



Seagrasses in coastal wetlands of the Algarve region (southern Portugal): Past and present distribution and extent

Paula Ito, Márcio Martins, Simon von Sachsen-Coburg und Gotha, Rui Santos, Carmen B. de los Santos*

Centro de Ciências do Mar do Algarve (CCMAR/CIMAR LA), Campus de Gambelas, Universidade do Algarve, 8005-139 Faro, Portugal

ARTICLE INFO

Keywords:

Seagrass
Coastal wetland
Habitat mapping
Machine learning

ABSTRACT

The global biodiversity crisis urges to update the distribution maps of natural habitats, especially those that are in rapid decline and play a key role in ecosystem functioning, such as seagrasses. In Portugal, seagrass meadows have declined substantially since the 1980s and are considered one of the most endangered marine habitats. Here we aimed to 1) compile records on the distribution and area extent of seagrass meadows in the four wetlands of the Algarve region (southern Portugal) with historical occurrence of seagrasses, based on a systematic review, and 2) update the distribution maps and area extent of seagrass meadows in this region using a combination of manual and machine learning mapping techniques. The systematic review showed a general lack of data on the distribution of seagrass meadows in the Algarve, with patchy information at different times and using incomparable mapping techniques. Based on the updated mapping from 2019 to 2023, well-developed seagrass meadows were only found in the Ria Formosa lagoon and the Guadiana estuary. In the Ria de Alvor, some sparse scattered patches of seagrass were observed in the intertidal zone, while no seagrass was found in the Arade estuary. The total extent of seagrass in the Algarve region was estimated at 1231 ha, with nearly all (99 %) occurring in the Ria Formosa, where 85 % was intertidal. Although assessing temporal trends remains challenging due to methodological differences and data limitations, the estimated 20 % decline and ongoing pressures on seagrass meadows in Algarve wetlands underscore the urgent need for continuous, standardized monitoring of their distribution, extent, and condition.

1. Introduction

The global biodiversity crisis urges an update of the distribution maps of natural habitats, especially those that are rapidly declining and play a key role in ecosystem functioning, supporting biodiversity and providing ecosystem services to people. Seagrasses are key coastal vegetated habitats for ecosystem functioning and are among the most valuable on Earth in terms of the immensely important services they provide to humanity, such as coastal protection, water purification and sanitation, biodiversity support, fisheries enhancement, carbon sequestration and recreational opportunities (Barbier et al., 2011; de los Santos et al., 2020). However, seagrass meadows have suffered severe losses and degradation worldwide in recent decades (Waycott et al., 2009; Dunic, Brown, Connolly, Turschwell, and Côté, 2021). Although in some places they have recovered (de los Santos et al., 2019; Dunic, Brown, Connolly, Turschwell, and Côté, 2021), likely following protective

measures to remove threats and pressures (de los Santos et al., 2019) and through active restoration interventions (e.g., Orth et al., 2020), these coastal vegetated habitats continue to be threatened by local and global anthropogenic stressors in many regions (Dunic, Brown, Connolly, Turschwell, and Côté, 2021). Obtaining and maintaining information on the distribution, extent, and condition of seagrass meadows is a priority in coastal and marine conservation (Unsworth et al., 2019). However, area extent assessment of seagrass habitats is rarely part of monitoring and research programmes (Unsworth et al., 2019). The absence of research efforts allocated to habitat mapping leads to a general lack of up-to-date seagrass maps in many regions, making it difficult to quantify trends in distribution and extent over time.

There are three seagrass species in Portugal, all of them are found in the Algarve region, the southernmost region of mainland Portugal stretching along 200 km of coastline: *Zostera marina* L., *Cymodocea nodosa* (Ucria) Asch., and *Z. noltei* Hornem, the latter being the only one

* Corresponding author.

E-mail address: cbsantos@ualg.pt (C.B. de los Santos).

occurring in the intertidal zone (Cunha, Assis, and Serrao, 2009). At the national level, the extent and condition of seagrass meadows have declined over decades, and seagrass meadows have even disappeared in some places (Cunha, Assis, and Serrao, 2013), which makes them a key habitat in need of protection and monitoring. Two of the three species, *Zostera marina* and *C. nodosa*, are listed as *Vulnerable* species in the Red List of the Vascular Flora of Continental Portugal, but *Z. noltei* was not assessed (Carapeto, Francisco, Pereira, and Porto, 2020). In the Algarve region, seagrass records are found in four coastal wetlands: Ria de Alvor, Arade estuary, Ria Formosa, and Guadiana estuary (Fig. 1). There are also some isolated patches of *C. nodosa* along the coast on some beaches (Cunha, Assis, and Serrao, 2013). Those four coastal wetlands are considered important areas for nature conservation and bird migration in Portugal and provide economic value through activities such as tourism and fishing (e.g., Oliveira, Castilho, Cunha, and Pereira, 2013; Erzini et al., 2022). Due to their natural value, they are protected at international level (recognition as Wetlands of International Importance by the Ramsar Convention), European level (as Sites of Community Importance - SCI - and/or Special Protection Areas - SPA) and national level (Natural Park or Nature Reserve) (Fig. 1).

The last mapping effort of seagrass meadows in the Algarve region dates back at least ten years. They were mapped in 2012 for the Ria de Alvor (Martins, 2014), in 2009 for the Arade Estuary and Guadiana Estuary (Cunha, Assis, and Serrao, 2013), and in 2007 for the Ria Formosa (Cunha, Assis, and Serrao, 2009; Guimarães, Cunha, Nzanga, and Marques, 2012; Cunha, Assis, and Serrao, 2013). Since the latter mapping effort, the seagrasses of the Algarve may have undergone significant changes in their distribution or extent. Changes may be due to their highly dynamic nature of the wetlands (e.g., Cunha, Santos, Gaspar, and Bairros, 2005; Vila-Concejo, Matias, Pacheco, Ferreira, and Dias, 2006), but especially to the numerous human interventions and impacts to which the four wetlands are subjected. Some of these impacts include: land reclamation for urban development, aquaculture, salt pans and other infrastructures (airport and fishing, commercial and recreational harbours) (Sousa, Cunha, and Ribeiro, 2020); shellfish harvesting and farming (Guimarães, Cunha, Nzanga, and Marques, 2012; Román et al., 2022); boat propeller scarring and anchoring; dredging activities (Ferreira, Matias, and Pacheco, 2016); artificial sediment nourishments

(Dias, Ferreira, Matias, Vila-Concejo, and Sá-Pires, 2003); opening and stabilisation of inlets (Kombiadou et al., 2019), coastal infrastructure constructions (Casal-Porras et al., 2022), and domestic and industrial pollution (Cabaço, Machas, Vieira, and Santos, 2008; Mateus et al., 2016). Thus, given the probable change in seagrass distribution and extent since the last mapping efforts and given that the conservation and management of coastal and marine ecosystems require accurate spatial data at a scale that matches human activities and impacts (Visconti et al., 2013), an update of the distribution maps and extent of seagrass meadows in the region is needed. Having current maps of seagrass habitats in the Algarve will be key for scientific and management purposes, such as mapping ecosystem services, conducting environmental impact assessment, monitoring their temporal trends, or re-evaluating their level of protection. This would also contribute to global seagrass distribution maps.

Here, we compiled existing data on the past distribution maps and extent of both intertidal and subtidal seagrass meadows of the four coastal wetlands of the Algarve (Ria de Alvor, Arade estuary, Ria Formosa, and Guadiana estuary), and generate maps of their current distribution and extent. The collection of past data was based on a systematic review of available spatial information. The current maps were created by combining manual and machine learning techniques with spatial information from unmanned aerial vehicle (UAV) and satellite imagery, field data, and digital elevation models. Based on the compiled data on past seagrass distribution maps and extent, along with the updated distribution maps, we assessed the temporal evolution of seagrass in the Algarve wetlands over recent decades.

2. Materials and methods

2.1. Study areas

The Algarve region presents four protected coastal wetlands with seagrasses (Fig. 1, Table 1, see Santos, Ito, & de los Santos, 2023 for full description of the sites). The Ria de Alvor is a protected estuary of 14.5 km² with intertidal seagrass meadows of *Zostera noltei* (Santos and Salgado, 1988; Cunha, 1991; Martins, 2014). The Arade estuary, a shallow protected system covering 21 km², also supports intertidal *Z. noltei*

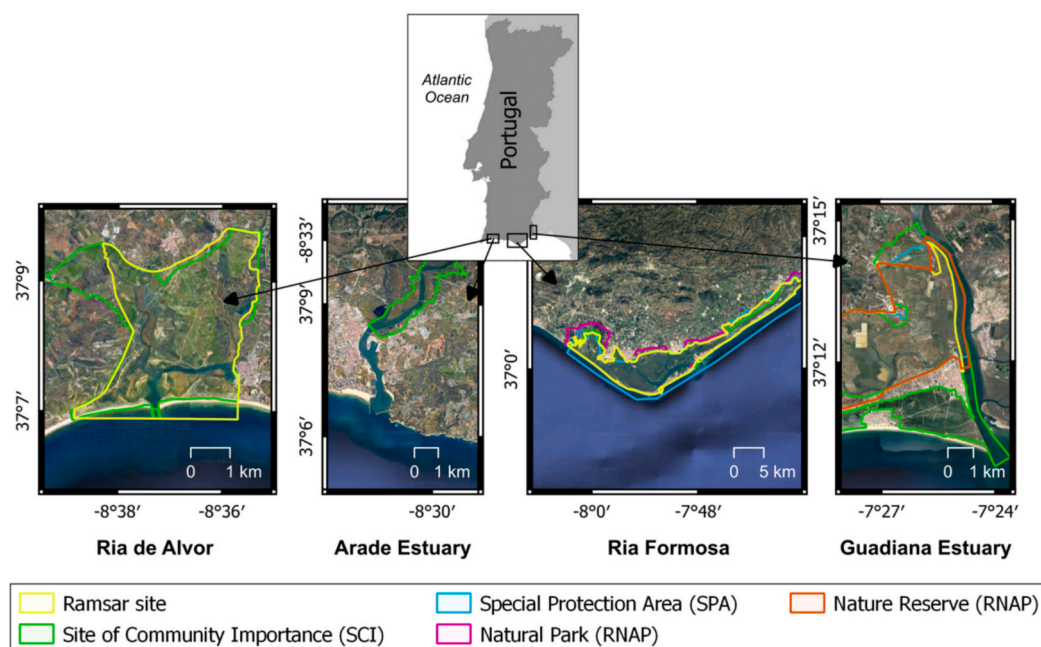


Fig. 1. Location of the four coastal wetlands of the Algarve region, in Portugal, and their protection status. RNAP: National Network of Protected Areas. Geographical information provided by the Portuguese Directorate General of the Territory and the Institute for Nature Conservation and Forests. Background map: Map data ©2024 Google.

Table 1

Protection designation, area and seagrass presence of the four wetlands in the Algarve region. RNAP: National Network of Protected Areas. SCI: Site of Community Importance. SPA: Special Protection Area. Seagrass species codes: Zn, *Zostera noltei*; Zm, *Z. marina*; Cn: *Cymodocea nodosa*. Years in brackets indicate designation years.

Feature	Ria de Alvor	Arade estuary	Ria Formosa	Guadiana estuary
Ramsar site	No. 827 (1996)	–	No. 212 (1980)	No. 829 (1996)
SCI	PTCON0058 (2008)	PTCON0052 (2008)	PTCON0013 (2008)	PTCON0013 (2008)
SPA	–	–	PTZPE0017 (2015)	PTZPE0018 (2015)
RNAP	–	–	Natural Park (1987)	Nature Reserve (1975)
Area (km ²)	14.5	21	180	22
Seagrasses	Zn	Zn	Zn, Zm, Cn	Zn

meadows (Santos, Silva, and Cunha, 2004; Cabaço, Machás, and Santos, 2007; Cunha, Assis, and Serrao, 2013), which consist of a single genetic clone (Diekmann et al., 2005). The Ria Formosa, a coastal lagoon of an approximate area of 180 km², presents intertidal meadows of *Z. noltei*, and subtidal meadows dominated by *Cymodocea nodosa* and *Z. marina*, with small patches of subtidal *Z. noltei* (Cunha, Assis, and Serrao, 2009, 2013; Guimarães, Cunha, Nzinga, and Marques, 2012). The Guadiana estuary, a protected area of 22 km², also hosts intertidal *Z. noltei* meadows (Lousã, 1986; Cunha, Assis, and Serrao, 2013).

2.2. Datasets

2.2.1. Compilation of extent and distribution seagrass data

The PRISMA protocol (Page et al., 2021; Supplementary Material, Figure S1) was used to perform a systematic review of information sources containing data on seagrass distribution and extent in the four wetlands. The Web of Science database (WoS; www.webofknowledge.com) was used on 4th July 2022, to extract records of documents using the search algorithm “seagrass*” AND (“Ria Formosa” OR “Alvor” OR “Arade” OR “Guadiana” OR “Algarve”) in the abstract. Other records known by the authors were added to the WoS-identified list of records, including online biodiversity datasets (GBIF, UNEP-WCMC and SeagrassSpotter) and grey literature (MSc and PhD theses and technical reports; Supplementary Material, Figure S1). The criteria to include a record in the final compilation was that it contained information: 1) on seagrasses in any of the four wetlands of study; and 2) on seagrass presence (georeferenced occurrence, as data point) or seagrass extent (either as a value of the area covered by the seagrass meadows or a visual representation of the polygons from which the seagrass area can be extracted). From each selected record, the data on seagrass distribution and extent was extracted from the text, figures, and tables, and further exclusion criteria were applied (see details in Supplementary Material, Figure S1). When necessary, data from figures were extracted using the software WebPlotDigitizer (Rohatgi, 2017), and images with polygons or points of occurrence were georeferenced using geographical information system (v.3.16.3; QGIS.org, 2023). Where selected records had data points from other intertidal or subtidal habitats in the vicinity of seagrass beds (bare sediment, low saltmarsh, or rhizophytic macroalgae), these were also extracted for later use in the seagrass classification model (section 2.3.2). Compiled seagrass meadows were classified as intertidal (*Z. noltei*) or subtidal (*C. nodosa* and *Z. marina*) when possible. Once extracted, the data was stored and homogenised in two databases: one for the compiled data points and another for the compiled extent data (Table S1, Table S2). For value or polygon data, the extent area was extracted as given in the source or based on spatial calculations using GIS. After being compiled, data was cleaned manually

by visually inspecting the data in QGIS, deleting points or polygons placed on land, on open ocean, or on unlikely locations, and duplicities were deleted as well. The obtained geographical data (points and polygons) were saved as geopackages using the coordinate reference system EPSG:3763 (ETRS89/Portugal TM06 – Projctado). Datasets generated in the compilation are available at Zenodo (doi:<https://doi.org/10.5281/zenodo.11510139>).

2.2.2. Digital elevation model

The Digital Elevation Model (DEM) was obtained from the most recent version of the Digital Terrain Model of the coastal areas of mainland Portugal acquired in 2011 by the Portuguese Environmental Agency and the Portuguese Directorate General of the Territory (licences no. 22190/23 and 25,677/23). The DEM has a resolution of 2 m and is derived from a set of aerial photogrammetric and airborne LiDAR data. The data uses the coordinate reference system PT-TM06/ETRS89 (EPSG:3763) and the vertical reference is the Altimetric Datum of Cascais Helmert 38, which corresponds to mean sea level (MSL). The DEM was masked to retain only the region of interest of each wetland of study.

2.2.3. Satellite imagery

A set of 3-m resolution satellite images from Planet satellite imagery (Planet Labs, 2018) was used to extract the spectral data in the regions of interest (Table 2). Images of each wetland were selected at low spring tide to cover as much of the intertidal area as possible. These were atmospherically corrected surface reflectance images and were obtained in raster format. The 2022–2023 images contained eight spectral bands, while the 2019 images (Ria Formosa) contained four bands.

2.2.4. UAV imagery

High-resolution aerial imagery was obtained in sites with known past or present records of seagrass presence of each wetland with UAV technology (Supplementary Material, Table S3). UAV surveys were conducted using a Phantom 4 drone (DJI®) equipped with a GPS for georeferencing and a 3-axis gimbal at its base with a 12.4-megapixel camera attached. Surveys were carried out at low altitude (30–60 m) during low tide and, where possible, during the time of the day at which sun glint was minimised. Drone flights followed a boustrophedon pattern with waypoints pre-programmed in pix4DCapture (version 4.11.0), capturing images of about 2 cm pixel size.

The images were unified into an orthophotomosaic after they were georeferenced and orthorectified with Agisoft PhotoScan (version 1.5.5; Agisoft LLC) or WebODM (version 2.1.0; OpenDroneMap). The orthoimages were exported as Geotiff files for processing in QGIS software. A total area of 439 ha was surveyed in the Ria Formosa, 61 ha in the Ria de Alvor, 60 ha in the Arade estuary, and 73 ha in the Guadiana estuary (Supplementary Material, Table S3). These orthophotomosaics were used in combination with field data as a backup in case manual

Table 2

Information of Planet satellite imagery used to map seagrass distribution and extent in the four wetlands of the Algarve region. Times are given in GMT (Greenwich Mean Time). Tidal information provided by the Portuguese Hydrographic Institute, with tide height referred to the Hydrographic Zero level (HZ).

Wetland	Satellite scene	Acquisition date and time	Low tide time	Tide height of low tide (m, ZH)
Ria de Alvor	PSB.SD	March 25, 2023, 10:44	10:33	0.7
Arade estuary	PSB.SD	March 25, 2023, 10:44	10:33	0.7
Ria Formosa	PS2	August 5, 2019, 09:45–10:53	12:16	0.6
Guadiana estuary	PSB.SD	March 4, 2022, 10:26	09:48	0.4

mapping was necessary (section 2.3.3) or to obtain virtual field data points by manually interpreting the imagery in areas of high confidence (section 2.3.2), as done in previous studies (e.g., Carpenter et al., 2022).

2.2.5. Field data

Field surveys to collect data for the training and testing of the seagrass classification model (section 2.3.2) were conducted from 2017 to 2020 for the Ria Formosa lagoon and in 2023 for the other wetlands (Supplementary Material, Table S5). Intertidal surveys were conducted on foot during spring low tide, using a handheld GPS (Garmin GPSMAP 60) to record seagrass presence and, in some cases, meadow boundaries. Subtidal surveys were conducted using a purpose-built underwater observation camera (Supplementary Material, Figure S2), with visual inspection performed from a kayak at low tide (< 1 m depth) or by snorkelling.

A total of 6932 point-data were collected in the intertidal and subtidal areas of the four wetlands, with 90 % of the data concentrated in the Ria Formosa (Supplementary material, Table S4, Table S5). Of these data, 52 % were points for intertidal seagrass, 17 % for unvegetated areas, 12 % for low salt marsh, 9 % for subtidal seagrass, 7 % for *Caulerpa prolifera* beds, and 3 % of unknown seagrass species. When needed, UAV orthophotomosaics were used to obtain virtual data points by manually interpreting the imagery in areas of high confidence (e.g., Carpenter et al., 2022), to be used in the classification model (section 2.3.2). Dataset generated from the field surveys is available at Zenodo (doi:<https://doi.org/10.5281/zenodo.11510139>).

2.3. Mapping process

2.3.1. General mapping approach

The seagrass mapping methods were applied only to the Ria Formosa lagoon and the Guadiana estuary, as no seagrass was found in the Arade estuary and only a few seagrass patches of a very low percentage cover (< 5 %) were observed in the Ria de Alvor. Seagrass mapping in the Ria Formosa was carried out using a combination of machine learning (ML) models and manual techniques (Fig. 2). The features used for the ML model consisted of spectral signatures extracted from the band data of the satellite imagery and elevation from the digital terrain model. These features, together with field data, were used to classify presence of seagrasses in the area of interest, with two categories, intertidal and subtidal.

A manual approach using UAV images was used as an alternative option in the Guadiana estuary for two reasons. Firstly, the model was not able to predict correctly due to the concentration of the seagrass meadows in a small area of approximately 25 ha. Since the area was too small, it was not possible to collect enough ground truth data that could

lead to a better model performance. Secondly, only two large continuous seagrass meadows, with clear upper and lower limits, were detected during our field surveys, so manual mapping would be the simplest and most accurate approach.

2.3.2. Machine learning mapping approach for the Ria Formosa

An image mosaic was created from the set of raw individual satellite images using the R package *raster* (Hijmans and van Etten, 2012), applying a median-based method to address overlapping pixels. The resulting mosaic was masked within the region of interest to reduce image size and processing time. The Normalized Difference Vegetation Index (NDVI) was calculated for each pixel of the mosaics using *rasterio* (Gillies, 2013) and *numpy* (Harris et al., 2020) packages in Python, based on the red (R) and near infrared (NIR) bands ($NDVI = (NIR - R) / (NIR + R)$). This index has been widely used for seagrass remote sensing since it quantifies the density and health of the vegetation (Barillé, Robin, Harin, Bargain, and Launeau, 2010; Valle et al., 2015; Benmokhtar, Robin, Maanan, and Bazairi, 2021; Zoffoli et al., 2021). The elevation data extracted from the DEM was down-scaled with bilinear interpolation to 3 m resolution to match the resolution of the satellite data. Finally, all raster datasets were merged into a 6-band raster stack (blue, green, red, NIR, NDVI and elevation), to be used for feature value extraction and as input for the seagrass distribution predictive model.

In addition, other mask approaches were implemented to reduce processing time and misclassification by the ML model. First, the upper elevation limit of intertidal seagrass meadows in the Ria Formosa (0.391 m MSL, de los Santos et al., 2022) was used to establish a limit for the vertical distribution of this habitat. Secondly, saltmarsh distribution data (Martins et al., submitted) and coastal infrastructures data (e.g., urban areas, clam farms) were also masked out from the raster stack.

The final dataset for the Ria Formosa was obtained by combining data from the compilation in the time period of the aerial imagery (2017–2020; 146 points) with the field data (6205 points) and field virtual points (500 points). Each data point was associated to the pixel values extracted from each raster stack band (Fig. 2). This dataset was standardized with labelled and predictor attributes: the seagrass class being the labelled attributes and the values of the six bands at the pixel level being the predictor attributes. The seagrass class label contains values of zero (absence of seagrass, which included unvegetated, salt marshes, *Caulerpa prolifera* beds habitats), one (presence of intertidal seagrass meadows) or two (presence of subtidal seagrass meadows). The density curves of the band signatures of intertidal and subtidal seagrass meadows were compared using asymptotic two-samples Kolmogorov-Smirnov tests (D), with a significance level of 0.05, and performed in the R programming language (R version 4.3.1; R Core Team, 2023) and RStudio software (version 2023.6.1.524; Posit team., 2023).

A Random Forest Classifier was employed using the *scikit-learn* library in Python (Pedregosa et al., 2011). The field dataset was divided into training and testing datasets (80 % and 20 % of the total available data points, respectively). To fit the model, a grid-search with 5-fold cross-validation was done with the training data, with the best model hyperparameters being determined by the kappa statistic. Cohen's kappa statistic measures the level of agreement between raster for categorical data, beyond what would be expected by chance alone (McHugh, 2012). The best trained model was selected to predict on the full raster stack (Fig. 2).

The evaluation of the classifier was done on the testing dataset. In addition to obtaining the kappa score for the classification, we created a confusion matrix to assess the classification accuracy with the metrics producer accuracy, user accuracy, and overall accuracy (Congalton, 1991). Overall accuracy is the most basic descriptive statistic, determined by dividing the total number of correct classifications by the total number of pixels in the confusion matrix. The producer's accuracy was calculated as the total number of correctly classified pixels within a class, divided by the total number of pixels of that class in the training data. The user's accuracy, also called reliability, was calculated as the

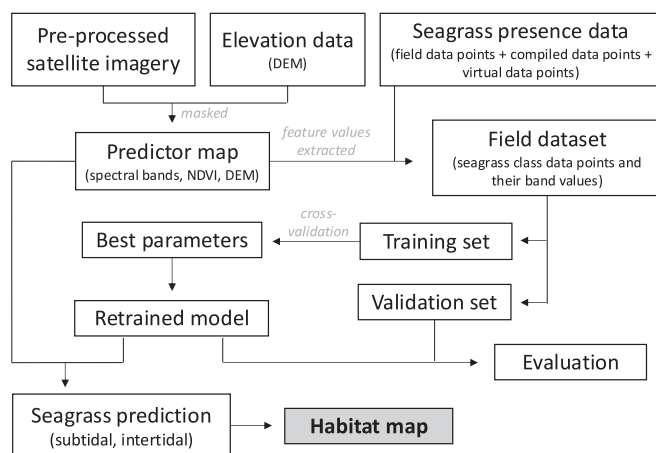


Fig. 2. Flow chart of the methodology used for seagrass habitat mapping in the Ria Formosa.

total number of correctly classified pixels within a class, divided by the total number of pixels classified in that class. The user's accuracy metric provides information on the probability that a pixel labelled on the map corresponds to what is on the field. The code and details used for the mapping process in the Ria Formosa are available on the GitHub repository: https://github.com/paulaito/seagrass_classification.

2.3.3. Manual mapping approach for the Guadiana estuary

The manual approach was based on visual analysis of field data (i.e., field data points and UAV orthoimages). Polygons of seagrass meadows were manually delimited on the orthoimages, using training data points as a visual guideline, which contained information both on seagrass presence and on the upper and lower limits of the meadow. The creation of manual polygons was performed with QGIS software.

2.3.4. Generation of seagrass habitat maps

The raster map resulting from the Random Forest Classifier model was converted into a vector format with both seagrass classes (intertidal and subtidal). A manual cleaning was performed in areas where it was certain that seagrasses did not exist, such as salt pans. The resulting vectors from both approaches were merged into one layer, with its attribute table containing for each polygon a unique identifier, the seagrass habitat class (intertidal or subtidal), the wetland name, the latitude and longitude (centroids of polygons), and the area (m²). The

reference coordinate system EPSG:3763 (ETRS89/Portugal TM06 - Projected) was used throughout the mapping process and in the GIS outputs. The predicted seagrass extent in each wetland was estimated from the resulting vector using basic geometry tools and expressed in hectares (ha). Raster and vector analysis were performed in QGIS. Final maps are available at Zenodo (doi:<https://doi.org/10.5281/zenodo.14924609>).

2.4. Temporal assessment of seagrass meadows

To estimate changes in seagrass extent over time, we assessed the compiled historical data and compared it with our updated assessment. Given the methodological differences among sources, including variations in mapping techniques, spatial resolution, and classification criteria, direct comparisons were not accurate. Although these estimates should be interpreted with caution, they offer an indicative assessment of long-term trends in seagrass coverage in the Algarve.

3. Results

3.1. Compilation of past seagrass distribution and area extent

Of the 108 records identified in the review process, only 40 presented data on the distribution and extent of seagrass in the four wetlands of the

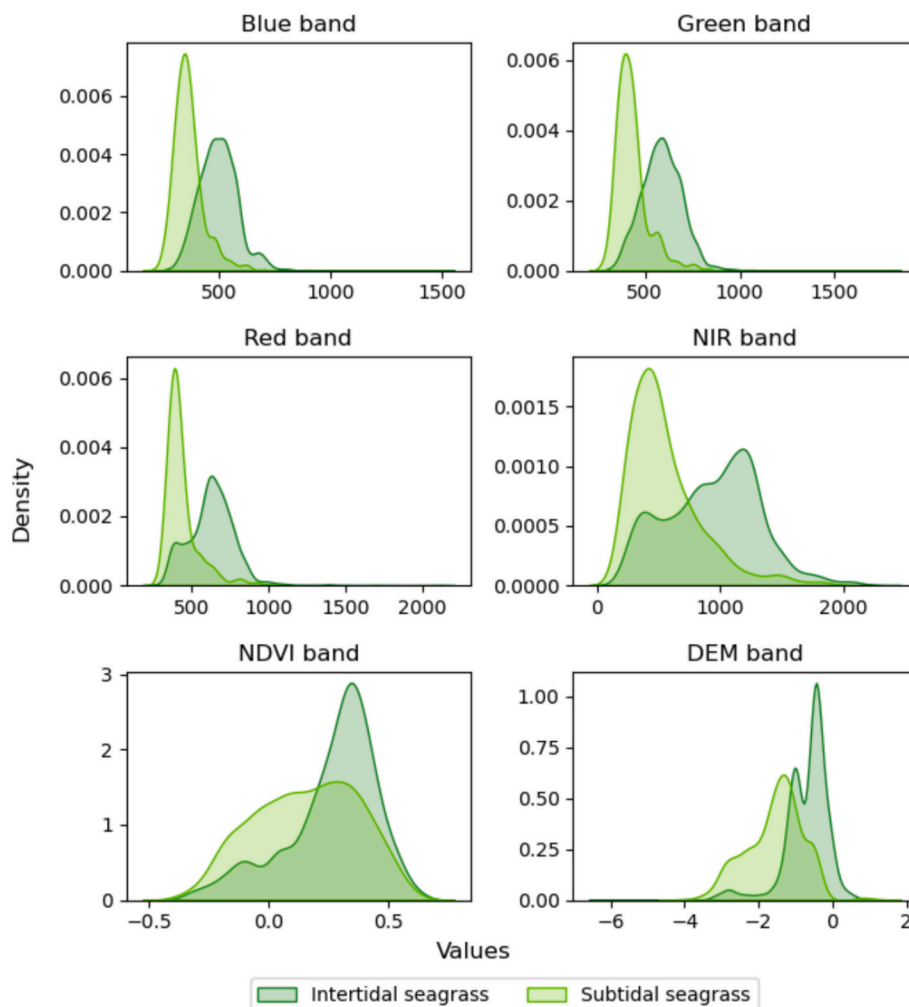


Fig. 3. Density plots of the spectral signature of the five bands extracted or calculated from satellite imagery and the elevation values extracted from the Digital Elevation Model (DEM) band for intertidal and subtidal seagrasses in the Ria Formosa. These bands were later used for the seagrass classification model. Values based on the training dataset. NIR: near infrared. NDVI: Normalized Difference Vegetation Index. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Algarve region (Supplementary Material, Figure S1). A total of 556 georeferenced data points were collected from these records from 1880 to 2023, with 443 being valid points (after removing duplicities and points on land, open ocean, or unlikely locations) spanning the period from 1987 to 2023. The majority of these data points (99 %) corresponded to the Ria Formosa, while only 4 points were recorded for Guadiana, 1 for Alvor, and none for Arade. *Zostera noltei* was the species with most data points (43 %), followed by *Z. marina* (34 %) and *C. nodosa* (23 %). Approximately 42 % of the observations (187 points) were made between 2017 and 2023. An additional 14 seagrass extent data (as value or polygons) were collected from 1986 to 2012 for the four wetlands.

3.2. Ria Formosa seagrass classification model

The density curves of the band signatures of intertidal and subtidal seagrass meadows in Ria Formosa presented overall different shapes, yet with some overlapping, especially for NDVI and DEM bands (Fig. 3). Despite of the overlapping, their statistical distributions were significantly different (Table 3), allowing the discrimination between both classes, as showed in the model overall accuracy (82.6 %).

Random Forest classification for seagrass habitats in Ria Formosa demonstrated an overall accuracy of 82.6 % and a Kappa value of 0.62, indicating a reasonable level of agreement between the predicted and the true classes. Confusion matrix suggests that the model had good capability of predicting the correct class, with user accuracies of 79.5 % and 81.8 % for intertidal and subtidal seagrass, respectively (Table 4). The DEM, green and NDVI bands were the most relevant features to discriminate the seagrass classes during the classification for the Ria Formosa according to the feature importance analysis performed in *scikit-learn* (Pedregosa et al., 2011). In a 0–1 scale, their feature importance values were 0.3 for the elevation band, 0.15 for the green and NDVI bands, 0.14 for both red and NIR bands, and 0.10 for the blue band.

3.3. Present seagrass distribution and area extent

Well-developed meadows between 2019 and 2023 were only found in two of the four wetlands with previous knowledge of seagrass presence: the Ria Formosa coastal lagoon and the Guadiana estuary. All of the three species that occur in Portugal were observed in the Ria Formosa, while only *Z. noltei* was observed in the Guadiana estuary. In the Ria de Alvor, some sparse scattered patches of short-leaved *Z. noltei* were observed in the intertidal area, with a cover of less than 5 % (Supplementary Material, Figure S3).

Based on the seagrass classification model, the estimated surface area covered by seagrass meadows in Ria Formosa was 1219 ha. The intertidal area accounted for 1033 ha, while the subtidal area covered 186 ha, representing 85.7 % and 15.3 % of the total seagrass area, respectively (Table 5, Fig. 4). As a result of the manual mapping, the area covered by intertidal seagrass meadows in the Guadiana estuary was estimated at 11 ha (Table 5). The seagrass distribution of the Ria Formosa extends throughout the wetland, while the Guadiana estuary has two continuous intertidal seagrass beds along the riverbank (Fig. 4). The

Table 3

Comparison of the density distribution of the 6 bands for the intertidal and subtidal seagrass meadows using asymptotic two-samples Kolmogorov-Smirnov tests. NIR: near infrared. NDVI: Normalized Difference Vegetation Index. DEM: elevation values extracted from the Digital Elevation Model.

Band	D	p-value
Blue	0.673	< 0.001
Green	0.669	< 0.001
Red	0.636	< 0.001
NIR	0.502	< 0.001
NDVI	0.273	< 0.001
DEM	0.579	< 0.001

Table 4

Confusion matrix for the seagrass mapping classification in the Ria Formosa, showing the user and producer accuracies. The model overall accuracy was 82.6 %.

True (right) and predicted classes (below)	Absence of seagrass	Intertidal seagrass	Subtidal seagrass	Total	User accuracy (%)
Absence	705	105	24	834	84.5
Intertidal seagrass	89	379	9	477	79.5
Subtidal seagrass	11	7	81	99	81.8
Total	805	491	114	1410	
Producer accuracy (%)	87.6	77.2	71.1		

Table 5

Estimation of the area covered by intertidal and subtidal seagrass in the Algarve from 2019 to 2023. Seagrass found in the Ria de Alvor was very scattered and sparse and was therefore not quantified. No seagrass meadows were found in the Arade estuary.

Wetland	Intertidal seagrass (ha)	Subtidal seagrass (ha)	Total
Ria Formosa	1033.26	186.08	1219.34
Guadiana estuary	11.32	0	11.32
Total	1044.58	186.08	1230.66

total extent of seagrass in the Algarve region for 2019–2023 was estimated at 1230 ha (Table 5), of which 85 % was intertidal seagrass and 99 % was in the Ria Formosa.

3.4. Temporal assessment of seagrass meadows

Based on the compiled data, an analysis of the temporal evolution of the area of *Zostera noltei* intertidal meadows in the Ria de Alvor between 1986 and 2009 showed a decrease of 92 %, from 2.1 ha - with a rather fragmented configuration of 32 patches - to 7 patches occupying a total area of 0.16 ha, which then recovered to 2.55 ha in 2012 (Martins, 2014, Figure S4). The last observation was recorded in 2020 (GBIF.org, 2023) in the southern part of the Ribeira de Odiáxere. Based on our results, seagrass loss in the Ria de Alvor was almost total, with only sparse and scattered patches remaining, representing an estimated decline of 2.55 ha since 2012.

Zostera noltei meadows in the Arade estuary were surveyed in 2004, occupying an area of 1.8 ha together with the co-existing species *Ruppia maritima* and the alga *Fucus vesiculosus* (Santos, Silva, and Cunha, 2004). In 2009, three patches were found, covering a total area of 0.004 ha, 78 % less than in 2004 (Cunha, Assis, and Serrao, 2013). In 2010, as part of the study to classify the ecological status of transitional waters, the seagrass area was estimated to be 0.24 ha (Neto et al., 2018). Since the latter study, the only available information on seagrass meadows is found in a 2013 publication, which reports their presence in an area adjacent to the Portimão Wastewater Treatment Plant (Gonçalves et al., 2013), although it does not provide geographical coordinates. Comparing the last record from 2010 to our field survey, where we did not find any well-developed meadow, we can estimate a decline of 0.24 ha since 2010.

The distribution and estimated extent of seagrass habitats in the Ria Formosa were last assessed more than two decades ago by different means (Fig. 5, Figure S4). The intertidal seagrass *Zostera noltei* was comprehensively mapped by Guimarães, Cunha, Nzinga, and Marques (2012) based on the interpretation of aerial orthophotos produced in

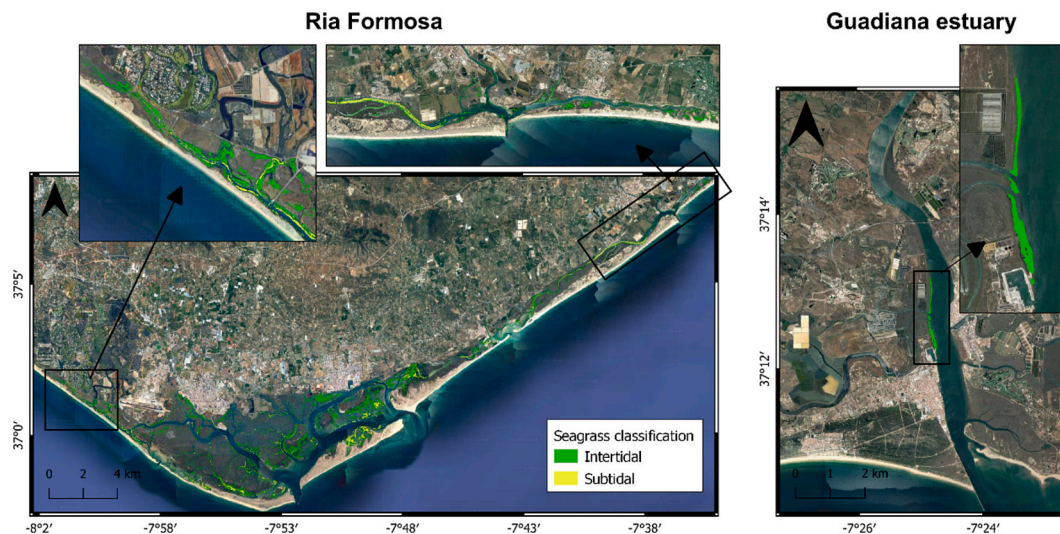


Fig. 4. Overview of the seagrass mapping results in the Ria Formosa and the Guadiana estuary. Background map: Map data ©2024 Google.

2002, revealing that 45 % of the intertidal area (1304 ha, with 640 polygons) was covered by *Z. noltei*. Three ICNF maps were created in 1996, 1998 and 2003. The 1990s maps only referred to a small area of the Ria Formosa, and the 2003 map estimated the area of intertidal seagrass to be 2872 ha, but no further information on the methods used for these habitat maps has been found. The area covered by subtidal seagrass was estimated in 2007, yielding 5 ha for *Z. marina* (42 patches), 91 ha for *C. nodosa* (15 patches) and 145 ha (7 patches) for *Z. noltei* (Cunha, Assis, and Serrao, 2009). Our results estimate 1033 ha of intertidal seagrass, a value comparable in magnitude to the 1304-ha reported by Guimarães, Cunha, Nzinga, and Marques (2012) for 2002. For subtidal seagrass, we estimated 186 ha, whereas Cunha, Assis, and Serrao (2009) reported 241 ha.

Information on seagrass meadows in the Guadiana estuary was very limited. In 2009, *Zostera noltei* intertidal meadows formed a 2–3 m wide band along 2 km of the estuary (Cunha, Assis, and Serrao, 2013). This 5.4 ha area is also mentioned in the 2010 technical report by Neto et al. (2018). Some data points were collected between 2019 and 2022 (GBIF.org, 2023), in a small lagoon next to the mouth and in the channel east of the N22 bridge. Based on the updated distribution map, we estimated 11 ha of seagrass, approximately 6 ha more than the 2010 estimate by Neto et al. (2018).

Overall, while methodological differences limit direct comparisons between historical and current maps, our approximate estimate indicates a 20 % decline in seagrass extent across the Algarve region since the most recent reference period (2002–2012, depending on the wetland). Seagrasses now persist in only two of the four wetlands with historical records.

4. Discussion

Our assessment of the seagrass distribution and area extent in the Algarve region covered four wetlands systems whose last mapping efforts date back ten years or more. The updated estimates show that well-developed seagrass meadows are lost from Ria de Alvor and Arade Estuary. These were only found in the Guadiana estuary and in the Ria Formosa lagoon. Within the time period 2019–2023, we estimated a total seagrass area in the Algarve region of 1230 ha, of which 99 % is in the Ria Formosa and 85 % is found growing in the intertidal zone.

4.1. Past and present seagrass distribution and extent

Comparison of our results on seagrass extent with estimates obtained in the past must be taken carefully since the technique we used differs

from those used in previous studies. For the Ria Formosa, our results estimated approximately 270 ha of intertidal seagrass and 55 ha of subtidal seagrass lower than the areas estimated by Guimaraes et al. (2012) and Cunha, Assis, and Serrao (2009), respectively. However, Cunha, Assis, and Serrao (2009) included the two subtidal species, *Z. marina* and *C. nodosa*, and a fraction of the subtidal area occupied by *Z. noltei*, while we included all the area covered by *Z. noltei* in the intertidal class. These different approaches may explain the difference in the estimated area for the subtidal area. Changes in data collection techniques and mapping processes could also explain the differences observed between past and present seagrass area in the Ria Formosa, yet a decline could be plausible as well since it is a wetland subjected to many human activities that normally cause seagrass loss. For the Guadiana estuary, we estimated an area of 11.32 ha, which is about 6 ha larger than the previous estimate in 2010 (Neto et al., 2018). Again, the contrasting techniques used for mapping seagrasses in this wetland makes the comparison over time difficult. However, the apparent increase in the seagrass area of *Z. noltei* in this area could be possible, since this species has a rapid growth, and can recover or colonise new areas when environmental conditions are favourable, as could be seen in other areas of Europe (de los Santos et al., 2019). In Alvor, well-developed seagrass meadows were absent, with only sparse and highly scattered patches of short *Zostera noltei* shoots observed (Figure S3). This fragmentation raises concerns about the long-term viability of the population, highlighting the need for targeted conservation efforts, including efficient habitat protection, water quality management, and potential restoration initiatives.

Based on our results, the overall status of seagrasses in the Algarve can be classified as poor, given the declining trend in their distribution and extent across most wetlands. This finding underscores the need for additional conservation and management measures beyond those currently implemented under existing protection frameworks, which appear insufficient to prevent seagrass loss or support their recovery. Possible activities causing seagrass loss in the region include the construction of coastal infrastructures (Casal-Porrás et al., 2022) and bivalve farming (Guimarães, Cunha, Nzinga, and Marques, 2012), which have a direct impact by decreasing the extent of the meadows. The results also highlight opportunities for seagrass conservation in the coastal wetlands of the Algarve, particularly through restoration efforts aimed at recovering the regional historical seagrass extent.

4.2. Strengths and limitations in the mapping model for the Ria Formosa

Mapping seagrasses present several challenges, many of which have

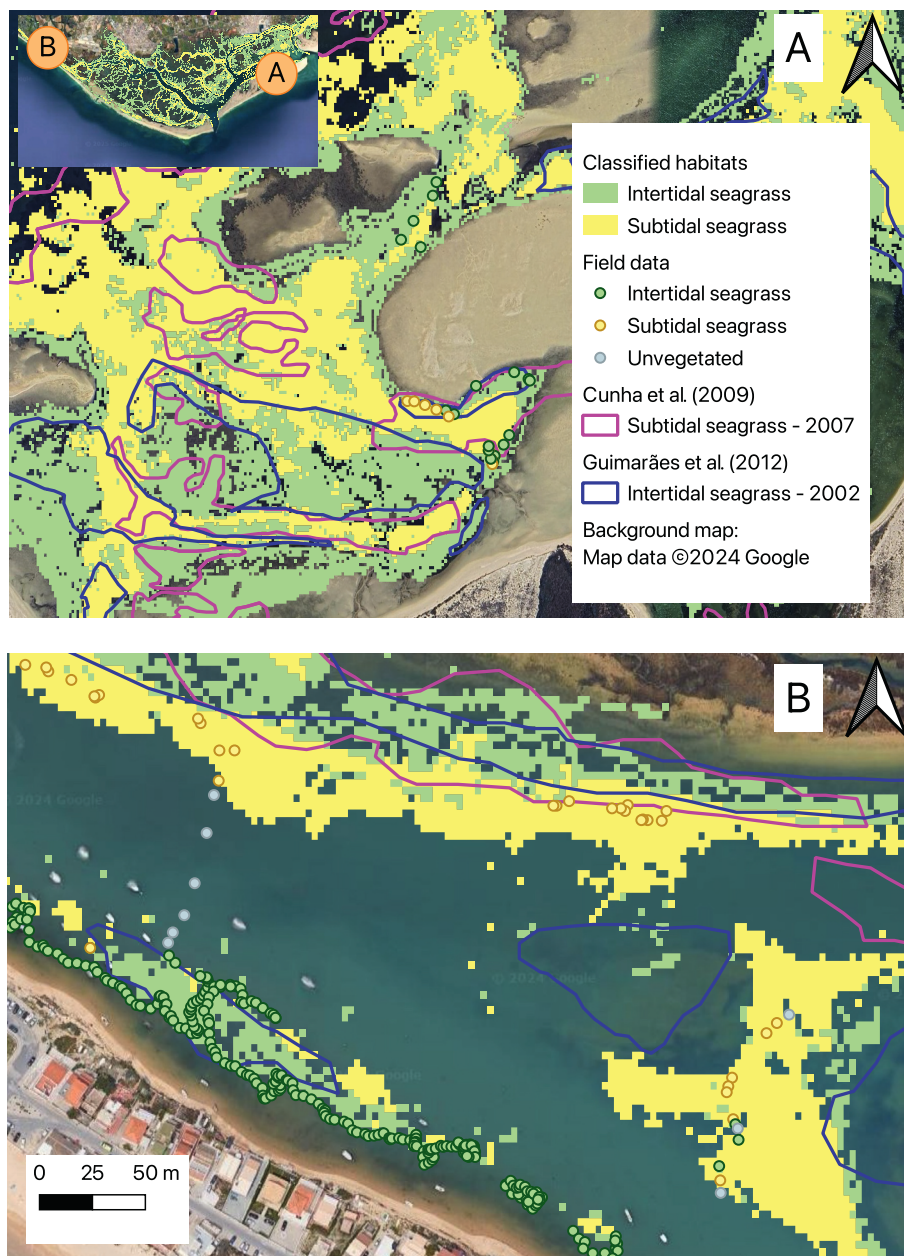


Fig. 5. Details of the seagrass mapping results in the Ria Formosa, showing the field data used in the model as well as the previous distribution of intertidal and subtidal meadows according to Guimarães, Cunha, Nzinga, and Marques (2012) and Cunha, Assis, and Serrao (2009).

been addressed through the development of new remote sensing techniques. In this study, we employed a combination of traditional and new techniques, integrating field data, drones, remote sensing and machine learning, following identified priority questions for seagrass research and conservation (Nordlund et al., 2024). We present the first model for seagrass classification and mapping in the Ria Formosa. The model exhibited strong performance, achieving an overall accuracy of 82 %, despite the challenge posed by typical water turbidity in the studied wetland, a key obstacle when mapping subtidal seagrasses (Pham et al., 2019). Notably, the producer accuracy for subtidal meadows was 71 %, slightly lower than the 77 % achieved for intertidal meadows, probably because the constraints imposed by turbidity in deeper waters. Future model will need to use compensatory techniques to address the limitations imposed by turbidity to map subtidal meadows, such as using multi-spectral or hyperspectral sensors or integrating optical and acoustic data sources.

Our seagrass classification model could be applied to assess changes

in seagrass area in the future. However, it is important to note that the model training, evaluation, and predictions were based on data collected from 2017 to 2020. Therefore, model transferability to other time periods cannot be guaranteed, and future work would benefit from additional data collection and model retraining to re-assess the area extent. We also acknowledge a series of constraints in the model that could be improved in a new version. First, the quality of the input datasets could be enhanced so that the temporal and spatial resolutions of all the bands are the same. In the present version, the asynchrony of the DEM band (2011), spectral bands (2019), and field data (2017–2020), might have been a potential error factor for the model training, since the Ria Formosa is a very dynamic system (e.g., Cunha, Santos, Gaspar, and Bairros, 2005; Vila-Concejo, Matias, Pacheco, Ferreira, and Dias, 2006). In particular, the elevation band holds great importance in the model so errors in this band may lead to misclassification of the habitat class by the model. Secondly, the model may not fully capture the entire extent of subtidal meadows, as the satellite imagery, even under the most

favourable low-tide conditions available, might have missed some areas. In fact, the satellite images were carefully selected based on proximity to low tide and other factors, such as cloud cover, but limitations in visibility remain.

Future work could involve conducting a comparative analysis of various machine learning models to identify the one with the best performance and efficiency in classifying seagrass presence in satellite imagery. Improving methods to determine elevation, or elevation proxies, in coastal environments should be one of the goals to improve the accuracy of remote sensing methods for aquatic ecosystems. Satellite-derived bathymetry methods have large spatial coverages and are becoming better both in spatial and temporal resolution but, as previously mentioned, struggle in turbid waters due to high attenuation of spectral information (Pham et al., 2019; Ashphaq, Srivastava, and Mitra, 2021). The increase in spatiotemporal imagery resolution is leading to the development of promising methods to deal with these issues in coastal areas (Sagar, Roberts, Bala, and Lymburner, 2017). Future research should also focus on high-resolution, longitudinal studies to better understand the trends of seagrass habitats over time in the Algarve region, and elsewhere. As remote sensing technologies and tools improve and become more accessible, implementing monitoring strategies based on remote sensing could greatly enhance our ability to monitor these vital habitats and support measures and policies for their protection.

4.3. The future of seagrass meadows in the Algarve

According to the results of the monitoring programmes implemented by the Portuguese Environment Agency (APA, 2022), the ecological status of the water bodies of the Guadiana estuary was classified from *Moderate* to *Poor*, for the Ria Formosa was *Good* or *Moderate*, for the Arade estuary as *Moderate* or *Poor*, and for the Ria de Alvor as *Moderate*. Since seagrasses are very sensitive to water quality (Orth et al., 2006), the improvement of the ecological status of these water bodies is essential for seagrasses to thrive in the future. In addition, other ongoing impacts must be addressed by local authorities to avoid future losses. One of the greatest threats to seagrass habitats in the Ria Formosa has been the massive expansion of the green alga *Caulerpa prolifera* in recent years (Parreira et al., 2021). This alga may be competing for space with subtidal seagrasses, leading to their decline (Alexandre and Santos, 2020 a, b). In the long term (2050–2100), seagrasses in the Algarve are threatened by rising mean sea levels (SamPATH and Boski, 2016), which could be mitigated if higher adjacent areas are made available for habitat migration into these areas. However, a large fraction of the coastal areas in the Algarve presents human constructions which may prevent the seagrass landward transgression. Losing and restricting seagrass meadows to a narrow area along the coastline will eventually cause a loss of their extent and the services they provide.

4.4. Conclusions

Seagrass meadows, once widespread across the four coastal wetlands of the Algarve, are now restricted to just two areas, the Ria Formosa and the Guadiana estuary, reflecting an estimated 20 % decline in area since the last mapping effort over two decades ago. The current seagrass area was estimated at 1230 ha, with 99 % located in the Ria Formosa and 85 % comprising intertidal seagrasses. The satellite-derived seagrass classification model for the Ria Formosa demonstrated strong performance, successfully distinguishing between intertidal and subtidal seagrass meadows, even in the typically turbid waters of a coastal lagoon. However, differences in the mapping methodologies limit our ability to assess robust temporal trends in the two wetlands where they were found; yet, the absence of seagrasses in the other two systems (Ria de Alvor and Arade estuary) underscores the continued vulnerability of these valuable ecosystems in the Algarve. Particular attention should be given to monitoring the extent of subtidal seagrass meadows in the Ria

Formosa, as previous studies suggest that the rhizophytic algae *Caulerpa prolifera* may be causing their displacement. Strengthened management actions are necessary to prevent further losses, while areas where seagrasses have disappeared present opportunities for restoration projects, provided that drivers of their decline are first addressed. Regular monitoring of seagrasses is crucial for understanding their trends over time, so regional stakeholders should collaborate to establish a monitoring program and allocate resources for it, as well as to implement adaptive management strategies aimed at conserving and restoring seagrass ecosystems in the Algarve.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the corresponding author, Carmen B. de los Santos, used ChatGPT, an AI language model developed by OpenAI, to improve English grammar and clarity. After using this tool, the author reviewed and edited the content as needed and takes full responsibility for the content of the published article.

CRediT authorship contribution statement

Paula Ito: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Márcio Martins:** Writing – review & editing, Methodology, Investigation, Data curation, Conceptualization. **Simon von Sachsen-Coburg und Gotha:** Writing – review & editing, Investigation. **Rui Santos:** Writing – review & editing, Resources, Methodology, Investigation, Funding acquisition. **Carmen B. de los Santos:** Writing – original draft, Supervision, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare no competing interests.

Acknowledgments

This study received Portuguese national funds from FCT - Foundation for Science and Technology through projects PTDC/MAR-EST/3223/2014, UIDB/04326/2020 (DOI:10.54499/UIDB/04326/2020), and LA/P/0101/2020 (DOI:10.54499/LA/P/0101/2020), fellowship SFRH/BPD/119344/2016 (C.B.d.l.S), contract 2020.03825.CEECIND (C.B.d.l.S; DOI:10.54499/2020.03825.CEECIND/CP1597/CT0005), and fellowship 2020.06996.BD (M.M.). This study also received funds from FAM Foundation through project Blue Carbon (Grants FAM 2023/2024). Márcio Martins thanks Earth data provider Planet for the Education and Research program data access. We are thankful to the colleagues from the Marine Plant Ecology Research Group (Cátia Freitas, André Silva, Ana Campos, Richard Mace, and Filipe Parreira) and students from the University of Algarve who helped with the collection of the field data.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.seares.2025.102580>.

Data availability

Data already available in repositories (links are given in the manuscript).

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