Multitemporal monitoring of Posidonia oceanica banquettes using UAV photogrammetry

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Abstract

Posidonia oceanica banquettes represent key coastal features in the Mediterranean, providing ecosystem services such as shoreline protection, sediment retention, and carbon storage. Despite their ecological importance, their spatial and temporal dynamics remain poorly quantified due to the lack of standardized monitoring approaches. This study presents a UAV-based photogrammetric methodology for the multitemporal analysis of banquette morpho dynamics, integrating NRTK-supported surveys, Structure-from-Motion processing, and uncertainty-aware DEM differencing. The method was applied to Maurizio Vitale Beach (Culuccia Island, Sardinia, Italy), a protected and low-impact coastal environment, using four UAV surveys acquired between 2022 and 2025. High-resolution Digital Elevation Models (DEMs) were generated and compared to quantify volumetric changes across seasonal and interannual timescales. Results show a highly dynamic system, characterized by alternating phases of erosion, redistribution, and accumulation. Seasonal analysis (June–October 2024) revealed moderate volumetric losses (−41.3 m³), mainly affecting the seaward edge, with localized deposition in inner sectors. Interannual comparison (2022–2024) highlighted a more pronounced net loss (−74.2 m³). Conversely, the 2024–2025 analysis showed significant recovery, with widespread accretion (+95.8 m³), indicating strong temporal variability. The proposed approach proved effective in capturing both horizontal and vertical changes, distinguishing between boundary retreat and surface lowering processes. These results demonstrate the potential of UAV photogrammetry as a reliable and scalable tool for standardized banquette monitoring, supporting coastal management strategies and contributing to the objectives of the POSEIDON project.

1. Introduction

Posidonia oceanica (PO) meadows represent one of the most valuable coastal ecosystems in the Mediterranean Sea, providing key ecological functions and ecosystem services, including carbon sequestration, habitat provision, oxygen production, and sediment stabilization (Vassallo et al., 2013). Even after detachment, PO leaves and rhizome fragments accumulate along the shoreline forming thick deposits known with the French term “banquettes” (Rotini et al., 2020; Jeudy De Grissac and Audoly, 1985). These natural structures play a crucial role in protecting beaches from erosion, buffering wave energy, trapping sediments, and contributing to the nutrient cycling of coastal systems (Fonseca and Cahalan, 1992).

1.1 Banquettes

Banquettes can vary greatly in thickness, sometimes reaching several meters, and can extend over hundreds of meters. Their development and stability are highly variable and, in the most stable cases, they become significant bio-geomorphological formations. Although temporary, these formations shape the coastal landscape, adding to its geomorphological and ecological diversity. Their formation, persistence, thickness, and spatial distribution are strongly influenced by hydrodynamic conditions, seasonal storm regimes, beach morphology, and the productivity of offshore seagrass meadows, resulting in high spatial and temporal variability. Typically, banquettes are primarily composed of Posidonia leaves, which, due to their ribbon-like shape and manner of accumulation, form a very compact and elastic layered structure (ISPRA, MLG 55/2010; Boudouresque and Grissac, 1983; De Falco et al., 2008). This structure effectively absorbs wave energy, diminishing its erosive impact and thereby helping to stabilize the beaches. Moreover, banquettes act as physical barriers that reduce shoreline retreat during storm events. Finally, banquettes also serve as habitats for macro and micro invertebrates, offering shelter, nursery areas, and feeding sites (Rotini et al., 2020). The typical dunal fauna as well as halophilous species may be observed. The higher the degree of undisturbed naturalness of the *banquette*, the greater the species richness, diversity, and abundance it will support. In contrast, increased anthropogenic disturbance leads to a less structured banquette, resulting in fewer macroinvertebrate species.

Despite their ecological importance, banquette dynamics are not consistently monitored, standardized monitoring procedures are lacking, and their spatial and temporal variability remains poorly understood. In addition, their management is often fragmented and context-dependent: beach cleaning operations are typically regulated at the municipal or regional level (MATTM-Regioni, 2018), especially during the bathing season, and are frequently driven by touristic and aesthetic requirements rather than ecological considerations. As a consequence, banquettes are often perceived as waste and mechanically removed, despite their natural origin and protective function.

National guidelines (ISPRA, MLG 55/2010; MATTM-Regioni, 2018) for coastal management in Italy highlight the need to distinguish between anthropogenic waste and natural biomasses such as Posidonia oceanica, emphasizing that the latter should not be systematically removed. More recently, the “Salvamare” Law (Law 60/2022) introduced a national regulatory framework for the management of stranded marine biomasses, recognizing their ecological role and promoting management strategies aimed at minimizing environmental disturbance. According to the legislation, management options should prioritize the preservation of banquettes in situ whenever possible, followed—only when necessary—by temporary displacement, relocation within the same physiographic unit, or experimental re-immersion at sea after separation of sand and anthropogenic waste fractions. Permanent removal and disposal are instead

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considered residual management options. Nevertheless, despite the existence of national guidelines and legislative frameworks, management practices remain heterogeneous and often influenced by tourism-related pressures, frequently leading to banquette removal and consequent alterations of natural coastal processes. This mismatch between ecological knowledge and actual management practices highlights the need for robust and quantitative monitoring approaches to support evidence-based coastal management strategies.

1.2 POSEIDON project

Within the framework of the POSEIDON (multitemPOral SEagrass mapping and monitoring of posIDONia meadows and banquettes for blue carbon conservation) project, funded by the Italian National Recovery and Resilience Plan (PNRR), innovative high-resolution mapping techniques are being developed to monitor PO ecosystems both underwater and along the coastline, aiming to establish standardized and scalable protocols for long-term assessment.

1.3 Related works

In this context, UAV (Uncrewed Aerial Vehicles) or UAS (Uncrewed Aerial Systems) photogrammetry has become a widely adopted tool for high-resolution coastal monitoring and topographic mapping. Compared to traditional surveying techniques (typically based on field measurements, visual inspections, or sporadic topographic profiles, which are often time-consuming, spatially limited, and difficult to replicate systematically), UAV systems provide rapid data acquisition, flexible deployment, and cost-effective coverage of relatively small and dynamic coastal environments. When combined with NRTK (Network Real Time Kinematic) positioning and well-distributed ground control points (GCPs), Structure-from-Motion (SfM) photogrammetry enables the generation of centimeter-scale Digital Elevation Models (DEMs) and high-resolution orthophotos (Zannutta et al., 2020; Vecchi et al., 2021; Yoo and Oh, 2016). UAV-based surveys have proven particularly effective in monitoring beach morpho dynamics, dune systems, cliff retreat, and sediment budgets, offering a valuable balance between spatial resolution, accuracy, and operational efficiency.

DEM differencing (DoD – Digital Elevation Model of Difference) is a consolidated approach for estimating surface elevation and volumetric change from repeated UAV surveys in coastal and fluvial environments (Kregar and Trajkovski, 2025; Yoo and Oh, 2016). By quantifying elevation changes between multitemporal DEMs while accounting for vertical uncertainty, this method allows for robust detection of erosion and deposition patterns and supports volumetric budget estimation.

This contribution presents a methodology based on UAV RGB photogrammetry for the multitemporal analysis of banquette morpho dynamics, demonstrating its potential for quantitative assessment of seasonal and interannual changes. By integrating high-resolution topographic data, NRTK-supported ground control, and uncertainty-aware DEM differencing, the proposed workflow aims to provide a replicable framework for standardized monitoring of Posidonia oceanica banquettes and to support coastal management strategies grounded in quantitative geomatics approaches.

2. Area of the study

The study focuses on Maurizio Vitale Beach, located on Culuccia Island (Sardinia, Italy) (Figure 1, Figure 2 and Figure 3), a natural and undisturbed site where the PO banquette persists throughout the year. It was selected as the testbed due to its significant thickness and structure and the fact that it remains undisturbed by human activity (Figure 2 and Figure 3).

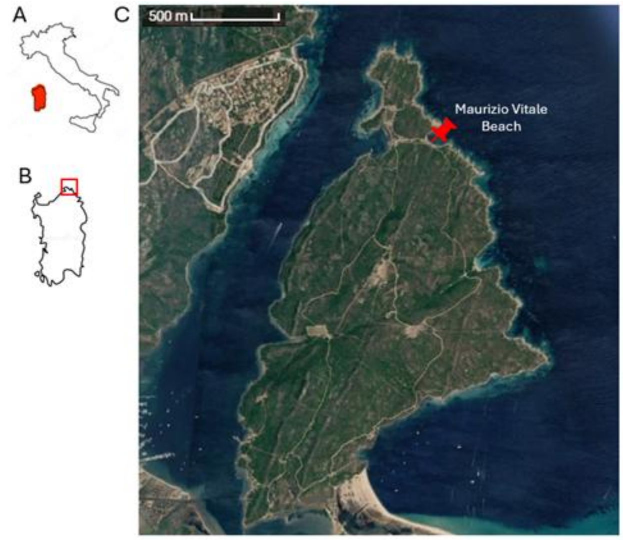

Figure 1 - Location of the study area, with particular reference to A, the location of the island of Sardinia; B, the location of the Culuccia Peninsula; and C, the location of the Maurizio Vitale beach.

Figure 2. Banquette on Maurizio Vitale Beach. Photo from June 2024.

This ensures that the observed morpho dynamic changes are primarily driven by natural processes rather than anthropogenic interventions, providing a controlled baseline for methodological development. In fact, the Culuccia peninsula is subject to multiple levels of environmental protection and is recognized for its high ecological value. The terrestrial area is designated as a permanent wildlife oasis under regional legislation (L.R. 23/1998), while the surrounding marine area is included within the Natura 2000 network as a Special Area of Conservation (SAC) under the EU Habitats Directive (92/43/EEC). Furthermore, the site is classified as an “area of notable public interest” under the Italian Cultural Heritage and Landscape Code (D.Lgs. 42/2004), which extends protection to coastal landscapes, dune systems, and adjacent marine environments. These protection frameworks aim to safeguard both terrestrial and coastal ecosystems, limiting anthropogenic pressures on the area.

Figure 3. Aerial photo of the banquette, acquired during one of the UAV surveys.

In this sense, the site represents an ideal reference condition for testing the proposed UAV-based workflow. Once validated in such a low-impact and well-preserved environment, the methodology can be more reliably transferred to more complex and human-impacted coastal settings, where distinguishing between natural dynamics and anthropogenic alterations is more challenging.

3. Materials and Methods

3.1 Data acquisition

In the area of study RGB imagery were acquired using UAVs. Four photogrammetric surveys were conducted: June 2022, June and October 2024, July 2025, enabling both intra-annual (seasonal) and inter-annual comparisons. The aerial surveys were conducted using various UASs: the specifications of the drones and the characteristics of the acquisitions are listed in Table 1.

UAS	DJI Phantom 4	DJI Matrice 300	DJI Matrice 4
Sensor	FC6360	Zenmuse P1	M4E
Resolution	1600 × 1300	8192 × 5460	5280 × 3956
Focal Length	5.74 mm	35 mm	12.29 mm
Pixel Size	3.01×3.01μm	4.39 × 4.39 μm	3.75 × 3.75μm
Flying altitude	56.4 m	35 - 64 m	78 m
GSD	3.07 mm/pix	4.5 - 7 mm/pix	17.2 mm/pix
Survey	2022	2024-2025	2025

Table 1. Main specifications of sensors and UASs.

To guarantee georeferencing accuracy, between 15 and 20 ground control points (GCPs) and check points (CPs) were distributed across the study area, ensuring both homogeneous spatial coverage and inclusion of the banquette and surrounding beach. The points were materialized using clearly visible targets and measured with a Stonex S900A GNSS receiver operating in NRTK mode (Figure 4). The specifications of the receiver are reported in Table 2. The NRTK corrections were provided in real time through the use of the Hexagon Smartnet network (https://it-sbc.nrtk.eu/) , allowing centimeter-level positioning accuracy.

Parameter	**Specification**
GNSS constellations	GPS, GLONASS, Galileo, BeiDou
Channels	555
RTK positioning accuracy (horizontal)	8 mm + 1 ppm
RTK positioning accuracy (vertical)	15 mm + 1 ppm

Table 2. Main specifications of Stonex S900A GNSS receiver.

Figure 4. Examples of target materialized using Stonex S900A GNSS receiver.

3.2 Data processing

The analysis of the acquired data involved the following steps:
1. Photogrammetric processing
2. Elevation change detection
3. Identification of the banquette areas of change
4. Volumetric change estimation

Photogrammetric processing was performed in Agisoft Metashape Professional (version 1.8 and later), while all the other steps were carried out in ArcGIS Pro (Esri, 2023).

For each survey epoch, the photogrammetric workflow followed a standard Structure-from-Motion (SfM) pipeline, including image alignment, sparse and dense point cloud generation, and georeferencing based on the available GNSS-NRTK information and ground control points as well as check points. For each campaign, the processing outputs consisted of high-resolution orthophotos and Digital Elevation Models (DEMs), which constitute the core datasets for the subsequent elaboration in ArcGIS Pro: the multitemporal analysis of banquette morpho dynamics.

To quantify changes in the banquette between two survey epochs, DEM differencing was applied in ArcGIS Pro using the Change Detection tool. DEM differencing is a consolidated approach for estimating surface elevation and volumetric change from repeated UAV surveys in coastal and fluvial environments (Kregar and Trajkovski, 2025; Yoo and Oh, 2016). For each pairwise comparison, the elevation difference (Δz) was computed as:

$$\Delta z = DEM_{t2} - DEM_{t1} \tag{1}$$

where DEM_{t1} and DEM_{t2} represent the elevation models from the earlier and later survey, respectively. In practical terms, this operation highlights spatial patterns of erosion and deposition and allows the identification of zones where the banquette surface increased, decreased, or remained stable over time.

Although in theory the limit value separating the three classes would be $\Delta z = 0$, in practice the interpretation must explicitly account for measurement uncertainty and the vertical accuracy of the input DEMs. Therefore, elevation changes were classified using a threshold based on the combined vertical accuracy of the two DEMs. The resulting classes were defined as:

- increase ($\Delta z > +\sigma_{\Delta z}$),
- no change ($-\sigma_{\Delta z} \leq \Delta z \leq \sigma_{\Delta z}$), and
- decrease ($\Delta z < -\sigma_{\Delta z}$).

where $\sigma_{\Delta z}$ represents the propagated vertical uncertainty of the DEM difference. Since each DEM has an associated vertical accuracy σ_z (estimated as the vertical RMSE on independent checkpoints during Metashape processing), the accuracy of the elevation difference between two epochs was computed through error propagation as:

$$\sigma_{\Delta z} = \sqrt{\sigma_{z_1}^2 + \sigma_{z_2}^2} \tag{2}$$

with σ_{z1} and σ_{z2} being the vertical RMSEs of the two DEMs compared. Across all datasets, the RMSE on checkpoints ranged between 5 and 10 cm, as estimated during SfM processing. Based on these values, the combined thresholds adopted for the change detection were: $\sigma_{\Delta z} = 0.064$ m for the 2022–2024 comparison, $\sigma_{\Delta z} = 0.107$ m for the seasonal 2024 comparison, and $\sigma_{\Delta z} = 0.056$m for the 2024–2025 comparison. This uncertainty-aware classification reduces the risk of misinterpreting small, noise-driven elevation differences as real geomorphic change, and ensures that only changes exceeding the expected vertical error are considered significant.

Once the raster map of Δz was classified, contiguous areas belonging to the same class (increase, decrease or no change) were converted into polygons representing spatially coherent zones of elevation variation. For each polygon, the surface area was computed, and the mean elevation change value was extracted from the Δz raster. Volumetric changes were then estimated by multiplying the mean elevation difference by the corresponding polygon area:

$$\Delta V = \overline{\Delta z} \cdot A \tag{3}$$

where (A) is the polygon surface area and $\overline{\Delta z}$ is the mean elevation difference within the polygon. The total volumetric budget for a given comparison was obtained by aggregating the volumes computed for the increase and decrease classes, enabling the quantification of net gains/losses as well as the identification of localized accretion or erosion zones within the banquette system.

Finally, to provide a conservative estimate of uncertainty associated with the computed volumes, an uncertainty term (T_V) was calculated for each volumetric estimate as the product of $\sigma_{\Delta z}$ and the area affected by elevation increase or decrease (A). In other words, for each class of increase and decrease, the uncertainty on volume was approximated as:

$$T_V = \sigma_{\Delta z} \cdot A \tag{4}$$

This approach propagates the DEM vertical uncertainty into volumetric space and allows reporting volumetric changes together with an uncertainty range, which is particularly important in coastal environments where surface roughness, vegetation remnants, and wet/dry sand conditions can locally affect photogrammetric performance.

4. Results and Discussion

The results presented here focus on the comparison between the June and October 2024 surveys, 2022 and 2024 surveys, and finally 2024 and 2025 surveys, which reveal marked seasonal and interannual variations (Table 3).

4.1 Seasonal change (June – October 2024)

The comparison between the DEMs from June and October 2024 revealed a net volumetric loss of 40.8 m^3 (± 11.6 m^3), accompanied by localized accretion areas totaling 6.9 m^3 (± 3.9 m^3) (Figure 5). The values in brackets represent the uncertainty bounds, as defined in the methodology. Spatially, erosion mainly affected the seaward edge of the banquette, while limited deposition occurred in more protected inner sectors. However, the observed patterns are not uniform along the shoreline: in some sectors, a clear landward regression of the banquette front can be identified, whereas in others no significant horizontal displacement is visible. In these areas, the detected volumetric decrease is primarily associated with a reduction in elevation, indicating a general lowering of the banquette surface rather than a retreat of its boundary. This pattern suggests a redistribution of material driven by increased wave energy and storm events typical of the late summer and autumn period, leading to a partial reworking of the banquette structure rather than a uniform loss.

4.2 Interannual change (June 2022 – June 2024)

The comparison between 2022 and 2024 (Figure 6Figure 5) showed a larger net loss of 74.2 m^3 (± 15.6 m^3), predominantly affecting the seaward edge of the banquette, indicating that erosive processes lead to overall landward retreat of the deposit. At the same time, localized gains (+22.8 m^3 ±7.5 m^3) were detected in the inner sectors of the banquette, suggesting a thickening of the pre-existing deposits rather than the formation of new accumulation areas. Unlike the seasonal comparison, the interannual analysis highlights a more persistent reduction in volume, suggesting that, perhaps, the annual rebuilding processes may not fully compensate for erosional losses. This pattern could be related to variations in offshore *Posidonia oceanica* productivity or to changes in hydrodynamic conditions, although further data are required to confirm these hypotheses.

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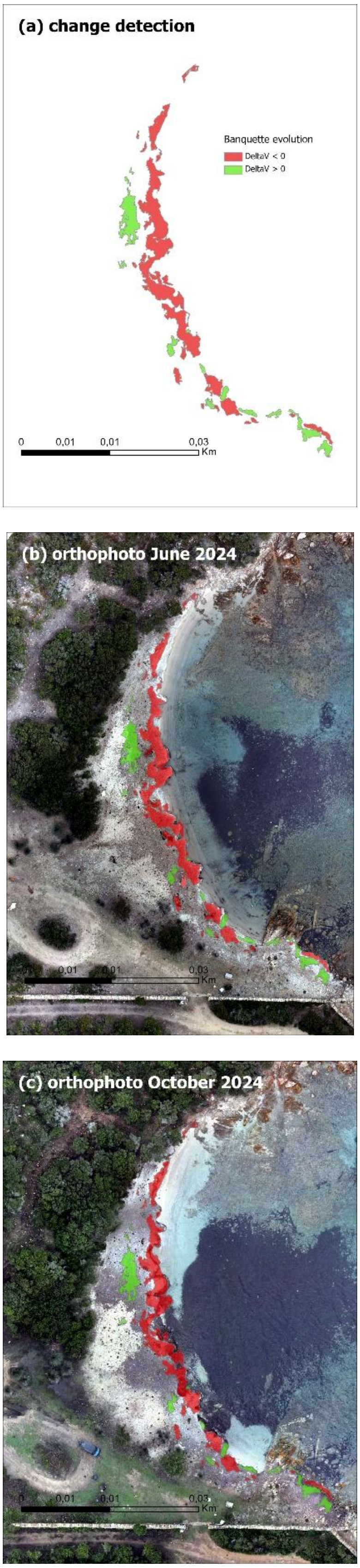

Figure 5. Estimation of the banquette volume evolution between June 2024 and October 2024. Change detection results (a) are computed from the two DEMs and are also shown in transparency on the two orthophotos.

Figure 6. Estimation of the banquette volume evolution between June 2022 and June 2024. Change detection results (a) are computed from the two DEMs and are also shown in transparency on the two orthophotos.

4.3 Interannual change (June 2024 – July 2025)

Comparing the DEMs from June 2024 and July 2025, it showed net volumetric losses of 11.2 m³ (± 3.7 m³) and vast accretion areas totalling 92.3 m³ (± 18.6 m³) (Figure 7). This result indicates a significant recovery phase of the banquette, characterized by widespread deposition and thickening. The observed gains were distributed both along the seaward edge, indicating a forward expansion of the banquette with the formation of new accumulation areas, and within the main body of the deposit, suggesting a general thickening of the existing volume. The measured accretion suggests a substantial input of new biomass and sediment, possibly linked to favorable hydrodynamic conditions or increased detachment from offshore meadows during the preceding seasons.

Overall, the multitemporal analysis highlights a highly dynamic system, characterized by alternating phases of erosion, redistribution, and accumulation.

The proposed methodology proved effective for quantifying volumetric evolution and visualizing spatial dynamics through DEM differencing maps (Figure 5, Figure 6 and Figure 7).

These outputs provide valuable information for coastal management, supporting the assessment of sediment retention processes and the role of *Posidonia oceanica* banquettes in coastal protection and carbon storage.

Comparison	Type of variation	Decreease (m³)	Increase (m³)
June – October 2024	Seasonal	40.8 ± 11.6	6.9 ± 3.9
June 2022 – June 2024	Interannual	74.2 ± 15.6	22.8 ± 7.5
June 2024 – July 2025	Interannual	11.2 ± 3.7	92.3 ± 18.6

Table 3 - Summary of the results

5. Conclusions and Future Work

This study demonstrates that UAV-based photogrammetry represents a reliable, accurate, and replicable approach for the multitemporal monitoring of Posidonia oceanica banquettes, enabling the generation of high-resolution 3D datasets suitable for quantitative change detection. The integration of NRTK-supported surveys, Structure-from-Motion processing, and uncertainty-aware DEM differencing proved effective in capturing both subtle and significant morpho dynamic variations. The proposed methodology contributes to defining standardized protocols for Posidonia oceanica banquette monitoring, consistent with the broader objectives of the POSEIDON project.

The results highlight a highly dynamic behaviour of the banquette system, characterized by alternating phases of erosion, redistribution, and accumulation. Seasonal analysis (June–October 2024) revealed moderate volumetric losses mainly associated with edge erosion and partial structural reworking. Interannual comparison between 2022 and 2024 showed a more pronounced net loss, with a pronounced erosive landward retreat of the deposit. Conversely, the 2024–2025 comparison revealed

Figure 7. Estimation of the banquette volume evolution between June 2024 and July 2025. Change detection results (a) are computed from the two DEMs and are also shown in transparency on the two orthophotos.

a strong recovery phase, with widespread accretion and thickening, indicating the episodic nature of banquette formation and the influence of environmental forcing factors. These findings confirm that banquette evolution cannot be described as a linear process but rather as a complex and non-uniform system, where horizontal retreat and vertical thinning may occur simultaneously and with different spatial patterns. The ability of the proposed methodology to distinguish between these processes represents a key advantage for understanding coastal dynamics.

From an applied perspective, the results provide valuable insights for coastal management, supporting the assessment of the protective role of banquettes in sediment retention and erosion mitigation. The quantitative information derived from UAV surveys can contribute to evidence-based decision-making, particularly in contexts where management practices (e.g., mechanical removal) may conflict with ecosystem conservation.

Future work will focus on extending the temporal dataset to better capture long-term trends, and testing the scalability of the methodology across different Mediterranean coastal settings with varying degrees of human pressure.

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