Doctoral thesis

Doctoral Program in Oceanography and Global Change

A historical ecological assessment of arid aeolian sedimentary systems responses to long-term land uses in the Canary Islands

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Ruina de volcán esta montaña
por la sed descarnada y tan desnuda
que la desolación contempla muda
de esta isla sufrida y ermitaña.

La mar, piadosa, con su espuma baña
las uñas de sus pies, y la esquinuda
camella rumia allí la aulaga ruda,
con cuatro patas colosal araña.

Pellas de gofio-pan en esqueleto-
forma a estos hombres, lo demás conduto;
y en este suelo de escorial, escueto,

arraigado en las piedras, gris y enjuto,
como pasó el abuelo pasa el nieto:
sin hojas, dando sólo flor y fruto.

Miguel de Unamuno

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PRESENTATION

This document presents the results of almost 4 years of my research as a member of the Research Group in Physical Geography and Environment (GFyMA), attached to the Institute of Oceanography and Global Change (IOCAG) of the University of Las Palmas de Gran Canaria (ULPGC), and as a student of the doctoral program in Oceanography and Global Change (IOCAG, ULPGC). As a result, this doctoral thesis is presented, which is based on 5 articles published in international journals with JCR impact (5 Q1) so it is presented through the compendium of publications procedure. These articles are the result of the exploration of the environmental changes that land uses have induced throughout history in three coastal aeolian sedimentary systems in the Canary Islands. Therefore, they represent an opportunity to improve their management by learning about the response mechanisms they have in the face of the different historical disturbances which they have suffered, but they also show that their dynamics and current state are the result of the legacy that the historical land uses have induced on these ecosystems. In short, the evolution of land uses, from grazing to becoming centres of the tourist industry, has caused that these systems behave as socio-ecological systems for centuries. Not being able, therefore, to understand its current dynamics without paying attention to the details of the human situation throughout history. To carry out this research, within the aforementioned doctoral program, I have counted on the direction of María Emma Pérez-Chacón Espino and the co-director Leví García-Romero. Likewise, the results of these investigations represent a contribution to the research project Analysis of natural and human processes associated with the beach-dune systems of the Canary Islands (code CSO2016-79673-R), financed by the State Plan of R + D + i (Ministry of Economy and Competitiveness, MINECO, Government of Spain), whose head lab is Luis F. Hernández Calvento.

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Abstract

In recent decades, coastal areas have been under significant human pressure due to the increasing process of littoralization that is taking place. However, many of these areas, such as the arid aeolian sedimentary systems, behaved as socio-ecological systems even before the arrival of tourism, that is to say, the influence of human activities has determined its natural dynamics for centuries. In this context, the general aim of this thesis is to analyse the anthropogenic alteration of the coastal arid aeolian sedimentary systems of the Canary Islands, and to determine, their environmental consequences in the natural dynamics. It is also intended to analyse the natural responses of these ecosystems to human alterations and the social relevance of such changes. The main results of this doctoral thesis show that traditional land uses (exploitation of vegetation for use as fuel, grazing, cultivation, etc.) produced important changes on vegetation, aeolian landforms and, therefore, in the natural aeolian sedimentary dynamics. These changes are still visible and determine the landscape on which the tourism industry is based, which has become the main activity of these ecosystems. These changes have also severely affected the populations that depended on them for their subsistence. The alteration of the historical provision of ecosystem services produced by land uses caused the population to change and adapt management measures to guarantee the productivity of these services by the ecosystem.

However, other important results of this doctoral thesis are related to the response capacity of ecosystems to historical alterations. It has been observed that these systems do not return to the conditions prior to human disturbances; on the contrary, they adapt and reorganize based on different factors such as the volume of available sediment, topography or the capacity of the vegetation to colonize the areas transformed by historical and current land uses. Finally, the results obtained in this doctoral thesis can serve as a tool to improve the management of not only the analysed beach-dune systems but also similar systems in other parts of the world.

Resumen

En las últimas décadas, las áreas costeras han sufrido una importante presión antrópica por el creciente proceso de litoralización que se está produciendo. Sin embargo, muchas de estas áreas, como los sistemas sedimentarios eólicos áridos, ya se comportaban históricamente como sistemas socio-ecológicos, incluso antes de la llegada del turismo, es decir, la influencia de las actividades humanas ha determinado su dinámica natural durante siglos. En este contexto, el objetivo general de esta tesis es analizar la alteración antropogénica histórica de los sistemas sedimentarios eólicos áridos costeros de Canarias, y determinar sus consecuencias ambientales en la dinámica natural. También se pretende analizar las respuestas naturales de estos ecosistemas a los efectos inducidos por la actividad humana y la relevancia social de dichos cambios ambientales. Los principales resultados de la presente tesis doctoral muestran que los usos del suelo tradicionales (explotación de la vegetación para su uso como combustible, pastoreo, cultivo, etc.) produjeron cambios importantes en la vegetación, las geoformas y, por tanto, en los procesos biogeomorfológicos. Estos cambios ambientales son aún visibles y determinan el paisaje sobre el que se sustenta la industria turística, que actualmente se ha convertido en la actividad principal, localizada principalmente en torno a estos ecosistemas. Al mismo tiempo, estas perturbaciones ambientales también afectaron gravemente a las poblaciones que dependían directamente de estos ecosistemas para subsistir. En este sentido, la alteración de la provisión histórica de los servicios ecosistemicos provocó que la población adaptase en ocasiones las medidas de gestión, para garantizar la productividad de estos servicios por parte del ecosistema.

No obstante, otros resultados importantes de la presente tesis doctoral se relacionan con la capacidad de respuesta de los ecosistemas a las alteraciones históricas. Se ha observado que estos sistemas no regresan a las condiciones previas a las alteraciones humanas; sino que se adaptan y reorganizan en función de diferentes factores, como volumen de sedimento

disponible, topografía o capacidad de la vegetación para colonizar las áreas transformadas por los usos del suelo históricos o actuales.

Finalmente, los resultados obtenidos en la presente tesis doctoral pueden servir como herramienta en la mejora de la gestión de los sistemas playa-duna analizados; así como, en sistemas similares en otras partes del mundo.

1. INTRODUCTION

1.1. Research context

This thesis is based on the conception that coastal dunefields are places where bio-physical and social processes converge. The research project is inserted in two research lines of the Group Geografía Física y Medio Ambiente (IOCAG-ULPGC): i) coasts of volcanic islands: natural processes and human interactions related to the study of coastal systems; ii) the integrated study of landscape and territorial planning of arid aeolian sedimentary systems. These lines have been developed from five R+D Spanish competitive projects, such as "Modeling of natural processes and analysis of the environmental consequences induced by tourism in the Special Nature Reserve of the Dunes of Maspalomas (Gran Canaria, Canary Islands, Spain)", "Environmental consequences induced by tourism development in island areas: alterations of natural processes in coastal dunes systems of the Canaries and Cape Verde archipelagos", among others. During the development of all these researches it is common the implementation of geographic information technologies (GIT); the use of historical sources; field work and statistical data processing.

In this context, five articles have been published, although they are not shown in order of publication date but in sequential order with respect to the topics and questions of this Doctoral Thesis (Figure 3).

The first one, entitled "An historical ecological assessment of land-use evolution and observed landscape change in an arid aeolian sedimentary system", analyzes the evolution of the Jandía aeolian sedimentary system. This aeolian sedimentary system has suffered serious erosion processes that are explained from the analysis of historical sources. The elimination of the vegetation cover for traditional uses caused an overfeeding of the Sotavento beaches which, when these uses were abandoned, now suffers from a sedimentary deficit.

The second article, titled "Biogeomorphological responses of nebkhas to historical long-term land uses in an arid coastal aeolian sedimentary system", is a result from the idea of comparing the historical processes that occurred on islands with fewer resources for traditional uses with islands that had greater availability. Hence, the study area is located in Tenerife, in this sense, El Médano is currently the largest aeolian sedimentary system and still shows signs of aeolian activity across aeolian landforms as nebkhas and shadowdunes. The analysis of the historical sources showed that the historical uses were less relevant compared to recent uses (aerodrome, cultivation, aggregate extraction, urbanization, among others). In addition, the field work allowed to identify that the nebkhas and the shadow dunes showed different distribution patterns in the plots affected by each historical use.

The third article entitled, "Deforestation by historical lime industry in an arid aeolian sedimentary system: an applied and methodological research", explores in an integrated way the impact on the vegetation that the lime kiln industry produced on the Jandía aeolian sedimentary system and the driving forces that characterized said exploitation. The main results showed that the collection of vegetation exceeded the recovery capacity of the system, and that the arrival of fossil fuels was decisive for the cessation of the use of vegetation. In addition, it is demonstrated, based on the physical characteristics of the kilns and oral interviews, that the deforestation process was species-selective. Finally, the methodology used represents an improvement to the quantification of the historical deforestation processes and its spatial distribution.

In the fourth article, called “Historical social relevance of ecosystem services related to long term land uses in a coastal arid aeolian sedimentary system in Lanzarote (Canary Islands, Spain)", the analysis of the evolution of land uses was combined with the social relevance that human-induced changes had on society and the economic services provided to them. In it, it was concluded that the social relevance of ecosystem services has varied throughout history. There are two stages: in the first stage the dependence of the ecosystem is related to the relevance of providing ecosystem services; in the second, the dependence on tourism as the main economic activity causes the regulation of natural hazards and cultural ecosystem services to gain relevance.

The fifth article, entitled "Can long-term beach erosion be solved with soft management measures? Case study of the protected Jandía beaches", analyzes from the history of the ecosystem and its current state the management possibilities that could be taken from now on to allow the ecosystem to evolve and readapt to the new existing conditions or, on the contrary, to carry out continuous contributions of sand to guarantee the continuity of the beach and the salt marsh.

After presenting the articles that form the body of this doctoral thesis, in ordered according to the questions raised before and throughout the investigation, it is necessary to highlight that in all the published papers there is a common methodological framework related to Historical ecology, which was also combined with methods and techniques that allow us to understand the current behavior of the study areas.

1.2. The Historical Ecology framework

Historical ecology is the methodological framework for research on the evolution of the interaction between societies and environments (Balée, 2006). This discipline has different objectives: preserving cultural heritage in ecosystems and landscapes; understanding historical trajectories of patterns and processes in ecosystems and landscapes; rebuild ecosystems in their state prior to human intervention; informing about historical ecosystem and landscape management; to use scientific and local knowledge in order to improve ecosystem management (Bürgi & Gimmi, 2007; Crumley, 2007; Rick and Lockwood, 2013).

Historical ecology studies use a large number of sources (Bürgi & Gimmi, 2007), including local archives (Raska et al., 2015), ecclesiastical archives, narrations of travelers or scientists from different periods, historical maps (Cousins, 2001; Petit & Lambin, 2002; Haase et al., 2007), historical aerial photographs (Miller, 1999), postcards, common photographs (Skovlin et al., 2001; Nüsser, 2001), press reports, oral sources (Fogerty, 2005; Gimmi & Bürgi, 2007; Pinto & Partidário, 2012), herbarium records (Hedenäs et al., 2002), toponyms (Zhong et al., 2020), archeological data (Panzacchi et al, 2013), land surveys records (Bürgi et al, 2000; Whitney & DeCant, 2003), legacy studies (Vellend et al, 2013), and management plans (Axelsson et al., 2002; Bürgi & Gimmi, 2007). Other techniques for the reconstruction of the distribution of species have been used such as polem records or charcoal remains (Nelle et al., 2019).

This methodological framework has been applied in numerous regions of the world and in numerous different ecosystems such as forests (Axelsson et al., 2002), valleys (Grossinger et al., 2007), rivers (Guillén & Palanques, 1997; Zhong et al., 2020), basins (Miller, 1999), dunes (Santana-Cordero et al., 2016), rangelands (Rohde & Hoffman, 2012), among others. It is also useful for reconstructing land uses (Hoffman & Rohde, 2007; Santana-Cordero et al., 2014); important natural events such as volcanic eruptions (Romero, 1991), storms (Bethencourt-González & Dorta-antequera, 2010), landslides (Raska et al., 2015), among others. Finally, it has also been used to reconstruct the distribution of plant and animal species and migration trajectories (Panzacchi et al., 2013).

1.3. Evolution of land uses and current management in the Canary Islands

Coastal areas are suffering from an increasing pressure from human activity (IPCC, 2001; Mimura et al., 2007). In the Canary Islands, aeolian sedimentary systems were marginally exploited until the 1960s. In an agrarian society that depended entirely on the primary sector, dune systems would only play a leading role on those islands where forest resources were scarce (Fuerteventura, Lanzarote and La Graciosa). In the 1960s there was a significant change in the economic change of the islands with the arrival of tourism. The dune systems became the support for the tourist industry which, lacking planning, suffered an important urbanization process that took place until the end of the 1980s, when the protection of these systems became effective.

Therefore, land uses have evolved from traditional uses such as grazing, cultivation or fuel extraction to uses such as urbanization or aggregate extraction (Santana-Cordero et al., 2016; García-Romero et al., 2016, 2019; San Romualdo-Collado et al., 2021). In some cases, both uses prevail in dune systems (Cabrera-Vega, 2010). Land uses alter the natural dynamics of ecosystems. Among the bibliographic background on which this doctoral thesis is based, we know the case of the historical evolution of La Graciosa. On the island of La Graciosa, located in the north of Lanzarote (Canary Islands, Spain), the demand for fuel and grazing caused intense deforestation that generated a mobilization of sand sheets (Santana-Cordero et al., 2016). In the case of the Guanarteme dune system (Gran Canaria, Canary Islands, Spain), the urbanization buried the sheets of sand causing its disappearance (Santana-Cordero et al., 2014). However, this thesis addresses, for the first time, the response and the legacy that land uses have printed on the arid aeolian sedimentary systems of the Canary Islands. This implies an advance, to understand that the analyses of the tourist impacts (Hernández-Calvento, 2002) and the effects of climate change that are leading the current research program of these systems are based on ecosystems that had been behaving as socio-ecological systems for centuries and that they continue responding to historical human alterations. In this sense, we know that the dune systems of the Canary Islands have interacted with human beings since the arrival of human beings on the islands and that their use has increased over time. The historical evolution has not been taken into account to date for management.

The management of dune systems is a complex action that in many cases has been carried out without adequate scientific knowledge. In this sense, in many parts of the world management has been based on the elimination of vegetation cover to guarantee the mobility of sediments; however, in a recent review by Delgado-Fernández et al. (2019) showed that remobilization is actually a process of destruction in which the dunes lose their natural trend and the sedimentary dynamics are frozen by the action of the managers. This can reduce their ability to respond to other shocks (storms, land use, or climate change).

The management of the dune systems of the Canary Islands has been based on the protection of its landscape as if it were a photograph. Therefore, in all cases the dynamic processes that characterize them and that determine their subsistence have been relegated to the background. Management measures implemented vary widely between different systems. In the case of El Médano, restoration measures have been carried out on numerous occasions, offsetting the impacts produced by the construction of an industrial port in the immediate vicinity of the system. The construction of sand collectors with fragments of volcanic rock, remobilization of sediments, closure of trails, replanting of native species with irrigation, among others, have been carried out.

Recently, in the Maspalomas dune system, an environmental restoration project has been carried out with the aims of increasing the population of *Traganum moquinii*, eradicating or controlling invasive exotic flora and fauna species, avoiding sand losses and improving public use (https://masdunas.es/). To achieve the formation of new dunes and regulate sand transport, different models of sand collectors are installed in Playa del Inglés (San Romualdo-Collado et la., 2021b). On the other hand, 60,000 m^3 of sand were reintroduced into the system through dredging in the exit sector. The extracted sand is relocated to the dry beach area of the sediment entry zone where the wind restarts the aeolian transport process.

In El Jable (Lanzarote), problems related to the illegal extraction of sand for construction continue. In addition, here the interruption of transport for the construction of the Arrecife city has caused the need to feed the beaches of Arrecife to alleviate the serious erosion processes that they suffered (Cabrera-Vega, 2010).

These management measures try to alleviate years of mismanagement: uncontrolled construction, extraction of aggregates for construction, unauthorized road and trail layout, uncontrolled grazing, extraction of vegetation beyond regeneration capacity, among others. However, the "restoration" projects, not only ignore the current state of these ecosystems, which in many cases are the consequence of historical and current land uses (Santana-Cordero et al., 2016; García-Romero et al. 2016); but also, of natural conditions. In this sense, it is worth considering whether we can conserve these ecosystems as they were sixty years ago or if we must allow them to evolve and readapt based on current factors (availability of sediments, vegetation cover, climatic trends, among others). Relieving, of course, the human pressure resulting from tourism and a management that has adapted them to the needs of users (Peña-Alonso et al., 2019).

2. HYPOTHESIS AND AIMS

2.1. Research hypothesis

The hypothesis on which this doctoral thesis is based consists in determining whether the evolution in land uses have altered or not the natural dynamics of the arid aeolian sedimentary systems of the Canary Islands. A second hypothesis raises the possibility of that the current state of these ecosystems in the Canary Islands are the legacy of historical human disturbances. A third hypothesis is the possibility that the populations that lived or depended on these systems were affected by the environmental changes caused by land uses.

2.2. General and specific aims

The general aim of this thesis is to analyse the anthropogenic alteration of the coastal arid aeolian sedimentary systems of the Canary Islands, and in determining their environmental consequences in the natural dynamics. It is also intended to analyse the natural responses of these ecosystems to human alterations and the social relevance of such changes.

To addressing the general aim, the following specific aims are proposed:

a) Identify and characterize the land uses that have occurred throughout history in the selected study areas.

b) Analyse recent changes in vegetation, landforms and sediment transport.

c) Discuss the relationship between the changes that have occurred in the aeolian sedimentary systems and the derived impacts as possible responses mechanisms of the ecosystem to the different land uses identified.

d) Understand the social response to changes in the natural dynamics of the ecosystem due to land uses.

e) Apply the results obtained to the determination of guidelines for the integrated management of selected areas.

3. STUDY AREAS

The aeolian sedimentary systems of the Canary Islands are characterized by their arid climate, which will determine the scarce presence of vegetation. The low vegetation density, together with the predominance of nebkhas as landforms and the arid climate, favor the mobility of the sediments inland, being therefore transgressive dune systems (Hernández-Cordero et al., 2019). However, the systems depend on several factors and vary in area and origin of sediments between the oldest and youngest islands. The oldest islands are characterized by large systems of dunes with sediments in which the biogenic portion of the sediments predominates. In the younger islands, the sediments are generally the result of the erosion of volcanic materials, so the carbonate content is lower. As these are younger islands, the flat surfaces on which these systems could develop are reduce than on the older islands. This will determine the typology of the landforms and the human uses that have been developed in them, as detailed in the following sections.

3.1. Justification of the study areas

The present investigation has had three study areas and in three different islands: Jandía (Fuerteventura) (Fig. 1T. 1), El Médano (Tenerife) (Fig. 1T. 2) and El Jable (Lanzarote) (Fig 1T. 3), which were studied according to the order that have the different questions of the Doctoral Thesis (Figure 3). In a first phase of the research, two study areas were selected (Jandía and El Médano), in which the first island (Fuerteventura) where this Doctoral Thesis has developed most of the questions and objectives raised, its resources were more limited. However, the second study area is located on an island which has abundant forest resources, serving as a study area (satellite of Jandía, Fuerteventura) to find out if all the aeolian sedimentary systems of the Canary Islands were used in the same way by the anthropogenic activity, assuming that the exploitation of the aeolian system as a grazing and fuel obtaining area were not important. In the second stage of the research, El Jable (Lanzarote) was selected serving as satellite of Jandía (Fuerteventura), because both lack of significant forest masses, so the aeolian sedimentary systems played a very relevant role in the subsistence of the inhabitants of these islands. In this sense, we assume that resources at the island scale, due to their scarcity, conditioned the land uses and exploitation of any ecological system (Mimura 2007), regardless of whether they are arid aeolian sedimentary systems. Finally, the third phase, after delving into Jandía (Fuerteventura) from different themes and having observed the socio-environmental behavior of other different or similar study areas, this study area is used to determine lines of integrated management with the purpose of improving the current state of the system.

3.2. Jandía (Fuerteventura)

The Jandía Isthmus, with an area of 54 km^2, is located on the southern coast of the island of Fuerteventura, between the old massifs of Jandía and Betancuria. The main characteristics of this area are its low altitude and its slightly uneven relief, in contrast with the surrounding old massifs. The basement, formed between 20.7 and 14.2 Mya, is comprised of alkaline basaltic lava and pyroclastics from a Miocene eruption of the Jandía stratovolcano (Coello et al., 1992). The isthmus is covered by sand, predominantly biogenic, which is subject to almost continuous aeolian transport by the dominant NE winds. The main dune morphologies are nebkhas, a rampant dune on the southern limit of the windward side and two falling dunes in Sotavento (Alcántara-Carrió, 2003). The dominant source of transported particles is the erosion of aeolianite deposits and quaternary calcareous crusts located in the inner part of the isthmus, while more scarce sandy contributions come from the current beaches or the erosion of the materials that constitute the cliffs of Barlovento (Alcántara-Carrió, 2003). Aeolian transport takes place in SSE direction (Alcántara-Carrió and Alonso, 2002). The climate of the area has been defined as warm desert with marked aridity (Alonso et al., 2011). The scarce and highly irregular precipitations are concentrated in just a few days of the year and do not usually exceed 100 mm (Máyer-Suárez & Marzol-Jaén, 2016). High temperatures (with annual averages of around 20ºC), intense insolation and strong and frequent winds result in evaporation (Alcántara-Carrió, 2003). Vegetation is scarce, land cover is limited and the plants, in general, do not exceed the shrub layer. There are three vegetation types in the isthmus which reflect the different habitats: psammophytes in the mobile sand areas; halophytes, concentrated in the backshore zones of Sotavento where salinity and tidal flooding are intense; and thickets of Chenopodiaceae on calcareous crusts and rocky outcrops (Martín-Esquivel et al., 1995).

The Isthmus of Jandía was exploited only as pasture land from around 600 BCE (Cabrera, 2001) until approximately 1850, at which point references about obtaining fuel in this area appear for the first time in the historical documents. These traditional activities ceased with the arrival of tourism to the island, starting in 1960, which gave rise to the extraction of aggregates for construction and the creation of infrastructures and tourist facilities on the isthmus. At present, this area has two main urban centers (Costa Calma and La Pared), as well as several scattered hotels south of the Sotavento beaches.

3.3. El Médano (Tenerife)

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

The climate is characterized by aridity, with an annual average rainfall of 83 mm and annual average temperature of around 21º C (García-Casanova et al., 1996). The vegetation that corresponds to these conditions is shrubby with poor cover and is adapted to the conditions of salinity and sediment mobility, although there are important inland variations where plant communities associated to ravines, rocky outcrops and areas of strong flooding appear. The system is partially urbanized in the form of the town of El Médano and scattered buildings towards Montaña Pelada.

3.4. El Jable (Lanzarote)

The El Jable coastal aeolian sedimentary system currently occupies an area of 90 km^2 and a width of between 10 km in its northern sector and 4 km in its southern sector. Sand transport is from the sediment entrance area (Caleta de Famara, N-NE) towards the leeward sector (Arrecife, S), crossing the central part of Lanzarote over an approximate 21 km length and covering areas belonging to four island municipalities (Tinajo, Teguise, San Bartolomé and Arrecife).

The substrate strip is made up of volcanic rocks (Miocene and Quaternary basaltic lava and pyroclasts) and sedimentary rocks (sandstones and quaternary conglomerates related to colluvial, alluvial and aeolian processes). The current aeolian sediments are interspersed at the edges of El Jable with alluvial and colluvial levels formed by lithoclasts (fragments of rock and basaltic minerals) and bioclasts (fragments of marine fauna and flora). The recognizable morphologies in this area are, generally, nebkhas formed from shrub individuals of *Traganum moquinii* in the foredune of the system (Caleta de Famara), which are replaced inland by individuals of *Launaea arborescens*. In addition to these aeolian landforms there are three isolated dunes of barchan morphology. The climate is arid with an average annual rainfall of around 110 mm (Máyer-Suárez & Marzol-Jaén, 2016) and an average annual temperature of 20.7ºC (Cabrera-Vega, 2010). The dominant winds come from the first and fourth quadrants. Average wind speed is 20 km/h, but can reach as high as 60-70 km/h (Alonso et al., 2011). Currently, the coastal aeolian sedimentary system is delimited in the northern part by tourist urbanizations around Caleta Caballo and Caleta de Famara and in the southern part by Arrecife, the island's capital. Finally, part of the northern section of the arid aeolian sedimentary system has been designated as a protected area as part of the Natura 2000 program.

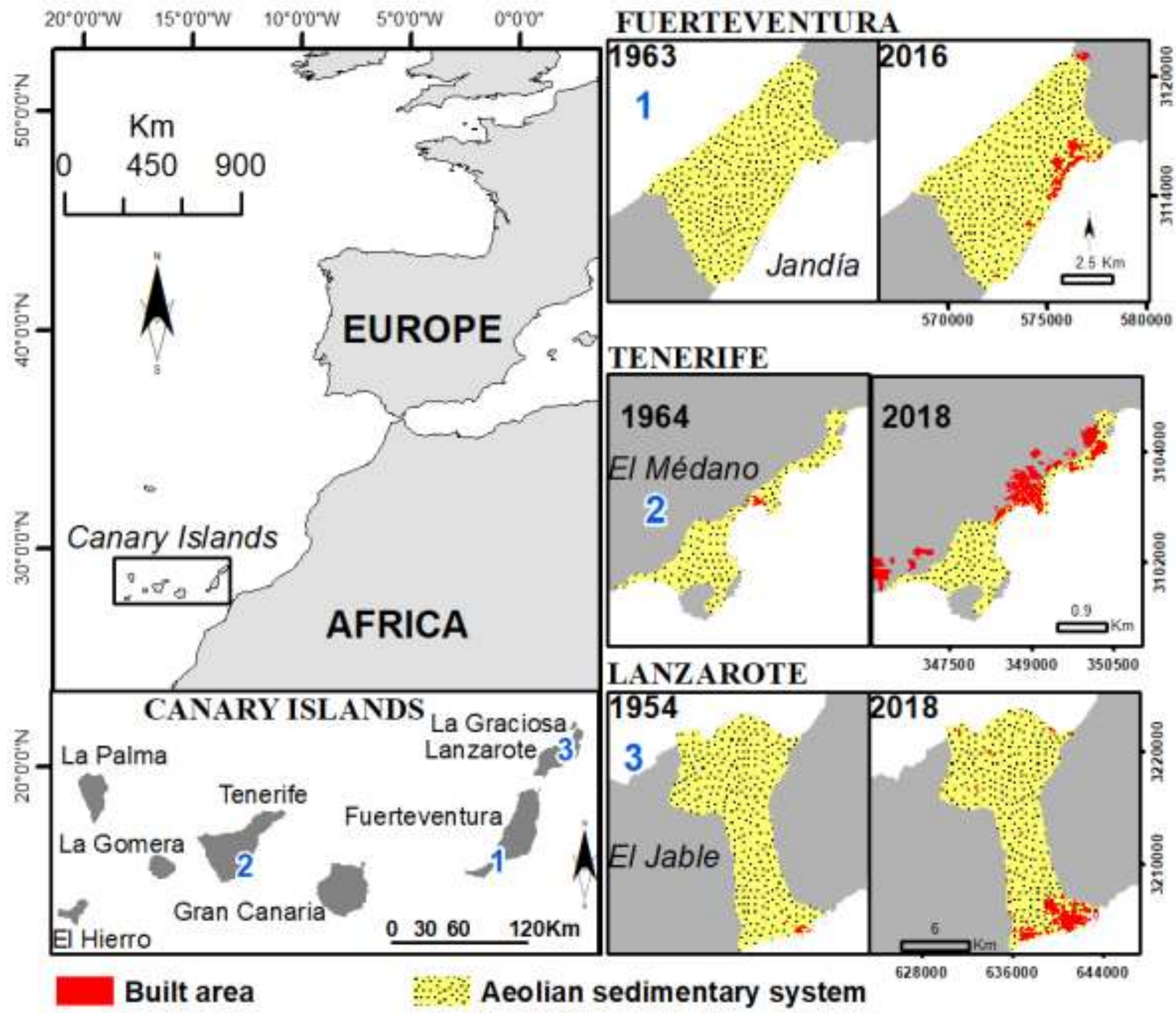

Figure 1T. Location of the study areas and surface built in 1964 and 2018.

4. GENERAL ASPECTS OF SOURCES AND METHODS

In order to respond to the proposed objectives, the methodology designed and developed in this work combined historical sources (Fig. 2T), statistical analyzes, field work, the analysis of management plans and the evaluation of the current state of the ecosystem. The phases and specific tasks have been defined in table 1.

Table 1. Phases and specific tasks during the doctoral thesis.

Phases	Specific tasks
Historical reconstruction	- Design of oral interviews - Search for historical references (according to the sources in figure 2) - Compilation of historical aerial photographs
Field work	- Oral interviews - Taking repeated photographs - Contrast of historical information - Measure the vegetation (Jandía) - Measurement of biogeomorphological variables in the nebkhas (El Médano) - Depth sampling points of the sand sheet (Jandía) - Inventories of protected species (Jandía)
Integration of historical and field information in the GIS	- Elaboration of historical cartography of changes in land cover - Evolution of the foredune of El Médano - Evaluation of changes in vegetation cover (Jandía) - Evolution of the Jandía coastline - Evaluation of the distribution and patterns of the nebkhas (El Médano) - Interpolation of the depth points of the sand sheet (Jandía)
Statistic analysis	- Correlations between the biogeomorphological variables of the nebkhas (El Médano)
Assessment of the current situation of the ecosystem	- Calculation of closing depth - Calculation of littoral drift - Available sediment mapping - Cartography of the distribution of protected species
Management proposal	- Review of the Management Plan of the Natural Park of Jandía - Review of management measures that can solve the problems found

The work to achieve the objectives of this thesis was divided into five phases (table 1). In the first one, the historical reconstruction was carried out by searching for historical references in different sources (Fig. 2T), field work was carried out in relation to it, and the information was integrated into a GIS.

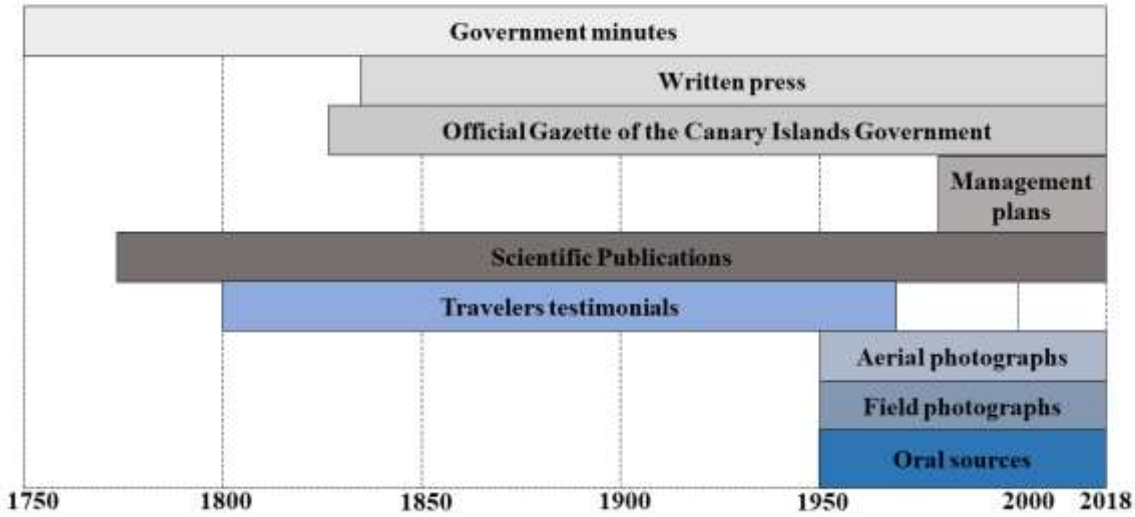

Figure 2T. Information sources used in historical reconstruction of the aeolian sedimentary systems.

In a second stage, field work was carried out to recognize the current state and land cover in the systems, data on vegetation was collected and the information was integrated into a GIS.

In the third stage, a statistical analysis was carried out that sought to know the correlation of the biogeomorphological variables of the El Médano nebkhas.

In the fourth stage, the current state of the aeolian sedimentary system of Jandía was evaluated by calculating erosion and accumulation rates, transport during different situations of littoral drift, the distribution of protected species, among others.

Finally, in the fifth stage, a review of the allowed and not allowed measures in the Jandía aeolian sedimentary system was carried out by the regional and European directive to determine possible measures that solve the problems that the ecosystem is currently facing.

5. RESEARCH PAPERS

The research papers that form this Doctoral Thesis are shown below, although the order in which they are shown and the relationships that exist between them through the sequence that this research has followed must first be explained (Figure 3T). This sequence is shown through the questions that were constructed to clear the hypotheses that were previously presented.

In the first place, all the articles have in common the methodological framework known as Historical ecology, and from here a first phase is proposed that intends to be developed mainly in Jandía, a study area that is located on an island with scarce agroforestry resources (Fuerteventura), and at a first level, the following questions are also raised: i) “What has been the evolution of land uses in the aeolian sedimentary systems of the Canary Islands?”. This question has the objective of "Identifying and characterizing the land uses that have occurred throughout history in the selected study areas", and that will also be common to all the articles, since it is necessary to know what land uses these systems occupied, where they were located and how they worked; ii) “What have been the environmental consequences?”, which serve to know and clear the hypothesis of whether they really altered the natural dynamics. In this sense, and to verify if in all arid aeolian sedimentary systems they were used in the same way by land uses, El Médano (Tenerife) is also studied as an example of an island with an abundance of agroforestry resources; iii) “How was the deforestation process of the aeolian sedimentary systems?”, although it belongs to the same research phase and continuing with the environmental consequences, it is intended to deepen this issue at a second level in Jandía (Fuerteventura) where it is quantified and spatialized. this environmental impact on the system. Therefore, the following objectives are set for questions ii) and iii), “Analyse recent changes in vegetation, aeolian landforms and sediment transport” and “Discuss the relationship between the changes that have occurred in the aeolian sedimentary systems and the derived impacts as possible responses mechanisms of the ecosystem to the different land uses identified".

The second phase is characterized by the fourth question of this research "Did environmental changes have social consequences?", since it was always an objective of this research, not only to understand the environmental consequences but also how society responds to these changes through the objective " Understand the social response to changes in the natural dynamics of the ecosystem due to land uses". For this, and due to the volume of information related to this subject that is obtained in El Jable (Lanzarote), this arid eolian sedimentary system is analyzed which, like Jandía, is located on an island with scarce forest resources, serving as a satellite to also understand what could have happened in Jandía.

The last phase questions the fifth and last question of this Doctoral Thesis "What applications in current management does the history of aeolian sedimentary systems have?" and its objective, after having delved into the arid aeolian sedimentary system of Jandía and having verified other systems as examples, was "Apply the results obtained to the determination of guidelines for the integrated management of selected areas".

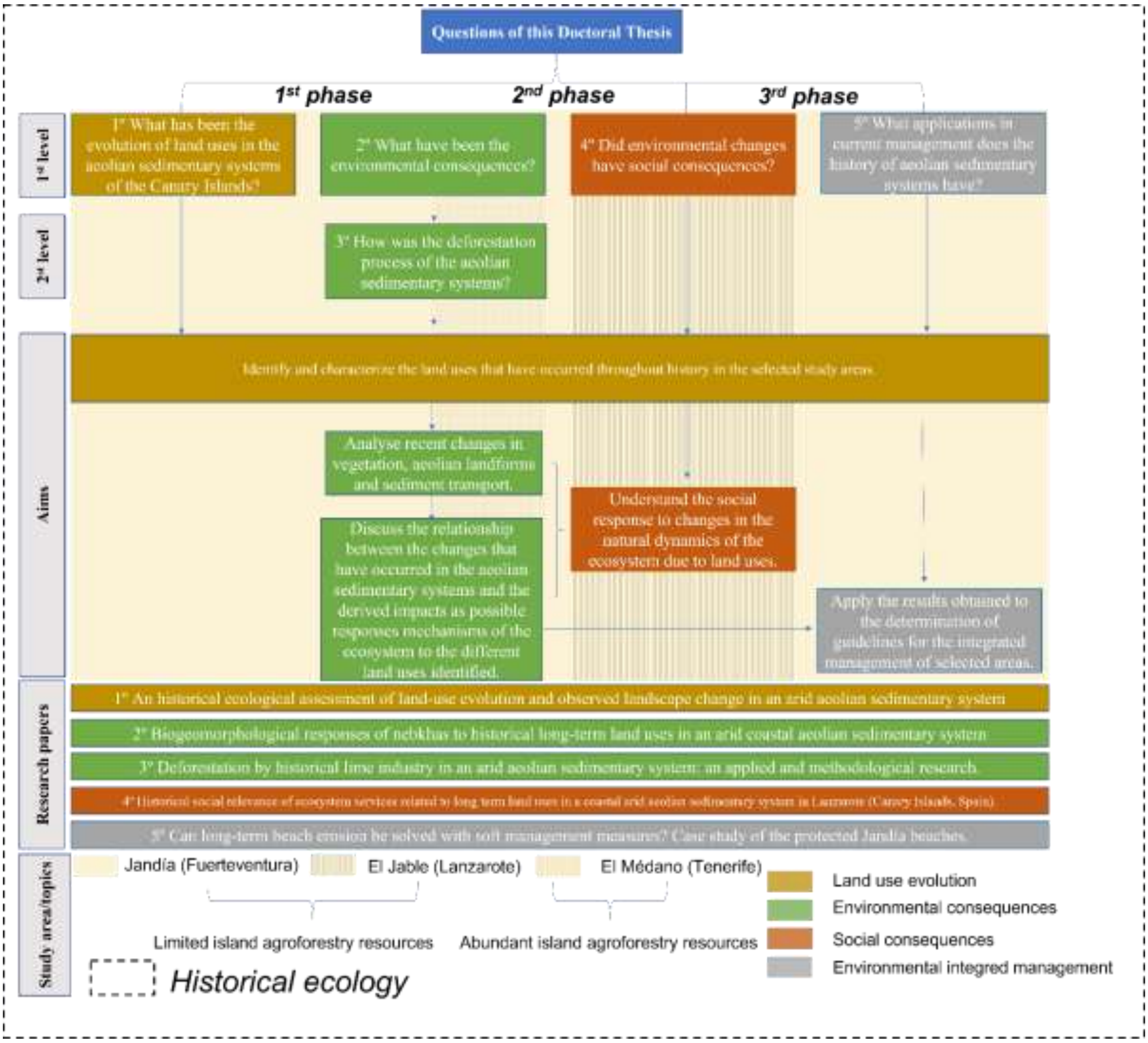

Figure 3T. Diagram representing the initial questions of the doctoral thesis, the aims in order to respond to these questions and the papers produced during the research process.

In this section, the published papers that addressed the aims of these thesis are presented. The information related to each paper is presented in table 2.

Table 2. Information of the papers and journal where were published (in order to the questions of this Doctoral Thesis).

	First paper*	Second paper**	Third paper***	Fourth paper****	Fifth paper *****
Aim [1]	X	X	X	X	
Aim [2]	X	X	X		
Aim [3]	X	X		X	
Aim [4]				X	
Aim [5]					X
JCR quartile	Q1	Q1	Q1	Q1	Q1
Impact factor (at the time of publication)	5.589	4.139	7.963	3.284	3.284
SCImago quartile	Q1	Q1	Q1	Q1	Q1
SJR	1.661	1.346	1.795	0.916	0.916
Date	May 2020	Nov 2020	Nov 2021	Sept 2021	Nov 2021
Reviewers	3	4	5	3	3

[1]Identify and characterize the land uses that have occurred throughout history in the selected study areas.

[2]Analyse recent changes in vegetation, landforms and sediment transport.

[3]Discuss the relationship between the changes that have occurred in the aeolian sedimentary systems and the derived impacts as possible responses mechanisms of the ecosystem to the different land uses identified.

[4] Understand the social response to changes in the natural dynamics of the ecosystem due to land uses.

[5]Apply the results obtained to the determination of guidelines for the integrated management of selected areas.

* An historical ecological assessment of land-use evolution and observed landscape change in an arid aeolian sedimentary system. Journal: Science of the Total Environment

** Biogeomorphological responses of nebkhas to historical long-term land uses in an arid coastal aeolian sedimentary system. Journal: Geomorphology

***Deforestation by historical lime industry in an arid aeolian sedimentary system: an applied and methodological research. Journal: Science of the Total Environment

**** Historical social relevance of ecosystem services related to long term land uses in a coastal arid aeolian sedimentary system in Lanzarote (Canary Islands, Spain). Journal: Ocean and Coastal Management

***** Can long-term beach erosion be solved with soft management measures? Case study of the protected Jandía beaches. Journal: Ocean and Coastal Management

5.1. An historical ecological assessment of land-use evolution and observed landscape change in an arid aeolian sedimentary system.

An historical ecological assessment of land-use evolution and observed landscape change in an arid aeolian sedimentary system.

Néstor Marrero-Rodríguez; Leví García-Romero; María José Sánchez-García; Luis Hernández-Calvento; Emma Pérez-Chacón Espino

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Abstract

Coastal areas worldwide are undergoing major changes and degradation due to a set of combined natural and anthropogenic stressors. In arid aeolian sedimentary systems these changes can be even more acute given their sensitivity to perturbances in landscape dynamics. While in many such areas recent (20 year) observations have been made regarding measurable differences in dune coverage and stability, few studies have assessed and quantified the long-term relationships of transitioning exploitation and land-use changes in order to fully evaluate their importance. Land management, therefore, does not always benefit from the more holistic picture that a combined deeper time historical ecology and geographical approach provides and can contribute to decision making. The Jandía isthmus, in Fuerteventura (Canary Islands, Spain) presented an ideal field laboratory in which to assess these phenomena in actual conditions and test a combined methodology using historical and current sources (historical documents, aerial photographs, orthophotos, LiDAR data, field work and oral sources). By doing so, different phases of land exploitation associated with changing land ownership were identified and the consequences of each on the dune system assessed. It is concluded that the transition from traditional land uses (livestock and fuel extraction) to more recent ones (aggregate extraction, construction of new roads and urban-

touristic resorts, and some recreational uses) has altered aeolian sedimentary transport, inducing stabilization of the landforms, as well as producing significant changes in the vegetation. The wider application of this type of study can benefit the many other areas worldwide that are facing similar pressures.

Keywords: land uses changes, land ownership, environmental changes, aeolian landforms, human impact, historical ecology.

1. Introduction

In the newly defined Anthropocene epoch, in which the natural processes of the planet are being altered by human activities, the emergence of a context of global change supposes an enormous challenge (Crutzen and Stoermer, 2000; Duarte et al., 2006). Coastal areas, for example, where human settlements account for 40%-70% of the world's population (Cohen et al., 1997; Nicholls and Branson, 1998; IPCC, 2001; Mimura et al., 2007), have had to support tremendous anthropogenic pressure (Steffen et al., 2004) which has resulted in their ecosystems suffering extensive and rapid degradation (Cerdá, 2002; Bajocco et al., 2012). Aeolian sedimentary systems have been particularly affected (Thomas & Wiggs, 2008), most notably due to the impact of human activities such as urbanization, livestock farming, agriculture and logging (Tsoar & Blumberg, 2002; Kutiel et al., 2004; Levin & Ben-Dor, 2004; Kiss et al., 2009; Miccadei et al., 2011; Malavasi et al., 2013). However, despite the multiple socio-ecological functions that they provide, including, amongst many others, contributing to coastal defense, acting as a habitat for species of conservation concern and serving as an attraction for tourism (Everard et al., 2010), the degree of resilience of these ecosystems has been severely tested by management measures carried out in dune systems over the last few years (Peña-Alonso et al., 2018).

Long-term human influence and land use changes over time are factors that have a major impact on the natural dynamics of aeolian sedimentary systems and need to be analyzed in depth to enable a better understanding of the ecological and landscape changes that such systems have experienced (Hoffman & Rohde, 2007). For such analyses, more and more studies are approaching the historical reconstruction of landscapes from the anthropological and ecological perspectives which form the basis of historical ecology (Szabó, 2015). Historical ecology can be defined as the study of the history of an ecosystem or landscape. A wide variety of sources and methods can be used which are mainly related to the fields of geography and history, although statistical procedures and paleoenvironmental techniques have also been employed, in the latter case to address reconstructions of thousands of years (Gimmi & Bugmann, 2013; Rick & Lockwood, 2013). Most studies carried out on historical human impacts on ecosystems have three main objectives: to preserve cultural heritage in ecosystems and landscapes, to understand historical trajectories of patterns and processes, and to inform about ecosystem and landscape management in the past (Bürgi & Gimmi, 2007). A thorough knowledge of how human activities have historically affected ecosystems can help to better understand their current status and, most importantly, contribute significantly to the development and implementation of effective restoration and management strategies (Bellarosa et al., 1996; Fritschle, 2009; Grossinger et al., 2007; Villagra et al., 2009; Stringer & Harris, 2014).

Historical ecology studies use a large number of historical information sources (Bürgi & Gimmi, 2007; Raska et al., 2015), including historical documents (government acts, ecclesiastical archives and narrations of travelers or scientists from different periods, among others) (Bürgi et al., 2000), historical aerial photographs (Miller, 1999), historical maps (Petit & Lambin, 2002; Santana-Cordero et al., 2016b), postcards, photography (Skovlin et al., 2001; Nüsser, 2001), press reports, oral sources (Fogerty, 2005; Gimmi & Bürgi, 2007; Pinto

& Partidário, 2012; Santana-Cordero et al., 2016b), and management plans (Axelsson et al., 2002; Bürgi & Gimmi, 2007).

Most of the dune systems of the Canary Islands are classified as legally protected nature areas. However, in many cases, tourism infrastructure has been developed around them and, in their interior, uses related to this economic activity are carried out. *Sun and beach* tourism is the main economic activity in the islands, especially the eastern ones where most of these beaches and dunes systems are concentrated. In this context, one of the main aims of the studies that have been carried out on the aeolian sedimentary systems of the Canary Islands has been to identify and differentiate between alterations caused by natural processes and those caused by human interventions. Another aim has been to find out how these aeolian systems have been managed historically and to know precisely the environmental consequences that such management has led to. The problems detected in these arid systems have been related to alterations in geomorphological processes (Hernández-Calvento, 2002; García-Romero et al., 2016; Hernández-Cordero et al., 2018), vegetation (Hernández-Calvento, 2002; Hernández-Cordero et al., 2012; Santana-Cordero et al., 2016a; Hernández-Cordero et al., 2017), and biogeomorphological processes (García-Romero et al., 2019a). In one extreme case, these alterations have culminated in the complete disappearance of a dune system (Santana-Cordero et al., 2016b). In general, their functions and degree of resilience have been heavily impacted by the management measures and approaches that have been used, especially over the last few decades (Peña-Alonso et al., 2018). However, the studies that have been carried out to date have not related land ownership to landscape changes, an issue that is intended to be addressed through this work.

With this background in mind, the objective of this paper is to verify the environmental changes (geomorphology and vegetation) observed in the dune system of Jandía Isthmus

(Fuerteventura, Canary Islands, Spain)and analyze the impact on them of historical and current land uses, considering the period from the 19th century to the present.

Like other dune systems in the Canary Islands, Jandía is an ideal research laboratory for studying changes in its functioning induced by human activities. This is so for two main reasons: i) firstly, as the systems are relatively small in size it is easier to isolate the determining factors of change and thereby analyze the link between causes and effects; ii) secondly, being an arid system, the observable effects of alterations are perceived faster than in the much more widely studied dune systems of temperate regions (Cabrera-Vega et al., 2013; Hernández-Calvento et al., 2014; Hernández Cordero et al., 2019). It should also be noted that the Canary Islands were colonized by humans relatively late (less than 3000 years ago) and their conquest by Europeans was in the recent past (15th century). In other words, there is a short period of human intervention in the territory and sources of information about land ownership and land uses are available for the last few centuries.

2. Study area

The Jandía Isthmus, with an area of 54 km^2, is located on the southern coast of the island of Fuerteventura, between the old massifs of Jandía and Betancuria (Fig. 1). The main characteristics of this area are its low altitude and its slightly uneven relief, in contrast with the surrounding old massifs. The basement, formed between 20.7 and 14.2 My ago, is comprised of alkaline basaltic lava and pyroclastics from a Miocene eruption of the Jandía stratovolcano (Coello et al., 1992). The isthmus is covered by sand, predominantly biogenic, which is subject to almost continuous aeolian transport by the dominant NW winds. The main dune morphologies are nebkhas, a rampant dune on the southern limit of the windward side and two falling dunes in Sotavento (Alcántara-Carrió, 2003). The dominant source of transported particles is the erosion of aeolianite deposits and quaternary calcareous crusts located in the inner part of the isthmus, while more scarce sandy contributions come from the current beaches or the erosion of the materials that constitute the cliffs of Barlovento (Alcántara-Carrió, 2003). Aeolian transport takes place in a SSE direction (Alcántara-Carrió and Alonso, 2002). The climate of the area has been defined as warm desert with marked aridity (Alonso et al., 2011). The scarce and highly irregular precipitations are concentrated in just a few days of the year and do not usually exceed 100 mm. High temperatures (with annual averages of around 20ºC), intense insolation and strong and frequent winds result in evaporation (Alcántara-Carrió, 2003). Vegetation is scarce, land cover is limited and the plants, in general, do not exceed the shrub layer. There are three vegetation types in the isthmus which reflect the different habitats: psammophytes in the mobile sand areas; halophytes, concentrated in the backshore zones of Sotavento where salinity and tidal flooding are intense; and thickets of Chenopodiaceae on calcareous crusts and rocky outcrops (Martín-Esquivel et al., 1995).

The Isthmus of Jandía was exploited only as pasture land from around 600 BCE (Cabrera, 2001) until approximately 1850, at which point references about obtaining fuel in this area appear for the first time in the historical documents. These traditional activities ceased with the arrival of tourism to the island, starting in 1960, which gave rise to the extraction of aggregates for construction and the creation of infrastructures and tourist facilities on the isthmus. At present, this area has two main urban centers (Costa Calma and La Pared), as well as several scattered hotels south of the Sotavento beaches.

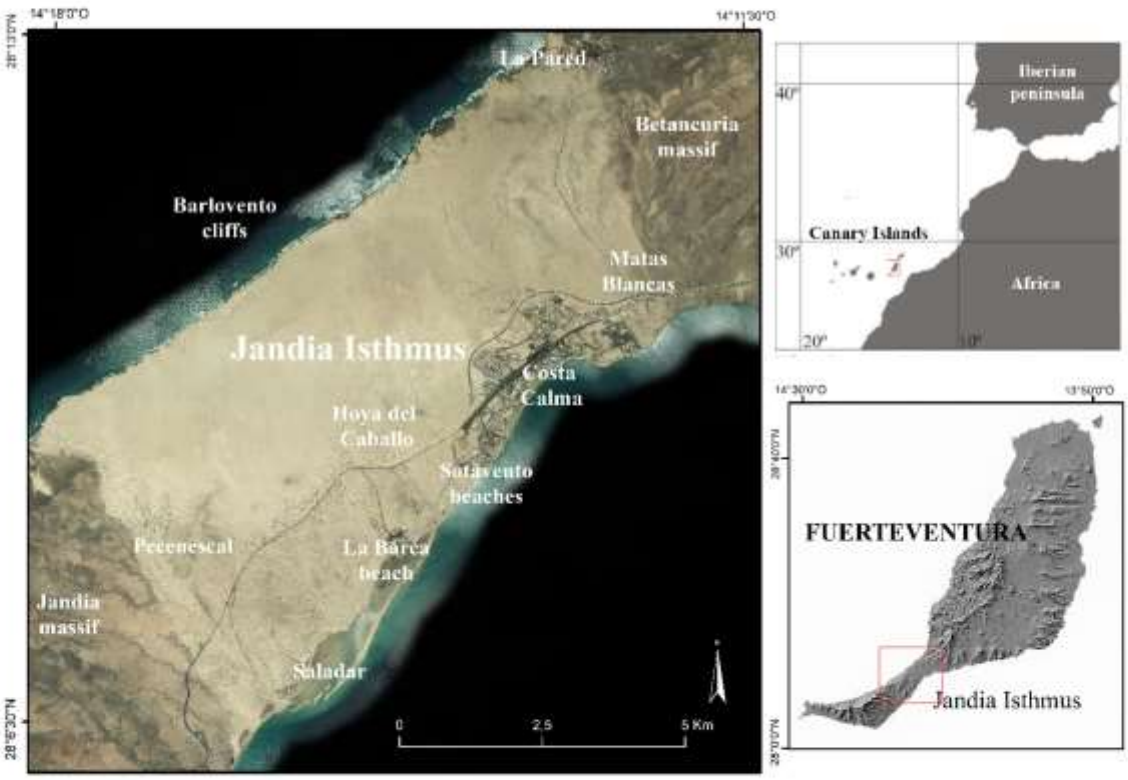

Figure 1. Location and general view of the study area in 2016. Orthophoto source: SDI Canarias (Canary Islands Government - Grafcan S.A.).

3. Materials and methods

The methodology that has been designed uses diverse sources of information, techniques and analysis tools.

Archival sources: historical documents from the historical archive of Fuerteventura and from the archive of the University of La Laguna. One of the most important historical documents for this work was a report written by the secretary of the Municipality of Pájara, Mr. Justo P. Villalba, in 1868, titled "Description of the Jandía Grazing Land Estate", which considers the uses and possibilities of exploitation of this farm in the mid-nineteenth century. It should be noted that the Jandía Grazing Land Estate was more extensive than the area currently known as the Jandía Isthmus, since it occupied approximately 200 km^2. In addition, official acts of the Cabildo de Fuerteventura and the rules for the management of the Grazing Land Estate (or *Dehesa* in Spanish), written by its owner Mr. Gustavo Winter, were analyzed, as well as written press reports obtained using the "Jable" search tool of the Las Palmas de Gran Canaria University Library. Finally, historical photographs were collected from press publications and the bibliography (Höllermann, 2009) and compared with current ones.

Field work: two field campaigns were carried out in January and May 2018 to contrast information obtained from the sources and to conduct interviews. Fourteen interviews were held with the objective of collecting information on human uses. They were conducted following an oral history methodology (Fogerty, 2005) based on a semi-structured conversation, with an open script, between an interviewer and an interviewee (see supplementary information). The interviews were carried out with shepherds and workers who exploited the lime kilns (known locally as *caleros*) born between 1925 and 1940. Interviews with the shepherds (9 interviews) allowed information to be obtained about pastures and grazing areas, essential to determine the anthropogenic pressure on the vegetation. Interviews with the *caleros* (5 interviews) enabled us to ascertain the species that were used for fuel, the areas where they obtained firewood and the extent of the lime industry's demand for vegetation, as well as the time period in which this activity was carried out. During these campaigns, the remains of lime kiln structures were also located, as well as the sites of other activities, including areas used relatively recently to extract aggregates and areas currently in use for the transit of 4x4 vehicles or goat pasturing.

Historical aerial photographs, orthophotos and LiDAR data (Table 1): these sources were used to obtain spatial data and to contrast information obtained from other sources. Their comparison allowed the identification and quantification of changes in land cover and their consequences: erosion (mobile sands, rock outcrops), accumulation (beaches), sedimentary stabilization (vegetated areas) and areas altered by human activity (urbanization, aggregate extraction and other anthropic activities). Historical aerial photographs (1963 and 1981) were georeferenced in a GIS using checkpoints. Through photointerpretation of these and the other aerial documents, spatial information on land cover, geomorphology and vegetation was obtained. Historical aerial photographs and current orthophotos were also used to analyze biogeomorphological changes around La Barca beach, where a network of roads could be altering the natural aeolian sedimentary dynamics. This was studied on the basis of vegetation density, using the aerial photography of 1981 and the orthophoto of 2017 and following the procedure developed by García-Romero et al. (2018).

The decision to analyze the vegetation density was made with the aim of quantitatively characterizing the vegetation in these arid systems. The calculation of the vegetation density variable not only provides data on the amount of vegetation per unit area, but also the mean distance between the individual plants, which is directly influenced by aeolian sedimentary dynamics (Hesp, 1991, 2002). Therefore, any alteration in the vegetation density also produces geomorphological changes. The green band was used by García-Romero et al. (2018) as this is the region of the visible spectrum that best detects vegetation characteristics (Chuvieco, 2010) in the absence of a near infrared band. The digital vegetation density model, obtained by vegetation density calculation through point vectors, was resampled to a 1 m pixel resolution to facilitate its comparison with historical aerial photographs and orthophotos of different spatial resolution. Finally, pixels were classified into the following four categories: (1) low densities, with vegetation covering 0-10.65% 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, which included areas with a vegetation cover of 49.26–84.25% (García-Romero et al., 2018). As the bush plants present in the zone are perennial and the method applied only detects bush plants, there were no phenological problems associated to seasonality (García-Romero et al., 2018).

LiDAR data from 2009 and 2015 were also used to obtain digital elevation models (DEM) with 1 m spatial resolution. From these DEMs, volumetric sediment changes were calculated from a DEM of Difference (DoD) using the geomorphic change detection methodology (Wheaton et al., 2010a; 2010b).

Table 1. Aerial photographs, orthophotos and LiDAR data used

Type (source)	Year	Scale	Resolution (m)	RMS (m)	Delineation error (m)
Historical aerial photographs	1963[1]	1:18000	1	1.05-2.05	3.6
	1981[2]	1:18000	0.5	1.25-2.05	3.6
	1998[1]	1:5000	1	*	1
Orthophotos	2016[1]	^	0.1	< 1.5	0.1
	2017[3]	^	0.25	< 1	0.25
LiDAR (DEM)	2009[2]	-	1	-	-
	2015[2]	-	1	-	-

* Information not available. ^flight with ground sampling distance (GSD) of 22.5 cm/pixel. [1]WMS Server from SDI Canarias (Canary Islands Government - Grafcan S.A.) [2]National Geographical Institute (Spain). [3]Raster file SDI Canarias (Canary Islands Government - Grafcan S.A.) RMS: Root-mean-square error. The delineation error was calculated according to Robinson et al. (1987).

Regional climate change: climatic variability in the Jandía Isthmus was analyzed to determine the existence of any patterns and/or changes in rainfall, temperature or wind speed over the period for which data were available that could have induced the environmental changes observed in the study area. Data registered by the meteorological station of the State Meteorological Agency (AEMET), located at Puerto del Rosario Airport (44 km northeast of the dunefield) were used. The analysis was carried out using daily averages of temperature (º) and annual precipitation (mm/year) for the period 1940-2017 and wind speeds (m/s^{-1}) for the period 1970-2017. Daily precipitation and temperature data were used to calculate annual potential evapotranspiration, using the Thornthwaite (1948) method (Fig. 2). The number of days per year when the wind speed exceeded 6.17 m/s (12 knots) was calculated and is shown with the threshold used by Fryberger & Dean (1979), which in turn is based on Bagnold (1954). Linear trends (R^2) were also calculated for the three variables analyzed (Fig. 2). Sedimentary mobility indices, such as the versions of Lancaster (1988) or Tsoar (2005), were not used due to an insufficient number of wind variables and because sediment size in the study area, reported in Álcantara-Carrió (2003), was measured after the remobilization and environmental alterations that are analyzed in this article. These alterations to the natural dynamics changed the distribution and structure of the sediments and generated erosion processes that removed the remaining lowest and largest sized materials, as occurs in other ecosystems (King et al., 2006).

4. Results

4.1. Climatic variability

The rainfall and evapotranspiration rates in the study area, constructed using AEMET data, show high variability (Fig. 2). Even in rainy years, rainfall does not normally exceed 200 mm and long periods of drought are common. This cyclic behavior can be observed in both variables in figure 2. In dry years, the precipitation varies between 50 and 100 mm. A trend towards lower precipitation (R^2= 0.0458) and evapotranspiration (R^2= 0.0174) can be observed, the latter as the result of a decrease in annual rainfall and a continuous increase in temperature (R^2= 0.6911). The wind series (1970-2017) are too short for trends or cyclical behaviors to be observable. There is only a small reduction between 1991 and 1998 in the total number of days per year in which the wind speed exceeded the threshold of 6.17 m/s^{-1}. During this same period, as can be seen in figure 2, rainfall was generally below and evapotranspiration generally above their corresponding trendlines. The series also show variable wind behavior in the study area, with wind speeds over 6.17 m/s^1 recorded on average 170 days per year.

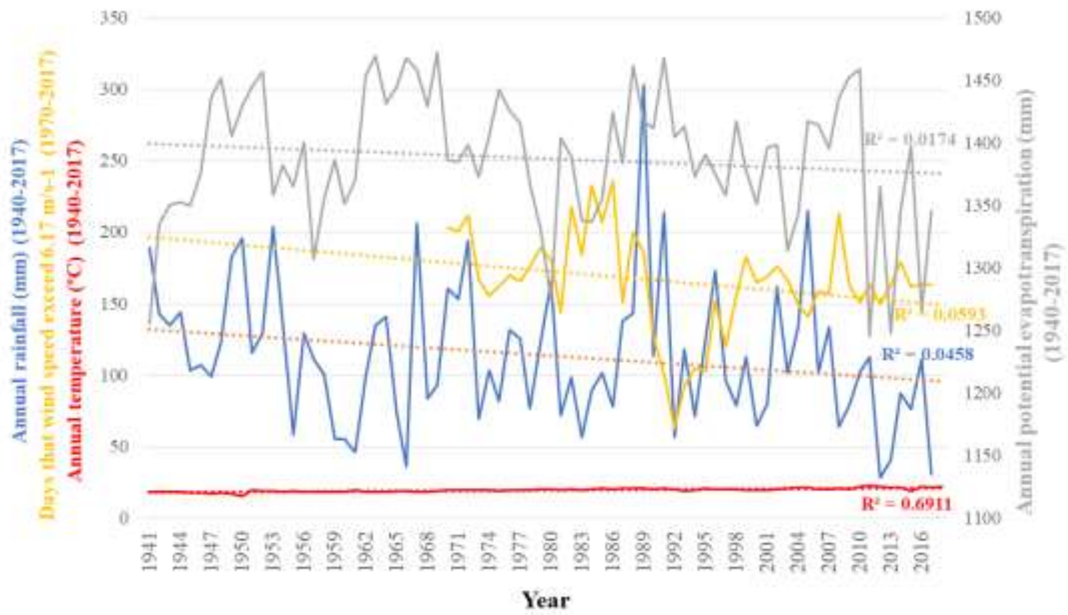

Figure 2. Annual rainfall, annual evapotranspiration, annual temperature (1940-2017) and days per year when wind speed exceeded 6.17 m/s^{-1} (1970-2017). Source: AEMET.

4.2. Evolution of land uses

Land uses in the Jandía Isthmus are studied in five periods considering different factors such as land ownership changes and economic trends at insular and regional levels (Fig. 3).

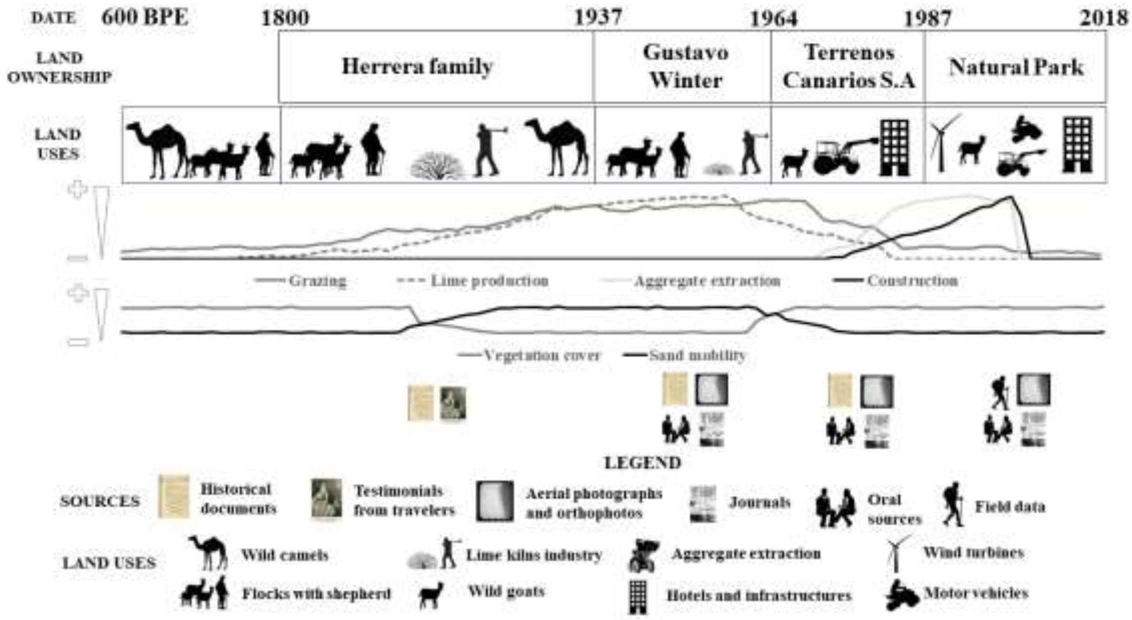

Figure 3. Periods of land ownership, land use changes, land use change intensity and sand mobility and vegetation cover changes established according to the sources used for each period.

Before 1800

The main pre-1800 land uses were livestock farming (mainly camels, sheep and goats) and the exploitation of *Roccella canariensis* (called locally *orchilla*, a lichen from which natural dye is extracted) for commercial purposes. The land use with the longest history in the Jandía Isthmus is that of grazing, with references to its existence since the first human settlements on the island around 600 BCE (Cabrera, 2001). In one record from 1675 of the proceedings of a local estate in Fuerteventura, the presence in Jandía is noted of 500 sheep, 20 mares, 4 horses, 70 camels and a large number of goats (Roldán, 1967). There are also numerous references to the entrance of animals from other parts of the island for grazing purposes, taking advantage of the abundant pasture land. From this period onwards, animal farming in Jandía was based on a free grazing model (called locally *apañadas*, a grazing technique that consists of allowing the livestock to roam free with specific periods each year to herd up the animals for selection purposes). In the minutes of the Regional Government of Fuerteventura (1605-

1728), there are references to this activity and the presence of a large number of feral goats and camels on the isthmus (Roldán, 1966; Roldán, 1970).

1800–1937

From 1811, the Jandía Estate was owned by the Herrera family, who rented the land to others with the objective of maximizing its exploitation, but did not reside on the island. Both the control of the property and its exploitation were carried out by local farmers. Until the middle of the 19th century, historical descriptions defined the study area as one whose only use was grazing. This situation changed a few years later with the growth of the lime kiln industry. In 1863, the naturalist Karl Von Fritsch visited Jandía and wrote a short description of the isthmus. About the vegetation, grazing and sand mobility he wrote the following (Fritsch, 2006: 151):

> On its loose sands, […] one sinks when walking as happens when there is a lot of snow. The rolling hills of the dunes change their shape with the wind. Great extensions of land present no other vegetation than *Euphorbia paralis*, avoided by the animals; but, especially where, under the loose sand, there is lime stone or basalt, some other plants appear […]. The voracious teeth of goats and camels turn the bushes of these woody shrubs into brambles and creeping and petrified weeds.

In 1868, the secretary of the Council of Pájara, Mr. Justo P. Villalba, wrote a report in which it was stated that Jandía only produced bushes that were shared by animals and lime kilns. In this report, it is explained that the vegetation was not so abundant near the coast as it was close to the kilns and had been used to feed them. However, it should be noted that the author did not say that the vegetation was scarce. Currently, there are six lime kilns in the study area, all of them on the Sotavento coast. Using these kilns, the lime was obtained and then exported to the islands of Tenerife and Gran Canaria. As for livestock, the document explained that keeping track of the number of animals was problematic as the flocks were free most of the year, and that the only method for counting was through *apañadas*. However, he estimated that there were a minimum of 3000 animals in the area, plus some 800 others from different municipalities which, in times of intense drought, came to graze on Jandía.

1937-1964

In 1937, the German family Winter rented the Jandía Grazing Land Estate, and in 1941 the Estate became the property of the trading company Dehesa de Jandía S.A., who kept Mr. Gustavo Winter on as its administrator. He undertook a far stricter control of the exploitation of the Estate compared to the previous owners. For example, in 1949, the laborers who came to graze from other municipalities were ordered to remove their flocks from the Estate. A set of regulations with new instructions regarding the management of the farm was also drawn up, including the construction of a fence at Matas Blancas to demarcate and isolate the Estate, as well as the incorporation of a security guard. In later years, Mr. Gustavo Winter increased the livestock load with a large number of sheep and rabbits. According to oral sources, intense deforestation took place during this period. In addition to an increased number of grazing animals, there was also a greater demand for fuel for the lime kiln industry from laborers on the Estate as well as from other municipalities who came to collect shrubs for their kilns.

> There were a lot of *aulagas* (*Launaea arborescens* plants) for the lime kilns. I used to go close to Jandía looking for woody plants for burning because there were none where I was. Sometimes we needed three months to collect all the firewood to burn in the lime kiln and if it was a good year, like in the past when it used to rain a lot, you only had to

> wait two or three years for the plants to grow. We'd clean all that area called Matas Blancas, and then make our way up to La Pared and from La Pared to the west and the east [Excerpt from the interview conducted with Mr. Francisco Cabrera].

The interviewees indicated that, for the lime kiln industry, vegetable species still present in the system were used as fuel. The most important of these were *Launaea arborescens*, *Lycium intricatum* and *Convolvulus caput-medussae*. These were preferred by the lime workers, because they combusted very quickly, produced abundant heat, did not clog the kilns and did not generate too much ash. According to these oral sources, the kiln had to be kept going for about 48 hours to burn 300 kg of limestone and, according to Manzano-Cabrera (2016) and oral sources, camels were required to transport the loads of kiln fuel. The number of these camel loads varied depending on the size of the kilns, with around 60-80 required for medium-sized kilns and 100-120 for the largest. According to the oral sources consulted, one camel load corresponded to 12 bundles, each 1 m long by 50 cm wide and deep, providing 3 m^3 of fuel. On this basis, a calculation can be made of the number of loads required for one lime kiln: the medium-sized kilns would require between 180 m^3 and 240 m^3, and the larger ones between 300 m^3 and 360 m^3. The demand for fuel resulted in the vegetation acquiring a market value which varied in price between five and twelve pesetas (0.03-0.12 Euros) per camel load, depending on whether it was obtained from public spaces or private fields. For this reason, and due to the reduction in the vegetation available, the traditional kilns were partially replaced by coal ovens around 1950. Limestone was also quarried and shipped without being burned for lime on site. Likewise, most of the industrial activity moved to the capital of the island until, finally, the lime industry gradually disappeared in Fuerteventura in the early 1960s, giving way to the import of cement and synthetic paints.

1964-1987

A new change in ownership of the land took place when it was divided into four separate plots. The isthmus was included in Lot Number 4, which encompassed the entire north of the Jandía Peninsula, with an area of 9,341 hectares. This was bought by the company Terrenos Canarios S.A. in 1964. The new owners changed the trend in terms of the exploitation of the land, promoting the development of tourism and its associated infrastructures. In the sale agreement, a right-of-way was established to ensure the free flow of the sands towards the beaches, and Terrenos Canarios S.A. were prohibited from extracting sand for industrial purposes. The sand corridor was never made or designed and the sand extraction prohibitions were eventually repealed. As tourism and its associated construction sector began to expand, Cementos Especiales S.A. was granted a license to begin new sand extractions (Martín-Luzardo, 2003) and quarries were opened, such as those located in Pecenescal and Hoya del Caballo (Fig. 5). At the end of the 1970s, construction began of the first hotel located on La Barca beach, as well as of the FV-2 road which, according to oral sources, was beset from the beginning by a problem of continuous coverage by sand and the consequent need for regular maintenance and cleaning.

From 1987 to the present day

In 1987, a large part of the aeolian system was declared a Nature Park along with the rest of the Jandía Peninsula (Law 12/1987, of June 19, on the Declaration of Natural Spaces of the Canary Islands). This environmental protection has been maintained until the present day through various territorial laws. This protection limits, to a certain extent, the ways in which the study area can be exploited by the owners, especially the Saladar area and the inner system. As a result of the rapid development of tourism, a series of impacts have been generated, related, on the one hand, to the need to obtain resources for construction and, on the other, to the tourism itself. The impact caused by the construction sector was essentially due to the extraction of aggregates, which was reported at the time only by environmentalist NGOs and in some newspaper articles (Malpaís Semanal newspaper, July 26, 1991). These documents show that extractions were taking place day and night and that, loaded onto cargo ships, the sand was exported from Fuerteventura to Gran Canaria to satisfy the latter island's demand for aggregates in the construction sector. The last extractions were made in the 1990s.

Another impact on the natural system has been the proliferation of off-road vehicles, especially those rented by tourists (4x4 vehicles). The offer of these vehicles has enticed more and more tourists to travel across the Jandía Peninsula using, most of the time, illegal tracks or forging new paths.

In 1995, the Cañada La Barca wind farm with its 50 wind turbines was inaugurated. The expansion of the FV-2 road also began in the same year, with work on it still ongoing. The animals grazing in the study area have gradually been reduced in numbers, with at present only a small number of goats in the western sector. During the 1990s, the erosion of beaches and dunes along the Sotavento coast was detected (Höllermann, 2009) (Fig. 4). In addition, new recreational activities began to appear, including sandboarding, which is not regulated but seems to be beyond the control of the administrations.

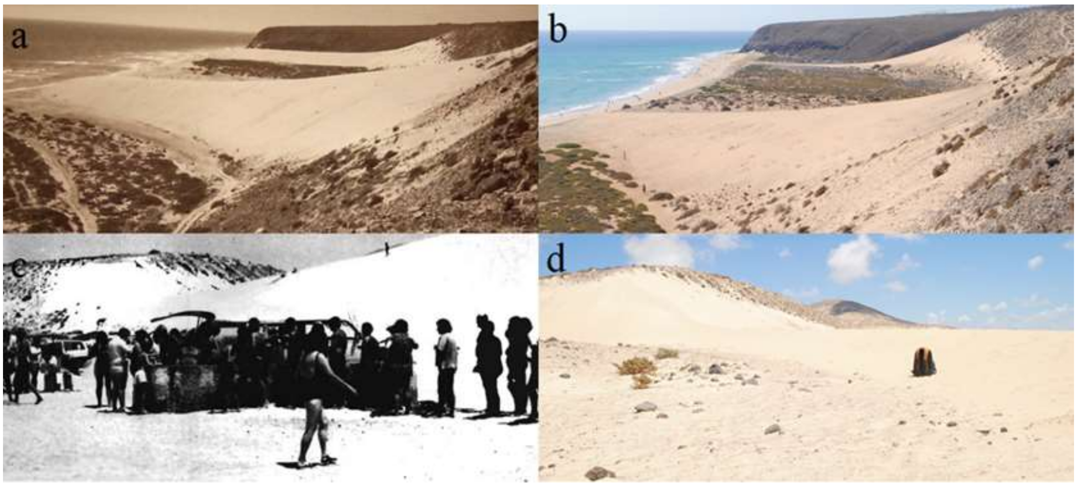

Figure 4. Repeat photographs of falling dunes in Sotavento: a) February 1990 (Höllerman, 2009), b) February 2018, c) 1989 (José A. Sierra, from Malpaís Semanal), d) April 2018.

4.3 Evolution of land cover (1963-2016)

The analysis of the evolution of land uses in the study area is completed, from the spatial point of view, by comparing the land cover, vegetation and landforms on the basis of the 1963 and 2016 aerial images.

Although the first hotel was built in the 1970s, it was in the late 1980s that construction for the tourism sector rapidly accelerated. The hotels are located parallel to the coastline of the Sotavento beaches, constituting a barrier that reduced direct contact between the beach and the rest of the aeolian sedimentary system from 9.6 linear km in 1963 to 5.2 km in 2016. In addition, the construction of the Costa Calma tourism and housing development has been accompanied by the planting of a vegetation barrier, the objective of which is to prevent sand entering the buildings. Finally, a paved road system of about 50 km has been constructed, comprising the FV-2 road, which crosses El Jable, and several secondary roads which connect this main road with hotels and housing and tourism developments. There is also an extensive network of approximately 250 km of unpaved and mostly illegal tracks. According to the planning that regulates the management of the protected area, only 22 km of such tracks are permitted. However, their number has been considerably increased as the result of the transit of vehicles opening new ways to access the Barlovento beaches.

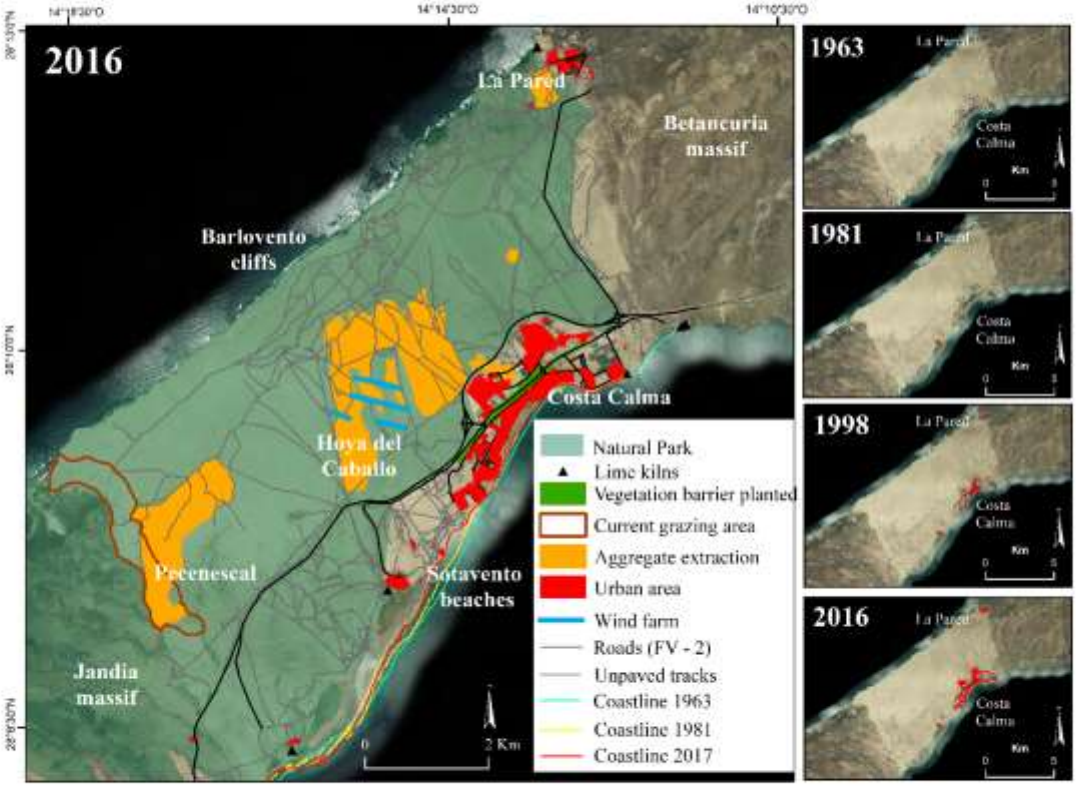

Figure 5. Left. Current main land uses. Sites of lime kilns now in disuse. Area affected by aggregate extraction since its inception. South coastline in 1963, 1981 and 2017. Right. Urban expansion between 1963, 1981, 1998 and 2016. Orthophoto source: SDI Canarias (Canary Islands Government - Grafcan S.A.).

The aggregates were extracted mainly between 1979 and 1991, and no new areas affected by extractions can be observed in recent aerial photographs. According to the current planning, there are only two areas affected by aggregate extraction, one in Pecenescal and another in La Pared (Fig. 5), comprising a combined area of 0.22 km^2. However, the analysis carried out for this work based on the digitalization of aerial photographs and orthophotos showed that the total area affected by extractive activity was about 5.57 km^2 (Table 2 and Fig. 5). In some cases, the extraction areas are large holes partially filled in by moving sands. In fact, the oral sources indicate that the voids that were left behind after the extraction process were filled up within just a few days by sand transported by the wind, making new resources available for extraction. In other cases, extractions were carried out on the surface sand sheet, without extensive digging. This caused outcropping of the rocky substratum, generally comprised of calcareous crusts.

In line with all these changes, the comparison of the aerial images of 1963 and 2016 shows an increase in the surface area of vegetation-stabilized sands, a significant reduction in mobile sand surface areas and an increase in rocky outcrops (Table 2).

Table 2. Evolution of land cover between 1963 and 2016 and types of processes: accumulation, erosion, stabilization and artificialization.

Land cover	1963		2016		*Variation*
	Area (km^2)	Area (%)	Area (km^2)	Area (%)	*(km^2)*
Mobile sands[1]	30.67	55.99	11.38	20.88	-19.29
Beaches[1]	2.71	4.95	2.54	4.66	-0.17
Rock outcrops[2]	11.83	21.60	16.07	29.50	+4.24
Sands stabilized by vegetation[3]	9.57	17.47	14.37	26.37	+4.8
Urbanized area[4]	0	0	1.97	3.62	+1.97
Area altered by aggregate extraction[4]	0	0	5.57	10.22	+5.57
Other areas with anthropic activities[4]	0	0	2.59	4.75	+2.59
Total	54.78	100	52.81	100	-1.97

Processes induced by changes in land cover according to García-Romero et al. (2016): 1 Accumulation, 2 Erosion, 3 Stabilization, 4 Artificialization

Vegetation changes in recent decades show an increase in vegetation cover, especially in the eastern sector. In the area shown in figure 6, representing 16.93% of the total study area, it can be seen that the increase in vegetation, between 1981 and 2017, occurred especially around the roads inside the Jandía Isthmus. Vegetation densities 2, 3 and 4 (the largest) occupied, in 1981, 42,793 m^2, 11,405 m^2 and 4,238 m^2, respectively (Fig. 6 A). In 2017, the corresponding values had increased by 125,690 m^2, 462,372 m^2 and 60,251 m^2 respectively. The lowest density (1) decreased from 6,117,868 m^2 in 1981 to 4,367,753 m^2 in 2017. In figure 6 (B), two sectors can be differentiated with respect to the increase in vegetation, with a larger increase south of the main road (Fig. 6B, S) compared to north of the main road (Fig. 6B, N). In the area of the Barlovento cliffs (north of the Jandía Isthmus) and in the western sector of the study area, most of the surface is covered by moving sands. In addition, it was found that the intertidal zone areas (south of the Jandía Isthmus) have decreased by 0.17 km^2.

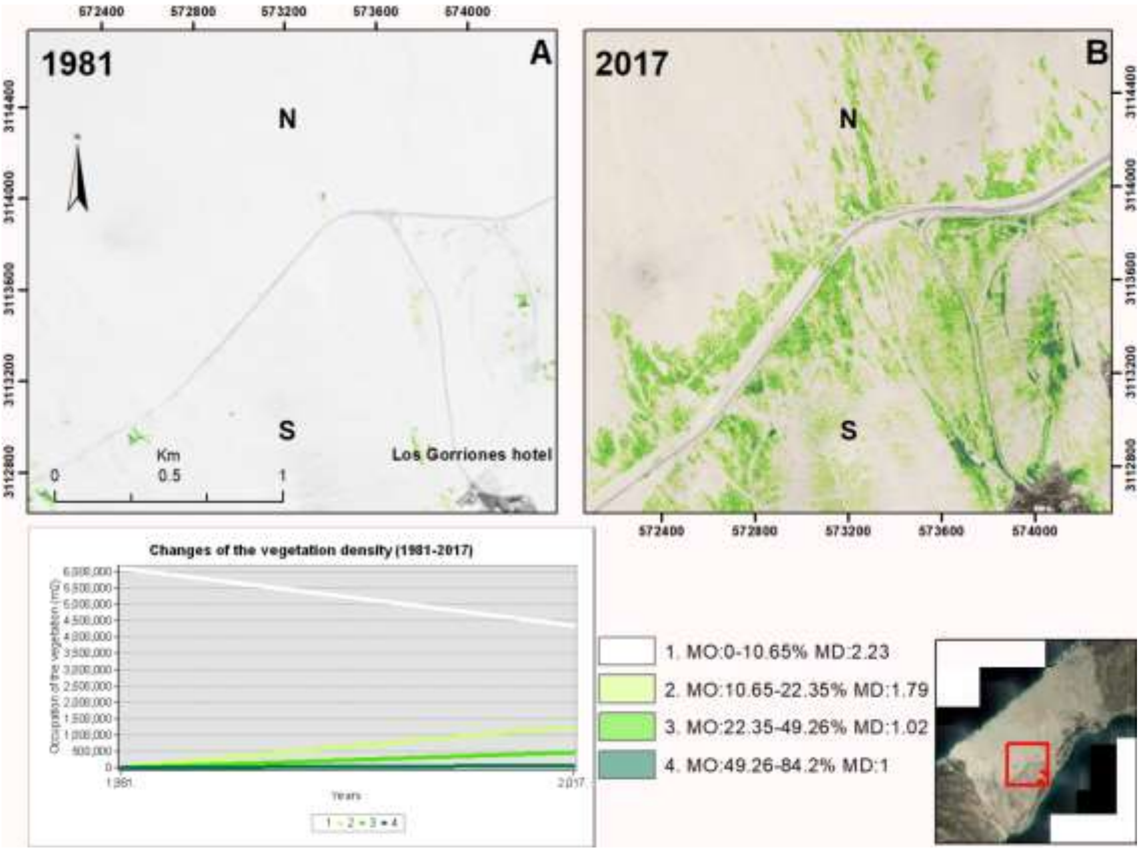

Figure 6. Vegetation in 1981 (A) and 2017 (B) in the area of the Sotavento beaches (expanded view in inset: bottom right-hand corner). Bottom left-hand side: Graphical representation of changes in vegetation density between 1981 and 2017 in the area considered in (A) and (B).

MO: Mean occupation of the vegetation (%). MD: Mean distance between plant individuals (m).

With respect to changes in sediment volume (Fig. 7 B), generalized erosion processes can be observed between 2009 and 2015, affecting 5,127,650 m^2 and 1,868,666.43 m^3, except in areas where a greater increase in vegetation occurred north of the main road (Fig. 7 A and Fig. 6 B, N). However, to the south of the main road, although vegetation increased, erosion processes were dominant except in a sector where accumulation was detected. In total, sediment accumulation in the area shown in figure 7 B corresponds to 187,425 m^2 and 41,792 m^3. On the coastline, erosion processes can also be observed (Fig 7 B) through changes in the topographic profile at La Barca beach (Fig. 7 inset). The 190 m long profile shows a continuous erosion that increases significantly at 60 m in the NW-SE direction, with an elevation decrease of between 1.35 m and 2.76 m. At the 99 m distance, the beach shows negative values, which is around 90 m of beach lost. A gradient color scale is provided in figure 6 to facilitate observance of the changes in vegetation density, and another in figure 7 to better understand the sedimentary balance variation in the NW-SE direction or, in other words, the erosion of the southern sedimentary coast (Fig. 7 B), as can also be seen in figure 5.

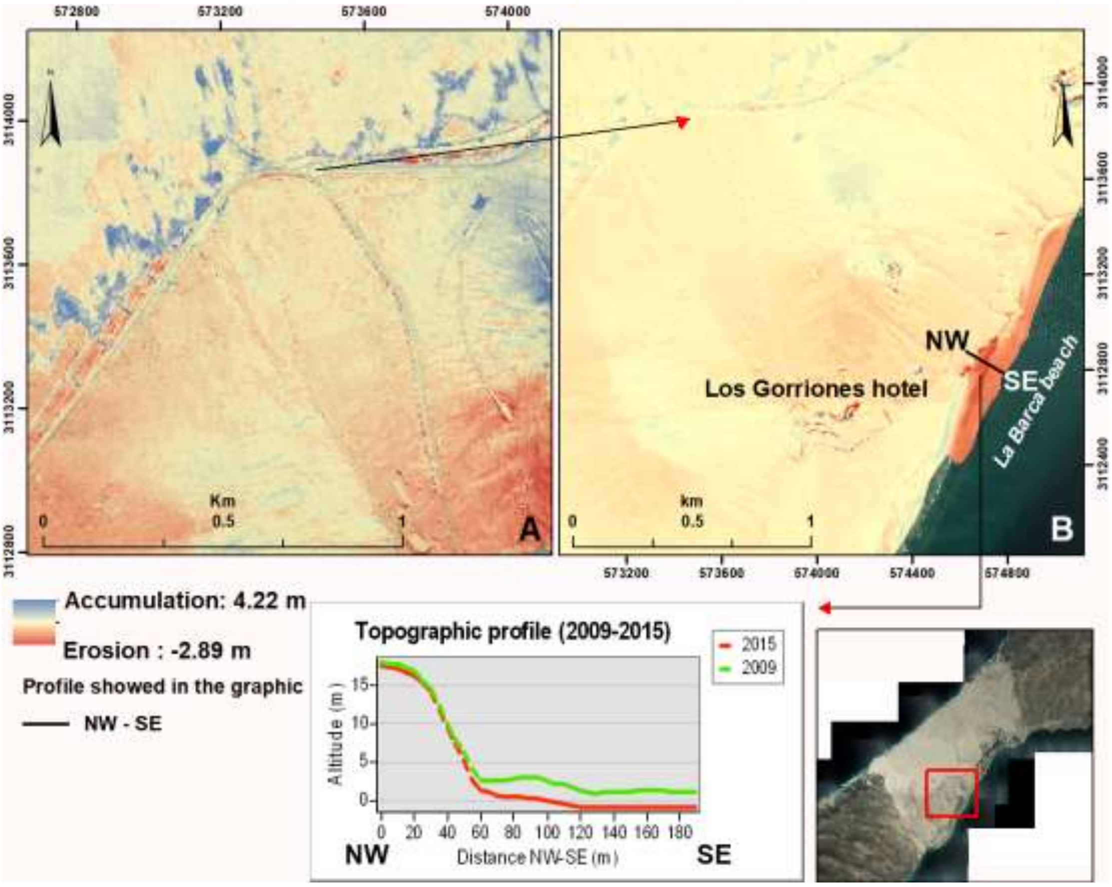

Figure 7. Volumetric sediment changes in a sector of the Jandía Isthmus between 2009 and 2015 (Sequence A and then B). DEM of Difference (DoD) error (%) of erosion: 9.33, and of accumulation: 7.55. A: at higher scale,

effect of the vegetation accumulating sediment (without obstacles) around the main road. B: at smaller scale, effect of the processes detected in A on the coast (La Barca beach).

5. Discussion

Several works have shown that the recent evolution and current status of sedimentary aeolian systems have depended, in general, on two factors. The first of these is the evolution of human uses (Jackson & Nordstrom, 2011), especially the transition from traditional uses, such as grazing and obtaining fuel (Kutiel et al., 2004; Levin & Ben Dor, 2004; Sciandrello et al., 2015), to new uses such as urbanization, recreational activities, the construction of infrastructures or the extraction of aggregates (El Banna & Frihy, 2009; Kiss et al., 2009; Miccadei et al., 2011; Malavasi et al., 2013; Hernández- Calvento et al., 2014; García-Romero et al., 2016; Smith et al., 2017). The second factor is that of changes in the environmental conditions of the systems themselves (Jackson & Cooper, 2011), especially as the result of climate change (Petit and Prudent, 2010; Sauter et al., 2013) and the reduction in the supply of sediments (Pye & Blott, 2012; Hernández-Calvento et al., 2014).

In the case of the Jandía isthmus, it would appear that decisions made by the owners on land uses (construction of a fence, increasing the grazing activity, giving the control to local farmers, tourist development, among others) and by the government (creation of a natural park) have greatly influenced environmental changes. These decisions have been the main causes of landscape alterations in the inner system and, therefore, the natural dynamics of the dune system, given that no significant local climatic variations were observed in the data period considered. The increase in vegetation cannot be related to an increase in rainfall because the precipitation data have shown a decreasing trend in the study area. Nor could it be caused by the reduction which was detected between 1991 and 1998 in days with high wind speeds (≥ 6.17 m / s^{-1}) (Fig. 2), as proposed by Tsoar (2005) - even though this period of time corresponds to the vegetation density changes (increase) shown in figure 6 as rainfall also decreased significantly during this same period, and hence there was an increase in evapotranspiration. In other words, the meteorological conditions are extreme for vegetation growth. It therefore seems to be the case that it is the human factor which has been directly determining environmental changes in the current Anthropocene context (Tsoar and Blumberg, 2002; Smith et al., 2017; García-Romero et al., 2019a; Delgado-Fernández et al., 2019), as opposed to natural factors such as climate or sediment supply which are important determinants of spatial variability in coastal dunes at global, regional and local scale (Hesp 2004; Pickart and Hesp 2019; García-Romero et al. 2019b).

The most prolonged land use has been for grazing, beginning around 600 BCE (Cabrera, 2001) and reaching its highest intensity around 1950. In Jandía, the free grazing technique does not allow the shepherd to have control of which areas are being grazed, and so the consequences have had to be generalized to the study area. Studies on pastoralism in temperate regions show that livestock induces processes of erosion and increased aeolian transport (Cerdà & Lavee, 1999; Tsoar and Blumberg, 2002; Kutiel et al., 2004; Levin & BenDor, 2004; Mekuria & Aynekulu, 2013; Angassa, 2014), in addition to other punctual or linear impacts, such as burrows, wallows, trails, etc (Zunzunegui et al., 2011).

From the mid-19th century, deforestation can be added to the impact of livestock, with the exploitation of vegetation now also associated with the lime kiln industry and the obtaining of fuel for households. Unfortunately, little research has been conducted on this activity despite its considerable impact on the ecosystems of the nearby eastern Canary Islands (Santana-Cordero et al., 2016a). It seems that the demand for fuel exceeded the regeneration capacity of the local vegetation system. This can be seen in the importation of coal in the 1950s, when limestone began to be shipped to other islands without being burned. In this period, the historical descriptions, oral sources and aerial photographs of 1963 point to an aeolian system with a vegetation coverage much lower than in the present day. Such rhexistatic conditions would have favoured mobilization of the sediments, as happened on the island of La Graciosa (Santana-Cordero et al., 2016a). This sedimentary remobilization took place over a period which lasted approximately one hundred years, between 1850 and 1960. The sources consulted also describe a surface of mobile sands much larger than today. From this, the existence, at this time (1859-1960), can be supposed of a sedimentary surplus on the Sotavento coast. In addition, and due to the conditions of the natural dynamics of arid systems, it is indeed possible for sedimentary remobilization to occur in a short period of time, since the aeolian sedimentary systems of arid zones manifest the consequences of human impacts faster than those located in temperate zones, because their potential sedimentary transport is much more significant (Cabrera-Vega et al., 2013; Hernández-Calvento et al., 2014; Hernández-Cordero et al., 2019). After livestock grazing began to decrease and logging activity ceased, there was an increase in vegetation cover which, in turn, favoured stabilization of the aeolian system (Kutiel et al., 2004; Hoffman & Rohde, 2007; Santana-Cordero et al., 2016a), generating a decrease in sedimentary transport. Additionally, the aggregate extractions resulted in a decrease in the volume of material that could be transported (Cabrera-Vega et al., 2013), creating large voids that acted as traps continuously being filled with sand, and generating a shortage of sediments along the Sotavento coast which facilitated erosion of the coastline. In the latter sector, erosive processes linked to a sea level rise due to the current climate change must have acted in a coincident manner, and it is expected that these erosive processes will be prolonged and aggravated over time (Fraile Jurado et al., 2014). In any case, the case study is adequate to represent global change processes, linked to environmental transformations by human actions.

The changes in land uses that have occurred in this system since the 1980s have reversed the biogeomorphological trends described in the preceding stage. Thus, between 1981 and 2016 there was an increase in vegetation cover and stabilization of the dune system, as well as increases in modified/developed surface area and erosional processes. This could explain why the dunes and beaches at Sotavento have begun to recede rapidly (Alcantará-Carrió & Alonso, 2002; Alonso et al., 2002; Höllermann, 2009). In short, sedimentary transport from dunes to the beach has been reduced by the natural recolonization of vegetation and vegetation barriers. This process has been widely observed in other parts of the world, but the reasons can differ from place to another. In similar systems in China, for instance, it has been observed that increased vegetation occurs as the result of changes in wind strength, interannual fluctuations in rainfall, and large ecological restoration projects implemented in recent decades (Xu et al., 2018), while in Israel an increase in vegetation was attributed to the disappearance of traditional activities such as grazing (Tsoar and Blumberg, 2002). Sedimentary transport can also be affected by the presence of obstacles, such as urban-tourist constructions (Hernández Calvento et al., 2017; Smith et al., 2017; García-Romero et al., 2019a) and highways, the planting of vegetation barriers, and a deficit of material susceptible to transportation due to extractions (Alcántara-Carrió et al., 1996; Alonso et al., 2002; Alonso et al., 2011). Vegetation has been found to increase especially around road networks, which act as corridors especially for exotic species (Trombulak & Frissell, 2000; Forman et al., 2002). Once the species are established on the roadsides, they can spread along these corridors, with traffic, wind, water or animals helping to homogenize the communities on either side of the road (Clifford, 1959; Greenberg et al., 1997). This issue needs to be addressed in future specific works on the type of vegetation that is recolonizing these systems and on the environmental conditions that are favouring this process. This work, as well as others carried out in different aeolian sedimentary systems of the Canary Islands (Santana-Cordero et al., 2014; 2016a, b), shows that before aerial photographs of these systems were available, these systems had already undergone important changes in terms of vegetation cover, landforms and sediment transport characteristics. This means that the current dune systems are the expression of their resilience to secular human interventions. In Jandía, these alterations were at least partly due to the results of decisions made by the owners, before and after land protection regulations, which led to massive exploitation of the system and its consequent degradation. Therefore, the decisions made by the owners and the government on land usage have been the driving force behind the transformation of the landscape. The environmental protection that the area has been afforded, unlike in other similar systems (Santana-Cordero et al, 2016a), has not served to diminish certain human impacts.

With respect to the methodology applied, the limitations of historical sources before 1800 should be noted, which is often the case in historical ecology studies (Szabó & Hédl, 2011). With respect to the study area, it seems that before the 1800s there were no periods of any notable significant settlement, only perhaps a consistent, gradual presence of grazing animals and, therefore, the lack of earlier sources may not be an issue. Some aspects are difficult to quantify from the sources used, as for example with certain effects of the livestock and lime kilns. In addition, in this case, no comparative method can be applied to the current situation, because, on the one hand, today the livestock density of sandy areas in Fuerteventura is much lower than in the historical records and, on the other, the lime kiln activity has completely disappeared. In this respect, it would be interesting to carry out more detailed studies on the impact of livestock grazing and the use of lime kilns on the dune systems of the archipelago. The integration of data from different historical sources in a GIS environment, and assigning them a spatial character, has previously been proposed by different authors (Trueman et al., 2013; Santana-Cordero et al., 2016b) who have highlighted the important role that it plays in the interpretation of the results.

This work and the methodology applied in the present work can be of interest not only for areas with similar characteristics and processes that the Jandía Isthmus, an unstable area due to its origin and with increased vulnerability due to anthropogenic alteration, but also for semi-temperate regions (Mediterranean, for example) where there is a growing possibility of aridification due to climate change.

6. Conclusions

The analysis of different historical and contemporary sources shows that sediment remobilization in the Jandía Isthmus, between 1850 and 1960, was mainly induced by the exploitation of vegetation for grazing and lime production. These activities produced environmental alterations in the aeolian sedimentary system, which will have resulted in an increase in sedimentary transport and a decrease in vegetation cover. It is possible that these processes led to an increase and sediment surplus on the Sotavento (south) coastline. Recent activities, which have generated numerous impediments to sedimentary transport (vegetation barriers, road networks and urban-tourist constructions), have also induced, along with the spontaneous recovery of vegetation due to the cessation of traditional activities, the erosion of the Sotavento dunes and the intertidal zone areas (south). Historical and recent land uses are related, on the one hand, to the decisions made by the owners of the land and, on the other, to regional economic trends in each period. Both these factors have acted as driving forces behind the transformation of the isthmus, generating different uses and, with them, different anthropogenic alterations to the natural system. We can conclude, therefore, that the current landscape of the Jandía Isthmus is an expression of its resilience to the human interventions that have been carried out over the centuries.

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

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

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Abstract

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

Key words: land uses, nebkhas, environmental changes, historical ecology.

1. INTRODUCTION

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

The coastal aeolian systems of the planet have been exposed to a process of anthropic degradation related to traditional activities such as grazing, obtaining firewood or agriculture (Tsoar & Blumberg, 2002; Kutiel et al., 2004; Levin & Ben-Dor, 2004; Provoost et al., 2011) and to recent uses such as aggregate extraction, the construction of urbanizations and tourist infrastructure, and recreational uses (Nordstrom & McCluskey, 1985; Nordstrom, 1994; Nordstrom, 2004; Smith et al., 2017; García-Romero et al., 2019b; Delgado-Fernández et al., 2019). All these uses have induced environmental transformations whose consequences have been, among others, changes in landforms and aeolian sedimentary activity (dune stabilization) (Cabrera-Vega et al., 2013; Hernández-Cordero et al., 2018), reductions of pioneer plants in mobile dunes and species richness (Kutiel et al., 1999; Curr et al., 2000;

Dolnik et al., 2011; Faggi and Dadon, 2011), sediment remobilization (Arens et al., 2013), accelerated erosion processes (García-Romero et al., 2016; García-Romero et al., 2019b), alteration of the direction and speed of wind flow (Hernández-Calvento et al., 2014; Smith et al., 2017; García-Romero et al., 2019a), and on occasions surface reduction (Hernández-Cordero et al., 2018). It can be argued, therefore, that most of the surviving ecosystems are an expression of their resilience and that their evolution after the land uses is not restricted to the recovery of the original functions and characteristics but to the adaptation and reorganization of the components of the landscape to the post-disturbance situation (Kombiadou et al., 2019).

Knowledge of the evolution of land uses, vegetation, landforms and environmental dynamics facilitates reconstruction of the historical trajectory of these ecosystems (Bürgi & Gimmi, 2007), as well as to understand the mechanisms of response to the different disturbances. In addition, historical data can help to improve the accuracy of predictive models of ecosystem or species response to such impacts (Gimmi & Bugmann et al., 2013). Historical reconstruction is therefore a useful tool that can be employed to facilitate the implementation of management strategies that foster ecosystem resilience (Fritschle, 2009; Grossinger et al., 2007; Villagra et al., 2009), to confront new anthropic disturbances caused by climate change (Petit & Prudent, 2010) or changes in land use (Jackson & Nordstrom, 2011), and to deal with changing environmental factors such as a reduced sediment contribution (Pye & Blott, 2012; Hernández-Calvento et al., 2014). An awareness and understanding of the historical processes that have taken place can contribute to reducing the vulnerability of these ecosystems to new impacts (Peña-Alonso et al., 2018) through the application of management measures adapted to the dynamics of socio-ecological processes (Garnåsjordet, 2012).

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

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

Arid coastal dune systems can change over relatively short periods of time (Hernández-Cordero et al., 2006) and are therefore a natural laboratory to investigate dune disturbances. The response of dune systems after erosion or remobilization processes has been well studied in reference to hurricane effects (Morton et al. 1994; Hourse & Hamilton, 2009), uses that modified sediment transport such as grazing or obtaining firewood (Kutiel et al., 2004; Levin & Ben-Dor, 2004), landform transformation (Tsoar & Blumberg, 2002) or ecological restoration projects (Xu et al., 2018). However, the analysis of the recovery process of landforms and the recolonization of vegetation after the cessation of land uses which have affected them has been less studied. This is because in many cases the systems have been partially or totally urbanized (Santana-Cordero et al., 2016b), with the constructions often occupying the areas where the sediment enters the aeolian sedimentary system (García-Romero et al., 2016). This makes it impossible to measure biogeomorphological variables from the coastline inland and, using this information, study how the system has responded to the cessation of the historical land uses. In view of all the above, the aim of this article is to analyze the transformation process of an aeolian sedimentary system situated in El Médano (Tenerife, Canary Islands, Spain), with particular emphasis on historical land uses. The subsequent process of plant recolonization and the development of associated landforms (especially nebkhas) after the cessation of the different land uses that are identified in the study is also analyzed. A further aim is to determine the land uses that generated the greatest impact on the foredune and, therefore, on the rest of the system. The final aim is to identify the different biogeomorphological gradients between the coastline and the interior of the aeolian sedimentary system.

2. STUDY AREA

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

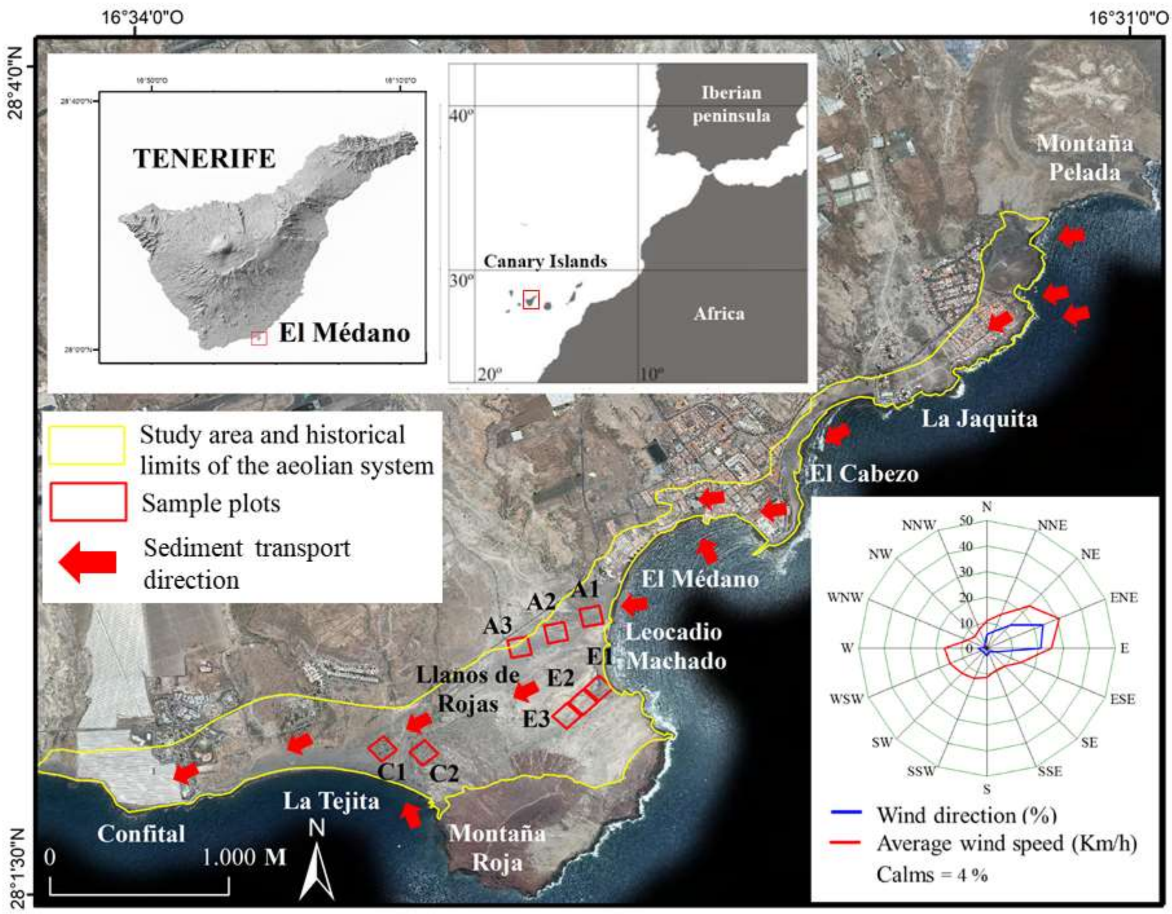

Figure 1. Location of the study area and historical limits of the aeolian system of El Médano. Bottom right-hand corner: mean wind direction and speed in the study area between 1980-2008. Aerial photo source: SDI Canarias (Canary Islands Government-Grafcan S.A.).

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

Fixed coastal dunes with herbaceous vegetation. The system is partially urbanized in the form of the town of El Médano and scattered buildings towards Montaña Pelada.

3. METHODOLOGY

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

3.1. Historical characterization and identification of land uses

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

3.1.1 Documentary sources and historical bibliographic references

An analysis was made of numerous historical documents of differing origin collected in the municipal archive of Granadilla de Abona and the archive of the Tenerife Friends of Nature Association (ATAN - Asociación Tinerfeña de Amigos de la Naturaleza) - who have drawn up restoration plans and fought through the courts to protect the area - as well as different historical bibliographies (Pedro de Olive, 1865; López-Soler, 1906; Escolar-Serrano, 1984). Historical field photographs were also used to visualize and determine the state of the system in the past. These were found in private archives, ATAN's photographic collection and the collections of the Foundation for Ethnography and the Development of Canary Crafts (FEDAC). In addition, the *Jable* search tool of the University of Las Palmas de Gran Canaria Library was used to find and review relevant articles in the local press and to obtain information from the records of the Official Gazette of the Canary Islands Government regarding licenses for the extraction of aggregates.

3.1.2 Historical aerial photographs, orthophotos and LiDAR data

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

3.1.3 Wind data

Wind variables (mean wind speed and direction and percentage of calms) were calculated from data recorded at a weather station owned by AEMET (State Meteorology Agency in Spain) and situated in Reina Sofía airport 2.5 km northwest of the study area (Fig. 1).

3.1.4 Field work

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

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

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

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

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

Table 1. Aerial photographs, orthophotos and LiDAR data used

Type (Source)	Year	Scale	Spatial resolution (m)	RMS* (m)	Delineation error (m)
Historical aerial photographs	1964[1]	1:30000	1	1.05-2.05	6.2
	1987[1]	1:18000	0.4	1.25-2.05	3.7
Orthophotos	2018[1]	^	0.1	< 1.5	0.1
LiDAR (DEM)	2009[2]	-	1	-	-
	2015[2]	-	1	-	-

* RMS = Root mean square. ^ flight with GSD de 22.5 cm/píxel. [1]SDI Canarias (Canary Islands Government-Grafcan S.A.) [2]National Geographical Institute (Spain). The delineation error was calculated according to Robinson et al. (1987).

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

Species	Origin	Height/Life forms	Environment
Astydamia latifolia	North of Africa and	Herb/Hemicryptophyte	Halophilous: rocky or

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

3.2. Relationship between biogeomorphological processes and land uses

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

4. RESULTS AND DISCUSSION

4.1 The historical land uses of the aeolian sedimentary system

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

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

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

Vegetation						
Groves	0.01	0.47	0	0	-0.01	-0.47
Total aeolian sedimentary system						
Total	2.10	100	1.03	49.05	-1.07	-50.95

4.1.1 Pre-1900

Seasonal grazing was the first land use that took place in the aeolian sedimentary system. This is confirmed by the presence of skeletal remains of livestock in different deposits found in more recent times, and references to sheep grazing in the vicinity of Montaña Roja around the year 1640 (Mederos-Martín & Escribano-Cobo, 2016). In addition, there are indications of the exploitation of limestone in references made about the presence of three lime kilns at the beginning of the 19th century (Escolar-Serrano, 1984). The development of El Médano as an urban settlement was driven by fishing, which would serve as the main economic support of the inhabitants, and the possibilities of beach anchorage and protection from the waves for the fishing vessels. The first reference to a resident population in the area dates back to 1857 (García-Casanova et al., 1996), although a few years later Pedro de Olive (1865) described the settlement as constituting just seven single-story buildings of which only one was inhabited. At the end of the 19th century, the port of Médano gained importance in the route between Santa Cruz de Tenerife and the south of the island, fostering the creation of new infrastructure in its role as an axis for economic growth. These constructions begin to occupy the aeolian sedimentary system, affecting areas of sediment input into the system, as has been found in other dune systems in the Canary Islands (Santana-Cordero et al., 2016b). In 1893, after a sample of sand from El Médano with a high iron content was displayed at the World's Columbian Exposition in Chicago, speculation began about the extraction of this mineral. British ships transported several tons of sand to study the profitability of possible extractions, and extraction requests were subsequently made for El Médano, Montaña Pelada, El Confital and La Jaquita. The extractions that were carried out in the study area took place much earlier than in similar systems in the Canary Islands, such as the Guanarteme isthmus in Gran Canaria (Santana-Cordero et al., 2014) and Jandía in Fuerteventura (Alcántara-Carrió et al., 1996). In this case, however, the extractions ceased after a few years as they were discovered to be unprofitable.

4.1.2 1900-1964

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

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

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

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

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

4.1.3 1964-1987

In this period, the abandonment of tomato cultivation occurs at the same time as tourism expands rapidly and extensively in the south of Tenerife and the exploitation of limestone ceases, replaced by the cement trade and imported synthetic paints. In 1965, the General Urban Development Plan of the municipality reclassified a large part of the aeolian sedimentary system as land for development, requiring a Partial Plan for its urbanization which was published in 1968 but never executed. In the corresponding Plans, a strategy of massive occupation of the coast is proposed with a coastal road as the main axis and a central road in the town of El Médano. The expansion of the construction sector and the demand for aggregates for the proposed new airport in the south of the island gave rise to the beginning of massive sand extractions in 1970. These extractions, which are clearly visible in the field (Fig. 3), generated a depressed area into which water could seep at high tide resulting in the formation of a small lagoon behind the current coastal dune. Extractions were carried out in an area covering some 175,000 m^2, and the approximate total volume of extracted material amounted to 200,000 m^3 (Canary Islands Government, 2004). In consequence, the coastal dune that existed at the time and the associated vegetation were eliminated (Fig. 4B), causing a significant decline in *T. moquinii* populations. The local aerodrome was finally closed in 1975, the same year in which the Reina Sofía International Airport was inaugurated in the south of the island. The urban development work proposed years earlier finally began in 1985 and led to the disappearance of various plant communities, including the groves of *Tamarix canariensis* (Table 3) shrubs which were situated next to the pier covering an area of 0.01 km^2 and forming part of the El Cabezo aeolian landforms (ATAN, 1989).

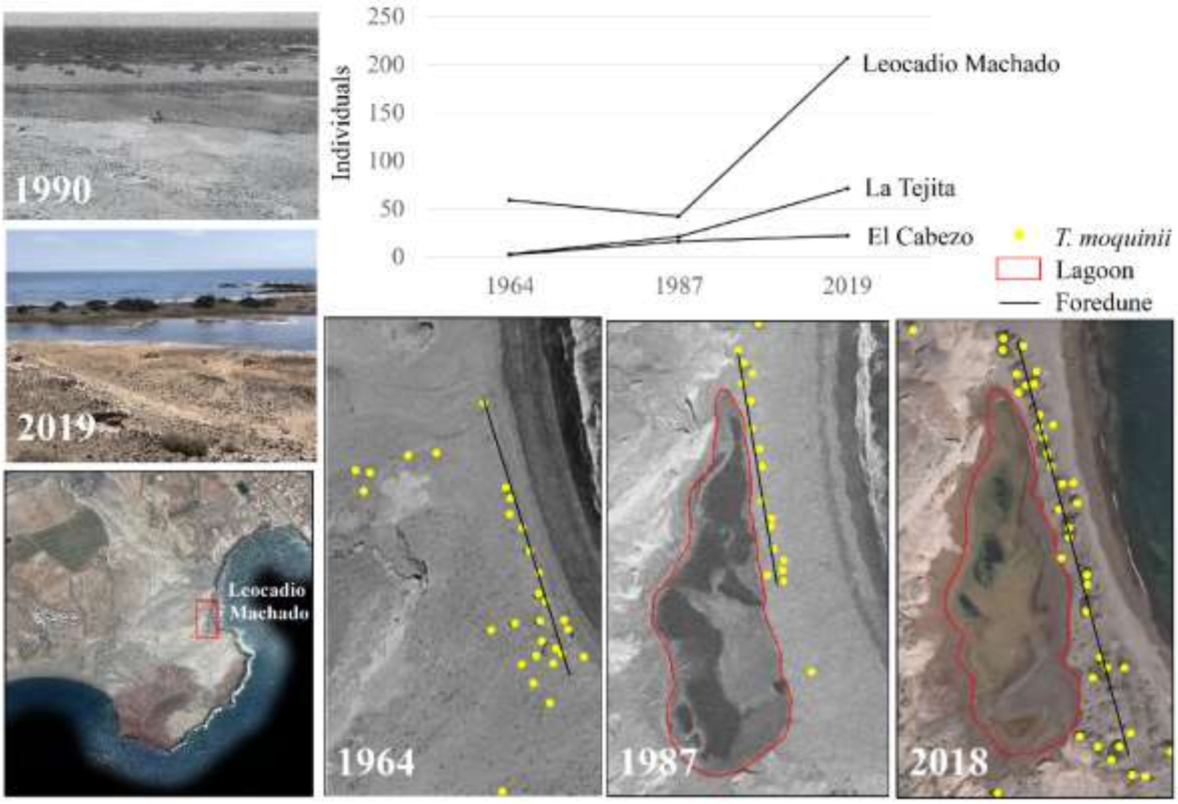

Figure 3. Evolution of the number of *T. moquinii* specimens in el Cabezo, La Tejita and Leocadio Machado between 1964 and 2019 (Graph). Repeat photograph of the foredune of Leocadio Machado in 1990 (Author: J. García-Casanova) and 2019. Aerial photograph and orthophoto of the foredune of Leocadio Machado.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

4.1.4 From 1987 to the present day

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

Likewise, new deposits of pyroclasts have been observed that have become detached from the volcanic cones present in the limits of the wind system.

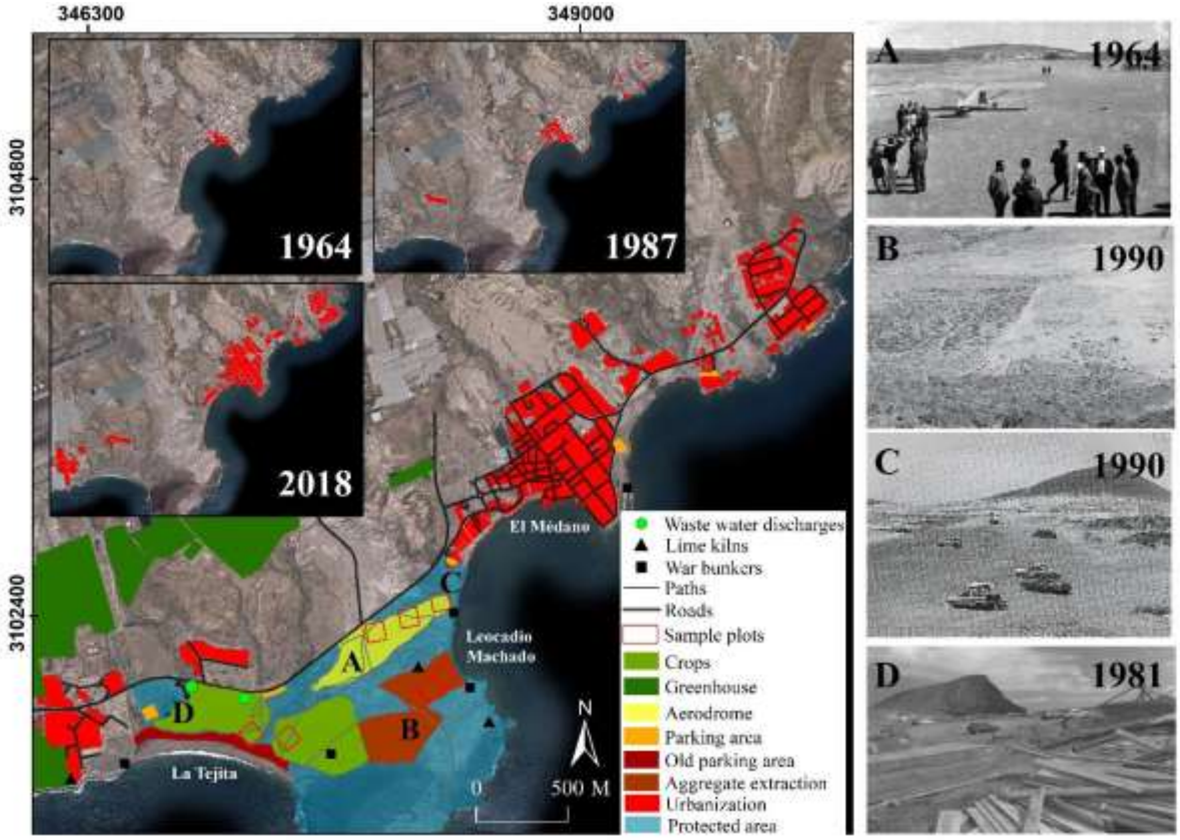

Figure 4. Left: Main historical land uses in the study area and built surface in 1964, 1987 and 2018. Orthophoto source: SDI Canarias (Canary Islands Government-Grafcan S.A.). Right: A: Aerodrome (Author: Alemany Nuez, P., 1964); B: Aggregate extraction (Author: García-Casanova, J., 1990); C: Car parking areas at Leocadio Machado beach (Author: García-Casanova, J., 1990); D: Car parking area and materials for building at La Tejita beach (ATAN, 1981).

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

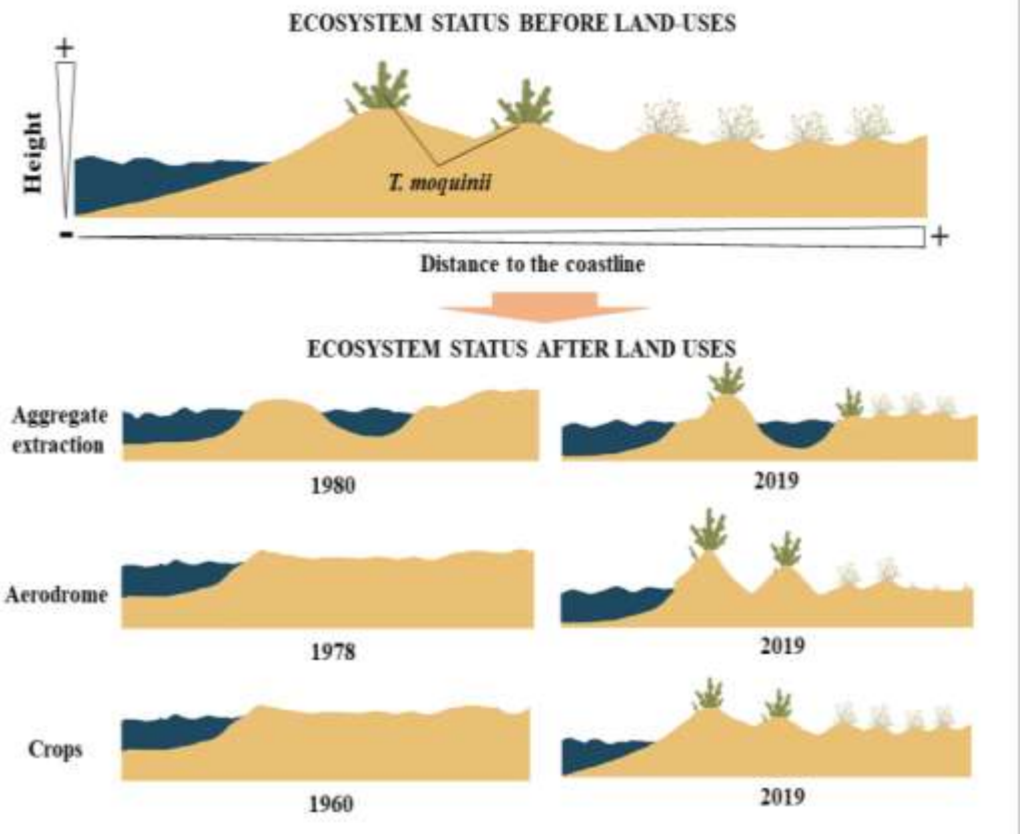

Figure 5. Ecosystem status before and after the historical land uses analyzed in this paper.

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

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

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

Contrast statistics (a,b)

	Height	Axis_ Long	Axis_ Trans	Cover	*T. moquinii*	Species richness	Exhumed roots	Dry plants	Dry front	Coast distance
X^2	62.3	22.4	16.6	145.1	13.7	13.6	4.6	13.5	30.1	48.6
p	0	0	0	0	0.001	0.001	0.102	0.001	0	0

a Kruskal-Wallis test

b Grouping variable: Area

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

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

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

Variables	Historical land uses		Dunnett's test	Sig.
Height	A	C	-0.29378(*)	0
	E	C	-0.29411(*)	0
	E	A	-0.00033	1
Axis_Long	A	C	-0.63137	0.461
	E	C	0.70049	0.4
	E	A	1.33186(*)	0.033
Axis_Trans	A	C	-0.34924	0.494
	E	C	-0.08364	0.958
	E	A	0.2656	0.632
Cover	A	C	-35.12686(*)	0
	E	C	-26.78374(*)	0

	E	A	8.34312(*)	0.002
T. moquinii	A	C	0.048	0.475
	E	C	-0.112(*)	0.036
	E	A	-0.160(*)	0.001
Species richness	A	C	0.414(*)	0.006
	E	C	0.411(*)	0.007
	E	A	-0.004	0.999
Dry plants	A	C	-0.004	0.994
	E	C	0.146(*)	0.006
	E	A	0.150(*)	0.002
Dry front	A	C	0.093(*)	0.028
	E	C	0.215(*)	0
	E	A	0.123(*)	0.001
Distance to the coast	A	C	89.69411(*)	0
	E	C	10.63572	0.575
	E	A	-79.05839(*)	0

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

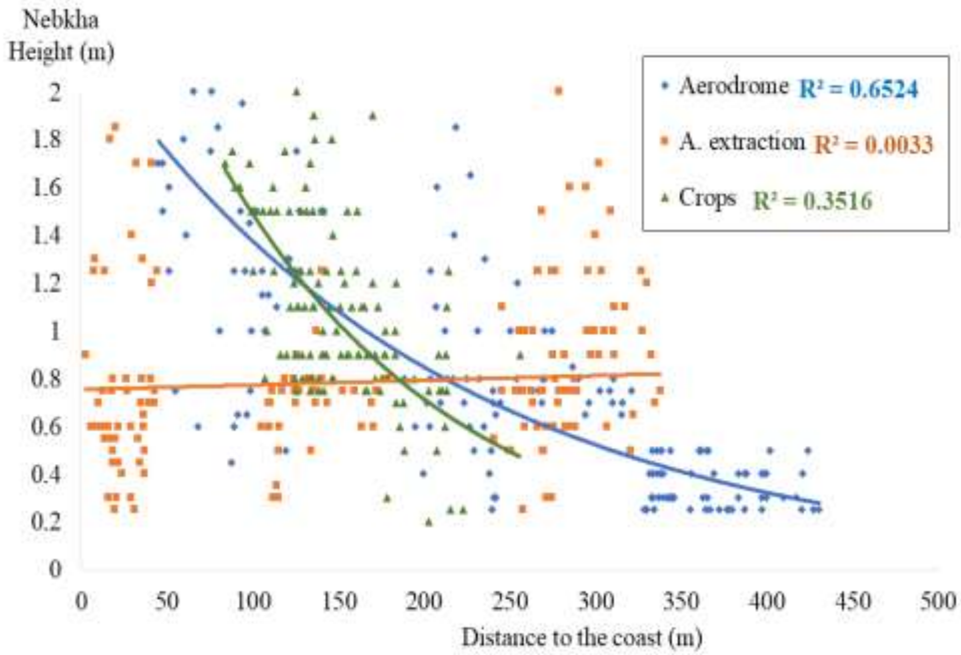

Figure 6. Relationship between distance to the coast (m) and nebkha height (m) in the aerodrome, aggregate extraction and crop cultivation areas.

4.2.1 Aerodrome

Important differences were found in dune morphology between the different plots of the *aerodrome* area, with a gradient in the morphological variables of the nebkhas which is dependent on *distance to the coast* as for example the height (R^2=0.6524). The height of the closest dunes to the beach (sample plot A1) was generally above 1 m, whereas those in the third plot (A3) did not exceed 0.5 m (Fig. 6). The same pattern is repeated for dune *longitudinal axis* and *transverse axis*, which in both cases present a negative correlation with *distance to the coast* (Spearman's rho. = -0.765; $p < 0.01$, in both cases) (Table 5). Given this correlation between dune morphology (*height*, *longitudinal axis* and *transverse axis*) and *distance to the coast*, it can justifiably be argued that there exists a gradient of recovery and that the foredune affected by this historical land use is now stabilized, allowing plant species to establish themselves (Hesp, 2002). The dunes closest to the coast are the first to undergo recovery, whereas the speed of recovery is slower for the dunes further away from the coast as they take longer to begin to capture sediment in significant amounts. In addition, the pattern of lower nebkha height as the distance to the coast increases is related to the decrease in the number of larger-sized plant species, such as *T. moquinii*.

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

vermiculata and *P. nivea*, there is a larger number of *F. capitata* and *L. pectinatum* individuals. This pattern is similar to that described for Maspalomas by Hernández-Cordero et al. (2015b), in that the gradient with the distance to the coastline and the topography are factors that influence the establishment of individual plant communities depending on their ecological requirements.

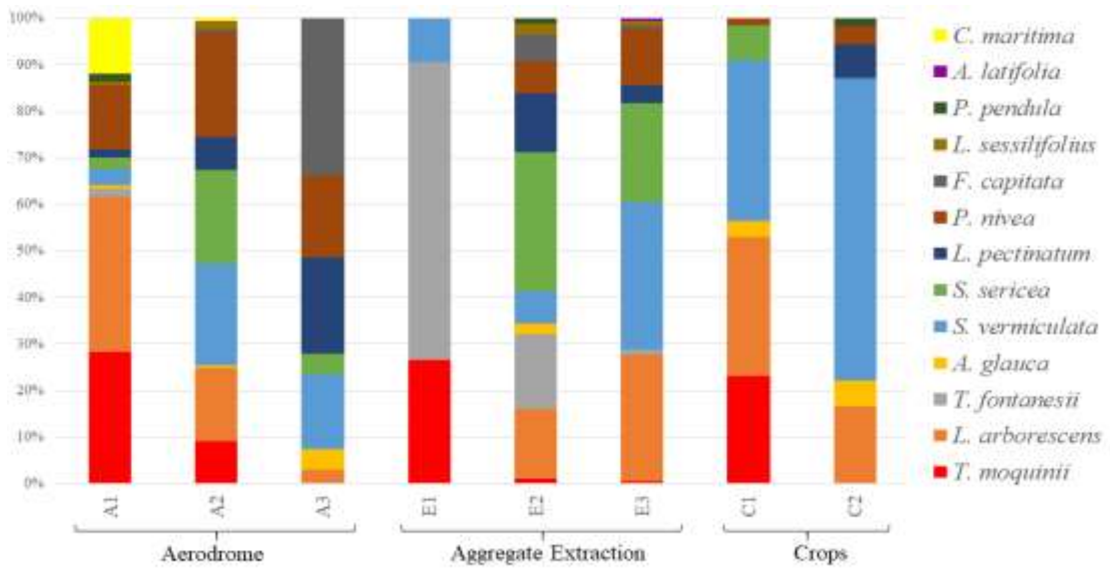

Figure 7. Plant species in the nebkhas of each plot.

4.2.2 Aggregate extraction

With respect to the *aggregate extraction* area, the most important consequences have been in the extractions made below sea level, the subsequent disruption to the original slope, and the elimination of the surface sand sheet, as occurs in other ecosystems with similar characteristics (Fernández-Montoni et al., 2014; Price et al., 2005; Garriga-Sintes et al., 2017). As a result of the extractions, an underground filtering of sea water generates a lagoon at high tide. However, in this case, the trend shown by the morphological and vegetation variables is for them to increase with *distance to the coast* (Table 6), with the exception of the

T. moquinii variable (Spearman's rho = -0.395; $p < 0.01$). This trend is the opposite to that observed in both the *crop cultivation* and *aerodrome* plots. In addition, the variables show low or very low levels of correlation (with the exception of *species richness*: Spearman's rho = 0.606, $p < 0.01$). Such patterns are not common and are difficult to explain in systems with natural sedimentary dynamics. In this particular case, as can be seen in Figure 4 (Aggregate extraction, R^2: 0.0033), the effect of aggregate extraction has been such that there is presently very little indication of a morphological gradient as was observed in the area affected by the aerodrome. Distance to the coast cannot therefore be considered a determining factor as it was in the *aerodrome* area (*height*: Spearman's rho = 0.195, $p < 0.05$; *length*: Spearman's rho = 0.363, $p < 0.01$; *width*: Spearman's rho = 0.237, $p < 0.01$) (Table 6). As a consequence of the topographic modifications generated by the extractions, changes have occurred in the capacity of the vegetation to recolonize the modified surface and, therefore, in the volume of retained sand, as shown by Duran & Moore (2013). In this respect, *T. moquinii,* a crucial element in coastal dune formation (Hernández-Cordero et al., 2015a, b) is only present in significant numbers in the first plot (E1), whereas further inland it is practically non-existent (Fig. 7).

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

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

	Distance to the coast					
	Aerodrome N=174		**Aggregate extraction** N=164		**Crops** N=123	
	Spearman's Corr.	Sig.	Spearman's Corr.	Sig.	Spearman's Corr.	Sig.
Morphology						
Height	-0.806(**)	0	0.195(*)	0.012	-0.208(*)	0.021
Axis_Long	-0.765(**)	0	0.363(**)	0	-0.117	0.197
Axis_Trans	-0.765(**)	0	0.237(**)	0.002	-0.178(*)	0.049
Vegetation						

Cover	-0.574(**)	0	0.136	0.082	-0.198(*)	0.028
T. moquinii	-0.557(**)	0	-0.395(**)	0	-0.096	0.293
Species richness	-0.376(**)	0	0.606(**)	0	0.145	0.11
Plant status						
Dry plants	-0.172(*)	0.023	-0.152	0.053	-0.055	0.543
Exhumed roots	-0.190(*)	0.012	-0.154(*)	0.049	0.071	0.433
Dry front	-0.353(**)	0	0.322(**)	0	-0.17	0.06

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

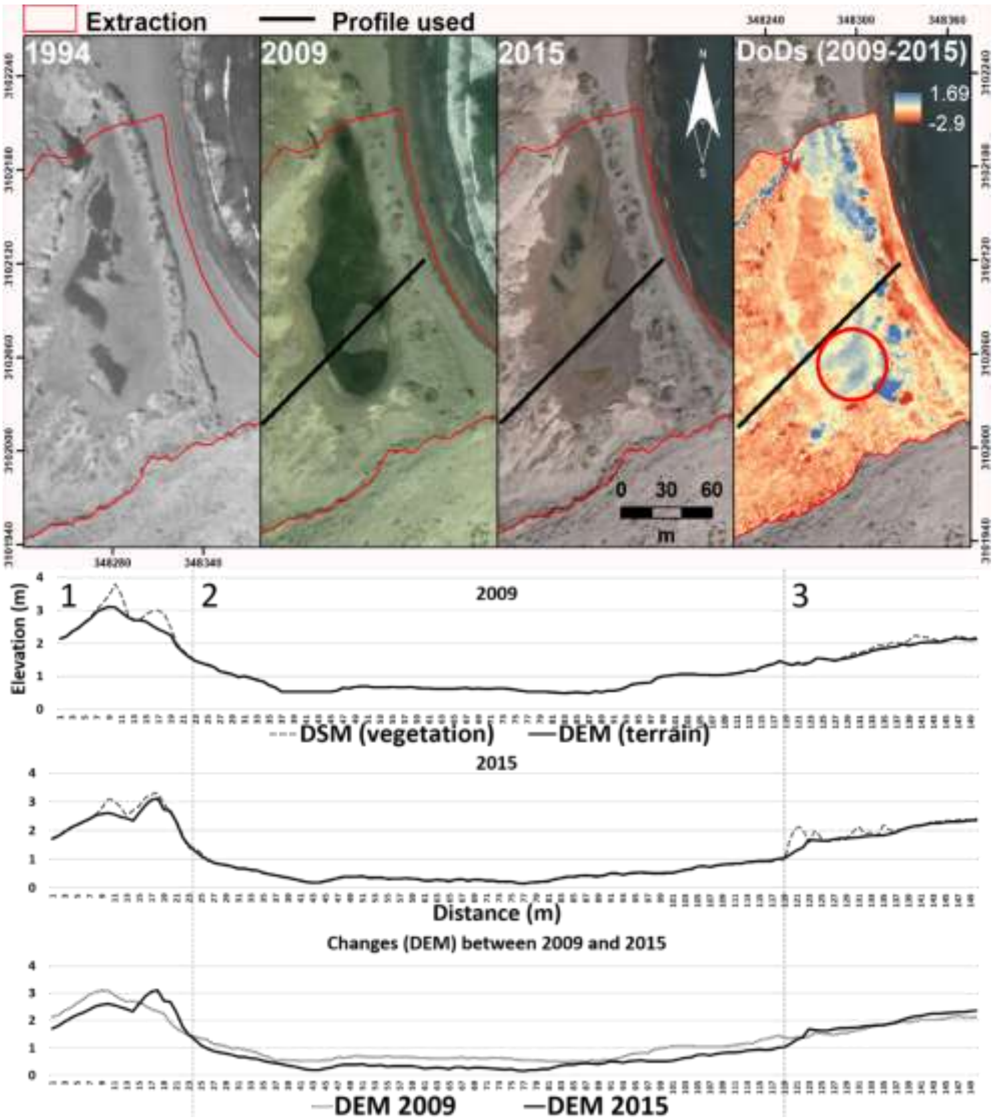

Figure 8. Above left and center: Biogeomorphological evolution of the aggregate extraction area between 1994 and 2015, especially in the foredune. Above right: DoDs (2009-2015): Erosion and accumulation near the foredune and lagoon. Below: 2009 and 2015 DEM profiles (terrain and vegetation) extracted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

4.2.1 Crops

In the *crop cultivation* area, no statistically significant differences were found between various variables (*length*, *species richness*, *T. moquinii*, *dry plants*, *dry front* or *exhumed* *roots*) and *distance to the coast* (Table 6). This pattern is reinforced by the absence of any significant correlation at the p <0.01 level. Statistically significant correlations at the p <0.05 level were obtained in just 3 variables, though these were low or very low (*height*: Spearman's rho = -0.208, p<0.05; *width*: Spearman's rho = -0.178, p<0.05; *cover*: Spearman's rho = -0.198 p<0.05). Thus, *distance to the coast* is not a determining factor in the crop area variables. The morphological variables of nebkha *height* and *width* presented the highest correlations. The correlation with *height* was greater than in the *aggregate extraction* area and, as in the case of the *aerodrome* area, the correlations were negative. Again, the pattern, though not statistically significant (Fig. 4, Crops; R^2: 0.3516), is common in the formation and development of the foredune and dune systems (Hesp, 2002). With respect to the plant species, *T. moquinii* is found in the foredune (Plot C1) along with *L. arborescens* and *S. vermiculata* as well as specimens of some other plants in fewer numbers. The most dominant plant by far in the nebkhas of the second plot is *S. vermiculata.*

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

4.3 Relationships between current biogeomorphological processes and historical land uses

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

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

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

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

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

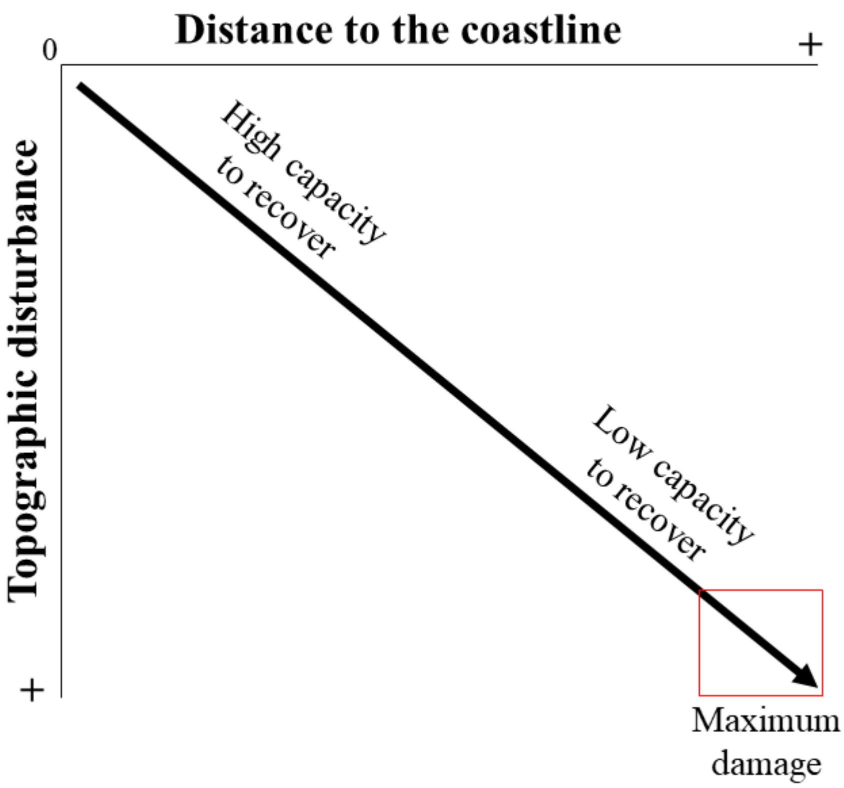

Figure 9. Conceptual diagram showing the relationship between the capacity of the system to recover related to the distance to the coastline and the topographic disturbance

5. CONCLUSIONS

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

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5.4 Deforestation by historical lime industry in an arid aeolian sedimentary system: an applied and methodological research

Deforestation by historical lime industry in an arid aeolian sedimentary system: an applied and methodological research

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Science of The Total Environment

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Abstract: Traditional land uses have been altering aeolian sedimentary systems for centuries through the removal of plant material for grazing, fuel or farming purposes, among others. This paper studies the impact on cut vegetation for the lime industry, which was burned through kilns as fuel. A methodology was developed and applied based on: i) the interpretation of historical documents, oral interviews and publications in the literature; ii) morphological measurements of the plants used to fire the lime kilns in order to determine the current available biovolume and to estimate the surface area affected by plant removal; iii) the integration and analysis of all the data through a geographic information system (GIS) in order to quantify the impact of the lime kiln industry on the vegetation in the study area. The oral sources indicate a preference for three particular plant species to fire the lime kilns: *Launaea arborescens*, *Lycium intricatum* and *Covolvulus caput-medusae*. It is calculated that to fill a big-sized lime kiln oven it would be necessary to clear a low density vegetation area of 21826.08 m^2 or 3075.72 m^2 with high density vegetation. The results obtained indicate that complex processes were generated as a result of the demands of the limestone industry. Meeting these demands resulted in modifications to the characteristics of the vegetation of the aeolian sedimentary system of Jandía, particularly in terms of plant communities, the abundance of certain species and flora richness, as well as in modifications

to geomorphological processes and the eventual collapse of the activity as a consequence of the continued overexploitation of the plant material until the 1960s. The present research allows us to learn from past experiences in which industries lacked proper planning and thus their activity led to their own collapse and rapid environmental degradation.

Keywords: deforestation, driving forces, lime kiln, historical ecology, limestone production, logging.

1. Introduction

Aeolian sedimentary systems are among the ecosystems that have suffered most as the result of human uses and their evolution over the course of time (Thomas & Wiggs, 2008), whether this use has been to obtain fuel or materials for construction or for grazing purposes (Kutiel et al., 2004; Levin & Ben Dor, 2004; Provoost et al., 2011; Sciandrello et al., 2015; Hoffman & Rohde, 2007) and, more recently, the recreational uses (San Romualdo-Collado et al., 2021) and the urbanization have been the leading degradation causes (Feng et al., 2021). The reconstruction of these uses in the present work is approached through the methodological framework of historical ecology (Szabó, 2015), using a wide variety of sources (Miller, 1999; Bürgi et al., 2000; Nüsser, 2001; Skovlin et al., 2001; Petit & Lambin, 2002; Axelsson et al., 2002; Pinto & Partidário, 2012; Raska et al., 2015), and with the aim of preserving cultural heritage in ecosystems and landscapes, understanding historical trajectories, and improving ecosystem and landscape management (Bürgi & Gimmi, 2007).

Apart from farming and grazing, one of the oldest human activities that has contributed to the alteration of aeolian sedimentary systems is the production of lime. At global level, the lime industry and the techniques used have evolved substantially over the course of history. Archaeological references indicate an industry with a 16,000-year-long history, while the first written references date back to Marcus Pourcious Cato (234-149 B.C.) and his description of how to build and use a lime kiln (Swallow & Carrington, 1995; Wernecke, 2008). One of the many historical uses of lime has been used to soak corn kernels in water to dissolve the outer shell, thereby releasing proteins and vitamins (FAO, 1992). Mesoamerican communities chewed lime and tobacco together to release nicotine (Miner, 1939; Marcus & Flannery, 2004), purify water, accelerate the decomposition of buried corpses, regulate the pH of agricultural soils, and as decorative paint, among other uses (Manzano-Cabrera, 2016). However, it has been for construction purposes that vast quantities of this product have been required and demanded, especially for local consumption or exportation (Marrero-Rodríguez et al., 2020a, b). This demand has resulted in substantial deforestation (Diamond, 2005) as huge amounts of fuel are required for its production (Abrams, 1994; Barba & Córdova-Frunz, 1999; Schreiner, 2002). In this regard, some works have analysed and discussed the environmental degradation process associated with the lime kiln industry in the Mayan civilization in Central America (Wernecke, 2008). However, there is a gap in the scientific literature when it comes to addressing reconstructions of the impact of specific historical activities that have led to the degradation of an ecosystem. Normally, the approach used when considering historical deforestation is that it is a general phenomenon, and this approach tends not to take into account the different species or the specific needs of each industry. In contrast, the approach used in the present study links and connects information gathered from historical and oral sources with specific characteristics of the lime kiln industry, as well as with the types of vegetation in the study area and their particular characteristics.

The lime kiln industry in the arid aeolian sedimentary systems of the Canary Islands seems to have been common and to have had three main consequences: the exploitation of large areas as quarries for limestone extraction, sediment remobilization, and massive deforestation associated with the fuel demand as it happened on the islands of La Graciosa and Fuerteventura (Santana-Cordero et al., 2016; Marrero-Rodríguez et al., 2020a). The amount of fuel that is demanded will be conditioned by the type of vegetation (Schreiner, 2002;

Marrero-Rodríguez et al., 2020b), the type of kiln used (Wernecke, 2008), the composition of the limestone (Schreiner, 2002), and the experience of the worker in charge of firing the kiln.

It has been shown in the literature that the use of vegetation produced alterations in the plant community population structures (Sala et al., 1986), changes in species richness (Kutiel et al., 1999; Faggi and Dadon, 2011; Báldi et al., 2013), the remobilization of sand sheets (Hoffman & Rohde, 2007; Marrero-Rodríguez et al., 2021), and erosion processes (Angassa, 2014).

In previous works, given the difficulty that this entails, the deforestation process is not quantified or spatialized; However, the proposed methodology to approach the present work allows combining oral sources, historical documents and field work for the quantification and spatialization of the information in a GIS. In this sense, the main aim of this work is to develop a methodology and its application that allows to reconstruct, evaluate, measure and locate the effects of deforestation processes and carry out a case study in an arid aeolian sedimentary system. This aim includes several specific aims: i) To know what species could be burned in lime kilns and what amount of vegetation was required by the industry; ii) Measure the effects of deforestation on the aeolian sedimentary system in term of surface affected and number of plants used; iii) Analyse the socio-economic changes and driving forces that occurred in the industry as determinants of deforestation intensity and vegetation recovery.

2. Study area

The aeolian sedimentary system of Jandía, with an area of 54 km^2, is located on the southern coast of the island of Fuerteventura in the municipality of Pájara (Fig. 1). The area has been described as having a warm desert climate with marked aridity (Alonso et al., 2011). The scarce and highly irregular precipitations are concentrated in just a few days of the year, and do not usually exceed 100 mm. The high temperatures, with annual averages of around 20ºC, the intense insolation and the strong and frequent winds favour evaporation (Alcántara-

Carrió, 2003). The isthmus is covered by sand, predominantly biogenic. The sediments come from the erosion of aeolianite deposits and quaternary calcareous crusts located in the inner part of the isthmus and from the scarce sandy contributions from the current beaches or the erosion of the materials that constitute the cliffs of Barlovento (Alcántara-Carrió, 2003; Alcántara-Carrió et al., 2010). The sediments are subject to almost continuous aeolian transport by the dominant NW winds which form the nebkha field, a rampant dune on the southern limit of the windward side and two falling dunes in Sotavento (Alcántara-Carrió, 2003; Alcántara-Carrió et al., 2010). Aeolian transport takes place in a SSE direction (Alcántara-Carrió and Alonso, 2002; Alcántara-Carrió et al., 2010; red arrows in Fig. 1) and marine dynamics are responsible for redistributing the sediments southwards (blue arrows in Fig. 1).

Vegetation at the present time consists of shrub and herbaceous plant communities, principally comprising xerophilic, halophilic and psammophilous species. According to the Canary Islands vegetation map (Del Arco et al., 2006), most of the area is occupied by the phytosociological association *Polycarpaeo niveae-Lotetum lancerottensis*, fundamentally constituted of chamaephytes like *Polycarpaea nivea* and *Lotus lancerottensis*, which establish themselves on compact sandy substrates or sandy-rocky substrates. Also of some importance is the *Euphorbio paraliae-Cyperetum capitati* association, a community comprising herbaceous psammophilic and chamaephyte species like *Euphorbia paralias* and *Cyperus capitatus*, associated to mobile sand areas. However, physiognomically, the dominant species are the shrubs *L. arborescens* and *Salsola vermiculata*. Jandía is also home to one of the most important populations of *C. caput-medusae*, a small halophilic shrub endemic to the Canary Islands and included through Act 4/2010, of June 4, in the vulnerable category of the Canary Islands Catalogue of Protected Species and in Appendices II and IV of the Habitat Directive.

The Isthmus of Jandía was exploited only as pasture land until approximately 1850, at which point references about obtaining fuel in this space appear for the first time in the historical documents. These traditional activities ceased with the emergence of tourism in the island, from 1960 onwards. The rise of tourism resulted in the extraction of aggregates for construction and the creation of urbanizations, infrastructures and tourist facilities along different coastal areas of the isthmus (Marrero-Rodríguez et al., 2020a). At present, the area considered in the study has two main urban centres (Costa Calma and La Pared). The development of tourism has led to alterations to the aeolian sedimentary system, especially in terms of the erosion of the beaches of the southern coast due to the reduction in the supply of sediments to the coast from the inland sedimentary deposits. This reduction has been due to the generation of physical barriers through the construction of tourist complexes and roadways, as well as sand extraction and landscaping along the roadways (Alonso et al., 2002).

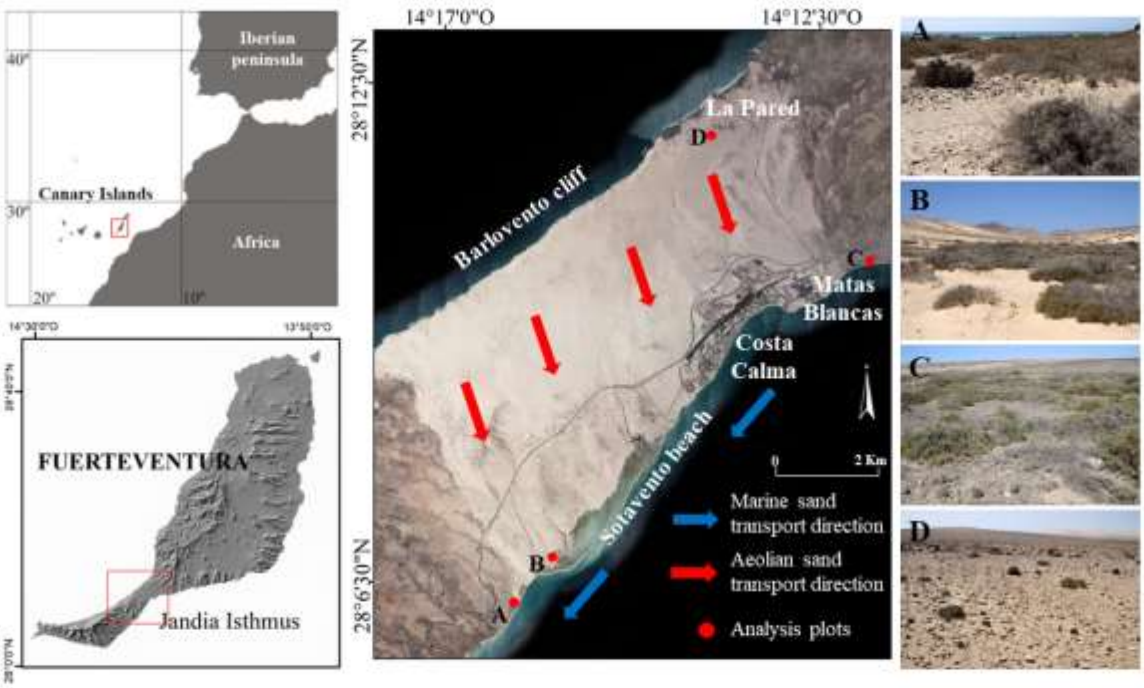

Figure 1. Location of the study area and plots. General view of the analysis plots in photographs on the right. 2019 digital orthophoto source: SDI Canarias (Gobierno de Canarias, GRAFCAN, S.A.).

3. Methodology

3.1. Historical sources

Among the most relevant historical documents used for this work is the report prepared by the secretary of the Pájara City Council (Fuerteventura, Canary Islands), Mr. Justo P. Villalba, in 1868, entitled “Description of the *Dehesa de Jandía*”. In this document, consideration is given to the uses of the land at the time and to its potential uses. The minutes of the corresponding Fuerteventura Island Council meeting are also reviewed. In addition, an analysis is undertaken of the information recorded in a video of the burning of limestone made in Tefía (Fuerteventura), as well as that contained in an inventory of lime kilns stored in the archives of the Island Council of Fuerteventura. In addition, 8 oral interviews to the last living lime kiln workers were held with the aim of gathering information on the activity. The interviews were conducted following the oral history methodology (Fogerty, 2005), which is based on a semi-structured conversation, with an open script, between an interviewer and an interviewee. The interviewees were aged between 73 and 101, and were people who had personally been involved in firing lime kilns in the study area. In this way, it was possible to find out which species were used as fuel, the areas from which it was obtained, the characteristics of the lime kilns (such as their shape and size), the number of firewood loads required to burn a single kiln (camels were used to transport the material), and the quantity of fuel (m^3) needed (the capacity of the small-sized kilns was 90 m^3, of the medium-sized ones 240 m^3, and of the large-sized ones 360 m^3). In the historical documents and oral interviews, the species are called by their common name. As an example, the genera *Salsola*, *Suaeda*, and *Schizogyne* are all commonly called *salty plants*. Therefore, the common names were taken, and all the species that receive this name and that have current populations or for which there are historical records of their presence on the island of Fuerteventura were selected. In addition, it was considered that when a common name appeared in a specific document, all the species of that genus would have potentially been introduced into the kilns.

3.2. Analysis of the impact on vegetation of the lime industry in the aeolian sedimentary system

In order to determine the impact of the lime industry on vegetation in the aeolian sedimentary system of Jandía, an estimation is first made of the surface area affected by the removal of the amount of plant material required to generate this product according to the particular characteristics of that material. For this, the first step is to calculate the biovolume that could be obtained through the removal of vegetation in a specific area and compare it with the amount required for lime kiln operation. That is, based on the amount of vegetation currently present in the area, it is possible to determine through extrapolation the amount that would have been required for each lime kiln size. Consideration is also given to the fact that not all plant species were suitable for lime kiln firing. Based on the information recorded in the historical sources, three species were selected: *Launaea arborescens, Lycium intricatum* and *Convolvulus caput-madusae* (see excerpt of the review and report to Francisco Cabrera and Justo P. Villaba in the Results section). These plant species were the preferred choices to fire the lime kilns. To determine the currently existing biovolume and compare it with what was required for a lime kiln operation according to the oral sources, a field campaign was carried out over the course of September 2020. This time of the year was chosen as the oral sources indicated that the best moment to harvest the vegetation was at the end of the dry season which is when it burns best. Disused lime kilns were located during the field campaign, and specimens of the three previously mentioned species were identified in the areas around the kilns. Plots were marked in areas close to the ovens where these species were present in order to measure the morphological characteristics of each plant. The variables that were measured in each specimen were height, largest diameter and smallest diameter. The data were recorded for a total of four plots (Fig. 1), with each plot having a surface area of 1,250 m^2 (50 m long x 25 m wide). Three plots were situated in the immediate surrounding area of the kilns (plots A, B and C), and one in a kiln-free area as the toponym of that particular area (The Wall) was cited by various of the oral sources as a plant collection site (plot D). The measured variables allowed calculation of the biovolume based on a cylindrical morphotype according to the following equation (Blanco Oyonarte and Navarro Cerrillo, 2003):

$$B_v = \pi * \left[\frac{Dm}{2}\right]^2 * h \quad (1)$$

where Bv is biovolume in cubic meters, Dm is mean diameter (metres) and h is height.

The result of this formula was then multiplied by a correction factor according to the porosity (Baldauf, 2017) of each of the three sampled plant species. This allows a more precise biovolume estimation. A correction factor of 1 was applied to the two low porosity species, *Launaea arborescens* and *Convolvulus caput-medusae*, and a correction factor of 0.5 to the species of higher porosity, *Lycium intricatum*, the result of its lower compactness.

Given the variable characteristics of the plants in the different plots, the different vegetation conditions were also identified during the field campaign in order to estimate with greater precision the affected surface area. For this, the following were calculated: the number of individual plants of the optimal species for lime kiln firing; plant cover (m^2): total biovolume and vegetation density. This latter datum was obtained based on the method developed by Mostacedo and Frederiksen (2000) to calculate tree density per hectare, as follows:

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

where Dh is density per hectare and $\bar{D}$ is average distance between central points.

With these variables, a cluster analysis was then performed using the Ward method (Euclidean distance) to group plots with similar vegetation conditions and to determine the surface area affected by removal of this vegetation according to its characteristics. Through the mean biovolume of each cluster group, and using plot size as reference (1250 m^2), it was determined how much surface area was affected by each lime kiln firing according to lime kiln size (small-sized = 90 m^3 capacity, medium-sized = 240 m^3 capacity, and large-sized = 360 m^3 capacity) and the different characteristics of the vegetation, using a direct proportion calculation.

3.2.1. Spatial model of the impact on vegetation of the lime kiln industry

In order to determine the spatial impact of the lime industry on the aeolian sedimentary system of Jandía, we considered the following questions:

i) Where did the vegetation removal take place? The optimal routes to the lime kilns were calculated using the toponyms that appear in the historical and oral sources (sites of vegetation removal and sites where the lime kiln workers lived), using as basepoint the digital elevation model (DEM) obtained from a LiDAR flight (spatial resolution of 1 m - corresponding to 2017). The routes, although adapted to the optimal conditions of the terrain (slope, secondary net path), were corrected to avoid large volumes of sand that would hinder transport by foot or with pack animals such as camels (slope + aeolian landforms, main net path).

ii) Where were the plots/zones of highest/lowest vegetation? The 2017 orthophoto was used (spatial resolution: 0.25 m and resampled to 1 m) to develop the procedure proposed by García-Romero et al. (2018) to calculate and classify vegetation density in arid aeolian sedimentary systems using airborne data sources. This procedure resulted in 4 vegetation density categories, the first two characterised as low vegetation densities and in which zones (fishnet tools in GIS) with dimensions that were calculated on the basis of the data of plots B and D (low vegetation) were placed, while the last two categories obtained correspond to higher vegetation density and in which zones were situated with dimensions that were calculated on the basis of the data of plots A and C (abundant vegetation).

iii) How many lime kiln firings could the aeolian sedimentary system of Jandía provide? A maximum count of all the zones with the dimensions and characteristics determined on the basis of the calculations of section 2.2.1 was performed, and these were situated in the zones obtained according to vegetation density in the answer to the previous question. Finally, the distance was calculated (near tools in GIS) to the optimal routes and kilns in order to interpret their spatial distribution.

3.2.2 Analysis of the driving forces

The analysis of driving forces was undertaken following a shortened version of the procedure proposed by Bürgi et al. (2004), as in that case the methodology was applied to an industry developed in a specific space and period of time rather than to the general evolution of a landscape. In this regard, although there are other driving forces that altered the aeolian sedimentary system of Jandía, in the present study only those related to the lime kiln industry are analysed. This analysis involved two main steps: i) definition of activity and landscape, in which basic information about the industry and study area is described; ii) system analysis, which focuses on driving forces, their scales, and changes to physical landscape elements. The driving forces are presented in two main processes related to the lime kiln industry, Firstly, the deforestation process associated to the activity, and secondly the recovery of vegetation associated to cessation of the activity.

4. Results

The lime industry activity began in the Canary Islands shortly after they had been conquered by the Spanish (15th century) and continued until approximately the end of the 1960s. However, the industry underwent important changes after the beginning of the 20th century that conditioned the demand for vegetation. These included shipments of unburnt limestone due to the demand for its use in other islands and shortage for plant material for lime kiln firing, the appearance of coal as an alternative fuel source, and the displacement of the lime kiln industry to industrial zones and ports as the demand for lime rose. From the 1960s onwards, the arrival in bulk of cements and synthetic paints replaced the lime business, which declined rapidly throughout the archipelago. The demand for plant material coincided with the commencement of the lime industry shortly after the conquest of the islands and continued as a relatively minor activity until the middle of the 19th century when demand began to increase significantly. It can therefore be concluded that the highest demand for vegetation in the Jandía peninsula took place in a period extending from approximately 1850 to 1960.

4.1 Species likely to be used as fuel in the kilns

A list of plants that could be used as fuel in the lime kilns was generated using the historical documents, the revised bibliography and the different oral sources consulted (Table 1).

To understand why a particular plant would have been chosen as fuel it is important to understand the lime kiln firing process and the structure of the kiln. The kilns have a grate under which a hole is dug that is filled with plant material which will burn when the kiln is initially fired. Here, the ashes left over from the burning of the plants will accumulate (Fig. 2A and B). At the base of the kiln is a small opening through which fuel can be introduced (Fig. 2C) and via which the kiln is fired. The size of the opening must be small enough to minimize heat escaping but large enough to allow the introduction of fuel. The kiln is fired at night (Fig. 2 D and E), as the lower temperatures allow the lime kiln operator to carry out his work next to the kiln, which can reach temperatures of up to 1,000º C. Each time a lime kiln operation is performed, fuel needs to be introduced via the lower opening of the kiln during a period lasting approximately 48 hours until the process is concluded (Fig. 2F).

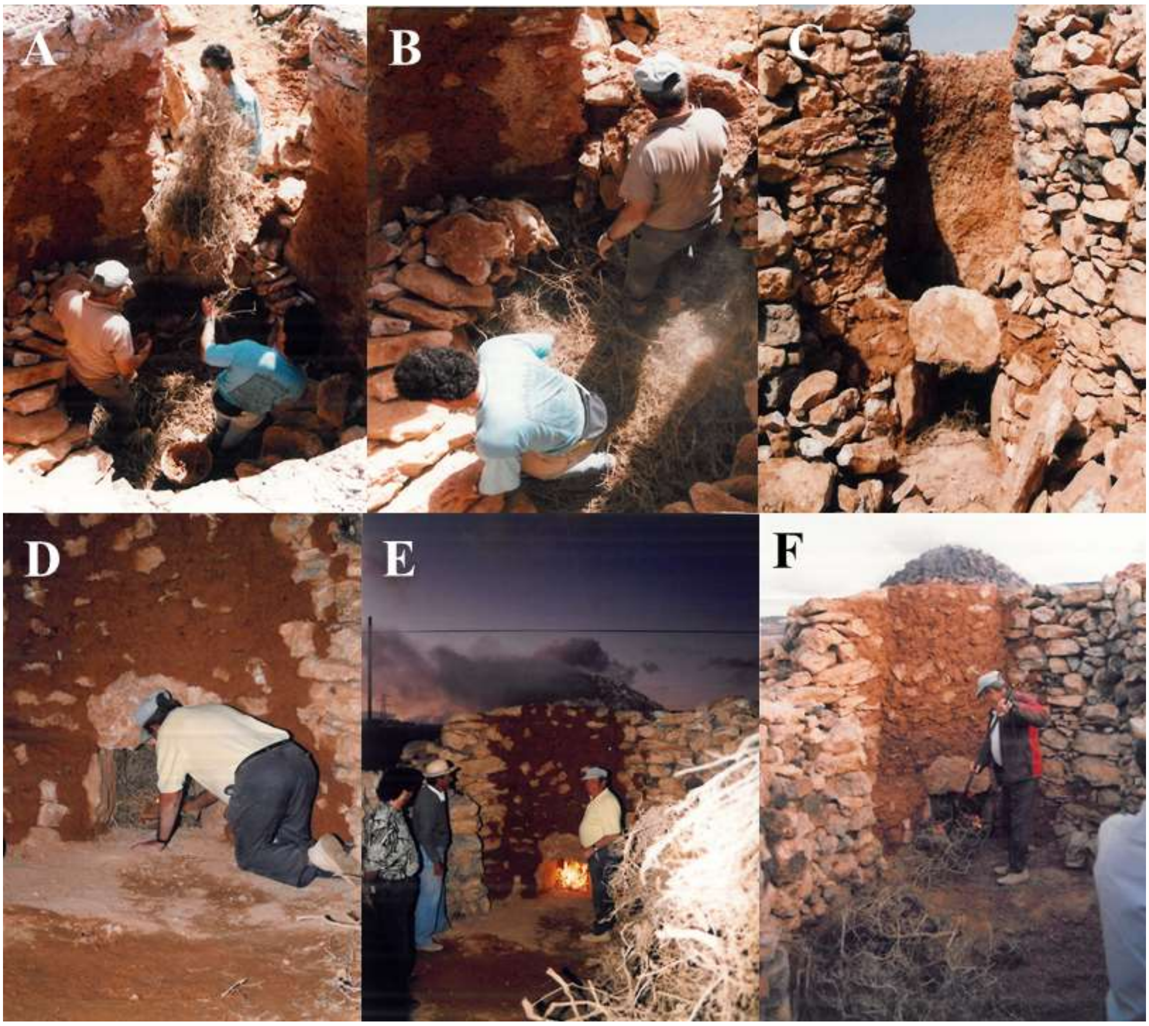

Figure 2. Lime kiln firing process (Source: Archivo Histórico of the Cabildo de Fuerteventura).

With these characteristics in mind and as ascertained in the oral interviews that were held, the species to be introduced into the kiln had to meet certain requirements. The plants that were introduced could not leave excessive amounts of ash after their burning as this could end up silting up the space dug beneath the grate bars of the kiln and result in the stone remaining raw and unsellable. In addition, according to the interviewees, some woody plants burn too slowly and do not give off enough heat to reach the upper part of the kiln where the stone is situated, and which could be up to 3 m high. In addition, if the plant material did not burn quickly enough, the opening through which the fuel was introduced could be blocked and impede the further introduction of fuel. As mentioned, fuel had to be introduced over the course of approximately 48 h (this task was normally performed with two operators working in turns), and the use of heavy plant material would make the firing process more difficult. This was commented on in the oral interviews:

> *Aulaga* [*L. arborescens]* was the most used because if there were too many *salty bushes* [*Salsola, Suaeda* and *Schizogyne* species] the kiln would fill up with ashes, and the ash would reach to where the stone was and you wouldn't be able to carry on firing it. *Espino* [*L. intricatum]* was also put in there and *chaparro* [*C. caput-medusae]*. The *chaparros*, when they're big like they are now, have roots like asphalt and burn in a moment. I used to spend the whole year firing the kilns, although there were times when it took up to three months to find all the vegetation needed […]. *Tarajales* [*T. canariensis*] we wouldn't use. They're too heavy and don't burn quickly enough and clog up the mouth of the kiln. They make charcoal and not ash. […]. That's why later the city council began to give out licenses because there was less and less vegetation to cut and they'd give you permission to cut only what was needed for the kiln […]. At the end, as I say, I was spending up to three months or more to gather the vegetation because there were no plants left to fire the kiln, and you could only fire the kiln three or four times a year unless you had money to buy coal [Oral report by Francisco Cabrera].

The species that met the requirements previously described were therefore as follows: *L. arborescens, L. intricatum* and *C. caput-medusae.* The use of *L. arborecens* was mentioned in several of the interviews and often appears in the sources consulted. It seems that it was the most commonly used plant species in the kilns due to its rapid growth, recolonization capacity and the diversity of habitats in which it grew. According to the oral sources, the sand surrounding the plant would have been removed and the roots of the plant, which could extend for several metres, extracted for burning. The use of *L. intricatum* must also have been very common as it is mentioned in many of the documents consulted. With respect to the genus *Aspargus,* there are very few references in the written sources to its use and none of the interviewees spoke of it being used in the kilns, although it is included in a 17th century contract for the collection of firewood required for the firing of a lime kiln in Fuerteventura. *Euphorbia canariensis* and *Plocama pendula* were referred to in the oral sources, but only as material used very occasionally when better and more commonly used alternatives were unavailable or in short supply. With respect to *E. canariensis*, this species does not tolerate sandy substrates, although it was found in the immediate surroundings of the study area and the oral sources described situations in which they would throw stones at specimens of this species that were found in inaccessible sectors so that they would fall and could be used. *P. pendula* is also mentioned in the historical documents as being used on the island of Fuerteventura, but there are very few populations left (Scholz, 1995). Finally, *Nicotia glauca* is an exotic invasive species in the Canary archipelago. It appears that it was used abundantly as firewood in the kilns according to the oral sources.

Among the species that can be considered doubtful in terms of their use in the kilns are the so-called *salty bushes* (*Salsola*, *Suaeda* and *Schizogyne* species). In this case, the oral sources contradict the information that appears in the historical documents, according to which these species silt up the kiln or, in the case of *Schizogyne sericea*, do not generate sufficient heat for combustion of the limestone. *Tamarix canariensis* is a small tree which is uncommon in Fuerteventura and its use was officially regulated as it was (and is) one of the few sources of wood on the island. It was the preferred choice to manufacture farm tools.

Table 1. Species likely to be used for lime kiln firing.

Name	Currently present in the study area	Reason for non use	References
Asparagus nesiotes	No		Historical documents
Asparagus pastorianus			
Asparagus umbellatus			
Asparagus scoparius			
Asparagus plocamoides			
Convolvulus caput-medusae	Yes		Oral and Manzano-Cabrera, 2016
Euphorbia canariensis	System limits		Oral and Sabaté-Bel, 1993
Launaea arborescens	Yes		Oral, historical documents, Viera y Clavijo (1866), Manzano-Cabrera (2016)
Lycium intricatum	Yes		Oral and historical documents
Nicotia glauca	Yes	Used for cooking	Oral and Santana-Cordero et al. (2016)
Plocama pendula	No	Other uses	Oral and Sabaté-Bel (1993)

Salsola vermiculata	Yes	Silts up kiln with ash	Historical documents
Salsola divaricata	Yes	Silts up kiln with ash	Historical documents
Schizogyne sericea	No	Insufficient heat generation	Historical documents
Tamarix canariensis	Yes	Other uses	Manzano-Cabrera (2016)

4.2 Methodology to measure the effects of the historical deforestation by lime industry

Through oral interviews the research obtained that a camel load corresponded to 12 sheaves which were approximately 1 m long x 0.5 m wide x 05 m high There were three kiln sizes: small ones which would requires 30 camel loads or 90 m^3 of fuel, medium-sized ones which would require between 60 and 80 loads (180-240 m^3 of fuel) and, finally, large-sized ones which would require between 100 and 120 loads (between 300 and 360 m^3 of fuel).

A total of 269 plants (333.85 m^3) were measured in the four plots (Table 2): 151 of *L. arborescens* (193.57 m^3), 80 of *L. intricatum* (137.61 m^3) and 48 of *C. caput-medusae* (2.67 m^3). The cluster (Fig. 3) shows 2 groups, plots A and C, which are characterised by abundant vegetation, and plots B and D, which are characterised by low amounts of vegetation. Table 2 shows the data used for the cluster analysis classified by plot and plant species.

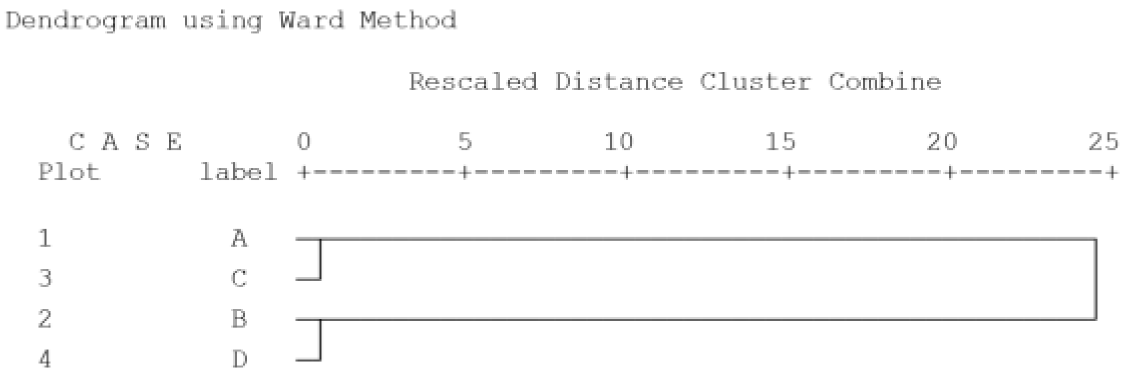

Figure 3. Dendrogram using ward method with plot density association.

Table 2. Data used in the cluster analysis. Vegetation density and cover of the plots, number of individuals and biovolume of analysis plots. La: *Launaea arborescens*; Li: *Lycium intricatum*; Cc: *Convolvulus caput-medusae*.

Plot	**Species cover (m^2)**	**Number of individuals**	**Total plot**	**Biovolume (m^3)**	**Total plot**

	La	Li	Cc	La	Li	Cc		La	Li	Cc	
A	52.5	191.6	0	18	26	0	44	35.4	102.4	0	137.8
B	0.9	66.2	0	2	13	0	15	0.4	33.4	0	33.8
C	186.4	0.8	0	85	3	0	88	154.5	0.3	0	154.8
D	9.7	8.7	8.9	38	28	58	124	3.2	1.5	2.7	7.4

Using this data, the number of plants required to fire a lime kiln varies depending on plant species (Fig. 4), age and size, as the use of adult specimens was prioritized: nonetheless, in all likelihood use would have been made of young specimens at times when vegetation was scarce. In summary, for the smallest kilns, a total of 70.3 specimens of *L. arborescens*, 52.5 of *L. intricatum* or 1,607.1 of *C. caput-medusae* would have been required, and for the largest size ones a total of 281.3 specimens of *L. arborescens*, 209.3 of *L. intricatum* or 6,428.6 of *C. caput-medusae*.

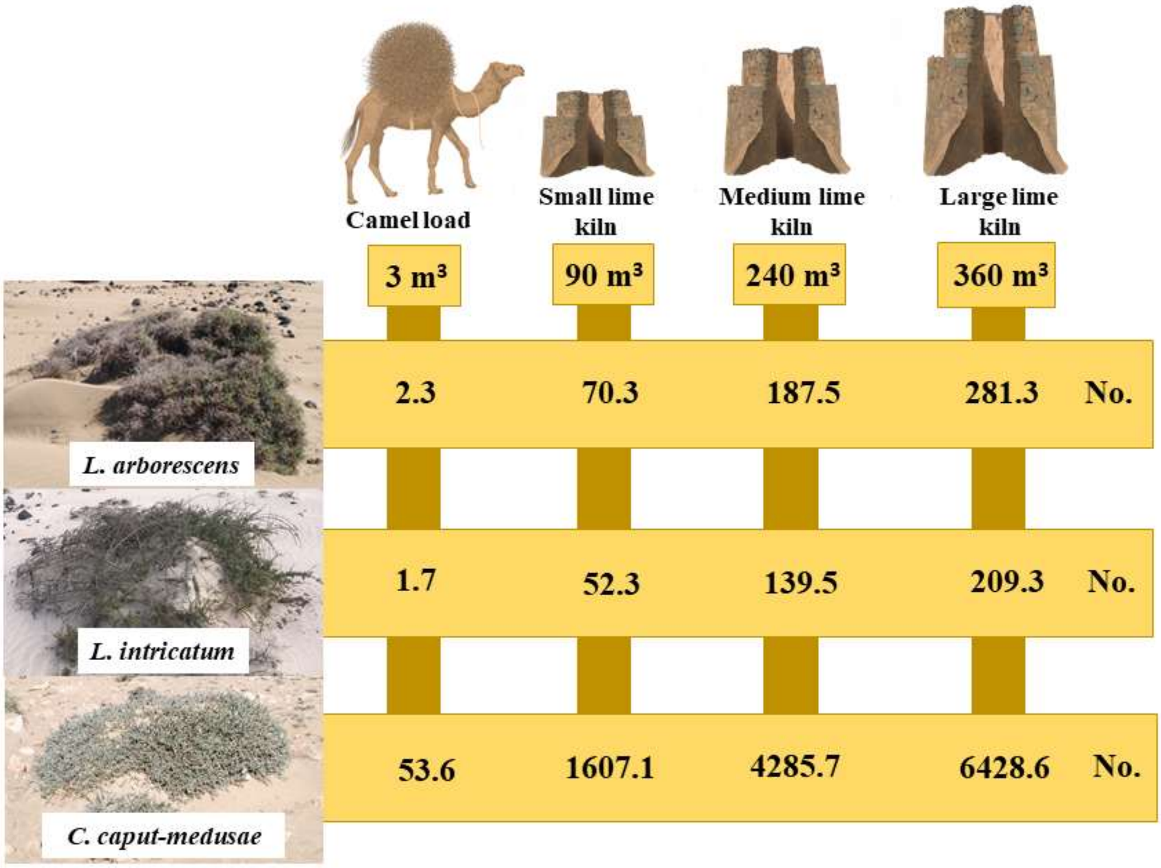

Figure 4. Number of individual plants required for the three lime kiln sizes. It can be seen in the photos on the left how the three species form nebkhas.

In terms of surface area, and according to the data obtained in the field sampling campaign, a total of 5,456.52 m^2 in areas of low vegetation density conditions or 768.93 m^2 in high density areas would have had to be cleared for the small-sized kilns. On the same basis, for the medium-sized (240 m^3) and large-sized (360 m^3) kilns, the totals for low density areas would have been 14,550.72 m^2 and 21,826.08 m^2, respectively, and for high density areas, 2050.48 m^2 and 3,075.72 m^2, respectively. This would have allowed 1,034 small-sized kilns to be fired in high vegetation density conditions and 3,193 in low vegetation density conditions (Fig. 5C); and for large-sized kilns 657 in high density conditions and 2,186 in low density conditions (Fig. 5D). The sources report that the lime kiln operators would travel distances of up to 37.80 km from Ajuy and 16.16 km to Moro Jable in Punta de Jandía to obtain vegetation. In addition, it can be seen that vegetation density is lower in the areas surrounding the optimal routes that the lime kiln workers would have used to obtain their fuel (Fig. 5).

In a report published by the Island Council of Fuerteventura in 1966, it is recorded that the lime kiln industry was the most important activity on the island and that in 1964 over 74,000 tonnes of lime product were exported. If the preparation of this product had been undertaken solely in the study area and using vegetation from the area to fire the kilns, a total of 246,667 camel loads would have been required, which in turn would be the equivalent of clearing an approximate surface area of between 6,322,075.21 and 6,7297,170.94 m^2.

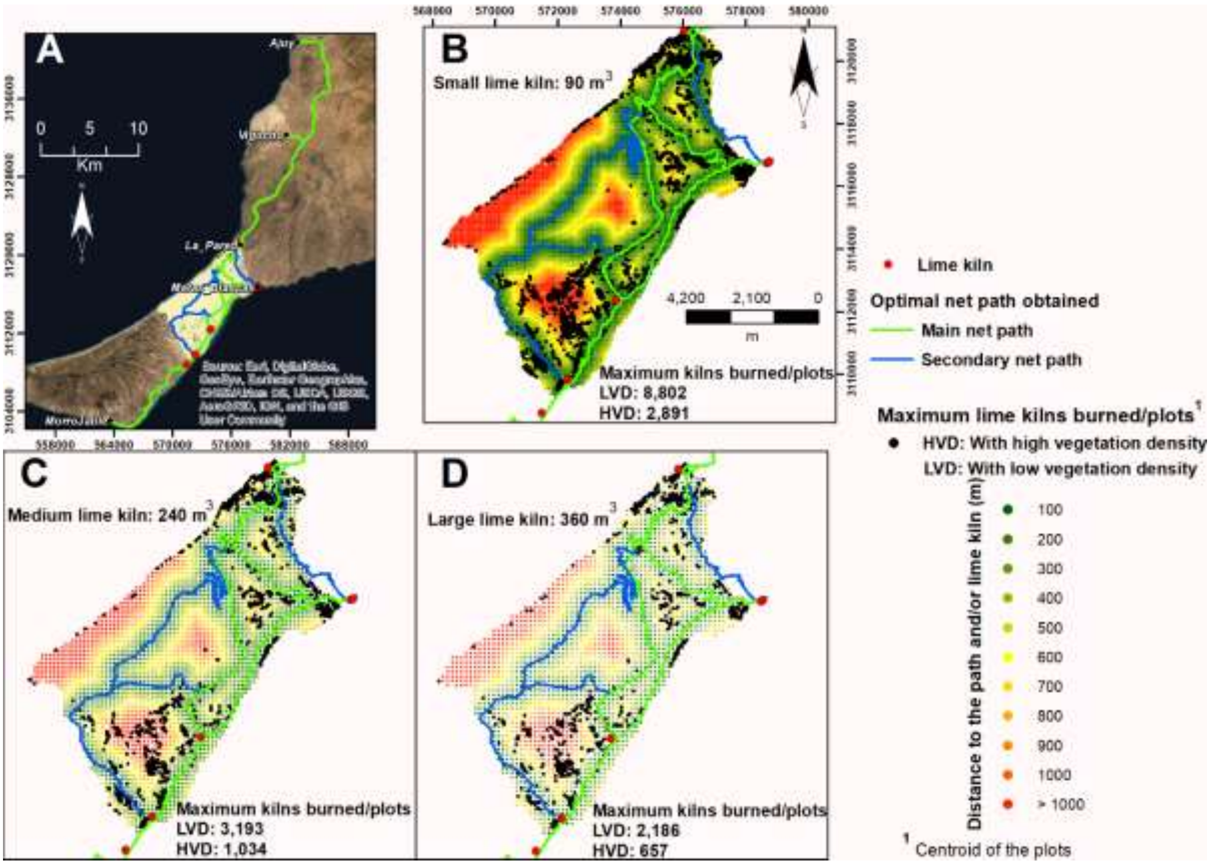

Figure 5. Distribution of lime kilns, optimal routes obtained and maximum number of lime kilns fired/plot according to vegetation density. A. Optimal routes and toponyms mentioned in the historical sources. B. Small-sized lime kilns fired/plot. C. Medium-sized lime kilns fired/plot. D. Large-sized lime kilns fired/plot.

4.3 **Driving forces of deforestation and vegetation recovery**

In Jandía, the lime kiln industry was an economic activity that served as an alternative to a system based on an extremely precarious primary sector that was highly dependent on arid climate conditions where water was (and continues to be) a very scarce resource due to the irregular and very occasional precipitations. It is frequently recorded in the minutes of the Island Government (Roldán, 1966; 1967; 1970) that, due to the continued absence of rains and the depletion of grain on the island, vessels leaving the island should only load limestone. That is, this market offered certain economic guarantees against other activities. This explains the mass proliferation of kilns along the coast of the Jandía peninsula given the export opportunities that were presented. In effect, the, mostly local, driving forces (Table 3) that were behind this industry and, hence, the deforestation process, are socioeconomic (6) and natural/spatial (2) (Fig. 6).

A report from 1868 comments that vegetation is becoming scarce along the Jandía coast due to its being used to fire the kilns that have been constructed nearby (Villalba, 1868):

The best limestone is found in large quantities along the east coast from from Matas Blancas to Pezenescal and is one of the biggest export items from Jandía [...]. There are significant amounts from Matas Blancas onwards all along the coast to Butihondo: it is also found from here to La Punta, though in lower quantities. The best quality limestone in Jandía, and perhaps even in the whole island, is found in Matas Blancas […]. What you find in Dehesa, as well as in all of Fuerteventura, are small bushes, such as *aulaga* [*L. arborescens*], *salty bushes* [*Salsola*, *Suaeda* and *Schizogyne* species], *espino* [*L. intricatum*], etc. They are used both for grazing and lime kiln firing. In Jandía you can find them in El Jable and in all the valleys, as well as fairly abundant amounts further inland and higher up. They are not found so frequently by the coasts, because as these are closer to the kilns, which are all along the coastline, they have been used to fire the kilns. Although they are not strictly speaking scarce, today there are not too many specimens to be found [Report from the Secretary of the City Council of Pájara: Justo P. Villaba, 1868].

Two types of kiln were used in Jandía, one type where the stone was used for local dwellings, and the other type for exportation of burned limestone to other islands in the archipelago. Only a few of the first type were built and they were generally situated close to the small population centres. By way of example, in the case of Punta de Jandía (some 20 km from the study area), the oral sources claim that the stage was reached when there was no more plant material to burn and that the lime kiln operations had to be carried out with coal imported from other islands. However, in other areas, and as the use of these kilns was only for occasional repair jobs in small villages, the oral sources claim that there were no shortages of plant material for the few kiln firings that took place. The kilns used for exportation purposes were found practically all along the Sotavento coast (Fig. 5) of the aeolian system, and the lime kiln firing was done with plant material. However, at the start of the 1950s, coal ovens began to be built or the existing kilns were modified in order to speed up the burning process.

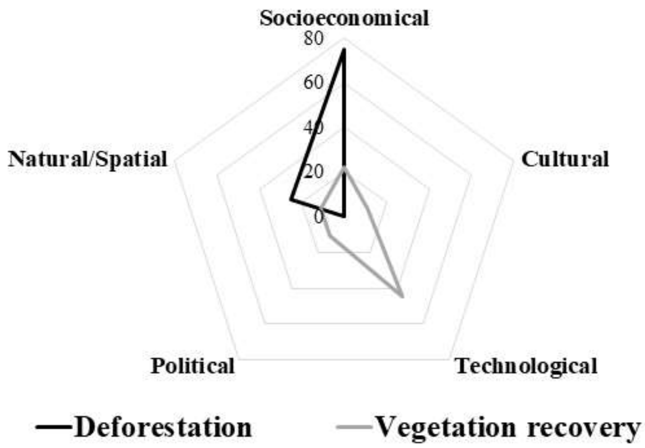

Figure 6. Types of driving force behind the deforestation and vegetation recovery process.

Table 3. Driving forces behind the deforestation and vegetation recovery process. Type of driving force: S: Socioeconomical; N/S: Natural/Spatial; C: Cultural; T: Technological; P: political. Scale: L: Local; R: Regional; N: National; I: International.

Deforestation	Vegetation recovery
S: High external demand (R, N, I) S: High local demand (L) S: Opportunity for job creation (L) S: Increase in the number of workers (L) S: Low monetary cost of *L. arborecens* in public property (L) S: Low cost of traditional kilns (L) N/S: Geological characteristics (L) N/S: Irregular climate conditions unfavourable to agriculture or livestock (L)	S: External demand reduction (R, N, I) S: Local demand reduction (L) C: Learning logging techniques from experienced workers (L) T: Importation of coal (I) T: Importation of synthetic paint and aggregates (N) T: Creation of kilns to burn the stone in exportation sites (R) T: Displacement of activity to industrial ovens in the capital (L) P: Government regulation for the removal of vegetation (L) N/S: Slow vegetation recovery (L)

The lime kiln operators who could not afford to buy coal would go to this area to collect plant material to fire the kilns. The oral sources, however, reflect the problem of the growing scarcity of vegetation. Some kiln operators remarked how they needed to walk further and further, up to 43 km, in search of fuel, requiring several days and thus increasing the time between one lime kiln firing and the next (up to three months) due to the difficulty in finding fuel. The depletion of the vegetation contributed to the transition to the use of coal, which also resulted in reduced profits as the coal had to be purchased and the final product was of a lower quality (and hence lower price) as the coal generated a considerable amount of impurities. In addition, the fact that kiln operators could not afford to buy coal saw an increase in the sale of raw limestone in the capital and in its exportation to other islands in the archipelago to be burned there.

The lime kiln industry began to decline from approximately 1960 onwards. The importation of synthetic paints and cement, as well as the use of coal, had the side effect of a spontaneous recovery of the vegetation (Marrero-Rodríguez et al., 2020a). This recovery was then the result of technological advances in the industry and the gradual reduction in local and external demand (Fig. 6 and Table 3).

5. Discussion

The discussion of this research is focused on two main topics: i) related to the development of the methodology that allows reconstructing, evaluating and analyzing the impact produced by the lime industry on the vegetation; ii) related to the application of the methodology, the information obtained and the effects detected on the vegetation.

5.1 Methodology to measure historical deforestation by lime industry

Regarding to the methodology, other studies have estimated that a 2-metre high lime kiln that generated between 8,000 and 8,400 kg of lime product would have required approximately 43 m^3 of firewood for its operation (Morris et al., 1931). Based on these initial data, other authors have estimated that 11 m^3 of wood is required to generate 10 m^3 of lime product, which in turn would mean felling 0.13 hectares of forest (Abrams & Rue; 1988; Wernecke, 2008). According to Santana-Cordero et al. (2016), a lime kiln on the island of La Graciosa (Canary Islands) would consume the equivalent of 20 camel loads. Consequently, it was estimated that in the final stage of lime kiln industry usage at least 5,100 camel loads were required just for new constructions and the restoration of existing dwellings. The same study also records that the kiln workers were obliged to travel longer and longer distances to obtain fuel, as the firewood became scarce in the immediate surroundings of the population settlements, causing them to have to go to the northernmost tip of the island some 6 km away. The comparison of the data obtained in the aforementioned studies and those reported in the present work requires a careful analysis as there are several aspects that need to be taken into account: for example, the capacity of the different plants to generate heat and the different types of kiln that were used (and not just their size), as more sophisticated kilns have a better heat-retaining capacity.

Nonetheless, the present study incorporates various advancements with respect to the works of other authors such as Morris et al. (1931), Abrams & Rue (1988) or Santana-Cordero et al. (2016), as it takes into account different variables in the analysis that is undertaken, including historical sources, field plant measurements, the number and exact dimensions of the sheaths or bundles of plant material transported by the camels, the different plant species that were used, and the size of the different kilns.

However, it should also be acknowledged that little is known as yet about the recovery capacity of the different plant species and the vegetation in general. In this respect, it is hoped to undertake a new research study. The present study also opens up the possibility of other research lines in order to better understand the deforestation process and other consequences of the lime industry. In this regard, the kilns and their immediate surroundings should be excavated with a view to extracting new information about the date of construction of the kiln, the approximate number of times the lime kilns were fired, and the species that were used to fire the kiln, especially about those that are no longer found in the isthmus as some species may have disappeared prior to those uncovered in the present reconstruction using oral sources and limited historical documents.

5.2 Deforestation process by lime industry

This work comprises a qualitative and quantitative approach in an analysis of the impact of the lime kiln industry on an arid aeolian sedimentary system. In the case study of Jandía, the removal of vegetation, and the resulting transformation of landforms, was due to the need to acquire fuel to burn in the lime kilns (Marrero-Rodríguez et al., 2020a). Determining the number of times that each kiln was fired was an impossible task on the basis of the sources used. However, it was found in the sources that the lime kiln operators had to travel some distance from the aeolian sedimentary system is search of vegetation. That is, the data obtained suggest that the number of possible times that a lime kiln could have been fired using plant material found in the system itself was exceeded, as too would have been the vegetation recovery rate.

Traditional uses that have a high fuel demand can *a priori* result in generalised deforestation but, in reality, their impact on ecosystems is far more complex. In the case of Jandía, the demand for plant material to fire lime kilns was massive, but at the same time selective (Marrero-Rodríguez et al., 2020a, b) as in other aeolian sedimentary systems (Santana-Cordero et al., 2016). This was due to the preference for certain species which were more efficient for lime kiln firing. These characteristics, revealed in the oral interviews, are in agreement with those reported by other authors in Portugal, although they propose that the use of bushes is related to the impurities that contaminate the lime product when other materials are used (Margalha et al., 2008) and not with the silting up of the kiln, as was the case in Jandía.

The most immediate consequence of the land clearing to obtain plant material to fire the kilns must have been reduction in species richness, as has been identified for other land uses also developed in dune systems (Kutiel et al., 1999). In addition, the fact that 2- and 3-year-old adult specimens were preferred would have had consequences on the population structure of the plant communities. Normally, plant age is important because it is often related to the reproductive stage, and is key to an entire population's growth or decline. This could even lead to the extinction of some species.

In a second stage, the reduced availability of the species that were preferred to fire the kilns would have meant the lime kiln operators being necessarily less selective, using less optimal species but at the same time younger specimens of the more preferred species. This would explain how some species would become scarce. By way of example, there was an scarcity in Fuerteventura in the 1970s of a plant species, *C. caput-medusae* (Kunkel, 1977), whose aerial and subaerial parts were both used to fire the lime kilns. The cessation of the lime kiln activity may have enabled the recovery of this plant species, though today its distribution is limited to specific locations in Fuerteventura and Gran Canaria (Brandes, 2001; Olangua Corral, 2009).

The deforestation of the Jandía peninsula contributed considerably to the decline of the lime kiln industry given the difficulties to obtain the plant material to fire the kilns. The external demand for this product conditioned the deforestation processes, whereas in other similar ecosystems in the archipelago like the island of La Graciosa the kilns were only fired for work in new constructions or occasional work repair (Santana-Cordero et al., 2016). The demand for vegetation was also high for cattle, sheep and goat grazing (Hoffman & Rohde, 2007), the manufacture of different farm tools, and as fuel for households and for the construction and other industries (Santana-Cordero et al., 2016). It would have been the combination of these uses together with the lime kiln industry that resulted in the generalized deforestation of the aeolian system.

The exploitation of the vegetation also had an impact on the dynamics of natural processes in terms of the remobilization of sand sheets (Marrero-Rodríguez et al., 2020a). Traditional land uses resulted in overexploitation of the vegetation and, consequently, its capacity to stabilize the sand. This resulted in highly mobile aeolian sedimentary landforms, including sand sheets (Santana-Cordero et al., 2016) which used to be considerably more widespread than in the present day when the predominant landforms are nebkhas indicating a recolonization of the vegetation (Marrero-Rodríguez et al., 2020c). In addition, the deforestation process also favoured generalised erosion processes due to the rhexistatic conditions (Marrero-Rodríguez et al., 2020a).

6. Conclusions

For a long period (1850-1960), the lime kiln industry was one of the most important economic activities on Fuerteventura Island. This was due, on the one hand, to the highly irregular income from agriculture and livestock-rearing as the result of difficult climate conditions and, on the other, to the abundance of limestone compared to the other, older islands in the archipelago.

The deforestation process was very selective as not all the vegetation could be used in the lime kilns. The three plant species that were most preferred to fire the lime kilns were *L. arborescens, L. intricatum* and *C. caput-medusae*. However, their long-term exploitation led to an important depletion of the population of some species and, consequently, to the collapse of the industry when insufficient plant material was available and other, expensive, fuel sources had to be imported to the island to fire the kilns. As these species serve to establish nebkhas, their removal for use as fuel in the lime kilns also resulted in sediment remobilization of the nebkhas.

To fire the smallest of the three kiln sizes used on the island, it would have been necessary to clear an area of 5,456.52 m^2 if the vegetation density was low, or 768.93 m^2 in the case of a high vegetation density area. In most studies, deforestation has to date been studied as a general process involving complete vegetation cover removal, but this research shows that some historical deforestation processes are selective, and not general, in that they may be subject to the specific needs of one (or more) particular industry/ies.

It is apparent from the results of the study that the lime kiln industry played a very significant role in terms of modification of the vegetation in the aeolian sedimentary system of Jandía and other areas of the island, impacting on the types of plant community currently present in the area, as well as their spatial distribution, and flora composition and structure. This is key to understanding the historical evolution of the flora, vegetation and the geomorphological processes of the dune systems of the Canary Islands. Finally, the methodology developed in the present paper can be applied to other historical and current land uses and for the planning of new land uses that depend on the removal of vegetation. Furthermore, it allows us to learn from past experiences in which industries lacked proper planning and thus their activity led to their own collapse and rapid environmental degradation.

7. Acknowledgements

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5.3. Historical social relevance of ecosystem services related to long term land uses in a coastal arid aeolian sedimentary system in Lanzarote (Canary Islands, Spain).

Historical social relevance of ecosystem services related to long term land uses in a coastal arid aeolian sedimentary system in Lanzarote (Canary Islands, Spain)

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Abstract

The loss of ecosystem services (ESs) is one of the main consequences of the inadequate management of natural environments. However, the drivers that shape the provision of ESs continue to be poorly characterized at local and regional scales, and their protection, generally, has not been a priority. This study analyzes the anthropic alteration process of an arid aeolian sedimentary system, the associated environmental consequences and changes in the social relevance of ESs for the local population. The social relevance of an ES was analyzed using historical sources (analysis of testimonies of travelers, press, government minutes, aerial photographs, field photographs and oral interviews, among others) for five land uses: *urbanization*, *aggregate extraction*, *grazing*, *cultivation* and *logging*. Using the available information, three criteria were selected to define their social relevance: *social sensitivity*, *economic* and *political*. Considering El Jable (Lanzarote, Canary Islands, Spain) as study area, the main results show that different historical land uses have generated different social reactions in relation to changes in the capacity of the ecosystem to provide its ESs. The ESs that directly benefitted the population (provision of food, fuel and raw materials, and the regulation of natural hazards) were found to have the greatest social relevance before 1960. However, since then, the change to the island's economic model has resulted in high levels of social relevance for ESs related to the promotion of tourism (cultural heritage, recreation and leisure, and aesthetic values), citizen security (regulation of natural hazards), wildlife (habitat preservation) and culture (cultural heritage). This type of analysis can provide information on the perception of society to changes in the local environment, the effects of such changes on people's lives, and the management response of the society in question.

Keywords: social relevance; land use change; ecosystem services; historical information sources; anthropic impacts.

1. Introduction

Arid coastal dunes are highly dynamic ecosystems that provide a wide range of ecosystem services (ESs) including, amongst others, food production and fuel or construction materials, as well as acting as a recreational space, a tourist attraction, a habitat for a large number of species, and a regulator of coastal erosion (Barbier et al., 2011; Everard et al., 2010).

Despite all these ESs, coastal dunes are among the most degraded and threatened ecosystems in the world due to human activities (Paskoff, 1993, 2001; Delgado-Fernandez et al., 2019). Their degradation is commonly the result of traditional human activities such as cultivation, grazing or the use of vegetation as fuel (Tsoar & Blumberg, 2002; Kutiel et al., 2004; Levin & Ben-Dor, 2004; Provoost et al., 2011), as well as modern activities such as recreational uses, urbanization or the extraction of aggregates (Nordstrom, 1994, 2004; García-Romero et al., 2019; Marrero-Rodríguez et al., 2020b). In consequence, dune surface areas and sediment budgets have been reduced (Hernández-Cordero et al., 2018), changes in vegetation (Hernandez-Cordero et al., 2017) and landforms (Tsoar & Blumberg, 2002) have taken place, and invasive species (used for grazing, as fuel, or for ornamental purposes) have successfully occupied large areas (Marchante et al., 2003; Esquivias et al., 2015; Parra-Tabla et al., 2018). Along with climate change (Clarke & Rendell, 1998; Tsoar et al., 2009), such degradation has compromised the capacity of ecosystems to provide services all over the world (Vilà et al., 2010; Van Oudenhoven et al., 2012; Walsh et al., 2016; Mehvar et al, 2019; Asmus et al., 2019; Weiskopf et al., 2020).

The reconstruction of historical management and the social relevance of ESs are described and analyzed in this paper through the methodological framework of historical ecology (Szabó, 2015), developed in recent decades as an important tool to: i) preserve cultural heritage linked to the exploitation of ecosystems, and understand the trajectory of the patterns, processes and behavior of landscapes (Bürgi, & Gimmi, 2007) and species (Panzacchi et al., 2013; Morris & Rowe, 2014); ii) report past examples of ecosystem management (Bürgi, & Gimmi, 2007); iii) test the effects of climate change (Vellend et al., 2013); iv) recognize the effects of different disturbances on ecosystem components (Dzwonko et al., 2002); v) plan management and restoration strategies (Fritsche, 2009; Trueman et al., 2013; Morgan et al., 2010; Dirkx, 2004); and vi) know the driving forces behind ecosystem degradation (Bürgi et al., 2010; Rohde & Hoffman, 2012).

In small islands, like those in the Canary Archipelago (Spain), the exploitation of resources is more significant than in continental environments (Mimura et al., 2007). Although human occupation of the archipelago took place less than 3000 years ago, meaning that the period of human intervention has been shorter than in many other ecosystems, anthropic intervention has been intense (mostly since the islands were colonized by the Spanish in the early-mid 15th century) and the number of sources is relatively large for the last centuries.

Some studies have addressed in depth the effects that climate change (Petit and Prudent, 2010; Sauter et al., 2013), the reduction of sediment budget (Pye and Blott, 2012; Hernández-Calvento et al., 2014), changes in environmental conditions (Jackson and Cooper, 2011) and changes in land use (Marrero-Rodríguez et al., 2020a) can have on aeolian sedimentary systems and, therefore, on the ESs they provide. However, there is a gap in the literature in relation to the evaluation of the extent to which changes in ecosystems have been relevant or not for the population that depended on or lived in that ecosystem. In this context, an analysis of the historical sources is carried out in the present study to know the evolution of the social relevance for the local population of the ESs provided by the arid aeolian sedimentary system of El Jable (Lanzarote, Canary Islands, Spain) (Fig. 1) between 1750 and 2018.

This type of analysis can provide information on how societies perceive such changes, how their lives are affected by changes in ecosystems and the management response of the society. With such knowledge, governments can take better and more informed decisions in terms of protection, restoration or regulatory measures. The aim of this work is to analyze the historical management of the aeolian system and to evaluate the social relevance for the local population of the ESs related to different land uses (urbanization, aggregate extraction, grazing, cultivation and logging).

2. Study area

The El Jable coastal aeolian sedimentary system (Fig. 1) currently occupies an area of 90 km^2 and a width of between 10 km in its northern sector and 4 km in its southern sector. Sand transport is from the sediment entrance area (Caleta de Famara, N-NE) towards the leeward sector (Arrecife, S), crossing the central part of Lanzarote over an approximate 21 km length and covering areas belonging to four island municipalities (Tinajo, Teguise, San Bartolomé and Arrecife).

The substrate strip is made up of volcanic rocks (Miocene and Quaternary basaltic lava and pyroclasts) and sedimentary rocks (sandstones and quaternary conglomerates related to colluvial, alluvial and aeolian processes). The current aeolian sediments are interspersed at the edges of El Jable with alluvial and colluvial levels formed by lithoclasts (fragments of rock and basaltic minerals) and bioclasts (fragments of marine fauna and flora). The recognizable morphologies in this area are, generally, nebkhas formed from shrub individuals of *Traganum moquinii* in the foredune of the system (Caleta de Famara), which are replaced inland by individuals of *Launaea arborescens*. In addition to these aeolian landforms there are three isolated dunes of barchan morphology. The climate is arid with an average annual rainfall of around 110 mm and an average annual temperature of 20.7ºC (Cabrera-Vega, 2010). The dominant winds come from the first and fourth quadrants. Average wind speed is 20 km/h, but can reach as high as 60-70 km/h (Alonso et al., 2011). Currently, the coastal aeolian sedimentary system is delimited in the northern part by tourist urbanizations around Caleta Caballo and Caleta de Famara and in the southern part by Arrecife, the island's capital. Finally, part of the northern section of the arid aeolian sedimentary system has been designated as a protected area as part of the Natura 2000 program.

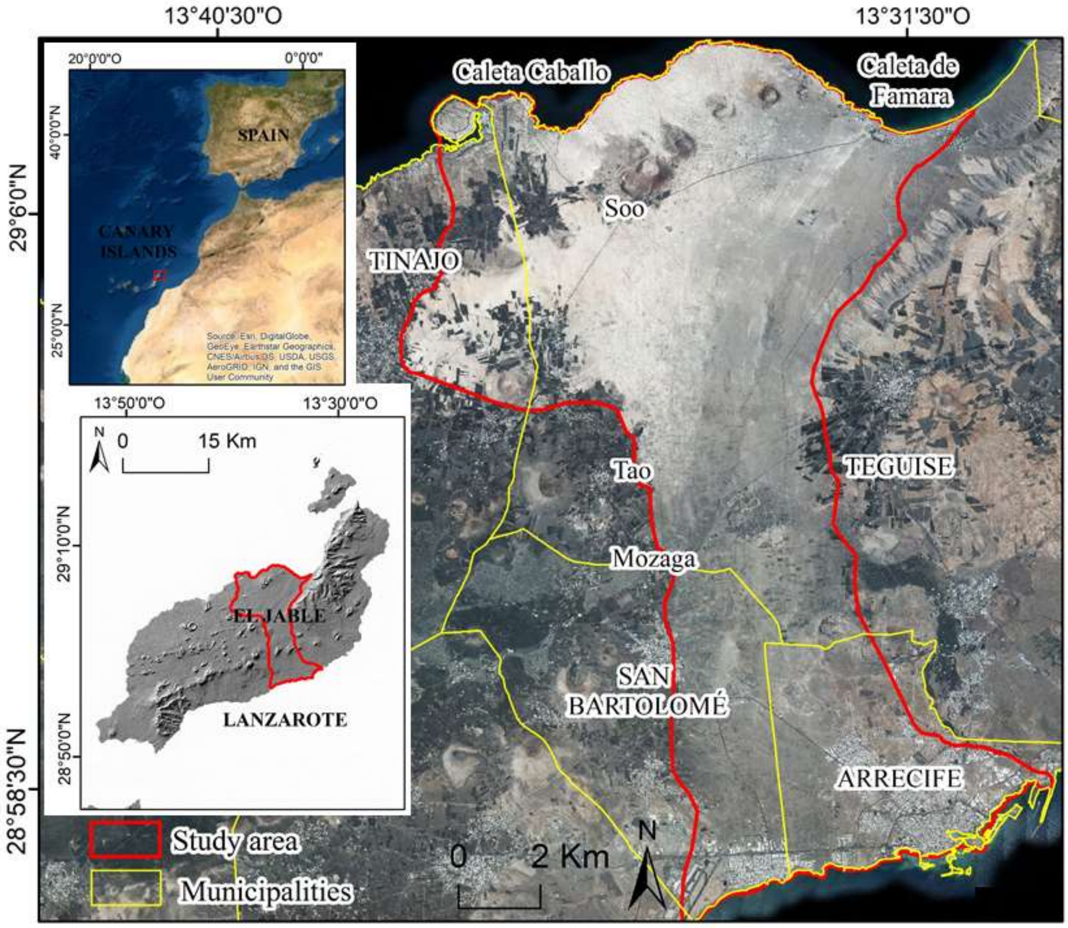

Figure 1. Location and study area limits. Aerial photo source of Lanzarote: SDI Canarias (Canary Islands Regional Government-Grafcan S.A.).

3. Methodology

Historical data sources were used to reconstruct the historical uses of the ecosystem and their environmental consequences and to analyze the evolution of the references of each ES and its historical social relevance.

3.1. Data sources

Data were collected from numerous historical documents of different origin for the purpose of a historical reconstruction of the study area. They were used to analyze: i) land uses and the historical evolution of the ecosystem; and ii) the recorded changes in ESs and their social relevance. In this respect, historical bibliographies and traveler testimonials were used (Torriani, 1959; Glass, 1764; Ruiz-Cermeño, 1772; Caballero-Mújica, 1991; Madoz, 1849; Álvarez-Rixo, 1866; Greff, 1868; Stone, 1887; Hernández-Pacheco, 1909; Rumeu de Armas, 1981), as well as acts of the Lanzarote Island Government from the 17th century (Bruquetas de Castro, 1997) and minutes of the plenary sessions of Teguise City Council (1610-2006). In addition, the *Jable* search tool (jable.ulpgc.es) of the University of Las Palmas de Gran Canaria Library (first references from 1843) was used to find and then review relevant articles in the local and regional written newspapers and the Official Gazette of the Canary Islands Government. Various keywords related to landscape, toponyms and land uses were employed, and a total of 410 relevant articles were found. Six recorded interviews were also consulted, taken from the "Rescuing Life Stories" project of the Historical Heritage Service of the Cabildo de Lanzarote published in 2010. The interviewees were farmers who grew their crops in sandy fields and were born between 1920 and 1940. The field photographs (1950-2018) were obtained from the online collection of the Lanzarote Island Government (www.memoriadelanzarote.com), and the aerial photographs and orthophotos from GRAFCAN S.A, a company belonging to the Canary Islands Regional Government. Finally, the data on the evolution of the number of inhabitants was obtained from the Canary Institute of Statistics (1768-2019).

3.2 Evolution of land uses and the ecosystem

The reconstruction of land uses and the evolution of the aeolian sedimentary system was undertaken using the historical sources mentioned above. The information obtained was organized into three different periods: pre-1750, for which the sources are scarce and the information obtained is very limited; 1750-1960, when traditional land uses were the most important activity; 1960-present, when recreation and leisure activities have been predominant in the study area.

3.3 Social relevance of the ecosystem services

To assess the social relevance of ESs, first we created a list of the ESs provided by El Jable based on other papers (Everard et al., 2010; Barbier et al., 2011) and historical sources (Table 1). The 21 ESs selected were classified into four different subgroups: i) *Provisioning*: food, fuel, raw materials, cosmetics, industrial use, genetic resource and medicines/pharmaceutics; ii) *Regulating*: of natural hazards and climate; iii) *Cultural*: cultural heritage, recreation and leisure, aesthetic value, inspiration for art, social relations, educational and research resource; and iv) *Supporting*: soil formation, nutrient cycling, photosynthesis, pollination and provision of habitat.

Table 1. Ecosystem services potentially supplied by El Jable, based on historical sources and ecosystem services literature.

Ecosystem services	Description	References
Provisioning services		
Food (F)	Wild food production [e.g. rabbits (invasive species), *M. crystallinum* plant species]	Madoz, 1849; Viera y Clavijo, 1982
	Meat production (goat and sheep grazing)	
	Miscellaneous crops (watermelons, sweet potatoes, onions, aloe vera, etc.)	
	Milk production (goat grazing)	
Fuel (FU)	For lime kiln industry, bakeries, moonshine production, household heating, cooking, etc. (e.g. from: *L. arborecens* or *Lycicum intricatum*)	Hernández-Pacheco, 1909
Raw materials (RM)	Wool and leather (goat and sheep grazing)	Viera y Clavijo, 1982
	Construction materials (limestone and aggregates)	
	Glass (from the combustion of *M. crystallinum)*	
	Timber from *Tamarix canariensis* for tillage tools	
Cosmetics (C)	Caustic soda (from the combustion of *M. crystallinum*), sand used in the manufacture of soaps, etc.	Madoz, 1849; Viera y Clavijo, 1982

Industrial use (IU)	Installation of ports, factories, etc.	Ruiz-Cermeño, 1772
Genetic resources (GR)	The habitat of a high number of species of endemic flora and fauna	
Medicines or pharmaceuticals (MP)	For people (e.g. *Euphorbia paralias*, *Erodium hesperium*.) or animals (*L. arborescens*)	Madoz, 1849; Viera y Clavijo, 1982
Regulating services		
Natural hazards (NH)	Coastal defense for protection against storms and other extreme events Vegetation acts as a control factor for sand storms	Hernández-Pacheco, 1909
Climate regulation (CR)	Carbon sequestration	Everard et al., 2010; Barbier et al., 2011
Cultural services		
Cultural heritage (CH)	Archeological sites (e.g. aboriginal deposits) and paleontological deposits	León-Hernández et al., 2016
	Historical fears about sand inundating villages	
	Ethnographic heritage: buried villages, cisterns, wells, tides, lime kilns, etc.	
Recreation and leisure (RL)	Sand dunes as a major tourist attraction	Peña-Alonso et al., 2018
	Sports (sandboard, cycling and running)	
Aesthetic value (AV)		Everard et al., 2010; Barbier et al., 2011
Inspiration for art (IA)	e.g. “Voices from the Badlands”	
Social relations (SR)	e.g. Jable Farmers’ Association of Teguise or Viento del Jable Association	
Education and research (ER)	Educational activities for students, informative hiking, international scientific publications	Cabrera-Vega et al, 2013; Martín et al., 1996
Supporting services		
Soil formation (SF)	Common to most habitats	Everard et al., 2010; Barbier et al., 2011
Nutrient cycling (NC)		
Photosynthesis (P)		
Pollination (PO)		
Provision of habitat (PH)	The habitat of a high number of species of flora and fauna	Greff, 1868; del Arco-Aguiar et al., 2010

The social relevance of each ES loss or modification was analyzed using historical sources and in relation to five land uses*: urbanization, aggregate extraction, grazing, cultivation* and *logging*. Using the available information, three criteria were selected to define the degree of relevance: *social sensitivity*, *economic* and *political*. The three criteria were selected based on the evaluation in environmental planning proposed by McAllister (1982) and following the main driving forces (socioeconomic and political) of the changes in the aeolian sedimentary systems of the Canary Islands defined by Santana-Cordero et al. (2017).

For the *social sensitivity* criterion, four categories with corresponding scores were established (none, low, medium and high) to define the impact produced by the loss of an ES on the society, including the generation of social mobilization/protests (social response). The *economic* criterion was based on three categories (low, moderate and high) defining the monetary costs associated with the loss of an ES. Finally, for the *political* criterion, four categories were created (none, regulation, prohibition and restoration/protection) to evaluate whether local or regional governments have regulated or prohibited land uses to protect an ES or, if lost, whether they have developed restoration plans (Table 2).

The overall historical social relevance when a land use had an impact on an ES was then calculated as the sum of the scores awarded for each criterion (*social sensitivity, economic* and *political*) divided by the maximum score possible (9).

Table 2. Criteria selected to assess the historical social relevance of the loss of an ES related to crops, aggregate extraction, urbanization, logging and grazing, and the categories, score, description and sources used for each criterion.

<table>
<tr><th colspan="2">Criterion</th><th>Category</th><th>Score</th><th>Description</th><th>Sources used</th></tr>
<tr><td rowspan="7">Historical social relevance</td><td rowspan="4">Social sensitivity</td><td>None</td><td>0</td><td>No mentions found.</td><td rowspan="4">Oral sources and written press</td></tr>
<tr><td>Low</td><td>1</td><td>Sporadic mentions (less than 5 references).</td></tr>
<tr><td>Medium</td><td>2</td><td>People show sensitivity to loss, but no mobilizations recorded (5 to 10 references).</td></tr>
<tr><td>High</td><td>3</td><td>People show sensitivity to loss or their lives were affected or there were protests, complaints, collections of signatures or strikes (10 or more references).</td></tr>
<tr><td rowspan="3">Economic</td><td>Low</td><td>1</td><td>The economic cost of the loss goes unnoticed (no references).</td><td rowspan="3">Written press, city council minutes, the Official Gazette of the province of Las Palmas de Gran Canaria, Official Gazette of the Canary Islands</td></tr>
<tr><td>Medium</td><td>2</td><td>The economic cost is discussed but is moderate (less than 5 references).</td></tr>
<tr><td>High</td><td>3</td><td>The loss causes significant economic losses and is frequently referred to (5 or</td></tr>
</table>

				more references).	Government
	Political	None	0	Not discussed in government minutes at any political level.	City council minutes, the Official Gazette of the province of Las Palmas de Gran Canaria, Official Gazette of the Canary Islands government
		Regulation	1	The government develops laws to regulate the land use.	
		Prohibition	2	The government develops laws to ban the land use.	
		Restoration/protection	3	The government starts to develop restoration measures or protection figures.	

4 Results and discussion

To understand the social relevance of ESs it is necessary to first know the trends in the local economic model and the historical evolution of the land uses and the ecosystem. Thus, the reconstruction of the evolution of the landscape and the land uses is presented in the first part of this section and is followed by the analysis of the social relevance of the ESs.

4.1. Evolution of land uses and the ecosystem

The historical documents analyzed allowed reconstruction of the land uses in the El Jable aeolian sedimentary system, the alterations they have induced, their period of occurrence and the reasons why they have occurred (Table 3). The information was organized into three stages according to sediment mobility and vegetation cover. The results indicate that the first stage (until 1750) is unrelated to human activity given the small population registered. The second stage (1750-1960) shows evidence of sediment remobilization, which had different consequences for the economic system and infrastructure, due to traditional uses (exploitation of vegetation for use as food, fuel, and for grazing purposes). The third stage (1960 to the present) has seen the abandonment of traditional human uses and the beginning of new ones (urbanization and extraction of aggregates) which have generated environmental changes in the aeolian sedimentary system (spontaneous succession of vegetation and a consequent reduction in sediment mobility) (Fig. 2).

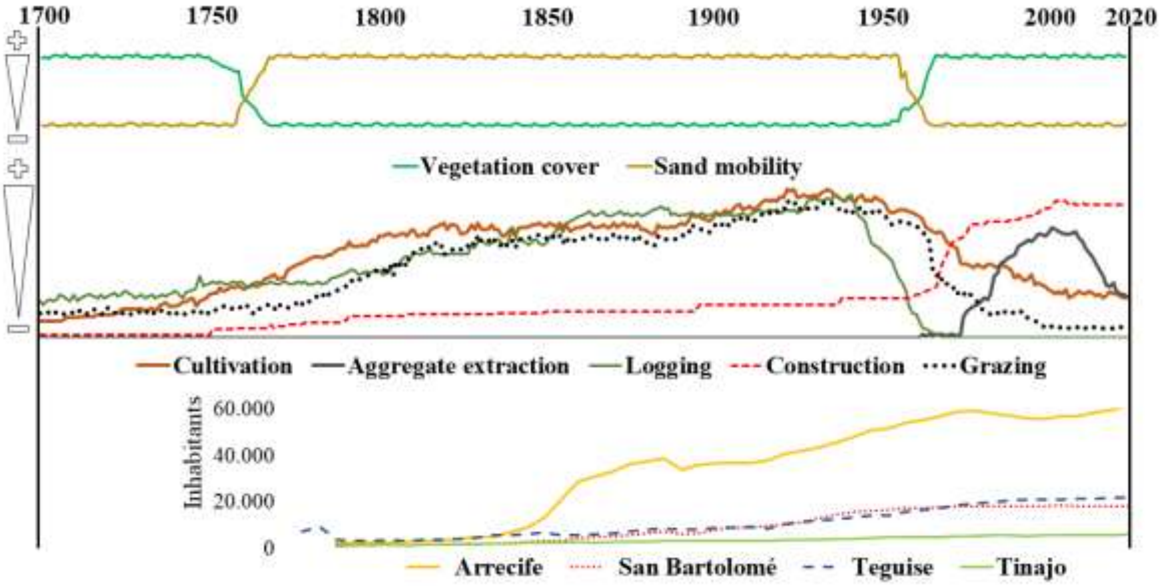

Figure 2. Evolution of sand mobility, vegetation cover and land uses according to the sources used. Number of inhabitants (1768-2019) (San Bartolomé became a separate entity from Teguise in 1787 and Arrecife in 1798). (Source: Canary Institute of Statistics, based on data from Local Councils, Island Governments, Communities of Municipalities and the Spanish National Institute of Statistics).

Table 3. Ecosystem evolution and effects of land uses on vegetation and landforms in El Jable from 1730 to the present.

Ecosystem evolution	Period	Induced by	Source
Vegetation			
Deforestation	1750-1960	Firewood collection Cleaning for cultivation	Historical documents (e.g. El Fénix newspaper, 15/07/1864)
Spontaneous recovery	From 1960	Fossil fuel importation Livestock reduction	Aerial photographs Orthophotos
Geomorphological			
Partial burial of the system	1730-1736	Volcanic eruption	Romero, 1991
Sediment remobilization	1750-1960	Deforestation	Historical documents (e.g. El Fénix newspaper, 15/07/ 1864)
Sediment stabilization	From 1960	Spontaneous recovery Reduction in sediment input	Cabrera-Vega, 2010
Sand flows	Rare occurrence	Deforestation Torrential rainfalls	Historical documents (e.g. Antena, 04/02/1958)
Beach progradation	1750-1960	Sediment remobilization Torrential rainfalls	Greff, 1868; Rumeu de Armas, 1981
Submarine sand bank enlargement	1750-1960	Sediment remobilization Torrential rainfalls	Greff, 1868; Rumeu de Armas, 1918
Beach erosion	From 1980	Sediment stabilization Barriers to sand transport	Historical documents (e.g. La Voz de Lanzarote, 13/10/1989)
Dune size enlargement	Unknown - 1960	Sediment remobilization	Hernández-Pacheco, 1909
Dune size reduction	From 2000	Sediment stabilization Reduction in sediment input Barriers to sand transport	Cabrera-Vega, 2010
Aeolian landforms destruction	Unknown to present	Urbanization Aggregate extraction	Aerial photographs Orthophotos
Direct human modifications			
Changes in accumulation areas	Unknown to present	Barriers to sand transport Vegetation changes	Aerial photographs Orthophotos
Beach regeneration	From 1990	Governmental administrative actions	Historical documents (e.g. La Voz de Lanzarote, 24/12/1994)
Reduction of sediment availability	From 1980	Sand extraction	Cabrera-Vega, 2010; aerial photographs; historical documents

4.1.1. Status of the arid aeolian sedimentary system before 1750

According to the archaeological evidence found in the study area, El Jable was first settled in aboriginal times a (De León et al., 2016; Santana-Cabrera, 2017). However, there are no references to its natural dynamics until the 15th century. In general, reconstructing the characteristics of an ecosystem before 1800 is a complex task due to the lack of sources (Szabó & Hédl, 2011). In El Jable, in the 17th century the Bishop of Murga stated that the “accumulation of sand is so high that six men could sink into it”. From the end of the 17th century, the cultivation of *Mesembryanthemum crystallinum* began to produce caustic soda and the manufacture of soaps, dyes and high quality glass in the north of the system.

In 1730, the eruption of the volcano Timanfaya covered a significant part of the island with lava, leaving that area with no grazing land, firewood or possibility of crop cultivation for a number of years. The eruption resulted in the burial of part of the ecosystem considered in the present study, damaging towns and villages in the system and disrupting its economic activity. The flow that affected El Jable (located east of the eruption) covered a total of 3.86 km^2.

In this period, no references were found in the city council minutes or the historical documents that were consulted to problems caused by the transit of the sand. It is possible that the mobility of the ecosystem during this stage was much lower and that it only began to increase at a later stage with the rise in the number of inhabitants and the consequent increase in demand for vegetation as fuel. The existence of aboriginal settlements (De León et al., 2016; Santana-Cabrera, 2017) can be seen as evidence of low sediment mobility prior to the increase in the intensity of land uses. Working on the reasonable assumption that aboriginal societies and farmers would have had a good knowledge and awareness of their natural environment (Dekens, 2007), it seems unlikely that they would have settled in the center of a stream of sand with the ability to repeatedly bury their homes and crops.

4.1.2. Deforestation and sand mobility (1750-1960)

At the beginning of this period, El Jable had about 10,000 inhabitants (Fig. 2) distributed in 11 towns and villages. The cultivation, grazing and exploitation of vegetation for use as fuel were the main activities. An important deforestation process began to take place for various purposes, including the burning of plant material to produce high alcohol content liquors and to generate tillable land for crop cultivation (Caballero-Mújica, 1991). The effects of the removal of vegetation to create fields for the cultivation of crops became evident. In this respect, numerous references were found from the years 1830 to 1840 to the problems being caused by sand (e.g. the burial of crops, infrastructure and houses) as the result of the cultivation of *M. crystallinum* and the use of vegetation as fuel.

The administration attempted to implement measures to slow down the progress of sand transport, as has also been reported for China (Qi and Luo., 2003; Qi and Wang, 2003). However, despite the implementation of an agreement for the planting of shrubs in 1842 and the publication by the Canary Islands Regional Government in the Official Gazette of 1843 that shrub removal was to be avoided, the situation would not change in the following years. However, the *M. crystallinum* trade would gradually diminish from this point on, as exportations to other countries began to decline.

The result of sand mobilization is similar to that found in other similar ecosystems in Israel (Tsoar & Blumberg, 2002; Kutiel et al., 2004). In El Jable, the erosion processes caused the partial or total burial of houses and forced migrations from San Bartolomé, Tao or Mozaga (towns in the interior of El Jable) (Madoz, 1849). Likewise, sand mobilization affected the remains of aboriginal villages and various infrastructures including a road that, according to travelers, was unusable due to the accumulation of sand. Frequent references can be found in press reports (1843-1864) and oral sources (1940).

It is possible that, because the aeolian sedimentary system discharges into the beaches of Arrecife, the historical land uses produced a progradation of the beaches or changes in the depth of the port area throughout the 19th century, forcing vessels to anchor at sea and use smaller boats to get to the island, as was reported by travelers (Álvarez Rixo, 1866; Stone, 1887). Such a process has also been observed in Jandía (Fuerteventura) due to the elimination of vegetation cover (Marrero-Rodríguez et al., 2020a). This reduction in depth due to the accumulation in the port area of Arrecife, located on the south coast of the aeolian sedimentary system and described as one of the best ports in the archipelago (Glass, 1764; Ruiz-Cermeño, 1772; Caballero-Mújica, 1991; Fritsch, 2006), raised concern that the port would be unusable within a few years. Greff (1868) also reported that species present on the Arrecife coast had changed due to these modifications to the depth of the coast and the burial of coastal ecosystems.

Because of the need to adapt to this sand mobility, the inhabitants of El Jable developed a system based on the installation of bulky bales of rye which were positioned perpendicular to the wind to block its effects and the impact of sand on the crops. However, in years of poor harvests, the inhabitants were faced with the problem of having insufficient spare material for the construction of these protective barriers (Fig. 3B) against the burial of their crops by sediment. In such years, it is described in the press of the time how the crops were uprooted by the force of the wind and how the farmers had to strive manually to keep the crops clean of sand.

4.1.3. Sand stabilization and erosion processes (1960-present)

Since 1960 there has been an important change in the economic model prevalent in the area, principally due to the emergence of tourism as an alternative to the traditional activities. The pressure of logging on the El Jable system for firewood collection purposes has ceased due to the rising importation of fossil fuels. However, there has been additional pressure on the system due to the increased demand for aggregates for construction purposes and the different recreational uses that have appeared there. The abandonment of traditional uses and the cessation of deforestation have favored plant recolonization and the reappearance of nebkhas in Caleta de Famara (Fig. 3). However, the beaches of Arrecife have also been modified as the result of these erosion processes. This has forced the local administration to carry out actions to regenerate the beaches with sand from underwater quarries or the transfer of sediment from other beaches, sediment that is usually lost after episodes of sea storms. On the other hand, the capacity of the ports to receive large ships is slowly recovering due to the disappearance of the entry of sediment from El Jable. As stated above, the new development model of the island, now based on tourist activity, has generated new land uses on El Jable, such as the extraction of aggregates for construction, the urbanization of the coastline and the proliferation of recreational activities.

The traditional practice of crop cultivation, along with the use of land for grazing by a small number of goats and sheep, continues to be present in El Jable. There are two types of crop cultivation: the first is carried out using an artificially arranged layer of pyroclastic material (Fig. 3A), while the second is established directly on the sand (Fig 3B). Even today, it can be seen how traditional practices are maintained to protect crops from the prevailing winds (using bales of rye or rows of *L. arborecens*).

By 2018, 9.35 km^2 of the sector had been urbanized, particularly in the area around the port of Arrecife and a few scattered built-up areas in the northern sector of the system. The buildings constructed across the sediment transport exit sector have acted as a barrier, isolating the beaches of this southern area. On the other hand, the constructions towards the north have acted as a barrier to the entry of sediment into the system and have consequently resulted in landform modifications (Cabrera-Vega et al., 2013), as also detected in other similar systems in the Canary Islands, including Maspalomas (Gran Canaria), Lambra and Jable Sur (La Graciosa) and Corralejo (Fuerteventura) (García-Romero et al., 2016).

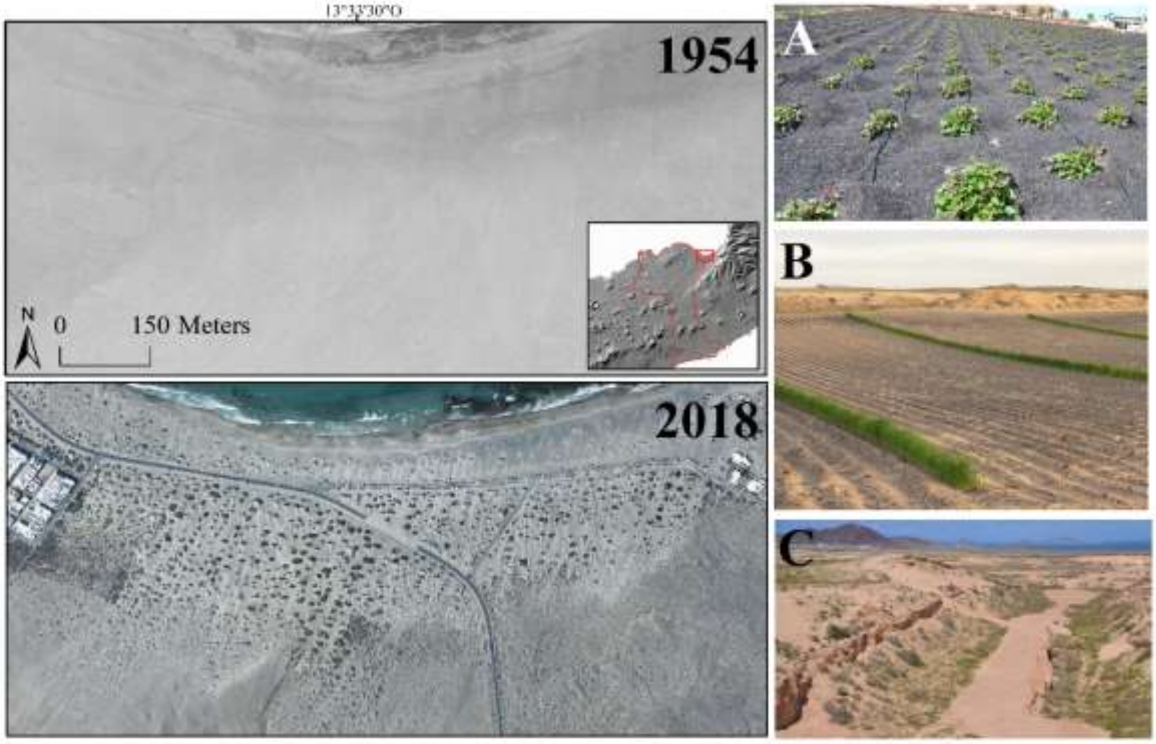

Figure 3. Status of vegetation cover in 1954 and in 2018 (Source: Web Map Service of the Canary Spatial Data Infrastructure) **A)** crops grown in pyroclastic material. **B)** crops grown in sandy material with vegetation barriers to protect against wind and sediment. **C)** abandoned aggregate extraction area (Source: Juan M. Hernández-Auta. 2018).

The extraction of aggregates that began in 1980 in the study area has had two main purposes. Firstly, to supply the demand for materials for the construction and creation of infrastructure and, secondly, for the agricultural sector. However, in the case of the extraction of biogenic sands, its destination has mainly been for construction purposes. The extractions were carried out 24 h a day, and in many cases illegally. In response to various limitations imposed by governmental bodies, the industrial sector held strikes to allow the extractions to continue. The extractions often generated large quarries up to 8 m deep (Fig. 3C). The total affected area amounts to 6.48 km^2. The extractions have generated a deficit in the final sediment balance that can be transported and large traps that retain the sediments from the Caleta de Famara and Soo sectors.

4.2. Social relevance of ecosystem services

The representation of the different ESs in the historical sources varies depending on the type of service (Fig. 4). Thus, *provisioning* services are those that have the greatest weight in historical sources with 52% of the references (632 references), including most notably *Food* (31.92%), *Fuel* (9.14%) and *Raw materials* (7.92%). In the case of references to *regulating* services (14%), only references to *Natural hazard regulations* appear (169 references). For *cultural* services, there are a total of 288 references that are divided between *Cultural heritage* (7.18%), *Recreation and leisure* (8%), *Aesthetic value* (7.51%) and *Education and research* (0.82%). Finally, *supporting* services (136 references) only appear represented by *Provision of habitat* (11%).

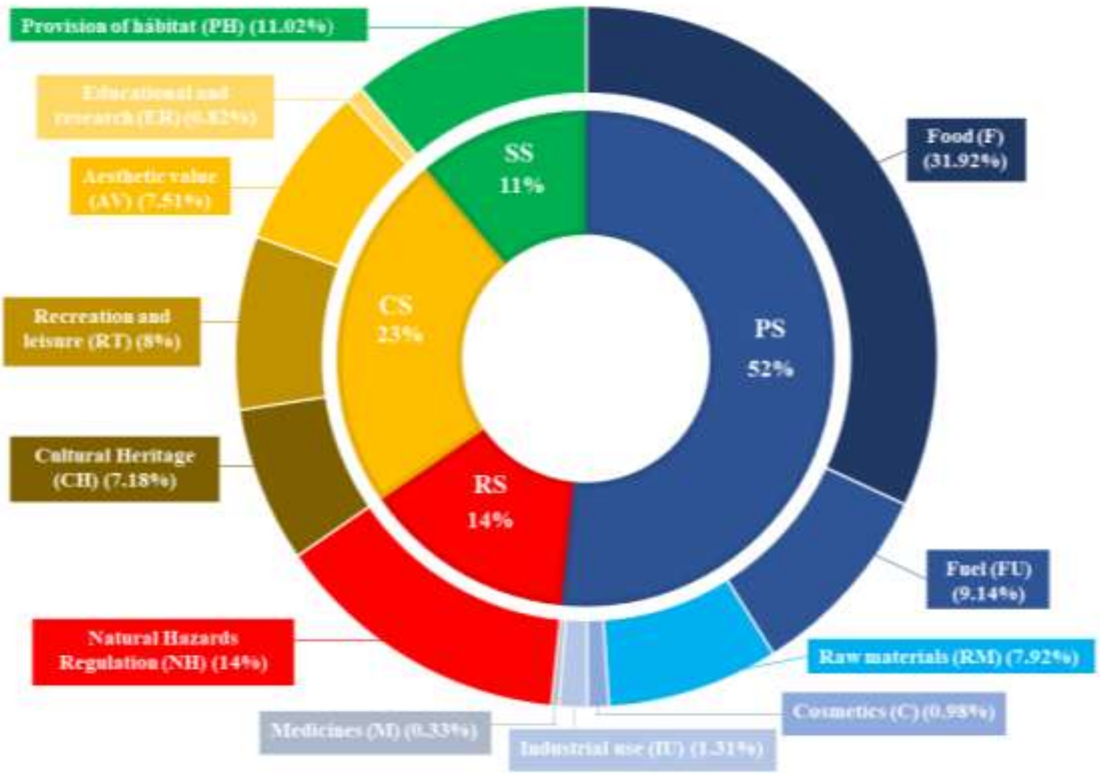

Figure 4. Representation of ecosystem services in historical sources. PS: Provisioning services; RS: Regulating services; CS: Cultural services; SS: Supporting services.

How aeolian sedimentary systems are managed can have an impact on the provision of ESs (Everard et al., 2010). In this respect, Table 4 shows the qualitative impact that land uses recorded in the historical sources have had on the ESs provided by El Jable.

In general terms, ESs are significantly affected by the elimination of vegetation cover as this exerts an important control on the sedimentary dynamics (Hesp, 1981; Moreno-Casasola, 1986). Likewise, urbanization processes reduce the area available for wildlife habitats and affect the provision of other ESs (*Fuel, Raw materials, Photosynthesis* and *Pollination*, among others).

In El Jable, the effects on the *provisioning* services provided by the ecosystem between 1750 and 1960 were principally due to the problem of the transport of sediment burying crops. Livestock grazing and the need for fuel also resulted in modifications to plant communities, with some species seeing their populations considerably reduced or even becoming extinct, as also observed in other areas (Hunt, 2001). However, in El Jable, attempts were made by regional and local government authorities to control the overexploitation of plant resources and repair the damage caused by the sedimentary dynamics. In addition, the important ecological movement that has emerged on the island since 1970 has exerted considerable social pressure, acting as a driving force behind, firstly, a successful campaign to ensure the legal protection of at least part of the system and, later, the regulation of sand extraction for construction purposes.

As for the *regulating* services provided by the aeolian sedimentary dynamics, in the pre-1960 period an oversupply of sediments increased the capacity of the system to limit beach erosion in the southern sector. At the same time, the removal of vegetation cover and the resulting changes led to in an increase in the transport of sand that caused significant damage to crops, homes, port areas and roads. From 1960 onwards, sand-induced damage has diminished considerably due to the resurgence in vegetation cover, while beaches in the southern sector have suffered erosion processes due to both extreme meteorological and marine phenomena and the limited supply of sediment as the result of the previously mentioned reduction in sand transport and the urbanization processes that have isolated the beach.

Less evidence of the loss of cultural services was found. In general, only a few losses related to cultural heritage (principally archaeological sites and wells) were detected. Local tourism and recreational activities were affected by sedimentary activity in the early 20th century due to damage to infrastructure such as roads and signage, although the number of visitors would have been low, and from 1960 onwards due to the effect on mobile sand areas of urbanization processes.

Finally, the *supporting* services have been affected by strong erosion and deforestation processes. The capacity of the system to serve as a wildlife habitat has been modified by anthropic land uses (Hernández-Cordero et al., 2017, 2018; García-Romero et al., 2019). By way of example, underwater habitats were gradually buried, which resulted in modifications to the species (fauna and flora) found in the submerged area of Arrecife (Greff, 1868). This shows that there is an important link between the different ecosystems of the insular areas and that proper management is vital for their proper operation and conservation. Although, from 1987 onwards, new environmental laws protecting the system have contributed to conserving these services, the introduction of invasive species and the urbanization process that began with the emergence of tourism has had a negative impact on wildlife habitats.

In summary, it seems that the uses that have most influenced the alteration of ecosystem services are those related to the removal of vegetation cover (grazing and obtaining fuel) and the urbanization process (Table 4), the effects of which have also been analyzed for the Mediterranean coast (Carranza et al., 2019). In the case of El Jable, the ESs are conditioned by important changes in the sediment transport rate of the aeolian sedimentary system.

Table 4. Changes and need for control induced by land uses in the ecosystem services recorded in historical sources. F: Food; FU: Fuel; RM: Raw materials; C: Cosmetics; IU: Industrial use; GR: Genetic resource; MP:

Medicines or pharmaceutics; NH: Natural hazards; CR: Climate regulation; CH: Cultural heritage; RL: Recreation and leisure; AV: Aesthetic value; IA: Inspiration for art; SR: Social relations; ER: Educational and research resources; SF: Soil formation; NC: Nutrient cycling; P: Photosynthesis; PO: Pollination; PH: Provision of habitat.

	1750-1960 (Low vegetation cover / high sand mobility)	**1960 to present** (High vegetation cover / low sand mobility)
Provisioning services		
F	Problems with the crops been buried	No references
FU	Resource shortage around mid-19th century	Abandoned
R M	Laws to control the exploitation of *M. crystallinum.* Numerous laws to control deforestation.	Aggregate extraction started to be controlled by government law
C	Laws to control the exploitation of *M. crystallinum*	Abandoned
IU	Silt accumulation in port area	Recovered
GR	Species in danger/lost via grazing/deforestation	Species in danger/lost via grazing/deforestation
MP	Species in danger/lost via grazing/deforestation	Species in danger/lost via grazing/deforestation
Regulating services		
NH	Sand flows associated with torrential rainfall and frequent sandstorms	South coast erosion (Arrecife) through building acting as a barrier and vegetation recovery
CR	Lower carbon sequestration	Recovered
Cultural services		
CH	Burial of archeological sites/high fear of sandstorms/development of crop system	Destruction and protection of archeological sites
RL	Infrastructure problems due to sediment accumulation (whole system). Municipal ordinances for road and port maintenance.	Infrastructure problems due to sediment accumulation (Famara)
AV	Changes in the visual aspect of the landscape through deforestation and sediment remobilization	Changes in the visual aspect of the landscape through urbanization, aggregate extraction, vegetation recovery and sediment stabilization
IA	No references	No references
SR	No references	No references
ER	No references	No references
Supporting services		
SF	No references	No references
NC	No references	No references
P	No references	No references
PO	No references	No references
PH	Changes through sediment remobilization/introduction of invasive species/species lost through massive grazing	Favored by land protection laws/deteriorated through introduction of invasive species and urbanization processes

Legend	**High losses**	**Moderate losses**	**Increase**	**No change detected**

The social relevance of the ESs shows an important relationship with the land uses. Before 1960, the ESs with a high score in social relevance are generally related to the safety of the population, the provision of an economic income (e.g. *Fuel* or *Raw materials*), or the guarantee of food (*Food*) as they alleviate poverty (Shackleton et al., 2008). This is also related to the fact that some ESs can produce tangible resources, while the intangible nature of others makes them less relevant to the population. Changes in the social relevance of the ESs were observed in the information collected from the historical sources, starting around 1960 (when the transition to tourism begins). From that moment, *Aesthetic values, Local culture, Provision of habitat* and *Natural hazards* gain in importance. The increase in the social relevance of *Provision of habitat* is related to the appearance of pro-environmental movements in the island. The references to *Raw materials*, which until 1900 are related almost exclusively to the extraction of limestone and firewood, later, from 1980 onwards, give greater prominence to the extraction of aggregates. Similarly, with respect to the *Natural hazards* regulating service, the references up to around 1950 speak of the problem of the massive aeolian transport of sand, whereas from 1980 onwards the problem of beach erosion because of marine storms is the main topic of discussion. However, the most important trend is the reduction of references to *Food* and *Fuel* and the increased number of references to questions related to *Cultural heritage, Aesthetic value*, *Recreation and leisure* and *Provision of habitat* (Fig. 5). This shows that there has been a profound change in the mentality of the population, who now depend on imported products from abroad (food and fuel), and in the main economic activity (from agriculture and livestock to tourism). It should be noted that some of the services considered in this section do not appear in the historical references. They are nevertheless included because of their punctual exploitation or because they are intangible services and the lack of scientific research on regulating and cultural (apart from recreation and leisure) services is mainly related to the complexity of assessing intangible values (Schaich et al., 2010). Rural society, and indeed in many cases society in general in the past, has traditionally not attached much importance to ESs such as *Genetic resource, Climate regulation, Inspiration for art, Social relations, Soil formation, Nutrient cycling, Photosynthesis* or *Pollination*.

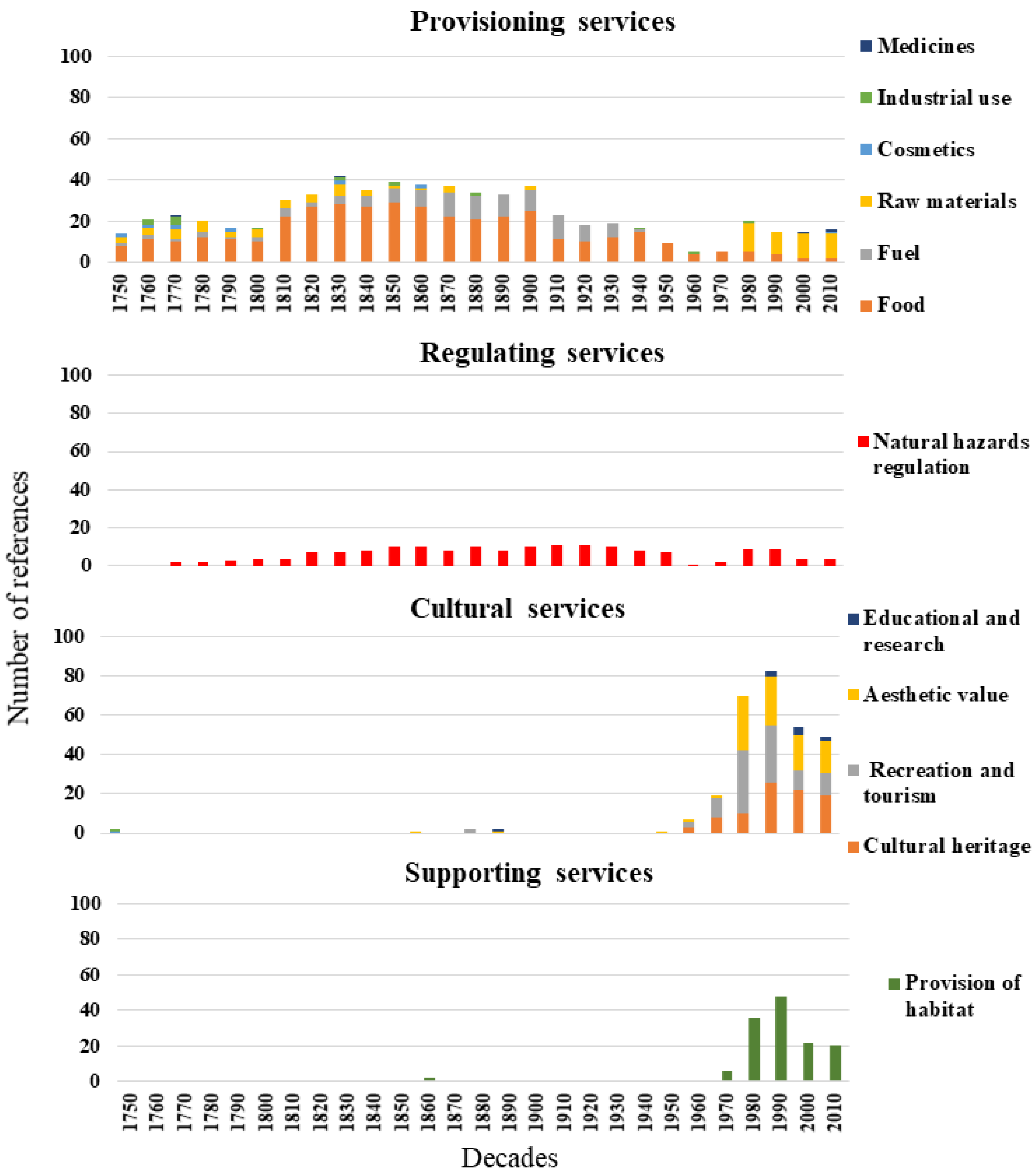

Figure 5. Evolution of the number of references to ecosystem services in the historical sources consulted

The historical social relevance of changes to or the loss of an ES related to different land use is shown in Table 5. As can be seen, the effects of the urbanization process since 1960 generally resulted in low scores despite the loss of ESs. The *Natural hazards* regulating service obtained a high score (0.89), given the wide-ranging debate held about the buildings of the city of Arrecife creating a barrier to the arrival of sand and, therefore, an increased vulnerability to marine storms. Likewise, the *Provision of habitat* service (0.67) scored high due to the emergence of the ecological movement and the tourist urbanizations in the surroundings of Caleta de Famara.

With respect to aggregate extraction, high social relevance scores were only obtained for the services of *Cultural heritage* (0.78) and *Aesthetic value* (0.67).

The ESs from which the population benefits directly are those that have the greatest social relevance. As such, grazing scored high in the provisioning services of *Food* (0.89), *Fuel* (0.67) and *Raw materials* (0.67). Likewise, logging also produced several changes in the capacity of the ecosystem to provide its services with various problems related to the elimination of vegetation, as can be seen in the scores for *Food* (0.89), *Raw materials* (0.44) and *Fuel* (0.89). In this respect, most of the references come from a time when food, fuel and raw materials were produced in the immediate environment. Because these three uses were competing for the same resources, the capacity of the ecosystem to provide them was compromised. By way of example, with respect to the *Food* service, both agricultural farmers and shepherds/goatherders would have been competing for the same resource, which explains the high historical social relevance score due to the loss of/damage to both these land uses. This produced a conflict between the two types of user, as has also happened in other areas (Kovács et al., 2015).

Grazing, cultivation and logging scored high in the *Natural hazards* regulating service (grazing = 0.89; cultivation = 0.67; logging = 0.89), in this case highlighting the debate around the increase in wind transport and the significant damage that this exerted in the period 1750-1960 (as described above). From 1960 onwards, beach erosion due to marine storms is mainly attributable to the urbanization process that has isolated the beaches from the rest of the aeolian sedimentary system.

Interestingly, in general terms, no type of management or prohibition measure has been taken by the administrations if there has been no social relevance or mobilization. In other words, political actions are directly related to social sensitivity or vice versa (McClurg, 2006). The only case that might be considered an exception is the case of the *Provision of habitat* service for grazing and cultivation, for both of which protective and regulatory measures have been established despite the fact that both the extraction of aggregates and urbanization are more harmful to the provision of that service (García-Romero et al., 2019; Marrero-Rodríguez et al., 2020b). Finally, despite the potential damage of some land uses, some of the ESs scored low in terms of social relevance. Those with the lowest scores are intangible services (including *Inspiration for art*, *Social relations*, *Education and research*, *Soil formation*, *Nutrient cycling* or *Photosynthesis*), or have only been sporadically exploited (*Cosmetics*, *Genetic resource* and *Medicines or pharmaceutics*).

Table 5. Social relevance of the change to or loss of an ecosystem service induced by land use. Horizontal axis: S: social sensitivity criterion; E: economic criterion; P: political criterion. Σav: Sum of all scores. Vertical axis: F: Food; FU: Fuel; RM: Raw materials; C: Cosmetics; O: Others; IU: Industrial use; GR: Genetic resource; MP: Medicines or pharmaceutics; OS: Ornamental source; NH: Natural hazards; CR: Climate regulation; CH: Cultural heritage; RL: Recreation and leisure; AV: Aesthetic value; IA: Inspiration for art; SR: Social relations; ER: Education and research; SF: Soil formation; NC: Nutrient cycling; P: Photosynthesis; PO: Pollination; PH: Provision of habitat.

	Urbanization (1960-present)				**Aggregate extraction (1980-present)**				**Grazing (Unknown-present)**				**Cultivation (Unknown-present)**				**Logging (Unknown-1960)**			
	S	E	P	Σav /9	S	E	P	Σav /9	S	E	P	Σav /9	S	E	P	Σav /9	S	E	P	Σav /9
Provisioning services																				
F	0	1	0	0.12	0	1	0	0.12	3	2	2	0.89	3	1	0	0.44	3	3	2	0.89
FU	0	1	0	0.12	0	1	0	0.12	2	2	2	0.67	2	1	0	0.33	1	1	2	0.44
RM	0	1	0	0.12	0	1	0	0.12	2	2	2	0.67	2	1	0	0.33	3	3	2	0.89
C	0	1	0	0.12	0	1	0	0.12	0	1	0	0.12	0	1	0	0.12	0	1	0	0.12
IU	0	1	0	0.12	0	1	0	0.12	0	1	0	0.12	0	1	0	0.12	1	3	1	0.56
GR	0	1	0	0.12	0	1	0	0.12	0	1	0	0.12	0	1	0	0.12	0	1	0	0.12
MP	0	1	0	0.12	0	1	0	0.12	0	1	0	0.12	0	1	0	0.12	0	1	0	0.12
Regulating services																				
NH	2	3	3	0.89	0	1	0	0.12	3	2	3	0.89	3	3	0	0.67	3	3	2	0.89
CR	0	1	0	0.12	0	1	0	0.12	0	1	0	0.12	0	1	0	0.12	0	1	0	0.12
Cultural services																				
CH	0	1	0	0.12	3	1	3	0.78	0	1	0	0.12	1	2	3	0.67	0	2	0	0.23
RL	0	1	0	0.12	0	1	0	0.12	0	1	0	0.12	0	1	0	0.12	2	2	2	0.67
AV	0	1	0	0.12	3	2	1	0.67	0	1	0	0.12	0	1	0	0.12	0	1	0	0.12

IA	0	1	0	0.12	0	1	0	0.12	0	1	0	0.12	0	1	0	0.12	0	1	0	0.12
SR	0	1	0	0.12	0	1	0	0.12	0	1	0	0.12	0	1	0	0.12	0	1	0	0.12
ER	0	1	0	0.12	0	1	0	0.12	0	1	0	0.12	0	1	0	0.12	0	1	0	0.12
Supporting services																				
SF	0	1	0	0.12	0	1	0	0.12	0	1	0	0.12	0	1	0	0.12	0	1	0	0.12
NC	0	1	0	0.12	0	1	0	0.12	0	1	0	0.12	0	1	0	0.12	0	1	0	0.12
P	0	1	0	0.12	0	1	0	0.12	0	1	0	0.12	0	1	0	0.12	0	1	0	0.12
PO	0	1	0	0.12	0	1	0	0.12	0	1	0	0.12	0	1	0	0.12	0	1	0	0.12
PH	2	1	3	0.67	3	1	1	0.56	0	1	3	0.45	0	1	3	0.45	1	1	0	0.23
Low social relevance								Moderate social relevance								High social relevance				

The methodology used in the present work has some limitations. The reconstruction of land uses and landscape has been widely carried out by numerous authors (e.g. Grossinger et al., 2007; Hoffman & Rohde, 2007), but the loss of ESs and the reaction that people and management entities have to such losses has not been studied in depth historically (Bálee, 2006). However, the relationship between ESs and land uses has been demonstrated in many studies (Su & Fu, 2013; Sun et al., 2019). It should be noted that the limitations of historical ecology for other works are also applicable to ours (Szábo, 2015). Nonetheless, the historical analysis carried out in the present work constitutes a tool to understand the driving forces behind the loss of a service, the reaction of society and political management. It should also be highlighted that many management measures are not applied until the moment when land uses have transformed or pushed the capacity of an ecosystem to provide an ES to its limit. In addition, this work shows the existence of conflicts for the exploitation of resources and the reaction of society to such conflicts through a methodology that integrates the social, political, environmental and economic dimensions using sources for a period of more than 200 years, which is commonly the limit of historical ecology studies (Szábo, 2015).

In terms of management, there is a tendency to integrate the physical and social sides under the framework of the integrated management of coastal areas (Scura et al., 1992; Thia-Eng, 1993; Post & Lundin, 1996) because society increasingly has more concerns about the environment and because management measures entail changes in the perception of users about the ecosystem (Pranzini et al., 2010). Therefore, this work offers an example of the monitoring of the reaction of societies to changes over an extensive period using the available sources. Works of this type can be useful in the decision-making process for societal integration in areas that depend heavily on a service sector-based economy, as well as in areas where traditional uses and subsistence economies are predominant. In both, planning, management and, later, monitoring (Micallef & Williams, 2002) are important to stop the degradation of ecosystems and, therefore, the loss of ESs.

In the present study, the aims of historical ecology as proposed by Bürgi & Gimmi (2007) have been taken into consideration in the reporting of the evolution of landscape management and how society has perceived the changes that have taken place. Knowledge of historical trends improves our understanding of the natural dynamics of landscapes and provides a framework for evaluating current patterns and present and future processes (Swetnam et al., 1999). Finally, this work can be of help to land managers who need to understand how management measures can provoke reactions in society or land custody entities, as well as to understand the reasons behind social reactions to changes in ecosystems and the services that they provide. Additionally, the reconstruction of land uses and their consequences for the natural dynamics of an ecosystem can help to understand the responses of that system to new environmental conditions, land uses or management measures (Swetnam et al., 1999; Berkes et al., 2000). In summary, the present work can help managers to plan the integrated management of coastal areas, using history as a tool to understand changes in the perception of society, the responses of ecosystem dynamics to land uses, and changes in ESs.

5 Conclusions

The methodology used to reconstruct historical social relevance related to the loss or modification of ecosystem services has shown the existence of a relationship with the different land uses that took place during varying timeframes of the study period. In this particular case study, environmental changes in El Jable (Lanzarote, Canary Islands) were found to have a social relevance in the past when the impacts were due to anthropogenic activities. Two main periods related to the loss of ecosystem services and environmental changes were identified: i) from 1750 to 1960, during which time traditional uses caused significant deforestation of the system and consequent sediment remobilization; ii) from 1960 to the present, during which time the abandonment of traditional uses has resulted in sediment stabilization due to the spontaneous re-emergence of vegetation. In both periods, the social relevance of the ecosystem services changed depending on the different land uses of each period. The analysis of historical sources reveals that the changes to or loss of ecosystem services which have had high social relevance are related to the social sensitivity, political or economic criteria that were considered, and that these depend to a large extent on the type of service provided (provisioning, regulating, cultural or supporting). The most direct and vital ecosystem services (the provision of food, fuel and raw materials, and the regulation of natural hazards) are those with the greatest historical social relevance until 1960. At this point in time, a change to the economic model involving the promotion of tourism resulted in other aspects (cultural heritage, recreation and leisure and aesthetic value) acquiring greater social relevance in terms of citizen safety (regulation of natural hazards), ecosystem conservation (provision of wildlife habitats) and culture (cultural heritage). This research also helps us understand that despite the fact that two ecosystem services may be lost due to the same land use, the social reaction may be different and, with it, the influence that society has had on the restoration, regulation and protection measures and on the political and economic decision-making processes. It additionally shows that most management measures are taken after the loss of an ecosystem service or after important modifications to the natural dynamics of the ecosystem.

ACKNOWLEDGEMENTS

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5.5 Can long-term beach erosion be solved with soft management measures? Case study of the protected Jandía beaches.

Can long-term beach erosion be solved with soft management measures? Case study of the protected Jandía beaches.

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Abstract: Land uses have long modified aeolian sedimentary dynamics as has occurred in the Jandía isthmus (Fuerteventura, Canary Islands, Spain), where changes in vegetation cover, the reduction of sediment available for transport and the building of barriers to sediment transport have induced beach erosion. In the last 62 years the beach area has experienced a reduction of 800,000 m^2. The aim of this paper is to analyse the current situation (in terms of sediment availability, longshore drift and the distribution of protected plant species) in order to make soft management proposals to respond to the current erosive situation. Based on a methodology that combines field work, coastline digitalization and longshore drift calculations, it is found that each year the system loses about 96,000 m^3 of sediment which needs to be replaced in order to stop erosion. Four possible ways to manage the system are discussed: passive non-intervention management to allow the ecosystem to evolve and adapt to the new conditions; remobilization of the sedimentary deposits of the isthmus that feed the beaches; beach nourishment from other areas of the system or from outside the system, and; mechanical recirculation of the sands. The viability of each management system is analysed, particularly with regard to long-term sustainability, as well as its compliance or otherwise with the protection measures that are in place. Paradoxically, the only measures that can alleviate the problem in the long term are incompatible with the current protective measures. In other words, the isthmus and the Sotavento beaches in Jandía

are an example of an ecosystem in which the restrictions imposed as a result of its protected status, that do not take into account the tendences of the ecosystem, in fact constitute an obstacle to its conservation and do not allow the adoption of measures that could slow down the degradation process and, ultimately, impede its disappearance.

Key words: coastal management; arid aeolian sedimentary system; beach erosion; beach nourishment; passive management.

1. Introduction

Beach-dune systems are an important tourism resource for many coastal economies (Klein et al., 2004). In recent decades recreational seashore activities have been concentrated mostly on sandy shores (Caffyn & Jobbins, 2003), with more than 70% of the world's beaches now experiencing erosion (E.g.: Bird, 1996; Sajinkumar et al., 2020; Bitan et al., 2020; Hasiotis, et al., 2021). Sandy shores are fragile environments and the adoption of management measures without the appropriate technical reports can produce irreversible long-term changes for these ecosystems. This has happened in many coastal areas and is commonly related with the need to adapt beaches and dune systems to user preferences (Peña-Alonso et al., 2018; San Romualdo-Collado et al., 2021a), the construction of marine infrastructure (Depellegrin et al., 2014; Mamo et al., 2018) and urban development (Alonso et al., 2002; García-Romero et al., 2016). In this process of transformation several changes can take place. For example, in the case of beaches, these changes include, among others, erosion (Bird & Lewis, 2015), progradation (Guillén & Palanques, 1997; Anthony et al., 2014; Moussa et al., 2019) and modifications to the type of sediment (Marrero et al., 2017). In the specific case of aeolian sedimentary systems, research studies have discovered changes in landforms (García-Romero et al., 2016) and aeolian sedimentary activity (dune stabilization) (Marrero-Rodríguez et al., 2020a), reductions of pioneer plants in mobile dunes and decreased species richness (Kutiel et al., 1999; Curr et al., 2000; Faggi & Dadon, 2011), sediment remobilization (Arens et al., 2013), alteration of the direction and speed of wind flows (Smith et al., 2017; García-Romero et al., 2019) and, on occasions, surface area reductions (Marrero-Rodríguez et al., 2020b).

The above shows that, although they provide an important variety of ecosystem services (habitat of many species, buffer against extreme events, among many others) including direct economic, recreational and wellness benefits for humans (Defeo et al., 2009; Schuhmann & Mahon, 2015), the conservation of aeolian sedimentary systems has been relegated to the background. It was observed in a recent review of dune management that management measures have been promoted (introduction of grazing, sand remobilization, creation of blowouts, etc.) which, despite their good intentions and the aim of conserving habitats where priority species appear, have actually contributed to the degradation of these systems (Delgado-Fernández et al., 2019). In this context, soft management measures have been applied in many areas (Roig et al., 2009) to slow down erosion and degradation. However, in some areas such solutions are insufficient to compensate the consequences of human interventions or changes in dynamic conditions. Large-scale measures and expensive solutions are therefore sometimes required to save what is often the driving force of a local economy (Landry et al., 2003; Huang et al., 2007).

In the case of the isthmus of Jandía (Fuerteventura, Canary Islands, Spain), management is complex due to the high number of protection status figures that have been declared and imposed on a relatively small area. As in other coastal areas, conflicts arise between the conservation of the economic resource identified by the majority of users (the beach) and the conservation of the habitat as a whole (beach-dune system and shallow waters) and its natural dynamics, since the erosion of the beach can suppose important economic losses, as has happened in other coastal systems (Thinh et al., 2019; Alexandrakis et al., 2015).

In this context, the aims of this work are:

i) To carry out an analysis of the current situation of the system with respect, above all, to the coastal dynamics (evolution of coastline and longshore drift), the state of the aeolian sedimentary system (sediment availability and vegetation), and the evolution of land uses.

ii) To discuss four soft management proposals (beach nourishment, remobilization of aeolian deposits, passive management or mechanical sand recirculation) that are appropriate for the dynamics of the system and which do not contravene the protection measures of the study area that are presently in place, or which, failing that, at least do not require significant changes in the current legislation.

2. Study area

The study area is made up of a set of beaches that are located in the municipality of Pájara in the south of the island of Fuerteventura (Fig. 1). The genesis of the Sotavento beaches is related to contributions of sediments, mostly biogenic and carried by the N wind component (Fig. 2) from the interior of the isthmus of Jandía, that resulted from the erosion of aeolianite deposits and quaternary calcareous crusts (Alcántara-Carrió et al., 2010).

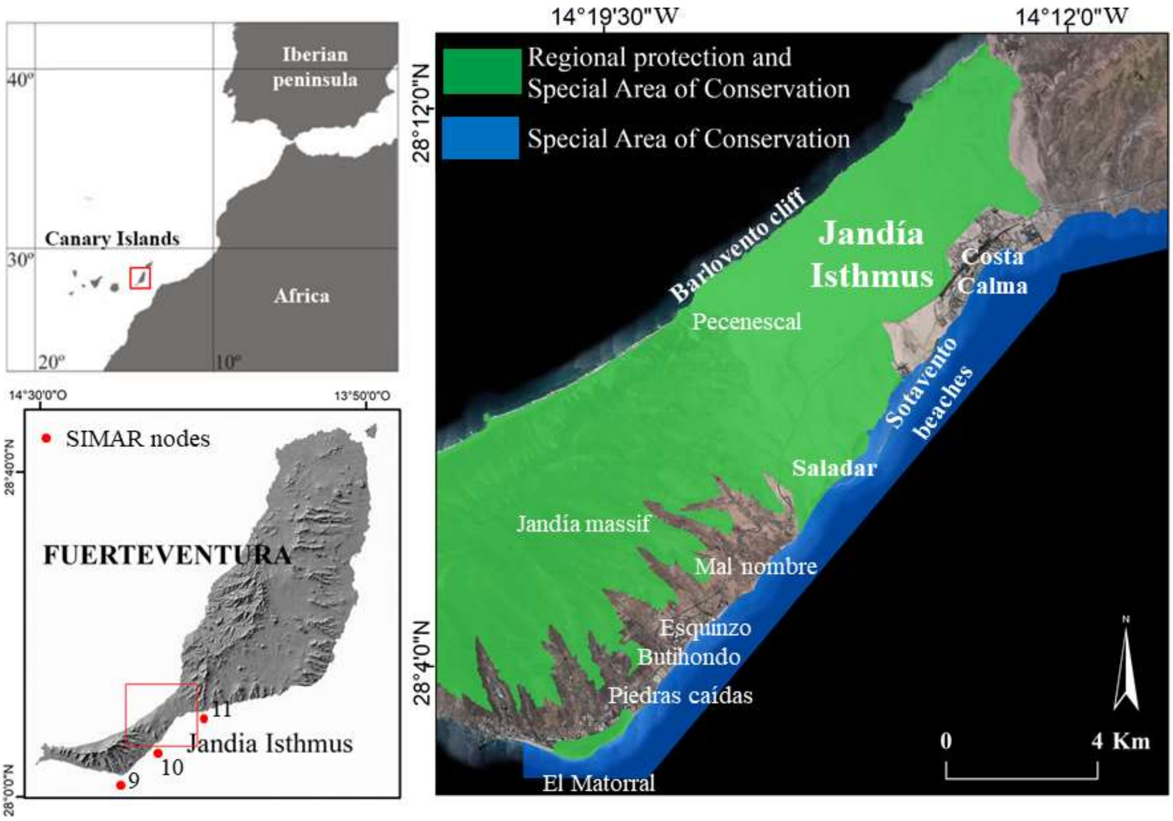

Figure 1. Location of the study area, protection status and location of the SIMAR nodes (Source of 2018 digital orthophoto: SDI Canarias, Canary Islands Government, GRAFCAN, S.A.).

The isthmus of Jandía corresponds to an area of approximately 50 km^2 covered to a large extent by sands of organogenic origin. The continued contribution of these materials in large quantities has allowed the formation of the extensive Sotavento beach. After being deposited in this sector, the dominant swell generates a longshore drift that transports the sediments from these beaches southwards. As a result of this longshore drift, new beaches formed south of the mouth of the Pecenescal ravine.

Along this approximately 5.8 km long stretch of coast, the most important beaches are: i) the Sotavento beach, generated by wind inputs from the interior of the isthmus (Alcántara-Carrió, 2003) and about 10 km in length. This practically uninterrupted beach is characterized by the presence of a coastal sand bar that delimits an intertidal coastal lagoon; ii) the beaches of Mal

Nombre, Esquizo and Butihondo. Along this stretch of coast, about 5.8 km long, the beaches are interrupted by ravine mouths which can fill up with sediment; iii) the El Matorral sector, which constitutes the last point to the south where biogenic sediments from the isthmus appear, is an open, pointed, 4.2 km long beach located opposite a salt marsh (Saladar).

The study area is partially protected as part of the Canary Islands Network of Protected Natural Spaces (Fig. 1 green), as well as being part of a Special Conservation Zone and a Special Protection Zone for Birds (Fig. 1 blue). In addition, the El Matorral-Saladar section is included in the List of Wetlands of International Importance, also known as the Ramsar List.

The climate of the area has been defined as arid with annual average temperatures of around 20ºC (Alcántara-Carrió, 2003), while the scarce and highly irregular precipitations are concentrated in just a few days of the year and do not usually exceed 100 mm (Alonso et al., 2011).

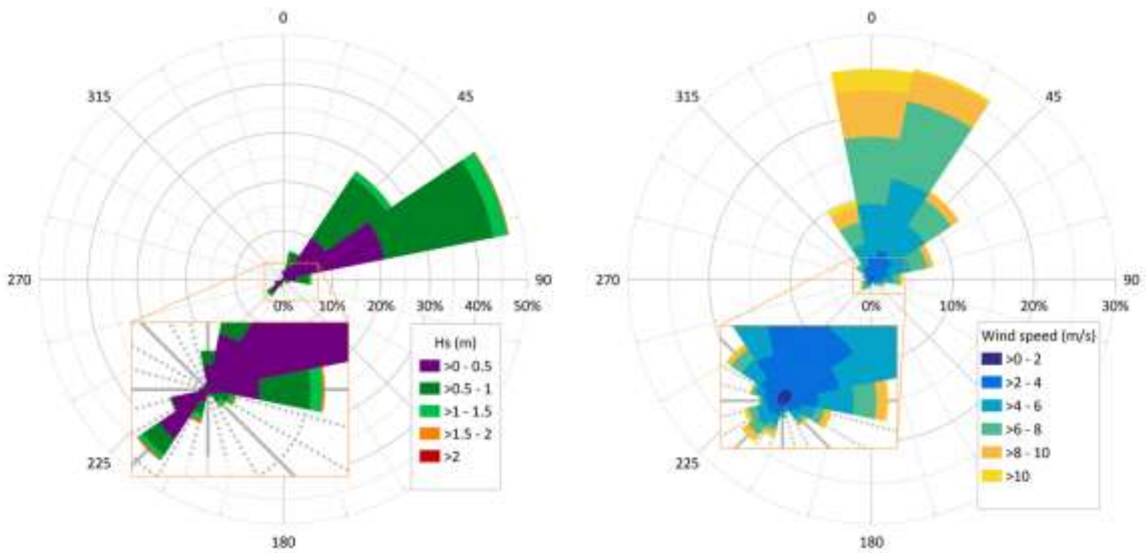

Figure 2. Wave rose (left) and wind rose (right) of SIMAR node 10 (Location in Fig. 1) (Source: Spanish State Ports (2006-2020)).

The study area is characterized by waves coming from the ENE and NE with small wave heights (H_s < 1 m) and low peak period values (5-10 s) (Fig. 2). That is, wind waves with a short fetch prevail due to the proximity to the African continent (Fig. 1). Stormy events are very scarce, mainly taking place during winter when the prevailing wave direction is from the SW.

Vegetation is scarce due to the high temperatures, intense sunshine and strong and frequent winds. Land cover is limited and the plants, in general, do not exceed the shrub layer (Alcántara-Carrió, 2003). There are three main vegetation types in the study area: psammophytes in the mobile sand areas; halophytes, concentrated in the backshore zones of Sotavento and El Matorral where salinity and tidal flooding are intense; and thickets of Chenopodiaceae on calcareous crusts and rocky outcrops (Martín-Esquivel et al., 1995).

3. Methods and data

3.1 Historical documents

Historical documents from the Fuerteventura archives were reviewed. The most important historical document considers land uses in the mid-nineteenth century and is titled "Description of the Jandía Grazing Land Estate". Official reports, acts and decrees of the Fuerteventura Island Government were also consulted. The rest of the historical information was obtained from Marrero-Rodríguez et al. (2020a).

3.2 Orthophotos and aerial photographs

The analysis of coastline evolution was carried out using a set of orthophotos and aerial photographs. The aim was for the study period to be as extensive as possible, with the first available orthophoto dating back to 1956. Although it would have been ideal to have a set of data homogenously distributed over time and the initial idea was to select one flight per decade from this starting date of 1956, this was not always possible. Consequently, the longest interval between images is 13 years and the shortest 7 (Table 1). After selecting the dates, the photograms were georeferenced and a database was created with the archive of available images of the study area. The coastline was manually digitalized on each of the selected photograms and orthophotos. Coastline advance/retreat was obtained on the basis of 27 outlines each separated by 750 m and spread along the entire study area. In each outline and in each orthophoto, the position of the shoreline was determined using the limit between dry and wet area as the defining point. In addition, the evolution of the urbanization process was analysed and digitalized on the basis of the historical photographs. The bathymetric model was obtained from the Ecocartography Plan of the Spanish coastline carried out by the General Directorate of Sustainability of the Coast and the Sea during 2000 and 2001.

Table 1. Photograms and orthophotos used in the digitalization process of the coastline. Source: Spanish National Geographic Institute (Initials in Spanish: IGN) and GRAFCAN.

Year	**Type**	**Resolution (orthophoto)**	**Scale (photogram)**	**Georeferencing error**	**Source**
1956	Orthophoto	20 cm/pixel			GRAFCAN
1969	Photogram		1:7000	2.83 m	GRAFCAN
1981	Photogram		1:18000	2.3 m	IGN
1994	Orthophoto	40 cm/pixel			GRAFCAN
2002	Orthophoto	100 cm/pixel			GRAFCAN
2009	Orthophoto	40 cm/pixel			GRAFCAN
2018	Orthophoto	20 cm/pixel			GRAFCAN

3.3 Wave climate

Wind and wave data were obtained from three SIMAR nodes managed by the Spanish State Ports Agency. These nodes are all located along the southern coastline of the study area. The corresponding codes of these nodes are 40500009, 4051010 and 4052011, renamed for the purposes of this paper as SIMAR 09, SIMAR 10 and SIMAR 11, respectively (Fig. 1). The entire SIMAR dataset comes from numerical models and therefore these are not wind and wave data recorded *in situ*. Nevertheless, comparisons between numerical model and wave gauge data have been performed by other authors, with good agreement and low bias found between the two datasets (Pilar et al., 2008; Rubio, 2020). Other advantages of the SIMAR dataset include its starting date of 1958, very close to that of the first orthophoto, and the fact that it represents an optimal series of wind and wave data covering a period of 62 years.

3.4 Sediment thickness and vegetation

A field campaign was carried out in November 2020 during which 144 field tests were carried out. These tests were distributed throughout the study area to determine the thickness of available sediment that could be transported to the beaches of the isthmus of Jandía. Sampling was performed by digging manually to a maximum depth of 75 cm whenever the hardness of the materials allowed it. In the cases in which all the excavated material corresponded to sand, the thickness was assumed to be 1 m. From these data, a digital terrain model was generated to represent the variation of the thickness of the sand sheet in the Jandía isthmus. ArcGIS software was used to apply the kriging interpolation tool.

With respect to vegetation data, a list of protected species in the study area was identified on the basis of information obtained from the Canary Islands Biodiversity Databank.

3.5 Calculation of sediment volume

The volume of eroded/accumulated sediment along the coast in the different time intervals was obtained assuming that the displacement experienced by the shoreline, ΔX, is translated into a horizontal displacement of the beach contour parallel to it, which would thus maintain a constant form. In consequence, the variation in volume, ΔV, is given by Eq.(1):

$$\Delta V = \frac{\Delta X}{\Delta t} \cdot \Delta Y \cdot (dc + S) \quad (1)$$

where ΔY is the length of influence of each contour, understood as half the distance between adjacent contours measured on both sides of each contour, *dc* is the depth of closure and *S* is the superelevation attained by the water level.

Of these terms, $\Delta X/\Delta t$ is obtained directly from the analysis of the evolution of the coastline and ΔY is a fixed measure of 750 m, which is the distance between the different contours. This was an arbitrary distance determined by considering that the studied coastline is slightly larger than 20 km; therefore, we defined 27 fixed lines separated by 750m from each other to cover the entire study area. In each of these lines the coastline position was measured from the aerial photographs. Depth of closure is a fundamental morphodynamic boundary separating a landward active zone from a seaward less active zone over the period defined by the profile observations used to define closure (Nichols et al., 1996). Its determination is essential to estimate the volume of sediment that is gained or lost in the coastal zone. The equation proposed by Hallermeier (1981) and shown in Eq.(2) was used:

$$d_c = 2.28 H_s - 68.5 (H_s^2 / g T_s^2) \quad (2)$$

where H_s and T_s are, respectively, the values of the significant wave height and period, representing high energy conditions (storms) in which contour modification can attain higher depths. In the original formulation of Hallermeier (1981), the characteristic wave is associated to a probability not exceeding 12 times/year. Both H_s and T_s were obtained from the wave dataset corresponding to SIMAR node 10 for the complete available data period (April 1958 to November 2020).

Given the temporal scale of the present study, three different methods were employed to estimate the depth closure. This approach has been followed by other authors in long-term studies to include the probability of the existence of exceptionally energetic years in the period of interest, as storm wave height on a particular coast can increase with longer control periods (Stive et al., 1996; Jiménez, 1997; Jiménez et al., 2001). In the first approach, the closure depth was calculated on the basis of the strongest storm recorded in the period (February 2010), and the H_s associated to a probability of 12 times/year is 2.87 m, while the associated T_s is 8.78 s. In the second approach, the maximum wave height "recorded" at SIMAR node 10 was used, with in this case the H_s value being 3.89 m and the associated period T_s = 8.52 s. The third approach was based on extreme wave climate data, obtained from the Las Palmas Este wave gauge during the period 1992-2017. Wave values for a 10-year return period are H_s= 4.37 m and T_s = 10.49 s (Spanish State Ports, 2020).

The depth of closure was obtained with each of these datasets using the equation proposed by Hallermeir (1981), and the mean of these values was used to calculate the sediment volume gained or lost in each sector of the study area.

Finally, the *S* term has two components, one due to the tide and the other to the swell. The tidal contribution can be calculated on the basis of the height of the tide at the time the different photograms were taken. However, for this, the indispensable information of the day and the hour when they were taken was not known, and so this term was estimated assuming that the tide was halfway between its mid level and high tide. Given that the mean tidal range for Fuerteventura is 1.72 m (Spanish State Ports, 2019), this tidal component is 0.43 m.

The component due to swell is the run-up, which was calculated through the expression of Holman and Sallenger (1985), Eq.(3):

$$R = 1{,}07\ H_0 \cdot \xi_0 \quad (3)$$

where H_0 is the significant wave height in undefined depths and ξ_0 is the Iribarren number, which is turn defined through Eq.(4) as:

$$\xi_0 = \frac{\tan\beta}{\sqrt{H_0 / L_0}} \tag{4}$$

where $\tan\beta$ is the beach face slope and L_0 is the wave length which in turns depends on the wave period.

Considering that H_0 = 0.42 m and T = 5.8 s are the mean values for SIMAR node 10, and assuming a value of $\tan\beta$ = 0.04, an R value of 0.2 m was obtained.

3.6 Surf zone width and breaking depth

For the calculation of longshore drift, which is preferentially produced in the surf zone between the breaker and the shore (Komar, 1998; Rogers & Ravens, 2008), the breaking index γ was used, which marks the relationship between the breaker wave height (H_b) and the depth (d) at which the wave breaks, Eq.(5):

$$\gamma = \frac{H_b}{d} \tag{5}$$

In the absence of direct measures of breaker wave height, this variable was estimated through the expression of Komar and Gaugham (1972), Eq.(6):

$$H_b = 0.39\, g^{1/5} \, (TH_0^2)^{2/5} \tag{6}$$

The breaking index γ was then calculated from the expression given by Sunamura (1980), Eq.(7):

$$\gamma = 1.1\xi_b^{1/6} \quad (7)$$

where ξ_b is the Iribarren number, but where H_b is used instead of H_0.

Knowing the mean values of H_0 and T both in situations of fair weather and storms for the SIMAR nodes 09 and SIMAR 10, the depth (*d*) at which the wave breaks can be calculated in both situations.

4. Results and discussion

4.1 Historical land uses

The isthmus of Jandía has been exploited as grazing land since practically the beginning of the colonization of the islands in the 15th century (Cabrera, 2001). The grazing model is based on the release of animals (in this particular case of goats and camels) (Roldan & Delgado, 1967; 1970) which are allowed to roam free before being herded together to obtain the animal produce. From approximately 1850 onwards, the vegetation in the area began to be exploited for use as firewood in lime kilns. This use continued until around 1960, resulting in a drastic reduction in plant cover. As reported by Marrero-Rodríguez et al. (2020a), in these conditions the isthmus of Jandía must have experienced important erosion processes which will have accelerated the natural sediment transport in the direction of the Sotavento beaches, resulting in progradation of the aeolian landforms and beaches. The local use of vegetation as fuel for the lime kiln industry fell into decline from 1960 with the arrival of fossil fuels (coal) and the pressure that had traditionally affected the vegetation in the isthmus began to decline as plants were no longer used with that purpose.

Tourist developments first appeared in Fuerteventura in the 1970s, affecting particularly the area surrounding Costa Calma. Numerous quarries were built, scattered throughout the area, as sand was in great demand as a raw material for the construction of the tourism complexes.

Practically the entire isthmus became an extraction zone, with numerous tracks and trails over which the material was transported also replacing the sand.

According to oral sources and as a result of the intensive aeolian transport, partially excavated quarries would rapidly and continuously fill up with sand, making its extraction easier. Today, however, there is little accumulation of sand in the old extraction areas and in many of them palaeosol outcrops can be observed. To the reduction of transportable sediment can be added construction of the FV-1 road, which crosses the isthmus lengthwise (10 km long and 20 m wide) and the tourist resorts. In the 1980s and 1990s this road had to be constantly cleared of sand deposited by the wind. Today, such maintenance work is not required, which evidences the decrease since then of aeolian transport.

For its part, the urbanization process reduced the line along which the sediments can freely circulate from the aeolian deposits to the beaches from 9.6 kilometres in 1956 to 3.3 in 2019 (Fig. 3). This partitioning effect was even more marked with the construction of the FV-1 road and its later upgrading.

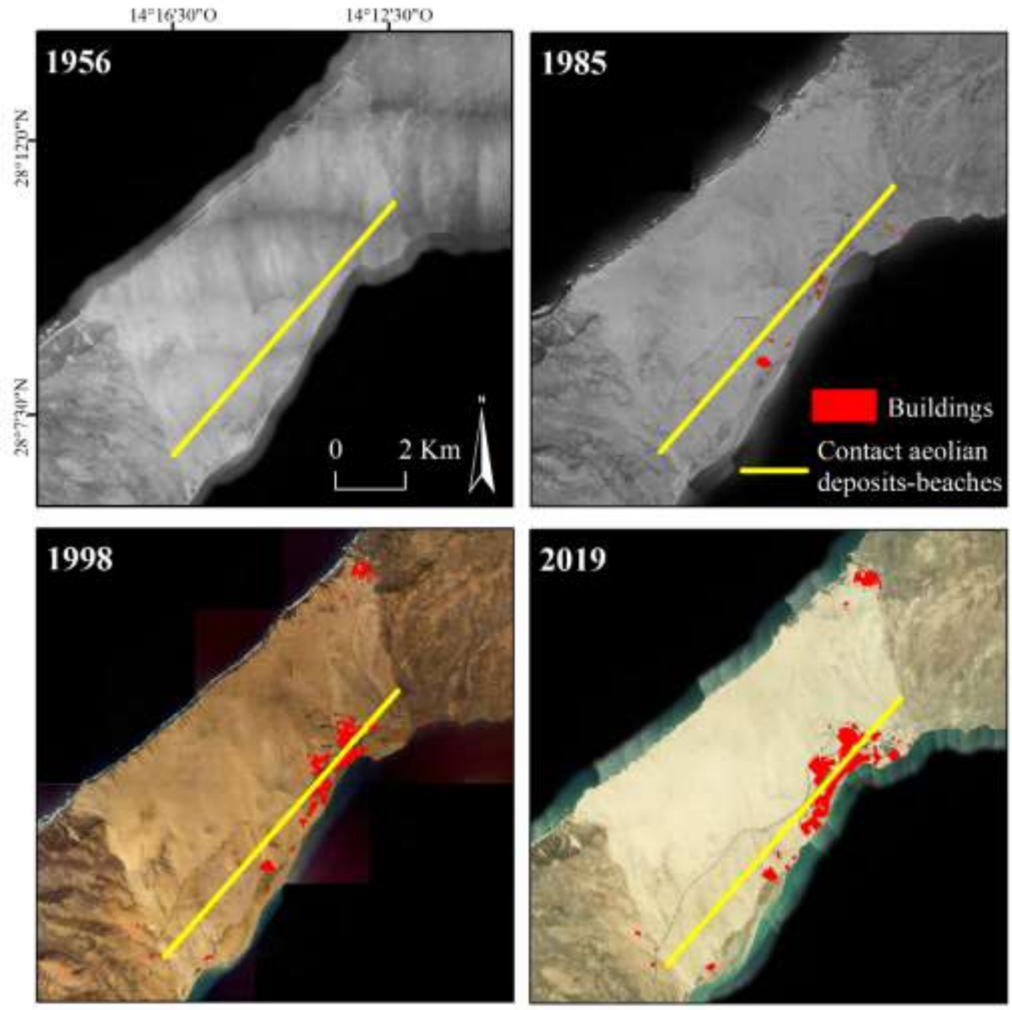

Figure 3. Urbanization process in the isthmus of Jandía. The line of contact between the aeolian deposits and the Sotavento beaches is marked in yellow (Source of digital orthophotos: SDI Canarias, Canary Islands Government, GRAFCAN, S.A.).

4.2 Availability of aeolian sediments

The current aeolian transport is conditioned by numerous factors, such as barriers to transport (urbanization and roads), the reduction of available sediment due to the extraction of aggregates and the recovery of vegetation since the traditional production of lime ceased. However, attention should also be paid to sediment availability in the deposits that have to date fed the Sotavento beaches (Alcántara-Carrió et al., 2010).

The amount of available aeolian sediment varies considerably in the isthmus. Fig. 4, created on the basis of the results of test pits made in the study area, shows that the sectors situated to the northeast of the isthmus have thicknesses that do not exceed 20 cm. However, thickness increases in the central sector of the isthmus, varying between 20 and 60 cm depth over a 24 km^2 area. The thickness is determined by the landforms, with larger amounts accumulating in the thalwegs and significant aeolian deflation being observed in more exposed areas. The greatest thicknesses were found in the Pecenescal ravine, varying between 75 and 100 cm over large areas exceeding 4.5 km^2.

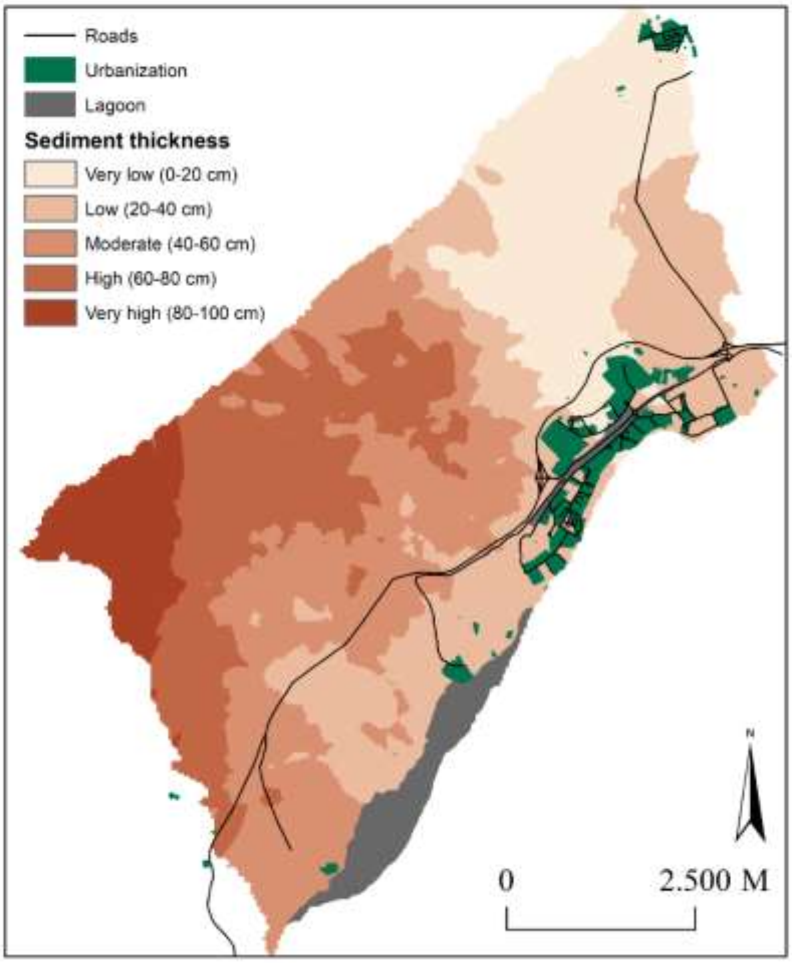

Figure 4. Thickness of the sand sheet in the isthmus of Jandía.

4.3 Vegetation

Vegetation cover in the isthmus has varied over the study period. It was reported by Marrero-Rodríguez et al. (2020a) that the area occupied by vegetation increased between 1963 and 2016, most notably in areas close to the road and to the south of it. As commented in section 4.1, grazing and the use of vegetation as fuel generated an important deforestation process. However, the vegetation has undergone a natural process of recovery in recent decades related to the abandonment of the aforementioned traditional land uses.

With respect to specific species distribution, this is strongly dependent in the isthmus on adaptation to the sandy substrates and ambient salinity. Species adapted to continuous ponding like *Arthrocnemum macrostachyum* appear along the Sotavento coast (Saladar - saltmarsh sector), while along the Barlovento coast the dominant species are those better adapted to higher sediment mobility and burial (*Euphorbia paralias*) and to saline spray (*Tetraena fontanesii*). In areas with caliche outcrops or substrates with less sand content situated in the northeast tip of the isthmus, the species that are found include *Convolvulus caput-medusae, Limonium papillatum, Lotus lancerottensis, Ononis serrata, T. fontanesii* and *Frankenia capitata*. Other species more generally distributed throughout the habitats of the isthmus include *Launaea arborescens*, *Lycium intricatum* and *Salsola vermiculata*. It should be noted that some species are in different protected categories (Table 2) and are found in different parts of the isthmus (Fig. 5).

Finally, it is important to note the presence of *Cymodocea nodosa* meadows in the submerged sectors between the beaches of Sotavento and Piedras Caídas where the low depth allows it. This phanerogam of up to 60 cm height is usually found on sandy bottoms at depths of between 2 and 10 m, though it can be found at depths of up to 30 m. It stabilizes the sandy substrate where it is located and acts as a natural defence against sea storms. However, in recent years these meadows have undergone significant declines in the Canary archipelago (Tuya et al., 2014).

Table 2. Protected species found in El Jable. Protected categories: Canary Catalogue: Act 4/2010, of June 4, on Canary Catalogue of Protected Species; National Catalogue: Royal Decree 139/2011, of February 4, on the development of the List of Protected Wild Species and the Spanish Catalogue of Threatened Species; Habitat Directive 92/43/EEC, dated 21 May of 1992, on the conservation of natural habitats and of wild fauna and flora; Flora Instruction, dated 20 February of 1991, on the protection of the wild vascular flora of the Canary Islands Autonomous Community. Source: Canary Islands Biodiversity Databank.

Scientific name	**Canary Catalogue**	**National Catalogue**	**Habitat Directive**	**Flora Instruction**
Tetraena fontanesii				Annex II
Herniaria fontanesii				Annex II
Limonium papillatum	Of interest for Canary ecosystems			
Traganum moquinii	Vulnerable			
Arthrocnemum macrostachyum	Of interest for Canary ecosystems			
Aichryson pachycaulon				Annex II
Aichryson pachycaulon ssp. pachycaulon				Annex II
Tamarix africana				Annex II
Tamarix canariensis				Annex II
Frankenia boissieri				Annex II
Convolvulus caput-medusae	Vulnerable	Special Protection Regime	Annex II and IV	
Pulicaria burchardii	Endangered species	Endangered species		
Pulicaria burchardii ssp. burchardii	Endangered species	Endangered species		
Artemisia reptans	Of interest for Canary ecosystems			
Cymodocea nodosa	Of interest for Canary ecosystems	Vulnerable		
Land species		Marine species		

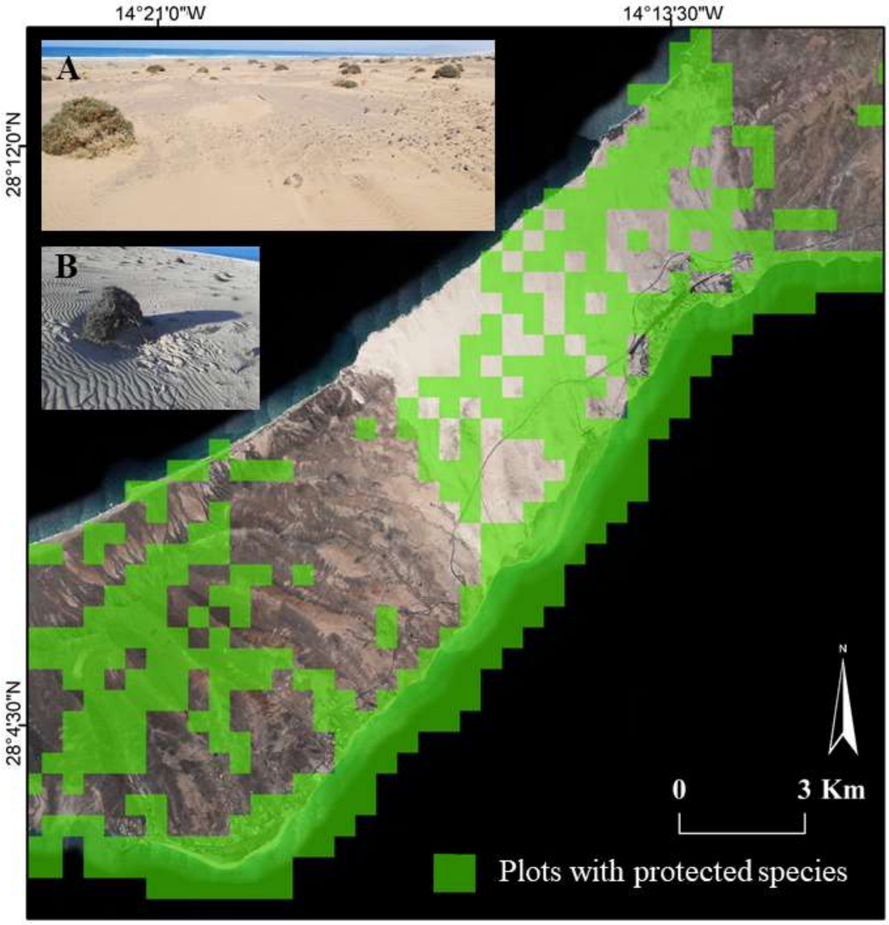

Figure 5. Distribution of protected species (Source: SDI Canarias, Canary Islands Government, GRAFCAN, S.A.). A: Monospecific thicket of *Launaea arborescens* in present day grazing land area. B: Goat resting area in a nebkha formed by *L. arborescens.*

4.4 Coastline evolution

The coastline of the study area displays a clear erosive tendency throughout the study period. However, there are some important spatial and temporal differences (Fig. 6). South of the Costa Calma tourist resort there is a clear erosive tendency (this area has the highest degree of erosion where 250 m of beach have been lost), causing the beginning of the sand bar to progressively shift southwards (Fig. 6a) with a consequent decrease in size of the lagoon area. The apex of the sand bar is the most varying coastal point in the whole study area and where the most significant changes are. The trend in this area is slightly in favour of progradation, indicating a net sediment accumulation. Finally, the southern tip shows no clear trend, with the final coastline position being the same as in 1956.

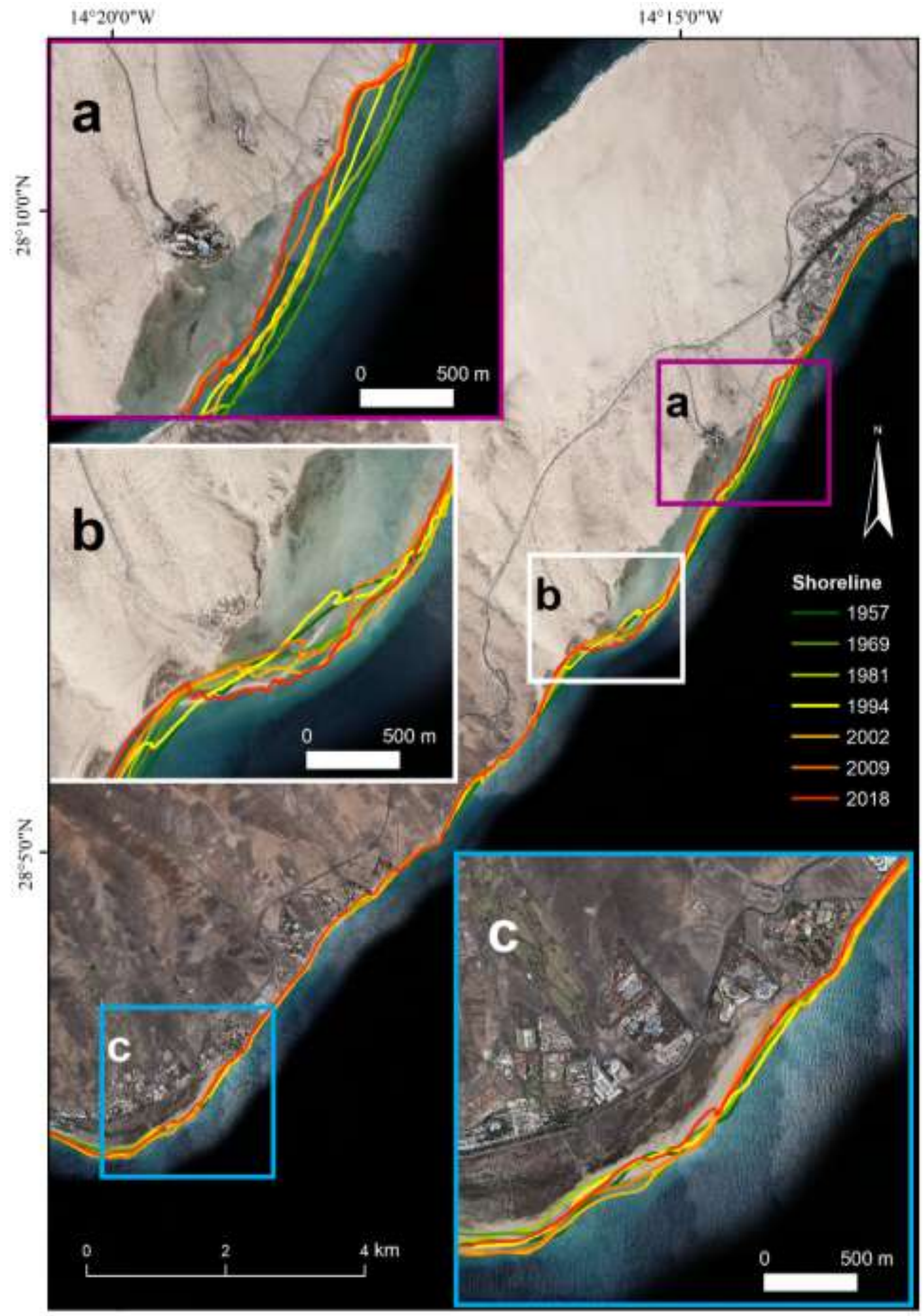

Figure 6. Evolution of the shoreline between 1956 and 2018 (Source of 2018 digital orthophoto: SDI Canarias, Canary Islands Government, GRAFCAN, S.A.).

The gain or loss in coastal area throughout the study period and between the different dates was calculated on the basis of the digitalized coastlines. In order to carry out a more detailed analysis the coastline was divided into 6 zones (Fig. 7). These six zones represent different environments of the study zone that present different changes among them: i) zone 1: beaches in front of the urbanization of Costa Calma; ii) zone 2: littoral bar; iii) zone 3: apex of the littoral bar; iv) zone 4: beaches located at the mouths of ravines; v) zone 5: eastern sector of the Matorral point; vi) zone 6: western sector of the Matorral point.

Zone 1 is a space which experienced both losses and gains in the study period, but in each case in small amounts. A loss of 80000 m^2 took place between 1956 and 1981, followed by a gain of 66000 m^2 in the period between 1981 and 2002, a further period of erosion from 2002 to 2009, and accumulation once again between 2009 and 2018. The net balance for the whole period was a negative one of some 40000 m^2. Given the size of this zone, this represents a mean coastline retreat rate of 0.25 m/year.

Zone 2 corresponds to the sand bar and underwent the highest losses, which were generally constant throughout the study period though with a particularly high incidence in the 2002-2009 period when 268000 m^2 were lost. A total negative balance of 580000 m^2 was recorded from whole study period (1956-2018), the equivalent of a mean coastline retreat rate of 2.3 m/year.

Zone 3, comprising the apex of the sand bar is a highly varying area influenced by the tides, with sharp losses between dates followed by sharp gains (Fig. 6B). Thus, this zone lost 18000 m^2 in the 1956-1969 period, gained 9600 m^2 in the 1969-1981 period, lost a further 76500 m^2 in the 1981-1994 period, recovered 97800 m^2 in the 1994-2002 period, and finally again lost 79000 m^2 between 2002 and 2018. The overall result is a negative balance of 66000 m^2, equivalent to a net coastline retreat of 0.36 m/year.

The longest of the six zones at 7 km is Zone 4 (Fig. 7). Here, the changes were less significant as the different beaches are narrower and separated by cliff sections and ravine mouths. Again, periods of erosion alternated with periods of accretion, with an overall net surface area loss of 54000 m^2, equivalent to a rate of retreat of just 0.12 m/year.

Zone 5 also has a negative 1956-2018 balance, in this case of 43000 m^2. Gains took place in the 1956-1969 and 1981-2002 periods of 21000 m^2 and 75600 m^2, respectively, while losses of 46600 m^2 and 93000 m^2 were found for the 1969-1981 and 2002-2018 periods, respectively (Fig. 7C).

Zone 6 was the only zone to have an overall positive balance (of 17500 m^2) when considering the entire study period (1956-2018). Losses in the 1956-1969 period (35000 m^2) and the 2002-2018 period (28000 m^2) were more than made up for by gains between 1969 and 2002 of 84000 m^2.

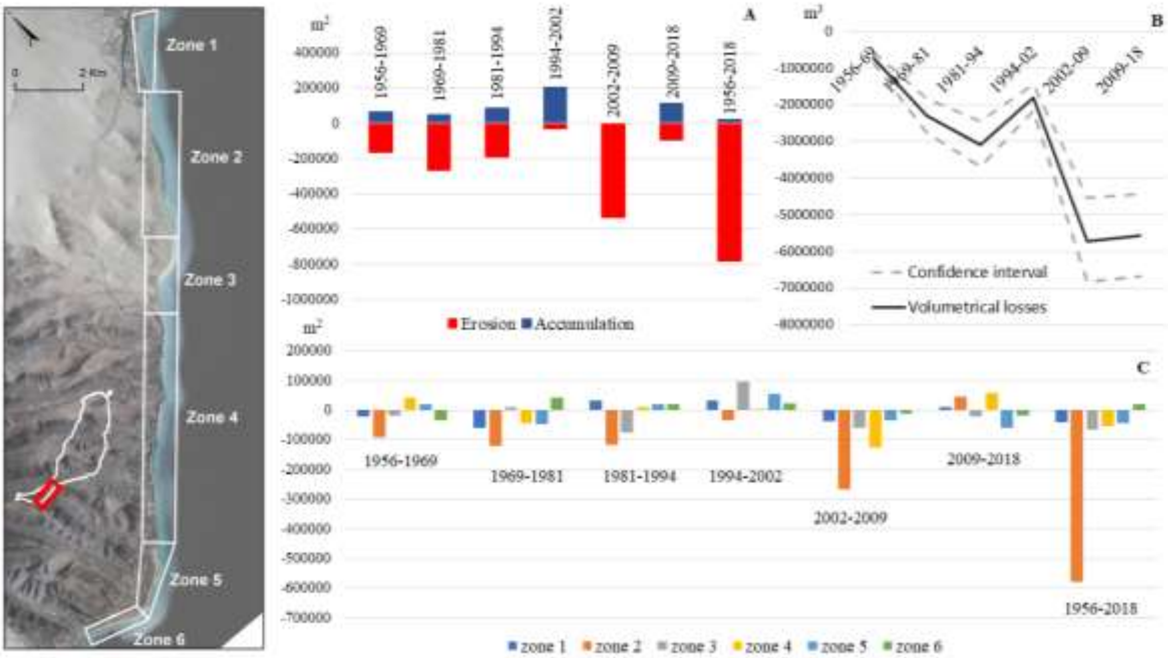

Figure 7. Erosion and accumulation balance in the study area for the period 1957-2018. A: Erosion and accumulation rates by periods for the entire study area; B: Sediment volumetric loss for the different study intervals between 1956 and 2018. The mean values are presented with the confidence interval between the values obtained on the basis of the SIMAR data and those obtained on the basis of the 10-year extreme climate data (Table 3); C: Erosion and accumulation by sector and period.

In short, the study area underwent a considerable surface area loss over the 62 years of the study period (Fig. 7C) of almost 800000 m^2, equivalent to nearly 13000 m^2 each year.

In volumetric terms, it was calculated that the coastal section covered in this analysis has experienced a mean sediment volume loss of some 96000 m^3/year during the period between 1956 and 2018. This is a similar amount to the value obtained by other authors who used different methods (Alonso et al., 2006). The total amount for the whole study period of 62 years amounts to 5900000 m^3 (Fig. 7C). Erosive processes are dominant throughout virtually the entire study area, and are particularly intense in the zone between the strip occupied by the sand bar and the mouths of the Pecenescal and ravines located at the south. The only exception to this generalized erosive tendency is Zone 6.

Table 3. Estimations of depth of closure (*dc*) on the basis of different methods of application of the formula of Hallermeier (1981).

	Data period	H_s	T_s	dc
Mean SIMAR values	1958-2020	2.87	8.78	5.80
Maximum SIMAR values	1958-2020	3.89	8.52	7.41
10-year extreme climate values	1992-2017	4.37	10.49	8.75
Mean value				7.32

4.5 Longshore drift

As can be seen in Fig. 8, the bathymetry of the study area is far from homogenous. In general, it can be said that the depth progressively increases along the coastal strip from the northernmost point to the tip of Piedras Caídas (Zones 1-4 in Fig. 7).

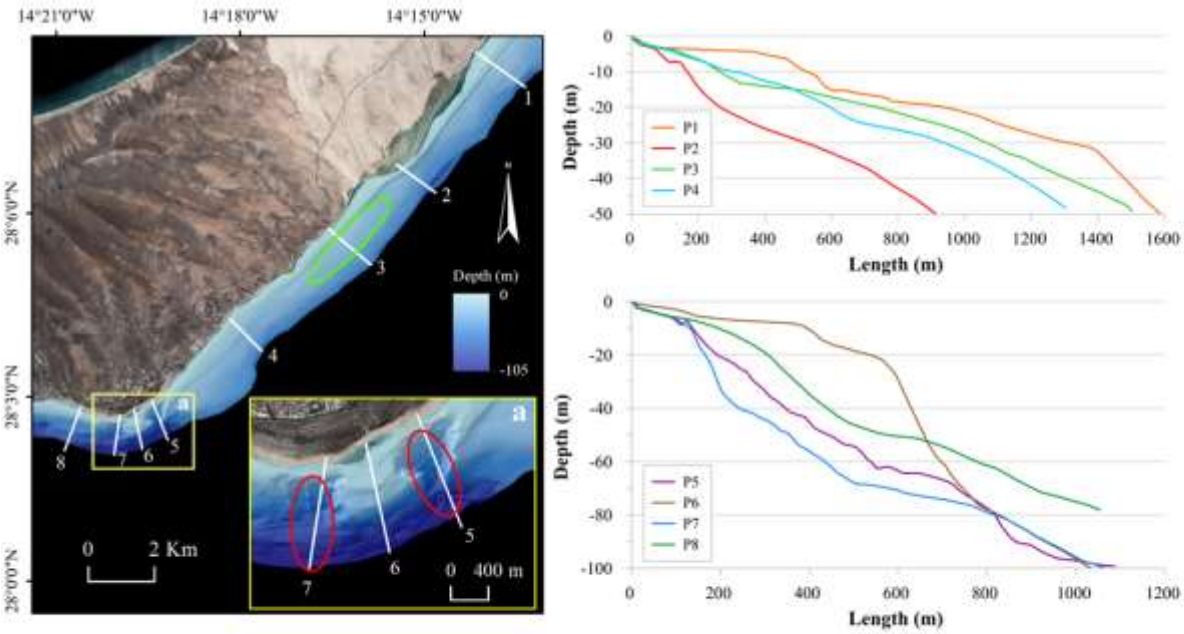

Figure 8. Bathymetric model of the study area. Different bathymetric profiles representative of the study area are shown (Source: General Directorate of Sustainability of the Coast and the Sea, 2001).

In general, the bathymetric depth of -50 m is around 1500 m from the coast, corresponding to a mean gradient of 3.3%. The only exception to this pattern is found at the apex of a cuspate foreland (Profile 2 (P2) in Fig. 8), where the slope is much more marked and a depth of 7 m is found just 100 m from the shoreline. A detailed analysis revealed a very sharp increase in the gradient from the depth of 3.2 m, with a potential consequential loss of sediment.

At the southern tip of the study area (headland of El Matorral), the gradient becomes dramatically steeper (Profiles 5-8 in Fig. 8). In this section, 100 m of depth are attained at a distance of 1000 m, corresponding to a mean gradient of 10%. In addition to this generalised gradient change, it is also important to note the presence of two large submarine canyons which begin just a few metres from the shore (red ellipses in Fig. 8a). These geomorphological elements have very steep flanks and exceed 100 m in depth. The mean wave and storm wave characteristics for SIMAR nodes 9 and 10 (the closest to El Matorral headland and the apex of the cuspate foreland, respectively) are shown in Table 3. The wave breaking depth is obtained applying the previously described equations for the mean and storm H_s and T_s values for both SIMAR nodes (Table 4).

Table 4. Wave breaking depths obtained for both fair weather and storm conditions recorded at each of the SIMAR nodes.

		Hs	*Ts*	*Hb*	γ	*d*
SIMAR 10	Mean wave	0.56	5.70	0.78	0.91	0.85
	Storm wave	2.82	8.78	3.37	0.87	3.88
SIMAR 09	Mean wave	0.87	9.54	1.36	0.95	1.43
	Storm wave	3.57	9.57	4.21	0.86	4.87

From the breaking depths obtained it was found that at the apex of the cuspate foreland (values of SIMAR node 10), the mean wave breaks at less than 1 m depth. In such circumstances, longshore drift is restricted to a narrow strip parallel to the coast along the whole cuspate foreland. However, in storm conditions the strip along which longshore drift takes place is considerably wider, reaching a breaking depth of 3.9 m.

Given that this depth is greater than the 3.2 m where there is a notable increase in the gradient, it is plausible to consider that in high energy wave situations part of the sediment escapes from the coastal strip in the area of the apex of the cuspate foreland. This sedimentary material would accumulate along a plain that extends between depths of 12 m and 25 m and covers an area of some 3 km^2 (green ellipse in Fig. 8).

If considering exclusively the data from the period 1996-2020, 0.17% of the H_s values exceed 2 m. This percentage corresponds to just 15 hours a year, during which it is very probable that part of the sediment escapes from the longshore drift and is deposited along the aforementioned plain (green ellipse in Fig. 8).

With respect to the El Matorral headland (values of the SIMAR 09 node, see Table 4), in normal conditions the breaking depth is 1.5 m, a value which rises to 4.9 m in storm conditions. Given that, in this case, the head of the canyons is found just a few metres from the shoreline, it could be argued that sediment will be lost even in mean wave conditions and a lot more in storm conditions. Only in conditions of a totally calm sea is it possible to imagine longshore drift restricted to such a narrow strip that no loss of material to the canyons would occur. Of the wave data in this area, 12% correspond to values of $H_s < 0.5$ m, circumstances in which longshore drift is very slight, but the small amount that would occur would accumulate on the El Matorral beach (Zone 6, Fig. 7). However, when there is a slight increase and $H_s \geq 1$ m (which occurs 30% of the hours of the year), the strip where longshore drift takes place would be sufficiently wide for sediment to be lost to the submarine canyons.

That is, the El Matorral beach acts as an area of deposition in calm sea situations, when the sediment accumulates in the headland area and preferentially in the strip closest to the shoreline. In contrast, in mean wave and storm wave situations, the accumulated sediment and the sediment transported in these conditions by longshore drift is lost to the submarine canyons.

Figure 9 shows an outline of sediment transport in these three conditions: practically calm sea (Fig. 9A), mean wave (Fig. 9B) and storm wave (Fig. 9C) conditions. Each image shows where the losses of material, remobilized as the result of longshore drift, would take place: In the first case, transport is weak and the sediment accumulates on the El Matorral beach. In the second, sediment transport is more intense and sediment is lost to the submarine canyons at the El Matorral headland. In the third, sediment transport is considerably more intense. The longshore drift branches off at the apex of the cuspate foreland, with part of the material lost in this area deposited on the plain shown in green in Fig. 8. The rest of the material continues its journey southwards before finally being lost to the submarine canyons (red ellipses in Fig. 8a).

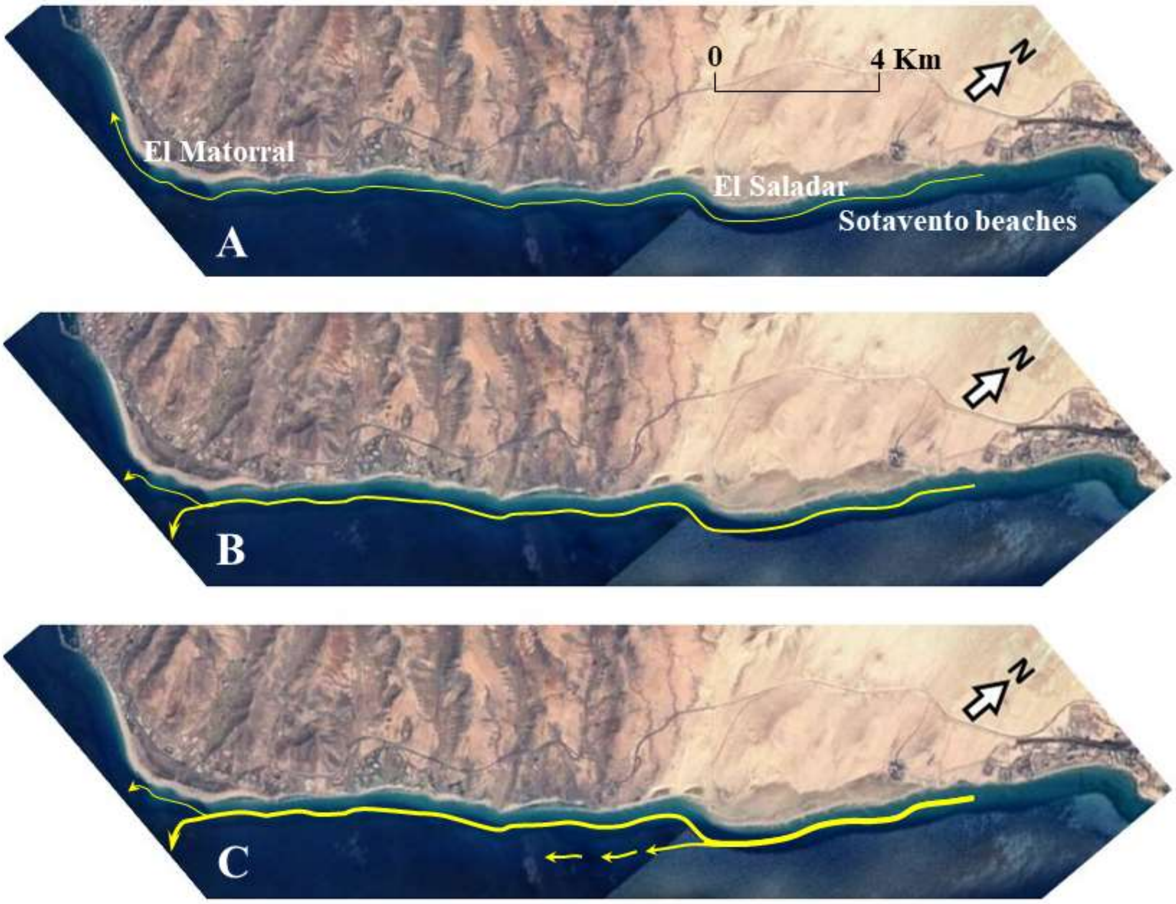

Figure 9. Conceptual diagram of longshore drift in the study area. A) calm sea conditions. B) Mean wave conditions. C) Storm wave conditions. The thickness of the yellow lines indicates sediment transport intensity.

5. Discussion of management proposals

There is no easy solution in terms of mitigating the changes that coastal areas undergo as the result of inappropriate human interventions (García-Romero et al., 2016; San Romualdo-Collado et al, 2021a) or the changes in environmental conditions (Petit and Prudent, 2010; Pye and Blott, 2012; Sauter et al., 2013). In this case, beach erosion is resulting in the loss of a basic natural resource for the development of the tourist activity. Consequently, conservation of this tourism resource has become a priority for management bodies. However, in many cases, the solution to erosion problems requires major interventions that can entail the loss of other sectors of the ecosystem, generate visual impacts that can negatively modify the perception users hold of that space, fall foul of the prevailing legislation, and/or represent significant economic investments (Edmondson & Velmans, 2001; Alexandrakis et al., 2015).

This is exemplified in Jandía by the fact that protection of the ecosystem and the Use and Management Master Plan established for it do not allow interventions that would minimize erosion of the saltmarsh and beaches. Therefore, the protection does not contemplate the necessary tools to guarantee the conservation of the ecological processes that characterize the functioning of the ecosystem, but only manages the land uses without taking into account that it is a dynamic environment that is currently responding to historical human alterations; as the erosive processes appear to be related to the abandonment of traditional uses (grazing and the gathering of vegetation for fuel), the appearance of barriers to aeolian transport and the spontaneous recovery of vegetation (Alcántara-Carrió et al., 1996; Marrero-Rodríguez et al., 2020a). Erosion of these beaches today is damaging certain infrastructures as well as causing the disappearance of an environmental resource that constitutes the basis of a tourist industry of great local socioeconomic importance. All of which has given rise to a search for possible alternatives to stop or at least slow down the loss of sediments.

For the purposes of this study, a review was undertaken of possible soft management measures along with an evaluation of their usefulness and potential application in the study area in view of the information and results given in the preceding section of this paper. On the basis of this review, four possible forms of action were determined; passive management, sediment remobilization, beach nourishment, and mechanical sand recirculation.

5.1 Passive management

Passive problem management means taking no action and allowing the system to evolve naturally. The paradox arises that this is the only measure allowed by current legislation but, if current trends continue, it would mean the disappearance of the Sotavento beaches and Saladar, the saltmarsh sector (Fig. 1), at least in the areas where the beaches do not reach equilibrium situations as they are protected by natural projections. In this respect, the study area has a basement of alkaline basaltic lava and pyroclastic material (Coello et al., 1992) which, by reaching it, would slow down the erosion processes. In this case, the beach area would be significantly reduced in many sectors but the impacts derived from other management measures on the ecosystem would be avoided. It is possible that, as Marrero-Rodríguez et al. (2020a) pointed out, the Sotavento beaches would have undergone a process of progradation between approximately 1850 and 1960 due to the gathering and use of vegetation as fuel which would have caused aeolian erosion of the isthmus. Beach erosion would be a natural response to the cessation of this land use, accelerated by the extraction of aggregates and the construction of barriers to sediment transport (roads and urbanizations). Furthermore, ecosystems do not always return to their original state prior to human intervention, but rather reorganize themselves based on the new environmental conditions (Kombiadou et al., 2019; Marrero-Rodríguez et al., 2020b) including, among others, sediment availability, topography and vegetation cover. Passive management would therefore allow the ecosystem to continue with its natural evolution or its response to human interventions, whether it is natural erosion processes (depletion of sediment inputs from the isthmus of Jandía), anthropic processes (creation of barriers to sediment transport) or a combination of both. This form of management has been proposed for other systems such as the small island of La Graciosa (Canary Islands, Spain) (Pérez-Chacón et al., 2010; 2012), which received a total of 250,000 tourist visits between 2011 and 2019 (ISTAC, 2020). The analysis of the aerial photographs shows that the beaches of Costa Calma, in front of the urbanized sector, are stabilized and that the buildings only suffer damage during storms, since they are not in the protected area, interventions to protect the buildings are allowed and could be carried out easily.

5.2 Reestablishment of sediment transport

This measure consists of restoring the flow of aeolian transport that once fed the Sotavento beaches. Remobilization of the sand by removing the vegetation, a measure used in other dune systems (Burton, 2001; Plassmann et al., 2010; Millett & Edmondson, 2013) is prohibited in the Use and Management Master Plan. In any case, for various reasons it is not recommended as a solution to the erosion problems of the Sotavento beaches. On the one hand, because the elimination of vegetation without damaging the plant communities and protected species is complex due to their extensive distribution in the study area. In this regard, the only viable way is to hire crews that perform manual species discrimination, thus avoiding the numerous negative effects of the removal of vegetation through mechanical means or by encouraging increasing livestock grazing. In the latter case, such negative effects include the creation of monospecific scrub and damage to the landforms due to the establishment of, for example, burrows, wallows and trails (Zunzunegui et al., 2012). Furthermore, the strong arid conditions of Jandía have traditionally only allowed goats, rabbits and camels to graze. However, given the transit of walkers, camel grazing is not recommended due to the aggressive behaviour they exhibit, especially in the reproductive season (Yagil & Etzion, 1980). The traditional grazing model in Jandía does not allow control over the animals and has therefore resulted in a considerable impact on the flora and substrates of the protected area (Gangoso et al., 2006; Rodríguez et al., 2005). With respect to the use of machinery, this would have a major impact on the aeolian system due to the need to create tracks for the machines to access the areas with the greatest sediment thicknesses. In addition, when machinery is used to eliminate vegetation it is difficult to select between, for example, protected and unprotected species.

Likewise, even if the sand sheets were remobilized, it would require a very large volume of sand to alleviate the long-term erosion of the Sotavento coast, which has been estimated at 96,000 m^3 per year (see section 4.4). In this sense, there are few sectors in which the free movement of the sand can occur due to the constructions and the highway. In addition, this measure would induce an intense process of erosion of the biogenic deposits of the isthmus of Jandía. According to Marrero-Rodríguez et al. (2020a), something similar occurred between approximately 1850 and 1960, on that occasion until their exhaustion as there are no current contributions from the beaches and cliffs of Barlovento (Alcantará-Carrió, 2003; 2010). It is also important to pay attention to the fact that sediment losses, once the sediment has been deposited on the beach, will continue over time.

5.3 Beach nourishment

Beach nourishment is a method that has been used in Spain since 1983, mostly along the Mediterranean coast (Hanson et al., 2002). It is a preferred method because of its economic advantages (Finkl and Walker, 2005), but can cause important ecological damage to beach habitats (Peterson and Bishop, 2005; Speybroeck et al., 2006). The factors that influence beach nourishment include the mechanical process employed, the time required, the amount of sediment contribution and the characteristics of that sediment (Speybroeck et al., 2006). Beach nourishment has also been found to have impacts on micro and macro fauna (Bishop et al., 2006; Beach, 2000; Speybroeck et al., 2006; Peterson et al., 2000; Menn et al., 2003; Bilodeau and Bourgeois, 2004). It often only functions as a temporary solution, with beaches likely to maintain their erosive tendency (Peterson and Bishop, 2005) and their recovery may be only for short periods of time (Defeo et al., 2008). Good long-term results are related to sediment quality and whether its characteristics are suitable for the beach conditions

(Peterson et al., 2000, 2006). For this reason, in many areas such interventions are accompanied by the construction of seawalls, breakwaters or groynes (Pilkey and Wright, 1989, Hsu et al., 2007).

In addition, beach nourishment is only allowed where beaches are not situated in a protected space and where longshore drift is limited (for example the Costa Calma beaches). However, in Jandía the whole coastal strip is a protected space (Fig. 1). This protection is fundamentally due to the presence of *C. nodosa* meadows which would be severely affected by the turbidity that beach regeneration would cause (Tuya et al., 2014; Fabbri et al., 2015). Nonetheless, four beach nourishment options are described below which differ in terms of the source of the sediment:

i) *Purchase of sediment from abroad*. There are numerous artificial beaches which have been constructed using sand imported from other countries, including several examples in the Canary Islands where sediment has been acquired from Morocco or the Bahamas. Importantly, in these cases the beaches are artificial in their entirety and the deployment of different coastal engineering works significantly reduces the energy of the incident waves ensuring that the sediment contribution remains relatively stable. It should also be noted that it is very complicated to obtain sediment from elsewhere with similar characteristics to those of the local area that do not have a negative effect on the beach (Goldberg, 1988; Peterson et al., 2000, 2006). It is also difficult to avoid the introduction of exotic invasive species, and so the sand needs to be fumigated.

ii) *Sand extraction from submarine banks*. This option has been employed on various occasions for the regeneration or construction of beaches in the Canary Islands. Examples include the Santa Cruz beach in La Palma, where 740000 m^3 of sand were used from the submarine sandbank in the Nogales area (Puntallana, La Palma) (MITECO, 2020). As in the previous case, regenerated beaches are artificial, with the sediment contribution maintained *in situ* thanks to a series of coastal engineering works. In addition, the area where the material is extracted should be as close as possible to where it is to be used. In the case of Jandía, as reported in section 4.4, 96000 m^3 of sand are lost each year, mainly to the canyons situated opposite El Matorral beach and some along the steep slope opposite the apex of the cuspate foreland (Fig. 8). The shape and depth that these canyons reach make the dredging of sand here an unfeasible option, with the most viable dredging site being the area identified in Fig. 9 where the bathymetry seems to indicate the existence of a submerged sandbank at depths of between 12 and 25 m. Both the depth and distance from the area where the sand would be deposited are ideal for this type of operation. However, given that nearly 100,000 m^3 of sediment would be needed each year, it is vital to ensure that the sandbank has a sufficiently appropriate volume of material for extraction to guarantee a periodic contribution to the beaches for various decades. In addition, care needs to be taken with respect to the presence of sea meadows of the phanerogam *C. nodosa*, which could suffer serious damage as a direct result of dredging activities and as an indirect result of the increased turbidity that would be generated and which has been shown to have negative effects on such meadows (Silva et al., 2013).

iii) *Crushed stone* Another alternative to nourish the beaches is to use crushed stone. An example of the results of this method can be seen at Martiánez beach in Puerto de la Cruz (Tenerife, Canary Islands), which was regenerated through the contribution of 132,000 m^3 of sand obtained from crushed stone (MITECO, 2020). While technically feasible, the production of sand obtained from crushed stone has some drawbacks, most notably a highly varied granulometry with the usual inclusion of pebbles, gravel and sand despite the sieving that takes place. Moreover, the composition of the material would be basaltic, which would mean a change of colouring given that the present beaches are mostly organogenic in nature.

Such a change could affect the perception held of the beach by its users (Pranzini et al., 2010). Finally, it should be noted that the production of large volumes of sand using this technique is very expensive, especially when considering the need to produce some 100000 m^3 of material each year, making it effectively unsustainable over time.

iv) *Sand extraction in the isthmus*. Loose sediments in the interior of the isthmus, as previously mentioned, are of marine origin and their origin is related to sea levels different to those of today. The present relative position of the sea level would seem to suggest that there could not be significant contributions from the Barlovento coast (Alcántara-Carrió et al., 2010). However, there are areas where the thickness of these materials is substantial (Fig. 4). One such area is the head of the Pecenescal ravine, where sand extractions have previously been carried out (Alcántara-Carrió et al., 1996). As far as the presence of protected species is concerned, this would also be a viable option given that, as can be seen in Fig. 5, no such species are found in the areas of greater sediment thickness. However, the effects of sand extraction have been widely studied. Some works have reported evidence of changes in the recovery patterns of vegetation cover and the species that recolonize the area (Fernández-Montoni et al., 2014; Price et al., 2005), while others have reported reactivation of the sand sheets (Garriga-Sintes et al., 2017) or the generation of flooded zones and areas of aeolian deflation (Marrero-Rodríguez et al., 2020b). In addition, isthmus-based extractions would only guarantee beach nourishment for a relatively low number of years as the resource in the area in question is limited. Finally, and very importantly, sediment extraction from the isthmus also happens to be prohibited by law.

5.4 Mechanical sand recirculation

This proposal involves taking sand from areas of accumulation and depositing it in areas of erosion overland through the use of machinery. This option has two main advantages. Firstly, it allows sediment reuse innumerable times, meaning that 100000 m^3 of new material each year would not need to be produced. Secondly, the deposited sand comes from the same system, and hence will have the same sedimentological characteristics (grain size, density, composition, etc.). Some drawbacks may also be encountered. These include sand extraction in the intertidal area increasing turbidity in the water and potentially affecting the marine phanerogams that inhabit the subtidal regions of nearby beaches (Silva et al., 2013). In addition, sand extraction can substantially alter the beach slope, which can directly impact beach sediment behaviour and potentially negatively affect the perception of the beach by its users.

The only part of the study area with sand accumulation is found in Zone 6. However, despite its cumulative tendency, its use would have to be discarded as there is sufficient sediment to cover just 2.63 % of the current annual deficit of the system.

6. Conclusions

The coastline of the study area on the island of Fuerteventura has shown a clear erosive trend since at least 1956. However, this erosive tendency is not homogenous, and there are significant spatial and temporal differences. The strip with the highest degree of erosion is situated south of the Costa Calma tourist resort, where some 250 m of beach have been lost. This in turn has caused the beginning of the reef to shift 1 km southwards with a consequent decrease in size of the lagoon area. The analysis of longshore drift that was undertaken revealed that some 96000 m^3 of sediment is transported southwards each year, and that most of it is lost to two submarine canyons situated opposite the El Matorral headland.

Proper management of this shoreline is necessary because of the danger of the loss of elements of important natural value and because of the damage that is being caused to the tourist industry that is the main driver of the island’s economy. However, the beaches of Costa Calma, in front of the urbanized sector, are stabilized and that the buildings only suffer damage during storms, since they are not in the protected area, interventions to protect the buildings are allowed and could be carried out easily. The rest of the shoreline despite its being declared a protected space with the aim of ensuring the continued existence of an area of exceptional natural values, the regulations that have come into force as a consequence of its protected status do not permit the interventions that are necessary to mitigate the erosion processes that the area has been experiencing for over 60 years. The only measures that could be undertaken in the study area are artificial regeneration and mechanical sand recirculation. Reestablishment of aeolian sediment transport is discarded because the ways available to carry out this task would not allow to keep the protected species undamaged. On the other hand, passive management would force new damage to infrastructure and the disappearance of the salt marsh. However, all the measures would imply a high and continuous economic cost and, therefore, are of doubtful long-term sustainability. Artificial regeneration with local sediment is also discarded because with the current sand volume available in the study area it will also not be sustainable in the long-term; the same problem is related to other ways of nourishment. In this sense, beach nourishment will have very limited succeed because of the high economic cost that will be continuous in time and the impossibility of building infrastructures for the retention of sediment. However, the combination of different measures (artificial regeneration and mechanical sand recirculation) could be the key to stop erosion problems.

7. Acknowledgments

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6. GENERAL DISCUSSION

The results of the present thesis are discussed in this section and are organized according the three main objectives of the studies carried out under the historical ecology framework according to Bürgi & Gimmi (2007), and which are similar to the 3 phases of this investigation: i) understanding historical trajectories of pattern and processes in ecosystems and landscapes; ii) informing ecosystem and landscape management; iii) and preserving cultural heritage in ecosystems and landscapes. Finally, a reflection is made on the methodological aspects and the achievement of the aims; as well as, the demonstration of the hypotheses raised at the beginning of the doctoral thesis. However, most of the results of the papers have been discussed in the discussion sections of each paper.

6.1 The evolution of land uses and its environmental consequences

To understand the historical trajectories of the arid aeolian sedimentary systems of the Canary Islands three systems have been studied and the relationship between land uses and environmental responses was stablished (Table 3). This table shows the relationship between land uses and natural dynamics. A close relationship can be observed between the uses that eliminate vegetation and the remobilization of sediments as was pointed for others dune systems (Santana-Cordero et al., 2016). In addition, the reduction of species richness, damage to the population structures of plant communities, among others. However, most uses cause direct damage to landforms; although others do indirect damage related to the introduction of changes in wind flows (García-Romero et al., 2019) or the introduction of invasive species.

Also, the changes in the natural dynamics exerted by land uses will also entail important changes in the economy by producing the burial of crops, damage to infrastructure (example: reduction in the depth of the port of Arrecife) and in urbanization.

Table 3. Land use main actions with its historical and current environmental and economic consequences. Legend: Historical (1); Current (2); Both (3).

Land use	**Main actions**	**Historical and current environmental consequences**	**Negative historical and current economic consequences**
Livestock	- Introduction of animals with livestock interest (camels, goats, sheep and rabbits).	- Permanence of invasive alien species (goats and rabbits)[2] - Damages to the population structure of plant communities[3] - Extinction of plant species[3] - Damages to the aeolian landforms[3] - Sediment remobilization associated to the removal of vegetation[1] - Altered vegetation distribution patterns[3]	- Damages in crops[1] - Reduction of the availability of plants used as fuel[1] - Camels been dangerous to visitors[1] -Damages related to sand transport in villages and infrastructures[1]
Crops	- Removing vegetation	- Sediment remobilization. -Existence of vegetation distribution patterns according to the period of abandonment of the cultivation fields[3]	-Damages related to sand transport in villages and infrastructures[1] - Reduction of the availability of plants used as fuel[1]
	- Planting crops	- Introduction of alien species with commercial interest[3]	
	-Construction of aeolian transport barriers	-Changes in sediments accumulation areas[3] - Wind disturbances[3]	
	-Use of pesticides	- Dominance of species which tolerate contamination by phytosanitary products[3] - Damages to native species[3]	
Obtaining fuel	- Cutting certain plant species	- Damages to the population structure of plant communities[1] - Sediment remobilization[1]	-Damages related to sand transport in villages and infrastructures[1] - Reduction of the availability of vegetation cover for livestock[1]
Hunting	- Introduction of hunting preys	- Permanence of invasive alien species (rabbits and partridges) [3] - Damages to the population structure of plant communities[3] - Extinction of plant species[3] - Damages to the aeolian landforms[3]	-Damages in crops[3]
	- Hunting native species	- Reduced population of native's species[1]	
Obtaining material for construction	- Extraction of sediments and stone for construction	- Damages in system topography by the creation of quarries[3] - Creation of permanent flooded areas[3] - Reduction of sediments available for transport[3] - Changes in vegetation distribution patterns[3] - Noise[3] - Creation of access tracks[3]	
	-Obtaining wood	-Disappearance of groves[1]	

Aerodrome	- Creation of a runway for take-off and landing	- Removal of aeolian landforms[1] - Compaction of sediments[1] - Removal of vegetation[1]	
Roads	-Installation of roads and shoulders	-Barriers to sand transport[3] -Corridors for alien species[3] -Modification of wind flow[3] -System surface reduction[3]	
Building	-Construction of building, gardens and other infrastructures	-Barriers to sand transport[3] -Introduction of alien species[3] -Modification of wind flow[3] -System surface reduction[3]	
Recreational	-Visiting the aeolian systems	- Damages on aeolian landforms[3] - Damages to vegetation[3] -Trampling[3]	
	-Sport practice	- Damages on aeolian landforms[3] - Damages on vegetation[3] -Trampling[3]	
	-Vehicle traffic	- Removal of aeolian landforms[3] - Compaction of sediments[3] - Removal of vegetation[3]	
Military	-Construction of infraestructures	-Barriers to sand transport[3] -Modification of aiflow dynamic[3] - Reduction of the system surface [3]	
Industrial	- Infrastructure installation		

6.2 Learning from the past to manage the aeolian sedimentary systems

Using historical ecology to inform about ecosystem and landscape management is a complex task. Land uses have caused drastic changes in most of these ecosystems, in some cases irreversible (Santana-Cordero et al., 2014); however, many arid aeolian sedimentary systems in the world are in the early stages of their development, so the application of this study may be useful for their management and conservation. In this sense, four main precepts are presented in which historical ecology can collaborate in the management of systems: i) supporting ecosystem natural trends; ii) the importance of preserving sediment budget and system topography; iii) to control building and road development; iv) the problem of invasive species as a land use legacy.

6.2.1 Support natural trends

The aeolian sedimentary systems of the Canary Islands show in recent years a gradual recolonization of vegetation that goes against climate trends (reduction in rainfall and increased temperatures) but which coincides with the changes in land use (Marrero-Rodríguez et al., 2020a). In this sense, there is a popular belief given the historical trajectory of these systems that the greater the vegetation cover, the greater the erosion processes suffered by the beaches. This has meant that in recent years, and given the current trends in beach erosion in these systems, projects to reduce vegetation cover by reintroducing grazing have been proposed for the remobilization of sand sheets or projects for remobilization using machinery (Pérez-Chacón et al., 2010; 2012). However, the scarce vegetation cover observable in the photographs of the 1950s and 1960s seems to be the result of land uses that obtained fuel from vegetation, grazing or clearing large areas for cultivation (Santana-Cordero et al., 2016). The abandonment of these traditional uses shows a slow recolonization of vegetation that has reduced the mobility of the sand sheets as in other areas (Kutiel et al., 2004; Hoffman & Rohde, 2007; Rohde & Hoffman, 2012). Although, there have already been important processes of aeolian and hydric erosion on these systems after years of overexploitation and the sediments that once fed the beaches have already been redistributed by marine dynamics. In most of these ecosystems there do not appear to be sediment inputs in the sand entry sectors, or at least sediment budgets are not detected functioning as these did decades ago (Cabrera-Vega, 2010); therefore, the losses are not replaced, having increased the rocky outcrops in the interior of the systems as evidence of aeolian erosion. Therefore, projects that propose remobilization must take into account the consequences that these will have in the long term, since it is expected that the patterns will be repeated or that the sediment budget of these systems will end up being exhausted. Since generating a large volume of sediment that prevents erosion of it would require thousands of years. In the aeolian sedimentary systems of the Canary Islands this idea can be applied to management projects that aim to induce remobilization and that therefore, they intend to go against the natural tendencies of the ecosystem. However, in systems in which traditional uses are maintained, controlled grazing and cutting of the vegetation should be carried out, allowing the permanence of areas that are not completely cleared.

6.2.2 Preserve sediment budget and system topography

The extraction of aggregates for construction has produced important footprints in these systems. Extractive areas vary widely between different systems but have produced two main effects by altering the topography and reducing the volume of sediment available for transport.

The alteration of the topography has produced depressed areas that act as sedimentary traps. In the case of El Médano, a coastal lagoon has been produced that limits the development of the foredune and alters the distribution pattern of nebkhas and vegetation. In Jandía and El Jable the extractions, located inside de systems, are sediment traps that reduce the volume of sediment that passes through the system, they in turn act as water collectors that flood during rainfall and favor plant colonization. According to Alcantara-Carrió (2003), they are also a zone of wind deflation that accelerates the flow of winds. However, they represent a drastic reduction in the sediments available for transport and therefore collaborate in the erosion processes of the system.

6.2.3 Control building and road development

The urbanization process of the aeolian sedimentary systems of the Canary Islands has produced severe impacts, fragmenting the ecosystems and supposing insurmountable barriers to the transport of sediments. At present, the processes of beach erosion threaten buildings and human infrastructures. Therefore, an adequate and early planning can prevent the risks derived from beach erosion. Maintaining right-of-way for the sand can reduce erosion processes through less disruption to transportation. Thus, it could be recommended that the buildings be adapted to the environment, elevated roads that allow the free movement of sand and buildings outside transport areas and in areas where they do not produce aeolian shadows (García-Romero et al., 2019a). Thus, other impacts would also be avoided, such as the excessive costs of cleaning the accumulations of sand, the need to create plant barriers or those derived from the regeneration of beaches (Alcántara-Carrió et al., 1996). The latter in the case of El Jable which beaches required nourishment and, in the case of La Jaquita in El Médano which the transport of sediments must be carried out by road from the current accumulation area.

6.2.4 Invasive species as a land use legacy

Invasive alien species have proven to be one of the main causes of ecosystem degradation and the ecosystem services they provide (Walsh et al., 2016). They produce serious economic and environmental impacts such as: damage to crops and protected areas, reduce plant cover, cause changes in the structures of species, favor the development and dominance of non-palatable species, among others (Zunzunegui et al., 2011).

In the case of the aeolian sedimentary systems of the Canary Islands, the main species that were introduced in these systems are camels, donkeys, goats, rabbits and sheep; however, currently only rabbits and goats can be found due to the eradication of some species and due to the strong arid conditions others have not been able to adapt.

Both goats and rabbits produce impacts on the aeolian landforms (creation of burrows, scavengers, stalls, etc.) and the vegetation (reduction of the size of the inviduals, changes in the population structure, creation of monospecific areas, digging up the plants) (Zunzunegui et al., 2011). Oceanic islands have developed without the presence of large herbivores, so the vegetation does not have the necessary adaptation mechanisms. In the past, the important livestock load of these systems had important consequences on the natural dynamics, by eliminating the vegetation and inducing the remobilization of the sand sheets (Hoffman & Rohde, 2007). However, at present, given the small number of individuals currently present in these systems, their ability to influence sediment transport is limited; therefore, its eradication is necessary to conserve palatable plant species and avoid the damage they cause to the aeolian landforms. Similar eradication actions with the same aims have been carried out in different areas of the world, since these species do not have current uses and come from the abandonment of hunting (rabbits) and grazing (goats) (Hamann, 1979; Parkes, 1990).

6.2.5 Historical ecology as a restoration tool

Learning from the past to predict the future (Bürgi & Gimmi, 2007) may not be decisive. In this sense, learning from the past can allow us to carry out restoration tasks in those sectors that require it. The methodology used in this doctoral thesis can be applied in numerous spaces with the aim of recovering landforms or even entire extinct ecosystems in areas where there is still permeable soil that have not been urbanized; as massive urbanization and associated changes in land ownership mean the extinction of these systems (Santana-Cordero et al., 2014). There are currently extinct systems that could be recovered all over the world. An example of this is figure 14. in which the old system of dunes and a garden space can be seen today that could be recovered with the original ecosystem.

Recovering patterns in certain ecosystems can help to recover others whose natural dynamics have been altered. Although all dune systems have certain peculiarities, if there is a lack of historical sources that allow knowing what the ecosystem was like, restoration measures can be applied taking into account the similarities with other ecosystems in which historical sources are abundant. However, as this doctoral thesis has shown, the restoration of ecosystems is complex because the systems have undergone changes such as alterations in the topography or the reduction in sediment budget that cause the original distribution of the landforms to not be the same throughout the system. Likewise, it is worth asking: are the dune systems that the methods in historical ecology allow to reconstruct natural?

Figure 4T. Repeated photograph of an ancient dune system in Portrush, Northern Ireland.

As an example of this concept, several restorations have been carried out and management proposals have been carried out in the Canary Islands. The most recent example is the restoration carried out in Maspalomas (Gran Canaria). In it, the technicians in charge of the restoration have carried out sand movements based on the recent evolution analyzed in aerial photographs (Hernández-Calvento, 2002) and the plantation of *Traganum moquinii* has been carried out studying its historical location in the system (Hernández-Cordero et al., 2012). The first aerial photographs correspond to the 1950s. However, despite the fact that the alterations suffered by the system are intimately linked to human alterations (Hernández-Calvento et al., 2014; García-Romero et al., 2019a, b; Sanromualdo-Collado et al., 2021a); There is another determining factor in the recent evolution of the system, which is the reduction of the sediment input (Hernández-Cordero et al., 2006). This reduction in sediments is not related to the availability of sediments in the subtidal zone, but rather to the scarcity of high-energy events that allow the remobilization of sediments and their availability to wind dynamics. However, despite the fact that the restoration is based on historical data, they do not delve into the long-term history of the ecosystem to understand and respect its natural dynamics.

6.3 Preserve the cultural heritage

The third aim of historical ecology is to preserve the cultural heritage in ecosystems and landscapes. Long term land uses produced an important cultural heritage that it is closely linked to the exploitation of the ecosystem and they even present important adaptations to it. From the selection of plant and animal species adapted to specific environmental conditions; as infrastructures that facilitated or were part of such exploitation. In order to preserve this heritage as part of the work under the methodological framework of historical ecology, the following table (table 4) has been made with the heritage associated with the exploitation studied throughout this research.

Table 4. Land use immaterial and material heritage and current hazards.

Land use	Immaterial heritage	Material heritage	Hazard to immaterial heritage loss	Hazard to material heritage loss
Livestock	- Knowledge of palatable and no palatable species - Traditional grazing techniques	- Breeds of livestock species adapted to local conditions by human selection - Livestock collection structures - Shepherds shelters	- Advanced age or death of traditional shepherds - Substitution of grazing techniques for intensive production - Protection of the space and prohibition of traditional grazing - Tourism dominance as an economic activity	- Substitution of breeds with higher productivity. - Cese del uso of livestock collection structures and shepherds shelters - Low maintenance
Crops	-Traditional cultivation techniques.	- Selection of varieties adapted to local conditions - Hydraulic structures (irrigation canals, tanks, wells, among others)	- Advanced age or death of traditional farmers - Substitution of traditional cultivation techniques for an intensive model - Tourism dominance as an economic activity	- Use of more productive varieties - Cessation of use of hydraulic structures - Low maintenance
Obtaining fuel	-Knowledge of species that can be use as fuel for different land uses.		- Advanced age or death of traditional births	

Hunting				
Material for construction extraction		- Quarries		-Vegetation colonization -Covered by aeolian landforms
Aerodrome		- Structures associated with the activity (control tower).		- Graffittis - Cessation of use
Roads		-Traditional paths		- Substitution by new roads and highways
Building		- Prehistoric dwellings - Post-conquest traditional houses		-Buried by sediment transport - Plunder - Low maintenance
Recreational				
Militar		- Structures associated with the second world war (bunkers, machine gun nests, trenches, lookouts, tunnels, among others)		-Buried by sediment transport - Plunder - Low maintenance - Garbage dumping
Vehicle traffic				
Industrial	-Knowledge of burning the lime kilns.	-Traditional lime kilns.	- Advanced age or death of limes - Cessation of activity	- Garbage dumping - Vertido de basuras - Cessation of use

6.4 Methodological aspects

The sources in historical ecology present some limitations that are generally related to the questions raised by Rymer (1979): i) How far was the writer interested in recording real events?; ii) Did the writer live close in time and space to the events described?; iii) Were the events recorded as they happened or long after?; iv) Did the writer have first-hand access to oral or written reports and, if so, were they transmitted correctly?; v) Would the writer have benefited by presenting incorrect information)?; vi) Do the different sources agree with one another?

In relation to the first and second question, the sources of information used were generally written by the local population (while the testimonials of travelers were hardly used). In addition, when the written press was used as a source, it was taken into account that several news items from different newspapers coincided in the information provided. In reference to the third and fourth question, most of the documents used were acts of local, island or regional governments, so the events that occurred in these systems were recorded periodically. The same thing happened with the press that records information as events occured.

In order to solve the question number six, this doctoral thesis has combined a significant number of sources, since exhaustive searches have been carried out in historical archives, in the press, oral interviews and aerial and field photographs have been used. In addition, field work has been carried out to, as far as possible, recognize the legacy that these human impacts have left on the ground. As an example, in the case of lime kilns, all the kilns that currently existed in the systems were located and compared with the information from historical sources.

Finally, an effort has been made to digitize and spatialize historical information. This is especially important in the methodological advance exposed in the third paper where a new methodology is created to measure historical deforestation processes. In this sense, the methodology combines for the first time the integration of oral sources and field work. Likewise, the spatialization of the biogeomorphological variables of 460 nebkhas together with the information on the historical land uses have made it possible to recognize distribution patterns associated with disturbances that are not present in the study area today. In short, the integration into a Geographic Information System of the historical information and the information obtained during the field work has been essential in the development of this doctoral thesis.

6.5 Aim and hipothesis discussion

The hypothesis raised at the beginning of this doctoral thesis was based consists in determining whether the evolution in land uses have altered or not the natural dynamics of the arid aeolian sedimentary systems of the Canary Islands. This hypothesis has been valid because, as has been shown, land uses have been decisive in the alterations of natural dynamics of these ecosystems, inducing changes that even go against current climate trends. This means that the second hypothesis has also been confirmed since the moment in which land uses have determined the evolution of the landscape, they are also a determining factor in the current landscape despite being protected and regulated land uses.

A third hypothesis is the possibility that the populations that lived or depended on these systems were affected by the environmental changes caused by land uses. This hypothesis has also been confirmed. As shown in the paper related to social relevance, land uses determined changes that influenced the provision of ecosystem services on which the population depended for subsistence.

In relation to the objectives of the thesis, the results are quite positive, since most of them have been achieved.

The first aim (identify and characterize the land uses that have occurred throughout history in the selected study areas) has been achieved for the three eolian sedimentary systems analyzed in this doctoral thesis with different degrees of depth.

The second aim (analyse recent changes in vegetation, landforms and sediment transport) has been achieved only for Jandía and El Médano; in addtion, some brief descriptions are made of the eolian sedimentary system of El Jable. However, new works can address this sedimentary system since we know that important changes took place that surely, when studied in detail, will lead to advances in the knowledge of these systems and their recent evolution.

Related to the third aim (discuss the relationship between the changes that have occurred in the aeolian sedimentary systems and the derived impacts as possible responses mechanisms of the ecosystem to the different land uses identified) the discussion has been achieved for the two aeolian systems for which both aspects were analyzed in greater depth (Jandía and El Médano). Especially, the changes produced by the lime kiln industry were analyzed, since this land use had been little studied until now.

The fourth aim (understand the social response to changes in the natural dynamics of the ecosystem due to land uses) was analyzed in the aeolian sedimentary system of El Jable due to several reasons: the abundance of sources, its early settlement and the high number of inhabitants it had.

The fifth (apply the results obtained to the determination of guidelines for the integrated management of selected areas) has partially been achieved. The management measures provided in this doctoral thesis will help the future management of these systems but also of other regions with similar systems. These measures are especially discussed for the Jandía aeolian sedimentary system. However, the information produced will make it possible to improve current management.

7. GENERAL CONCLUSIONS

Finally, the general conclusions are presented, which do not keep an order with respect to the phases of the Doctoral Thesis, but instead propose an exercise to merge the main conclusions of all the published research papers. However, these conclusions demonstrate the fulfillment of the three hypotheses raised at the beginning of this doctoral thesis. It can be concluded, in a general way, that the current landscape of aeolian sedimentary systems is the result of the evolution of land uses that altered its natural dynamics and its natural components for centuries. This also produced important changes in the capacity of these systems to provide ecosystem services and, therefore, the population suffered changes in natural dynamics.

i) The analysis of different historical and contemporary sources shows that sediment remobilization in Jandía (Fuerteventura) and El Jable (Lanzarote) was mainly induced by the exploitation of vegetation for grazing and lime production. These activities produced environmental alterations in the aeolian sedimentary system, which will have resulted in an increase in sedimentary transport and a decrease in vegetation cover. However, once the human interventions based on the extraction of the vegetation cease and the protection of the space comes into force, a process of spontaneous recolonization of the vegetation takes place.

ii) In Jandía and El Jable recent activities, which have generated numerous barriers to sediment transport (vegetation barriers, road networks and urban-tourist constructions), have also induced, along with the spontaneous recovery of vegetation, the erosion of the intertidal zone areas located at the exit sector of the systems.

iii) The coastline of the Sotavento has shown a clear erosive trend since at least 1956. The analysis of longshore drift that was undertaken revealed that some 96,000 m^3

of sediment is transported southwards each year, and that most of it is lost to two submarine canyons situated opposite the El Matorral headland.

iv) The Sotavento shoreline despite its being declared a protected space with the aim of ensuring the continued existence of an area of exceptional natural values, the regulations that have come into force as a consequence of its protected status do not permit the interventions that are necessary to mitigate the erosion processes that the area has been experiencing for over 60 years. The measures that could be undertaken according to the current planning in the study area are artificial regeneration and mechanical sand recirculation. On the other hand, passive management would force new damage to infrastructure and the disappearance of the salt marsh. However, all the measures, but passive management, would imply a high and continuous economic cost and, therefore, are of doubtful long-term sustainability. The combination of different measures (artificial regeneration and mechanical sand recirculation) could be the key to stop erosion problems.

v) The aeolian sedimentary system of El Médano presents different responses to the long-term land uses (aerodrome, aggregate extraction and crop cultivation), but it seems that in the biogeomorphological recovery process, the distance to the coastline and the conservation of the characteristic topography of the system are the two most important factors.

vi) The present research shows that when the land uses cease, the system does not return to its natural conditions but adapts and reorganizes depending on the new conditioning factors (topography, availability of sediments, vegetation's ability to recolonize degraded areas, among others).

vii) The evolution of the systems is determined by the availability of resources on each island. In the islands with fewer resources (Lanzarote and Fuerteventura) the evolution of the systems has been determined by traditional uses; while, in the case of El Médano, traditional uses were not so relevant as there were abundant resources in the summit area for grazing and obtaining fuel.

viii) The analysis of historical sources reveals that the changes to or loss of ecosystem services which have had high social relevance are related to the social sensitivity, political or economic criteria that were considered, and that these depend to a large extent on the type of service provided (provisioning, regulating, cultural or supporting).

ix) The most direct and vital ecosystem services (the provision of food, fuel and raw materials, and the regulation of natural hazards) are those with the greatest historical social relevance until 1960. At this point in time, a change to the economic model involving the promotion of tourism resulted in other aspects (cultural heritage, recreation and leisure and aesthetic value) acquiring greater social relevance in terms of citizen safety (regulation of natural hazards), ecosystem conservation (provision of wildlife habitats) and culture (cultural heritage).

8. PERSPECTIVES

In this section, a presentation is made of the possible lines of research that are opened from the research of this doctoral thesis:

i) The sources and the methodology followed in the present research can be applied to other ecosystems. Especially, the methodology designed in the study of lime kilns applied to the production of coal, tools for agriculture, elements for the construction of houses and infrastructures, pine resin, among other. Furthermore, it would be interesting to know if the effects of these uses are similar to the effects of land uses in systems located in different climatic regions.

ii) The impact of controlled grazing can be studied in El Jable (Lanzarote) and the uncontrolled one in Jandía (Fuerteventura) in order to better understand how the transformation of plant communities (coverage, species richness, changes in the ability to capture sand) and in the landforms (impact of continuous animal activity on nebkhas or sediment remobilization) have been and continues to be. In addition, studies on livestock carrying capacity must be carried out in systems that continue to support this activity. Also, changes in soil composition due to the presence of excrement can be analysed. Likewise, during field work in El Médano, such impacts were detected due to the presence of rabbits in the nebkhas.

iii) Land uses that used vegetation can lead to the extinction of species; however, knowing this information through historical sources is very complex. In this sense, in the immediate surroundings of the lime kilns and inside the kilns themselves, there are remains of ash and coal that could be analysed to know in detail which plants were burned and if the industry caused the extinction of some of them.

iv) Despite the fact that numerous works have been carried out on vegetation in arid dune systems; still very little is known about the plant species that inhabit them.

Most of the studies focus on the role of *Traganum moquinii* and its historical evolution: however, delving into other species would allow us to understand even better the changes that grazing or the use of vegetation as fuel could have on these systems.

v) Even though many works talk about the depletion of aeolian deposits and the lack of new contributions from the inlet areas, few studies have quantified this aspect. Therefore, it is interesting to carry out an analysis of the submarine deposits and the sediment available for transport. If it is found that there are no new sedimentary contributions in the systems, it is necessary to know the reason in order to understand the trends towards which the systems are going to change.

vi) The social effects of changes in the natural dynamics of aeolian sedimentary systems have been vaguely studied in this doctoral thesis; however, new works would allow knowing the effects that the current changes have on the users of the systems. In this sense, the provision of Ecosystem Services could be an interesting topic to deepen the perception of the population. As an example, the doctoral student during his stay in Galway (Ireland) between the months of February and July 2022 has been working on the motivations behind the community restoration of a dune system and the actions implemented voluntarily by its inhabitants. This type of restoration can be applied in the Canary Islands systems.

vii) An increase in vegetation cover has been detected in the systems that goes against climatic trends. It would be interesting to monitor the evolution of vegetation from now on and its relationship with climate trends. Since a decrease in rainfall and an increase in temperatures have been detected; therefore, it is feasible to think that the vegetation will undergo changes in the near future.

viii) There are numerous land uses whose impact analysis has not yet been studied in depth. Especially, uses that are currently present in these systems such as sandboarding, vehicle traffic, the effects of cleaning machinery, etc. These uses are key to understanding the current operation, how these systems will evolve and the impacts that will appear in the coming years.

ix) Other sources can be included in this type of study. An example of this would be to implement the use of toponymy. Toponyms could offer relevant information on land uses, flora, fauna, geographical features, among other. These could correspond to the current reality or could differ thus offering useful information on changes.

x) Finally, despite the fact that this is not a research perspective or a possible line of research, an important perspective for the future in relation to the management of these ecosystems is the need to learn from their capacity to respond to human disturbances. In this sense, this thesis concludes that these systems hardly resort to returning to their conditions prior to human interventions but are forced to readapt or reorganize based on these alterations and the conditions created by human interventions. Therefore, it is necessary to learn about new land uses and the long-term impact they will have on dune beach systems that are still recovering from interventions that occurred more than a century ago.

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