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HUMAN-DERIVED ENVIRONMENTAL CONSEQUENCES FOR THREE SEDIMENTARY SYSTEMS OF THE CANARY ISLANDS (SPAIN) – A STUDY OF CHANGES AND IMPACTS: A SYNTHESIS

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ABSTRACT. This paper explores the relationship in three sedimentary systems of the Canary Islands (Spain) between four major land change processes (resource extraction, urbanization, tourism and nature protection) and six main environmental consequences (impacts on aeolian sedimentary dynamics, changes in sand landforms, disappearance of sand landforms and entire systems, changes in vegetation, impacts on the socioeconomic system, and changes in land use patterns). The results show that all the environmental consequences have impacted all three study sites, except in one of them (La Graciosa island) in producing disappearance of sand landforms and entire systems. It should be noted that the environmental consequences described concerns different scales (from entire systems to landforms). All the impacts are described and analyzed separately, and the results are discussed in detail and in relation to the presence of these environmental consequences in other parts of the world.

Consecuencias ambientales derivadas del desarrollo humano en tres sistemas sedimentarios de las islas Canarias – estudio de cambios e impactos: una síntesis

RESUMEN. Este artículo explora la relación existente en tres sistemas sedimentarios de las islas Canarias (España) entre cuatro procesos de cambios territoriales primordiales (extracción de recursos, urbanización, turismo y protección natural) y seis principales consecuencias ambientales (impactos sobre la dinámica sedimentaria eólica, cambios en las geoformas sedimentarias, desaparición de geoformas sedimentarias y sistemas enteros, cambios en la vegetación, impactos sobre el sistema socioeconómico, y cambios en los patrones de usos del suelo). Los resultados muestran que todas las consecuencias ambientales han impactado en los tres sistemas estudiados, excepto en uno de ellos (en isla de La Graciosa), donde la desaparición de geoformas sedimentarias y sistemas enteros no se ha dado. Se debe tener en cuenta que las consecuencias ambientales descritas se refieren a diferentes escalas (desde sistemas enteros hasta geoformas). Todos los impactos han sido descritos y analizados separadamente, y los resultados son discutidos en detalle y en relación con la presencia de dichas consecuencias ambientales en otras partes del mundo.

Key words: Dunes, major land change processes, environmental consequences, coastal arid environments, Canary Islands.

Palabras clave: dunas, procesos de cambios territoriales primordiales, consecuencias ambientales, ambientes áridos costeros, islas Canarias.

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1. Introduction

Human activity has resulted, at a global level, in the alteration of most ecosystems and landscapes (Vitousek *et al.*, 1997), especially impacting on their structures and processes (Wenbin *et al.*, 2018). Studies into both the natural and anthropic causes and consequences of ecosystem change are crucial to enable a better understanding of landscape dynamics. In this respect, studies on land-use/cover changes (LUCC) can contribute to establishing the main observable changes over different spatio-temporal scales (Kothari and Arnall, 2019; Müller *et al.*, 2014). However, there are differences in such studies in terms of the relative weight of the impact of natural and anthropic-related events; while land cover changes may be due to natural and/or human processes, land use changes require human intervention. The next important step in the study of ecosystem changes is to conduct more in-depth analyses of the causes, including economic, politic and cultural questions which often remain invisible when using solely cartographic sources (e.g. Santana-Cordero *et al.*, 2017). Lambin *et al.* (2001) considered this point when reviewing the underlying causes of LUCC.

The argument proposed in the present study is that a thorough LUCC investigation needs to identify the causes, analyze the processes and establish the environmental consequences, as in the following sequence: "Scenario 1 (before the changes) – Change Processes – Scenario 2 (after the changes)".

Focusing on sandy coastal areas, it has been acknowledged that natural systems have been studied in far greater detail than those altered by human activity (Jackson and Nordstrom, 2019). Nonetheless, as more than 40% of the planet's human population lives in coastal areas (Martínez *et al.*, 2007), such systems clearly need to be studied so that their dynamics can be better understood, predictions of their future evolution made, and solutions to problems proposed. With respect specifically to sandy coastal areas, Jackson and Nordstrom (2011) highlighted the impact of the location, size and stability of dunes and the importance of sand-trapping fences, vegetation plantings and bulldozers or the replacement of dunes with shore-parallel structures. Landward zones importantly include infrastructures such as buildings, roads and parking lots. Some studies, including Goudie *et al.* (2000), Hoffman and Rohde (2007), Otto *et al.* (2007) and Pickart and Hesp (2019) have diachronically explored the changes to coastal sandy areas in different parts of the world, verifying the land changes described above.

Although the environmental consequences of human action can be observed globally, they are particularly important in islands due to their limited resources. As the present study is undertaken on sedimentary systems of the Canary Islands (Spain), some background data is first required. A good evidence of this can be seen in a study by Ferrer-Valero *et al.* (2017) who recorded and quantified changes along the coast of Gran Canaria which were mostly related to its occupation. Cabrera-Vega *et al.* (2013) reported the causes of change and the consequences for three dune and beach-dune systems of the Canary Islands (Maspalomas, Corralejo, Famara), with specific emphasis on sedimentary dynamics. Other studies have focused on Maspalomas (Gran Canaria), revealing the consequences of the establishment of a tourist resort in this system on the sedimentary dynamics (García-Romero *et al.*, 2019a; Hernández-Calvento *et al.*, 2014). Other (historical based) analyses have considered Maspalomas, Guanarteme (Gran Canaria) and La Graciosa island, recording the substantial changes that have occurred and the disappearance of landforms and even entire systems (Hernández-Cordero *et al.*, 2018; Santana-Cordero *et al.*, 2014, 2016a, 2016b, 2017).

The aim of this study is to identify and characterize human-derived environmental consequences for three sedimentary systems of the Canary Islands: Guanarteme, Maspalomas and La Graciosa island.

It constitutes the second part of the paper *A century of change in coastal sedimentary landscapes in the Canary Islands (Spain) — Change, processes, and driving forces* by Santana-Cordero *et al.* (2017), in which the causes of changes in the same three sedimentary systems were studied. In that previous study, 81 driving forces were identified, and four derived major land change processes were explained (resource extraction, urbanization, tourism, and nature protection). In the present work, the relationships between the major land change processes and the environmental consequences (impacts on aeolian sedimentary dynamics, changes in sand landforms, disappearance of sand landforms and entire systems, changes in vegetation, impacts on the socioeconomic system, and changes in land use patterns), related to different scales (from entire systems to landforms), are examined.

1.1. Study sites

The Canary Islands is an Atlantic archipelago situated a short distance from the coast of northwest Africa (Fig. 1). From a geological point of view, these islands are the result of a volcanic hot spot – a magmatic camera in the mantle creating a chain of islands due to the movement of the plate which is above. The location of the archipelago places it in the limit of a desert climate and a temperate one as the result of wind currents from the west. The trade winds and the cold sea current of the Canary Islands also help to reduce temperatures. The temporal distribution of temperature and precipitation follows the same pattern in different parts of the archipelago: temperatures present a normal distribution (higher temperatures in summer) with some differences between different sites (ranging from 4-25ºC), while precipitation rates are high during the winter but virtually non-existent in at least one month of the summer (ranging from 0-130 mm). Annual average temperature is 18.5-21ºC in coastal zones, and total average annual precipitation is 400 mm (Morales-Matos and Santana-Santana, 2005).

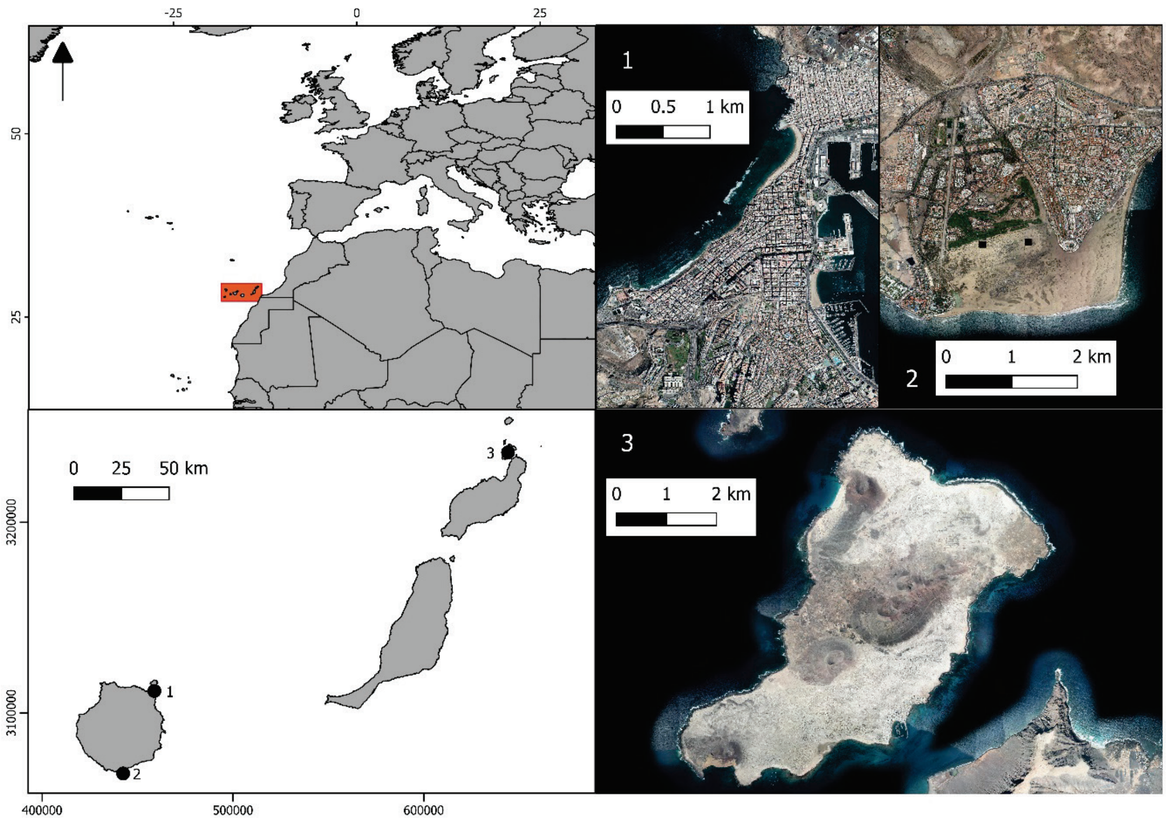

Figure 1. Study area showing the three study sites considered: Guanarteme (1) and Maspalomas (2) dune fields on Gran Canaria island; and La Graciosa island (3). In 2 (view of Maspalomas dune field); the two small black squares correspond to Masp-plot 1 (left) and Masp-plot 2 (right).

In economic terms, the main activity of the Canary Islands is tourism, overwhelmingly of the so-called ‘sun-and-beach’ type. As the name itself indicates, this type of tourism tends to occupy coastal areas, with the result that several coastal systems on the islands have been subjected to alteration. In this research, three study sites are considered: the Guanarteme and Maspalomas dunefields, and La Graciosa island.

The Guanarteme dunefield is situated in the NE of Gran Canaria in the island’s capital city of Las Palmas de Gran Canaria. In 1954, Guanarteme was a dune system, with an extension of 2.4 km^2 (Santana-Cordero *et al.*, 2016b). This dune system has undergone several phases in terms of the amount of sediment and the movement of its landforms throughout its history. A historical reconstruction of the dune system made by Santana-Cordero *et al.* (2014) reveals that there were between one and three very large, semi-stabilized dunes in the XVIII century and that in the last third of the XIX century there were barchan dunes and sand sheets which constituted a mobile dunefield. According to Santana-Cordero *et al.* (2014) vegetation cover was scarce in this latter period. This system disappeared towards the 1960s due to human intervention (Santana-Cordero *et al.*, 2016b).

The Maspalomas dune system is located at the southernmost tip of Gran Canaria and had an extension of 4.8 km^2 in 1961. Since then, this system has evolved with the development of tourism - tourist facilities, urbanization, golf course – both in its interior and at its borders. Typical landforms found here include a foredune, comprised of hummock dunes parallel to the eastern coastline, barchan dunes and deflation surfaces which have been shaped by tourist activity. Consequently, sectors can be found of accumulation, stabilization and erosion, parts of which interact with the vegetation cover which is more important here than it used to be in Guanarteme before its disappearance.

La Graciosa is located at the northeastern tip of the archipelago, north of the island of Lanzarote. In 1954, the island had a sedimentary system of 13.1 km^2 (that not suffered relevant variations due to its protection status). Its sedimentary system is divided into a northern and southern parts and present stabilized landforms, especially since 1987 when the prohibition of grazing and other traditional activities (as imposed by Law 12/1987, of 19 July, of the Declaration of Natural Sites in the Canary Islands) resulted in the disappearance of human pressure on the natural vegetation. This system presents sand sheets and nebkhas (small dunes to the leeward of plants, especially shrubs) stabilized by the vegetation cover (Santana-Cordero *et al*., 2017).

2. Material and methods

Different sources were used for the purposes of this study. First, a brief review was made of papers, books and reports on the morphological characteristics and the vegetation cover at the three study sites. Of these, special mention should be made about the importance and usefulness of the studies of Hernández-Cordero *et al.* (2018), Hernández-Calvento *et al.* (2014) and Hernández-Calvento (2006). Aerial photographs and orthophotos (Table 1), some of them obtained via the Web Map Service (WMS) of the IDECanarias (The Canary Islands SDI), were also used to digitize, measure and analyze some of the LUCC patterns and processes revealed in the results. Statistical data were used to support important population data and economic events related to the results of impacts on the economic system.

The results of this paper are structured to reflect the 6 main human-derived environmental consequences at the three study sites. These environmental consequences are as follows: i) impacts on aeolian sedimentary dynamics; ii) changes in sand landforms; iii) disappearance of sand landforms and entire systems; iv) changes in vegetation; v) impacts on the socioeconomic system; and vi) changes in land use patterns.

Table 1. Aerial images used and their basic characteristics.

Year	Study site	Type	Resolution (cm/pixel)
1949	Guanarteme	Aerial photograph	38.3
1954	La Graciosa	Aerial photograph	100
1961	Maspalomas	WMS	12.5
1987	Maspalomas	Orthophoto	15
2003	Maspalomas	Aerial photograph	15
2006	La Graciosa	WMS	50
2009	La Graciosa	Aerial photograph	10
2018	Guanarteme	WMS	20
2018	Maspalomas	WMS	20
2018	La Graciosa	WMS	20

The land uses have been established according to Santana-Cordero *et al.* (2016b) with some additions based on what it has been seen in the aerial photographs. They are as follows: abandoned land, agriculture, industrial, infrastructure, mixed, unused land, recreational and residential. Mixed land use refers to areas where different uses have been carried out. Unused lands refer to areas with forbidden uses or where natural processes appear to be the main feature, incompatible with human uses (e.g. sandy extensions). Residential land use includes the tourist resort in Maspalomas.

Continuous changes along beach shorelines due to natural processes have methodological implications in the area of the study sites. Therefore, changes in the study sites in terms of their area are registered. Furthermore, although in the case of Maspalomas the study area changed because the sandy surface has been reduced over time due to the urban expansion, the extension used here is that of 1961, namely 4.8 km^2.

2.1. Analysis

The different data were analyzed using a number of techniques. Photo-interpretation was employed to compare geomorphologic maps, as indicated in Hernández-Calvento (2006), shedding light on the establishment of changes in sand landforms. Diachronic measurements and analyses, including a GIS-based quantification of changes, were also performed. For the study of the impacts on aeolian sedimentary dynamics, alterations were detected through photo-interpretation of the 2018 aerial photograph in Maspalomas. For the study of vegetation cover, the evolution of four aerial photographs/orthophotos was used (1961, 1987, 2003 and 2018) in Maspalomas. For this purpose, two plots (polygons) of 1 ha were established in sectors where there was no vegetation in 1961 (Masp-plot 1 and Masp-plot 2). Digitization of the vegetation elements in the other aerial photographs then gave us the corresponding vegetation cover values in each plot. After digitization of the vegetation cover, a statistical correlation was established with a good fit ($R^2 = 0.89$ and 0.83). Digitization was also used to establish and measure the land uses at the three study sites. In relation to these measures, the mean, standard deviation and normalized standard deviation were calculated, with the latter employed as an indicator of the degree of homogeneity in terms of land-uses areas.

3. Results

The results are presented in the following subsections: causes-consequences matrix, Impacts on Aeolian sedimentary dynamics, Changes in sand landforms, Disappearance of sand landforms and entire systems, Changes in vegetation, Impacts on the socioeconomic system, and Changes in land use patterns.

3.1. Causes-Consequences matrix

In Table 2, causes (understood here as major land change processes) and consequences are linked by a symbol when a relationship between a cause and a consequence exists at one of the study sites, according to the literature.

Table 2. Major land change processes and their environmental consequences. Key - circle: Guanarteme; square: Maspalomas; and triangle: La Graciosa.

Major land change processes/ environmental consequences	Impacts on aeolian sedimentary dynamics	Changes in sand landforms	Disappearance of sand landforms and entire systems	Changes in vegetation	Impacts on the socioeconomic system	Changes in land use patterns
Resource extraction	● Δ	● ■ Δ	●	Δ	●	●Δ
Urbanization	● ■	■	● ■	■ Δ	● ■	● ■ Δ
Tourism	■ Δ	■	■	■	■	■ Δ
Nature protection	■ Δ	Δ		Δ	Δ	Δ

3.2. Impacts on aeolian sedimentary dynamics

The sand extractions that took place in Guanarteme should have provoked alterations to the aeolian processes. The rapid changes in the topography modified the intensity of the transport of sediment through the deceleration/acceleration of the sediment flows (Fig. 2) (Santana-Cordero *et al.*, 2016b). This effect created different landforms in terms of sediment movements, so semi-stabilized dunes were naturally revegetated while in the other side, high movement rates led to erosion.

Figure 2. Guanarteme dunefield (1949). Center-top arrows represent the modification of the sediment transport; left-top arrows indicate the wind corridors.

In La Graciosa, sand extraction has had an important impact on aeolian sedimentary dynamics, causing similar alterations to sediment flows as in Guanarteme (Pérez-Chacón *et al.*, 2010). Sand extraction extended to 1.3 ha in 2006 and 1.0 ha in 2009, years in which this alteration had considerable dimensions (Fig. 3). The presence of a network of car tracks across the island also needs to be taken into consideration, as they cause erosion and soil compaction.

In Maspalomas, the urbanization of El Inglés over the high sedimentary terrace, which began in the early 1960s, has had two major impacts on the aeolian sedimentary dynamics due to alteration of the wind stream. Firstly, the conditions were created for the generation of a wind vortex that triggers wind acceleration and dune erosion in one sector of the dunefield (Hernández-Calvento *et al.*, 2014). Secondly, the normally westward-flowing winds have been deviated to the southwest, which has resulted in dune stabilization in the northwestern sector of the system, leeward of the urbanization. This stabilization affected between 21.6 and 90.9 ha in this sector in the period 1961-2003 (Hernández-Cordero *et al.*, 2018), also triggering changes in vegetation cover. Additionally, small dunes running above big dunes were detected in 2018, constituting new landforms caused by the wind acceleration described above (Fig. 4). These new landforms occupy 1.151 ha.

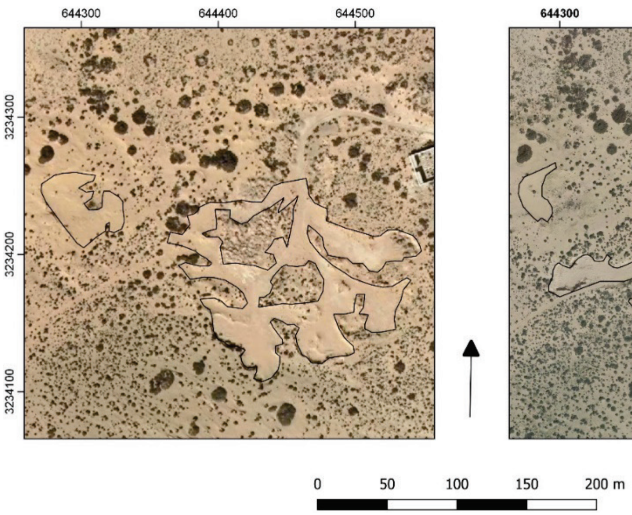

Figure 3. Extractions in La Graciosa in 2006 (left) and in 2009 (right).

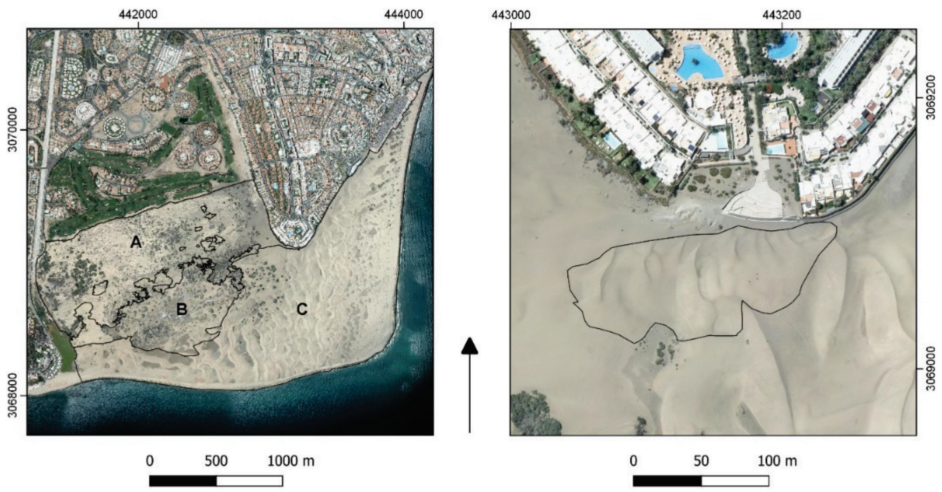

Figure. 4. Maspalomas dunefield (2018). Sedimentary dynamics sectors (left; A: stabilized area; B: semi-stabilized area; and C: active area) and small dunes alteration (right). *Source: Hernández-Cordero* et al. *(2015).*

In the case of Guanarteme, coastline urbanization had already altered the sedimentary dynamics of this dunefield, as seen in the image of 1949, with the streets acting as wind corridors (Fig. 2). This phenomenon accelerates winds, altering sediment flows inside the system and increasing the erosion process.

Tourist activities and their associated facilities have also affected the aeolian sedimentary dynamics in Maspalomas and La Graciosa. In the first case, the dynamics have been changed as the result of the presence on El Inglés beach in Maspalomas of hammocks, umbrellas, 'goros' (handmade stone shelters), *Red Cross* lifeguard posts and kiosks, with the latter for example generating the formation of deflation surfaces at either side of the kiosk as the result of acceleration of the wind and the accumulation of sand leeward of this obstacle ('shadow dune'), causing foredune vegetation modifications (Fig. 5). The deflation surfaces in the system, although not only provoked by kiosks, increased in the period 1961-2003 from 10.1 to 32.2 ha (Hernández-Cordero *et al.* 2018). In La Graciosa, the presence of tourists, especially on El Salado beach - where tents can be set up interfering in aeolian sedimentary transport - and in Caleta del Sebo, has resulted in the dumping of debris and waste and the trampling of vegetation by hikers (Fig. 6) (Pérez-Chacón *et al.*, 2010).

Nature protection measures have also had an impact on the Maspalomas dunefield and the La Graciosa sedimentary system. Maspalomas (the dunes, not beaches) and La Graciosa island were protected in 1987 through the Declaration of Natural Sites in the Canary Islands (Canarian Law 12/1987, dated 19 July). In addition, Law 12/1994, dated 19 December, on Protected Natural Areas of the Canary Islands ensured increased protection in Maspalomas and the establishment of tracks for tourists to cross the dunefield without damaging it. Periodic displacement of the kiosks was also established in 1995-96 to minimize their impact (Hernández-Calvento *et al.*, 2002). In La Graciosa, the prohibition of traditional land uses from 1987 onwards (grazing, agriculture, firewood extraction, lime kilns exploitation) contributed to retrieving and conserving the vegetation and sedimentary processes (Santana-Cordero *et al.*, 2016a).

Figure 5. Kiosk on El Inglés beach; Maspalomas.

Figure 6. Tents on El Salado beach; La Graciosa. Photo: Yamilé Sarmiento, 2019.

3.3. Changes in sand landforms

In Guanarteme, sand extraction was detected through at least two different means: aerial photographs and oral sources. The aerial photographs allowed measurement of the extent of sand extraction in two different years (1949 and 1954) and thus calculate the mean annual extraction rate, 0.34 ha per year (3412 m^2 per year) (Santana-Cordero *et al.*, 2016b). This impact provoked changes in a sand sheet of the system. In Maspalomas, in 1961, sand mining was concentrated in two points in the western section of the terrace, while in 2003 this activity continued in the same location and had been extended to the western border of the dunefield (Hernández-Cordero *et al.*, 2018). In La Graciosa, resource extraction was mainly vegetation based, as fuel for lime kilns and domestic purposes (Fig. 7). The best species for the lime kilns was *Launaea arborescens*, whereas *Traganum moquinii* and *Nicotiana glauca* were the best for household consumption (Santana-Cordero *et al.*, 2016a). Extraction of this resource triggered movement of the sand, thus changing the shape or type of landforms among the sand sheets and dunes (mainly nebkhas and hummocks).

The urbanization of El Inglés terrace (Maspalomas dunefield) also triggered changes in the landforms of two parts of the system. The zone where the wind is accelerated presents landforms altered as the result of erosion processes, generating deflation surfaces. On the other hand, the wind *vacuum* in the northwestern system has transformed mobile dunes into stabilized ones. According to Hernández-Calvento (2006), changes took places in the eastern and southwestern sections of the terrace during the 1960s and 1970s, with the eastern side transforming from a barchanoid ridge to an echo dune. In the southwestern section, erosion processes now predominate (García-Romero *et al.*, 2019b) where falling dunes existed before.

Tourism in Maspalomas has affected, for example, the foredune, with a change in area from 13.2 ha in 1961 to 9.5 ha in 2003 (Hernández-Cordero *et al.*, 2018). Thousands of tourists pass through it all year round, as well as numerous vehicles and other heavy machinery providing services such as cleaning. For the foredune, *Traganum moquinii* plays an essential role in sedimentary regulation. However, this species is under intense pressure as the result of human and vehicular traffic (Fig. 8) (Peña-Alonso *et al.*, 2012, 2017). In La Graciosa, nature protection measure has severely reduced vegetation extraction through the prohibition of traditional land uses, releasing the system from a major anthropic pressure. In this way, the active landforms become stabilized, and it can be argued that the type of ecosystem found on the island has changed, at least in some sectors.

Figure 7. Remnants of a lime kiln in La Graciosa used before their prohibition in 1987. Photo: Luis Hernández Calvento, 2011.

Figure 8. Impacts on the foredune of Maspalomas. Photo: Carolina Peña Alonso, 2016.

3.4. Disappearance of sand landforms and entire systems

The Guanarteme dune system disappeared after sand extraction was carried out systematically from at least the last quarter of the XIX century for the purposes of brick manufacturing and freeing up land for construction (Santana-Cordero *et al.*, 2016b). Barchan dunes and sand sheets, as well as climbing, cliff-top and falling dunes, associated with the high sedimentary terrace of this system, all disappeared. In this case, sand extraction was carried out indistinctly in sand dunes and sand sheets. The result was the loss of an ecosystem of high value to the island, partly because development of the area was planned in the mid-XIX century (Santana-Cordero *et al.*, 2017) when ecological awareness was non-existent and the development model was based exclusively on developmental premises.

Due to the general dynamics of the extinct Guanarteme dunefield, sand continues arriving from the northwest and now accumulates on Las Canteras beach due to the obstacle or barrier to wind and sand flows caused by the urbanization of the Guanarteme isthmus (Fig. 9). This has created an environmental problem because sand on this beach has had to be extracted and deposited elsewhere to avoid its over-accumulation. Two major sand extraction operations have been carried out: 34,000 m^3 of sand were extracted from the northern part of Las Canteras beach in 2003 and deposited on Las Alcaravaneras beach (also located in the northeast of Gran Canaria), and a further 56,400 m^3 were extracted from the same sector of the beach in 2009 and deposited on other beaches in the south of Gran Canaria (Alonso-Bilbao *et al.*, 2015; Copeiro del Villar Martínez and García-Campos, 2002).

In Maspalomas, cliff-top dunes, occupying 14.1 ha in 1961 (Hernández-Cordero *et al.* 2018), disappeared in the following twenty years with the development of the El Inglés urbanization on the terrace. These landforms had previously co-existed on the terrace with agricultural activities (Fig. 10). Part of the foredune of El Inglés beach also disappeared, losing 3.7 ha in its southern sector. This latter loss can partly be related to the presence of tourists as well as beach services (e.g. transit of vehicles), as mentioned above.

Figure 9. Las Canteras beach. Polygon: sector of the beach where the sand was extracted in 2003 and 2009.

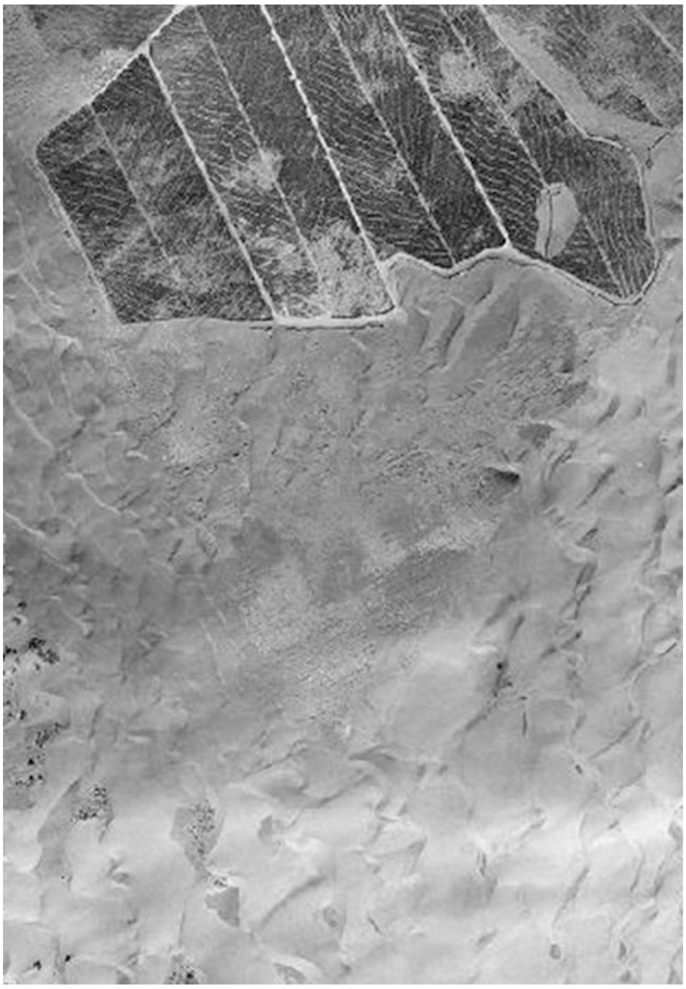

Figure 10. Cliff-top dunes and agriculture on the El Inglés terrace of Maspalomas (1961).

3.5. Changes in vegetation

The stabilized dune sector of Maspalomas, in the northwest sector (Fig. 4), allowed the establishment of new plant species. In this area, 92.08 ha were colonized by plant communities: '*Cyperus capitatus-Ononis tournefortii* (psammophilous perennial and annual forbs), *Tamarix canariensis* (hygrophilous tree) and *Launaea arborescens* (xerophilous shrub)' (Hernández-Cordero *et al.*, 2017, 2018). This increase has followed an exponential progression, measured through the two plots (Masp-plot 1 and Masp-plot 2) established in this study for vegetation cover monitoring, with an R^2 fit of 0.89 and 0.83, respectively (Table 3; Figs. 1 and 11).

Table 3. Evolution of main land covers (vegetation and bare sand) at the two established plots from 1961 to 2018 in the last 57 years.

Masp-plot 1	**1961 (m^2)**	**1987**	**2003**	**2018**
Vegetation	0 (0%)	220.8 (2.2%)	1,644.0 (16.4%)	2,637.5 (26.4%)
Bare sand	10,000 (100%)	9,779.2 (97.8%)	8,356.0 (83.6%)	7,362.5 (73.6%)
Masp-plot 2				
Vegetation	0 (0%)	135.6 (1.4%)	1,965.9 (19.7%)	2,586.7 (25.9%)
Bare sand	10,000 (100%)	9,864.4 (98.6%)	8,034.1 (80.3%)	7,413.3 (74.1%)

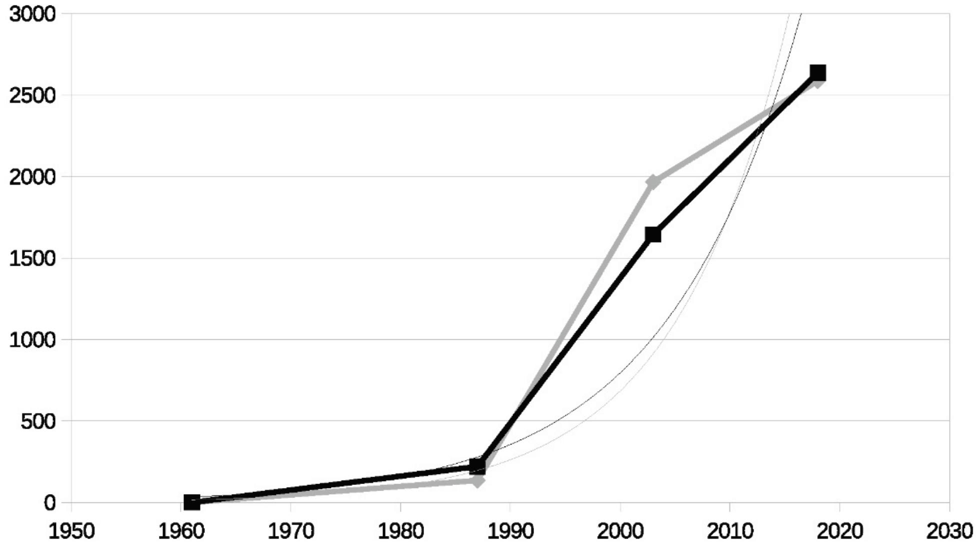

Figure 11. Evolution of vegetation cover and the exponential trend lines at the two plots. Masp-plot 1: black; Masp-plot 2: grey.

In La Graciosa, vegetation regeneration has taken place, especially since the prohibition in 1987 of resource extraction for domestic consumption and lime kilns. In 1954, the two main land covers, bare sand and vegetation, were 479.4 ha (37.4%) and 803.5 ha (62.6%), respectively. In 2009, the respective values were 132.7 ha (10.5%) and 1137.1 ha (89.5%). These data refer to two of the four sedimentary systems of this island (Lambra and El Jable Sur) (García-Romero *et al.*, 2016). At the time of resource extraction, the various species included *Mesembryanthemum nodiflorum*, *Mesembryanthemum crystallinum, Traganum moquinii, Nicotiana glauca* and *Launaea arborescens* (Santana-Cordero *et al.*, 2016a). Recently, 17 plant communities were found to be present in the island, with by far the most abundant being *Salsola vermiculata*, followed by *L. arborescens* and *T. moquinii* (Pérez-Chacón *et al.*, 2010).

3.6. Impact on the socioeconomic system

In Guanarteme, sand extraction was a factor in the growth of the economy in the island. Urban fabric construction and the demands of the new port (mid-XIX century) and its associated services had a major impact on the socioeconomic system. These activities replaced, in part, agricultural activities in Las Palmas and resulted in the abandonment of land and the import of labor from the Gran Canaria countryside, as well as from the islands of Fuerteventura and Lanzarote. In this scenario, urbanization also occupied cultivated land, *e.g.* south of the Las Alcaravaneras district (Santana-Cordero *et al.*, 2016b). Urbanization of the El Inglés terrace, in Maspalomas, contributed to changes to the socioeconomic system at regional level at a time when tourism was taking its first steps to becoming the main economic activity in the Canary Islands and coinciding with the beginning of the establishment of mass tourist destinations in other parts of the world. Tourism required the development of numerous auxiliary services, such as the development of promenades with restaurants, sea-based recreational activities (*e.g.* jet ski rentals) and car parking for visitors. A number of beach services were also established, as noted above: hammocks, umbrellas, kiosks, and *Red Cross* lifeguard posts. Unfortunately, historical data series on tourist visits to the islands are only available from 1993 onwards. Even so, they offer an overview of the growth in the volume of tourism in Gran Canaria (Fig. 12). In La Graciosa, nature protection, with the prohibition of traditional uses in 1987, resulted in a transformation to a tourism-based economy, in line with the regional economic trend.

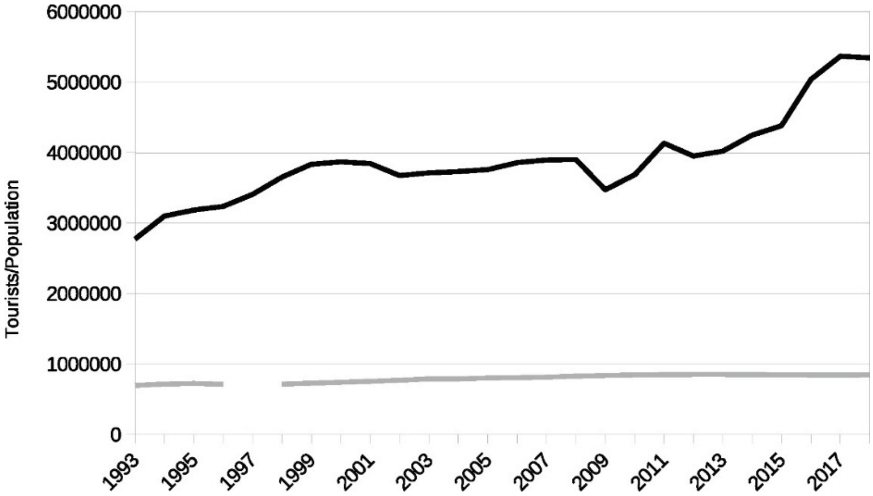

Figure 12. Evolution of tourists (black) and the population of Gran Canaria (grey) for the period 1993-2018.

3.7. Changes in land use patterns

Santana-Cordero *et al.* (2016b) identified four land uses in the XX century in Guanarteme before urbanization spread over almost all the system: agriculture, residential (urbanization), recreational, and sand extraction. Currently, residential use extends over almost all the area, except the beaches of Las Canteras and Las Alcaravaneras. Additionally, other land uses of lesser importance have been observed: industrial, mixed, infrastructure, abandoned and no use. In Maspalomas, land use in the past (before 1960) was restricted to agriculture on El Inglés terrace, and no use and recreational in the rest of the area. Currently, tourist resort use, treated here as residential, is present along with urbanization and recreational use through a golf course and the beaches. In La Graciosa, the land use pattern was defined by grazing, agriculture, firewood extraction and lime kilns exploitation, but this dramatically changed in 1987 with the prohibition of traditional land uses (Santana-Cordero *et al.*, 2016a). Nonetheless, some farms remain today, but residential use, tourism and no use make up the current land use pattern.

In short, it can be said that land use patterns have retained the same degree of complexity. This complexity can be viewed using the normalized standard deviation, calculated for two years (1954/1961 and 2018) for each study site. The normalized standard deviation explains the degree of homogeneity by measuring the mean distance of the values to the average value, i.e. the standard deviation (Table 4). The normalized value allows the ordering (from less to more) of the degree of heterogeneity: Guanarteme 1954, 2018, Maspalomas 2018, 1961, La Graciosa 1954, and 2018.

Table 4. Land use evolution in the three study sites. Key - G: Guanarteme; M: Maspalomas; Lg: La Graciosa. The first values in each cell are expressed in ha and the second, in brackets, are %.

Land uses	G - 1954	G - 2018	M - 1961	M - 2018	Lg - 1954	Lg - 2018
Abandoned	10.841 (4.4)	1.551 (0.6)	0 (0)	0 (0)	23.361 (1.8)	4.069 (0.3)
Agriculture	12.419 (5.1)	0 (0)	0 (0)	0 (0)	0 (0)	2.268 (0.2)
Industrial	11.863 (4.8)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Infrastructure	11.818 (4.8)	25.764 (10.6)	0 (0)	5.734 (1.2)	0 (0)	0.752 (0.1)
Mixed	13.996 (5.7)	0 (0)	0 (0)	0 (0)	0 (0)	0.306 (0)
No use	46.437 (18.9)	8.305 (3.4)	441.532 (92.9)	347.09 (75.1)	1,286.837 (98.2)	1,302.822 (99.4)

Recreational	12.749 (5.2)	26.27 (10.8)	33.784 (7.1)	50.971 (11)	0 (0)	0 (0)
Residential	125.613 (51.1)	181.821 (74.6)	0 (0)	58.237 (12.6)	0 (0)	0 (0)
Total	245.736	243.711	475.316	462.032	1,310.198	1,310.217
Average	30.717	30.464	59.415	57.754	163.775	163.777
Std deviation	40.173	62.175	154.851	119.409	453.859	460.246
Normalization	0.235	0.510	0.616	0.516	0.639	0.644

4. Discussion

All the environmental consequences seen above can also be understood as part of the phenomenon of global change, and all are well represented in different parts of the world. Gössling (2002) listed the main factors of the environmental consequences of tourism, including two found in this study - LUCC processes and the biotic exchange and extinction of wild species - which can affect biodiversity. Defeo *et al.* (2009) identified the various threats to sandy shores worldwide, including recreation, cleaning, nourishment, pollution, exploitation, biological invasion, coastal development and engineering, mining, and climate change. Nordstrom (1994) reviewed anthropic alterations to coastal beaches and dunes, categorizing them as: (i) large-scale landscape conversion, (ii) creating, reshaping or eliminating landforms to suit human needs, and (iii) effects of protection structures and buildings. The paradigmatic case of large-scale landscape formation in this work can be seen in the case of the Guanarteme dunefield, which disappeared towards the 1960s. Likewise, landforms have been partially eliminated in the sedimentary terrace of the Maspalomas dunefield, where the existence of cliff-top dunes in 1961 has been corroborated. In this same dunefield, effects on the wind currents as the result of urbanization of the terrace have been verified and measured (García-Romero *et al.*, 2019a; Hernández-Calvento *et al.*, 2014).

In Mediterranean shores, Pintó *et al.* (2014) established the following, which are particularly well represented along the Costa Brava (Spain), as having the most important impact: built environments, car parking/car tracks, beach raking, erosion pathways, dune breaches, invasive species and fixed dunes. Fragmentation (or erosion pathways) of the dune front (and its vegetation cover) can result in blowouts, one of the main erosional landforms, which are frequently observed in the western Mediterranean (Mir-Gual *et al.*, 2013). This last impact can be observed in the foredune of Maspalomas, affected by the transit of tourists walking around and through it. Garcia-Lozano *et al.* (2018) reported dune fragmentation along the coast of Catalonia (Spain) as the result of human activity due to trampled paths and car tracks, as also observed in the present study in Maspalomas and La Graciosa. The same authors additionally observed the disappearance of dunes due to urbanization processes, as in the dunefields of Guanarteme and Maspalomas. On the coast of Italy (Campany), the extensive erosion process of a foredune as the result of natural and human activities has been measured, with the results indicating that it has retreated 35-90 m landward in the last 55 years (Pennetta *et al.*, 2011). According to the same authors, the most important anthropic impacts on the dune system have been river protection infrastructures and other urban development structures. Paradoxically, although the study area of Pennetta *et al.* (2011) has been declared a protected natural area, as in the case of Maspalomas and La Graciosa, this has been insufficient to impede a number of human impacts. Similarly, another study on the Northern Tyrrhenian coast (Italy), a place under touristic and residential urbanization pressure since the mid-XX century, reported a significant historical coastal retreat in a beach-dune system and an almost complete occupation of the beach, especially since the 1970s (Bertacchi and Lombardi, 2014). This last case is very similar to that of Maspalomas, where tourist activity has played the most important role in the land change.

Sedimentary areas impacted by human activities can also be found on Atlantic shores. In Valdelagrana beach (SW Spain), historical - from Roman times - and current human interventions have affected a barrier spit. This sandy platform was historically altered about 2,000 years BP by a constructed straight channel, and roads, port facilities, and coastal and fluvial works. Then, in 1721 an artificial cut was excavated in the inner marshlands. Additionally, the coastline has been considerably changed in the last 60 years. Whereas in the northern sector accretion rates of 6 m/year have been recorded, in the southern sector the rates fall to -14 m/year (Del Río *et al.*, 2015). Port facilities and coastal infrastructures have similarly been determining LUCC factors in the dunefield of Guanarteme. In Belgium, Doody (2013) found that 50% of the coastal dunes had disappeared since the 1950s as the result of urbanization projects. In the same study, pressure on sedimentary systems in Portugal was reported to be the result of the establishment of illegal huts in the 1970s in Leira district and Ria Formosa Natural Park. Another important impact on sand beaches and dunes is onshore sand mining. This has been reported along many Atlantic coastlines, including Northern Ireland, Scotland, the Caribbean, the Azores, Africa, and most especially northern Morocco and the USA (Doody, 2013). Hernández and Suárez (2006) characterized the sedimentary systems of Boa Vista (Cape Verde), which are very similar to those of the Canary Islands, and found that the city of Sal Rei (capital of the island) constitutes an obstacle to sedimentary dynamics. In addition, during the period 2005-2010, a tourist resort along with roads leading to and from it were developed in the Rabil coastal sector where a sand sheet and some large barchan dunes existed, as could be discerned in Google Earth (orthophoto from 2016). As in Maspalomas, in Boa Vista this urbanization is altering the sedimentary flow by stopping it and, possibly, deviating the wind current. Marcomini *et al.* (2017) reported that the northeastern coastal dunes of Buenos Aires (Argentina) have been altered by urbanization since 1935, causing changes in dune landforms and vegetation cover.

The Indian and Pacific shores are not exempt from human-altered sandy coasts. In South Korea, various alterations to sand dune systems found along its coastline have been caused by the development of port facilities and recreational resort facilities (Kim, 2005). Such changes are well represented in the present study in the examples of Guanarteme and Maspalomas. Land development has also been the main driver in the reduction and disappearance of coastal dunes in Japan (Iwasatu and Nagamatsu, 2018). The Tottori sand dunes, the largest coastal dune system of Japan, are being impacted by coastal erosion as the result of human activities (Yasumoto *et al.* 2007). As at the three study sites of the present study, beach sand excavation and sand erosion have been reported in the Maldives Islands (Kothari and Arnall, 2019). Thompson and Schlacher (2008) examined the damage that car tracks associated with beach camping areas caused to coastal dunes, especially the foredune, in Fraser Island (Australia), finding that they caused accelerated erosion, shoreline retreat and the removal of dune vegetation. Similarly, the existence of camping areas and roads on La Graciosa island has had a direct impact on the sedimentary dynamics.

Focusing on changes in vegetation cover, many dune areas have been stabilized along the Catalonian coast (Spain, Mediterranean basin) by planting pines to avoid the inland movement of the sediment. Such actions date back as far as the XIX century (Pintó *et al.*, 2014). This contrasts with the changes in vegetation reported in this study which were unintentionally provoked by human actions (cases of Maspalomas and La Graciosa). Nevertheless, according to some historical sources, and with the purpose of stabilizing the sediments in the now-disappeared Guanarteme dunefield, measures such as the planting of *Tamarix canariensis* were employed to block sediment movement along the road that connected the old city with the port of La Luz in the XIX century (Santana-Cordero *et al.*, 2014). By contrast, Moulton *et al.* (2019) reported an increase in vegetation in a transgressive dunefield in the Younghusband Peninsula (Australia) due to natural factors. In almost 70 years, vegetation cover grew from 7% to 40% of the area, and the authors found that the effects of human activities in this case were negligible. However, Provoost *et al.* (2011) highlighted the link in Europe between land use change, especially from its traditional use, and vegetation cover in such systems.

With respect to impacts on the socioeconomic system, Domínguez-Mujica *et al.* (2011) point out the strong correlation with the development of tourism and changes in population. All these factors are found in Maspalomas. In addition, while tourism-based economies of coastal zones may be a powerful economic resource they are also frequently the main cause of environmental consequences that alter and destroy such coastal environments (Hernández-Calvento *et al.*, 2014). This is a trend which has been observed on a global scale since at least 1950 (Gormsen, 1997), and is evident in two of the sites studied here, Guanarteme and Maspalomas (Santana-Cordero *et al.*, 2017).

Globally, the leading driving force behind LUCC is tourism (Gössling, 2002). In this respect, it is to be expected that most tourist areas in the world are undergoing or have had undergone LUCC processes. This is demonstrated in the Mediterranean coasts, the Canary Islands and the Maldives, where one of the results has been the expansion of the built environment (Kothari and Arnall, 2019). In this respect, Pintó *et al.* (2014) suggest that human occupation of beaches through tourist activity triggers irreversible impacts given the current legal and socioeconomic circumstances. Davenport and Davenport (2006) argue that the implementation of new land uses in tourist areas triggers ecosystem fragmentation, as also described by Mir-Gual *et al.* (2013), and reduces biodiversity. In the present study, ecosystem fragmentation can be observed in Maspalomas, specifically in its foredune. Finally, Goudie *et al.* (2000) noted that LUCC can lead to the installation of engineering structures that can modify the transport of the sediments. A similar situation in which human structures have interrupted sediment flows is found in the present study along Las Canteras beach, in Guanarteme, as a consequence of the barrier imposed by its promenade.

5. Conclusion

As the results of this study show, the sedimentary systems considered here have been altered by a variety of causes which have resulted in, at least, six lines of evidence (the environmental consequences), all of which are the product of human action in these coastal systems. Highlighted in this study is the importance of tourism, which has transformed the coast at an unprecedented rate. Of the six environmental consequences considered in this investigation, four are present in all three study sites: impacts on the aeolian sedimentary dynamics; changes in the sand landforms; impacts on the socioeconomic system; and changes in land use patterns. Despite the differences in the developmental models followed at the study sites (Santana-Cordero *et al.*, 2017), the environmental consequences are shared, tending to the existence of the same impacts. The paucity of literature on human impacts on coastal sedimentary systems/dunefield systems, in line with the findings of Jackson and Nordstrom (2019), is confirmed in the present study. There is therefore a clear need for further research studies in this field to enable a proper understanding of these ecosystems and to provide a satisfactory and sufficient background for sustainable interventions. It should also be noted that the environmental consequences studied here constitute a global phenomenon, as demonstrated throughout the discussion section.

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