water

MDPI

Article

Dune Systems' Characterization and Evolution in the Andalusia Mediterranean Coast (Spain)

Rosa Molina [1], Giorgio Manno [2,*], Carlo Lo Re [2] and Giorgio Anfuso [1]

[1] Department of Earth Sciences, Faculty of Marine and Environmental Sciences, University of Cádiz, Polígono Río San Pedro s/n, 11510 Puerto Real, Spain; r.molina.gil@gmail.com (R.M.); giorgio.anfuso@uca.es (G.A.)

[2] Department of Engineering, University of Palermo, Viale delle Scienze, Bd. 8, 90128 Palermo, Italy; carlo.lore@unipa.it

* Correspondence: giorgio.manno@unipa.it; Tel.: +39-091-23896524

Received: 26 May 2020; Accepted: 21 July 2020; Published: 23 July 2020

check for updates

Abstract: This paper deals with the characterization and evolution of dune systems along the Mediterranean coast of Andalusia, in the South of Spain, a first step to assess their relevant value in coastal flood protection and in the determination of sound management strategies to protect such valuable ecological systems. Different dune types were mapped as well as dune toe position and fragmentation, which favors dune sensitivity to storms' impacts, and human occupation and evolution from 1977 to 2001 and from 2001 to 2016. Within a GIS (Geographic Information System) project, 53 dune systems were mapped that summed a total length of ca. 106 km in 1977, differentiating three dune environments: (i) Embryo and mobile dunes (Type I), (ii) grass-fixed dunes (Type II) and (iii) stabilized dunes (Type III). A general decrease in dunes' surfaces was recorded in the 1977–2001 period (-7.5×10^6 m^2), especially in Málaga and Almería provinces, and linked to dunes' fragmentation and the increase of anthropic occupation ($+2.3 \times 10^6$ m^2). During the 2001–2016 period, smaller changes in the level of fragmentation and in dunes' surfaces were observed. An increase of dunes' surfaces was only observed on stable or accreting beaches, both in natural and anthropic areas (usually updrift of ports).

Keywords: dune characterization; anthropic occupation; fragmentation index; dune surface

1. Introduction

Human interest in coastal processes and evolution has greatly increased in recent decades due to the increment of human developments recorded in coastal areas [1] and the impacts of extreme events, such as hurricanes and storms [2,3], the effects of which are enhanced by sea level rise and other climatic change-related processes, such as the increasing height of extreme waves, or changes in the tracks, frequency and intensity of storms [4–7]. Coastal development, which is essentially linked to tourism—one of the world's largest industries [8]—continues to increase, and some 50% of the world's coastline is currently under pressure from excessive development [1]. In Europe, the rapid expansion of urban artificial surfaces in coastal zones during the 1990–2000 period [9] has occurred in the Mediterranean and South Atlantic areas, namely Portugal (34% increase) and Spain (18%), followed by France, Italy and Greece.

Activities and infrastructures related to tourism and other human developments too (e.g., fishing and industrial activities) are significantly affected by the impacts of storms and hurricanes that, over the past century, have caused huge economic losses along with high mortality rates along the world's coastlines [10–13]. Coastal erosion and flooding processes have reduced beach and dune ridges' width and produced the loss of associated touristic, aesthetic and natural values [14–17].

Beach erosion/accretion cycles are often recorded at an inter-annual time scale and are related to seasonal wave climate variations due to temporal and spatial distributions of high-latitude storms and hurricanes/typhoons [3,18–22]. Erosion is observed after storm events, at high latitudes recorded during winter months, but beach recovery takes place during fair weather conditions, which is known as "seasonal" beach behavior [10,23], and in general happens at longer time intervals, from weeks to months [24,25]. Hence, natural beach recovery guarantees the reformation of a wide beach and its associated protection function and touristic use, but dune response to erosive events is very different. Meanwhile, dune erosion is always very rapid and time located accretion is a process that usually takes place with low rates over a long time, from several months to years in the Andalusia Atlantic littoral [26]. Hence, the determination of coastal dune characteristics, behavior and evolution need special attention in the attempt to reduce erosive/flooding processes' impacts on natural and urbanized coasts. Several recent investigations [27,28] have identified dunes as one of the most relevant coastal ecosystems as a natural defense able to reduce flood sensitivity/vulnerability and hence, dunes' maintenance/emplacement has been considered as an effective coastal protection measure included among possible "Disaster Risk Reduction" (DRR) strategies in several European directives [28–32]. In fact, dune ridges protect large sections of low-lying coasts against flooding during extreme storms [9,33,34], and hence, lateral dune continuity and level of fragmentation are extremely relevant [35–38].

This paper is the first one that deals with the characterization and evolution of all dune systems along the Mediterranean coast of Andalusia (South of Spain), and this is a first step to assess their great ecological value, sensitivity and relevance in coastal flood protection. Different dune types have been mapped as well as their level of fragmentation (by means of a new index proposed in this paper) and present human occupation and evolution from 1977 to 2016. Results obtained are of relevance to enhance the general database on dune characteristics along the Mediterranean coast of Andalusia and the possibility of use ecosystem-based solutions in coastal protection along with, or instead of, traditional engineering approaches [27,28].

2. Study Area

Located in South Spain, the Mediterranean coast of Andalusia administratively belongs to the provinces of Cádiz, Málaga, Granada and Almería (Figure 1). It has a prevailing rectilinear E-W outline, with two NE-SW easterly facing sectors, i.e., the Gibraltar Strait and the Almería easternmost coastal sector (Figure 1). It is a micro-tidal environment (tidal range < 20 cm) with a total length of ca. 546 km, including rocky sectors (ca. 195 km) and intermediate to reflective beaches (ca. 350 km) [39], usually composed of medium to coarse dark sands and/or pebbles. Dune systems, which have a total length of ca. 76 km, are especially observed along the provinces of Cádiz and Almería (Figures 1 and 2) [25,40,41].

The Betic Range, a tectonically active mountain chain that, at places, reaches relevant elevations higher than 2200 m above sea level (m a.s.l.) close to the coast, determines coastal orography and morphology, forming cliffs, embayments and promontories. Several small coastal plains are especially extended at the mouth of short rivers and *ramblas* (seasonal streams) draining the chain, the most important being the Guadiaro, Guadalhorce, Guadalfeo, Adra and Andarax rivers (Figures 1 and 2). In the past decades, river basin regulation plans devoted to water management for tourist and agricultural purposes have enhanced the construction of dams and reservoirs that have reduced sediment supplies to the coast and have promoted coastal retreat in most deltas [39,42–44].

Large coastal towns are Málaga (>500,000 inhabitants), Almería (ca. 200,000 inhabitants) and the tourist towns along the western part of Costa del Sol area, namely Marbella (150,000 inhabitants), Fuengirola (80,000) and Torremolinos (70,000). Málaga is the province that has experienced the most important coastal occupation, in particular due to the construction of structures related to national and international tourism [45]. Main commercial ports are located at Almería, Algeciras, Cádiz and Málaga, and several marinas at Costa del Sol [46–48].

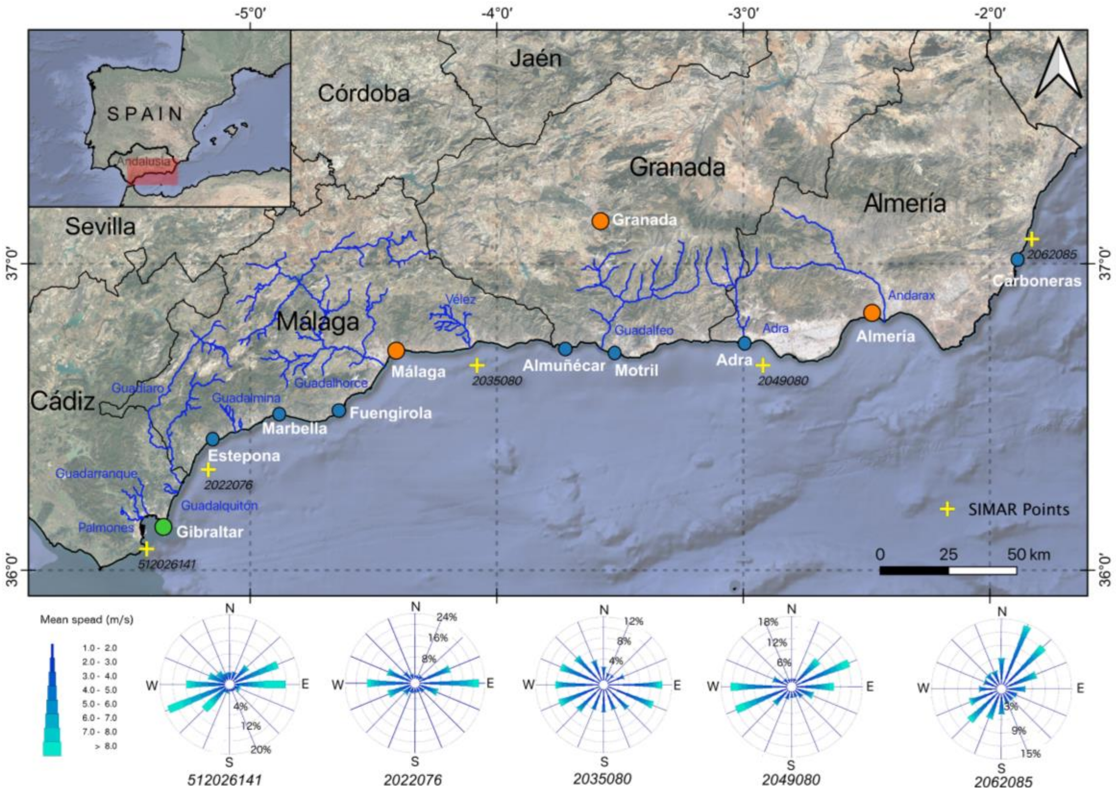

Figure 1. Location of the study area and average wind speed roses at 5 points of SIMAR (SImulación MARina), from the wave reanalysis model by Puertos del Estado (PdE).

Concerning weather characteristics, the provinces of Cádiz, Málaga and Granada have a Mediterranean climate with sub-tropical characteristics, with coastal orientation and the Betic Chain favoring average annual temperature of ca. 13 °C and, in July and August, the average is 19 °C. Annual rainfall ranges from 400 to 900 mm, with the most abundant values observed at Gibraltar Strait. The province of Almería presents a Mediterranean climate with sub-desert characteristics, i.e., rainfall is extremely limited (ca. 200 mm/year), average annual temperature is 21 °C and in July–August, temperature is 26 °C [49].

The coast is generally exposed to winds blowing from E to W and from NNE to SW in the easternmost part of Andalusia (i.e., at Carboneras, Figure 1), with minimum and maximum velocities ranging from 0.4 to 9.0 m/s [50]. The wave climate and storm energy are very variable [13,50]: the coast of Cádiz province is mainly affected by eastern storms, Málaga, Granada and (partially) Almería provinces are exposed both to western and eastern storms, whereas the easternmost portion of the coast of Almería province is primarily exposed to eastern storms [13,50].

The mean duration of storm events ranges from 0.9 to 7.0 days, despite their intensity. Waves show a clear seasonal behavior with storm conditions being recorded during November–March, i.e., the winter season [42,50,51], with mean values of significant wave height that reaches 5.18 m in extreme storm conditions [50]. A storm characterization for the studied area was developed by Molina et al. [50], using the Energy Flux parameter to classify storm events into five classes, from weak (Class I) to extreme (Class V). They observed that the most energetic area was the central part of the Mediterranean Andalusian coast, i.e., the coast between Málaga and Almería provinces, highly exposed to storms belonging to all classes, and specially to most energetic ones that can have a great impact on both natural and urbanized sectors [50].

Due to shoreline orientation, predominant easterly winds (Figure 1) and associated storm waves give rise to sea wave conditions generating a prevailing westward littoral drift [51]; meanwhile, an opposing drift is particularly important in certain coastal sectors and/or periods [42,50].

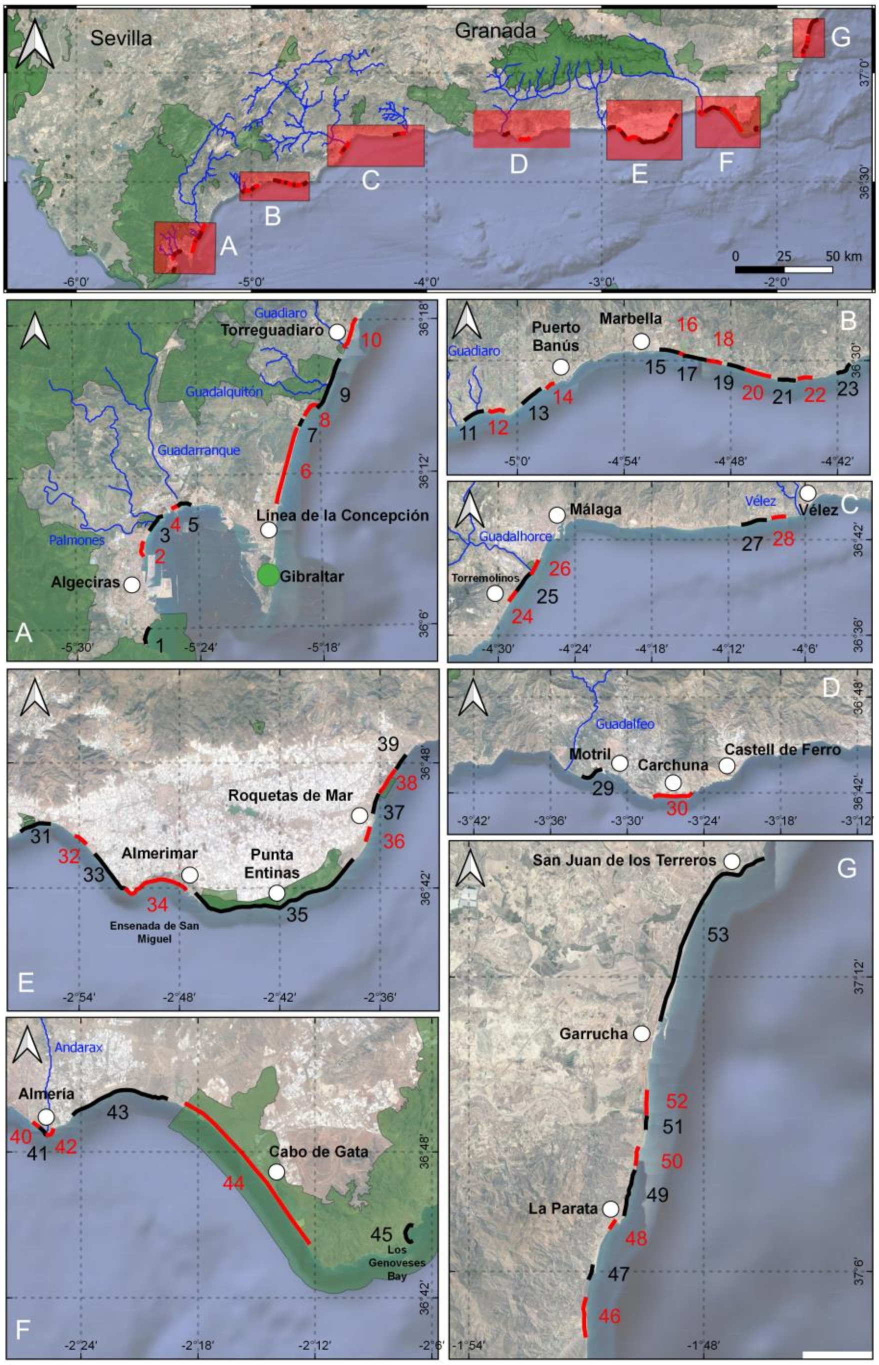

Figure 2. Location of the studied dune systems. Natural protected areas are in green. The capital letters A–G in the main subplot refer to the zoomed areas in the other subplots.

3. Materials and Methods

Aerial orthophotographs dated 1977, 2001 and 2016 (Table 1) were used to map different dune systems, and to quantify their surface evolution, level of fragmentation and the progression of human occupation. Aerial orthophotographs were obtained from the Web Map Services (WMS) of the Open Geospatial Consortium (OGC) of the Andalusia Regional Administration [52].

Table 1. Aerial orthophotos used [52], 2001 and 2016 orthophotos are from Plan Nacional de Ortofotografía Aérea (PNOA).

Year	Scale	Spatial Resolution(m)	Flight
1977	1:5000	0.5	Iryda flight 1977
2001	1:10,000	0.5	PNOA 2001
2016	1:5000	0.25	PNOA 2016

Orthophotographs were elaborated within a GIS project (reference system WGS84–UTM 30N) by means of the ArcMap application from ArcGIS Desktop, Release 10 Redlands, CA: Environmental Systems Research Institute. All dune systems with a minimum longshore seaward front of 100 m in length were mapped, summing a total of ca. 106 km in 1977, including 53 systems (Figure 2). Within each system, three dune environments were mapped according to Sanjaume Saumel and Gracia Prieto [25], who defined, on the base of the most important coastal dune habitats in Spain [53], i.e., (i) embryo and mobile dunes (Type I), (ii) grass-fixed dunes (Type II) and (iii) stabilized dunes (Type III). Coastal dune habitats described at the study area corresponded to the Sites of Community Importance (SCI's) of the European Commission Habitat Directive listed in Table 2.

Table 2. Sites of Community Importance (SCI's) described in the study area and their correspondence with the dune typologies mapped in this work [54].

Sites of Community Importance (SCI's)	Classification
2110—Embryonic shifting dunes 2120—Shifting dunes along the shoreline with *Ammophila arenaria* ("white dunes")	I—Embryo and mobile dunes
2130—Fixed coastal dunes with herbaceous vegetation ("grey dunes") 2150—Atlantic decalcified fixed dunes 2210—*Crucianellion maritimae* fixed beach dunes 2230—*Malcolmietalia* dune grasslands 2240—*Brachyopodietalia* dune grasslands with annuals	II—Grass-fixed dunes
2250—Coastal dunes with *Juniperus* spp. 2260—*Cisto-Lavanduletalia* dune sclerophyllous scrubs 2270—Wooded dunes with *Pinus pinea* and/or *Pinus pinaster*	III—Stabilized dunes

The first group (Type I) comprises embryo and mobile dunes, which are the first band of colonizing vegetation and the first important continuous sandy relief. The second group (Type II) comprises grass-fixed dunes, which develop in a more stable soil and form a more continuous plant cover based on lawns or even some woody plants and bushes. The third group (Type III) comprises the stabilized dunes, is the innermost band of the dune system, and is made up of fully fixed vegetated dunes, with structured and stabilized soils. Its vegetation evolves into forests and a dense and diverse vegetation cover is developed.

The main characteristics used to distinguish between each dune type was the color and vegetation density, so that as systems evolve, color darkens and plant density increases, i.e., embryo and mobile dunes are often called "white" or "yellow" dunes and fixed dunes are called "grey" dunes because of their characteristic color. Díez-Garretas et al. [55], in their study on spatio-temporal changes of coastal ecosystems in Southern Iberian Peninsula (Spain), used a similar classification, taking into account the phytosociological plant communities present at the location studied and the habitat code. They related the habitat code with the ecological units present in their study, including mobile dunes, semi-fixed dunes and stable dunes. Pintó et al. [56] recognized the distinct habitats present in their study area and related them to the sea-to-land ecological gradient and the Habitats of Community Interest. Their classification is more detailed, attending more to morphological than ecological criteria.

The position, evolution and fragmentation of the dune toe position was also reconstructed, and the latter aspect favors dune sensitivity to storms' impacts [40,57–59]. Further, the total surface of each one of the 53 system and dunes' surfaces occupied by human structures/interventions was calculated.

The proxy used to map the dune toe was the seaward dune vegetation line, manually detected by a GIS operator [13,39,48,60–62]. To calculate dune fragmentation, a database was obtained for each dune system containing three shape files: the first file included a polyline of the total length of the dune toe line, the second file included the length of all breaks observed along the dune toe line of each system, and a third file, which was the result of the differences between the two previous shape files. The level of fragmentation was calculated by determining the ratio between the length of all breaks and the whole dune toe length at each dune system and year. These values were normalized according to a constant length of 100 m by dividing the total length of all breaks in the shorefront dune toe ("l") by the entire length of the dune toe ("L"):

$$F = \frac{l}{L} \tag{1}$$

The F Index is a new index proposed for the first time in this paper vaguely based on the coefficient of infrastructural impact "K" [63]. It was applied along unitary coastal sectors of 100 m in length in order to reduce the importance of dune seaward length. The F Index was calculated for the systems present in all investigated periods (37 out of 53 systems), that is, the dune systems that disappeared in the second period were not taken into account to avoid interpreting a decrease in fragmentation when, in the reality, the entire system was lost. Values of the F Index used to express the fragmentation level were classified into three classes using the Natural Breaks Function [64], from Class 1 ("Null or very low fragmentation", $0.00 < F < 0.06$), Class 2 ("Medium fragmentation", $0.06 < F < 0.16$) to Class 3 ("High fragmentation", $0.16 < F < 0.41$).

4. Results

4.1. Dune Systems' Distribution and Evolution

Of the 53 dune systems investigated in the Mediterranean coast of Andalusia, 10 belonged to natural protected areas and, from an administrative point of view, 10 were located in Cádiz province, 18 in Málaga, 2 in Granada and 23 in Almería province (Figure 2, Appendix A Table A1). In Cádiz province, dune systems were equally divided between the Algeciras Bay and an exposed, rectilinear shoreline, including both natural and urbanized areas (Figure 2A). In Málaga province, they were mainly located at the westernmost part of the littoral (Figure 2B), and south of the Guadalhorce river mouth and west of the Vélez river delta (Figure 2C). In Granada province, only 2 dune systems were observed, located in an area updrift of the port of Motril and at Carchuna (Figure 2C). In Almería province, 5 systems were located close to delta areas, namely at Adra and, especially, at Andarax river delta (Figure 2E,F), and 8 were located at rectilinear coastal sectors limited by ports, promontories or river deltas (Figure 2E–G). Very developed dune systems were located in the relevant protected area of Punta Entinas-El Sabinar (Figure 2E); meanwhile, several systems were located at the easternmost area of Almería province and the most relevant system was observed in a large pocket beach (Los Genoveses) (Figure 2F,G).

A total of 15 dune systems disappeared from 1977 to 2016, 7 of them located in Málaga, 7 in Almería and 1 in Cádiz provinces. Dune systems' extension was changing during the periods studied without a clear trend; meanwhile, a clear decrease in size was evident for the three largest dune systems (Appendix A Table A2). Surfaces of "Embryo and mobile dunes" (Type I), "Grass-fixed dunes" (Type II) and "Stabilized dunes" (Type III) were calculated within each one of the 53 dune systems and per each time span considered. The progressive decrease of typologies I and II was observed, meanwhile, "Stabilized dunes" (Type III) recorded a decrease from 1977 to 2001 and a slight increase from 2001 to 2016 (Figure 3).

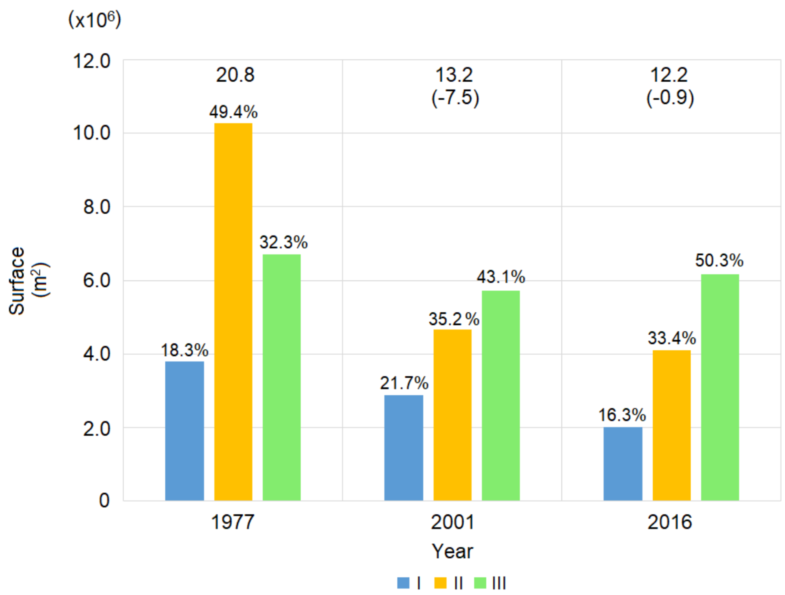

Figure 3. Yearly surface values of each dune typology, i.e., "Embryo and mobile dunes" (Type I), "Grass-fixed dunes" (Type II) and "Stabilized dunes" (Type III). Value on top represents the surface of all dune typologies and in brackets the surface that was lost with respect to the previous year is reported.

The distribution of the different dune typologies within each dune system varied during the studied period (Figure 4). At all provinces (but Cádiz), a reduction of all dune typologies was recorded during the 1977–2001 period; meanwhile, a decrease in all provinces (but Almería) of types I and III and an increase of Type II was recorded in the 2001–2016 period (Figure 4).

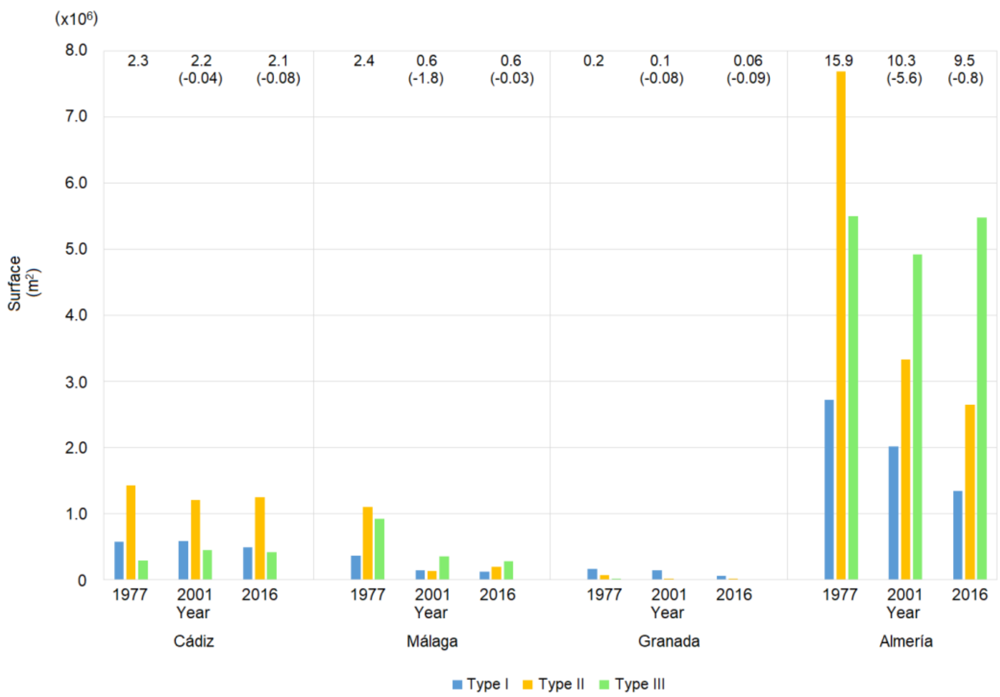

Figure 4. Distribution of dune surface typologies, i.e., "Embryo and mobile dunes" (Type I), "Grass-fixed dunes" (Type II) and "Stabilized dunes" (Type III), by province during the studied periods. The value on top represents the sum of dune surfaces (in m^2) and in brackets the value of lost dune surface with respect to the previous year is presented.

The comparison of the total amount of eroded/accreted surfaces recorded in each system for the periods 1977–2001, 2001–2016 and 1977–2016 showed a clear negative balance for 49 systems and a positive one for 4 systems (Figure 3). The dune systems that showed a positive balance were located at Playa del Rinconcillo (System no. 2, 38,884.4 m^2), at the Guadarranque (no. 5, 19,262.8 m^2) and at the Guadalquitón (no. 9, 260,531.7 m^2) rivers' mouths in Cádiz province (Figure 2A), and in the Albufera de Adra (no. 31, 6708.5 m^2), a natural protected area at the Adra river delta (Almería province, Figures 1 and 2E). The most eroded dune systems were located at Ensenada de San Miguel (System no. 34, −557,765.0 m^2), Punta Entinas–El Sabinar (no. 35, −4,166,157.9 m^2) and Vera (no. 53, −567,841.2 m^2) areas, in Almería province.

Comparing the evolution of each system in the 1977–2001 and 2001–2016 periods, it was observed that 3 systems recorded accretion and 23 erosion in both periods, and the others showed different behaviors. Regarding the distribution of these records, the 3 accreting dune systems were located in Cádiz province and most of the dune systems that recorded erosion or disappeared were located in Málaga province, and dunes in Granada province presented erosion for both periods. In Almería province, the systems located in Almería Bay and at the easternmost part of the province presented a negative trend for both periods, and the group located from the Adra river delta to Ensenada de San Miguel presented erosion and then accretion. The two dune systems located at Roquetas de Mar disappeared in 2001–2016 (Figures 2E and 5).

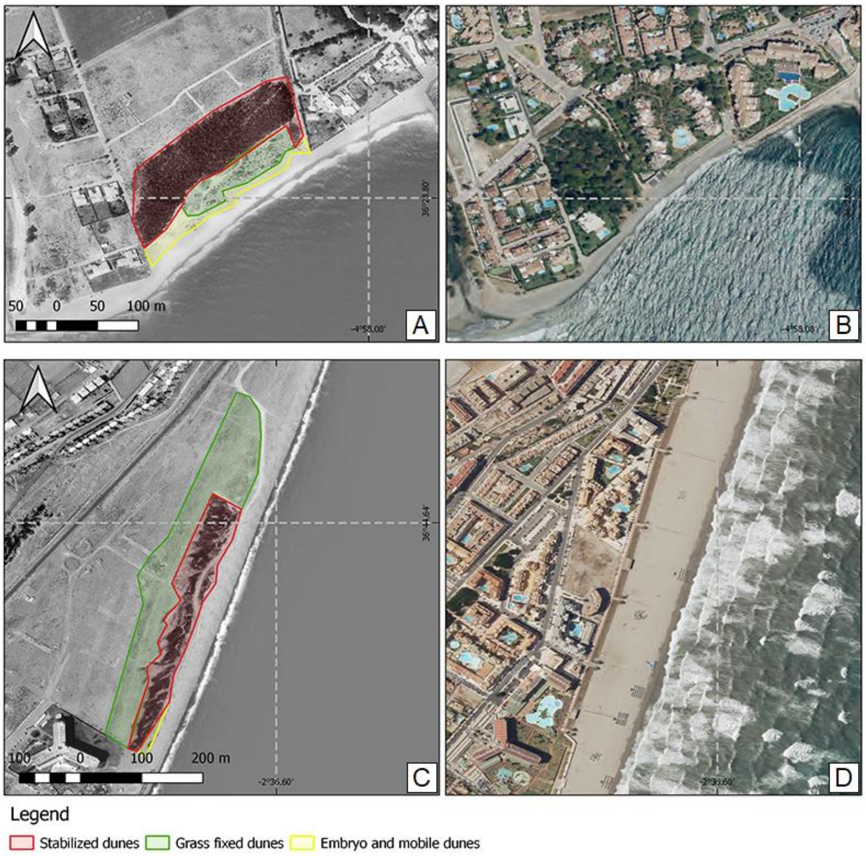

Figure 5. Dune systems urbanized in Málaga and Almería provinces. System no. 14 Playa Nueva Andalucía in 1977 (**A**) and 2016 (**B**), and System no. 36 Playa de Roquetas in 1977 (**C**) and 2016 (**D**).

4.2. Anthropic Occupation Evolution

Surfaces occupied by human structures/interventions were calculated within each one and per each year of the 53 dune systems (Figure 6). The greatest increase (ca. 2.3×10^6 m^2) was observed in the 1977–2001 period.

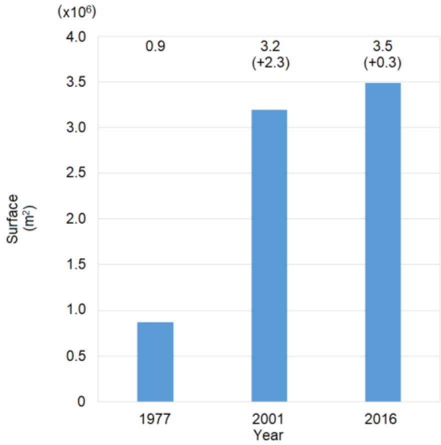

Figure 6. Evolution of the surfaces occupied by anthropic interventions during the studied periods. The number on top of histograms represents the total value of surface occupied, and in brackets shows the increment recorded among successive periods.

Comparing the evolution of human occupation of each system in the 1977–2001 and 2001–2016 periods, it was observed that 21 out of 53 systems presented an increase of human occupation in both periods and 2 systems a decrease due to the removal of small installations (Figure 7). Further, 4 systems recorded an increase in the first period and a decrease in the second due to the urbanization of a part of the dune system, and the removal of small installations, and the opposite was true for 1 system due to coastal erosion problems since the shoreline retreatment forced the removal of human structures (Figure 7).

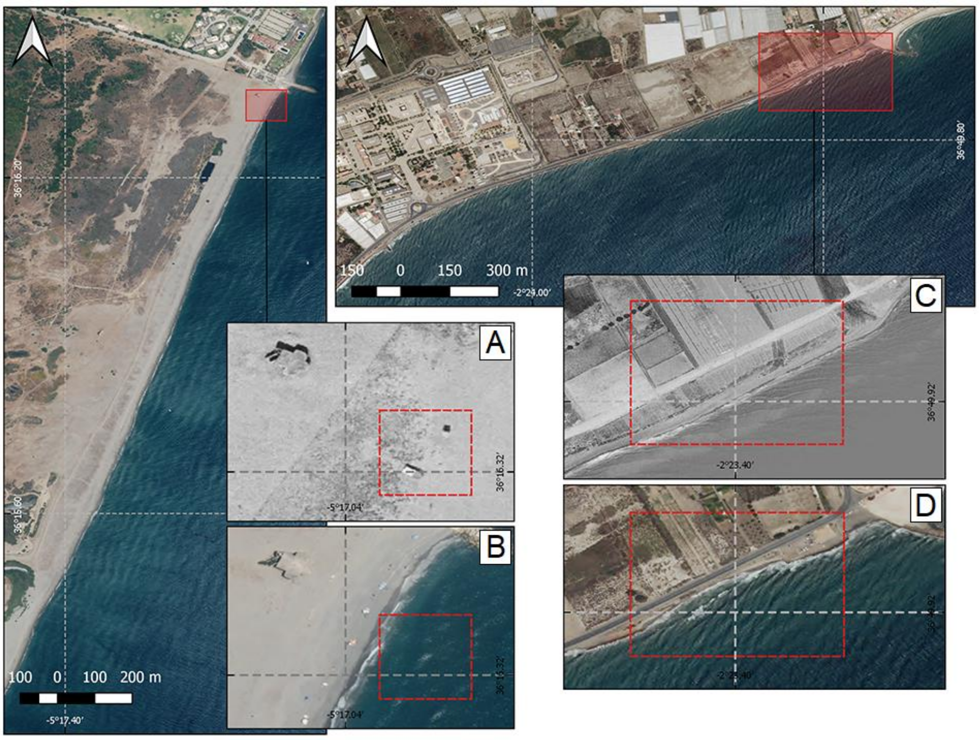

Figure 7. Removal of small constructions in Cádiz and croplands in Almería provinces. System no. 9 Guadalquitón 1977 (**A**), 2016 (**B**), with a decrease of the occupation area of 112.90 m^2 in 1977–2001 and 263.31 m^2 in 2001–2016. System no. 43 Las Algaidas-Las Marinas in 1977 (**C**) and 2016 (**D**), with a decrease of 117.14 m^2 in 1977–2001 and 184.07 m^2 in 2001–2016.

At places in System no. 2 Playa del Rinconcillo (in Cádiz province), the increase of dune surface and anthropic occupation was linked to the formation of a new beach at the northern side of the port of Algeciras (Figure 8). Summing up, the decrease of occupation was essentially due to the removal of buildings and was always very small.

Figure 8. System no. 2 Playa del Rinconcillo registered an increase of dune surface of 732.26 m^2 in 2001–2016. (**A**) 1977, (**B**) 2001 and (**C**) 2016.

4.3. Dune Fragmentation

Analysis of the dune toe fragmentation was carried out for such systems (37 out of 53) that were observed in all investigated periods and a general increase of fragmentation was evident (Figure 9), confirming the trend observed for the evolution of human occupation.

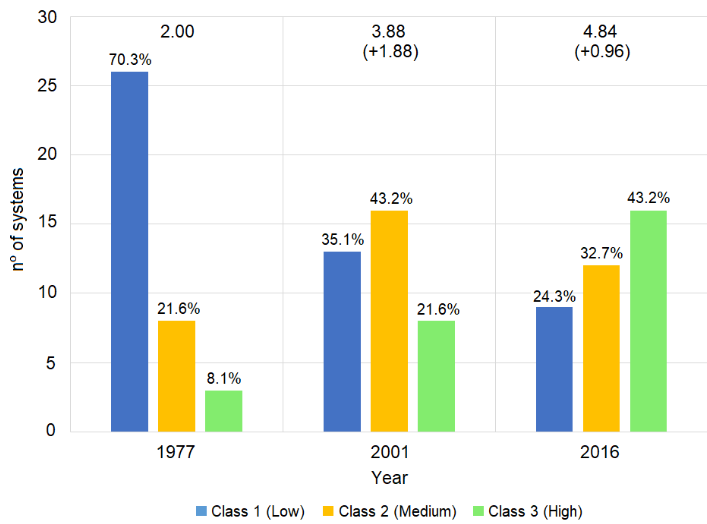

Figure 9. Fragmentation Index. The number on top of histograms represents the total value of fragmentation per year and in brackets is the increment recorded among successive periods.

Considering the 1977–2016 timespan, 23 dune systems presented an increase of fragmentation, 3 systems recorded a decrease (they were located in erosive coastal sectors within natural protected areas) and 11 presented no variations. The two systems that recorded a major increment of fragmentation were Punta del Río (no. 41), in Almería province, and Playa de las Chapas (no. 20), in Málaga province, with an increase of +0.25 and +0.22, respectively. Conversely, the two systems that recorded the major decrease of fragmentation were Playa de Río Real (no. 16) and Playa de la Misericordia (no. 26) in Málaga province, with a decrease of −0.20 and −0.09, respectively. Comparing the evolution of fragmentation at each dune system in the 1977–2001 and 2001–2016 periods, it was observed that only 7 out of 23 presented an increase of the fragmentation at both periods, in general due to coastal zone urbanization (Figure 10A–C). Only 1 dune system showed a decrease of fragmentation (no. 16) (Figure 10D–F), and 8 presented no variation in both periods.

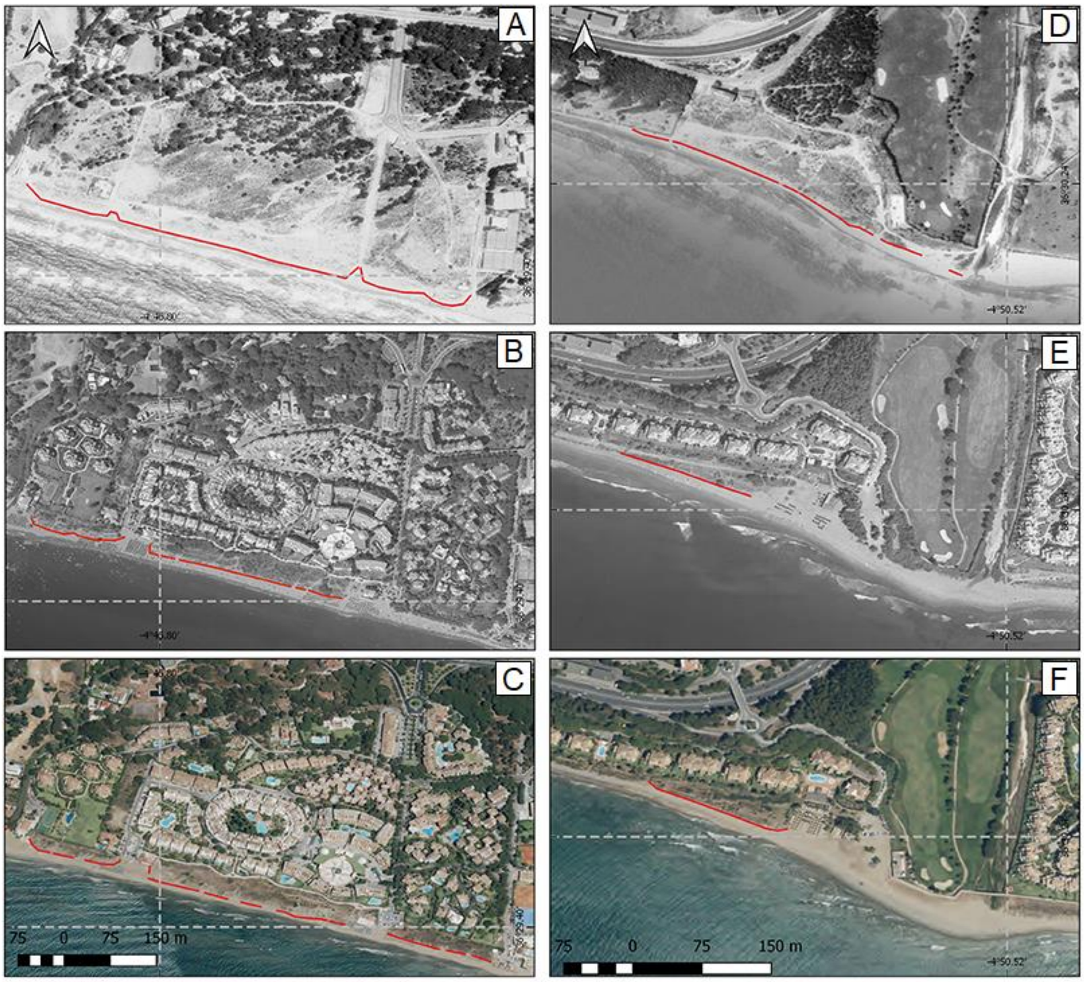

Figure 10. System no. 20 Playa de las Chapas, in Málaga province, recorded an increase of fragmentation due to the increment of anthropic pressure, changing from (**A**) Class 1 (F = 0.003) in 1977 to (**B**) Class 2 (F = 0.12) in 2001 and to (**C**) Class 3 (F = 0.22) in 2016. System no. 16 Playa de Río Real, in Málaga province, where the modification of the coastal zone and the emplacement of a touristic urbanization produced the destruction of the already fragmented dune system. Remnant dune systems presented a lower Fragmentation Index, changing from (**D**) Class 3 (F = 0.20) in 1977 to (**E**) Class 2 (F = 0.15) in 2001 and to (**F**) Class 1 (F = 0.0) in 2016. Red line represents dune toe position.

Other dune systems presented a different behavior at both periods: 4 systems recorded an increase in the first period and a decrease in the second and the opposite was true for 1 system (Figure 11). In general, the increase in fragmentation occurred along with the increase of urbanization and anthropic pressure, while the opposite was observed in natural protected areas. At places where systems were already fragmented, their erosion implied a reduction in their fragmentation since: (i) very fragmented sectors often disappeared and the remaining ones presented low fragmentation (Figure 10D–F and Figure 11A,B) and (ii) coastal erosion produced the loss of the most fragmented part of dune toe (Figure 11B,C). An increase of fragmentation in 7 dune systems was due to the increment of erosion processes and/or the formation of pedestrian pathways.

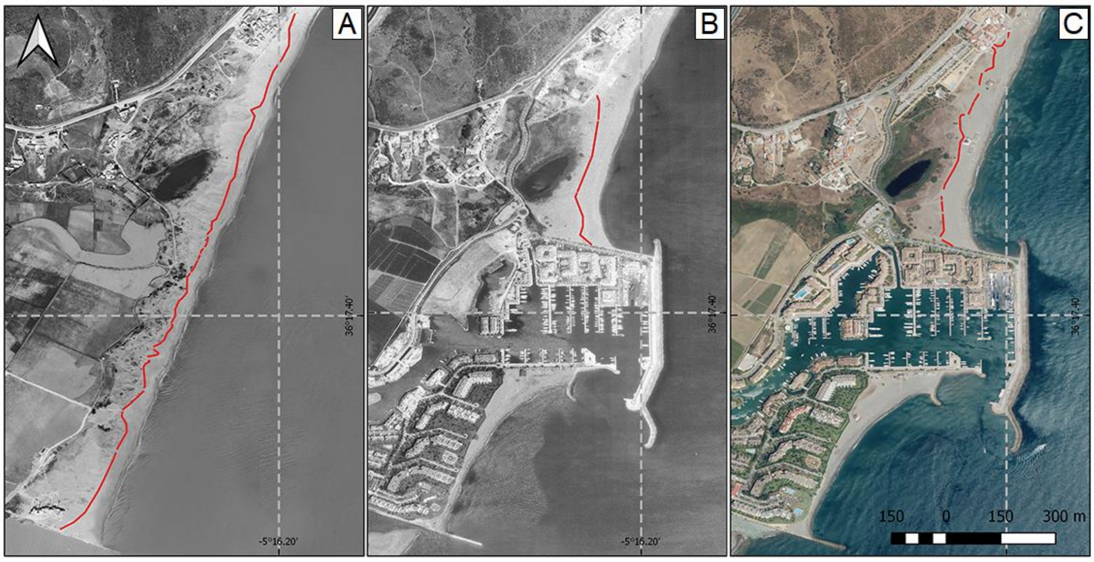

Figure 11. System no. 10 Torreguadiaro (in Cádiz province) recorded a slight decrease of fragmentation in the 1977–2001 period and an increase in the 2001–2016 period due to the reduction of a high fragmented dune sector that was replaced by the port structure. The dune system located in front of the natural protected Torreguadiaro Lagoon was not modified. In the 2001–2016 period, the growth of new dunes at the northern part of the system and the increase of pathways at both sides of it was observed. This resulted in a decrease of fragmentation that changed from (**A**) Class 1 (F = 0.08) in 1977 to (**B**) Class 2 (F = 0.03) in 2001 and an increase of fragmentation to (**C**) Class 3 (F = 0.20) in 2016. Red line represents dune toe position.

5. Discussion

5.1. Erosional Dune Systems

Erosion or complete disappearance of dune systems can be produced by human activities or natural processes [65–67]. Anthropic impacts were related to: (i) urban developments, mainly due to the coastal tourist demand, and the associated opening of pathways on dune ridges, which was especially evident in Málaga province (Figure 5) [41,46,48,55,68], (ii) dunes' occupation due to the demand for agricultural uses, as observed at different locations in Andalusia, and reported by References [67,69–73] in other Mediterranean Spanish areas (in Catalonia, [56]) or on the Mediterranean coast of Morocco [74] and (iii) the decrease of sediments' inputs to coastal environments due to the construction of ports and harbors, as observed along the study area by Malvárez et al. [46] and Manno et al. [48], and the reduction of the sedimentary load of rivers due to the construction of dams in river basins, especially in Málaga and Almería provinces [43,46,75], also observed in other Mediterranean rivers, e.g., for the Ebro [76] and the Arno [77] rivers.

Among natural processes, there are the impacts of chronic erosion processes and of extreme storms, the impacts of which are often enhanced by climatic change-related processes, e.g., an increase of storm intensity and frequency and Sea Level Rise [11,35,37,67,78–83]. Specifically, for the studied area, storm characterization was described by Guisado et al. [42] and Molina et al. [50]; meanwhile, it seems that Sea Level Rise is not relevant at the studied area [84–86].

Of the 53 dune systems studied, all but 4 recorded a reduction of their surface, or even disappeared, and this was especially evident where the systems were affected by hard human interventions [41,55,68–73] and, secondarily, by shoreline erosion [71,87,88]. The greatest loss of dune surface was recorded in the 1977–2001 period due to the massive urban occupation of coastal areas, although in the 2001–2016 period, a decrease in the loss of dunes' surfaces was observed because the main causes of their destruction recorded in the previous period partially ceased. Cases of disappearance due to urban occupation were still observed, especially in Málaga province [41], but the anthropic pressure derived from the tourist use of beaches and the decrease in river contributions were not so evident as in the 1977–2001 period [46,68–73].

The loss of dune surface was at places and times linked to the progressive fragmentation of the dune toe (i.e., the increase of dune discontinuity), which is a factor that has to be considered in order to estimate coastal and dune vulnerability [40,57–59] since a fragmented dune system is more vulnerable to temporary flooding and hence, it is less effective against storm surges [35,40,58,59,89–91]. In this study, the most fragmented (and hence susceptible sectors) were observed at the west side of the Andarax river delta in Almería province (no. 41, Figures 1 and 2), which was the most fragmented dune system located in a natural area (Appendix A Table A2) and the system at Las Chapas beach in Málaga province (no. 20, Figures 1, 2 and 10), located in a strongly developed urban area.

At almost all sectors, dunes' fragmentation was mainly due to the opening of pathways and to their progressive expansion due to marine- and wind-induced erosion processes, as also observed by Gracia et al. [40], Pintó et al. [56], Rangel-Buitrago and Anfuso [58] and Rizzo et al. [59]. Due to the accuracy of the orthophotos used in this study, dune discontinuities caused by overwash processes were only detected at few places (Figure 12). Such processes were distinguished from other types of fragmentation due to the absence of vegetation at the areas presenting the characteristic shape of a washover fan; meanwhile, pathways showed narrow rectilinear shapes.

Summing up, the majority of the dune systems that showed an aerial decrease were affected by anthropic factors, highlighting the importance of urban and agricultural occupations that were very relevant in Málaga and Almería administrative districts.

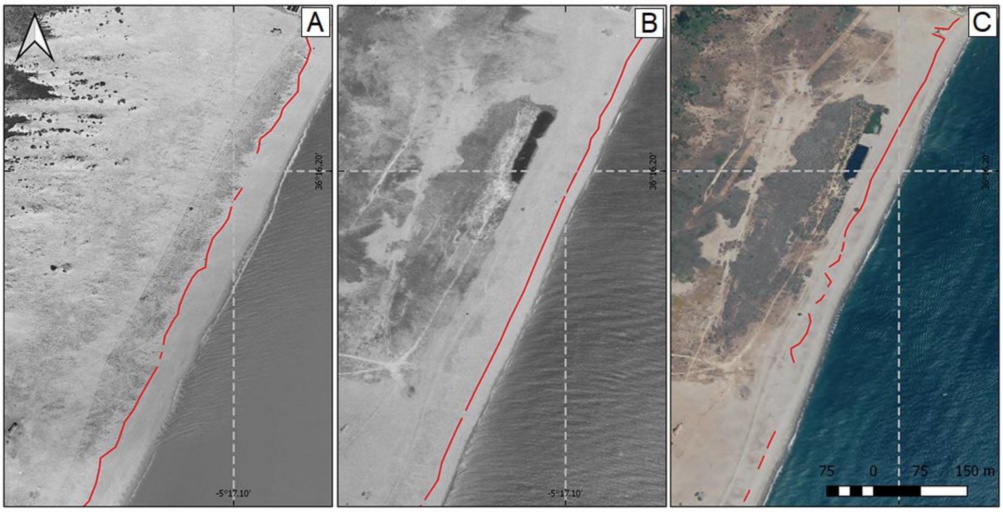

Figure 12. Details of the central area of System no. 9 Guadalquitón (Cádiz province), where washover fans and pathways were observed. Red line represents dune toe position. (**A**) 1977, (**B**) 2001 and (**C**) 2016.

5.2. Accretional Dune Systems

Conditions for dune formation and development were discussed by a large number of authors who agree that the temporal variation of the sedimentary contribution and the wind regimes are the most important factors controlling the beach–dune system relationship [65,92–95].

The increase of systems located in the Bay of Algeciras (Figure 2A) was associated with the sedimentation processes recorded in such beaches [96] that receive the sediment supplies of the Palmones and Guadarranque rivers [73]. Such beaches are located next to two large coastal protection structures that promote sedimentation processes. In the case of the system observed at El Rinconcillo in 2001, it began to form after the expansion of the port of Algeciras (Figure 8). Instead, systems at Guadalquitón and Albufera de Adra (Figure 2) were located in areas that registered an important erosion [39,96] and a significant human occupation linked to urban development in the case of Guadalquitón and intense agricultural occupation in Albufera de Adra. The Guadalquitón dune system recorded the highest increase during the 1977–2001 period, and it was due to the degradation of the vegetation that facilitated the inland dune migration. The formation of large mobile dunes in this area was also due to strong east winds (Figure 1), especially on the east-facing beaches [73]. In the case of the Albufera de Adra system, an important loss of dune surface in the 1977–2001 period was caused by shoreline erosion and the significant anthropic pressure (intense agricultural activities) [39,43,96]; however, the sedimentation produced at the north side of the system [39,96] supported the development of mobile dunes.

5.3. Dune Types' Evolution

Several dune systems studied in this paper were described by different authors [41,55,68–73,87,88], but none of them provided a description of all dune systems along the whole Mediterranean coast of Andalusia.

Unlike tidal-influenced coasts, in which the sedimentary contribution can be obtained through periodic exposure of the intertidal plain, on micro-tidal coasts such as the Mediterranean one, the beach itself is the main source of sedimentary contribution to the dune systems. In addition, when the beaches are composed of gravels, as is the case of many beaches of Málaga and Almería, it is more difficult to ascertain the source of sandy sediment necessary for the dune systems, so the rivers become the main sediment suppliers of the system [72]. As stated before, river systems at the Mediterranean coast of Andalusia are mostly short or seasonal streams and, in general, provide a coarse grain size on the beaches. Further, the accentuated relief observed nearby the coast and the presence of reflective beaches represent great limitations for the development of coastal dunes [72].

Further points to be taken into consideration are the intensity and direction of predominant winds that, to be effective in dune formation, should be shore normal. Due to their coastal orientation, which is normal to predominant winds, the provinces of Cadiz (especially) and Almeria constitute areas favorable for dune formation. According to Bardají et al. [72] and Gracia et al. [73], the central part of the Andalusia coastline is parallel to predominant winds that give rise to a relevant longshore transport that supplies different dune systems, e.g., at Artola-Cabopino [72,88].

Analyzing the evolution of each dune typology is of relevance since each typology represents a clear evolution state from Embryo and mobile dunes (Type I) to Stabilized dunes (Type III) [65,92]. The increment over the 1977–2016 period of the Stabilized dunes (Type III) (Figure 3) was due to the progressive evolution of Grass-fixed dunes (Type II), a natural process described by Hesp [65,92].

Surface variations of the different types of dunes' systems were relatively homogeneous (Figure 4). With the exception of the province of Cádiz, the rest of the provinces showed a decrease of the three types of dunes in the first period and, in the second period, a decrease of types I and III and an increase of Type II in all provinces except Almería. The general decrease recorded in the period 1977–2001 was mainly due to urban occupation, intensive agricultural exploitation and the extraction of sand—such activities were not regulated until the approval of the Coastal Law in 1988 [41,46,47,55,68–73]. Dune destruction was especially evident in Málaga and Almería provinces, where entire dune systems disappeared: in Málaga province, a total surface of 1,766,711 m^2 was lost, of which ca. 1×10^6 m^2 were Type II dunes and ca. 600,000 m^2 were Type III dunes, and in Almería, ca. 56,300,000 m^2 of dune surface was lost, of which ca. 4,360,000 m^2 were Type II dunes. Some examples of papers that quantified the loss of dune surfaces in specific areas were by Viciana Martínez-Lage [71], who quantified a loss of 262 ha of dunes in Punta Entinas–El Sabinar, in Almería province, due to sand extractions, or Gómez Zotano [41], who quantified a reduction of 44.5% of the dune surface in Saladillo area, in Málaga province, during the 1956–2007 period.

The increase, in the 2001–2016 period, of the Type II in Málaga province was linked to the degradation of Type III dunes, especially evident in an area west of Marbella (Figure 2B) that was greatly impacted by urban developments, a quite common trend in Málaga province [41,46,47]. The increase of Type III in Almería was due to the stabilization of Type II dunes, especially in the area from Albufera de Adra to Almerimar and at Cabo de Gata (Figure 2E,F), which are areas where the shoreline is stable [39]. Overall, in Cádiz province, a slight increase of Type III was observed, and the other dunes' types recorded small variations (Figure 4). Such behavior was due to the low human pressure, the stable or even accreting conditions of the area [39,96] and the action of strong east winds (Figure 1) that favored dunes' growth and mobility [73].

6. Conclusions

This study analyzed the evolution of the dune systems along the Mediterranean coast of Andalusia, focusing on their characterization, level of fragmentation and anthropic occupation, for the 1977–2001 and 2001–2016 periods. Within a GIS project, there were 53 dune systems mapped that summed a total length of ca. 106 km in 1977 and ca. 76 km in 2001 and 2016.

Of the 53 dune systems, all but 4 recorded a reduction of their surface, or even disappeared, and this was especially evident in 1977–2001 when dune systems were affected by hard human interventions, such as the emplacement of buildings and touristic constructions, especially at Málaga province, and agricultural expansion at Almería province, and secondarily, at places by shoreline erosion processes.

Dunes' loss was at places and times linked to the progressive fragmentation of the dune toe, mainly due to the opening of pathways and to their progressive expansion due to marine- and wind-induced erosion processes. An increase of dunes' surface was observed in both natural and anthropic areas in Cádiz and Almería provinces, in accreting and stable beaches, usually on the updrift side of ports or due to strong east winds on the east-facing beaches.

Concerning the evolution of the Embryo and mobile dunes (Type I), Grass-fixed dunes (Type II) and Stabilized dunes (Type III), most of the provinces showed a decrease of the three types of dunes in the 1977–2001 period and, in the 2001–2016 period, a decrease of types I and III and an increase of Type II in all provinces. The increase of Type II dunes was linked to the degradation of Type III, observed in the 2001–2016 period at very anthropized areas; meanwhile, an increase of Type III was observed in stable and accreting areas.

Results obtained could be used to enhance the general database on dune characteristics along the Mediterranean coast of Andalusia and the possibility of utilizing ecosystem-based solutions in coastal protection, along with, or instead of, measures based on traditional engineering approaches. The methodology used in this study could be applied in other locations with a similar database.

Author Contributions: Data curation, R.M., G.M. and C.L.R.; Formal analysis, R.M., G.M., C.L.R. and G.A.; Methodology, R.M., G.M., C.L.R. and G.A.; Software, R.M., C.L.R. and G.M.; Geological and geomorphological supervision, G.M.; Hydraulic analysis, C.L.R.; Supervision, G.A.; Writing—original draft preparation, R.M., G.M., C.L.R. and G.A.; Writing—review and editing, G.A. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Acknowledgments: This work is a contribution to the Andalusia Research Group PAI RNM-328 and to the PROPLAYAS network and has been partially developed at the Centro Andaluz de Ciencia y Tecnología Marinas (CACYTMAR), Puerto Real (Cádiz, Spain).

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Name and protection typology of each dune system and balance for the entire studied period.

System No.	Name	Protection	1977–2016 Dune Surface (m^2)	1977–2016 Occupation (m^2)	1977–2016 Fragmentation
1	Playa de Getares	Estrecho (1)	−70,477.70	41,768.39	0.16
2	Playa del Rinconcillo		38,884.38	732.26	
3	Marismas del Río Palmones	Marismas del Río Palmones (2)	−47,670.51	3352.14	0.12
4	Guadarranque W		−59,167.52	57,534.25	
5	Guadarranque E		19,262.80	2136.58	0.22
6	La Línea de la Concepción		−102,603.90	30,682.41	0.04
7	La Alcaidesa S		−3796.38	3967.45	0.03
8	La Alcaidesa N		−14,072.90	20.88	0.17
9	Guadalquitón		260,531.70	−376.21	0.09
10	Torreguadiaro	Laguna de Torreguadiaro (3)	−145,337.38	89,006.50	0.11
11	Playa del Saladillo W		−65,592.18	25,389.60	0.15
12	Playa del Saladillo E		−52,295.06	37,351.43	0.01
13	Playa de San Pedro de Alcántara		−97,452.20	28,411.01	
14	Playa Nueva Andalucía		−29,702.08	26,131.94	
15	Playa del Pinillo		−27,738.26	9490.44	0.06
16	Playa de Río Real		−16,322.02	3643.28	−0.20
17	Playa de los Monteros		−373,156.19	355,081.76	0.14
18	Playa del Alcate		−49,725.72	32,996.16	0.16
19	Playa Real de Zaragoza		−200,549.55	41,358.39	0.10
20	Playa de las Chapas		−171,835.74	152,819.73	0.22
21	Playa de Artola	Dunas de Artola (4)	−21,575.89	5068.88	0.16
22	Cabopino-Calahonda		0.00	0.00	
23	Torrenueva - Mijas		−64,545.36	64,344.35	
24	Playa de Canuela - Torremolinos		−44,014.67	970.12	
25	Playa de San Julián		−412,157.55	2085.54	0.10
26	Playa de la Misericordia	Desembocadura del Guadalhorce (2)	−98,481.69	84,116.14	−0.09
27	Arroyo de los Íberos		−54,160.94	90.78	
28	El Hornillo		−19,501.79	2698.63	
29	Playa del Poniente - Motril		−59,813.96	15,990.88	0.05
30	Carchuna		−115,558.06	38,433.86	0.00
31	Albufera de Adra	Albufera de Adra (5)	6708.50	0.00	−0.01
32	Playa de Balerma N		−17,100.05	994.82	0.01
33	Playa de Balerma S		−294,158.23	260,649.68	0.10
34	Ensenada de San Miguel		−557,765.03	259,966.94	0.06
35	Punta Entinas-El Sabinar	Punta Entinas – El Sabinar (2,5)	−4,166,157.86	239,842.20	0.03
36	Playa de Roquetas S		−65,618.01	32,255.48	
37	Playa de Roquetas N		−36,963.45	66.72	
38	Playa de los Bajos	Arrecife Barrera de Posidonia (4)	−18,995.79	408.82	−0.07
39	Playa Urbanización de Aguadulce		−14,309.26	5344.12	
40	Playa Ciudad Luminosa		−11,118.95	3916.61	

Table A1. *Cont.*

System No.	Name	Protection	1977–2016		
			Dune Surface (m^2)	Occupation (m^2)	Fragmentation
41	Punta del Río W		−2429.22	0.00	0.25
42	Punta del Río E		−8830.07	0.00	0.16
43	Las Algaidas-Las Marinas		−109,308.76	−1102.88	0.01
44	Cabo de Gata	Cabo de Gata-Níjar (1)	−395,189.20	404,678.11	0.14
45	Los Genoveses	Cabo de Gata-Níjar (1)	−31,645.57	−40.32	0.12
46	Playa de Bolmayor		−27,747.41	−301.21	0.04
47	Playa Venta del Bancal		−11,300.77	3577.15	0.08
48	Playa Cueva del Lobo		−11,748.40	4166.26	
49	El Cantal		−35,578.88	15,662.30	0.02
50	Playa del Descargador		−15,373.75	3011.05	
51	Playa de Rumina		−12,937.51	41.41	
52	Playa Marina de la Torre		−29,181.18	365.40	0.00
53	Vera		−567,841.25	233,429.88	0.10

Typologies of protection: (1) Natural Park, (2) Natural Site, (3) Special Plan for the Protection of the Physical Environment, (4) Natural Monument, (5) Natural Reserve. Fragmentation index was not calculated for periods where the dune system disappeared.

Table A2. Results obtained at each dune system.

System No.	1977			2001			2016		
	Dune Surface (m^2)	Occupation (m^2)	Fragmentation	Dune Surface (m^2)	Occupation (m^2)	Fragmentation	Dune Surface (m^2)	Occupation (m^2)	Fragmentation
1	144,188.37	9597.20	0.03	77,746.64	51,237.13	0.18	73,710.67	51,365.59	0.19
2	0.00	0.00		12,339.80	0.00		38,884.38	732.26	
3	205,724.64	3178.45	0.23	157,943.70	6516.26	0.31	158,054.13	6530.60	0.36
4	59,167.52	1633.27		0.00	59,167.52		0.00	59,167.52	
5	6316.76	1510.25	0.00	22,658.14	3717.80	0.13	25,579.56	3646.84	0.22
6	684,586.98	2295.32	0.07	719,675.84	3095.54	0.07	581,983.08	32,977.74	0.11
7	5370.58	0.00	0.00	2877.63	0.00	0.00	1574.20	3967.45	0.03
8	31,114.12	70.97	0.03	21,839.17	58.06	0.09	17,041.22	91.85	0.20
9	947,015.74	807.87	0.06	1,167,066.53	694.96	0.02	1,207,547.44	431.65	0.15
10	194,657.12	504.84	0.08	51,787.89	89,372.03	0.04	49,319.73	89,511.34	0.19
11	78,121.80	273.30	0.04	18,609.35	25,662.89	0.08	12,529.62	25,662.89	0.18
12	82,690.38	0.00	0.04	40,109.17	37,351.43	0.05	30,395.32	37,351.43	0.05
13	97,452.20	6377.47		36,487.89	22,027.47		0.00	34,788.48	
14	29,702.08	0.00		0.00	26,131.94		0.00	26,131.94	
15	39,444.19	0.00	0.04	21,835.12	5905.71	0.17	11,705.93	9490.44	0.10
16	19,307.50	0.00	0.20	2956.27	3643.28	0.15	2985.49	3643.28	0.00
17	412,867.48	0.00	0.03	38,602.94	348,097.72	0.12	39,711.29	355,081.76	0.17
18	67,942.45	0.00	0.03	6744.90	32,996.16	0.05	18,216.73	32,996.16	0.19
19	286,323.39	5333.48	0.11	82,951.01	46,657.53	0.15	85,773.84	46,691.87	0.21
20	199,167.71	1830.11	0.00	21,955.35	154,649.83	0.13	27,331.97	154,649.83	0.22
21	306,301.24	6506.44	0.00	246,613.13	11,448.04	0.22	284,725.35	11,575.32	0.16
22	0.00	0.00		4837.91	0.00		0.00	0.00	
23	64,545.36	201.01		0.00	64,545.36		0.00	64,545.36	
24	44,014.67	2722.12		0.00	3692.24		0.00	3692.24	
25	430,219.96	799.40	0.10	33,563.96	797.38	0.16	18,062.41	2884.93	0.20
26	153,324.54	0.00	0.11	63,109.77	84,116.14	0.02	54,842.86	84,116.14	0.02
27	54,160.94	635.79		0.00	726.58		0.00	726.58	
28	19,501.79	0.00		0.00	2698.63		0.00	2698.63	
29	68,178.56	1102.48	0.10	8705.37	17,108.96	0.29	8364.60	17,093.36	0.15

Table A2. *Cont.*

System No.	1977			2001			2016		
	Dune Surface (m^2)	Occupation (m^2)	Fragmentation	Dune Surface (m^2)	Occupation (m^2)	Fragmentation	Dune Surface (m^2)	Occupation (m^2)	Fragmentation
30	165,721.54	115.73	0.04	142,747.51	38,473.11	0.01	50,163.48	38,549.59	0.04
31	21,286.91	0.00	0.04	8193.76	0.00	0.05	27,995.40	0.00	0.03
32	27,651.90	39.11	0.05	9352.84	826.33	0.07	10,551.85	1033.93	0.05
33	440,474.93	701.17	0.01	125,373.21	257,051.80	0.09	146,316.70	261,350.84	0.11
34	806,346.40	5696.20	0.03	199,426.12	264,867.83	0.09	248,581.37	265,663.15	0.10
35	9,389,288.69	653,813.65	0.03	6,030,071.83	895,307.46	0.03	5,223,130.83	893,655.85	0.06
36	65,618.01	0.00		0.00	32,255.48		0.00	32,255.48	
37	36,963.45	0.00		0.00	66.72		0.00	66.72	
38	36,092.39	218.00	0.08	30,662.57	311.90	0.05	17,096.59	626.82	0.01
39	14,309.26	0.00		4399.52	3429.40		0.00	5344.12	
40	11,118.95	1182.32		0.00	5098.93		0.00	5098.93	
41	17,274.33	0.00	0.08	9693.33	0.00	0.10	14,845.11	0.00	0.08
42	16,891.37	0.00	0.03	13,529.19	0.00	0.08	8061.30	0.00	0.16
43	582,481.36	15,199.95	0.05	477,646.62	10,837.79	0.12	473,172.60	14,097.07	0.17
44	3,305,029.98	118,675.34	0.03	2,950,549.49	321,804.73	0.11	2,909,840.78	523,353.44	0.07
45	231,633.59	95.61	0.05	198,067.08	55.29	0.12	199,988.03	55.29	0.17
46	42,559.55	561.69	0.03	17,828.63	444.56	0.11	14,812.14	260.48	0.07
47	13,831.67	0.00	0.00	1729.15	3496.24	0.00	2530.90	3577.15	0.08
48	11,748.40	0.00		6694.07	697.64		0.00	4166.26	
49	45,547.32	4386.12	0.05	9285.69	15,269.76	0.01	9968.44	20,048.42	0.07
50	15,373.75	165.32		2855.83	1601.84		0.00	3176.38	
51	12,937.51	1214.63		4958.36	2923.88		0.00	1256.04	
52	29,896.87	0.00	0.00	11,900.67	365.40	0.06	715.69	365.40	0.00
53	722,709.90	21,902.89	0.03	152,125.47	240,022.68	0.06	154,868.65	255,332.76	0.13

Fragmentation index was not calculated for periods where the dune system disappeared.

References

1. Finkl, C.W.; Kruempel, C. Threats, obstacles and barriers to coastal environmental conservation: Societal perceptions and managerial positionalities that defeat sustainable development. In Proceedings of the First International Conference on Coastal Conservation and Management in the Atlantic and Mediterranean, Algarve, Portugal, 17–20 April 2005; pp. 3–28.
2. Meyer-Arendt, K.J. Grand Isle, Louisiana: A historic US Gulf Coast resort adapts to hurricanes, subsidence and sea level rise. In *Disappearing Destinations: Climate Change and Future Challenges for Coastal Tourism*; Jones, A., Phillips, M., Eds.; CAB International: Wallingford, UK, 2011; pp. 203–217, ISBN 978-1-84593-548-1.
3. Anfuso, G.; Loureiro, C.; Taaouati, M.; Smyth, T.A.G.; Jackson, D.W.T. Spatial variability of beach impact from post-tropical cyclone Katia (2011) on Northern Ireland's North coast. *Water* **2020**, *12*, 1380. [CrossRef]
4. Jones, A.; Phillips, M. *Disappearing Destinations: Climate Change and Future Challenges for Coastal Tourism*; CAB International: Wallingford, UK, 2011; ISBN 978-1-84593-548-1.
5. Cid, A.; Menéndez, M.; Castanedo, S.; Abascal, A.J.; Méndez, F.J.; Medina, R. Long-term changes in the frequency, intensity and duration of extreme storm surge events in southern Europe. *Clim. Dyn.* **2016**, *46*, 1503–1516. [CrossRef]
6. Nguyen, T.T.X.; Bonetti, J.; Rogers, K.; Woodroffe, D. Indicator-based assessment of climate-change impacts on coasts: A review of concepts, methodogical approaches and vulnerability indices. *Ocean Coast. Manag.* **2006**, *123*, 18–43. [CrossRef]
7. Wolf, J.; Woolf, D.; Bricheno, L. Impacts of climate change on storms and waves relevant to the coastal and marine environment around the UK. *MCCIP Sci. Rev.* **2020**, 132–157. [CrossRef]
8. Klein, Y.L.; Osleeb, J.P.; Viola, M.R. Tourism-generated earnings in the coastal zone: A regional analysis. *J. Coast. Res.* **2004**, *20*, 1080–1088. [CrossRef]

9. European Environmental Agency. *The Changing Faces of Europe's Coastal Areas*; Office for Official Publications of the European Communities: Bruxelles, Belgium, 2006.
10. Carter, R.W.G. *Coastal Environments*; Academic Press: San Diego, CA, USA, 1988; p. 617, ISBN 0-12-161855-2.
11. Houser, C.; Hapke, C.; Hamilton, S. Controls on coastal dune morphology, shoreline erosion and barrier island response to extreme storms. *Geomorphology* **2008**, *100*, 223–240. [CrossRef]
12. Anfuso, G.; Rangel-Buitrago, N.; Cortés-Useche, C.; Castillo, B.I.; Gracia, F. Characterization of storm events along the Gulf of Cadiz (eastern central Atlantic Ocean). *Int. J. Climatol.* **2016**, *36*, 3690–3707. [CrossRef]
13. Molina, R.; Manno, G.; Lo Re, C.; Anfuso, G.; Ciraolo, G. A Methodological Approach to Determine Sound Response Modalities to Coastal Erosion Processes in Mediterranean Andalusia (Spain). *JMSE* **2020**, *8*, 154. [CrossRef]
14. European Environement Agency. The Millennium Ecosystem Assessment. Available online: https://www.eea.europa.eu/policy-documents/the-millennium-ecosystem-assessment (accessed on 22 July 2020).
15. Mir Gual, M.; Pons, G.X.; Martín Prieto, J.A.; Rodríguez Perea, A. A critical view of the blue flag beaches in Spain using environmental variables. *Ocean Coast. Manag.* **2015**, *105*, 106–115. [CrossRef]
16. Semeoshenkova, V.; Newton, A. Overview of erosion and beach quality issues in three southern European countries: Portugal, Spain and Italy. *Ocean Coast. Manag.* **2016**, *118*, 12–21. [CrossRef]
17. Anfuso, G.; Williams, A.T.; Martínez, G.C.; Botero, C.; Hernández, J.C.; Pranzini, E. Evaluation of the scenic value of 100 beaches in Cuba: Implications for coastal tourism management. *Ocean Coast. Manag.* **2017**, *142*, 173–185. [CrossRef]
18. Dolan, R.; Davis, R.E. An intensity scale for Atlantic coast northeast storms. *J. Coast. Res.* **1992**, *8*, 840–853.
19. Masselink, G.; Pattiaratchi, C.B. Seasonal changes in beach morphology along the sheltered coastline of Perth, Western Australia. *Mar. Geol.* **2001**, *172*, 243–263. [CrossRef]
20. Donnelly, J.P.; Bryant, S.S.; Butler, J.; Dowling, J.; Fan, L.; Hausmann, N.; Westover, K.; Webb, T. 700 yr sedimentary record of intense hurricane landfalls in southern New England. *GSA Bull.* **2001**, *113*, 714–727. [CrossRef]
21. Anfuso, G.; Gracia, F.J. Morphodynamic characteristics and short-term evolution of a coastal sector in SW Spain: Implications for coastal erosion management. *J. Coast. Res.* **2005**, *21*, 1139–1153. [CrossRef]
22. Komar, P.D.; Allan, J.C. Increasing hurricane-generated wave heights along the US east coast and their climate controls. *J. Coast. Res.* **2008**, *24*, 479–488. [CrossRef]
23. Rangel-Buitrago, N.; Anfuso, G. Winter wave climate, storms and regional cycles: The SW Spanish Atlantic coast. *Int. J. Climatol.* **2013**, *33*, 2142–2156. [CrossRef]
24. Rangel-Buitrago, N.; Anfuso, G. Coastal storm characterization and morphological impacts on sandy coasts. *Earth Surf. Processes Landf.* **2011**, *36*, 1997–2010. [CrossRef]
25. Sanjaume Saumel, E.; Gracia Prieto, F.J. *Las Dunas en España*; Sociedad Española de Geomorfología: Zaragoza, Spain, 2011; ISBN 978-84-615-3780-8.
26. Anfuso, G.; Dominguez, L.; Gracia, F. Short and medium-term evolution of a coastal sector in Cadiz, SW Spain. *Catena* **2007**, *70*, 229–242. [CrossRef]
27. Duarte, C.M.; Losada, I.J.; Hendriks, I.E.; Mazarrasa, I.; Marbà, N. The role of coastal plant communities for climate change mitigation and adaptation. *Nat. Clim. Chang.* **2013**, *3*, 961–968. [CrossRef]
28. Fernández-Montblanc, T.; Duo, E.; Ciavola, P. Dune reconstruction and revegetation as a potential measure to decrease coastal erosion and flooding under extreme storm conditions. *Ocean Coast. Manag.* **2020**, *188*, 105075. [CrossRef]
29. European Union. Directive 2011/92/EU of the European Parliament and of the Council of 13 December 2011 on the Assessment of the Effects of Certain Public and Private Projects on the Environment. Available online: https://eur-lex.europa.eu/legal-content/en/TXT/?uri=CELEX:32011L0092 (accessed on 22 July 2020).
30. European Union. Directive 92/43/EEC of 21 May 1992 on the Conservation of Natural Habitats and of Wild Fauna and Flora. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A31992L0043 (accessed on 22 July 2020).
31. European Union. Directive 2001/42/EC on the Assessment of the Effects of Certain Plans and Programmes on the Environment. Available online: https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX%3A32001L0042 (accessed on 22 July 2020).

32. European Union. Directive 2009/147/EC on the Conservation of Wild Birds. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32009L0147 (accessed on 22 July 2020).
33. Nicholls, R.J.; Wong, P.P.; Burkett, V.R.; Codignotto, J.O.; Hay, J.E.; McLean, R.F.; Ragoonaden, S.; Woodroffe, C.D. Coastal systems and low-lying areas. In *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*; Parry, M.L., Canziani, O.F., Palutikof, J.P., van der Linden, P.J., Hanson, C.E., Eds.; Cambridge University Press: Cambridge, UK, 2007; ISBN 9780521880107.
34. Bochev-van der Burgh, L.M.; Wijnberg, K.M.; Hulscher, S.J.M.H. Decadal-scale morphologic variability of managed coastal dunes. *Coast. Eng.* **2011**, *58*, 927–936. [CrossRef]
35. Carter, R.W.G. Near-future sea level impacts on coastal dune landscapes. *Landsc. Ecol.* **1991**, *6*, 29–39. [CrossRef]
36. Church, J.A.; Gregory, J.M.; Huybrechts, P.; Kuhn, M.; Lambeck, K.; Nhuan, M.T.; Qin, D.; Woodworth, P.L.; Anisimov, O.A.; Bryan, F.O.; et al. Changes in sea level. In *Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*; Houghton, J.T., Ding, Y., Griggs, D.J., Noguer, M., van der Linden, P.J., Dai, X., Maskell, K., Johnson, C.A., Eds.; Cambridge University Press: Cambridge, UK, 2001; ISBN 0521-80767-0.
37. Pye, K.; Blott, S.J. Decadal-scale variation in dune erosion and accretion rates: An investigation of the significance of changing storm tide frequency and magnitude on the Sefton coast, UK. *Geomorphology* **2008**, *102*, 652–666. [CrossRef]
38. Sterr, H. Assessment of vulnerability and adaptation to sea-level rise for the coastal zone of Germany. *J. Coast. Res.* **2008**, *24*, 380–393. [CrossRef]
39. Molina, R.; Anfuso, G.; Manno, G.; Gracia Prieto, F.J. The Mediterranean Coast of Andalusia (Spain): Medium-Term Evolution and Impacts of Coastal Structures. *Sustainability* **2019**, *11*, 3539. [CrossRef]
40. Gracia Prieto, F.J.; Sanjaume, E.; Hernández, L.; Hernández, A.I.; Flor, G.; Gómez-Serrano, M.Á. Dunas marítimas y continentales. In *Bases Ecológicas Preliminares Para la Conservación de los Tipos de Hábitat de Interés Comunitario en España*; Ministerio de Medio Ambiente, y Medio Rural y Marino: Madrid, Spain, 2009; p. 106, ISBN 978-84-491-0911-9.
41. Gómez-Zotano, J. La degradación de dunas litorales en Andalucía: Aproximación geohistórica y multiescalar. *Investig. Geogr.* **2014**, *62*, 23–39. [CrossRef]
42. Guisado, E.; Malvárez, G.C.; Navas, F. Morphodynamic environments of the Costa del Sol, Spain. *J. Coast. Res.* **2013**, *65*, 500–506. [CrossRef]
43. Prieto, A.; Ojeda, J.; Rodríguez, S.; Gracia, J.; Del Río, L. Procesos erosivos (tasas de erosión) en los deltas mediterráneos andaluces: Herramientas de análisis espacial (DSAS) y evolución temporal (servicios OGC). In *Tecnologías de la Información Geográfica en el Contexto del Cambio Global, Proceedings of the XV Congreso Nacional de Tecnologías de la Información Geográfica, Madrid, Spain, 19–21 September 2012*; Martínez Vega, J., Martín Isabel, P., Eds.; CSIC—Instituto de Economía, Geografía y Demografía: Madrid, Spain, 2012; pp. 185–193, ISBN 978-84-695-4759-5.
44. Félix, A.; Baquerizo, A.; Santiago, J.; Losada, M. Coastal zone management with stochastic multi-criteria analysis. *J. Environ. Manag.* **2012**, *112*, 252–266. [CrossRef]
45. DGPC. Dirección General de Puertos y Costas. In *Actuaciones en la Costa 1988–1990*; MOPV: Madrid, Spain, 1991; p. 307.
46. Malvárez, G.; Pollard, J.; Rodriguez, R.D. Origins, management, and measurement of stress on the coast of southern Spain. *Coast. Manag.* **2000**, *28*, 215–234. [CrossRef]
47. Malvárez, G.; Pollard, J.; Domínguez, R. The planning and practice of coastal zone management in Southern Spain. *J. Sustain. Tour.* **2003**, *11*, 204–223. [CrossRef]
48. Manno, G.; Anfuso, G.; Messina, E.; Williams, A.T.; Suffo, M.; Liguori, V. Decadal evolution of coastline armouring along the Mediterranean Andalusia littoral (South of Spain). *Ocean Coast. Manag.* **2016**, *124*, 84–99. [CrossRef]
49. Chica Ruiz, J.A.; Barragan, J.M. *Estado y Tendencia de los Servicios de los Ecosistemas Litorales de Andalucía*; Consejería de Medio Ambiente: Sevilla, Spain, 2011; p. 112.
50. Molina, R.; Manno, G.; Lo Re, C.; Anfuso, G.; Ciraolo, G. Storm Energy Flux Characterization along the Mediterranean Coast of Andalusia (Spain). *Water* **2019**, *11*, 509. [CrossRef]

51. López, M.F.P. El clima de Andalucía. In *Geografía de Andalucía*; Ariel Geografía: Barcelona, Spain, 2003; pp. 137–173, ISBN 84-344-3476-8.
52. REDIAM. Ortofotografía Regional. Available online: http://www.juntadeandalucia.es/medioambiente/site/rediam/menuitem.aedc2250f6db83cf8ca78ca731525ea0/?vgnextoid=867122ad8470f210VgnVCM1000001325e50aRCRD&lr=lang_es (accessed on 22 July 2020).
53. Hidalgo, R. *Bases Ecológicas Preliminares Para la Conservación de los Tipos de Hábitat de Interés Comunitario en España*; Ministerio de Medio Ambiente, y Medio Rural y Marino: Madrid, Spain, 2009; ISBN 978-84-491-0911-9.
54. European Commisison. The Mediterranean Region—List of Sites of Community Importance (SCI's) for the Mediterranean Biogeographical Region. Available online: https://ec.europa.eu/environment/nature/natura2000/biogeog_regions/mediterranean/index_en.htm#list_of_sites (accessed on 22 July 2020).
55. Díez-Garretas, B.; Comino, O.; Pereña, J.; Asensi, A. Spatio-temporal changes (1956–2013) of coastal ecosystems in Southern Iberian Peninsula (Spain). *Mediterr. Bot.* **2019**, *40*, 111–119. [CrossRef]
56. Pintó, J.; Martí, C.; Fraguell, R.M. Assessing current conditions of coastal dune systems of Mediterranean developed shores. *J. Coast. Res.* **2014**, *30*, 832–842. [CrossRef]
57. García-Mora, M.R.; Gallego-Fernández, J.B.; Williams, A.T.; García-Novo, F. A coastal dune vulnerability classification. A case study of the SW Iberian Peninsula. *J. Coast. Res.* **2001**, *17*, 802–811.
58. Rangel-Buitrago, N.; Anfuso, G. *Risk Assessment of Storms in Coastal Zones: Case Studies from Cartagena (Colombia) and Cadiz (Spain)*; Springer: Dordrecht, The Netherlands, 2015; p. 63. [CrossRef]
59. Rizzo, A.; Aucelli, P.P.C.; Gracia, F.J.; Anfuso, G. A novelty coastal susceptibility assessment method: Application to Valdelagrana area (SW Spain). *J. Coast. Conserv.* **2018**, *22*, 973–987. [CrossRef]
60. Manno, G.; Lo Re, C.; Ciraolo, G. Shoreline detection in a gentle slope Mediterranean beach. In Proceedings of the 5th International Short Conference on Applied Coastal Research, Aachen, Germany, 9–11 June 2011; ISBN 978-3844011326.
61. Anfuso, G.; Martínez-del-Pozo, J.Á.; Rangel-Buitrago, N. Morphological cells in the Ragusa littoral (Sicily, Italy). *J. Coast. Conserv.* **2013**, *17*, 369–377. [CrossRef]
62. Manno, G.; Lo Re, C.; Ciraolo, G. Uncertainties in shoreline position analysis: The role of run-up and tide in a gentle slope beach. *Ocean Sci.* **2017**, *13*, 661–671. [CrossRef]
63. Aybulatov, N.A.; Artyukhin, Y.V. *Geo-Ecology of the World Ocean's Shelf and Coasts*; Hydrometeo Publishing: Leningrad, Russia, 1993; p. 304.
64. Jenks, G.F.; Caspall, F.C. Error on choroplethic maps: Definition, measurement, reduction. *Ann. Assoc. Am. Geogr.* **1971**, *61*, 217–244. [CrossRef]
65. Hesp, P. Foredunes and blowouts: Initiation, geomorphology and dynamics. *Geomorphology* **2002**, *48*, 245–268. [CrossRef]
66. Ley Vega de Seoane, C.; Gallego Fernández, J.B.; Vidal Pascual, C. *Manual de Restauración de Dunas Costeras*; Ministerio de Medio Ambiente. Dirección General de Costas: Madrid, Spain, 2007; ISBN 978-84-8320-409-2.
67. Sanjaume, E.; Pardo-Pascual, J.E. Degradación de sistemas dunares. In *Las Dunas en España*; Sanjaume Saumel, E., Gracia Prieto, F.J., Eds.; Sociedad Española de Geomorfología: Zaragoza, Spain, 2011; ISBN 978-84-615-3780-8.
68. Castaño Camero, N.; Arteaga Cardineau, C.; Gómez Zotano, J. Erosión en la playa del "Saladillo-Matas Verdes" (Estepona, Málaga): Situación actual y causas potenciales. *Geotemas* **2017**, *17*, 59–62.
69. Bayo Martínez, A. Tratamiento técnico del borde litoral almeriense. In *Actas de las Jornadas sobre el Litoral de Almería: Caracterización, Ordenación y Gestión de un Espacio Geográfico Celebradas en Almería, 20 a 24 de Mayo de 1997*; Instituto de Estudios Almerienses: Almería, Spain, 1999; pp. 207–232, ISBN 84-8108-175-2.
70. Viciana Martínez-Lage, A. Las extracciones de áridos en el litoral de Almería para su utilización en la agricultura intensiva (1956–1997). In *Actas de las Jornadas sobre el Litoral de Almería: Caracterización, Ordenación y Gestión de un Espacio Geográfico Celebradas en Almería, 20 a 24 de Mayo de 1997*; Instituto de Estudios Almerienses: Almería, Spain, 1999; pp. 83–110, ISBN 84-8108-175-2.
71. Viciana Martínez-Lage, A. La costa de Almería: Desarrollo socio-económico y degradación físico-ambiental (1957–2007). *Paralelo 37* **2007**, *19*, 149–183.
72. Bardají, T.; Zazo, C.; Lario, J.; Goy, J.L.; Cabero, A.; Dabrio, C.J.; Silva, P.G. Las dunas costeras del presente y último interglaciar en Málaga, Almería y Murcia. In *Las Dunas en España*; Sanjaume Saumel, E., Gracia Prieto, F.J., Eds.; Sociedad Española de Geomorfología: Zaragoza, Spain, 2011; ISBN 978-84-615-3780-8.

73. Gracia, F.J.; Benavente, J.; Alonso, C.; Del Río, L.; Abarca, J.M.; Anfuso, G.; García de Lomas, J. Las dunas del litoral gaditano. In *Las Dunas en España*; Sanjaume Saumel, E., Gracia Prieto, F.J., Eds.; Sociedad Española de Geomorfología: Zaragoza, Spain, 2011; ISBN 978-84-615-3780-8.
74. El Mrini, A.; Anthony, E.J.; Maanan, M.; Taaouati, M.; Nachite, D. Beach-dune degradation in a Mediterranean context of strong development pressures, and the missing integrated management perspective. *Ocean Coast. Manag.* **2012**, *69*, 299–306. [CrossRef]
75. Del Río, J.L.; Malvárez, G. Impacto de la regulación del río Verde en la erosión del sistema sedimentario litoral de la ensenada de Marbella, Costa del Sol. In *XV Coloquio Ibérico de Geografía*; Universidad de Murcia: Murcia, Spain, 2016; pp. 1–10, ISBN 978-84-944193-4-8.
76. Jiménez, J.A.; Sánchez-Arcilla, A. Medium-term coastal response at the Ebro delta, Spain. *Mar. Geol.* **1993**, *114*, 105–118. [CrossRef]
77. Pranzini, E. Airborne LIDAR survey applied to the analysis of the historical evolution of the Arno River delta (Italy). *J. Coast. Res.* **2007**, *50*, 400–409.
78. Arteaga Cardineau, C.; González, J.A. Natural and human erosive factors in Liencres beach spit and dunes (Cantabria, Spain). *J. Coast. Res.* **2005**, *49*, 70–75.
79. Feagin, R.A.; Sherman, D.J.; Grant, W.E. Coastal erosion, global sea-level rise, and the loss of sand dune plant habitats. *Front. Ecol. Environ.* **2005**, *3*, 359–364. [CrossRef]
80. Saye, S.E.; Pye, K. Implications of sea level rise for coastal dune habitat conservation in Wales, UK. *J. Coast. Conserv.* **2007**, *11*, 31–52. [CrossRef]
81. Costa, S.; Coelho, C. Northwest Coast of Portugal—Past behavior and future coastal defense options. *J. Coast. Res.* **2013**, *65*, 921–926. [CrossRef]
82. Houser, C.; Ellis, J. Beach and Dune Interaction. In *Treatise on Geomorphology*; John, F., Ed.; Academic Press: Cambridge, MA, USA, 2013; Volume 10, pp. 267–288, ISBN 9780123747396.
83. De Winter, R.C.; Ruessink, B.G. Sensitivity analysis of climate change impacts on dune erosion: Case study for the Dutch Holland coast. *Clim. Chang.* **2017**, *141*, 685–701. [CrossRef]
84. Criado-Aldeanueva, F.; Del Río Vera, J.; García-Lafuente, J. Steric and mass-induced Mediterranean sea level trends from 14 years of altimetry data. *Glob. Planet. Chang.* **2008**, *60*, 563–575. [CrossRef]
85. Tsimplis, M.; Spada, G.; Marcos, M.; Flemming, N. Multi-decadal sea level trends and land movements in the Mediterranean Sea with estimates of factors perturbing tide gauge data and cumulative uncertainties. *Glob. Planet. Chang.* **2011**, *76*, 63–76. [CrossRef]
86. Puertos del Estado. *REDMAR—RED de MAReógrafos de Puertos del Estado. Resumen de Parámetros Relacionados con el Nivel del Mar y la Marea que Afectan a las Condiciones de Diseño y Explotación Portuaria*; Puertos del Estado: Madrid, Spain, 2017; p. 33.
87. Fernández-Salas, L.M.; Dabrio, C.J.; Díaz del Río, V.; Lobo, F.J.; Sanz, J.L.; Lario, J. Land-sea correlation between late Holocene coastal and infralittoral deposits in the SE Iberian Peninsula (Western Mediterranean). *Geomorphology* **2009**, *104*, 4–11. [CrossRef]
88. Malvárez, G.; Navas, F.; Guisado-Pintado, E.; Jackson, D.W.T. Morphodynamic interactions of continental shelf, beach and dunes: The Cabopino dune system in southern Mediterranean Spain. *Earth Surf. Proc. Land.* **2019**, *44*, 1647–1658. [CrossRef]
89. Kraus, N.C.; Militello, A.; Todoroff, G. Barrier breaching processes and barrier spit breach, Stone Lagoon, California. *Shore Beach* **2002**, *70*, 22.
90. Ceia, F.R.; Patrícia, J.; Marques, J.C.; Dias, J.A. Coastal vulnerability in barrier islands: The high risk areas of the Ria Formosa (Portugal) system. *Ocean Coast. Manag.* **2010**, *53*, 478–486. [CrossRef]
91. Raji, O.; Niazi, S.; Snoussi, M.; Dezileau, L.; Khouakhi, A. Vulnerability assessment of a lagoon to sea level rise and storm events: Nador lagoon (NE Morocco). *J. Coast. Res.* **2013**, *65*, 802–808. [CrossRef]
92. Hesp, P.A. Foredune formation in southeast Australia. In *Coastal Geomorphology in Australia*; Thom, B.G., Ed.; Academic Press: London, UK, 1984; pp. 69–97, ISBN 0126878803.
93. Nordstrom, K.F. *Beaches and Dunes of Developed Coasts*; Cambridge University Press: Cambridge, UK, 2000; ISBN 0-521-47013-7.
94. Martínez, M.L.; Psuty, N.P. *Coastal Dunes. Ecology and Conservation, Ecological Studies 171*; Springer: Dordrecht, The Netherlands, 2008; ISBN 978-3-540-74001-8.

95. Psuty, N.P. The coastal foredune: A morphological basis for regional coastal dune development. In *Coastal Dunes. Ecology and Conservation, Ecological Studies 171*; Martínez, M.L., Psuty, N.P., Eds.; Springer: Dordrecht, The Netherlands, 2008; ISBN 978-3-540-74001-8.
96. REDIAM. WMS, Tasas de Erosión en el Litoral Andaluz. Available online: http://www.juntadeandalucia.es/medioambiente/site/rediam/menuitem.04dc44281e5d53cf8ca78ca731525ea0/?vgnextoid=97136276467e2510VgnVCM1000001325e50aRCRD&vgnextchannel=8ca090a63670f210VgnVCM2000000624e50aRCRD&vgnextfmt=rediam&lr=lang_es (accessed on 22 July 2020).