ONE-YEAR EVOLUTION OF A MEDITERRANEAN SANDY BEACH WITH *POSIDONIA OCEANICA* BANQUETTES (ARBOREA, SARDINIA, ITALY)

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Abstract: Sandy coasts represent 40 % of global shorelines and are essential for coastal protection and for their eco-biological value. Natural solutions are increasingly studied to provide beach protection while enhancing ecosystem services, such as seagrass protection and planting. This study investigates the morphological evolution of a beach characterised by a low human impact, where *Posidonia oceanica* is present and forms banquettes. Fieldwork campaigns, including topographic surveys and drone mapping, were conducted over a period of 1.5 years. During one of the campaigns a storm led to the formation of extensive Posidonia banquettes, particularly in the southern part of the beach, a trend that was observed in all surveys. This distribution influenced erosion trends, with long medium-term analysis showing overall erosion, especially in northern areas with fewer banquettes and a dune retreat of around 3 meters. These findings highlight the critical role of Posidonia banquettes in protecting the dunes from erosion, at least locally, although significant erosion over 1.5 years occurred in the whole studied area, suggesting that further investigations are needed.

Keywords: *Posidonia oceanica*; Banquettes; Beach Morphology; Coastal Storms; Geomorphological evolution.

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Introduction

Sandy coasts represent 40 % of the world's coastline [1], making them the first line of defences from storm events. They have an important eco-biological value and are essential for the conservation of dune ecosystems. They also provide multiple services, including to the local economy [2]. The characteristics of sandy beaches can vary depending on wave exposure, tidal regime and several other factors, such as the presence of inlets, promontories and cliffs [3], which leads to different beach morphologies. A highly influential factor controlling a beach's morphological response is sediment supply. In the last century, human interventions have highly affected sediment transport due to the construction of beach protections, dams, and other infrastructures, limiting longshore transport and the supply from rivers [4]. The lack of sediment can lead to changes in beach dynamics and beach retreat in the medium term, affecting the response of the beach to short-term coastal events, such as coastal storms [4].

The beach morphology is highly susceptible to coastal storms, whose frequency and intensity vary seasonally. During the winter months, the storm influence is higher, resulting in a so-called winter beach profile, while during the summer months, the beach presents a summer beach profile [4]. The typical winter beach profile corresponds to a steeper slope and narrower beach profile, while during summer, the opposite condition occurs[5]. If a beach does not have the proper sediment supply to recover from the storm impact, which can remove sand from the beach cell, long-term erosion may occur [4].

During the last decades, several studies were carried out to identify the most efficient methods to mitigate the impact of storms on the beach without affecting beach ecosystems. In many cases, building "grey" structures to reduce erosional trends might indirectly affect the equilibrium of nearby systems. Since hard coastal defences are becoming unsuitable due to high maintenance costs and undesired ecological impacts [6], natural "green" solutions are preferred to reduce beach erosion [7], such as introducing seagrass to mitigate the wave action on the shoreface. Seagrass provides high ecological value to the area as it represents an ecosystem service (e.g. first producers, acting as a nursery and home to different species ranging from foraminifers to macrozoobenthos) [7,8]. Seagrass meadows' presence improves sediment production and trapping and can mitigate the effects of waves on the beach by attenuating the wave height and the currents associated with it, either in normal or extreme conditions [9–12]. Although some studies have investigated how the seagrass influences the beach response during an extreme event, more in-depth investigations are needed.

A typical seagrass species present in the Mediterranean Sea is the *Posidonia oceanica*, which has been studied throughout the years [7,13–23]. It has medium-height leaves between 30 cm and 40 cm and can be found in depths up to 40 m [8,19]. The *Posidonia oceanica* is also known for forming banquettes on the emerged beach [16,20,24–28]. Banquettes are produced by the deposition of dead seagrass leaves on the beach, often creating a compact and cohesive mound on the shoreface (Figure 1). These structures and the meadows of Posidonia are responsible for the mitigation of wave action and beach erosion [14,20,24,27,29]. The presence of banquettes can be important in controlling beach morphology, especially during extreme events. However, due to their visual impact on beach users and tourists, banquettes of *Posidonia oceanica* are often removed as people dislike of its presence on the beach. However, since a certain amount of sediment is trapped in the banquettes, a portion of the total sediment budget is lost out of the system [24,27,28], exacerbating the negative effects of removing a natural beach protection layer.

Figure 1 – *Posidonia oceanica* banquettes (Arborea Beach, refer to Figure 2 for the location).

An example of a beach characterised by the presence of unaltered banquettes is Arborea Beach, located in the Gulf of Oristano on the western coast of Sardinia (Italy) (Figure 2a). The Gulf of Oristano is a semi-enclosed embayment with a depth average of 15 m and a maximum depth of 25 m, with a total area of 150 km^2 characterised by salt marsh systems and lagoons located between an industrial harbour and a touristic-fishermen harbour in the northern portion. The Gulf is exposed to three different wind regimes from the northwest (Mistral, the most common), Southwest (Libeccio) and Southeast (Sirocco). The area has a microtidal regime with a maximum range of 20 cm (+/-10 cm) [30]. The Gulf of Oristano presents a high amount of Posidonia meadows, covering around 70 % of the seabed [31]. Arborea Beach, located in the southern part of the Gulf of Oristano, was selected because of the presence of banquettes of Posidonia (Figure 2b). Due to its positioning, the beach is more exposed to waves from the NW.

Human infrastructures are found on Arborea Beach, such as a road and a car park crossing the dunes, some walking paths on the dunes, and a bunker from WWII located on the beach. Nevertheless, the *Posidonia oceanica* on the beach is not influenced by human intervention (i.e. banquette removal), turning the area into a good example for understanding the natural morphological evolution. The study analyses on one and a half years beach dynamics (September 2022- April 2024) and the effects of a storm that occurred in September 2022 (Figure 3). The 2022 storm had a maximum significant offshore height value of 2.83 m, mainly from the WNW (Figure 3).

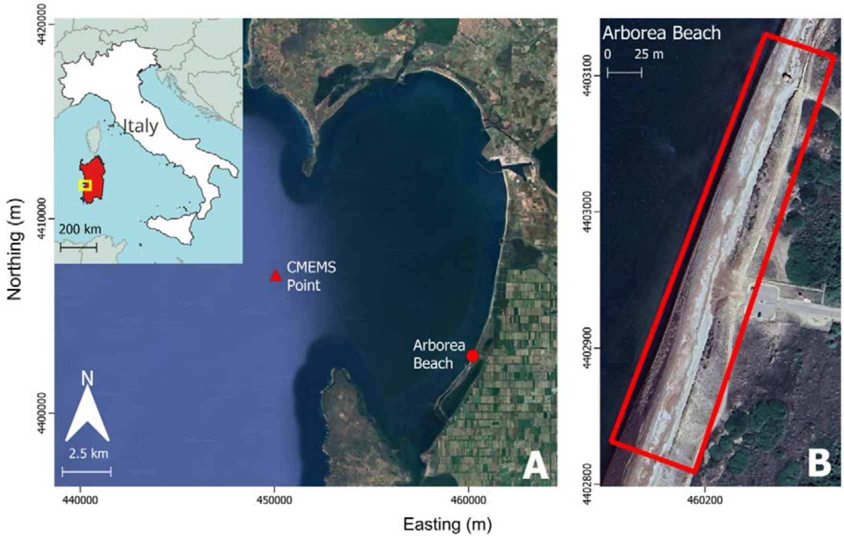

Figure 2 – a) The yellow square on the top left image represents the Gulf of Oristano. The red circle represents the location of the case study, Arborea Beach, on the Gulf of Oristano, on the west coast of Sardinia Island, Italy, while the red triangle represents the Wave data extraction point from Copernicus Marine Environment Monitoring Services (CMEMS). b) The area highlighted in red represents the surveyed area of Arborea Beach.

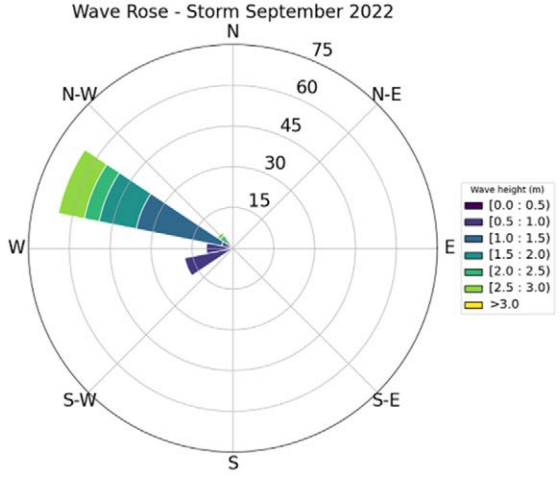

Figure 3 – Wave direction and heights offshore during the event of 2022. The wave information was extracted from the CMEMS point.

Materials and Methods

The medium- and short-term (Storm 2022) morphological evolution of Arborea Beach was investigated, focusing on profile evolution, volume changes, and the impact of Posidonia banquettes on controlling beach changes. Four surveys were undertaken over one and a half years (September 2022, May 2023, October 2023 and April 2024), where topographic data was collected using an RTK-DGPS Trimble R8 and an aerial drone (DJI Phantom Vision 3+). The RTK-DGPS was used in two contexts: (1) using the stop-and-go technique to collect the ground elevation for four cross-shore profile locations on the emerged beach (Figure 4), and (2) to collect the position of the ground control points (60 cm x 60 cm red and white squares) for the aerial drone flights. The aerial drone took multiple photos of the emerging beach, which were processed through the photogrammetric technique Structure-from-Motion (SfM) using the "Agisoft Metashape" software, creating high-resolution digital elevation models (DEMs) and orthophotos of the area of interest. The orthophotos were mainly used to identify the position and extension of *Posidonia oceanica* banquettes. The DEMs were used to calculate the difference in volume between fieldwork campaigns. The accuracy of each DEM was evaluated by estimating the root mean square error (RMSE) using the points obtained from the profiles as validation. After validation, the DEMs of Difference (DoD) were calculated using the Geomorphic Change Detection software [32]. This tool estimates vertical and volume variations between DEMs, considering the propagation of individual errors.

Knowing the related uncertainties (i.e. RMSE), it is possible to estimate a threshold for change detection (TCD) below which the variations are not considered significant. This will allow the program to detect and consider only changes higher than the threshold, improving the quality of the interpretation of the analyses. A limitation of the DoD calculation is that it can only be applied to emerged areas; therefore, the underwater changes are not detected.

Regarding the presence of *Posidonia*, the difficulty in quantifying the seagrass debris volume limits the analysis since no reference level can be used due to the vertical changes occurring on the surface under the banquettes. Therefore, the analysis of *Posidonia* was restricted to the total area where the seagrass accumulated. The identification of banquette limits was made manually using the orthophotos. The criteria used were based on the presence of *Posidonia* structures, colour and sand.

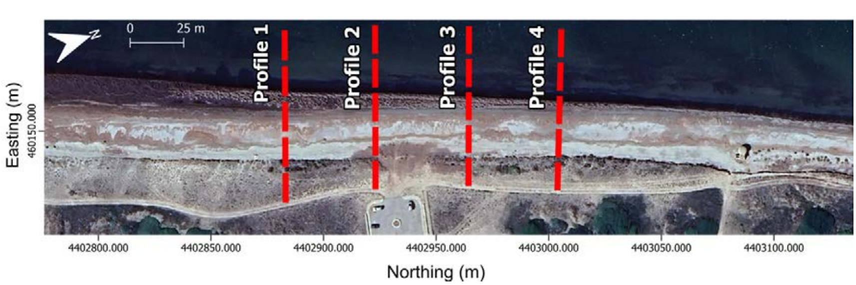

Figure 4 – The four cross-shore profiles were located using the RTK-DGPS in all the field campaigns. Geographical coordinates are in the WGS84/UTM zone 32N system (EPSG:32632).

Results

When comparing the profile data throughout the year and a half of the field surveys, large horizontal and vertical changes are detectable in all profiles (Figure 5). Assuming 0 m as the limit between subaerial and wet environments, there is a clear shoreward displacement of the water line. Regarding the vertical changes, there is a noticeable decrease in elevation along the four profiles. A vertical decrease above 1 meter can be noted in all profiles. Although a dune retreat can be detected in all profiles, the most affected ones were profiles 3 and 4; the dune retreated around 3 meters with a vertical erosion of 1 meter over the whole analysed period (Figure 5).

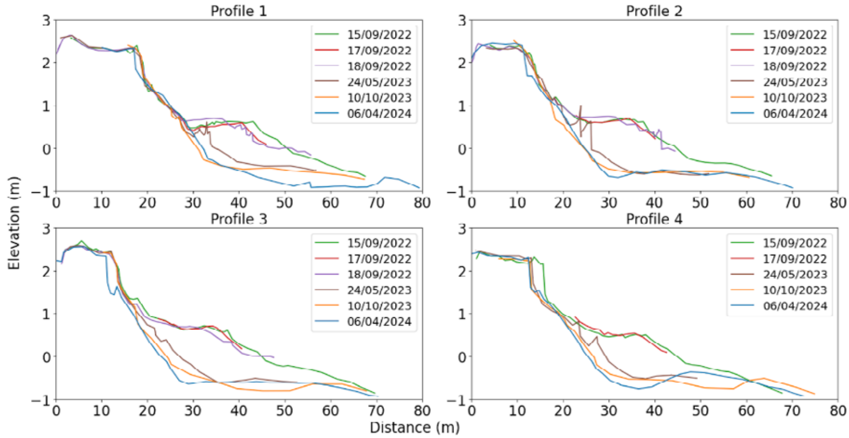

Figure 5 – Cross-shore elevation of the four profiles using the most inland point of each profile as the reference point.

In Figure 5, some "peaks" in the profiles associated with the presence of *Posidonia oceanica* banquettes can be observed. The presence of Posidonia banquettes were observed during the different fieldwork campaigns. As mentioned, a coastal storm occurred during one of the fieldwork campaigns. The storm caused the formation of *Posidonia oceanica* banquettes along the beach, which occupied an area close to 2250 m^2, while the total study area is about 1.62x104 m^2 (Figure 6). The banquette thickness and extension decreased northward; a tendency observed during the fieldwork campaigns after September 2022.

Although the *Posidonia oceanica* banquettes were formed on the foreshore after the storm, the foreshore area of Arborea shows a general decrease in elevation where the *Posidonia oceanica* banquettes were formed, while the berm elevation increased (Figure 7a). Also, during this event, the dune was not affected. It is not possible to quantify the amount of erosion and accretion of sediment volumes for the whole study area correctly due to the lack of information on the volume of the banquette.

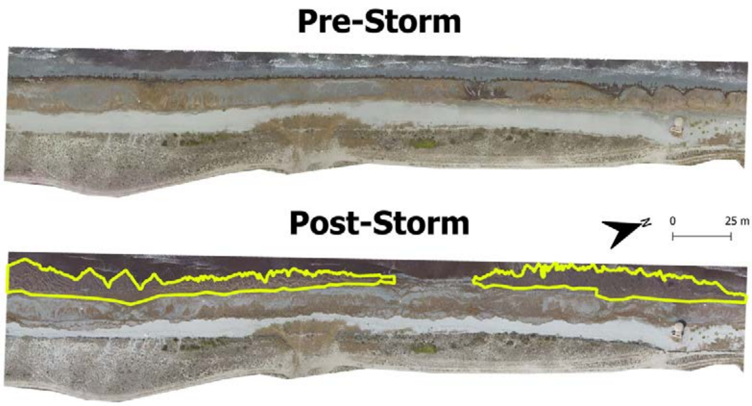

Figure 6 – Pre- and Post-Storm orthophotos. The Posidonia banquettes are highlighted in yellow. In the pre-storm picture on the top, there were no Posidonia banquettes on the beach.

This limitation did not affect the medium-term evolution analysis, where the DEMs did not show Posidonia banquettes on the beach (Figure 7b). Regarding the medium-term analysis, the beach shows a major erosion in the common part between the DEM from 2022 and 2024, reaching a sediment loss of about 1500 m^3 (Table 1). An hotspot of erosion is focused mainly on the dune on the northern part of the beach, which is the major contributor to the erosion values. The accretion values are very limited compared to erosion, with a value of about 10 m^3 (Table 1).

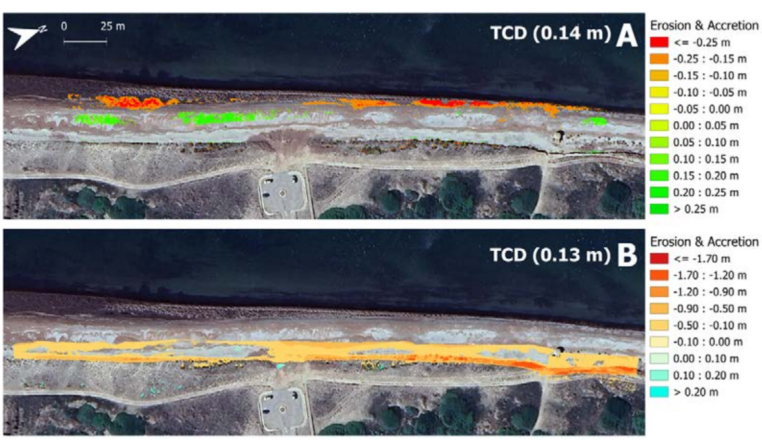

Figure 7 – DEMs of Difference where the beach is analysed according to a reference DEM. a) The Storm's DEMs of Difference, being the DEM of reference the one of 15/09/2022 and final DEM the one of 18/09/2022, pre and post-storm, respectively. b) the DEMs of Difference for the whole period of the fieldwork campaigns (medium-term), being the DEM of reference the one of 15/09/2022 and the final DEM the one of 06/04/2024.

Table 1 – The table shows the volume of accretion and erosion related to the DEMs of Difference of the Storm event (15th to 18th of September 2022) and medium-term evolution (15/09/2022 to 06/04/2024).

	Storm (TCD 0.14m)	Medium-term (TCD 0.13 m)
Accretion (m^3)	66.1	10.2
Erosion (m^3)	164.0	1571.4
Total (m^3)	-97.8	-1561.4
Error ($\pm m^3$)	119.1	431.0

Discussion

The results of this study regarding the morphological evolution of Arborea Beach are divided into two periods: short-term and medium-term. The short-term event did not affect the dune of the Arborea beach; however, important changes occurred on the beach, such as the deposition and formation of the *Posidonia oceanic* banquettes. The evolution of a banquette due to a coastal storm, from 0 m^2 to around 2250 m^2 (Figure 6) is in agreement with the literature regarding the combination of wave action, suspended *Posidonia* and banquette formation [26]. Although the dune did not suffer any erosion during the analysed storm event, other parts of the beach showed changes. The presence of *Posidonia* banquettes on the coast increased the beach height, behaving as small "cliffs" of organic matter (Figure 1 and profile 1,2,3 in Figure 5); however, even with the newly formed banquette, the beach face area witnessed surface lowering, as evidenced in figure 7a. This suggests a strong erosion on the beach face because the surface level of the banquette on 18/09/2022 was even lower than the pre-storm (15/09/2022) elevation. This observation is supported by Figure 5, where the post-storm (18/09/2022) beach profiles showed up to 40 cm of lower elevations compared to pre-storm (15/09/2022). In this case, it is not possible to know the volume of sediment eroded since there is a layer of *Posidonia oceanica* above the sand, and no reference layer was used. The accretion after the storm event represented 40% of the sediment loss (Table 1), though this value might be lower due to the inability to detect the changes underwater. Figure 7b shows that accretion is localised in the berm zone. Although it is not possible to quantify the percentage of sediment, part of the eroded sediment from the foreshore was likely moved to the berm.

The results presented in this study regarding the medium-term morphological evolution demonstrated an overall erosional trend. The northern part of the investigated beach is the hotspot of erosion; the dune retreated almost 3 meters between September 2022 and April 2024 (Figure 5). Although the storm of September 2022 did not affect the dune, it cannot be stated that the storms are not responsible for the erosion as they can cause the collision or overwash regimes [33]. However, a factor that can affect the discrepancy in dune erosion between the northern and southern parts of the studied beach is the recurring presence of *Posidonia oceanica* banquettes on the southern part of the beach compared to the northern portion. As mentioned, the analysis shows a larger number of *Posidonia* *oceanica* banquettes in the southern portion; the authors have also witnessed a higher presence of banquettes in the southern part of Arborea during all fieldwork campaigns. The banquettes' presence might have protected the dune from erosion as the banquettes could mitigate the effect of waves on the coast [34]. Although their formation may also be due to wave action during storm events and the presence of suspended dead *Posidonia* [26], once they remain on the coast, the *Posidonia oceanica* banquettes can behave as a first layer of protection for the dune, limiting swash elevation [34]. The lower distribution and thickness of the beach banquettes on the northern part makes the beach more exposed to wave action than the southern portion, thus leading to a higher erosion rate.

An erosive trend is ongoing along the beach; however, identifying the factors that may contribute to this evolution is not straightforward. Since Arborea beach presents a highly limited human influence (i.e. no removal of banquettes), which affects the sediment budget or surface lowering due to the operations (i.e. presence of machines on the beach) [24,25,27], the erosional trend might be caused by other factors. One important factor is the lack of sediment supply; one of the main direct sediment source might be the Tirso River on the Gulf's northern side. However, its mouth is located between structures, which can limit longshore transport, a common problem for several beaches worldwide [4]. Furthermore, the beach is situated in a gulf, which can limit sediment supply and favour erosion. Since this study is focused on a portion of the beach, it would be necessary to extend the analysis to other portions of the Gulf of Oristano, as the eroded sediment was probably transported outside the investigated area, including the submerged beach, also focusing on current and wave patterns and shoreline retreat over more extended periods.

Although it is possible to understand the erosional trend and the influence of banquettes on the beach, the analysis of the impact of additional and different storms could provide better indications on the morphodynamic behaviour of the beach, that should also include the analysis of submerged profiles.

Conclusion

This study used cross-shore profiles and aerial drone flights to discuss the short-term (i.e. storm event) and medium-term (September 2022-April 2024) morphological evolution of a beach on the West coast of Sardinia Island, where *Posidonia oceanica* banquettes are a common deposit that characterises this system. The beach showed an erosional trend, with a horizontal retreat of the shoreline and dune erosion along the beach. The results highlighted different behaviours between the study northern and southern parts, where the dunes are subjected to higher erosion on the northern section while the southern part showed an increase of *Posidonia* banquettes that became denser protecting the dune system. The changes in erosion and the banquette deposition might be related, as the deposition of *Posidonia* may reduce the effect of the waves and, therefore, protect the southern portion of the beach. According to the literature, wave action is the main factor responsible for Posidonia deposition. This coincides with the data collected from the fieldwork, especially during September 2022, when a coastal storm affected the area, which favoured the deposition of *Posidonia* on the beach. However, a lower elevation of the area was observed while the banquettes were on the beach.

The possible lack of sediment supply and the effects of the change in thickness of the banquettes may be the main factor controlling its evolution, at least in the short term. However, more analyses that cover a larger spatial-temporal interval integrated with hydrodynamic processes must be addressed to better understand the overall trend.

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