.0	-3.3	-100.0
Beach	18.5	3.9	32.3	8.9	13.8	74.6
Hummock dunes	44.8	9.4	11.8	3.3	-33.0	-73.7
Stabilized dunes	22.4	4.7	90.9	25.2	68.5	305.8
Deflation surfaces	10.1	2.1	32.2	8.9	22.1	218.8
Anthropogenic deposits	0.0	0.0	5.4	1.5	5.4	100.0
Sand mining	5.3	1.1	3.2	0.9	2.1	39.6
Anthropogenic deposits with sand	0.0	0.0	2.7	0.7	2.7	100.0
Slope with anthropogenic deposits	0.0	0.0	1.7	0.5	1.7	100.0
Total	474.9	100.0	360.9	100.0	-114.0	-24.0
Vegetation	90.1	19.0	125.1	34.7	35.0	38.8
Bare sand	384.9	81.04	235.8	65.3	-149.1	-61.3

Accumulation	Stabilization	Erosion	Anthropization

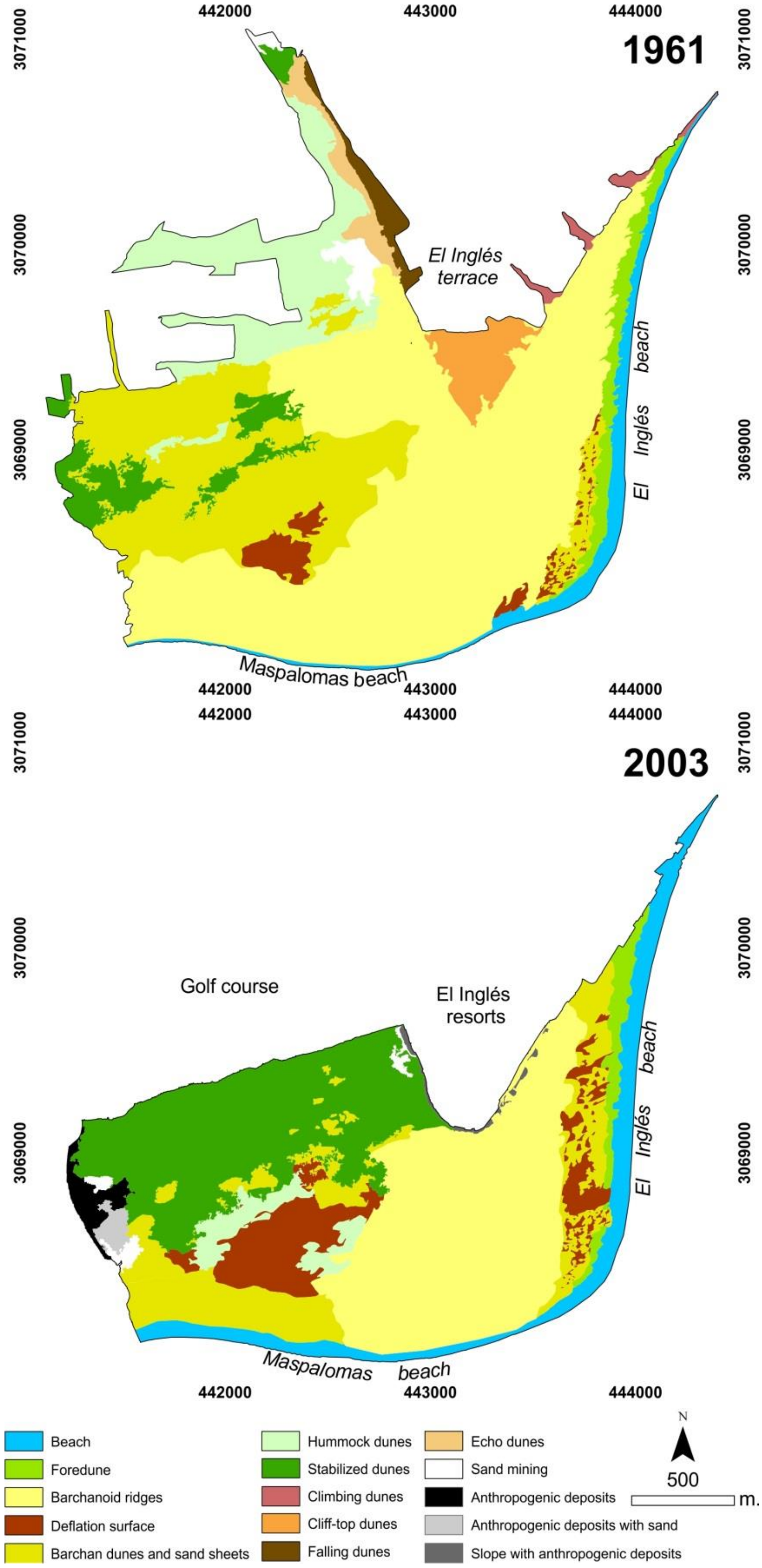

Figure 2: Landform changes in Maspalomas (1961- 2003)

Corralejo (1969-2009)

Changes in landforms in Corralejo are similar to those that occurred in Maspalomas. It is noted that landforms with higher aeolian sedimentary activity have reduced surface areas (barchanoid ridges, foredune, barchan dunes and sand sheets). The foredunes in some sectors have been replaced by buildings. However, landforms with less aeolian sedimentary activity, such as hummock dunes and stabilized dunes, have increased their surface areas (Table 4, Figure 3). Finally, in recent decades a landform that did not appear in 1969 is detected; these deflation surfaces correspond to erosive areas in the dune system. Vegetation has also changed significantly an increase in its area of 8.9%. The opposite has occurred with the bare sand surfaces that decreased by 32.0% (Table 4).

Table 4: Environmental changes in Corralejo (1969-2009).

Landform	Surface area 1969 (ha)	% in the system 1969	Surface area 2009 (ha)	% in the system 2009	Variation (ha)	Variation (%)
Barchanoid ridges and barchan dunes	782.1	37.5	369.7	20.4	-412.4	-52.7
Foredune	28.0	1.3	12.1	0.7	-15.9	-56.7
Sand sheets	167.8	8.1	10.6	0.6	-157.2	-93.7
Hummock dunes	623.7	30.0	780.8	43.1	157.1	25.2
Stabilized dunes	479.5	23.0	633.6	35.0	154.1	32.1
Deflation surfaces	0.0	0.0	5.6	0.3	5.6	100.0
Total	2081.3	100.0	1812.4	100.0	-269.0	-12.9
Vegetation	926.9	44.5	1009.8	55.7	82.9	8.9
Bare sand	1149.4	55.2	781.3	43.1	-368.5	-32.0

Accumulation Stabilization Erosion

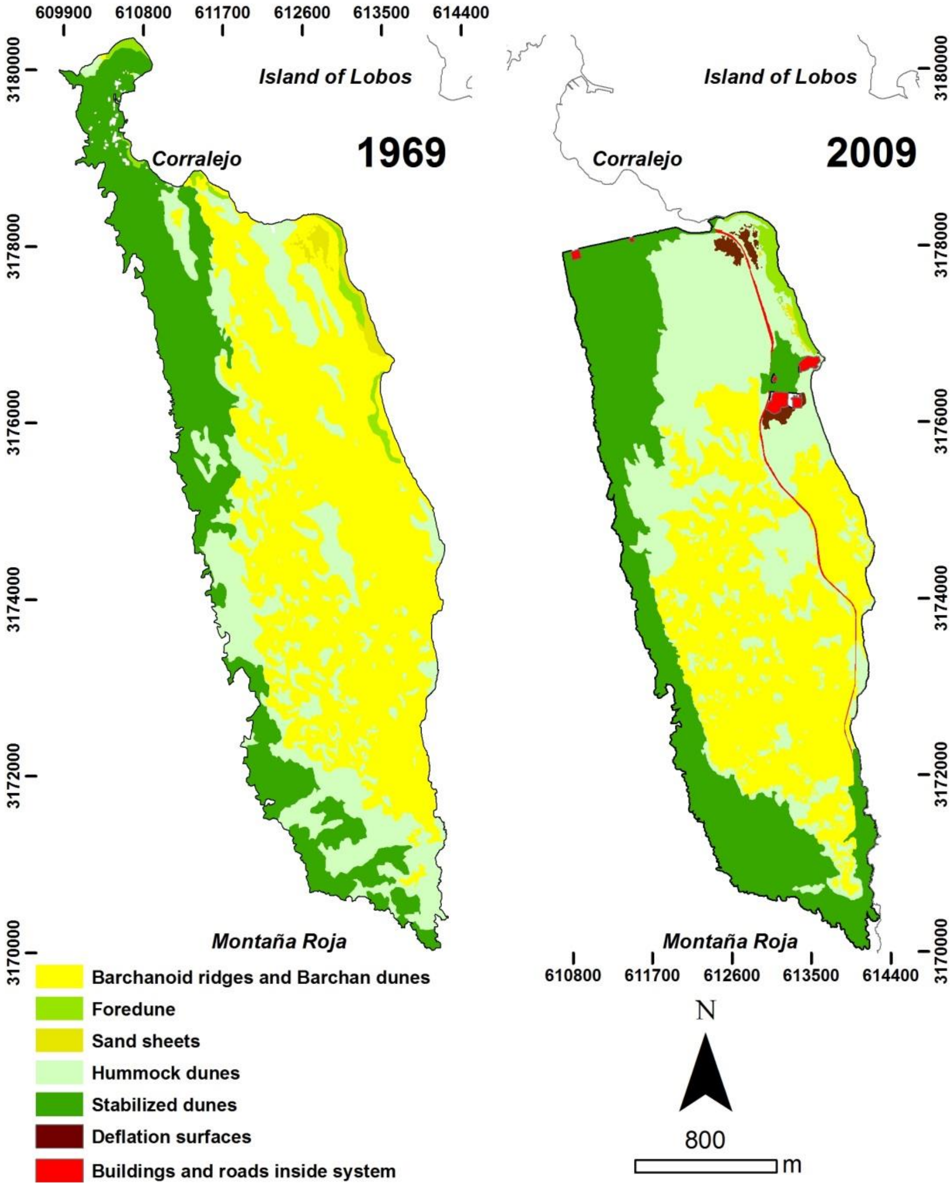

Figure 3: Landform changes in Corralejo (1969-2009)

Lambra (1954-2009)

The changes in Lambra are less significant than those detected in Maspalomas and Corralejo, but their trend is similar. The landforms with higher aeolian sedimentary activity, such as sand sheets, reduced their surface areas by 74.7%. In contrast, the hummock dunes, a landform associated with individual plants and indicative of the start of system stabilization, increased their surface areas by 1.8%. Finally, rocky outcrops remained virtually unchanged (Table 5, Figure 4). As for the vegetation surfaces, their areas also increased by 12.1%, while the bare sand area decreased by 47.1% (Table 5).

Table 5: Environmental changes in Lambra (1954-2009).

Landform	Surface area 1954 (ha)	% in the system 1954	Surface area 2009 (ha)	% in the system 2009	Variation (ha)	Variation (%)
Sand sheets	16.2	4.0	4.1	1.0	-12.1	-74.7
Hummock dunes	364.6	118.4	371.0	119.9	6.4	1.8
Rocks outcrops	16.4	4.0	16.5	4.1	0.1	0.6
Total	401.2	100.0	401.1	100.0	-0.1	0.0
Vegetation	319.2	79.6	357.7	89.2	38.5	12.1
Bare sand	82.0	20.4	43.4	10.8	-38.6	-47.1

Accumulation	Stabilization	Erosion

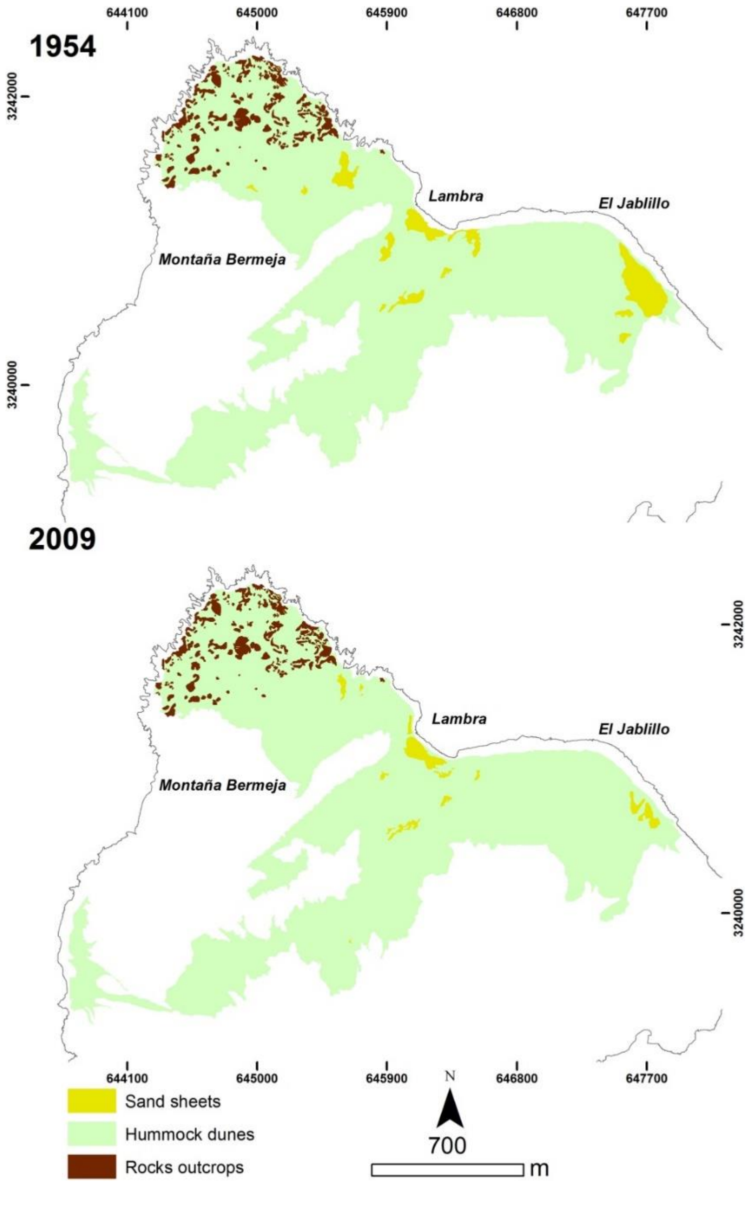

Figure 4: Landform changes in Lambra (1954- 2009)

Jable Sur (1954-2009)

In the south of La Graciosa, the landforms that experienced major changes are those related to higher aeolian sedimentary activity, such as sand sheets, which have been reduced by 98.1% (this means their virtual disappearance). However, the rest of the landforms, related to processes involving stabilization and erosion, show increased surface areas, as in the case of the hummock dunes, the same that in other systems. The marine lagoon landform, undetected until the 1950s, is a new emergence that suggests a sedimentary deficit in the system because the level of the sand decreased causing the sea level to rise (Table 6, Figure 5). The vegetation surface area has increased significantly, with a variation of 60.9%; however, the bare sand surface areas decreased by 77.5%, suggesting an additional sedimentary deficit in the system (Table 6). These latest results indicate a plant colonization process to be underway in the aeolian sedimentary system.

Table 6: Environmental changes in Jable Sur (1954-2009).

Landform	Surface 1954 (ha)	% in the system 1954	Surface 2009 (ha)	% in the system 2009	Variation (ha)	Variation (%)
Sand sheets	159.3	18.0	3.1	0.4	-156.2	-98.1
Hummock dunes	710.8	80.6	846.05	97.4	135.3	19.03
Rocks outcrops	11.6	1.4	12.2	1.4	0.6	5.2
Marine lagoon	0.0	0.0	6.3	0.7	6.3	100.0
Sand mining	0.0	0.0	1.05	0.12	1.05	100.0
Total	881.7	100.0	868.7	100.0	-13.0	-1.5
Vegetation	484.3	54.9	779.4	89.7	295.1	60.9
Bare sand	397.4	45.1	89.3	10.3	-308.1	-77.5

Accumulation	Stabilization	Erosion	Anthropization

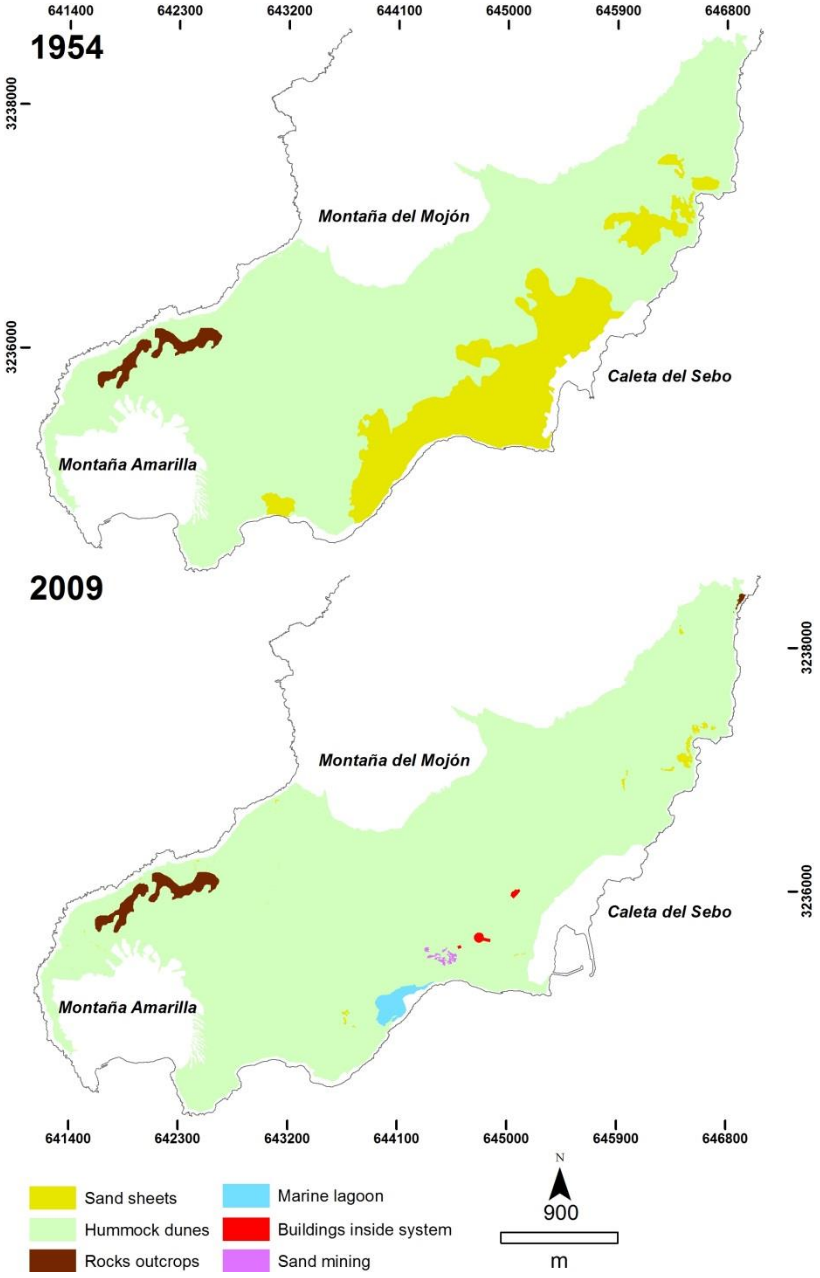

Figure 5: Landform changes in Jable Sur (1954- 2009)

3.3.Changes in built surface area

The built surface area produced by urban-touristic development has increased very significantly in Maspalomas, Corralejo and Jable Sur (Table 7). This phenomenon has been the cause of the reducion in the surface areas of these aeolian sedimentary systems by 114 ha, 269 ha and 13 ha, respectively (Tables 3, 4 and 6). In Corralejo and Jable Sur, this development is primarily located in sediment input areas (Figure 6). Only Lambra is not affected by the urban-touristic development, and its surface area has not reduced significantly.

Table 7: Changes in the surface area occupied by buildings in aeolian sedimentary systems.

Dunes systems	Surface area in 1º date (ha)	% in the system 1º date	Surface in 2º date (ha)	% in the system 2º date	Variation (ha)	Variation (ratio)
Maspalomas (1961-2003)	6.3	1.3	121.3	33.6	115.0	19.2
Corralejo (1969-2009)	4.6	0.2	233.4	12.8	228.8	50.7
Lambra (1954-2009)	0.0	0.0	0.0	0.0	0.0	0.0
Jable Sur de La Graciosa (1954-2009)	1.4	0.1	14.3	1.6	12.9	10.2

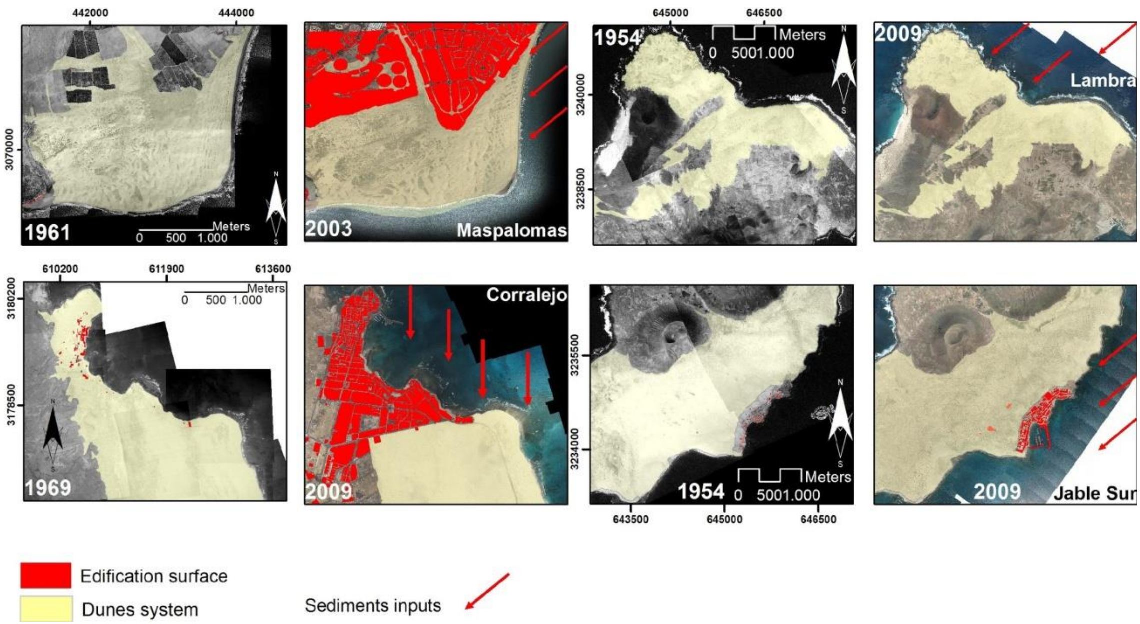

Figure 6: Evolution of the surface area occupied by buildings in aeolian sedimentary systems. Sediment input areas are indicated.

Sources: Maspalomas (Canary Islands Gobvernment´s IDE Canarias, Grafcan S.A.); Corralejo (Cartography and Photography Center, CECAF (Air Force); Grupo de Geografía Física y Medio Ambiente, IOCAG, ULPGC); Jable Sur, Lambra and La Graciosa (Cartography and Photography Center, CECAF (Air Force); Organismo Autónomo Parques Nacionales, Spanish National Ministry for Agriculture, Food and the Environment).

3.4.Relationship between environmental changes and urban development

These results suggest that environmental changes are associated with the urban-touristic development that has occurred in the Canary Islands during recent decades. Virtually all landforms with active aeolian sedimentary activity (foredune, sand sheets, barchanoid ridges and barchan dunes) have experienced a reduction in all the sandy systems studied. Even in some cases, for example Maspalomas, four types of landforms have completely disappeared and have been replaced by buildings. In contrast, those landforms with less aeolian sedimentary activity or anthropogenic landforms have seen increases in their area, or are newly emerging.

As for the area occupied by vegetation, it has increased in all systems; this explains the increase in hummock dunes and stabilized dunes because they involve the presence of vegetation. This plant colonization is mainly due to a decrease in aeolian sedimentary activity, which promotes the growth of vegetation after reduction through burial by sand.

In the case of the Maspalomas dune field, most of the tourist resorts have been built on a high terrace, located NE of the system. This has changed the dynamics of the wind, reducing the wind speed downwind of the terrace and accelerating it to the south of the terrace, which has induced changes in a significant part of the landforms (Hernández-Calvento *et al.*, 2014): free dunes located downwind of the terrace have been stabilized while, in the central part of the system and leeward of the foredune, deflation surface areas have increased. These geomorphological changes have also affected plant colonization, due to both the stabilization of the dunes in the inner areas of the system and to the outcropping of wet sands and alluvial deposits at the deflation surfaces. Some human construction hase affected the sediment input area, as it has been built on parts of the foredune.

In the dune field of Corralejo the tourist resorts have been built on the northern coast, in the theoretical sediment input area (Alonso *et al.*, 2006; Malvárez *et al.*, 2013) (Figure 6). This sedimentary blockage has caused changes in the aeolian sedimentary dynamics, which in turn results in significant geomorphological changes such as decrease of the free dunes, the appearance of deflation surfaces, and the increase of stabilized and hummock dunes.

The Lambra system is not affected by urban-touristic development, leaving the sediment input area free of any human construction. However, there have been impacts from human activities such as agriculture or vegetation removal for fuel (Santana-Cordero *et al.*, 2015). Since its declaration as a Natural Park in 1987 (Law 12/1987, of July 19, Declaration of Canary Island Natural Areas) these activities have stopped. Still, the sand sheets have reduced their surface areas, probably by a sedimentary deficit or because their existence was linked to traditional activities (Grazing and cutting of plants for firewood); they have been replaced by hummock dunes, indicating an increase of vegetation cover. Finally, rocky outcrops increased in some areas, probably due to the existence of the previously mentioned sedimentary.

Jable Sur, unlike Lambra, has been affected by urban-touristic development. This is due to the increase in size of the village of Caleta de Sebo, where residential and tourist development have been permitted. The construction of buildings and infrastructure (port) has occurred in the sediment input area (Figure 6). Thus, some sand sheets that existed in 1954 have been occupied by buildings; others have been stabilized by the increasing vegetation cover. This increase of vegetation has resulted in a predominance of hummock dunes. The rocky outcrops also showed a slight increase, probably due to the sedimentary deficit. The same change has prompted the emergence of a marine lagoon that was previously covered by sand that prevented the entry of sea water inland.

4. Discussion

In general, morphological and ecological changes in aeolian sedimentary systems have been a consequence of the development of traditional activities such as agriculture, grazing or deforestation (Ratas and Puurmann, 1995; Doody, 2004; Kutiel *et al.*, 2004; Levin and Ben-Dor, 2004; Provoost *et al.*, 2011; Sciandrello *et al.*, 2015), a phenomenon that has also been identified in the Canary Islands (Santana-Cordero *et al.*, 2015). However, since the mid-twentieth century, major environmental changes in these ecosystems have been linked to urban-touristic development (Gormsen, 1997; Nordstrom and Arens, 1998; El Banna and Frihy, 2009; Kiss *et al*., 2009; Bochev-van der Burgh *et al*., 2011; Miccadei *et al*., 2011; Jackson and Nordstrom, 2011; Malavasi *et al*., 2013). Similarly, tourism-induced changes are also identified in the Canary Islands (Alonso *et al*., 2002; Cabrera-Vega *et al*., 2013; Hernández-Calvento *et al*., 2014).

Aeolian sedimentary systems in the Canary Islands have undergone significant environmental changes. These changes include increases in vegetation surface areas, stabilized dunes, and erosional processes. These are manifested in the formation of deflation surfaces and decline of the free dune characteristics of these transgressive systems (barchanoid ridges, barchan dunes and sand sheets), while buildings and infrastructure surface area have increased. The systems that showed the most significant changes are Maspalomas, Corralejo and Jable Sur. This is because buildings and infrastructure have been placed over sediment input areas that leads to blocking of sediment sources, such as at Jable Sur and Corralejo (Malvárez *et al*., 2013), or in areas where wind dynamics have been changed , as has happened in Maspalomas (Hernández-Calvento *et al*., 2014). Similar environmental changes associated with touristic development have occurred in other dune systems on the island of Fuerteventura (Alonso *et al*., 2002). In this sense, we must consider that erosional geomorphological changes are key to the existence of sedimentary deficits (Hughes and Chiu, 1981; Van Thiel de Vries, 2009; Jackson and Nordstrom, 2011). Likewise, changes in vegetation cover are indicators of aeolian sedimentary inactivity, because the decreased mobility of the dunes favors the development of vegetation (Kutiel *et al*., 2004; Levin and Ben-Dor, 2004; Faggi and Dadon, 2011).

Lambra has experienced less significant changes, both in the geomorphology and vegetation. Recent studies indicate that the transformation of sandy systems on the island of La Graciosa is related to changes in land use (Santana-Cordero *et al*., 2015). Thus, the abandonment of traditional practices (grazing, firewood, etc.) since the 1990s has favored plant recolonization and subsequent stabilization of sand sheets (García et al., 2012). However, differences in the environmental changes between the two systems studied in La Graciosa, Lambra and Jable Sur indicate the existence of other factors. These include the construction of buildings in the system sediment input area which occurred in Jable Sur but not Lambra. The sandy systems that are not affected by urban-touristic development have changed little in their environmental characteristics, as has been observed in other dune systems in the Canaries (Alonso *et al*., 2004). This is the case of the Cotillo-Tostón system on the island of Fuerteventura, located a few kilometers west of Corralejo, which has a sedimentary deposit with similar characteristics to Corralejo (Meco and Stearns, 1981; Criado, 1991; Coelho *et al*., 1992; Ancoechea *et al*., 1996; Zazo *et al*., 2002, 2003). This example suggests that systems with similar environmental characteristics, but with different human pressures, have developed different dynamics.

However, it is possible that environmental changes in aeolian sedimentary systems of the Canary Islands are also related to natural factors, such as depletion of marine sediments (Hernández-Calvento *et al*., 2014) and climate change (Petit and Prudent, 2010; Sauter *et al*., 2013). This phenomenon has been observed in various dune systems in Wales, where it has become evident that environmental changes are related to climate change and reductions in sedimentary input (Pye and Blott, 2012).

Although a relationship between urban-touristic development and geomorphological and vegetation changes in aeolian sedimentary systems of the Canary Islands has been detected in this work, the causes that have led to these changes are probably a combination of natural and anthropogenic factors (Pye and Blott, 2012; Hernández-Calvento *et al*., 2014). This may be the explanation for the existence of stabilization processes (decrease of sand sheets) in the Lambra system, where there has not been any urban development, leaving the input sedimentary area free of any buildings or infrastructure. Nevertheless, of the four systems this is the one with only minor environmental changes. Therefore it is probable that environmental changes that would have occurred through natural causes (due to lower inputs of sand, for example) have been accelerated by human disturbance, as has happened in the dune field of Maspalomas (Hernández-Calvento, 2006; Hernández-Calvento *et al.*, 2014).

5. Conclusion

We have studied environmental changes in four aeolian sedimentary systems of the Canary Islands (Maspalomas, Corralejo, Jable Sur and Lambra). These changes are linked to urban-touristic development. The main environmental changes are increases in vegetation surfaces, in stabilized dunes, and in erosional landforms. Furthermore, there has been a decrease in free landforms such as barchanoid ridges, barchan dunes and sand sheets. In turn, the area occupied by urbanization has increased.

Aeolian sedimentary systems that have experienced major environmental changes coincide with those where there has been higher urban-touristic development (Maspalomas, Corralejo and El Jable Sur). In contrast, the Lambra system, which has not been affected by development, shows less significant changes. However, the existence of certain environmental changes in the latter system opens the possibility that environmental changes of aeolian sedimentary systems in the Canary Islands are also related to environmental factors, such as depletion of marine sediments and climate change.

Environmental changes associated with urban-touristic development indicate deficiencies in the management of these protected areas, as sufficient steps have not been taken to foster a favourable conservation environment for the dune systems.

Acknowledgments

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Procedure to automate the classification and mapping of the vegetation density in arid aeolian sedimentary systems

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Abstract

The temporal variation in vegetation cover in aeolian sedimentary systems, especially those in arid regions, provides an indication of environmental change. Based on this, the objective of this paper is to design a simple method for classifying the vegetation density of arid aeolian sedimentary systems through the digital processing of aerial images. The green band of a high resolution orthophoto of La Graciosa island (Canary Islands, Spain) is used as an example. The pixels identified as vegetation were vectorized to point geometry, the vegetation density was then calculated, and a digital vegetation density model (DVDM) thereby obtained. Both spatial and statistical analyses were performed to find the optimal procedure to achieve the objective. Speed, objectivity, cost, and the possibility of working with historical records are discussed, and the proposed method is compared with others based on visual analysis or digital remote sensing. The importance of this method for countries with less research funding or low GDP per capita is also discussed. The proposed procedure opens up future lines of research for comparison of results across various environmental and anthropogenic variables. In addition, vegetation density can be used as a variable in computational fluid dynamic modeling of vegetation in arid dune systems.

Keywords: Dune vegetation, arid aeolian sedimentary systems, density, geographical information technologies, method

1. Introduction

Globally, in recent decades, there have been environmental problems related to the instability of coastal dune systems (Jackson and Nordstrom, 2011; Nordstrom, 1994). Regardless of the environmental effects of climate change on them, it has been suggested that their sedimentary activity is a "geo-indicator" of environmental changes (Berger and Iams, 1996).

The presence of vegetation in these dune systems leads to a reduction in rates of sediment transport (Lancaster and Baas, 1998; Levin et al., 2008; Okin, 2008; Sherman and Bauer, 1993). This is due, among other things, to plants increasing the roughness of the ground surface, which results in the reduction of wind speed and thereby the reduction of aeolian sediment transport (Hesp, 1981; Moreno-Casasola, 1986). Thus, plants capture sand grains that are transported by saltation, favoring the retention of sediments. There is therefore a direct link between the formation of sand dunes and vegetation. Some aspects of the vegetation, such as cover, density, height, volume, biotype, and conservation, condition the retention levels of sediments (Carter, 1988; Hesp, 1984, 1989, 1991, 2002). Vegetation cover, and its variations, is a determining factor in the generation of landforms and in dune dynamics, given the interactions that take place between vegetation and aeolian sediment transport (García-Romero et al., 2016; Hesp, 2002; Kuriyama et al., 2005; Luna et al., 2011; Tsoar, 2005). In fact, vegetation cover is the most often used factor in the characterization of stabilization processes (García-Romero et al., 2016; Hesp, 2013; Levin et al., 2008). The dynamics of vegetation cover are particularly interesting in coastal sandy systems, because it is easy to identify changes, whether due to natural alteration or induced by human activities over short time periods (especially arid ones), which produce significant environmental modifications such as dune stabilization, erosion, or remobilization (Cabrera-Vega et al., 2013; Hernández-Calvento et al., 2014; Kutiel et al., 2004; Santana-Cordero et al., 2016; Hernández-Cordero et al., 2017).

Most works which focus on the characterization of vegetation in dune systems give special importance to the percentage of vegetation cover in the space. These works use different concepts, such as plant density (Konlechner et al., 2014), vegetation density (Kutiel et al., 2004), vegetation cover (Carlson and Ripley, 1997; Ritzen and Straatsma, 2002; Zehm et al., 2003), plant cover (Floyd and Anderson, 1987), vegetation recovery (Costa et al., 1996; Hayden et al., 1995; Stallins, 2002), or vegetation covering (Qin et al., 2006). Depending on the methodology applied, the techniques used vary from field work (Canfield, 1941; Daubenmire, 1959; Goodall, 1952; Greig-Smith, 1983; Konlechner et al., 2014) to parallel photography and terrestrial laser scanning (Warmink, 2007), while special mention should be given to techniques that use airborne information sources (Bannari et al., 1995; Hugenholtz et al., 2012).

Aerial photographs are important airborne information sources for the study of the vegetation and its dynamics in dune systems (Carmel and Kadmon, 1998; Delgado-Fernández and Mir-Gual, 2015; Dunn et al., 1990; Green et al., 1993; Hellesen and Levin, 2014; Kadmon and Harari-Kremer, 1999; Okeke and Karnieli, 2006). Traditionally, studies of the vegetation (especially vegetation cover) with aerial photography have been made from visual analysis (Akashi and Mueller-Dombois, 1995; Coppedge et al., 2001; Delgado-Fernández and Mir-Gual, 2015; Dirzo and Garcı´a, 1992; García et al., 2012; García-Romero et al., 2016; Gaylord and Stetler, 1994; Harrington and Sanderson, 1994; Hernández-Cordero et al., 2015b; Johnston and Naiman, 1990; Miller et al., 1995; Simpson et al., 1994; Turner et al., 1996). Among the limitations of this method, the problem of subjectivity is of particular importance (Morgan et al., 2010). Alternative approaches to visual photo interpretation of aerial photographs and other information sources involve the application of automated methods (Avery and Berlin, 1992; Hugenholtz et al., 2012; Jauhiainen et al., 2007; Okeke and Karnieli, 2006; Tsoar and Blumberg, 2002). Some of these methods classify the vegetation using multispectral and hyperspectral images, captured by satellite or airborne sensors. The technique implemented usually entails the development of vegetation indices. One of the most commonly used indices is the normalized difference vegetation index (NDVI) (Carlson and Ripley, 1997; Chen et al., 2012; De Lange et al., 2004; Elmore et al., 2000; Hall et al., 1998; Lambin and Ehrlich, 1997; Schmidt and Karnieli, 2000; Underwood et al., 2003; Woodcock et al., 1994; Zeng et al., 2013). However, in areas with high soil reflectivity values, the soil-adjusted vegetation index (SAVI) produces better results (Huete, 1988; Levin et al., 2006, 2008). These vegetation indices can also be combined (NDVI+SAVI) (Soria et al., 2007) or used in relation with LiDAR data (Collin, Long and Archambault, 2010, 2012).

In arid aeolian sedimentary systems, independently of soil brightness (Huete, 1988), the use of vegetation indices or other methods based on near-infrared bands is not feasible because the permanent vegetation (formed usually by bush specimens) endures almost constant wáter stress due to low rainfall and high wind speeds, especially in summer. In these circumstances, the vegetation displays different morphological adaptations, such as the total or partial loss of leaves (Figure 1). Thus, the vegetation exhibits a low spectral response to infrared bands, even though the plants are alive and, therefore, intervening in the aeolian sedimentary dynamics.

In short, the most commonly used methods for the characterization of vegetation in dune systems through airborne information sources are either qualitative, usually based on the identification of vegetation cover through visual interpretation, or quantitative, based on the identification of the state of the vegetation, from the data provided by the infrared channels of digital images. In the case of arid dune systems,
the first option is valid and widely used when the objective is to characterize plant species, or perform an analysis of the space-time dynamics of the vegetation cover in relation with aeolian geomorphology. However, the second option lacks accuracy, because certain adaptations of the vegetation to these environments (such as the loss of leaves) prevent accurate records of the surfaces actually covered by vegetation.

A possible alternative to quantitatively characterize the vegetation in these arid systems would be to calculate its density, instead of its coverage, since this calculation not only provides data on the amount of vegetation per unit area, but also the mean distance between the vegetation individuals, which is in direct relation with aeolian sedimentary dynamics (Hesp, 1991, 2002). In this context, the concept of vegetation
density has been defined as the number of plant individuals in an area (Herna´ndez et al., 2000). In addition, a second definition includes the mean distance between plant individuals in the characterization of vegetation density (Mostacedo and Frederiksen, 2000). This second concept is more appropriate in aeolian sedimentary dynamics, because the distance between plant individuals in an area (Hernández et al., 2000). In addition, a second definition includes the mean distance between plant individuals in the characterization of vegetation density (Mostacedo and Frederiksen, 2000). This second concept is more appropriate in aeolian sedimentary dynamics, because the distance between plant individuals influences the wind flows, the sedimentary transport and the formation of aeolian landforms (Hesp, 1983). The vegetation density shows the possibility that the wind flows act or not, depending on the density, and therefore generate dune landforms. In this sense, the vegetation density could be the next step in computational fluid dynamic (CFD) modelling of the vegetation, at least at regional scale, which, according to Smyth (2016), is a perspective in the future.

Calculating the vegetation density of dune systems has been performed through the processing of digital images, though not analogic ones. One of the most commonly used methods is to employ automatic classifications using near-infrared bands (Hugenholtz et al., 2012). Another method involves statistical reclassification of the digital levels of color aerial photographs, related to aspects such as intensity and tone (as HSI) or texture (Hudak and Wessman, 1998; Barry and Bowman, 2006; Nurminen et al., 2015), correlated with field data. Object-oriented methods have also been applied to digital images (Laliberte et al., 2004; Platt and Schoennagel, 2009). Finally, new sensors have been introduced, as well as the use of synthetic-aperture radar (SAR) imagery (Rozenstein et al., 2016).

However, to date no method has been developed to calculate actual values of the vegetation density using the visible bands of digital orthophotos applied to black and white historical aerial photographs, enabling spatio-temporal studies about vegetation changes and their relationship with aeolian sedimentary dynamics.

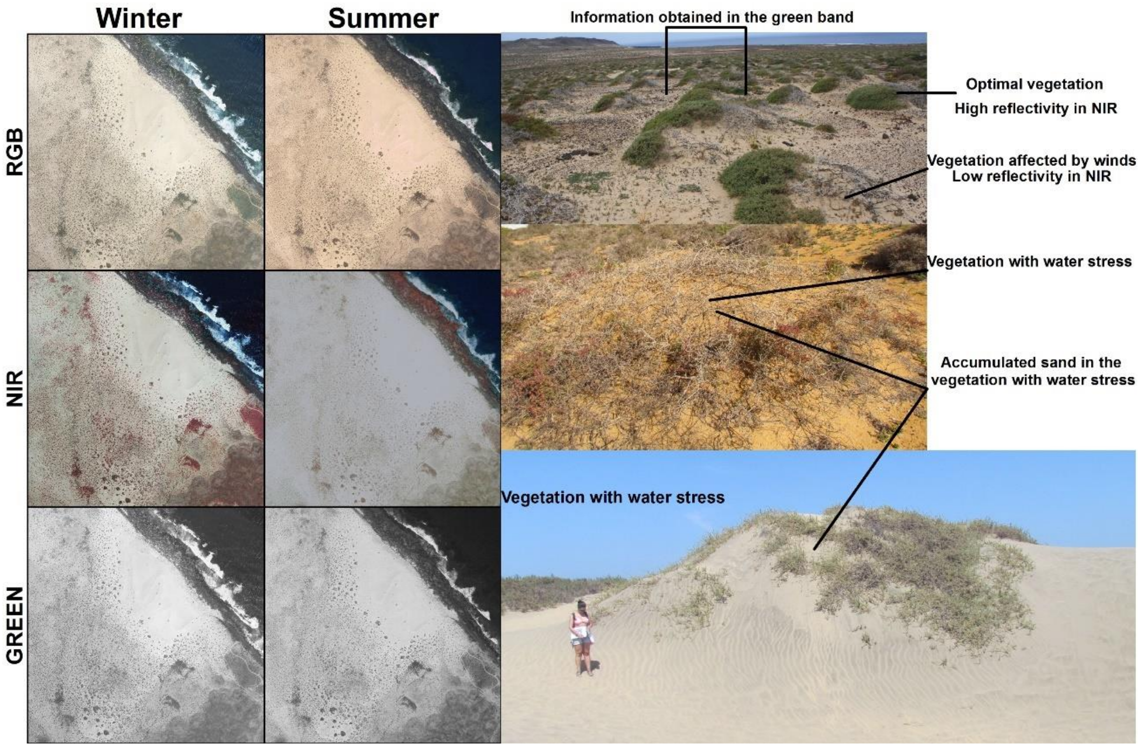

Figure 1. Water stressed vegetation in arid aeolian sedimentary systems forming nebkhas.

Considering this background, this paper proposes a simple automated procedure to calculate the vegetation density in arid aeolian sedimentary systems. For this purpose, a small island called La Graciosa (Canary Islands) was used as a laboratory. The developed method uses visible channels of current digital orthophotos to facilitate a comparison with the results obtained after its application to black and white aerial historical photos. The specific objectives are the following: a) characterization of the vegetation density in a 200 x 200 m plot in La Graciosa using both empirical and automated methods; b) calculation of the optimal sampling of the automated method, considering the overlaying with the results obtained when using the empirical method and by statistical analysis; c) application of the optimal sampling to the 200 x 200 m plot to verify its feasibility when using historical aerial photographs in black and white; and finally d) application of the optimal sampling to all the current aeolian sedimentary systems of the island.

1.1.Study area

The island of La Graciosa (27.05 km2) is located in the north-eastern area of the Canary Archipelago (Figure 2), on a Quaternary marine platform, formed as a result of the emission of volcanic material during the Upper Pleistocene and Holocene (De la Nuez, Quesada and Alonso, 1997). In parallel, the Quaternary sedimentary processes gave rise to soil and sand deposits that are currently slightly cemented (aeolianite) (Ortiz et al., 2006; Meco et al., 2006). Marine terraces and beachrock deposits were formed in the coastal areas.

In the Holocene, a significant part of the island (13.96 km2) has been covered by aeolian sedimentary deposits of variable thickness. The sands are medium-coarse organogenic (>75% of bioclastic grains, with abundant fragments of Corallinaceae algae mesh, and with a carbonate content of >84%) (Mangas et al., 2012). Although there is currently aeolian remobilization, the landforms showing substantial levels of sediment transport, such as ripples, are fairly insignificant, so semi-stabilized aeolian sand sheets and nebkha dunes predominate, stabilized by vegetation specimens. The dominant vegetation is made up of shrub and herbs of halophilous, psammophilous and xerophilous species, as Traganum moquinii, Salsola vermiculata, Launaea arborescens, Ononis hesperia, Polycarpaea nivea, Euphorbia paralias and Ononis tournefortii (González et al., 1996; Pérez-Chacón et al., 2010; Hernández-Cordero et al., 2015b). Vegetation cover, in turn, is significant, and in some winters covers more than half of the surface area of the island's aeolian systems.

This vegetation is adapted to the arid-like conditions of the island's climate. Mean annual precipitation barely tops 100 mm, distributed over an average of just 32 days of rain a year. This rain is torrential and very irregular, both by season and year, with the rainiest months being between November and February (Pérez-Chacón et al., 2010). Temperatures are mild, with a mean annual temperature of 19.7ºC and mean variation over the year of 5.7ºC (Pérez-Chacón et al., 2010). The prevailing winds are the trade winds, blowing mostly in NE, ENE and NNE directions at an average speed of 22 km/h. These winds, which are effective for aeolian sedimentary transport, are more significant in January, March and April, while in September they blow less frequently (Pérez-Chacón et al., 2010). In winter, south-westerly storms are customary, generating erosional processes on the island's southern coast and temporarily changing the direction of aeolian sedimentary transport and marine dynamics (Pérez-Chacón et al., 2010). From an anthropic point of view, the island is sparsely populated, with just 700 inhabitants in 2014 according to the Spanish National Institute of Statistics (Instituto Nacional de Estadística, INE, 2014). However, over recent decades there has been a notable increase in the number of buildings and port infrastructures, as well as a change in the economic model of the island from one based on traditional farming and fishing to one based on tourism. La Graciosa is legally protected by numerous national and international forms of environmental protection: Biosphere Reserve, Special Area of Conservation (SAC), Special Protection Area for Birds (SPAs), Nature Park and Geopark

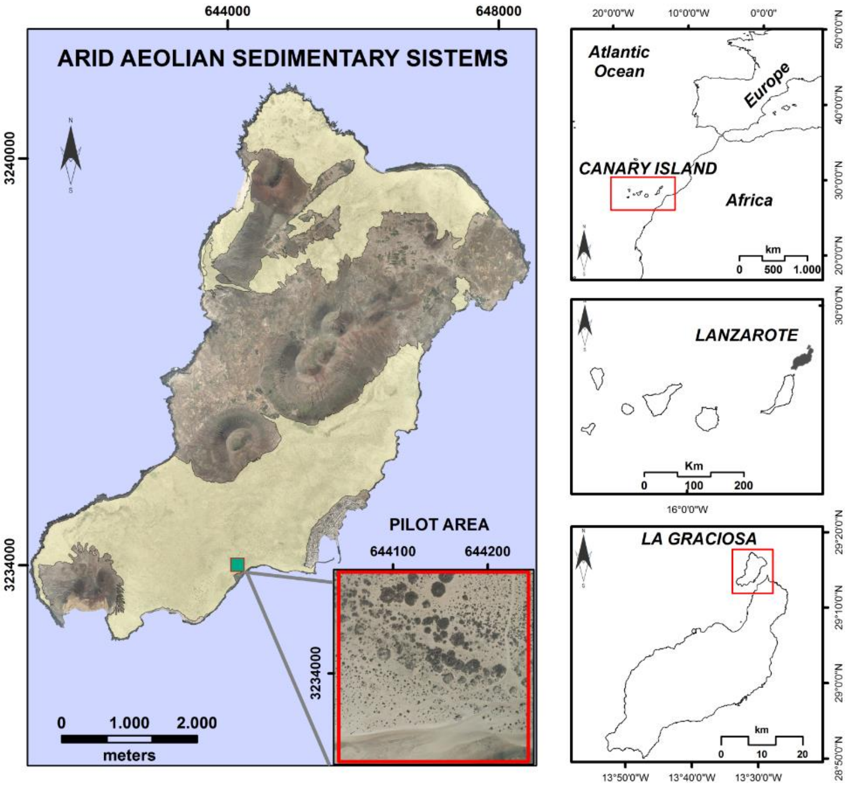

Figure 2. Location of the study and pilot area. In yellow color with transparency (left), the aeolian sedimentary systems.

2. Materials and methods

A digital orthophoto was used for the development of the procedure described in this paper. The orthophoto was taken in February 2009 with a spatial resolution of 10 cm and using four spectral bands, three in the visible spectrum and one near-infrared. For the criteria of using only visible bands, so that the method could also be applied to historical images (normally in black and white and without infrared bands), the green band was chosen for this study, since it provides the most vegetation cover information of the bands in the visible domain (Chuvieco, 2010). This choice was favored by the fact that the vegetation was in an optimal state of vigor at the time the orthophoto images were produced. In addition, for the application of the procedure in the observation plot (Figure 9), historical aerial photographs were used (Table 1) taken in the winter season (the rainiest months according to Pérez-Chacón et al., 2010). In this way, it was hoped to show that the method described in the present paper is applicable to historical aerial photographs.

Table 1. Sources used in this paper.

Sources	Date	Scale	Spatial resolution (m)	RMS (m)
Historical aerial photography	12/1954	1:18,000	1	1.05- 2.01
Historical aerial photography	01/1987	1:5,000	1	0.55- 1.04
Orthophoto	02/2009	*	0.1	*

In order to carry out the spatial and statistical analyses required to define the method, we worked first with a 200 x 200 m pilot area or observation plot located in the south of the island (Figure 2). This area is considered representative of the whole of the island, in the context of aeolian sedimentary systems, as it presents the different degrees of vegetation coverage identified in the island and also the surfaces characterized by the presence of sand sheets without vegetation cover in the recent past.

2.1.Procedure for calculating the vegetation density

2.1.1. Preparation of the green band of the orthophoto

Firstly, we proceeded to eliminate those areas outside the scope of the study, extracting from the processing, following Kutiel et al. (2004), volcanic cones, lava flows, buildings, etc., and focusing the analysis on the aeolian sedimentary systems defined by Pérez-Chacón et al., 2010 (Figure 2). The following step was related to spatial resolution and involved resampling the pixel size to 1 m. Its aim was to facilitate the rest of the procedure and to make this information source comparable with the historical information sources also used (Figure 3).

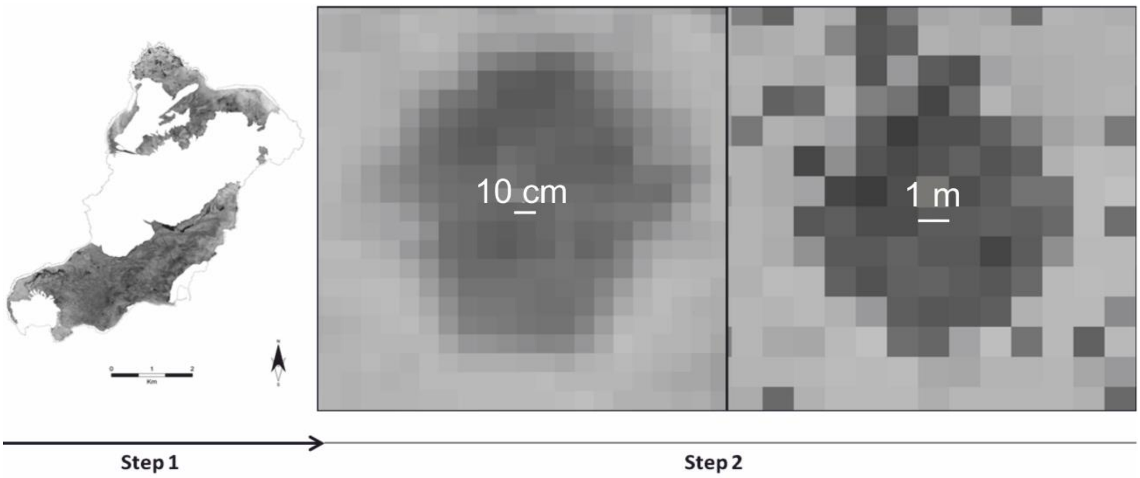

Figure 3. Removing the areas without aeolian sedimentary systems (step 1) and resampling the green band (step 2).

2.1.2. Empirical method and categories of vegetation density

The empirical method was based on a visual analysis of different vegetation densities, according to their degree of coverage per area. For this, four categories of vegetation cover were manually defined in the observation plot at a scale of 1:1000 (Figure 6), following the method developed by Shanmugam and Barnsley (2002). To scan the areas with a similar vegetation density, an adaptation of the graphs for visual appreciation of coverages by Folk and Ward (1957) was used, selecting the following coverage intervals per area: 0-25%, 25-50%, 50-75% and >75% (Figure 4).

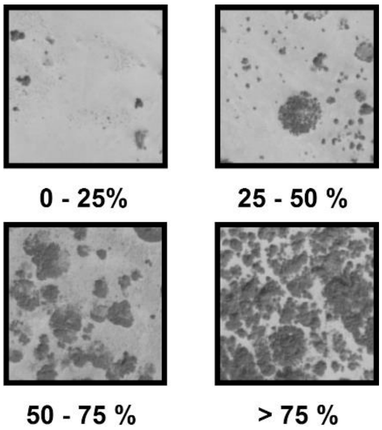

Figure 4. Categories used to estimate the percentage of vegetation cover per area.

2.2. Automated method for digital vegetation density model (DVDM)

2.2.1. *Reclassification.* A reclassification in the resampled green band of the orthophoto (February 2009) was performed, using the Jenks natural breaks method. Each class obtained was characterized by similar values, maximizing the differences between classes. The result (Figure 5 A) was a classification of the green band which identifies those grey values that represent vegetation. As a result of the previous resampling, it was noted that the vegetation detected normally corresponded to semi-shrubby and shrubby plants, while small seasonal herbaceous species, as therophytes, were not detected.

2.2.2. *Measuring the vegetation density*. The vegetation density calculation was based on the method developed by Mostacedo and Frederiksen (2000) to calculate the density of trees per hectare because the shrub vegetation in arid aeolian sedimentary systems has usually a random distribution in the landscape, similar to trees, and shows as follows:

$$Dh = \frac{10000}{(\overline{D})^{2}} \quad (1)$$

where: *Dh* is the density by hectare and $\overline{D}$ is the average distance between central points. In our case, the central points are every pixel representing vegetation values obtained in the reclassification, vectorized to point geometry (Figure 5 B).

The vegetation density could then be estimated based on the vectorization process. This density can be understood as the degree of vegetation coverage, also considering that the smaller the distance between points, the higher the vegetation density, and vice versa. A digital vegetation density model (DVDM) was thus obtained following all the previous steps. This model was reclassified in the same four vegetation density categories used in the empirical method, using GIS tools. One example with different conditions with respect to quantity and distance is shown in figure 5 C.

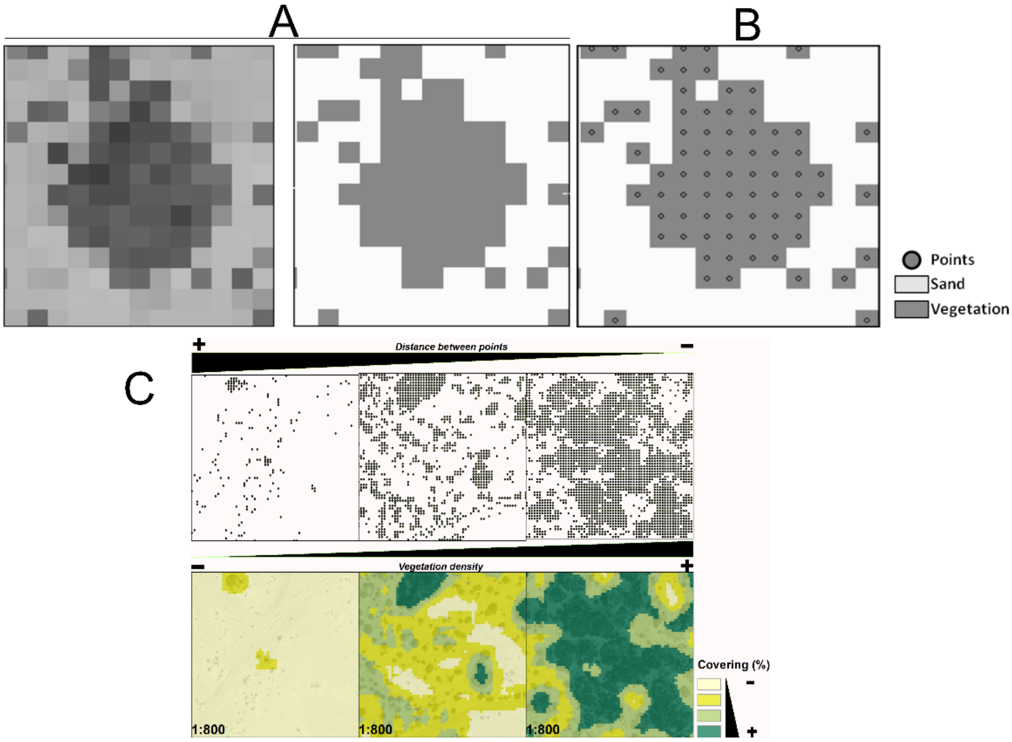

Figure 5. (a) Result of the reclassification of the green band using the Jenks natural breaks method. (b) Pixel vectorization with vegetation cover to points. (c) Different vegetation cover densities obtained.

2.3.DVDM: Optimal sampling

The calculation of density started with neighborhood sampling around each point. This operation can be carried out using any free or commercial GIS software which normally incorporates these tools. The next step was estimation of the optimal distance to sample and calculate densities around each point. The first sampling was performed using the 1 x 1 m option. Then, multiples of 3 units (meters) were applied, as Hudak and Wessman (1998) proposed, i.e., 3 x 3, 6 x 6, 9 x 9, 12 x 12, 15 x 15, 18 x 18, 21 x 21 and 24 x 24 m. The results are shown in Figure 7 and Table 2. Two types of analyses were performed to determine the optimum neighborhood sampling. Firstly, the results obtained from the automated samplings and those obtained from the visual analysis (empirical method) of the image were compared. This comparison was made through spatial analysis performed with geoprocessing tools (GIS) to determine the percentage of coincidence. Secondly, a statistical analysis was performed to determine the best neighborhood sampling that separates the four categories obtained from the automated method.

2.3.1. *Spatial analysis*. To perform the spatial analysis, a comparison was performed between the results obtained applying the DVDM in the observation plot (Figure 6) and those provided by the empirical method (Figure 7, right). The comparison between the various results obtained with the different neighborhood sampling sizes and the result obtained through the empirical method was designed to determine the percentage of vegetation cover coincident with the visual analysis (Cva) for each neighborhood sampling size. For this, a spatial analysis using GIS geoprocessing tools (overlaying) was performed to determine which sample, among those obtained automatically, presented the closest relationship to the results obtained through the empirical method.

2.3.2. *Statistical analysis*. The aim of the statistical analysis was to determine which sampling best separated the four vegetation density categories obtained by the automated method. For this, we calculated the coefficient of variation of the distances between each points obtained in area resulting from the different neighboring samples taken in the observation plot. Because density results have no direct relationship with the surface, the coefficients of variation were calculated inversely proportional to the surface areas of the resulting samples tested. To interpret the results obtained for the coefficient of variation (Cv), the starting point is that the lesser the Cv, the greater the homogeneity. Data preparation for this statistical analysis was performed with GIS tools for distance calculation, overlaying and statistical summaries using the vegetation vector points and their proximity and overlapping in the area resulting from the different neighboring samples.

$$Cv = \frac{\sigma\, dist}{\overline{x}\, dist} \,/\, area \qquad (2)$$

where: *Cv* is the coefficient of variation, $\sigma\ dist$ is the standard deviation distance between central points in the resulting areas and $\overline{x}\,dist$ dist is the mean distance between central points in the resulting areas.

2.3.3. *Final index*. The results of the two analyzes performed (spatial and statistical) were integrated into a final index (S). This index should contain, firstly, a greater uniformity between the distances between vegetation points (i.e. a low Cv) and, secondly, the highest percentage of occupation coincident with the visual analysis (Cva). The difference between the two variables should determine an optimal neighborhood sampling, corresponding to that which obtained the lowest Cv and the highest level of coincidences with visual analysis (Cva). This index is defined as follows:

$$S = Cva - Cv \qquad (3)$$

where: S is the final index of the sampling, Cv is the coefficient of variation of the sampling and Cva is the agreement with the visual analysis.

The optimal sampling vegetation density is applied finally to the rest of the aeolian sedimentary systems of La Graciosa and to the pilot area to see if it is possible to apply this method to historical aerial photographs.

3. Results

3.1.Empirical method. Result.

Figure 7 (right) shows the results of the empirical method applied to the 200 x 200 m pilot plot. As can be seen, category 1 corresponds to low densities (bare sand sheet and isolated individual plants). The intermediate categories (2 and 3) correspond to areas where the distribution of vegetation is more concentrated. The difference between the two is the distance between shrubs, a variable used to calculate the vegetation density. Finally, the category of high density (4) includes areas completely covered by vegetation, without bare sands.

3.2.Automated method. Results of the different neighboring samples.

Figure 6 shows how the results of the different DVDM vary with respect to the neighboring sample used, since each of the four defined vegetation density categories share different surfaces, depending on the neighborhood sampling. To understand the information provided by these results, an occupancy rate of vegetation located in the interior of each resulting area was calculated for each area obtained as a result of the samplings. Finally, an average occupancy rate was obtained for each category. In the same way, the mean distance between shrubby individuals through vector points was also calculated. Table 2 shows the mean percentage occupied by vegetation per area in each category obtained for the neighborhood sampling used and the mean distance between shrubby individuals. To make the results easier to interpret, the vegetation density values (number of individuals per area) have been converted into percentage of vegetation cover.

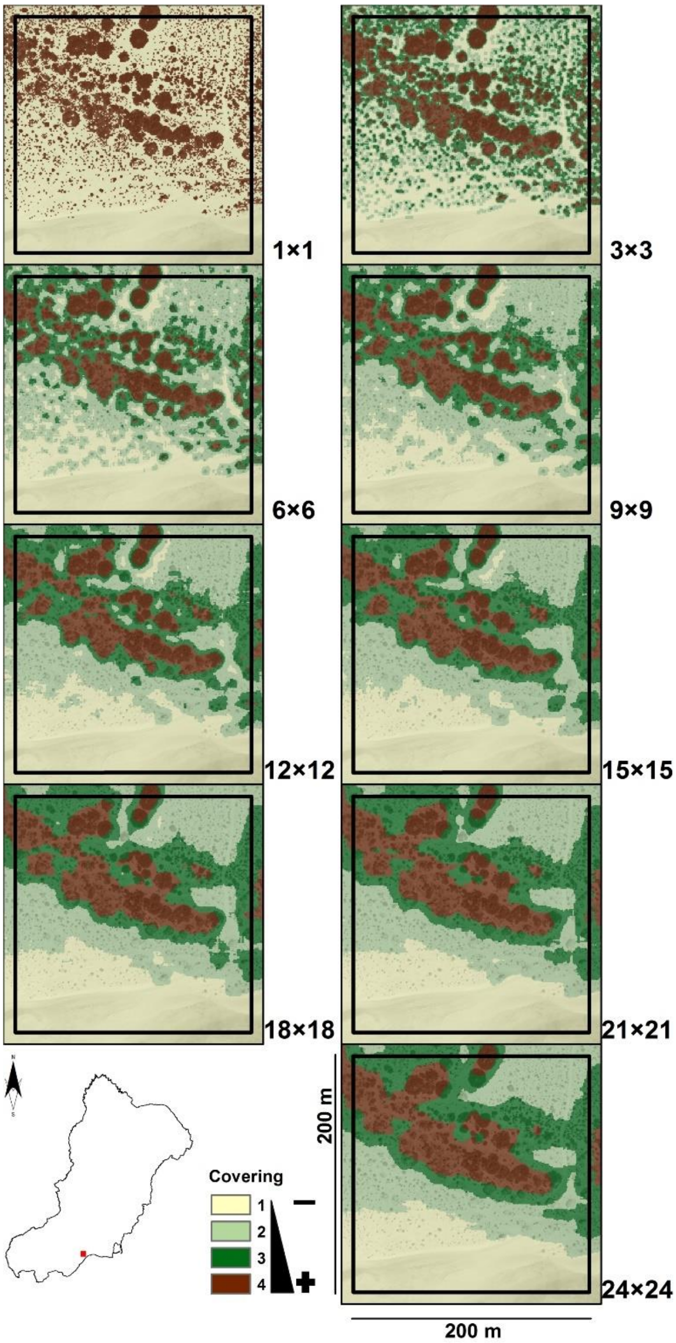

Figure 6. Results for each neighborhood sampling used.

Table 2. Mean occupancy percentage of vegetation cover in the area studied, for each neighborhood sampling used and mean distance between shrubby individuals.

Neighborhood sampling	1		2		3		4	
	MO	MD	MO	MD	MO	MD	MO	MD
1x1	34.48	1.03	-----	-----	-----	-----	88.65	1.00
3x3	25.88	2.07	34.50	1.12	82.50	1.00	99.78	1.00
6x6	19.53	1.51	19.50	1.21	60.13	1.02	90.07	1.00
9x9	10.65	2.23	22.35	1.79	49.26	1.31	84.25	1.00
12x12	17.77	2.03	22.84	1.19	49.97	1.02	86.13	1.00
15x15	8.82	1.46	19.89	1.26	43.47	1.05	72.62	1.00

18x18	2.53	1.57	26.18	1.62	44.15	1.03	78.47	1.00
21x21	4.14	1.70	43.81	1.28	55.92	1.02	75.17	1.21
24x24	4.64	1.91	24.62	1.20	45.52	1.06	64.64	1.42

MO: Mean percentage of occupation of the vegetation by category studied (%). MD: Mean distance between shrubby individuals (m).

3.3. *Spatial and statistical analysis*.

The comparison between the results obtained with the empirical and the automated methods was performed using geoprocessing tools, integrated in GIS (Figure 7). The highest percentage of matching surfaces classified in the same category in both methods (*Cv*a column, Table 3), corresponds to a neighborhood sampling of 9x9, and was 66% (*Cva* column, row 4, Table 3).

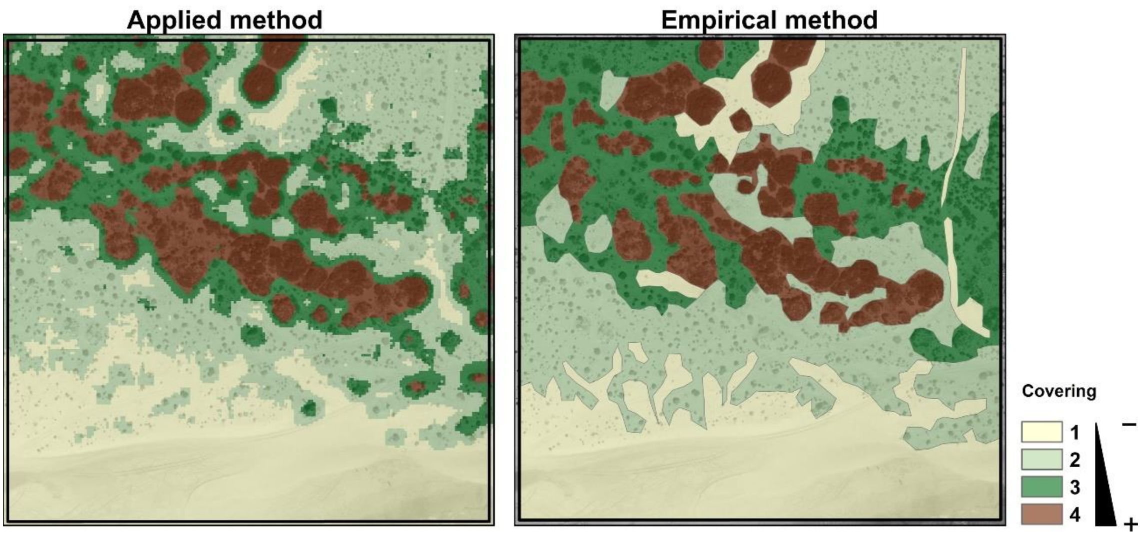

Figure 7. Categories of vegetation density obtained from the automated (neighboring sample 9×9) and empirical methods, considering the degree of vegetation cover and the distance between pixels with vegetation. Results from the photo interpretation at a scale of 1:1000. Categories: 1. <25%, 2. 25%–50%, 3. 50%–75% and 4. >75%.

The results of the statistical analysis based on the coefficient of variation inversely proportional to the surface (*Cv* column, Table 3) show the lowest values for the 1x1 sampling, as no neighborhood analysis was actually performed. The 3x3, 9x9 and 21x21 samples were best suited to the aims of the present study, though the neighborhood samplings of 3x3 and 21x21 had lower *Cva* values than the 9x9 sampling. Finally, the results of the final index (S column, Table 3) show that the optimum neighborhood sampling is 9x9 meters.

Table 3. Coefficient of variation inversely proportional to the surface (*Cv*), percent coincidence with the visual analysis method (*Cva*), and final index of each sampling performed (*S*).

Sampling	*Cva*	*Cv*	*S*
1x1	0.2912419	0.0000995	0.2911424
3x3	0.5405697	0.0021797	0.5383900
6x6	0.6433146	0.0154515	0.6278631
9x9	**0.6601342**	**0.0132641**	**0.6468701**

12x12	0.6446270	0.0223336	0.6222934
15x15	0.6199838	0.0271803	0.5928035
18x18	0.6113266	0.0219582	0.5893684
21x21	0.6008308	0.0091786	0.5916522
24x24	0.5891559	0.1927782	0.3963777

3.4.Application of the method (9×9) to 1954 and 1987 aerial photographs in the observation plot and determination of the evolution of the vegetation density.

The application of the automated method described above for the observation plot shows that this procedure can be used to work with historical aerial photographs in white and black (figure 8), which is very important with respect to the vegetation of arid aeolian sedimentary systems, characterized by low height and coverage. Once the pixels that represent the vegetation are identified through dark colors by the reclassification method used (Jenks natural breaks), and then vectorized to points, as explained above, the procedure is fast, inexpensive and easy to perform with any GIS software (the algorithms used are quite common and high technical skills are not required). As for the results, the optimal digital vegetation density model (DVDM) was considered for both dates and reclassified in the four vegetation density categories studied. Although the information shown is the vegetation density, due to the relationship between vegetation and sedimentary dynamics, wind flow, geomorphology and other environmental factors, quantified studies of environmental changes could be made in arid aeolian sedimentary systems. One such example is shown in Figure 8.

The procedure developed also allows us to determine the areas that are being colonized by vegetation, and more importantly, the degree of plant colonization that impacts on the aforementioned environmental factors (sedimentary dynamics, wind flow, geomorphology). In addition, based on the information obtained the changes that the plot has experienced can be observed where vegetation has increased both in terms of coverage and density. And the way highest densities have rolled the location depending on the amount of vegetation. For example, the highest densities at the beginning (1954), were in the north of the pilot area, and currently have covered principally the center of the observation plot.

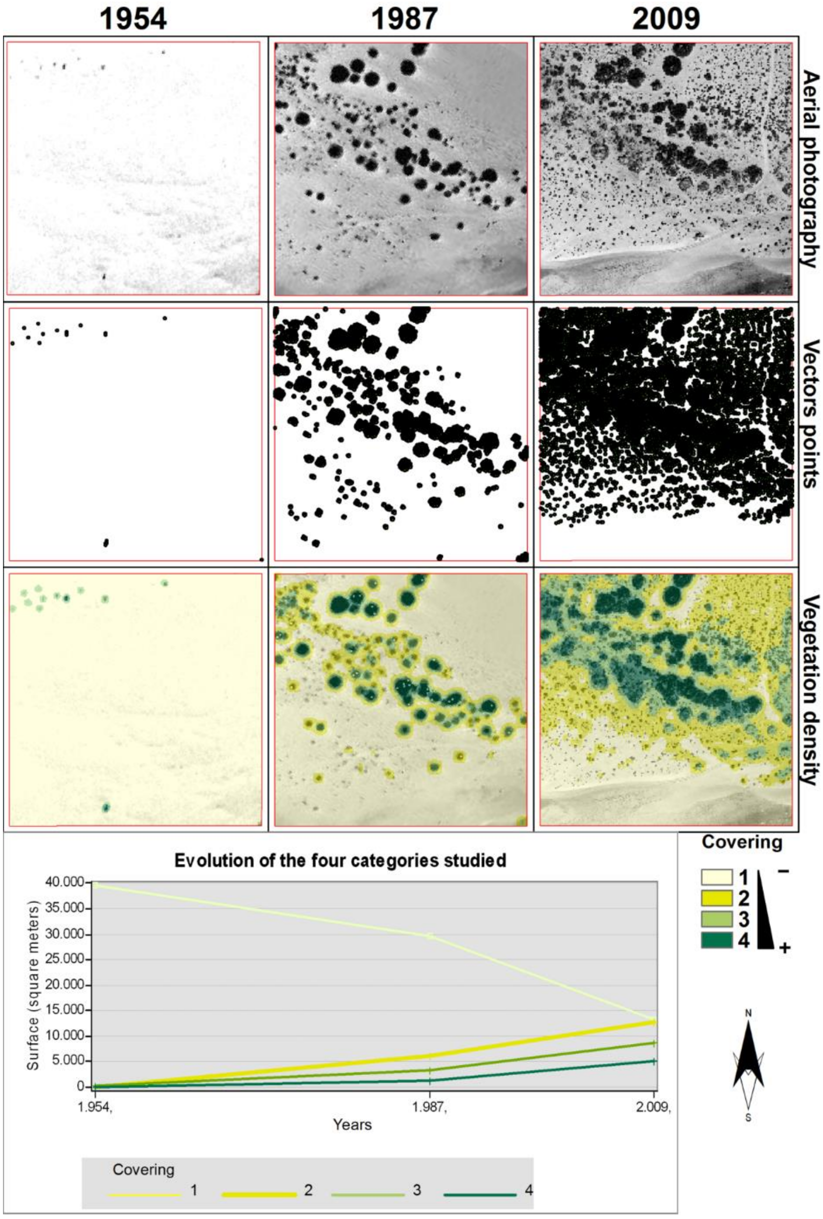

Figure 8. Results of the application of 9 × 9 m sampling to the observation plot in 1954, 1987, and 2009.

3.5. The vegetation density applied to all the aeolian sedimentary systems of La Graciosa in 2009.

The estimate of the vegetation density in the aeolian sedimentary systems of La Graciosa, as the result of the application of the optimum neighborhood sampling of 9×9 m (Figure 9 and Table 4), shows the following percentage results: the categories high vegetation density (3) and very high vegetation density (4) occupy more than 36%; the category medium vegetation density (2) accounts for more than 41% (this category coincides with areas that are being colonized by vegetation); and, finally, the category of low vegetation density (1) represents just over 22%, lower than what might be expected for the characteristic dry environmental conditions. In short, we can say that the aeolian sedimentary systems of La Graciosa presented, in February 2009, a significant vegetation cover. Considering that the analysis was performed on a winter-based orthophoto, the vegetation cover is near its yearly maximum value.

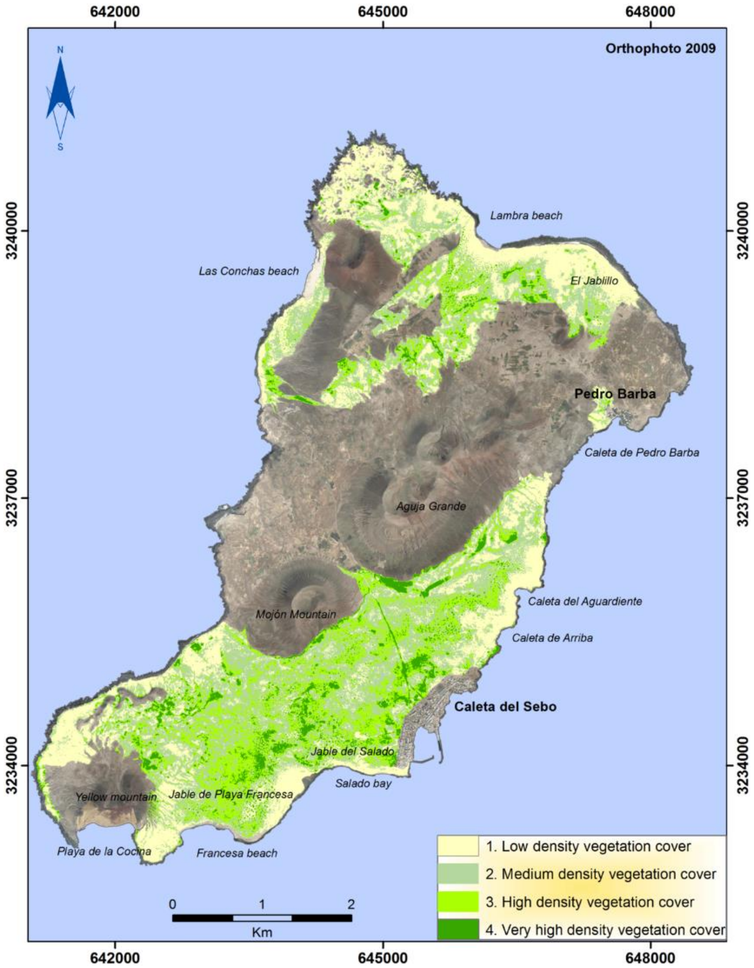

Figure 9. Results of the application of 9 × 9 m neighborhood sampling to all aeolian sedimentary systems of La Graciosa in 2009.

Table 4. Percentage occupied by each category as a function of the vegetation density in aeolian sedimentary systems in La Graciosa in 2009.

Vegetation density categories	Area (%)
1 (MO:10.65; MD: 2.23)	22.17
2 (MO:22.35; MD: 1.79)	41.79
3 (MO:49.26; MD: 1.31)	27.37
4 (MO:84.25; MD: 1.00)	8.67

MO: Mean percentage of occupation of the vegetation by category studied (%). MD: Mean distance between shrubby individuals (m).

4. Discussion

The proposed method to classify the vegetation density of arid aeolian sedimentary systems has significant advantages over other existing methods, as well as some limitations. The three main advantages are as follows:

1. First, as with any automated method, the aim is to obtain results not conditioned by subjectivity, as is the case of visual analysis (Kadmon and Harari-Kremer, 1999; Morgan

et al., 2010). So, when a photographic interpretation is used to analyze certain elements, the analyst must make decisions to delimit each degree of density. The probability that another analyst would interpret the reality differently is quite high. In this respect, the training and experience of the analyst determines the accuracy of the analysis and, therefore, of the results obtained (Morgan et al., 2010). In the method developed in this paper, density calculations are made from simple algorithms implemented in any GIS (free or commercial), providing results which are not conditioned by any analyst.

2. From a technical point of view, two advantages of the method can be emphasized. Firstly, it can be easily implemented because it can be applied using any GIS software, both commercial and free, which implements simple classification algorithms like those used in this case. Secondly, the advantage of this method compared with other commonly used techniques which are based on the digital analysis of satellite or airborne imagery lies in its degree of applicability. The extent of this applicability is based on the non-requirement of near-infrared bands when using this method, and is centered on four factors: a) Use of the green band of the visible spectrum allows the use of commonly available images and less costly as digital images with infrared bands; b) From a global perspective, there are more available images of aeolian sedimentary systems of the planet captured by this type of conventional sensor; c) The historical record of aerial photography is longer than that of satellite images (Kadmon and Harari-Kremer, 1999; Morgan et al., 2010). In this sense, this method is adapted to the availability of these historical images to be applied to diachronic vegetation studies. To date, this type of vegetation density classification using aerial photographs has been mainly performed from photo interpretation (Shanmugam and Barnsley, 2002), or automatic classifications, which link the digital value to vegetation density with validation in the field but the vegetation density value obtained were relative and not actual (Kutiel et al., 2004); and d) Finally, we consider that the proposed method has advantages over other commonly used methods which are based on the calculation of vegetation indices, especially NDVI and SAVI. These vegetation indices do not calculate different types of vegetation density, but rather the vigor of the vegetation, according to its reflectivity (Lambin and Ehrlich, 1997; Carlson and Ripley, 1997; Schmidt and Karnieli, 2000; Elmore et al., 2000). In this respect, it should be noted that in arid regions, like the coastal areas of the Canary Islands, the vegetation has a marked seasonality. Thus, during the dry season, the plants show significant variations in biomass as a strategy to prevent water loss through evapotranspiration (partial or total loss of leaves, reduced size, etc.), presenting an aspect of scarce vigor. Therefore, calculation of these vegetation indices in these circumstances cannot detect all the existing vegetation, but only that with chlorophyll in large leaf surfaces, missing those plants with a reduced leaf surface. This type of vegetation, however, has an important role, from the environmental point of view, in the stabilization of sandy deposits and in the formation of aeolian landforms. In view of the above, implementation of this simple method in other regions of the world with similar environmental conditions can be used as the basis for a more comprehensive environmental analysis in which the most important question would be the relationship between vegetation cover and aeolian landforms. This is of considerable interest, because the interaction between vegetation and aeolian sedimentary dynamics is a major explanatory factor for understanding dune systems and the consequences of the changes they undergo as the result of both natural and anthropic causes. In this sense, the digital vegetation density model (DVDM) presented in the present paper could open up future lines of research in computational fluid dynamic (CFD) modelling where precise simulations have not yet been obtained in vegetated landforms. It is important to note that

the distance between plant individuals conditions the airflow path: the shorter the distance between plant individuals the greater the disruption to the airflow and, consequently, the greater the likelihood of sedimentary accumulation. The density concept proposed in this paper considers the distance factor and the number of plant individuals that spatially occupy an arid aeolian sedimentary system. Implementing the DVDM with additional variables such as plant height or plant porosity from photogrammetric techniques or LiDAR sensors would add even further to an understanding of how a fluid such as air is conditioned by the vegetation. These are very important aspects because the vegetation represents a roughness for the airflow conditioning sediment transport (Smyth, 2016). These systems can thus be monitored from a historical perspective, given the possibility of identifying natural or induced processes. Such analyses of aeolian sedimentary systems may help to explain some features of global change. From an ecological point of view, it is also possible that the categories obtained may have a relationship with the distribution of certain plant communities of La Graciosa, whose survival strategies follow a pattern directly related to their density. In this respect, there may be communities that are more sensitive to high densities and, conversely, others that need low and medium densities to survive in an arid environment where water resources are scarce.

3. Another key advantage of the application of this simple method is related to the result of greater source availability, the ease of technical implementation and the low cost required for its application: a) application of this method is less expensive than that based on traditional visual analysis (Kadmon and Harari-Kremer, 1999), as no lengthy training is required; b) images with visible bands are cheaper than those with infrared bands, and in many cases, depending on the processing, can achieve greater spatial resolution; c) algorithms are easily implemented using GIS free software. These aspects are very important because by using this method studies can be undertaken in countries with less research funding or less technical qualification in environmental management. Furthermore, such countries tend to have the highest percentage of occupation of aeolian sedimentary systems. This can be seen in Figure 10 which relates their percentage of occupation (Kelso and Patterson, 2012) with the gross domestic product (GDP) of each country (The World Bank, 2015). Consequently, it can be argued that studies on aeolian sedimentary systems, and especially their vegetation, are relevant for the future in the actual scenario of global change.

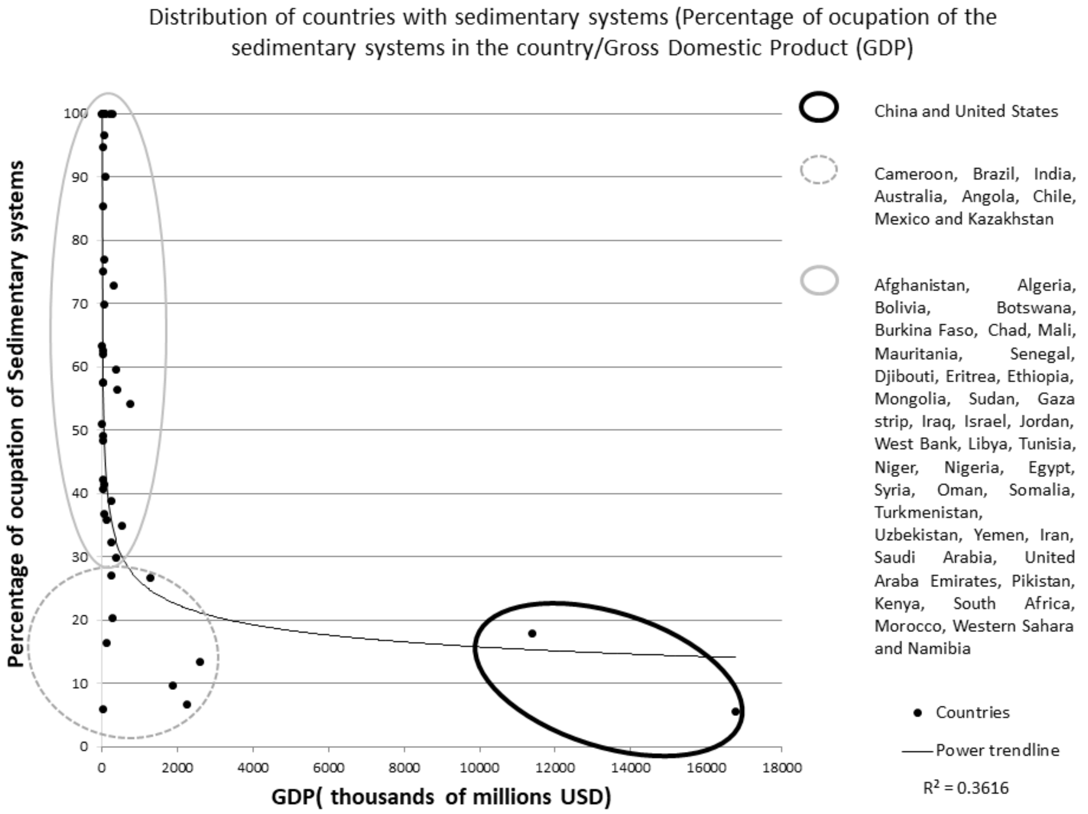

Figure 10. Distribution of countries with aeolian sedimentary systems (percentage of occupation of aeolian sedimentary systems in the countries)/gross domestic product (GDP).

Three limitations have been detected for this method, two of them regarding the use of the green band of the orthophoto, and the other related to the use of the tool for calculating densities:

1. This method is only applicable in sandy systems where the sands have a high reflectance in the visible spectrum. In this respect, we start from the premise that the lowest digital levels correspond to vegetation, while the highest digital levels correspond to sand. Therefore, in areas where other low reflectance coverings appear, as may be the case of rocks, or where the sand presents low reflectance levels (volcanic, for example), it may not be easy to distinguish between the types of covering, at least using only a visible band. In this regard, other complementary analyses, as for example calculations of roughness or texture, could be useful to improve the classification.
2. Another limitation is the result of the size of herbaceous therophyte vegetation, which is not discriminated by the proposed method. For this reason, in arid dune systems, it is important to remember the role played by seasonal therophytic vegetation in stabilized dunes and nebkha dune fields (Hernández-Cordero et al., 2015a).
3. The final limitation we have detected is related to the tool that calculates the density of points. As the size of the sampling unit is increased, the results become more generalized. This requires clarification, in each case, of the optimal sampling unit size, although in this work we have already made a more precise approximation.

5. Conclusions

5.1.Aspects related to the usefulness of the method.

A simple procedure to automatically classify vegetation density in arid sandy systems using digital orthophotos has been developed, termed the digital vegetation density model (DVDM). This method allows the use of historical information sources, such as aerial photographs in natural color or black and white, enabling studies to be undertaken on evolution of the vegetation by using the density variable. This method provides an alternative to those used to date, including those which need more expensive and less historical recorded information, as satellite images with near-infrared bands, as well as traditional photo-interpretation methods with a greater workload and heavy reliance on the analyst's subjectivity.

5.2.Aspects related to the application of the method.

The procedure requires an optimal neighborhood sampling unit size, determined in our case to be 9×9 m. This optimal neighborhood sampling size was also applied to two historical aerial photographs to check its effectiveness when using black and white images. The changes in vegetation density between 1954, 1987 and 2009 can be seen and quantified objectively. The use of GIS software, commercial or free, facilitates its application as well as helping to understand the patterns of spatial distribution of density degrees, relating this variable with aeolian sedimentary dynamics.

5.3.Aspects related to the results and their usefulness.

The results allowed characterization of the vegetation density in the aeolian sedimentary systems of La Graciosa (Canary Islands, Spain) through application of the digital vegetation density model (DVDM). Given the relationship between vegetation and aeolian sedimentary processes in dune systems, the results are of particular interest for management of such natural areas, especially to avoid human impact in those areas considered more sensitive.

Acknowledgements

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Biogeomorphological processes in an arid transgressive dunefield as indicators of human impact by urbanization

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Abstract

Urban and tourist developments can have long-lasting impacts on coastal environments and fundamentally alter the evolution of coastal dune systems. This is the case of the Maspalomas dunefield (Gran Canaria, Canary Islands), hosting one of the largest tourist resorts in Spain. The resort was built on top of a sedimentary terrace at 25m above sea level (El Inglés) in the 1960s, and has subsequently affected local winds and therefore aeolian sediment transport patterns. Buildings on the terrace deflect the winds to the south of the dunefield, where the rate of sediment transport accelerated. A shadow zone appeared to the lee side of the resort with a consequent decrease in wind speed and aeolian sediment transport and an increase in vegetation cover. In this paper, first we characterize the environmental changes around El Inglés terrace in recent decades, and describe the changes in the shadow zone through an analysis of the evolution of sedimentary volumes and vegetation characteristics (density, spatial patterns, and plants communities). A series of historical aerial photographs, recent orthophotos and digital elevation models obtained by digital photogrammetry and LiDAR, as well as fieldwork were used to characterize plant communities and spatial-temporal changes in erosive landforms. Results show changes in the pattern and migration rates of dunes located at the southern edge of the urbanization, as well as the formation of blowouts and large deflation areas, where the vegetation increases in density and number of plant communities. We discuss eco-anthropogenic factors that have produced these environmental changes.

Keywords: arid coastal dunes system, aeolian shadow zones, biogeomorphological evolution, blowout, environmental changes, urban-tourist buildings

1. Introduction

The coast has a great diversity of environments and resources, making it a particularly attractive area for human settlements, both as a place of residence and as an ideal location for multiple recreational and economic activities (Cendrero et al., 2005). The last few decades have seen an accelerated littoralisation process (accelerated rate of human occupation at the coast) (Cerdá, 2002), with a significant increase in human pressure, which alters natural processes due to human developments, therefore increasing the vulnerability of coastal environments, especially sandy coasts (Brown and McLachlan, 2002; Martinez et al., 2006). This process has accelerated on some arid coastlines, especially those with beach-dune systems, with good climate conditions during the winter driving the development of both tourist and residential urbanization (Hernández-Calvento et al., 2014). The poor, or incorrect location of buildings and infrastructure can generate serious impacts, partial to total destruction of coastal dunes and their vegetation, including building on top of the dunes and interfering with natural beach-dune dynamics (Cooper and McKenna, 2009; Nordstrom, 2004). This has significant implications for both society and management of dunefields, decreasing the ecosystem services and the ability of beach-dune systems to act as a natural coastal defense against storms (Everard et al., 2010; Liquete et al., 2013). It also creates a paradox, where the impacts of anthropogenic activities are directed towards natural resources that are in turn the base of these anthropogenic activities (Cooper and McKenna, 2008; Cabrera-Vega et al., 2013).

Much research has focused on human impacts on beaches and coastal dunes (Bauer, 2009; Jackson and Nordstrom, 2011; Curr et al., 2000; Martínez et al., 2013a, Martínez et al., 2013b) especially in temperate zones. However, studies on the direct impacts of urbanization on coastal dune fields landwards from the foredune are scarce (Jackson and Nordstrom, 2011; Hernández-Calvento et al., 2014; Smith et al., 2017). Buildings located near or inside dune fields act as rigid and impermeable structures that intrude and modify the Internal Boundary Layer (IBL) and alter aeolian sediment dynamics (Nordstrom and McCluskey, 1984; Gundlach and Siah, 1987; Nordstrom and Jackson, 1998; Tsoar and Blumberg, 2002; Wiedemann and Pickart, 2004).

Recent research on this topic demonstrated the effects of buildings on modifying the airflow regime and aeolian sediment transport patterns reducing the wind speed by 50% in some places at the dune system of Maspalomas, Gran Canaria, Spain (Hernández-Calvento et al., 2014; Smith et al., 2017), an excellent example of the conflict between urban-tourist development and conservation (García-Romero et al., 2016). At this location, three different geomorphological areas can be identified based on regional disturbances of the wind patterns: an area of air flow acceleration to the south of a terrace upon which much of the tourist infrastructure has been developed; and two 'shadow' areas in the lee-side of the urbanized area, characterized by airflow deceleration, with different degrees of sedimentary stabilization and vegetation growth. All these areas have been described by Hernández-Calvento et al. (2014) and Hernández-Cordero et al. (2017). It has also been shown that these environmental changes have not been produced by a regional climate change: according to Smith et al. (2017), the mobility index (Lancaster, 1988) has been maintained since the 1960s with a value > 200, indicating a fully active mobile dunefield or aeolian processes.

While airflow patterns in shadow zones within a dunefield have been described in general (Hernández-Calvento et al., 2014; Smith et al., 2017), little is known about the evolution and temporal dynamics of these aeolian zones, which are determined by a combination of several variables including feedbacks between topographic change, vegetation growth and aeolian processes. Previous research including the combination of geomorphology and biota has aided in the understanding of such dune systems (Stallins, 2006; Corenblit et al., 2011) and can improve our knowledge of, for example, the operation of barrier-island dunes (Stallins, 2001, Stallins, 2002; Stallins and Parker, 2003). Vegetation type and density becomes in these cases a good indicator of environmental changes (Moreno-Casasola, 1986; Hesp, 1988; Arens, 1996; Lancaster and Baas, 1998; Martinez et al., 2001; Hernández Calvento, 2006; Miot da Silva et al., 2008; Hernández-Cordero et al., 2017). Similarly, comprehensive analyses of the combined evolution of vegetation cover and density, plant communities and topographic changes within the shadow zone can provide valuable information on how these previously active areas adapt to new environmental conditions as a result of building and developing infrastructure.

This paper analyses the evolution of a shadow zone within an arid transgressive dune field where sediment supply was cut off following the construction of a large resort. First, we quantify volumetric changes and vegetation patterns using a set of orthophotos, historical aerial photographs and digital elevation models (DEMs) since the 1960s. Second, we then focus on the relationship between these parameters, as well as the impact of urbanization on the overall biogeomorphological evolution of this area.

1.1. *Study area*

The arid transgressive dunefield of Maspalomas (360.9 ha), is located on the fan-delta of the Fataga ravine at the south of Gran Canaria, in Canary Islands (Fig. 1). Sediment input to the dune system comes primarily from its eastern beach (El Inglés), where the foredune is located. Above threshold, effective winds are >5.1 m/s according to Pérez-Chacón et al. (2007) and the aeolian sediment transport is predominantly ENE-WSW (Máyer-Suárez et al., 2012), with the sand eventually returning to the sea at the southern end section of the dune system (Maspalomas beach; Fig. 1). One of its most foremost geomorphological features is the existence of a high Pleistocene wedge-shaped terrace on its north-eastern boundary. Building of one of the largest tourist resorts in Spain started in the 1960s on this terrace (Domínguez-Mujica et al., 2011), with the consequent alteration of local winds and aeolian sediment transport patterns, and the generation of the shadow zone studied here (Hernández-Calvento et al., 2014; Smith et al., 2017). A few erosive landforms have been detected in this area at a similar distance from the resort (García-Romero et al., 2017). A trough blowout according to the classification of Hesp (2002) has also been identified within these landforms (Mir-Gual et al., 2015). However, the origin and evolution of these landforms have not been studied in detail.

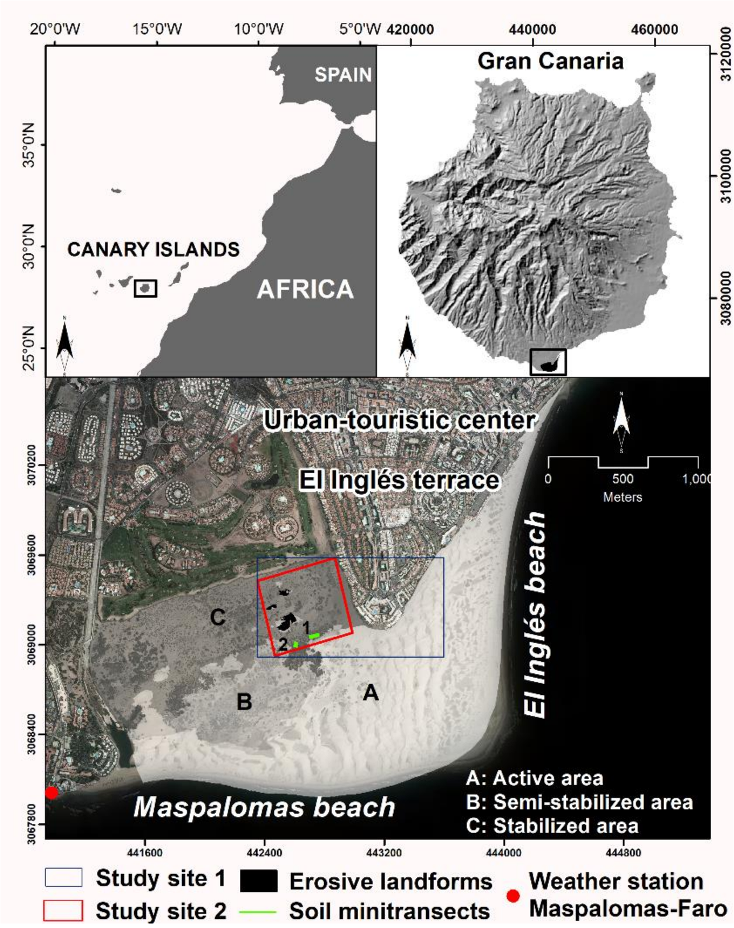

Figure 1. Location of Maspalomas' dunefield. Areas with different aeolian sedimentary activity (Hernández-Cordero et al., 2015a) are indicated on the map (A: active area, B: semi-stabilized area, and C: stabilized area). Study site 1 for examining environmental changes around El Inglés terrace at a regional scale is indicated in blue. Study site 2 for examining the aeolian shadow zone at a local scale is indicated in red. The erosive landforms (in black) and soil mini-transects (in green) in the shadow zone are also shown.

2. Methodology

Analyses were conducted at two spatial scales and at two study sites. First, a regional scale is used to evaluate if the aeolian shadow zone could be related to disturbances of the sedimentary dynamics induced by the presence of the urban-touristic buildings, or related to a regional climate change (study site 1). Second, a local scale is used to analyze the biogeomorphological processes in the aeolian shadow zone (study site 2). The cartographic documents (aerial photographs, orthophotos and DEMs) which were used in this study are listed in Table 1.

Table 1. Cartographic documents utilized in this study.

Type (source)	Year	Spatial resolution (m)	Use
Historial aerial photographs (1, 2, 3)	1961 (1:5,000)	0.25	Vegetation
	1977 (1:6,500)	0.9	
	1981 (1:4,000)	0.15	
Orthophotos (2, 3, 4)	1987, 2003, 2009, 2012, 2015, 2017(only in the study site 2)	0.15 – 0.25	Topography
DEMs (5)	05/1987, 11/2003	4	
DEMs (6)	10/2006, 03/2009, 03/2011, 03/2015, 03/2017(only in the study site 2)	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) Photogrammetric restitution; (6) LiDAR (2006, 2009, 2011, 2015) and real photogrammetric restitution (2017) from a drone flight (file.las).

2.1. *Regional scale*

Precipitation data from the 1950s were analyzed to investigate potential changes to the amount of rainfall received by vegetation at the study sites. These could affect the growth rates of vegetation and hence alter the sedimentary dynamics at the study sites, additional to the impact of urbanization. Smith et al. (2017) observed no changes to the mobility index (Lancaster, 1988) in Maspalomas since the 1960s using data from a weather station 25 km northeast of Maspalomas. We have refined previous analyses and used data recorded by a meteorological station of the Agencia Estatal de Meteorología (Meteorology Statal Agency, AEMET) Maspalomas-Faro (Fig. 1), approx. 2 km southwest of the study sites, and including some of the oldest meteorological datasets on the island (since 1952). Monthly rainfall was analyzed to identify potential seasonal changes. The time series were 85% complete, so some of the missing data was extrapolated from two weather stations at 4 and 11 km from the study site using regression analyses with R2 of 0.94 and 0.84 respectively.

2.1.1. *Changes to the sedimentary dynamics*

Changes to the sedimentary dynamics of study site 1 were analyzed in two steps: first by calculating changes in the direction of the dune brinks (i.e. the top edge of the dune slipface), and, second, by calculating changes in the volume of sediments. The first step was carried out by mapping dune brinks (vector lines), through visual analysis with GIS support, on the 1961 and 1977 aerial mosaics and on the 1987, 2003, 2009 and 2015 orthophotographs (Fig. 3, white lines). The direction of each dune brink (each line) was calculated using GIS tools. First, the dune brink lines were converted to points, second, using the central point as the reference and through near-location tools to calculate the direction of the others points corresponding to each dune brink line, the mean direction was calculated to determine the main movement of the dunes. Finally, to show spatially this movement an inverse distance weighting interpolation was carried out, using a local sample (4 points sample), and obtaining a minimum error (4.41°). The movement is represented by arrows every 100 m (Fig. 3, red arrows). In addition, the height of the dunes is calculated through topographic profiles on the 1987, 2003, 2009, 2011 and 2015 LiDAR derived DEMs noted in Table 1. Erosion and accumulation volumes were also calculated between 2006 and 2015 from the DoDs using the methodology (Geomorphic Change Detection software) developed by Wheaton et al., 2010a, Wheaton et al., 2010b. DoD error (%) of the erosion: 7.79 and the accumulation: 7.82 from LiDAR data (Fig. 3, A).

2.2. *Local scale*

For the local scale, the study is focused on study site 2, which covers 27.76 ha inside the aeolian shadow zone (Fig. 1, study site 2). The medium-term evolution of this zone is characterized based on three variables: spatial patterns of plant communities, vegetation density, and sedimentary volumetric changes. Additionally, the shape and volume of the erosive landforms is also studied. Processing and analyses were conducted using a GIS.

2.2.1. *Vegetation*

Vegetation density was calculated following the procedure developed by García-Romero et al. (2018), using black and white and color historical aerial photographs and digital orthophotos (Table 1). The green band is the region of the visible spectrum that best captures vegetation characteristics (Chuvieco, 2010) in the absence of a near infrared band (NIR). Hence, this can be used to equate the behavior of digital levels with black and white historical aerial photographs, and differentiate bush vegetation (low digital levels) from bare sand (high digital levels). Bush plants, present in the zone, are perennial, and the method applied only detects bush plants; hence there are no phenological problems associated to seasonality (García-Romero et al., 2018). The digital vegetation density model was resampled to 1 m pixel resolutions so they can be compared due to historical aerial photographs and orthophotos having different spatial resolution, and pixels were subsequently classified into the following four categories: (1) low densities, with vegetation covering between 0 and 10.65% of the area (including sand sheets and isolated shrubs); (2) low-moderate densities, with vegetation covering 10.65–22.35%; (3) moderate-high densities, with vegetation covering 22.35–49.26%; and (4) high densities, including areas with a vegetation cover of 49.26–84.25% (García-Romero et al., 2018).
Changes in plant communities were characterized through elaboration of vegetation maps of the years 1961, 2003 and 2017, using GIS and imagery (Table 1). The plant communities' maps for the years 1961 and 2003 were obtained from Hernández-Cordero et al. (2017). The vegetation mapping of 2017 was developed through visual interpretation of digital orthophotos (using variables such as color, size, density, texture and spatial pattern) and supported by field work.

2.2.2. *Topography*

Sediment volume changes were characterized using digital elevation models (DEMs). Two DEMs were derived from digital photogrammetry (1987 and 2003), another four from LiDAR (2006, 2009, 2011 and 2015) and the last one from real photogrammetric restitution on photography captured by an unmanned aerial vehicle, UAV (only in the shadow zone) (Table 1). The latter included field control from a total station Leica TS06-

laser (March, 25th 2017). Occlusion-based methodology (Chang et al., 2008) was applied to produce a digital elevation model (DEM) and a digital surface model (DSM).
DEMs of difference (DoD) were calculated from 1987 and 2003 DEMs (4 m pixel), and from 2006 and 2017 DEMs (1 m pixel). Although the dates of the DEMs do not coincide, it was considered preferable to work with all information sources available and with the highest precision in order to analyze the trends occurring in the past few decades. The DEMs and DoDs, have been cleaned, corrected and calculated through Geomorphic Change Detection (GCD) software, including the calculation between raw and threshold error (Wheaton et al., 2010a, Wheaton et al., 2010b). DoD error (%): Accumulation (15.49) erosion (18.32) from photogrammetric restitution (Fig. 5, C). DoD error (%): Accumulation (7.06) erosion (8.80) from file .las data (Fig. 5, D).

2.2.3. *Erosive landforms characterization*

Erosive landforms were digitized using historical and current orthophotos and DEMs. These were delimited by visual criteria through photo interpretation and using slope change analyses.

2.2.4. *Relationships between variables*

Geoprocessing tools in GIS (overlay) were used to investigate spatial trends and relationships between variables. For the characterization of the relationship between vegetation and topography, an algorithm implemented in GRASS software, that produces a covariate-correlation matrix between raster data, was used. This analysis was carried out for the period between 1987 and 2017 because DEMs were only available from this period. The areas occupied by the vegetation cover each year were related to their corresponding DEM classified by similar altitude intervals (m.a.s.l.).

3. Results

3.1. *Regional scale*

3.1.1. Rainfall in the Maspalomas dune system

Fig. 2 shows the monthly mean rainfall from 1952 to 2017. Rainfall is concentrated in winter and autumn months (November–February). Little rain occurs in spring (0.4–5.9 mm), and in summer the rainfall is close to zero. The total monthly rainfall in the year before the vegetation density calculation is also shown in Fig. 2. Temporal patterns are similar to the ones for monthly mean rainfall using the entire data set (1952–2017), with rainfall concentrated in winter and autumn. The years 1960 and 1976 were dry with no rainy months. 1980 was also a dry year although in January rainfall reached 39.1 mm. 1986 was also a dry year with rain only in March and September (4 mm). In 2002, December was the highest rainfall (78.3 mm) registered in a month, but the rest of the year the rainfall was not significant. 2008 was also a dry year, with December being the rainiest month (15.3 mm). 2011 was the rainiest year, with a total of 132.7 mm year, with November the rainiest month (57.7 mm), followed by December (42.9 mm). Finally, 2014 and 2016 were dry years with November having the highest rainfall recorded, with 30.2 and 22.4 mm respectively. In general, they are dry years, with rainfall concentrated in one month, except 2011, with two rainy months.

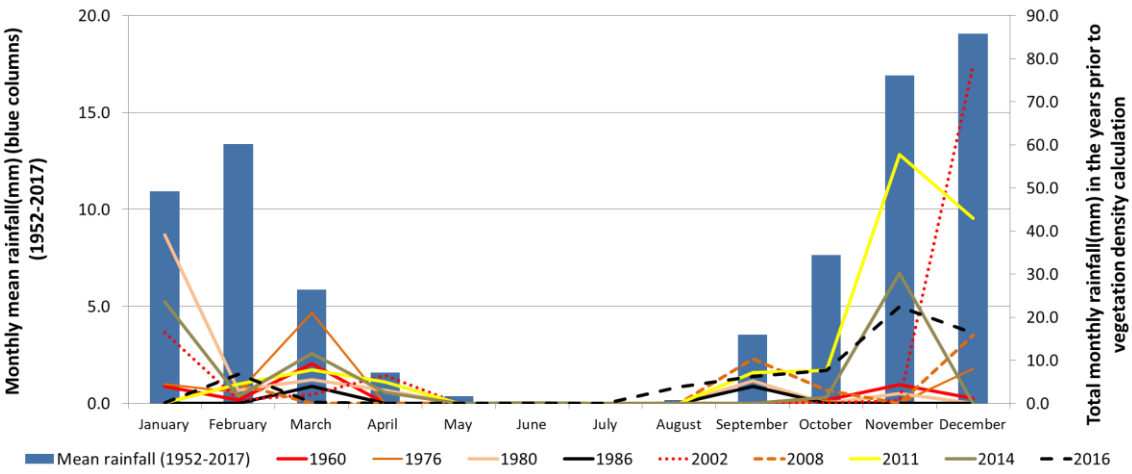

Figure 2. Monthly mean rainfall between 1952 and 2017 (blue columns).Total monthly rainfall in the years prior to vegetation density calculation (lines).

3.1.2. Changes in the sedimentary dynamics

Figure 3 shows results for the directions of dune movement indicated by dune brink orientations and their volumes calculated within study site 1. In 1961 the main dune directions were ENE-WSW, with only a few dune brinks facing E-W. This year dune brinks were detected practically throughout the entire area, and continuous, linked barchanoid dunes displayed along-brink lengths of up to 640 m. Where continuous dune brinks were not observed, Hernández-Cordero et al. (2018) mapped cliff-top dunes formed by nebkha dunes (not barchanoid dunes) which were removed to gain agricultural land (Hernández Calvento, 2006). In 1977, when construction had occurred on a large part of the terrace, the number of dunes and dune brinks was reduced, and the maximum brink length is around 360 m. Dune continuity was therefore beginning to break up. As for the direction of dune movement, three sectors can be observed: i) the dune brinks to the east and south of the terrace face to the ENE-WSW direction, although some of them are oriented to the E-W, especially those closest to the terrace; ii) the second sector is formed by the dunes closer to the southern edge of the terrace. Their dune brinks are clearly oriented to the W-NW; iii) finally, the dune brinks in the current shadow zone of the terrace display both orientations, E-W and ENE-WSW. Similar aspects can be identified in 1987, although there is more infrastructure present on the terrace, and the eastern and western sides have been completely occupied by urban development (Fig. 3, A). Also on the southern edge of the terrace, the dunes show some changes: the last dune brink facing E-W is located 30 m to the south in relation to the last brink in 1977 (Fig. 3, A), and the number of dunes moving westward has reduced slightly. In 2003 the terrace is fully covered with built structures (Fig. 3, A), and the orientations of the dune brinks maintain the same pattern as in 1987. In addition, the last dune brink facing W-NW is now about 105 m south of the last dune brink in 1987. Also the number of dunes in the aeolian shadow zone (in the west) has reduced. The same tendency can be seen in the images of 2009 and 2015.

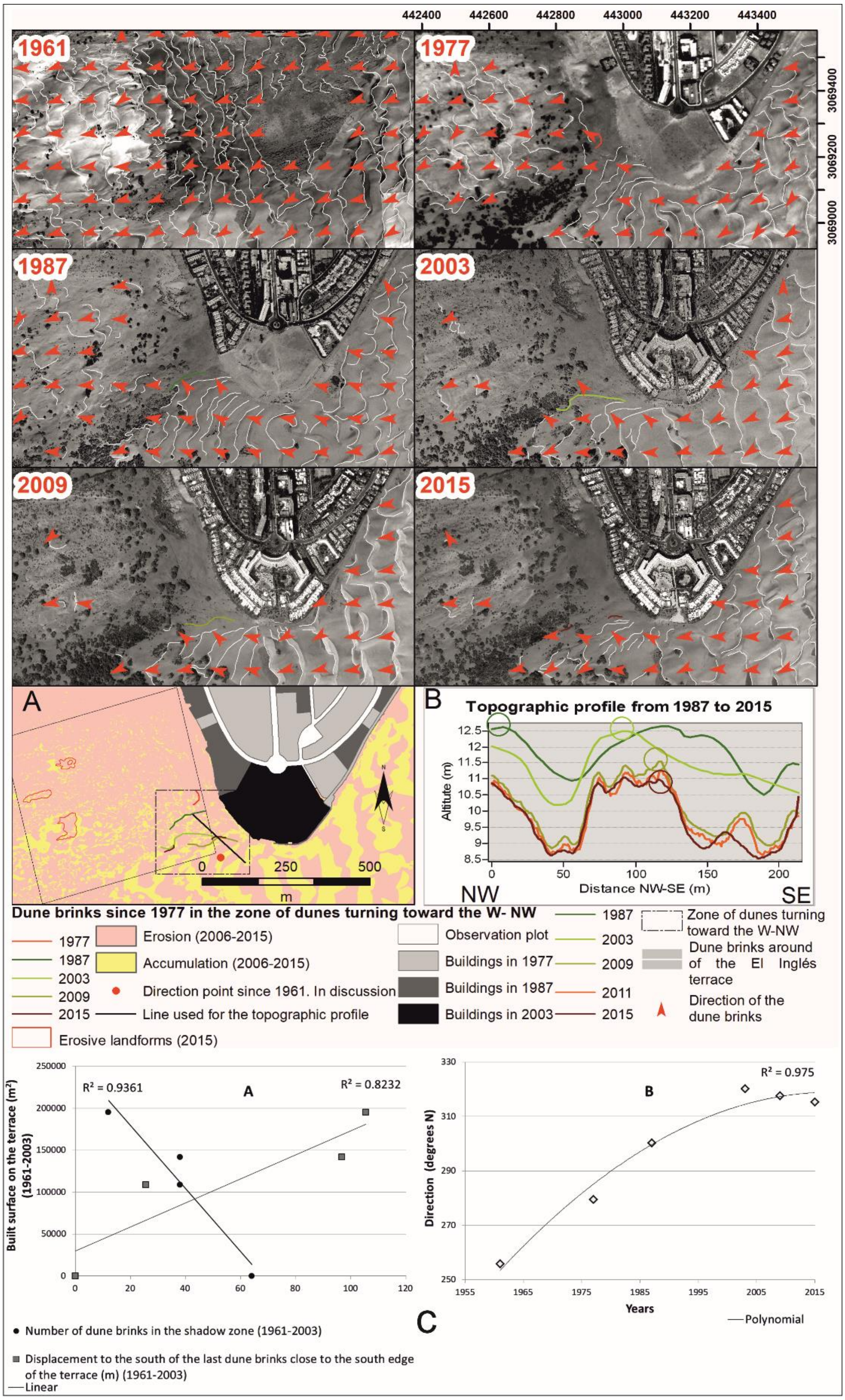

Figure 3. Changes in the orientation of the dune brinks and in the dune heights in relation with the building development on El Inglés terrace. C (left, A) Disappearance of the dune brinks in the shadow zone and displacement to the south of the last dune brinks close to the south edge of the terrace, while increasing the built surface on El Inglés terrace. C (right, B) Changes in the direction of the dune brinks (red point in A) close to the southern edge of the terrace over the years before, and during which construction occurred on the El Inglés terrace.

3.1.3. Topographic changes around El Inglés terrace

From the DoD between 2006 and 2015 DEMs, three different zones can be observed (Fig. 3, A): i) to the east and south of the terrace, accumulation processes predominate over erosion; ii) the erosion predominates in practically the entire shadow zone; iii) erosion predominates on the southern edge of the terrace, as shown in the profile between 1987 and 2015 (Fig. 3, B). Elevation differences range from 1 m in some areas and up to 3.5 m height at 150 m from the profile in the NW-SE direction. The circles on the profiles show where the last dune brinks in the zone where the dunes turn to the W-NW were/are located. The location of the circles indicates a migration to the southern edge of the terrace (125 m). The lower height of these dunes also indicates a reduction in the transport of sediments towards the shadow zone since 2003 (Fig. 3, 2003).

3.2. *Local scale*

3.2.1. *Vegetation density in the aeolian shadow zone*

Figure 4 shows an increase in vegetation density from 1961 to 2017. 1961 was characterized by lower vegetation densities (0–10.65) and isolated plants, with some aggregate units to the south of the study area. Vegetation density was highest in 2017 where the category 1 (lower vegetation density) decreased −53.58%, while the categories 2, 3 and 4 increased 368.62%, 574.51% and 1513.64% respectively, with the species Tamarix canariensis and Launaea arborescens dominating the area (Fig. 4, C).

Vegetation growth was mainly concentrated in the southern and central areas of the study site between 1961 and 1977. In 1981, isolated plants started to grow to the east, close to the resort. Moderate-high and high vegetation densities increased to the north of the study area, close to the golf course bordering the plot, from 2003 to 2009, with the remaining of the study period characterized by a general increase in vegetation densities everywhere within the study site (Fig. 4, A).

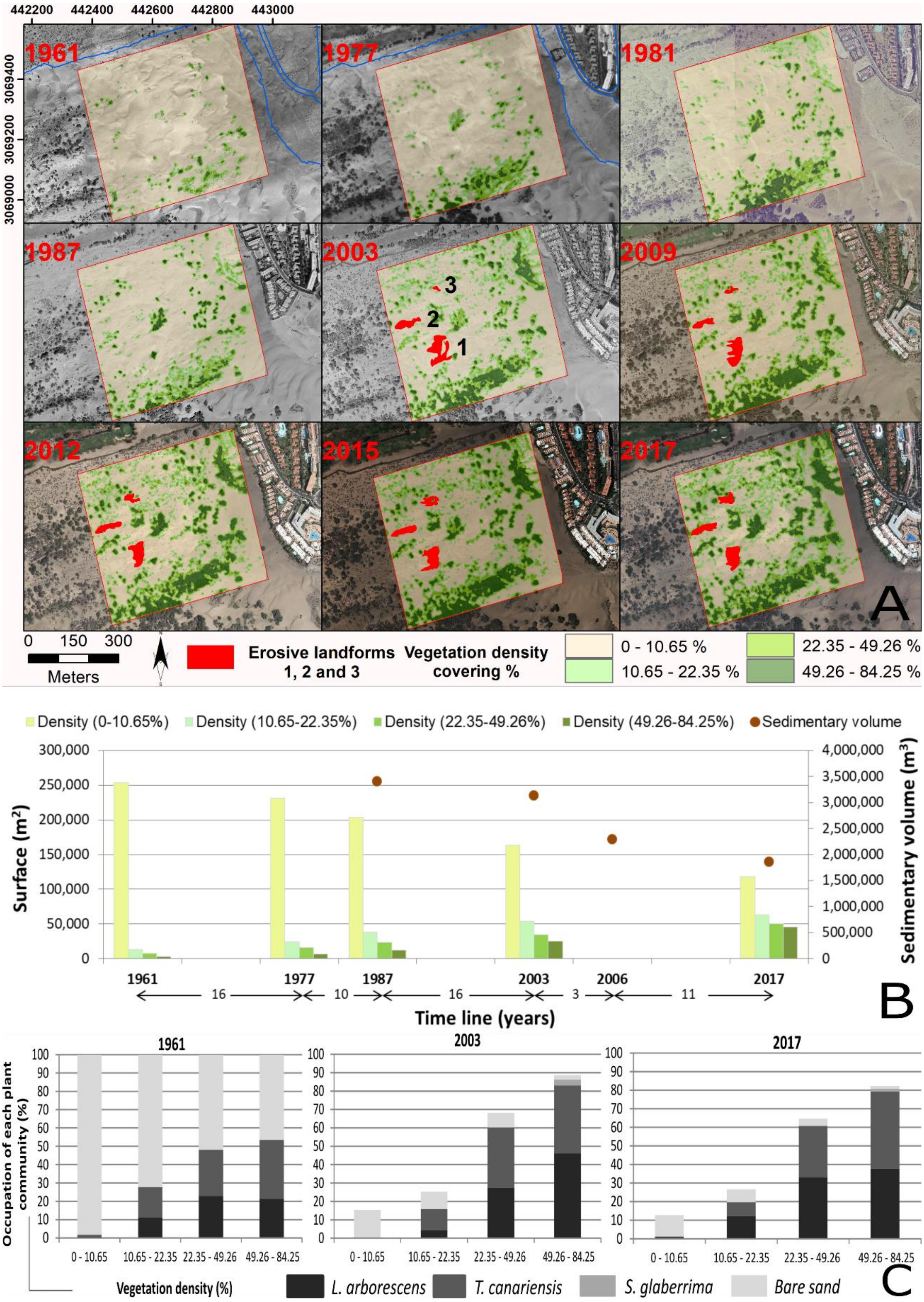

Figure 4. Evolution of the vegetation density in study site 2. The three erosive landforms first detected in 2003 are shown in red. B: Changes in the vegetation density per categories and variation of the sedimentary volume in the study site. C. Evolution of plant communities and vegetation density in the study site.

3.2.2. *Plant communities and bare sand in the aeolian shadow zone*

Vegetation spread widely at the study site from 1961 to 2017 (Fig. 4, A) which lost up to 92.28% of the original bare and mobile sand in 56 years (at a rate of 1.6% bare sand loss per year) (Table 2). Only two plant communities were identified in 1961: Launaea arborescens (xerophilous low shrub), principally located in dry slacks in stabilized and mobile dunes, and Tamarix canariensis (hygrophilous low tree), a typical plant community of wet slacks in mobile, semi-stabilized and stabilized dunes. In 2003, six additional plant communities were identified: Cyperus capitatus-Ononis tournefortii (psammophilous perennial rhizomatous forb; psammophilous annual forb), belonging to stabilized dunes; Mesembryanthemum crystallinum (nitrophilous annual forb); Aizoon canariense (nitrophilous annual forb); Volutaria canariensis (annual forb); Cenchrus ciliaris (perennial grass) and Schizogyne glaberrima (xerophilous low shrub), belonging to ruderal areas. All plant communities expanded spatially from 2003 to 2017, especially the Cyperus capitatus-Ononis tournefortii community.

Table 2. Changes of the plant communities since 1961 in the aeolian shadow zone.

Plant community	Surface area 1961		Surface area 2003		Surface area 2017		Variation (1961-2017	
	m^2	%	m^2	%	m^2	%	m^2	%
A. canariense	0.00	0.00	987.26	0.36	960.64	0.35	960.64	100
C. ciliaris	0.00	0.00	262.03	0.09	287.66	0.10	287.66	100
C. capitatus-O. tournefortii	0.00	0.00	190505.87	68.60	173370.23	62.43	173370.23	100
L. arborescens	5420.39	1.95	23685.71	8.53	42893.46	15.45	37473.07	691
M. crystallinum	0.00	0.00	544.31	0.20	510.42	0.18	510.42	100
S. glaberrima	0.00	0.00	904.46	0.33	873.41	0.31	873.41	100
T. canariensis	7795.71	2.81	27299.48	9.83	38126.84	13.73	30331.13	389
V. canariensis	0.00	0.00	224.98	0.08	261.00	0.09	261.00	100
Bare sand	264474.01	95.24	33276.02	11.98	20406.43	7.35	-244067.58	-92

3.2.3. *Relationships between vegetation density and plant communities in the aeolian shadow zone*

The relationships between vegetation density and plant communities were analyzed to identify which communities expanded the most and were more competitive (Fig. 4, C). In 1961, only two shrub plant communities were detected (Tamarix canariensis and Launaea arborescens) scattered all over the study plot (Hernández-Cordero et al., 2017), but forming some groups to the south of it. Bare sand occupied a large part of the low densities range (0–10.65) as one would expect. In 2003, the bare sand had practically disappeared, occupying just around 15% of the lower density range. Tamarix canariensis is the community that occupied the most area in the intermediate densities, followed by Launaea arborescens. This last community represents the highest density range, followed by Tamarix canariensis. That year (2003), a new shrub community was detected, the Schizogyne glaberrima community, represented also in the highest density range. These trends are similar in 2017, but with some differences: bare sand has decreased; the Tamarix canariensis community has decreased in the highest densities range, while the Launaea arborescens community has increased in this range, so both communities have a similar percent cover. Finally, in contrast with 2003, the Schizogyne glaberrima community has lost cover in the highest density range.

3.2.4. *Volumetric changes in the aeolian shadow zone*

Study site 2 shows a negative sediment budget between 1987 and 2017 (Fig. 4, B). The largest erosion rate was registered between 2003 and 2006. Sediment losses of up to 279,445.68 m3 (8.19% of its volume above 0 m.a.s.l.) between 1987 and 2003. Erosion was larger from 2006 to 2017, with a deficit of 429,791.27 m3 (18.76% of the total sand volume in the study site 2; García-Romero et al., 2017). Some sediment accumulation areas are observed locally in zones with topographic lows or dense vegetation, or both. A substantial amount of these accumulation areas are located to the southwest of erosional ones (Fig. 5, C, D). Since regional predominant winds in this area are ENE-WSW, these particular spatial patterns indicate active aeolian processes in this shadow zone, with wind erosion, sediment transport, and surface growth as a result of sand accumulation towards the W and in the direction of the predominant winds.

In the erosive zones there is a sector (to the west and southwest of the study site 2) with significant erosion (Fig. 5, C, D). In this sector there have been losses of around 5 and 6 meter depth and these coincide with the erosive landforms that will be explained in the next section.

3.2.5. *Relationships between vegetation and topography in the aeolian shadow zone*

The vegetation cover has increased from 1961 to 2017. As shown in Fig. 5, E, there is a relationship between the topography of study site 2 and the increase in the vegetation cover from 1987 (first DEM available) to 2017 (last DEM obtained from drone flight). The graph shows that the tendency of vegetation in 1987 was to occupy the lowest elevations, while its presence in relatively high elevations is not significant. However, from 2003 to 2017, vegetation has not only increased its cover at lower elevations by 30%, but also it has done so in the rest of study site 2. Currently, this trend has changed and vegetation also colonizes higher elevations, although between 4 and 7 m.a.s.l. the increase in the vegetation cover has been insignificant.

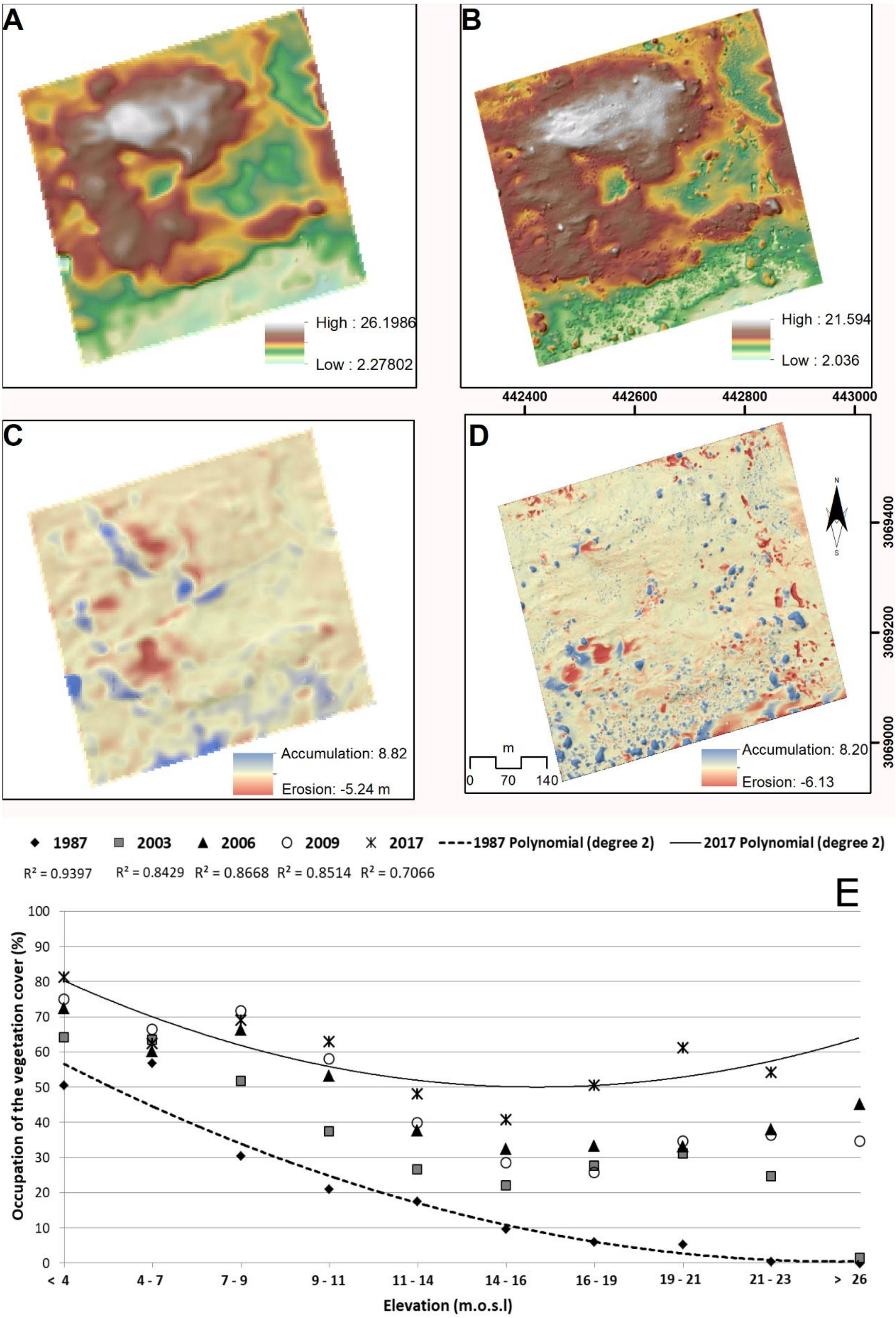

Fig. 5. A. DEM in 1987 (resolution: 4 m); B. DEM in 2017 (resolution: 1 m); C. Net topographic changes for the period of 1987 to 2003 (resolution: 4 m); D. Net topographic changes between 2006 and 2017 (resolution: 1 m); E. Relationship between the vegetation cover (%) and elevations in in study site 2. The <4 m altitude zone shows a greater percentage vegetation cover compared to the zone above 26 m in 1987. In 2017, the highest elevations do not reach 26 m.a.s.l., and for this reason there are no vegetation data.

3.2.6. *Erosive landform evolution*

Since 2003 three erosional landforms were detected at a similar distance from the urbanization area, with an ENE-WSW direction (Fig. 1, Fig. 4; erosive landforms 1, 2 and 3). These landforms experienced an increase in surface area and a decrease in volume between 1987 and 2017 (Fig. 6). They have different morphologies: landform 2 is a trough blowout with a relatively stable shape over time. Landforms 1 and 3 are characterized by aeolian deflation surfaces characterized by exhumation of plant roots, but little development yet of actual blowouts. The sediment eroded from these landforms was deposited around the shrub vegetation that has grown downwind of them.

3D views of the erosional surfaces in 2006 and 2017 can be observed in Fig. 6, 1–3. Erosional surface 1 shows considerable spatial change and it has increased in deflation area, while the principal downwind accumulation landform, present as a barchan dune in 2006 (Fig. 6-1, right and bottom) has been stabilized in 2017 due to plant colonization, especially by herbaceous plants. The volumetric deficit measured in the area is 924.23 m3 (-24.11%). Blowout No. 2 (Fig. 6-2) has maintained a similar surface area over time but has eroded by 557.35 m3 (-20.19%). Two depositional lobes are associated with this blowout. The erosional deflation surface 3 has increased while adjacent accumulation landforms, such as the shadow dunes (Fig. 6-3) have disappeared or stabilized. The sedimentary volume has decreased by 73.46 m3 (-33.42%).

4. Discussion

4.1. *Changes to environmental conditions in the Maspalomas dune system*

In line with previous climate studies (Smith et al., 2017), there were no significant changes in precipitation levels or patterns from the 1950s in the study area. Fig. 2 shows that 1960, 1976, 1980, 1986, 2008, 2014 and 2016 were dry years but these were linked to increasing trends in vegetation density. In 2002 and 2011 there was high rainfall but this was mainly concentrated in one or two months (November and December), with close to zero rainfall from April to September as is characteristic of arid climates (Köppen, 1900).

In contrast, the development of the urban-tourist infrastructure has been significant as shown in Fig. 3, and appears to have been a primary control on the sedimentary dynamics of the dune field. First, the buildings occupied a section of the old bypass dune system on the top of the terrace (Hernández-Calvento et al., 2014, García-Romero et al., 2016; Hernández-Cordero et al., 2018). Second, dune directions and movement trends changed around the terrace following development with dune migration directions being steered by the infrastructure as it developed. The geomorphology of the dunes in the shadow zone have changed also, with the number of free and mobile dunes decreasing at site 2 simultaneously with an increase in the number of buildings on El Inglés terrace (Fig. 3, C: A).

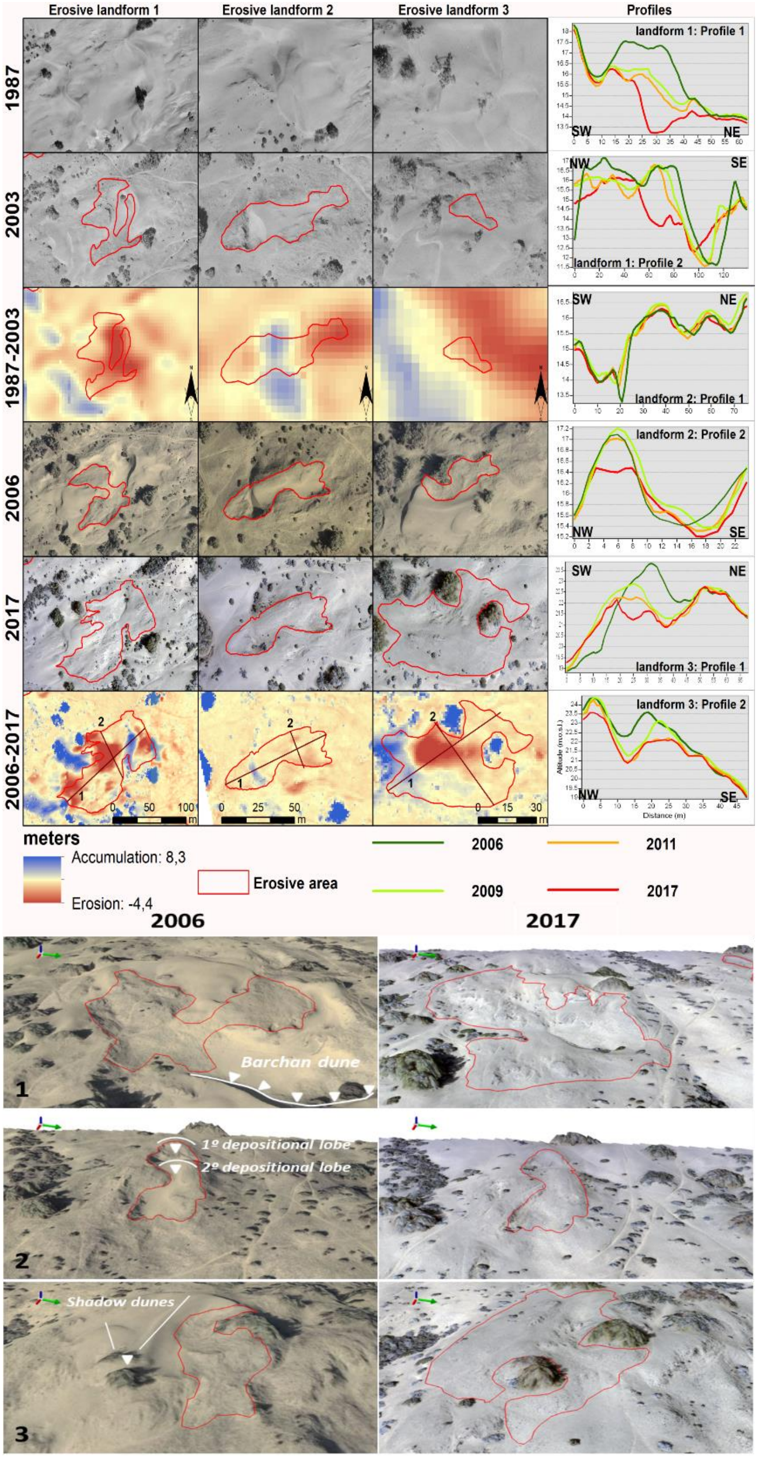

Figure 6. Surface area (in red) and height evolution of the erosional surfaces and landforms between 1987 and 2017 (illustrated in the photographs). Topographic profiles (right hand column) showing differences in elevation from 2006 (dark green) to 2017 (red). 1–3. Erosive landforms in 2006 and 2017. 1. Erosive landform 1 has increased in aeolian deflation area while accumulation landforms, such as a barchan dune, have disappeared or stabilized (pictures 1 and 2 are not at the same scale because there is more visible erosional area in 2017). 2. Trough blowout with two depositional lobes. 3. Erosional landform 3 has increased the deflation area while accumulation landforms, such as shadow dunes, have disappeared. In landforms 1 and 3 the scale is different between 2006 and 2017 (lower in 2017) because the deflation areas have increased by the second date.

This decrease can be explained by the changes which occurred on the southern edge of the terrace. In this area, the dunes moved to the SW before the terrace was built. The construction of new buildings in the 1970s created a barrier to dune movement, with dunes being deflected around the edge of the terrace and adopting new migration directions towards the W-NW as indicated by dune crest and brinkline orientations in Fig. 3. New constructions at the southern edge of the terrace in 1989 had a marked impact on decreasing the number of actively moving dunes (Fig. 3, C: B). In the last 13 years, the trend of the dune brinks is not to turn towards the W-NW but instead take a W-WSW direction. This new turn is accompanied by the movement of the dune brinks towards the southern edge of the terrace (Fig. 3, C: B), and causing the movement of these active landforms away from the terrace, and a decrease in the sediment inputs to the current shadow zone. These changes are related with changes in the direction of the wind flow, as Smith et al. (2017) explain. Since the original dune migration path across the terrace has been eliminated by development, and the further infrastructure changes have produced a marked shadow zone, dunes can no longer migrate into the shadow zone region. In consequence, vegetation growth has occurred stabilizing the region. The existence of some wind corridors between the buildings on the terrace induces limited sand transport in the shadow zone, but overall there is a net reduction in the volume of sand being transported through this portion of the dunefield. In summary, the construction of buildings at Maspalomas has generated an erosive (negative budget) zone in an area that was previously active and had pronounced dune mobility and dynamic aeolian activity.

4.2. *Spatio-temporal trends in vegetation cover in the aeolian shadow zone and their relationship with the topography*

The results show that the vegetation density has increased between 1961 and 2017.This is common in places where the wind regime has been altered by buildings (Nordstrom and McCluskey, 1985; Nordstrom, 1994), leading to a stabilized dune area (Hernández-Calvento et al., 2014; Hernández-Cordero et al., 2015a). This is unlike other studies, for example, in Israel, where plant colonization was promoted by agricultural and pastoral activity, producing a negative rate in dune advance (Tsoar and Blumberg, 2002), and in China, where the vegetation cover has increased due to the decadal changes in wind strength, interannual fluctuations in precipitation, and large ecological restoration projects implemented in recent decades (Xu et al., 2018). Results of this study indicate that medium to high density vegetation does not first appear close to buildings, but rather to the south and in the central areas of the study site further away from urbanization. This trend could be related to the topography, because these areas are located in the lower elevation and deflation zones (Fig. 5, E) where one would expect more shallow sub-surface moisture. Additionally, findings by Hernández-Cordero (2012) across transects in Fig. 1 and Table 3 suggest a strong correlation between vegetation species and water table heights leading to differences in soil characteristics potentially involved in this process. Tamarix canariensis and Launaea arborescens communities and Launaea arborescens and Schizogyne glaberrima communities predominated in areas with a higher water table. Both communities first colonized slack and deflation areas with higher water tables than adjacent areas with lower water tables, and soil and stratigraphic type then determined community type. Slacks or deflation and interdune zones are fundamental sites for plant colonization in mobile dune fields such as Maspalomas (Hernández-Cordero et al., 2015b) and elsewhere in transgressive dunefields (Hesp et al., 2011; Hesp, 2013). However, since the 1970s and more clearly during the 1980s, dense vegetation began to colonize other areas closer to buildings. As shown in Fig. 5, E, plants first occupied lower elevations followed by higher elevations. Some of this could be related to aeolian deflation and dune erosion because these result in the local groundwater table being relatively closer to the surface hence increasing moisture availability to plants. A reduction in the process of plant burial has also likely favored plant colonization, since high rates of dune migration and arid climates are the main constraints of vegetation growth in mobile dunes at Maspalomas (Hernández-Cordero et al., 2015b; Hernández-Cordero et al., 2017). Additionally, human activities such as garden irrigation and/or the presence of adjacent golf courses could also have favored vegetation growth similar to other sites in Argentina and Germany (Grunewald, 2006; Grunewald and Schubert, 2007; Faggi and Dadon, 2010, Faggi and Dadon, 2011).

Table 3. Soil characteristics in the south of study site 2.

Transect (with 2 extractions of 125 cm depth)	Plant communities	Soil layers composition
1	- *Launaea arborescens* - *Schizogyne glaberrima*	- 0-5 cm (dry sand) - 5-7 cm and 5-36 cm (wet sand) - >7 cm (wet alluvial deposit) and >36 (wet sand with rocks)
2	- *Tamarix canariensis* - *Launaea arborescens*	- 0-8 and 0-10 cm (dry sand) - 8-84 cm and 10-85 cm (wet sand) - > 84 cm (wet alluvial deposit with rocks) and >85 cm (water)

(Adapted from Hernández-Cordero (2012).)

Before the tourist development (post-1970) mobile dunes were present and migrating downwind of El Inglés high terrace. At the beginning of the study only two plant communities where found, formed by one bush species and one tree species. As described above, the construction of new buildings in the 1970s blocked aeolian transport and slowed down dune migration leeward of the terrace, with vegetation burial being now produced only by local re-mobilization of sand deposits. A total of eight plant communities have colonized study site 2 since then with marked growth during the 1970s and 1980s. The community that has experienced the greatest expansion has been the Cyperus capitatus-Ononis tournefortii community, herbaceous species very common in the dune systems of the Canary Islands (Del Arco Aguilar et al., 2010). Hernández-Cordero et al. (2017) suggested that this plant community benefits and expands the most in stabilized and semi-stabilized dunes of Maspalomas, being a clear indicator of the stabilization of the dune system. This is contrary to what happens in stabilization areas in other climatic regions, such as Israel, where stabilization is produced by shrub species (Levin et al., 2008). Cyperus capitatus is thus a pioneer species in the colonization of semi-stabilized dunes in the Canaries (Hernández-Cordero, 2012; Hernández-Cordero et al., 2015a). This species is the only psammophilous perennial rhizomatous species in study site 2, what likely favors its colonization ability. In dune systems, water and nutrient resources are usually very limited, so the clonal growth of these species, mainly through the production of rhizomes, contributes more to the colonization of plants than the reproduction of seeds (Dong and Alaten, 1999). So the responsiveness of clonal growth, due to the scarcity of resources, may allow the rapid occupation of new habitats by plants (Cook, 1985; De Kroon and Van Groenendael, 1990; Hutchings and De Kroon, 1994). Launaea arborescens is the second plant community that has increased its cover in the study site 2, as it has in the rest of the Maspalomas dune system, according to Hernández-

Cordero et al. (2017). This growth has taken place especially in the new stabilized dunes, but also in ruderal areas due its ecological plasticity (Hernández-Cordero et al., 2017). The Tamarix canariensis community has also shown an increase in cover and again is strongly related to the deflation which has occurred in the study area The rest of the plant communities began appearing after 2003 and their increase in cover, although not significant, is observed mainly near, or downwind of the infrastructure/developed area further indicating the impact that development has had on plant growth.

The evident plant colonization shows a decrease in the low vegetation density range (0–10.65), which corresponds to bare sand and isolated individuals of plants. However, among the shrub communities that have been detected, and could be related to vegetation density (due to the limitations of the procedure for calculating this last variable) the Launaea arborescens and Tamarix canariensis communities have been remarkable in colonizing the dune system and establishing intermediate and high density covers. Each community replaced the other community, especially the Tamarix canariensis community by the Launaea arborescens community, as also detected by Hernández-Cordero et al. (2017), even in the stabilized areas. In the case addressed in this study, the substitution of Tamarix canariensis by Launaea arborescens is around 40%, while the substitutions of Launaea arborescens by Tamarix canariensis is 25% of the cases until 2003 (Hernández-Cordero et al., 2017). In recent years the changes in both communities show a similar percentage change.

So far, a relationship between an increase in the vegetation cover and elevation has been observed. This relationship is likely conditioned by the height of the local groundwater table, but also possibly by areas experiencing lower wind speeds. This latter variable should be added into future research to establish what role it truly plays. But potentially, feedback is observed between plant colonization and sedimentary stabilization/erosion as the constructed area has increased. A greater construction of the hotel area triggered a reduction of the local wind speed, and a decrease in aeolian sediment transport, favoring the vegetation encroachment and therefore the dunefield stabilization. These feedbacks produce on the one hand the alteration of the natural environmental conditions, and on the other hand, introduce new unknowns related to the biodiversity and geodiversity of the landscape. To better understand these feedbacks an approach examining the adaptation of diversity indices such as those proposed by Shannon (1948), Shannon and Weaver (1949) or Ferrer-Valero et al. (2017) in the transgressive dunesfield of Maspalomas might be useful.

4.3. *Topographic changes and erosional landforms in the aeolian shadow zone*

Net erosion dominated over net accretion in site 2 as a direct consequence of the decrease in wind speed by >50%, as well as the blocking/restriction of sediment input by wind because of construction on top of El Inglés terrace (Hernández-Calvento et al., 2014). Erosion is common in dune systems where some type of human impact has occurred, regardless of the issue studied (e.g. Tsoar and Blumberg, 2002; Wiedemann and Pickart, 2004; Hilton et al., 2006; El Banna and Frihy, 2009; Kiss et al., 2009; Bochev-Van der Burgh et al., 2011; Jackson and Nordstrom, 2011). In this study area, erosion in site 2 is a direct consequence of the presence of buildings and infrastructure. In this case, a well-delimited area where erosion is significant can be detected, corresponding with the location of the erosive landforms detected since 2003 (Figs. 4, A and 6) and the re-mobilization of sand deposits. Accretion was also measured in site 2 and was locally related with the presence of vegetation, in line with previous studies (Hesp, 1991, Hesp, 2013). Finally, there are other areas where the sediment has been fixed, a process that should be considered normal, because this is an aeolian shadow area. The observed erosional landforms have been subject to some mobility and change, despite relatively lower winds in this section of the dune field. This is potentially indicative of some localized wind acceleration or wind ´hot-spots´ (García-Romero et al., 2017) leading to sediment erosion in an area that is otherwise subject to low wind flows and limited sediment transport (Hernández-Calvento et al., 2014; Smith et al., 2017). Interestingly, these erosive landforms are all at a very similar distance downwind from the buildings.

Future analyses at this location should incorporate detailed records of wind variables collected at a high temporal and spatial resolution in this area, to allow detailed quantification of airflow processes involved in the evolution of this erosional and/or stabilizing landscape. This would permit identifying the reasons for the existence of erosive landforms at the same distance downwind of the buildings/infrastructure. It is possible to speculate that streets between the buildings on the top of El Inglés terrace act as wind corridors that channel the airflow, locally increasing wind speed in the shadow zone. In fact, this hypothesis is reinforced by checking how these processes do not occur in areas located behind the higher-rise buildings (Mir-Gual et al., 2015). Also it is possible to speculate that the blowouts or the other erosive landfoms appear due to the topographic influence of the infrastructure (Garés and Pease, 2015). The increase in the area of the erosive landforms and deflation zones with exhumed roots of herbaceous plants at this distance from the buildings, could be an indication that currently, and in the future, a large deflation zone will appear rather than a stabilized zone as has been indicated up to now (Hernández-Calvento et al., 2014; Hernández-Cordero et al., 2015a). This may depend on the functioning of the shrub vegetation.

5. Conclusions

This work presents a study of the environmental changes on a portion of a transgressive dunefield and the biogeomorphological processes produced in an aeolian shadow zone detected and formed downwind a high terrace completely changed due to tourist infrastructure development between 1986 and 2003. This construction altered the aeolian sedimentary input to the region and created an aeolian shadow zone in the dunefield. Climate change, and particularly rainfall variations do not appear to have had any real effect in driving the changes observed. The effect of the touristic development has been to drive changes in the local wind field and hence the direction of dune movement and migration. The changes in the sedimentary dynamics have also altered dune migration directions with dunes turning more towards the W-NNW than previously, and reduced the volumetric input of sediments into the Maspalomas dune system. In addition, there has been a reduction in the number and length of dune brinks and a displacement of the dune brinks to the south, well downwind of the aeolian shadow zone. For these reasons, the Maspalomas dunefield has been significantly environmentally altered due to the development of a human-induced aeolian shadow zone. If these trends continue, or change to other paths (e.g. expansion of the deflation areas), ecosystem services such as tourism and the protection against storms and possible tsunami provided by the dunes would be adversely affected.

With respect to the biogeomorphological processes within the aeolian shadow zone of the Maspalomas dunefield, the following processes and spatio-temporal changes have been observed:

Vegetation trends

1. The vegetation has experienced an increase in cover, density and number of plant communities.
2. The most successful colonizing plant community is Cyperus capitatus-Ononis tournefortii, comprising herbaceous species. The case of Cyperus capitatus is relevant, since it is the only species detected in this area that reproduces from rhizomes. In other dune environments, due to this rhizomatous characteristic, its reproduction is conditioned by clonal growth, and seed production is unimportant.
3. Other plant communities, comprising shrub and tree species, namely Tamarix canariensis and Launaea arborescens communities, also play an important role in colonization of the dunefield in the study area.

Topographic changes

1. There is an aeolian sedimentary deficit caused by the urban tourist buildings located on the top of the El Inglés terrace blocking the aeolian sedimentary transport pathway, and reducing overall wind energy and sediment transport in the study area.
2. Although the sedimentary deficit has been detected throughout the study area, there are areas of accretion associated with deposition within vegetation, as well as other stable areas. Since 2003, when the top of the terrace had been totally covered by buildings, three erosional landforms have developed. All three of them are located at a similar distance from the new urban development area.
3. These three erosional landforms correspond to a trough blowout and two deflation zones currently characterized by surfaces covered with exhumed roots.
4. The increase of the vegetation is related to the sedimentary deficit, which facilitates the growth of plant species. This process is possible since the sand cannot cover the vegetation, and deflation leads to the presence of groundwater closer to the surface.
5. The groundwater table can be detected in the lowest elevations of the study area, and therefore, there is a strong relationship between plant colonization and topography.
6. Plant colonization within about 400 m of the building/infrastructure development is lower than further downwind, coinciding with the presence of erosional landforms and zones with higher water tables.

Acknowledgements

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Airflow dynamics, vegetation and aeolian erosive processes in a shadow zone leeward of a resort in an arid transgressive dune system

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Abstract

Structures and infrastructures can modify aeolian sedimentary dynamics as has occurred in the arid transgressive dunefield of Maspalomas (Gran Canaria, Canary Islands), where an aeolian shadow zone has been formed leeward of a tourist resort (Playa del Inglés). The aim of this paper is to analyse spatial and statistically the influences of vegetation and topography on wind flow across this shadow zone. An experiment was carried out in March 2017, collecting wind speed and direction from 5 transects with anemometers at 0.40 m height. Simultaneously, a drone flight was carried out, from which an orthophoto and digital elevation and surface models (DEM and DSM) were obtained. Distance from the resort, and the presence of vegetation were found to influence transects dominated by erosional processes. Transects that do not display erosional processes were primarily affected by the presence of vegetation. The local wind field changes at a similar distance across the transects downwind from the resorts indicating an acceleration or reattachment of the wind at this distance downwind. The vegetation role in this aeolian shadow zone could be a key to the future evolution of the area resulting in either further stabilization, or alternatively, the continued deflation of the area.

Keywords: aeolian shadow zone, arid transgressive dune system, wind flow, dune vegetation, topography, human impact

1. Introduction

Coastal dune systems have been significantly altered in the Anthropocene, which is characterized by the modification of natural processes due to human development (Crutzen and Stoermer, 2000), especially in recent decades (Nordstrom, 2004, Jackson and Nordstrom, 2011). Arid coastal dune systems of the Canary Islands constitute a clear example of this process. Their mild climate has attracted millions of tourists over the last decades, and urban-tourist buildings around these systems are producing significant environmental changes (Hernández-Calvento et al., 2014, García-Romero et al., 2016, Hernández-Cordero et al., 2017).

The urban-tourist occupation induces alterations in the natural processes of coastal dune systems, the greatest of which are related to geomorphological and vegetation changes (Cabrera-Vega et al., 2013, Hernández-Calvento et al., 2014, García-Romero et al., 2016, Hernández-Cordero et al., 2017, Garcia-Romero et al., 2019). When buildings or infrastructure are located near or inside dune fields they act as rigid and impermeable structures that intrude upon and modify the regional wind flow and local Internal Boundary Layer (IBL), and alter aeolian sediment dynamics (Nordstrom and McCluskey, 1984, Gundlach and Siah, 1987, Nordstrom and Jackson, 1998, Tsoar and Blumberg, 2002, Wiedemann and Pickart, 2004). Although many natural and anthropogenic factors influence dunefield mobility, the direct interaction between urbanization and physical processes remains largely unexplored (Nordstrom, 1994, Jackson and Nordstrom, 2011). To address this lack of studies, pioneering research on the direct impact of urban-tourist buildings on dune systems has been developed in Maspalomas dune field (Gran Canaria) within the last few years, specifically on changes to airflow dynamics. Hernández-Calvento et al. (2014) developed a simplified numerical wind model based on a logarithmic wind velocity profile, and Smith et al. (2017) investigated regional airflow modeling during successive stages of urbanization using Computational Fluid Dynamic (CFD) modelling. These studies have allowed exploration of how the resort development on a high terrace overlooking the dunefield has modified the aeolian sedimentary dynamics in this dune system (Hernández-Calvento et al., 2014, Smith et al., 2017).

Regional disturbances of the air flow due to the development of the resorts gave rise to three geomorphological zones, namely, an acceleration zone south of the terrace, and two deceleration zones with different degrees of sedimentary stabilization and an increase in plant cover in the west (Hernández-Cordero et al., 2017). One of these deceleration zones was characterized by García-Romero et al. (2019) based on its biogeomorphological processes (Fig. 1, study plot). Two processes were identified in the aeolian shadow zone (leeward of the terrace): a progressive sedimentary deficit, and the increase in vegetation density. Also, three erosional aeolian landforms, located at a distance of about 400–500 m from the resort, are expanding. These erosional landforms are the result of wind acceleration at a local scale resulting from the interaction of the buildings on the airflow (García-Romero et al., 2017, Garcia-Romero et al., 2019). Mir-Gual et al. (2015) speculated that streets between the buildings on top of El Inglés terrace can act as wind corridors that channel the airflow, locally increasing wind speed in the shadow zone and generating these three erosional landforms. In fact, these processes do not occur in areas behind taller buildings (Mir-Gual et al., 2015). The increase in size and area covered by these erosional landforms, resulting in exhumed roots of herbaceous plants, is a direct consequence of blocking sediment transport following the completion of the urbanization on top of the terrace (García-Romero et al., 2019). As suggested, it is possible to argue that a large deflation landform will dominate in this area in the future rather than stabilized landforms (Hernández-Calvento et al., 2014, Hernández-Cordero et al., 2015), which could depend on the functioning and evolution of shrub vegetation (García-Romero et al., 2019). New studies are therefore required to characterize aeolian processes in this area at a local scale, including the relationship between wind flow and environmental variables, such as topography and vegetation, as well as the distances from the resort.

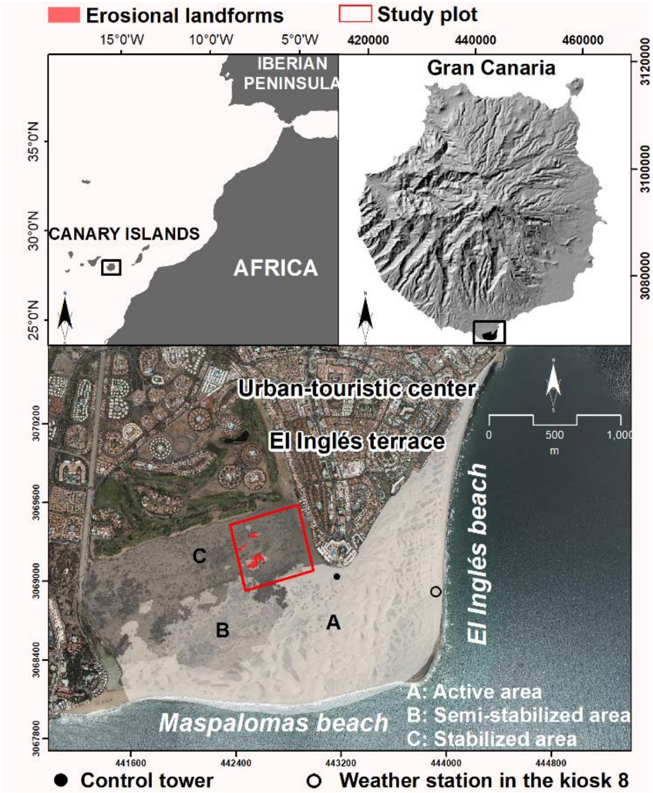

Figure 1. Arid transgressive dune system of Maspalomas, with the study plot (red box), erosional landforms (in red) and location of two wind sensors for determining local wind data. A (area of airflow acceleration), B and C (areas of airflow deceleration), as defined by Hernández-Cordero et al (2015).

The aim of this study is to characterize and analyze aeolian processes in the aeolian shadow zone of the Playa del Inglés resort, and to relate local wind flows to topography, vegetation and distance to buildings. This follows previous suggestions by Garcia-Romero et al. (2019) who highlighted the need to acquire high temporal and spatial resolution wind records in this area to allow detailed quantification of airflow processes involved in the evolution of this erosional and/or stabilizing landscape, as well as to identify the reasons for the erosional landforms on similar distances downwind of the buildings.

2. Material and methods

2.1. Study area

The arid transgressive dune system of Maspalomas (360.9 ha.) is located on the south of Gran Canaria (Fig. 1), on a fan-delta. Effective winds and the predominant aeolian sediment transport, are ENE-WSW (Máyer-Suárez et al., 2012). The sediment enters the dune system by the eastern beach (El Inglés) and is transported toward the southern beach (Maspalomas), where it returns to the sea. A Pleistocene high wedge-shaped terrace (about 25 m above sea level (m.a.s.l.)) on the north-eastern boundary interacts with the wind flow and the sedimentary transport. Construction on this terrace from the 1960s resulted in one of the largest tourist resorts in Spain (Domínguez-Mujica et al., 2011). The urban-tourist resort has a strong impact on aeolian processes, altering the wind flow and therefore the sediment transport, and generating different processes resulting in the three geomorphological areas described in section 1 (Hernández-Calvento et al., 2014, Smith et al., 2017, Hernández-Cordero et al., 2017). In this work we focus on the aeolian shadow zone, located leeward of the tourist resort (see area C in the study plot, Fig. 1).

A study plot of 27.76 ha was delimited leeward and westward of the tourist resort, where the data were collected (Fig. 2). The experiment was conducted on 24th and 25th March 2017, consisting of simultaneous capture of wind, topography and vegetation characteristics. Distances to the resort were measured using geographical information system (GIS) tools. Plant communities data inside the erosional landforms were collected to explain the role of vegetation in this zone.

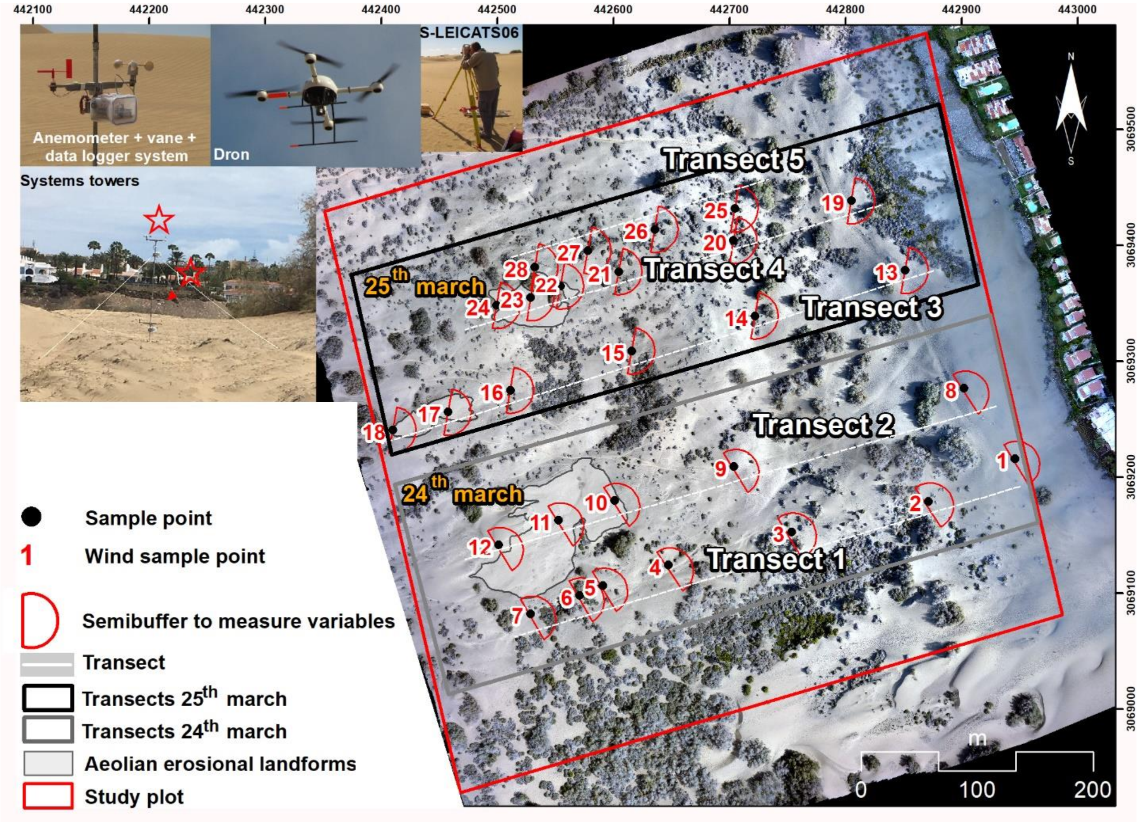

Figure 2. Transects and wind sampling points on March 24th and 25th, 2017. Transects 1 and 5 were outside the aeolian erosional landforms area, and transects 2, 3 and 4 were inside the area. The semibuffer (red) with a radius of 20 m indicates areas where other environmental variables (vegetation and topography) were measured. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2.2. Wind data

Airflow data were collected by 10 mobile wind stations with wireless communication. The stations consisted of an anemometer-vane-data logger system and were deployed in towers at two different heights: at 0.4 m height above the surface (data presented in this paper) and at 2.10 m above the surface (Fig. 2). The inclusion of two wind stations per tower reduced to 5 the number of locations that could be sampled simultaneously but provided synchronous information on the dynamics of the local airflow at 2.10 m height, and on the dynamics of near-surface airflow (where most sediment transport occurs). This allowed the possibility to know if these airflows are affected by the resorts and at the same time also influenced by vegetation or topography. Sampling at all locations was completed by moving four towers sequentially, while the fifth (control tower) remained in a fixed position, outside the wind shadow zone (Fig. 1). A total of 5 transects were completed from 28 sample points (Fig. 2) across areas with and without observed sediment erosion processes, as well as near the vegetation, allowing complete cover of the shadow zone and ensuring that all data could be collected within the same experiment. The transects were strategically located to measure airflow around and inside erosional landforms, and in front and behind vegetation and in the topographic lows and highs. The order to collect the data was from the simultaneous sample Run 1 (Fig. 5. wind sample points 1–4) closer to the control tower (Fig. 1), Run 2 (Fig. 5. wind sample points 5–8), Run 3 (Fig. 5. wind sample points 9–12), Run 4 (Fig. 6. wind sample points 13–16), Run 5 (Fig. 6. wind sample points 17–20), Run 6 (Fig. 6. wind sample points 21–24), to the Run 7 (Fig. 6. wind sample points 25–28). Additionally, wind data were collected every 10 min at a station located on a beach kiosk (number 8), at 4 m height, on El Inglés beach (Fig. 1). Data were collected at each location for 40 min. The regional wind direction varied during the data collection period. Following previous studies (Delgado-Fernández et al., 2013), wind records were filtered by wind direction, specifically between 40° and 70° on the 24th and between 70° and 100° on the 25th of March. These ranges were calculated from the data collected at the El Inglés beach stations and the control tower (Fig. 3). This allowed the isolation of periods of time in all stations during which the incident wind direction was similar, with changes in wind characteristics between stations due to a range of other variables including topographic factors, vegetation, and distance to the resort.

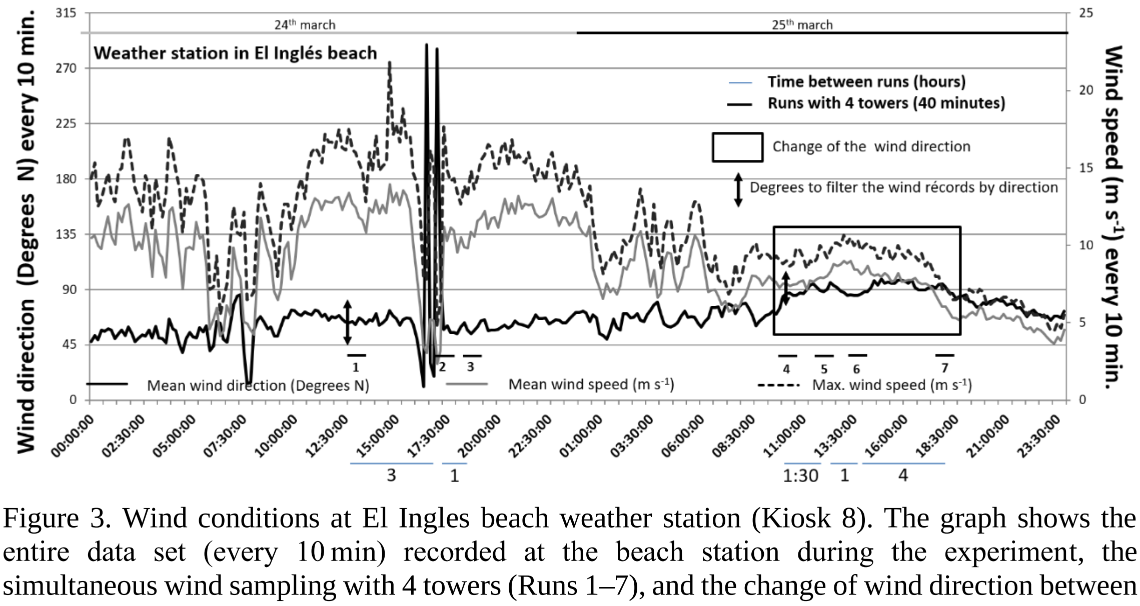

Figure 3. Wind conditions at El Ingles beach weather station (Kiosk 8). The graph shows the entire data set (every 10 min) recorded at the beach station during the experiment, the simultaneous wind sampling with 4 towers (Runs 1–7), and the change of wind direction between both days (black square).

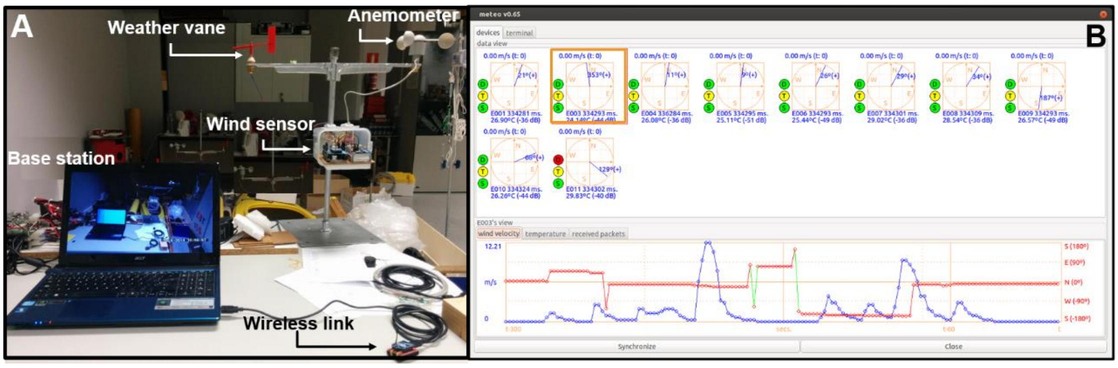

Figure 4. Characteristics of the wind sensors. A. Base station with wireless link (Xbee) to connect with the wind-vane + anemometer + data logger system. B. Software developed to check and synchronize the wind sensors in an experiment with 10 wind sensor systems. The data of the second wind sensor system (orange square) can be observed in the graphics at real time (wind speed (blue), wind direction (red)). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

In Table 1, standard deviations (m/s^{-1}) are shown to explain the errors of the mean wind speed which are indicated in Fig. 5, Fig. 6 in each run. In general, the standard deviations have a low significance with respect to the wind speeds collected. The biggest standard deviations occured in the first 2 runs, especially in the minutes 10, 15, 25, 30 and 40 when the wind speed is constantly changing.

Table 1. Standard deviations of the mean in every 5 min timeslot (Fig.5, Fig. 6) to show the errors (m/s^{-1}) in the wind speeds analyzed.

Run	Wind sample point	wsmin5	wsmin10	wsmin15	wsmin20	wsmin25	wsmin30	wsmin35	wsmin40
	Control	0.335	0.375	0.521	0.327	0.746	0.399	0.295	0.218
	1	0.354	0.497	0.432	0.371	0.578	0.408	0.582	0.493
1	2	0.309	0.33	0.322	0.292	0.558	0.467	0.52	0.401
	3	0.353	0.325	0.3	0.372	0.519	0.491	0.514	0.408
	4	0.323	0.348	0.231	0.272	0.529	0.47	0.364	0.368
	Control	0.379	0.432	0.294	0.236	0.859	0.493	0.486	0.495
	5	0.467	0.455	0.326	0.371	0.081	0.361	0.243	0.299
2	6	0.434	0.411	0.343	0.142	0.189	0.208	0.177	0.072
	7	0.159	0.044	0.107	0.202	0.094	0.42	0.079	0.083
	8	0.456	0.419	0.398	0.23	0.27	0.182	0.245	0.144
	Control	0.217	0.421	0.389	0.316	0.247	0.262	0.326	0.283
	9	0.236	0.207	0.384	0.203	0.34	0.259	0.313	0.272
3	10	0.155	0.274	0.368	0.308	0.19	0.238	0.331	0.222
	11	0.178	0.222	0.4	0.365	0.244	0.208	0.305	0.267
	12	0.258	0.381	0.446	0.348	0.335	0.303	0.314	0.329
	Control	0.279	0.289	0.271	0.252	0.383	0.242	0.232	0.257
	13	0.309	0.317	0.338	0.236	0.592	0.269	0.266	0.348
4	14	0.308	0.31	0.297	0.324	0.398	0.365	0.231	0.304
	15	0.2	0.144	0.228	0.23	0.203	0.172	0.175	0.209
	16	0.339	0.426	0.261	0.259	0.38	0.201	0.216	0.208

5	Control	0.232	0.148	0.228	0.251	0.223	0.224	0.245	0.220
	17	0.291	0.16	0.283	0.374	0.313	0.265	0.308	0.349
	18	0.255	0.094	0.254	0.216	0.189	0.25	0.271	0.23
	19	0.143	0.168	0.194	0.202	0.221	0.178	0.207	0.136
	20	0.24	0.169	0.182	0.212	0.168	0.204	0.193	0.163
6	Control	0.261	0.256	0.257	0.264	0.337	0.290	0.351	0.437
	21	0.243	0.287	0.259	0.254	0.308	0.327	0.379	0.479
	22	0.216	0.194	0.189	0.228	0.342	0.359	0.348	0.394
	23	0.378	0.319	0.344	0.297	0.398	0.24	0.328	0.453
	24	0.168	0.182	0.197	0.195	0.259	0.193	0.31	0.38
7	Control	0.253	0.243	0.247	0.233	0.380	0.348	0.421	0.337
	25	0.368	0.365	0.362	0.296	0.438	0.341	0.408	0.354
	26	0.179	0.295	0.26	0.211	0.49	0.364	0.438	0.355
	27	0.221	0.206	0.24	0.242	0.414	0.324	0.486	0.362
	28	0.283	0.144	0.164	0.184	0.217	0.324	0.39	0.237

The anemometer-vane-data logger systems to collect the wind data (Fig. 4) are wireless devices (Fig. 4A) that measure wind characteristics (direction and speed). All instruments store measurements in their data loggers, which are synchronized with other devices. A software specifically designed for this application controls and executes measurement options from the base station (Fig. 4A and B). The base station also communicates wirelessly with the rest of the sensors and controls the correct functioning of the entire grid in real time.

Wind speed and direction were averaged every five minutes with the purpose of ensuring a sufficient time of observation and to guarantee that the entire area was affected by the same wind flow over a given period. Each average speed (m s^{-1}) of 5 min duration in the towers (*ASP*) was normalized with respect to the average corresponding to the control tower of the same simultaneous sampling (*ACT*) (Delgado-Fernández et al., 2013). This normalization (*WN*) was carried out in order to eliminate the differences in wind speed changes during the experiment due to changes in the position of the wind sampling points to cover the transect completely, and thus be able to compare the data taken in the same day (Eq. (1)). Fig. 5, Fig. 6 show these results stored in a shapefile with point geometry, where the average direction is shown by rotation and the speed normalized from the size of the chosen symbology.

$$WN = ASP/ACT \quad (1)$$

2.3. *Topography and vegetation*

For each wind sampling point, a semibuffer with a radius of 20 m distance was established oriented into the predominant wind direction (Fig. 2) through GIS vectors (polygon) digitalitation. This distance was defined by Alonso-Bilbao et al. (2007) as the distance along which the wind flow is influenced by a plant obstacle of the shrub species *Traganum moquinii* in Maspalomas. Topographic and vegetation variables were measured inside this semibuffer using a digital orthophoto (spatial resolution of 0.05 m) from a photogrammetric drone flight carried out on March 25th, 2017. The point mesh was used to derive topographic information (in las format). The precision of the data was tested using ground data collected with a Leica TS06 total station with laser device. For the topographic information, algorithms were applied to detect occlusions (Chang et al., 2008), deriving a digital elevation model (DEM) and a digital surface model (DSM). The average degree of slope and the average altitude of the surface inside the semibuffers were calculated using basic algorithms implemented in GIS on the MDE. The vegetation variables calculated were the mean vegetation density and the maximum vegetation height in each semibuffer. The first one was calculated applying the procedure developed by García-Romero et al. (2018), making use of the orthophoto obtained by the drone flight. The maximum vegetation height was extracted from the MDS. The vegetation cover shown in the Fig. 8 to relate distance to the urbanization and the distribution of the vegetation was calculated through GIS reclassification using the same orthophoto, the areas every 100 m were calculated through proximity GIS tools and the spatial analysis using overlay tools. The plant communities data for the year 2003 were obtained from Hernández-Cordero et al. (2017). The vegetation data of 2017 were obtained from Garcia-Romero et al. (2019). Both data were developed through visual interpretation of digital orthophotos (using variables such as color, size, density, texture and spatial pattern) and supported by field work.

2.3.1. Distance to the urbanization

Distances between individual wind stations and the resort were measured through algorithms implemented in GIS, calculating the closest distance between vector layers: a point geometries layer representing each wind station and a polygon geometry representing the resort.

2.4.Principal components analysis

Principal Component Analyses (PCA) was used to explore a first statistical approximation of what variables measured in the semibuffers best represent each transect. A series of components and the significance of the variables that best represent each transect were obtained. To achieve a more robust analysis, we use the normalized winds shown in Fig. 5, Fig. 6 (for the averages 20 and 30 min in transects 1–2 and 3–5 respectively) because these time periods show greater similarity to the higher wind speeds recorded. In addition, the same analysis was also done with the average centered around minutes 5 and 10 for transects 1–2 and 3–5 respectively, because they show greater similarity than the previous ones, although with lower speeds, especially in transects 1 and 2. From transect 1 to transect 4 (averages of minutes 20 and 30), only the first and second component were obtained because they explain 84.9%, 88.41%, 90.6%, 97.58% respectively of the variance, except transect 5 (average centered in minute 30) where the first component explains 96.61% of the variance. In the same way, the first and second components explain the 81.9%, 88.5%, 85.7%, 92.7% of the variance in the averages centered around minutes 10 and 5 (transects 1–4) and the first component in the transect 5 (minute 5) explains 96.7% of the variance. Finally, the relationship between the variable with greater significance in the first component and the wind data (speed $m\,s^{-1}$), at normalized scale, was analyzed. These relationships are shown by dispersion diagrams, adjusted with second order polynomial except the distance to urbanization in transects 2 and 3 that were adjusted with third order polynomial. These graphics illustrate the behavior (when and where) of the wind speed (acceleration or deceleration) with respect to the environmental variables measured.

3. Results and discussion

3.1. Wind data and aeolian processes

Fig. 5 (C, Run 1–3) shows the temporal variability of wind speeds (m s^{-1}) collected at each sampling location and in the control tower every 5 min on March 24th, 2017. In Run 1, wind speeds at points 1 and 2 (closer to the resort) were slower than those recorded at points 3 and 4 (further away from the resort). The trend showed some temporal variability: on average, centered around minute 25, winds were similar at all points, while, on average, centered on minute 35, the areas closest to the urbanization had higher wind speeds as a result of a change in wind direction closer to 70° (Fig. 3, Run 1), which produce more obliquity on wind toward the aeolian shadow zone, and the wind can penetrate this area more directly and strongly. With respect to the control tower, the wind speeds were significantly higher until the average of minute 25, where the shadow effect practically disappeared. Also, in the average centered in minute 35 the sampling point closest to the urbanizations (1) had a faster wind speed than the control tower, which could be explained because of a change in wind direction and the possible urban obstacle that generated accelerations within the wind shadow area. This behavior is similar to that explained previously, that is, the wind direction near to 70° displays higher obliquity and accelerates the winds towards the area with the greater aeolian shadow because they penetrate more directly. In terms of points 5 to 8 (Run 2), and similar to the previous transect, locations furthest away from the resort (6 and 7) showed fast wind speeds compared to those closest to the resort, with changes to this trend found in averages centered in the minutes 20, 25 and 35. The control tower presented significant differences in wind speeds (faster) with respect to the sampling points. Finally, in terms of points 9 to 12 (Run 3), although the control tower collected faster wind speeds, the difference was not significant. Wind speeds between sampling locations did not show clear differences either, although point 35 (at a greater distance from the resort) recorded faster wind speeds.

For the purpose of analyzing spatial patterns in wind data collected at all sampling locations, (Fig. 5, A and B), the average centered on minute 20 of all runs was selected because of relatively strong wind speeds and because winds collected by the control tower were similar (black circle in the wind time series of Fig. 5, C). Also, because higher speeds can produce greater erosional processes if this occurs inside the study plot. In general, winds accelerated away from the resort. However, in transect 1 (Fig. 2, Fig. 4, sampling points 1–7), winds were reduced in the last three sampling points, coinciding with the presence of vegetation, especially shrubby plants (Fig. 7 profile of the transect 1). This increased the roughness of the terrain and reduced both wind speed and sedimentary transport (Hesp, 1981, Moreno-Casasola, 1986). In transect 2 (Fig. 2, Fig. 5 sample points 8–12), there was only a negligible drop in the wind speed of the points located within an erosional landform, which may be caused by the topographic features or by the roughness of the vegetation (Hesp, 1981, Moreno-Casasola, 1986), especially and currently the herbaceous plant community *Cyperus capitatus-Ononis serrata* (table 3). This also happened at the beginning of the transect, which can be explained by the shadow effect of the resort (Hernández-Calvento et al., 2014, Smith et al., 2017).

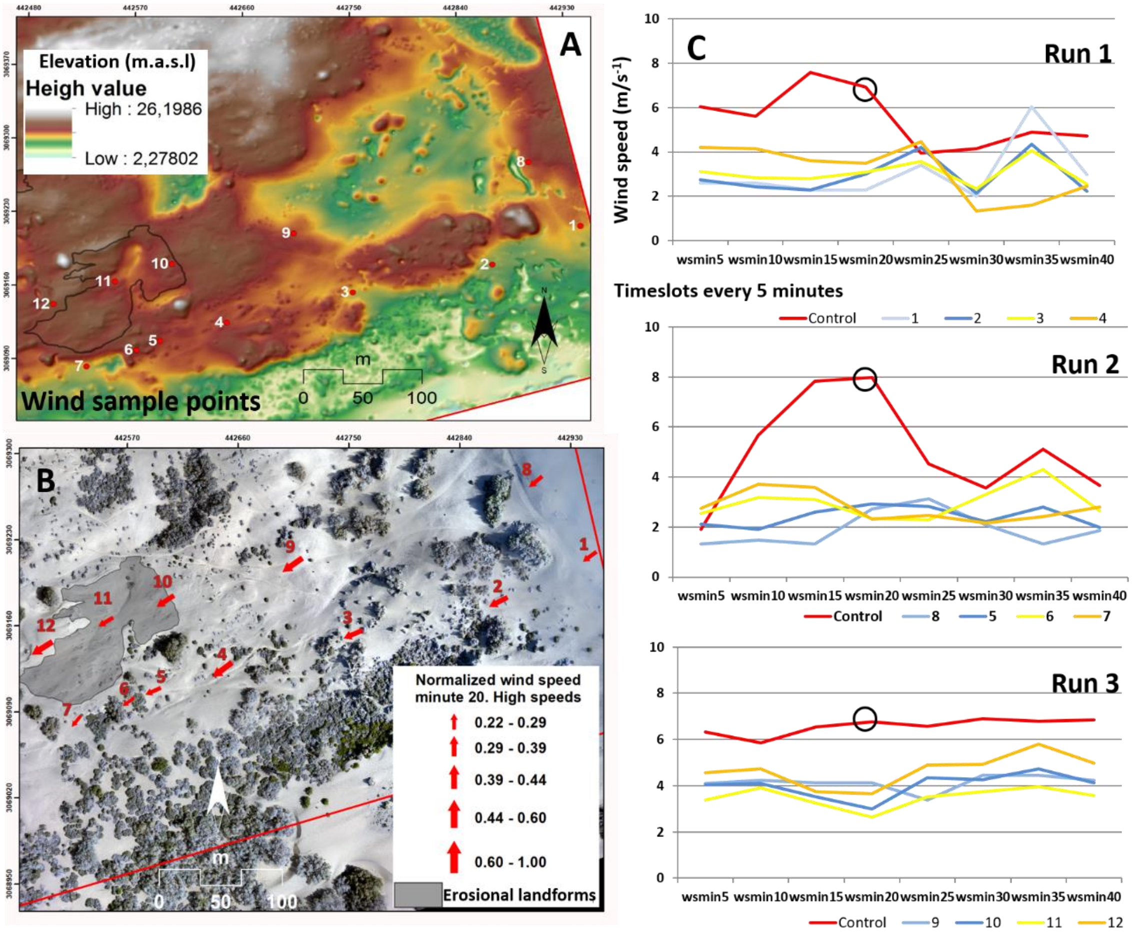

Figure 5. (A) Position of the sampling points. (B) results of the normalized wind speed (ASP/ACT) (minute 20, black circle of the Run's graphs) with respect to the control tower in each simultaneous sampling. (C) Wind speeds (m s^{-1}), average every 5 min in the sampling points on March 24th, 2017 (right, Run 1–3).

In terms of the data obtained on March 25th, 2017 (Fig. 6, C), a reduction in wind speed was observed closest to the resort between the sampling points 13 and 16 (Run 4). Wind speeds increased as the distance from the resort increased (e.g., point 16) and were higher than at the control tower. A similar trend is observed between points 17 and 20 (Run 5), although wind speeds at locations farthest away from the resort did not exceed those recorded by the control tower.

There were no significant differences between points 21 and 24 in Run 6 (ranging from 3 to 4 m s^{-1}), although point 21, the closest to the resort, registered the highest wind speeds, except for the average centered on minute 30, when all points record similar speeds, but still exceeding those recorded by the control tower.

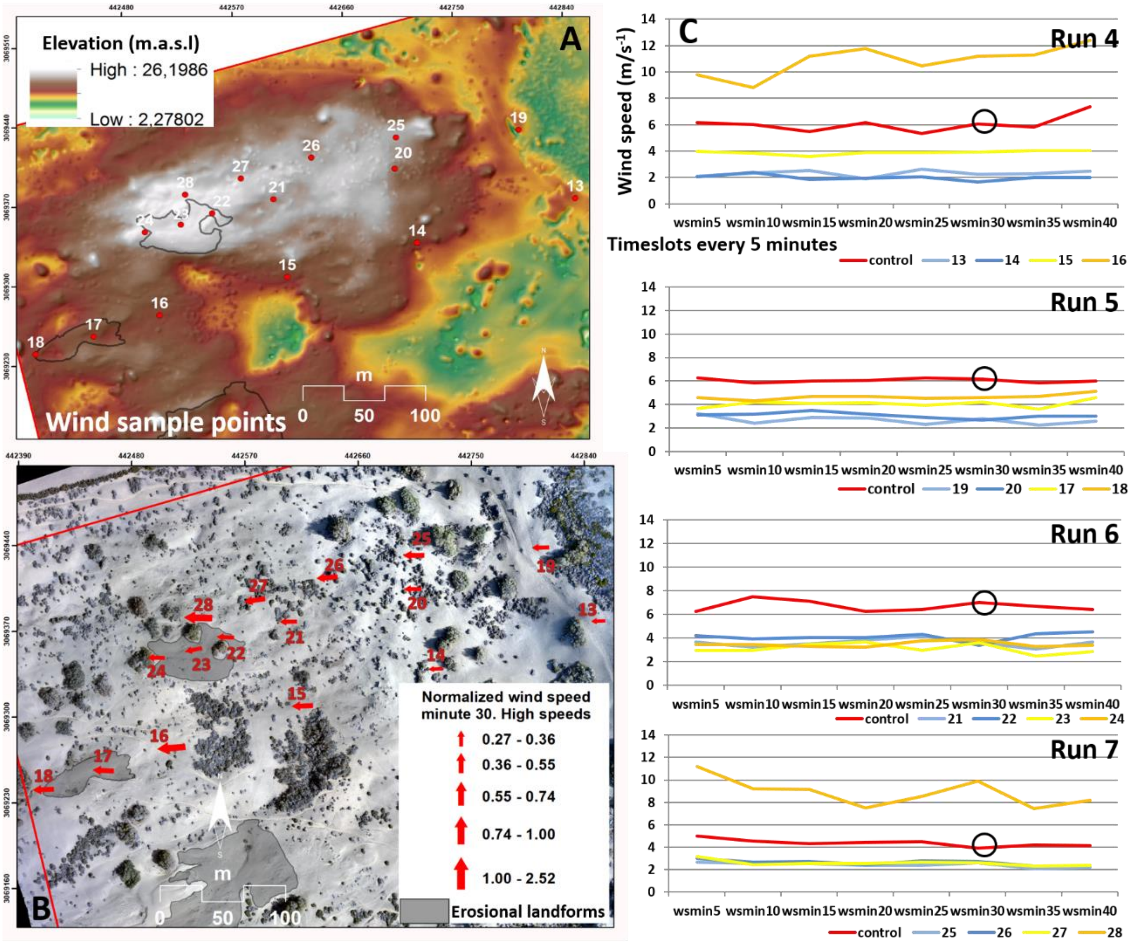

Figure 6. (A) Position of the sampling points. (B) results of the normalized wind speed (*ASP/ACT*) (minute 30, black circle of the Run's graphs) with respect to the control tower in each simultaneous sampling. (C) Wind speeds (m s^{-1}) average every 5 min in the sampling points on March 25th, 2017 (right, Run 4–7).

Finally, in Run 7, points 25, 26 and 27 showed similar wind speeds at all times. Point 28, at a greater distance from the resort, registered higher wind speeds than the control tower. Similar to Fig. 5, normalized wind speeds were plotted at all instrument locations (Fig. 6, A and B) for the average centered on minute 30 (black circle in Fig. 6, C) coinciding with the lowest differences in wind speeds in the control tower. The wind, again, accelerated as it moved away from the resort, regardless of the presence of erosional landforms. In transect 3 (Fig. 2, Fig. 6, sampling points 13–18), a wind speed reduction was observed at the first two points (13 and 14). In relation to the first one, this could be explained by the shadow effect of the resort, as detected by Hernández-Calvento et al., 2014, Smith et al., 2017. In relation to the second one, it could be due to the presence of vegetation, as in the aforementioned case. From this location, the wind accelerated constantly, although within the erosional landform there was a setback that could be explained by the topographic features, which slowed the wind slightly because it is a trough blowout (Hesp, 2002), or by the presence of vegetation due to the roughness of the terrain that can reduce the wind speed and sediment transport (Mayaud et al., 2017). In the latest case, there was only a herbaceous plant community (*Cyperus capitatus-Ononis serrata*, Table 3) between 2003 and 2017 according to Hernández-Cordero et al., 2017, Garcia-Romero et al., 2019. Transect 4 (Fig. 2, Fig. 6, sample points 19–24) had constant wind speeds likely regulated by vegetation (Mayaud et al, 2016), similar to transect 1 where there was shrubby vegetation at the beginning of the transect (Fig. 6, profile of the transect 4). In this case, the vegetation detected inside the erosional landform was the herbaceous plant community *Cyperus capitatus-Ononis serrata* and null or low vegetation (table 3).

There were no erosional landforms along transect 5 (Fig. 2, Fig. 6, sample points 25–28). Wind speeds recorded at the first points along this transect were affected by shrubby vegetation (Fig. 7, A. profile of the transect 5), similar to transects 1 and 4. Wind speeds significantly accelerated at the last point coinciding with the erosional landform of transect 4.

3.2. PCA analysis of vegetation, wind and proximity to infrastructure data

Table 2 shows significant variables in the first and second components obtained from PCA analyses in each transect. Transect 1 was characterized by variables related to vegetation. Normalized wind data at averages centered in the minutes 20 and 10 (transect 1, day 24th) correlated well with vegetation density ($R^2 = 0.8774$ and 0.777). Although wind is a multifactorial variable, the graph shows that as vegetation density increased, the wind speed decreased. In transect 2 (day 24th), the averages centered in minutes 20 and 10 showed a higher correlation with the mean slope of the sampling point taken from the DEM (i.e., with a topographic variable) ($R^2 = 0.9184$ and 0.8393). According to the dispersion graphic (Fig. 7, B), the steeper the slope, the lower the wind speed. However, slopes steeper than 5° led to wind acceleration as a result of speed up processes (Garés and Pease, 2015). Transect 3 (day 25th), averages centered in the minutes 30 and 5 were influenced by all variables, although winds were best correlated with slopes ($R^2 = 0.753$ and 0.7382). Interestingly, wind speed decreased with increasing slopes on this occasion, with maximum wind acceleration coinciding with average slopes of 5°. In the two last cases (transects 2 and 3), the wind behavior is not aerodynamic related to the mean slope. In transect 2, maybe the answer lies in the next significant variables in the first principal components such as the distance to the buildings, or the elevation, or the combination of both, because in these scatter diagrams, an increase in wind speed is observed. For example in transect 3, the slope also does not show an aerodynamic behavior, because the speed is reduced when the slope increases, but maybe the answer is in the second variable of the first principal component (vegetation density), because in this case, maybe the wind at 40 cm height it is being slowed down by the vegetation regardless of whether the slope increases, the scatter diagram is similar to the mean slope. Transect 4 (day 25th), the averages centered in the minutes 30 and 5 were influenced mainly by distance from the resort ($R^2 = 0.8132$ and 0.6718), with increasing wind speeds correlated with increasing distance. The elevation also shows a similar behavior increasing the wind speed, and finally the vegetation density role tends to cushion the wind speed. Finally, transect 5 (day 25th) the averages centered in the minutes 30 and 5 were also characterized by altitude ($R^2 = 0.9983$ and 0.999), with more wind acceleration at higher elevations. In the scatter diagrams it is possible to observe that as the elevation increases and also the slope increases, the wind speed increases. However, the vegetation density produces a deceleration of the wind if it increases. This last transect, perhaps the least reliable due to the few wind sample points, can affect the statistics, and results in an incomplete understanding of this area of the aeolian shadow zone.

Table 2. Results of the Principal Components Analysis in each transect using all measured variables and normalized wind speed. Units shown in transect 1.

Variables	Principal Components (minutes 20 and 30)		Principal Components (minutes 10 and 5)	
Transect 1 (minutes 20 and 10)	1	2	1	2
Mean vegetation density (normalized between 0-1) *	-0.907	0.194	-0.898	
Max. Vegetation height (m)*	-0.814	0.345	0.856	
Distance to the urbanization (m)*	0.733	-0.229	-0.801	-0.346
Elevation (m.a.s.l.)	0.358	-0.862	0.333	-0.901
Slope (degree)	0.567	0.711	0.664	0.662
Transect 2 (minutes 20 and 10)	1	2	1	2
Slope*	0.954		0.892	0.359
Distance to the urbanization*	0.915		0.844	0.467
Elevation*	0.803	0.1	0.933	
Max. Vegetation height	-0.693	0.833	-0.521	-0.893
Mean Vegetation density	-0.523	0.712	-0.63	-0.772
Transect 3 (minutes 30 and 5)	1	2	1	2
Slope*	-0.925	0.27	0.915	
Mean vegetation density*	-0.811	0.33	-0.892	0.351
Distance to the urbanization*	0.745	0.661	0.765	0.643
Max. Vegetation height	-0.741	0.398	0.439	-0.793
Elevation	0.652	0.73	0.69	0.707
Transect 4 (minutes 30 and 5)	1	2	1	2
Distance to the urbanization*	0.923	0.128	0.899	
Mean vegetation density*	-0.878	-0.363	-0.857	-0.453
Elevation*	0.867	-0.448	0.853	
Slope	-0.129	0.968	-0.651	0.745
Max. Vegetation height	-0.201	0.962	0.67	-0.713
Transect 5 (minutes 30 and 5)	1	2	1	2
Elevation*	0.969		0.968	
Mean vegetation density*	-0.936		-0.933	
Slope*	0.844		0.891	
Max. Vegetation height	-0.878		0.871	
Distance to the urbanization	0.839		0.831	

* Variables showed in the scatter diagrams of the figure 7

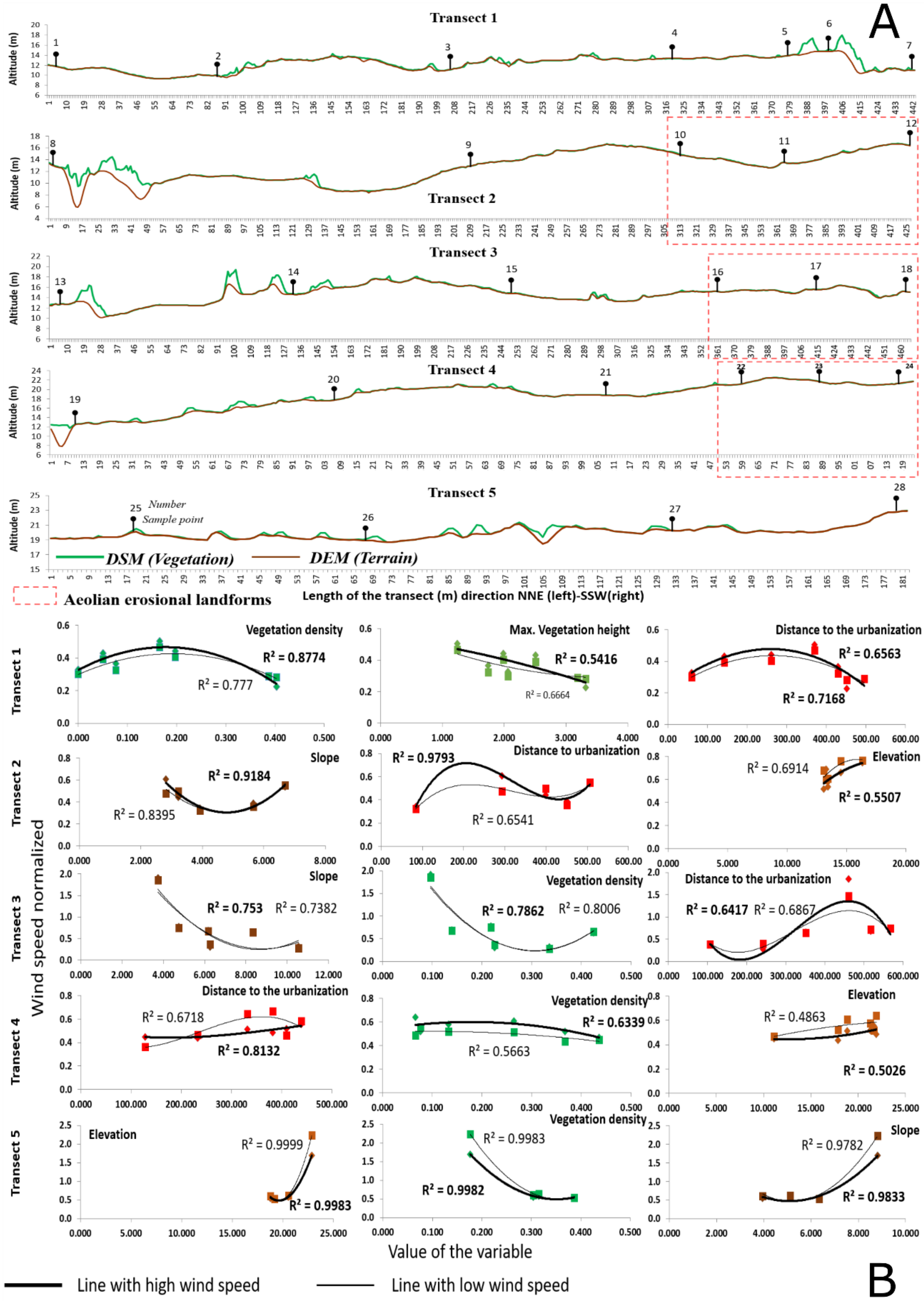

Figure 7. Profiles of the <u>transects</u> studied (DEM and DSM) and the wind sampling points locations (A). Scatter diagrams of the most significant variables obtained by the Principal Components Analysis (B).

Overall, transects with no erosional landforms presented a greater influence of vegetation variables on wind speed reduction. In transect 5, elevation had the greatest significant correlation, followed by plant density. In general, winds across transects with erosional landforms (2, 3 and 4) were more affected by variables related to topography. Distance to the resort was significant in all transects, which reinforces the hypothesis that, although the wind speed in this area has been reduced by 50% by urbanizations (Hernández-Calvento et al., 2014), there are local wind accelerations (Smith et al., 2017) that result in the formation of erosional landforms. However, this variable in transects 2 and 3 is adjusted with a third polynomial order due to deceleration inside the aeolian erosional landforms 2 and 3. This pattern has also been observed in parabolic dunes and trough blowouts (Hesp and Walker, 2013, Delgado-Fernandez et al., 2018) because under oblique winds, the topography of these aeolian erosional landforms is highly efficient at steering the incoming winds such as the airflow inside the landform becomes parallel to its main axis (Byrne, 1997, Hansen et al., 2009, Hesp and Pringle, 2001, Pease and Gares, 2013). Transect 3 could also be explained by the topographic features and the roughness of the vegetation (Hesp, 1981, Moreno-Casasola, 1986, Mayaud et al., 2016). In both cases (transects 2 and 3), in the last point of the transect (the end of the erosional landform to the SSW), winds are accelerated facilitating erosion because the airflow is accelerated along the basin toward the depositional lobe, with wind speeds at the crest in this location being roughly double of those measured in the basin (cf. Delgado-Fernandez et al., 2018). These landforms appear at a similar distance from the urbanization (400–500 m) (García-Romero et al., 2017), suggesting that this is the distance at which wind speeds recover after being decelerated by the urbanization.

3.3. Vegetation role in the aeolian shadow zone

3.3.1. Distribution of the vegetation cover in the aeolian shadow zone

Increases in vegetation cover were classified into 100 m buffers from buildings (to the northwest of the study site, Fig. 8). This allowed exploration of the effect of human activities on vegetation based on the distances to buildings. The vegetation cover continually increases to the southwest from the edge of the buildings, to 400 m distance. A relationship ($R^2 = 0.7616$) can be observed when only the buildings are considered (Fig. 8). The results also provide information about the changes experienced by the vegetation in the aeolian shadow area, related to the urban-tourist infrastructures. Actions such as the existence of gardens and its irrigation do occur, as has happened in Argentina or Germany (Grunewald, 2006, Grunewald and Schubert, 2007, Faggi and Dadon, 2010, Faggi and Dadon, 2011). However, in the analyses carried out, around 400 m from the urban-touristic buildings is where less vegetation is concentrated, coinciding with the appearance of the erosional landforms. This is the sector that has experienced the greatest erosion since 1987 (García-Romero et al., 2019). It also coincides with the distance proposed in Fig. 9 where the wind data analyses allow to deduce that between 400 and 600 m with respect to the urbanization, acceleration processes were detected. This reason could be conditioning the non-colonization of plants in this area, and not the presence or absence of water. We must consider that one of the plant communities that have experienced a greater increase in surface in the areas of greater volume of sand is *Cyperus capitatus-Ononis tournefortii* (Table 3). It is a strictly psammophilous plant community, so it does not need the existence of a water table (Hernández-Cordero et al., 2015, Hernández-Cordero et al., 2017). In this sense, the hypothesis presented in the previous section is also reinforced, thus justifying an experiment with empirical wind data (speed and direction) and maybe a model derived from them.

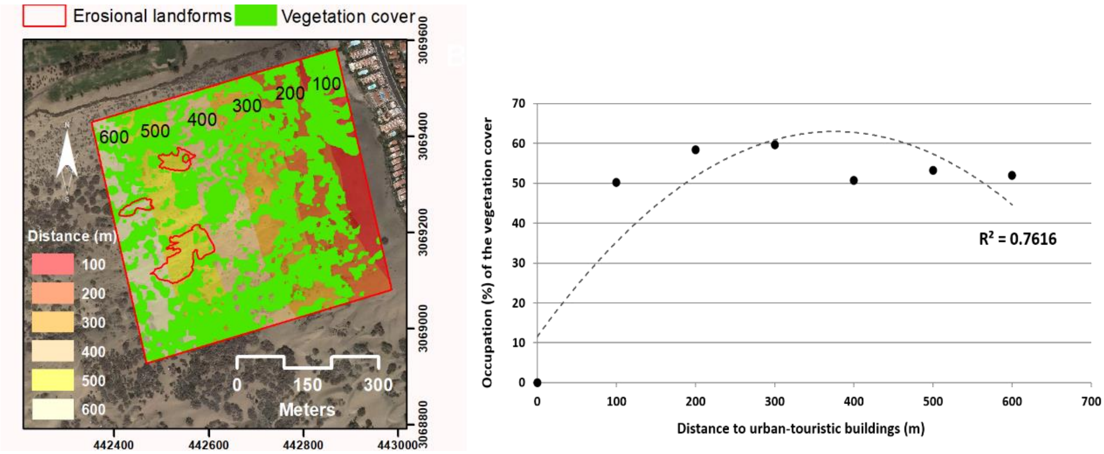

Figure 8. Distribution of the vegetation cover from the urban-tourist buildings to to the southwest of the study area. The relationship between vegetation cover (%) and distance to the urbanization (m) is showed with polynomial (degree 2).

3.3.2. Plant communities and their role of the aeolian erosional landforms

Table 3 shows the percent change in plant communities between 2003 and 2017 inside the aeolian erosional landforms area in the study area. In 2003, the erosional landform detected in transect 2 (Fig. 2) was covered by a community of herbaceous plants *Cyperus capitatus-Ononis serrata* (79.95%). Other areas where the vegetation was not detected were classified as null or low vegetation cover (20.04%). In 2017, the plant community *Cyperus capitatus-Ononis serrata* covers 100% of the erosional landform. The only community detected in the erosional landform located in transect 3 (Fig. 2) was also the herbaceous *Cyperus capitatus-Ononis serrata*, both in 2003 and 2017. 44.92% of the aeolian erosional landform in transect 4 (Fig. 2) was covered by *Cyperus capitatus-Ononis serrata* community in 2003, with an increase to 81.03% in 2017. The rest of erosional landform 4 was not occupied by vegetation in 2003 (55.08%) and in 2017 (18.97%). All erosional landforms were detected in 2003 (García-Romero et al., 2017) but they have evolved in different ways depending on the vegetation cover. Landforms in transects 2 and 4 showed a greater increase in area and eroded volume (Garcia-Romero et al., 2019) because a portion of their surface was not covered by vegetation in 2003 (Table 3). This lack of vegetation favored wind acceleration and sediment erosion. Landform 3 showed greater stability since 2013 due to the presence of vegetation, which reduced wind speeds and prevented strong erosion (Hesp, 1981, Moreno-Casasola, 1986). Note that all landforms showed visible exhumated roots of *Cyperus capitatus-Ononis serrata* (psammophilous perennial rhizomatous forb; psammophilous annual forb) (García-Romero et al., 2019). This is a herbaceous species common in the dune systems of the Canary Islands (Del Arco Aguilar et al., 2010) and a pioneer plant in the colonization of semi-stabilized dunes in the Canaries (Hernández-Cordero et al., 2015), and hence successful at growing in locations with strong sediment transport such as the ones studied here.

Table 3. Changes of the plant communities between 2003 and 2017 inside the aeolian erosional landforms detected in the study area.

Transect/Erosive landform	Plant communities	% 2003	% 2017
2	C. *Cyperus capitatus-Ononis serrata*	79.95	100
	Null or low vegetation	20.04	0
3	*C. Cyperus capitatus-Ononis serrata*	100	100
4	*C. Cyperus capitatus-Ononis serrata*	44.92	81.03
	Null or low vegetation	55.08	18.97

In general, the results indicate that the urban-tourist buildings play a predominant role influenecing wind speed patterns over the shadow zone, and that influence is less when incident winds are not across the resort but oblique to it. However, when incident winds flow across the urban-touristic center, an acceleration is detected as the wind moves away from the urbanizations, coinciding with the aeolian erosional landforms detected and with the area where the buildings have lower heights (Fig. 9). Slower wind speeds in the shadow zone lead to a more rapid vegetation colonization and growth, which in turns plays an important role in decreasing wind speeds and where aeolian erosional landforms are not detected currently.

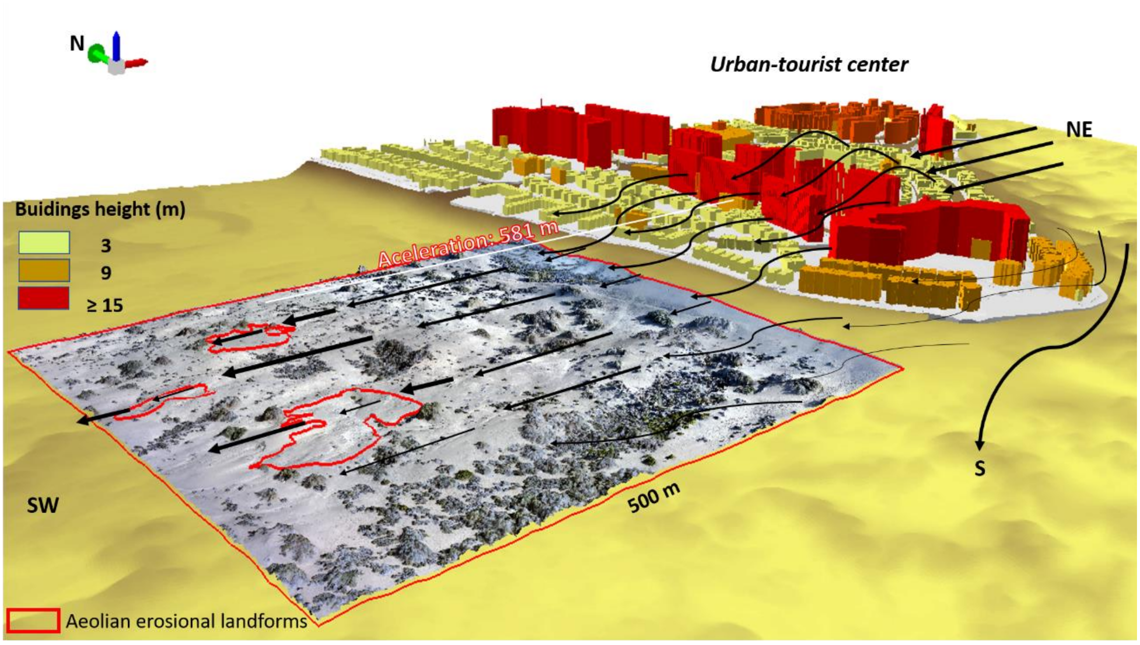

Figure 9. General scheme of the wind behavior in the aeolian shadow zone crossing the urban-tourist buildings. The thicker the black arrows across the study site (boxed in red) the greater the wind speed.

4. Conclusions

This work presents preliminary results from experiments carried out on March 24th and 25th, 2017 to study airflow dynamics in an aeolian shadow zone developed as a result of a tourist development in an arid transgressive coastal dune system. Results indicate that:

(i) the regional wind direction influences the degree of wind speed change across the study area such that when winds blow across the urban development the wind speed is more affected than when winds blow at an oblique angle or from outside the urbanization; (ii) in general, tourist infrastructure moderately (transect 3) to strongly (transects 4 and 2) influences wind speeds and directions in the study area with PCA correlations ranging from 0.7 to 0.9; (iii) vegetation cover and height have a significant influence in some of the transects (transects 1 and 5) and modify the flow fields accordingly. As vegetation density increased, the wind speed decreased.

In this aeolian shadow zone, a suite of erosional landforms is present, located at a similar distance from the urban-touristic infrastructure. This could indicate an acceleration or reattachment of the wind at this distance downwind. The simultaneous collection of wind data, topography and vegetation, as well as distances from the urbanizations and the Principal Components Analysis, indicate that the surface wind (at 0.40 m height) accelerates as it moves downwind from the urbanization, with topography and vegetation introducing variations in the local wind speed. These data provide a valuable field data set for validating future numerical modelling using Computational Fluid Dynamics (CFD) tools, which will allow a greater statistical and spatial analyses of wind speed, direction and turbulence, and to better elucidate the reasons for the presence of erosional landforms in this area.

The role that the community of herbaceous plants *Cyperus capitatus-Ononis serrata* is playing in this aeolian shadow zone could be a key to the future evolution of this area. So far, we know that this community is growing spatially in those places where erosion is taking place. If this continues into the future, this community will possibly minimize the role that these erosional processes may have (cf. Hernández-Calvento et al., 2014, Hernández-Cordero et al., 2015).

Acknowledgements

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2D decadal monitoring of Traganum moquinii's role in the morphometry of the foredune in an arid dunefield

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(No publicado)

Abstract

Foredunes in arid zones has been little studied and are significantly different than tropical and temperate foredunes. In the case of the foredune of the arid Canary Islands' dune systems, Traganum moquinii is the predominant plant species, forms nebkhas and nebkhas fields, and acts as a structuring element in the aeolian sedimentary system. In this work, the evolution of both the morphometry of the foredune and the morphology of Traganum moquinii species in the Maspalomas dunefield (Gran Canaria, Canary Islands) is analysed. In ten plots, eight variables have been analysed by statistical means, to detect the function exerted by Traganum moquinii on the foredune. The variables were measured at five different times, from the 1960s to the present, through historical aerial photographs and orthophotos, integrated in a GIS. Significant decadal changes in the number and morphology of Traganum moquinii plants and also in the morphometry of the nebkhas and foredune zone are observed, although not in a spatially homogeneous manner. The largest changes occurred in the northern Plot 1 and plots 9 and 10 (south). The number of nebkhas declined in plots 2, 3 and 4 between 1961 and 2012, while they increased in plots 7 and 8 since 1987. The vegetation density decreased in all the plots with respect to the 1960's except plot 8, while the mean diameter of T. moquinii forming the nebkha nearest to the beach increased in all plots. The distance between individuals of Traganum moquinii, as well as measured variables in the first line of the foredune (foredune front, where the first sand deposition by vegetation on the backshore of beaches is produced), such as the diameter of the individuals, have significant relationships with other variables. The greater the distance between plant individuals in the first line behind the backshore, the greater is the distance of T. moquinii individual plants in the rest of the plot with increasing landwards distance. In addition, using linear mixed models, the relationship between the foredune surface and variables measured in the observation plot or in the first line of the foredune (foredune front) is obtained (gains or losses according to the type of relationship). The alongshore variations in foredune development are due to natural processes (e.g. natural decline or growth of plants), and human impacts (e.g. carpark and kiosk construction, heavy tourist use). The results may be useful for the management of foredunes in arid, and other fragmenting/fragmented coastal dune systems.

Keywords: arid dune systems, *Traganum moquinii*, nebkha, foredune, biogeomorphology, morphometry.

1. Introduction

The Anthropocene is characterized by the alteration of natural processes due to human development (Crutzen, 2006), and many environmental problems related to the operation of coastal dune systems have emerged in recent decades (Nordstrom et al., 2000). In addition to the environmental effects of climate change or natural processes, the alteration of sedimentary dynamics by humans has led to an increase in the vulnerability of these systems (Fernández and Neves, 1997). Coastal dunes have historically been exploited for the extraction of their resources and animal grazing, but human pressures have increased in recent decades due to urban, tourist and industrial development or other activities (Martinez et al., 2013a). This development has accelerated the degradation and, in some cases, the total destruction of dune fields around the world (Paskoff, 1993; European Environmental Agency, 2006; Jackson and Nordstrom, 2011; Martínez et al., 2013a, b; Santana Cordero et al., 2014).

To achieve the conservation of coastal dune systems, it is essential to understand their processes and dynamics. In order to do this, it is important to study the dynamics of key landforms and to understand their relationships to the maintenance of the structure and functionality of dune dynamics. In the case of a foredune, various ecosystem services are provided, such as the provision of protection from storms (Avis and Lubke, 1996; Ley et al., 2007), habitats (Hernández-Cordero et al., 2015a), regulation of coastal erosion, and maintenance of the sedimentary balance of dune fields (Everard et al., 2010). The formation, dynamics and evolution of the foredune depends on many factors, such as the sediment supply (Psuty, 1988; 2004; Sherman and Bauer, 1993; Aagaard et al., 2004), the rate and magnitude of sediment transport (Nickling and Davidson-Arnott, 1990; Bauer and Davidson-Arnott, 2002; Davidson-Arnott et al., 2005; Bauer et al., 2009; Namikas et al., 2010; Delgado-Fernández, 2011), surfzone-beach type and interactions (Short and Hesp, 1982; Hesp, 1988; Carter, 1988; Carter and Wilson, 1990; Hesp and Smyth, 2016), wind flow (Rasmussen, 1989; Arens et al., 1995; Hesp et al., 2005; Walker et al., 2006) and vegetation cover (Moreno-Casasola, 1986; Hesp, 1988; Arens, 1996; Lancaster and Bass, 1998; Martinez et al., 2001; Miot da Silva et al., 2008; Hernández-Cordero, 2012). Since foredunes are located at the rear of a beach, they can range from quite stable to highly dynamic (Hesp, 2002), and vary considerably in vegetation cover from scattered nebkhas, to nebkha fields, to large, continuous ridges (Hesp, 1981; 1988; Moreno-Casasola, 1986; Arens, 1996; Arens et al., 1995; Levin et al., 2008; Hernández-Cordero et al., 2012; Garcia-Romero et al., 2019). In order to understand the processes in these systems as a whole, temporo-spatial 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).

A foredune is a aeolian sedimentary landform generated by aeolian sand deposition in vegetation, since its genesis, morphology and dynamics depends on (among other things) the types of plant species present (grass, herb, shrub), the plant density, distribution and cover, and its temporal and spatial development (Hesp, 1991; 2002; Biel et al., 2019). Foredunes can be formed by deposition of sand in individual plants or groups of plants located above the spring high tide line parallel to the beach (Hesp, 1989), resulting in nebkhas, nebkha fields, and, commonly, attendant shadow dunes (Hesp, 2002). The formation of semi- to continuous dune ridges occurs in regions with greater vegetation cover on, and above the backshore (Hesp and Walker, 2013; Garcia-Romero et al., 2019). The vegetation of the foredune zone in the dune systems of arid regions displays certain differences with respect to that of temperate and tropical systems. In arid systems, the

vegetation usually is low density shrubs, and the relative sparseness does not give rise to semi-continuous or continuous foredune ridges parallel to the coastline as in temperate and tropical zones. Instead, nebkhas and nebkhas fields typify the foredune zone (Hernández-Calvento and Mangas, 2004; Hernández-Calvento, 2006; Hernández-Cordero et al., 2012; 2019).
To date, arid coastal dune systems have been poorly studied on an international scale. The systems located in the Canary Islands are the only ones with these characteristics in Europe (Hernández-Cordero et al., 2015a, García-Romero et al. 2016). Some plant communities of these systems are recognized as habitats of European interest, as in the specific case of Traganum moquinii. In addition, the role of Traganum moquinii is very important because it is the main plant species that generates the foredune, formed by discontinuous nebkhas, in these Islands and other places of northwestern Africa (Hernández-Cordero et al., 2015a). With respect to Traganum moquinii´s characteristics and ecology, it is a nanophanerophyte or shrubby species. It occurs on the northwest coast of Africa, from Essaouira (Morocco), along the W. Sahara coast, and down to Cape Timirist (Mauritania) (Charco, 2001), and in the Canary Islands and Cape Verde. T. moquinii adult individuals have heights ranging between 1.30 and 3 meters, but some may reach 5 meters. It is usually a monospecific species that is distributed openly (Hernández-Cordero et al., 2012). In the case of Maspalomas, the plant occupies two main areas: in the area of sediment input to the Maspalomas dune system in El Inglés beach (foredune), where the sand is captured by these individuals (the area studied in this paper), and in the wet interdune depressions (slacks) between the dune ridges closest to Maspalomas beach (Hernández-Cordero et al., 2012).

The principal objective of this paper is to analyse, from a 2D long-term view, the relationship between the morphological characteristics of T. moquinii and the morphometric changes of the foredune zone in an arid transgressive coastal dunefield in Maspalomas.

2. Study area

The dunefield of Maspalomas is located in the south of the island of Gran Canaria (Canary Islands, Spain), constituting a Special Natural Reserve with an area of 403.9 ha (figure 1). Within the reserve lies the Maspalomas dune field, which occupies 360.9 ha and covers a quaternary delta (Hernández-Calvento, 2006; Hernández-Cordero et al., 2015b). The most important tourist center of Spain (Domínguez-Mujica et al., 2011), has been constructed around this system, since the 1960's. The beach and dunefield, besides the weather, is the major tourist attraction. The construction of large urban and tourist facilities has altered the dune system (Hernández Calvento, 2006, Alonso et al., 2011, Cabrera-Vega et al., 2013, Hernández-Calvento et al., 2014, García- Romero et al., 2016; Hernández-Cordero et al., 2017; Smith et al., 2017). In this dune system, tourism use is constant throughout the year, without any low use period for the system to recover from the impacts generated by services and users (Cabrera-Vega et al., 2013).
This system constitutes a transgressive dunefield, according to Hesp and Walker (2013), and has a mean migration rate of 8 m/year (2003-2006) (Pérez-Chacón et al., 2007). The sources of sediments are mainly marine, with the sand containing a high proportion of organogens (forams, shells molluscs, seaweed meshes). The terrigenous composition corresponds to fragments of volcanic materials contributed by the Island ravines and the erosion of marine cliffs (Hernández-Calvento and Mangas, 2004; Mangas et al., 2012). The sediments are input into the system at El Inglés beach (on the east), where the first

aeolian landforms are formed in the foredune zone. They are transported into the system by the trade winds, blowing from the E-NE, as active (free) dunes, and finally exit the dunefield to the sea via Maspalomas beach (in the south) (Hernández-Calvento, 2006). The dunefield comprises three separate zones, according to the aeolian sedimentary activity and the landforms (Hernández-Cordero et al., 2015b). Firstly, an active area (figure 1, A), from the coast to the inner area, which has the following landforms: the beach, the foredune, barchan dunes, sand sheets, deflation surfaces, barchanoid and transverse ridges and interdune depressions. Secondly, a semi-stabilized area (figure 1, B), with deflation surfaces, barchan dunes and sand sheets or nebkhas; and thirdly, a stabilized area (figure 1, C), with stabilized dunes and interdune depressions. A total of 19 plant communities have been detected in the dunefield including Cyperus capitatus-Ononis tournefortii, Tamarix canariensis, Launaea arborescens, Suaeda mollis and Traganum moquinii communities (Hernández-Cordero et al., 2017). Mean annual rainfall is 81 mm (1952-2008, AEMET and Hydraulic Service of Las Palmas data) and mean annual temperatures is 21 °C (1997-2007), with a dry period throughout the year (Hernández-Cordero et al., 2015b).

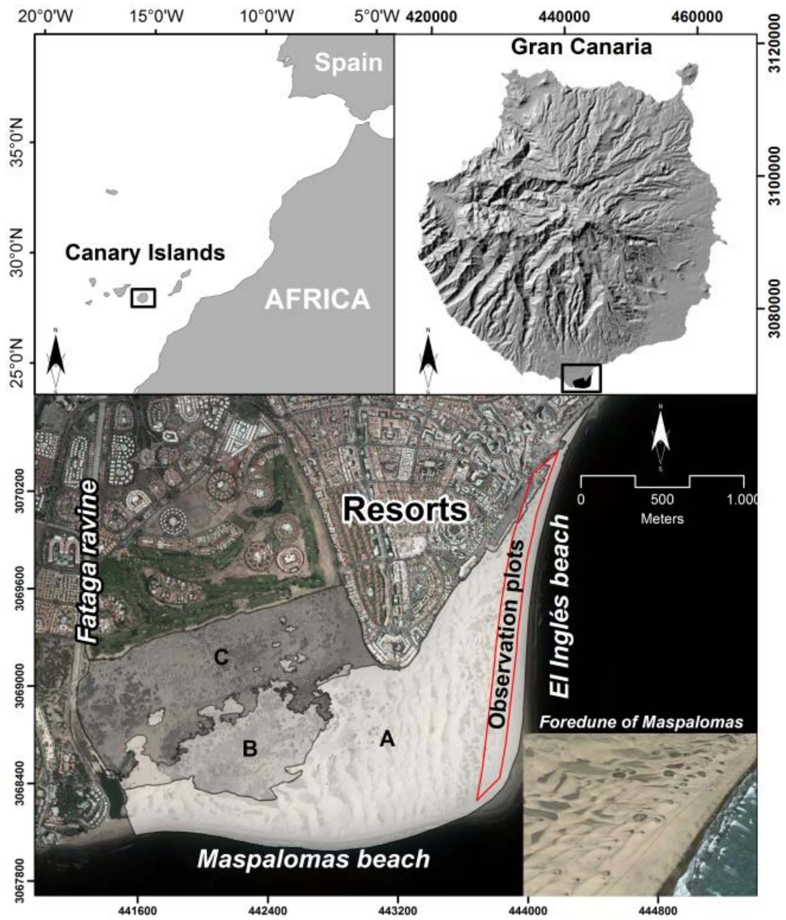

Figure 1. General view of the Maspalomas dunefield with the three principal geomorphic zones and the location of the foredune zone where the observation plots were located. A. active area; B. semi-stabilized area; C. stabilized area (modified from Hernández-Cordero et al, 2015b).

The height of the foredune at Maspalomas varies between 1 to 5 m and is formed by isolated nebkhas formed in T. moquinii plants (Hernández-Cordero et al., 2012). Small interdune depressions, and on occasions, sand tongues (parabolic-shaped, unvegetated, arcuate ridges) are present between the nebkhas, which vary spatially and temporally depending on the dynamics of the active aeolian sedimentary processes (Viera-Pérez, 2015). These dynamics has been altered in the last decades due to a reduction in the number of T. moqunii plants caused by infrastructure building and by the pressure of beach users, as well as other natural or anthropogenic processes, such as storm wave erosion (Hernández-Calvento et al., 2014; Hernández-Cordero et al., 2012) or light pollution (Viera-Pérez et al., 2019), among others. A priori, these changes have not been homogeneous spatially and temporally; thus, the function of T. moquinii on the foredune has changed depending on the degree of alteration.

3. Methodology

The foredune was divided into 10 plots (figure 2). In each of these a series of variables of the morphology of T. moquinii and the foredune were measured, using digital orthophotos and historical aerial photographs. The variables were analysed statistically in order to examine their relationships.

3.1. Information source

The information sources used were orthophotos and historical aerial photographs from 1961, 1977, 1987, 2003 and 2012 (Table 1). The orthophotos of 1961 and 2012 were consulted through the WMS service of the Canary Islands' SDI (Grafcan, S.A.- Government of the Canary Islands), while the 1987 and 2003 ortophotos are provided by the Grupo de Geografía Física y Medio Ambiente (IOCAG-ULPGC). Aerial photos of 1977 were georeferenced from control points using GIS. Although historical aerial photographs of the 1990s are available, they were discarded because reliable information on the characteristics of the flights were unavailable.

Table 1: Aerial photographic data.

Date	Scale	Spatial resolution (m)	RMS (m)	Delineation error (m)
1961	SDI WMS service	0.12	*	0.12
1977	1:6,500	0.15	1.54	1.3
1987	*	0.15	*	0.15
2003	*	0.15	*	0.15
2012	SDI WMS service	0.25	*	0.25

*missing data

3.2. Observation Plots

The 10 observation plots (figure 2) are distributed from north (plot 1) to south (plot 10). They have dimensions of 200 × 200 meters and are oriented in a northeast-southwest direction (45º-225º), corresponding with the orientation shown by the shadow dunes formed leeward of plants in the whole series of aerial photography and orthophotos used. The eastern limit of the plots corresponds to the individuals of T. moquinii located closer to the coastline throughout the years studied.

Individuals of T. moquinii were identified in each of the observation plots from photointerpretation, using the maximum resolution offered by the sources. The centroid of each specimen was digitized with a point geometry stored in shapefile format in GIS.

With this criterion we aimed to objectively identify plant individuals regardless of the source´s resolution.

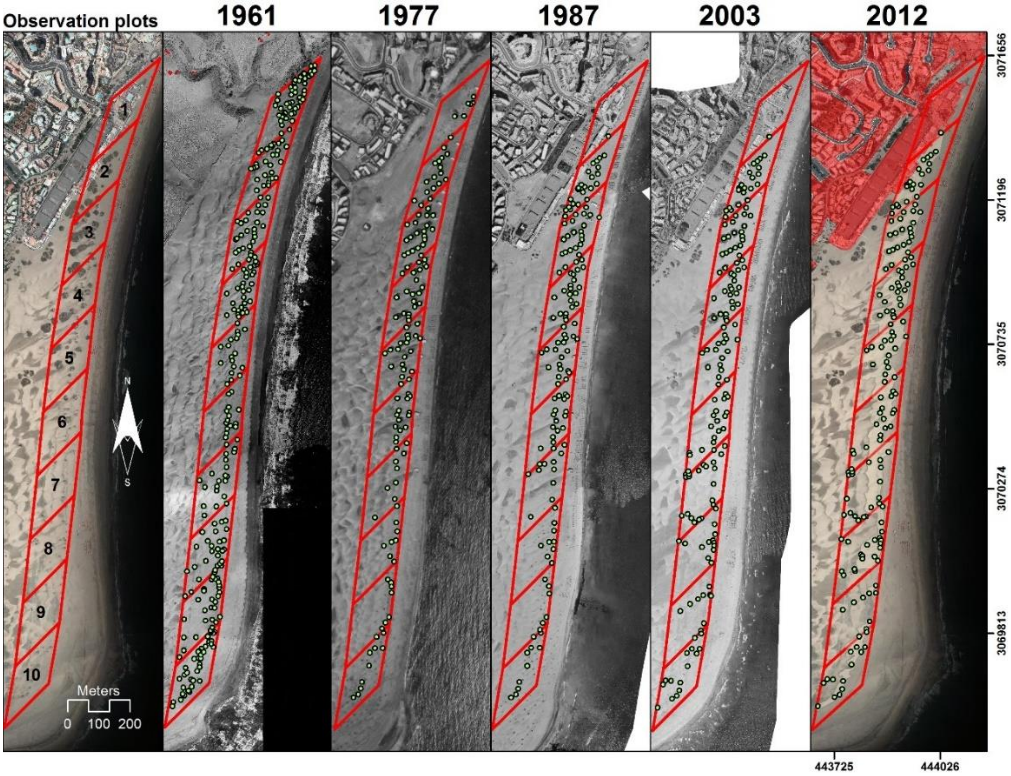

Figure 2. Plots and T. moquinii plants (green points) for each year. The built environment is shown in red in the 1961 (insignificant) and 2012 (significant) images.

3.3. Variables measured

The variables measured as well as the method used, are shown in table 2. Due to the morphological and ecological characteristics of T. moquinii, which is distributed openly and reaches significant heights similar to trees (Heights: 1.3 – 5 meters) (Hernández-Cordero et al., 2012), the calculation of the vegetation density used is that proposed by Mostacedo and Fredericksen (2000).

Table 2: Morphometric (foredune) and morphology (T. moquinii) measured variables.

	Variables	**Methods**
Foredune	Number of nebkhas (in each plot) (*NN*)	According to the total number of *Traganum moquinii* plants.
	Foredune surface (m^2) (in each plot). Response morphologic variable. (*FS*)	Calculated for the polygons digitalized from visual interpretation, using GIS.
Traganum moquinii	Vegetation density (in each plot) (*D*)	*According to Mostacedo & Fredericksen, 2000
	Number of *T. moquinii* individuals in line 1 (*B1*)	Visual interpretation
	Mean diameter of *T. moquinii* individuals in line 1 (m) (*D1*)	Calculated for wider diameters with orientation NE-SW, based on lines digitized from visual interpretation, using GIS
	Mean distance between *T. moquinii* individuals in line 1 (m) (*DB1*)	Using geoprocessing tools in GIS

$*Dh = \frac{10000}{(\overline{D})^{2}}$, where: Dh is density by hectare (in our case is the surface of the plot) and $\overline{D}$ is the average distance between central points (between *T. moquinii* individuals).

Line 1, or the first line, refers to the T. moquinii individuals (and nebkhas) located on the front of each plot, closest to the coastline. These individuals are the first obstacle in the aeolian transport pathway from the beach, and then they accumulate sand and form nebkhas, and it is possible that they interfere in the distribution of the rest of T. moquinii individuals in each full plot. In addition, these individuals are exposed to natural marine and anthropogenic processes.

3.4.Statistical analysis

The variables measured from the 1960's to the present allowed us to analyse the evolution of T. moquinii plants and the nebkhas and foredune zone associated with them. In order to evaluate the relationship between T. moquinii morphologic variables and the morphometric variables (number of nebkhas and foredune surface) we have fitted a linear mixed model of the form:

$$FS_{ij} = \beta_0 + \beta_1 NN_{ij} + \beta_2 D_{ij} + b_{0i} + \varepsilon_{ij} \quad (1)$$

Using as predictors the variables measured in line 1, the next model is used:

$$FS_{ij} = \beta_0 + \beta_1 DB1_{ij} + \beta_2 B1_{ij} + \beta_3 D1_{ij} + b_{0i} + \varepsilon_{ij} \quad (2)$$

Where FS_{ij} is the response morphologic variable (the foredune surface). In model (1) NN_{ij} is the number of nebkhas or number of *T. moquinii* individuals in the plot in the year i at the plot j, and D_{ij} is the density of *T. moquinii* in the year i at the plot j. In model (2), $DB1_{ij}$ is the mean distance between nebkhas or mean distance between *T. moquinii* individuals in line 1 in the year i at the plot j, and $B1_{ij}$ is the number of *T. moquinii* in line 1 in the year i at the plot j, finally $D1_{ij}$ is the mean diameter of the *T. moquinii* plants in line 1 the year i at the plot j. These are fixed factors in the model. Year has been introduced in the model as a random factor as the observed years are a random sample of all possible study years. The term b_{0i} represents random annual variation in the mean foredune surface. b_{0i} is assumed to follow a normal distribution with zero mean and variance σ_0^2. ε_{ij} are the residual terms, and are also supposed to follow a normal distribution with zero mean and variance σ_ε^2. Heteroscedasticity between observation plots was also taken into account and has been modelled using a different variance per plot as shown in Pinheiro and Bates (2000), so that $(\varepsilon_{ij}) = \sigma_j^2$. The significance level for all tests has been 0.05. The fit of the model has been carried out by using the library nlme (Pinheiro et al., 2017), in the statistical software environment R (R Core Team, 2016). The models' estimation is shown in table 3. Data have been removed in some cases to calculate model 1 and 2, especially related to plot 1 because the changes detected have no other explanation than the alteration because the plot has been occupied by construction (see figure 2). For this reason, the DF in model 1 is 36, and in model 2 is 39.

In addition, a Principal Components Analysis (PCA) was carried out in order to determine the main variables measured in line 1 that can explain our response variable (FS).
Finally, to determine the possible existence of differences in the foredune of Maspalomas and the consequences on the T. moquinii individuals as species, a classification by clusters was made (Ward's method with Euclidean distance squared) where only morphometric variables of the foredune were used. Finally, the relationship between the variables of T. moquinii plants was analysed, in order to understand their importance in

the distribution and evolution of this species. This analysis was made from the different groups of plots obtained in the cluster studied using a Pearson correlation. This should allow the elucidation of variables that have a significant relationship in each of the three groups whose evolution and behaviour of T. moquinii has been different in the last few decades.

4. Results and discussion

4.1. Evolution of the morphometric characteristics in the foredune

The data indicate significant differences in the evolution of the foredune, both spatially and temporally (figure 3). First, the number of nebkhas and, therefore, the number of individuals of T. moquinii, has decreased between 1961, when the dune system had much less human pressure, and 2012, as previously indicated by Hernández-Cordero et al. (2012). The largest changes are detected in plot 1 (north of El Inglés beach), and in plots 9 and 10 (south). The most stable plot over time is plot 5, located in the central area. The number of nebkhas declined in plots 2, 3 and 4 between 1961 and 2012, and, in contrast, plots 7 and 8 experienced an increase in the number of T. moquinii and nebkhas since 1987. Plot 6 is the only plot with a stable number of T. moquinii plants and nebkhas between 1961 and 1977, and then increasing in numbers progressively since then.

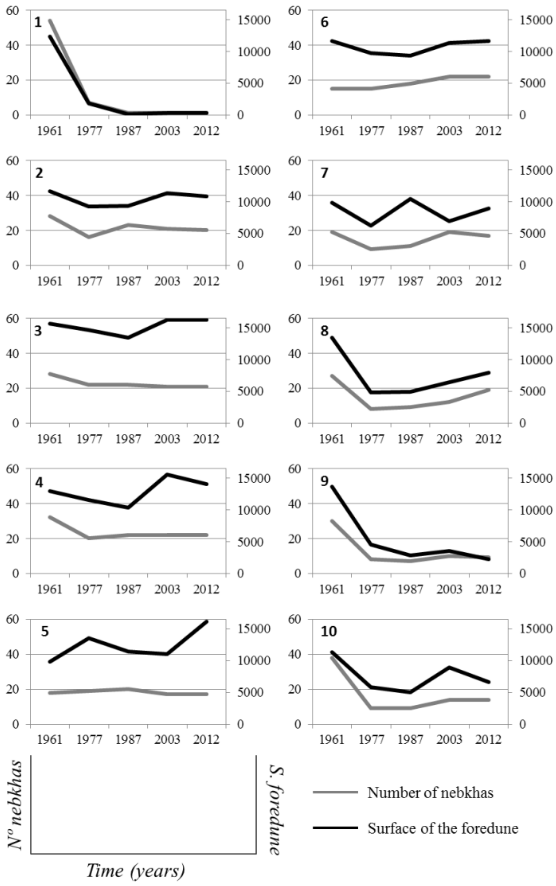

Figure 3: Evolution in the number of nebkhas and changes (m^2) in the foredune surface since 1961 to 2012 in each observation plot extending from the north (Plot 1) to the south (Plot 10).

As for the surface covered by the foredune (i.e. the area occupied by nebkhas, shadow dunes and inter-nebkha parabolic-shaped tongue dunes according to Viera-Pérez (2015)), plot 5 has increased in surface area since 1961 (figure 3). Plot 1 is the only one that has experienced a reduction in the area of the foredune. The same is observed in plots 8, 9 and 10, although these plots have had periods of increased surface area also. Plots 2, 6 and 7 have in common that the surface area of the foredune decreased slightly with respect to 1961. In addition, all plots have had periods of stability or even increased their surface area. Finally, plots 3 and 4 experienced a decline in foredune area until 1987, showing a recovery since then.

4.2. Evolution of the morphological characteristics of the T. moquinii

In general terms, there are significant changes in the morphological variables of T. moquinii over the last decades in practically all the plots, although there are differences depending on their location (table 3). One example is the vegetation density, and it has decreased in all the plots with respect to the 1960's except plot 8. In plot 8 the number of individuals in line 1 (the foremost line of nebkha) increased, while the mean distance between them decreased. The mean diameter of T. moquinii in line 1 also increased in all plots. In terms of mean distance and density, in plot 1, individuals disappeared as can be observed in figure 2. However, in plots 2, 3 and 8 the mean distance between individuals decreased while the mean density increased.

Table 3: Temporal evolution of the *T. moquinii* variables.

Variables	Years	Plots									
		1	2	3	4	5	6	7	8	9	10
Density (*D*) (in each plot)	*1961*	239.82	117.07	85.50	122.12	63.56	118.52	53.08	60.01	99.86	229.52
	1977	59.25	50.58	62.86	68.33	54.64	94.22	23.17	45.96	75.38	48.14
	1987	6.06	97.60	65.94	79.02	66.68	78.33	25.05	44.74	50.70	48.90
	2003	6.21	96.81	73.08	76.81	48.49	95.87	68.84	85.03	55.94	48.38
	2012	6.21	101.90	73.08	80.92	48.49	91.40	48.74	124.21	42.68	48.38
Number of *T. moquinii* individuals in line 1 (*B1*)	*1961*	13	6	9	13	10	11	10	6	13	20
	1977	5	7	9	7	9	10	6	6	7	8
	1987	1	5	8	7	7	8	5	7	6	7
	2003	1	5	7	9	10	9	7	9	4	7
	2012	1	5	8	9	7	8	5	9	5	6
Mean diameter of *T. moquinii* individuals in line 1 (m) (*D1*)	*1961*	8.55	10.48	10.40	7.78	8.87	6.95	7.49	5.93	4.16	3.32
	1977	10.44	13.56	12.65	12.39	11.31	8.18	8.99	8.78	7.25	6.32
	1987	11.82	13.34	13.17	11.52	11.57	8.86	10.64	6.69	5.36	6.25
	2003	10.88	13.29	13.01	11.45	13.12	9.91	8.32	7.59	6.59	5.83
	2012	11.11	13.59	15.66	12.08	13.64	8.44	9.82	8.12	5.45	7.05
Mean distance between *T. moquinii* individuals in line 1 (m) (*DB1*)	*1961*	10.35	20.41	12.74	9.79	15.42	15.44	13.83	21.50	9.99	10.32
	1977	20.64	16.38	11.18	13.90	15.15	13.04	25.96	16.96	11.73	22.94
	1987	0.00	18.17	9.91	14.66	17.32	15.60	26.90	18.70	16.94	22.22
	2003	0.00	17.78	12.17	11.52	14.64	15.55	22.11	9.31	15.54	21.50
	2012	0.00	20.34	11.95	11.27	21.23	15.65	25.13	8.98	17.45	26.68

The morphometry of the foredune of Maspalomas experienced spatial-temporal variations between 1961 and 2012 (table 3). These changes are related to the variations in the number of individuals of T. moquinii (Hernández-Cordero et al., 2012). The greatest reduction in the number of nebkhas and the surface of the foredune has occurred in the far north and south of El Inglés beach, where the decline of the T. moquinii community has been greater, due directly and indirectly to tourism development (García-Romero et al., 2016; Hernández-Cordero et al., 2017).

The reduction in the number of T. moquinii individuals, and therefore the alteration of the foredune, has not generated the formation of blowouts, as sometimes occurs in temperate regions (Leatherman, 1976; Godfrey et al., 1979; Ritchie and Penland, 1990; Saunders and Davidson-Arnott, 1990; Hesp, 2002; Mir-Gual et al., 2013). This fact seems to be related to the differences between arid and temperate foredunes. The arid foredune of Maspalomas comprises discontinuous nebkhas, and thus, in this case, the effect of degradation of an arid foredune is the reduction or nullification of nebkha formation, and the formation of deflation surfaces or free (mobile) landforms such as barchan dunes and sand sheets (Hernández-Cordero et al., 2012; Hernández-Calvento et al., 2014). Moreover, the disappearance of the foredune has resulted in an acceleration of dune mobility, since the regulatory effect of the foredune on the sedimentary transport disappears or is reduced (Hernández-Calvento et al., 2014).

Interventions or eco-anthropogenic impacts have had a direct effect on the morphology of dune systems elsewhere (Nordstrom, 1994, Nordstrom et al., 2000, Jackson and Nordstrom, 2011, Cabrera-Vega et al., 2013). An example of the evolution of T. moquinii under the influence of anthropogenic activities is detected in plot 1. From 1977, individual plants were eliminated to facilitate a parking area for beach users. One decade later this parking area was a commercial center oriented to tourists (figure 2). This building occupied part of the surface of the foredune, a fact that has undoubtedly altered the sedimentary dynamics of the Maspalomas dune system, reducing the number of nebkhas and other landforms (García-Romero et al., 2016, Hernández-Cordero et al., 2017).

In addition, in plots 2, 6 and 7, the disappearance of T. moquinii, possibly due to anthropogenic actions, is detected. These actions are more evident in the case of plot 2, given its proximity to the urban-tourist area. The majority of beach services have been historically located in the surrounding area of this plot and within its inner area, which has meant, from the mid-1970's and until the late 1980's, the presence of kiosks of 120 m2, as well as a number of hammocks and umbrellas. A continuous trafficking of vehicles along the backshore was linked to these kiosks and other tourist activities (e.g. umbrellas), in order to supply services to the beach-going public and tourists (Hernández Calvento, 2006). In regard to plots 6 and 7, the remoteness of the urban-touristic center and the beach facilities was still not sufficient for their conservation. Around these plots, facilities of hammocks and umbrellas have been historically limited, which have made these areas places of attraction for tourists looking for greater naturalness. The lack of basic public services in these areas, such as urinals, has led tourists to constantly use T. moquinii plants as improvised urinals, with negative consequences for the plants (Hernández-Calvento, 2006). Also, these plants have often served as a base for the construction of windbreaks by tourists, since in this area a higher wind speed is detected, partly due to the influence of the tourist development (Hernández-Calvento et al., 2014). This has led to the alteration of the plants (broken branches, for example) and the modification of the aeolian sedimentary dynamics around the plants (Hernández-Calvento, 2006).

Plot 5 may be an example of a foredune for the development of T. moquinii plants, and therefore for the development of nebkhas due to coastal exposure which favors the marine and wind incidence. Results show it is located in the most stable zone, where the number of nebkhas is best maintained in the last few decades (figure 3) (Viera-Pérez, 2015).

Figure 4 shows a normalized mean of the variation experienced in the morphometric variables in each plot (number of nebkhas and foredune surface) and their distance to tourist infrastructures (access to the beach, resorts, etc.). In the first 150m tourist activities and services are intense, hence the relatively lower numbers of nebkha and surface occupied by a foredune. At around 450m tourist services again increase and nebkha numbers diminish. In the middle zone (250 – 400m) tourist activities are relatively low (Figure 4).

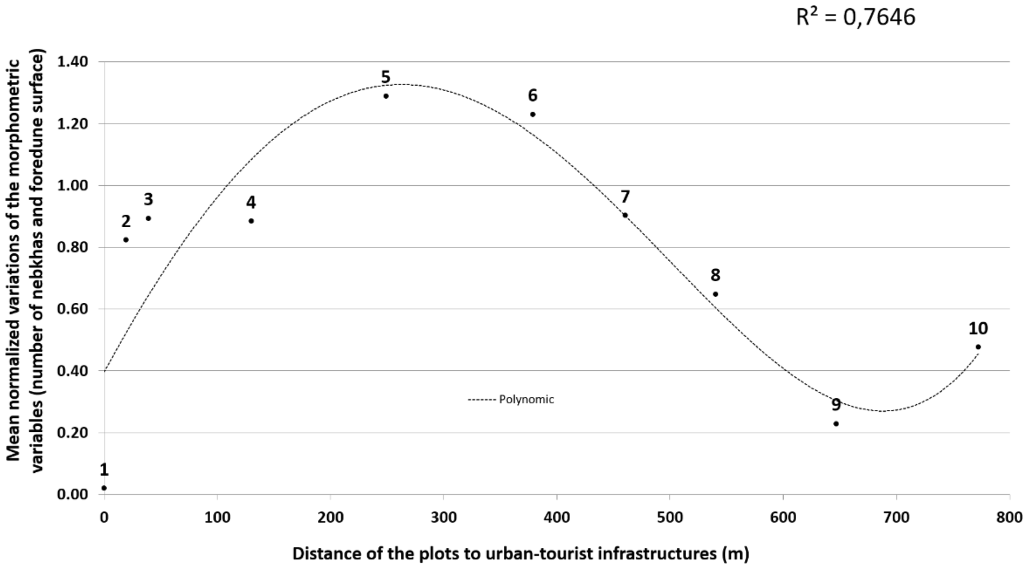

Figure 4. Relationship between the variation of the morphometric variables studied and the distance to the urban-tourist infrastructures of each plot. The number of the points is the observation plot. Plots with values closer to 1 have had less changes in the two variables used (number of nebkhas and foredune surface).

4.3. Relationship between T. moquinii´s variables and foredune morphometry

The equations obtained for models 1 and 2 show that the different variables are significant according to the p-value (table 4). In model 1, the number and density of nebkhas variables are related in each plot with respect to the response variable or foredune surface. In this case, there is a direct relationship between both variables due to the low values obtained in the residual variability σ_0= 0.3544 and σ_ε= 1385.56. In. In addition, the p-values are also low values with 4.98E-11 in the number of nebkhas and 0.01751 in the density. This indicates that when one nebkha unit increases, the foredune surface increases by 548.8 m2, and when the density increases one unit, the foredune surface decreases by 39.12 m2. This density equation is influenced by the distance between the T. moquinii individuals or nebkhas, because when the distance between them increases, it is possible that the foredune is fragmented and as a result, the foredune surface decreases.

Table 4. Estimation of the models (1) and (2).

	Variables	Value	Std.Error	DF	t-value	p-value
Model 1	(Intercept)	2127	816.4	36	2.606	0.01325
σ_0= 0.3544	NN	548.8	59.42	36	9.235	4.98E-11
σ_ε= 1385.56	D	-39.12	15.71	36	-2.49	0.01751
Model 2	(Intercept)	4499	1266	39	3.553	0.001014
	DB1	-182.6	25.15	39	-7.259	9.46E-09
σ_0= 1483.116	B1	266.1	32.28	39	8.243	4.50E-10
σ_ε= 4790.96	D1	744.7	44.09	39	16.89	1.57E-19

σ_0 and σ_ε: Residual variability

Model 2 (Table 4) shows relationships between the variables DB1, B1 and D1 to explain the behavior of the foredune surface, due to the low p-values obtained (9.46E-09, 4.50E-10 and 1.57E-19 respectively). Although high values in the residual variability are found (σ_0= 1483.116 and σ_ε= 4790.96) these are not valid to predict the foredune surface variable. In this case, if one DB1 unit increases so foredune surface decreases 182.6 m^2, producing a fragmented foredune. If one B1 unit increases, the foredune surface increases 266.1 m^2 and then, if one D1 unit increases, the foredune surface increases by 744.7 m^2.

In the analysis of principal components (PC) (Table 5), the variables measured in line 1 which could explain the response variable (FS) are classified through three PC's. The first two components explain 90% of the variance (Table 5, PC2; cumulative proportion) in the three variables measured in line 1 (number of T. moquinii, mean diameter of T. moquinii individuals, and mean distance between T. moquinii individuals).

Table 5. Principal components of the variables measured in line 1 and correlation with the foredune surface.

	PC1	PC2	PC3
Standard deviation	1.282	1.041	0.522
Proportion of variance	0.548	0.361	0.091
Cumulative proportion	0.548	0.909	1.000
Foredune surface correlation	0.327	0.590	

Rotation (n x k) = (3 x 3)

In the case of PC1, B1= -0.72 DB1= 0.64. This component practically explains the density of nebkhas or number of T. moquinii individuals. The higher its value, the greater the number of T. moquinii and/or the closer they are to each other, whereas, the more negative its value, there are less T. moquinii and/or the greater the distance between individuals.
In the case of PC2, D1= 0.89 and DB1= -0.44. This component expresses a combination between the size of the T. moquinii individuals and the distance that separates each individual. The larger they are and/or the closer they are, the higher the positive values, and the smaller they are and/or greater the distance apart, the higher the negative value. This could be due to the intraspecific competition.
The trend observed in table 6 is that while PC1 and PC2 (nebkhas density in line 1 or number of *T. moquinii* and intraspecific competences) increases, the foredune surface

increases 723.145 m^2 and 2,040.920 m^2 respectively because the p-values obtained are 0. Although due to the residual variability being very high (σ_0= 1432.923 and σ_ε= 4737.174), these results do not allow one to predict the behaviour of the foredune.

Table 6. Model using explanatory variables from principal components 1 and 2 to explain the response variable (FS).

	Principal components	Value	Std.Error	DF	t-value	p-value
	(Intercept)	10604.709	667.786	40	15.880	0
σ_0= 1432.923	PC1	723.145	71.801	40	10.072	0
σ_ε= 4737.174	PC2	2040.920	51.135	40	39.913	0

σ_0 and σ_ε: Residual variability

This analysis indicates that there is a natural adjustment between the number of nebkhas, the T. moquinii size and the distance between them in line 1 (or the foremost plant-nebkha line) on the foredune without natural or anthropogenic alteration. In figure 5, values with further separation (red circles) were obtained in observation plots with the biggest environmental changes detected, especially in the observation plots 8, 9 and 10 (to the south).

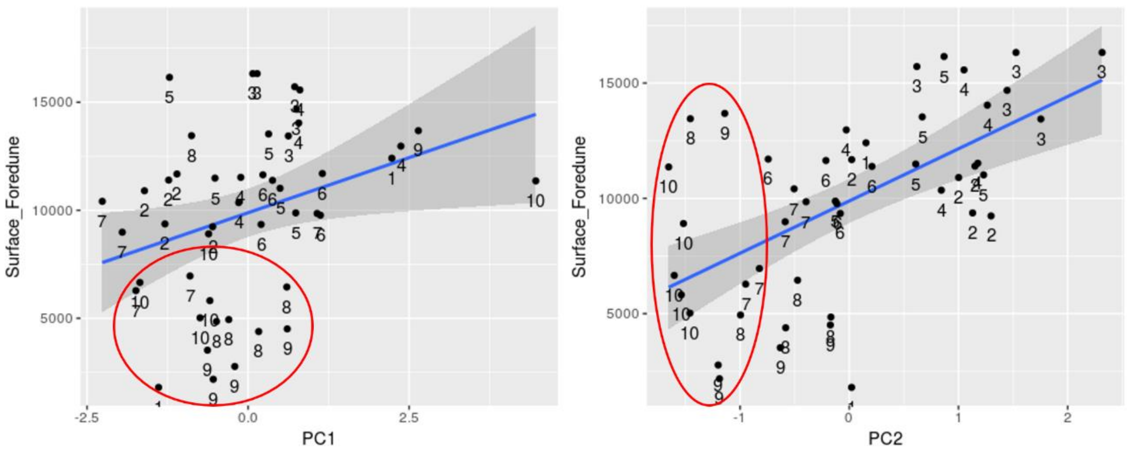

Figure 5. Scatter diagrams using the principal components (PC1 and PC2) as explanatory variables to explain the response variable (FS). The blue lines indicate linear trend, and the red circles indicate values located in observation plots which have the biggest environmental changes.

4.4. Morphometric differences in the Maspalomas` foredune and consequences on the T. moquinii variables

The cluster analysis examining the evolution of the variables related to the morphometry of the foredune (number of nebkhas and foredune surface), indicates the existence of three groups of plots (figure 6).

Group 1: plots 2, 6 and 7

This group is located in the north (plot 2) and in the central area of the study area (plots 6 and 7). These plots are characterized by variations in the morphometric characteristics of the foredune. Thus, plots 2 and 7 present a decrease in the number of nebkhas and the surface of the foredune, while plot 6 in 2012 experienced an increase in the area of the foredune while the number of nebkhas has remained similar to 1961.

Group 2: plots 3, 4 and 5
The plots of this group are located in the north and center of El Inglés beach. These are plots that have had greater stability since 1961, although plots 3 and 4 present low decreases between 1961 and 1987. However, these are plots that have increased in the area of foredune in the last few decades (2003-2012).

Group 3: plots 1, 8, 9 and 10
This group of plots are located in the north (plot 1) and south (plots 8, 9 and 10) (as also seen in Figure 4). They are the plots that have shown a larger decrease in the number of nebkhas and in the surface of the foredune area.

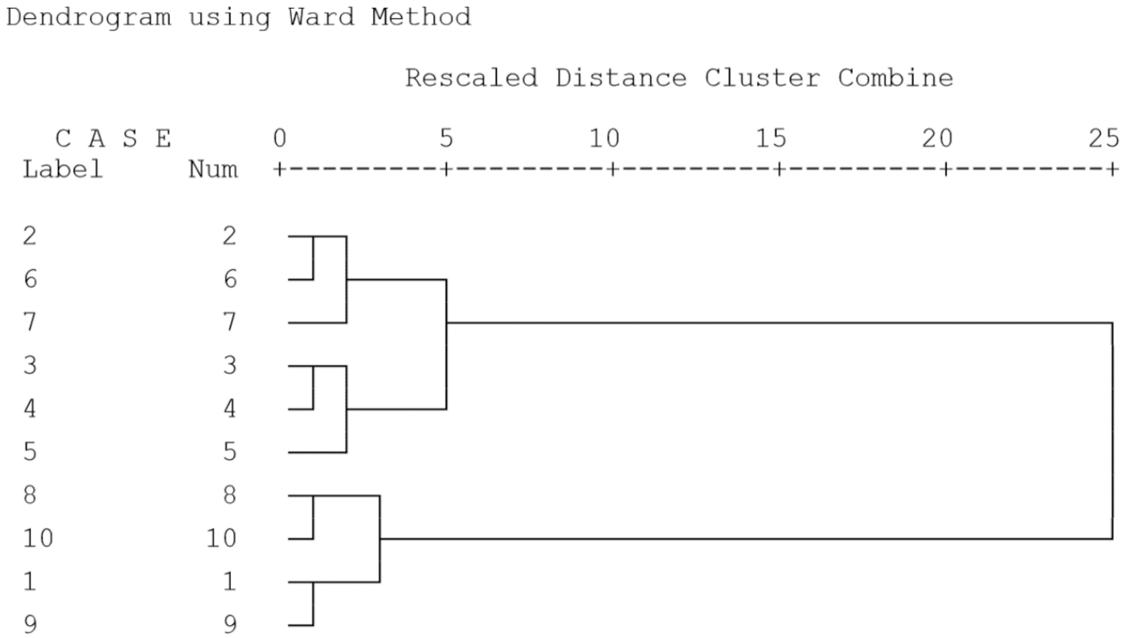

Figure 6. Dendrogram from cluster analysis using Ward method. Variables related to morphometry of the foredune (number of nebkhas and foredune surface) are used.

The evolutionary differences in the morphometric characteristics of foredune (number of nebkhas and foredune surface) indicated the presence of three groups, in contrast to Amini et al. (2012) who found 4 zones in a study on concentration, stabilization, height and biological cover on a foredune in North Iran. However, in the case of Maspalomas, the anthropogenic factor is determined by tourist pressure (users, beach services) as opposed to the study area studied by Amini et al (2012) where the anthropogenic pressure level is low. Group 1 comprised irregular dynamics but tended to stability, group 2 had a predominantly stable dynamic, while group 3 showed a regressive evolution, with a significant decrease in the number of nebkhas and in the surface of the foredune. This differential behavior has also been detected in other foredunes in the world, although in non-arid regions, such as in the Doñana National Park (Huelva, Spain), where Vallejo et al. (2006) differentiated five types of foredunes. This variability could be related to two of the three main variables that have been observed in the Emilia-Romagna littoral, in Italy (Corbau et al., 2015): (a) orientation of the coast, and the foredune, with respect to marine and aeolian forces; and (b) human activities. The second variable (human activities) is here stronger than the first option, because El Inglés beach is virtually a straight long beach with almost no change in orientation. Although it cannot be ruled out that topographic factors related to the perimeter/shape of the Gran Canaria island have an effect, such that it could modify the aeolian dynamics and give rise to zonal differences between north and south in El Inglés beach (see Figure 1 (study area), north of El Inglés beach), this seems to be unlikely.

4.4.1. T. moquinii's role on the morphometry of the foredune

T. moquinii shows a relationship with the variables associated with the morphometry of the foredune of Maspalomas, being a structuring element in the formation of accumulation landforms (nebkhas, shadow dunes and inter-nebkha parabolic-shaped tongue dunes), which corroborates the findings of other studies (Hernández-Calvento, 2006; Hernández-Cordero et al., 2012; Viera-Pérez, 2015). In general, the number of nebkha has a (obvious) strong relationship with the plant density of the plot and the distance between the individuals of T. moquinii. These variables have a natural relationship that favors the formation and conservation status of the foredune (Hesp, 1983). However, it should be clarified that as the number of nebkhas associated with the presence of T. moquinii specimens has been used for the calculation of plant density, their relationship is logical. The correlation between the number of nebkhas and the distance between plants (Table 6, PC1) is remarkable by the morphologic characteristics that T. moquinii specie shows. In all groups, except 3, there is a certain relationship between these two variables, so that as the number of nebkhas increases, the distance between T. moquinii plants naturally decreases. In essence, one is merely stacking more plants in a given space. It should be considered that the plots of group 3 are the most exposed to external factors of anthropogenic origin (in the case of plot 1) and natural and human ones (in the case of plots 8, 9 and 10). Plot 1 is located adjacent to the tourist urbanization, so this area experiences significant human pressure. The other three plots are located in the southern end of the foredune, where the wind velocity is more significant, which is reflected in the lower height of T. moquinii plants in this area (Hernández Calvento, 2006). These eco-anthropogenic factors have limited the development of these plant species in those plots. This could explain why there is not a constant distance between individuals.

It is also worth noting the relationship between the foredune surface and the other variables of T. moquinii measured such as diameter, number and density of T. moquinii plants in line 1. This may explain why the plots of this group are the most stable morphometrically over time. The correlation between these variables could be indicating a balance in the system, which reinforces the relationship between vegetation and sediment transport, leading to the formation of nebkhas and the foredune itself. With respect to the plots with greater stability, it is also important to note the correlation with the variables of T. moquinii measured in the first line of the foredune, because the behavior of this species in the front of this landform is important for its morphometry. As for the variable of the surface of the foredune, this does not have any relation with any variable related to the morphology of T. moquinii, quite the opposite to that which occurs with the number of nebkhas. This behavior can be explained by the fact that it is a plot where a locally greater or significant wind velocity has been detected (Máyer et al., 2012), and therefore has an accelerated aeolian transport, as also occurs in plot 5. As a result, it might be that wind velocity in this area is a significant and structuring factor, as seen in other case studies (Nordstrom and Jackson, 1993; Davidson-Arnott and Law, 1996;

Jackson and Cooper, 1999; Davidson-Arnott, 2002; Hesp et al., 2005; Miot da Silva and Hesp, 2010; Corbau et al., 2015).

Group 3, although characterized by the greater instability of the foredune, highlights the relationship with the behavior of T. moquinii in the first line. In this case, the number of individuals and the density at the front of the foredune correlate with both the number of nebkhas and the surface of the foredune in the plot. This means that the role of T. moquinii in the first line has repercussions on the morphometry of the foredune in the rest of these plots.

4.4.2. Understanding intraspecific competences through T. moquinii individual's evolution and distribution

In this paper the morphology of T. moquinii plants has been studied to understand their spatial-temporal distribution, in order to understand the patterns of distribution of this species in the arid foredune of Maspalomas.

Table 7: Pearson test of the variables in three groups obtained through cluster analysis. Correlations between T. moquinii variables.

Groups	Variables	Density	Dist_Traganum	Nº Traganum_line 1	Diameter_ line 1	Dist_Traganum_line 1	Density_line 1
Group 1. 2, 6, 7 N= 15	Density	1	-.944(**)[a]	0.267	0.064	-,574(*)	0.407
	Dist_Traganum		1	-0.305	-0.068	,683(**)	-0.511
	Nº Traganum_line1			1	-.725(**)	-.730(**)	.817(**)[a]
	Diameter_line 1				1	0.177	-0.334
	Dist_Traganum_line1					1	-.956(**)[a]
	Density_line1						1
Group 2. 3, 4, 5 N= 15	Density	1	-.966(**)[a]	.531(*)	-.568(*)	-.595(*)	.635(*)
	Dist_Traganum		1	-0.375	0.493	.651(**)	-.640(*)
	Nº Traganum_line1			1	-.648(**)	-0.431	0.477 [a]
	Diameter_line 1				1	0.121	-0.129
	Dist_Traganum_line1					1	-.936(**)[a]
	Density_line1						1
Group 3. 1, 8, 9, 10 N= 15	Density	1	-0.036 [a]	.886(**)	-0.394	-0.033	.746(**)
	Dist_Traganum		1	0.170	-.602(**)	.911(**)	0.022
	Nº Traganum_line1			1	-.670(**)	0.143	.728(**)[a]
	Diameter_line 1				1	-.521(*)	-0.358
	Dist_Traganum_line1					1	-0.191 [a]
	Density_line1						1

**. Correlation is significant at the 0.01 level (bilateral). *. The correlation is significant at the 0.05 level (bilateral). [a] The correlation is discarded because the density calculation is related to the average distance between the individuals of *T. moquinii* on the plot or on line 1 and the number of *T. moquinii* on the plot or in line 1.

In group 1, the density has a negative correlation with the distance between the individuals of T. moquinii in the first line. The distance between individuals of T. moquinii presents a positive correlation with the distance between individuals in the first line of the plot. The number of T. moquinii individuals in the first line has a strong negative correlation with the distance between individuals and the diameter of the T. moquinii specimens in the first line.

In group 2, density is the variable with the highest correlation, as it is positively correlated with the density and number of individuals of T. moquinii in the first line, and negatively with the distance between individuals of T. moquinii in the first line, and with the diameter of the specimens of this species in the first line. The distance between individuals of T. moquinii is positively related to the distance between individuals of this species in the first line, and negatively with the density in the first line. The number of plants in the first line has a negative correlation with the diameter of the individuals in the first line.

In group 3 the density correlates positively with the number of T. moquinii individuals and with the density in the first line. The distance between individuals of T. moquinii correlates positively with the distance between individuals of this species in the first line and negatively with the diameter of the specimens of T. moquinii in the first line. The number of individuals in the first line has a negative correlation with the diameter of the individuals. Finally, the diameter of the individuals of T. moquinii in the first line correlates negatively with the distance between them in the first line.

The largest number of significant correlations observed in group 2 (plots 3, 4 and 5), indicate that this portion of the foredune is in an equilibrium state, because it corresponds to plots that have displayed greater stability throughout the study period. In group 1 (plots 2, 6 and 7), as well as in group 3 (plots 1, 8, 9 and 10), a significant number of correlations between the variables are detected, although they exhibit a regressive dynamic in that the number of plants has been declining over time.

The results indicate the importance of the variables measured in the first line of the foredune, and, in particular, the distance between the individuals of T. moquinii. This distance is a key factor to be taken into account for the proper development of the species. The density in the whole plot, as well as the distance between individuals of T. moquinii in the plot, and the number of them in the first line are closely related to the rest of the morphologic variables of this species. These results could be applied to the ecological restoration of the foredune in those areas where it has been degraded, as has happened in the south of El Inglés beach, where there has been a fragmentation of the foredune (Hernández-Cordero et al., 2012; Hernández-Calvento et al., 2014). They could also be applied to arid zone foredunes in other coastal regions of the world.

The variable distance between T. moquinii in the plots is positively related to the distance that the individuals keep in the first line in both groups. This means that the greater the distance between individuals in the first line, the greater is the distance of T. moquinii in the rest of the plot. This shows that the distribution pattern of T. moquinii in the foredune depends directly on the distance between the specimens of this species in the first line at the backshore. This result is key to the management of this protected natural space, since it is precisely the individuals of the first line which experience greater anthropogenic pressure by users, facilities and services on the beach.

The number of T. moquinii in the first line has a close relationship with the diameter of the specimens in the first line. Thus, in the 3 groups the greater the number of individuals in the first line, the smaller the diameter of these individual plants. This result may be related to the competition that exists between individuals in the front of the foredune or by local impacts, at least in the north of El Inglés beach, where artificial lighting induces inhibition in flower production and, thus, reduced possibilities in reproduction of the Traganum moquinii species; on the other hand, individuals exposed to light have greater growth (Viera-Pérez et al., 2019). It should be considered that T. moquinii under suitable conditions is a shrub that can reach up to 5 meters in height and occupy a large area (Hernández-Cordero et al., 2012), so it needs significant room for its maximum development. Therefore, when the number of individuals is significant they cannot reach their maximum size, as also occurs in shrubs of other species in semi-arid zones (Kambatuku et al., 2011). These variables should be taken into account in order to understand the distribution of vegetation in arid coastal foredunes because in most of the studies conducted so far (Van der Valk, 1974; Maun and Lampierre, 1986; Hernández - Cordero, 2012, Zhang et al., 2015), the distribution of vegetation would be conditioned especially by the sediment transport and it´s accumulation. Future work could examine such relationships further by adding the third dimension through LiDAR and photogrammetric altimetry. In this way, the relationships between the T. moquinii species and foredune morphometry could be analysed using variables such as plant height with respect to variables such as volume (sediment supply) and foredune height.

5. Conclusions

The conclusions that derive from this investigation are the following:

1. The morphology of the shrub species *Traganum moquinii* has been analysed over a multi-decadal historical time frame, to examine the morphometric function exerted by this species on the foredune of an arid coastal dunefield. The importance of this analysis is that this plant species is a structuring element in the dynamics of the arid coastal dune systems in the Canary Islands as well as in a significant part of northwest Africa.
2. The evolution of the nebkha dominated foredune of Maspalomas has not been spatially homogeneous due to eco-anthropogenic processes. This is evidenced by the detection of 3 types of foredune, a stable dynamic zone (group 2), a zone with irregular dynamics but tending towards stability (group 1) and a regressive (degenerating) zone (group 3).
3. The function of the specimens of *Traganum moquinii* is different in the foredune groups identified, due to the environmental limitations or the alterations induced by the tourist activity that these individuals have experienced, which has had subsequent repercussions on the evolution of the foredune.
4. *Traganum moquinii* was related to the morphometry of the foredune, so that certain morphological variables of this species (distance between individuals, number of individuals in the plot, density of individuals in the first line of the foredune and diameter of individuals in the first line of the foredune), are the variables that provide greater stability to this landform.
5. The morphological variables of *Traganum moquinii* studied in the first (foremost) line of the foredune (number of *Traganum moquinii* individuals, diameter of individuals, distance between individuals and density) seem to be the most significant in the spatial distribution pattern of *Traganum moquinii* and sediment accumulation especially for the evolution and development of the foredune further landwards.
6. The relationships between the morphometric variables of the foredune and the morphological variables of *Traganum moquinii* could be useful information for the environmental restoration of the foredune of Maspalomas in those areas where it has been degraded, as well as for an adequate management of the dune system.

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Discussion and general conclusions

The interactions that take place between plants and geomorphological landforms generated by aeolian sedimentary transport (biogeomorphological processes) in arid regions of the planet with little human interference can give rise to a type of sand dune known as a nebkha. These sedimentary systems are present in several environments in the Canary Islands (Spain). Depending on the sediment input or supply, they can result in two different types according to the classification made by Hesp and Walker (2013) and in agreement with Hernández-Cordero et al. (2019): i) dune fields (represented by Maspalomas and most of Corralejo); ii) aeolian sand sheets-nebkha fields (represented, among others, by the dune fields of La Graciosa island, Cotillo-Tostón in Fuerteventura, Lobos islet and Famara (Lanzarote). At all these sites, the nebkhas are structural aeolian landforms of their foredunes (Hesp, 2002). The aeolian sedimentary systems of the Canary Islands can therefore be considered representative examples of arid coastal types. Though in this case they are found on volcanic islands, this does not appear, in principle and insofar as it has been possible to determine through an analysis undertaken in the Great Australian Bight (GAB), to be a determining factor in the biogeomorphological processes that take place in this type of system compared to those located in other coastal areas of the planet. It can therefore be argued that the results obtained from the study of such processes in the arid aeolian sedimentary systems of the Canary Archipelago should also be valid for other such systems in the rest of the planet. It should also be added that this type of system has been barely studied in comparison with the vast bibliography available for dune systems in temperate regions. As a result, the knowledge acquired in the study of the dune systems of the Canary Islands can be considered, to a certain degree, pioneering.

One of the peculiarities of these systems is that, under stable conditions (that is to say, without the impact of any significant environmental changes), they are naturally highly active, dynamically speaking, unlike the dune systems of temperate regions. From the technical-scientific perspective, this is the main reason why their monitoring through geographic information sources and technologies enables valid scientific knowledge to be obtained about how these systems function, as has been demonstrated by, among others, Hernández Calvento (2006) and Hernández Cordero (2012).

It should also be stressed that these systems have experienced important human impacts, as indeed is the case with most of the world's arid aeolian coastal sedimentary systems. These impacts have taken place in different stages and at different levels, from the remobilization of stabilized systems (Santana-Cordero et al., 2016) to the disappearance of transgressive dune fields (Santana-Cordero et al., 2014), and from wind flow modification due to urban development (Hernández Calvento, 2014; Smith et al., 2017) to the general transformation of processes in a dune field (Hernandez-Cordero et al., 2017, among others).

From the perspectives outlined above, the conclusions that are drawn in the present Doctoral Thesis with respect to biogeomorphological processes modified by anthropic activity in arid coastal aeolian sedimentary systems may be considered valid for other such systems, which are considered in this work from continental/global scale to local and regional scales.

In the first approach, at continental/global scale, it is found that in other parts of the globe, as for example in the GAB, biogeomorphological processes without any significant anthropic-related modifications tend to be climate related and the structural aeolian landforms of the foredune, including nebkhas, are formed under similar climatic conditions to those of the Canary Islands.

In the second approach, at regional scale, differences are found in the natural processes that take place among systems that are dependent on the extent of urban development in their corresponding environments.

In the third approach, at local scale, a more detailed analysis is undertaken of these interactions in different areas of these arid coastal aeolian sedimentary systems, including inland areas where the aeolian flow has been altered through human activity (especially urban development) and foredune areas where modification has been observed of aeolian transport and even the nebkhas themselves.

From the perspectives outlined above, the present Doctoral Thesis is comprised of six important contributions. Firstly, in García-Romero et al. (2019 c), work is undertaken, at global/continental scale and in a study area of low anthropic pressure (the GAB, Australia), on identifying foredune mode in accordance with a climatic gradient. Secondly, an analysis is made of environmental changes in arid aeolian sedimentary systems in the Canary Islands, at different spatial scales, induced by tourism-related urban development (García-Romero et al., 2016; García-Romero et al., 2019 a, b; García-Romero et al. (under peer review)). Thirdly, an analysis is made of the specific repercussions for the biogeomorphological processes at different temporal scales (García-Romero et al., 2019 a, b; García-Romero et al. (under peer review)). A further contribution of this thesis is the development of a procedure to automatically calculate, using data obtained with airborne sensors (orthophotos) and historic aerial photographs, the vegetation density variable from the distance between individual plants (García-Romero et al., 2018). This procedure has been tested twice in García-Romero et al. (2019 a, b). From the academic-scientific perspective, the first paper (García-Romero et al., 2019 c) tackles the first specific objective of the present Doctoral Thesis and, in addition, tests and verifies the first hypothesis considered in this research work. In this first paper, it is concluded that there are statistically significant correlations between the appearance of different foredune and transgressive dune field morphologies along the GAB coast (2668 km) and the climate, at least, in an area of low anthropic pressure. More specifically, the distribution of the morphologies studied and of the transgressive systems is related with dune mobility indices, most notably the one proposed by Lancaster (1988), and certain features of the vegetation. A marked climatic gradient, particularly with respect to rainfall, is shown to be an important factor for foredune development and the occurrence of active transgressive dune fields. Nebkha landforms predominate the foredune morphology when the annual rainfall rates are in the 200-300 mm range, serving to contextualise the type of foredune detected in the Canary Islands. At 32° latitude, with annual rainfall rates of 300-400 mm, no clear pattern is observed in foredune mode and all types are present in varying numbers. This is described as a transitional range. Finally, foredunes with continuous and discontinuous morphologies are strongly represented in regions with annual rainfall rates higher than 400 mm.

The second hypothesis of the present Doctoral Thesis, and the one that is most fully developed, is considered in a total of four papers (García-Romero et al., 2016; 2019 a, b; and paper 6 (under peer review)), and tested and verified through four of the specific objectives (2, 4, 5 and 6). It is clear that not all the aeolian coastal sedimentary systems in the Canary Islands have experienced the same degree of environmental changes. This is made clear in García-Romero et al. (2016), where, on the basis of an analysis of four of these systems in the islands, it is shown that, at regional scale, the systems that have experienced the greatest environmental changes are those where there has been more intensive tourism-related urban development (Maspalomas, Corralejo and El Jable Sur). In contrast, the system at Lambra, unaffected by any tourism-related urban development, shows less significant changes, as is also the case with a similar aeolian sedimentary system at Cotillo-Tostón (Alonso et al., 2004). However, the occurrence of some environmental changes at Lambra opens the door for the possibility that these are related to external environmental changes including, for example, natural changes causing the depletion of marine sedimentary sources and/or anthropic-induced changes as the result of climate change. The environmental changes are, in general, indicators of deficiencies in the territorial planning that took place at the time of the tourism-related urban development around these systems. That is, sufficiently adequate measures were not and have not been taken to ensure a situation favourable for the preservation of the dune systems. At the same time, insufficient, if any, consideration was given to the distances that should be maintained between constructed elements and the arid aeolian sedimentary systems to ensure that their natural sedimentary dynamics were not altered (this in relation to the objectives considered in papers 4 and 5).

In paper 4 (García-Romero et al., 2019 a), a study was carried out of the biogeomorphological processes in an aeolian shadow area generated as the result of tourism-related urban development. This long-term study was performed with a high spatial resolution. The work presents the environmental changes that take place with respect to vegetation and geomorphology when urban constructions modify the sedimentary dynamics. At the same time as changes are taking place in the sedimentary dynamics, there occurs an increase in vegetation cover and density and in the number of plant communities due to a sedimentary deficit. Plant colonization is very low at distances of around 400 m from the urban-tourism constructions, coinciding with the presence of three erosive aeolian landforms, namely a trough blowout and two deflation areas currently characterized by surfaces with exposed roots. The peculiarity of the trough blowout is that it is located in the interior part of the coastal dune system and not in the foredune, as normally occurs in temperate regions.

The fifth paper (García-Romero et al., 2019 b) was written to clarify certain doubts as to what exactly was occurring to wind flows in the aeolian shadow area detected in Maspalomas. The analysis undertaken in the paper was based on a short-term experiment at high spatial scale. The results show that: (i) regional wind flow direction has an impact on the degree of wind speed change throughout the study area; (ii) in general, the tourism infrastructure has an impact on wind speeds and directions in the study area, with correlations determined in a principal component analysis (PCA) that varied between 0.7 and 0.9; (iii) vegetation and height both have a significant impact on some of the transects through modification of wind flows, with a consequent wind speed reduction as plant density increases. In the aeolian shadow area, the presence of erosive aeolian landforms situated at a similar distance from the urban-tourism infrastructure could indicate an acceleration or reconnection of the wind at this distance. The tests that were undertaken show that at a height of 0.4 m the wind accelerates as it advances downwind from the resort.

A further line of research in the present Doctoral Thesis considered the foredune of the Maspalomas dune system, in particular the role played by *Traganum moquinii* as a structural element of the morphology of this sedimentary system, and entailed a multi-decadal and high spatial resolution study. This topic is considered in paper 6 (García-Romero et al. (under peer review), which forms part of stage 4 of the large-scale study undertaken of an arid aeolian sedimentary system altered *a priori*, in this case, by beach users and services. Improvements to the paper with respect to the statistical analysis undertaken are currently underway. Though as yet under peer review, the main findings of the study are nevertheless presented in this thesis. The results show, in general, a non-homogenous spatial evolution of *T. moquinii* due to eco-anthropogenic processes, with 3 foredune types detected with their respective spatial patterns, one stable dynamic area, one area with irregular dynamics but tending to stability and one regressive (degenerative) area. *Traganum moquinii* has been related to the morphometry of the foredune, with certain morphological variables of this plant species (distance between individual plants, number of individuals in the plot, and density and diameter of individuals on the first line of the foredune) found to provide greater stability to this geomorphological unit (foredune). Certain morphological variables of the *Traganum moquinii* studied on the first line of the foredune (number of plants, diameter of individual plants, distance between individuals, and plant density) also seem to be the most significant with respect to the spatial distribution pattern of *Traganum moquinii* and sediment accumulation, especially for the evolution and development of the foredune.

The third hypothesis of the present Doctoral Thesis is tested and verified through the methodologies, results and conclusions which served to meet the specific objectives 1, 2, 4, 5 and 6, which were also used with respect to the first two hypotheses. As for specific objective 3, the third paper (García-Romero et al., 2018) is perhaps the first attempt to propose objective variables that are adapted to different working scales. The aim was to find a simple procedure to automatically classify and calculate the vegetation density variable in arid sandy systems using digital orthophotos. The procedure employed gave rise to the digital vegetation density model (DVDM), obtained with a spatial resolution of 1 m. The method allows the use of historical information sources, including colour or black and white aerial photographs, to facilitate diachronic studies and analyse biogeomorphological processes, relating them with environmental or anthropic variables with a view to studying possible alterations in sedimentary dynamics. The proposed method serves as an alternative to others used to date, including those which require sources with a considerable economic cost and which are unable to consider longer historical records, or traditional methods, such as photointerpretation, which require a higher workload and greater subjectivity. Finally, it should also be noted that the results of this procedure were also used in papers 4 and 5. They were used in paper 4 to calculate the spatial variation of the vegetation density in study zone 2, and in paper 5 to relate the vegetation density with wind flows, showing a negative tendency since, as explained in the bibliography, at higher vegetation densities an increase in terrain roughness is generated along with a reduction in wind speed and, consequently, in sediment transport (Hesp, 1981; Moreno-Casasola, 1986).

In view of the above, it can be concluded that the specific objectives proposed have been met. It is therefore also concluded that the general objective of the present Doctoral Thesis has also been met, namely **“to define multi-scalar, natural and human activity-induced processes related to the geomorphology and vegetation of coastal aeolian sedimentary systems in the Canary Islands as a model of such systems in arid regions”**. It can also be concluded that the initial hypotheses of this Doctoral Thesis have been tested and verified.

Perspectives

A presentation is made below of various lines of research that arise as a result of this Doctoral Thesis. They are ordered in accordance with the papers in which they are presented.

In the GAB, various specific objectives can be proposed in view of the results obtained in García-Romero et al. (2019 c). To meet these objectives, the general idea is to work with greater spatial resolution and introduce a combined long-term and short-term temporal scale to determine whether environmental changes are taking place in the aeolian sedimentary systems that have been identified there. If changes are detected and, consequently, alterations to the biogeomorphological processes, the first step will be to determine the potential factors that are inducing these alterations, including the possibility of anthropic factors. In this respect, Peña-Alonso et al. (2019) have detected impacts with a moderate-low pressure. Thus, the research lines will continue to be centred on the study of anthropic impacts from a detailed scale, which will enable identification of activities and/or land uses which alter the systems, to a 'climate change' scale, considering this as a possible triggering factor of environmental changes, if they are detected.

With respect to the arid aeolian sedimentary systems in the Canary Islands, differences have been identified in the current research between systems which have seen significant tourism-related urban development and those which have experienced less anthropic activity. In this respect, and as far as the second (less studied) type is concerned, although a lesser degree of environmental change was observed, the fact remains that some change was detected. The aim of future works will be to find out why these small changes are occurring or, in other words, to answer the following question: What natural external factors could be causing these changes? An analysis of other similar transgressive sand sheets to those of Lambra, as well as of the submerged part, could provide useful information to understand their behaviour.

With respect to the third paper, various lines of work need further refinement. Firstly, an attempt needs to be made to try to finetune the details of the optimal neighboring sampling achieved to date (9 m), as there are some gaps with vicinity sampling that were not used due to the need to follow the criterion of multiples of 3 m. This can then be followed by the possibility of correlating the wind flow rates and sedimentary transport with the DVDM through multiple testing, using wind sensors and sediment traps at a height of at least 0.4 m. If it is possible fit the DVDM/wind speed/wind direction/sediment transport correlations, a useful model will have been obtained for sedimentary dynamics at regional scale through the direct use of GIS. In addition, the possibility of calculating the DVDM with historical information sources would allow a diachronic calculation and study of these models.

Increasing the number of observations in other aeolian sedimentary systems of the Canary Islands through studies at high spatial resolution and on a long-term scale, as was the case in Maspalomas, could provide new information about what is happening with the biogeomorphological processes when one or various constructions modify or block the aeolian sedimentary dynamics of a transgressive dune system. In this respect, Corralejo and Jable Sur could be future study areas given their similar behaviour to that of Maspalomas, as reported in García-Romero et al. (2016). The interference in sediment transport by the constructions could have resulted in new aeolian shadow areas where environmental changes may have generated new alterations to the biogeomorphological processes. These can be studied not only to identify their number but also to analyse any differences or similarities with Maspalomas.

With respect to the above, the first priority is to determine whether there are in fact aeolian shadow areas. The second priority will be to determine if there are deflation surfaces or erosive aeolian landforms at a certain distance from the constructions of Corralejo and Jable Sur, as were detected in Maspalomas (at around 400 m from the constructions) where it would appear that they are the result of a shifting of the winds after crossing the constructions which interfere in the aeolian sedimentary dynamics. If this is verified and it is possible to calculate new distances from the deflation areas and/or aeolian erosive landforms to the constructions and to detect a correlation with the height of the constructions, then this would be of particular interest from the perspective of territorial planning and ordinances which aim to include urban developments close to transgressive aeolian sedimentary systems, as is the case in the Canary Islands, with a view to ensuring that the impacts caused by the constructions are minimal, if any.

It is also of vital importance to continue monitoring the evolution of erosive aeolian landforms, like trough blowouts and deflation surfaces, situated in the aeolian shadow area some 400 m from the constructions. Checks need to be made as to whether these are expanding (which would allow confirmation of the prediction made by García-Romero et al. (2019 a) that a large deflation area could develop in the future) or whether, in contrast, herbaceous plant communities, like *Cyperus capitatus-Ononis serrata,* or shrub communities will play a stabilizing role in this area. For this reason, it is of scientific interest to identify and analyse the different distribution patterns of the various plant species in the aeolian shadow area and their capacity to impede the erosion that is taking place at the present time. With this in mind, experiments have already been carried out to capture wind data (wind speed and direction) in the interior part of the three erosive landforms to verify the effect of the wind *in situ* and the wind direction which is having the most significant impact on the erosion process.

With respect to paper 6 (under peer review), there is the possibility in the future of working in 3 dimensions. This third dimension would enable a potential study that could provide information about the correlation between the morphology of *T. moquinii* and the sediment inputs (in m^3) that can be retained and accumulated in the foredune. For this, foredune tests will have to be carried out under different environmental and even social conditions. This line of research is of particular interest to determine exactly how vulnerable the foredune and the aeolian sedimentary systems in the Canary Islands are when facing a scenario of climate change and a sea level rise.

At a technical level, there are several aspects that can be further improved, including the know-how required to develop numerical models and algorithms that are indispensable in practical terms given the new challenges that are being faced, most notable the study of the role of coastal aeolian sedimentary systems in a situation of climate change. Although there has been insufficient time to develop such methods in the present Doctoral Thesis, one of my short/long term objectives is to understand and apply computational fluid dynamic (CFD) models which will serve to support and better understand the empirical wind data that are being used from the different perspectives outlined in this thesis. Such models will be, in practice and together with GIS, a transversal tool.

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