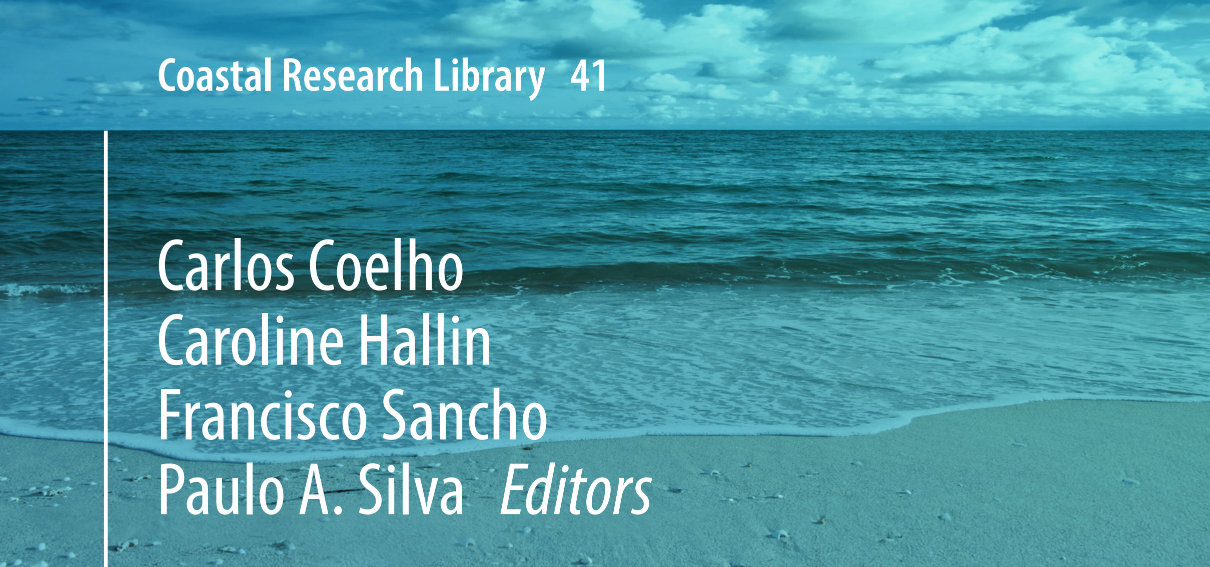

Coastal Research Library 41

Carlos Coelho
Caroline Hallin
Francisco Sancho
Paulo A. Silva *Editors*

Coastal Dynamics 2025

Volume 1

OPEN ACCESS

Springer

Coastal Research Library 41

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ISSN 2211-0577 ISSN 2211-0585 (electronic)
Coastal Research Library
ISBN 978-3-032-15472-9 ISBN 978-3-032-15473-6 (eBook)
https://doi.org/10.1007/978-3-032-15473-6

This work was supported by the Coastal Dynamics 2025 conference.

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Use of Sub-Pixel Imagery Classification to Assess Salt Marsh Plants' Adaptation

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Abstract. The inherent heterogeneity of coastal wetlands and the small size of halophytic plants present challenges in accurately sensing plant species, even with very high-resolution satellite imagery. This study used sub-pixel imagery classification methods on high spectral and spatial resolution imagery from Worldview-3 to predict plant species distribution in a mesotidal coastal wetland system. The predicted sub-pixel fractional abundance of plant species is discussed for three targeted wetland categories in the Ria Formosa lagoon: naturally evolving patches, patches modified by human activities, and patches affected by coastal squeeze.

The Random Forest Regression algorithm was proven to be highly effective in unmixing the spectral signal of halophytic vegetation, enabling the retrieval of plant species distribution (7 plant species). To train the algorithm, field observations were used to classify satellite images. Differences in band feature importance for key species and bare soil were observed across the various sites. The comparison of species distribution between sites suggests that, in addition to biotic factors, other environmental influences likely affect ecological succession; therefore, large-scale mapping approaches based on remote sensing should be undertaken with caution. The results are important for understanding the diverse ecological behavior of marsh plants within the same system and highlight the variability in plant reflectance and the need for ground truthing when sensing plant cover from satellite data.

Keywords: salt marsh · satellite imagery · species fractional cover · reflectance · environmental pressures

1 Introduction

The temporal and spatial evolution of coastal wetlands is complex and challenging to forecast and made even more complicated by changing climatic conditions [1]. While remote sensing offers many clear benefits for marsh monitoring [2], greater care should be taken when generalizing patterns of ecosystem service provision to larger scales (e.g., blue carbon assessments). Satellite imagery has shown a strong potential for acquiring comprehensive and long-term observations in extensive areas, enabling the characterization of habitat change in various spatial and temporal scales [3].

C. Coelho et al. (Eds.): CD 2025, CRL 41, pp. 381–387, 2026.
https://doi.org/10.1007/978-3-032-15473-6_59

Image classification methods applied to salt marshes have been developed for and applied to multi- and hyperspectral remote sensing data in a diverse set of biomes worldwide, to determine vegetation zonation and species abundance. Tracking such ecological variables is important to conclude about the health of wetlands and their adjustments to climate change, particularly to sea-level rise effects and limited sediment supply [4]. This study uses very high spectral and spatial resolution imagery (Worldview-3, WV3), combined with spectral unmixing methods, to assess their ability to identify the subpixel fractional cover of marsh species, focusing on zones of different physical, ecological, and anthropogenic conditions.

2 Methods and Data

2.1 Satellite Imagery and Field Data

The research was conducted in Ria Formosa, one of the main coastal lagoons of Portugal. Subpixel classification methodologies, such as the Random Forest Regression (RFR; [4]) were employed to assess their accuracy in predicting marsh plant fractional abundance in challenging marsh environments from very high-resolution EO products (WorldView-3, WV3, pansharpened imagery with pixel of 0.5x0.5 m). WV3 satellite data from May 2023 was used for the subpixel plant's fractional abundance prediction within three salt marsh sites, i.e., Site 1 - patches evolving naturally, Site 2 - patches highly affected by human activities, and Site 3 - patches facing coastal squeeze (Fig. 1). At Site 1, a 'natural' development of ecological succession is observed, with vegetation distributed in bands/zones according to topography and the wide accommodation space; sediment is characterized by a heterogeneous composition, predominantly sandy mud, with smaller contributions of muddy sand and sand. At Site 2, a modified ecological succession is observed, where vegetation zonation is interrupted over areas of high active sedimentation (burial); sediment is mainly composed of sandy mud and muddy sand, with contributions from slightly gravelly sandy mud and mud. At Site 3, due to the limited accommodation space, species are distributed in bands but with some degree of mixing of plants, especially between the medium and low marsh; sediment is homogeneous and predominantly composed of sandy mud.

The RFR algorithm was written in Python, using the open Scikit-learn package [5]. Training/testing data were collected at the three sites during 2023–2024, using RTK-DGPS and visual assessment of plant species cover. The marsh plant species present in each of the three sites determined the classes used (increased by one for the bare soil). The importance of each WV3 spectral band (i.e., feature importance used in the classification; [4]) in key plant species was extracted based on the WV3 bands.

2.2 Performance Analysis

To estimate model performance, the root-mean-square error (RMSE) and the coefficient of determination of the prediction (R^2) between predicted and observed fractional abundance were calculated for each class for both training and testing populations.

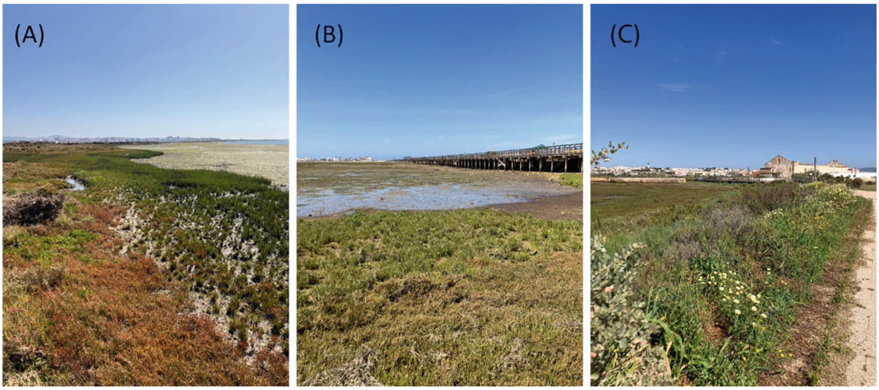

Fig. 1. Views of the test-sites: (A) Site 1, (B) Site 2, and (C) Site 3.

3 Results and Discussion

The proposed method was successfully tested against field observations. RFR proved to be highly effective in unmixing halophytic vegetation (average train population $R^2 > 0.83$ and test population overall accuracy of RMSE < 5.12 and $R^2 > 0.83$; Table 1), allowing for reliable predictions of species coverage (see Fig. 2); some of the plant species had to be grouped in pairs to improve the prediction results. The predicted and observed percentages for the classes (plant species) closely align with a 1:1 prediction line at all three sites, especially for Sites 1 and 2 (Fig. 2A and Fig. 2B). Still, Site 3, which corresponds to a wetland patch facing coastal squeeze, shows lower accuracy (higher values of RMSE) than the other two sites, mostly for the classes *Spartina maritima* and the pair *Salicornia fruticosa* and *Sarcocornia perennis* (Fig. 2C and Fig. 2D). This is likely due to the shortened development of the ecological succession and mixture of species observed at this location, which leads to a 'noisy' signal and should not be deemed as a diminished predictive ability of the algorithm.

Table 1. Accuracy assessment (averaged values) for the RFR in training and testing (RMSE; R^2).

Sites	$RMSE_{test}$	R^2_{test}	R^2_{train}
Site 1	4.58	0.90	0.89
Site 2	4.42	0.83	0.83
Site 3	5.12	0.87	0.88

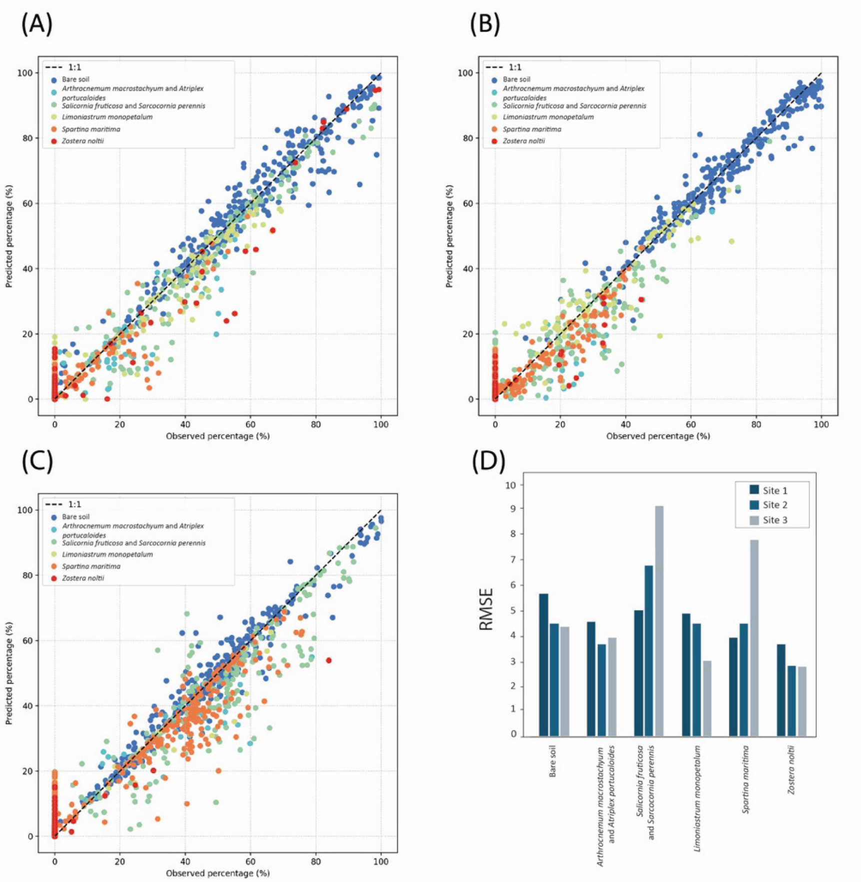

Fig. 2. Model skill (observations *vs.* predicted probabilities in each class) for Site 1 (A); Site 2 (B); Site 3 (C); and a comparison of the root-mean-square error (RMSE) for each class (bare soil, *Arthocnemum macrostachyum* and *Atriplex Portucaloides*, *Salicornia fruticosa* and *Sarcocornia perennis*, *Limoniastrum monopetalum*, *Spartina maritima*, and *Zostera noltii*) between sites (D).

The results indicate variability in band importance (feature importance shown in Fig. 3) for key species, including bare soil. Notably, the findings suggest that NIR1 (near-infrared 1, 765–901 nm) is critical for bare soil (corroborating the results of [4]). Greater variability in the NIR1 band feature importance for bare soil among the sites suggests differences in sediment composition and texture that are likely to impact ecological zonation (as observed in recent experiments of [6]). In the low marsh, for the pair *Salicornia fruticosa* and *Sarcocornia perennis*, and the *Spartina maritima*, the critical band is the NIR2 (near-infrared 2, 856–1043 nm; Fig. 3). Variability in the NIR2 band importance reveals differences in water presence, likely linked to variations in the elevation of these plant species. In the tidal flat, for *Zostera noltii* is the Red (0.64–0.67 nm; Fig. 3). Variability in this band importance implies deviations in chlorophyll absorption regions [7] associated with differences in coverage and biomass between the monitored sites.

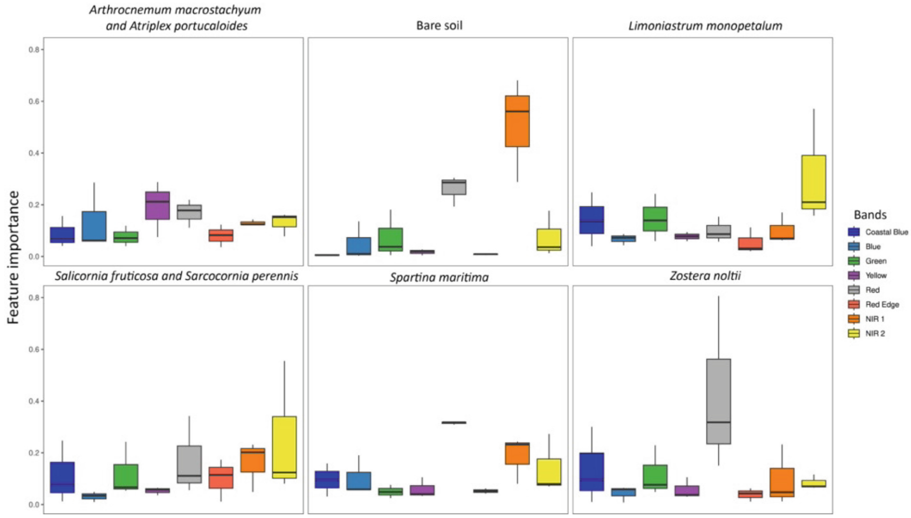

Fig. 3. Feature importance of each band for *Arthrocnemum macrostachyum* and *Atriplex Portucaloides*; bare soil; *Limoniastrum monopetalum; Salicornia fruticosa* and *Sarcocornia perennis*; *Spartina maritima*; and *Zostera noltii*, in the three sites.

The referred variability suggests that ecological succession develops differently within the same coastal system due to various natural and human pressures. The study raises concerns about the representativeness of training data and the upscaling of mapping results in wetland systems that may experience different adaptations to environmental drivers. This has already been suggested by other authors, such as [8], in the classification of UAV images in mesotidal wetlands.

4 Concluding Remarks

Improving the accuracy of remote sensing for mapping wetlands is in high demand because it offers an effective way to accurately inventory plant species and provides essential baseline data for climate change mitigation strategies. This study applied sub-pixel imagery classification methods to examine the distribution of salt marsh plants to environmental characteristics. The application of the RFR approach proved skillful in unmixing halophytic plants in mesotidal marshes, enabling accurate predictions of percentage cover for each species. When comparing sites, differences in band importance for key species were observed, indicating variability in vegetation coverage and density. This interspecific variability may be attributed to differences in life cycles or the plants' adaptive responses to the unique environmental factors at each site.

The study makes two significant contributions: first, it addresses the challenges of large-scale mapping using satellite imagery, and second, it provides insights into how environmental conditions within the same basin system may influence the development of salt marsh plants.

Acknowledgments. The work contributes to projects TraceLands (ESA-ID PP0090200) and DEVISE (https://doi.org/https://doi.org/10.54499/2022.06615.PTDC), funded by the European Space Agency (ESA) and the Fundação para a Ciência e Tecnologia (FCT).

A. R. Carrasco and K. Kombiadou were supported by the individual contracts https://doi.org/https://doi.org/10.54499/CEECINST/00052/2021/CP2792/CT0007 and https://doi.org/https://doi.org/10.54499/CEECINST/00146/2018/CP1493/CT0011, respectively, and had the support of the funding attributed to CIMA (https://doi.org/https://doi.org/10.54499/LA/P/0069/2020) and the Associate Laboratory ARNET (https://doi.org/https://doi.org/10.54499/LA/P/0069/2020), all funded by the FCT. The authors would like to thank Zhicheng Yang for kindly making available the code on the Random Forest Regressor.

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