RESTORATION AND MANAGEMENT OF DUNE SYSTEMS. CASE STUDIES

Francesc Xavier Roig-Munar
(coordinador)

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Xavier Quintana

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Sumary

Introduction

Coastal dune systems have been one of the ecosystems most altered in recent decades by growing human pressure on coastal areas. They are habitats that are very sensitive to excessive use and trampling in the bathing season. Because of their dynamic characteristics as a shifting sand substrate, they are also very much affected by human activities associated with beach maintenance, such as mechanical cleaning or the clearing of organic matter and remains of logs washed up on shore, which not only affect sand balance and encourage erosion, but also alter the content of organic matter and nutrients available for dune vegetation. As a result of their progressive deterioration, dune systems are now protected by different directives. The European Commission's Habitats Directive defines up to 17 types of coastal dunes as sites of community importance the protection of which requires the designation of special conservation zones. Of these 17 types, 6 are classified as priority habitats. Coastal dunes are also home to numerous species of associated fauna that are highly-endangered and need specific conservation programmes. All these habitats and species require proper geomorphological and ecological functioning of the dune ecosystem.

Dune systems provide other ecosystem services, over and above their importance in the conservation of the associated biodiversity. A dune system in good condition is involved, together with the adjacent coastal systems, in protecting inland zones from the impact of sea storms. In this respect, aerial images are very useful in comparing the limited effects of a sea storm in a coastal area that has a well preserved dune ridge with its intense impact in an area with altered dune vegetation. Furthermore, the sand of an altered dune system does not just move occasionally during storms. Aeolian transport is another major cause of erosion to the dune system that has a more frequent impact than the sand moved by the water during storms. In a context of global change, the conservation of the foredunes and their sand balance is of key importance in easing the possible impact inland of the gradual rise in sea level. Also crucial is the conservation of different natural coastal areas (marine grasslands, lagoons, marshes, etc.). It is said that the organisation of these coastal systems, parallel to the coastline, is such that the deterioration of a single system will jeopardise all the others, just as the books on a bookshelf hold one another up so that the removal of one affects the balance of the others.

Given how important it is to conserve dune ecosystems and the ease with which they deteriorate, different governmental authorities responsible for nature conservation have made considerable effort at local, regional, national and European level and there are numerous examples of restoration of dune ecosystems along the coast. Seen through a layperson's eyes, the principle of dune restoration is simple. It involves the installation of retention systems to stabilise the soil shifted by a lack of vegetation to fix it. These retain the sand and allow for the growth of vegetation that cannot otherwise establish itself on a bare, shifting and highly unstable sand substrate. Fencing is also meanwhile installed to prevent trampling, which is usually the main cause of deterioration. The dune vegetation responds very well to restoration and grows quite quickly (either spontaneously or assisted through planting) and therefore a reasonably structured dune system can be generated in a just few years. This principle is conceptually simple yet meanwhile very complex, as the success of restoration depends on many factors. The size of the sand traps, their orientation and position in relation to the prevailing wind, the distance to the sea and the alignment of the dune system, the balance of inputs and outputs, the location of the accretion and erosion zones and knowledge of the system's sedimentary evolution are some of the key elements to be considered and need to be known in order to ensure that dune restoration is successful and yields structured and functional foredunes. In short, this requires knowledge of how the dune system's geomorphology works, not only from a theoretical perspective (dune formation mechanisms, etc.), but also with regard to geomorphological and meteorological elements that either operate locally (orientation, sand balance, prevailing winds) or remotely yet influence the sand balance (the existence of barriers, dykes or breakwaters that alter the coastal dynamics or sand supply). Therefore, a seemingly simple restoration method in practice becomes a complex process that requires knowledge of the geomorphological processes operating on both a local and a larger scale. Dune restoration efforts are therefore frequently unsuccessful.

This eighth volume of the "Recerca i Territori" collection, which in this case has received European funding within the Life Pletera project (LIFE13 NAT/ES/001001), contains a series of case studies on dune restoration projects undertaken at different sites on the Atlantic and Mediterranean coasts and in several countries (Spain, Portugal, Italy and France), with a view to providing examples of dune restoration and how successes and failures have been tackled. This volume is neither intended as a monograph on dune systems nor as a manual of restoration methods. There are other significant publications that fulfil these functions. Here, as in the previous monographs in the collection, the purpose is to provide examples that prompt reflection on everything that needs to be considered to restore dunes successfully and to help the managers of natural areas in decision-making and in developing best practices for dune restoration.

Xavier Quintana
Director of the Chair of Mediterranean Coastal Ecosystems

Jaume Vicens
Deputy Director-General for Biodiversity. Ministry of Territory and Sustainability of the Government of Catalonia

An analysis of the impact of the law on the conservation of beach-dune systems and government liability in the management of these systems*1

Ferran Pons[1], Carme Garriga[2]

1 Department of Public Law and Historical-Legal Sciences, Universitat Autònoma de Barcelona
2 Law graduate. Member of the Balearic Islands Bar Association (no. 3.903)

1* Ferran Pons is the author of sections 1, 2 and 4.4. Carme Garriga wrote sections 3, 4.1, 4.2, 4.3 and 5.

1. Introduction. Beach and dune systems have received unequal treatment by the law and the government, which in many cases has led to their degradation

Beaches and dunes are undoubtedly one of the most fragile geomorphic systems, either owing to their exposure to waves, the rising sea level or the strong anthropogenic pressure on them. Not only are dunes an inseparable part of beaches and contribute to their existence as sediment reserves, they are also true ecosystems themselves. Indeed, in accordance with Annex I of Council Directive 92/43/EEC of 21 May 1992 on the conservation of natural habitats and of wild fauna and flora (Habitats Directive), dunes are a natural habitat type of community interest whose conservation requires the designation of special areas of conservation and in some cases even priority protection.

Figures 1 and 2. Dunes at Rec del Molí beach, L'Escala (Girona), June 2010. Source: Ferran Pons.

In an unhappy phase in Spain's regulatory history, beaches and dunes were either not expressly categorised as marine and terrestrial public domain (MTPD) and were included implicitly in the coastal zone (1880 and 1928 Port Laws, *Ley de puertos*), or beaches were restrictively defined as virtually flat surfaces of sand or stones with either sparse and characteristic or no vegetation (1969 Coastal Law, *Ley de costas*), which excluded dunes from being defined as beach and also from the category of public domain. As a result, dunes could be used and owned under the provisions of private property law. Given the characteristics of dune land — largely unsuitable for agricultural and grazing activities, dunes were used mainly for extracting sand for construction and for haphazardly constructing residential, tourist and recreational buildings at a time when the urban development legal framework was still in its infancy. The passing of the Consolidated Land Law of 1976 (*Ley del suelo*) brought with it an impulse for general planning instruments (i.e., a general urban development plan and subsidiary planning regulations) for spatial planning at the local Government level, and also for specific planning instruments (i.e., partial plans, detailed studies and special plans) for regulating development operations on developable land.

From the 1960s to the 1980s, private land on the coast, including the dunes, became the prime objective of the developers, who were, on the whole, protected by the developmentalism prevalent in the approach to planning of the time and defended by the expansionist policy implemented by many local councils. Thus, the fate of dunes depended upon the type of land upon which they were located (urban, developable or non-developable).

The Spanish Constitution of 1978 provided the foundations that would subsequently allow for broader protection of beach-dune systems. Article 45.2 requires public authorities to ensure the rational use of all natural resources to protect and improve the quality of life and defend and restore the environment, based on the indispensable principle of collective solidarity. Furthermore, it classifies beaches and the coastal zone as public property. Thus, the specific defining of this property was crucial and required subsequent legislating. Also as a result of the constitution and the passing of the various statutes of autonomy, coastal autonomous communities assumed competences on spatial planning matters, including the coast, urban planning, and the protection of the environment and protected natural areas.

The Coastal Law of 1988 represents a firm commitment to protecting and conserving marine and terrestrial public domain (MTPD) and to recuperating its integrity and guaranteeing it for public use. Specifically, the statute stated that all dunes, fixed or shifting, with or without vegetation and of natural or artificial origin, form part of beaches and must be considered public domain, meaning that the provisions of this statute for the protection and use of this type of property are applicable. Unfortunately, the new regulations on coastal development, set out in Law 2/2013, of 29 May, on the protection and sustainable use of the coast and in amendment of the 1988 Coastal Law and the new General Coastal Regulations, may represent a very big step backwards owing to, on the one hand, the fact that, through the changing of the current partitions, considerable areas of dune systems may no longer be classified as public property and, on the other hand, the impact the new regulations on the use of beaches may have on dune systems.

Concurrently, dunes have been recognised in regulations on the environment and the protection of natural areas. As stated above, the 1992 Habitats Directive classifies dunes as a natural habitat of community interest, worthy of SCI/SAC status. An example of this implementation is Balearic Islands Law 1/1991 on natural areas and the urban development framework for natural areas deserving special protection, which states that, in Natural Areas of Special Interest (NASI) (*Área Natural de Especial Interés*), dunes are to be provided the highest level of protection. The special plans approved to set down the regulations of the respective NASIs made up for the lack of coastal development regulation plans, despite there being, since 1994, a decree in force regulating the approval of such plans. In Catalonia, there are dune systems included both in the natural areas deserving special protection set out in Catalan Law 12/1985, of 13 June, on natural areas and also in the Catalan Plan for Areas of Natural Interest (*Pla d'espais d'interès natural, PEIN)*, in addition to any impact generated by the application of the Master Plan for the Urban Development of the Coastal System (*Pla director urbanístic del sistema costaner (PDUSC-1))* passed in 2005.

Beach-dune systems are defined as an essential element of the natural heritage and biodiversity. The Natural Heritage and Biodiversity Strategic Plan 2011-2017, passed by Royal Decree 1274/2011, of 16 September, states that another endangered landscape "is that formed by beaches — one of the most valuable environments from a socioeconomic point of view. Furthermore, all Spanish beaches are in a process of retrogradation owing to, among other factors, a lack of sediments being provided by rivers, a rise in the sea level and the construction of coastal infrastructures that distort the coastal sediment dynamics. There is a generalised process of erosion that very few beaches escape." In particular, this plan states that coastal dunes “are ecosystems of great environmental value subject to strong pressures. They are marine and terrestrial public domain for which effective protection and ecological restoration must be a priority.”[2]

These priority objectives must be achieved not only by applying the regulations and the plans in force but also through regulating and managing these systems. The integrated coastal zone management (ICZM) model has great potential for meeting the needs of beach-dune systems, although it appears that in practice the competent Governments have not made much use of it. In this paper, we firstly aim to show how the applicable regulations on ports, coastal development, and the protection of natural areas and biodiversity have contributed to the preservation or deterioration of these systems. Secondly, we analyse various Government actions that may have a significant detrimental impact on these natural elements and point out how this could be avoided under the aforementioned ICZM framework. Finally, we conclude with a reflection on whether there are legal grounds for attributing liability to public authorities for the damage caused to beach-dune systems as a result of poor management.

Before concluding this introduction, we must make a clarification. As we, the authors, are both Minorcan, we have decided to make special reference to provisions affecting the Balearic Islands and to management cases observed in Minorcan beaches. With regard to the management of Catalan beaches, we refer to the relevant literature (among others, Breton, 2004; Ariza *et al.*, 2008; Ariza, 2011).

2. Analysis of the evolution of the treatment of dune systems by government regulations on ports and coastal development

2.1. The application of the 1880 and 1928 Port Laws and the 1969 Coastal Law: the seed of destruction for many dune systems

The Port Laws of 7 May 1880 and 19 January 1928 regulated, exclusively up until the Coastal Law of 1969, the defining and use of marine and terrestrial public domain. They did so from a predominantly port perspective, concentrating on the exploitation of the sea and beaches, the execution of port works, and on defining the port regulatory framework, police and services. When they were introduced, the pressures on the coast were limited, and as it was not a particularly threatened area, the legal provisions had no protective focus.

The content of these two statutes on the ports was almost identical. The first article of both stated that the coastal zone and coastal waters were state-owned and for public use. The coastal zone (CZ) was defined as the coastline or sea borders of Spanish territory that met the ebb and flow of the sea (where affected by tides) and where the most extreme storm waves reached (in areas not affected by

2 Spanish State Gazette (BOE) no. 236, of 30 September 2011, pp. 103148 and 103149.

tides). The beaches were not expressly mentioned as they were considered included in this concept of the coastal zone. Public ownership of the coastal zone and coastal waters was recognised without prejudice to the rights of private individuals as stated in the aforementioned Article 1 of both statutes. Interpreting this provision alongside Article 7[3] leads to the conclusion that private enclaves in these areas were recognised. Private property of this nature could be claimed by registering it in the property registry or even by obtaining a declaration by court ruling, as occurred in the judgements of the Spanish Supreme Court of 2 February 1974 and 13 October 1981, which recognised the private ownership of the entire Santa Cristina beach in Oleiros (A Coruña) and a property located in Grande beach in Miño (A Coruña), respectively.

Article 1 of the Regulations of the 1928 Port Law, passed by the Royal Decree Law of 19 January 1928, set out that the Ministry of Public Works was to carry out the partitioning or demarcation and boundary marking in the coastal zone at places of suspected misappropriation, when necessary for whatever reason, when requested by the owners of adjacent properties or when a concession for exploitation of the CZ was granted. It was on the basis of these provisions that sections of the coast were partitioned, particularly in the 1950s, 1960s, and 1970s. Dunes were usually excluded from the strip of public land. Thus, as they were considered private property, there were only subject to the easements for coastal security and rescue (Articles 7 to 10 of the Port Laws), which constituted very lax restrictions. Lastly, neither of the two aforementioned statutes set out any possible offences or sanctions for violating any of their provisions.

Towards the 1950s, the concept of the coastline had changed significantly. The progressive concentration of the population on the coast had become a reality, and the political regime of the time had seen the potential of the coast for economic growth and tourism. That fact that it was an extremely attractive area was demonstrated by the many conflicts over competence that occurred towards the end of the 1950s and the start of the 1960s between different public bodies regarding each other's intentions for exercising various powers and levying taxes on MTPD properties: on the one hand, between Government ministries, including the army, the navy, public works, tourism, commerce and treasury; and on the other, between departments of these ministries and local councils. To fix what was considered a deficient legal framework for the CZ, in 1964 an interministerial committee was set up. The studies carried out by this committee were the basis for the drafting of Law 28/1969, of 26 April, on coastal development (the "Coastal Law").

When this statute was passed, there was a very high degree of deterioration of the public and private coastal landscape and resources owing to the emergent urban development and the appearance of all types of infrastructures, industries and buildings for accommodation, catering and recreation. In public areas (the beaches, the CZ and the sea), this statute permitted an abusive and disproportionate occupation for all types of uses, activities and constructions. In the case of private property (dune systems), to encourage economic growth and create wealth, priority was given to allowing landowners to exercise their rights in detriment to the preservation of the resources and the ecosystems. Thus, following the Coastal Law of 1969, the situation became even worse, as we will see.

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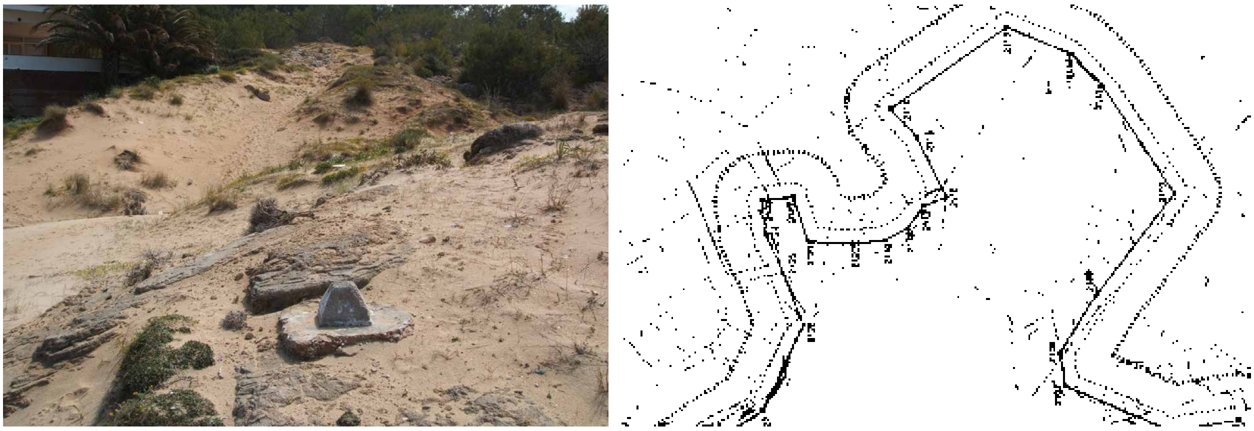
3 According to which, "Privately-owned land bordering the sea or enclaved in the coastal zone are subject to the easements for coastal security and rescue". [Italics ours.]

The main aim of the Coastal Law was to regulate MTPD property uniformly and harmoniously between the different Government bodies and services and between these entities and local councils. It completely overlooked matters of protection. Although it did expressly classify beaches as public property — separated from the coastal zone, its definition was very restrictive. Article 1.1 defined beaches as "nearly flat riverbanks or seashores formed by sand or stones with either sparse and characteristic or no vegetation". Dunes, therefore, were excluded from the concept of the public beach for not meeting the requirements of being nearly flat and having little vegetation.

In addition, the consideration and designation of MTPD property was without prejudice to legally acquired rights on private enclaves (Articles 1 and 4.1). The 1969 statute included coastal security and rescue easements on private property adjacent to the MTPD with the same leniency as the Port Laws. Also as in these early statutes, it did not set out any offences or sanctions for violating any of its provisions. It was not until Law 7/1980, of 10 March, on the protection of the Spanish coastline, passed following the Constitution of 1978, that offences and sanctions for offenders were specified in legislation.

The important point to note is that, in practice, the application of the aforementioned provisions of the Port Laws and 1969 Coastal Law that defined beaches, implemented through the establishment of boundaries, meant the exclusion of an infinite number of dune systems from the MTPD. Thus, the legal framework for areas with similar geomorphological elements was fragmented (Fig. 3 and 4).



Figures 3 and 4. Dunes at S'Arenal d'en Castell Beach (Es Mercadal, Minorca), in April 2007, excluded from the MTPD in the partitioning of the 1960s. The photo on the left shows the boundary marker for the delimitation of the MTPD and the existing dunes inside it. The image on the right is a demarcation map of the same zone approved by the Order from the Ministry for the Environment and Rural and Maritime Areas of 20 February 2009, showing both the old partition boundary line (broken line) and the new MTPD polygonal line, which includes the above-mentioned dunes. Source: Ferran Pons.

Thus, on private dunes, owners could exercise the usual rights of use and exploitation inherent in private property law, although in accordance with any applicable planning regulations. Such planning regulations either allowed for the developing and building on the aforementioned areas, as occurred often given the clearly pro-expansion and developmentalism approach prevalent in the plans of coastal municipalities during the 1970s and 80s (Fig. 5), or they allowed for constructing detached single-family dwellings on land classified as non-developable (Fig. 6).

Figure 5. General shot of S'Arenal d'en Castell beach taken in April 2007. Source: Ferran Pons.

Figure 6. Detached houses and other constructions on the dunes at Migjorn Beach, Formentera, March 2006. Until the partition approved in 1997, these dunes were not in the MTPD. Source: Ferran Pons.

For beaches and dunes classified as MTPD in the corresponding partitions, it was possible to authorise or legalise after-the-fact all types of activities, uses and constructions, including boat sheds, toilets, restaurants, accommodation and dwellings; in addition to, of course, the authorised or permitted extraction of sand. Furthermore, there were also the effects on these areas caused by the construction of maritime facilities and marinas, which, in accordance with Article 9.1 of Law 55/1969, of 26 April, on marinas, could be built anywhere along the coast, regardless of whether the land in question had beach or CZ status and its landscape and environmental value. The construction of these marinas was initially instigated and authorised by the central Government, although these functions were transferred to the respective autonomous community regional Governments via the relevant instruments introduced following the passing of the Spanish Constitution of 1978 and the statutes of autonomy.

2.2. The 1988 Coastal Law (Law 22/1988 of 28 July) on coastal development: a firm commitment to recovering the integrity of the beach-dune system

Article 132.2 of the Spanish Constitution of 1978 states that public property is determined by law and, in all cases, includes the coastal zone, beaches, territorial waters and the natural resources of the economic zone and the continental shelf. This provision is unique in the constitutions of Western Europe. It was incorporated with the firm intention of ending the actions of individuals for misappropriating enclaves situated in these areas, enclaves that had been respected, as we have seen, by the Port Laws of 1880 and 1928 and the Coastal Law of 1969. Therefore, the aforementioned property is state-owned and in the public domain, in accordance with the definition established by law, which must be approved by Parliament and that, at the same time, may determine other state-owned property.

The legal regulation the aforementioned provision refers to is Law 22/1988, of 28 July, on coastal development, implemented in the Coastal Regulations passed by Royal Decree 1471/1989, of 1 December. Law 22/1988 was amended by Law 2/2013, as mentioned above. And, by virtue of Spanish Royal Decree 876/2014, of 10 October, the General Coastal Regulations were approved, which completely replace the regulations of 1989. Over the following pages, we look at how beaches and dunes were dealt with in the 1988 version of the Coastal Law and the 1989 Coastal Regulations. In the next section, we look how they are affected by both Law 2/2013 and the new General Coastal Regulations (see also Pons Cànovas, 2015).

In implementing Article 132.2 of the Constitution, Law 22/1988 defined the MTPD more broadly than its predecessor. The definition of beaches, which are included under estuary and seashores (Article 3.1), changes from areas of nearly flat surface with either sparse and characteristic or no vegetation in the 1969 statute to areas of loose material deposition (sand, gravel, pebbles), including escarpments, berms[4] and dunes, *with or without vegetation, formed by the action of the sea or sea winds or other natural or artificial causes* (Article 3.1.b).[5]

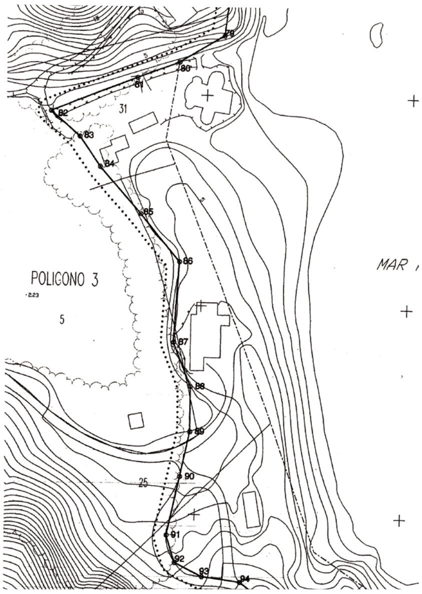
The express classification as public property of all dunes, fixed or shifting, with or without vegetation, formed by natural or artificial causes, far or near to the sea, was necessary and represented an attempt at repairing historical errors with catastrophic consequences from an environmental, landscape and territorial perspective. Article 4.d of the Coastal Regulations pointed out that the delimitation of the beaches would preferentially include dunes shifting or evolving owing to natural causes: “Dune ridges that are developing, shifting or evolving owing to the action of the sea or sea winds are to be included in the delimitation of the beach.” Dunes fixed by vegetation or that were stable were to be included “to the extent necessary to guarantee the stability of the beach and protect the coastline”.

The dune delimitation in the 1989 Regulations has been taken with reservations by more recent case law, which establishes a broader interpretation of the dunes to be included in the MTPD, regardless of whether active or stable. This is seen in the Supreme Court’s judgements of 13 July 2001 (RJ 2001/7660), of 17 December 2009 (RJ 2010/2905) and 14 December 2011 (RJ 2012/2738), and also the National Court (*Audiencia Nacional*) rulings of 20 April 2011 (JUR 2011/154772) and 6 May 2014 (JUR 2014/144415). The Supreme Court’s judgment of 17 December 2009 states that “the solution is found in the wording of Articles 3.1.b) of the Coastal Law and its Regulations, which include the dunes as part of the seashore, with or without vegetation, formed by the action of the sea or sea winds and other natural and artificial causes, *without leeway for restricting the scope of either concept* under an interpretation of Article 4.d) of the aforementioned Regulations such as that made by the trial court, *so that, whether shifting or evolving or not, coastal dunes formed by the action of the sea or sea winds must be included as part of the seashore*

4 The Coastal Law of 1989 defined berm and escarpments in the following terms (article 4.c): “Berm is understood to be the nearly horizontal part of the beach, within the escarpment of sharply-sloped embankment caused by the waves”.
5 This point does not appear in Law 2/2013.

and, therefore, also the marine and terrestrial public domain,[6] in contrast to the opinion of the ruling court" (Point of Law 7).

The actual demarcation of the coastline in accordance with the delimitation of the marine and terrestrial public domain under the Coastal Law of 1988 and its Regulations was done via partitions approved from the early 1990s, which replaced those carried out under the previous legislation or, on occasions, was implemented where none had existed. On many occasions, the approval of these partitions entailed including in the MTPD large areas of private property, specifically, land reached by extreme storm waves, wetlands, lagoons, marshes and flooded or floodable lowlands and, especially, active or inactive dunes (Fig. 7 and 8).



Figures 7 and 8. Plan from the 2009 ministerial order approving the Es Mercadal demarcation for Cala Pregonda beach showing the inclusion in the MTPD of stabilised dunes that formed part of the Son Ametller property. The photo on the right, taken in July 2010, is of the dunes included in the MTPD delimitation. Source: Ferran Pons.

2.3. Law 2/2013, of 29 May, on the protection and sustainable use of the coast in amendment of the Coastal Law, and the new General Coastal Regulations. The dangers of a regression in the protection of the system. The evident case of Formentera

Despite the protectionist connotation sought by more broadly interpreting the MTPD in the 1988 statute and implemented via the partitions, from the point of view of social perception, there was an unforeseen negative effect because many citizens, both Spanish nationals and foreigners, lost, under these partitions, ownership of lands and constructions located in dune systems in application of the rigid mechanism for transforming private into public property via the granting of a 60 year compensatory concession as set out in the temporary provision of the statute. A very high percentage of the complaints filed against the resolutions approving the partitions confirmed the delimitations, demonstrating that they had not been

6 Italics, ours.

done arbitrarily. However, given the pressures from many spheres, the new coastal regulations permit reducing the scope of the MTPD. Thus, in the near future, large extensions of dune systems could be excluded from the MTPD and, therefore, from the protection inherent to the status of public property, even though, in any case, Law 2/2013 diminishes this protection.

Indeed, according to paragraph b of Article 3.1 of the Coastal Law, the seashore and estuary shore include the beaches, which are considered areas of loose material deposits, such as sand, gravel and pebbles, including escarpments, berms and dunes. Dunes, regardless of their definition, are included "to the extent necessary to guarantee the stability of the beach and the protection of the coast", with the removal of the reference to them having or not vegetation and being formed by the action of the sea or sea winds or by other natural or artificial causes. However, the true extent of the regulatory change lies in the General Coastal Regulations, which allow excluding stabilised dunes from the MTPD, aside from exceptional cases in which the best scientific evidence available demonstrates that they are necessary to guarantee the stability of the beach and the protection of the coastline. These new Regulations also incorporate criteria targeted at excluding parts of active or shifting dunes to define the limit that must be observed for guaranteeing the aforementioned stability and protection (Pons Cànovas, 2015).

In accordance with these criteria, the higher the of trees or shrubs on a dune, the greater the possibilities that the dune will be considered stabilised, regardless of whether activity may be occurring. Thus, the characteristics of each area and dune system are what should be considered for delimiting which part of a stable dune is necessary to guarantee the stability of a beach and the protection of the coast, taking into account that the coastline is a dynamic system.[7] Furthermore, aside from the fact that some fixed dunes form part of natural habitat types of community interest, which must be preserved through the designation of special areas of conservation, with the current and future outlook regarding the effects of climate change on the coast, guaranteeing the stability of the beach and protecting the coastline must be seen as a strategic measure against the more than likely regression of the system (according to the National Court's judgment of 6 May 2014). It is paradoxical that the clause that allows for a broader interpretation of the guarantees for stabilised dunes, introduced at the last minute in the Regulations by the Ministry for Agriculture, Food and the Environment at the request of the Council of State, is reserved for exceptional cases, when the "best scientific evidence available" requires preserving all the dunes with regard to the effects of climate change.

For beaches and dunes still forming part of the MTPD, the new coastal regulations allow increasing both the uses and activities and the magnitudes of any associated buildings on beaches located in urban areas, which could have a negative effect on their integrity.

Lastly, particular attention needs to be paid to the *ad hoc* defining of the MTPD in Formentera set out in Law 2/2013 in reaction to the significant effects of the partitioning of the island approved in 1997. In accordance with Section 1 of its Fourth Additional Provision, beaches are defined as "nearly flat

7 Of interest here is the Supreme Court's judgment of 16 December 2009 (RJ 2010/2872), which alludes to dunes fixed by tree vegetation, which, in accordance with the distinction made in the General Coastal Regulations, would be classed as stabilised dunes: "[…] it is one thing to say that the pine wood –and the dunes found in it, held together by the pine trees, the vegetation and the superimposed anthropogenic– is not required to act as protection for the beach because the beach's self-protection –so to speak– carried out by the beach itself is sufficient, in a vulgar sense; it is something else to say that it is not these dunes classified as grey, black or fixed– that, as a belt of contention held together by the pine trees, the vegetation and the fills, maintain the stability of what is known as embryonic and white dunes, and, as a result, of the beach itself and, in short, the coast" (Point of Law 5).

riverbanks or seashores formed by sand or stones with either sparse and characteristic or no vegetation". This concept, appearing exactly as it did in Article 1.1 of the Coastal Law of 1969, was intended to reduce the public strip of beaches and dunes, in particular at Migjorn Beach, so the original owners could recover ownership of these lands and the buildings on them. The Constitutional Court's judgment of 5 November 2015, handed down just when the new partition was being formulated,[8] ruled that Sections 1, 2 and 4 of this provision were unconstitutional and null and void under Article 132.2 of the Spanish Constitution, as the abstract elements defining the coastal zone or the beaches must be the same for the entire national territory, on the peninsula and on islands (Point of Law 12).

3. Regulations protecting natural areas and biodiversity

3.1. Community law

Although other international environmental policies exist, we believe it more relevant to examine EU environmental policy given that it forms the basis for the Spanish environmental regulations. The European Community treaties signed between 1951 and 1957 made no explicit reference to environmental protection. It was not until the signing of the Single European Act in 1986 and the successive amendments to the treaties that objectives, principles, competences and conditions for action for community institutions on environmental issues were set out.

However, the protection of natural areas originates with the passing, in 1979, of the Birds Directive (79/409/EEC), replaced in 2009 by the current directive (2009/147/EC), which imposes on member states the obligation to preserve, maintain or restore a sufficient diversity and area of habitats essential for conserving all species of birds that live there. EU nature protection is completed with the Habitats Directive (92/43/EEC), which aims to guarantee the biodiversity by conserving the habitats and wild flora. This directive also creates the Natura 2000 ecological network, which also includes the areas of special protection designated under the provisions of the Birds Directive. In Annex 1, dunes are listed as a natural habitat of community interest.

Regarding this habitat, which is what concerns us here, and particularly in the case of the Balearic Islands, neither the obligations nor the deadlines established by the Directive have been observed given that it was not until 27 March 2015 that the Balearic Islands Government approved, by decree, the first of the management plans for the special areas of conservation (SAC), three of which are for areas containing dune habitats: Mondragó, Es Trenc-Salobrar de Campos and Albuferes de Mallorca. According to official Balearic sources, over the coming months the remaining management plans will be drafted, so the islands will have, in total, 25 management plans.

This failure to meet the deadlines and obligations set out by the Directive was the basis of the Court of Justice of the European Union's judgment of 22 September 2011, which convicted Spain for not having

8 On 28 July 2015, the Coastal Department of the Balearic Islands established the demarcation procedure of the MTPD in Formentera and opened a period for public information of one month (Balearic Islands Gazette no. 118, 6 August).

a conservation system that guaranteed the legal protection of the Macaronesia biogeographic region, of which the Canary Islands forms part.

3.2. National law

When the Spanish Constitution was enacted, Law 15/1975, of 2 May, on Protected Natural Areas, was in force. This statute established the protection of particular areas –therefore offering no broad concept for safeguarding the environment– and set out a classification of protection schemes: integral reserves of scientific interest, national parks and natural sites of national interest declared so by law, and nature parks ruled by decree. This designation by law was criticised on the grounds that it precluded having a declaration process in which all stakeholders could participate (Pérez de Andrés, 1998).

This statute was replaced by Law 4/1989, of 27 March, on the Conservation of Natural Areas and Wild Flora and Fauna, which provided protection to natural resources that went beyond the protected natural areas. This statute meant the introduction of plans regulating natural resources, which opened the doors for citizen participation in public matters when the decisions adopted affected their interests. These plans place a limit on spatial planning instruments and reflect the distribution of competences set out in the Spanish Constitution, given that "the declaration and management of parks, nature reserves, natural monuments, protected landscapes and areas included in the European Natura 2000 ecological network correspond to the autonomous communities in which these elements are situated" (Article 21.1); national parks being the only exception, which are declared by law. This legal regulation consolidated the protection schemes created by Law 15/1975, of 2 May, on parks, nature reserves, natural monuments and protected landscapes.

Subsequently, Law 4/1989 was replaced by the current Law 42/2007, of 13 December, on Natural Heritage and Biodiversity. The most important aspects of this statute include the obligation of all public authorities to ensure the conservation and rational use of the natural heritage (Article 5); the creation of a Natural Heritage and Biodiversity National Strategic Plan that defines conservation objectives and actions; the sustainable use and restoration of heritage and natural resources; the maintenance of plans regulating natural resources and the implementation of the European Natura 2000 ecological network introduced by the Habitats Directive. The same concepts are protected with the addition of the marine protected areas.

3.3. Regional, autonomous community law

When it became an autonomous community, the Balearic Islands had urbanisation plans aimed at legitimising development; towards the end of the Franco regime and prior to the Transition, planning was carried out to promote urban development (Rullán Salamanca, 2010).

During the 1980s, local council development plans followed the same model of growth as seen in the plans in the Franco period. The first statute passed by the Balearic Parliament was 1/1984, of 14 March, on the Regulation and Protection of Natural Areas of Special Interest (NASI), which allowed protecting areas threatened by development projects (Rullán Salamanca, 2010). The legal provisions of this statute were applied to specific cases. In 1991, for a more general application, Law 1/1991, of 30 January, on Natural Areas and the Development Regulation of Special Protection Areas in the Balearic Islands was introduced with the aim of establishing a framework for urban development in areas requiring special protection. This statute defines the special protection areas of interest and determines that these areas are to be regulated by special plans (Article 9). Furthermore, it provides dune systems in these areas the highest level of protection (Article 11).

Nonetheless, in the case of Minorca, in some locations cars parked in dune systems in NASIs accessible by road (Fig. 9 and 10). It was not until 2003 that Minorca had four special plans for beaches and dune systems.

Figures 9 and 10. Vehicles parked in the dune system at Cavalleria Beach, Es Mercadal, 1994. Source: Minorcan Island Council. Vehicles parked in the dune system at Binimel·là Beach, Es Mercadal, 2003. Source: Josep Lluís Florit.

Law 5/2005, of 26 May, for the Conservation of Areas of Environmental Relevance bears resemblance to Spanish Law 4/1989 and represents the legislative recognition in the Balearic Islands of the Natura 2000 network (Carreras and Truyol, 2009). In accordance with this statute, protected natural areas in the Balearic Islands are classified as nature parks, natural sites, nature reserves (integral and special), natural monuments, protected landscapes, and sites of scientific interest and micro-reserves.

In conclusion, this body of regulations offers a general approach to the beach-dune system and limits its specific regulations to special and management plans to regulate them; these are plans that contain, at the most, definitions of this habitat, but in which there is a lack of technical criteria for adequately managing and conserving them according to their morphological characteristics.

4. Analysis of dune system management

Since the 1970s until the present day, the management of beaches and coves has been marked by the observance of basic hygiene regulations and the installation of leisure services for users. These habitats are seen as appendages of urban and tourist areas, without taking into account environmental aspects (Roig Munar, 2010).

On the Balearic Islands, tourism and leisure activity on the coast, especially in summer, has a significant environmental impact. Studies performed on the Minorcan dune systems (Roig Munar, 2010) have found high levels of degradation in the dunes attributable, in some cases, to incorrect use and management. Although the law protects the natural areas from a development point of view, appropriate management is also required, based on a knowledge of the environment.

In the following sections, we briefly analyse some of the actions undertaken by the Government that have an impact on this natural environment.

4.1 Beach cleaning system

Article 115 of Chapter III, Title VI of Coastal Law 22/1988, of 28 July, gives responsibility for cleaning the beaches to local councils by establishing that they are competent to, among other functions, keep the beaches in an appropriate state of cleanliness, hygiene and health. This article was not amended in the reform of the Coastal Law approved in 2013.

Public authorities focus on maintaining the hygiene of the more urban beaches and disregard the consequences this may have owing to the use of a specific type of cleaning system. For many years in coastal tourist areas, it has been standard practice to use mechanised cleaning equipment without taking into account their environmental and geomorphological characteristics.

According to Roig Munar (2010), the systematic removal of *Posidonia oceanica* and the mechanical cleaning of beaches has caused, over recent decades, the degradation of dune systems. Owing to a lack of information, among other reasons, berms covered with *Posidonia oceanica* are seen as dirty. As a result, tourist operators ask the Government responsible for cleaning the coast to “clean” the beach when it is precisely this cleaning that degrades the beach.

We should point out that in the case of Minorca, since 2000, an integral management plan for the beach-dune systems has been in place, which has entailed applying management methods based on morphological, social and scenic criteria that has allowed halting the degeneration of these systems (Roig Munar, 2010). The Minorcan Beach Cleaning Service is a joint service set up by the Minorcan Island Council and seven local councils of the island.

Figures 11 and 12. Examples of mechanical cleaning and the removal of Posidonia oceanica. Source: Francesc Xavier Roig Munar.

4.2. Car parks near the beach

Car parks close to the beach are an indicator of the pressure that beach-dune systems are subject to as a result of the presence of users (Roig Munar, 2010). High beach frequentation rates cause alterations to the morphological balance of the system and its flora and fauna and endanger its natural operation and conservation (Roig Munar, 2010). In the case of the natural areas of special interest (NASI), the special protection plans regulate the technical characteristics of the car parks located in these areas by calculating the number of cars authorised depending on the usable surface area of the beach. However, in some cases this provision is violated, as can be seen in the following example.

On 16 June 2003, the Island Town Planning Commission of the Minorcan Island Council approved the Special Protection Plan for the Me-3 NASI, which includes a 4000 m² car park for a maximum number of 200 vehicles for Cavalleria Beach (Es Mercadal). This car park was to be split in two modules, each of 2000 m² and for 100 cars (Fig. 13). However, as we can see from its current state, the car park was extended without any amendment to the regulations (Fig. 14 and 15).

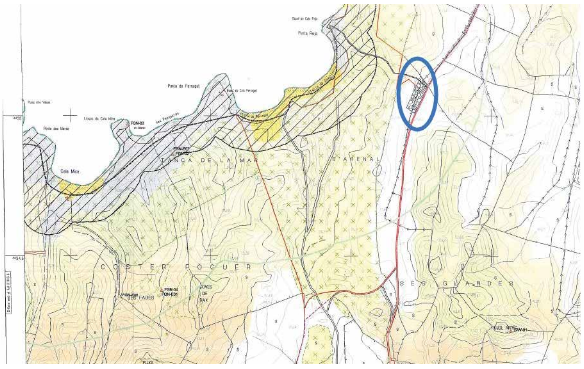


Figure 13. Plan for the Cavalleria car park (Me-3 NASI Special Plan). Source: Minorcan Island Council.
Figure 14. Image of this car park retrieved from Google Maps in the summer of 2015. The yellow circle shows the car park extension. Source: Google Maps.

Figure 15. Cavalleria car park in July 2015 — the part corresponding to the yellow circle in figure 14. Source: Carme Garriga.

4.3. Vehicles parking in dune systems

In some areas of Minorca, vehicles have been observed to park in dune systems. This was shown by Roig Munar and Juaneda Franco (2009) as part of the 15th anniversary of Minorca as a biosphere reserve, where they brought attention to, among other courses of action for environmental management, the eradicating of parking on beaches and dune systems, which still occurred.

One of these areas is Portitxol Beach, located in the S'Albufera des Grau Nature Park. Article 2 of the Plan Regulating Natural Resources , approved on 16 May 2003, states that one of the plan's objectives is to protect the natural resources, and the dune communities are one of the environment types categorised for the park.

Article 30 of this plan explicitly addresses dune systems and establishes, among other aspects, the following: "Dune systems must be subject to specific conservation measures, and, except where justified for reasons of conservation or security, the use of motor vehicles, bicycles and horses is prohibited on both dunes and beaches." Despite this provision, we find cars parked in dune systems violating the existing regulations (Fig. 16).

Figure 16. Vehicles parked in the dune system of the Portitxol Beach, summer 2015. Source: Carme Garriga.

Another area with the same problem is Viola de Ponent cove, near Cavalleria Beach in the Me-3 NASI, in the north of Minorca. In this area, the Special Protection Plan provides for a car park for 10 vehicles with a surface area of 300 m², but the cars park on the sand (Fig. 17).

Figure 17. Vehicles parked at Viola de Ponent cove in summer 2015. Source: Carme Garriga.

4.4. Dune systems and integrated coastal zone management

Beach-dune systems should always be managed using the integrated coastal zone management (ICZM) model, without discarding the option for implementing environmental management systems (EMAS, ISO

14401), as has been done in several beaches in Catalonia (Ariza *et al.*, 2008; Ariza, 2011). Of particular interest in Recommendation 2002/413/EC of the European Parliament and of Council, of 30 May 2002, concerning the implementation of integrated coastal zone management in Europe, is the Protocol on Integrated Coastal Zone Management in the Mediterranean,[9] approved by Council Decision on 13 September 2010 (OJEU L 279, 23 October 2010). This protocol came into force on 24 March 2011 and must be observed by Spain, one of the signing countries.

The importance of this protocol lies in the defining of the integrated coastal zone management model and its objectives and principles. Specifically, this model is defined as “a dynamic process for the sustainable management and use of coastal zones, taking into account at the same time the fragility of coastal ecosystems and landscapes, the diversity of activities and uses, their interactions, the maritime orientation of certain activities and uses and their impact on both the marine and land parts” (Article 2). Its objectives include to: “facilitate, through the rational planning of activities, the sustainable development”; “ensure preservation of the integrity of coastal ecosystems, landscapes and geomorphology”; “achieve coherence between public and private initiatives and between all decisions by the public authorities, at the national, regional and local levels, which affect the use of the coastal zone” (Article 5). The general guiding principles for signing parties include: guaranteeing “cross-sectorally organised institutional coordination of the various administrative services and regional and local authorities competent in coastal zones”; conducting preliminary assessments on “the risks associated with the various human activities and infrastructure so as to prevent and reduce their negative impact”; preventing “damage to the coastal environment” and, where it occurs, carrying out “the appropriate restoration” (Article 6). Furthermore, in accordance with Articles 11 and 12, special protection of coastal and island landscapes must be guaranteed.

Therefore, the application of this management model could prevent damage and other negative impacts similar to those detailed above. These guidelines, which are compulsory, might allow overcoming the bleak prospects foreseen in new regulatory framework on coastal development. Basically, it entails a firm commitment to a dynamic, active, coherent and participative form of management. Such an approach faces needs even prior to disputes arising and takes into account the integrity and fragility of the beach-dune systems. It is based on rationally planning the permitted public and private services and activities and how these interact. It also addresses marine areas. Furthermore, it coordinates the actions of the different public authorities with competences in all these areas.

5. Government liability in protecting beach-dune systems

Public authorities, within the scope of their respective powers, must protect the environment, policing and penalising actions and activities of individuals that damage natural resources, including beaches and dunes. However, the authorities themselves, in their interventions or lack thereof and in providing services, can also damage these resources. In such cases, are there grounds for some form of Government liability?

9 Officially, the “Protocol to the Convention for the Protection of the Marine Environment in the Coastal Region of the Mediterranean”, or the Barcelona Convention, signed in Barcelona on 16 February 1976 and effective as of 9 July 2004.

The general framework for Government liability is governed by Articles 139 to 146 of Law 30/1992, of 26 November, on the legal framework for Government agencies and the common administrative procedure. This statute's basis is found in Article 106.2 of the Spanish Constitution, which establishes that individuals are entitled to compensation for any harm caused to any of their property or rights where such harm is a result of the operation of public services. In accordance with these provisions and the case law, various elements must be present to establish Government liability: the existence of harm or damage to property or rights of the individual in question; effective damage economically assessable and individually assignable to the person or group of people in question; attributability to the Government of the acts causing the injury or harm; a causal relationship between the act attributed to the Government and the injury caused; and the filing of the liability action within one year from the act for which compensation is sought.

According to Conde Antequera (2004), taking into account these requirements, which are not usually present in cases of environmental damage, we must distinguish between Government liability for damage caused to individuals — where reparation takes the form of compensation, and Government liability for damage caused to the environment as an independent legally protected asset, in which case reparation is based on restoring the environment to its Government prior to the damage caused by the normal or abnormal operation of the Government . In the second case, liability would be pursued through a people's action, in which case standing to sue usually falls to environmental protection associations. This author goes on to state that the existence of liability for environmental damage cannot be denied and that this liability is based on Article 45.2 and 45.3 of the Spanish Constitution:

> "Public authorities must ensure the rational use of all natural resources to protect and improve the quality of life and preserve and restore the environment, based on the indispensable principle of collective solidarity.
> In accordance with the law, criminal and, where applicable, administrative sanctions shall be established for violators of the provisions in the previous paragraph, who will be required to repair the damage caused."

With regard to period of limitation for the action, Conde Antequera (2004) considers that the term of one year from when the act occurs is not applicable given that if the harm is prolonged over time, the period of limitation cannot start until the act(s) giving rise to the liability cease.

Jordano Fraga (2006) believes that denying the possibility for Government liability for independent environmental damage would amount to giving the Government carte blanche to violate a collective legal right. He believes that even if the damage was caused by individuals, there still may be grounds for Government liability if environmental protection is considered a function of the Government. The Supreme Court's ruling of 28 April 2010, on a landfill against which complaints had been filed by the Spanish Nature Protection Service (*Servicio de Protección de la Naturaleza*), confirms the existence of Government liability owing to abnormal operation in the managing of the landfill because the Government did not duly carry out its duty of inspection, apply corrective measures, etc., even though the individual guilty for starting the fire that caused the damage to the adjacent property is unknown. This case, however, involves damage caused to specific individuals and not to the community.

What do we consider the normal and abnormal operation of the Government? The Government can cause damage in providing services (*culpa in committendo*), either through actions of public servants or intermediary companies, but it can also cause damage through not carrying out its duty of supervising or controlling actions (*culpa in vigilando*) or through not having provided the environmental protection service required of it (*culpa in omittendo*), in other words, by omission. However, according to Lozano Cutanda (2009), this system of extra-contractual liability is ineffective for repairing damage to *public* or *independent* natural resources. For instance, take the destruction of a habitat in a public nature park. In this case, no harm is done to the rights of any particular individual and, therefore, the harm cannot be assigned to any individual that could cause citizen action against such harm. Furthermore, on some occasions, damage repair is not the priority; rather, the focus is on compensation. To make up for the deficiencies in the systems of extra-contractual liability for providing coverage to environmental damage, the EU passed Directive 2004/35/EC, which was transposed to Spanish law in Law 26/2007, of 23 October, on environmental liability. Thus, this system of environmental protection complements the others existing in the law.

The aim of this statute is to govern the liability of operators to prevent, avoid and repair environmental damage caused in the exercising of their economic or professional activities (Articles 1 and 3). Its definition of operator includes entities carrying out non-profit activities (Articles 2.10), as, according to Lozano Cutanda (2009), the Government providing public services. However, as Soro Mateo (2009) states, public authorities are included in this statute's scope of application when they act directly and not indirectly via subcontractors or concessionaires, as Article 2.10 defines operators as Government contractors and concessionaires. This fact is seen by De Miguel Perales *et al.* (2007) as an unjustified privilege of the Government. Indeed, this contrasts with numerous judgements of the Supreme Court, including those of 18 December 1995 and 25 October 1996, which find the state liable for damage caused through the normal or abnormal operation of public services, regardless of whether directly or indirectly managed by the Government. In other words, the Government, when providing a public service in accordance with its powers, cannot transfer its liability to the contractor, without prejudice to the Government's right to file for recourse against the contractor.

The Environmental Liability Law (26/2007) states that environmental damage includes damage to habitats set out in the Habitats Directive and damage to the seashore (in both cases, dunes are included) that causes significant adverse effects to the possibility of achieving or maintaining a favourable state of conservation (Article 2.1.a. and c). However, what happens when these effects are not significant? Soro Mateo (2009) believes that national regulations should adopt an all-encompassing definition of environmental damage that includes significant, less significant, severe and less severe damage so that all damage, regardless of how minor, is repaired, given that this type of damage is usually the result of a combination of diverse minor deteriorating actions, which in isolation may not be very severe but together can be devastating and require costly reparation.

An important provision in this statute is its recognition of nonprofit organisations with a mission to protect the environment as having standing to sue on the grounds of liability (Article 42). A clear example of such entities would be environmental non-Governmental organisations.

Thus, having analysed the system for pursuing Government liability for environmental damage, we find there is a whole range of procedural problems, despite the existence of environmental regulations that must be observed, both by the Government and citizens.

The Government must be liable for its actions or omissions in managing public services as the party responsible for protecting and conserving our environment and, notwithstanding the procedural labyrinth, as citizens, we have the right to demand the attribution of liability, specifically identified under our rights for effective judicial protection and access to justice on environmental matters.

In the specific case of beach and dune management, local Government, in particular local councils, have often subcontracted the cleaning of beaches to private companies without establishing criteria that guarantee minimum standards for the recuperation and stability of beach-dune systems. Furthermore, and with regard to regulating beach frequentation and access, through the cases examined and without forgetting the Coastal Department’s liability in control and monitoring duties, we have seen that in recent years the Minorcan Island Council, as the competent organ for spatial planning, which includes the coast, has not provided the protection that it should.

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Management of dune fields on the coasts of Asturias, Cantabria and the Basque Country (Cantabrian Sea, NW Iberian Peninsula)

G. Flor-Blanco[1] and G. Flor[1]

1 Department of Geology. Universidad de Oviedo. Asturias, Spain. Geomorphology and Quaternary Group (GeoQUO)

1. Abstract

This article details the main interventions carried out on dune systems on beaches managed by the coastal authorities and autonomous communities on the Cantabrian Sea (northwest Spain). Environmentally and extensively, the actions carried out have been relatively compatible; in particular, creating artificial dunes and homogenising their geometries, protecting zones with deterrent fencing, sand traps and walkways, planting native dune vegetation in different fields, as well as dunes created by lengthening breakwaters. However, these actions have been relatively scarce, partial and, in some cases, unnecessary, while numerous beach and dune locations that require some type of improvement have been overlooked, although the Basque Country greater sensitivity to this issue is worth mentioning. Overall, the most negative interventions are those linked to the ports of Avilés and Santander, which have led to intense recession of the associated dune fields, and the construction of a large artificial dune at El Puntal de Laredo and other much smaller ones, such as reduced sections to the south of Laredo (La Salvé), in Somo and in Navia. This study proposes creating some form of protection, expanding the small area of dunes within the El Espartal Beach Natural Monument, the lobular climbing dune at Xagó and the Sonabia dunes. In addition, the authors suggest monitoring and analysing all the dune sites to reduce the risk of current and future loss associated with the gradually rising sea level, which calls for research into sedimentology, environmental and historical information.

2. Introduction

The Cantabrian region has a temperate-humid Atlantic climate and has developed on a steep rocky coast that follows a W-E direction reaching heights of up to 100 m, higher in the Basque Country, and not as steep at the western edge. The Cantabrian Mountains rise up along the southern fringe, running parallel to the coastline, with drainage divides unevenly situated at a distance of between 40 and 60 km. Numerous coastal rivers and streams empty out into the sea forming estuaries, between which lie coves and beaches, both sandy (the predominant type) and gravelly, and to a lesser extent mixed.

The drainage basins supply the coast with siliciclastic sands that form beaches and dunes and, in some fluvial systems with fast-flowing runoff in floods, with gravel fraction as well. The sands are transported by a continuous longshore drift towards the east generated by the prevailing winds and swells from the Atlantic in the third and fourth quadrants. Bioclastic carbonate sediments have formed along the coastline as a result of local upwelling and the extrusion of nutrients and organic material from the estuaries in well developed mud flats and marshes. The benefitting organisms form part of the mainly cliff habitats (Flor *et al.*, 1982).

Variations in sea level have played a long-term role (from centuries to millennia) in the formation of the estuaries, beaches and coastal dunes. The estuaries filled with sediment during the Holocene and most of the oldest dunes were created from the eustatic maximum onwards (Flandrian transgression: 4500-5000 years BP). The subsequent drop in sea level left wide stretches of beach behind, which migrated towards the sea and were susceptible to deflation, forming dune fields on the upper beach. In recent decades, the level of the Cantabrian Sea has risen at rates of 1.7 ± 0.2 mm year-1 (García-Artola *et al.*, 2014), leading to the irreversible loss of a great number of dunes, which was compounded by severe storms during the winter of 2014 (Flor *et al.*, 2014). These two mechanisms essentially control the evolution of beach systems and the associated dunes, while the management of dredging and civil construction can have a substantial impact on the dynamo-sedimentary balance.

The beaches are generally enclosed between promontories, but they also form part of the confining barriers and internal bays of the estuaries, and are mainly sandy but occasionally made up of gravel. If the beaches have or at some point had a surplus of sandy sediment, this permits the development of dune fields formed by sea winds blowing inland. Generally, this type of dune barrier is most common, towards the east of large rivers, due to west-east flowing longshore currents.

Along this coastline, sandy beaches are abundant and very popular with the public, which means that managing them requires maintaining, from a geological perspective, the dynamo-sedimentary balance in order to ensure sustainable development. The same could apply to the dune systems, which are in much greater need of conservation because of their unique plant colonisation and the processes of recession due to erosion that are currently occurring. A great deal of legislation applies to these coastal environments, from the general coverage of the 2013 Spanish Coastal Law and its Regulations, to those seeking environmental protection, many of them managed on a European level –the Natura 2000 network (SCI and SPA) and biosphere reserves–; at national and regional level –the Plan Regulating Natural Resources (PORN) (Vacas Guerrero, 2005), Coastal Management Plan (POL), with the inclusion of the figure of the *park-beach* in Asturias, and others (Florido Trujillo and Lozano Valencia, 2005)–; and also on a local level, such as urban and territorial plans and environmental protection plans, which are more directly related to beach use.

The classification of dunes that governs the protection of their habitats was proposed by European Union Directive 91/43/EEC; but other legislation should also be taken into account, such as Spanish Law 42/2007, which includes the need to establish a Spanish Catalogue of Invasive Exotic Species, and Royal Decree 1274/2011, of 16 September, approving the Strategic Plan for Natural Heritage and Biodiversity 2011-2017, under Spanish Law 42/2007, of 13 December (http://www.magrama.gob.es/es/costas/temas/proteccion-costa/TODO_tcm7-338467.pdf).

During the first third of the 20th century, a great deal of resources were invested in this coast to enlarge its fishing and commercial ports; important examples include work carried out in the estuaries to secure the main channels and lengthen the inlets with breakwaters. These actions caused the confining barriers to migrate out to sea with the subsequent formation of new and very extensive dune fields (Flor-Blanco *et al.*, 2015), as illustrated by the cases of Navia and Nalón, and to a lesser extent in Avilés, Villaviciosa, San Vicente de la Barquera, Plentzia, Deba, Santiago and Santixo (Zumaia), Orio or Antilla and Bidasoa. In addition, while the above mentioned interventions were being carried out, the estuaries were being dredged with increasing intensity when, from the 1980s, the ports were enlarged even further; one of the consequences was the dramatic recession that affected the dune fields associated with the confining estuarine barriers: Salinas-El Espartal because of the port of Avilés (Flor-Blanco *et al.*, 2013) and El Puntal-Somo-Loredo because of Santander.

The beaches and dune fields in this Cantabrian coastal zone (Fig. 1) remained relatively stable until urban development took off in the 1960s, both in terms of direct and indirect changes in these areas and those caused by rising sea levels, which played an increasingly important role in the recession of these morpho-sedimentary environments. Subsequently, the coastline has undergone a significant degree of artificialisation, essentially due to urbanisation based on the dispersed city model, which leads to a high consumption of land (Arenas Granados, 2009). It was precisely the demand for aggregates for construction and the establishment of large industrial complexes that prompted the first sand extractions from beaches and dunes from the 1950s onwards, which in turn led to the loss of sedimentary volume and the devastation of dune morphologies. This sand mining was intensive on the beach at Laida (confining estuarine barrier of Oka), in order to rebuild the city after it was levelled, and on the transition from the beach to the dunes in Xagó to supply the iron and steel industry in Avilés. Later, other sand quarries were installed in numerous dune fields — inland area of Xagó, Salinas-El Espartal, Liencres, Loredo, etc.— which eventually closed, in some cases after more than a decade of activity. Other practices, such as the introduction of housing developments, factories, industrial estates, industrial waste ponds, roads, seaside promenades, etc., have destroyed vast swaths of coastal dunes (Salinas-El Espartal, Gijón, Ribadesella, Noja, Laredo, Las Arenas on the right shore of the Nervión estuary, Plentzia, Zarautz, Zurriola...). When the sand extractions ended, the zones were refilled with urban rubble (Salinas) and domestic waste (Los Quebrantos).

A previous contribution on the beaches and dunes of Asturias and Cantabria (Flor *et al.*, 2012) has already proposed some environmental modifications in these coastal areas, which in the case of dune fields, are detailed in this study and includes dune systems of geological interest which have been environmentally managed using practices worthy of recognition. However, the application of techniques proven to have low environmental impact when recovering dune systems in Cantabria and the Basque Country has not been replicated in Asturias. Nevertheless, the experience should serve as a reference for future management, to learn from previous successes and mistakes and to determine the applicability of these practices in new interventions.

In addition, this article calls for funding and support for studies that seek to understand the formation of these natural spaces, which, due to anthropisation and the gradual and alarming rise in sea level, are currently in a critical situation in which much of the data that is so important to ensure sufficient understanding and comparison with future climate change could be lost. Dune deposits are not only useful for comparing sedimentation and recession phenomena, they also provide information about the palaeoenvironments in which these phenomena were produced, making them an extremely valuable source of information for the research community. The data contained in these deposits allows researchers to study aspects such as fluctuations in sea level during the Holocene, cyclical and exceptional storm systems, sedimentation rates before and after human intervention, traces of contamination and metals, the origin of the sedimentary contributions from the continental shelf and supplying river basins and their characteristics. As habitats protected by the European Community (Gracia *et al*., 2009), their evolution and vegetation allow us to study the species that have occupied these sites, making them an inexhaustible source of highly valuable palaeoenvironmental data thanks to woody debris, rhizoconcretions, paleosols, fauna, etc.

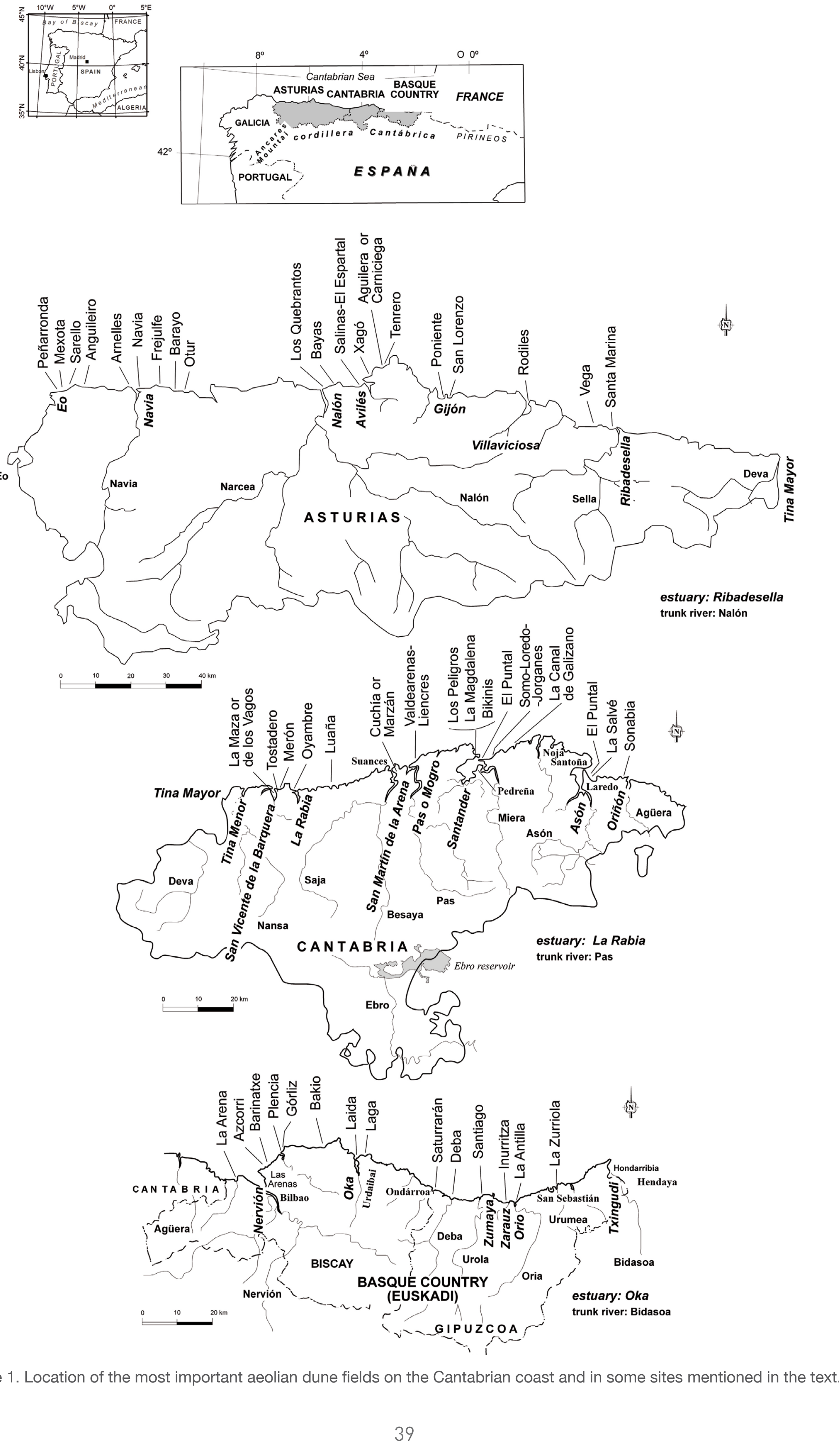


Figure 1. Location of the most important aeolian dune fields on the Cantabrian coast and in some sites mentioned in the text.

3. Dune Management

Most beaches and dunes evolve without any type of intervention, except for tasks related with cleaning, lifeguard services and other services (showers, changing rooms, etc.), which are most common during the summer. In recent years numerous dune fields have receded horizontally by metres and even tens of metres, without any remediation measures having been taken to slow down the process. These areas commonly contain car parks, disabled access points, kiosks, etc., built to provide user services, with the consequent loss of sediment and dune morphologies. If we also factor in the damage caused by storms over more than a decade, it is clear that these areas must be recovered and most of the abovementioned elements and services provided for beach users removed.

The management of the morphology and sedimentation of beaches and dunes on this coast, designed to maintain the natural balance, has been very varied, with different interventions concentrated in certain environments. On the dune fields, the usual techniques have been applied (Ley de Vega *et al.*, 2007), such as 1) fencing and roping off certain areas, 2) placing sand traps, 3) planting characteristic plant species grown in nurseries (Colmenar, 2001), 4) reconstructing new dunes and 5) extending walkways for beach access and also as paths for pedestrians. This work is usually complemented by installing informative display panels to raise public awareness of the dunes' importance in order to better enjoy and preserve them.

In the case of the beaches, some practices have led to the induced regeneration of the associated dunes. Among the most widespread we would highlight the following actions: 1) adding sediment to existing beaches to increase the surface area, 2) nourishing receding beaches with sand from the subtidal area of the same beach or from the nearby continental shelf, 3) transferring sediment from an area of the beach with a surplus to a deficient area, and 4) creating generally new embayed beaches.

Surplus sediment from the creation of the new beach at Poniente (Gijón) in 1995 was shaped into dunes at both ends of the beach by northeast and northwest wind components, respectively; the sand in the western dunes is mechanically removed and returned to the beach (Flor *et al.*, 2007-2008).

Generally speaking, the destructive effects of extraordinary storms are remediated with almost immediate interventions on public infrastructure (seafront promenades, street furniture, breakwaters, etc.), but much less effort is spent on re-establishing the morpho-sedimentary stability of beaches and even less on dunes.

4. Examples in Asturias

Asturias' beaches, including those with dunes, remain relatively unspoilt in the cases where improvements have only been made to access points and parking areas, some of which are privately owned. Urban beaches have been enclosed with walls and promenades, sometimes built on former dune fields, with the added problem of being exposed to the damage that storms can wreak on public engineering works and street furniture.

Most of the dune fields in Asturias develop without any type of intervention, despite the fact that during the past two decades they have receded by several metres. Some have been partially rehabilitated by closing vehicle access and homogenising morphologies in zones where sand was previously extracted, building toilets for use in summer, laying walkways to access the beach, etc., as is the case with Penarronda, Los Quebrantos, Salinas-El Espartal, Xagó and Rodiles. One of the negative aspects identified on the best preserved beaches is that roads and car parks are being built to the detriment of the sand dunes, such as in Navia, Frejulfe, Los Quebrantos, Bayas and Vega. Some beaches have suffered irreversible development, such as San Lorenzo (Gijón) and Santa Marina (Ribadesella), inland areas of Los Quebrantos and Rodiles and, rather extensively, Salinas-El Espartal beach.

4.1. Barrier beach-dunes of the Barayo estuary

This morpho-sedimentary unit, which has developed at the mouth of the Barayo coastal river (Fig. 1, western Asturias), covers a surface area of 3.42 km^2 which is protected as a Partial Nature Reserve (Decree 70/1995) and is also part of the Site of Community Importance (SCI) and Special Protected Area (SPA) of Penarronda-Barayo.

A wide beach area and dune system form the confining barrier of a small estuary with very little saltwater intrusion. Behind this barrier, sub-halophilic marshes populated by sea rush *(Juncus maritimus)* and reeds *(Phragmites australis)* have developed, as have hygrophilous meadows with the riverbed and main estuarine channel following a meandering path. The beach is dissipative with the development of a broad low-tide terrace, temporarily sectioned most frequently by a central riptide.

The dunes, which are suffering considerable recession, constitute an extremely important dune field formed by the progradation of two systems of foredunes, interrupted by lee-projection or tongue-like dunes which were stabilised using pine trees. Thus, during the past 15 years the first foredune has been eroded by an average of approximately 19 m; catastrophic winter storms in 2014 resulted in dune recession of up to 18 m (Flores-Soriano, 2015), and the ridge front now has a permanent escarpment of 6-8 m (Fig. 2A and B).

The singularity of the positive management of this space stems from a decision taken by Valdés Town Council to apply the simple solution of closing the road to vehicles on the eastern side and Coastal Authority approval to install a car park and, about one hundred metres away, a wooden access walkway for pedestrians on the opposite side.

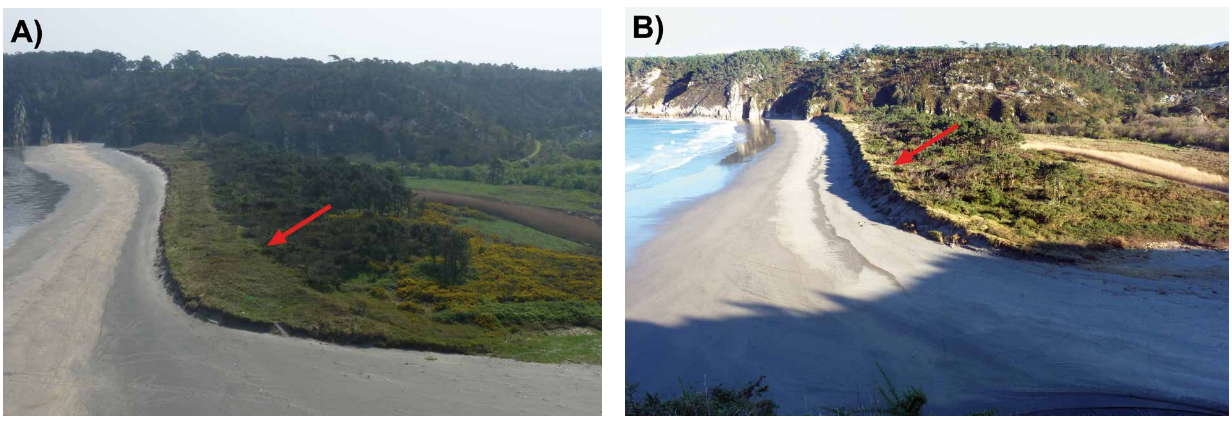
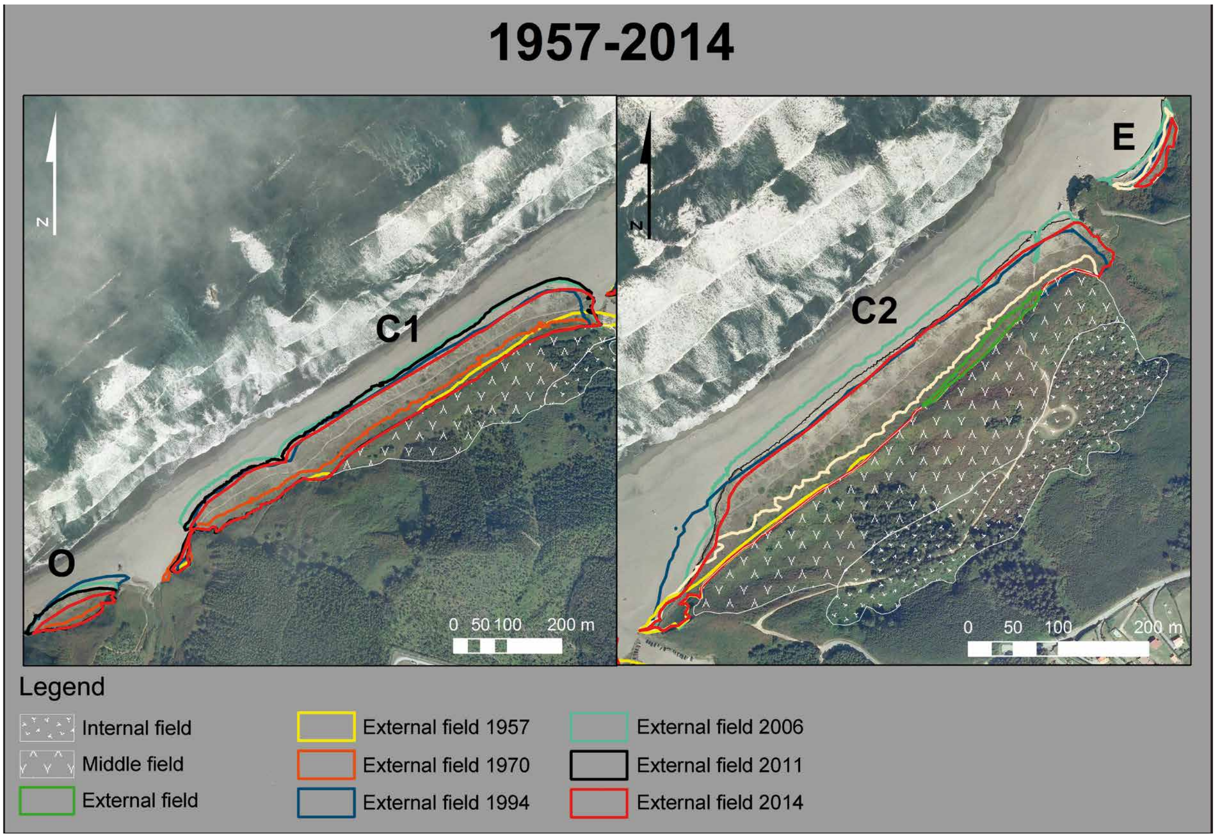


Figure 2. A) Evolution of the Barayo dune system between 2011 and B) after the storms that battered the Cantabrian coast in early February and March in 2014, showing significant recession.

4.2. Bayas beach

The beach of Bayas, together with La Deva island, was declared a Natural Monument in 2002 and also enjoys SCI and SPA protection. It is located in the municipality of Castrillón (central western coast of Asturias) and is close to 3 km long, making it one of the largest beaches in Asturias. Its considerable size is due to its proximity to the mouth of the Nalón river and estuary, which drains a very wide river basin (Nalón and Narcea rivers, which make up the largest basin on the Cantabrian coast). The sediment supplied, in particular the sand fraction, is mobilised again by dynamic longshore agents until it is finally deposited on the beach, at which point the wind transports it, by deflation, to the upper beach to form the associated dune fields.

The port of San Esteban de Pravia, situated in the Nalón estuary, became the principal coal port on the Cantabrian Sea in the late 19th century and, mainly, the 20th century. This called for the construction of an adequate port and continuous dredging of large volumes of sand to maintain suitable draughts for shipping. This process brought about a sedimentary deficit in the system that was noticed at the adjacent Bayas beach, where for more than half a century there was intense erosion of the dune field (Fig. 3A and B). In the last quarter of the previous century, El Musel, in Gijón, took over as Asturias' main port, sending San Esteban de Pravia into decline and reducing the amount of dredging which, in turn, led to the creation and progradation of the dune field of the Bayas beach (Diego-Cavada, 2014).



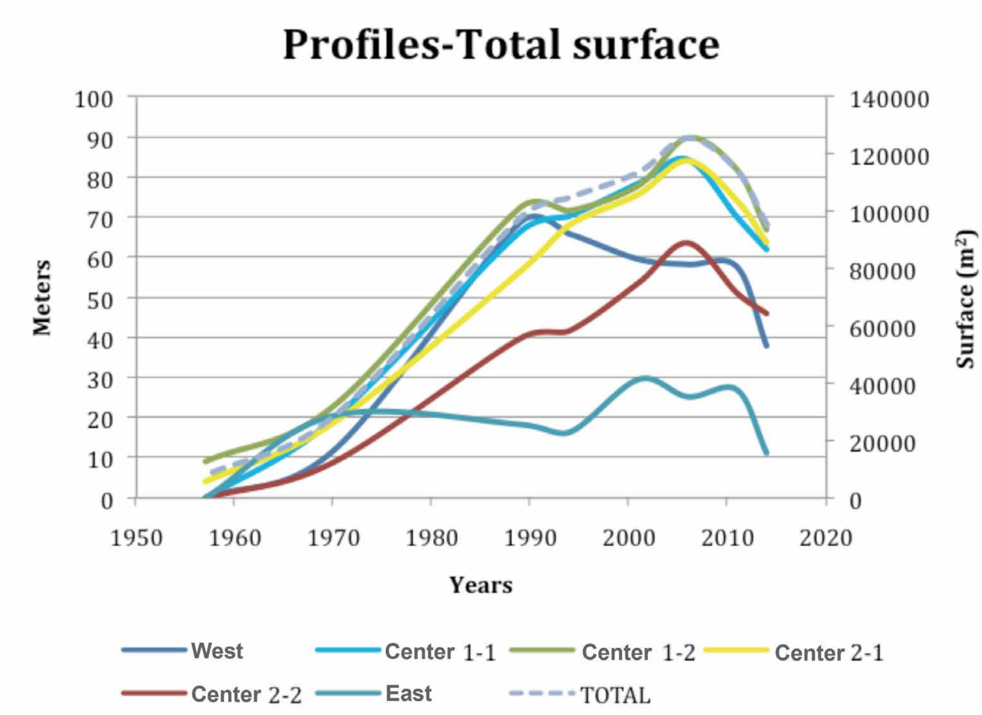


Figure 3. A) Evolution of the Bayas dune field up to 2014 (adapted from Diego-Cavada, 2014). B) All the profiles, including the total variation of the outer belt of the Bayas dune field (Diego-Cavada, 2014).

This dune field still has an inner field made up of climbing dunes, a central field —the most extensive— represented by foredunes (up to three) and important lee-projection dunes, and an outer field composed of a sand sheet and incipient dunes. This outer belt has formed over the past 50 years (Fig. 3), after the intense dredging of the Nalón came to a halt (Diego-Cavada, 2014), but is today experiencing important recession.

4.3. Salinas-El Espartal beach and dunes

This system forms part of the confining barrier of the Avilés estuary (Fig. 1, central Asturias). The representative sands are of a medium and fine siliciclastic type, although the beach also contains natural and residual gravel (tiles, cement, bricks, etc.) that was not removed after the former promenade was destroyed. The beach is large, measuring 3,260 m at the highest point of its original curve. The beach morpho-dynamics are cyclical and dissipative and intermediate in type with a low-tide terrace, and numerous rip currents develop, in some cases linked to the talus of the old promenade, where processes of wave reflection are more pronounced.

The Salinas-El Espartal dunes make up the largest dune field in Asturias, covering more than 395 ha of original surface area, and are spread out in three belts lying parallel to the beach —the inner, central and outer fields (Flor, 2004)— of which the inner (oldest) belt has been almost entirely developed and industrialised. The central belt is the largest (mainly at the eastern edge), and in places reaches heights of 30 m; the western third has been urbanised and the eastern sector has been occupied by factories and building plots as well as port and railway facilities.

Only the dunes bordering the beach were included in the El Espartal Beach Natural Monument designation, declared by Decree 81/2006 and covering an area of 0.056 km^2. Part of these dunes at the edge of the beach are on private land owned by Aldergarten S.L., with valid planning permission to build houses; the Town Council intends to exchange this land for the El Pinar de Salinas property, also located on natural dunes but further away. The space falls within the Cabo Busto-Luanco Site of Community Importance (SCI) and the Cabo Busto-Luanco Special Protected Area (SPA), and also holds Natural Beach status under the sub-regional planning guidelines for the coastal fringe of Asturias.

The area along the edge of the beach is formed by successive foredunes lying parallel to each other and to the shore, the largest of which, both in terms of width and height, is the one that borders the beach. Here there are examples of plant communities of white and grey dunes (Díaz González and Fernández Prieto, 1993; Lastra López, 2005; Díaz González, 2009). The rest of the dune, between this artificial dune and the eastern end of the previously mentioned promenade, is in quick recession (Flor-Blanco *et al.*, 2013). The same is occurring with the beach, which since 1985-1990 and onwards has been losing considerable sedimentary volume due to dredging operations in the Avilés estuary (Fig. 4A), the confining barrier of which are the beach and dunes.

The management of this dune field has consisted of the following actions:

- In the eastern sector, approximately 70,000 m^2 of beach that formed part of a filled-in building plot on the same intertidal beach, as well as a car park and toilet block, was recovered. This intervention is currently still underway as sand is being brought in by the predominantly easterly longshore transport on the beach, forming sandy lobes and an incipient foredune.

- Landfill material was cleared and the far eastern area of the beach was recovered. In the back area, 50,000m^3 of sand was used to build an artificial dune, crossed by walkways, which was then covered with sand and planted with marram grass.

- On the inner leeward side of the active foredune several warehouses and municipal buildings were eliminated and sand quarry sites were filled in.

- As an extension of the promenade on Salinas beach, in the section known as El Espartal, wooden walkways were installed running along the back of the dunes, with a total length of 1.2 km. Other smaller walkways ending in viewpoints were also installed across the dunes.

Until the 1960s, the beach continued transitionally with a gentle slope along the first dune front, except at the western boundary, where the town of Salinas was built, and the road to the Arnao factory in the east. The construction of a seafront promenade and the gradual urbanisation and installation of factories on the dune area continued to extend eastward, meaning that the active dunes only reached as far as the beach in a section measuring slightly less than half the total length.

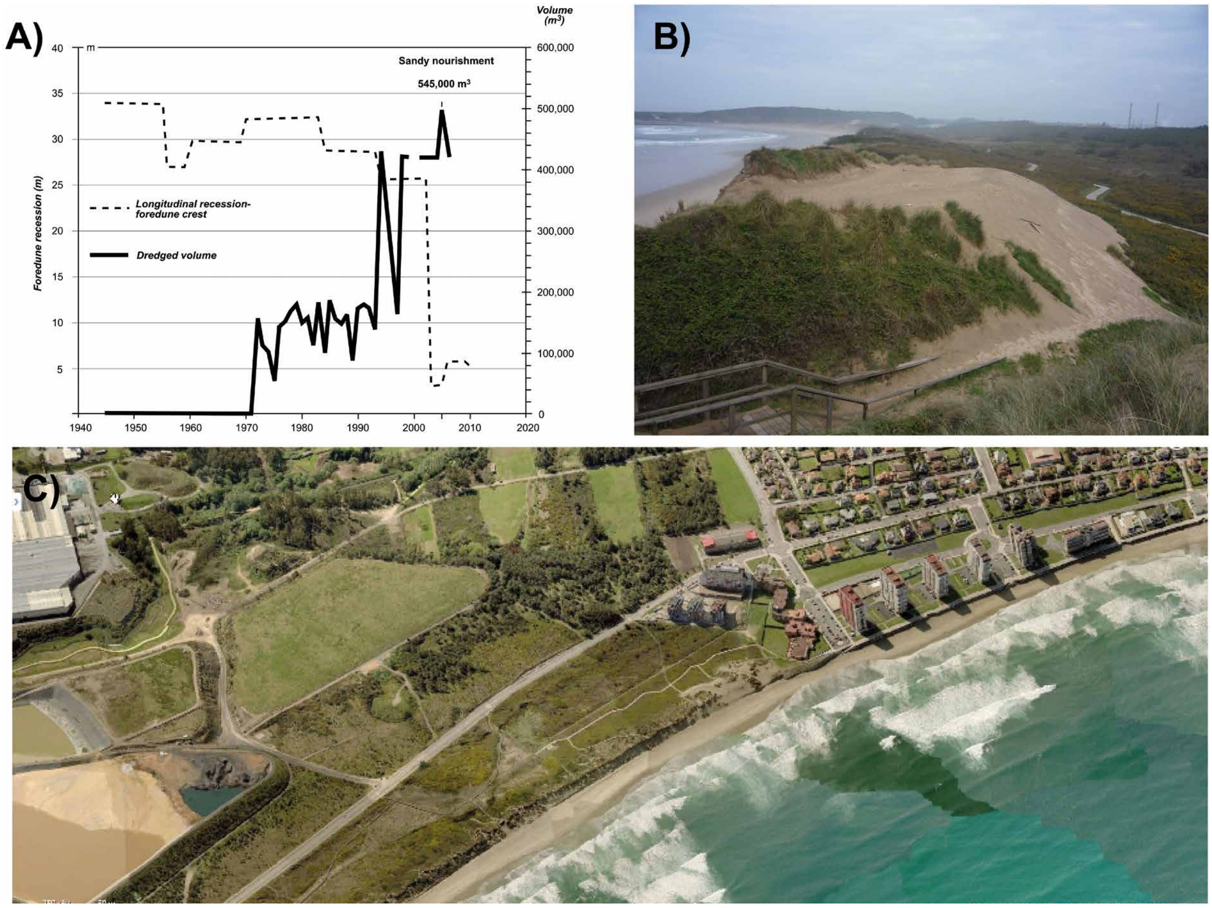


Figure 4. A) Evolution of the recession of the Salinas-El Espartal dune front in relation to the volume of dredging at the adjacent port, located in the Avilés estuary (adapted from Flor-Blanco et al., 2013). B) Lee-projection dune currently being eroded by deflation and which invades the paths crossing the dune field. C) Oblique view (Bing Maps, 2014), with the natural El Espartal dune field and its erosive front in contact with the beach, the town of Salinas, which has occupied a large part, and the jarosite spill pond (bottom left), which has distorted part of the central field.

From the 1980s, to accommodate ships of large tonnage, the installations at the port in the Avilés estuary were enlarged and the channel deepened with intense dredging campaigns. Much of the dredged material was dumped in front of the nearby Xagó beach, situated just to the east. Since then, the Salinas-El Espartal dune front has acquired a sub-vertical profile with slopes of more than 7 m.

In two areas of this dune complex in contact with the beach, trampling and use by the public in summer have led to the development of blowouts, unleashing processes of deflation with sand being transported to the leeward face of the foredune (Fig. 4B) in the form of lee-projection dunes (Cooper, 1958) or tongue-like dunes (Flor, 1986), which Favennec (2002) mentions in passing as *en tas* or *en dos en baleine* (whaleback) dunes in Aquitaine. Thus, the free dune began to suffer a process of recession that peaked during the winter storms of 2014, with horizontal losses of more than 25m close to the end of the seafront promenade (Flor *et al.*, 2014), and averaging 15.52 and 2.55m along the dune front (Flores-Soriano, 2015).

The beach, in turn, lost part of its volume to the point that the original promenade on the urban area of Salinas, built on top of the foredune, collapsed when the foundations were exposed in late-

January and mid-February 1990. The new promenade, opened in 1994, currently has serious stability problems, despite the fact that in recent years a stretch of breakwater has been built at the base to protect the footings.

CEDEX (2010) considers it necessary to supply the beach with 600,000m^3 of sand and lengthen the San Juan de Nieva breakwater, built in 2004 and 400 m long; this new replenishment would add to the 438,478 m^3 of sand dredged from the inner continental shelf in the northwest (close to cape Vidio) and dumped on the beach in 2004. The same organisation has estimated that a total of 302,633 m^3 of sand was lost between 2005 and 2009 as a result of dredging in the estuary, more than half of which (176,748 m^3) was carried out in the mouth, which is the transitional zone with the submerged beach of the confining barrier.

The proposals that the authors of this study deem necessary for the abovementioned space can be summarised as follows:

- Reuse the clean sand fraction dredged from the mouth and outside stretch of the main channel of the Avilés estuary, dumping it in front of Salinas-El Espartal beach at depths of 5 to 8 m, ideally along the western half so that the dominant incident swells from the northwest gradually transport the sand towards the foreshore and the east.

- Replenish the beach over the next two decades with volumes of 400,000m^3 every 3-4 years until reaching a total of 2,500,000 m^3, which will ensure the stability of the beach and its dunes.

- Clearly, these actions must be complemented by environmental monitoring of the backshore and submerged beach, focusing on detailed bathymetric reconstruction for each annual calm-storm cycle, and identifying gains and losses.

The recession of the dune front during the storms of 2014 destroyed some viewpoints that there are now plans to rebuild, taking advantage of an overhaul of the walkways and removal of sand mantles that have built up in some sections since they were created (Fig. 4C).

4.4. Xagó beach and dunes

Located to the east of the Avilés estuary (Fig. 1), is composed of medium and fine siliciclastic sands with some scattered gravel that tends to concentrate at the western end. This wide system of beach and dunes has suffered important direct alterations, such as intensive sand mining, several extractions of sand and dumping of sand and gravel dredged from the Avilés estuary – operations that were carried out without the necessary permits during the last quarter of the last century (Fig. 5). This oversedimentation has led to the development of a new dune in the form of a sand sheet or incipient foredune in contact with the beach. However, for the past few years the beach has contained a high proportion of coarse fractions that come from the previously mentioned dredging operations carried out in the Avilés estuary, and which become more noticeable during stormy seas.

The extensive dune complex is made up of three fields spreading out from the inner dunes to the beach: the inner field (climbing dunes), generated in the SE corner, central (large foredune) and outer (anterior foredune and sand sheet or incipient foredune). For more than a decade, a large area of the central field, to the west, was subjected to sand quarrying, while smaller sand extraction operations were also carried out on the eastern side.

Once the dispute over the demarcation of this dune system was resolved, the Asturias Coastal Authority excavated the former sand quarry site, allowing ground water to rise to the surface to create a wetland area for birds, and a perimeter road was built. The site was then included within the special protected area for birds (SPA). At the same time, certain zones were remodelled to create car parks and toilets, culminating in the installation of longitudinal and transverse wooden walkways.

In 2012, a 2,588 m-long submarine outfall was installed in the western zone to discharge treated and industrial wastewater, without any detrimental effect on the area. Today, the numerous walkways that crisscross the different foredunes continue to be used by visitors, although those located in the corridors close to the outer foredune have been covered by sand transported by deflation. This space is currently rather neglected, with a lack of waste bins and information panels and even the circular wooden structures that were used for showers and toilets have been dismantled. The current image greeting visitors is of an unkempt perimeter, with excavated dune boundaries and debris left behind from these operations.

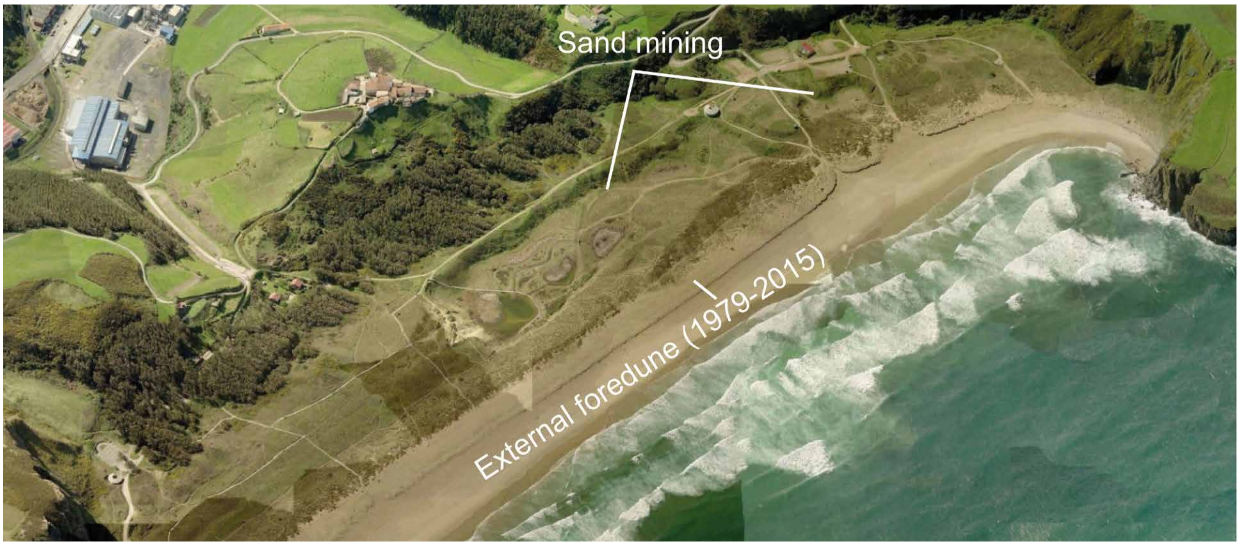


Figure 5. Appearance of the Xagó dune field (Bing Maps 3D, 2014). A large part of the central dune field was cleared for sand quarrying activity. Continuous dredging in the Avilés estuary, to the west, and the later dumping of the dredged material in front of Xagó beach has led to the formation of a foredune with a maximum width of 60 m since 1979.

4.5. Aguilera or Carniciega and Tenrero dunes (Podes and Verdicio)

These two adjacent beaches, situated on the western coast of Cape Peñas (Fig. 1) have developed dune fields; of these, the Aguilera dunes have been receding for more than sixty years, transferring sand to the eastern dune fields of Tenrero beach. Here, at an earlier stage, a field of poorly cemented eolianites was formed on top of which a number of villas were built. The outer, more recent and active group contains types of lee-projection, cliff-top and climbing dunes, one of which is vegetated while another is used for free falls as a leisure activity, which reduces the sedimentary volume. This area is ideally suited for closing off sections to encourage sand capture and the growth of some dunes.

Between 12 and 13 June 2010, the biggest cold drop ever recorded in Asturias affected above all the northern sector of Cape Peñas, Avilés and surrounding area, and western Asturias, causing severe destruction on the coast. Some of the most important damage included the collapse of the access bridge to the urbanised zone built on the old longitudinal dunes of Tenrero beach, which crossed the stream that empties out at this beach. The damming action generated by poor maintenance of the bridge's arches led to an enormous build up of mud, waste, tree trunks and water which eventually caused the structure to collapse, dragging part of the perimeter of the residential development with it and cutting across the dunes located just in front. This, in turn, resulted in the formation of escarpments more than 10 m high and the exposure, in a longitudinal slice, of the old dunes that had been covered by construction (Fig. 6). This phenomenon led to the addition of thousands of cubic meters of sand to the beach, although this was still not enough to stop the erosion caused by the storms, which together with the rise in sea level have generated eroded slopes along much of the dune front.

Figure 6. Image of the broken talus on the foredune at Tenrero beach (left), caused by the Bedular stream, and the damaged outcrop of the inner dune field in the built-up zone (right).

4.6. Rodiles dunes (Villaviciosa Estuary. Partial Nature Reserve)

The Rodiles dune complex forms the end of the confining barrier of the Villaviciosa estuary (Fig. 1, eastern Asturias) which migrated northwards following the construction and lengthening of breakwaters at the mouth since 1926 (Fig. 7A, black and white photo of 1900 previous of jetties), reaching a total length of 356 m in 1945.

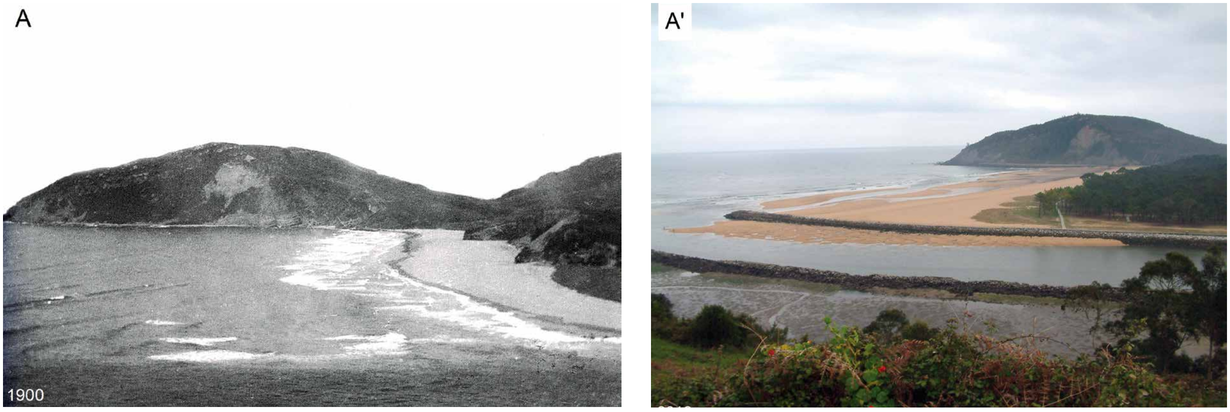


Figure 7. A) Evolution of the Rodiles dune field since the photograph taken in 1900, in its natural state. A') After the construction and lengthening of breakwaters in 2012.

This led to the formation of a wide dune field with smooth topography, due to the rapid growth of this new field. In the 1950s, eucalyptus and pine trees were planted (Flor-Blanco *et al.*, 2015) until a certain morphodynamic and sedimentary balance was achieved (Fig. 5B) before the end of the 20th century.

Around 1990 the first signs of recession were detected, reaching as far as the first trees in the western sector of the beach, the roots of which were exposed –a process that had already been seen with greater intensity in the eastern zone (Fig. 8A). Furthermore, the practice of parking vehicles on the old vegetated dunes encouraged the continuous degradation of the complex, with many of the dune morphologies altered due to the deterioration of the space and the continuing occupation of the outer foredune, most of which had by that point disappeared. From the end of the 20th century, the Asturias Coastal Authority closed off access to the vegetated dunes by planting eucalyptus and pines. Several sectors were enclosed with rope fences supported by treated cylindrical trunks 10cm in diameter and 1m tall above ground (Ley Vega de Seoane *et al.*, 2007). The showers were strategically placed at the height of the installed walkways, in what could be considered one of the best examples of good management to protect a dune system.

Figure 8. A) View of the dune escarpment at the height of the eucalyptus and pines (western end) at the edge of the beach and vehicles parked on the outer dune field, in 1995. B) View from the opposite side taken in 2014, with the loose foredune formed after the area was roped off and replanted at the end of the 20th century.

In recent years, the front of this dune has been recovered with the construction of an incipient foredune and dense natural colonisation by vegetation, with a particular profusion of *Ammophila arenaria* (Fig. 8B). Later interventions to fence off the main access walkway and the eastern side have also yielded relatively rapid and positive results.

Finally, the Asturias Ports Service's management has ensured that the system has not suffered a sedimentary deficit by dumping sediment dredged from the El Puntal channel and dock near the closure depth (Flor *et al.*, 2015).

5. Examples in Cantabria

The beaches and dunes of Cantabria follow the same pattern as in Asturias, remaining mainly in a natural state, although frequently subject to minimal alterations to facilitate access to the beaches. These dune fields have also been evolving freely, with the degree of recession varying from one beach to another.

In general, interventions have included installing vegetable fibre collectors, planting dune species with a certain level of biodiversity and closing off areas, and a series of supported and raised walkways have been built to control user access.

To remediate the destruction wreaked by storms over the past decade, particularly those of winter 2014, on some of the busiest beaches it was decided to carry out controlled regeneration operations using material from the same system, such as sand deposits from dredging the harbour channels and transfers from the submerged zone to the backshore.

5.1. Beaches and dunes of the San Vicente de la Barquera estuary

The exposed beach of Merón, located on the confining barrier of the San Vicente de la Barquera estuary (Fig. 1, western Cantabria), presents the peculiarity that in 1944 it was modified by the construction of a jetty extending beyond the original mouth, which was designed to channel the inlet and facilitate port traffic (Flor-Blanco *et al.*, 2015a). This enclosing intervention has led to a progradation of the dune belt that has fluctuated around a maximum of 200 m over the past seventy years. Due to the rapid progradation of the system, the foredunes and sand sheets generated are not extensive. From the 1970s, the dune field began to be occupied by buildings constructed on the eastern edge and a campsite installed at the rear. To accommodate the growing number of tourists, in less than two decades much of the relict dune field has been destroyed to make way for a car park, without any measures having been taken to preserve the outer foredune, not even in relation to the beach access.

Both the port and these beaches and dunes lie on the edges of the sandy bay of the estuary. To facilitate shipping access to the fishing port, the secondary channel and mouth of the estuary are frequently dredged (Flor-Blanco *et al.*, 2015a). Some of the dredged sand has been dumped on the beach and the El Tostadero estuarine dune (in a phase of recession), or has been used to create the very small new estuarine beach of La Maza or Los Vagos (east of the bridge) close to the previous one (Flor-Blanco *et al.,* 2015b). The dunes on the exposed beach, both belonging to the confining barrier of the estuary, have suffered substantial degradation, although there is a strong possibility of their recovery. The first step would be to remove the large car park situated beside the beach and relocate it further inland. Secondly, a large section bordering on the beach should be closed off to allow an active dune to develop.

5.2. Luaña dunes

The Luaña beach and dune complex (Fig. 1, western Cantabria) occupies a triangular area opening out towards the sea at the mouth of the Conchuga stream. Sand sheets formed here on an area covering 1.64 ha, over which an illegal car park and campsite were built between 1975-1988; bordering the beach there is a foredune ranging from decimetres to barely one metre in height and with widely varying widths, from just a few metres at the eastern edge to just over ten metres on the western reaches. The restored and consolidated dune in the section adjoining the beach covers a total area of 5,620 m^2.

At the end of the 1990s, a minor intervention was carried out in the outer third of the dune system (https://www.youtube.com/watch?v=6luktpRP9G4) consisting of eliminating the campsite while maintaining the recreational areas and pedestrian access crossing the stream. In addition, sand traps were installed and marram grass was planted and the dunes were closed off with staked rope fences, while the two inner thirds were set aside for parking. (https://www.youtube.com/watch?v=6luktpRP9G4).

5.3. Beach and dunes of Cuchía (Suances)

The small beach of Cuchía or Marzán (Fig. 9) has formed on the right or eastern bank of the mouth of the river Besaya, in the San Martín de la Arena estuary (Fig. 1). This beach, in turn, encloses a wide west-east valley that once contained one of Cantabria's most interesting dune complexes: the Cuchía longitudinal dunes (Flor, 1980).

The evolution of the Cuchía or Marzán dune field has been particularly traumatic, as the abovementioned longitudinal dunes were completely destroyed and the sand used as aggregate. By 1956, just over half —around 381,362 m^2 (56.62%)— of the dune area of the original field remained. Nineteen years later the most dramatic change occurred, with the destruction of virtually the entire field and its subsequent occupation. At the end of the 1980s, with the introduction of the Spanish Coastal Law in 1988, sand quarrying was halted and part of the area where this activity had been carried out was filled in, leading to a gradual increase in the use of the land to install infrastructure and facilities and to build homes.

In the 21st century dune recovery measures were taken on an area covering just 1.50% of the original field, while the 36% of anthropised dunes in the quarry areas have been abandoned and colonised by invasive vegetation (Martínez Cedrún, 2008). The regeneration actions, which have managed to consolidate the existing dune field, involved reproducing a foredune geometry in contact with the beach, most developed towards the inner part of this managed dune sector. As a consequence of capturing sand with *Ammophila arenaria* var. *australis* (marram grass), very loose pyramid dunes have formed. Further inland, the inner dune field is made up of highly altered dunes which makes geometrical assignation rather difficult (Flor *et al.*, 2011). In addition, the space has been provided with a series of infrastructures designed to grant access to the beach, including roads on the north side.

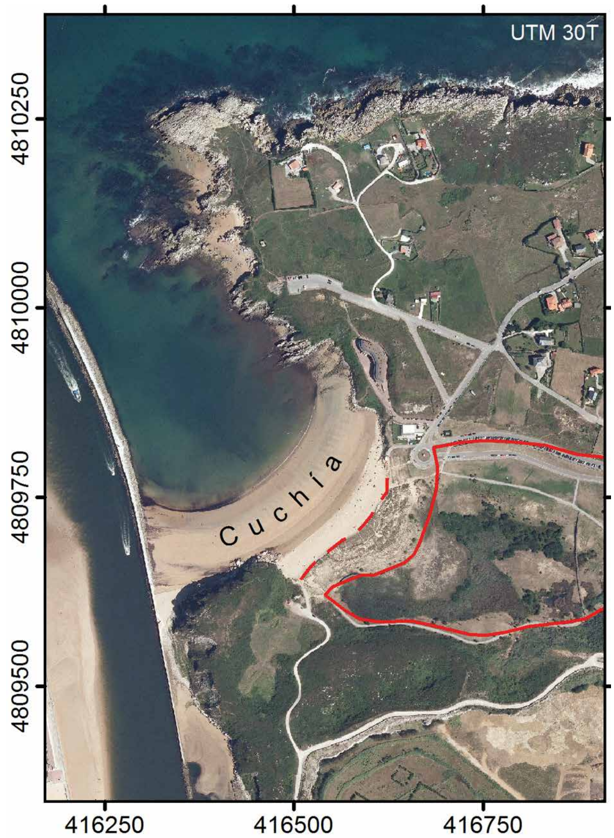


Figure 9. Orthophotograph of the Cuchía dune field. The dashed red line indicates the current dune field, and the sector marked with a solid red line shows the old, now altered, part.

5.4. Liencres dunes

This extensive dune complex, which forms part of the confining barrier of the Pas estuary (Figs. 1, central coast of Cantabria, and 10), has been declared the Liencres (Piélagos) Dunes Nature Park by Decree 101/1986, of 9 December; Liencres Dunes Site of Community Importance (SCI) and Site of Geological Interest (LIG) in the national inventory of the Geological and Mining Institute of Spain due to its important geomorphological value.

In the 1950s, the pine trees were repopulated along the inner sector, where there was active aeolian transport, particularly on the climbing dunes and also the rear parabolic dunes (Martínez Cedrún & Flor, 2008; Arteaga *et al.*, 2008).

Until the mid-1970s sand quarrying was being carried out on the dunes and a disproportionately large (2.72 ha) car park was built, which still remains today (Fig. 10). In 1996, the Cantabria Coastal Authority undertook a restoration process involving two types of interventions. Firstly, stabilisation work was conducted by installing two types of sand traps: 1) structural, in the form of dry wicker fences in the zones without vegetation and the practically nonexistent foredune; and 2) supporting, by planting a little vegetation, where the foredune still maintained its structure. The deteriorated topographies were homogenised and the dune morphologies evened out.

Secondly, vegetation cover was regenerated with marram grass and, to a much lesser extent, with *Elymus farctus* (sand couch-grass) on the unvegetated dune fronts and the parabolic and lee-projection dunes, the latter developed in the depressions left by sand quarrying. In 2004, 88,000 marram grass plants were introduced and 1,500 new sand traps were installed, and to remediate damage suffered in the summer, 35,200 plants were introduced into the affected zones with high and low density (8 plants/m^2 and 3 plants/m^2), respectively.

In addition, three treated wooden walkways were installed along the entire foredune and continuous rustic fencing placed along the sides, with 1.50 m-high stakes and a progressive wire mesh, to stop people walking on the vegetated dunes. Finally, various informative signs were also added. Today, several fences and walkways have been covered by sand sheets, an indication of the active function of this dune complex, as it receives additional sand volumes from the erosion of the inner dune field caused by the shrinking process of the main channel of the estuary.

Figure 10. Oblique aerial view (Cartographic Service of Cantabria) of Valdearenas beach and the associated Liencres dune field, one of the largest on the Cantabrian coast. The exposed beach forms part of the sandspit, culminating with embryonic dunes, which border on the Pas estuary (in the background).

5.5. El Puntal of Somo and Loredo dunes

This is one of the Cantabrian Sea's most spectacular beach and dune complexes, with the peculiarity that on the eastern edge of the mouth of the Santander estuary a sandspit has developed which acts as a confining barrier (Fig. 1). The zone is composed of various dune fields that run its entire length, and in the case of the spit, the foredunes and dune slacks are formed by opposing winds from the northwest and southwest. In addition, this structure is crisscrossed by numerous erosion corridors caused by high waves, lobes and washover fans from the exposed beach to the estuarine beach. The eastern half is mainly composed of climbing dunes (Martínez Cedrún, 2008).

The Somo-El Puntal spit was declared an SCI 1300005 protected space within the El Puntal Dunes and Miera estuary (Decree 4/2006, of 19 May). This space includes the islets of Mogro and Santa Marina or Jorganes and covers an area of 675 ha, 417 ha of which are bodies of water.

Intensive dredging of the entrance channel to the port of Santander has caused the bar to narrow and its apex to extend towards the southwest as it continues to spread towards the mouth of the estuary (Fig. 11). with a decrease of the sand spit total surface of 536942 m^2 from 1956 to 2014 (Borguero, 2015).

In 1993, the Cantabria Coastal Authority carried out regeneration work on the El Puntal of Somo foredune, which basically consisted of adding 230,000 m^3 of sand, placing sand trap fences, planting dune species, mainly *Ammophila arenaria*, to attempt to stabilise the dunes, enclosing the entire perimeter with rustic wooden fencing and installing 14 wooden walkways to channel pedestrian traffic between the two beaches bordering El Puntal (the estuarine and exposed beaches) and avoid trampling on the remediation work and plantings. To replenish the dunes on the southern part of El Puntal of Somo, some 25,000 m^3 of sand dredged from the estuary was dumped onto this beach and also on El Rostro beach (Pedreña).

In 1979, towards the eastern shore, in the town of Loredo, sand quarrying operations began in an area covering approximately 4.5 ha, and continued until 1982, when they were permanently suspended. Years later, in 1990, part of this space was used to develop a nursery for dune plants and a raised walkway with viewpoints was built over the beach in order to promote it as an educational dune.

Figure 11. Historical evolution of El Puntal de Somo from 1956 to 2010, following the profile of the upper intertidal zone and taking the sandspit area as a reference in each photograph.

During the autumn-winter of 1995 and spring 1996, the eastern sector of El Puntal of Somo was repopulated with dune vegetation. In total, more than 100,000 species were planted, mostly marram grass and sand couch-grass. In 1997 a further repopulation with 27,000 new plants was carried out in fenced off areas of the planted zones for protection, given the pressure from tourism at this beach. In addition, 1,550 m of 1.5 m-high wire fencing was installed and 20 signs were put up to inform the public and raise beach-users' awareness of the importance of respecting the actions being carried out.

In the town of Somo, the permissive administration approved the construction of a row of 18 terraced houses very close to the beach, the fronts (terraces and steps) of which were destroyed in the storms of 2014. Subsequently, a soft defence was built consisting of a sand bank 4-5 m high and 20 m long which storms in early 2015 reduced by half (Fig. 12A). In addition, erosional scarps were carved into numerous sections along the entire exposed front of El Puntal of Somo beach, but sites were also created with sand spillover sheets (Fig. 12B), erosion corridors were reopened and washover fans formed on the estuarine beach.

Figure 12. A) Remains of the artificial sand bank built to protect the urbanisation on the Somo dunes, the front of which was eroded, leaving a subvertical scarp and reducing the length. B) Widespread erosional scarps and spillover sand sheets on the highest dune of the El Puntal de Somo spit.

Dredging carried out to expand the port of Santander from 1969 led to the beaches of Los Peligros, La Magdalena and Bikinis (Santander) all losing sand –up to one metre in height in some cases. In 1970, dredgers returned a large volume of sand to La Magdalena, and in 1973 sand began to be delivered from El Puntal of Somo to consolidate this beach. These transfers continued two years later (reaching a total of 80,000 m^3), allowing the beach to be stabilised during the summers, and went on to become a continuous practice during the 1980s (GIOC, 2007). The successive sand replenishments have encouraged the formation of aeolian accumulations, such as sand sheets and climbing dunes, at the rear of the three abovementioned beaches, which are regularly maintained in a discontinuous manner.

At the end of the 1990s, sand was extracted with a suction dredge from the submerged area and dumped into the intertidal zone. However, from time to time in the area behind Bikinis beach, invasions of windblown sand would cover the access road to Palace of La Magdalena and the nearby slopes, also forming climbing dunes. Due to its high cost, this technique was replaced by sand transports brought by road from the western zone, with a volume in recent years of between 25,000 and 30,000 m^3/year (up to 43,000 m^3 in 2013).

5.6. La Canal of Galizano dunes

This estuary of Galizano or La Canal, is protected under Cantabria Law 4/2006, of 19 May, on nature conservation, as it forms part of the Central Coast and Ria de Ajo Site of Community Importance (ES1300006). Consisting of a small winding estuary located on the central eastern coast of Cantabria (Fig. 1), the area is drained by La Colina stream, which has patches of marsh vegetation growing at its tail. The high proportion of sand covering this space and its incomplete confinement by the low-tide terrace on the exposed beach make this area quite unique.

On the outer cove of the beach there is a western dune complex measuring 90 m in length and on average 38 m in width and occupying an area of 3,033 m^2. At the outer eastern edge, winds from the northwest have formed climbing dunes which are attached to the subvertical cliff, covering an area of approximately 278 m^2. Adjacent to the inner western edge there is a larger patch of dunes stretching over 180 m, with a width ranging from 48 m at the front to 21 m at the southernmost edge and a total surface area of 3,442 m^2; these dunes include a NNW-SSE elongated foredune that forms an internal 9 m-wide barrier prograding towards the channel, where it reaches 14 m.

In the 1970s, the outer estuarine dune field decreased in size with the construction of a car park, in addition to damage caused by pedestrian traffic and trampling, and this trend continued during the following decades.

The recuperation of the deteriorated zones was defined in the project 'Restoration and management of the Galizano beach-estuary system', which was executed in 2004 over an area covering approximately 2,800 m^2. The project included the restoration of the beach and regeneration of the dunes, which was carried out through five actions (Fig. 13):

- Installation of three rows of sand trap fences, 70 m in length.
- Introduction of 10,000 Ammophila arenaria var. australis marram grass plants.
- Installation of 250 m of rustic fencing to enclose the planted zones, with a service gate to access the area.
- Placement of six information signs to raise visitor awareness of the importance of respecting the planted zones in order to ensure the success of the action.
- Installation of a wooden walkway over the dunes, raised 1 m above ground level and fitted with the corresponding access steps; the 270 m-long, 2.5 m-wide walkway ran along the entire edge of the beach parallel to the public footpath.

Figure 13. Oblique aerial view of the tail of the Galizano or La Canal estuary, showing the abundance of sand and estuarine dune fields. The field located at the starting point, where the path begins, with a vegetated foredune, was the focus of the restoration detailed in the text.

The project also included adding a seasonal car park situated on the upper part of the cliff, with a surface area of 3,500 m^2 and space for 150 cars. The cliff bordering Galizano beach has subvertical slopes of between 25 and 30 m. Thus, measures were taken to clean up and stabilise the talus and install protection against rockfalls through the following actions:

- Installation of provisional wire mesh along the entire edge of the cliff.
- Elimination of issues and removal of unstable blocks.
- Protection of the entire length of the talus by installing a two-metre-high rockfall barrier.

5.7. Puntal-La Salvé of Laredo dunes

This wide and long dune complex situated in eastern Cantabria (Fig. 1) presents a triangular geometry, with a more extensive arch towards the city of Laredo (Fig. 14), and covers a total area of 267.15 ha. The dunes form part of the culmination of the confining barrier of the Asón estuary and probably developed through south to north progradation over a relatively short period, as revealed by the fact that they have acquired geometries on a metric scale similar to those produced by the lengthening of the previously mentioned breakwaters.

The receding profile of El Puntal de Laredo (northernmost edge), at the mouth of the estuary, is more pronounced on the eastern side and apex, and has been acutely obvious for at least two decades. However, the surplus accumulation produced in the La Salvé zone, close to the city of Laredo, by the persistent longshore drift is quite remarkable and was partially removed by mechanical means.

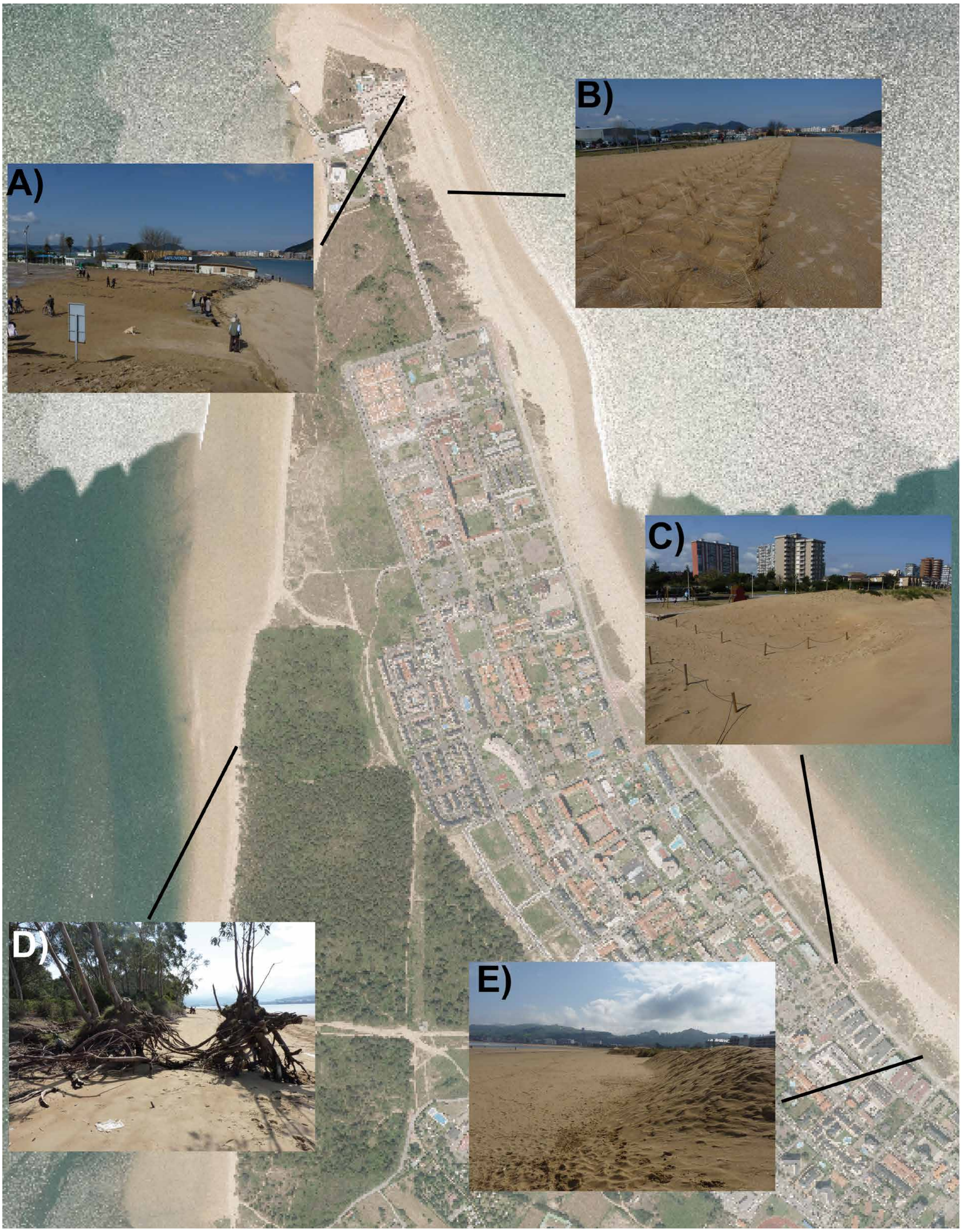


Figure 14. Image of the Laredo dune field (orthophoto from 2014, Government of Cantabria-PENOA), widely occupied by buildings alongside La Salvé beach and with eucalyptus plantations on El Regatón estuarine beach, with a sub-rectilinear layout. After the winter storms of 2014 (A), sand accumulated to form a barrier with slopes of up to 7 m high at the end of the dunes on top of which marram grass vegetation was planted (B) and cordoned off (C). The apex and the western edge of El Regatón, despite already being in recession, was also seriously affected (D). Close to the city of Laredo smaller defensive sand barriers were built (E).

The most important and continuous deterioration of El Puntal of Laredo began in 2007, with the recession becoming so noticeable between 2012 and 2014 (Fig. 14A) that the Cantabria Coastal Authority was obliged to fill in some sections of the beach with rubble and, at the start of summer 2014, to build what was known as 'the great artificial dune' (Fig. 14B and C), for which more than 250,000 m^3 of sand were used, at a cost of €1.9 million. Sand was taken from the active estuary sandbar using a suction dredge and pumped onto the beach to be redistributed with shovels, creating a sand prism with a truncated pyramid section of just under 1 km long. The dune reached a height of 7 m, while the width varied, with a maximum of 20 m. On top, 200,000 marram grass plants were rooted along the entire length of the prism, but due to later erosion many were never planted (video: http://www.eldiariomontanes.es/castro-oriental/201410/10/duna-solo-dias-20141010111718.html). These defences were rather ineffective in what was considered a very expensive protective measure, but never a definitive solution. The dunes adjoining El Regatón estuarine beach have also receded since the 1990s, as demonstrated by the presence of eucalyptus trees, now growing on the intertidal zone (Fig. 14D), albeit in a rather precarious position. In winter 2014, coinciding with spring tides, a large part of this sand structure suffered notable erosion.

At the end of March, the natural access points to the beach in the southern segment of La Salvé were protected with the construction of a new artificial dune measuring 1.5 m high and 5 m wide (Fig. 14E); the existing dunes and their vegetation were respected, with the intention of returning them to their natural state when the storm season ends.

Furthermore, the Government of Cantabria and its Coastal Authority have run various campaigns, launched in 2009, to remove invasive plants from numerous dune fields in Cantabria in general and at El Puntal in particular.

6. Examples in the Basque Country

As mentioned in previous paragraphs, some beaches on the Basque coast have migrated out to sea as a result of breakwaters being lengthened on the mouth of the corresponding estuaries. A long breakwater was also built on the eastern bank of the mouth of the River Ibaia, in Ondarroa, on the eastern side of which Saturraran beach has migrated out to sea. The mouth of the River Bidasoa (Txingudi estuary) was profoundly transformed by the extension of breakwaters along both its sides, requiring the reconstruction of the current beaches of Hondarribia and Hendaia at the western end, where an induced dune field has developed: in fact, the former is located around 2 km from the original natural beach. Most of the associated dune fields remain as testimony to their original size or have completely disappeared due to anthropogenic action.

The two zones with remaining dunes of greatest environmental interest in the Basque Country are both small and subject to intense human pressure. Examples in Biscay include La Arena, Gorliz and Laga, and in Gipuzkoa, above all, the beaches of Zarautz and Zumaia. Beaches such as Azkorri (where the dunes have been fenced off), Barinatxe, Bakio, Santiago and Deba contain vestiges of what were in the past more extensive dune fields; other dune fields developed behind the beach at Zurriola, in San Sebastián (Gros district in the eastern area).

6.1. La Arena beach and dunes (Muskiz-Zierbena)

This beach and dune complex forms part of the confining barrier of the Barbadun estuary (Fig. 1, western edge of the Basque Country), and are listed as a LIG 94 Site of Geological Interest and the dunes have been included in the Ría del Barbadun Natura 2000 Network Site of Community Importance (SCI code ES2130003). The marshlands suffered extraordinary degradation after the Petronor refinery was built in Somorrostro in the 1970s (Cearreta *et al.*, 2008). During the past few decades important efforts have been made to regenerate different spaces; after removing the large fuel tanks some 170,000 m^2 of marshland were recovered, leaving a transition area of 20,000 m^2 to revegetate the dunes. The sand in this zone has taken on a brown hue due to the introduction of barren rock from iron ore exploited in the Somorrostro, Ortuella and San Salvador del Valle mines between the 16th century and early 20th century.

In the 1980s, pebbles and gravel accumulated on the easternmost point of the beach after swells with angles averaging 20° caused the collapse of the fill slope of the access road to the super-port of Bilbao, transforming this point into a reflective segment with more energy than the rest of the sandy beach (Losada *et al.*, 1987). Large quantities of material were removed, but even by mid-2015 more of these fractions continued to wash up on the beach. Access roads were opened and a large car park built on the dune zone in the central area of the beach, in the middle of the public shoreline. In contrast, the recovery of this semi-natural dune field, covering an area of 10.4 ha, began to materialise from the 1980s and 90s with the installation of wooden sand traps designed to encourage the accumulation of sand from the beach.

In 2008, the Lurgaia Foundation launched a project to protect the La Arena or Muskiz dunes, consisting of placing exclusion fences around the most important zones and those most sensitive to trampling and removing some of the most dangerous exotic invasive species, such as *Oenothera* spp. and *Carpobrotus edulis*. To complement these actions, in 2009 another project was launched to preserve the Basque Country's only population of the species *Ononix natrix* spp. *ramosissima*.

The public have been encouraged to participate in preserving plant species through environmental volunteering, which has led to many people taking part in the projects in an altruistic way. Continuous fortnightly maintenance has been carried out on the fencing to reposition fallen stakes and put up new information signs.

The winter storms of 2014 eroded a large part of the dune field which, despite support from the local councils, raises numerous doubts about its future.

6.2. Laida beach and dunes (Oka estuary, Urdaibai Biosphere Reserve)

The Gernika or Oka estuary and surrounding area (Fig. 1, western Basque Country) has been included within the Urdaibai Biosphere Reserve, as approved by Law 5/1989, of 6 July, on the protection and management of the Urdaibai Biosphere Reserve. In addition, the zone has a Master Plan for the Use and Management of the Urdaibai Biosphere Reserve, approved on 3 August 1993, implementing the previously mentioned law. The estuary, together with the Laida dunes, is included in the Urdaibai Coastal and Marshland Zones SCI (ES2130007) and in the Ria de Urdaibai SPA (ES0000144).

Dredging in the main channel of the estuary to facilitate shipping access to the Murueta shipyard has proved disastrous to maintaining the sedimentary balance (Monge-Ganuzas *et al*., 2013) The dredged sand was dumped outside the active beach system or in areas inside the lower estuary where, in 1994, the estuarine beaches of Kanal and Sukarrieta formed and were later colonised by dune vegetation. In addition, to rebuild the city of Gernika sand was mined from the area, and in recent decades sand has been transferred by the action of washover fans during storms towards the inner part of the confining barrier. All of this has contributed to reducing the estuary's sand prism (Flor & Flor-Blanco, 2006), causing the barrier to lose height and migrate upstream, while storm intrusions are becoming increasingly intense.

The dune ecosystem on Laida beach in Urdaibai (LIFE/NATURE/000031/ES) degraded in a particular way from the 1960s due to trampling, sand mining, etc. These dunes covered an area of 13.3 ha, of which only 6 ha was regenerated to add it to the previous. The area in question is made up of 50% shifting dune habitats with embryonic vegetation (code 2110) and 50% habitats with marram grass (code 2120).

From 1999, it was decided to improve the dunes, which between 2001 and 2004 materialised in the form of a dune regeneration project and later, between 2004 and 2007, in a LIFE project (Fig. 15A-D) to regenerate the dune ecosystem on Laida beach (LIFE04NAT/E/000031).

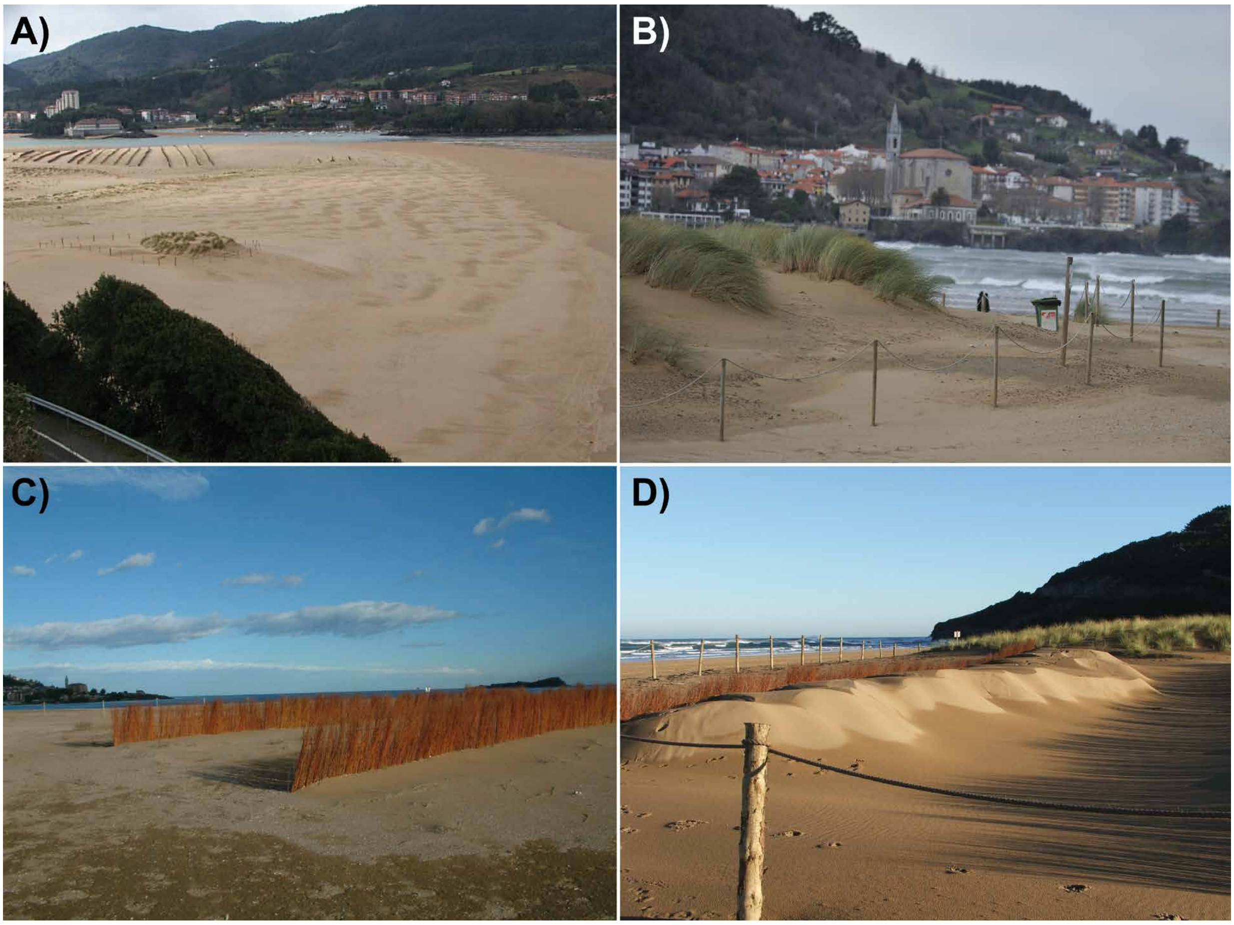


Figure 15. Actions on the exposed beach of Laida, which forms part of the estuarine barrier of the Oka or Gernika estuary. A) Rows of planted Ammophila arenaria. B) Roped off vegetated dunes. C) Fences to retain aeolian sediment. D) Sand traps and accumulations of sand transported by deflation in a cordoned off area. Images granted by: Harea Coastal Geology Group (UPV/EHU).

In the first project period, from 2001 to 2004, dredged sand was dumped on top of the estuarine barrier, where wicker sand traps were placed along a 2,500 m stretch and *Ammophila arenaria* began to be planted (Monge-Ganuzas *et al.*, 2003). This process was repeated in 2004 and 2005, following parallel lines over three rectangular areas close to the town of Laida (right side) that were closed off with perimeter rope and stake fencing; in total, the intervention area covered 60,000 m^2.

In 2004, 205,000 marram grass and 45,000 *Elymus farctus* plants were introduced, with a further 250,000 marram grass plants added the following year. Informative panels were also installed, mainly at access points to the dune field, and a pamphlet and leaflet were produced in addition to educational and environmental information material (http://www.ingurumena.ejgv.euskadi.eus/r49-6172/es/contenidos/memoria/actividades_life_laida/es_memoria/adjuntos/2004_2005.pdf).

It is also important to mention the 240,000 m^3 of sand dredged from the estuary channel that was dumped on the enclosing barrier in spring 2003 which, according to subsequent studies (Monge-Ganuzas *et al.*, 2008), caused a variation in the mouth of the channel and also affected the way the waves broke on the shore, leading to serious management and tourism problems when the 2005 world surf championship had to be cancelled. The situation returned to normal naturally three years after the dredging and dumping operation.

The geomorphological (Iriarte *et al.*, 2004) and sedimentological (Ikerketa Taldea *et al.*, 2004) results of the intervention were published, taking into account the dynamic factor of the incident winds and their interaction with sand transport, and the growth of the dune, as well as recognising the sedimentary structures, including the internal ones. It was found that in the first year the volume of aeolian sand accumulated was 3,708 m^3, falling to 3,500 m^3 in the second year and 2,056 m^3 in the third (Cearreta *et al.*, 2007).

From 2007, the mouth of the estuary began to suffer intense erosion to the point at which the supratidal zone of the beach had lost around 40,000 m^2 and was reduced to 20,000 m^2. There was also intense recession caused by the last big storms of winter 2014, which delivered a serious blow to the residual dune belt, completely destroying the dunes that had been subject to intervention in the abovementioned projects.

6.3. Laga beach and dunes

This exposed beach between promontories, situated just to the east of the Oka estuary (Fig. 1), belongs to the Urdaibai Biosphere Reserve, where actions have been taken to recover the associated dunes and remove pressure from tourism and the service facilities previously located in the zone. It has also been listed as a Site of Geological Interest (LIG 92 Laga Beach and Dunes) and various geo-conservation measures have been proposed (Mendia *et al.*, 2011).

In this case, the intervention consisted of establishing a protective perimeter using 200 treated pine stakes and 1000 nylon ropes to stabilise the embryonic dunes that were under greatest pressure from tourism; wicker sand traps were set up to catch aeolian sand and several thousand marram grass plants were introduced. In addition, informative panels measuring 68 x 96 cm were installed at strategic points and an interpretative leaflet describing the wealth of flora and fauna in the zone was produced.

6.4. Plentzia-Gorliz beaches and dunes

This complex is subject to the Special Plan for the Protection and Conservation of Gorliz Beach in the town of Plentzia (Fig. 1). This eastern zone contains eolianites and quadrupedal ichnites (Flor, 1989) dating back to between 5,710 ± 50 and 6,020 ± 50 years BP (Cearreta et al., 1990), which are protected under LIG 91 (Astondo Fossil Dunes) and included in the Natura 2000 Network as a Site of Community Importance (ES2130004), as well as the regional ZEC (special conservation zone) Astondoko Haremunak/Astondo Dunes, property of the Biscay Provincial Government.

Originally, the longitudinal profile of the beach had a sub-rectilinear layout, coinciding more or less with the road. In 1928, as a result of the first phase of construction of the seawall and dyke-dam in the Butrón estuary, the beach sand advanced and continued to do so with each successive lengthening operation that took place between 1956 and 1973. As a consequence, the sand was displaced laterally, dragged by drift currents, to accumulate at the ends (Hernández-Pacheco & Asensio Amor, 1967). The sand came from the centre of the beach, making it necessary to build defences in this segment to prevent erosion affecting the road. The beach acquired a marked curvature with the concavity facing seaward, a very stable shape in which low dunes developed that disappeared.

To increase the surface area of the dry beach, the road was moved 35 m further inland in the northern zone and the wall of the hospital was set back by 14 m. In the area of influence of the mouth of the Txatxarros brook, with a basin of 2.3 km^2, the average recession was 135 m and required the demolition of the existing wall. A pickling factory occupying 1,600 m^2 was also removed, and behind the supratidal zone a 1.25 ha dune area with marram grass plantations was created.

In addition to this regeneration, after the storms of 2014, it was proposed to shorten the beach's western breakwater along the bank of the estuary to allow the surf to reduce the curvature so that the line of the beach would retreat from the reinforced talus in the central zone.

6.5. Zarautz dunes (Iñurritza)

In the easternmost area of the Basque Country (Fig. 1) dune complexes formed as a result of the filling in of the estuary of the Iñurritza coastal river, the sedimentary record of which was studied by Edeso (1994) and which includes cemented aeolian sands. The greatest sand volume on the beach accumulates in the eastern section, coinciding with sand transport by the drift from the incident swells from the northwest, which have supplied the most abundant dune sedimentation in this zone.

Figure 16. State of the Zarautz dunes after damage from the 2014 storm was repaired. Sand traps and treated wooden walkways have been installed on the supratidal zone.

The dune system has been greatly transformed and is under threat from, among other things, the occupation of a large area of fixed dunes by a golf course (16.5 ha), pressure from summer recreational activity and the presence of invasive species. It is protected by the Special Plan for Protected Biotopes (Decree 40/1997, of 11/03/97) and Iñurritza SCI, as well as the Document on Conservation Measures in the Iñurritza Special Area of Conservation. Almost 80% of the plant species are psammophiles native to the Basque coast, with shifting dune and stabilised dune varieties well represented.

The active dunes were reduced to a narrow talus between the beach and the golf course which was destroyed by the storms of 2014 (Fig. 16); the former foredune was located here to rebuild the eroded dune front. In fact, this broad area could be recovered in the future as a dune environment.

7. Future Solutions

A transition between the upper beach and adjacent dune field that guarantees sand transportation by deflation is usually produced by a smooth surface sloping towards the sea and by the consequent availability of dry sand.

In these cases, plant colonisation has sufficient margin to establish the zonation of species and fulfil its role of stabilising the sand sediment. In these conditions, and even on beaches that may have contained dune fields in previous decades, it is feasible to apply some of the techniques mentioned in this paper, such as installing sand traps, cordoning off areas, planting native species of vegetation and channelling foot traffic along a limited number of wooden walkways.

In the case of dunes that develop steep slopes bordering the beach, representative of periods of intense recession, it is not advisable to carry out any type of intervention because of the visual impact this may cause, as it would require harsh actions (removing sand to contain the dune growth, building gabions, etc).

In these Cantabrian provinces, there are relatively few dune fields that require immediate and continued preservation; those that do include Penarronda, Sarello, Navia, the eastern end of Salinas-El Espartal, Rodiles, Vega, Merón (San Vicente de La Barquera), Luaña, La Concha de Suances, Liencres, Somo-Loredo, Ris and Trengandín (Noja), the south-eastern half of La Salvé (Laredo), Oriñón, La Arena (Muskiz-Zierbena), Laida and Laga.

This paper details some cases of sandy beach management relating to the formation of dunes carried out by the coastal authorities on the Cantabrian Sea. The creation of the new Poniente beach has resulted in the construction of areas of embryo dunes on both sides. New artificial dunes have been created at Salinas-El Espartal by raising a loose geometry onto which species of marram grass were planted and wooden walkways constructed; the persistent drift of sand from the beach provides volumes that are accreted onto the dune front, forming lobular-shaped transgressive dunes with a thickness ranging from decimetres to metres. Another less common practice is the homogenisation of the dune relief in areas where sand mining had previously been conducted or some small construction had been built, such as in the cases of Penarronda, Salinas-El Espartal and Xagó.

Dunes have been protected by means of deterrent fencing, sand traps, walkways and the reintroduction of native plant species in different dune fields (Penarronda, Xagó, Rodiles, Luaña, Liencres, Somo, La Arena, Plentzia, Laida, Laga, etc.). However, these actions have been relatively few, partial and in many cases unnecessary (e.g. covering erosion corridors at El Puntal de Somo), while other equally important types of beach and dune complex that require attention have been ignored (Penarronda, Sarello, Otur, Vega, Rosal de San Vicente de la Barquera, Luaña, Tagle, La Concha de Suances, Usgo, Cuberris, Trengandín, Berria, La Salvé and Oriñón). It is necessary to come to some agreement with the coastal authorities on how to address specific serious cases where disastrous management of port dredging in the estuaries is leading to the destruction of beach-dune systems, such as the one in Salinas-El Espartal and Somo-Loredo; to this end, it would be wise to collaborate with coastal specialists, whose perspective is much more realistic and documented. Negative interventions in the area mainly centre on the construction of the great artificial dune at El Puntal of Laredo.

The authors propose extending the protected dune areas to include certain sites, such as those in Asturias: Salinas-El Espartal, with its unique successive foredunes (parallel dunes), indicative of a process of progradation, and the lobular climbing dune in the inner field at Xagó.

The unique nature of the Sonabia dune complex (Flor, 1980; Flor and Martínez Cedrún, 1991; Martínez Cedrún, 2008; Flor *et al.*, 2011), with its mixed dune typology caused by the interference of longitudinal and barchanoid dunes, calls for it to be protected within the Autonomous Community of Cantabria's Plan Regulating Natural Resources (PORN).

In the Oka estuary it would be feasible to move the sand on Kanal and Sukarrieta beaches, as well as the volumes from maintenance dredging, so that it could be recycled naturally to construct the barrier, thereby increasing the available volume. As the sand is relatively coarse on average, the best option would be to dump it onto the shallow littoral zone of the beach, within the first 5 m of depth. This way, the waves would select and distribute the sand fraction towards the exposed beach and help to consolidate the confining barrier. The authors also recommend continuing the projects to create and regenerate new dunes.

Thus, we propose that the management is overseen and advised by universities or research centres in each of the studied regions, as close collaboration is required between the various administrations with environmental competences and the different groups of experts on the subject. Furthermore, we would call upon these organisations to preserve these habitats in accordance with European Union Directive 92/43/EEC, taking the document *Dunas marítimas y continentales* (Coastal and inland sand dunes) (Gracia *et al.*, 2009) as a guide.

This paper also recommends joining forces and boosting funds that permit the short-term study of most of the dune fields that are suffering from almost irreversible erosion caused mainly by rising sea levels, as these records are a valuable source of information about the environmental phenomena and processes of the Holocene.

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Conservation and restoration of coastal dune habitats in Sardinia: the experience of the LIFE+ PROVIDUNE project

Mario Durán[1], Maria Silvia Pinna[2], Martino Orrù[1], Alberto Sanna[3], Giuseppe Fenu[4], Donatella Cogoni[1], Anna Nebot[1], Gianluigi Bacchetta[1]

[1] Centro Conservazione Biodiversità (CCB), Dipartimento di Scienze della Vita e dell Ambiente, Università degli Studi di Cagliari, Viale S. Ignazio da Laconi 11-13, I-09123 Cagliari, Italy.

[2] DIAEE (Dipartimento di Ingegneria Astronautica, Elettrica ed Energetica), Sapienza Università di Roma, Corso Vittorio Emanuele II 244, I-00186 Roma, Italy.

[3] Provincia di Cagliari - Settore Ambiente, Ufficio Protezione Coste, Via Cadello 9/b, 09121 Cagliari, Italy.

[4] Dipartimento di Biologia Ambientale, Sapienza Università di Roma, Piazzale A. Moro 5, I-00185 Roma, Italy.

1. Introduction

The PROVIDUNE (LIFE07NAT/IT/000519) project, financed by the LIFE+ “Nature and biodiversity” programme, was undertaken in the period from 2009 to 2014. It was mainly intended to help to implement the Habitats Directive locally through the performance of actions to safeguard the priority habitats of the directive in five Sites of Community Importance (SCI) where several environmental dangers exist:

- Porto Campana (ITB042230), Stagno di Piscinnì (ITB042218), Isola dei Cavoli, Serpentara, Punta Molentis and Campulongu (ITB040020), in the province of Cagliari;
- Pineta della Foce del Garigliano (IT8010019), in the province of Caserta;
- Bosco Pantano di Policoro and Costa Ionica Foce Sinni (IT92220055), in the province of Matera.

PROVIDUNE endeavoured to implement best practices and actions to safeguard both the priority habitat of community interest 2250* (Fig. 1) and the adjacent habitats (2270, 2230, 2240, 2110, 2120, 2210). It achieved this through a common strategy adopted by the provinces of Cagliari, Caserta and Matera, the TECLA association and the departments of Chemical Sciences and Geology (OCEANS: Osservatorio Coste e Ambiente Naturale Sottomarino) and Life and Environmental Sciences (CCB: Centro Conservazione Biodiversità) of the University of Cagliari, which assumed scientific coordination of the project.

Figure 1. Priority habitat ˚2250 “Coastal dunes with Juniperus spp.”.

In order to achieve the project’s general objective, it was divided into more specific objectives. The expansion of and improvement in knowledge of the state of conservation of the habitats under study, both from a geomorphological and botanical perspective, helped to establish the preparatory actions on the basis of which the dune systems were mapped and understanding of the beach-dune system was enhanced. The structure of the beach, its origin and its evolution over time, the directions of sand dispersion and its composition, and the places where sediments accumulate were analysed. Separate study was performed of the marine conditions that control the hydrodynamic processes and the impact of meteorological events on the system. Lastly, the plant species present at the sites of intervention, their distribution and development, the presence and abundance of exotic and invasive species and the different types of habitats were also studied.

As a result of the preparatory actions several habitat restoration projects and a management plan were drawn up with a view to reducing anthropogenic impact on the system and promoting its natural balance through interventions with low environmental impact and of support for natural processes based on protecting plant species that are crucial in the process of dune stabilisation.

The conservation measures were aimed at turning the good intentions of the preparatory actions “into reality”, while allowing all of these environments of extraordinary beauty to be enjoyed by all. Special attention was therefore placed on the environmental and landscape impact of these interventions. In order to raise awareness of the project and of its objectives among local people and tourists, different acts of communication were run in order to inform and sensitise all interested parties of the importance of what was being undertaken and at the same time encourage a responsible and respectful use of a heritage that we are lucky to enjoy yet does not belong to us.

2. Envisaged benefits

- Implementation of best practices and actions for the protection of habitats of community interest, and specifically the priority “Coastal dunes with Juniperus spp.” habitat and adjacent habitats in the five SCIs.

- Development and implementation of a common plan for the long-term protection of these habitats.

- Reduction and eradication, insofar as possible, of the endangering factors present in the dune habitats of the sites of intervention, such as uncontrolled pressure from tourism, coastal erosion, inefficient management and the spread of invasive species.

- Enhancement of public (students, residents, tourists) awareness of the importance of these habitats, not only on account of their landscape value, but also of their role in protecting the coastal system itself and as a means of mitigating the effects of climate change.

3. Project actions

A series of actions with different purposes were undertaken in order to meet the project’s objectives. These actions have been divided into two groups: preparatory actions and conservation actions.

- Preparatory actions: development of management plans and plans of action. These included a multidisciplinary study of the intervention sites. The evolution of coastlines and the sedimentological flows of dunes (Fig. 2) were examined on the basis of sedimentological and marine coastal dynamics studies. The monitoring system also allowed for comprehensive analysis of meteorological events and of the impact thereof on the system itself.

Figure 2. Production of the geodesic network, bathymetric sampling and study of marine currents.

Geobotanical studies meanwhile revealed both the characteristics of the flora (Fig. 3a) and vegetation (Fig. 3b-3c), and also their state of conservation, and were indispensable in the proper planning of preliminary work (dimensions and placement of infrastructures, etc.) for the reduction of impacts, and recovery and protection of habitats.

Figure 3. a. Flora (galbuli of Juniperus macrocarpa Sm.). b-c. Types of vegetation: white dunes of *Ammophila arenaria* and fixed coastal dunes of *Crucianellion maritimae*.

- Conservation actions. First, to ensure the conservation of the species characteristic of coastal dune vegetation and, in particular, priority habitat 2250*, germplasm (seeds and fruits) from 52 taxa were collected from within the SCIs and conserved (Fig. 4) at the Germplasm Bank of Sardinia (BG-SAR), which reports to the Department of Life and Environmental Sciences of the University of Cagliari.

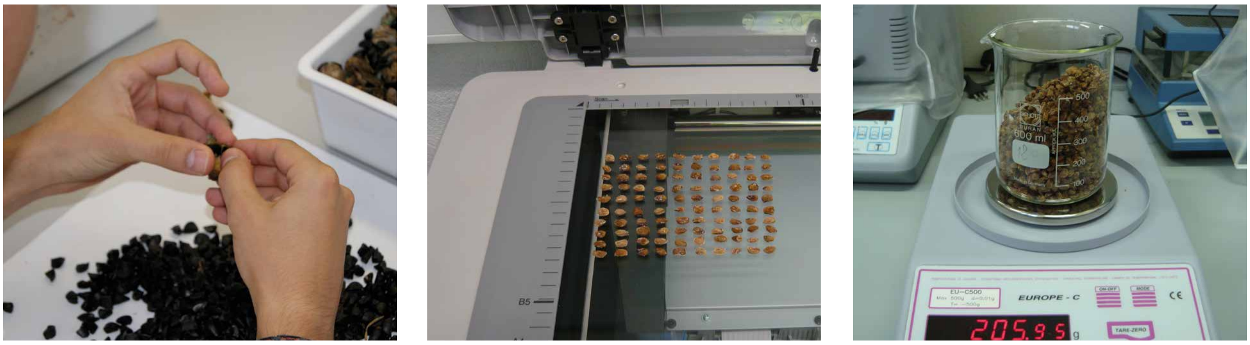

Figure 4. Phases of management and conservation of germplasm.

Another objective was the individualisation of effective germination protocols of twelve key species for their subsequent multiplication in a nursery. In order to recover and rehabilitate degraded habitats, coconut fibre netting (Fig. 5a) and cane fencing (Fig. 5b) were installed. The former helped to stabilise dunes and to protect seedlings while the latter (triangular or square-shaped wooden and cane structures) were successfully used in retention of the sand, thus reducing erosion caused by the wind. The restoration involved the eradication of invasive species from the habitat and subsequent seeding of local structural species. To mitigate the impact of tourism, accesses to the beaches were controlled by installing wooden duckboards (Fig. 5c), which acted both to channel access flows and to restore some of the sand that tourists carry away with them. Lastly, in order to ensure lasting results, a management plan was devised and supported by the creation of a flora-vegetation and abiotic sediment databank, which can be consulted at http://webgis.osservatoriocostesardegna.com/providune/.

Figure 5. a. Coconut fibre netting. b. Cane fencing. c. Wooden duckboards.

4. Results obtained

The work undertaken yielded a number of results which have provided knowledge of the characteristics of the dune habitats (Pinna *et al*, 2015a), and allowed both for ex situ and in situ conservation of dune flora and vegetation in the five intervention sites and for the development of maps of the habitats on these sites.

Ex situ conservation actions involved the collection of a total of 159 samples corresponding to 52 taxa kept at the BG-SAR at temperatures of 5 °C (active collection; Fig. 6a) and -25 °C (base collection; Fig. 6b). Germplasm was collected and conserved in accordance with international guidelines for the ex situ collection, study, conservation and management of germplasm (Bacchetta *et al*, 2006, 2008).

Figure 6. Conservation of germplasm: a. Active collection. b. Base collection.

In accordance with the species collected and its importance in terms of conservation, 12 taxa were selected [*Ammophila arenaria* (L.) Link subsp. *australis* (Mabille) Laínz, *Anthemis maritima* L., *Cistus salviifolius* L., *Crucianella maritima* L., *Elymus farctus* (Viv.) Runemark *ex* Melderis subsp. *farctus*, *Eryngium maritimum* L., *Juncus maritimus* Lam., *Juncus subulatus* Forssk., *Juniperus macrocarpa* Sm., *Juniperus phoenicea* L. subsp. *turbinata* (Guss.) Nyman, *Pancratium maritimum* L., *Pistacia lentiscus* L.] and experimental germination tests were performed upon them. From the germplasm collected in the province of Cagliari, work was also undertaken on the germination of the species *Juniperus macrocarpa* (Fig. 7). The results of this work revealed low seed vitality (40%) and reduced germination percentages (average of 10% with peaks of 45%) for the species; *J. macrocarpa* seeds proved to be latent (Pinna *et al*, 2014a).

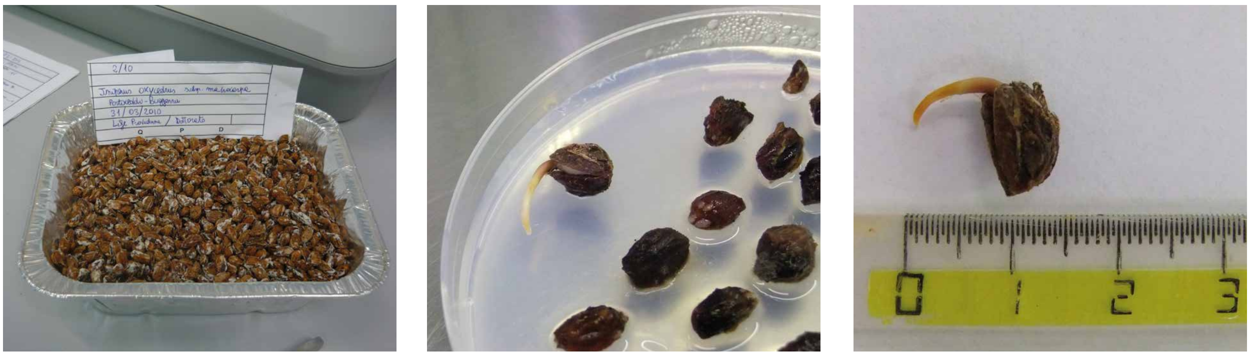

Figure 7. Study of the germination of *Juniperus macrocarpa* Sm.

Insofar as in situ conservation is concerned, a pilot trial was run for the reintroduction of habitat 2250* structural species (*Juniperus macrocarpa*, *Pistacia lentiscus* and *Pancratium maritimum*) in all the areas of intervention, with a view to strengthening structural species, containing the fragmentation of habitats and ensuring ecological functionality. To this end, the effects of reintroducing structural species within the cane fencing (2.5 m2) and permanent squares of coconut fibre (20 m2) were sampled. The preliminary results have specifically shown the effectiveness of using cane fencing and of reintroduction (Fig. 8). In particular, the species *Pancratium maritimum*, on account of the easy collection of its seeds and rapid germination, does not require pre-treatment and has proved particularly suitable for future measures of recovery and restoration in all the coastal areas of the Mediterranean basin. The permanent squares of coconut fibre meanwhile were confirmed to be efficient systems for the prevention of aeolian erosion and dispersal of sediment.

Figure 8. Results of sowing *Pancratium maritimum* L. in the cane fencing.

Different in situ studies on the status of the populations of *Juniperus macrocarpa* have, moreover, been presented at various scientific conferences (Pinna *et al*, 2012, 2011, 2010). A specific study (Pinna *et al*, 2014b) was also made of the germination, survival and mortality of *J. macrocarpa* seedlings sampled inside the permanent squares (1x1 m) located at the sites of intervention in the province of Cagliari (Fig. 9a-b). The results of these studies showed:

- an emergence of seedlings strongly limited by aridity, mainly during the winter period;
- a low survival rate of seedlings (15%);
- a high mortality rate in correlation with the presence of herbivores during the summer period.

Figure 9 a. Study of the initial stages of the life cycle of *Juniperus macrocarpa* within permanent squares 1x1 m. b. *Juniperus macrocarpa* seedling.

The specific conservation actions were completed towards the end of the project; the results will therefore be evaluable over the coming years. For the time being, it can be concluded that all the operations undertaken represent a check to the threat factors and particularly to the intense impact of tourism during the summer months. The effectiveness of the cane fencing and coconut fibre netting became evident from the very start (Fig. 10), while the duckboards and other structures that were introduced have already begun to yield a positive impact and have been welcomed by all on account of their usefulness and of their low visual impact. With the Post-LIFE conservation plan, it will therefore be very important to ensure the maintenance of these structures.

Figure 10. Effectiveness of the coconut fibre netting and cane fencing.

5. Benefits and impacts of the project in habitats

All the habitats under study and their characteristic species benefitted directly from the installation of the duckboards, the eradication of invasive species and the environmental engineering interventions addressed to recovering the dunes. Experimental sowing also helped to restore and control the impacts of the installation work.

The economic benefits can meanwhile be channelled into environmental benefits, as the improvement in environmental quality will yield an increase in the value of sites used for tourism and, in turn, economic benefits for all activities present.

It is therefore important to consider that, like other conservation studies performed at different coastal areas of Sardinia (Cogoni *et al*, 2013, Fenu *et al*, 2015th, b: Pinna *et al*, 2015b), the results of the project can be extrapolated to all coastal and dune settings, not only in Sardinia, Basilicata and Campania, but also generally throughout the Mediterranean basin.

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Recent historical transformation and current situation of the dune landscape in Catalonia

Josep Pintó i Carla Garcia-Lozano

Laboratory of Landscape Analysis and Management (LAGP). Universitat de Girona

1. Introduction

1.1. Coastal dunes in Catalonia

Coastal dunes form a unique landscape that has traditionally either been undervalued or perceived as a problem. Dunes are landforms generated by the action of the wind on beaches. The wind carries and transports grains of sand, which it deposits upon encountering an obstacle that causes a reduction in its speed and therefore in its transportation capacity. The accumulation of grains of sand creates dune forms that vary depending on the volume and the height of the sand deposited, on the obstacle that has given rise to them and on colonisation by plants.

Although dune morphologies can be created in any sector of the beach, the action of the waves, particularly in storms, prevents them from growing large or from becoming established on the most exposed parts of the beach. It is on the inland edge where the dunes develop most, both in width and in height, and where they can form the dune ridge typical of dune landscapes parallel to the shoreline. The largest dunes form on beaches that are broader and better supplied with sand, if there are strong enough winds that blow often. The dunes may then stretch inland to form shifting dune fields, a phenomenon that now only occurs on the Catalan coast in some areas of the Ebro delta. The largest and most extensive dunes in Catalonia are the two large inland dune fields at Montgrí and on the hills of Begur, which were stabilised with pine trees in the late nineteenth and early twentieth centuries. These dunes have developed over decades on account of the action of the northerly *Tramuntana* wind, which has blown southwards the sands transported by the Fluvià and Ter rivers to the beaches of Empúries and Pals respectively.

The environmental conditions on the coastal dunes respond to the values of factors such as salt spray, the movement of sand by the wind, soil moisture, temperature, the presence of nutrients and the erosion of dune morphologies (Moreno-Casasola, 1986; Hesp, 1991; Maun, 1998; Wilson and Sykes, 1999; Ruocco *et al*, 2014). Most of these factors vary according to a gradient from the sea landwards that yields characteristic zonation of plant communities and habitats (Bolòs, 1967; Perdigó and Papió, 1985; Curcó, 1990 and 1996; Gesti, 2001).

Dune habitats have great biodiversity and species of interest and have therefore been awarded Community interest status and included in the 92/43/EEC Habitats Directive (European Commission, 1992; European Commission, 2007). In Catalonia, 11 habitats associated with dune and upper beach environments (Vigo *et al*, 2005) and up to 37 vascular plants with a habitat exclusive to the beaches and dunes of the Catalan coast (Pintó *et al*, 2012; Pintó *et al*, 2014) have been identified.

Dune habitats are, however, receding throughout Europe (European Commission, 2008) and the biodiversity to which they are home is seriously endangered even in the best protected dune systems (Cori, 1999; La Posta *et al*, 2008). It is estimated that nearly 70% of European dunes systems have disappeared over the last century in connection with the urban development of the coastline and other associated factors (McLachlan and Brown, 2006). The Mediterranean coast is no exception. According to Fabbri (1997), this is due to scant development of dune systems in many sections of the Mediterranean coast compared to the coasts of other seas. Local populations, moreover, have traditionally shown little appreciation of dunes, which were perceived as unproductive, problematic areas rather than as a valuable component of the natural and scenic heritage of the coast.

The importance of dune landscapes has only recently been acknowledged and most are now protected from the most destructive human activities either by European, national or local legislation (Baeyens and Martínez, 2004). Despite such protection, dune systems are located on coasts that receive a large number of tourists over the summer months. The trampling of dunes and other disturbances arising from human influx and the introduction of invasive alien species (Panareda and Pintó, 2015; Pino *et al*, 2006) threaten the conservation of dune morphologies and of the most sensitive species and communities .

The purpose of this work is to show how coastal dune landscapes are evolving using data taken from documentary, photographic and cartographic sources from the late eighteenth century to the present day, and to explain the types of dune system that currently exists in Catalonia.

The work focuses on the dunes located on the inland boundary of beaches, known as foredunes, and includes a series of dune habitats and morphologies that range from shadow dunes and shifting dunes to stabilised dunes. It also discusses the inland dunes of Montgrí and Begur, which have been stabilised with pine trees for over a century and are currently subject to dynamics and processes that differ from those influencing the evolution of the foredunes.

2. Methodology

The starting point for establishing past dune distribution on the Catalan coast is the *Diario de los viajes hechos en Cataluña (1785-1790)* by Francisco de Zamora and the *Diccionario geográfico-estadístico-histórico de España y sus posesiones de ultramar* (1845-1850) by Pascual Madoz, two works of reference that provide valuable information about the demographic, economic and territorial nature of Catalonia in the late eighteenth century and in the first half of the nineteenth century.

Francisco de Zamora (1757-1812) was a figure of the Enlightenment and a magistrate who was assigned to the Court of Barcelona during the reign of Charles III. Partly through personal curiosity and partly upon commission by the Count of Floridablanca, he made five trips to different regions in Catalonia upon which he took notes on the geographical facts he considered significant and upon which, according to Font and Llobet (1989), he recorded the characteristic traits of human action on the land and described the constituent features of the physiognomy of the landscape of Catalonia.

Pascual Madoz (1806-1870), on the other hand, was a liberal politician who, after returning from exile and living for some time in Barcelona –where he worked on the production of the universal geographical dictionary that was published in the city– was appointed Minister of the Treasury in 1855 during the Progressive Biennium (1854-1856) led by Espartero. From here he encouraged a disentailment to the lands belonging to the municipalities known as 'the seizures of Madoz'. The *Diccionario geográfico-estadístico-*

histórico de España contains an inventory of territorial, demographic and historical matters, and of the resources and economic activities of each Spanish municipality of that time. It is therefore a valuable source of information on the main geographical features of the first half of the nineteenth century.

In addition to the information contained in these two works from the late eighteenth and mid-nineteenth centuries, the information included in regional monographs published in the early decades of the twentieth century was also consulted. These include the *Geografia General de Catalunya* (1908-1918) by Francesc Carreras Candi, *El paisatge de Catalunya*, published in 1928 by Marcel Chevalier, and the *Resum de geografia de Catalunya*, by Pau Vila, published in several volumes between 1928 and 1936. Lastly, the *Geografia de Catalunya* published in four volumes from 1958 to 1968 by the Aedos publishing house was also referred to. These works cover the entire territory of Catalonia and offer a summary of the knowledge existing at each given time.

The collections of old photographs relating to images taken in the initial decades of the twentieth century provide another source of information. These are often postcards of landscapes produced by photographers such as Louis Roisin, Àngel Toldrá and Adolfo Zerkowitz, some of which had already been published in local or county monographic publications such as *La Costa Brava abans de la Costa Brava, Costa Brava panoràmica* and the collection of books of old photographs "L'Abans", on different municipalities and other works deposited with different bodies and institutions such as the collection of oblique aerial photographs by Josep Gaspar i Serra in 1929, deposited with the Cartographic and Geological Institute of Catalonia (ICGC), and the collections of postcards of the Postcard Society of Catalonia. The collections of old photographs of Girona Provincial Council have also been consulted for details regarding the beaches of the Costa Brava. Lastly, information contained in postcards by different authors acquired from collectors' shops and owned by the Laboratory of Landscape Analysis and Management (LAGP) of the Universitat de Girona (UdG) has also been taken into account. The information contained in oblique photographs is always reliable if the object of interest –dunes in this case– are clearly visible in the picture. It is another matter when the photograph shows a long-distance view and dune morphologies are incipient or scarcely developed. In this case their presence can therefore not be verified properly, as they could be confused with other elements such as embankments, deposits or remains of seaweed or accumulations of different waste materials, given the extensive use of many beaches in the early twentieth century by fishermen and for fishing-related activities. In other cases, when the picture spans only a section of the beach, the presence of dunes can be determined, but not the total area that they occupy.

The first editions of the sheets of the 1:50,000-scale *Mapa Topográfico Nacional* produced in the early twentieth century and compiled in the *Atles topogràfic-històric de Catalunya 1:50.000* (ICGC, 2012) were also consulted. The keys of these maps include dune systems, which are mapped, at least on the beaches where the areas of dunes were largest. Although in some cases the accuracy of the area occupied by dunes and its boundaries is rather questionable, it is an item that may confirm data regarding their presence obtained from other sources.

The layer of the geological map of Catalonia in digital format has been used to locate adjacent outcrops of sand on today's beaches, and attempts have been made to determine whether there was a correlation between these sands and the pine trees as land cover for these geological materials, because many dune areas are known to have been stabilised at some time or other in the twentieth century with the plantation of pines (Valverde, 1998), both to prevent the advance of the dunes towards crops and properties adjacent to the coast, and to yield some type of economic return from these areas.

Aerial photographs from the 1946-47 American Flight Series A, available on the ICGC's online server (Geoservices, historical Web Map Service) have also been interpreted in order to determine whether the dunes identified using one of the previously mentioned sources could be recognised in the aerial photographs and their location and size pinpointed better. Where the photographs from the above-mentioned flight did not allow for identification of the area of dunes, shots on paper from the 1956-57 American Flight Series B, available from the Universitat de Girona map library, were used.

As regards diagnosis and classification of the current status of dunes on the Catalan coast, the methodology followed was based on photo interpretation of 1:2,500 colour orthophotomaps from the 2014 flight of the ICGC and digitisation of all the dune systems and bodies identified.[1] In some cases, in order to define the limits of the dune systems more accurately, the 2014 Catalan coast flight at a scale of 10 cm was used. Doubtful cases were, moreover, verified in the field. Several campaigns in the field were performed on a parallel basis between the spring and autumn of 2013, 2014 and 2015 in order to collect data on morphological variables, processes and disturbances (height, type, stage of development, erosive processes, impacts) and on habitats and the vegetation of the main dune systems of the Catalan coast.

3. Results

3.1. Dunes in the past

Information taken from the bibliographic sources is scarce and refers only to the more developed and better-known dune systems. In the works of Francisco de Zamora and Pascual Madoz little attention is generally paid to the coast. Francisco de Zamora visited the Baix Empordà region in 1790 on one of his trips and in his diary he referred to the inland dunes of Montgrí and Begur as follows:

> "Salimos de aquí [L'Escala] pasando al poco rato por algunos montes de arena finísima, que a impulsos de la tramontana mudan de situación. Son muy grandes. Más aún sucede esto en Bagur, lo que ha dado lugar al adagio: es como las montañas de Bagur, que en verlas mudan."

> "Salimos de Torroella para ir a Palamós, pasando a vado el río Ter [...] A sus orillas vimos los montes que forman las arenas movidas del viento, lo que también sucede a orillas del Fluviá. [...] Empezamos a caminar por las famosas montañas que el aire las muda y dieron motivo al adagio que apuntamos. Hay viñas cerca de ellas, las cuales entierra la arena muchas veces. Y para remediarlo siegan una hierba larga que aquí llaman *borró* y se cría sobre los mismos montes de arena. Pasa algunos años sin mudarse y la extienden sobre la arena de las viñas, para que el aire no la levante. Este arenal tiene media hora."

1 The layer of the digitised dune polygons can be consulted on the "Platges i Dunes-CAT" viewer at: http://geofis1.udg.edu/mapadunes/map.phtml

> “We left here [L’Escala] and passed through some mountains of fine sand, which, driven by the northerly Tramuntana wind, change location. They are very large. This occurs even more in Begur, which has given rise to the adage: like the mountains of Begur, which move as you watch them.” (p. 362, in the R. Boixareu edition, 1973)

> “We left Torroella to go to Palamós and forded the river Ter [...] On its bank we saw the mountains formed by sands moved by the wind, which also occurs on the banks of the Fluvià. [...] We began walking over the famous mountains that the wind moves and that gave rise to the adage mentioned before. There are vineyards nearby, which are very often buried by the sand. To remedy this, they plant a long grass which is known as ‘borró’ (marram grass) here and grown on the mountains of sand themselves. The “borró” (marram grass) remains unchanged for several years and it is then grown on the sand in vineyards, to stop the wind from blowing it away. It takes half an hour to walk over this area of sand.” (p. 366, in the R. Boixareu edition, 1973)

As mentioned above, the inland dunes of Montgrí and Begur are the largest systems in Catalonia and, as apparent from the text, were already known and admired as a curiosity in the late eighteenth century. One remarkable fact, which is repeated by other later authors, is that the Begur dunes are described as taller and more extensive than those of Montgrí.

Pascual Madoz’s work meanwhile focuses mainly on the production and trading of goods, except for brief descriptions of the relief of each municipality that in most cases ignore the coast. The coast is considered solely with regard to any fishing and maritime trade that might take place. Unlike the wetland areas, which are referred to often for several towns, often in relation to the fevers caused to neighbouring villages, only the coastal dunes of the town of Castelldefels are mentioned:

> “El Terreno participa de monte y llano; es de buena calidad a excepción de la parte cercana al mar, en que es flojo y arenoso, en cuyo litoral han formado los recios vientos que soplan de continuo una cordillera de montes de arena que parecen estar marcando límites a las aguas del Mediterráneo [...].”

> “The land is formed by mountain and plain; it is of good quality except for the part close to the sea, where it is loose and sandy, and on its shoreline the strong winds that blow continuously have formed a range of mountains of sand that appear to be setting limits to the waters of the Mediterranean [...].” (P. Madoz, volume VI, p. 95, 1847)

This description seems to suggest that the dunes of Castelldefels must have been rather large, first because of the fact it was the only town where the dunes were worth a mention, and second because of the terms used: “a range of mountains of sand...”. In fact, reference to the large size of the dunes on Castelldefels beach can also be found in Chevalier (1928) and in photographic documents from the start of the twentieth century (see Fig. 1).

Figure 1. The dunes of Castelldefels at the start of the twentieth century. Source: ICGC collection of old images.

Large dunes are also mentioned at the Cape of Salou by the geologists Lucas Mallada and Father Bataller in the initial decades of the twentieth century. Indeed, in an article by Bataller in the *Butlletí del Centre Excursionista de Catalunya* in 1923 there appears a sketch (see Fig. 2) of the area occupied by the dunes produced by the mistral or northwest wind that dragged sand from the beach of Salou in a NW-SE direction.

New data on the presence of dunes on the coast of Catalonia can be found in the work *El paisatge de Catalunya* (Chevalier, 1928), as we have not been able to find any information on their presence in any of the volumes of the *Geografia General de Catalunya* by Carreras Candi, which is, moreover, a historically oriented work, as befitting the author's training as a historian.

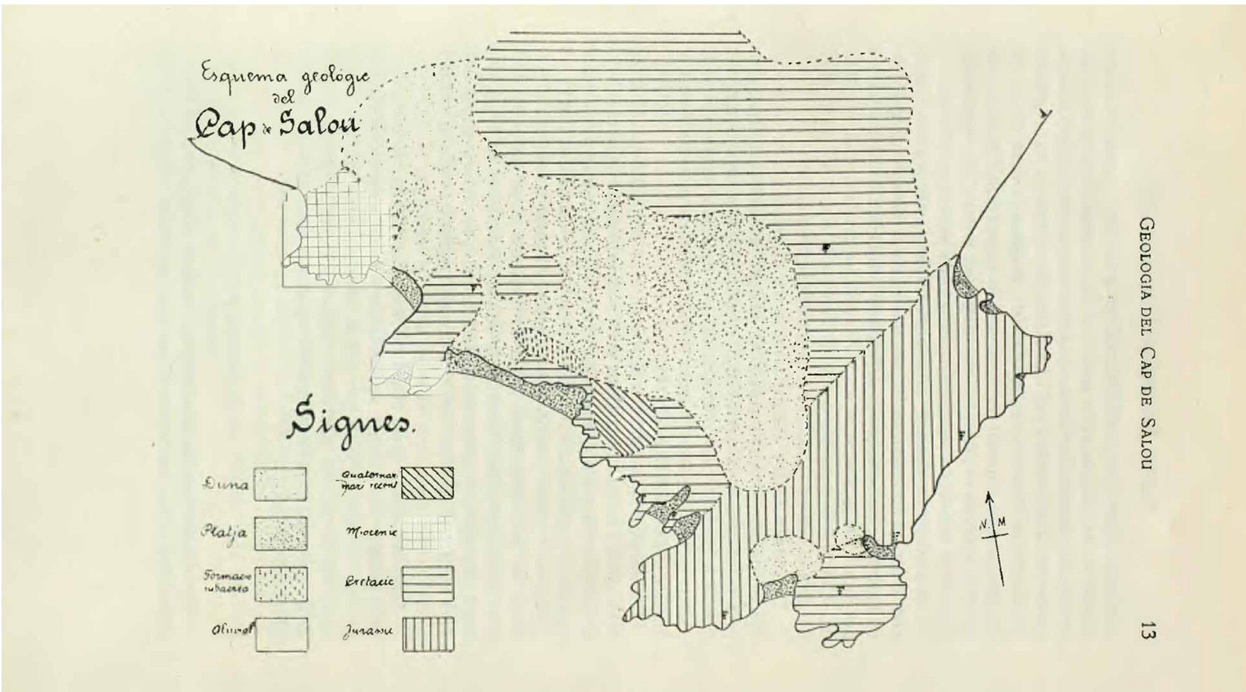

Figure 2. Sketch of the area of dunes at Cape of Salou in the early twentieth century. Source: J.R. Bataller and S. Vilaseca, 1923, p. 13.

In the work by Chevalier referred to above, the dunes of the Empordà region are mentioned and more details are once again given about the dunes of Begur than those of the Montgrí:

> "Al N i al S d'Emporion hi ha dunes que començaren a formar-se, sens dubte, a la mateixa època [es refereix al període no especificat en què el port d'Empúries es va reblir de sediments i la línia de costa va retrocedir] i que la vegetació va afermar més tard. Altres dunes més importants i molt properes a l'Escala semblen haver-se format amb la sorra que, havent entrat per la cala de la Clota, empesa després pels vents dominants del N i del NE, assaltà el massís cretaci del Montgrí; aquesta sorra, prenent el massís per darrere, ha escalat cap al sud. [...] Cal remarcar també que s'han format dunes importants al S d'aquesta línia de costes i que la sorra empesa pels vents N i NE, com a l'Escala, s'ha llençat pel mas Matilde a l'assalt de les muntanyoles paleozoiques de Begur, i ha arribat al poble i àdhuc més enllà, és a dir, a més de 4 km del seu punt d'origen, fins a assolir una altura de 210 m [...]."

> "In the N and S of Emporion there are dunes that started to form, no doubt, at the same time [referring to the unspecified period in which the port of Empúries filled with sediments and the shoreline retreated] and the vegetation stabilised later. Other, larger dunes very close to L'Escala seem to have formed with sand that, having arrived from La Clota cove, driven by the prevailing winds from the N and from the NE, assailed the cretaceous Montgrí massif; this sand, having reached the massif from behind, has climbed southwards. [...] It should be noted also that major dunes have formed to the S of this coastline and that the sand blown by the N and NE winds, as at L'Escala, has arrived by way of the Mas Matilde farmstead to the Palaeozoic hills of Begur, and has reached the town and even beyond or, in other words, over 4 km from its point of origin, and risen to a height of 210 m [...]." (Chevalier, *op. cit.*, p. 99)

Besides mentioning the inland dunes of the Empordà region, Chevalier makes a brief list of other places on the coast where there are dunes:

> "Ultra les dunes de l'Empordà, a Catalunya hom en troba al delta del Llobregat, al sud de Castelldefels, on tenen una certa importància; a Calafell; i sobretot a les platges del Cap de Salou, on han assaltat els arbres i on alguns d'aquests, mig ensorrats, no deixen veure més que el cim. A la desembocadura mateixa de l'Ebre hi ha també algunes dunes de poca importància, sobretot si hom en compara la superfície amb la que ocupen els sediments del delta."

> "In addition to the dunes of the Empordà region, in Catalonia there are also dunes in the Llobregat delta, to the south of Castelldefels, where they are quite large; at Calafell; and particularly on the beaches of the Cape of Salou, where they have climbed the trees and where only the top of some of these, half buried, is visible. At the very mouth of the Ebro there are also some dunes of lesser importance, particularly upon comparison with the area occupied by the sediments of the delta." (Chevalier, *op. cit.*, p. 115)

For the first time, this list mentions the dunes at Calafell, which have now disappeared without there being any other references to them. It also refers to the significance of the dunes of Castelldefels, also mentioned in Madoz's work, while making light of the dunes of the Ebro delta. Chevalier also points out how developed the dunes at the Cape of Salou were, a fact also mentioned in later works, as we shall observe later.

No new information about the presence of dunes on the coast appears until *Geografia de Catalunya* (GC) directed by Lluís Solé Sabarís and published by Editorial Aedos between 1958 and 1968, as Pau Vila's *Resum de geografia de Catalunya* makes no mention of them. The GC, published by Editorial Aedos, mentions the dunes of the Empordà region and emphasises how large the Begur dunes were:

> "La costa del golf de Roses [...] es tracta d'una costa baixa, pantanosa, sorrenca, en gran part voltada de dunes, com les que sepultaren les ruïnes d'Empúries. Aquestes dunes, arrossegades per la força de la tramuntana, s'han enfilat pels vessants del massís de Begur fins als dos-cents metres d'alçària i han envaït camps i veïnats, per la qual cosa han hagut de fixar-se amb plantacions de pinedes que les han transformat en dunes mortes."
>
> "The coast of the Gulf of Roses [...] is a low, marshy, sandy coast, largely surrounded by dunes, like those burying the ruins of Empúries. These dunes, driven by the force of the Tramuntana wind, have climbed the slopes of the Begur massif to a height of two hundred metres and have invaded fields and neighbourhoods, which has made it necessary to stabilise them by planting pines, which have transformed them into dead dunes." (GC, volume III, p. 145, 1958)

The dunes of the Llobregat delta are also mentioned and data are provided on their size and the area they covered, as well as on the pine trees planted to stabilise them:

> "Petits cordons de dunes, de 6 a 8 m d'altura, paral·leles a la platja, arriben en el sector de Castelldefels un quilòmetre terra endins i s'enfilen pels costers del massís de Garraf [...]."
> "[...] I més amples que la sorra [de la platja], les esplèndides pinedes de Nou Rals, plantades a finals del segle passat per deturar l'avenç de les dunes, i anomenades així perquè el terreny, no conreat, era venut a nou rals la mujada (unes 4,60 pessetes l'hectàrea). Avui aquestes pinedes de pi pinyer donen nom a una magnífica urbanització."
>
> "Small ridges of dunes, of 6 to 8 metres in height, parallel to the beach, in the Castelldefels sector, stretch a kilometre inland and climb the slopes of the Garraf massif [...]." (GC, volume III, p. 457, 1968)
> "[...] And wider than the sand [from the beach], the splendid pine woods of Nou Rals, which were planted at the end of last century to halt the advance of the dunes, and are so named because the land, which is not cultivated, was sold at nine reals per *iugera* (around 4.60 pesetas per hectare). A magnificent housing development has now been named after these stone pine groves." (GC, volume III, photograph caption on p. 457, 1968)

This work also refers to dunes "of very little importance" (GC, volume III, p. 197) on Creixell beach and on Cape Gros, which we believe must refer to Els Muntanyans in Torredembarra that also stretch to Creixell beach.

There is also mention of the existence of large dunes at Cape of Salou, which other authors had also previously referred to:

"Al cap de Salou, però, les anomenades "muntanyes d'arena", fins que l'edificació ha cobert tot el promontori, oferien volums molt considerables. Mn. Bataller, en el present segle, n'esmenta de 50 m d'alt i dos quilòmetres i mig de llarg, i Mallada, al segle passat [es refereix al segle XIX], diu que en veié d'un centenar de metres d'alt. S'internaven fins a un parell de quilòmetres terra endins i inutilitzaven les vinyes. L'avenç es feia en direcció a Tarragona, empeses pel vent serè."

"On the Cape of Salou, however, the so-called 'mountains of sand' were of a considerable size until building covered the entire promontory. Father Bataller, this century, mentions a height of 50 metres and a length of two and a half kilometres while Mallada, last century [referring to the nineteenth century], states that he saw some of a hundred or so metres high. They stretched inland for a couple of kilometres and made the vineyards unworkable. They advanced towards Tarragona, blown by the north-westerly wind." (GC, volume III, p. 197, 1968)

Conventional photographs from the early twentieth century have yielded more information than bibliographical sources. Observation of the images of landscapes on postcards shows the presence of dunes on most beaches. These are often dunes of modest size. They are hummocks or ramp-type dunes on walls and embankments that marked out the inland limit of the beach. On some beaches, such as Sa Riera (Fig. 3), dune ridges can be observed whilst on others, such as the beach of Platja d'Aro (Fig. 5), there are more developed systems, stabilised by pine trees. Table 1 shows the beaches for which we have found old photographs showing the presence of dunes and also the current status of these dunes.

Municipality (1)	Beach (2)	Aerial photo (3)	Current status of dunes (4)
Roses	L'Almadrava	No	Built-up
	La Perola	No	Built-up
	Santa Margarida and El Salatar	Flight 47	Built-up / disappeared
L'Escala	Beaches of Empúries	Flight 47	Reduced in size
Pals	Pals	Flight 47	Built-up / reduced in size
Begur	Sa Riera	Flight 57	Built-up
	Sa Tuna	No	Built-up
Palafrugell	Tamariu	Flight 57	Disappeared
	Llafranc	Flight 57	Disappeared
	Port Pelegrí	No	Built-up
Palamós	La Fosca	Flight 57	Built-up / reduced in size
	Gran de Palamós	Flight 47	Built-up / disappeared
Calonge	Monestri and Sant Antoni	Flight 57	Built-up
	Roques Planes	No	Disappeared
Castell-Platja d'Aro	Gran d'Aro	Flight 47	Built-up
St. Feliu de Guíxols	Sant Pol	Flight 57	Reduced in size
	Sant Feliu	Flight 57	Built-up / disappeared
Tossa de Mar	Gran de Tossa	Flight 57	Built-up / disappeared
Lloret de Mar	Lloret	No	Built-up
	Santa Cristina	Flight 57	Disappeared
Blanes	Blanes	Flight 47	Built-up
Calella	Gran de Calella and Garbí	Flight 47	Disappeared
Canet de Mar	El Pla	Flight 47	Reduced in size
	Canet	Flight 47	Disappeared
	El Cavalló	Flight 57	Disappeared

Arenys de Mar	El Cavalló	Flight 47	Disappeared
	Primera Platja	No	Disappeared
El Masnou	El Masnou and Ocata beaches	Flight 47	Built-up
Montgat	La Morera	Flight 57	Disappeared
El Prat de Llobregat	El Prat	Flight 47	Built-up / disappeared/reduced in size
Sitges	Garraf	Flight 57	Disappeared
	Sailing Club-Les Anquines section	Flight 47	Disappeared
Tarragona	El Miracle and Llarga	Flight 47	Built-up / Disappeared

Table 1: Beaches where dunes have been identified in old photographs

1. Name of the municipality where the beach is located. 2. Name of the beaches where dunes have been observed in old photographs. 3. This column indicates whether in aerial photographs from 1947 or 1957 the dunes observed in the old images are still visible. 4. Current status of the dunes: whether they have disappeared, have been built up or whether their size has reduced.

Figure 3. Sa Riera cove with a field of ramp-type dunes in front of the houses and at the end of the riverbed. Source: Gaspar collection, ICGC.

The presence of dunes on most beaches indicates the existence of conditions conducive to their creation. The scant development apparent in many photographs is due, firstly, to use of the beach as an area for fishing and marine activities, and therefore one with a high influx of people, together with their use extensively for the housing, construction and repair of boats and any associated activities, a fact that would limit any possible development of the dunes. At the start of the twentieth century, moreover, dune systems were not perceived as a valuable item of natural heritage, a consideration that might have led to the establishment of limits to prevent their disappearance.

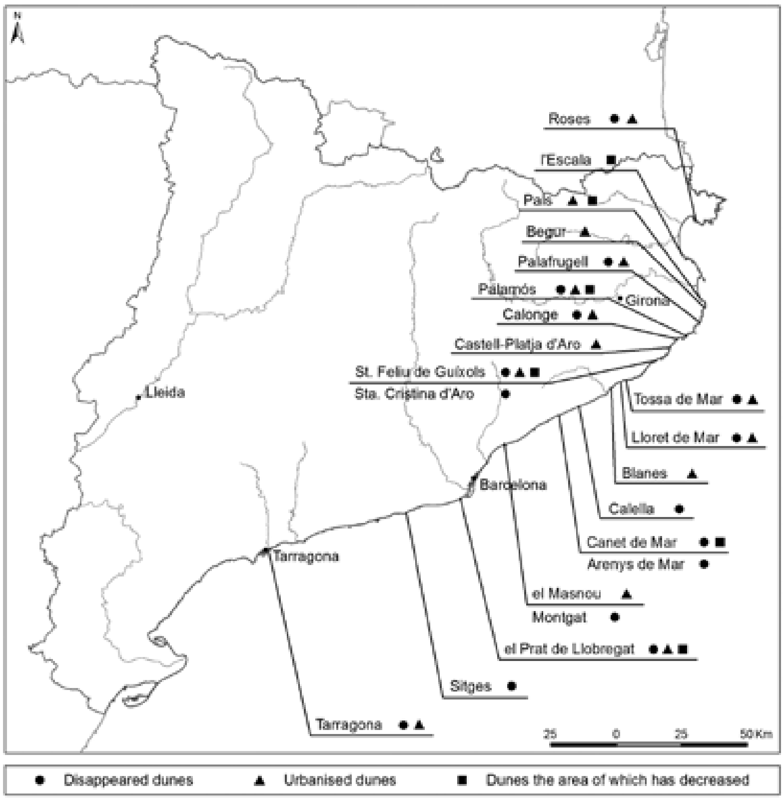

Figure 4. Location of dunes observed in old photographs, with an indication of the current status.

Figure 5: Field of dunes stabilised by pines at Platja d'Aro, cf. 1920-1925. Source: Girona Provincial Council photographic archive.

The map in figure 4 summarises the information gathered to date on the presence of dunes on the coast of Catalonia in the past, based on information taken from old photographs. It indicates whether the dunes have disappeared, generally on urban and tourist beaches, and whether they have been built up or their area has been reduced.

3.2. Dunes today

The dune systems and morphologies that currently exist on the coast of Catalonia are limited in size. Even the largest and most developed cannot be compared with the size of dune systems in other areas of the coastline of the peninsula that are better supplied with sand and have more favourable wind systems, such as those at Guardamar del Segura, Cádiz or Doñana. The largest preserved dunes are the inland systems at Montgrí and on the hills of Begur, which have been mentioned in the introduction.

The Ebro delta is home to the largest coastal dune system –the dune fields of El Fangar spit and of Riumar (see Table 2)–, although large dunes, like the sand dome at the beginning of El Fangar spit, have disappeared in recent years because of coastal erosion.

Table 2 shows the largest dune systems in Catalonia, which are located in only five sectors: the Ebro delta, the Llobregat delta, the coast of the Baix Ter, the Gulf of Roses and Torredembarra beach.

Ha	**Inland dunes**	**Municipality**	**Province**
770	Hills of Begur	Pals, Begur, Regencós	Girona
510	Montgrí	Torroella de Montgrí, L'Escala	Girona
Ha	**Coastal dunes**	**Municipality**	**Province**
51.8	El Fangar spit	Deltebre	Tarragona
41.3	Riumar	Deltebre	Tarragona
33	Pals southern sector	Pals	Girona
15.0	Castelldefels	Castelldefels	Barcelona
14.7	El Prat	El Prat de Llobregat	Barcelona
13.8	Mas Pinell (La Fonollera)	Torroella de Montgrí	Girona
13.5	Els Muntanyans	Torredembarra	Tarragona
11.6	Buda	Sant Jaume d'Enveja	Tarragona
11.2	La Rovina	Castelló d'Empúries	Girona

Table 2: Area occupied by dune systems in Catalonia

Outside these five areas of coast, other dune morphologies are very small. Table 3 shows that 60% of digitised dune polygons cover an area of less than 0.5 ha, while 17% cover less than 0.05 ha.

Ha	Number of dunes	%
0-0.05	41	16.9
0.05-0.5	105	43.4
0.5-1	23	9.1
1-5	52	21.5
5-10	12	5.0
10-20	7	3.3
> 20	3	0.8
Total	243	100

Table 3: Range of areas occupied by dune morphologies

The different types of dune systems and morphologies that have been observed on the coast of Catalonia are expressed in pictorial form in figure 6. Most of the coast of Catalonia is built-up and many dune forms have resulted from the presence of different types of artificial barriers that line beaches (piers, dykes, sea promenades, buildings, etc.). The dune forms observed have been classified as the following dune types:

a) Barchan and transverse dunes: Barchan dunes are free, crescent-shaped dunes that form on broad beaches upon the action of strong winds. They can be observed on the beaches of Can Comes, Sant Pere Pescador (Roig, 2008), El Fangar spit (Rodríguez *et al*, 2009) and other beaches in the Ebro delta. They do not rise to a great vertical height on the coast of Catalonia. Transverse dunes are formed on the same beaches as above, often because of the coalescence of barchan dunes that come into contact sideways. Waves and beach-cleaning with heavy machinery change these morphologies considerably and prompt their disappearance after a storm or in high season.

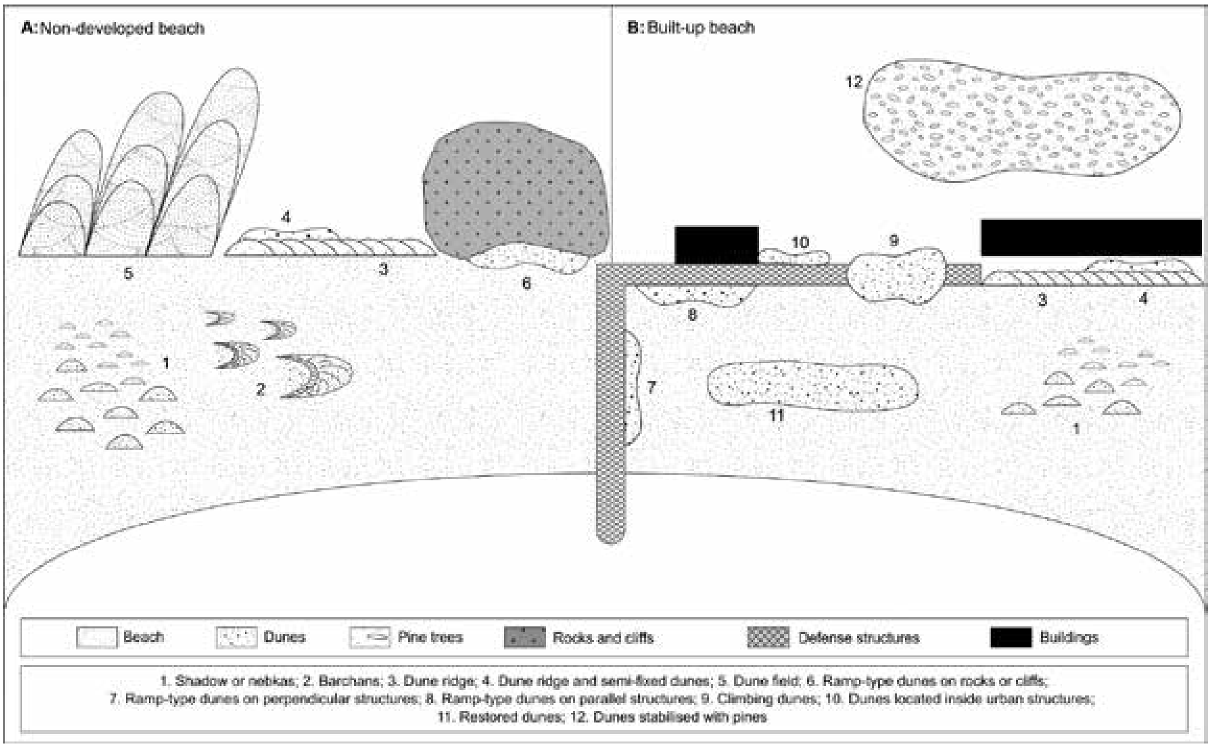

Figure 6. Outline of the different types of dunes currently found on built-up and non-developed beaches of the Catalan coast.

b) Shadow dunes: small mounds of sand that form on the upper beach, often induced by the presence of a particular type of plant. Their existence is very often fleeting and they can disappear on account of the action of the swell in storms. They occur on nearly all beaches. When these dunes are found further inland, they can survive for years while increasing in size, and form mounds of 1 m or more in height, in which case they are known as *nebkas*. They may be observed particularly on the beach of El Fangar in the Ebro delta.

c) Ramp-type dunes: these dunes are adjoined to different structures on the edges of the beach, which may be walls that close off the beach in the case of urban beaches bounded by a sea promenade, or breakwaters perpendicular to the coastline or any other structure that obstructs the wind. There are numerous examples and such dunes, albeit small, can be found on almost all beaches.

d) Climbing dunes: on some beaches bounded by rock slopes or embankments, the sand driven by the wind covers or climbs up the slope. Such dunes can be found, for example, on the Riuet beach at Empúries, at the far eastern end of La Fosca beach, and in Borró cove, as well as a dune ridge. This type of dune, now subject to urban development, was also found at Cape of Salou.

e) Isolated dune crests: these may respond to natural dynamics and result from the evolution and development of *nebkas* that combine and form a dune ridge on the inland edge of the beach, or may have been generated artificially in order to protect the land adjacent to the beach from flooding by waves in storms. On some beaches they form a continuous ridge parallel to the shoreline, albeit with large or small discontinuities caused by wind erosion or by human activity "Can Comes beach (Castelló d'Empúries), La Pletera beach (Torroella Montgrí), Cortal de la Devesa beach (Sant Pere Pescador)" and are sometimes only small remaining fragments that survive in isolation on beaches with major influxes (Sant Pol beach at Sant Feliu). The heights of the ridges are very variable and range from approximately 1 m on the dune ridge of the El Prat beach (El Prat de Llobregat) to 10-12 metres on the crest of the Riumar beach (Ebro Delta).

f) Dune ridge with backdune: on some beaches, on the leeward side of the dune ridge and protected thereby from the wind, there persists a sand sheet that can stretch several metres inland where plant coverage on the ground is densest, thus preventing the sand from being easily moved. These backdune environments are therefore sometimes known as semi-fixed dunes. The backdune is, significantly, one of the dune landscapes that has receded most with urban development on the beachfront. They are still to be found on La Rovina beach, in some sections of the dunes on Can Comes beach, on La Fonollera beach, at Pals, in the Llobregat delta, at Torredembarra and on some beaches in the Ebro Delta.

g) Fixed dunes: As mentioned above, many dune systems were stabilised in the late nineteenth and the early twentieth centuries with the planting of pine trees in order to prevent fields and properties from being affected by shifting sands. The Empordà region is home to the large inland dune systems of Montgrí and the hills of Begur, as well as other smaller stabilised dunes, scattered over different parts of the plain. The dunes of the beaches of Empúries were also stabilised in the same period, and at places such as Pals, Platja d'Aro, Blanes and Castelldefels, stabilised coastal dunes were eventually built upon and today are sites for second homes, golf courses and campsites.

h) Restored dunes: In recent years, some councils and public authorities have implemented measures to conserve the dune systems of their coastlines and, in some cases, to restore dune morphologies on beaches where they had disappeared. Such interventions indicate a change in perception of these areas and acknowledgement not only of the environmental and landscape value of dunes, but also of the fact that dunes provide an excellent mechanism for the defence and conservation of beaches against the negative impacts that may result from the rise in sea level envisaged in the reports of the IPCC (Hesp, 2007; Tsoar and Blumberg, 2007).

4. Conclusions

As regards the information taken from documentary sources, this work has mainly involved review of geographical sources relating to the territory of Catalonia as a whole. If the research were extended to local monographic studies, new data could perhaps be acquired to yield further knowledge about the status of the dunes in the past. If the research were extended to the field of old photographs, perhaps we would find more beaches upon which dune previously existed, as there are some beaches for which it has not been possible to find images.

Analysis of documentary sources and old photographs has highlighted the fact that the dunes were a common feature of the beaches before widespread urbanisation processes on the coastline. They were more developed on beaches well supplied with sand, where ridges and dune systems formed, and less developed, albeit also present, on others.

The current situation is very different. The dunes have disappeared from most beaches and have shrunk and are subject to different impacts on the beaches where they do remain, as a result of the use of beaches for tourism. The diversity of elements present on the beach and in the vicinity also yields a broad range of wind-generated sand accumulations with their own specific dynamics and characteristics.

The protection and restoration of the remaining dune systems is a measure of coastal management that has grown widespread only recently and there is still much room for improvement. The restoration of dunes should entail much more than the reconstruction of dune shapes. It should also incorporate measures to enhance beach users' awareness of the fragility and the values of dune landscapes. In addition to the aesthetic, natural and symbolic values of dune landscapes, emphasis should be placed on their role in defending the coast against storm swells, and in forming a reservoir of sand on beaches affected by erosion.

Both beach users and coastal managers should therefore adopt a more dynamic view of the coast and of the changes that marine and wind processes entail, rather than approaches that opt for stabilisation or even to make forms and processes rigid. It is not, however, realistic to try to recreate former natural dune landscapes exactly on today's urban coasts. Restored dunes could therefore be different from what was perhaps there before. They may be smaller, but that is no reason to give up the mosaic of environments and processes that characterise them.

Thanks
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Ecological restoration of coastal sand dunes: Guincho beach study case (Portugal)

Vasco Silva[1], Irene Correia[2], Alexandre Neto[3], José Romana[2] and Sara Saraiva[2]

[1] Centro de Ecologia Aplicada Prof. Baeta Neves, Instituto Superior de Agronomia, Universidade de Lisboa, Lisboa, Portugal.
[2] Department of Natural Areas, Cascais Ambiente – Empresa Municipal de Ambiente de Cascais, Alcabideche, Portugal
[3] Direcção-Geral de Recursos Naturais, Segurança e Serviços Marítimos, Algés, Portugal

1. Abstract

The Guincho beach dunes account for a small portion of the Guincho-Oitavos dune complex located in Sintra-Cascais Natural Park (Portugal). It is a system exposed to intense anthropogenic pressure that has led to its degradation. To recover its natural value requires measures of restoration and protection. Habitat management actions have been aimed essentially to ease and manage the impacts on the sand dunes, through the installation of biophysical structures (which reduce the wind speed and promote sand deposition), planting of characteristic species (e.g. *Ammophila arenaria*) plus the removal of non-native species (e.g. *Acacia* sp. pl.). The material for constructing biophysical structures was based on bibliography and installed on the primary frontal dune, perpendicular to the prevailing wind direction. The levels of sand accumulated by the biophysical structures were monitored. Four years after intervention, the planted native species are now well-established and natural vegetation occurs spontaneously, although it has been necessary to replace some plants and sections of biophysical structures. Modelling sand accumulation and monitoring the establishment of vegetation continues.

2. Introduction

The Guincho-Cresmina sand dunes account for a small part of the Guincho-Oitavos dune complex, located in the Sintra-Cascais Natural Park, Portugal (Fig. 1).

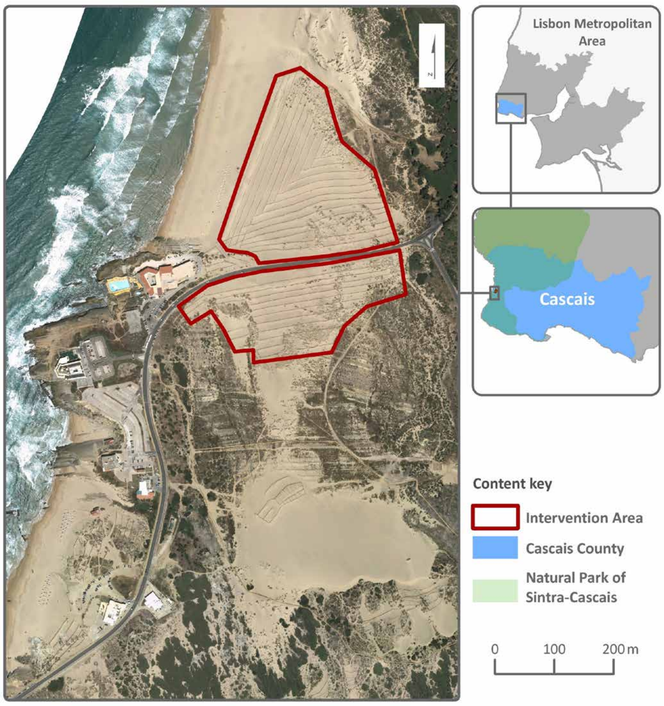

Figure 1. Map showing the location of the area of intervention in the Guincho-Cresmina dune system, Cascais (Portugal).

This dune system, known as the Cresmina-Oitavos aeolian dune field, is rather unique as the sand coming from the Guincho and Cresmina beaches returns to the sea further south, between Oitavos and Guia, after migrating on the flat rocky platform of Cabo Raso (Roxo *et al*., 1978).

The Guincho-Cresmina dune system is active on account of the constant drifting of sand particles blown by the prevailing winds (Rebêlo, 1992). The wind patterns on the site are complex, given that N and NW winds are dominant (Alcoforado, 1984). The existence of impermeable barriers (e.g. restaurants, road) has narrowed the sand transportation corridor and thus accelerated its dynamic. With increasing wind speed, deposited sediments began to appear in an area further away from the coastline, with a consequent reduction in beach area (ICN, 2003) (Fig. 2). Studies show that the Cresmina dune is moving in a north-south direction at about 10 m per year (Rebêlo *et al.*, 2002).

Figure 2. Cresmina dune and Guincho beach, Cascais.

In the long term, these circumstances may have dramatic impact and cause a loss of arable soil, infrastructures and dwellings. Dune ridges are fragile yet very important geological structures, as act to protect inland terrain from a rising sea level (Taborda *et al.*, 2010; Van der Meulen & Salman, 1996).
On account of their dynamic nature, the natural habitats exhibit a delicate ecological balance, with a gradient of poor soil (sands) and adverse climatic conditions (strong winds laden with salt spray) (Martins *et al.*, 2013). Furthermore, there is a rich and diverse flora and fauna associated with the dune system. It is a system subject to strong anthropogenic pressure, which has led to its degradation, and in order to safeguard its natural value requires restoration and protection measures as recommended in the Coastal Zone and Natural Park Management Plans (ICN, 2003; Taveira Pinto, 2004).

The main purpose of this study is to characterize the Guincho-Cresmina dunes and analyze the response to the installation of biophysical structures on embryonic and primary dunes with a view to fomenting sand deposition and recovering vegetation (Correia *et al.*, 2014). This intervention is intended essentially to restore and manage impacts on the beach-dune system through the implementation of specific habitat management actions, which include raised wooden walkways connecting the beach to the Interpretive Centre (Silva *et al.*, 2012). As regards monitoring of sand deposition, only the northern area of the Guincho beach was analysed (cf. Fig. 1).

2.1. Previous experience of dune restoration in Portugal and characterization of the method used

On the west coast of Portugal and of the Algarve, where there is both severe coastal erosion and threats from tourism and urban development (Taveira Pinto, 2004), the rehabilitation of sand dunes was traditionally achieved through revegetation with native species (Reis *et al.*, 2008; Pereira *et al.*, 2011) or through the implementation of what are known as "*ripado móvel*" techniques (Martins, 1989). More recently, garden shadow net attached to treated wood trunks was used to trap sand in the Peniche-Baleal dune field (Borges *et al.*, 2009). The method of sand capture used at Guincho beach (ACN, 2011) was unprecedented in Portugal. It is, however, similar to dune restoration techniques applied in Spain (Gomez-Pina *et al.*, 2002). The dry wicker biophysical structures used have a low cost, are simple to acquire and easily assembled, and pose no environmental hazard. This system counteracts wind erosion and yields a more extensive homogeneous accumulation of sand, thus achieving much more aerodynamic and stable topography (Gallego Fernández *et al.*, 2003). It replaces the function that pioneer vegetation naturally plays in dune formation. Its function is to reduce wind speed and therefore also sand transportation by encouraging the deposition of sand at a greater height and width. With these flexible biophysical structures, sand deposition is more regular and occurs on the leeward side, which allows for the creation of dunes with the shape characteristic of the Mediterranean coast (Ley *et al.*, 2007). A combination of the use of these materials and plantation proved to be more suitable for restoring dunes than earlier techniques implemented in Portugal.

2.2. Biophysical characterization

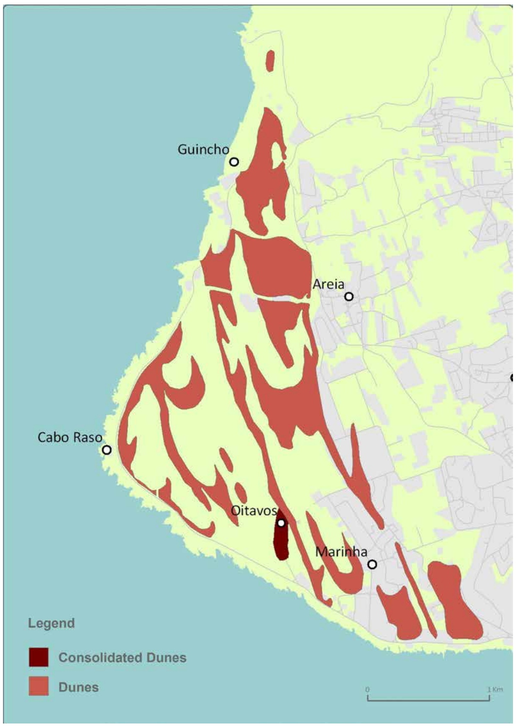

Figure 3. Guincho-Oitavos aeolian dune field and parabolic dunes. Adapted from Roxo *et al.*, (1978).

The Guincho-Cresmina coastal dune system is quite unique as the sand from these beaches returns to the sea further south, between Oitavos and Guia, after migrating through the Cabo Raso flattened rocky platform (Fig. 3). This system is active, semi-open and extremely unstable on account of the coastal morphology, orientation and constant mobilization of sand by the prevailing wind (NW-SE) (Rebêlo, 1992).

The dune system overlaps the Cretaceous limestone layers of the rocky platform of Cabo Raso (Ramalho *et al.*, 2001). The area of intervention corresponds to the aeolian corridor entrance, where for morphological reasons wind velocity is topmost and natural vegetation finds it hard to take root. The amount of sand depends on the coastal drift of sediment and beach level fluctuations. In the study area, a higher availability and transportation of sand can be observed during the summer. Prior to intervention, the formation of *ripples*, sand sheets and *hummocky* dunes was observed (Hesp, 2002; Rebêlo, 1995).

The spatial distribution of natural vegetation is intrinsically related to the dune system dynamics (Roxo, 1978). Hence, the dune vegetation is well adapted to these conditions of dry, nutrient-poor soils and strong winds (Alcoforado, 1984). Unaltered plant community structures which exhibited high floristic diversity are listed as important habitats in the Natura 2000 natural ecological network (Martins *et al.*, 2013). A simplified (predictive) model of matches between geology (sand dunes and beaches consolidated in the Quaternary Period), sandy soils, bioclimatology (thermo-Mediterranean stage) and the remaining plant communities was used to determine the potential natural vegetation of Guincho beach (Costa *et al.*, 1998; ICN, 2003). On the seashore, exposed to wind and occasionally submerged there was previously halonitrophile vegetation *Salsolo kali-Cakiletum maritimae*, the first dune community that was missing on account of high anthropogenic pressure, although occasional specimens of *Cakile maritima* can be identified. On the embryonic dune it is possible to find formations of *Elytrigia juncea* subsp. *boreoatlantica (Elytrigietum junceo-boreoatlantici*), which are occasionally located at the base of what is left of the primary dunes (habitat 2110). On Guincho primary dune there are communities of *Ammophila arenaria* subsp. *arundinacea, Lotus creticus, Otanthus maritimus, Eryngium maritimum and Pancratium maritimum* (*Loto cretici-Ammophiletum australis*) (habitat 2120), mainly on the dune ridges throughout the system. In the sands of fixed dunes of Guincho, mature-stage natural vegetation consists in a thicket of *Juniperus turbinata* (*Osyrio quadripartitae-Juniperetum turbinatae*) (habitat 2250) (Costa *et al.*, 2000; Martins *et al.*, 2013). When the sands are less cohesive, a community of *Armeria welwitschii* (habitat 2130) emerges with an annual primocolonizing grassland of *Tuberarietea guttatae* in the clearings. On stretches of waterline, which are subject to long periods of drought, there are *Tamarix africana* or *Tamarix gallica* (*Polygono equisetiformis-Tamaricetum africanae)* characteristic of sub-saline soils (ACN, 2011). As regards conservation, the greatest diversity of plant species and lowest resilience (to perturbations) were observed in the community of *Armeria welwitschii* (Martins *et al.*, 2013) (Fig. 4).

Figure 4. Plant species and natural vegetation of Guincho-Cresmina dunes.

The sea-inland vegetation gradient should reflect the coastal vegetation zonation from annual beach communities to shrub-covered fixed dunes. However, due to the effects of disturbance (e.g. non-native species dissemination, trampling, urban development), fragmentation and regression occur (Van der Meulen & Salman, 1996).

2.3. Habitat management actions

The ecological restoration of the sand dunes of Guincho beach and the reestablishment of vegetation involved three main habitat management actions (detailed in table 1). The density and the construction material, as well as the distance between the rows of the biophysical structures, were established with reference to the dune restoration handbook for the Iberian Peninsula (Ley *et al.*, 2007). The eradication method and plant spacing were determined on the basis of the literature and on the authors' previous experience (ACN, 2011).

Order	Action	Procedure
1	Eradication of invasive species	Hand-pulling of seedlings and small plants with root system removal (e.g. *Carpobrotus edulis*) and cut stump method for adult plants (*Acacia pycnantha, A. retinodes*).
2	Installation of biophysical structures on the embryonic and primary dune	Built with dry wicker (willow) with a length of 1.80 m (1/4 buried), in parallel tracks with a spacing of 8-10 m between rows, perpendicular to the direction of the prevailing wind, placed vertically where vegetation was absent and distributed homogeneously at a rate of 3 kg per linear meter.
3	Plantation of perennial herbaceous dune species	Plantation of *Elytrigia juncea* ssp. *boreoatlantica on the embryonic* dune and *Ammophila arenaria* ssp. *arundinacea*, *Lotus creticus*, *Eryngium maritimum* on primary dune, during the dormancy period (November-February), at 1 m apart.

Table 1. Habitat management actions with the following order of implementation in Guincho dunes.

In addition, fences were placed in the study area along with raised wooden walkways to avoid trampling and vehicular access, and wooden benches, litter bins and interpretive panels on the Guincho-Cresmina dune system were established to control the impact of visitors (Correia *et al.*, 2014).

2.4. Data collection and analyses

To monitor sand accumulation levels, 52 nozzled wooden sticks (poles) treated in autoclave and measuring 140 x 20 x 10 cm (length, width and thickness) were previously graduated and painted with protective wood oil to enhance their durability. These were then placed in the study area in rows parallel to the biophysical structures from the beach inland, spaced about 12 meters from one another. The poles were distributed uniformly in alternate rows, not only to cover the area fully, but also to minimise the time required for measurement (C.Ley, pers. comm.). All poles were spatially referenced using a

Global Positioning System (GPS) and later also with a topographic survey, to improve the accuracy of their planimetric and altimetric coordinates.

The measurement process was initiated in November 2010 and lasted until December 2012. During this period the poles were monitored each month on site and the levels of sand accumulation were registered. All the stolen, broken or vandalized poles were replaced in the shortest time possible. Two surveys were performed with differential GPS (in November 2012 and November 2013) in sections of the poles to measure the differences. All pole measurements were recorded on a spreadsheet, differentiated by date and by their planimetric coordinates. Because of the constant disappearance and vandalism of the poles during the monitoring period, it was not possible to keep a continuous record of the total sand accumulation on each pole. Although this method was suitable for measuring dune evolution, it did not provide reliable estimates of the volume of sand transported, unlike the measurements using differential GPS that were taken in a second phase. To overcome this difficulty, the height (m) of sand deposition was calculated on a monthly basis for each pole with respect to the previous measurement, without consideration for unavailability of data on account of the absence of a pole. A Geographic Information System (GIS) script (http://www.qgis.org) was used to develop a spatial analysis model (Fig. 5) for creating the envisaged deposition surfaces of the total study area corresponding to each measurement date, and totalling them for prolonged periods for the purpose of comparison (2010-2012 and 2012-2013). To create smooth surfaces attached to the measurement points, the spline interpolation method was chosen (Correia *et al.*, 2014).

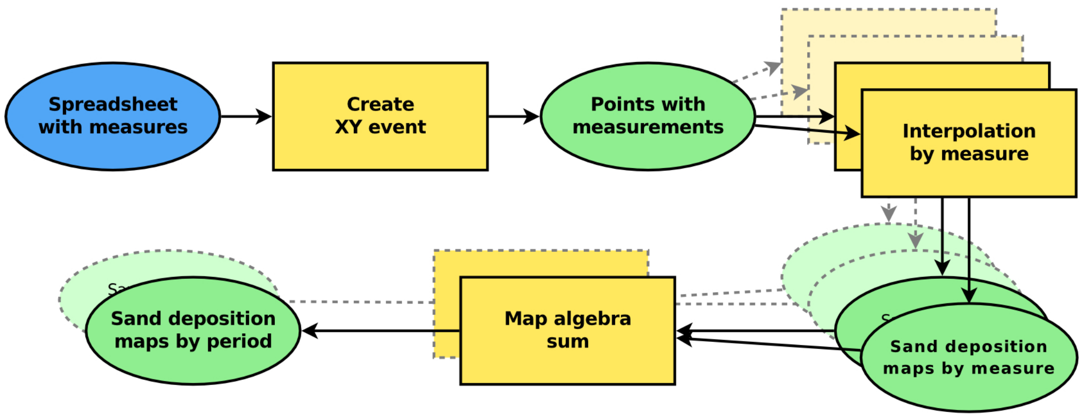

Figure 5. Data analysis procedure with GIS. Diagram created using Dia (http://dia-installer.de).

New habitat management actions were outlined at the end of each year. These included the placement of biophysical structures on the primary frontal dune, control of invasive alien species, as well as planting and/or replanting of *Ammophila arenaria*. Summary data of the development and establishment of spontaneous vegetation and the planted species was also registered.

2.5. Actions and monitoring results

Work began with manual/mechanical cutting with herbicide application and hand-pulling of invasive alien species (1st action, table 1). The 2nd action (table 1) involved the installation of biophysical structures in late October 2010 (Fig. 6 and 7). After the period of greatest accumulation of sand (summer), dune species were then planted - 3rd action (table 1). This action was intended to assist the natural process of establishment of other species such as *Pancratium maritimum, Otanthus maritimus* and *Artemisia crithmifolia.*

Whenever biophysical structures became non-functional due to burial, new structures were installed the following winters (December-January), using the same material and technique, on each sand deposition in the first three rows, to proceed with the accumulation of sand (Fig. 8).

Figure 6. Habitat management actions in the Guincho dunes.
Figure 7. Biophysical structures in the first act of intervention (November 2010) on Guincho beach.

Figure 8. Sand deposition on biophysical structures in December 2011.

Following the initial installation of the biophysical structures, a one year measurement period was established (November 2010 until December 2011) (Fig. 9). During this period the maximum incidence of sand deposition observed on the dune ridge front was 197 cm high, whereas the minimum was -25 cm. This represents an average sand deposition of 16 cm (Fig. 7 and 8).

After the second intervention in January 2012, there followed a second measurement period (January 2012 until December 2012) (Fig. 9) in which the maximum incidence of sand deposition on the dune ridge front was 82 cm high and the minimum around -27 cm. This represents an average sand deposition of 3 cm. On the highly mobile frontal dune, the planted vegetation was partly lost on account of its lower development and of dune movement that buried the plants. The *Ammophila arenaria* plants were not able to adapt to the sudden deposition of sand. The loss of sand from the root area was also observed in the intradune depression plantation.

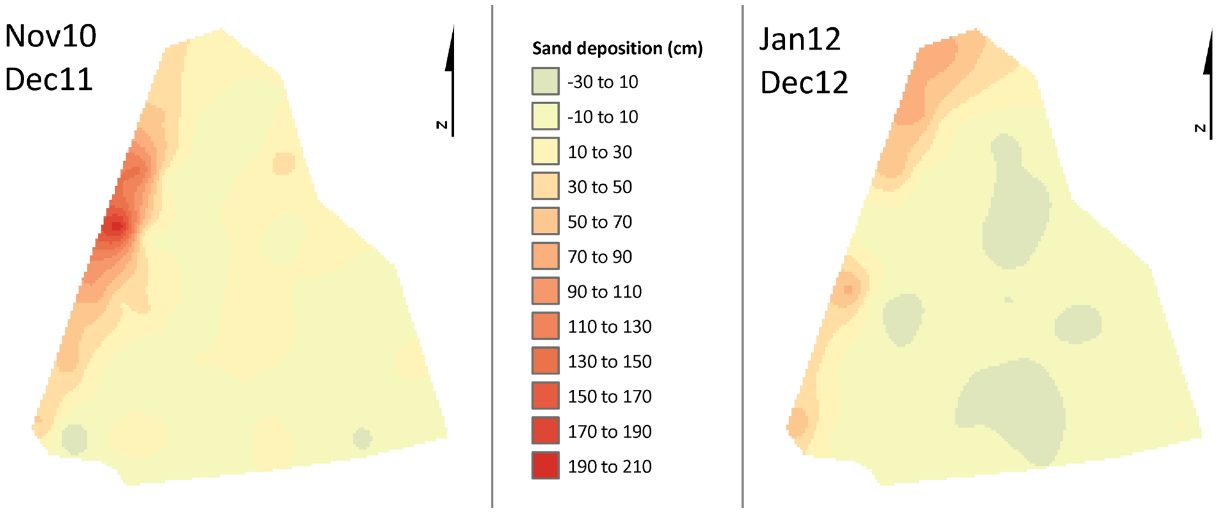

Figure 9. Expected deposition surfaces.

The third intervention occurred in January 2013 and was followed by differential GPS measurement (November 2013) (Fig. 10). The map and profiles were based on accurate data collected with topographic measurement (2010) and differential GPS (November 2012 and 2013) (Fig. 11).

Figure 10. Sand deposition on biophysical structures in early January 2013.

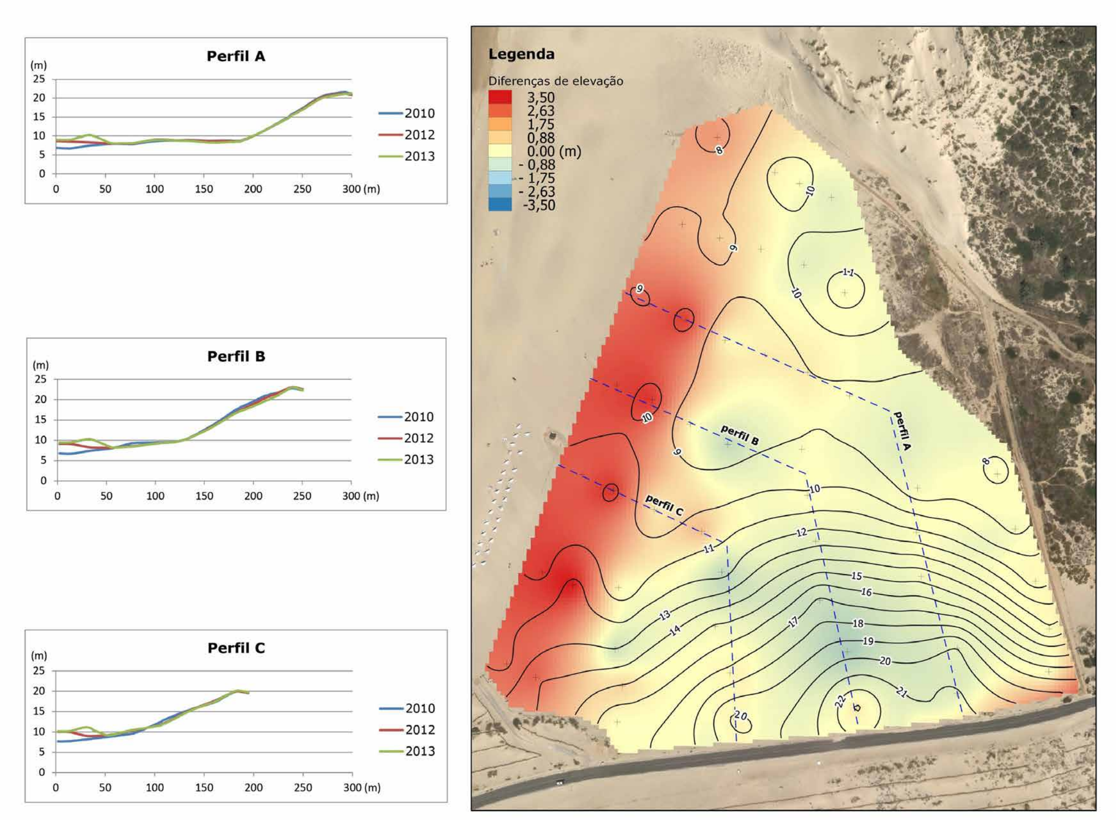

Figure 11. Guincho dune evolution 2010-2013.

Table 2 shows the quantities of plants and biophysical structures that were used in the dune restoration project between 2010 and 2013, as well as the yearly implementation of habitat management actions.

Quantities	**Actions**
5.8 ha	Plantation of perennial herbaceous dune species:
8,640 plants	*Elytrigia juncea* subsp. *boreoatlantica*
42,000 plants	*Ammophila arenaria* subsp. *arundinacea*
7,182 plants	*Lotus creticus*
702 plants	*Eryngium maritimum*
10 km	Biophysical structures to sand trapping

Table 2. Planted area, number of plants and quantity of biophysical structures installed on the Guincho dunes.

The fourth and final intervention took place in January 2014 and was followed by differential GPS measurement. This study is an ongoing part of a Master's degree thesis still in progress, the data of which are not discussed here.

2.6. Discussion

The levels of sand accumulated by the biophysical structures were monitored using poles distributed uniformly over the area of intervention. In the first 12 months a sand deposition of about 1.7 m was recorded on the leeward side of the first row (Fig. 8). In the 2nd year it reached a height of 82 cm. In the

3rd year, records show a sand accumulation height of 0.71 cm. The results show that after the first 3 years the primary dune crest had reached a height of 3.5 m. Once sand deposition occurred, common errors were noticed after the instalment of raised wooden walkways as they became buried when installed. The high susceptibility of the poles to vandalism, despite the installation of fences and gates, raised questions about the method of sand measurement because of its influence on monitoring the results. Another measurement method should therefore be sought. The plantation area on the primary frontal dune was excessive and premature. It should have been implemented gradually, after a prior study of sand deposition in order to determine how the system would react to intervention. The planted vegetation is, meanwhile, well established although it has been necessary to replace some plants after this one-year period. The natural vegetation occurs spontaneously in the first three rows, with presence of *E. juncea* subsp. *boreoatlantica* and *Cakile maritima*. In the back rows of the system some stabilization was observed. The reduction of disturbance, combined with plantation, led to widespread establishment of *Lotus creticus*, a situation that has already been observed in Vila Nova de Gaia with leguminous plants of *Medicago marina* (Laranjeira & Pereira, 2013).

This method consisting of sand trapping, fences and revegetation –designated passive techniques (Lithgow *et al.*, 2013)– seems to be a viable alternative for relieving problems of erosion in the coastal dune systems of Portugal. These types of biophysical structures, built with dry wicker (willow), can intensify the process of foredune development and can be considered as an effective and reliable method with which to encourage the recuperation of the dune ridge. Recently, other projects in Portugal, such as the ReDuna project on São João da Caparica beach (Almada) (P. Pinto da Silva, pers. comm.), in which these materials and mixed techniques have been used, back up the positive results obtained at Guincho.

Management plans should be outlined to ensure that actions are effective. Successful restoration can be achieved and encouraged when decisions are taken with consideration for scientific knowledge and social needs. The next objective is therefore to model the required profile of sand accumulation on Guincho beach, without entering into conflict with the presence of the road (N247).

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La devesa de l'Albufera of Valencia: a case of dune restoration

Amelia Quintana Trenor[1], Antonio Vizcaíno Matarredona[1], Francisco Collado Rosique[1], Joan Miquel Benavent Olmos[1], Jesús Soriano González[2]

[1] Valencia City Council La Devesa-Albufera Service
[2] Oceanographer and environmental and land manager

1. Introduction

La Devesa de l'Albufera is an 850-ha coastal dune area to the south of the city of Valencia. Currently owned by Valencia City Council, it belonged to the Crown from the thirteenth century until the late nineteenth century, when it became property of the Spanish state. In 1905, Valencia City Council began negotiating its acquisition, a process that culminated in 1948, the year in which it was registered in the municipal inventory together with Valencia's Albufera lagoon. Since 1986, both sites have formed part of the Albufera Natural Park.

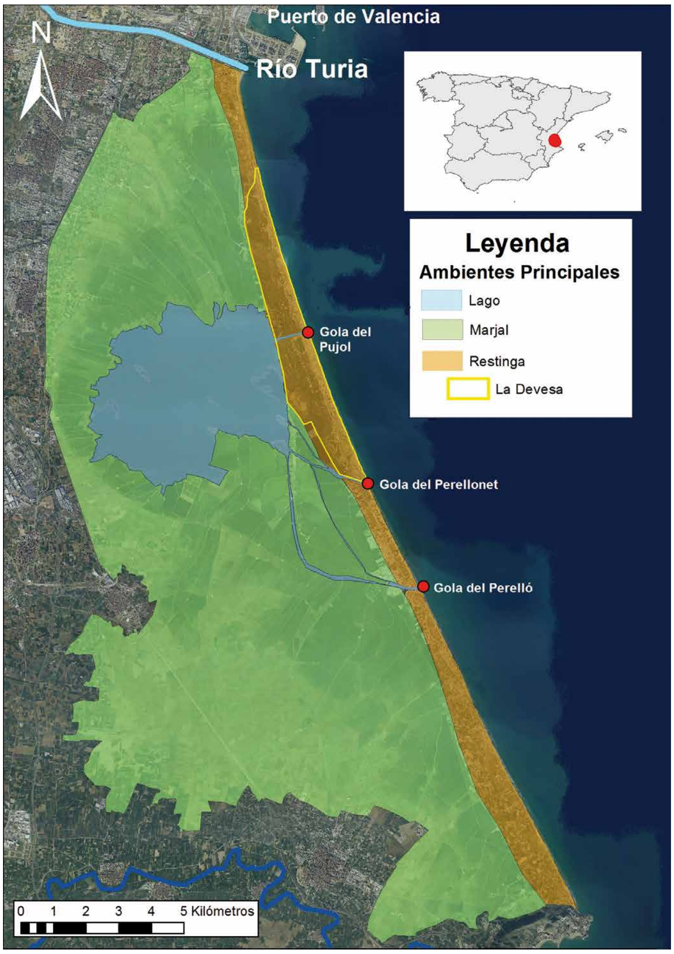


Figure 1. Albufera of Valencia Natural Park: environmental units. Location of La Devesa.

La Devesa is located in the northern section of the barrier beach that was formed in the Holocene and that sealed off the former Gulf of Valencia to create the Albufera lagoon. This barrier beach, which stretches over 30 km in length between the mouth of the new Turia river course and Cape Cullera, was originally formed by a major dune field of which today there remains very little. La Devesa is currently the best preserved sector of this dune system. As the use of irrigation expanded, many of the sandy zones of the barrier beach were made into vegetable gardens that later, with the urban development of the second half of the twentieth century, were largely allocated residential uses, which caused dune formations to recede considerably along the entire barrier beach. This zone retained its natural condition on account of its status as royal or public heritage. In 1965, however, at the height of the tourist boom in Spain, there began a process of urban development that seriously altered its ecosystems and nearly destroyed La Devesa as a natural site.

La Devesa is a natural area of a compact size (approximately 10 km long by 1 km wide) that features a series of climatic and soil factors that have given rise to four major ecosystems. These have significant and diverse flora, fauna and landscape that afford it great biodiversity and considerable environmental value, which is internationally acknowledged.

Photo 1. La Devesa de l'Albufera of Valencia.

1.1. Ecosystems of La Devesa

- The beach is an ecosystem formed by three sub-ecosystems —submerged beach, wet beach and dry beach— that are very much interrelated. On the wet beach there is commonly an abundance of detrital material, typically occupied by a community that includes crustaceans, insects and also birds that come in search of food. The dry beach, which is colonised by the *Salsolo kali-Cakiletum aegyptiacae* plant community, generates accumulations of sand —embryonic dunes— that in a normal, natural process without intervention such as the passage of cleaning tractors, would yield the emergence of shifting dunes.

Photo 2. Foredunes.

- The exterior dune system is the area closest to the beach, formed both by foredunes or first-line dunes and also transitional dunes. It consists of dunes parallel to the sea between which the wind has formed hollowed-out abrasion craters with a high degree of soil moisture. The typically harsh environmental conditions of this ecosystem have led its vegetation and its fauna to adopt special strategies in order to survive here. Further away from the sea, shrubby plant species are more abundant and species typical of the coastal maquis begin to appear.

Photo 3. Interdune depression or dune slack.

- The interdune depressions or dune slacks typically have silty soils that are waterlogged in rainy periods and upon which salty crusts form when water evaporates in the high temperatures. Vegetation grows in concentric circles according to the salinity level. In the central part, where the salt level is very high, there is no vegetation. Salt marsh vegetation, consisting mainly of Salicornia, grows around this area and in the outermost zone, where the salinity is lower, there are reeds and grasses.

- The interior dune system is typically the location of the oldest dunes, where vegetation cover is much denser. The zone nearest to the exterior dune system, still influenced by the sea wind, is home to rockrose, open scrubland with abundant sandy clearings. The most remote areas, where the sea has less impact, are predominated by Mediterranean coastal maquis, where coverage, density and diversity are typically considerable.

Photo 4. Interior dunes.

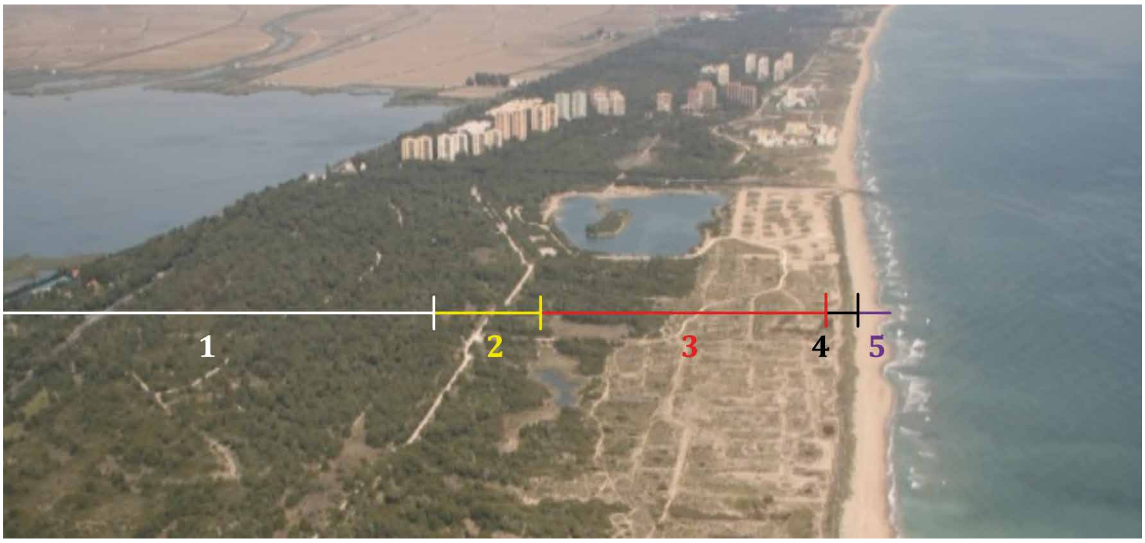


Photo 5. Ecosystems of La Devesa. (1) Interior dunes; (2) Dune slacks; (3) Transition zone; (4) Shifting dunes; (5) Beach.

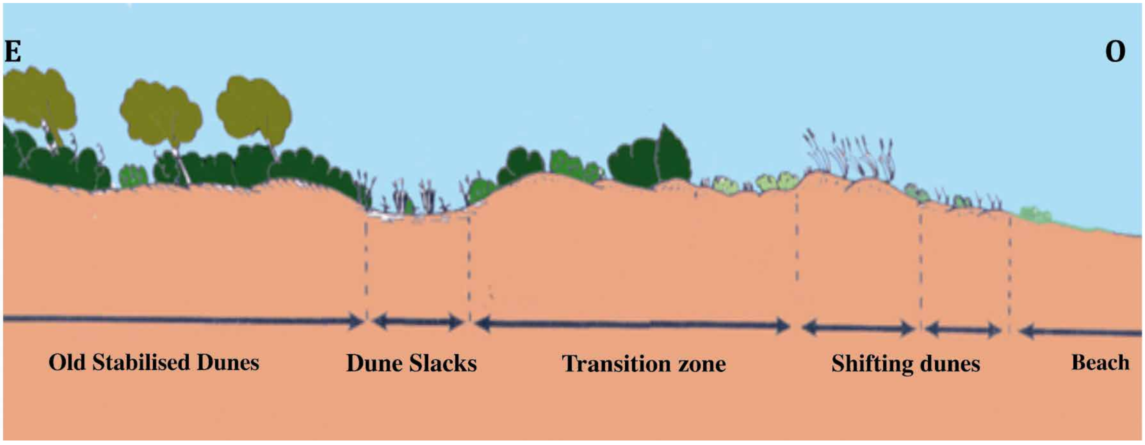


Figura 2. Simplificación del perfil de los ecosistemas de la Devesa.

As a result of the urban development process, which began in 1965, the exterior dune system was destroyed almost in its entirety for the construction of a sea promenade, roads, car parks and housing; the interdune depressions or dune slacks were filled with sand from the destruction of the exterior dune system and repopulated with eucalyptuses, and the interior dune system was broken up upon the construction of roads, car parks, housing and infrastructures. These interventions changed the geomorphological structure of La Devesa, destroyed its ecosystems and gave rise to an artificial and fragmented landscape that completely altered the balance of the system.

Photo 6. Detail of the sea promenade raised 4 m above sea level that stretched for 2.5 km along El Saler beach. Below the promenade different premises that engaged in different activities, particularly food and catering and public services.

Significantly, the impact of urban development was different in the south and the north of La Devesa. Although the extent of urban development planned was greater in the southern section (from Gola del Pujol to Gola del Perellonet), the full process was only implemented in one stretch of the northern section. In the south, although the exterior dune system was destroyed completely and infrastructures were built, no building was erected as the process of urban development was successfully paralysed beforehand. This has facilitated the restoration process in this zone.

Photo 7. Detail of the sea promenade that stretched for 5.5 km to the south of the raised sea promenade and along the entire beach of La Devesa. It was formed by a 1.2-m high wall, which on the inside was joined to a road of some 5 m wide with accesses to the beach at specific intervals.

Today, this southern section is the best preserved and enjoys the highest level of protection. The foredunes of La Devesa and the transition zone, the dune slacks and the inland dunes of the southern section have now been recovered and are in a process of renaturation.

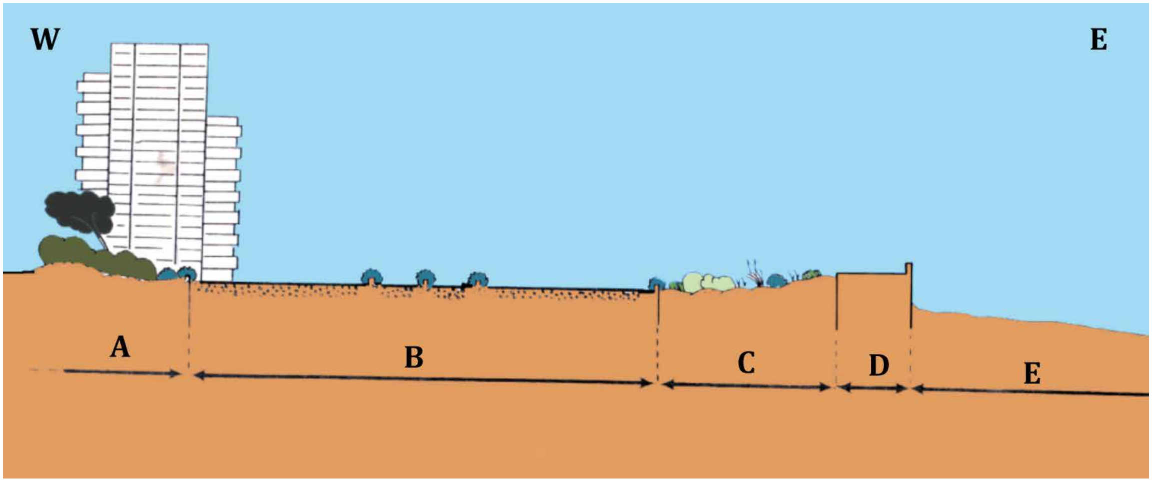


Figure 3. Profile of the ecosystems of La Devesa after urban development. A) Housing developments on stabilised dunes; B) Filling in of dune slacks and destruction of part of the transition zone to build roads and car parks; C) Reduction of the transition zone; D) Destruction of dunes and construction of the sea promenade; E) Beach.

Since the decision was taken, over thirty years ago, to recover the landscape and the natural values of La Devesa, numerous measures have been undertaken to this end.

One of the first steps taken was the creation of a nursery of native plants to repopulate and restore the degraded areas. New land use of the zone aimed at preserving areas of special value was also implemented at the same time. Vehicular traffic in the most sensitive areas was restricted, pedestrian access to the areas of highest value was also limited and the most intensive recreational use was concentrated in the areas of least natural value or most deteriorated zones. In addition to the new allocation of land uses, different measures aimed at accelerating the natural regeneration of ecosystems affected by the urban development process were implemented with a view to encouraging restoration of the ecosystems of La Devesa.

As regards the recovery measures undertaken by the Devesa-Albufera Service and the type of investment made, work to restore La Devesa can be divided into three stages. In the early years, from 1982-1988, the work done was experimental and entailed testing different techniques and materials with a view to establishing the most suitable restoration methodology. The initial restoration work was undertaken from 1988 to 2000 with own resources and on small budgets. Since the year 2000, large projects have been performed using the same methodology but with European, Spanish and regional funding and this has allowed for the recovery of extensive areas.

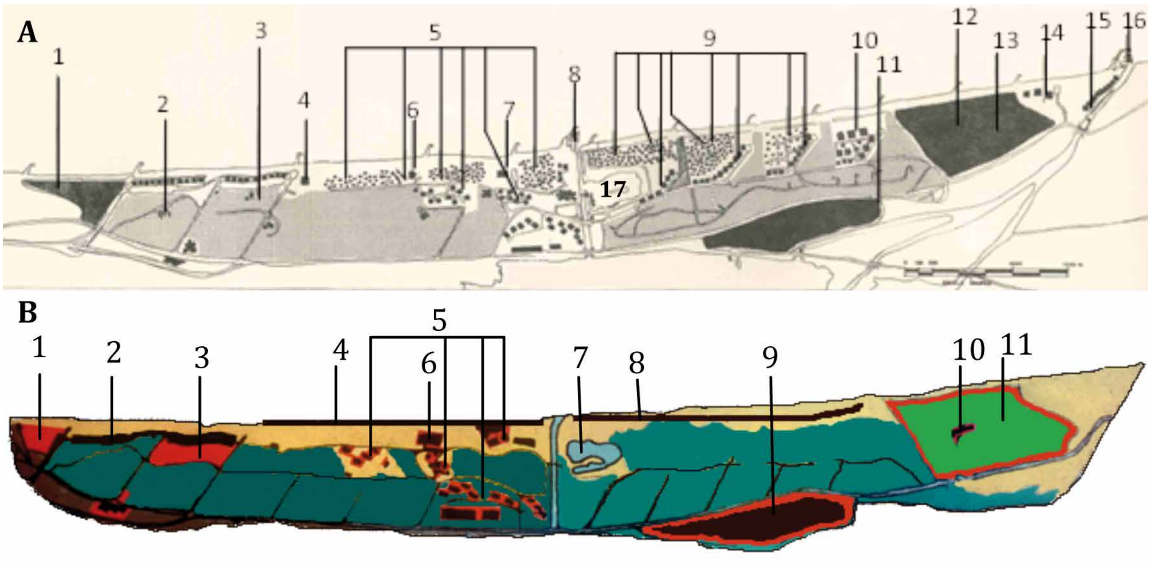


Figure 4. A) Simplification of the 1974 plan (modification of the 1965 plan). B) What was eventually built.

A) 1) Sports centre; 2) Funfair; 3) Campsite; 4) Hotel; 5) Built-up areas, apartment buildings and housing developments; 6) Hotel; 7) Hotel; 8) Marina; 9) Built-up areas, apartment buildings and blocks; 10) Hotels; 11) Racecourse; 12) Parador hotel; 13) Golf course; 14) Hotels; 15) Blocks; 16) Marina; 17) Artificial lagoon.

B) 1) Sports centre; 2) Raised sea promenade; 3) Campsite; 4) Ground-level sea promenade; 5) Apartment buildings and housing developments; 6) Hotel; 7) Artificial lagoon; 8) Ground-level sea promenade; 9) Racecourse; 10) Parador hotel; 11) Golf course.

Also significant is the fact that the restoration work carried out in the southern section of La Devesa was undertaken by the City Council and the sand used in this case originated completely from La Devesa itself. In the northern section, restoration was carried out by the Coastal Department of the Ministry and/or the Government of the Autonomous Community of Valencia, and the sand came mainly from

Photos 8 and 9. Trials with different types of material and arrangements to stabilise the sand. Left: Plastic meshes. Right: Bundles of eucalyptus branches originating from the removal of these trees.

Photo 10. Left: 2002. North Malladeta beach and Brava beach. Removal of infrastructures. In the LIFE DUNA project, 270 man-holes with a depth ranging from 2.45 to 4.25 m were removed.

Photo 11. Right: Regeneration of interior dunes of southern Devesa. Detail. Removal of obsolete infrastructures (here a former electrical substation).

outside La Devesa (dredged from submerged beach or extracted from dry beach to the north of the port of Valencia, from quarries, or from opening the mouth of the channels, etc.). In these cases, the City Council has worked with both administrations. The plants used in all the restoration work came entirely from the municipal nurseries of the Devesa-Albufera Service or from La Devesa itself.

The general restoration measures undertaken by the Devesa-Albufera Service in each of the ecosystems are described below.

1.2. Foredunes and transition zone

1. - Extraction of plant species of interest and/or collection of seeds and removal of non-native species. This second task must be checked subsequently.
2. - Removal of the sea promenade, roads, car parks and all types of infrastructures.
3. - Reconstruction of the dune morphology by means of the mechanical accumulation of sand and dune stabilisation by building fencing and planting species typical of each ecosystem.

The fencing is built from giant reed *(Arundo donax)* and cord grass (*Spartina versicolor*), and has a permeability of 50%, a height of 70-80 cm and an orthogonal grid arrangement. On the primary front, longitudinal ridges of dunes are formed parallel to the coast. Their profile is asymmetrical and steepest slope is on the leeward side. These are very often set back to create a broader beach and, therefore, make the system more stable.

The sand used comes from the creation of new craters or from the enlargement of those that currently exist and the emptying of the dune slacks. When the dunes in the transition zone region are destroyed, the vegetation quickly colonises this space to yield a homogeneous surface with no differences in height. With the creation of new craters, sand is obtained for the formation of dunes and the dune landscape is reconstructed. The dune slacks filled in by urban development are recovered by emptying them and returning the sand filling them to its place of origin, to the foredunes and to the transitional dunes. The dune slacks should be recovered with care, without breaking the layer of silt and with very gentle slopes. Dunes recover faster than the dune slacks and can reach an optimal state within four or five years after their creation, while dune slacks require an average of nine years.
Design of the new morphology involves consideration of the relief prior to 1965 and the circumstances of the time the intervention is to be undertaken.
4. - In some cases, stakes and ropes are used to close off the recovery area temporarily.

Photo 12. Stabilisation of sand using stakes of giant reed (Arundo donax) and cord grass (Spartina versicolor). Cord grass is a plant that grows at the outermost part of the dune slacks and was traditionally used for the roofing of huts.

1.3. Interior or stabilised dunes

1. - Extraction of plant species of interest and/or collection of seeds and removal of non-native species. This second task must be checked subsequently.
2. - Removal of car parks, infrastructures and roads or a reduction of their width. For reasons of safety and emergencies, some sections of roads built during the urban development process have been kept. In these cases, their width has been reduced (from 14 to 3.5 metres), they have been given a winding pattern, and their surface has been replaced with coloured concrete. In the southern part of La Devesa, the total area occupied by roads has been reduced by 75%.
3. – Planting in recovered zones to integrate these areas in their surroundings.
All measures have been accompanied at all times with widespread information campaigns involving several educational and cultural activities aimed at informing the public of the natural values of the area with a view to encouraging public involvement and collaboration.

In order to restore the plant cover in each recovered ecosystem, the vegetation in areas that have not been destroyed or altered by the process of urban development has been analysed to establish repopulation modules that reproduce the composition and structure of the plant community as closely as possible and by sector. The repopulation module has been established as the basic unit of repopulation for each sector of the dune and for an area of 25 square metres. It simplifies calculation of the plants required in each restoration zone and facilitates planting.

The table below presents a summary of the restoration measures carried out in La Devesa de l'Albufera. It is preceded by a map upon which the beaches and other points of interest may be localised. They have been described according to the order of the measures undertaken by section of beach, from south to north. The measures implemented on the foredunes, in the transitional dunes and in the interior dunes have been differentiated. No specific section has been devoted to the dune slacks or interdune depressions as these are being recovered at the same time as the first-line and transitional ecosystems.

The tables are followed by a photographic appendix featuring evolving series from different zones showing both the process and the result of restoration over the years. The general stabilised dune shrub repopulation module (*Phillyreo angustifoliae-Rhamnetum angustifoliae*) has been included by way of an example.

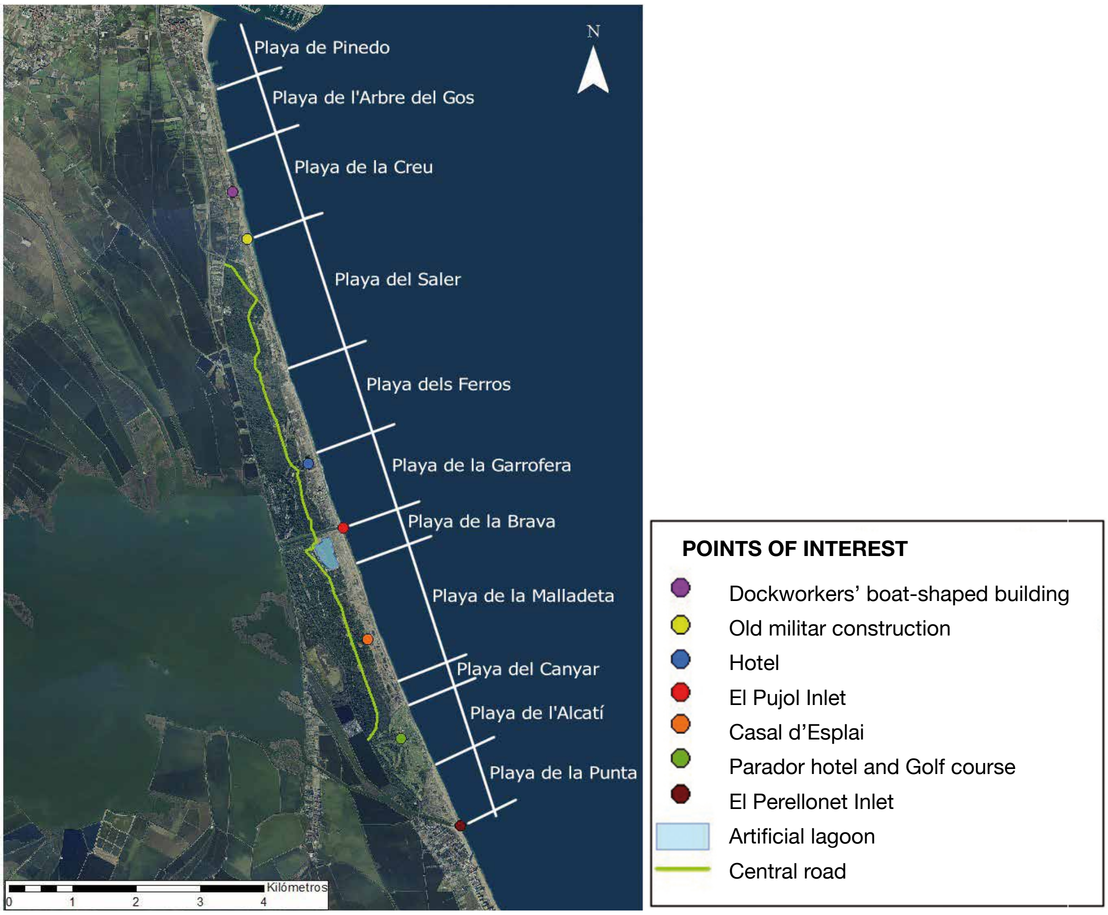


Figure 5. Beaches of La Devesa de l'Albufera of Valencia and other points of interest for understanding and pinpointing the different interventions detailed in the tables.

ZONE OF INTERVENTION	DATES	INTERVENTION	AREA (linear m or m^2)	PLANTATION	ORIGIN OF SAND	PERFORMED BY	INVESTMENT
El Canyar beach	1982	There is no sea promenade. A 7-m dune was made but disappeared because of sparse vegetation and proximity to the sea.	100 ml		From La Devesa itself: from the creation of new abrasion craters and/or enlargement of existing craters.	Valencia City Council (one of the first regeneration trials; performed with its own mechanical and human resources)	
	1991	It was rebuilt, this time further from the shore. Average width of the base: 20-22 m. Height: 4.80 m.	100 ml 2200m2				87.495,19 €
South Malladeta beach	1988	The sea promenade was covered with a dune ridge. Dune height: 5 m (0.5-1.5 m on wall).	800 m 16.000 m2	The embryonic (*Cakiletum aegyptiacae*) and shifting (windward —*Agropiretum mediterraneum*—, crest —*Medicago marinae-Ammophiletum arundinaceae*) — and leeward —*Crucianelletum maritimae*—) dune repopulation module was used.	From La Devesa itself: from sand accumulated on the sea promenade. From the creation of new abrasion craters and/or enlargement of existing craters. From creating lagoons. From El Canyar dune slack.	Valencia City Council. Performed with its own mechanical and human resources	187.425,72 €
	1997	The dune was dismantled, retaining the frontal embryo dunes. The sea promenade was removed and the dune ridge was reconstructed with a base of 20 m. Experimental measure.	62 m 4.800 m2			Machinery hire	
	1998	The dune was dismantled, retaining the frontal embryo dunes. The sea promenade was removed and the dune ridge was reconstructed with a base of 20 m.	547 m 10.940 m2			Machinery hire	136.610,16 €
North Malladeta beach and Brava beach	2001-2004	The sea promenade was removed and a dune ridge with a 25-m base and a height of 4-5 m was constructed. This measure completed the reconstruction of the foredunes of southern Devesa.	2.100 m 52.500 m2		From La Devesa itself: sand accumulated on the sea promenade. From La Mata del Fang and La Sanxa dune slack. From the creation of a lagoon with permanent water in the centre of La Mata del Fang dune slack (4,000 m2). Introduction of two endemic species of fish: the Spanish toothcarp (Aphanius iberus) and the Valencia toothcarp (Valencia hispanica).	Valencia City Council. LIFE DUNA Project (model for the restoration of dune habitats in La Devesa de l'Albufera of Valencia)	1.931.481,57€ 50 %Europe 50 % Council

Table 1. Interventions on the foredunes of southern Devesa (from Gola del Pujol to Gola del Perellonet).

ZONE OF INTERVENTION	DATES	INTERVENTION	AREA (linear m or m²)	PLANTATION	ORIGIN OF SAND	PERFORMED BY	INVESTMENT
La Garrofera beach and Els Ferros beach	1990	The sea promenade was removed. A dune ridge with a 16.5 m base and a height of 4.75 m was constructed. It was set back by 19 m in one section.	1.825 m	The embryonic *(Cakiletum aegyptiacae*) and shifting (windward —*Agropiretum mediterraneum*—, crest —*Medicago marinae-Ammophiletum arundinaceae*— and leeward —*Crucianelletum maritimae*—) dune repopulation module was used.	500,000 m3 of sand dredged from the seabed to the north of the port of Valencia (very fine grain size).	Coastal Department and Government of the Autonomous Community of Valencia	2.404.424 €
	1991	Construction of accesses to the beach, closure of the zone of intervention, informative signs and leaflets.				Valencia City Council	228.657,51 €
		Se reparan los cercados y los accesos. Más carteles y folletos.					145.754,16 €
El Saler beach	1997-2000	The raised sea promenade was removed. A dune system with an average width of 43 m and a height of 6.5-7 m was built. A ground-level sea promenade was built.	1.500 m		Sand from the north of the port of Valencia, from the dry beach and from recovery of the dune slacks.	Coastal Department	2.404.424 €
		The City Council provided the plan for the project.				Valencia City Council	142.050 €
La Creu beach	1997-2000	The old dockworkers' school was removed to leave a boat-shaped building that had existed inside.	1.700 m			Coastal Department and Government of the Autonomous Community of Valencia	
	2007-2012	The northern part of the sports centre, Sebastián Burgos school and an old plastics factory were removed.	960 m			Coastal Department	
	2014-2015	Removal of some of the old sports centre and reconstruction of a dune ridge throughout the zone. Currently in progress.			Sand from the north of the port, from Gola del Perellonet and from the Redona dune slack.	Coastal Department	
L'Arbre del Gos beach	2007	The existing embryonic dunes were retained, agricultural land was expropriated and a two-ridge dune system, a ground-level sea promenade at the back, a cycle lane and car parks were all constructed.	1.350 m	The embryonic (*Cakiletum aegyptiacae*) and shifting (windward —*Agropiretum mediterraneum*—, crest —*Medicago marinae-Ammophiletum arundinaceae*— and leeward —*Crucianelletum maritimae*—) dune repopulation module was used.	The sand came from dredging to the north of the port of Valencia and from quarries (Villar del Arzobispo zone).	Government of the Autonomous Community of Valencia	14.766.135,03€ (8.976.799,03€ for the work and 5.789.336 € in expropriations)

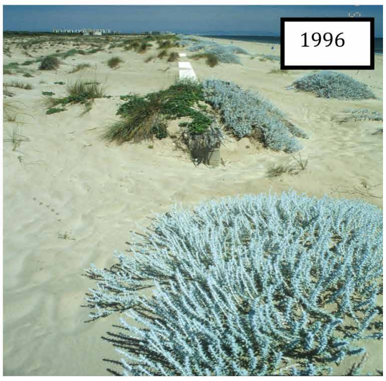
Table 2. Interventions on the foredunes of northern Devesa (from Gola del Pujol to Pinedo).

ZONE OF INTERVENTION	DATES	INTERVENTION	AREA (m^2)	PLANTATION	ORIGIN OF SAND	PERFORMED BY	INVESTMENT
El Canyar beach	1997	A dune was constructed by reinforcing the first ridge.	2.542	The semi-fixed transitional dune module was used (*Crucianelletum maritimae*).	Excavation of lagoons in two dune slacks.		
Malladeta beach and Brava beach	2001-2004	35,000 m2 of roads and car parks, 85 collection boxes, 270 manholes and 10,000 m of piping were removed. A 2,100-m section of road was replaced with a concrete road just 3 m wide, which was laid on the sand and adapted to the terrain.	134.000		A lagoon with permanent water was created in the centre of a dune slack.	Valencia City Council and LIFE DUNA	Included in investment in the foredunes
	2004-2008	The dune morphology was reconstructed. A lagoon of permanent water was created and Valencia toothcarp (Valencia hispanica) were introduced. Completion of the regeneration of the southern Devesa transition zone.	620.300	Repopulation with 912 prickly junipers (*Juniperus macrocarpa*). Repopulation modules *Teucrio belionis-Halimietum halimifoli* were used	Creation of new craters. Enlargement of existing craters, emptying of dune slacks and creation of a lagoon with permanent water in the transition zone of El Canyar beach.	Valencia City Council and LIFE ENEBRO	3.278.216 € (50 % Europe, 50 % City Council)
Els Ferros beach	1988	Removal of car parks, roads and infrastructures.	250.000			Valencia City Council	116.103,85 €
	1995	The dune morphology was reconstructed by reinforcing the primary dune ridge and creating new alignments behind. The dunes reached a height of 5 m.	26.320	The leeward part was repopulated with modules of *Crucianelletum maritimae.*	The sand used originates from the same zone of intervention where new craters and dunes have been recreated.		143.621,22 €
	1998		22.262				24.629,26 €
El Saler beach	1997-2000	Removal of roads and car parks. Construction of new car parks with 1/3 the number of spaces. Construction of a cycle lane and recreation zone. Reduction of roads from 14 to 7 m in width, with a winding design.		The semi-fixed transitional dune module was used (*Crucianelletum maritimae*).	Sand from the recovery of dune slacks and from the north of the port of Valencia, and from the dry beach.	Government of the Autonomous Community of Valencia and Coastal Department	Included in investment in the foredunes
Municipal campsite	1999-2000	Removal of facilities and some non-native vegetation. Some of the floor was maintained (complete recovery pending finalisation)	87.300	It has not been repopulated for the moment. Some non-native species were removed.		Valencia City Council	
Municipal sports centre	2014-2015	In the process of removal.				Coastal Department	
L'Arbre del Gos beach	2007	Agricultural land was expropriated and a ground-level sea promenade, a cycle lane, a recreation zone and car parks were constructed.		The semi-fixed transitional dune module was used.		Government of the Autonomous Community of Valencia	Investment in the foredunes

Table. 3 Interventions in the transition zone of La Devesa de l'Albufera of Valencia.

ZONE OF INTERVENTION	DATES	INTERVENTION	SURFACE	PLANTATION	ORIGIN OF SAND	PERFORMED BY	INVESTMENT
Southern Devesa; initial intervention	1986-1996	Removal of kerbs and some of the road surfaces. These were reduced from 14 to 7 m in width. Removal of some obsolete infrastructures.				Valencia City Council	
Southern Devesa: central road and side roads, southern section to the Casal d'Esplai. The T section and Y section are included.	2011	The sanitation network and remains of obsolete infrastructures were removed. Roads were removed and those that remained were reduced from 7 to 3.5 m in width. The surface was replaced with coloured concrete. By narrowing the roads the recovered zone was integrated into the surroundings. A total of 17,931.62 m2 of road surface were removed and replaced with 9,980.86 m2 of coloured concrete on the new roads.	3,970 m	The general stabilised dune shrub planting module was used (*Phillyreo angustifoliae-Rhamnetum angustifoliae*).	To fill the zone at the edges of the new road and integrate it in the surroundings, sand extracted from nearby dune slacks was used.	Valencia City Council	1.118.572,66€ Project financed with funds of the Government of the Autonomous Community of Valencia: Special Plan of Support for Productive Investment (PIP)
Southern Devesa: central road, side roads and car parks, Casal d'Esplai section to the north, central road and artificial lagoon.	2009	The sanitation network and remains of obsolete infrastructures were removed. Roads were removed and those that remained were reduced from 7 to 3.5 m in width. The surface was replaced with coloured concrete. A total of 28,499.32 m2 of tarmac and aggregate were removed and replaced with 9,993.12 m2 of coloured concrete.	2,955 m	The general stabilised dune shrub planting module was used (*Phillyreo angustifoliae-Rhamnetum angustifoliae*).	To fill the zone at the edges of the new road and integrate it in the surroundings, sand extracted from nearby dune slacks was used.	Valencia City Council	1.022.729,68€ Project financed by the Spanish Local Investment Fund (FEIL)

Table 4. Interventions on interior stabilised dunes of La Devesa de l'Albufera of Valencia.



Initial experiences of the OTDA

1988. South Malladeta beach. Because of lack of budget and in order to minimise the negative impact of the sea promenade wall on the beach, the latter was covered with a dune ridge.

1989. South Malladeta beach. Dune ridge reconstructed on the sea promenade.

1994. South Malladeta beach. Dune ridge with the promenade underneath, five years after intervention.

1996. South Malladeta beach. Sections of the promenade began to show through. Two years later the dune ridge "was disassembled" while retaining the zone of embryonic dunes. The promenade, foundations included, was removed completely and the dune ridge was reconstructed again.

Regeneration of the foredunes and transition zone. Southern Devesa. LIFE DUNA and LIFE ENEBRO. OTDA (I)

1965. North Malladeta beach and Brava beach prior to the urban development process. View from north to south. La Gola del Pujol in the foreground. The artificial lagoon had not yet been built.

1974. North Malladeta beach and Brava beach. Aerial view of southern Devesa. View from north to south. Artificial lagoon built for nautical centre, foredunes and transition zone destroyed, dune slacks filled and altered and interior dunes fragmented.

2000. North Malladeta beach and Brava beach. Before the LIFE DUNA project was undertaken. Roads and car parks.

Regeneration of the foredunes and transition zone. Southern Devesa. LIFE DUNA and LIFE ENEBRO. OTDA (II)

2003. North Malladeta beach and Brava beach. LIFE DUNA project. The sea promenade was removed and replaced by a dune ridge, which was set back 5 m inwards with respect to the promenade. Removal of road infrastructures and car parks. Construction of the service road.

2008. North Malladeta beach and Brava beach. LIFE ENEBRO project. Of note are the dunes with stakes, recently repopulated with plants, and the craters from which some of the sand was extracted. Foredunes totally restored.

2010. North Malladeta beach and Brava beach. Restoration complete. Foredunes recovered with the LIFE DUNA project and the transition zone with the LIFE ENEBRO project.

Regeneration of the foredunes and transition zone. Northern Devesa (El Saler beach). Coastal Department and Autonomous Government of Valencia

1970. El Saler beach. The entire foredune system destroyed for the construction of car parks and a raised sea promenade (see photo No. 6). The municipal campsite facilities are on the left, next to the zone destroyed for the car park.

1999. El Saler beach. Regeneration undertaken by the Coastal Department and the Autonomous Government of Valencia. Removal of the sea promenade to transfer the space it occupied to the beach. Construction of dunes in two alignments and, behind these, execution of a sea promenade and a cycle lane at ground level. Behind this, parking spaces. In red, municipal campsite facilities.

2008. El Saler beach nine years after intervention. The municipal campsite facilities have been removed. There are some remains of the floor at the former entrance.

Regeneration of the foredunes and transition zone. L'Arbre del Gos beach. Autonomous Government of Valencia

2001. Aerial view prior to the intervention. Beach affected by a gale.

2007. L'Arbre del Gos beach. Regeneration undertaken by the Autonomous Government of Valencia. Expropriation of agricultural land, retreat of the coastline, regeneration of the dune system and construction of a sea promenade and a cycle lane at ground level.

2010. L'Arbre del Gos beach three years after intervention.

Creation of lagoons with permanent water in dune slack and in abrasion crater

2002. North Malladeta beach and Brava beach. La Mata del Fang dune slack. Extracting sand and creating a lagoon with permanent water. Introduction of two native species of fish, the Spanish toothcarp (Aphanius iberus) and the Valencia toothcarp (Valencia hispanica). LIFE DUNA project.

2009. South Malladeta beach. Detail of lagoon made in the transition zone by enlarging an abrasion crater. LIFE ENEBRO project. Introduction of Valencia toothcarp (Valencia hispanica).

Regeneration of interior dunes in southern Devesa. OTDA

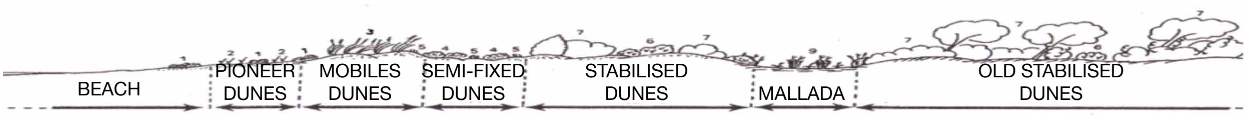
1988. Regeneration of interior dunes of southern Devesa. Physical appearance of former roads. In this case, the tarmac and the aggregate have been removed from the right part of the road in order to reduce its width from 14 to 7 m.

2009. Regeneration of interior dunes of southern Devesa. Removal of former roads. Some sections were maintained to provide access for surveillance and emergencies. The road surface was changed and the width of these sections was reduced. In the photo, new, narrower road constructed with coloured concrete (reduced from 7 to 3.50 m). The space reclaimed was repopulated with vegetation typical of the interior dune ecosystem to blend it in with the surroundings.

2014. Regeneration of interior dunes of southern Devesa. New road integrated into the surroundings. Repopulation of vegetation implementing the module “GENERAL STABILISED DUNE SHRUB PLANTING X25 m^2 Phillyreo angustifoliae-Rhamnetum angustifoliae”.

STABILISED DUNE SHRUB (maquis) PLANTING MODULE X 25 m²

Phillyreo angustifoliae-Rhamnetum angustifoliae



Species	Cutting	Bulbs	Roots	Seeds	Seedlings
Phillyrea angustifolia / Narrow-leaved mock privet					2
Pistacia lentiscus / Mastic					1
Rhamnus alaternus / Mediterranean buckthorn					2
Quercus coccifera / Kermes oak					3
Chamaerops humilis / Mediterranean fan palm					2
Smilax aspera / Common smilax				6	
Lonicera implexa / Minorca honeysuckle				1	
Scirpus holoschoenus / Round-headed club rush					4
Sedum sediforme / Pale stonecrop	1				
Cistus salviifolius / Sage-leaved rockrose				1	
Cistus clusii / Clusiuss rockrose	1				
Dianthus broteri / Iberian carnation				2	
Pinus halepensis / Aleppo pine					1
Rhamnus oleoides subsp. angustifolia / Mediterranean buckthorn					1
Rubia peregrina / Wild madder				2	
Clematis flammula / Fragrant virgin's bower					1
Erica multiflora / Mediterranean heath				1	

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Evaluation of the impact of dune management on the coast of huelva using repeat photography techniques (1986, 2001 and 2015)

Daniel Sánchez Escalera, Pablo Fraile Jurado and Carolina Peña Alonso

1.Introduction

1.1 Repeat photography as a technique for evaluating environmental changes

Since the very beginnings of photography, it has been used in different scientific and humanistic disciplines to document and to research different processes and phenomena subject to study. Since the early nineteenth century it has had a clear scientific purpose and has been used particularly in research and on expeditions. During colonial times, the great European powers produced a considerable number of photographic anthropological research works, significant among which were those of Im Thurn (1893), and others produced during the course of expeditions to the western United States such as the work by O'Sullivan (during the geological exploration of the 40th parallel, from 1867 to 1869), Jackson (Hayden expedition to Yellowstone in 1871) and Watkins (Yosemite expedition in 1861) (Webb, 2010).

Photographic records (documentary, artistic, scientific and journalistic) have provided a basis for developing the technique of repeat photography, which involves shooting an archive photograph again from the same perspective and from the same angle, while following a set of given rules. French forest rangers were pioneers in the use of this technique, which they used to perform work with a clear educational and political purpose. According to Carré and Métailié (2008), the intention was to provide the public and the authorities with evidence of the degradation of the mountains and the effectiveness of forestry policy. In the late nineteenth century, Finsterwalder included the use of repeat photography in studies of glaciology, and produced work considered pioneering in the use of this tool in scientific study (Webb, 2010).

In 1905, the technique of repeat photography had been so widely accepted that handbooks on ecology recommended it for the spatial monitoring of vegetation (Clements, 1905). In this field, one of the first studies to document the loss of grassland species was the work produced on the Santa Rita Experimental Range, to the south of Tucson (Webb, 2010).

In the field of geology, the technique began developing with studies on the weathering and erosion of bedrock in southern Utah, produced by Bryan and La Rue (1927), and work by Longwell on waterfall erosion. Shantz, at the University of Arizona, Tucson, pioneered the use of repeat photography to document the changes recorded in plant populations in large spaces (Carré and Métailié, 2008).

In the early twentieth century, the Desert Laboratory, which performed numerous scientific studies to analyse the adaptation of flora and fauna in desert environments, was established in the Sonoran Desert (USA) as a biological research station. In the early nineteen-eighties, the work of Webb led to the Desert Laboratory Collection, one of the world's largest repeat photography archives, which currently belong to the United States Geological Survey (USGS). The archives contain around 35,000 negatives and slides and approximately 9,762 pairs of photographs taken in the same place (Webb, 2010).

It is important to mention that although coastal zones are very dynamic environments and are therefore suited to research with repeat photography, analysis of this type is not as common as in other areas mentioned above. This is perhaps due to the excessive dynamism typical of some coastal environments (particularly mesomareal and macromareal), and also to the difficulty in using photographs to show change in zones that –except for steep coasts– are essentially dominated by horizontality.

Early work produced in coastal areas was limited to the observation of coastal glaciers –like those in Alaska studied by Field (1937)– or was intended to document the effectiveness of the planning and management measures implemented. The best examples of this, however, are the works undertaken in environmental disaster zones such as the projects for analysing recovery after Hurricane *Katrina* (Carré and Métailié, 2008).

Significant in Spain are two projects focused on the Balearic Islands: the work of the Mediterranean Institute for Advanced Studies (IMEDEA), which uses repeat photography as a primary tool and, closely related to the above, that of the Landscape Photographic Observatory of the University of the Balearic Islands, albeit in this case study is not restricted to the coast.

2. Area of study

2.1 Physiographic description of the coast of Huelva. Identification of erosive sectors in recent years

One of the main features of the coast of Huelva is the presence of large sandy coastal formations that form a succession of beaches, barrier islands and coastal spits, depending on the local characteristics of the coast. Until human intervention, which occurred in the twentieth century, there was a long coastal dune ridge that runs practically continuously along the 80-km coastline, which is now discontinuous because of the presence, every few kilometres, of housing developments with sea promenades, marinas or fishing harbours, jetties and dykes.

The coast of Huelva is conditioned by different macro-structural factors such as the existence of a broad continental shelf some 50 km wide, which has a great capacity to refract the waves that originate mainly from the SW (and, occasionally, from the SE). This shelf is an extension of the Guadalquivir valley, which during the glacial episodes of the Quaternary remained mostly above sea level.

The coast generally runs along two main axes: an almost straight stretch of around 30-km from Ayamonte to Huelva, following the direction of the lines of latitude, and a section featuring a smooth but constant convex curve that ends at the beaches of Doñana, and runs at an angle of around 50°. This curvature, as detailed later, plays a crucial role in the transport of sandy sediment.

The combination of the characteristics of the coastline and the direction of the waves gives rise to westward longshore drift that is strongest in the initial section of coast and loses its capacity to transport sediment as it advances towards the coast of Doñana, where the swell is parallel to the coastline in the final section of this sector.

The existence of a series of N-S faults has channelled most of the final stretches of the major rivers that drain the province of Huelva and has thus led to an efficient transport of sandy sediment –and even fine particles– in the final stretches of the river courses, which is explained by the relatively steep slopes that they must negotiate in the final stretches. This is the case of the Guadiana, Carreras, Piedras, Tinto and Odiel rivers and even of the Guadalquivir.

On account of the nature of the longshore drift, it is the Guadiana that carries the sand eastwards and is the Huelva coast's main source of sediment. The drastic change in land use that occurred from around the second century BC onwards in the basins of the Guadiana and of the other rivers has yielded an exceptional surplus of sediment that has supplied the coasts of the entire province. This has meant not only the compensation of the typical erosive tendency of a coast to adapt to the new sea level that has existed since 6000 BP (Zazo *et al.*, 2013), but also the development of sandy elements.

The exceptional surplus of available sand on the coast of Huelva in the last two millennia (Pendón, 2000) filled in the numerous structural-type inlets, which were eventually closed off by coastal spits and barrier islands and to become tidal marshes. In the most exposed sectors there formed beaches, which connected with the existing coastal spits and barrier islands.

Apart from minor fluctuations in sea level (Zazo *et al.*, 2013), which caused successive advances and retreats of the coastline, a long ridge of dunes formed from 6000 BP that extended continuously from the mouth of the Guadiana to that of the Guadalquivir (Vallejo, 2007).

Today, after regulation by dams constructed in the hydrographic network during the course of the twentieth century, which has removed the original source of sediments (the Guadiana and other smaller rivers), sediment transport processes remain the same and the sand transported by the rivers has been replaced by sediments from the sandy coastal formations themselves, which are basically beaches and dunes. This process has led to intense erosion that in some zones has been quantified at levels of over 2 metres per year. In addition, the different intensive uses to which the coast has been subject, and in particular the construction of sea promenades, have led to the removal of long sections of the original dunes, which in some cases have been replaced by embryonic dunes that have not developed fully. Another activity that has led to intense coastal erosion has been tourism, which in some currently undeveloped sections (such as Isla Cristina - La Antilla), and in light of the lack of regulated access during the nineteen-eighties and -nineties, gave rise to intense aeolian deflation processes. The result has been a large decrease in volume of the dunes, the height of which in the early 2000s went from an average of 10 metres to just over 1 metre (Ojeda *et al.*, 2002).

From around the year 2000, the Spanish Government launched a series of measures to protect and regenerate different sectors of the coastal dunes of Huelva. There were basically three types of measures: I) the protection of dunes with fencing systems designed to prevent trampling by beach users; II) the introduction of plant species capable of capturing sand such as *Ammophila arenaria*; and III) the regeneration of beaches with sand from the foreshore in the most attractive sectors for tourism.

3. The technique of repeat photography on the coast of Huelva

a. Objectives

This paper is mainly intended to evaluate the changes that have occurred to coastal dunes in the province of Huelva using the technique of repeat photography. To do so it was necessary to develop a method of analysis that, once the repeat photograph had been taken, allows for identification of the changes occurred to the dunes and to their surroundings. Categorisation of both the changes that have taken place and the impact of management initiatives on the changes observed was also established as a complementary target.

b. Sources

Two types of data were used to undertake this work: photographs and spatial data. Three sources of photographic data were used:

a) Digital photographs taken in late 2001 with a SONY DCR-PC 100 digital video camera and belonging to the SIGLA (Geographical Information System for the Coast of Andalusia), which is now part of the Coastal Subsystem for the Environmental Information Network of Andalusia (REDIAM). In the system there are some 7,000 geotagged and classified photographs of the entire coast of Andalusia.
b) Analogue photographs taken in 1986 with an analogue 35 mm camera and included in the same system. The system currently has some 700 images of this type.
c) Digital photographs of new views (54), taken with an Olympus E-420 digital SLR camera, equipped with a 4/3 sensor and an optical zoom with a focal length of 14 to 42 mm. Application of the full frame conversion factor (2x) makes it a 28-84 mm wide-angle to telephoto lens. The output file format chosen is RAW, as it is a file with data compression but without loss of information. All image data are therefore contained in the file just as they were captured by the sensor. The metadata of these files contain all the details of how the photograph was taken (camera sensor, angular distance used, shutter speed, diaphragm aperture, etc.), which facilitates any possible future repetition.

Vector files were also occasionally used and these show the coordinates of each photograph taken in 1986 and in 2001, included in the same GIS as the previous data.

c. General methodological process

The work was undertaken according to the following methodological process:

Selection of the photographs to be repeated. 54 images from the Isla Cristina – Matalascañas sector were selected in the SIGLA's database of photographs of the coast. These photographs were selected according to the place that appears in the shot and also to the number and quality of existing images available.

1. Selection of the photographs to be repeated. 54 images from the Isla Cristina – Matalascañas sector were selected in the SIGLA's database of photographs of the coast. These photographs were selected according to the place that appears in the shot and also to the number and quality of existing images available. In theory, the SIGLA has photographs of the entire Andalusian coast. This area of work,

however, has been reduced according to a criterion of geographical proximity with respect to the photographer's location and proximity between the points to be photographed. The eventual area of study was therefore limited to the coast of Huelva. The photographs were taken at the end of 2001.

2. Location of the points. The coordinates of the selected points were identified in the field using GPS location. The place should be explored by viewing the original photograph on a tablet, as differences between the original point from which the shot was taken (2001) and the 2015 position may yield errors. It is therefore necessary to determine the exact point from which the base photograph was taken. The objective here is to find what Mark Klett (2011) calls 'the vantage point', which is the exact place from which the photographer should repeat the photograph in order to be as faithful as possible to the original. This point depends both on the laws of optics, and particularly on the focal length of the camera lens, and also the photographer's ability to align the elements present in the composition of the photographs. In a hypothetical landscape in which a photograph is to be repeated, for example, the photographer should move until the objects in the shot's different planes are aligned just as they are in the original image. This will yield the same composition in both photographs. Although the exact repetition of perspective is very important in this work, when that is not possible in repeat photography, moving a few metres is permissible if that generates a more representative view of the change the place has experienced.

3. Taking the repeat photograph. The tripod and camera were installed at the exact shooting point of the new view, with consideration for the original photograph (viewed using a tablet, a highly versatile tool for consulting metadata) and the landscape's permanent elements. Framing, which is essential at this stage, was based on certain fixed elements of reference, avoided mobile items (like dunes or the coastline) while making use of others such as infrastructures, buildings or trees. The approximate framing of the original photograph was obtained by playing with different focal lengths of the zoom lens. The camera was set in manual mode, which allowed for more precise control of exposure (diaphragm aperture/shutter speed, ISO), based on accurate measurement and thus providing greater precision (focused on 5% of the image), and a selection of base ISO value (100) to avoid camera noise. To ensure that most of the photo was in focus (sharp), a small diaphragm aperture (f10) was used and the hyperfocal distance for selected parameters was determined to set the lens focus at the resulting distance.

4. Analysis of photographic pairs. Once the pair of photographs had been obtained (the original photo from 1986 or 2001 and the current repeat from 2015), they were then analysed. It is important to mention from the outset that when the repeat photographs were being taken in the field it was noted that it would be impossible to take an identical shot to the original because of sensor differences in the photographs used. The pairs of photographs are nevertheless quite similar. Each pair was subject, first, to qualitative analysis in order to identify changes in the landscape that may be ascribed to variations related to modifications in the volumes of dunes, changes of shape or position of the coastline, an increase or loss of vegetation or changes in coastal infrastructures. This was then followed by quantitative analysis, which is detailed below.

d. Procedure for analysing dunes using repeat photography

The quantitative analysis of the dunes that appear in the pairs of photographs for the period of study (1986/2001-2015) involved the development of a synthetic index that includes the two types of main variables that can be observed in a photograph: morphological changes of the dunes, defined by variations in the gradient and the height, and changes in vegetation cover, defined by appearance, permanence or disappearance of plant species according to their bearing (herbaceous, shrub or arboreal) and by variations in the area of vegetation cover.

I) Morphological changes of dunes

Evaluation of the morphological changes that occur in a dune requires definition of the criteria for assigning a score to each photo based on two variables: changes in gradient and changes in height. Table 1 establishes the criteria for assessing the changes in the dune's gradient with the corresponding numerical value.

GRADIENT	INCREASE IN GRADIENT		STABLE GRADIENT	DECREASE IN GRADIENT	
VALUE	–2	–1	0	1	2
CRITERION	INCREASE IN GRADIENT >30°	INCREASE IN GRADIENT <30°	INCREASE IN GRADIENT ±10°	DECREASE IN GRADIENT <30°	DECREASE IN GRADIENT >30°

Table 1. Criteria for assigning values to evaluate the increase in the dune's gradient.

The changes observed in the gradient of the coastal dune were assigned values ranging from -2 to +2 that are negative when an increase in the gradient is observed in the repeat photograph. This increase is considered a negative factor for a dune's stability and may be related to erosion processes that take place on the backshore and affect the foot of the dune. A reduction in the gradient of the front of the dune was therefore considered a positive factor, as it is linked to the presence of surplus sediment (Fig. 1).

Figure 1. Increase in the gradient of a dune located in the western sector of La Antilla from 2001 (left) to 2015 (right).

The maximum negative value (-2) was associated with the dunes that exhibited an increase in gradient of over 30°. The other negative value of table 1 (-1) corresponds to the dunes that experienced an increase in gradient of between 10° and 30°. A value of 0 was assigned to the dunes the gradient of which had stabilised, with an increase or a reduction of no greater than ± 10°. Adobe Photoshop CS6 software was used to measure changes in the gradient of the dune.

The second criterion for measuring the morphological changes of the dune is height. Table 2 lists the evaluation criteria used to assess this factor. As in the case of gradient, the values of the variable fluctuate from -2 to +2. A value of -2 was assigned to particularly significant losses in height (losses of over 1 m) and also to the total disappearance of the dune, regardless of the height it had previously reached. For increases, the criterion is similar: increases of between 0.5 and 1 m were assigned a value of +1, and those of over 1 m, were given a value of +2. For fluctuations of under ± 0.5 m, the value was left as nil, which actually has more to do with the limitations of this method of measuring such changes on photographs than to the geomorphological implications that vertical changes of up to 0.5 m would have.

HEIGHT	LOSS IN HEIGHT		STABILITY	INCREASE IN HEIGHT	
HEIGHT RATING	−2	−1	0	1	2
EVALUATION CRITERIA	DECREASE IN HEIGHT >1 m OR TOTAL APPEARANCE OF THE DUNE	DECREASE IN HEIGHT >0.50 m	INCREASE OR REDUCTION OF THE DUNE <0.50 m	INCREASE IN HEIGHT >0.50 m	INCREASE IN HEIGHT >1 m

Table 2. Criteria for assigning values to evaluate the impact of the dune's increase in height.

Figure 2. Loss of over 1 m in height recorded between 1986 (left) and 2015 (right) on the dune of Isla Cristina, which has almost disappeared completely.

Figure 3. Increase in height of the dune rated with +2, as it is higher than 1 m. La Redondela, 2001 (left) and 2015 (right).

A combination of the two variables (changes in gradient of the front of the dune and variations in its height) yielded a morphological stability index, which is defined in table 3.

HEIGHT/GRADIENT	–2	–1	0	1	2
–2	–4	–3	–2	–1	0
–1	–3	–2	–1	0	1
0	–2	–1	0	1	2
1	–1	0	1	2	3
2	0	1	2	3	4

Table 3. Criteria for assigning values to evaluate the evolution of a dune's condition on the basis of its height and the gradient of its front. The negative values refer to dunes that have undergone morphological changes, generally caused by erosion, while positive values indicate a dune in good condition, usually associated with a positive sedimentary balance.

II) Changes in vegetation cover

Two variables were analysed to assess the changes recorded in dune vegetation: variations in the dominant type of vegetation stratification on the dune and in its immediate vicinity, and the changes in dune vegetation cover, measured as a percentage of land covered by vegetation in the current picture with respect to the old photograph. Table 4 contains the valuation criteria for changes in the type of dominant stratification.

CHANGES IN STRATIFICATION	LESS COMPLEXITY		STABILITY	MORE COMPLEXITY	
VALUE	–2	–1	0	1	2
EVALUATION CRITERION	TWO-DEGREE DECREASE: FROM ARBOREAL TO ERBACEOUS, FROM SHRUBBY TO NOTHING	ONE-DEGREE DECREASE: FROM SHRUBBY TO HERBACEOUS, FROM HERBACEOUS TO NOTHING	STABILITY IN VEGETATION STRATIFICATION	ONE-DEGREE INCREASE: FROM NOTHING TO ERBACEOUS, FROM HERBACEOUS TO SHRUBBY	TWO-DEGREE INCREASE: FROM NOTHING TO SHRUBBY, FROM HERBACEOUS TO ARBOREAL

Table 4. Criteria for assigning values to evaluate the impact of changes in the vertical stratification of vegetation on dune condition.

The last controlled variable involved evaluating the changes in the area of the dune covered by vegetation. The values assigned were negative for loss of vegetated area and positive if the area of the dune covered by vegetation had increased. Table 5 summarises the evaluation criteria for this variable.

CHANGES IN COVER	LESS COMPLEXITY		STABILITY	MORE COMPLEXITY	
VALUE	–2	–1	0	1	2
EVALUATION CRITERION	LOSS OF OVER 50% OF DUNE AREA COVERED BY VEGETATION	LOSSES OF BETWEEN 15 AND 50% OF DUNE AREA COVERED BY VEGETATION	VEGETATION COVER SIMILAR TO THE ABOVE (±15 %)	INCREASE OF BETWEEN 15 AND 50% OF DUNE AREA COVERED BY VEGETATION	INCREASE OF OVER 50% OF DUNE AREA COVERED BY VEGETATION

Table 5. Criteria for assigning values to evaluate the impact of changes in dune vegetation cover on dune condition.

A combination of the two variables (changes in vertical stratification and in the area covered by vegetation) yielded a vegetation stability index of the dune that is defined in table 6.

STRATIFICATION/COVER	**–2**	**–1**	**0**	**1**	**2**
–2	–4	–3	–2	–1	0
–1	–3	–2	–1	0	1
0	–2	–1	0	1	2
1	–1	0	1	2	3
2	0	1	2	3	4

Table 6. Criteria for assigning values to evaluate the evolution of a dune's condition based on its vegetation. Negative values refer to dunes the vulnerability of which has increased due to a loss in quality or in area of vegetation, while positive values indicate a dune in good condition, generally associated with a positive sedimentary balance.

III) Evolution of dune geoforms

Lastly, the results obtained with each of the two sub-indicators (morphology and vegetation) were combined in a final indicator of dune evolution, resulting from the sum of the sub-indicators mentioned previously. Although the final indicator is a summary of the recent evolution of dune condition, interpretation of the results obtained requires consideration of both sub-indicators and of the four variables considered.

The data eventually obtained were processed statistically to determine the impact of the dune management policies, and each pair of photographs was included in one of the following categories:

Type 1) Dunes that have been subject to management policies aimed at the protection (placement of fences) and/or regeneration of local vegetation (introduction of *Ammophila arenaria*).
Type 2) Dunes that have not been subject to management policies, located in front of a cliff.
Type 3) Dunes that have neither been subject to management policies not are located in front of a cliff.

These three groups were subjected to analysis of statistical reliability based on the chi-squared test for a confidence level of 95%.

An analysis of linear regression was also conducted between the mean values obtained for each repeat photography parameter measured and the erosion rates recorded in the 1956-2007 period, in order to determine the impact of the dune management measures implemented in the study zone.

4. Results obtained and discussion

56 photographs were analysed for the sites that appear in figure 7. Photo by photo analysis reveals clear spatial patterns, and points grouped together with identical values are commonly identified because photographs have been repeated of the same phenomenon from different angles.

To avoid awarding greater importance in statistical analysis to areas with more photographs than those in which fewer have been taken, a mean value was calculated for each of the sites analysed. It was not possible to identify any spatial pattern in the distribution of this variable (Fig. 4).

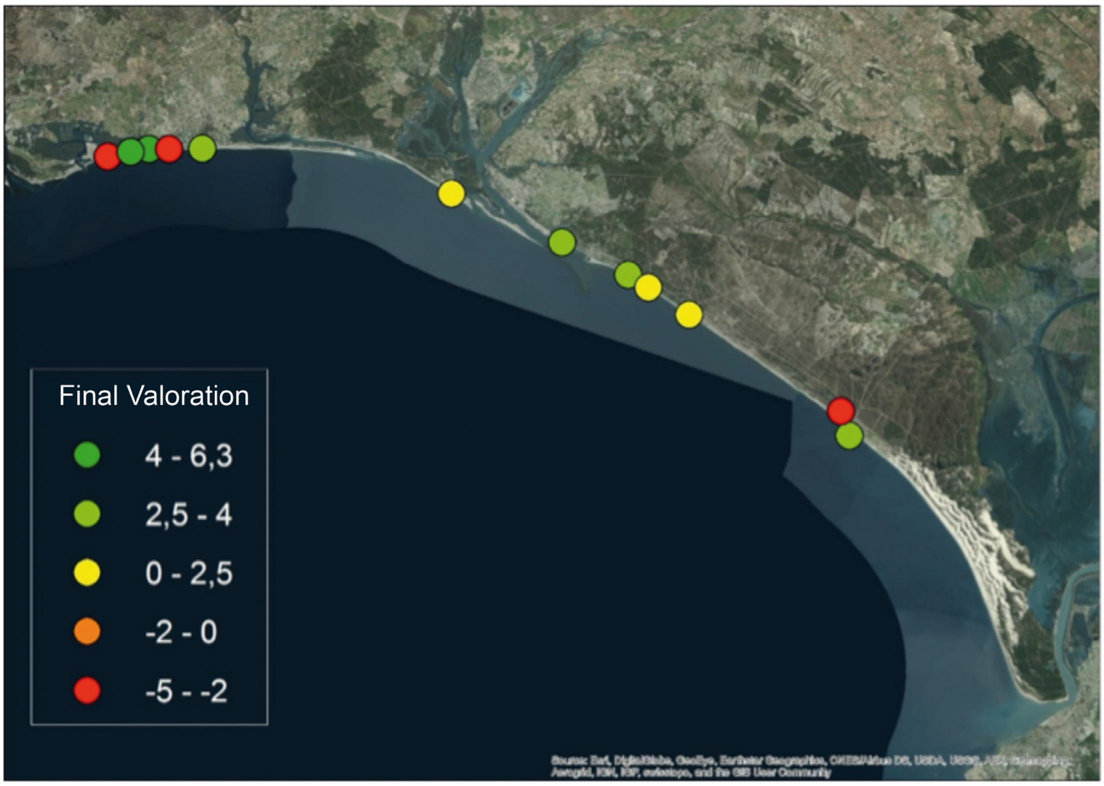

Figure 4. Map of final evaluations obtained in each area of study.

In table 7, however, when the results obtained are associated with the type of management (or lack thereof) there appears to be a clear relationship between type-1 areas (with very high values that indicate a development of the dune), type-2 areas (with lower positive values than the above, which indicates some dune stability) and type-3 areas (with negative values in the recent evolution of the dune).

AREA		TYPE	TOTAL	TOTAL EROSION	HEIGHT	GRADIENT	TOTAL VEGET.	COVER	FORMATION
1	MATALASCAÑAS	3	–5.0	–3.0	–2.0	–1.0	–2.0	–1.0	–1.0
2	MATALASCAÑAS II	1	4.0	0.7	0.0	0.7	3.3	1.7	1.7
3	CASTILLA I BEACH	2	1.0	0.0	0.0	0.0	1.0	1.0	0.0
4	CASTILLA II BEACH	2	2.5	2.2	1.6	0.6	2.6	1.6	1.0
5	EL PARADOR BEACH	2	2.5	0.5	1.0	–0.5	2.0	1.0	1.0
6	MAZAGÓN EAST	1	4.0				4.0	2.0	2.0
7	MAZAGÓN WEST	2	2.7	1.3	1.0	0.3	1.3	1.0	0.3
8	PUNTA UMBRÍA	2	2.0	1.0	1.0	0.0	1.0	0.0	1.0
9	LA ANTILLA WEST	1	3.0	0.0	0.0	0.0	3.0	2.0	1.0
10	LA REDONDELA I	1	6.3	3.3	1.5	1.8	3.0	2.0	1.0
11	LA REDONDELA II	1	5.7	3.0	1.3	1.7	2.7	1.7	1.0
12	ISLANTILLA	3	–2.0	–0.5	0.5	–1.0	–1.5	–1.5	0.0
13	ISLA CRISTINA	3	–5.0	–4.0	–2.0	–2.0	–1.0	0.0	–1.0

Table 7. Results obtained.

Table 8 is therefore particularly revealing, as the order of the results obtained shows that all the higher values correspond to type-1 management, followed by type-2, and, finally, type-3.

ZONE 10	LA REDONDELA I	1	6.3
ZONE 11	LA REDONDELA II	1	5.7
ZONE 2	MATALASCAÑAS II	1	4.0
ZONE 9	LA ANTILLA WEST	1	3.0
ZONE 6	MAZAGÓN EAST	1	4.0
ZONE 4	EL ASPERILLO	2	2.5
ZONE 7	MAZAGÓN WEST	2	2.7
ZONE 8	PUNTA UMBRÍA	2	2.0
ZONE 5	EL PARADOR BEACH	2	2.5
ZONE 3	PICO DEL LORO	2	1.0
ZONE 12	ISLANTILLA	3	–2.0
ZONE 1	MATALASCAÑAS	3	–5.0
ZONE 13	ISLA CRISTINA	3	–5.0

Table 8. Results obtained.

Statistical analysis based on a Student's t-test was performed to determine whether, as appears at first glance, each of the three dune management categories proposed in the methodology —dunes for which management measures designed for their protection and regeneration have been implemented (type 1), dunes for which management measures have not been implemented and that are located in front of a cliff (type 2), and dunes for which management measures have not been implemented and are not located in front of a cliff (type 3)— implies a different evolution in the dune condition, with a 99% certainty. As this test compares two sets of samples, it therefore had to be performed three times: comparing groups 1 and 2, groups 2 and 3 and groups 1 and 3.

The test results showed, first, that the samples analysed belong to different populations as regards the recent evolution of the dunes. The management to which each dune has been subject is therefore a critical factor in their recent evolution. The results obtained also indicate that the most positive evolution of dunes occurs in those in which some type of management has been implemented (type 1), followed by dunes where none has been implemented but which have a cliff behind them (type 2).

The explanation for this conduct lies not so much in geomorphological variables, but rather in the number of people passing through the dune area. On protected dunes the movement of people is zero (because there is a fence) while on dunes that are unprotected but have a cliff behind them it is very low (there is no destination for the average tourist to head for). Lastly, on unprotected dunes without a cliff behind them, the movement of people is high (with free and undetermined access to roads, hotels, leisure areas, etc.).

The correlation between the erosion rates recorded (Fraile and Ojeda, 2007) and the scores awarded to each area, meanwhile, yielded straight linear regression with a linear correlation coefficient of less than 0.3 which is not significant given the total number of data analysed. This result suggests that the changes observed in the dunes are not related to the erosion rates recorded.

When analysed by sector, area 1, which is located on the coastal dune of Matalascañas, exhibits some modest negative values on account of the absence of a dune of considerable size since 2001. In 2015, in most of the areas studied, the protodune has been replaced by a breakwater that protects the sea promenade (Fig. 5).

Figure 5. Dune of the sea promenade of Matalascañas in 2001, which was replaced by a breakwater in 2015.

Figure 6. Climbing dune of Matalascañas before (2001) and after protection (2015).

On the western limit of the housing development of Matalascañas (area 2), however, a series of climbing dunes was identified. Following intervention focused on marking out pedestrian paths using platforms and establishing fences around the entire perimeter, these dunes have experienced a significant increase not only in vegetation cover (Fig. 6) but also in the volume of sand.

On Castilla beach, in 2015 the El Loro sector had made significant progress on 2001 insofar as dune volume is concerned (Fig. 7). The protodunes that were there initially had accumulated a considerable amount of sediment and therefore in this large area of study as a whole the morphology variable rose to an average of 1.7. There was also a significant change in the vegetation cover of the dunes, which went from virtually non-existent to so abundant that it almost completely covers everything. Significantly, this semi-natural beach, which in the middle of the year experiences a major influx of tourists, has not been subject to any human intervention addressed to the management of the dunes (it is therefore considered type 2).

Figure 7. Embryonic dunes at the foot of the El Asperillo cliff in 2001 (left) and dunes at the same point in 2015 (right).

The dunes analysed at Mazagón exhibit significant changes (Fig. 8) as a result of different types of human intervention that has not always been intended to restore them. In the eastern sector of the Mazagón coast, the transverse profile of the beach changed completely. In 2001, it showed signs of erosion, with a micro-cliff built on tertiary sandstone. The remarkable rates of coastal erosion recorded in this sector (Fraile and Ojeda, 2007) partly explain the presence of the micro-cliff in 2001. The situation was radically different in 2015, with the appearance of a recently created artificial dune vegetated with exotic species. The rarity of this situation made it necessary to disregard the significance of the results obtained and therefore the analyses performed have not been included.

Figure 8. The dunes of Mazagón in 2001 (left) and in 2015 (right).

The western section of Mazagón beach is sheltered from storms from the SW on account of the presence of the town's marina. The area under study is located so near the port that the main impact of the storms from the SE represents a net increase in the zone's sedimentary balance. Management tasks to improve access to the beach have also been undertaken. As figure 9 shows, this has allowed for the protection of the zone's dunes.

Figure 9. Dunes of Mazagón in 2001 (left) and 2015 (right).

At Punta Umbría, human intervention has not involved management tasks because in 2015 the same measures apply to the area analysed as in 2001, i.e., absence of not only a sea promenade, but also of dune perimeter fences (Fig. 10). Nevertheless, the exotic species introduced, such as highway ice plant (*Carpobrotus edulis*), have colonised all the dunes analysed. In this case, the values obtained in evaluation of the change are positive both for the morphological and the vegetation parameters. The appearance of alien species, however, cannot be considered management intervention and has therefore been excluded from the statistical analyses performed.

Figure 10. Dunes of Punta Umbría in 2001 (left) and in 2015 (right).

La Antilla has sectors that are different enough for the dunes to be dealt with separately. In the eastern sector dunes were neither observed in 2001 nor in 2015, as the site where coastal dunes should be, when considering a transverse profile of the beach, was occupied by housing. In 2015, however, some peculiar management interventions were observed, as artificial embryonic-type dunes have been generated on non-developed plots (Fig. 11).

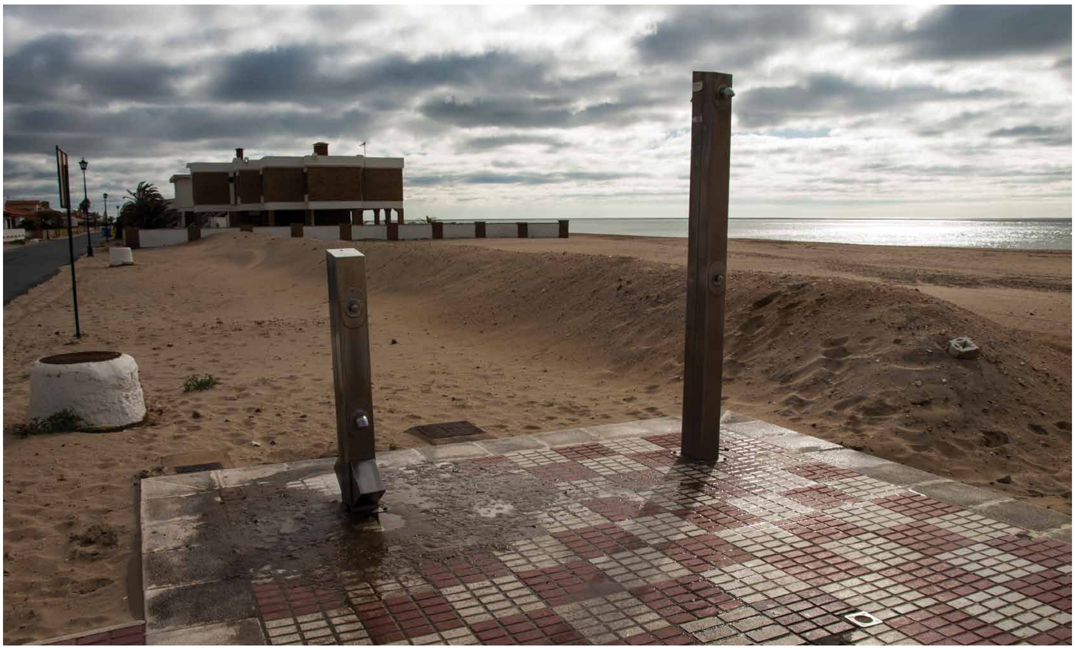

Figure 11. Detail of the micro-dunes of La Antilla in 2015.

The central sector of La Antilla beach shows clear signs of degradation of the dune ridge, with negative values both for morphology- and vegetation-related variables in most of the re-photographed areas (Fig. 1). Profound changes (Fig. 12 and 13) have been observed in the western sector following the construction of a sea promenade for pedestrians in the place of the road that existed in 2001. This has led to a regeneration of the dune and the development of an abundant herbaceous layer on top of it.

Figure 12. La Antilla in 2001 (left) and in 2015 (right).

Figure 13. La Antilla in 2001 (left) and in 2015 (right).

In the La Redondela section more significant changes are appreciable and have coincided with management tasks designed to protect the dunes and to regenerate native vegetation, which here is *Ammophila arenaria* (Fig. 14). All the repeat photographs in this zone have very high values for both variables, and it is here where the most positive changes of all the areas studied have been identified. The photograph from 2001 shows a micro-dune that had recently been closed off with a fence, with *Ammophila arenaria* newly introduced and sown at an angle of 45° to ensure greater uptake of sand, as it was located perpendicular to the direction of the prevailing winds. Now, in 2015, this management measure has yielded results that are so significant that dunes of more than 1 m higher than in 2001 have formed. There is also more vegetation cover and a significantly more complex variety of plants, with the presence of shrubs and even trees in the inter-dune areas behind the coastal dune (Fig. 14 and 15).

Figure 14. Dunes of La Redondela in 2001 and in 2015.

Figure 15. Dunes of La Redondela in 2001 and in 2015.

On Isla Cristina, the reference photograph was taken in 1986 and not in 2001. It nonetheless shows one of the most extreme changes that were observed: the total destruction of a dune of over 5 m in height and its replacement with a sea promenade (Fig. 2).

5.Conclusions

In the recent evolution of different types of dunes significant differences have been observed with reference to two variables: first, management policies applied during the period of analysis and, second, the presence or absence of cliffs behind the dunes.

It is significant that in the groups of dunes studied, the main agent of erosion identified is the movement of people, as positive values are obtained both on protected dunes and on dunes where there is no movement of beach users. Dune management policies are therefore extremely important for the protection and regeneration of this land form in the stretches of the coast of Huelva analysed.

The lack of linear relationship between the dune's stability values and coastal erosion is not the result of a disconnection between the erosion processes to which the beaches and the coastal dunes of Huelva are still subject, but rather of an efficient management capable of transforming the evolution of a dune, even in conditions of sparse sediment input into the system. It is also necessary to study whether the retention of sand on the coastal dune has led to a decrease in the sedimentary volume of the foreshores, midshores and backshores in the sections analysed.

From a methodological perspective, it has been demonstrated that repeat photography techniques are useful for analysing spatial processes even if the periods are relatively short. Such methods, however, should be put to the test in other areas and for different lengths of time in order to determine their scope in less dynamic areas.

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Management versus coastal erosion on the island of Oléron: Gatseau beach (France)

Carlos Arteaga Cardineau

Department of Geography, Universidad Autónoma de Madrid

1. Abstract

The purpose of this work is to present the latest results obtained from Gatseau beach (island of Oléron, France) with regard to the severe erosion it is suffering. A coastline that has been retreating over 17 m/year in the 2006-2014 period threatens the continuity of a zone preserved by the Natura 2000 network that seems to be on the verge of disappearance. The work also discusses the potential triggers (dykes, breakwaters and other engineering works) and the need for coastal planning that involves a series of not only coastal but also fluvial areas.

2. Introduction and objectives

The island of Oléron rises from the Atlantic and closes off the small, approximately 3,000-hectare bay of Marennes-Oléron, just 3 km from the French coast. More specifically, it is located on the northern edge of the department of Charente-Maritime. Covering over 174 km2, it forms a rhombus shape the upper diagonal (or length) of which measures some 33 km, and the bottom (width) some 11 km, at their longest parts. It has a coastal perimeter of 90 km, most of which is sandy, although in the north there are rocky cliffs from the Mesozoic and Pleistocene. The sands that cover it, which form some significant dune and beach systems, on the whole have many source areas that notably include the fluvial systems of the Seudre, Charente, Sèvre Niortaise and Garonne rivers. The strait between the island and continent and the confluence of the sediments carried by currents from more northerly sectors with those from the mouth of the Garonne River to the south culminate in the formation of spectacular dune complexes that juxtapose even current-subrecent dunes with other ancient-origin fossil dunes from the Holocene. There is also, meanwhile, a very characteristic marsh area that for centuries —since Roman times and particularly during the Napoleonic period— was used by people for the extraction of salt. These marshes also favour the breeding of prawns and oyster farming, the latter being one of Oléron's main sources of income.

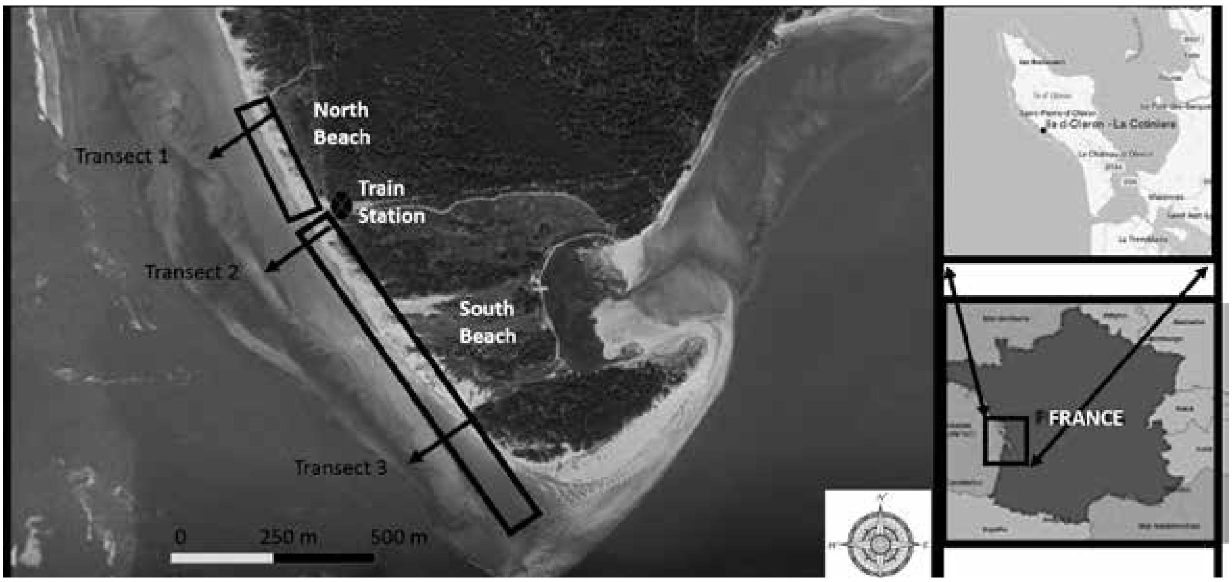

Figure 1. Location of Gatseau beach on the island of Oléron (France) and transects studied.

The island has an estimated residential population of around 21,700 inhabitants (CCIO - Communauté de communes de l'île d'Oléron, 2009). Although its income originates mainly from activities associated with shellfish (oysters and mussels), it also comes from fishing, and from wine and spirits (Pineau des Charentes, cognac), hunting and, since the second half of the last century particularly, tourism. Its cultural and natural heritage is highly attractive because of its rich and varied nature: citadels built by Cardinal Richelieu and designed by the Sun King's exceptional architect, Vauban, World War II bunkers from what was known as the "Atlantic Wall", etc. These have given rise to a tourist appeal that was boosted in 1966 by the construction of a bridge joining the island to the mainland.

The island of Oléron has an oceanic climate, with annual rainfall ranging between 710 mm and 1,000 mm. Temperatures are very mild, with a yearly average of around 13 °C; in January they are therefore not excessively cold because of the thermoregulatory effect of the sea (around 6 °C), while summers are relatively hot (over 20 °C in August). There are scarcely ten days of frost a year and dense fogs are frequent because of the thermal differences between the sea and the air above. In summer, moreover, there are significant thermal contrasts between the island and the nearby continental domain, with differences of up to 10-12 °C (IGN-INF, 2013; Infoclimat, 2015). This circumstance is significant because it facilitates very violent storms that, as will be seen later, can prolong coastal erosion processes beyond winter.

The island also has some significant protected natural areas —ZNIEFF (Zone naturelle d'intérêt écologique, faunistique et floristique), Natura 2000, Site classé, etc.—, which are managed by different bodies such as the Conseil général, ONF (Office national des forêts), the Conservatoire du littoral, etc. This is the situation, in the south of Oléron, of the beach discussed in this work: Gatseau. Whereas, as mentioned above, the north is rocky, the southern fringe of the island is extremely sandy and ends in a coastal spit that has undergone significant changes in recent centuries. On the leeward side of the sandy spit is a small bay called Maumusson, a name that appears to have come from the expression "difficult way" in reference to the dozens of shipwrecks that have occurred at this point since time immemorial. Gatseau is currently one of the Natura 2000 reserves within the "Dunes et forêts de l'île d'Oléron" ('Dunes and forests of the island of Oléron') protected area, which covers an area of nearly 2,000 hectares and the management of which is the responsibility of the ONF. It includes not only a dune system-estuary and bay, but also a forest of pines and oaks currently of high ecological value.

Oléron is a unique setting in which to understand the effectiveness of the phytostabilisation methods favoured by people to counter the constant threat of coastal erosion. In fact, over 130 years ago a series of rows of maritime pines were planted in its north-western (forest and dunes of Domino), west-southwestern (forest and dunes of Saint-Trojan) and north-eastern (forest of Saumonards) flanks, and until the nineteen-eighties their success at phytostabilisation was remarkable. As a result of this work, 2,800 hectares were reclaimed from sea, land that has been very carefully preserved by the managing bodies.

The situation since then, however, particularly since the nineteen-nineties, has reversed dramatically and there has been a very pronounced coastal retreat that has affected virtually the entire island (Arteaga, 2007). Indeed, the beaches of Oléron have the world's highest rates of erosion, which are only comparable to others in Namibia, the United States and Brazil (Arteaga, 2011). Over the last 10-20 years almost everything gained in the previous century has therefore been lost. Gatseau is the most characteristic example of this phenomenon: since 2000 we have effectively tracked or monitored the evolution of the island's coastline (Arteaga, 2007) and the extent of deterioration and retreat at Gatseau beach has been truly significant. The purpose of this work is therefore to provide new data and to update, for the 2008-2014 period, the evolution of this beach, which in the past was a true example of dune protection and regeneration.

Historically, this beach has in some ways been a perfect laboratory for different issues explored in this work.

3.Methodology and objectives

The initial phase mainly involved:
1. Fieldwork with GPS support, involving identification of several recognisable points on maps and satellite images for which access was available. The purpose of this was to locate and monitor the evolution of the coast in relation to buildings close to the beach: World War II bunkers, housing, crossroads and roads, etc.

2. Given that the island is a 13-km continuous stretch of sand until it connects with Gatseau, it was decided to investigate the most sensitive and variable section of approximately 1.2 km, which coincides with the final spit and southernmost point of the island.

The cartographic and documentary information dates from the seventeenth century —in the form of different historical maps— to the present day and was processed and georeferenced in AutoCAD initially and thereafter in ArcGIS 9.2. The methodology can be found in the publication from 2007 (Arteaga, 2007). However, as we were focusing on the beach of Gatseau because of its great interest, we explored the dune system in greater depth, inventorying the major plant species, its degree of phytostabilisation and its area by analysing transects more or less perpendicular to the beachfront. Unfortunately, it was impossible to conclude this work because of rapid disappearance in all the zones inventoried.

In this 2006-2014 study, the existence of World War II bunkers or *blockhäuser* proved very helpful for monitoring. The great utility of these buildings had already been observed in work on other parts of the Atlantic and the Mediterranean coast (Migniot and Lorin, 1979; Petit-Maire and Marchand, 1993; Regnauld *et al*, 2004; Poulain *et al*, 2011). Here, the Gatseau bunkers had been covered and concealed by the dune masses and phytostabilisation of the forest. The existence of only one was known until 2006, when erosion uncovered two further bunkers to coincide with the start of the fieldwork. Their location at the extreme southern tip of the beach where the waves are generally less active on account of their north-south orientation (perpendicular to the predominant wave orientation) suggested that it would be a good idea to monitor them.

The help of such a useful tool as Google Earth, and its "historical imagery" option proved of great value, as shown by the 116 known and georeferenced points (mapping, GPS and Google satellite images from 2006 and 2014) that were juxtaposed with an error of less than one metre.

To study the beach we meanwhile differentiated two zones of analysis with three monitoring transects, established on the basis of dissimilarities in the rate of the erosion process observed in past studies (Fig. 1):

- The north beach, the smallest portion monitored, has a NW-SE orientation and is some 300 m in length. As shall be seen later, it has the lowest erosion rates. It stretches from the station of the tourist railway, which is the only way of reaching the beach (besides walking), to the intersection of the beach with the northern path that crosses the forest of Saint-Trojan. Monitoring will take place from transect 1.

- The south-central beach is around 900 m in length and stretches from the tourist railway station to the very tip of the island. In this segment two transects (transects 2 and 3) and the retreat of the beach with regard to the bunkers will be monitored.

4. Gatseau beach, characteristics and sedimentary balance

4.1. Status of the nearby coast

Gatseau beach is exceptionally located as a recipient of sediments. Of the different coastal currents that converge in its vicinity and that encourage deposition, two are of some importance: the island's north-south drift current and the coastal current that runs along the mainland in a S-N direction, which originates at the mouth of the Garonne River. Both are rich in sediments, especially the S-N current, which has a sediment concentration of between 10 and 40 mg (Omer and Pajot, 2000). The coastal bathymetric depth of Oléron is very low and may occasionally descend to 10 m, which favours water temperatures that can even exceed 25-26 °C in summer and very pleasing microclimatic conditions for tourists.

80% of the incident waves on Gatseau is WNW, and very secondarily, N, NW and W (Bertin *et al*, 2004; Billeaud *et al*, 2005; Musereau *et al*, 2007). Average wave height is 1.5 m, and 75% of waves are less than 2 m. It is estimated that in situations of very active storms, waves reach a maximum height of 6 m, although some authors recorded waves of up to 10 m for the explosive cyclogenesis Xynthia in 2010. The predominant wave direction encourages the formation of coastal drift from the north. The tidal range meanwhile fluctuates between 2 and 5 m while tides are semidiurnal, although in the exceptional circumstances of very strong spring tides, the water level may rise up to 6 m.

4.2. The Gatseau beach-dune complex

The Natura 2000 document on the dunes and forests of the island of Oléron (Natura 2000, 2013) determines that the coastal area of the island is marked and protected by significant massive dunes of a type that when fully developed is described in figure 2a. The conservation managers of the coastline of the regions of Landes and Charente-Maritime, as in other places, have established a system of classification based on phytostabilising species. Using their criteria, we shall now focus on Gatseau beach and inventory the characteristic species for each dune field drawn up in the 2006 study. From the seashore to the interior of the dune system, the following sequence can be established (Fig. 2):

- First, the area of **emerged beach** or **berm**. In the nineteen-eighties and -nineties, Gatseau beach still had a width of over ten metres of berm and its sands were exposed at high tide, except during spring tides. The berm, however, now only emerges at times of falling and low tides, both in the southern section and in the northern sector of the beach. In other words, at high tide the waves impact the dunes directly to form cliffs by erosion, which are then dismantled by sapping. The very sparse vegetation is predominated by *Cakile maritime*, which has now been relegated to small protected areas not reached by the waves.

- Next are the **embryonic dunes** that, because of their exposure and proximity to the sea, are occasionally impacted by waves during the most aggressive storms (overwash). They generally form a transversal "step" to the prevailing winds. On Gatseau, like other beaches on Oléron, this space has, however, been significantly reduced. The vegetation observed consists of species such as *Elymus farctus*, *Agropyron junceiforme* and *Elytrigia juncea*.

- There are then the **white dunes** (*dunes blanches*), which are larger. On Gatseau, these dunes measured up to a height of 10 to 15 m in the nineteen-eighties. Although they are still moving, this space can be breached by more penetrative waves, leaving furrow-like scars and erosive depressions with overwash morphologies. Where this phenomenon has not arisen it is possible to find *Ammophila arenaria* in the zones most exposed to wind and *Euphorbia paralias*, *Eryngium maritimum* and *Calystegia soldanella* in areas sheltered from the wind or downwind. In the transition section between the shifting and the fixed dunes (semi-fixed dunes), in addition to these species, there are also others such as *Festuca juncifolia*, *Galium arenarium, Medicago marina* and *Artemisia campestris* ssp. *maritima.*

- Meanwhile, scarcely any sand reaches the **fixed dunes**, also known as **grey dunes;** these have greater coverage and variety of flora, with species such as *Helichrysum stoechas, Dianthus gallicus, Koeleria glauca, Juncus acutus, Pancratium maritimum, Tuberaria guttata, Cistus salvifolius*, etc. In the past, people favoured the grey dunes of Gatseau to reclaim land from the sea to use them for different purposes.

There are other species of particular value located in the immediate surroundings of the Natural Reserve of Saint-Trojan and Gatseau. They are less common and are associated with the transition space of fixed-semi-fixed dunes (species listed in appendix II of Directive 92/43/EEC and other important Natura 2000 species of flora): *Omphalodes littoralis*, *Liparis loeselii*, *Anacamptis coriophora*, *Arctostaphylos uva-ursi*, *Asparagus maritimus*, *Cistus inflatus*, *Epipactis phyllanthes*, *Hornungia procumbens*, *Linaria arenaria*, *Ononis reclinata*, *Pyrola chlorantha*, *Serapias parviflora*, *Spiranthes aestivalis*, *Dianthus gallicus* and *Silene uniflora* ssp. *thorei*.

- Lastly, there come the **dunes phytostabilised by tree formations.** On Gatseau beach, this is a domain that has been completely developed by people for over 180 years with the plantation of *Pinus pinaster* (which already existed) for resin farming and for reclaiming land from the sea. On account of the protection and shelter afforded by this forest mass, however, over time clearings in the forest have been colonised by other arboreal species such as *Quercus ilex* and *Quercus suber*.

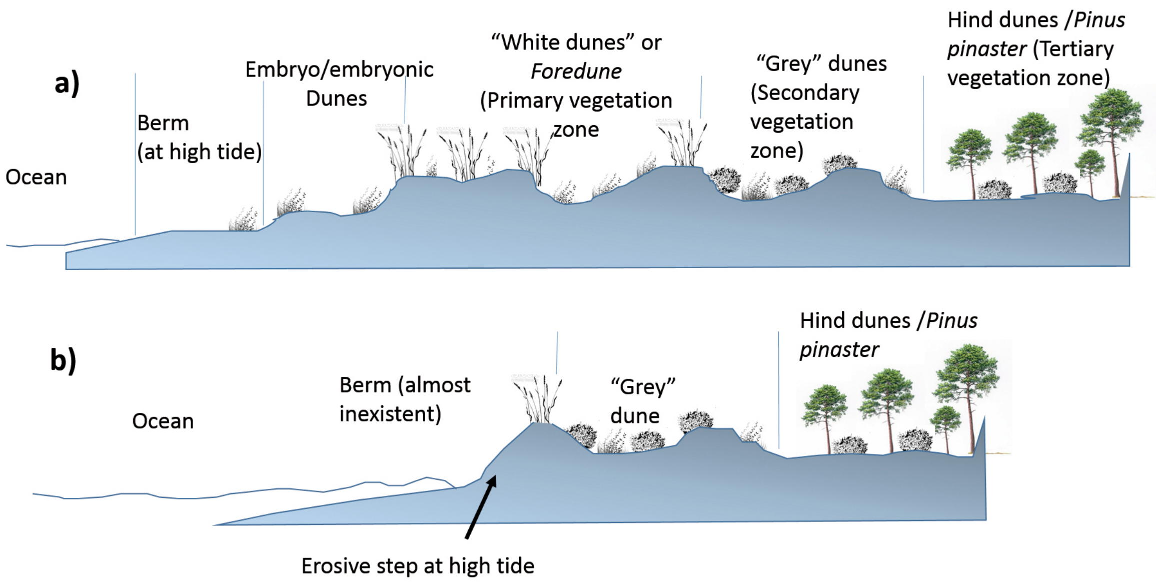

Figure 2. a) Type of fully developed dunes on the island of Oléron, and b) erosion in transect 2 of Gatseau beach with the disappearance of the berm at high tide.

4.3. The system "inputs": origin of the sands

The sands that arrive on Gatseau spit-beach have many origins. There are some that originate in the sea and river currents, which are mentioned above, and others that come from the destruction of the Mesozoic cliffs in the north of the island, which supply the beaches of Oléron on a minority basis with calcareous sands, gravel and stones. The other quartz-rich sediments, with average particle sizes of 0.2-0.3 mm, meanwhile, are brought by currents associated with the continental margin. In short, there are four river enclaves of some importance external to the island: to the north, the river Sèvre Niortaise and the Charente river; to the west, materials dislodged by the river Seudre; and to the south, those evacuated by the Garonne estuary, one of the rivers with the highest sediment loads in Europe (Froidefond, 1977). Hence, until recently, when the sediments transported by sea reached the strait between the mainland and the southern part of the island (Pertuis de Maumusson), they tended to accumulate in this sector. This process encouraged progradation that lasted for over a century and at least until well into the twentieth century.

Between the seventeenth and nineteenth centuries, large volumes of sand came to the island, brought by the wind, and penetrated its interior. This clearly threatened to bury towns such as Saint-Trojan, which forced urgent measures to be taken. It is known, for example, that in the fifteenth century the town of Saint-Trojan had to be relocated on account of the invasion of the dune field. The measures that were taken include the construction of fences and planting of pines for the phytostabilisation of the advancing dunes. This meanwhile allowed for the recovery of resin farming, which had disappeared from the island (Calonnec, 2006). Different infrastructures and plantations were installed in four consecutive phases, specifically in 1820, 1876, 1881 and 1948, the year of the last intervention involving not only the construction of a new fence, but also the recovery of others which had been seriously affected by the bombings of World War II.

Dune fixation was based on the technique of Vasselot de Régné, a water and forest officer (see Fig. 3); after constructing the fence and its subsequent concealment by sand over time, he then built another fence on top and so on, consecutively, until the dune reached a height of around 10 m. While this process was being undertaken, pine saplings were planted in the shelter of the fences.

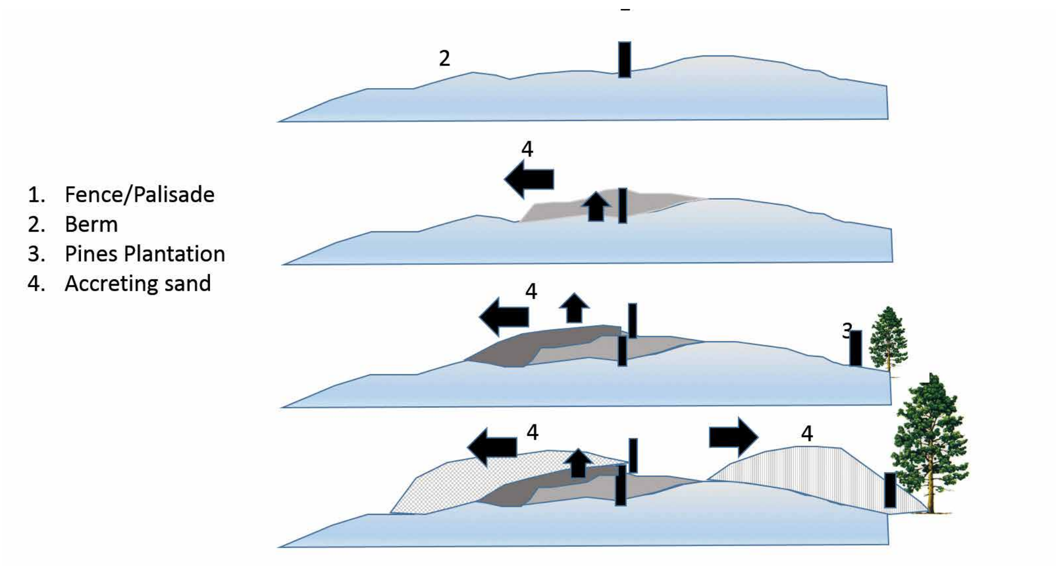

Figure 3. Vasselot de Régné fencing system.

This all meant land reclaimed from the sea, with values approaching one kilometre in width of the beach-dune system (Bourgueil and Moreau, 1972; Guinet, 2001; Arteaga, 2007). In short, until a few years ago Gatseau represented a zone of sedimentary accumulation of great importance for the island. Controlling or monitoring occurrences in this sand system helps to diagnose what is happening in the sedimentary evolution of Oléron. It should not be forgotten that the deposition of sand on this spit currently provides a protective barrier and a refuge for several plots of crops of oysters and mussels that play an important role in the economy of the island's inhabitants.

4.4. Erosion: results of monitoring and causes

Until 2005, supporting maps, GPS and different satellite and aerial images showed three phases of erosion on Gatseau beach (Arteaga, 2007): a) 1959-1972, with significant rates of retreat of the beach of around 27 m/year; b) 1972-1999, with rates of retreat of around 10 m/year; and c) 1999-2005, with retreats of 18 m/year.

Other researchers have obtained very similar values. Prat (2004), after several field experiments, estimated the volume of sand arriving from the berm to the dunes at between 10 and 25 m3/linear m/year, while that lost to the waves and erosion is much greater: 40-140 m3/linear m/year. Hence, the alignments of marram grasses cultivated on the dune ridge in the nineteen-nineties to curb degradation had disappeared completely by the end of that decade. Even the site that the tourist railway station occupied in the nineteen-seventies (PTST, 2015) currently lies under the waters of the Atlantic, 800 m west of the current dune field (equivalent to transect 2 of the study). Bertin *et al* (2004) determined that sediment transport to the SE of the island is extremely variable and estimated that the mobility of the sand fluctuates between 50,000 and 170,000 m3 (3 to 10 times lower than that observed by other authors). This transport is conditioned not only by the most intense waves, but also, and particularly, by the capacity of the swell to impact the beach frontally or perpendicularly.

There follows an update of the data for the 2006-2014 period, which is the main contribution of this work. It was collected on the basis of the space occupied by embryonic dunes, white dunes and grey dunes with regard to the current framework of erosion. Monitoring the Gatseau berm was ruled out, as it is scarcely visible and emerges only at low tide and on some days in the summer period with a low tidal coefficient (Fig. 4 and 5).

Transect 1 - North beach. 194.12-m WSW-ENE segment. Affected mainly by perpendicular or frontal waves. In 2006, after the measurements taken in the field, in the transect the embryonic dunes covered a linear extension of around 11 m, the white dunes of around 33.30 m, and the grey and fixed dunes of some 149.82 m up to its edge or to the border with the forest area. By 2014, the progression of erosion could be observed and was visible even on Google Earth. There were now embryonic dunes located where the grey dunes had been, and the system of white dunes had disappeared completely. In other words, the sea has engulfed over 136 linear metres. The new embryonic dunes cover an area of a little over 22 m and are defined and cut by the effect of overwash resulting from strong waves in storms. The distance between the grey dunes and the forest is now scarcely 51.9 m. The result therefore is that, in this transect, the beach has receded by an average of 17 m/year, a value that is very similar to the values monitored for the period 1999-2006.

Transect 2 - Tourist railway station. 215.65-m segment chosen on account of the broad assortment of landmarks that can be used for reference purposes (crossroads and roads, fences, etc.). The west-east section that in 2006 had a small embryonic ridge of some 8.7 m; the sands of this section fossilised the old railway line that ran to a stop currently covered by the sea. The space occupied by the white dunes that flanked the railway on the right (or northern) side covered around 39.3 m, while the grey dunes stretched some 167.75 linear metres up to the initial line of forest. By 2014, the situation was no less dramatic than in the previous transect: a retreat of over 157.78 m and erosion of the beachfront. Although, once again, the white dunes have disappeared, even more spectacular is the total disappearance of the grey dunes, which have been replaced by embryonic sandy masses that cover them, encouraged by the action of the wind and the waves. In total, there remain just over 54 metres of dunes, a figure that represents a linear retreat of 19.7 m in this sector.

Transect 3 - Gatseau spit or head. SW-NE section of 153.39 m. In 2006, this section still conserved the entire catalogue of dunes described and was therefore even then an exception on the southern stretch of the beach, which was very much affected by erosion and where the dunes phytostabilised by pines were generally being washed away by the waves. It is also surprising that this is the sector where sedimentation and growth has been greatest since the seventeenth century. The result of measurements taken in 2006 showed that the embryonic dunes had a width of 32.64 m, the white dunes a width of 34.44 m and the grey dunes (with some patches of pines) a width of 86.31 m. Very recently (2014), only 29 m of the transect remained. In eight years, therefore, some 124 linear metres of profile have disappeared from a total of 153.39 metres. This represents an erosion rate of 15.54 m per year.

Monitoring of the bunkers. In 2006, a World War II bunker was located 32.34 m from the beach, within the dune system and under some trees. In 2011, as a result of coastal erosion, three more came to light. After the review of summer 2015, these were determined to have been submerged in the beach's surf zone. The waves beat against them beyond the high tide mark and over 7 m from the dune erosion escarpment (Fig. 5d and 5e). In other words, the first of these constructions indicates a coastal retreat of 40 m in nine years, which amounts to around 4.4 m per year.

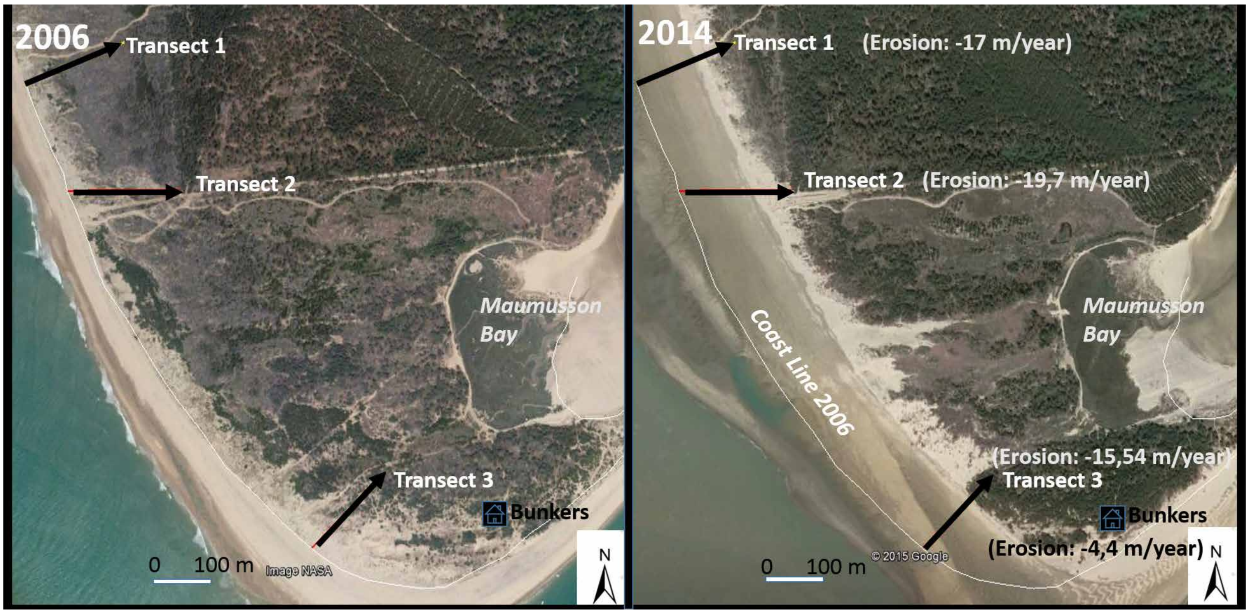

Figure 4. Evolution of the transects (from Google Earth images), erosion and retreat of Gatseau beach for the 2006-2014 period.

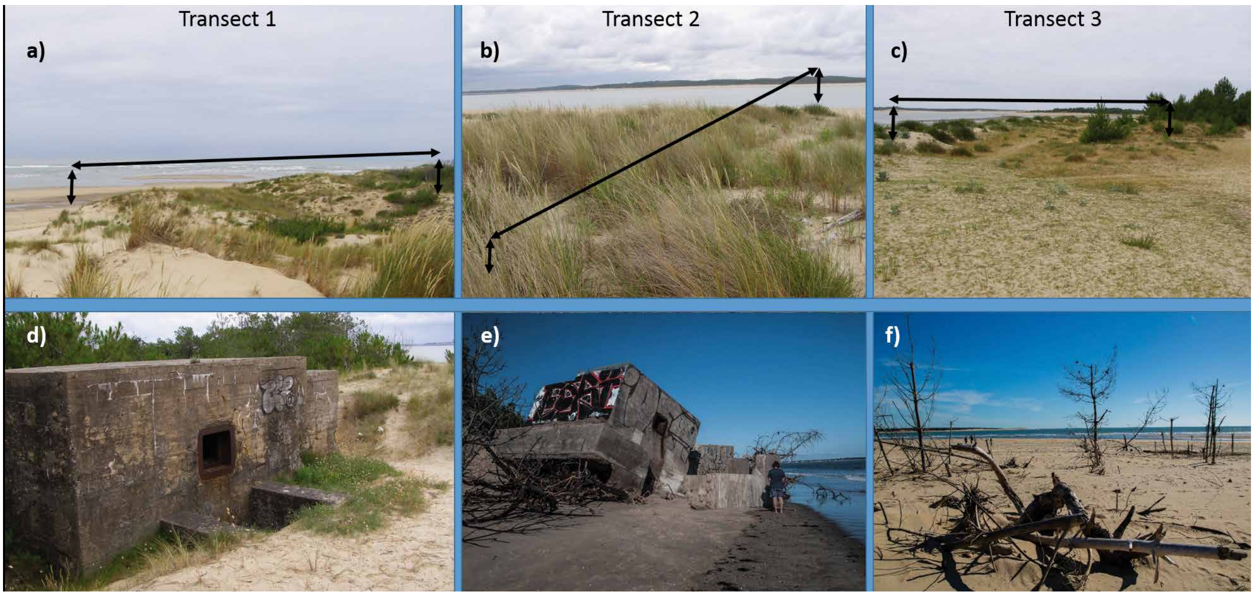

Figure 5. a, b and c) Photographs of the transects researched among the embryonic dunes, the white dunes and the grey dunes; d) Bunker from World War I when it was over 30 m from the beach, in 2006; e) The same bunker, which nine years later had been affected by action of the waves; f) Overwash scar in transect 3. Note that the pines are dead because of the onslaught of the waves and saltpetre. Ten years ago, these pines were over 200 m from the sea.

In Spain, comparable losses have only been observed on the Bay of Biscay coast, specifically on the spit of Liencres (Arteaga and González, 2005), where a 20 m/year decrease in the length of the head was observed, even though erosion to the beachfront was not so noticeable because disintegration of the spit transferred sediment to the other sandy zones.

Over the last eight years the area researched has lost an area of over 20 hectares, even though it is common for beaches to undergo erosion in one section and for deposits to be received in another. At Gatseau, however, such a process ceased long ago and along its whole length there is now only loss. It should therefore be assumed, first, that it has not accumulated the same volume of sand as for the 1820-1950 period and, second, the eroded material has been deposited in areas outside the system. This leads to the question of what factors might be contributing to the loss of sand.

5. Potential factors of erosion

Erosion on Oléron is not exclusive to Gatseau beach. It is also an urgent matter on all its other beaches, particularly because of the most violent storms, which have a major impact on account of the flatness of the island. The regression is ongoing and there is no chance that beaches and dunes will recover, as happened in the relatively recent past. We should therefore address the new elements that have appeared and have been influential since the second half of last century, the moment when the intensity of this erosive phenomenon became more noticeable. As Arteaga observed (2007), a distinction can be made between natural and anthropogenic factors:

5.1. Natural factors

Although there are several, we shall emphasise two major factors that are currently on the increase. First is the rise in sea level, albeit associated with the indirect factor of climate change. The information here is from buoys and the tide gauges closest to the island, analysed by the ONERC (Observatoire national sur les effets du réchauffement climatique; in Various Authors, 2014; Various Authors-ONERC, 2015; and Gouriou *et al*, 2013). These are installed in the bay of Pertuis Charentais, in the port city of Rochefort. The results obtained confirm a gradual rise in sea level of 2.1 mm/year during the period from 1944 to 2013. There is a marked increase after 1944, compared to the rates for the 1824-1909 period, when the sea rose at 0.4 mm/year. If we base our calculations on the Bruun Rule (1962), which is the criterion applied to certain beaches to which Gatseau can be likened, for each millimetre of rise in sea level a retreat of 1 m may occur. Although the application of this rule was brought into question by Bruun himself (1988), we shall use it because of the absence of other possible variables and formulations that may be applicable to Oléron. The linear decline in Gatseau Beach in the past 59 years would amount to 145 m, a figure very much less than that observed (almost 1,000 m) and not always consistent with that observed on other nearby mainland beaches (Arteaga, 2009).

The other element to consider is the erosion caused by a potential increase in violent storms, which is also a phenomenon related to climate change. In the last sixteen years there were three particularly extreme events: the storm of 27 December 1999 (which was even initially considered a hurricane); the explosive cyclogenesis Xynthia of 27-29 February 2010; and the recent storm of 31 January to 2 February 2014. All of these affected the French and English Atlantic and the Bay of Biscay coast in Spain. Prat (2004) shows that some of these extreme events can cause the beach to retreat by values of close to 50 m on just one occasion. Xynthia wiped out 60% of the forest of Saint-Trojan adjacent to Gatseau beach and also destroyed the former phytostabilisation fencing.

There are also records of other historical extreme events on the island (Various Authors, 2013), one of which occurred on 29 January 1645 and about which we have very little information; another, which occurred on 2 February 1702, destroyed all the protective dykes of the southernmost part of the island; the storm of 8 January 1924, in which the sea level rose by 1.66 m; the gale of 22 February 1935, accompanied by hurricane force winds of over 245 kph, also known as “the Cataclysm” by the islanders; and, lastly, the event of 16 November 1940, which submerged the area closest to the sea on the coast of Oléron. Of the eight major gales of the past three centuries, three took place over the course of 15 years. However, according to the French meteorological agency (Météo-France, 2015), in the last 30 years, there has been no appreciable increase either in the number of storms with winds in excess of 110 kph or in their intensity. In terms of frequency, in the decade from 1980 to 1990 there were 15 episodes, 12 which occurred from 1990 to 2000 and 14 from 2000 to 2010. Even so, the agency’s graphs show that the windstorms of 1999 and 2010 were the most violent of the past 30 years.

Despite the island’s wind history, these extreme events should not be considered the main cause of the continued erosion. Remember that two centuries ago, in the period between one storm and the next, the affected beaches recovered, although this should not belittle the impact of these phenomena as the size of the waves that accompanies them is a major factor in their retreat.

It should be noted, lastly, that that these highly aggressive phenomena, so unpleasant for the island’s inhabitants, tend to occur in the months of January and February. Oléron, moreover, is extremely sensitive to these storms on account of the altimetry of its coast. During these episodes the sea can therefore occupy thousands of hectares around its perimeter and can even immerse areas in towns.

The subsequent factor, the waves, accompanies the effects of the windstorms. Official bodies in France and bodies responsible for investigating wave variations (Various Authors, 2011: 31) have concluded that, for the time being, there are no significant variations on past periods, yet they have however acknowledged that the data series available from 1973 are biased and feature significant gaps. Although the role of natural factors is important, it should be assumed that those resulting from human activity are no less so. The most significant are detailed below.

5.2. Anthropogenic factors:

Roland Paskoff (1998) warned of the role played by different coastal infrastructures and of their direct and indirect relation to coastal geomorphological changes. The island of Oléron is not free from such constructions, some of which date all the way back to ancient times.

An initial group consists of those on the island itself. The largest is the port of La Cotinière, located 13 km north of Gatseau beach. Its docks have scarcely been altered since they were built in the nineteenth century and historical records make no mention of significant subsequent erosive changes or processes (which would obviously have their consequences). The process of growth of Gatseau beach after the installation of the fences to stabilise the dunes even happened to take place at the same time as the building of the port. The proliferation of dykes, together with the existence of other works of engineering, has been directly responsible for the interruption of coastal sand mobility and has therefore affected the sediment transported. Adjacent to our area of study, there is, notably, a series of structures that were installed successively from the second half of last century, including embankment and breakwater protection dykes and the installation and recovery of fish traps (*écluses à poissons*) from the Middle Ages articulated by stone enclosures.

Fieldwork revealed a large number of measures on the western shore of the island the purpose of which was, precisely, to prevent coastal erosion in the areas close to the small fishing villages and the housing developments created for emergent tourism. There is a total of 38 dykes perpendicular to the beaches of the west coast, eight of which are relatively close to Gatseau, and 18 locks and fish traps, facilities that interfere with the main current for transporting sediments that runs along the coastline of the island from one end to the other, and that ends at Gatseau. In fact, as can be observed in figure 6, inside the traps it is common to see sandbars that have been captured by the system. In addition, around 3 km of protective breakwaters adjacent to the beach have upset the natural beach-dune dynamics, and impaired the sediment transport cycle.

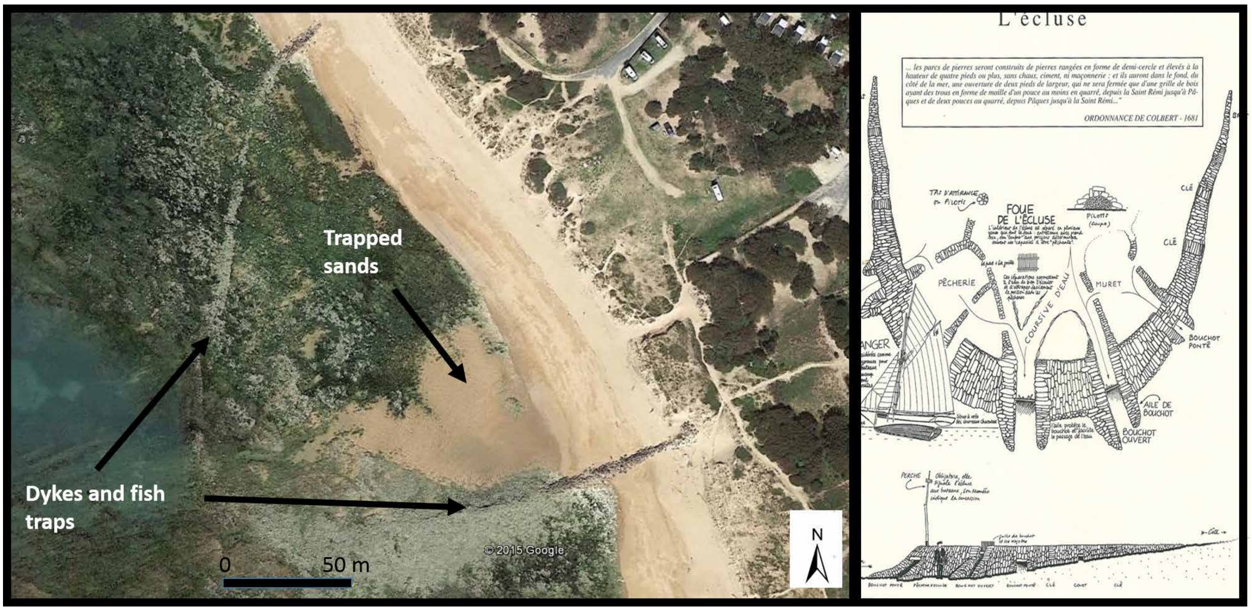

Figure 6. Tidal fish traps and old etching with a diagram showing how they work.

A second group consists of those buildings that potentially capture materials arriving on the island from allochthonous effluent areas —the rivers Sèvre Niortaise, Charente and Seudre and Garonne, mentioned previously— and the construction of dykes and breakwaters on the mainland coast. Although it is extremely hard to estimate the exact value of these alterations, in the nineteen-seventies Froidefond

(1977) asserted the direct relation and interference of the dykes and dredging in the estuary of the Garonne River (Gironde), one of the main suppliers of sediments to Marennes-Oléron bay (Benaouda, 2008), with erosive processes and a resulting reduction in the volume of sediment transported by its waters.

Indeed, in the Garonne River estuary it has initially been estimated that over 4,000 tons of sand and clay sediments (of the 5 million tons carried by the river system in the estuary zone) are dislodged and introduced to the coastal and marine area. Although the exact amount is unknown, a very high percentage has been found to reach the beaches of the island of Oléron. The main threat to this is possibly the 336 km of breakwaters and dykes that theoretically prevent the task of sapping-erosion, transport and subsequent sedimentation along the riverbank, which is over 500 km in length from its source. If a further 500 km that line the coast of Aquitaine are added, the possible alterations caused cannot be ignored. Similar constructions can, moreover, also be found in the mouths of the Seudre for the protection of the oyster marshes, of the Charente and the Sèvre Niortaise.

Some of these defences are historic as reclamation of the coastline in the bay has been ongoing since the twelfth century (D'Hollander, 1961). These are zones that today, with extreme storm events, are quite easily submerged by the sea and this causes a whole series of problems. To date, the only response to this circumstance has been the reconstruction and the introduction of more breakwaters.

It should lastly be mentioned that this coast is home to five ports of different sizes. Although exactly how they affect the sedimentary balance of the bay-estuary system of Marennes is unknown, the implications of these infrastructures should not be forgotten.

6. Discussion and conclusions

The island of Oléron and, particularly, Gatseau beach constitute a veritable natural laboratory, and present a long history of practices and measures to counteract the onslaught of the sea, with some highly contrasting responses by the coast.

Almost two centuries ago, the people of Oléron not only overcame the retreat of the entire beach-dune system of Gatseau, but reclaimed land from the sea in a very short space of time. The use of measures that could be considered "soft", with a low impact on nature, subsequently yielded a rich and new ecological territory of flora and fauna. In fact, until that time, the beach and forest of Gatseau were clear examples of good dune phytostabilisation practice and measures. This was very similar to what is being done in other parts of the world, with priority application of measures that do not entail complex engineering involving construction work predominated by the use of stone. This led to the formation and extension of what was later to be acknowledged as one of the most interesting and acclaimed protected areas of the coast of the Charente-Maritime, which covers almost 2,000 hectares.

This success appeared to change in the mid-twentieth century and, perhaps by chance, coincided with a boom in tourism on the island after the opening of the bridge that joined the island to the mainland, and the resulting proliferation of new urban developments close to the coast in order to meet the needs for sun and sand of the new seasonal inhabitants.

The choice of location for new constructions in the west and centre of the island's coast and in areas that tend to suffer more frequently from the onslaught of the waves because of their greater openness and exposure to the Atlantic forced managers to protect homes. To do so, they opted for the construction of dykes and breakwaters, which may have been temporarily effective but in the long term had dramatic consequences for the southernmost sectors of Oléron and only served to shift the problem.

This, together with the difficulties and problems of a bay subject to considerable human pressure, does not give much hope for the future. In light of what has occurred in the storms of recent years, particularly Xynthia, the solutions proposed by different authorities rather involve resorting once again to breakwaters and dykes. This is established in the Programmes of Measures for the Prevention of Floods (PAPI), which are new coastal protection plans involving different regional and state organisations and institutions with a view to the year 2030 and with a planned investment for the island of nearly 20 million euros (PAPI, 2013).

All this raises some very unsettling questions that can be extended to other beaches in the world: first, why has it not been possible to preserve a properly managed system like Gatseau beach, which until the nineteen-fifties maintained a succession of dunes that had attained a certain balance, nor to withstand the attack of marine agents, even with additional measures of support (the increased plantation of marram grasses and the unsuccessful construction of new fences)?; and second, in connection with the first, why do beaches dependent on the arrival of allochthonous-origin sediments appear to be extremely fragile given that the specific measures of conservation and recovery, if not properly addressed to other factors that may arise between the point of origin of the sediment and the specific beach, have zero or minimal effectiveness?

Once again there is a need for genuine coastal management that not only covers large areas of coast that research has shown to be related to one another, but also takes into account the rivers responsible for the sediment. Coastal planning should involve more than just small regions and towns. The sea is a "huge conveyor belt" of sediment, fauna and flora, and is just as responsible for the workings of climate as the atmosphere. Care for it should start on the shore, where human presence is greatest.

Lastly, we wish to contemplate a future scenario that we hope will never happen because of its inherent consequences. Perhaps the future of Gatseau was marked out with the building of the infrastructures to meet the demands of tourism. It is foreseeable, at this rate, that the deterioration of the beach will continue and in a few years the entire spit of the island of Oléron (or of Maumusson) will have been lost, as well as wetlands of high ecological value and zones used for farming oysters, which were previously sheltered from the waves. This would be truly economically dramatic for the islanders, as 72 hectares could disappear in less than 24 years. The southern morphology of

Oléron would, however, return to the original shape of the seventeenth century. Meanwhile there are questions referring to not too distant a time in the future: How long and how much can Oléron, which is 11 km wide, resist this erosive onslaught? Will it end with a system of dykes and beaches that are accessible only at low tide?

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State of conservation of the foredunes of the Canary Islands

Peña-Alonso, C., Hernández-Cordero, A.I., Hernández-Calvento, L.

1. General characteristics of the coast of the Canary archipelago

The Canary archipelago consists of seven main islands and four smaller islands of volcanic origin that are located in the eastern sector of the mid-Atlantic and on the African tectonic plate. The group of islands covers an area of some 515 km from east to west. The closest distance from the African continent to the Canary Islands is between the island of Fuerteventura and Cape Juby (Western Sahara) with a distance of scarcely 95 km. It is the most extensive archipelago of Macaronesia (7,447 km2) and covers 50.87% of the region's total area (Fernández-Palacios and Dias, 2001). As they are islands their coastal perimeter (1,553 km, ISTAC, 2012) is considerable in comparison to the area they cover. Given the insular nature of the Canaries, there are differences with the rest of the Spanish coast related to their volcanic-type geomorphology and geology, oceanography, climate, biodiversity and the history of their human occupation.

The volcanic formation of the Canary Islands has occurred from the Miocene to the present day, although each island has materials of different ages (Fig. 1).

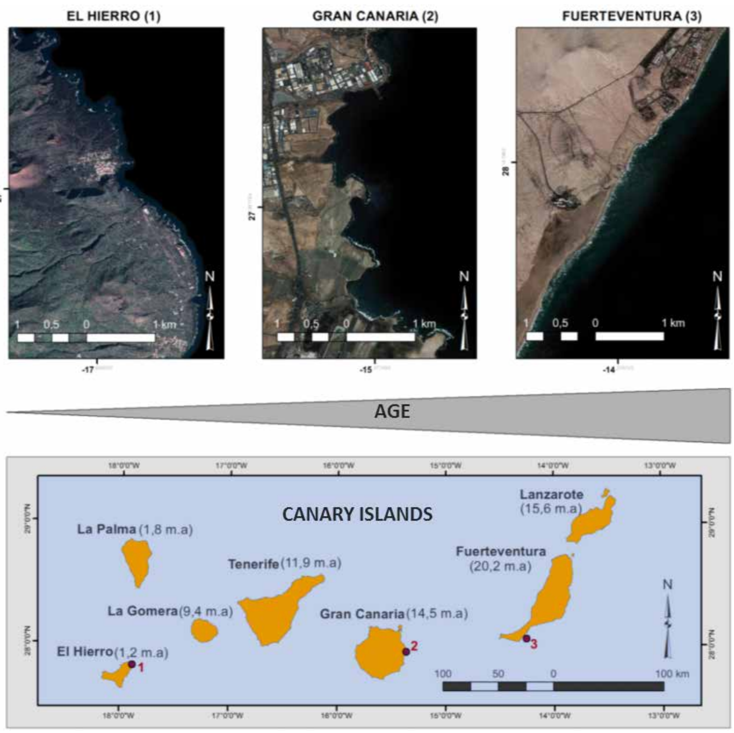

Figure 1: Age of the Canary Islands. The age of each island, in millions of years (Ma), corresponds to the start of the subaerial phase of the shield stage of development (Carracedo *et al*, 2008). The top images (GRAFCAN S.A., 2012) represent stretches of coastline with different degrees of erosion and belong to islands ranging from a lesser to a greater age.

The oldest island is Fuerteventura (20.2 Ma), with subaerial eruptive phases between the Lower and Middle Miocene (up to 12 Ma), while the islands of La Palma (1.8 Ma) and El Hierro (1.2 Ma) are the archipelago's youngest, as their shield stages of development occurred during the Pliocene and the Quaternary respectively (Hernán, 2001). There has been less study of the submarine eruptions that formed these islands, although on Fuerteventura submarine basalts have been dated from the Oligocene (some 33.4 Ma, Anguita *et al*, 2002).

The age of each island determines its morphological characteristics, and significant differences can be observed between the eastern and western islands (Fig. 1). The coast of the western islands, the most recent in the archipelago from a geological perspective, is therefore characterised by its ruggedness. The presence of coastal projections and the scant marine insular shelf prevent the existence of long longshore drifts. The beaches formed tend to be small coves (100-300 m in length), associated with the mouths of gorges or with retreating cliffs. They are generally formed by coarse black sand and rounded stones or boulders (Gracia *et al*, 2009)

The eastern islands, meanwhile, are geologically older, have been exposed to erosive processes for longer, and have straighter coastlines and longer littoral and marine shelves. On these platforms there are significant accumulations of sand-size grains with a high percentage of organogenic-origin elements (Gracia *et al*, 2009). Larger, rectilinear beaches and occasional associated dune systems are typical features of these islands. Tenerife and Gran Canaria, on the other hand, have mixed coastal landforms that are apparent in a combination of different-sized cliffs, on the northern and western coasts, and a gentler terrain in the coastal sections in the south of these islands, with beaches of varying length and sedimentology (Haroun, 2001).

The particular features of the foredune systems of the Canary Islands are the result not only of the islands' volcanic nature. Other aspects that also determine how they are shaped and their dynamics include the climatic characteristics, oceanographic factors (currents, tides and swell), relief and types of vegetation. In the archipelago, these systems are the result of successive processes of aeolian reactivation over geological time, from the Miocene until the present day. Currently, however, a feature common to all the aeolian systems of the Canaries is a loss of sand on account of the reduction in supply, thus encouraging the stabilisation of mobile dune fields.

1.1. Unique features of foredunes in the Canary Islands

Some sectors of the coast of the Canary Islands, particularly in the eastern islands, have a significant formation of dune systems associated with different landforms such as fan-deltas (at Maspalomas, on Gran Canaria), sedimentary tombolos (Guanarteme), or mixed volcanic-sedimentary platforms (Corralejo, Jables de Lanzarote and La Graciosa). The area covered by dune systems in the Canary Islands is, however, very low. This is because 70% (ISTAC, 2012) of the perimeter of the Canary Islands consists of rocky landforms that in most cases contain narrow beaches associated with cliffs and the mouths of gorges. The scarcity of insular shelves (subtidal zones and continental shelf) is a factor that limits the generation of extensive aeolian sedimentary systems in the archipelago (Hernández-Calvento *et al*, 2009).

The aeolian sedimentary systems found in the Canaries are in different states of activity (Fig. 2) that depend on the amount of available sediments, on the extent of vegetation cover, and on the surrounding land uses that have developed.

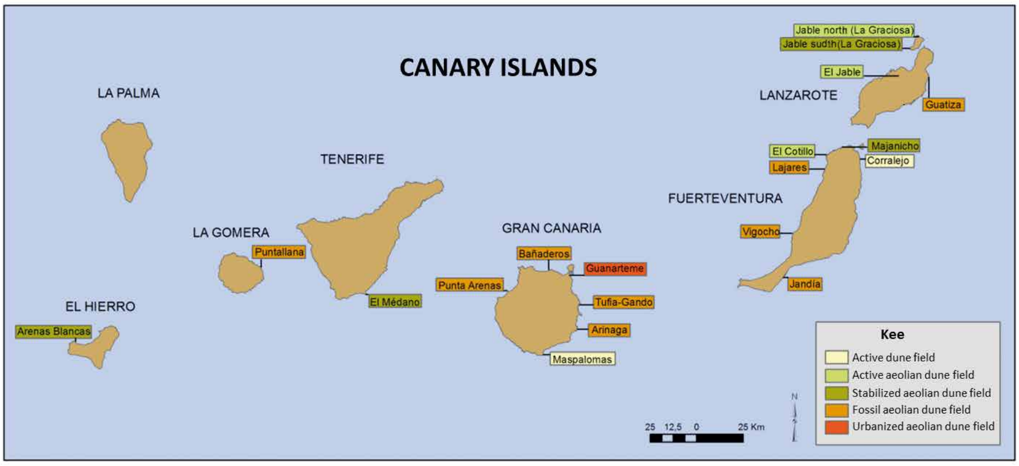

Figure 2: Main aeolian sedimentary systems of the Canaries (updated by Hernández-Calvento *et al*, 2009).

It is therefore possible to come across fossil dune fields like those at Puntallana (La Gomera), Punta de Las Arenas, Bañaderos, Tufia-Gando and Arinaga (Gran Canaria), Lajares, Vigocho and Jandía (Fuerteventura) and Guatiza (Lanzarote), dune fields that have disappeared on account of urban development of the space they occupied (Guanarteme, on Gran Canaria), or that are now stabilised (Arenas Blancas, on El Hierro; El Médano, on Tenerife; Majanicho, on Fuerteventura; the systems on the Island of Lobos, and Jable Sur, on La Graciosa). Lastly, there are some that are active (Jable Norte, on La Graciosa; Famara, on Lanzarote, and El Cotillo, on Fuerteventura), and others with mobile dune systems such as Maspalomas (Gran Canaria) and Corralejo (Fuerteventura).

Unlike in temperate and tropical regions, when the appropriate sedimentary conditions (abundance of sand) arise, the Canary Island dune systems exhibit quite high rates of mobility, a circumstance that is related to low rainfall, a frequency of winds of ≥5 m/s (considered the threshold speed of sedimentary mobility typical of these systems, according to Pérez-Chacón *et al*, 2007, Máyer *et al*, 2012), and a scarcity of plant species capable of colonising the foredunes. Some dunes that move over 30 metres a year have thus been identified (Pérez-Chacón *et al*, 2007). These, therefore, are arid transgressive systems, the deposits of which occasionally reach sections of the coast away from the sources of sediments to yield marine-aeolic systems, as occurs on other older islands such as Boa Vista on the Cape Verde archipelago (Hernández-Calvento and Suárez, 2006).

Plant species that favour the formation of foredunes also vary between temperate and arid regions. While *Ammophila arenaria* (herbaceous plant) performs this function in European temperate regions, *Traganum moquinii* (shrub) does so on the Canary Islands and in its surrounding geographical area (Gracia *et al*, 2009) (Fig. 3).

The difference in the reproductive system (sexual vs. asexual) and cover and behaviour of the two species yield different aeolian morphologies. Foredunes formed from *Ammophila arenaria* therefore have a characteristic continuous ridge. This is because this herbaceous plant has a system of asexual reproduction based on rhizomes, often grows to a uniform height and is arranged linearly parallel to the coast.

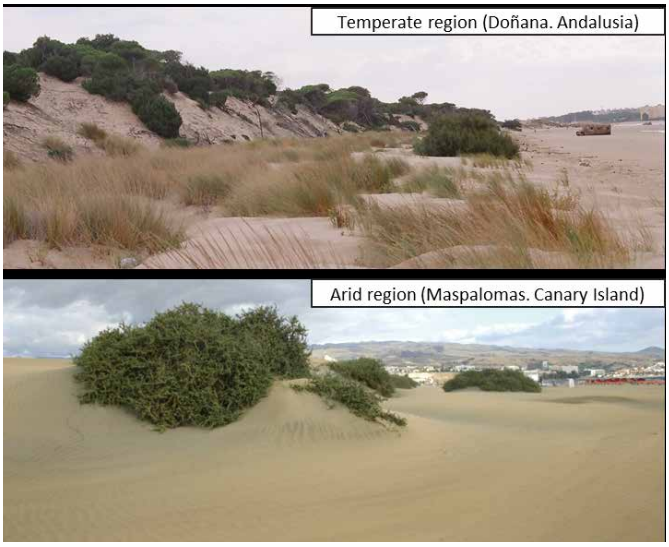

Figure 3: Geomorphological differences and plant colonisation on foredunes of temperate and arid regions.

Figure 4: Example of retentive and transgressive dune systems in the Canary Islands.

Foredunes formed by *Traganum moquinii* are, meanwhile, characterised by the creation of a group of hummock dunes of variable height (Hernández-Cordero *et al*, 2012). These are fragmented foredune, with deflation corridors interspersed between the hummocks, which allows for greater transport of sand towards the interior of the system. In this latter case, the width of the foredune is variable, as it depends on the arrangement of individual shrubs and on input of sand into the system (Hernández-Cordero *et al*, 2015).

From a morphodynamic perspective, the foredunes of the Canary Islands are associated with dune systems that can be classified as retentive or transgressive (Rust and Illenberger, 1996) (Fig. 4) depending on their characteristics. Stabilised or retentive dune systems are those in which the accumulation of sand is generated by the presence of vegetation, which acts as a dispenser by retaining and releasing sediments according to the aeolian activity in each period of the year, an aspect that dominates other processes. In this case, landforms such as hummock dunes, shadow dunes and remnant dunes have been identified in an environment widely characterised by the presence of a sand sheet of variable power, in which ripples are identified, thus indicating some superficial aeolian sediment dynamics. Transgressive dune systems, meanwhile, are those in which aeolian sand mobility is the process that shapes the dune system. In the Canary Islands, such systems are characterised by hummocky foredune as the primary landform generated by the interposition of isolated plant specimens in the aeolian sediment dynamic. Behind this front, a field of free dunes with scant vegetation is generated. The main landforms are barchan dunes, barchanoid ridges, sand sheets, deflation surfaces and interdune depressions (slacks).

1.2. Environmental problems of the dune systems of the Canary Islands

The tourism sector in the Canaries has become a major economic driving force and thus exerts significant influence on financial, and therefore, political and territorial decision-making. The power groups that have controlled this sector since the nineteen-sixties until the present day have therefore very much influenced measures of planning and territorial management, particularly those implemented in the coastal areas that are both the most attractive for tourists and also the most fragile, such as beaches and dunes. The impacts of activities on the environment are, however, evident (Fig. 5).

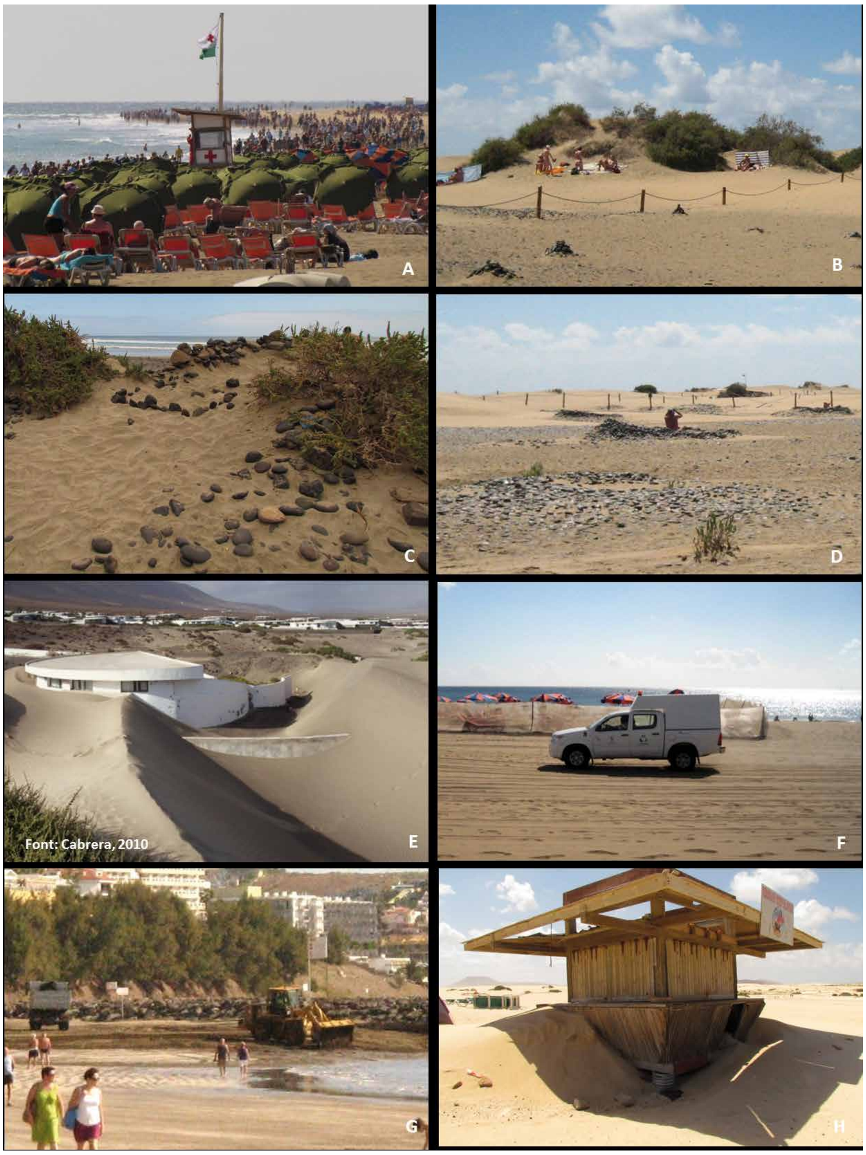

Figure 5: Examples of impacts associated with pressure exerted through use. A: pressure from visitors on the foredune of Maspalomas; B: occupation of the environment by specimens of *Traganum moquinii* as elements that protect against the wind and aeolian transport; C: windbreak (goro) and human-made corridor affecting a specimen of *Traganum moquinii* on the foredune of Caleta de Famara; D: windbreaks (goros) on El Inglés beach (Maspalomas) made with rounded stones from paleobarriers; E: disturbance of input of sand caused by obstruction of the Famara housing development (Caleta de Famara); F: movement of vehicles on the beach; G: measures to manage El Inglés beach (Maspalomas); H: disturbance of the aeolian sedimentary dynamics caused by a kiosk on the upper beach of Corralejo.

Significantly, these include the disappearance of the Guanarteme dune system (Las Palmas de Gran Canaria, Gran Canaria) on account of the urban development of the city of Las Palmas de Gran Canaria (Santana *et al*, 2014); the disturbance of the aeolic sediment dynamics by housing developments (Hernández-Calvento, 2006; Hernández-Calvento *et al*, 2014) and the loss of plant communities such as the reducing of populations of *Traganum moquinii* at Maspalomas (Hernández-Cordero *et al*, 2012) caused by human disturbance, and the occupation of mobile dunes by private facilities (Annex II Shopping Centre at Maspalomas, Hernández-Cordero, 2012). These impacts, which alter the original natural conditions of these systems, are sometimes considered by the public as necessary in order to yield economic benefit, yet are strongly opposed by other sectors.

Not even the measures established to protect the natural heritage have helped to solve the existing dilemma between development and conservation in the Canary Islands, set against a background of insularity, in which resources are limited and used intensively and few sustainability criteria are implemented.

2. Analysis of the vulnerability of the dune systems of the Canary Islands as socio-ecological systems

The foredune systems not only owe their existence to the presence of sand and vegetation and to the incidence of the wind and waves, but are also influenced by human activity in their vicinity. They can therefore be defined as socio-ecological systems or, in other words, systems involving interaction between the bio-physical system and social (human) system (Gallopín, 1991) that may be affected by external forces relevant to their dynamics (Fig. 6).

In these socio-ecological systems, “resources”, which in this case are the foredunes (Fig. 6: A), are used by “users” (Fig. 6: B), although users can also act as “providers of public infrastructures” (Fig. 6: C). “Public infrastructures” (Fig. 6: D) are meanwhile defined as capital of a physical or a social kind, created by human beings: physical capital is associated, among other things, with engineering works (dams, jetties, ports, etc.) while social capital refers to the regulation, management and use of socio-ecological systems.

In a socio-ecological system (Fig. 6), vulnerability is the relation between the factors of exposure to which the system is subject, its susceptibility or intrinsic characteristics, and its resilience (Cardona and Barbat, 2000; IPCC, 2007). The vulnerability of foredunes is related to factors of external exposure, which may disturb their dynamics. On one hand there are disturbances of bio-physical origin (Fig. 6: arrow 7), which affect infrastructures and beach and beach-dune systems. These are disturbances of a natural origin (climatic, tectonic, volcanic, etc.) that can alter the marine and fluvial dynamics of these coastlines, and yield impacts that cause an increase in geomorphological vulnerability. On the other, there are disturbances of a socio-economic origin (Fig. 6: arrow 8), associated with changes in demographic, economic and political patterns that mainly affect the users of resources and providers of infrastructures. In this latter case, modification of these elements would particularly affect the quality (in terms of recreation and conservation) of these spaces and, therefore, the measures taken to manage them. This aspect also involves changes in the management of natural resources and in their dynamics.

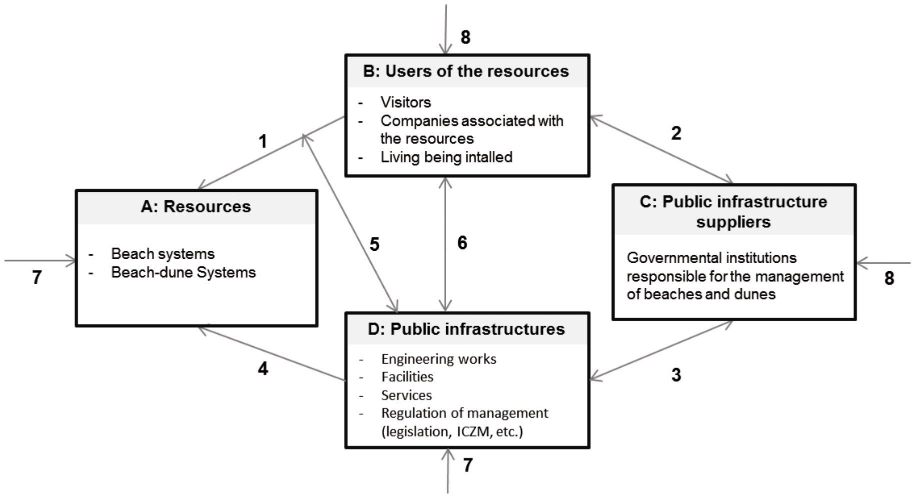

Figure 6: Diagram showing the elements of beach-dune systems and their interactions, as socio-ecological systems (adapted from Anderies *et al*, 2004).

The disturbances and the interactions that arise within this model generate a state in the system that indicates its capacity to maintain itself properly. Variations depend on the degree of susceptibility the beach-dune resource (A) has, from a geomorphological perspective, to deal with the disturbances to which it is exposed (Fig. 6: arrows 7 and 8). A resilient system would therefore be one able to adapt to disturbances, to absorb impacts and to remain functioning. Resilience is thus linked to the maintenance of the resource or, in other words, the basic (geomorphological) structures of foredunes.

In this analytical context there is a need for all the stakeholders involved to take active part in planning and monitoring the management of foredunes (Defeo *et al*, 2009). Numerous works have therefore been dedicated to the development of indicators for the environmental evaluation of beach-dune systems (Williams *et al*, 1993b; Klein *et al*, 1998; García-Mora, 2000; Martínez *et al*, 2006; Gracia *et al*, 2009; Chousa *et al*, 2014), with a view to determining their capacity to respond to natural or anthropogenic disturbances. These works were preceded by that in 1991 of Bodéré and collaborators, who developed a vulnerability index for dune systems (Bodéré *et al*, 1991). This research was conducted using a list of indicators that included geomorphological, biological, marine, anthropogenic and aeolian aspects.

Since this work, dune vulnerability indices have been adapted to the particular features of dune systems in different parts of the world such as eastern France (Williams *et al*, 1993a), the United Kingdom (Williams *et al*, 1993b), southeast Portugal (Alveirinho-Dias *et al*, 1994), south and southeast Spain (García-Mora *et al*, 2000; Chousa *et al*, 2014), and the Gulf of Mexico (Martínez *et al*, 2006). These experiences have shown the validity of these lists of indicators in identifying the source of impacts suffered by these systems.

In Spain, the national government has promoted a series of measures, based on studies, recommendations and strategies for managing these spaces. The work conducted by García-Mora *et al* in the 2000s (García-Mora *et al*, 2000; García-Mora *et al*, 2001) provided a benchmark with which to compare the problems of the dunes in Spain with reference to the Manual de restauración de dunas costeras (Ley *et al*, 2007). The purpose of this document, which was commissioned by the Ministry of the Rural and Marine Environment (currently the Ministry of Agriculture, Fisheries and the Environment), was to establish a basis upon which to analyse problems, and to monitor and manage foredunes in Spain.

To date, studies on the vulnerability of foredunes in the Canaries have concentrated on research by scientific (Hernández-Calvento, 2006; Alonso *et al*, 2006; Medina *et al*, 2007; Cabrera, 2010; Pérez -Chacón *et al*, 2010; Hernández-Cordero, 2012) and government institutions (Gobierno de Canarias, 2004; Gobierno de Canarias, 2006a; Gobierno de Canarias, 2006b).

Since these studies were undertaken, it has been noted that the “Manual de restauración de dunas costeras” (Ley *et al*, 2007) is not directly applicable to the aeolian sedimentary systems of the Canary Islands, as they differ significantly from those of mainland Spain and the Balearic Islands on account of their geological (intra-plate hot spot volcanic islands) and climatic conditions (Hernández-Calvento *et al*, 2009).

As regards geological circumstances, each Canary Island is an individual insular structure (except for Lanzarote and Fuerteventura, which form a single structure) that rises from the oceanic lithosphere (Carracedo *et al*, 2008). The stock of sediments that supplies these systems is located on shallow or non-existent submarine insular shelves. There is thus a greater abundance of sandy sediments on the older eastern and, therefore, more eroded islands. The climatic conditions of the Iberian Peninsula and the Balearic Islands are temperate, as in other regions where these indices have previously been applied, while the dune systems of the Canary Islands are located in arid and semi-arid climates. This factor has a key impact on the vegetation characteristics of these systems and, therefore, on aeolian sediment transport and its associated landforms. The insular nature of both the Canary and the Balearic Islands also exerts a strong influence as, unlike in the Iberian Peninsula, there are no major continuous rivers and therefore the source and type of sediments, as well as the way in which they are transported, are different. Upon the basis of this evidence, many of the recommendations made in this handbook are therefore clearly not applicable to the foredunes of the Canary Islands.

It is therefore necessary to establish a system to evaluate vulnerability applicable to arid sandy coastal systems, which also allows for analysis of the phenomena to which these systems are exposed and the intensity with which they may be affected.

3. Methodological adaptation and application to the Canary Islands

With reference to previous work on this subject, vulnerability is defined as the state of coastal systems, given their sensitivity to the impact of the agents to which they are exposed.

The methodology used is an adaptation of the method proposed in the handbook of the Ministry of Agriculture, Food and the Environment for the management of foredunes in Spain (Ley *et al*, 2007). Hence the design of the "vulnerability index for foredunes in arid regions (IVDRA)", adapted to the specific nature of Canary Island dune systems. It allows for evaluation of the current capacity of beach-dune systems to respond to the processes shaping them, and the degree to which their main landforms have varied since the nineteen-fifties and -sixties. Evaluation of these processes reveals the behaviour of the Canary beach-dune systems. The sub-indices considered to estimate vulnerability are exposure, susceptibility and resilience.

Of these sub-indices, the sub-index related to susceptibility is the one that defines the degree of internal fragility of systems for dealing with a threat and/or receive a possible impact resulting from the occurrence of an adverse effect (ISDR, 2009). This is an opposite aspect to the resistance to change of a system exposed to modelling agents (Klein *et al*, 1998). When extrapolated to coastal environments, this definition refers to a system's elements of intrinsic weakness (Füssel, 2007). In this case, the "geomorphology-sedimentology" and "characteristics of vegetation cover" (the latter sub-index only considered in the "vulnerability index for foredunes in arid regions – IVDRA") have been selected as components (secondary sub-indices) of the main sub-index.

This work analyses the susceptibility of Canary Island foredunes as part of a study of their vulnerability, while allowing for classification of their intrinsic elements and comparing them among the foredunes of the Canaries. One of the aspects analysed is the existing vegetation of the immediate shoreline as this explains the formation of primary dunes (derived directly from the beach). The other concerns landforms, which indicate the degree of sediment mobility in the foredunes area. The higher the volume of sediment entering the system, the greater is the system's capacity to absorb impacts and, therefore, its resistance. In developing the original method (Boderé *et al*, 1991) 100-m2 plots were established as units with which to work. For the dune systems on the Canaries, this area was extended to 200 m2 on account of the surface area of the foredunes, which in most cases stretches a distance of around 200 metres inland with respect to the shoreline. Definition of the size of the plots included consideration, as a common criterion, of the direction of prevailing winds in every area of study, in order to ensure consistency of the plots from a geomorphological perspective.

The variables established (table 1) are the result of adapting the initial methodology (Ley *et al*, 2007) to the peculiarities of the foredunes of the Canary Islands, a process in which some variables have been removed and modified and new variables have been introduced. The specific evaluation of each variable is based on a rating system from 0 to 4 in which the value "0" means a low or zero value, while the "4" represents maximum susceptibility.

Table 1. Variables for evaluating susceptibility in foredunes of the Canary Islands.

SUSCEPTIBILITY	Vegetation cover (VC)	% of vigorous plants on the windward primary frontal foredunes
		Max. vegetation cover by strata on first frontal hummocky foredunes
		Max. vegetation cover by strata on hummock foredunes
		% of the area of windward first frontal foredunes with vegetation
		Average cover of plant individuals
		Vegetation cover on dry beach
	Geomorphology-sedimentology(GS)	% of area of the plot covered with wet slacks
		Relative area of foredunes with escarpments or erosion
		Quantity of hummock dunes on the plot
		Average height of the foredunes
		Particle size of the windward slope of the foredunes (ϕ)
		% of the dry beach line occupied with embryonic dunes
		% of the dry beach with shells
		% of the dry beach with gravel
		Particle size of the dry beach sediment (ϕ)
		Width of the dry beach
		Number of submerged or emerged sandy or rocky embankments.
		Width of the intertidal zone
		Modal state of the beach
		% of the foredunes zone without vegetation
		% of the area of the plot occupied by deflation areas
		Maximum distance of plant individuals from first frontal hummock dunes

The value of the sub-indices (Is) is calculated by dividing the sum of the values assigned per variable (Vi) by the sum of the possible maximums obtained in each sub-index (Vpmax) (eq. 1). The result of the sub-indices (VC and GS) is standardised with values between 0 and 1 (where 0 equals no susceptibility and 1, maximum susceptibility).

$$Is = Vi / Vpmax \quad \text{(eq. 1)}$$

After performing this exercise, the susceptibility (Sus) of each plot is evaluated as the mean value of the results of VC and GS. The variable evaluation procedure is based on field and laboratory work, and on spatial analyses performed with geographical information systems (GIS).

4. The susceptibility of foredunes in the Canary Islands

To evaluate susceptibility, three plots were selected in Maspalomas (Gran Canaria), four in Corralejo (Fuerteventura), four in Caleta de Famara (Lanzarote) and one in Las Conchas (La Graciosa) (Fig. 2). These systems are representative of the types defined by Rust and Illenberger (1996), with those at Caleta de Famara and Las Conchas being retentive, and those at Maspalomas and Corralejo transgressive. Given these characteristics, this work presents analysis of the foredunes, as it is an area of interaction between marine and terrestrial processes that determines the condition of each dune system. The geographical, geomorphological and ecological characteristics and dynamics of each system are different, and therefore the cases selected are a representative sample of the types of dunes of arid regions.

These systems also exhibit different eco-anthropogenic characteristics related to the performance of tourism-related activities (vehicular traffic on the beach, construction of perimeters to the dune systems, installation of kiosks and loungers, etc.). These attract a large number of users to the foredunes analysed, with the exception of Las Conchas (La Graciosa), where the protection measures in place are observed and the site is some distance from urban nuclei. This procedure is accompanied with a comparison of the processes that determine the current dynamics in the selected plots. The characteristics of the plots marked off in the foredunes under study are as follows:

MASPALOMAS

The plots are located to the east of the system, along El Inglés beach, sediments input area (Fig. 7).

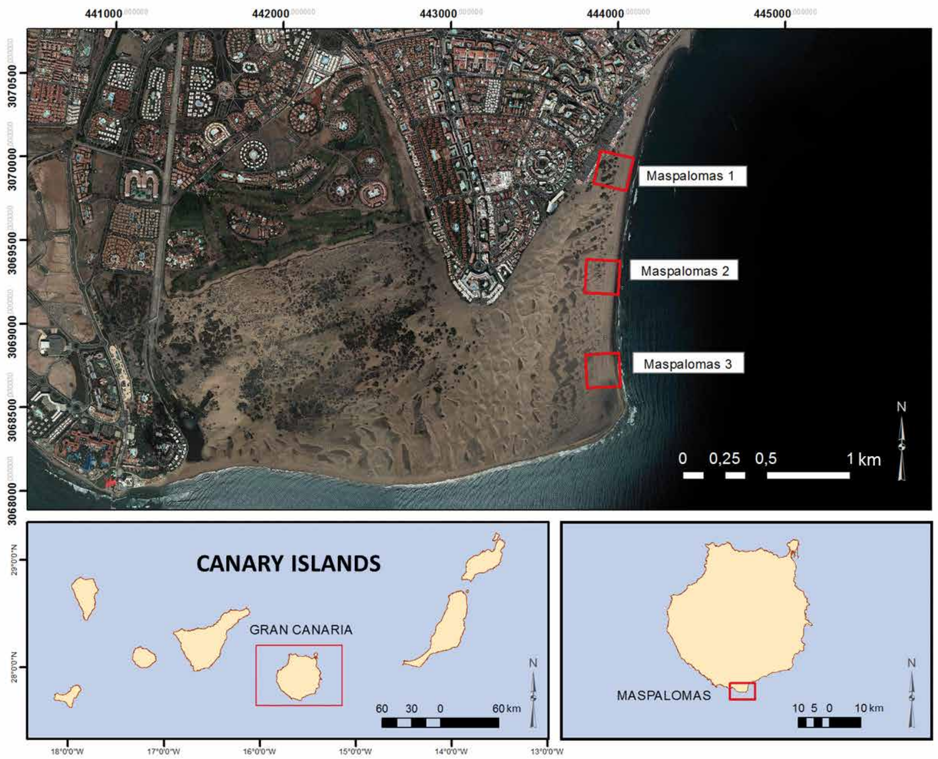

Figure 7: General view of Maspalomas and location of the plots.

Human impact on this coastal strip is high, although a graduation of its intensity from north to south can be observed. The plot located in the north (Maspalomas 1) is surrounded by a consolidated urban environment. There are many direct accesses from the urban zone, which is a fairly busy area with many services (bars, restaurants, cafes, ice-cream shops, mini-markets, clothes stores and kiosks) and facilities (showers and footbaths, parasols and loungers) offered as part of the leisure available. On the Maspalomas 2 plot, the housing development is about 750 metres away. Despite the distance, the zone is widely used, although the presence of users is lower than that of the Maspalomas 1 plot as there are no kiosks or loungers. Although the last plot, Maspalomas 3, is the farthest from the housing development, it is the site of a nudist zone and there are therefore a fair number of users, albeit smaller in number than in plots 1 and 2.

The foredune vegetation consists of the *Traganum moquinii* species of shrub. In the northern plot (Maspalomas 1) the vegetation has the greatest substance and cover of all the plots selected. This circumstance decreases gradually towards the south, as the distance between plant specimens grows. The vegetation located in the southern part of the foredunes is subject to stress on account of the force exerted by the wind in this zone. The vegetation pattern observed influences the morphology of the hummock dunes that form this foredune and also those entering the system (Hernández-Calvento, 2006).

Lastly, as far as its natural dynamics are concerned, this coastal strip is oriented east-southeast and the north-easterly prevailing wind therefore enters perpendicular to the system. There is evidence of some sedimentary deficit as there are deflation surfaces downwind to the foredunes, in the direction of the prevailing winds (Hernández-Calvento *et al*, 2007; Díaz-Guelmes and Hernández-Calvento, 2004). In the southern zone (Maspalomas 3), the foredunes are fragmented. The hummock dunes that form them are small and, on the leeward side, large deflation surfaces have been identified (Hernández-Calvento, 2006; Díaz-Guelmes and Hernández-Calvento, 2004; Hernández-Cordero *et al*, 2012).

CORRALEJO

As in Maspalomas, the foredunes of Corralejo are located at the east of the system (Fig. 8) and vary in characteristics from north to south.

The selected plots are exposed to constant pressure from users. Behind the strip of foredunes runs one of the main roads of the island of Fuerteventura (FV-1), upon the shoulder of which it is possible to park and to access the sea. The path leading to and from the beach is not marked out and therefore users can freely access the entire zone, thus exerting constant pressure. It is only the central plots (Corralejo 2 and 3), however, that are directly influenced by different facilities (beach kiosks, loungers, parasols, etc.) and hotel buildings. The Corralejo 2 plot is located to the north of the Riu Tres Islands hotel and the Corralejo 3 plot to the south of the Riu Oliva Beach hotel. On these, user traffic is even higher. On the plot in the south (Corralejo 4) there are no facilities yet the presence of human activity is evident in the windbreak structures installed by users (“goros”), located on the upper beach and very often attached to specimens of *Traganum moquinii*. As regards vegetation cover, along the entire coastal strip it is common for the first plant individuals that impede the entry of sand from the sea to be of the species *Traganum moquinii*. This species coexists with others that vary according to the plots selected. They include *Euphorbia paralias*, *Ononis hesperia* and *Launaea arborescens*, which are common in areas with an active aeolian process (Fernández-Cabrera *et al*, 2011). On the central plots there is a more widespread presence of herbaceous plant communities and, in this environment, where the hotels are sited, this fact indicates greater system stabilisation, thus facilitating their germination and survival, particularly in the internal zone of the plots furthest from the sea. On the southernmost plot, only *Traganum moquinii* is observed, indicating greater transport of sediments, which prevents the development of the herbaceous plants.

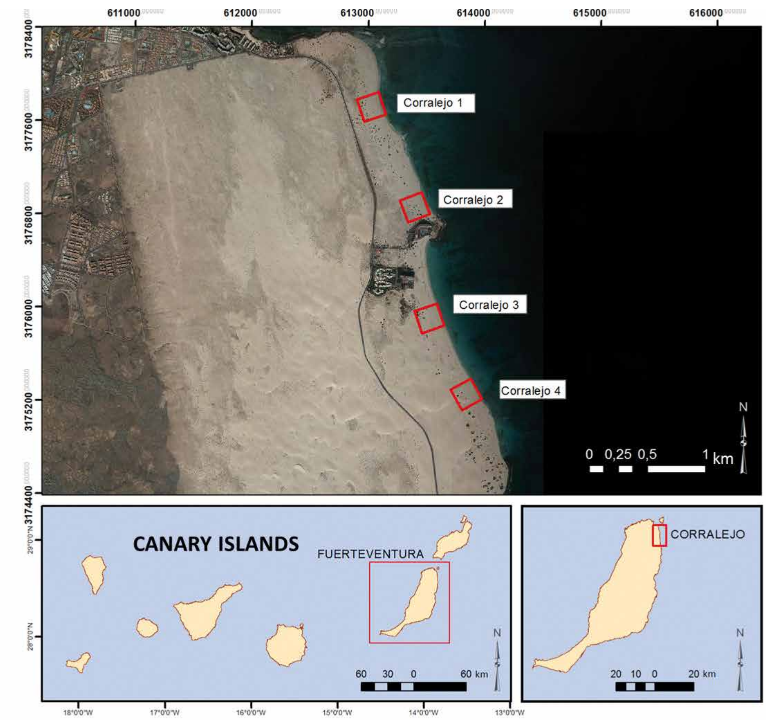

Figure 8: General view of Corralejo and location of plots.

The wind is mainly N-NW (Malvárez *et al*, 2013), an aspect that influences the landforms that appear along the foredunes. In the first two plots analysed, landforms typical of deficit processes, such as deflation surfaces, were not identified. However, in the north of the Corralejo 3 plot there is a hotel zone, the buildings of which could be acting as an obstacle to the free transport of sediments. No deflation surfaces have been observed on this plot, although outcrops of Pleistocene sedimentary rock deposits have been found in the intertidal zone (García, 2013), which could indicate that the plot has a negative sediment balance (Alonso *et al*, 2006). To the south, on the Corralejo 4 plot, there are paleosols (García, 2013), which also indicate a negative sediment balance, a fact confirmed by the recent appearance on the shoreline of a coastal shelf made of volcanic and sedimentary materials that correspond to the Middle and Upper Pleistocene and to the Holocene. This plot is located in a mixed area where there occurs not only the entry of sediment on the beach, but also the movement of sand from the north of the system to the sea (Malvárez *et al*, 2013).

CALETA DE FAMARA

This system is the zone with the highest available sediment and greatest rate of effective transport of what is known as Jable de Lanzarote. It is the entry zone for marine-origin sediment to the system (Cabrera, 2010). The selected plots in these foredunes are arranged from west to east (Fig. 9).

Human occupation of this coastal strip is associated with the town of Caleta de Famara, to the west, and the Los Noruegos housing development to the east. Two major roads run between both areas:

the LZ-402, from N to S, which connects the town of Caleta de Famara and southern Lanzarote; the second, which runs across the first (E to W), crosses the plot through the middle and joins the town of Caleta de Famara to Los Noruegos. The shoulders of this second road are used as a parking area for vehicles from which users access the beach. Although it is a very busy area, there are no beach facilities such as loungers or parasols. However, the construction by users of windbreaks (goros) along the first line of vegetation has been observed. The availability of round stones on the beach favours the construction of these structures. The easternmost plot (Caleta de Famara 4) is the least affected by human disturbance, as there are no roads or housing developments in the immediate surroundings, although it can be accessed on foot from the Los Noruegos tourist development, 100 metres to the west.

As regards vegetation, the western plots (Caleta de Famara 1 and 2) are characterised mainly by the presence of specimens of *Traganum moquinii* and *Launaea arborescens*, which form the foredunes (Cabrera, 2010).

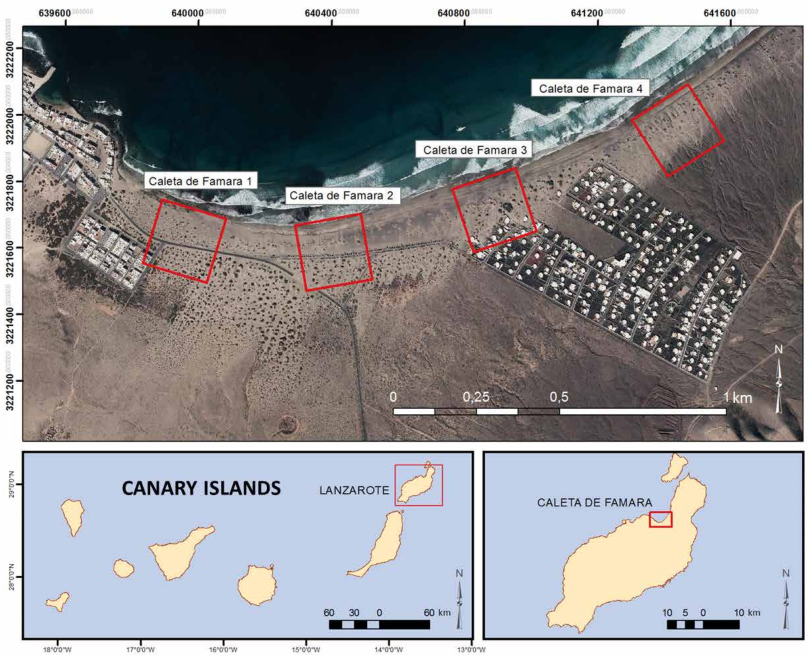

Figure 9: General view of Caleta de Famara and location of the plots.

The substratum is sandy throughout the plot, except in the zone closest to the sea, where there are outcrops of rounded stones. On the Caleta de Famara 4 plot a higher percentage of colluvial sediments from Riscos de Famara (Cabrera, 2010) can be observed and in intertidal zones there are sands and rounded stones alike, the proportion of which varies according to the period of the year. The hummock dunes can reach two metres in height, although this varies among the plots selected.

LAS CONCHAS

In the dune system associated with the beach of Las Conchas a single plot was established because of this system's small stretch of waterfront (Fig. 10). This plot is located in a place with little human disturbance, away from the island's two towns.

On the plot there are no facilities of any type and access is only possible on foot, by bicycle or using one of the taxis that travel around the island. The rules governing the protected area (Gobierno de Canarias, 2006a) prohibit cars from travelling on the beach and access has been cut off about 200 metres from it. On the beach in general and the plot in particular there is therefore no great influx of people, except in summer.

The plot's vegetation consists of herbaceous communities formed by *Cakile maritima*, *Lotus lancerottensis* and *Euphorbia paralias,* as well as subshrub communities of *Astydamia latifolia*. The individuals in these communities have given rise to small hummock dunes, which run to the foot of Montaña Bermeja, the adjacent volcano. Also significant is the presence of some specimens of *Traganum moquinii* (Pérez-Chacón *et al*, 2010), which provide fairly extensive coverage and are located on the plot's waterfront.

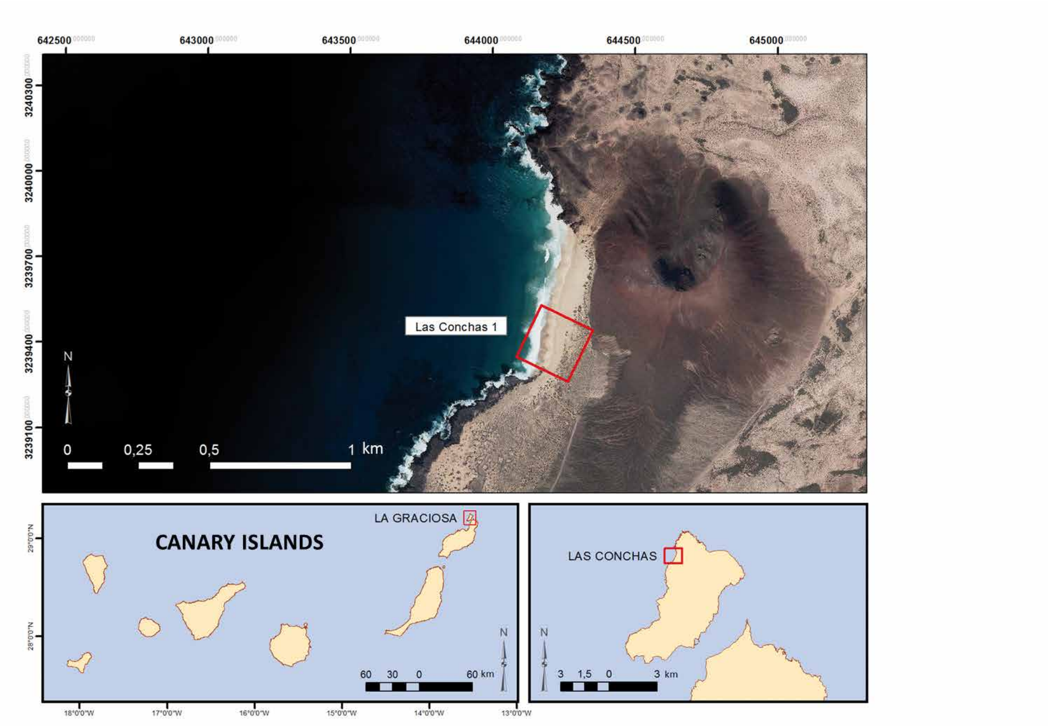

Figure 10: General view of Las Conchas and location of the plot

Significant from a geomorphological perspective is the presence of the Montaña Bermeja volcanic structure, which acts as an obstacle for the westward transport of sediment. In some parts it encourages the accumulation of sediments, while in others it helps to channel the flow of wind from the north thereby facilitating the creation of a N to S corridor in which this aeolian sedimentary system occurs. The supratidal zone of the plot has a one-metre layer of reddish sandy-loam paleosol, containing the shells of marine molluscs, land gastropods, ichnites of Hymenoptera and black and reddish lapilli. This paleosol provides a base for the foredunes, the limits of which are not easily defined, as the vegetation is distributed homogeneously towards the interior of the selected plot. Hummock dunes of different sizes can be observed. There are currently neither inputs into the system significant enough to maintain a mobile dune field (Pérez-Chacón *et al*, 2010) nor signs of erosion. It may therefore be considered a system in dynamic equilibrium.

5. General diagnosis of the susceptibility of foredunes on the Canary Islands

The selected dune systems have geomorphological and vegetation characteristics that differ from plot to plot yet have a state of moderate susceptibility. Plots with extreme susceptibility values are located on the foredunes of Maspalomas. The least susceptible plot is Maspalomas 1, while Maspalomas 3 has the highest susceptibility.

The results of “geomorphology-sedimentology” variables were similar among plots, except for those related to the number of hummock dunes, average height of foredune, percentage of beach with shells and gravel and maximum distance of plant individuals on the first frontal hummock dunes. These variables therefore identify the geomorphological-sedimentological elements that differentiate foredune.

Of the values indicative of a high degree of susceptibility, significant are the variables related to the particle sizes (ϕ) of the windward slope of the foredune and of the dry beach, presence of embryonic dunes, submerged or emerged sandy or rocky embankments, and proportion of foredune without vegetation. Results that suggest low susceptibility are related to the presence of wet slacks, the lack of erosion escarpments on the foredune, the width of the beach, dissipative modal states and scarcity of deflation surfaces.

“Vegetation cover” was analysed in three zones within each plot: dry beach, first frontal hummock dunes and foredune zone. On the dry beach, the results show there is no vegetation on any of the plots analysed.

Figure 11: Significant landforms on the foredunes analysed. GS-A: area of stones on the dry beach of Caleta de Famara; GS-B: embryonic dunes among the foredunes of Las Conchas; GS-C: zone with scant sand cover in the south of El Inglés beach (Maspalomas).

On the first frontal hummock dunes, the state of vegetation vigour yields susceptibility on the Maspalomas 3 plots, where the foredunes are fragmented and vegetation is sparse, and on the Caleta de Famara 2 plot, which has been disturbed by the presence of “goro” windbreaks built by users and by the drying of the branches exposed to incident wind. The maximum vegetation cover by strata of height and the percentage of the area of the initial line downdrift of foredune with vegetation are variables that determine generally scant susceptibility on the plots.

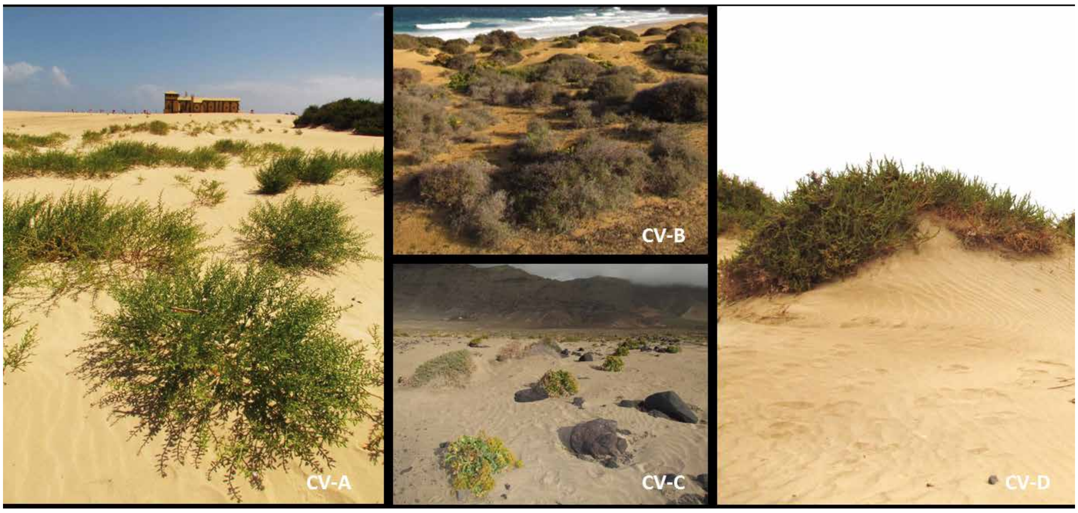

Figure 12: Vegetation on the foredunes analysed. VC-A: embryonic dunes associated with *Cakile maritima* and, in the background, foredunes with *Traganum moquinii* (Corralejo); VC-B: specimens of *Launaea arborescens* (Las Conchas); GS-C: low hummock dunes formed by specimens of *Astydamia latifolia* and *Salsola vermiculata* (Caleta de Famara); GS-D: hummock dune of moderate height formed from a specimen of *Traganum moquinii* (Caleta de Famara).

The values of the remaining variables refer to vegetation throughout the plot. The variable related to maximum vegetation cover per stratum on hummocky foredune only yields susceptibility in Corralejo 2 and Las Conchas 1, on account of the widespread presence of herbaceous plants. The variable related to average cover of the plant individuals of the plot reveals that susceptibility is significant on the plots analysed, except for the Maspalomas 1 plot, where the specimens with greater coverage among the selected plots are located.

As a final conclusion of the diagnosis based on the susceptibility of the foredunes analysed, it was observed that among the plots located within each foredune, there are significant differences resulting from the state of conservation of the landforms and the vegetation. In general, however, the foredunes of Las Conchas and Caleta de Famara are more susceptible while those of Maspalomas and Corralejo are less so.

In addition to this analysis, it is also important to study the natural and anthropogenic agents to which these systems are exposed, as well as changes undergone by structural landforms over time, which indicate their resilience. These dimensions provide a broader context for the vulnerability analysis proposed in this work, which is based on adaptation to the specific characteristics of the Canary Islands as an example of an arid region. They are therefore considered useful tools for the bodies that manage these spaces.

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Coastal dune systems and the concept of integrated coastal and marine management (ICMM)

Pablo Balaguer Huguet[1], Francesc X. Roig-Munar[2]

[1] Societat d'Història Natural de les Balears. C/ Margarida Xirgu, 16. 07011 Palma
[2] QU4TRE, consultoria ambiental. Es Migjorn Gran (Menorca). www.quatreconsultors.com

1. Abstract

Coastal dune systems are highly sensitive and fragile types of coast that fulfil functions in the natural defence of coastal areas against erosion, have a biodiversity mainly shaped by species (most of which are cosmopolitan) that are highly adapted to sandy soils and temperature and humidity fluctuations, play an important role in nutrient recycling, act as a buffer to seawater intrusion, have considerable scenic value and are recreational areas of great social and economic interest. These systems require sustainable management that entails consideration of the maximum number of variables and stakeholders involved in their function and evolution. The paper is intended to associate such coast types with the theoretical concepts of Integrated Coastal Zone Management (ICZM), Marine Spatial Planning (MSP) and Global Change. Although these are very common and versatile concepts, here they are defined and related to the coastal dune systems as they point the way for science-based sustainable management of these systems.

Key words: Coastal Dune System, beach, ICZM, MSP, Management.

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2. Introduction

The coastal zone is an environment in its own right located between the land and the sea. It is a transitional zone that exists on all the world's shores in zones in which the terrestrial or continental environment comes into contact with stabilised water masses. Its transitional nature makes its boundaries unclear and dependant on local and regional conditions, and it is therefore a space defined by relatively dynamic thresholds (both in theory and in practice). This zone's complexity increases with the incorporation of socioeconomic components. It has therefore historically been considered as a strategic area both with regard to aspects associated with territorial defence and to aspects connected with the opportunities yielded by its location, which prompt considerable trading activity and economic growth.

A high coincidence of natural, socioeconomic, historical-cultural and legal-administrative factors makes the coastal zone an environment with different degrees of fragility, the management of which requires consideration of all its constituent elements. Changes to any of the factors in a given coastal area could influence factors in another area and cause changes (often unwanted) over an indeterminate space of time that could range from short- to long-term.

Globally, coastal zones experienced considerable change over the twentieth century, with an average rise in sea level of around +17 cm (Church *et al*, 2010); in the Mediterranean area, this rise was greater and measured between +20 and +30 cm (EEA, 1999). These variations, which are attributed to climate change (EEA, 1999, 2000; Church *et al*, 2010), suggest that we are immersed in a process of global change in which the climate changes that affect the biosphere and the geosphere are affecting how socioeconomic structures function. 10% of the world's population currently lives in coastal areas less than +10 m from sea level (McGranahan *et al*, 2007; Nicholls *et al*, 2008). The Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2007) predicted a rise of between +0.20 and +0.80 m for the period 1980-2100; the Fifth Assessment Report maintained these predicted rates and indicates that in the 1900-2010 period highs of close to +0.20 m were observed (IPCC, 2014). Some studies indicate that the rise in sea level has recently been accelerating and is even higher than the +3 mm/year described in the report by Church *et al* (2010).

The coastal dune systems represent a type of coastline that combines all the features described above. Spatially, they are highly variable systems (hence the limits to the coastal zone can therefore vary a great deal), highly dynamic (with a constantly changing shoreline owing to the active dynamism in the sedimentary distribution both in the terrestrial and in the marine environment), with a high socioeconomic value (both in built-up beach systems and in beaches and in beach-dune systems with their natural values intact), and inherently extremely fragile (on account of the associated biodiversity and the balance between the different external agents acting upon them) and very vulnerable to allochthonous elements, usually deriving from human activity, which may arise within the system itself or originate from changes that occur or are caused in other coastal sections or units. The importance of these systems lies in their role in defending the coast against sea storms. Such types of coast have a greater capacity to adapt to changes in sea level than rocky coasts and coasts where there has been considerable human intervention. Adaptability is determined by the availability of sediment, both in the submerged and in the emerged zones, which ensures progressive adaptation of the shape of the coastline against rises in sea level, and also guarantees the biogeographical and ecological features typical of these areas.

This paper is intended to establish a context for the concepts of sustainable management and development of the coastal zone (Integrated Coastal Zone Management, Marine Spatial Planning) and their relation with coastal dune systems. In keeping with the general characteristics of such coasts, the incorporation of sustainable management concepts is felt to be necessary both to understand the characteristics and processes acting and also to establish proper channels to attain a rational balance among the different interests created, based on scientific knowledge as a tool for supporting decision-making.

3. General description of the coastal dune systems

The coastal dune systems and shorelines are composed mainly of unconsolidated materials: usually sand-sized sediment (with a grain size diameter of less than 2 mm). They have varying degrees of sensitivity and fragility in their different constituent sectors (Fig. 1). The general pattern of these coast types consists of a nearshore submerged zone of sandy beds, a coastline with a beach, foredunes located at the rear of the beach and a dune surface formed by dunes that shift to a larger or lesser extent depending on the degree of vegetation cover and the availability of sediment (Fig.

1). A wet zone at the rear of the foredunes or dune field occasionally develops. The coastal dune systems are very important in the provision of certain ecosystem services, as the foredunes act as a natural defence for the shoreline against swells and coastal erosion (Koutrakis *et al*, 2011), play a role in accelerating nutrient recycling (Nel *et al*, 2014), provide a habitat for species adapted to extreme conditions and to a broad variety of wildlife (Nordstrom, 2008), have considerable scenic value on account of their relief and unique habitats and ecosystems (Pintó *et al*, 2013), are important for tourism and recreation (García de Lomas *et al*, 2011) and act as buffer against saltwater intrusion into freshwater aquifers (Bonnet, 1989; Ley *et al*, 2007). They constitute a type of coast for which all factors (natural and anthropogenic) should be considered in interpreting their origin and evolution so that the most suitable management measures can be implemented to make sure that they last and can also remain a place for public enjoyment and economic development in a manner that befits the environment.

In the European continent as a whole, around 25% of the area occupied by coastal dune systems was lost during the twentieth century; 45% are currently in good state of conservation, a figure that only amounts to 25% in the Mediterranean area (Salman & Koijman, 1998). In Spain, in 2007, coastal dune systems represented 40% of the coastline while 45% remained in their natural state, according to Ley *et al* (2007). These data, however, are generalised mean data and, on the island of Mallorca, for example, authors such as Schmitt (1994) consider that there are still around 50% (33 systems) of the original coastal dune systems, of which 14 can be considered to have been completely destroyed because of overbuilding and intensive use of the beach.

From a morphodynamic and geomorphological perspective, it is necessary to consider the submerged zone (tidal flat/subtidal zone) to the most distal part of the system in the backshore zone (Sherman & Bauer, 1993; Servera, 1998; Woodroffe, 2002) (Fig. 1). The arrangement of sediment and the physical characteristics of the coast (morphology and maritime climate) are essential elements that determine the existence of the beach-dune systems. The main sources of sediment supply are: erosion of cliffs, river inputs, biogenic inputs, inputs from the continental shelf, aeolian inputs and human inputs (regeneration, dumps, etc.). The major sediment sinks or losses, meanwhile, are due to: sedimentation in estuaries, ports, sedimentation on the backshore and in inland areas of the system, leakage of sediments to the continental shelf, decomposition of sand and human extraction (Ley *et al*, 2007). According to Sherman & Bauer (1993), the establishment of a coastal dune system (beach-dune) is very closely linked to the dynamics of beaches and depends on three basic factors:

1) availability of inputs of sand-sized sediments,
2) existence of winds from the sea landwards, and
3) existence of marine currents and suitable swell.

Broadly speaking, the general structure of the coastal dune systems in their natural state, according to the description by Servera (1998) for the Balearic Islands, is considered to define types of coast as it covers both the submerged and the emerged zones. A brief description of the different sub-zones is therefore given below (Fig. 1):

1) Submerged zone

In the submerged zone, the offshore sector, which is the deepest and furthest from the coastline (up to approximately -40 m) up to the point where the seagrass meadows grow, can be differentiated from the nearshore sector, which is closest to the shoreline and where sediment is continuously redistributed. It is an area of considerable dynamism and fragility, characterised by the formation of underwater bars of sediment, where processes of sediment exchange initiate in order to ensure maintenance of the beach-dune system (Komar, 1998) (Fig. 1). The origin of the sediment supply is perhaps the factor with the greatest influence on most coastal dune systems, as its continuity depends on supply not being altered by any factor at all. It is this area where processes of sediment transfer from the submerged zone to the beach constitute the main variable to be taken into account, and where most of the sources of sediment are located.

In the systems of the Mediterranean, seagrass meadows play an important role in the production of sediment, which is of biological origin in over 80% of cases (Servera, 1998; Rodríguez *et al*, 2000; Roig-Munar *et al*, 2011). The development of homoclinal coastal platforms, the absence of turbulence from river inputs and the environmental conditions allow seagrass meadows to develop (Servera, 1998; Díaz *et al*, 2009). Elsewhere on the Mediterranean coast of the Iberian Peninsula, sediment supply is largely conditioned by the inputs of rivers (Pintó *et al*, 2013; Marqués *et al*, 2011; Sanjaume and Pardo, 2011a; Barjadí *et al*, 2011). For the Mediterranean coastal dune systems near the Strait of Gibraltar, periodic exposure of tidal flats also provides a source of sediment. The dune systems located in the SW of the Iberian Peninsula and on the Bay of Biscay coast depend on fluvial origin inputs, on sedimentary prisms immersed in estuaries, on tidal flats and on the influence exerted by longshore drift currents (Gracia *et al*, 2011; Rodríguez-Ramírez, 2011; Flor *et al*, 2011). These same factors, in addition to the erosion of granitic alteration mantles and the erosion of sediments accumulated during the cold phases of the Quaternary, are the main sources of sediment for the Galician systems (Pérez-Alberti and Vázquez-Casado, 2011). In the Canary Islands, riverine inputs are limited and the main source is the erosion of coastal reliefs and packs of Pleistocene relict sediments (dunes and packs of fossil conglomerates), the erosion of rocky coasts and cliffs and, to a lesser extent, aggregates from canyons and aeolian inputs from the west coast of Africa (Criado *et al*, 2011).

2) Beach zone

The beach zone is the area most commonly frequented by the general public, particularly in the summer months, and it is where many of the management and maintenance measures are usually undertaken with a view to ensuring the beach is in good condition for the use and enjoyment of users. It is the zone in which the sedimentary balance of the submerged area with the exposed sectors (subaerial sectors) is most apparent (Woodroffe, 2002). The lower beach sector, or foreshore, and the backshore are differentiated (Fig. 1). On the foreshore, in zones with tidal regimes, in this subzone there develop tidal flats (foreshore), which are exposed to the air, flooded in alternate periods and play an important role in supplying sediment to the exposed beach zone (backshore) and to the dune system (Sanjaume *et al*, 2011). The swash area is located in this subzone. From a morphodynamic perspective, marine and aeolian processes alternate in this subzone. The backshore zone is characterised by predomination of aeolian and accumulation processes and is only affected by marine processes during exceptional wave episodes. In this subzone the first ephemeral aeolian landforms appear (embryonic dunes) with pioneer vegetation (shadow dunes, nebkas) (Servera, 1998), a feature also observed in many altered coastal dune systems and even on beaches affected by urbanisation (Pintó *et al*, 2013).

3) Foredune zone

The foredune zone is the area immediately after the backshore and the zone with the first permanent dune formations (foredunes), which are formed as sediment is transported by the wind and trapped by herbaceous vegetation (Fig. 1). Any alteration to the vegetation cover in this area can lead to its rapid destabilisation and the disappearance of the sediment, which results in blowouts (Hesp, 2002). These dune accumulations, as sediment reservoirs, can ensure the equilibrium of the beach in severe storms and when the waves reach their base, thus enabling recovery of the beach area; they also dampen the force of the wind and reduce the transport of sea spray into the system, which allows for the development of vegetation at their rear (Martínez-Taberner, 1983; Martín Prieto and Rodríguez-Perea, 1996; Servera, 1998).

4) Shifting and semi-stabilised dune zone

Between the foredune zone and the shifting and semi-stabilised dune zone there is normally a depression known as a dune slack (Ley *et al*, 2007). This area is also known as a secondary dune or grey dune zone (Fig. 1). The conditions for plant growth are more suitable and the development of vegetation allows for the production of a layer of humus, which helps the formation of soil (Ley *et al*, 2007). The size of this zone is not uniform and usually depends on the state of conservation/degradation of the foredunes, which conditions the development of different types of dune shapes (parabolic, hummock, shadow, nebkas).

5) Stabilised dune zone

This zone can also be defined as a zone of tertiary dunes or shrub and forest zone (Ley et al, 2007) (Fig. 1). The formation of edaphic soil increases as one enters further into this zone. Aeolian deflation processes are rare, and dunes (normally parabolic) are completely stabilised by vegetation. Vegetation cover is of a shrubby and arboreal nature. The supply of sand is scarce and only occurs in strong winds. Vegetation in these zones is often limited by human intervention and natural vegetation is hard to find (Ley *et al*, 2007).

There are also fields of coastal dunes that are non-vegetated because rainfall is insufficient for the development of plant cover. These are formed of dunes with morphologies similar to those that develop in desert areas with a high mobility (Ley *et al*, 2007). Mention should also be made to the influence of erosive forms in dune systems: such is the case of depressions, or blowouts, which may eventually condition the structure of the entire system (Mir-Gual, 2014) system. One clear example is the blowout of Cala Mesquida (Mallorca, Balearic Islands), which stretches up to the area of stabilised dunes. These morphology types should therefore be considered in the classification criteria for coastal dune systems.

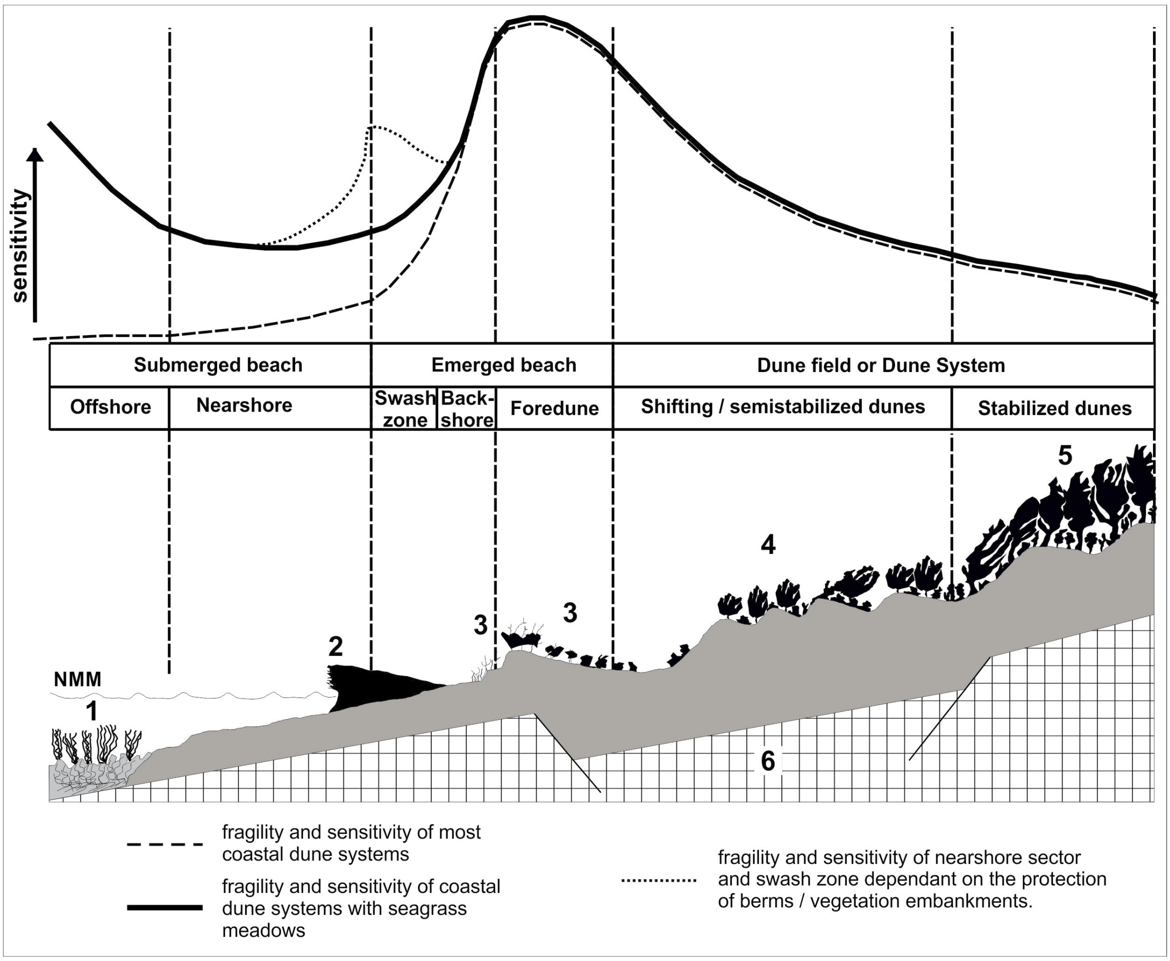

Figure 1. General diagram of coastal dune systems and their different degrees of sensitivity in accordance with the geographical area in which they develop. According to Brown and McLachlan (1990), Rodríguez-Perea et al (2000) and Roig-Munar and Martín-Prieto (2006). 1: seagrass meadows; 2: embankments/berms with vegetation formed by seagrass meadows (mainly Posidonia oceanica); 3: backshore and foredune herbaceous vegetation; 4: shrub-type vegetation; 5: arboreal-type vegetation; and 6: substrate upon which the coastal dune system develops.

4. The concept of integrition in coastal zone management

From a management perspective, the coastal zone should be understood as a space with a variety of natural (defined as those combining physical-geomorphological factors and biodiversity as a whole) and socioeconomic (resulting from human activity) factors and determinants. There follows a definition of the concepts of: 1) Integrated Coastal Zone Management, 2) Marine Spatial Planning and 3) Global Change, which are mentioned in most scientific works on coastal management (particularly on beaches and coastal dunes) and on management and planning initiatives in the coastal zone (Ley *et al*, 2007).

A brief explanation of these concepts may help to clarify the objectives pursued and their complementary nature, and assist both users of the coastal zone and managers and researchers in establishing a context for the different management plans and measures being implemented constantly along the coast and, particularly, in zones of beaches and beach-dune systems.

1) Integrated Coastal Zone Management

As its name suggests, it would be ideal for the coastal zone to be managed, insofar as possible, on the comprehensive basis of the concept of Integrated Coastal Zone Management (ICZM), also sometimes referred to as Integrated Coastal Management (ICM). ICZM is a concept in which a management process or initiative should be a continuous and dynamic process that involves: a) government institutions and social spheres, b) science and management and c) public and private interests, with a view to designing and implementing a comprehensive plan for the protection and development of coastal zone ecosystems and resources (Olsen *et al*, 1997). Cicin-Sain & Knetch (1998) specify that it should be a process involving rational decisions that take into account the conservation and sustainable use of resources and the coastal and marine area. Doménech *et al* (2010) define the concept of ICZM as a process that must be dynamic, multidisciplinary and iterative with a view to encouraging the sustainable development of coastal zones, and that must embrace the entire cycle ranging from the initial gathering of information and diagnosis to planning (in its broadest sense), decision-making, active and effective management and the monitoring of implementation. Barragán (2004) agrees with the above definitions but adds some nuances and also defines Integrated Coastal Management as an iterative process addressed to encouraging the sustainable development of coastal zones by integrating policies, objectives, strategies and sectoral plans in space and time and including the terrestrial and marine components of the coast, as an instrument of public policy based on cooperation and participation.

ICZM should not only provide a way to encourage the conservation of natural heritage and economic development, but also prove effective in solving a broad range of conflicts of uses and exploitation of resources in the coastal environment (Clark, 1997). It is a process of participation and cooperation including all parties for the evaluation of the objectives and approaches of the different stakeholders involved (economic and social) and is oriented at achieving sustainable development in the coastal zone. ICZM seeks a long-term balance of environmental, economic, social, cultural and recreational objectives within the limits established/permitted by the natural environment. It is important to note that the concept of integration refers both to the objectives established and to the tools necessary to achieve those objectives; integration should affect all levels (policy, planning, economic sectors) and terrestrial and marine spatial elements, both in time and in space. The concept of ICZM must therefore be a cyclical and ongoing process (Olsen *et al*, 1997; IOC-UNESCO, 1997) (Fig. 2).

The implementation of management plans based on ICZM is challenging, as their cyclical and comprehensive nature requires sufficient time for them to become cyclical iterative processes (Fig. 2), rather than the typical four-year terms of conventional initiatives. ICZM initiatives should not be bound by completion dates but, rather, dates should only be set for targets to be met in their different phases (Fig. 2). The concept should not be answerable to any interest other than the sustainable development of the coastal zone and should not be subject to any political, personal and economic interests that may hinder it.

2) Marine Spatial Planning

The initial steps in Marine Spatial Planning (MSP) date back 30 years. It is a practical process intended to establish a rational organisation of the marine environment and an objective balance among the different uses made of it (Ehler & Douvere, 2009). MSP should be a public process of analysis and localisation of the temporary and spatial distribution of the activities that people undertake in marine environments, with a view to meeting goals of an ecological, economic and social nature that an area or region should establish through a political process (ibid.). In coastal areas, MSP initiatives must be complemented by ICZM measures, which in many cases focus their attention more on the terrestrial environment than on the coastal zone. ICZM also requires the management of coastal resources (both in marine and terrestrial environments) to be fully integrated, just as the ecosystems that belong to these areas.

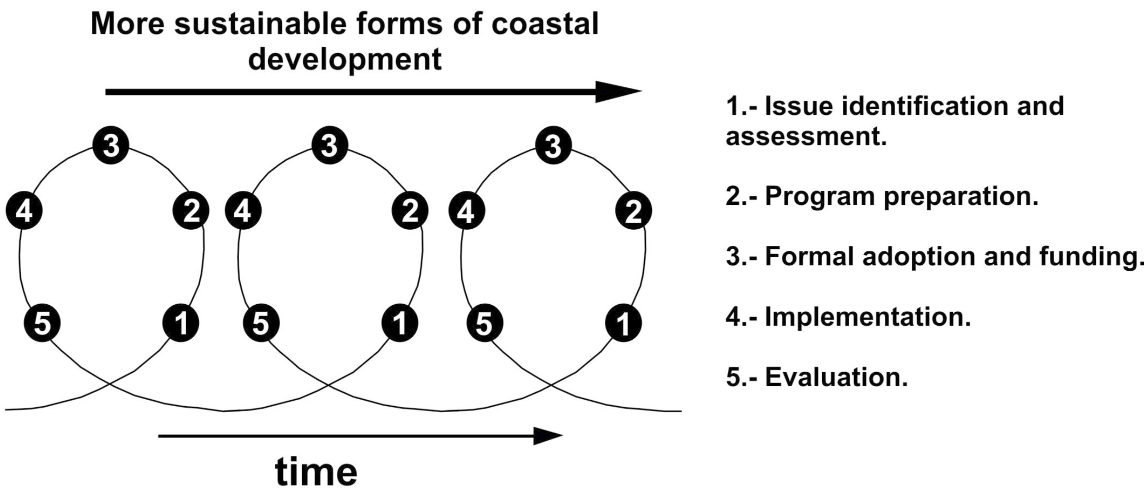

Figure 2. Continuous cycle of policies and plans in accordance with a concept of Integrated Coastal and Marine Management (ICMM). According to Olsen *et al,* 1997.

The overlapping of the zones subject to study or analysis in ICZM and MSP brings us to the term of Integrated Coastal and Marine Management (ICMM), which "officially" incorporates the marine environment in the coastal zone as a complementary and obligatorily connected element (Cicin-Sain & Belfiore, 2005). For beach-dune systems, this notion is considered essential because determinants such as the system's dynamics or the source or origin of sediment require in-depth understanding of the marine environment of the coastal zone (Fig. 1). Hence, spatial classification and rational and coherent management of coastal dune systems and the modelling agents acting thereupon require understanding of the (marine and terrestrial) areas that exert a direct influence on them.

MSP is a priority for the EU and involves some important scientific teams and groups. Achieving optimal environmental status and a sustainable use of marine ecosystems and resources are the main objectives of the European Union's Marine Environment Policy through the Marine Strategy Framework Directive (MSFD, Directive 2008/56/EC) and, retrospectively, of the Water Framework Directive (Directive 2000/60/EC) and the directives on Habitats and on Birds (Directive 1992/43/EEC and Directive 1979/403/EEC, amended in Directive 2009/147/EC, respectively). Directive 2008/56/EC (MSFD) is intended to optimise the state of the EU's marine waters, on the basis of an integrated approach and of common consensus regarding their management, with the Ecosystem Approach as a framework guide for reference. The Ecosystem Approach can be defined as an approximation involving the integrated management of resources and an acknowledgement of the connection among marine, terrestrial and atmospheric environments and all their living components (including people, economic activities and institutions). The coastal zone and, specifically, coastal dune systems (Fig. 1) represent the geographical connection among the areas under study both in MSP and in ICZM, which implies that both processes are necessarily intended to merge and to identify with one another.

3) Global Change
According to the 1990 US Global Change Research Act, "'Global Change' means changes in the global environment (including alterations in climate, land productivity, oceans or other water resources, atmospheric chemistry, and ecological systems) that may alter the capacity of the Earth to sustain life".

The coastal zone can be defined not only as a complex, but also as a fragile area, in which the fragility increases as the natural habitats of which it is formed become more unique. The fragility of coastal habitats and ecosystems and their socioeconomic fabric is evident when referring to forecasts of climate change and, consequently, global change (Ricketts, 2009).

Coastal zones, and coastal dune systems particularly, are extremely sensitive to possible future changes concerning climate inheritance and eustasy. Forecasted Global Change will influence the future of coastal zones while requiring measures of integrative management capable of bringing together all factors and processes and all authorities (as far as jurisprudence is concerned) and stakeholders. Integrated Coastal and Marine Management (ICMM) is not simply another way of managing the coastline, but rather an "essential" need that should apply to all coastal environments without exception (Ricketts, 2009).

Of all the functions of coastal dune systems, it is the defence of coastal zones that is jeopardised most by a scenario of Climate Change-induced Global Change.

5. Coastal dune systems vs. conservation and sustainable management

Coastal dune systems are contained within coastal units that transcend the boundaries of the dune systems. Management based on the concept of integration (ICMM) can therefore consider and take appropriate proactive, corrective or reactive measures if sediment sources and sinks are well known. Very often, sediment sources and sinks are altered by imbalances arising from changes that have occurred in other coastal areas and these ultimately affect the development of the coastal dune systems.

As described in previous chapters, the natural and socioeconomic significance of dune systems currently makes their management and conservation one of the main environmental priorities at national and international level (Bonnet, 1989; García de Lomas *et al*, 2011). Any study which describes and analyses a dune system helps to generate a better understanding of these systems and, therefore, assist in the design of effective and sustainable management. Greater knowledge of these systems will help to establish the origin of many of the impacts and imbalances that affect them, which will encourage a transition from management approaches focused on users to approaches focused on how the system works by integrating the highest number of factors and variables. From a theoretical perspective, management based on a concept of integration will avoid measures involving the short-term solutions (mechanised beach cleaning) that are usually implemented on urban beaches (Iribas, 2002), and will seek sustainable measures befitting natural dune systems (Jiménez and Valdemoro, 2003; Roig-Munar, 2010).

Knowledge of the beach sediment balance is essential to understand the development of coastal dune systems and this will help to determine whether the system is regressive, neutral or progradient (Ley *et al*, 2007). Proper management of coastal dune systems requires adequate knowledge of the morphodynamic processes taking place and of the impact of human action on landforms and on the stability of the systems; the ICMM concept must therefore be contemplated in any management initiative. Supplies of artificial sediment (artificial regenerations) provide extraordinary sediment input that in some cases may not be effective because of subsequent leakage of sediments on account of longshore currents and swell, if the grain diameter of the transported sand is not large enough (Medina *et al*, 2001), or it may cause seagrass meadows to be buried (Gacia and Duarte, 2001; Rodríguez *et al*, 2000), thus further compromising the supply sources of sandy sediment (of a biogenic type in this case). Seagrass meadows form part of the submerged zone of the coastal dune systems on the Mediterranean coast. Study of different impacts to which they are subjected is therefore necessary. The effect of anchors and the mooring of boats (most of which are recreational) on *Posidonia oceanica* beds represents a threat as they break up these types of bed and have an irreversible impact (Milazzo *et al*, 2004; Díaz and Marbà, 2009); management measures should therefore include regulation of anchorages through the use of fields of mooring buoys and, most importantly, campaigns to raise awareness about moorings on sand (Roig-Munar, 2003, Balaguer *et al*, 2011; Diedrich *et al*, 2013).

Spanish Coastal Law (Law 2/2013 on the protection and sustainable use of the coast and amending Law 22/1988) and subsequent amendment of its Regulations (Royal Decree 876/2014 approving the General Coastal Regulations) do not show sufficient commitment to dune systems in accordance with studies on the management of these types of coast (García de Lomas *et al*, 2011). Article 3 of the Regulations of Law 2/2013 considers coasts consisting of beaches and coastal dune systems to be part of the maritime-terrestrial public domain and includes them as coasts of the utmost importance on account of their role in natural defence. The same article defines six types of dunes: 1) developing or embryonic, 2) shifting or evolving, 3) primary, 4) secondary, 5) stabilised and 6) relict. Article 4 describes the controversial arguments of this Law insofar as coastal dune systems are concerned, and the way in which it excludes stabilised dunes and relict dunes from the maritime-terrestrial public domain (Fig. 1) on the grounds that “they are not necessary to guarantee stability of the beach and defence of the coast except in exceptional cases in which the best scientific evidence available demonstrates that a stabilised dune is necessary to guarantee the stability” of the system. From a critical perspective, Spanish Coastal Law 2/2013 can therefore be described as defining these coast types with a somewhat sectoral and not very integrative approach, as all efforts at protection are based on ensuring the existence of the beach as an element of defence, while ignoring its role as an impediment to saltwater intrusion and their functions as a reservoir of biodiversity and a source of ecosystem services. As its name indicates, this law and royal decree are intended to regulate the use and exploitation of the coast and its resources, despite the fact that their rigid definitions of different types of coast may enter into conflict with integrated and sustainable approaches to coastal management. Article 4 of the Regulations of Spanish Coastal Law 2/2013 points to a need for the performance of quality scientific studies showing that they are dynamic areas or that their preservation is essential in order to preserve the coastal dune system as a whole. Consideration of the coastal dune systems within a framework of integration would have helped in classifying all dune fields as maritime-terrestrial public domain.

The main impacts affecting the coastal dune systems further support the need for proper management of these types of coast and coastal areas in general, which should be linked to the concept of integration not only locally but also regionally (large bays, estuaries, long coastal areas highly influenced by longshore drift, subtidal zone, continental shelf, etc.). The determination of coastal zone thresholds in accordance with an integrated approach and in keeping with the ICMM has been dealt with in works like that by Balaguer *et al* (2008), which includes a proposal for a classification of the coast in Coastal Units, differentiated according to the type of land use, protection of natural areas and the types of coasts (soil, height), with determination of the areas of influence (complementary and adjacent zones) in which any factor may affect how both the coastal unit itself and nearby and even more distant units function (e.g. drainage basins that drain into the unit itself or the subtidal zone). Explanation of the main impacts and problems of management in general that affect the dune systems in accordance with Ley (2012) shows that the proper functioning of these systems depends on factors beyond their limits, and their conservation could be jeopardised both by action taken in other coastal areas of a very different nature and also by human action (e.g. building of infrastructures, dumps or moorings on seagrass meadows). The main impacts and problems of conservation affecting coastal dune systems, based on the proposals of Ley *et al* (2007), García de Lomas *et al* (2011), Sanjaume and Pardo (2011b), and Ley *et al* (2011) are:

1) Dredging of sand
   The dredging of sand, both from the submerged shelf opposite the dune system and in any nearby coastal sector can jeopardise the supply of sandy sediment that provides stability to the beach and to the foredunes. These impacts can complicate management strategies as the main input of the system may disappear and, meanwhile, threaten the seagrass meadows (as well as other habitats and ecosystems of interest) of the coastal dune systems.

2) Extraction of aggregates in the dune system
   The extraction of aggregates from the dune zone and from the beach itself for the provision of building material throughout the twentieth century has proved to be an unsuitable practice as far as conservation of the dune system is concerned, as the values of diversity and scenic uniqueness are lost while the structure of the system is changed irreversibly. Use of coastal dune systems for this purpose has historically been closely linked to a low appreciation of these spaces, which are regarded as wastelands and/or unhealthy.

3) Extraction of groundwater

The extraction of groundwater from aquifers connected to the coastal dune systems leads to salt water intrusion and causes wetlands areas located in the backshore zone (if they exist) to dry up. In such cases, the system's biodiversity and even its geomorphological stability (disappearance of vegetation and reactivation of dune migration) will become a challenge for management initiatives. Note that Spanish Coastal Law 2/2013 does not cover impact that coastal dune systems exert in "buffering" seawater intrusion.

4) Agricultural use

Transformation of the dunes into fields of crops completely changes the landscape and the geomorphic dynamics of the system. Climax vegetation is eliminated thus jeopardising the associated fauna and modifying the natural structure of the soil and the aquifer, and pesticides and fertilisers are introduced. These processes cause a loss of diversity, elimination of natural disturbances and loss of landscape value (García de Lomas, 2011).

5) Use for livestock

Grazing can lead to the disappearance of vegetation, soil compaction and cause increased erosion. All these processes give rise to a reduced capacity to intercept sand, even though controlled grazing may help to increase diversity.

6) Forest plantations

Stabilisation of coastal dune systems through forestry plantations in order to stop fields of crops being invaded by dunes has been a common process all over the world and also in Spain since the eighteenth century (Granados *et al*, 1984; García-Novo and Marín, 2005; Roig-Munar *et al*, 2009;. Mir-Gual *et al*, 2010). The arboreal vegetation introduced (usually *Pinus* sp.) causes a loss of diversity and reduces indigenous communities and species. For the authorities, these forest masses introduced are often defined as coastal forests and they are usually an obstacle that requires consideration in management initiatives seeking to restore indigenous communities.

7) Urbanisation

According to the literature consulted, the processes of urbanisation and transformation of the territory undertaken within the dune system itself not only adversely affect the urbanisation of nearby areas, but they also lead to the disappearance of natural zones associated with the system, to the detriment of the biodiversity and geomorphology of these coastal systems. Transformation of coastal zones (housing estates, ports, etc.) during the twentieth century has conditioned the existence of most coastal dune systems. The construction of ports, military defences and maritime protection structures such as dykes and breakwaters can alter currents and jeopardise the supply of sediment. As far as governance is concerned, regional planning policies (e.g. general urban development plans, subsidiary legislation, sectoral development plans) should be coordinated in order to respect these natural areas by not developing them, by attempting to maintain their values and even by helping to regenerate any that so require.

8) Recreational activities
   Coastal dune systems in our country are highly appreciated and much visited recreational areas. User excesses and breaches of instructions displayed on panels for the conservation and restoration of coastal dune systems lead to their gradual degradation. This section also includes the activities of beach maintenance and cleaning, which is considered a necessity given the large number of daily visitors, particularly during the summer months. To this end, in natural coastal dune systems the least mechanised possible techniques should be used in order not to alter the structure of the system and to prevent the leakage of sediment (Rodríguez-Perea *et al*, 2000; Roig-Munar, 2010). The building of walkways to provide users access to the beach that interfere as little as possible with dune field development, the restoration of dune slacks, the installation of barriers to trap sediment in the backshore and the foredune zone, and policies to control the mooring of boats addressed to preserving seagrass meadows are some of the general contingency measures associated with coastal dune system management plans.

9) Construction of dams and extraction of aggregates from riverbeds
   The construction of dams provides a clear example of the need to consider the concept of coastal zone integration in river basin planning policies. Dam-building and the extraction of aggregates from the riverbed generate changes in the transport of aggregates from drainage basins, a fact that has jeopardised numerous beach and beach-dune systems as the supply of sediment ends. The coordination of initiatives to manage coastal dune systems with water policies (which are necessarily of general interest) is certainly one of the most sensitive issues on coasts where sediment supply depends on river inputs. The decrease in sediment supply from river systems may also be due to a decline in rainfall, associated with climate change. S'Abanell beach (Blanes, Catalonia) is a good example, as it has almost disappeared on account of the elimination of the dune system resulting from urbanisation processes and a decrease in sediment supply from the Tordera River (Sardá *et al*, 2013).

In conclusion, management of coastal dune systems should be based on integrative initiatives and should very often feature consideration not only of the coastal zone but also of any activity or initiative in the territory that may impact this zone. Coordination and adaptation of territorial development policies are required to ensure the integrated management of these systems, both in space and in time, and to determine the ecosystems and habitats that may be affected in order to guarantee their sustainability over time, to maintain their essential characteristics, to prompt a good state of conservation and to guarantee the coast's function as a natural defence against climate change.

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