Diachronic analysis of vegetation dynamics in the Stagnone di Marsala Lagoon through satellite images

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Keywords: Submerged vegetation mapping, Vector-based classification, Light Gradient Boosting Machine classification

ABSTRACT

A comprehensive analysis of underwater ecosystems is crucial for preserving marine biodiversity, particularly in regions subjected to significant anthropogenic stress. This study focused on the multi-temporal analysis of satellite imagery to accurately map the submerged vegetation within the Stagnone di Marsala lagoon (Sicily, Mediterranean basin). This coastal lagoon is distinguished by unique submerged ecological habitats, including quasi-emergent Posidonia oceanica structures forming atolls and cordons, which are exposed to persistent anthropogenic and natural pressures. Satellite images utilized in the study were obtained from commercial platforms, including WorldView, QuickBird, and Pleiades, covering a 21-year period (2003–2024). The images span visible and near-infrared spectral bands and have a spatial resolution of 2 meters. Before processing, the images were calibrated to the Bottom of Atmosphere (BOA) reflectance and corrected for water column contributions. The diachronic analysis of vegetation dynamics was based on the Light Gradient Boosting Machine classification methodology. Validation efforts involved in-situ data collection from 79 surveyed points, yielding an overall accuracy of 0.84, which was adjusted to 0.80 when accounting for causal concordance probabilities. Results indicate a substantial decline in the extent of atolls and cordons, with satellite observations revealing a reduction of approximately 75% over the study period. The outcomes underscore the critical role of remote sensing in monitoring underwater vegetation dynamics and enhancing conservation strategies.

1. INTRODUCTION

The analysis of the submerged environment represents a fundamental practice for safeguarding the biological life of the sea. In fact, the anthropic pressures pose risks for the survey of fish and marine plant ecosystems and may modify water biodiversity[1–3]. At the same time, the latest advances in remote sensing satellite elaborations allowed the experimentation of new approaches for the analysis of shallow depth underwater environments such as the lagoons [4,5]. The main challenges in mapping benthic habitats and bathymetry regard the presence of several spectral features, considering the different shallow water environments in the world[6]. In fact, the quality of benthic habitat classification, based on multispectral information from satellite images, is deeply limited by the low spectral separability[7]. At the same time, the atmospheric correction, sun glint removal, and bathymetry determination are image processing techniques necessary to obtain the radiometric behaviour of the seabed[8,9].

This research focuses on the analysis of the Stagnone di Marsala Lagoon (Italy), where anthropogenic pressures increasingly threaten coastal ecosystems. The Stagnone di Marsala Lagoon, located on the western coast of Sicily, stands out as a unique and fragile habitat. Its shallow waters and distinctive geomorphological features support a rich mosaic of submerged vegetation, including quasi-emergent structures of Posidonia oceanica that form atolls and cordons. These formations are not only ecologically significant but also serve as indicators of environmental health, making their monitoring a priority for conservation efforts[10].

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Over the past two decades, the lagoon has experienced notable ecological changes, driven by both natural dynamic and human activities such as coastal development, sedimentation, and water quality degradation. Traditional field-based monitoring methods, while valuable, are often limited in spatial and temporal scope. In this context, satellite remote sensing offers a powerful alternative, enabling large-scale, multi-temporal analysis of submerged vegetation with high spatial resolution and repeatability.

The study presents a diachronic analysis of submerged vegetation in the Stagnone di Marsala Lagoon using satellite imagery acquired from commercial platforms, including WorldView, QuickBird, and Pleiades. The dataset spans a 21-year period (2003–2024) and includes visible and near-infrared spectral bands at a spatial resolution of 2 meters.

Although object detection techniques have significantly advanced, the effectiveness of satellite imagery for vegetation classification remains closely dependent on the spatial resolution relative to the size of the target features. When the resolution is too coarse to capture the structural complexity of vegetation—such as small, fragmented, or heterogeneous formations—classification accuracy can be substantially compromised. Ahmed et al. (2023)[11] demonstrated that imagery with insufficient resolution is inadequate for distinguishing fine-scale vegetation patterns, while Horion et al. (2007)[12] emphasized that even aggregated low-resolution data may fail to capture the spatial heterogeneity essential for monitoring ecologically sensitive areas.

Thus, although low-orbit satellites provide high-resolution imagery, the resolution is often insufficient to accurately characterize complex vegetation structures, such as atolls and cordons, even when employing the latest classification techniques. To map and quantify changes in submerged vegetation over time, the methodological framework goes beyond radiometric calibration by integrating advanced classification methods. Specifically, it utilizes the Light Gradient Boosting Machine (LGBM) algorithm for prairie mapping and a vector-based classification approach for identifying atolls and cordons.

2. STUDY AREA

The Stagnone di Marsala Lagoon, located along the western coast of Sicily (Italy), is the largest coastal lagoon in the region and a site of exceptional ecological and cultural significance (Figure 1). It is bordered to the north by the mouth between Punta Tramontana and San Teodoro, and to the south by that between Punta Stagnone and Punta d'Alga. It spans approximately 50 km^2 and is characterized by shallow waters, typically less than 2 meters deep, which foster the development of unique submerged habitats, including Posidonia oceanica meadows, atolls, and cordons.

The area is bound by key morphological features, including Punta Stagnone, Punta Tramontana, Punta Palermo, and Punta d’Alga, and features active salt pans and submerged archaeological remains. These elements contribute to its designation as a protected area under the Riserva Naturale Orientata Isole dello Stagnone.

The Stagnone di Marsala has been extensively studied over the past 45 years by numerous authors, providing valuable insights into its ecology, benthic features, and hydrodynamic processes: Calvo et al, 1980[13]; Pusceddu et al, 1997[14]; Calvo et al, 2003[15]; La Loggia et al, 2004[16]; Maltese et al, 2007[17].

The lagoon’s unique bathymetry and optical properties make it particularly suitable for remote sensing applications. However, the ecosystem is under continuous pressure from anthropogenic activities and natural stressors, as several seagrass species in the Mediterranean basin[18], leading to significant changes in submerged vegetation over time. The study area was therefore divided into distinct sectors for analysis, corresponding to historical and newly acquired satellite datasets, to facilitate diachronic monitoring and classification of submerged vegetation.

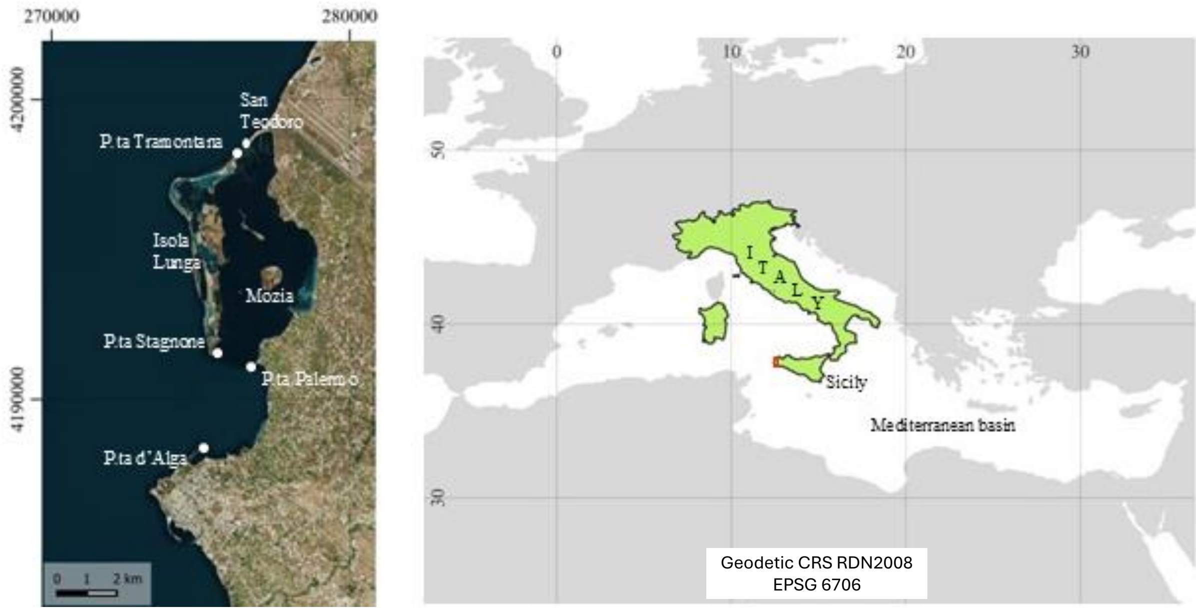


Figure 1. Coastal region that encompasses the Egadi Islands Archipelago (left panel) and the study area located on the western coast of Sicily between the cities of Trapani and Marsala (right panel).

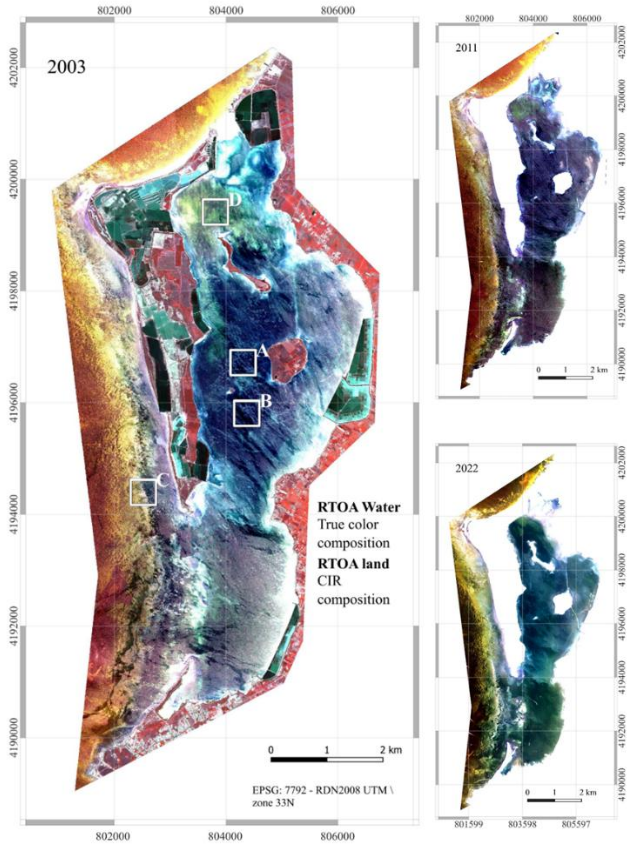
The ecological and geomorphological continuity between the Stagnone di Marsala lagoon and the surrounding marine protected areas makes this region particularly significant for studying submerged vegetation dynamics and coastal habitat conservation.

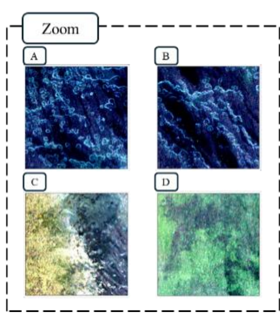
3. MATERIALS

This study is based on a comprehensive set of high-resolution multispectral satellite images acquired from commercial platforms such as WorldView, QuickBird, and Pleiades. These sensors provided data across visible and near-infrared bands, with a spatial resolution of approximately two meters, which proved suitable for detailed mapping of submerged vegetation in the shallow waters of the Stagnone di Marsala Lagoon.

All satellite data underwent radiometric preprocessing, including calibration to BOA[19,20], sunglint correction[21,22], and attenuation adjustments for water column effects using the Lyzenga Depth Invariant Index (DII)[23]. These corrections were essential to ensure consistency across datasets and to enhance the reliability of vegetation classification.

Raster datasets were aligned and subsequently converted into vector formats to facilitate integration with ancillary data. The ground truth data also served as training input for the LGBM classifier[24], which was employed to perform zonal classification of submerged vegetation. Field campaigns were carried out in August of 2022, 2023, and 2024, georeferencing the surveyed locations by a GNSS survey in Network Real-Time Kinematic (NRTK) mode, ensuring sub-pixel positional accuracy[25]. Each site was documented through underwater photography, and a total of 79 validation points were obtained across all field campaigns.





Date	Sensor	λ_1 [nm]	λ_2 [nm]	λ_3 [nm]	λ_4 [nm]
7/7/2003	QuickBird	450-520	520-600	630-690	760-900
8/4/2006	QuickBird	450-520	520-600	630-690	760-900
6/8/2011	WorldView 2	450-510	510-580	630-690	770-895
15/08/2012	WorldView 2	450-510	510-580	630-690	770-895
25/08/2016	WorldView 2	450-510	510-580	630-690	770-895
16/06/2020	Pleiades 1b	430-550	490-610	600-720	750-950
6/8/2022	Pleiades 1a	430-550	490-610	600-720	750-950
12/8/2023	Pleiades 1a	430-550	490-610	600-720	750-950

Figure 2. On top, true color compositions of the Reflectance at the top of atmosphere (R_{TOA}) at the acquisition dates. On the lower left, some details of some bottom coverage (atolls, cordons, plateau, etc.) On the lower right, a list of acquisition dates, imaging sensors, and bands' nominal wavelengths.

To support classification and validation efforts, extensive ground truth data were collected to assess submerged vegetation coverage. These field observations enabled the identification of key vegetation types, including *Posidonia oceanica*, *Cymodocea nodosa*, *Caulerpa prolifera*, and various non-vegetated substrates.

4. METHODS

The mapping of submerged vegetation was carried out through a semi-automated procedure that integrates two complementary approaches (Figure 3). The first focuses on the classification of Posidonia oceanica atolls and cordons, while the second targets the distribution of submerged meadows and homogeneous benthic areas. This dual strategy was essential to account for the distinct morphological and ecological characteristics of the lagoon's vegetation and to enable a diachronic analysis spanning over two decades.

In the classification of atolls and cordons, the methodology assumes that these structures remain horizontally stable. However, they are subject to anthropogenic pressures and climate change, which can lead to canopy degradation or even structural die-off. Consequently, the spatial geometries identified in 2003 – the earliest available satellite image – served as an initial reference dataset. These geometries were digitized into vector format and aligned across all subsequent raster images to ensure consistency in temporal analysis. Land and water pixel separation was performed for each image using the Isoradiometric algorithm [26], while boat pixels were manually excluded.

The baseline for diachronic analysis of submerged vegetation was, indeed, the satellite image acquired in 2003 (Figure 4), here reported to illustrate the sequential data processing steps.

Since atolls and cordons are located just beneath the water's surface, the temporal variation in bottom-of-atmosphere reflectance (Figure 4, panel a) and eventually corrected for sunglint effects (Figure 4, panel b), was analyzed using three-image time windows. To perform this analysis, the reflectance modulus of the visible spectral bands was employed. Additionally, polygon buffers were generated to compensate for potential orthorectification inaccuracies in the imagery. Zonal statistics—mean and maximum reflectance values—were calculated for each buffered polygon, and a normalized gradient was derived to detect significant declines in reflectance over time. A threshold value, calibrated through field surveys conducted in 2022, was used to identify areas where atolls and cordons were likely to have disappeared. Given that meadows and other homogeneous areas are submerged, water column effects were corrected by applying the Lyzenga Depth-Invariant Index (DII), as illustrated in Figure 4 (panel c). Then, a principal component analysis (PCA) was performed on the Lyzenga-corrected layers across three-image time windows (Figure 4, panel d) to minimize images' radiometric noise[27]. In particular, the first five principal components, capturing over 99% of the variance, were selected for subsequent classification. Since the submerged meadows and homogeneous benthic areas were characterized by a not undefined shape, a machine learning approach based on categorical features was employed in the classification. In particular, the Light Gradient Boosting Machine algorithm (LGBM)[28] was applied. LGBM is an open-source machine learning framework based on boosting algorithms that work with iterative training processes. The input data for LGBM classification were:

- The outputs of PCA analysis performed on the Lyzenga-corrected layers.
- The ground truth data (raster of ground truth) derived from in-situ campaigns conducted in 2022 and 2023, supplemented by visual interpretation and historical surveys[29].

The classification outputs were subsequently refined using a clumping and elimination process[30], which removed small, isolated elements while preserving the overall prairie morphology. Clumping and sieve parameters were configured based on the minimum dimensions of atolls and cordons digitized from the 2003 image. The filtered classification was finally converted into vector format for integration with the atoll and cordon maps.

Finally, the two classification layers – atolls/cordons and meadows/homogeneous areas – were merged within a GIS environment. Raster and vector overlays were used to reconcile class boundaries and unify attribute tables. This integrated dataset enabled a robust submerged classification mapping, ensuring a high level of spatial and temporal accuracy, allowing for the detailed monitoring of vegetation dynamics within the lagoon.

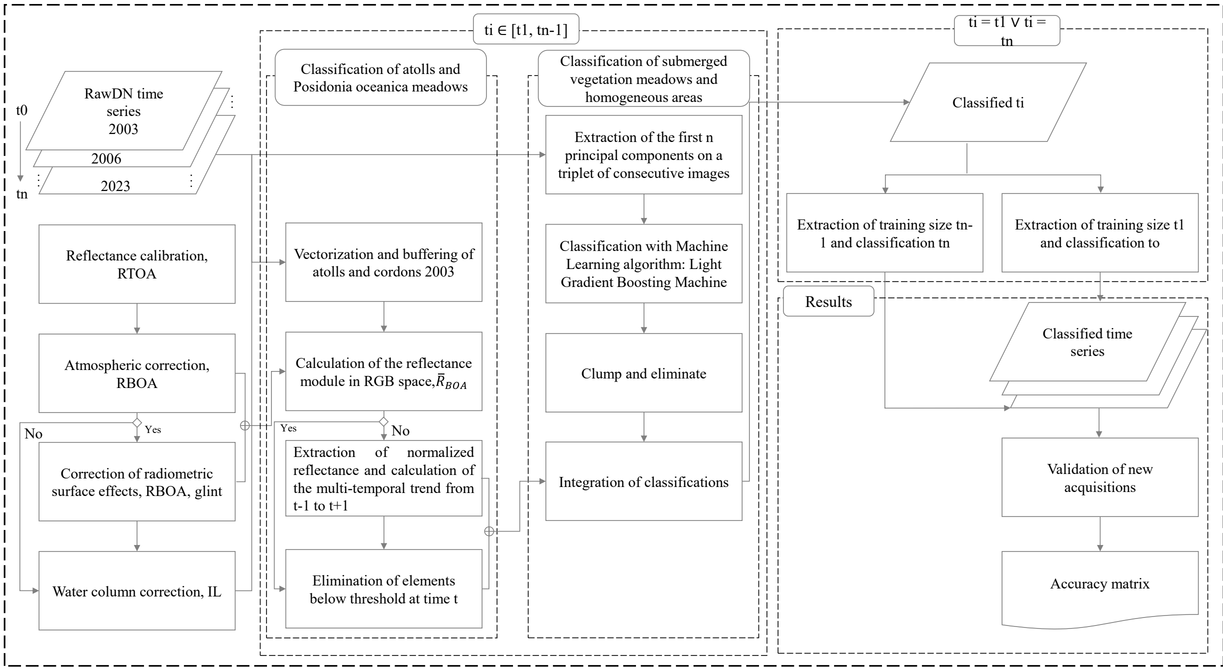
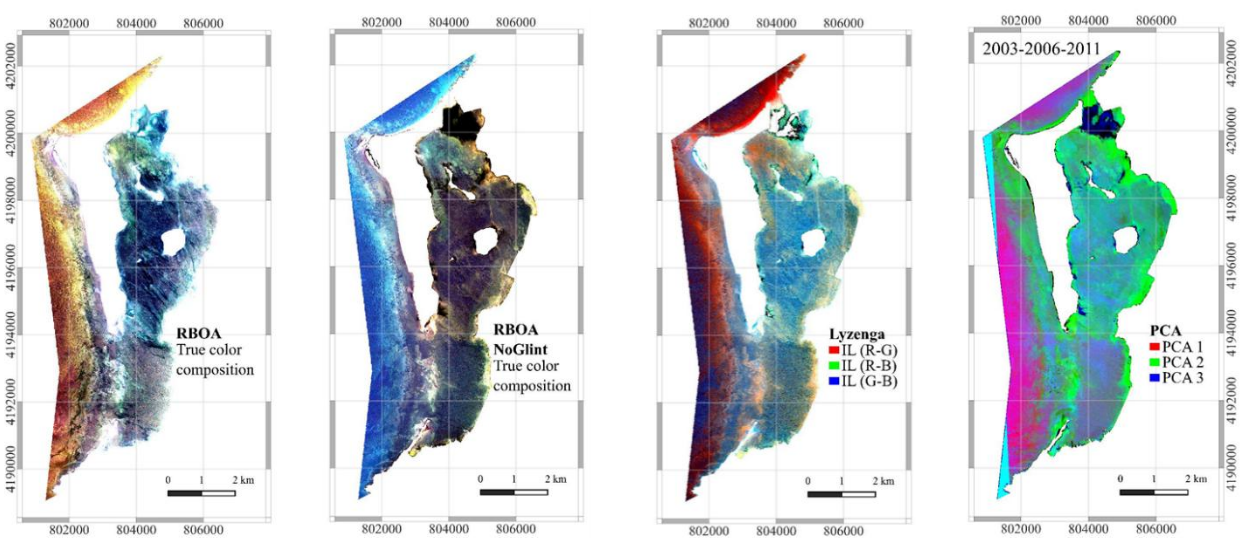


Figure 3. Data processing flowchart.

Since the analysis is based on image triplets, the first classification requires separate consideration. It was generated using the classes derived from the 2006-labeled triplet as training sites to classify the 2003 image.

The approach was validated through extensive field data, by evaluating overall classification accuracy, user and producer accuracies, and a Cohen's Kappa[31] to take into account the agreement by chance.



(a) (b) (c) (d)

Figure 4. Data processing of 2003 image: a) Reflectance bottom of atmosphere (left panel); b) Reflectance bottom of atmosphere with sunglint correction (center-left panel); c) water column correction with Lyzenga indexation (center-right panel); d) Principal Components of Lyzenga indexes (right panel).

5. RESULTS

The diachronic analysis of satellite imagery revealed significant transformations in the submerged vegetation of the Stagnone di Marsala Lagoon over the 21-year study period. The most striking trend was the progressive reduction in the spatial extent and distribution of Posidonia oceanica atolls and cordons, which were used as ecological indicators of lagoon health. By comparing the reflectance gradients of these structures across successive satellite acquisitions, it was determined that approximately 75% of the original geometries identified in 2003 had either disappeared or exhibited reflectance values below the calibrated threshold by 2023. This may indicate the degradation of atolls and cordons—either the complete loss of their canopy, the persistence of underlying rhizomes despite canopy death, or simply their disappearance from view due to the resolution limits of the imagery. This decline was particularly pronounced in the inner sectors of the lagoon, where anthropogenic pressures and sedimentation dynamics are known to be more intense.

Regarding the validation, the confusion matrix demonstrated robust classification performance across all major classes. The overall accuracy of the classification was calculated at 0.84, indicating a high level of agreement between predicted and observed classes. When adjusted for chance agreement using Cohen's Kappa, the concordance index was 0.80, further confirming the reliability of the classification model. Producer and user accuracy varied slightly across classes, with Posidonia oceanica and *Cymodocea nodosa* showing particularly strong performance, while transitional or mixed classes such as *Cymodocea nodosa with Caulerpa prolifera* exhibited moderate levels of confusion due to spectral overlap and seasonal variability.

The maps produced for 2003, 2011, and 2023 illustrate the spatial distribution of submerged vegetation at the beginning, midpoint, and end of the study period (Figure 5), offering a visual representation of the lagoon's ecological evolution over two decades.

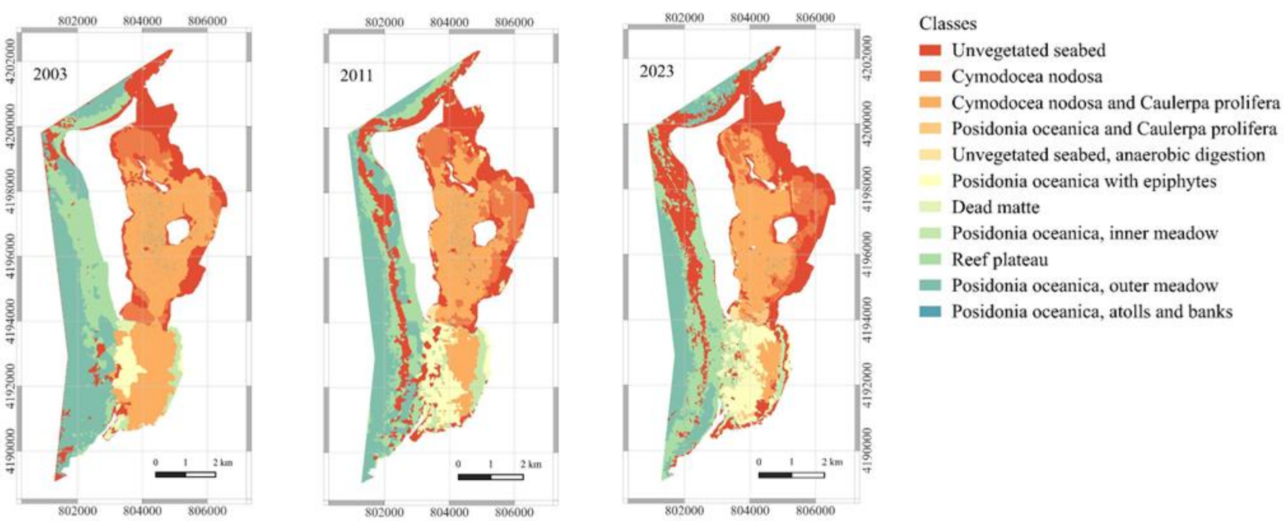


Figure 5. Thematic map of benthic substrate classification in 2003, 2011, and 2023.

The spatial distribution of these points encompasses both the inner and outer sectors of the lagoon, enabling a balanced evaluation across varying bathymetric and ecological conditions. Indeed, the validation dataset includes a well-distributed representative sample of the major classes mapped in the lagoon, such as Posidonia oceanica, Cymodocea nodosa, Caulerpa prolifera, dead matte, and non-vegetated areas (Figure 6).

The overall accuracy of the classification reached 0.84, indicating a strong level of agreement between the satellite-derived outputs and field observations. When adjusted for chance agreement using Cohen's Kappa, the concordance index was 0.80, further confirming the robustness of the classification framework.

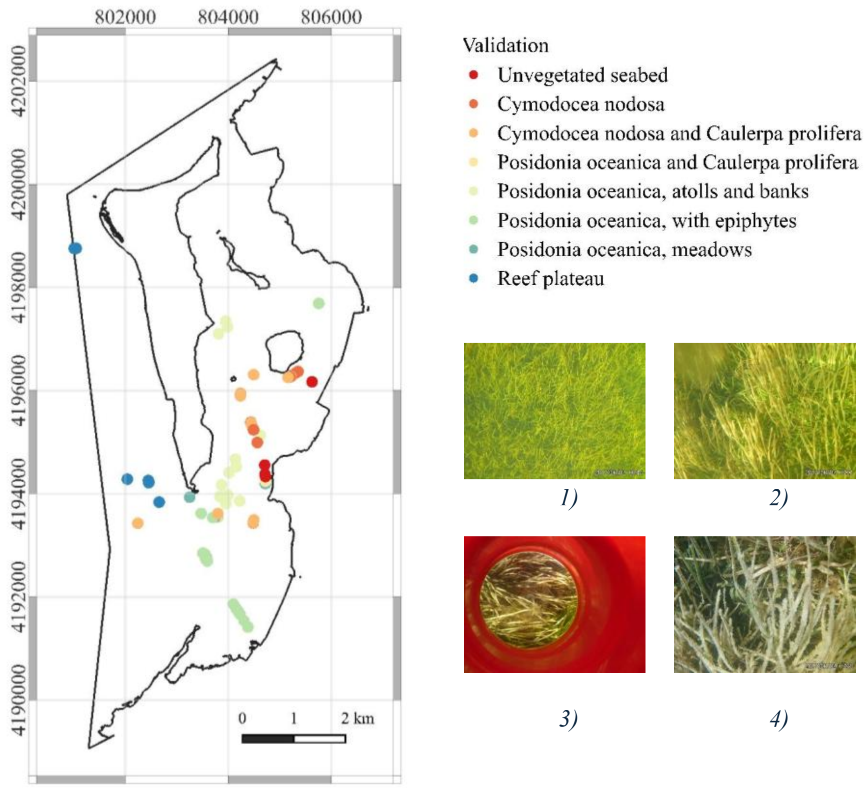


Figure 6. In situ points used for the validation of images' classification: (a) spatial distribution within the study area. (b) sample pictures of the main classes of vegetation cover.

These metrics reflect the effectiveness of the LGBM algorithm, especially when combined with radiometric corrections and principal component analysis of Lyzenga-indexed layers.

6. CONCLUSIONS AND RECOMMENDATIONS

This study demonstrates the effectiveness of integrating high-resolution satellite imagery with advanced classification techniques to monitor the submerged vegetation dynamics of the Stagnone di Marsala Lagoon over 21 years. The diachronic approach, combining radiometric analysis and machine learning, enabled a detailed reconstruction of ecological transformations within one of Sicily's most sensitive coastal ecosystems.

The results reveal a substantial reduction in the spatial extent of Posidonia oceanica atolls and cordons since 2003. This decline, confirmed through normalized reflectance gradients and validated by in-situ surveys, underscores the vulnerability of these quasi-emergent structures to both anthropogenic pressures and natural stressors. Their disappearance not only signals a loss of biodiversity but also threatens the lagoon's sediment stability and water clarity, given the ecological role these formations play.

The classification of submerged meadows and homogeneous benthic areas, supported by the LGBM algorithm and corrected for water column effects (Lyzenga DII), yielded high thematic accuracy. The overall classification accuracy reached 0.84, with a Cohen's Kappa of 0.80, indicating strong agreement between predicted and observed vegetation classes. These metrics validate the robustness of the methodological framework and its applicability to similar coastal environments.

Further investigation is required to quantify whether the proposed radiometric calibration, correction procedures, and noise reduction enhance class spectral separability[32].

The observed decline in Posidonia oceanica structures suggests a need for predictive modeling. Coupling remote sensing data with ecological models (e.g., species distribution models or hydrodynamic simulations) could forecast future vegetation shifts under different climate and anthropogenic scenarios. Formalizing a long-term monitoring protocol, possibly in collaboration with regional conservation authorities, would ensure continuity in data acquisition and analysis. This could include standardized seasonal acquisitions, in-situ campaigns, and periodic updates to classification models.

Expanding the methodology to other Coastal lagoons could reveal broader patterns of submerged vegetation decline or resilience. Comparative studies would also help refine classification thresholds and validate the transferability of your workflow.

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