Discriminating Seagrass From Green Macroalgae in European Intertidal areas using very high resolution multispectral drone imagery

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# 1. Introduction

Coastal areas are vital hotshots for marine biodiversity, with intertidal seagrass meadows playing a crucial role at the interface between land and ocean (Unsworth et al., 2022). Seagrass meadows provide a myriad of ecosystem services to humanity, including carbon sequestration, oxygen production, protection against sea-level rise and coastline erosion, and limitation of eutrophication. They serve as vital habitats for a diverse array of marine and terrestrial species, providing living, breeding, and feeding grounds (Gardner and Finlayson, 2018 ; Zoffoli et al., 2022 ; Jankowska et al., 2019). Due to the concentration of human activities in coastal zones, seagrass meadows are directly exposed to and impacted by anthropogenic pressures. Global regression and fragmentation are currently observed due to climate change, diseases, urbanization, land reclamation, dredging, competition with alien species, and water quality decrease (Nguyen et al., 2021 ; Soissons et al., 2018 ; Orth et al., 2006 ; Lin et al., 2018 ; Duffy et al., 2019). While improvements in water quality have been recently reported in Europe, allowing an overall recovery of seagrass ecosystems at local scale, many coastal waters worldwide are still subjected to strong eutrophication processes (Los Santos et al., 2019; Zoffoli et al., 2021). Coastal eutrophication has been associated to anomalous accumulation of green macroalgae, the so-called green tides (REF MISSING). Green tides produce shade and suffocation over seagrass individuals, thus threatening the health of seagrass ecosystems (**Duarte2002?** ; Wang et al., 2022).

The importance of seagrass meadows and the variety of ecosystem services they provide have led to the enhancement of both global and regional programs monitoring Essential Oceanic Variables (EOVs) such as seagrass coverage and composition (Miloslavich et al., 2018), as well as Essential Biodiversity Variables (EBVs) such as seagrass taxonomic diversity, species distribution, population abundance, and phenology (**Pereira2013?**). Seagrass monitoring is all the more important as it makes it possible to identify which pressures should be addressed in priority to facilitate effective mitigation actions. Traditionally, indicators of seagrass status have been quantified using in situ measurements. The acquisition of field data in intertidal zones is however notoriously challenging. Intertidal seagrass meadows are only partially exposed during low tide and can be situated in difficult-to-reach mudflats, potentially leading to inaccurate and limited estimations with conventional sampling techniques (Nijland et al., 2019). Satellite observations have proved effective in complementing in situ sampling, allowing for near real-time and consistent retrieval of seagrass EOVs and EBVs over extensive meadows (Zoffoli et al., 2021 ; Xu et al., 2021 ; Traganos and Reinartz, 2018 ; Coffer et al., 2023).

While satellite remote sensing provides temporally consistent observations over large spatial scales, it is limited by several constraints. Satellite missions with a high temporal resolution (e.g., daily MODIS observation) are limited by a too coarse spatial resolution (> 100 m). Missions with a high spatial resolution such as Sentinel-2 (10 m) and Landsat8/9 (30 m) can be limited by a low spectral resolution. The limited number of spectral bands is indeed a challenge to accurately discriminate seagrass from others co-existing macrophytes. In particular, Chlorophyceae (green algae) and marine Magnoliopsida (seagrass) share the same pigment composition (Ralph et al., 2002 ; Douay et al., 2022). As a result, their respective spectral signatures can be considered similar by a non-expert observer (Davies et al., 2023a; Bannari et al., 2022). Recently, using advanced a machine-learning classifier trained with a large hyperspectral library of > 300 field reflectance measurements, Davies et al. (2023a) demonstrated that it was possible to discriminate Magnoliopsida from Chlorophyceae using radiometric data acquired at Sentinel-2’s spectral resolution. The application of this approach to satellite remote sensing remains however to be validated. Moreover, patches of green algae can develop at small spatial scales that are not observable using non-commercial satellite imagery (Tuya et al., 2013), especially during the initial stage of the event.

Drones can potentially fill the gaps left by satellite remote sensing and in situ measurements, due to their ability to provide spatially-explicit observations at very high spatial resolutions (pixel size from cm to mm), and still capturing data at multi-spectral resolution (Fairley et al., 2022 ; Oh et al., 2017). The versatility of drones allows for their application across a diverse thematic range, from coastal zone management (Adade et al., 2021 ; Casella et al., 2020 ; Angnuureng et al., 2022) to mapping species distribution (Joyce et al., 2023 ; Tallam et al., 2023 ; Roca et al., 2022 ; Román et al., 2021 ; Brunier et al., 2022). However, when applied to coastal habitat mapping, most drone studies were limited to a single flight, restricting the generalizability of their application over wider geographical scales (Román et al., 2021 ; Collin et al., 2019 ; Rossiter et al., 2020 ; Brunier et al., 2022). The present study aimed at analyzing the potential of multispectral drone remote sensing to map intertidal macrophytes, with a particular focus on discriminating Magnoliopsida and Chlorophyceae. Ten drone flights were performed over soft-bottom intertidal areas along two European countries (France and Portugal), covering a wide range of habitats, from monospecific seagrass meadows to meadows mixed with green or red algae. A deep learning algorithm was trained and validated for macrophyte discrimination, emphasizing applicability across diverse sites without a loss of prediction accuracy.

# 2. Material & Methods

## 2.1 Study sites

Seven study sites distributed between France and Portugal were selected for their relatively extensive intertidal seagrass beds. Two sites are located in Gulf of Morbihan ([Figure 1](#fig-map) A), France (47.5791°N, 2.8018°W). This gulf covers an area of 115 km² and is only connect to the sea through a 900m wide channel. A total of 53 small islands are scattered across the gulf leading to 250 km of shorelines. Patchy seagrass meadows can be found on a lot of these islands. Within the Gulf of Morbihan we have chosen two sites : one is located in one of these islands (Arz island); the other one is located in the southern part of the gulf (Duer). Two others sites are located in Bourgneuf Bay, France (46.9849°N, 2.1488°W). This bay is a semi-enclosed macrotidal bay, protected from waves by Noirmoutier Island. Bourgneuf Bay hosts a large, intertidal seagrass meadow of about 6 km² (Zoffoli et al., 2020). Within this meadow, the sites observed by drone (L’Epine and Barbatre, [Figure 1](#fig-map) B) contain monospecific beds of *Zostera noltei*, with very little mixing with other macrophytes. Three sites have been surveyed in the Ria de Aveiro Lagoon in Portugal (40.6887°N, 8.6810°W). The extent of this lagoon is about 80 km² with many narrow channels, large salt marshes and many mudflats that uncovers at low tide. It is connected to the open sea through a single channel, with a tidal lag between the North and the South of the lagoon. The southern site (Gafanha) is a mudflat located in an affluent of the lagoon whereas the two other sites are situated in the middle of the lagoon and are only accessible by boat ([Figure 1](#fig-map) C). The Portuguese sites are characterized by a more diverse intertidal vegetation, where patches of seagrass could intermingle with red algae (Rhodophyceae), brown algae (Phaeophyceae), and green algae (Chlorophyceae).

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| Figure 1: Sites observed by drone. A: Gulf of Morbihan, B: Bourngeuf Bay, C: Ria de Aveiro Lagoon. Light green represent terrestrial areas whereas dark green represent intertidal areas. |

## 2.2 Drone Data

At each location, a DJI Matrice 200 quadcopter drone equipped with a Micasense RedEdge Dual MX multispectral camera was flown to take 1.2 million pixel reflectance photographs in 10 spectral bands from 444 (blue) to 840 nm (near infrared, NIR). An angle of 90° was maintained between the sun and the drone’s route to guarantee uniform lighting conditions between flight lines. A side overlap of 70% and a front overlap of 80% between each image was set for each flight. A downwelling light sensor (DLS2) was used to acquire irradiance data concomitantly with the camera measurements. Raw data were calibrated in reflectance using a calibration panel reflective at ~50% provided by the manufacturer. A structure-from-motion photogrammetry software (Agisoft Metashape) was used to process images to obtain multispectral orthomosaics of each flight. The workflow for orthomosaicking was the same for every flight. First, tying key points were detected inside each image and between overlapping images in order to obtain a sparse point cloud. This cloud was cleaned using reprojection accuracy metric in order to remove noisy points. A dense point cloud was then produced using a structure from motion algorithm. A surface interpolation of this dense point cloud was made to obtain a digital surface model (DSM), used to reconstruct the multispectral ortho-image. Across all sites, flights were made at two different altitudes : 12 m or/and 120 m. Low altitude drone flights produce ortho-images with a very high spatial resolution (8 mm per pixel), making it simple to visually distinguish between the various types of vegetation. High altitude fights on the other hand allow to cover large areas and produced images with a pixel size of 80 mm (Table 1).

**Table** **:** List of drone flights, summarising the date, the altitude and the purpose of each flight.

| Country | Site | Name | Altitude | Utility |
| --- | --- | --- | --- | --- |
| France | Morbihan | Arz Island | 12m | Training |
| Duer | 12m | Training |
| Duer | 120m | Validation |
| Bourgneuf Bay | Barbâtre | 120m | Validation |
| L'Epine | 120m | Validation |
| Portugal | Aveiro Lagoon | Inner Lagoon | 120m | Validation |
| Mataducos | 120m | Validation |
| Gafanha | 120m | Validation |
| Gafanha | 12m | Training |

## 2.3 Field sampling

Before each flight, targets used as ground control points (GCPs) were distributed over the study site and georeferenced with a Trimble © Geo XH 6000 differential GPS (dGPS). GCPs were used to correct georeferencing imprecision of orthomosaics with an horizontal and vertical accuracy of 10cm. dGPS was also used to georeference quadrats of 0.25cm² used to assess the presence or absence of 5 key classes of vegetation : Bacillariophyceae (Benthic diatoms forming large biofilm over the sediment during low tide), Phaeophyceae (brown algae), Magnoliopsida (seagrass), Chlorophyceae (green algae) and Rhodophyceae (red algae) ([Figure 2](#fig-vegetation)). Pictures of each quadrat were uploaded on the Global Biodiversity Information Facility (GBIF) platform (Davies et al., 2023b), a public open portal to store and share biodiversity data. Each photograph was also processed to estimate the percent cover of each type of vegetation using an image processing software (imageJ). For all quadrats, the hyperspectral reflectance signature of each vegetation class was measured using an ASD FieldSpec HandHeld 2 spectroradiometer, which acquires reflectance between 325 and 1075 nm, with 1 nm of spectral resolution. The methodological scheme followed in this study is presented in [Figure 3](#fig-workflow).

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| Figure 2: Class of vegetation used to train the CNN model and their standardised spectral signature |

## 2.4 Intertidal vegetation mapping

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| Figure 3: Schematic representation of the workflow. Diamonds represent input or output data, and rectangles represent Python processing algorithms. The overall workflow of this study is divided into two distinct parts based on the spatial resolution of the drone flights: high-resolution flights were utilized for training and prediction of the CNN model, whereas low-resolution flights were solely employed for prediction purposes. |

The spectral similarities of the reflectance signatures between intertidal green macrophytes (Magnoliopsida and Chlorophyceae) make their discrimination challenging using simple classification algorithms ([Figure 2](#fig-vegetation) F). To overcome this challenge, a deep learning classification method was developed, trained, validated, and applied to each drone flight ([Figure 3](#fig-workflow)).

### 2.4.1 Neural Network model building

| Class | Training Pixels | Validation Pixels |
| --- | --- | --- |
| Bacillariophyceae | 4,475 | 3,371,920 |
| Chlorophyceae | 17,140 | 6,258,737 |
| Magnoliopsida | 221,065 | 69,079,189 |
| Phaeophyceae | 169,936 | 18,481,141 |
| Rhodophyceae | 5,771 |  |

A dataset containing photo-interpreted drone reflectance pixels was built to train a Convolutional Neural Network (CNN) model with 2 hidden layers. The training pixels were categorized into 7 different classes, representing the various habitats encountered at the different study sites: Sediment, Water, Chlorophyceae, Magnoliopsida, Bacillariophyceae, Phaeophyceae and Rhodophyceae. Only low-altitude flights (Table 1) were used for training purposes because their 8 mm spatial resolution allowed to avoid spectral sub-pixel mixing and to accurately differentiate various vegetation classes. More than 418,000 pixels at 8 mm resolution from the 3 training flights were used to train the model (Table 2). Twenty one variables were used by the model as predictors: 10 raw spectral bands of the Micasense RedEdge Dual MX multispectral camera (ranging from 444 nm to 840 nm), the same 10 spectral bands standardized using a min/max transformation ([Equation 1](#eq-std) ; Cao et al. (2017)), and the normalized difference vegetation index (NDVI, [Equation 2](#eq-ndvi)). Standardisation of spectral bands is used to eliminate the scaling differences between spectra and to limit the effect of biomass on the shape of the spectra (Douay et al., 2022 ; Davies et al., 2023a).

where is the reflectance at the wavelength of each individual spectra , , and are the minimum and maximum value of the spectra

where is the reflectance at 840 nm and is the reflectance at 668 nm.

### 2.4.2 Validation

The CNN model was applied to all flights at both 12 and 120 m of altitude. In situ information on georeferenced class type and percent cover collected during each flight was used to assess model accuracy. The images were used to construct a validation dataset indicating the presence or absence of each class. Additionally to the quadrat-based validation dataset, polygons of each class were photo interpreted in order to increase the number of pixels of the validation dataset. A confusion matrix, along with precision metrics such as global accuracy, sensitivity, specificity, and Kappa coefficient, was generated for each site. All validation matrices were then merged to create a unique matrix. Altogether, a total of 536,000 pixels was used to validate the CNN model, thus providing a geographically robust validation dataset.

# 3. Results

## 3.1 Classification

A total of 9 prediction maps corresponding to the 9 drone flights were obtained. Each prediction map is associated with a probability map, indicating the probability of the selected class for every pixel. The low-altitude flight conducted in Gafanaha, Portugal, represents the site with the highest complexity ([Figure 4](#fig-GafLow)). Among the 5 vegetation classes on which the CNN model was trained, 4 were present on this site. On this site, there is a mixture of Chlorophyceae and Rhodophyceae over the seagrass meadow. This is also where Bacillariophyceae is most abundant. Although the seagrass bed is solely composed of *Zostera noltei*, various colors can be observed: dark green (indicating healthy beds with 100% coverage) and whitish/brown (indicating beds where leaves are dying). Regardless of the color, the meadow is predicted as Magnoliopsida by the CNN model.

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| Figure 4: RGB orthomosaic (Left) and Prediction (Right) of the low altitude flight of Gafanaha, Portugal. The total extent of this flight is 3000m² with a resolution of 8 mm per pixel. Background colors means intertidal area (Light Green) and land area (Light Grey). The zoom covers an area equivalent to a 10-meter Sentinel-2 pixel size. |

The high-altitude flight over Gafanha covered nearly 1 km² in total ([Figure 5](#fig-GafHigh)). A channel delineating a small island was masked in the prediction map due to sunglint and misclassification caused by the turbid shallow water. Most of the intertidal area has been classified as Magnoliopsida by the model, even though there is discoloration of seagrass blades. Only a few pixels have been classified as Chlorophyceae at this scale. Furthermore, the area that was classified as Bacillariophyceae in the low-altitude flight remains mostly classified as such in the high-altitude flight, though some pixels were classified as Magnoliopsida. Patches of Rhodophyceae were correctly classified. In the northern part of the scene, near the land limit, patches of *Spartina sp.* were misclassified, either as Magnoliopsida or as Phaeophyceae.

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| Figure 5: RGB orthomosaic (Left) and Prediction (Right) of the high altitude flight of Gafanaha, Portugal. The total extent of this flight is about 1 km² with a resolution of 80 mm per pixel. Background colors means intertidal area (Light Green), land area (Light Grey) and water (Light Blue). The red triangle shows the extent of the low altitude flight of Gafanha. The zoom covers an area equivalent to a 10-meter Sentinel-2 pixel size. |

The high altitude flight acquired over the inner lagoon of the Ria de Aveiro is the largest of all flights, covering almost 1.5 km² ([Figure 6](#fig-Boat)). On this site, only seagrass and red algae where seen on the field. The classification provided consistent results, with a patchy Magnoliopsida meadow mixed with Rhodophyceae on the eastern part of the scene. As shown in the zoom ([Figure 6](#fig-Boat)), the edges of the meadow can be colonised by Chlorophyceae.

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| Figure 6: RGB orthomosaic (Top) and Prediction (Bottom) of the flight made in the inner part of Ria de Aveiro Lagoon, Portugal. The total extent of this flight is about 1.5 km² with a resolution of 80 mm per pixel. Background colors means intertidal area (Light Green), land area (Light Grey) and water (Light Blue). The zoom covers an area equivalent to a 10-meter Sentinel-2 pixel size. |

The flight over L’Epine in Noirmoutier Island, France ([Figure 7](#fig-Dike)) was conducted near a dike crossing the northern part of the scene from west to east. Alongside this dike, brown algae attached to rocks and stranded green algae could be found. Despite the high mixture between Chlorophyceae and Magnoliopsida, these two classes were correctly discriminated by the classifier.

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| Figure 7: RGB orthomosaic (Top) and Prediction (Bottom) of Northern part of Noirmoutier Island, France. The total extent of this flight is about 28 000 m² with a resolution of 80 mm per pixel. Background colors means intertidal area (Light Green) and land area (Light Grey). The zoom covers an area equivalent to a 10-meter Sentinel-2 pixel size. |

## 3.2 Validation

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| Figure 8: A global confusion matrix on the left is derived from validation data across each flight, while a mosaic of confusion matrices from individual flights is presented on the right. The labels inside the matrices indicate the balanced accuracy for each class. The labels at the bottom of the matrices indicate the User’s accuracy for each class, and those on the right indicate the Producer’s Accuracy. The values adjacent to the names of each site represent the proportion of total pixels from that site contributing to the overall matrix. Grey lines within the mosaic indicate the absence of validation data for the class at that site. The table at the bottom summarizes the Sensitivity, Specificity, and Accuracy for each class and for the overall model. |

A total of 536,000 pixels was used to validate the Neural Network classifier. The sites with the lowest and highest number of validation data were Kerdrean (5,557 pixels) and Marinha Lanzarote (159,713 pixels), respectively. Model global accuracy was 94.26%, with a Kappa coefficient of 0.92 ([Figure 8](#fig-Validation)). The least performing site was Gafanha High (global accuracy of 75.45%) whereas Mataducos was the site with the most accurate prediction (global accuracy of 98.05%). Overall, the classes Phaeophyceae, Magnoliopsida, Sediment and Rhodophyceae were correctly classified with a balanced accuracy of 1, 0.96, 0.96 and 0.91 respectively. Bacillariophyceae was the least performing class (accuracy of 0.72) mainly due to the confusion between Magnoliopsida and Sediment.

## 3.3 Variable importance

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| Figure 9: Variable Importance of the Neural Network Classifier for each vegetation class. The bigger the slice, the more important is the variable to predict accuratly this class. The bottom right plot shows the drone standardised reflectance spectra of each class. |

The computation of variable importance makes it possible to identify which wavelengths are the most useful for class prediction ([Figure 9](#fig-VIP)). The spectral bands at 444, 717, and 842 nm of the Micasense camera are important for none of the vegetation classes. The band at 531 nm is the only important predictor for the classifier to accurately predict chlorophyceae. In fact, at this wavelength, the Chlorophyceae spectra has the maximum reflectance among of all vegetation classes. The bands at 531 and 740 nm are the most important predictors for Phaeophyceae, corresponding to the minimum reflectance among all classes. Bands at 475 and 560 nm are the most important predictors for Bacillariophyceae and Rhodophyceae, respectively. Four predictors, ranging from the green (560 nm) to the RedEdge (705 nm) bands are important to accurately predict magnoliopsida.

## 3.4 Effect of the flight height on the prediction

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| Figure 10: Kernel density plot showing the proportion of pixel well classified based on the percent cover of the class in high altitude flight pixels of Gafanha, Portugal. Each subplot shows all the pixels of the same classes on the hight altitude flight. Percent cover of classes is retrieve using the result of the classification of the low altitude flight of Gafanha, Portugal. The vertical dashed line shows the 0.85 probability of the model. Everything on the right of this line has a probability higher then 0.85 and everuthing on the left of this line has a probability lower. |

Using the very high precision low altitude flight, we determined the minimal percent cover required to correctly classify a given class using the high altitude flight ([Figure 10](#fig-upscaling)). When the percent cover of the class is 100 %, big pixels are well classified for all the classes excepted for Bare Sediment, where it’s well classified 80% of the time. A vegetative percent cover of at least 80% is need to have all the big pixels well classified, at the exception of Magnoliopsida that needs an higher percent cover (>90 %) to be well classified. Concerning the probability of each class, a really high Percent cover is needed to confidently predict Bacillariophyceae. To predict Chlorophyceae with a confidence of 0.85, a percent cover of 93 % is needed, 90 % for magnoliopsida, 92 % for Rhodophyceae and 97 % for Bacillariophyceae.

# 4. Discussion

# 5. Conclusion

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