Exploring Flora as a Nature-Based Solution to Combat Beach Erosion in the Cádiz Province

By
Veronica Crispin Garcia
Filippo Marcantoni
Olivia Spielberger
Anthony Titcombe

Exploring Flora as a Nature-Based Solution to Combat Beach Erosion in the Cádiz Province

An Interactive Qualifying Project
Submitted to the Faculty of
WORCESTER POLYTECHNIC INSTITUTE
In partial fulfillment of the requirements for the
Degree of Bachelor of Science

By
Veronica Crispin Garcia
Filippo Marcantoni
Olivia Spielberger
Anthony Titcombe

Date: 04/29/2024

Abstract

Cádiz province faces increasing beach erosion resulting from climate change and human construction. This report explored using native, sand-binding flora as a nature-based solution to combat erosion on four beaches. We investigated the current coastal practices and flora presence through archival research, stakeholder interviews, and transect walks. A comparison of four beaches' dune system characteristics and protection techniques yielded targeted recommendations of suitable floras and dune protection measures necessary for local agencies to protect their treasured beaches.

Acknowledgments

We would like to thank everyone who made our report possible. Special thanks to our University of Cádiz sponsors, Dr. Antonio Contreras de Villar, Dr. Juan J. Muñoz Pérez, and Dr. Francisco Contreras de Villar. We appreciate the time and effort you dedicated to the success of our project. We especially want to thank our advisors from Worcester Polytechnic Institution, Professor Kira Kovnat and Professor Nikitina Svetlana. Their time, unparalleled guidance, and attention were instrumental to our paper's success. We would additionally like to thank our interviewees for their time and collaboration. From the University of Cádiz:

- Professor Ignacio Hernández
- Professor Fernando Ojeda
- Professor Giorgio Anfuso

Our team would also like to thank our interviewees from various environmental and coastal management agencies for providing helpful insight into these perspectives on mitigating beach erosion and the realities of using flora to curb beach erosion.

- Carlos Ley of Ecología Litoral
- Jurgi Areizaga of Tecnoambiente
- Patricio Poulett of Demarcación de Costas de Atlántico-Andalucía

Finally, we would like to thank Worcester Polytechnic Institute and the University of Cádiz for their support and fruitful collaboration, which gave us the support we needed for this paper's success.

Authorship

Veronica Crispin, Filippo Marcantoni, Olivia Spielberger, and Anthony Titcombe researched and wrote this report. All participants made key contributions to and from this project. The report was written according to the following outline.

Section in Paper	Primary Writer(s)
Introduction: The Challenge Facing Cádiz Province	All
Sponsor Contributions	V. Crispin
Study Sites in the Cádiz Province	F. Marcantoni & O. Spielberger
Background: Rationale of Beach Erosion and its Natural Solutions	All
Context and Causes of Beach Erosion	All
Impacts of Climate Change on Beach Erosion	F. Marcantoni & O. Spielberger
Beaches and Wave Action	F. Marcantoni
Destructive Consequences of Human Activity on Beach Erosion	A. Titcombe
Impacts of Dunes on Beach Erosion in the Cádiz Province	V. Crispin
Coastal Management Practices	F. Marcantoni
Flora as a Nature-based Solution	O. Spielberger & A. Titcombe
Defining Nature-based Solutions	A. Titcombe
Role of Coastal Flora in Beach Protection	A. Titcombe
Relevant Flora in the Study Sites	O. Spielberger
Existing Projects in Using Flora as an Nature-based Solutions	A. Titcombe
Methodology: Using Flora as an Nature-based Solutions	All
Introduction	All

Justification of Study Sites	F. Marcantoni & O. Spielberger
Data Collection Methods	All
Interviews with Stakeholders	V. Crispin & A. Titcombe
Granularity Tests	V. Crispin & O. Spielberger
Transect Walks and Flora Comparison	F. Marcantoni & O. Spielberger
Results	All
Thematic Code Analysis from Interviews	V. Crispin & A. Titcombe
Insights from Transect Walk: A Thematic Analysis	F. Marcantoni & O. Spielberger
Sand Granularity Test Findings	O. Spielberger
Discussion	All
Analyzing Stakeholder Perspectives: Insights from Interviews	V. Crispin & A. Titcombe
Discussion of Transect Walk Observations	F. Marcantoni & O. Spielberger
Granularity Testing: Implications and Insights	F. Marcantoni & O. Spielberger
Conclusions and Future Considerations	All
Beach Protection Targeted Recommendations	All

Table of Contents

List of Figures

List of Tables

1.0 Introduction: The Challenge Facing the Cádiz Province

The Cádiz coast faces a growing threat of beach erosion. Beach erosion occurs when the rate of sediment loss outweighs sediment gain (Prieto-Campos et al., 2018). This complex issue, driven by natural processes like wind and wave action and exacerbated by human activities, is further intensified by climate change. Rising sea levels and intensifying storms contribute to coastal flooding and erosion, jeopardizing ecosystems, infrastructure, and the very livelihoods of coastal communities. Within the province of Cádiz, the coastal town of Algeciras serves as a stark reminder of these consequences. Two beaches, El Chorruelo and Los Ladrillos, have already been lost, and Playa El Rinconcillo is at risk of facing a similar fate due to human port expansion efforts (Pérez, 2020).

The disappearance of beaches has significant environmental and economic consequences. It disrupts coastal ecosystems, leading to the loss of habitat for various species of flora and fauna. As a result, marine life is negatively affected, and biodiversity is lost. Beaches in the Cádiz province are crucial for tourism and are a prominent local economy driver. Their loss will decrease tourism revenue, impacting businesses that rely on beach visitors. Humans have advanced beach erosion with destructive residential housing and port structure expansions. Houses are being built directly on the beaches of Playa El Rinconcillo and Playa de El Palmar, tightening the available area to the shore (Domínguez et al., 2007).

Plant life protects sandy coastlines and offers a natural defense against storms and flooding. However, climate change and coastal development significantly threaten coastal biodiversity, diminishing this vital protection (Feagin, R. A., 2019). Preserving beaches in the Cádiz province is essential for sustainable tourism, maintaining a healthy ecosystem, and safeguarding the region's natural beauty and cultural heritage.

Our sponsors were Professors from the University of Cádiz: Dr. Antonio Contreras de Villar (area of Hydraulics Engineering) and Dr. Francisco Contreras de Villar (area of Transport Engineering and Infrastructure) from the Faculty of Civil and Industrial Engineering in the Campus of Algeciras, and Dr. Juan J. Muñoz Pérez (area of Coastal Engineering) from the Campus of Puerto Real. People interested in our project topic span from environmental agencies to coastal management agencies. The stakeholders assisting with the project's focus include professors from the University of Cádiz, such as Professor Fernando Ojeda, Professor Ignacio Hernández, Professor Giorgio Anfuso, and Professor Antonio Contreas de Villar. In addition, Carlos Ley of Ecología Litoral and Jurgi Areizaga of Tecnoambiente expressed interest in our investigative findings.

This project explored the feasibility of using flora as a nature-based solution to combat beach erosion in the Cádiz province. By investigating how flora can be utilized effectively, this project:

1. Identified current coastal management practices and policies used to address beach erosion: Conducted interviews, established relevant individuals interested in our project findings, and assessed the limitations of these practices to integrate the use of nature-based solutions.
2. Evaluated the similarities in morphological conditions of the study sites of Playa de Bolonia, Playa de Getares, Playa de El Palmar, and Playa El Rinconcillo: Conducted lab

granularity tests to understand beach morphology, erosion patterns, and habitat suitability for various plant species.

3. Executed a comparative study of coastal flora species for dune protection characteristics (such as deep stem and root networks, nativeness, and maturation rate) within the study sites to identify how specific flora and their abundance can combat beach erosion and assess the dune conditions.

These objectives helped our team analyze the beach's health to design practical beach protection strategy recommendations that used flora as a nature-based solution as a final deliverable. This beach protection outline included specific guidelines for preserving two of the most eroded beaches studied and discussed species presence and effectiveness of using this flora as a nature-based solution. The project developed on-site informative signage for the Playa de El Palmar and Playa El Rinconcillo to promote awareness of the beaches' ecosystem to the general public. These informative signage provides information about species identification and their importance in protecting dune systems, briefly explaining how dunes are essential to combat beach erosion. We provided the informative signage and outline to ecological companies with the idea of making targeted recommendations that would help their efforts in protecting these beaches.

1.1 Sponsor Contributions

Dr. Antonio Contreras de Villar is a professor from the University of Cádiz specializing in hydraulics engineering. He is a Doctor from the University de Cádiz with the thesis "Design Parameters for the Contribution Profile in Beach Regenerations, in tidal seas, based on field data from the Cádiz Coast" which is based on the collection of beach profile data on the coast of the province of Cádiz, to analyze said data and proposing new formulations on the design parameters of the equilibrium profile, application, for future beach regeneration projects on sand coastlines (A. Contreras de Villar, 2017). Dr. A. Contreras was the primary sponsor for this project. He played a crucial role in the project's execution by assisting the team in several key areas. Dr. A. Contreras supported study site justification and selection, ensuring the team had a solid foundation for their research.

Additionally, he conducted granularity tests in the lab, contributing valuable data to the project's analysis. He led transect walks during fieldwork, offering expertise to guide the team's data collection efforts. Moreover, he shared his knowledge through lectures on wave action and beach erosion mechanisms, enriching the team's understanding of the subject matter. His multifaceted contributions were instrumental in advancing the project towards its objectives.

Dr. Juan José Muñoz Pérez is a professor from the University of Cádiz affiliated with the Coastal Engineering research group. He is a Doctor from the University de Cádiz with the thesis "Analysis of the morphology and variability of beaches supported by rocky slabs," which aims to address the existing knowledge deficit about the profiles of beaches that have their feet on rock slabs (Muñoz Perez JJ,1997). Dr. Muñoz contributed to putting our team in contact with different stakeholders to help fulfill the project's first objective.

Dr. Francisco Contreras de Villar is a Doctor from the University de Málaga with the thesis "Validation of electric arc furnace slag through its use as an addition in concrete" (F. Contreras de Villar, Francisco, 2017). Dr. F. Contreras played a pivotal role in refining and solidifying our project plan and strategy. His expertise was instrumental in shaping our methods and guiding us toward achieving our desired outcomes. His contributions ensured that our project remained on track and aligned with our goals, ultimately leading to a successful implementation and realization of our objectives.

1.2 Study Sites in the Cádiz Province

The investigation of four beaches with varying levels of erosion along the Cádiz province coast will provide a complete study of their state and how erosion can best be prevented and combatted. These beaches were chosen due to their similar coastal settings and contrasting stabilities. The beaches include Playa El Rinconcillo and Playa de Getares on the eastern coast and Playa de Bolonia and Playa de El Palmar on the western coast, with the coasts' erosion rates shown in Figure 1.

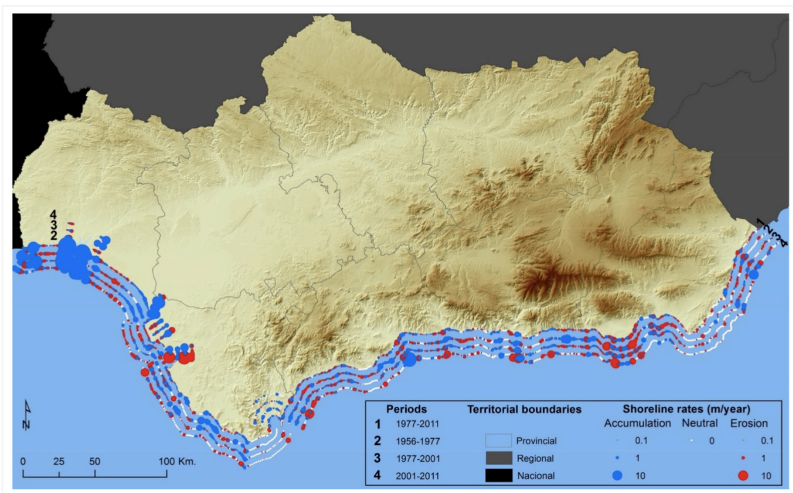


Figure 1. Erosion rates map of the Andalusian coast.
(Prieto-Campos et al., 2018).

Playa El Rinconcillo, located in the Bay of Algeciras, provides an extreme case of beach erosion. The industrial city of Algeciras, which has an expansive port area, has already suffered the loss of two beaches, El Chorruelo, and Los Ladrillos, and it is currently suffering the loss of Playa El Rinconcillo. This has caused a public uprising championed by 'Salvemos Rinconcillo', a group of concerned locals and ecologists. Their publications convey that the beach is continuously battling changes in coastal dynamics dating back 20 years. Rinconcillo is also home to a bunker, which once was about 80 meters from the shore but is now in the sea throughout the tide, displaying the recent erosion (Pérez, 2020).

Playa de Getares stands before the port in the Bay of Algeciras. Due to its location, it is not subjected to the later diffraction caused by the port's presence and, therefore, is an example of a stable beach. When the beach is subjected to storms and rains, the southern Picaro River opens up, causing minor erosion. This seasonal process is not concerning, as the river restores itself during summer. Vegetative dunes are present throughout the southern backshore, with typical flora and fauna (A. Contreras de Villar, Personal Communication, 2024).

Among the most recognized beaches in the Cádiz province is the Playa de Bolonia, Tarifa. The Bolonia Dunes were declared a Natural Monument in 2021, serving as a crucial element within the beach ecosystem due to its multifaceted roles and contributions. This stable beach is an exceptional example of natural and dynamic dune systems. It hosts a large population of pollinators, making fauna and flora health valuable for all living and nonliving aspects of the ecosystem and locals (F. Ojeda, Personal Communication, 2024).

Playa de El Palmar is a site with acute erosion on the western coast caused by storm wave action and the easterly Levante winds. Playa de El Palmar has been facing increased erosion in the Torre Nueva area due to house development and tourist activities, where environmental recovery and protection of the dune system have become necessary. With its length of approximately 8 kilometers and an average width of 80 meters, this beach is distinguished for its fine, golden sand and full dune systems, which require further protection from human development (A. Contreras de Villar, Personal Communication, 2024).All beaches are illustrated on Figure 2.

Based on the different coastal settings, the study sites on the west coast are more affected by easterly Levante winds, which heavily influence sediment transport; meanwhile, the east coast is affected by westerly Poniente winds, which are more significant in wave generation. Despite being in different coastal settings and erosion conditions, the four study sites exhibited similar morphological factors such as similar bathymetry conditions, sediment types, typologies, and types of beaches across coasts, which are discussed in depth in section 3.1.1.

Figure 2. Shows each of the study sites. Playa de Bolonia, Playa de Getares, Playa de El Palmar, and Playa El Rinconcillo.

This section further justifies the selection of these beaches due to their similarities and differences. The most valued characteristics include the beach erosion rate, beach types and typologies, established beach protection measures, geographic location, vegetation, human development presence, and sand type. The selected beaches differ greatly in these regards to provide for a compelling comparative study.

2.0 Background: Rationale of Beach Erosion and its Natural Solutions

2.1 Context and Causes of Beach Erosion

2.1.1 Impacts of Climate Change on Beach Erosion

Climate change casts a long shadow over coastal communities worldwide, including Cádiz. Greenhouse gases cause ocean temperatures to rise, resulting in rising sea levels, which threatens marine life and disrupts coastal ecosystems (The Climate Reality Project, 2019). This direct correlation intensifies storm frequencies and wave heights, increasing coastal flooding and beach erosion (Environmental Protection Agency, 2021).

Storms are an essential natural factor in shoreline erosion because they trigger beach flattening, erosion escarpments on beaches and dunes, and overwash processes (Cooper et al., 2004). Increased storm frequencies are not the only natural factors influencing shoreline evolution. Consistent factors, such as winds, waves, and coastal settings, are crucial in shoreline changes. Easterly Levante winds heavily influence sediment transport, while westerly Poniente winds are significant in wave generation, especially during winter storm conditions. Coastal settings, including nearshore coastal orientation and bathymetry, which study water bodies and their depths, also shape shoreline evolution (Benavente et al., 2005a).

Climate change projections indicate extensive and potentially catastrophic risks for the Spanish ecosystems and economy. This continuous receding of beaches would disrupt coastal ecosystems, causing the loss of the natural habitat for various species of flora and fauna. Beaches in the Cádiz province have significant tourism and economic value, and the loss of these would decrease tourism revenue, impacting businesses that rely on beach visitors (Pérez, 2020).

2.1.2 Beaches and Wave Action

Wave action has a crucial role in beach creation and erosion. Beaches result from atmospheric pressures and sediment transport through waves and wind. Wave action influences the geometry and composition of beaches, providing energy for beach conformation and sediment distribution (LSU Center for GeoInformatics, 2011). Understanding the waves' mechanisms is essential for studying beaches and coastal morphology.

Influenced significantly by wind and temperature, wave action plays a crucial role in shaping coastlines and sediment transport. Sand moves dynamically along a beach through a process referred to as longshore drift. The angle of the current and directionality of waves cause the net movement of sand to be dragged back and forth, flowing downstream along the coastline, illustrated in Figure 3. Additionally, all beaches within the Cádiz province have different conditions throughout the seasons. The powerful winter waves erode sand from the beach's slope, depositing it offshore as sandbars, a process that is exaggerated during storm occurrences. In contrast, summer waves are smaller and carry less energy, migrate these built sandbars and restore the beach's slope. This cycle is the leading cause of alterations within the coastline (LSU Center for GeoInformatics, 2011).

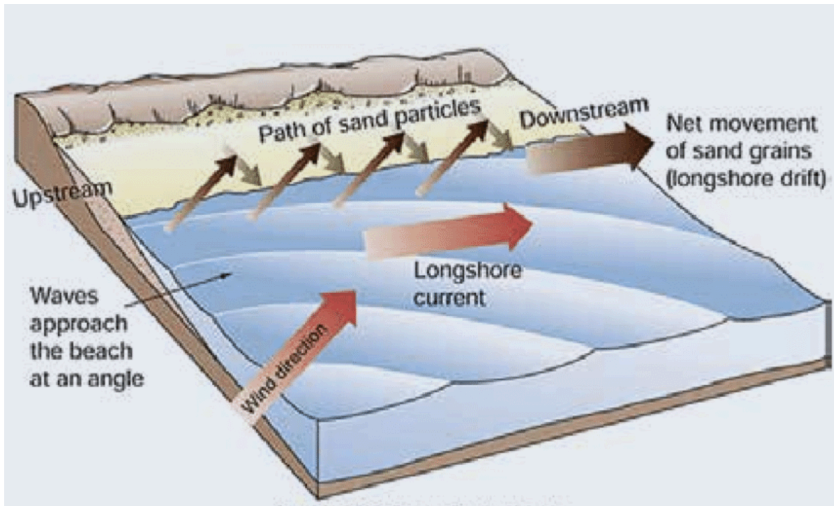


Figure 3. Longshore Current and Transport
Reproduced with permission (Reguero, 2014).

One major factor in designing beach morphology is refraction. Refraction occurs when waves approach the shoreline at an angle and align the wavefront in shallow water, matching the beach's profile, as depicted in Figure 4. This has a decisive influence on wave height and energy distribution, as well as altering the bathymetry (LSU Center for GeoInformatics, 2011).

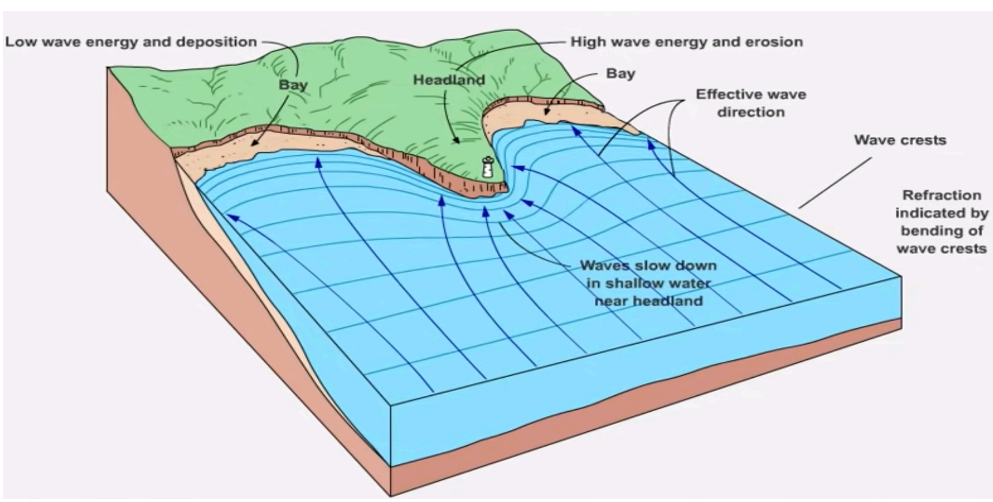


Figure 4. Wave Refraction
Reproduced with permission (Meldahl, 2011).

Another wave phenomenon to consider when studying beaches and coastal morphology is diffraction. Diffraction occurs when the tide hits an obstacle, causing a reflex effect that generates a curve, as shown in Figure 5. This phenomenon is fundamental when looking at beaches with coastal structures, particularly around the Bay of Algeciras, as it is the leading cause of the loss of two beaches and the intensive beach erosion in Playa El Rinconcillo (LSU Center for GeoInformatics, 2011).

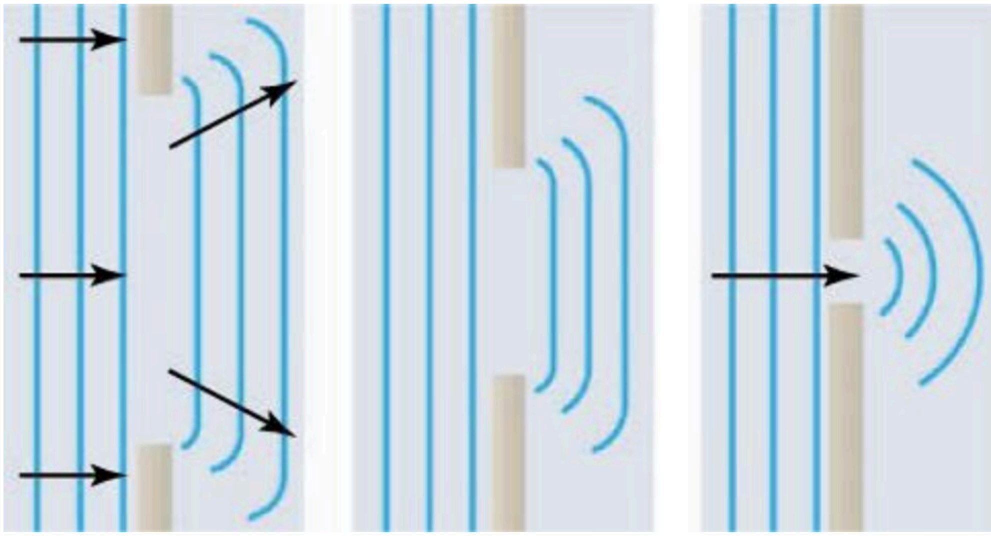


Figure 5. Wave Diffraction.
Reproduced with permission (Texas Gateway, 2024).

2.1.3 Destructive Consequences of Human Activity on Beach Erosion

Coastal erosion is a complex issue with a long history (Davis, 2019). In Cádiz, human activities mirror a global trend, exacerbating natural erosion processes at Playa El Rinconcillo. Disruptions to natural sediment flow and wave patterns are key culprits, often stemming from port development projects and residential growth (Hapke, 2013).

A prime example of human impact lies in the bustling Port of Algeciras, Spain's second-largest port, which handles millions of cargo containers (TEUs) annually(APBA, 2023). However, extensive dredging and expansion to accommodate these behemoths are costly. Disruptions to natural sediment patterns are significant. For instance, the Juan Carlos terminal project caused sand accumulation on Playa El Rinconcillo's south side due to wave diffraction, while the north side experienced severe erosion (Dempwolff, 2022). This highlights the delicate balance between economic development and environmental sustainability.

Residential development on beaches further exacerbates erosion. A 2007 study documented that increased settlements across Cádiz beaches, like Playa El Rinconcillo and Playa de El Palmar, heighten shoreline vulnerability by disrupting sediment transport (Domínguez et al., 2007). Insufficient sediment deposition leaves the beach vulnerable to erosion by natural wave action and tidal currents (Komar, 1998). These human structures can amplify the effects of climate change and rising sea levels. Notably, Spain's Ministry for the Ecological Transition and the Territorial Challenge (MITECO) suggests human structures in Cádiz might have a greater impact on sediment alteration than climate change alone (MITECO, n.d.).

Our study was crucial in recognizing the significant role of human activity in Playa El Rinconcillo's erosion patterns. We assessed the effectiveness of existing flora in mitigating erosion caused specifically by human activities and developed targeted recommendations. This two-pronged approach acknowledges the historical context and focuses on solutions that address the ongoing challenges.

2.1.4 Impacts of Dunes on Beach Erosion in the Cádiz Province

Dunes are mounds of sand formed by the wind, usually along the beach or in a desert (National Geographic, n.d.). These protect natural coastal areas against storm surges and powerful waves, preventing or reducing coastal flooding and structural damage. They are situated right behind the beach and host the coastal vegetation. These systems also provide vital ecological habitats, contributing to beach health. Beaches and dunes are integral parts of a dynamic cycle in which sand is constantly exchanged. Dunes also act as sand storage areas, supplying sand to eroded beaches. Preserving dune systems helps protect coastal stability, especially in areas with low or moderate erosion (UConn et al.,1977).

The evolution of the Cádiz coast's dune systems is highly conditioned by the meteorological and climatic factors prevailing in the area (Garcia, 2011). The dunes that border this province's landscape also serve an invaluable purpose, as they absorb the impact of high-energy storms and delay the intrusion of waters into inland areas (Gregorio Gómez-Pina, 2022).

The Bolonia Dune, exhibited in Figure 6, exemplifies a well-preserved dune ecosystem. It maintains ecological balance and provides a habitat for a diverse formation of plant species, many specially adapted to thrive in the harsh conditions of sandy environments. These plants, such as pine trees and beach grasses, help stabilize the dune structure by trapping sand with their roots and preventing it from being washed away by wind or water (Junta et al.) (A. et al., 1999).

Figure 6. View of Bolonia Dune.

However, not all dunes in Cádiz share the same fate. The dune system in Playa El Rinconcillo, once situated at a safe distance from the shore, is now rapidly eroding. Experts caution that their ecological significance and crucial role in safeguarding the Palmones River marshes are being exhausted. Carmen Fajardo, a professor and member of the Institute of Campo Gibraltarian Studies and the Cádiz Society of Natural History, expresses deep concern "[that] the current state of the dunes is alarming". She stresses that "recent storm activity is leading to the degradation of this dune system, resulting in reduced sand volume, surface area, and height in certain regions" (Las dunas de El Rinconcillo, en peligro, 2020).

Neglecting dune preservation will aggravate beach erosion, with harsh consequences for coastal environments and communities. Loss of dunes increases coastal vulnerability to storms, diminishes vital habitats, and threatens economic stability through property devaluation and loss of livelihoods. Understanding the intricate relationship between dunes, beaches, and coastal dynamics was the foundation of our project. It explored flora and nature-based solutions for erosion mitigation across key beaches like Playa de El Palmar, Playa de Getares, Playa El Rinconcillo, and Playa de Bolonia.

2.1.5 Coastal Management Practices

The Cádiz province faces a crucial challenge in balancing essential urban development with the need to safeguard beach ecosystems. Dr. Muñoz Pérez authored strategies for achieving these balances in a research analysis report. The strategies identified and implemented are divided into three categories: social and institutional prevention, physical and structural prevention, which includes most known nature-based solutions, and coastal protection recovery and review. Social measures involve improving information and public awareness through hazard mapping and coastal erosion monitoring. Physical methods aim to restore natural processes like sediment management and dune system maintenance through vegetation replanting. Our team's on-site lecture with Professor Giorgio Anfusa at the Playa de Camposoto provided valuable insights into dune morphology. Professor Anfusa explained that the primary protection measures for dune systems include dune signage, dune protection fences, sand trap fences, and walkovers, considered soft structures. These structures play a crucial role in dune preservation by discouraging foot traffic through physical barriers and increasing public awareness. Sand trap fences are structures limiting the movement of sediment by wind. These fences trap sediment, promoting sand accumulation and contributing to the dunes' health (G. Anfusa, Personal Communication, 2024).

Recovery efforts focus on restoring affected eroded areas and analyzing the root causes to prevent future damage. These strategies were successfully implemented in the Cádiz province and neighboring provinces of Málaga and Almería (Munoz Perez et al., 2021). The approach emphasized the correlation between beach erosion and flora, advocating for nature-based solutions like vegetation replanting and dune system maintenance to mitigate erosion impacts.

2.2 Flora as a Nature-based Solution

2.2.1 Defining Nature-based Solutions

Nature-based solutions (NBS) offer a promising approach to addressing environmental and societal challenges in the Cádiz province. As defined by the International Union for Conservation of Nature, NBS involves protecting, restoring, and sustainably managing natural and modified ecosystems to provide simultaneous benefits for people and the environment (IUCN, 2023). Some examples of nature-based solutions include profile recontouring and stabilizing dunes with vegetation (Washington State Aquatic Habitat, n.d). In the context of Cádiz, NBS can be employed to address pressing issues of coastal erosion and biodiversity loss and promote sustainable development.

A key strength of NBS lies in its ability to leverage the natural functions of ecosystems to solve environmental problems. Dunes, for example, naturally absorb wave energy, offering a defense against coastal erosion while providing critical habitat for diverse plant and animal species (World Bank, 2022). This highlights the multi-beneficial nature of NBS, where a single intervention can address multiple challenges simultaneously.

Flora is a nature-based solution necessary for dune stabilization. Our project explored its use as an erosion curber, essential for aligning beach protection and ecological balance (The Nature-Based Solutions Initiative, n.d.). Potential users of our recommendation of this solution are environmental agencies, such as Tecnoambiente, which focus their efforts on maintaining ecologically balanced beaches.

2.2.2 Role of Coastal Flora in Beach Protection

In the Cádiz province, where human development, climate change, and other natural factors put pressure on beaches, coastal flora plays a vital role in beach protection (Davis, J.H., 1975; Van Loon-Steensma et al., 2017). The flora provides ecosystem balance and fortification to the soil through their intrinsic properties. The coastal plants' properties on dunes include an extended network of roots, stem strength and height, and leaf characteristics.

Coastal floras are crucial for dune stabilization. Research has proven that coastal flora can increase the resilience of the dune systems. In a 2014 pilot study, Jacob B. Sigren ran streams of water for 45 seconds with constant velocity configurations through soils with and without *Sporobolus virginicus*, a perennial dune grass. Results showed that the shear strength of matured roots to withstand the velocity in soil was significantly higher compared to bare soil, as shown in Figure 7. The reason for this is that the anchoring ability of coastal plants lies within their extensive and complex root networks that grip individual sand particles, binding them together. This intricate web acts like a natural geotextile, preventing wind erosion and resisting the shearing forces exerted by waves during storms (Bertoni et al., 2019).

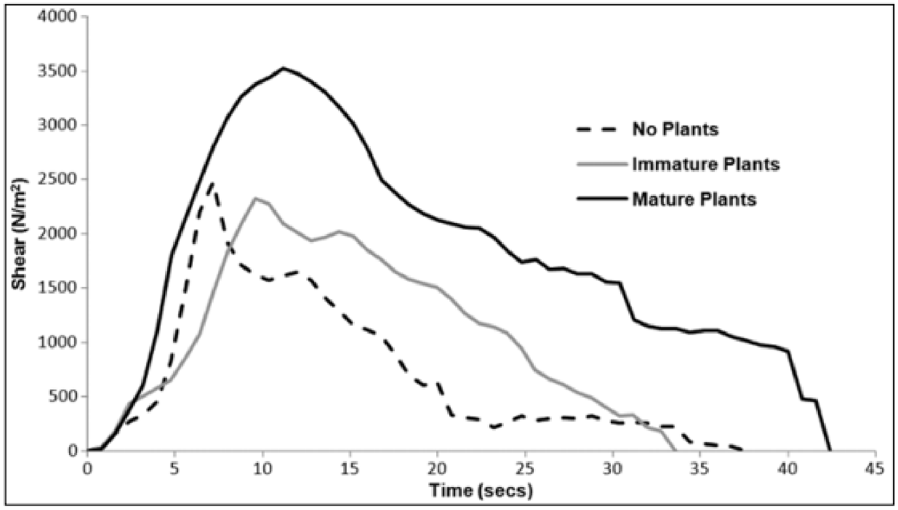


Figure 7. Soils containing varying levels of *Sporobulus virginicus* growing in dunes are subjected to constant velocity (Sigren Jacob, 2014).

Additionally, coastal floras enrich the soil organic matter by decomposing their leaves, stems, and roots. This organic material provides essential nutrients for various soil organisms, fostering a diverse and thriving microbial community. These organisms further break down the organic matter, releasing vital nutrients like nitrogen, phosphorus, and potassium in forms readily available for plant uptake (Lodha, 2012). Organic matter plays a crucial role in soil aggregation, the process by which individual soil particles clump together to form larger structures. This aggregation improves both soil aeration and water-holding capacity, creating a more favorable environment for plant growth and enhancing the soil's resistance to erosion from wind and wave currents (Merckx et al., 2001).

By understanding the valuable role of coastal flora, our team used them effectively when suggesting practices to protect the study sites in the Cádiz province.

2.2.3 Relevant Flora in The Study Sites

Cádiz is a unique province as two water bodies meet at the Strait of Gibraltar, producing substantial biodiversity. The flora found along these coasts includes both terrestrial and marine vegetation. Of our study sites, both floras have essential contributions to beach health and beach erosion mitigation (I. Hernández, Personal Communication, 2024).

Terrestrial floras are critical to stabilizing dynamic dune systems. Pioneer plants refer to the plants that stand at the foot of the dune, which are essential in stabilizing dunes and facilitating the growth of other plants. A common pioneer beachgrass species on our team's study sites is *Ammophila arenaria*, which stabilizes dune formations and facilitates the growth of other plants within the dune environment. This species is most used in restoration projects because of its ideal characteristics, such as root networks and long stems (GISD, 2010). Another pioneer species on the study sites' dunes is *Pancratium maritimum*, a plant that plays a crucial role in the accretion of sand and supporting other life within the ecosystem, such as shelter and food (*Sand Dunes*, 2024).

Marine vegetation, specifically seagrasses, stabilize subaqueous or underwater dunes in addition to slowing wave speeds. Extensive research by the International Union for Conservation of Nature has been done on the seagrass species *Posidonia oceanica*. Endemic to the Mediterranean region, these beds reduce the speed and strength of waves by about 70%, helping to prevent destructive flooding events. Neptune Grass also has remarkable carbon-sequestering properties, estimated to conceal 10% to 40% of the Mediterranean's greenhouse gases since the Industrial Revolution (Interreg Mediterranean). The realities of using seagrasses as a nature-based solution, such as *Posidonia oceanica*, are powerful but still require more research until they are feasible. It is challenging and tedious due to its slow maturation rate and highly specific implementation techniques and conditions, such as temperature, salinity, and wave movement speeds (I. Hernández, Personal Communication, 2024).

Identifying and researching terrestrial and marine plant species on each study site was necessary because knowing each plant's seasonal growth patterns and environmental contributions helps to maintain the ecosystem and dune health. Some important guiding points to better understand the feasibility of using these species as nature-based solutions are their dune protection characteristics, such as deep root and stem networks, whether they are invasive or native to the beach, their rate of maturation, and how they may affect the location's fauna (I. Hernández, Personal Communication, 2024). This data told the group which plants would thrive in the specific environment and the best strategies for a potential restoration project.

2.2.4 Existing Projects on Using Flora as a Nature-based Solution

A past project that effectively utilized flora for restoration was the *Elymus farctus* restoration in North Brittany, France. The flourishing dunes of North Brittany accounted for 13% of its coast until mass depletion by the mid-20th century. This was mainly because nature preservation methods needed to match increased development. Overgrazing by sheep and unsustainable sand extraction prevented the growth of stabilizing vegetation, leaving the dunes and their coastal flora vulnerable to windblown sand erosion. Increased tourism added to the problem because it brought uncontrolled foot traffic and recreational activities that compounded the erosion (Roze, 2004).

The consequences were evident as dunes lost up to 80% of their height and volume, jeopardizing their ability to shield inland areas from storm surges and flooding. This erosion also negatively impacted the region's ecological health, as degraded dunes offered limited habitat for coastal wildlife (Roze, 2004).

Restoration projects were initiated in the 1970s in response to this critical situation. These projects embraced a nature-based solution, focusing on planting native *Elymus farctus*. Its long, sand-trapping stems and rhizomes capture windblown sand particles, promoting dune formation. *Elymus farctus* is readily available in nature, and its fast-growing characteristics make it a cost-effective option for large-scale restoration efforts (Roze, 2004).

The restoration efforts employed various techniques, including direct seeding of *Elymus farctus* following specific patterns to maximize sand trapping. In some cases, pre-grown seedlings or "plugs" were planted to accelerate the establishment of the grass cover. Temporary fencing was often installed to protect newly planted areas, restrict public access, and allow the grass to settle (Roze, 2004).

These efforts yielded significant and measurable improvements. Planting *Elymus farctus* reduced erosion rates by up to 70-80% compared to unplanted areas. The dunes regained their natural form, with documented increases in height and volume in various locations. This enhanced coastal protection, as the restored dunes improved protection against storm surges and flooding, safeguarding inland areas and infrastructure. Roze's continuous study monitoring of the dunes confirmed that the re-accumulation of sand post-flora planting efforts resulted in a 2-meter increase in the rear face of the dune (Roze, 2004).

The North Brittany study highlighted the effectiveness of stabilizing dunes with nature-based solutions and restoring ecological functions while emphasizing the need for ongoing monitoring in the face of evolving environmental pressures. Our team valued these methods and reinforced the project's beach protection efforts with soft structures such as grass planting, fencing, signage, and walkovers.

3.0 Methodology: Flora as a Nature-based Solution

3.1 Introduction

Our project explored the feasibility of using flora as a way of combating beach erosion processes on four beaches on the Cádiz province's coast: Playa El Palmar, Playa de Getares, Playa El Rinconcillo, and Playa Bolonia. With this focus, the team established the following objectives to guide our research:

- Identified current coastal management practices and policies used to address beach erosion. We conducted stakeholder interviews to understand existing approaches to beach erosion management and their limitations and explore potential opportunities for integrating flora as nature-based solutions.
- Evaluated the similarities and differences in morphological conditions of the Playa de Bolonia, Playa de Getares, Playa de El Palmar, and Playa El Rinconcillo study sites. We obtained sand samples from study sites and conducted granularity tests in labs to understand beach morphology, erosion patterns, habitat suitability for various plant species, and the feasibility of our comparative study.
- Executed a comparative study of present coastal flora species for dune protection characteristics, such as deep stem and root networks, nativeness, and maturation rates, within the study sites to identify how specific flora and their abundance can combat beach erosion. We conducted transect walks across the study site to document the presence and abundance of existing plant species, assess their suitability, and evaluate the beach morphology for nature-based solutions applications.

These objectives helped our team identify strategies to incorporate nature-based solutions, assess their feasibility and limitations around current coastal management practices, and design a beach protection plan outline for preserving the unstable beaches in our study sites as a final deliverable. These outlines included informative signage for Playa de El Palmar and Playa El Rinconcillo to improve public awareness of the importance of dunes and coastal flora in combating beach erosion. These informative signage included how dunes are important in combating beach erosion, some causes of beach erosion and erosion rates, and identified flora species and their importance in protecting dune systems. These are to be permanently placed at the entrance of the beaches so beachgoers can enrich themselves with essential ecological insights and dune regulations before venturing to the beach.

3.1.1 Justification of Study Sites

The selection of the four study site beaches within the Cádiz province involved a rigorous analysis of their morphologic characteristics. Our initial selection consisted of four beaches from a list of eleven provided by Dr. Patricio Poullet: Playa de Bolonia and Playa de El Palmar on the West Coast facing the Atlantic Ocean, and Playa de Getares and Playa El Rinconcillo on the East Coast facing the Mediterranean. We selected them based on vegetation on the dune systems, their geographical location, and contrasting stabilities. We then carefully evaluated whether these study sites were appropriate for our comparative study.

Spain's Atlantic and Mediterranean coastlines offer contrasting landscapes and experiences due to their differing geographical and climatic conditions. The Atlantic coast experiences a maritime climate with milder temperatures and higher rainfall and is exposed to the Levante wind, which carries sediment transport. This results in rugged terrain with cliffs and lush greenery. In contrast, the Mediterranean coast has a climate with hot summers and mild winters, featuring sandy beaches and varied landscapes. This coast is subject to the Poniente wind, which plays a significant role in wave generation. These factors contribute to varied landscapes with abundant forests on the Atlantic Coast, while the Mediterranean Coast has drought-resistant flora like olive groves and pine forests (Spain Country Information, 2024).

With the help of our sponsor, Dr. Antonio Contreas de Villar, our team assessed multiple beach characteristics using a beach classification report developed by Ministerio De Medio Ambiente and ArcGIS 10.3 software to visualize the erosion lines and rates from 1956 to 2011.

The beach classification report provided data on each beach's total surface, perimeter, longitude, and morphologic characteristics, such as sediment type, average granularity thickness (D50), beach type, and typology (Ecocartografía de Cádiz, 2013).

Beach type refers to the classifications based on the human presence on these beaches; meanwhile, typology refers to the nature of the beaches. Additionally, it included bathymetry maps and beaches' profile graphs, showing the distribution patterns of different sized or shaped deposited material on the beaches (Prieto-Campos, Antonio, et al, 2018).

Using the ArcGIS 10.3 software, we visualized the evolving erosion rates from 1956 to 2011 on each study site, as shown in Figure 8. We interpreted these erosion rates using the following legend: the dashed black line represents the baseline for erosion rates calculations, the solid purple line represents the erosion line calculated in 2011, and the red/blue dotted line represents the erosion rates from 1956 to 2011, where the first line is onshore, the second line has a buffer of 450 meters, and the third line has a buffer of 800 meters (Prieto-Campos, Antonio, et al, 2018).

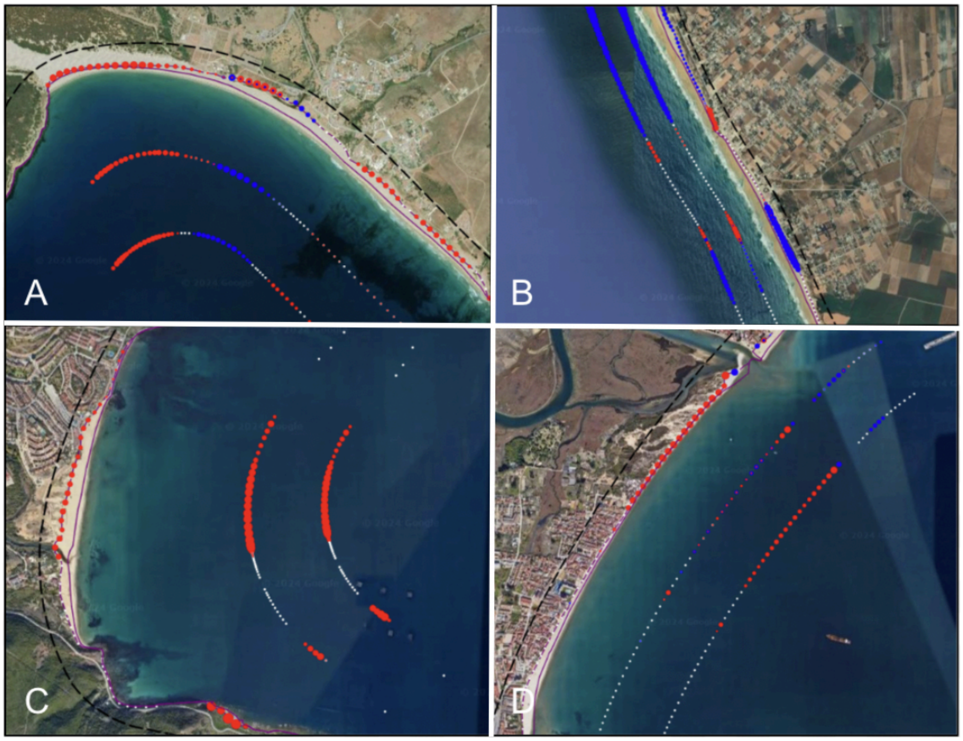


Figure 8. Erosion rates in the study sites, Playa de Bolonia (A), Playa de El Palmar (B), Playa de Getares (C), and Playa El Rinconcillo (D).
Reproduced with permission (Prieto-Campos, Antonio, et al., 2018).

Erosion maps revealed clear differences between the beaches. We saw that in Playa El Rinconcillo (D) and Playa de El Palmar (B), the erosion rates were exacerbated by human development and urbanization on the coast, as people built many houses and other infrastructures on these beaches. Regarding the Playa de Bolonia (A) and the Playa de Getares (C), these beaches are more stable because the erosion lines are much closer to the baseline. This means that these beaches were not as affected by erosion from 1956 as the other two study sites (Prieto-Campos, Antonio et al., 2018).

From the beach classification report, we identified that the most important morphological characteristics are sediment type, D50, and the beaches' type and typology. We analyzed these different characteristics for each of the study sites to evaluate if the beaches' morphological conditions, despite varying erosion rates, were sufficiently similar to support a robust comparative study assessing the ability of the flora on these beaches to combat beach erosion. The report analysis revealed some key findings: both beaches on the West Coast (Playa de Bolonia and Playa de Palmar) have a typology of open beaches with dune systems. On the Mediterranean, Playa de Getares is considered an open beach, while Playa El Rinconcillo typology is classified as "in diffraction" caused by the expansion of the Port of Algeciras. Beach types also showed some correlation; the two stable beaches are isolated (Playa de Bolonia) and semi-urban (Playa de Getares), while the two unstable beaches are semi-urban (Playa de El Palmar) and urban (Playa El Rinconcillo). Even though they don't share the same types, overall the beach type and typology indicated a degree of proportionality between the sites. Regarding the sediment type information, the sediment type of all the beaches is golden sand, with the only exception being in Playa El Rinconcillo, where the sand's color is gray/brown. The D50 slightly varies among the different beaches in a range of 0.24-0.29 mm, except for Playa El Rinconcillo, which has a much lower D50 of 0.17 mm due to the ongoing beach nourishment processes, classifying the sand type of all the beaches as fine (Ecocartografía de Cádiz, 2013).

The maps in Figures 9 and 10 represent the bathymetry and topography of the study sites. The green and red lines are cross profiles, representing the emerging beach, elevation above 0, and the submerged beach, elevation below 0.

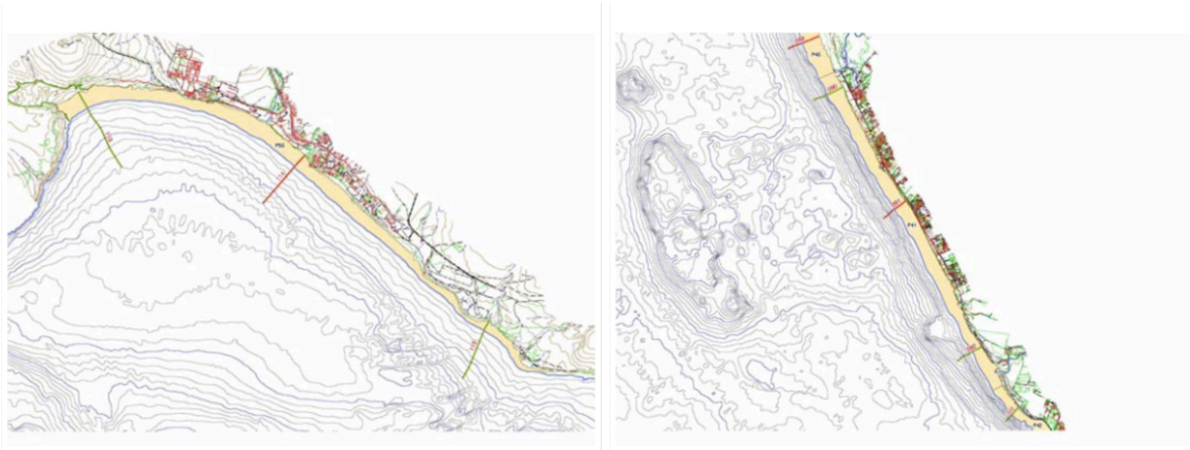


Figure 9. Bathymetry and topography maps of Playa de Bolonia (left) and Playa de El Palmar (right).
Reproduced with permission (Ecocartografía de Cádiz, 2013).

In bathymetry maps, closer contour lines represent steeper slopes or more rapid changes in water depth, indicating areas where the underwater terrain changes more abruptly. In the case of Playa de Bolonia and Playa de El Palmar, the map on the right (Playa de El Palmar) has a much steeper slope in the front submerged part; meanwhile, the left map (Playa de Bolonia) shows a gradual slope that is less steep, showing no such rapid change in water depths. After the first part of the submerged slope, the Playa de El Palmar is characterized by close contour lines among the entire map, representing rapid changes in water depth and steeper slopes, with a clear case of an underwater canyon. In the case of Bolonia, the bathymetry map shows that, after the initial steeper slope in the front part of the submerged slope, the lines are widely spaced, indicating more gradual changes in depths.

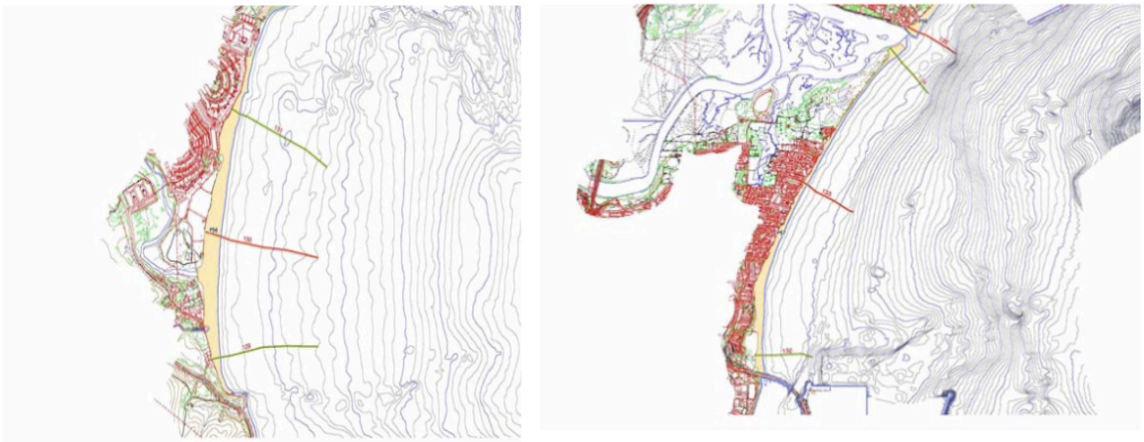


Figure 10. Bathymetry and topography maps of Playa de Getares (left) and Playa El Rinconcillo (right).
Reproduced with permission (Ecocartografía de Cádiz, 2013).

In the case of Playa de Getares (left) and the Playa El Rinconcillo (right) in Figure 10, we saw a clear difference in the separation of the contour lines. The Playa de Getares map showed a gradual and slow slope in the front part of the submerged area, and it's characterized among the entire map with widely spaced contour lines, representing more gradual changes in depths. The case of Playa El Rinconcillo is much different. This map is characterized by closer contour lines, specifically after the first part of the submerged slope, which is more gradual, representing steeper slopes and more rapid changes in water depth the further from the shoreline.

Analyzing these maps revealed a correspondence and similarities between the west and east Coast. The Playa de Getares and the Playa de Bolonia shared characteristics of widely spaced contour lines indicating more gradual changes in depths. Meanwhile, Playa El Rinconcillo and Playa de El Palmar have much more complex bathymetry lines representing steeper slopes and more rapid changes in water depth. This analysis supports our selection of the study sites as the beaches on the West and East Coasts are in conditions that are similar enough to carry out this comparison study.

Our team compared beach protection measures already implemented to indicate how advanced coastal management practices are at the selected beaches. This allows our team to recommend improving the beaches' protection measures based on morphological characteristics and needs. These measures included dune signage, dune protection fences, sand trap fences, and walkovers, as shown in Figures 11, 12 and 13.

Figure 11. Sand trap fences photographed at Playa El Rinconcillo.

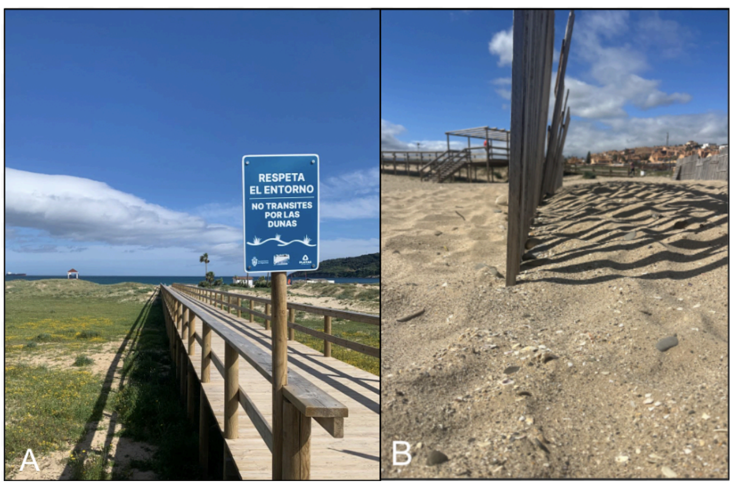


Figure 12. Playa de Getares walkover, signage (A), and sand trap fence (B).

Figure 13. Dune signage at Playa de El Palmar.

Table 1 displays the leading beach and morphology characteristics, including the type and typology of the beaches, erosion rates, established beach protection measures, geographic location, human development presence, and sand type.

Study Site Comparisons					
Beaches		Bolonia	Getares	Palmar	Rinconcillo
Erosion Rate		Low	Low	Medium	High
Typology		Open with Dune System	Open	Open with Dune System	In Diffraction
Beach Type		Isolated	Semi-urban	Semi-urban	Urban
Vegetation Present		X	X	X	X
Dune Protection Methods	Dune Signage	X	X	X	
	Dune Protection Fences			X	
	Sand Trap Fences		X		X
	Walkovers	X	X	X	
Mediterranean Coast			X		X

Atlantic Coast	X		X	
Harmful Human Development present			X	X
Sand Type	Fine	Fine	Fine	Fine

Table 1: Depicts the several conditions and characteristics accounted for in selecting the project study sites.

Evaluating the similarities and differences in morphological conditions of the study sites was an important factor in confirming these selected study sites. The varying environments of these beaches allowed for a quality comparative study to evaluate the flora's ability to combat beach erosion in the study sites.

3.2 Data Collection Methods

3.2.1 Interviews with Stakeholders

The team conducted semi-structured interviews with key stakeholders, environmental agencies, coastal management bodies, and ecological/flora researchers to understand current coastal management practices, limitations, and perspectives on using flora to combat beach erosion. This approach allowed for in-depth discussions and exploration of individual concerns while maintaining a focus on our research questions. Our academic advisors reviewed interview questions to guarantee neutrality and avoid leading questions.

We identified interviewees through sponsor connections and snowball sampling, resulting in six interviews. We employed email outreach to contact all potential interviewees (n=15) and received a 60% response rate, with nine individuals expressing interest in our project. We conducted in-person interviews whenever possible, accommodating the interviewee's preferred location; meanwhile, we extended Zoom as an alternative for those unavailable for in-person meetings. Where time was a constraint, we offered email communication for the interviews.

Before beginning each interview, we briefly introduced our research team, project goals, and the purpose of the interview. We then obtained signed consent using the form in the interview protocol that addressed anonymity considerations, informing interviewees that their responses would be used in the research paper. Interviewees had the right to terminate the interview at any point, as explained in the interview protocol, which can be found under Appendices in Appendix A.

After the consent process and exchanging personal introductions, we followed a cause-and-effect flow of interview questions:

- Understanding the Current State of Coastal Management: We explored the interviewee's knowledge of beach erosion and current management practices. This included questions about the approval process for coastal projects, collaboration among stakeholders, and limitations of these coastal management policies.

- The Potential of Nature-Based Solutions: The conversation transitioned to using flora as a feasible solution to combat beach erosion. We discussed the sustainability, feasibility, and limitations of implementing these solutions into current management practices.

To encourage detailed discussions, we used a mix of pre-written open-ended questions and follow-up prompts throughout the interview. All interviews were recorded, audio for in-person, audio/video for Zoom, to ensure data quality. The recordings served as transcripts for reference and data integrity.

3.2.2 Granularity Tests

Sand granularity tests allowed our team to compare sand types between the selected study sites, providing essential data for understanding beach morphology, erosion patterns, and habitat suitability for various plant species. Granularity testing refers to the fineness or coarseness of the test subject; in our study, we evaluated the topsoil's particulate size collected from the study sites. This experiment was crucial in identifying which coastal flora are most effective for beach and dune protection, considering how different sand textures influence plant root systems and stability. Additionally, these findings aided in developing tailored conservation strategies, enabling more effective management of coastal areas to mitigate erosion and enhance biodiversity.

Figure 14. Illustrates sand collection at Playa de Getares. Topsoil must be collected (7-10 centimeters deep) to ensure accurate test results.

This study began by collecting sand from the topsoil of each study site, which allowed the samples to be free of any additional matter from the beach, such as seashells or plant matter (Figure 14). The topsoil sand is wet. Therefore, sand has to be dried in an oven for at least 24 hours before beginning lab work experiments. The lab started with measuring 100 grams of sand from each study site. The sand was then sifted through 9 layers of sifters stacked in a tower form, decreasing in particle size, starting at 2.00 mm and transitioning through 1.00, 0.710, 0.500, 0.355, 0.250, 0.180, 0.125, 0.063, and ending at 0.039 mm. The tower of shifters has to be shaken for about 3 minutes or until no more grains of sand are falling through layers. Once sifted, the sand collected at each layer was weighed using a scale and recorded on an Excel sheet provided by Dr. Antonio Contreras; a sample of the Excel sheet can be found under Appendices, in the Appendix C. Figure 15C illustrates the process of sand sifting through the sifter tower.

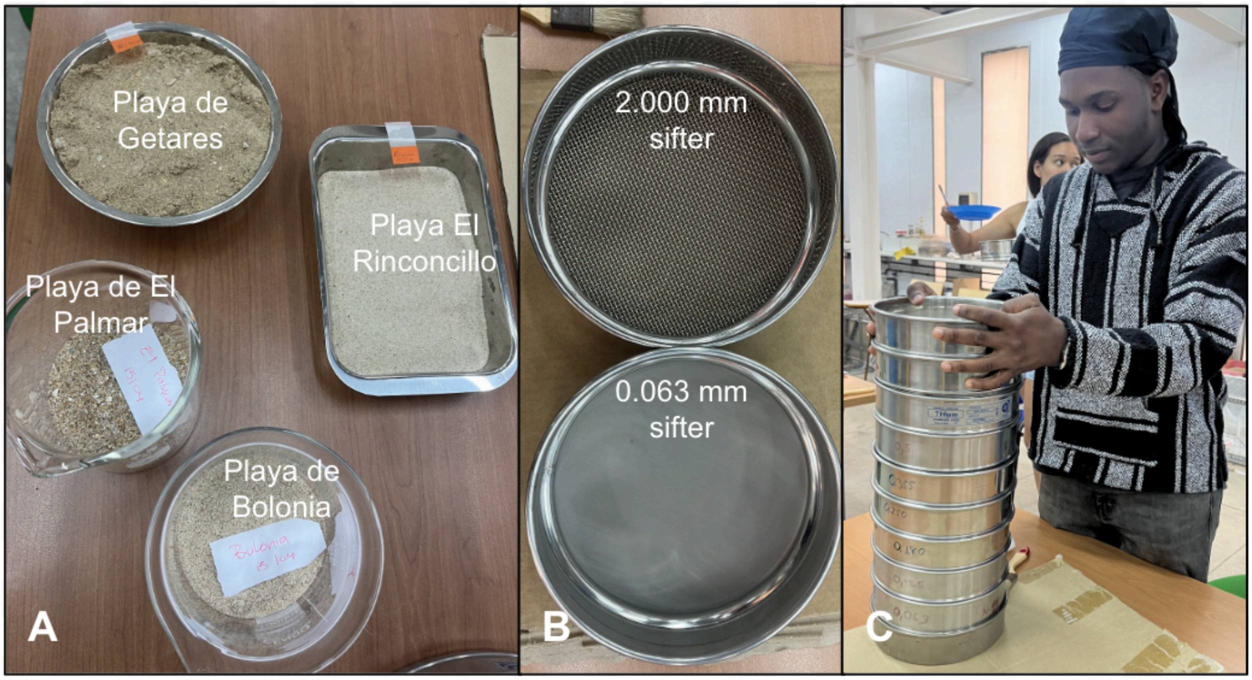


Figure 15. Illustrates the process of the sand granularity experiment and sifting. Image (A) shows sand collected at each study site. Image (B) shows the largest (2.000mm) and smallest (0.063mm) sifters used to filter the sand particles. Image (C) shows the process of sifting.

The Microsoft Excel sheet calculated the values of the median grain diameter (D50) using an Interpolation formula. This formula calculated the diameter at which 50% of the sand grains are sifted through. Depending on the D50 values, the sand is categorized as fine, medium, or coarse. Table 2 specifies the diameter classifications.

Sand Type	Grain Diameter (mm)
Fine	0.02-0.50
Medium	0.50-2.00
Coarse	2.00-5.00

Table 2. The classification of sand type to grain diameter. These values were applied to our grain diameter findings.

By following this objective, the team meticulously measured and analyzed the composition and behavior of coastal sediments. These tests have provided a detailed analysis of sand types across different coastal sites, enabling a deeper understanding of site-specific erosion dynamics and vegetation compatibility. This systematic approach allowed for strategically selecting flora that thrives in particular sandy environments, enhancing dune stabilization and erosion control.

3.2.3 Transect Walks and Flora Comparison

The team conducted transect walks to achieve our goal of documenting and understanding the flora presence in the study area, shown in Figure 16. A transect walk is a systematic walk along a defined path across the project area to explore the composition and density of coastal flora. We discussed the best transect walk techniques with professors from the University of Cádiz, such as Professor Fernando Ojeda, Professor Ignacio Hernández, Professor Giorgio Anfuso, and Professor Antonio Contreas de Villar. In addition, Carlos Ley of Ecología Litoral and Jurgi Areizaga of Tecnoambiente identified important considerations for effectively observing the beach's features. These observations included beach morphology, type of sand grain, and elevation.

The team conducted transect walks on four beaches across the Cádiz province's coast. Two beaches, Playa de Bolonia and Playa de Getares, were chosen for their stability, while the other two, Playa de Rinconcillo and Playa de El Palmar, are actively eroding. We ensured these beaches had similar coastal settings, such as wind patterns, bathymetry, and granularity, despite being in different locations. This selection strategy, explained more in-depth in section 3.1.1, allowed for a focused comparison between stable and eroding beaches to evaluate flora's ability to combat beach erosion accurately. The contrasting beach stabilities were reflected in their flora composition and the density of the dune systems.

Figure 16. A map of the Cádiz province highlighting the four study sites where the team conducted transect walks.

The team gathered data on the composition and density of the flora population on the four study sites, conducting a vegetative survey to measure existing vegetation cover in a portion of a study area to extrapolate the percent cover in the entire study area. The tools used to conduct these transect walks were a 30-meter measuring tape, GPS, a notebook, and a pen. We established three transect lines, 30 meters apart, that started at the dune's foot and laid across the dune perpendicularly to the shoreline. The team used the transect lines to identify the flora composition for each meter using an app called iNaturalist, to then calculate each flora species' density among each line. After analyzing these results for the comparable beaches and identifying the density of each flora species in each of the study sites, the team executed a comparison study to understand the ability of specific flora and abundance to combat beach erosion and any significant relationship between the study sites.

4.0 Results

4.1 Thematic Code Analysis from Interviews

Following the interviews, the audio recordings were transcribed verbatim. We then conducted a thematic analysis of the transcripts to identify recurring themes and patterns within the participants' responses. This analysis involved coding the transcripts based on predetermined codes related to the research questions (e.g., “benefits of flora,” “challenges of implementation”) (Patton, 2001). We then reviewed the codes and refined them to ensure consistency. Finally, we analyzed the coded data to identify key themes and comprehensively understand the participants' perspectives on using native flora for erosion control, shown in Table 3. We then organized an illustrative table from the interview participants’ responses to display the themes from the interviews, supported by the direct quotations and the code words used to obtain the theme.

The following table shows quotes from the primary stakeholder interview responses divided into codes.

Emerging Themes	Codes	Interview Quotes
Effectiveness of plants: Praising how effective flora as a nature-based solution is for beach erosion mitigation and recommending solutions to support its effectiveness.	Roots, plants, preserve, birds	“[*Posidonia oceanica* has a] very big system of roots…, so this is why it's so interesting regarding CO2 sequestration.” “[Plants] also provide [habitats] where birds can stay and can live.” “Beaches that preserve their dune systems quite well behave very well in the face of storms because the dunes are still a reserve.” “Dune protection fences help to restrict foot traffic.” “Sand trap fences will accumulate the sand that the wind blows.”
Challenges surrounding flora as a nature-based solution: Mention the possible environmental challenges associated with implementing and preserving flora and the	Condition for growth, wind	“The light must penetrate into the ocean, so if the water is not very clear, the [seagrass] won't grow.” “*Posidonia oceanica* grows about one centimeter per year.” “Well, I mean, you can't and shouldn't bring plants

dunes they live on.		from France, for instance… they need to be taken from the region." "You have to monitor for many years. No, not only five years, so maybe 20, 30 or 40 years." "So, for me, the main problem is that many beaches in Spain are too modified, and there is no space." "The Levante wind is very strong, so it blows sand, leading to beaches like Rinconcillo accumulating sand on the southern end." "They have a greenhouse nursery in Santander where they plant the dune plants for restoration. However, many plants are lost once transplanted partly because the weather changes and the rain doesn't fall."

Table 3. Thematic code analysis from interviews. Quotes from stakeholders are organized into different codes and themes.

This thematic code analysis allowed our team to understand the participants' perspectives about specific themes related to our project. The stakeholder interviews provided valuable insights into current coastal management practices and perspectives on using native flora for erosion control in Cádiz. This information, combined with the data collected from the transect walks, has allowed for a comprehensive understanding of the challenges and opportunities in using flora as erosion control in our study sites.

4.2 Sand Granularity Test Findings

This section presents the findings from our comprehensive sand granularity tests conducted across various coastal study sites. The results detail the specific grain size distributions and median grain diameters (D50) calculated for each location. As described in the methodology, we categorized the sand samples into fine, medium, and coarse types through careful sifting and measurement processes, shown in Table 4.

Study Sites	Grain Diameter (D50 mm)	Sand Type
Playa de Bolonia	0.314	Fine
Playa de Getares	0.311	Fine
Playa de El Palmar	0.374	Fine

Playa de Rinconcillo	0.268	Fine

Table 4. Granularity test results at the study sites. D50 was calculated through interpolation in Microsoft Excel and was classified by sand type based on Table 2.

Playa de Bolonia			
Sifter Size (mm)	Sample Weight (gr)	% Retention	% Accumulative Sand Passing
2.000	0.00	0.00	100.00
1.000	0.00	0.00	100.00
0.710	0.20	0.20	99.80
0.500	4.70	4.73	95.07
0.355	28.50	28.67	66.40
0.250	42.10	42.35	24.04
0.180	19.00	19.11	4.93
0.125	4.90	4.93	0.00
0.063	0.00	0.00	0.00
0.039	0.00	0.00	0.00
Total Sample	**99.40**		

Table 5. Granularity test of Playa de Bolonia.

Playa de Getares			
Sifter Size (mm)	Sample Weight (gr)	% Retention	% Accumulative Sand Passing
2.000	1.30	1.30	98.70
1.000	1.90	1.90	96.79
0.710	3.60	3.61	93.19
0.500	10.10	10.12	83.07
0.355	19.40	19.44	63.63
0.250	32.60	32.67	30.96
0.180	24.20	24.25	6.71
0.125	5.90	5.91	0.80
0.063	0.60	0.60	0.20
0.039	0.20	0.20	0.00
Total Sample	**99.80**		

Table 6. Granularity test of Playa de Getares.

Playa de El Palmar			
Sifter Size (mm)	Sample Weight (gr)	% Retention	% Accumulative Sand Passing
2.000	1.60	1.63	98.37
1.000	6.40	6.53	91.84
0.710	6.80	6.94	84.90
0.500	14.40	14.69	70.20
0.355	22.70	23.16	47.04
0.250	28.60	29.18	17.86
0.180	15.10	15.41	2.45
0.125	2.40	2.45	0.00
0.063	0.00	0.00	0.00
0.039	0.00	0.00	0.00
Total Sample	**98.00**		

Table 7. Granularity test of Playa de El Palmar.

Playa El Rinconcillo			
Sifter Size (mm)	Sample Weight (gr)	% Retention	% Accumulative Sand Passing
2.000	0.20	0.20	99.80
1.000	0.10	0.10	99.70
0.710	0.10	0.10	99.60
0.500	2.00	2.02	97.58
0.355	14.40	14.55	83.03
0.250	39.30	39.70	43.33
0.180	31.70	32.02	11.31
0.125	10.50	10.61	0.71
0.063	0.70	0.71	0.00
0.039	0.00	0.00	0.00
Total Sample	**99.00**		

Table 8. Granularity test of Playa El Rinconcillo.

The data compiled and analyzed in this section forms the basis for further discussions on the viability of nature-based solutions in managing coastal erosion effectively (Tables 4-8). These results suggested that all four study sites in the Cádiz province are similar as they are classified as fine sand types. Playa de El Palmar and Playa de Getares have D50 values within a range of 0.003 mm, while the outliers are Playa El Rinconcillo, with a smaller D50 of 0.043 mm from this range, and Playa de Bolonia, with a larger D50 by 0.060 mm from this range (Figure

17). The consistent beach characteristics of sand type throughout the study sites allow for comparable coastal floras with similar root systems to grow and grip fine sand particles.

Figure 17. Depicting the different particles sized among the four study sites.

4.3 Insights from Transect Walks: A Thematic Analysis

After collecting data for each transect walk, our team analyzed the individual densities of each plant species per transect line to calculate the density presence of each species in the entire study site (Figure 18 and 19).

Figure 18. Illustrates an example of how the transect line was executed with 30-meter measuring tape along the vegetation. Photographed at Playa de El Palmar.

Figure 19. Illustrates how the 30-meter transect lines were placed along the four study sites. Playa de Bolonia (A), Playa de El Palmar (B), Playa de Getares (C), and Playa El Rinconcillo (D).

For the Playa de Bolonia, the flora species *Ammophila arenaria* and *Pancratium maritimum* were the most abundant, as seen in Table 9, with densities of 38.89% and 32.22%, respectively. In much smaller densities, other species, such as *Lotus creticus* and *Crucianella maritima*, were discovered along the transect lines at the Playa de Bolonia.

Playa de Bolonia	
Species	Density
Ammophila arenaria	38.89%
Pancratium maritimum	32.22%
Crucianella maritima	26.11%
Lotus creticus	12.22%
Genus Pistacia	6.67%
Genus Retama	5.55%
Pinus pinea	3.33%

Table 9. Densities of each species found in the study site of Playa de Bolonia.

For Playa de El Palmar, the most abundant species discovered was *Crucianella maritima,* with a density of 39.16%, as seen in Table 10. However, *Ammophila arenaria, Reichardia gaditana* and *Lotus creticus* were also noted at the Playa de El Palmar, with much smaller densities than those uncovered at the Playa de Bolonia.

Playa de El Palmar	
Species	Density
Crucianella maritima	39.16%
Ammophila arenaria	23.33%
Reichardia gaditana	18.33%
Lotus creticus	17.08%
Pancratium maritimum	10.83%
Glebionis coronaria	10.83%
Eryngium maritimum	7.08%
Centaurea polyacantha	4.16%
Malcolmia littorea	3.75%
London Rocket	1.67%
Cyperus capitatus	1.67%
Silene nicaeensis	1.25%
Orobanche densiflora	0.83%

Table 10. Densities of each species were found in the study sites of Playa de El Palmar.

For the Playa de Getares, *Elymus farctus* and *Pancratium maritimum* were the most abundant flora species discovered, with densities of 57.77% and 32.77%, respectively, as seen in Table 11. Other species present on this beach were also *Silene nicaeensis*, *Lotus creticus*, and *Eryngium maritimum*, with densities of 20%, 18.89%, and 10%.

Playa de Getares	
Species	Density

Elymus farctus	57.77%
Pancratium maritimum	32.77%
Silene nicaeensis	20.00%
Lotus creticus	18.89%
Eryngium maritimum	10.56%
Crucianella maritima	2.22%
Cyperus capitatus	2.22%
Ammophila arenaria	1.67%
Centaurea polyacantha	1.44%
Reichardia gaditana	1.11%
Daucus pumilus	0.33%

Table 11. Densities of each species were found in the study site of Playa de Getares.

For Playa El Rinconcillo, the most abundant species discovered in the study site area included *Carpobrotus acinaciformis* and *Ammophila arenaria,* with densities of 30% and 23.33%, respectively, as seen in Table 12. Other species with a strong presence at the Playa El Rinconcillo were *Pycnocomon rutifolium, Elymus farctus*, and *Lotus creticus,* with 12-13% densities. This transect line is depicted in Figure 20.

Playa El Rinconcillo	
Species	Density
Carpobrotus acinaciformis	30.00%
Ammophila arenaria	23.33%
Pycnocomon rutifolium	13.30%
Elymus farctus	12.78%
Lotus creticus	12.77%
Cyperus capitatus	5.00%
Anthemis maritima	3.89%
Bromus diandrus	3.89%

Reichardia gaditana	3.33%
Helichrysum stoechas	3.33%
Dittrichia	1.67%
Centaurea polyacantha	1.11%
Pancratium maritimum	1.11%

Table 12. Densities of each species were found in the study site of Playa El Rinconcillo.

Figure 20. Dune photographed at Playa El Rinconcillo during transect walks.

5.0 Discussion

5.1 Analyzing Stakeholder Perspectives: Insights from Interviews

Our research explored the feasibility of using native flora for erosion control on Cádiz province's beaches. While the interviews suggested that flora can be a potent solution, implementing flora projects requires navigating various ecological, social, and coastal factors that influence its effectiveness.

All participants in our interviews emphasized the ecological and structural benefits of native flora as a method of erosion control. Dr. Patricio Poullet of Demarcacion de Costas highlighted that "beaches that preserve their dune systems quite well behave very well in the face of storms because the dunes are still a reserve." Dr. Ignacio Hernández, Biology Department, research group of the ecology of aquatic systems, at the University of Cadiz, added that "with seagrass species, such as *Posidonea oceanica,* the big roots and stems makes it one of the most important for carbon sequestration, accumulating deposits and keeping the carbon from reentering the atmosphere." Jurgi Areizaga from environmental agency Tecnoambiente, mentioned that "the plants also provide a place where birds can live, and insects can pollinate." We also saw this during the transect walks as many pollinators thrived, showcasing the full efficacy of plants for erosion control. The major stakeholders' only positive sentiments towards flora signify that our project's efforts to explore the use of flora as an erosion control would be regarded highly, and ideological reproach would not be a problem.

However, all participants also expressed that there are limitations when using flora as a nature-based solution. Dr. Hernández acknowledged the slow growth rate of seagrasses and the intensive care required during cultivation and initial establishment. He pointed out, "though *Posidonea oceonica* is very effective in slowing wave speed and sinking carbon, it only grows around 1 cm per year, making it hard to grow substantial beds in the ocean from seeds" (I. Hernández, Personal Communication, 2024). They are incredibly fragile and require preservation efforts to safeguard their presence from human activities on the beach. Fences and signage must be implemented to prevent humans from stepping on the planted seeds. Others mentioned that it requires further research as it is a relatively new field of thought in the Cádiz province. Overall, ongoing monitoring and research are critical during their growth to maintain their stability within the ecosystem.

Additionally, replicating conditions to grow some flora requires intensive time and resource management, where every natural condition must be critically adhered to. Dr. I. Hernández manages two labs where he develops and tests the different types of grasses (Figure 21). He described that "the salinity also had to be tested every 24 hours to ensure evaporation did not alter the salinity level because a distinct change in salinity can kill the plants. It had to be mandatorily maintained between 30% and 35% in a salt/water ratio", as illustrated in Figure 22. Even after transplanting, the work does not end as "you have to monitor for many years. No, not only five years, [but 20, 30 or 40] years" (I. Hernández, Personal Communication, 2024). The intense conditions for growing flora indicate that wide-scale use costs much money and time. Nonetheless, the ecological benefits of flora-based solutions make them a compelling alternative.

Figure 21. Dr. Ignacio Hernández Carrero's seagrass laboratory. This figure illustrates seagrass *Zostera marina* growth and development from (left) seeds to (right) mature plants. The tank's ideal conditions include saltwater movement, salinity, soil type, and temperature.

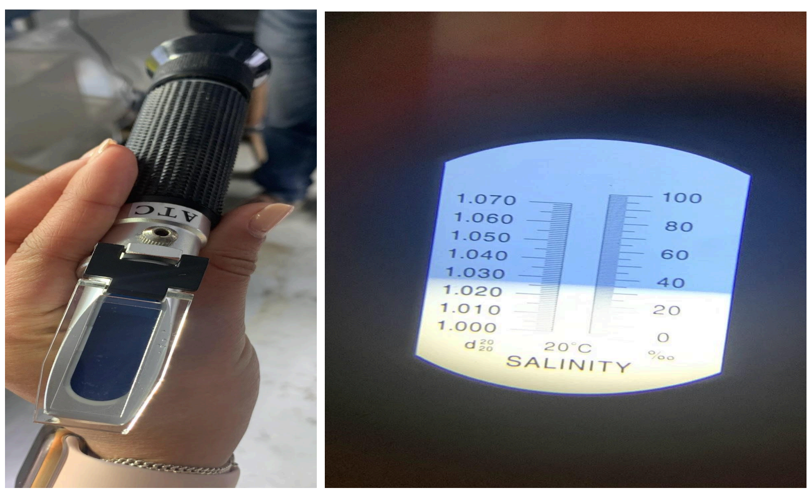


Figure 22. From left to right, the refractometer is used to test tank salinity levels, and the test channels show the tank's actual salinity level.

Additionally, we found that using flora largely depends on the coastal conditions of the beaches. Three interviewers iterated that when a beach reaches certain levels of erosion, nature-based solutions are not enough to mitigate erosion, and other solutions, such as hard structures, have to be implemented to stabilize the beach. Dr. Poullet said that a combined approach may be necessary for beaches with severe erosion, with hard structures like breakwaters used for initial stabilization followed by flora for long-term erosion management. It is because "floras are often considered on beaches with minor levels of erosion as short-term solutions since they only assist in the control of erosion. They are much more suited for shoreline stabilization." This was new information regarding its feasibility. He cited the case of Playa El

Rinconcillo, explaining the necessity of implementing three underwater breakwaters in a new restoration project that will start at the face of the beach to prevent offshore movement from dragging the sand to the southernmost point of the beach, ultimately helping stabilize the erosion rates of the beach.

Finally, we learned that successfully planted flora need elaborate maintenance mechanisms to ensure their effectiveness. Professor Giorgio Anfuso emphasized the need for plant fences to prevent the public from walking on the plants and dune fences to help trap sand blown by the Poniente and Levante winds. We integrated these measures when we recommended strategies for protecting our study sites.

5.2 Granularity Testing: Implications and Insights

The granularity values we initially considered were those gathered from the beach classification report developed by Ministerio De Medio Ambiente, which our sponsor provided, Dr. Antonio Contreras de Villar. These values are slightly lower than our team's granularity test data from the laboratory work at the University of Cádiz. Presented the grain diameter (D50) of the report presented the grain diameter (D50) of the Playa de Bolonia at 0.26 mm, the Playa de El Palmar at 0.29 mm, Playa de Getares at 0.24 mm, and Playa El Rinconcillo at 0.17 mm. These values indicate that the sand type for all the study sites is fine.

Although our results vary slightly, they follow the same pattern, with Playa de El Palmar having the largest grain diameter (0.371 mm), followed by Playa de Bolonia (0.314 mm), Playa de Getares (0.311 mm), and with significantly lower medium grain diameter, Playa El Rinconcillo (0.268 mm).

The granularity across all study sites is of fine sand type, allowing our other comparisons to have a more substantial influence. Notably, this provides consistency between our flora investigations, as similar root networks are required for fine sand types.

5.3 Discussion of Transect Walk Observations

From the results of the transect walks, our team identified the most abundant flora species in each of the study sites. The results portray each study site's different erosion processes and morphologic characteristics. These formed the basis of our comparative study to evaluate flora's ability to slow down the erosion processes protecting the dune systems, particularly for the most abundant flora species.

On the eastern side, facing the Atlantic Ocean, on the exemplary dune system of Bolonia, the most abundant flora species identified were *Ammophila arenaria* and *Pancratium maritimum*, followed by other species such as *Crucianella maritima* and *Lotus creticus*. Similarly, in Playa de El Palmar, the most abundant flora species were *Crucianella maritima* and *Ammophila arenaria,* followed by *Reichardia gaditana*, *Lotus creticus,* with some presence of *Pancratium maritimum* and *Glebionis coronaria*.

Ammophila arenaria is the principal native plant across dune systems, and it is characteristic of dune stabilization because of its fundamental role in fixing the sand (Figure 23). Critical structural components of this plant include rhizomes. Rhizomes are underground horizontal shoots that root systems of new plants and further bind the sand. These root systems are dense and fibrous throughout the upper meter of the soil profile. The stems themselves have rolled-up, waxy-coated leaves that are functional in preventing water loss. These shoots reduce wind velocity due to the accretion of windblown sand. The growth of *Ammophila arenaria* is vigorous in dunes where fresh sand is deposited by wind, although it diminishes from the vegetation once dunes stabilize (Putten, W. H. van der. 1989). This species has successfully been grown from sowing seeds in a plant nursery for restoration practices. This process takes about two years for the plant to mature and be implemented in the dune, making it an ideal flora in the feasibility of a nature-based solution (Herbari Virtual del Mediterrani Occidental, 2019).

Figure 23. *Ammophila arenaria* photographed at Playa de Getares.

The distribution of these flora species varies based on the study site due to the different environmental and climate conditions that lead to erosion. In the case of the Playa de Bolonia, the beginning of the dune (dune's foot), the first 10 meters of our transect walks, is mainly characterized by a scarce presence of *Ammophila arenaria*, with some presence of *Crucianella maritima* and *Pancratium maritimum.* After the first 10 meters, the flora abundance significantly increases, showing other species such as *Lotus creticus, Genus Pistacia,* and *Genus Retama* (Figure 28, Appendix B).

In Playa de El Palmar, the dune foot is mainly characterized by the scarce presence of *Ammophila arenaria, Pancratium maritimum, Crucianella maritima,* and *Reichardia gaditana.* After the first 10 meters of each transect line, the density of the flora significantly increases, showing other flora species such as *Lotus creticus*, *Glebionis coronaria,* and *Eryngium maritimum* (Figure 29, Appendix B).

Along Cádiz province's eastern coast, bordering the Mediterranean Sea, Playa de Getares and Playa El Rinconcillo allow for quality comparisons due to their proximity in geographic location and beach characteristics.

The most abundant flora that was identified in the Playa de Getares were *Elymus farctus* and *Pancratium maritimum*, followed by other species such as *Silene nicaeensis*, *Lotus creticus,* and *Eryngium maritimum*. In the case of Playa El Rinconcillo, the most abundant flora species identified were *Carpobrotus acinaciformis* and *Ammophila arenaria*, followed by *Pycnocomon rutifolium*, *Elymus farctus,* and *Lotus creticus*.

Elymus farctus, similar to *Ammophila arenaria*, is native and frequently observed on beaches and dunes. It is smaller in size, opposing the dense bushes of *Ammophila arenaria,* but similarly forms loosely dense carpets on the sand due to rhizomes. This plant is also considered a pioneer plant, or plant present at the start of dunes (Herbari Virtual del Mediterrani Occidental, 2019). Due to the above-mentioned properties, this species is highly feasible for a flora nature-based solution.

Carpobrotus acinaciformis is an invasive succulent perennial, although it is considered neutralized in dunes (Figure 24). Branches of this plant produce 12 cm purple flowers and long succulent leaves that bud near the surface to increase its coverage and minimize exposure to the wind. This plant can establish itself in sandy and rocky substrates, making it versatile as an indicator of an invasive species. This plant is not preferable when considering nature-based solutions, mainly due to its invasive relationships with other native plant species in the area (Herbari Virtual del Mediterrani Occidental, 2019).

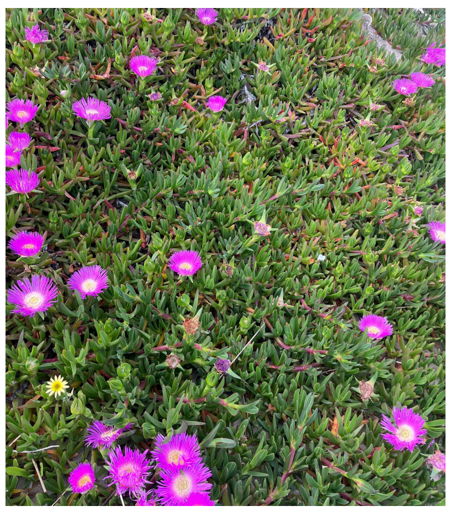


Figure 24. *Carpobrotus acinaciformis* photographed at Playa El Rinconcillo.

In the case of the Playa de Getares, the dune foot is characterized by a medium-dense presence of mainly *Silene nicaeensis*, *Eryngium maritimum*, *Elymus farctus*, *Pancratium maritimum,* and *Lotus creticus*, with a smaller presence of *Ammophila arenaria* and *Daucus pumilus*. After the first 10 meters, the flora density can still be considered medium-high as our results showed the presence of other species, such as *Crucianella maritima*, *Cyperus capitatus*, *Centaurea polyacantha* and *Reichardia gaditana* (Figure 30, Appendix B).

Regarding Playa El Rinconcillo, the flora presence on the dune foot can be considered medium, including species such as *Ammophila arenaria*, *Lotus creticus*, *Pycnocomon rutifolium*, *Bromus diandrus*, *Reichardia gaditana,* and *Carpobrotus acinaciformis*. After the first 10 meters, other species of flora were identified at a medium-low density, such as *Elymus farctus*, *Cyperus capitatus*, *Anthemis maritima*, *Helichrysum stoechas*, *Dittrichia*, *Centaurea polyacantha,* and *Pancratium maritimum* (Figure 31, Appendix B).

We can see a path in the different species on the opposite coasts, as both beaches on the Atlantic Coast see a recurrence in the presence of flora species such as *Ammophila arenaria*, *Pancratium maritimum*, *Crucianella maritima,* and *Lotus creticus*; meanwhile, on the west coast, both study sites share a relevant number of species that include *Ammophila arenaria*, *Elymus farctus*, *Lotus creticus*, *Cyperus capitatus*, *Reichardia gaditana*, *Centaurea polyacantha,* and *Pancratium maritimum*.

From these results, we can evaluate the conditions of each study site based on the number of pioneer species. Pioneer species are the first plants to grow in dune systems, creating conditions suitable for colonizing other species. These plants can live in salty, dry, and unstable conditions as they adapted “thick outer layers and succulent leaves that protect them from sand scour and water loss” (*Sand Dunes*, 2024). The pioneer species in our transect walks include *Ammophila arenaria*, *Pancratium maritimum*, *Crucianella maritima*, and *Elymus farctus*. All these species tolerate salt sprays and wind, making it a useful first plant to line the dunes.

As reported by Professor Giogrio Anfuso, beaches that contain only one pioneer species are considered to be in poor conditions and particularly subject to erosion. Based on this information, both the Playa de Bolonia and Playa de El Palmar can be classified as stable and in good dune conditions as it contains three flora species of pioneer species that are *Ammophila arenaria, Pancratium maritimum,* and *Crucianella maritima.* Even though Playa de El Palmar can be classified as stable and in good condition, there’s been a process of dune occupation, along with increasing erosion in the Torre Nueva area due to house development and urbanization, which has made clear that environmental recovery and protection of the dune system have become necessary.

Regarding the study sites on the Mediterranean coast, the Playa de Getares and Playa El Rinconcillo can be defined as in good dune conditions. Playa El Rinconcillo contains *Ammophila arenaria, Elymus farctus,* and *Pancratium maritimum*, and *Crucianella maritima*. Even though Playa El Rinconcillo contains three pioneer species, the density of *Pancratium maritimum* is significantly lower than all the other species, highlighting its unstable nature.

Pioneer Plant Study Sites Comparison				
	Elymus farctus	*Pancratium maritimum*	*Crucianella maritima*	*Ammophila arenaria*
Density at Playa de Getares	57.77%	32.77%	2.22%	1.67%
Density at Playa El Rinconcillo	12.78%	1.11%	0.00%	23.33%
Density at Playa de Bolonia	0.00%	32.22%	26.11%	38.89%
Density at Playa de El Palmar	0.00%	10.83%	39.16%	23.33%

Table 13. Displays the comparison of pioneer plant densities at the four study sites.

5.4 Conclusions and Future Considerations

Our team discovered that using flora as a nature-based solution is feasible; however, depending on the overall condition of the beach. In the case of Playa El Rinconcillo, the initial integration of hard structures is crucial for beach stabilization, allowing the basis of future implementation of flora as a nature-based solution. In the case of Playa de El Palmar, the implementation of soft structures helps preserve dune systems and existing vegetation. Though more research is needed to evaluate the effectiveness of this measure in eroding spots affected by human development and with narrow dune systems, soft structures are a promising beach and dune protection method.

This initial implementation would allow for future integration of flora as a nature-based solution. After analyzing our comparative study, we constructed recommendations of specific soft structures and ideal flora species to use as nature-based solutions for the Playa de El Palmar and Playa El Rinconcillo.

Beachgrass vegetation, such as *Ammophila arenaria, Pancratium maritimum,* and *Elymus farctus*, is considered feasible to use as a nature-based solution in the Cádiz province due to the similar conditions of the study sites and the plant structures themselves. The factors of geographic location, coastal setting, and sediment type provide similar biological living conditions as various species were observed throughout all study sites. The main difference among the sites under study was the harmful human development on the coast, such as port and building development near the shore. The harmful human development previously mentioned has been continually worsening beach erosion rates, especially in the Playa de El Palmar and Playa El Rinconcillo.

The use of marine vegetation, such as seagrass, like *Posidonia oceanica*, as a nature-based solution is exceptionally effective once developed. However, this species is challenging and tedious to implement now due to its slow maturation rate and particular conditions such as temperature, salinity, and wave movement speeds (Dr. I. Hernández, Personal Communication, 2024).

Reviewing the project as a whole, our team agrees that more time would allow the incorporation of more tested conditions. Additional conditions useful for investigating coastal floras include the value of soil pH. The pH value is an important component in the growth and development of plants, mainly as climate change (increase of carbon emissions) affects the ocean's acidity. Changing acidity within the beach soil would harm many existing coastal vegetation, especially pioneer plants at the foot of the dunes (*Sand Dunes*, 2024). We also recommend considering the seasonal cycle of flora blooming in the Spring, as it can be more challenging to identify the plant species in the winter months. In addition to lab testing, more formal communication with environmental agencies and community-based organizations, like Salvemos Rinconcillo, would encompass a more complete interview/stakeholder study and strengthen our team's data.

6.0 Project Outcomes

Based on the results we gathered from the transect walks, our team evaluated the dune and flora conditions on each study site. As we identified, although the Playa de El Palmar and Playa El Rinconcillo can be considered in good condition, the erosion rates in these sites are exacerbating due to the extensive human development near the coast. Due to Playa de El Palmar's increasing erosion in the Torre Nueva area caused by house development and urbanization and, Playa El Rinconcillo, which is suffering severe erosion on the north side due to the expansion of the Port of Algeciras and house development, the need for more soft structures such as dune signage, dune protection fences, wind trap fences, and walkovers, are crucial for the stabilization of the dunes and for the mitigation of beach erosion. As for Playa de Bolonia and Playa de Getares, we concluded that they were exemplary stable beaches. We drew some of their strengths to support our beach protection recommendations towards the other eroding beaches. As our team was initially planning to implement flora as a nature-based solution, through our study sites' evaluation and information gathered from environmental experts, we can assert that flora is feasible; however, it depends on the erosion conditions of the beach and dune stabilization.

The beach protection recommendation outline included signage for Playas de El Palmar and Playa El Rinconcillo to improve public awareness of the importance of dunes and coastal flora in combating beach erosion. These signage included how dunes are essential in tackling beach erosion, some causes of erosion and erosion rates, and identified flora species and their importance in protecting dune systems. These are meant to be permanently placed at the entrance of the beaches. These recommendations and the informative signage our team developed was forwarded to the environmental agencies of Ecología Litoral and Tecnoambiente.

6.0.1 Targeted Recommendations for Playa de El Palmar

This means that since the implementation of flora as a nature-based solution is limited, our team will focus on restoring and protecting the dune systems in these two less stable study sites. As in the case of the Playa de El Palmar, we need to focus on the area of Torre Nueva to protect the dune systems facing increased erosion due to the road and buildings built on the beach. As this area has already implemented certain soft structures such as dune signage, dune protection fences, and walkovers, we evaluated their efficiency during our visit and generated a series of recommendations:

1. Dune protection fences: From what we saw, the dune protection fences are made of small wooden poles planted very close to the ground and connected by ropes, which were broken and disconnected most of the time. We suggest changing the nature of these dune protection fences because they could be more effective and are not kept in good condition. For material, we recommend using woven brushwood, which can be constructed from various locally sourced shrubs or small trees common in coastal areas. For the exact species to make the woven brushwood, we recommend the willow (Salix alba). We chose these because they are native to Spain, flexible enough to withstand the beach's strong winds, and have proven success in previous restoration projects

(Gallego-Fernández et al., 2011). Changing these fences would not disrupt the landscape's beauty and would prevent people from entering the dunes more effectively.

2. Dune walkovers: Regarding walkover measures, despite having examples of these, these should be placed in more strategic zones such as around restaurants and other infrastructures facing the beach, along with areas close to the road targeting where most of the people would arrive or leave the beach, effectively avoiding locals and tourists not walking on the dunes.
3. Sand trap fences: Using sand trap fences in the zone of Torre Nueva would help mitigate the sediment loss caused by the wind. However, more research should be done on the effectiveness of this measure in this zone, evaluating how much sand would be trapped with respect to the sediment dispersed on the infrastructure behind the narrow dune system. Wind dispersal is a current engineering problem the government is still working on (F. Ojeda, Personal Communication, 2024).
4. Dune signage: Although the Playa de El Palmar includes dune signage measures, they are minimal signage placed 15 centimeters from the ground, making them inefficient. Our team developed on-site informative signage to promote awareness of the beaches' ecosystem to the general public, highlighting the role of dune systems and coastal flora in mitigating beach erosion. This informative signage provided information about the beach erosion processes, species identification and importance in protecting dune systems, and a brief explanation of how dunes are essential to combat beach erosion, shown in Figures 25 and 27.
5. Flora as a nature-based solution: Our team devised recommendations for which coastal flora species are best to integrate into Playa de El Palmar, serving as a nature-based solution to the beach's erosion problems. This list was determined by comparing collected densities of pioneer plant species between the Playa de Bolonia and Playa de El Palmar study sites on the western coast of the Cádiz province (Table 13). Other considerations are the plant's nativeness to ensure the plant's integration does not disrupt the existing ecosystem and the plant's overall structure and importance within the dune system to ensure the plant will positively grow and protect the dune. Table 14 depicts our team's recommendation for integrating flora below.

Playa de El Palmar: Flora Recommendations			
Species to be Implemented	Native to the Area	Plant Structure	Importance
Pancratium maritimum 	X	● Firm, elongated, twisted leaves. ● Deep grounded roots (to avoid drying).	● Pioneer plant that stands at the foot of the dune. ● Resilient seeds with capsule and ability to float in water. ● Supports fauna (*Brithys crini*). ● Feasible implantation.

Ammophila arenaria 	X	• Rhizome, dense and fibrous horizontal root structures. • Rolled and waxy long stems to prevent water loss). • Long shoots reduce wind velocity and accrete sand to the dunes.	• Pioneer plant that stands at the foot of the dune. • Facilitates other plant growth. • Fundamental dune stabilization plant. • Relatively fast maturation rate. • Historically successful and feasible implementation.

Note. Sourced from Herbari virtual del Mediterrani occidental (2019), Diputacíon Provincial de Málaga (2024), and Putten, W. H. van der. (1989).

Table 14. Depicts the coastal flora species and their characteristics that our team recommended in using as nature-based solutions at Playa de El Palmar to preserve dune stability and combat beach erosion.

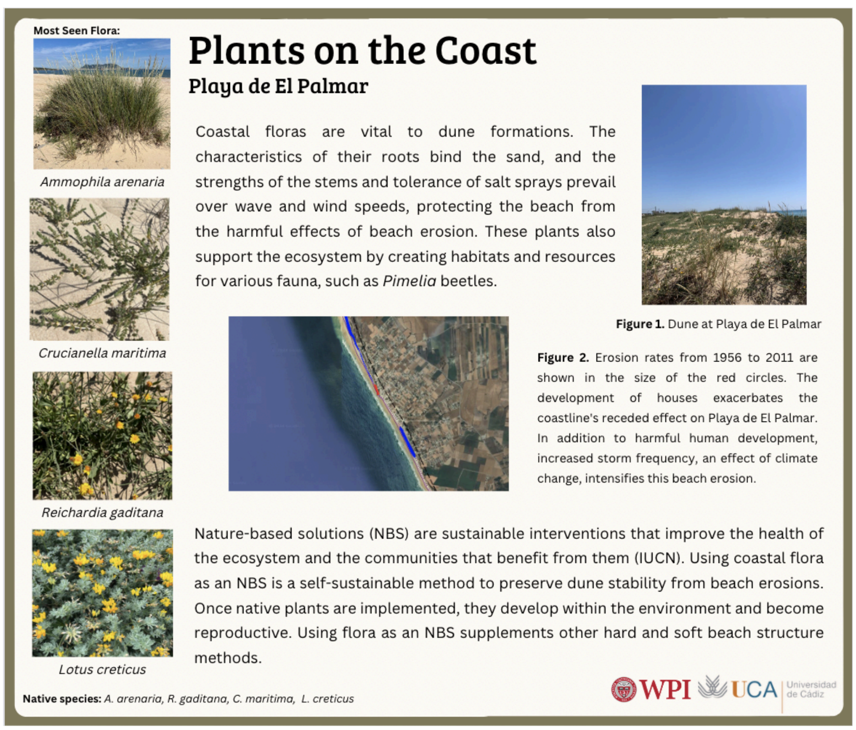
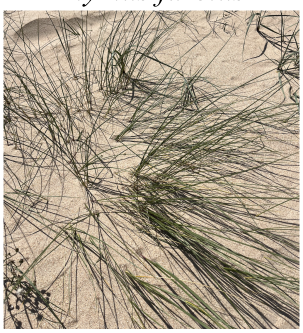


Figure 25. Informative signage implemented for Playa de El Palmar. The signage includes beach-specific information of species identification, erosion rates, views of the dunes, and the importance of using flora as a nature-based solution to mitigate beach erosion.

6.0.2 Targeted Recommendations for Playa El Rinconcillo

Because increased flora planting would only yield net positive impacts when the government completes its ongoing breakwater project to stabilize the beach, we focused our recommendation on protecting the dune system and the existing vegetation of Playa El Rinconcillo (Poullet, Personal Communication, 2024). These are our targeted recommendations:

1. Sand trap fences: We recommend sand trap fences to ensure that new and existing sand moved by the wind can be trapped. These fences should be made of natural materials because they are biodegradable and avoid soil contamination. We recommend the Giant reed (*Arundo donax*) because it is natural and easily accessible as it is local to Spain (Port of Valencia, 2021). Additionally, its dense structure is effective for capturing windblown sand. The sand fences should be 2 to 4 feet high and lifted and repositioned before the accumulating sand is 50% buried. The exact placement of the sand fence depends on wind measurement (Florida Department of Environmental Protection, n.d). Due to Playa El Rinconcillo's landscape and building infrastructure, it is difficult due to the narrow space between inland development and the start of the dunes. Nonetheless, the ideal placement is at the edge of the houses and restaurant building development, where the sand starts blowing inland.
2. Dune protection fences and signage: We saw that there weren't any protections and found a lot of human waste and forced paths on the dune vegetation. We recommend installing sturdy dune protection fencing around the entire dune perimeter to restrict foot traffic and prevent damage to vegetation. This would be around the beach's northern end, where the mass dune vegetation is. We recommend installing these fences around the perimeter of the existing foredune, closer to the water than the sand-trapping fences (G. Anfuso, Personal Communication, 2024). For material, we also recommend using woven brushwood constructed from willow. For added protection against foot traffic, we recommend signage at strategic points to explain the importance of dune preservation. Our team developed this informative signage with details encompassing all this, shown in Figures 26 and 27.
3. Flora as nature-based solution: Our team devised recommendations for which coastal flora species are best to integrate into Playa El Rinconcillo, serving as a nature-based solution to the beach's erosion problems. This list was determined by comparing collected densities of pioneer plant species between the Playa de Getares and Playa El Rinconcillo study sites on the eastern coast of the Cádiz province (Table 13). Other considerations are the plant's nativeness to ensure the plant's integration does not disrupt the existing ecosystem and the plant's overall structure and importance within the dune system to ensure the plant will positively grow and protect the dune. Table 15 depicts our team's recommendation for integrating flora below.

Playa El Rinconcillo: Flora Recommendations			
Species to be Implemented	Native to the Area	Plant Structure	Importance
Pancratium maritimum 	X	● Firm, elongated, twisted leaves. ● Deep grounded roots (to avoid drying).	● Pioneer plant that stands at the foot of dune. ● Resilient seeds with capsule and ability to float in water. ● Support fauna life (*Brithys crini*). ● Feasible plantation and thriving.
Elymus farctus 	X	● Forms sparse carpets with rhizomes, dense and fibrous horizontal root structures. ● Long stems accrete sand	● Pioneer plant that stands at the foot of dune. ● Facilitates other plant growth. ● Long stems reduce wind velocity. ● Sand-binding structures. ● Feasible plantation and thriving.

Note. Sourced from Herbari virtual del Mediterrani occidental (2019) and Diputacíon Provincial de Málaga (2024).

Table 15. Depicts the coastal flora species and their characteristics that our team recommended in using as nature-based solutions at Playa El Rinconcillo to preserve dune stability and combat beach erosion.

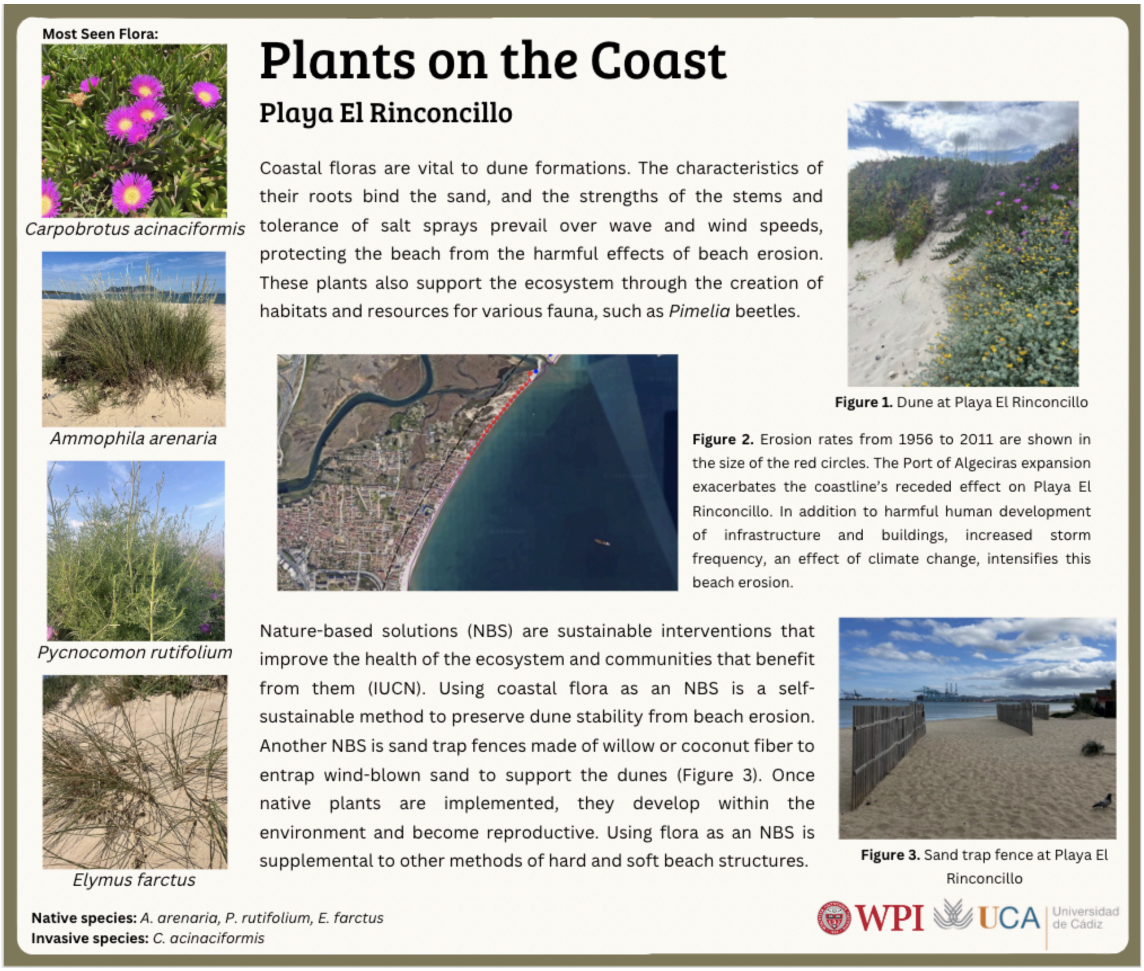


Figure 26. Signage implemented for Playa El Rinconcillo. The signage includes beach-specific information on species identification, erosion rates, dunes' views, and the importance of using flora as a nature-based solution to mitigate beach erosion.

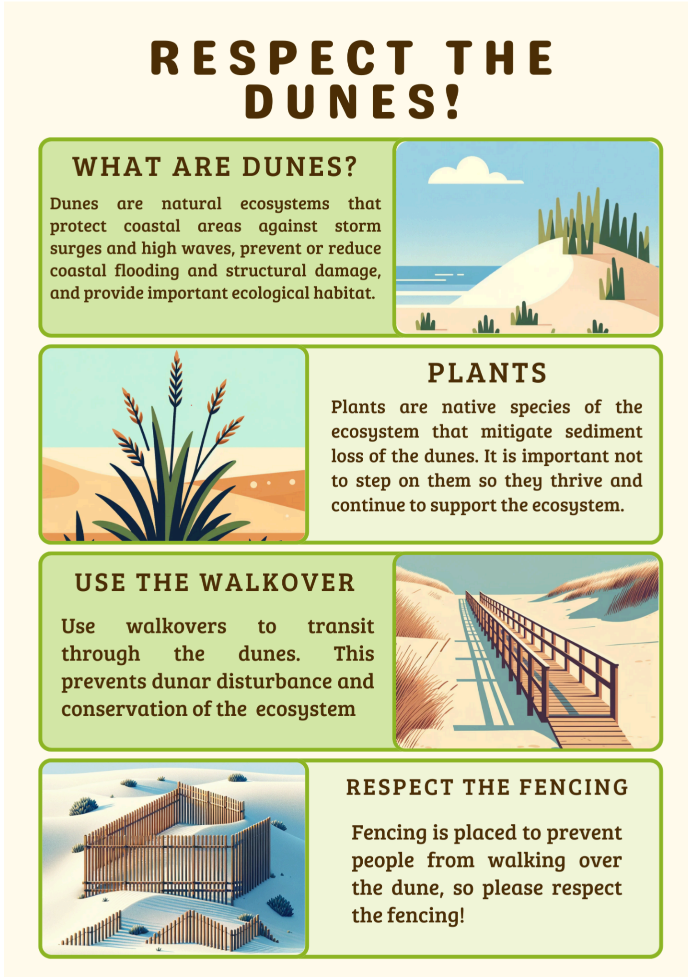


Figure 27. Illustrates informative signage to be implemented at any beach to raise dune protection awareness. It defines and specifies the role of dunes and flora and gives alternatives for preserving them.

Appendices

Appendix A: Interview Guide

This appendix details the interview guide used to gather data from the stakeholders regarding the use of native flora for erosion control for Cádiz beaches. The interviews were conducted between 13th March and 11th April, 2024. The average length of interview was 45 minutes.

Interview Participants:

A total number of 9 stakeholder participated in the interviewees. The participants included representatives from the following groups:

- Demarcatión de Costas de Atlántico (Cádiz): Dr Patricio Poullet
- Junta de Andalucia (Regional Government): José L. Reyes, the head
- Local Universities (Marine Biology/Ecology): Dr. Ignacio Hernández Carrero, researcher and professor at Centro Andaluz Superior de Estudios Maritimos (CASEM); Prof. Giorgio Anfuso, researcher at CASEM; Prof. Juan Vidal, CASEM; Professor Juan Miguel, CASEM; Prof. Fernando Ojeda, CASEM.
- Ecologia Litoral: Carlos Ley, owner
- Tecnoambiente: Jurgi Areizaga

Interview Structure:

The interview guide consisted of semi-structured questions designed to explore the participants' knowledge, perceptions, and experiences related to current coastal management practices, use of native flora for erosion control, and recommendations for implementation.

Interview Protocol:

- All interviews were conducted face-to-face or virtually using Zoom, with informed consent obtained before each interview.
- The interviews were audio-recorded with permission from the participants.
- The interviewer followed the interview guide but allowed for flexibility to explore topics raised by the interviewees in more detail.

Interview Consent Form

Interview with ______________________________
Date: _____________
Time:_____________________
Location: ___________________________
Attendee(s):____

Introduction and Informed Consent:

Hello,

We are a group of university students from Worcester Polytechnic Institute (WPI) located in Massachusetts, USA. We are currently working on a project in collaboration with the University of Cádiz, aimed at exploring flora as a nature-based solution to combat beach erosion in the Cádiz Province. We are conducting interviews with coastal management and environmental agencies to learn more about the current practices that are in place to understand the main challenges among these practices and how nature-based solutions could be integrated. We intend that our research will contribute insights to implement further policies to combat beach erosion and mitigate loss of biodiversity.

Your participation in this interview is entirely voluntary and you are free to withdraw from the interview and discontinue our discussion at any time. By signing this form, you would be giving us your permission to record this interview and your answers to utilize in our report. If you prefer, we can ensure the confidentiality of your answers by excluding your name, and any personal information that may be associated with any of your responses. If you would like, we are willing to provide you with the results at the end of the project. Feel free to contact our team at Cadiz_24_Coastal_Structures@wpi.edu.

_________________________ ____________________
Signature of Participant Date

Questions:
CMA: Coastal Management Agencies; EA: Environmental Agencies

Num	Questions	CMA	EA
1	Name and job position within the company		
2	Are you aware of any current practices that are in place to combat coastal and beach erosion? Can you describe them?	X	X
3	Do you think that these practices are effective? Why? From your organization's perspective, what are the biggest strengths and weaknesses of the current practices toward beach erosion?	X	X
4	How do these practices mitigate the environmental impacts due to beach erosion?	X	X
5	Are you familiar with the environmental concerns arising from the extensive development of the Port of Algeciras? How might authorities and agencies currently address these concerns?	X	X
6	What is the process behind the approval of coastal development concerning environmental impacts?	X	X
7	Are you aware of any nature-based solutions implemented to mitigate beach erosion control in other coastal regions? If so, can you name and explain them?	X	X
8	Would you envision the potential role of coastal flora as a nature-based solution, in mitigating some of the environmental concerns associated with port operations and beach erosion?	X	X
9	What challenges do you foresee in implementing flora as a nature-based solution to combat beach erosion?	X	X
10	If you were to implement a similar restoration project/nature-based solution, which product format would be most helpful to you? A planning outline, presentation, projections, etc.	X	X
11	Is there anything else you would like to mention that might be important for our project?	X	X

Table A1. This table depicts the team's interview questions.

Appendix B: Data Collection of Transect Walks

	Line 1					Line 2					Line 3				
Meters	Type 1	Type 2	Type 3	Type 4	Other	Type 1	Type 2	Type 3	Type 4	Other	Type 1	Type 2	Type 3	Type 4	Other
0-2											x				
2-4						x					x - 3.5m				
4-6		x - 1m				x - 3.5m									
6-8				x - 1m											
8-10	x - 2m														
10-12												x - 1m			
12-14															
14-16	x - 2m	x - 1m		x - 1.5m		x	x	x	x			x - 1m		x - 1m	
16-18								x	x		x - 3m	x - 3m			
18-20	x - 3m	x - 3m		x - 3m		x	x	x	x			x - 2m		x - 2m	
20-22						x	x	x	x					x	GP
22-24						x	x	x	x		x - 2m	x - 1m		x - 4m	GP
24-26	x	x				x - 9m	x - 9m	x - 11m	x - 11m						GP- (6m)
26-28	x	x								PP - 1m		x			GR
28-30	x - 5m	x - 3m				x - 2m	x - 2m					x - 2m			GR - 5m
30 +										PP - 2m					
Density per line:	40%	26.67%	0%	18.33%	0%	48.33%	36.67%	36.67%	36.67%	PP- 10%	28.33%	30%	0%	23.33%	GP - 20%
															GR - 16.66%

Specie Identification	
Type 1	Ammophila arenaria
Type 2	Pancratium maritimum
Type 3	Lotus creticus
Type 4	Crucianella maritima
Other	Genus Pistacia (GP)
	Genus Retama (GR)
	Pinus pinea (PP)

Table B1. Data collection table for the transect walk in Playa de Bolonia with calculated densities for each flora species for each transect line.

	Line 1					Line 2					Line 3				
Meters	Type 1	Type 2	Type 3	Type 4	Other	Type 1	Type 2	Type 3	Type 4	Other	Type 1	Type 2	Type 3	Type 4	Other
0-2					OD - 1m										
2-4	x	x		x	RG										
4-6	x - 1.5m	x - 1m		x - 3m	RG - 2m										
6-8					RG & CP										
8-10					RG - 3m & CP - 5m	x	x				x	x		x	
10-12	x - 2m		x - 2m	x - 2m	RG & GC	x - 2.5m	x - 2.5m		x	RG	x - 3m	x - 3m		x - 3m	
12-14				x - 1.5m	RG - 5m & GC - 5m	x - 1.5m			x - 1.5m	RG - 1.5m	x			x	EM
14-16	x		x	x	GC						x - 3.5m			x - 3.5m	EM - 3.5m
16-18	x		x	x	GC			x	x		x			x	
18-20	x - 2m		x - 4m	x - 4m	GC			x	x		x			x	
20-22			x - 1.5m		S - 1.5m, EM - 0.5m && GC - 7m			x	x	RG	x	x		x	EM & RG
22-24					ML		x	x	x	RG	x	x - 2.5m		x	EM - 3.5m & RG - 2.5m
24-26					ML		x - 4m	x	x	RG	x			x	
26-28					ML - 4.5m			x - 13m	x - 13m	RG - 8m	x - 10m			x - 12.5m	
28-30	x - 2m				CC - 2m				x - 1m	EM - 1m				x - 2m	LR - 2m
30 +	x														
Density per line:	25%	0%	25%	38%	S - 5%	13.33%	21.66%	43.33%	51.60%	RG - 31.66%	55%	18.33%	0%	70%	EM - 23.33%
					ML - 15%					EM - 3.33%					RG - 8.33%
					EM - 1.66%										LR - 6.66%
					CC - 6.66%										
					RG - 3.33%										
					CP - 16.67%										
					GC . 40%										
					OD - 0.33%										

Specie Identification	
Type 1	Ammophila arenaria
Type 2	Pancratium maritimum
Type 3	Lotus creticus
Type 4	Crucianella maritima
Other	Reichardia gaditana (RG)
	Silene (S)
	Eryngium maritimum (EM)
	Cyperus Capitatus (CC)
	Malcolmia littorea (ML)
	London Rocket (LR)
	Centaurea Polyacantha (KW)
	Glebionis coronaria (GC)
	Orobanche Densiflora (OD)

Table B2. Data collection table for the transect walk in Playa de El Palmar with calculated densities for each flora species for each transect line.

	Line 1							Line 2							Line 3						
Meters	Type 1	Type 2	Type 3	Type 4	Type 5	Type 6	Other	Type 1	Type 2	Type 3	Type 4	Type 5	Type 6	Other	Type 1	Type 2	Type 3	Type 4	Type 5	Type 6	Other
0-2						x - 1m			x - 2m	x - 2m						x					
2-4	x - 1.5m						EM - x		x - 1m				x - 1m	DP - 1m		x - 3m					
4-6						x - 0.5m	EM - 3m		x - 1.5m	x - 1.5m			x - 1.5m	EM - 1.5m		x - 1m	x - 1m	x			
6-8										x - 1.5m	x - 1.5m			EM - 1.5m		x - 2m	x - 2m	x - 3.5m			
8-10		x - 2m				x - 1m	EM - 0.5m			x - 1.5m			x - 1.5m	EM - 1.5m		x		x			
10-12		x - 1m	x - 1m						x - 1m				x - 1m			x - 4m	x - 2m	x - 2.5 m			
12-14		x					DP - 0.3m			x - 1.5m	x - 1.5m			EM - 1.5m		x - 1.5m	x - 1m	x - 0.5m			
14-16		x	x - 2m						x	x	x		x			x - 1.5m	x - 1.5m	x - 1m			
16-18		x - 4m				x			x - 2m	x - 2m	x - 2m		x - 2m			x - 2.5m				x - 0.5m	
18-20		x	x	x - 1.5m		x			x - 2m	x - 2m	x - 2m					x				x	CC - 0.5m
20-22		x	x			x			x	x						x - 2.5m	x - 0.5m			x - 2m	
22-24		x - 4.5m	x - 2m			x - 3m			x	x						x					
24-26		x - 2m			x	x	RG - 1m		x	x						x					
26-28		x - 1.5m			x - 2m	x - 1m			x	x						x - 3.5m	x - 1m	x - 1m			
28-30		x - 1.5m				x - 1.5 m			x - 3m	x - 2m				KW - 1m		x - 1.5m	x - 1.5m			x - 0.5m	
30 +														CC - 1.5m							
Density per line:	5%	55%	16.67%	5%	6.67%	26.67%	EM - 11.67%	0%	41.67%	46.67%	23.33%	0%	23.33%	DP - 3.33%	0%	76.67%	35%	28.33%	0%	10%	CC - 1.67%
							DP - 1%							EM - 20%							
							RG - 3.33%							KW - 3.33%							
														CC - 5%							

Specie Identification	
Type 1	Ammophila arenaria
Type 2	Elymus farctus
Type 3	Pancratium maritimum
Type 4	Lotus creticus
Type 5	Crucianella maritima
Type 6	Silene
Other	Eryngium maritimum (EM)
	Daucus pumilus (DP)
	Centaurea Polyacantha (KW)
	Cyperus Capitatus (CC)
	Reichardia gaditana (RG)

Table B3. Data collection table for the transect walk in the Playa de Getares with calculated densities for each flora species for each transect line.

Line 1

Meters	Type 1	Type 2	Type 3	Type 4	Type 5	Other
0-2		x			x	
2-4		x			x	RG
4-6		x - 4m			x - 1m	RG - 1m
6-8	x					
8-10	x					
10-12	x					D - 1.5m & AM
12-14	x - 8m					AM - 2m & KW - 1m
14-16			x - 1m			AM - 1.5m
16-18						
18-20	x		x			
20-22	x		x			
22-24	x - 6m		x - 6m			
24-26						HS
26-28		x			x	HS - 3m
28-30		x - 3m			x - 3m	
30 +						
Density per line:	46.67%	23.33%	23.33%	0%	13.33%	D - 5%
						AM - 16.67%
						KW - 3.33%
						RG - 3.33%
						HS - 10%

Line 2

Meters	Type 1	Type 2	Type 3	Type 4	Type 5	Other
0-2						
2-4		x	x		x	B & RG
4-6		x	x		x	B & RG
6-8		x	x		x	B & RG
8-10		x - 1m	x - 2.5m		x - 5m	B - 3.5m & RG - 2m
10-12	x		x		x	
12-14	x - 2.5m		x - 2.5m		x - 2.5m	
14-16	x - 1.5m			x - 2.5m		CC - 1.5m
16-18	x	x	x - 1m			
18-20	x - 2.5m	x - 3m		x - 2.5m		
20-22		x - 3m	x - 3m			
22-24						
24-26	x - 2m			x - 2m		CC - 2m
26-28						
28-30						
30 +						
Density per line:	28.33%	23.33 %	30%	23.33%	25.00%	B - 11.67%
						RG - 6.67%
						CC - 11.67%

Line 3

Meters	Type 1	Type 2	Type 3	Type 4	Type 5	Other
0-2						
2-4						
4-6						
6-8	x		x			
8-10	x - 3.5m		x - 2m			
10-12						
12-14			x - 1m			PM - 1m
14-16		x				CC
16-18		x				CC
18-20		x - 5m				CC - 1m
20-22						
22-24						
24-26						
26-28						
28-30	x - 1m	x - 2m				D - 1m
30 +						
Density per line:	15%	23.33%	10%	0%%	15%	PM - 3.33%
						CC - 3.33%
						D - 3.33%

Specie Identification	
Type 1	*Carpobrotus acinaciformis*
Type 2	*Ammophila arenaria*
Type 3	*Pycnocomon rutifolium*
Type 4	*Elymus farctus*
Type 5	*Lotus creticus*
Other	*Pancratium maritimum (PM)*
	Reichardia gaditana (RG)
	Dittrichia (D)
	Centaurea Polyacantha (KW)
	Anthemis maritima (AM)
	Cyperus Capitatus (CC)
	Bromus (B)
	Helichrysum Stoechas (HS)

Table B4. Data collection table for the transect walk in Playa El Rinconcillo with calculated densities for each flora species for each transect line.

Appendix C: Granularity Tests Excel Sheets

ANALISIS GRANULOMETRICO POR TAMIZADO

Trabajo:

Muestra: Playa Bolonia **Fecha:** 18-abr

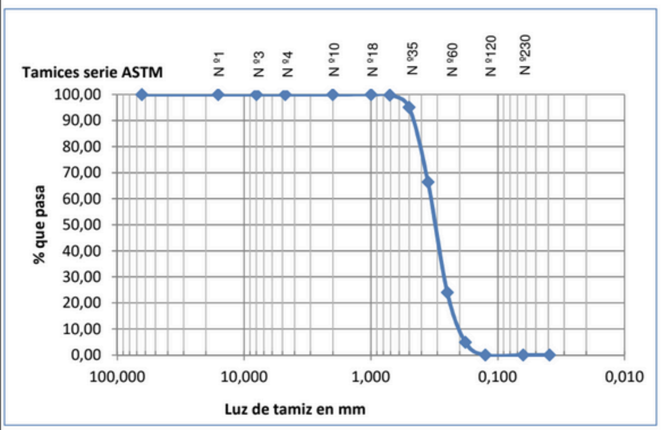
Localización:

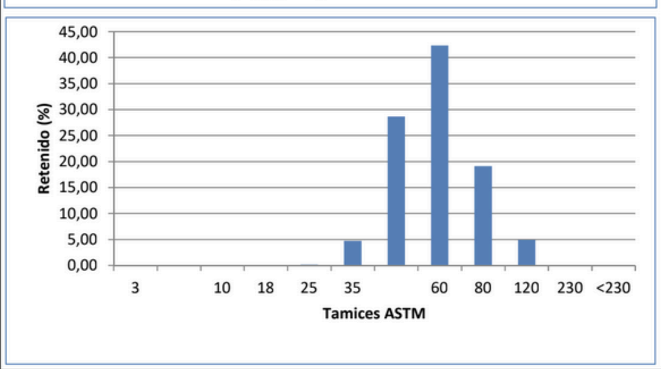
Nº TAMIZ (ASTM)	Luz de malla (mm)	muestra (gr)	% Retención	% Retenido acumulado	% Que pasa acumulado
	64,000	0,00	0,00	0,00	100,00
1	16,000	0,00	0,00	0,00	100,00
3	8,000	0,00	0,00	0,00	100,00
	4,750	0,00	0,00	0,00	100,00
10	2,000	0,00	0,00	0,00	100,00
18	1,000	0,00	0,00	0,00	100,00
25	0,710	0,20	0,20	0,20	99,80
35	0,500	4,70	4,73	4,93	95,07
	0,355	28,50	28,67	33,60	66,40
60	0,250	42,10	42,35	75,96	24,04
80	0,180	19,00	19,11	95,07	4,93
120	0,125	4,90	4,93	100,00	0,00
230	0,063	0,00	0,00	100,00	0,00
<230	0,039	0,00	0,00	100,00	0,00
	Total muestra	99,4			

COORDENADAS ETR89 (HUSO 29)	
x=	789.568
y=	4.562.325
z (m)=	10,0

D_5 (mm):	0,500
D_{16} (mm):	0,444
D_{25} (mm):	0,399
D_{50} (mm):	0,314
D_{75} (mm):	0,252
D_{84} (mm):	0,221
D_{95} (mm):	0,180

ø (D_5):	1,00
ø (D_{16}):	1,17
ø (D_{25}):	1,33
ø (D_{50}):	1,67
ø (D_{75}):	1,99
ø (D_{84}):	2,18
ø (D_{95}):	2,47





CATEGORIA	%
Gravas (<2 mm)	0,00
Arenas (2-0,063 mm)	100,00
Lutitas (<0,063 mm)	0,00

Observaciones:

Figure C1. Granularity test Excel Sheet to find D50 of sand for Playa de Bolonia.

ANALISIS GRANULOMETRICO POR TAMIZADO

Trabajo:

Muestra: El Palmar **Fecha:** 18-abr

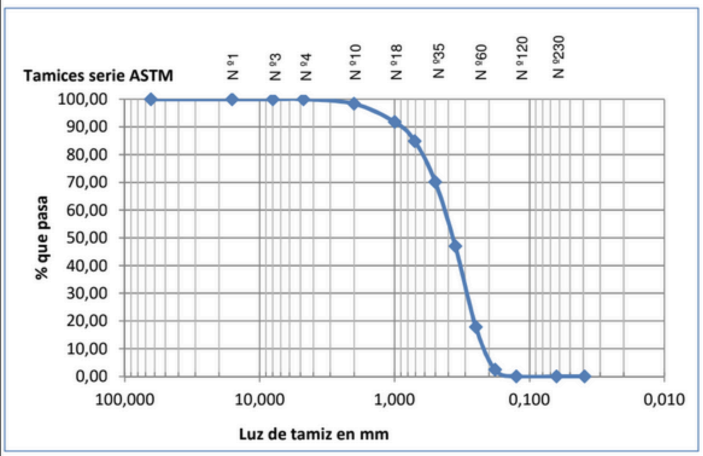
Localización:

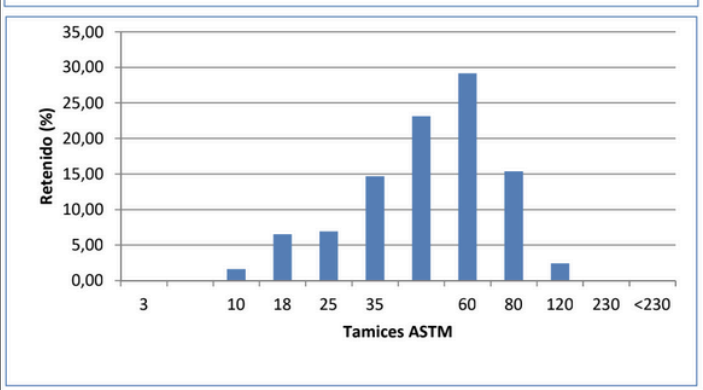
Nº TAMIZ (ASTM)	Luz de malla (mm)	muestra (gr)	% Retención	% Retenido acumulado	% Que pasa acumulado
	64,000	0,00	0,00	0,00	100,00
1	16,000	0,00	0,00	0,00	100,00
3	8,000	0,00	0,00	0,00	100,00
	4,750	0,00	0,00	0,00	100,00
10	2,000	1,60	1,63	1,63	98,37
18	1,000	6,40	6,53	8,16	91,84
25	0,710	6,80	6,94	15,10	84,90
35	0,500	14,40	14,69	29,80	70,20
	0,355	22,70	23,16	52,96	47,04
60	0,250	28,60	29,18	82,14	17,86
80	0,180	15,10	15,41	97,55	2,45
120	0,125	2,40	2,45	100,00	0,00
230	0,063	0,00	0,00	100,00	0,00
<230	0,039	0,00	0,00	100,00	0,00
	Total muestra	98			

COORDENADAS ETR89 (HUSO 29)	
x=	789.568
y=	4.562.325
z (m)=	10,0

D_5 (mm):	1,484
D_{16} (mm):	0,697
D_{25} (mm):	0,569
D_{50} (mm):	0,374
D_{75} (mm):	0,276
D_{84} (mm):	0,242
D_{95} (mm):	0,192

ø (D_5):	-0,57
ø (D_{16}):	0,52
ø (D_{25}):	0,81
ø (D_{50}):	1,42
ø (D_{75}):	1,86
ø (D_{84}):	2,05
ø (D_{95}):	2,38





CATEGORIA	%
Gravas (<2 mm)	1,63
Arenas (2-0,063 mm)	98,37
Lutitas (<0,063 mm)	0,00

Observaciones:

Figure C2. Granularity test Excel Sheet to find D50 of sand for Playa de El Palmar.

ANALISIS GRANULOMETRICO POR TAMIZADO

Trabajo:

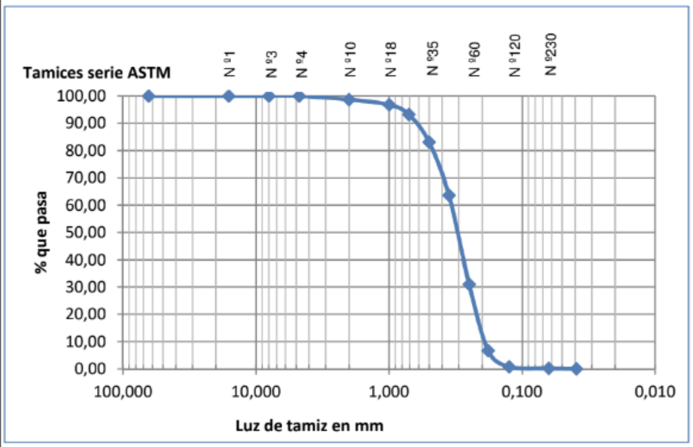
Muestra: Playa de Getares **Fecha:** 18-abr
Localización:

Nº TAMIZ (ASTM)	Luz de malla (mm)	muestra (gr)	% Retención	% Retenido acumulado	% Que pasa acumulado
	64,000	0,00	0,00	0,00	100,00
1	16,000	0,00	0,00	0,00	100,00
3	8,000	0,00	0,00	0,00	100,00
	4,750	0,00	0,00	0,00	100,00
10	2,000	1,30	1,30	1,30	98,70
18	1,000	1,90	1,90	3,21	96,79
25	0,710	3,60	3,61	6,81	93,19
35	0,500	10,10	10,12	16,93	83,07
	0,355	19,40	19,44	36,37	63,63
60	0,250	32,60	32,67	69,04	30,96
80	0,180	24,20	24,25	93,29	6,71
120	0,125	5,90	5,91	99,20	0,80
230	0,063	0,60	0,60	99,80	0,20
<230	0,039	0,20	0,20	100,00	0,00
	Total muestra	99,8			

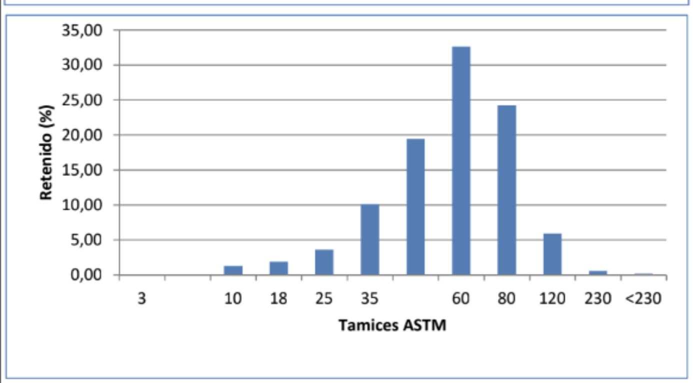
COORDENADAS ETR89 (HUSO 29)	
x=	789.568
y=	4.562.325
z (m)=	10,0

D_{5} (mm):	0,856
D_{16} (mm):	0,519
D_{25} (mm):	0,440
D_{50} (mm):	0,311
D_{75} (mm):	0,233
D_{84} (mm):	0,207
D_{95} (mm):	0,164

ø (D_{5}):	0,22
ø (D_{16}):	0,95
ø (D_{25}):	1,18
ø (D_{50}):	1,68
ø (D_{75}):	2,10
ø (D_{84}):	2,27
ø (D_{95}):	2,61



CATEGORIA	%
Gravas (<2 mm)	1,30
Arenas (2-0,063 mm)	98,50
Lutitas (<0,063 mm)	0,20



Observaciones:

Figure C3. Granularity test Excel Sheet to find D50 of sand for Playa de Getares.

ANALISIS GRANULOMETRICO POR TAMIZADO

Trabajo:

Muestra: Playa del Rinconcillo **Fecha:** 18-abr

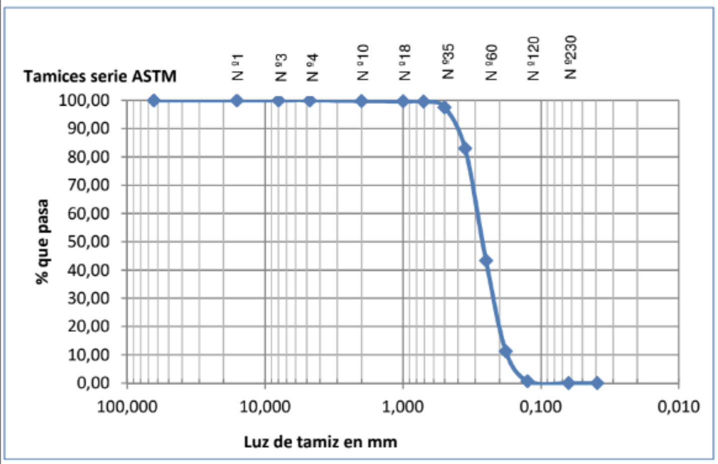
Localización:

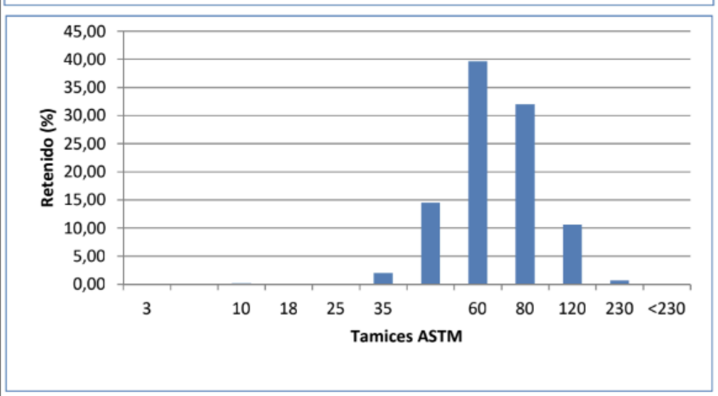
Nº TAMIZ (ASTM)	Luz de malla (mm)	muestra (gr)	% Retención	% Retenido acumulado	% Que pasa acumulado
	64,000	0,00	0,00	0,00	100,00
1	16,000	0,00	0,00	0,00	100,00
3	8,000	0,00	0,00	0,00	100,00
	4,750	0,00	0,00	0,00	100,00
10	2,000	0,20	0,20	0,20	99,80
18	1,000	0,10	0,10	0,30	99,70
25	0,710	0,10	0,10	0,40	99,60
35	0,500	2,00	2,02	2,42	97,58
	0,355	14,40	14,55	16,97	83,03
60	0,250	39,30	39,70	56,67	43,33
80	0,180	31,70	32,02	88,69	11,31
120	0,125	10,50	10,61	99,29	0,71
230	0,063	0,70	0,71	100,00	0,00
<230	0,039	0,00	0,00	100,00	0,00
	Total muestra	**99**			

COORDENADAS ETR89 (HUSO 29)	
x=	789.568
y=	4.562.325
z (m)=	10,0

D_{5} (mm):	0,474
D_{16} (mm):	0,365
D_{25} (mm):	0,334
D_{50} (mm):	0,268
D_{75} (mm):	0,210
D_{84} (mm):	0,190
D_{95} (mm):	0,147

ø (D_{5}):	1,08
ø (D_{16}):	1,46
ø (D_{25}):	1,58
ø (D_{50}):	1,90
ø (D_{75}):	2,25
ø (D_{84}):	2,39
ø (D_{95}):	2,76





CATEGORIA	%
Gravas (<2 mm)	0,20
Arenas (2-0,063 mm)	99,80
Lutitas (<0,063 mm)	0,00

Observaciones:

Figure C4. Granularity test Excel Sheet to find D50 of sand for Playa de El Rinconcillo.

Appendix D: Informative Dune Signage

Figure D1. Informative signage implemented for Playa de El Palmar translated in Spanish. The signage includes beach-specific information on species identification, erosion rates, dunes' views, and the importance of using flora as a nature-based solution to mitigate beach erosion.

Figure D2. Informative signage implemented for Playa El Rinconcillo translated in Spanish. The signage includes beach-specific information on species identification, erosion rates, dunes' views, and the importance of using flora as a nature-based solution to mitigate beach erosion.

Figure D3. Illustrates signage to be implemented at any beach to raise dune protection awareness, translated in spanish. It defines and specifies the role of dunes and flora and gives alternatives for preserving them.

References

Ammopila arenaria. GISD. (2010). https://www.iucngisd.org/gisd/species.php?sc=1518

APBA. (n.d.). Algeciras Port. Stats. https://www.apba.es/en/stats

Bertoni, Duccio, et al. "Implementing a coastal dune vulnerability index (CDVI) to support coastal management in different settings (Brazil and Italy)." Ocean & Coastal Management 180 (2019): 104916.

Contreras de Villar, Antonio (2017). “Parámetros de diseño para el perfil de aportación en regeneraciones de playas, en mares con marea, basados en datos de campo del litoral gaditano”.Universidad de Cádiz. Departamento de Física Aplicada. https://produccioncientifica.uca.es/documentos/5febd92e5ef7446310f94df4

Contreras de Villar, Francisco (2017). “Validación de escorias de horno de arco eléctrico mediante su uso como adición en hormigón”. Universidad de Málaga. https://produccioncientifica.uca.es/documentos/5febd9355ef7446310f950fc

Cooper, J.A.G., et al. “Identifying Storm Impacts on an Embayed, High-Energy Coastline: Examples from Western Ireland.” *Identifying Storm Impacts on an Embayed, High-Energy Coastline: Examples from Western Ireland*, Elsevier, 15 Sept. 2004, www.sciencedirect.com/science/article/abs/pii/S0025322704001409.

Davis, J. H. (1975). Stabilization of beaches and dunes by vegetation in Florida.

de Andrés, M., Barragán, J. M., & García Sanabria, J. (2018). Ecosystem Services and urban development in coastal social-ecological systems: The Bay of Cádiz case study. Ocean & Coastal Management, 154, 155–167. https://doi.org/10.1016/j.ocecoaman.2018.01.011

Dempwolff, L.-C., Melling, G., Windt, C., Lojek, O., Martin, T., Holzwarth, I., Bihs, H., & Goseberg, N. (2022). Loads and effects of ship-generated, drawdown waves in confined waterways - a review of current knowledge and methods. Journal of Coastal and Hydraulic Structures. https://doi.org/10.48438/jchs.2022.0013

Domínguez, Leovaldo & Gracia, F. & Anfuso, Giorgio. (2007). Evaluación de la vulnerabilidad del litoral noroeste de la provincia de Cádiz frente a la erosión. Territoris. 7. 99-113.

“Ecocartografía de Cádiz.” *Ministerio Para La Transición Ecológica y El Reto Demográfico*, Ministerio de Agricultura, Alimentación y Medio Ambiente, 14 Feb. 2013, www.miteco.gob.es/es/costas/temas/proteccion-costa/ecocartografias/ecocartografia-cadiz.html.

Environmental Protection Agency. (2021, August 16). *Spain Climate Resilience Policy Indicator*. EPA. https://www.iea.org/articles/spain-climate-resilience-policy-indicator

Feagin, R. A., Furman, M., Salgado, K., Martinez, M. L., Innocenti, R. A., Eubanks, K., … & Silva, R. (2019). The role of beach and sand dune vegetation in mediating wave run up erosion. Estuarine, Coastal and Shelf Science, 219, 97-106.

Figlus, J., Sigren, J.M., Armitage, A.R., & Tyler, R.C. (2014). Erosion of Vegetated Coastal Dunes. https://pdfs.semanticscholar.org/efa9/41cc39faea075d859b2f8c5ec6fea364e4c8.pdf

Florida Department of Environmental Protection. (n.d.). Sand Fencing Guidelines. https://floridadep.gov/sites/default/files/Sand-Fencing-Guidelines-2020.pdf

F. Javier Gracia, Javier Benavente, Carlos Alonso Villalobos, Juan Lomas. (2011)Las dunas en España. Sociedad Española de Geomorfología. https://www.researchgate.net/publication/278023458_Las_dunas_del_litoral_gaditano

Gallego-Fernández, J. B., Sánchez, I. A., & Ley, C. (2011). Restoration of isolated and small coastal sand dunes on the rocky coast of northern Spain. *Ecological Engineering*, *37*(11), 1822–1832. https://doi.org/10.1016/j.ecoleng.2011.06.017

Gregorio Gómez-Pina, Juan J. Muñoz-Pérez, Jose L. Ramírez, Carlos Ley. (2002). Sand dune management problems and techniques, Spain. J. of Coastal Research, 36(sp1):325-332. https://bioone.org/journals/journal-of-coastal-research/volume-36/issue-sp1/1551-5036-36.sp1.325/Sand-dune-management-problems-and-techniques-Spain/10.2112/1551-5036-36.sp1.325.full?tab=ArticleLinkCited

Halkos, George, and Steriani Matsiori. "Determinants of Willingness to Pay for Coastal Zone Quality Improvement." *The Journal of Socio-Economics*, North-Holland, 17 Apr. 2012,www.sciencedirect.com/science/article/abs/pii/S1053535712000303?via%3Dihub.

Hanley, M. E., Bouma, T. J., & Mossman, H. L. (2020). The gathering storm: optimizing management of coastal ecosystems in the face of a climate-driven threat. *Annals of Botany*, *125*(2), 197–212. https://doi.org/10.1093/aob/mcz204

Herbari virtual del Mediterrani occidental. (2019, October 8). http://herbarivirtual.uib.es/

Houston, J. R. (2002). *The economic value of beaches*. Florida Shore & Beach Preservation Association.

Houston, J. R. (2008). The economic value of beaches: a 2008 update. *Shore and Beach*, *76*(3), 22-26.

Houston, J. R. (2013). *The economic value of beaches: a 2013 update*. American Shore & Beach Preservation Association.

Interreg Mediterranean. (n.d.-b). Enhancing mediterranean coastal resilience https://www.act4posidonia.eu/pdfs/94/iucn-coastalresilience.pdf

Junta de Andalucía. (n.d.). Tarifa - Espacios Naturales - Duna de Bolonia. https://www.andalucia.org/es/tarifa-espacios-naturales-duna-de-bolonia

Kearney, John & Charles, Anthony & Pinkerton, Evelyn & Wiber, Melanie. (2007). The Role of Participatory Governance and Community-Based Management in Integrated Coastal and Ocean Management in Canada. Coastal Management - COAST MANAGE. 35. 79-104. 10.1080/08920750600970511.

Kraus, Nicholas C., and Francis A. Galgano. "Defense Technical Information Center." *Beach Erosion Hot Spots: Types, Causes and Solutions*, US Army Corps of Engineers, Sept. 2001, apps.dtic.mil/sti/tr/pdf/ADA588792.pdf.

Komar, P. D. (1998). Beach processes and sedimentation (2nd ed.). Prentice Hall.

Lodha, B. C. (2012). Decomposition of digested litter. Biology of plant litter decomposition, 1, 213-241.

Las dunas de El Rinconcillo, en peligro (2020). 8Directo. https://www.8directo.com/destacadas/las-dunas-de-el-rinconcillo-en-peligro_126345_102.html

LSU Center for GeoInformatics. *Beach: A River of Sand*, Youtube, 6 Sept. 2011, www.youtube.com/watch?v=FqT1g2riQ30&t=6s.

Meldahl, Keith. Wave Refraction, YouTube, 18 Dec. 2011, www.youtube.com/watch?v=G1FIBuybN78&list=PLlEhiDmxNumd9xacUshvovBDjWf2FmL4p&index=4.

Merckx, R., Diels, J., Vanlauwe, B., Sanginga, N., Denef, K., & Oorts, K. (2001). Soil organic matter and soil fertility. Sustaining soil fertility in West Africa, 58, 69-89.

MITECO, & Uceda Cendrero , A. (n.d.). Impacts on coastal areas. https://www.miteco.gob.es/es/cambio-climatico/temas/impactos-vulnerabilidad-y-adaptacion/11_Impacts%20on%20coastal%20areas_ing_tcm30-178525.pdf

Moreno Saiz, Juan Carlos, et al. "(PDF) Plant Conservation in Spain: Strategies to Halt the Loss ..." *ResearchGate*, June 2018, www.researchgate.net/publication/326068030_Plant_Conservation_in_Spain_strategies_to_halt_the_loss_of_plant_diversity.

Muñoz Pérez JJ.(1997). Analysis of the morphology and variability of beaches supported by rocky slabs. Cadiz University. https://produccioncientifica.uca.es/documentos/5ebf1f002999524bdf7a1057

Muñoz Pérez, Juan José, et al. "Strategies for Coastal Protection for the Provinces of Cádiz, Málaga and Almería Considering the Effects of Climate Change." *Strategies for Coastal Protection for the Provinces of Cádiz, Málaga and Almería Considering the Effects of Climate Change | Proxectos - Universidad de Cádiz*, Producción Científica, 21 Feb. 2021, produccioncientifica.uca.es/proyectos/53426/detalle?lang=gl

National Geographic Education. (n.d.). Dune. Retrieved from https://education.nationalgeographic.org/resource/dune/

Pérez, Rosario. *"Salvemos Rinconcillo": El Rinconcillo Residents Unite to Save Beach & Palmones Marsh*, ReachExtra, 15 Oct. 2020, reachextra.com/salvemos-rinconcillo/.

Pérez, Rosario. *Vecinos de El Rinconcillo Se Unen Para Salvar Su Playa y Las Marismas de Palmones*, Reach Alcance, 15 Oct. 2020, reachextra.com/es/salvemos-rinconcillo/.

Playa de El Palmar En Cádiz., Apartamentos Conil, 28 Dec. 2023, www.apartamentosconil.es/playa-del-palmar/.

Port of Valencia, *The Port of Valencia to restore the dune system of La Creu Beach in El Saler*. Valenciaport. (2021, February 7). https://www.valenciaport.com/en/the-port-of-valencia-to-restore-the-dune-system-of-la-creu-beach-in-el-saler/

Prieto-Campos, Antonio, et al. *Methodology for Improving the Analysis, Interpretation, and Geo-Visualisation of Erosion Rates in Coastal Beaches-Andalusia, Southern Spain*, Multidisciplinary Digital Publishing Institute, 5 Sept. 2018, www.mdpi.com/2076-3263/8/9/335.

Putten, W. H. van der. (1989, June 14). *Establishment, growth and degeneration of Ammophila Arenaria in coastal sand dunes*. Research@WUR. https://research.wur.nl/en/publications/establishment-growth-and-degeneration-of-ammophila-arenaria-in-co

Reguero, B. G. *Depiction of Longshore Current and Longshore Drift*, Research Gate, www.researchgate.net/figure/Depiction-of-longshore-current-and-longshore-drift_fig9_316688450. Accessed 4 Apr. 2024.

Roberts, Callum M., et al. "Climate Change Mitigation and Nature Conservation Both Require ..." *Climate Change Mitigation and Nature Conservation Both Require Higher Protected Area Targets*, The Royal Society, 27 Jan. 2020, royalsocietypublishing.org/doi/10.1098/rstb.2019.0121.

Rosa Molina, Giorgio Manno, Carlo Lo Re, Giorgio Anfuso. (2020). Dune Systems' Characterization and Evolution in the Andalusia Mediterranean Coast (Spain). Department of Engineering, University of Palermo.

https://iris.unipa.it/retrieve/71d2bd2c-c073-4bf6-b0bd-b914e26b074f/water-12-02094-v2.pdf

Roze, Françoise & Lemauviel-Lavenant, Servane. (2004). Sand Dune Restoration in North Brittany, France: A 10‐Year Monitoring Study. Restoration Ecology. 12. 29 - 35. 10.1111/j.1061-2971.2004.00264.x.

Sand Dunes. Scottish Seabird Centre. (2024). https://www.seabird.org/habitats/sand-dunes

Sea daffodil (pancratium maritimum), Coastal Path. Diputacíon Provincial de Málaga. (2024). https://www.malaga.es/en/laprovincia/naturaleza/lis_cd-10002/azucena-de-mar-pancratium-maritimum-senda-litoral

Secretariat of the Convention on Biological Diversity. (n.d.). *Status and trends of biodiversity, including benefits from biodiversity and ecosystem services*. Convention on Biological Diversity. https://www.cbd.int/countries/profile?country=es

Sigren, J. M., Figlus, J., & Armitage, A. R. (2014). Coastal sand dunes and dune vegetation: restoration, erosion, and storm protection. Shore Beach, 82(4), 5-12.

Society for Ecological Restoration. (n.d.). France: Dune Restoration in North Brittany. Retrieved from https://old.ser-rrc.org/project/france-dune-restoration-in-north-brittany/

"Spain Country Information." *Natucate*, www.natucate.com/en/destinations/travel-guide-spain. Accessed 24 Apr. 2024.

"Spain Is Feeling the Impacts of the Climate Crisis – and It Is Fighting Back." *The Climate Reality Project*, The Climate Reality Project, 27 Nov. 2019, www.climaterealityproject.org/blog/spain-feeling-impacts-climate-crisis-and-it-fighting-back.

"17.1 Understanding Diffraction and Interference." *17.1 Understanding Diffraction and Interference*, Texas Gateway, www.texasgateway.org/resource/171-understanding-diffraction-and-interference. Accessed 26 Feb. 2024.

UN Environment Programme (UNEP). (n.d.). UN Environment Programme and Nature-Based Solutions. https://www.unep.org/unga/our-position/unep-and-nature-based-solutions

Van Loon-Steensma, J. M., & Schelfhout, H. A. (2017). Wide Green Dikes: A sustainable adaptation option with benefits for both nature and landscape values?. Land Use Policy, 63, 528-538.

Vegetative Survey Transect Procedure, Colorado Department of Transportation, 29 June 2023, www.codot.gov/programs/environmental/landscape-architecture/swmp/vegetative-transect-procedure-1-1.pdf.

Washington State Aquatic Habitat. (n.d.). Marine Shoreline Design Guidelines. https://wdfw.wa.gov/sites/default/files/publications/01583/wdfw01583.pdf

Werner, P. A. (1977). Plant ecological studies in the dune vegetation of Bolonia (Southern Spain). Vegetatio, 56(2), 65-78. https://doi.org/10.1007/BF01552874

World Bank. (2022, May 19). What you need to know about nature-based solutions to climate change. https://www.worldbank.org/en/news/feature/2022/05/19/what-you-need-to-know-about-nature-based-solutions-to-climate-change