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An integrated mapping approach highlights extended distribution and high environmental status of Irish seagrass meadows

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ABSTRACT

To address the remaining knowledge gap regarding the distribution of seagrasses in Ireland, this study aimed a) to create an updated seagrass (*Zostera* spp.) distribution map, and b) to evaluate the environmental quality to which seagrass meadows are exposed. To achieve the first objective, we (i) combined the available data on seagrass distribution published to date, and (ii) mapped additional meadows by implementing an integrated method based on species distribution models, satellite-derived images, and snorkelling-based surveys. We mapped 209 new seagrass meadows (14.98 km^2), representing a 37.03 % increase over previously reported extents. Consequently, the total extent of Irish seagrass meadows is estimated to be at least 54.85 km^2. To address the second objective, we assessed the level of anthropogenic pressure of seagrass meadows based on the index provided by the Water Framework Directive of the European Environment Agency. This study demonstrates that Irish meadows are primarily located in areas with 'HIGH' and 'GOOD' water status.

1. Introduction

Seagrasses are marine flowering plants that are globally distributed across sheltered and shallow nearshore areas. Similar to tropical forests and saltmarshes, they fulfil important ecosystem services (Nordlund et al., 2018) including the provision of shelter and nursery habitat, coastal protection, and sequestration of atmospheric CO_2 into sediments (Barbier et al., 2011; Kennedy et al., 2010; Fourqurean et al., 2012; Beltran et al., 2020). However, despite their ecological importance, seagrass habitats are globally under threat due to mechanical anthropogenic disturbances, eutrophication, and climate change impacts (Orth et al., 2006; Waycott et al., 2009). Noteworthy, recent studies have suggested that local conservation efforts can succeed in restoring degraded seagrass habitats, highlighting the potential for significant habitat recovery worldwide (de los Santos et al., 2019; Dunic et al., 2021).

Over the last two decades, seagrasses have gained global recognition for their ecosystem services and their role as nature-based solutions (NbS) (Lavery et al., 2013; Nordlund et al., 2018; Crespo et al., 2023). This growing public awareness has led to the emergence of numerous seagrass citizen initiatives aimed at characterizing, monitoring, and conserving seagrass meadows (Nordlund et al., 2018), including various online platforms (e.g. SeagrassSpotter https://seagrassspotter.org) and programs (e.g. CoastWatch https://coastwatch.org/). Seagrass conservation and management are current priorities within the European framework, as reflected in the EU Habitats Directive, the Water Framework Directive (2000/60/EC), and the EU Biodiversity Strategies to 2020/2030. These initiatives align with global strategies such as the Barcelona Convention (1995), the United Nations Convention on Biological Diversity, and the International Union for Conservation of Nature.

One of the global challenges in seagrass conservation is the insufficient data on the distribution of large seagrass meadows and the environmental conditions that support them (Unsworth et al., 2019). To address this, accurate and up-to-date species distribution maps are essential to monitor species habitat changes and environmental impacts (Roelfsema et al., 2013; Egoh et al., 2012). Over the last decades, the mapping of seagrass meadows has employed several approaches (i.e.

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Hossain et al., 2015; Traganos et al., 2022); these have included the use of satellite or hyperspectral images, multibeam sonar techniques or autonomous underwater vehicles (AUVs) (Komatsu et al., 2003), or in-situ data collection through diver-operated field surveys to map these habitats (Winters et al., 2017). The mapping of benthic habitats including seagrasses and marine macroalgae, particularly subtidal or deep meadows, has proven to be highly challenging, often requiring considerable human and economic effort and time (Aswani and Lauer, 2006; Rossiter et al., 2020; Unsworth et al., 2022). Spatial or species distribution models (SDMs) have been used to estimate habitat suitability for marine primary producers, including seagrasses, by considering ecological and environmental factors at local, regional, and global scales, even in data-deficient areas (e.g., Valle et al., 2014; Beca-Carretero et al., 2020a; Mendoza-Segura et al., 2023). These models have helped to forecast seagrass biodiversity patterns, prioritize areas for habitat protection, and identify optimal zones for restoration (Adams et al., 2016). SDMs also predicted shifts in seagrass habitat suitability due to environmental changes, such as climate change, and assess the potential spread of invasive species (Beca-Carretero et al., 2020a, 2020b; Chefaoui et al., 2018). In fact, spatial models suggest that global seagrass distribution may be more extensive than currently reported (Jayathilake and Costello, 2018). The integration of diverse mapping approaches can enhance the accuracy of spatial information and provide complementary spatial and ecological data, leading to a more comprehensive understanding of seagrass meadow distribution and extent (Beca-Carretero et al., 2020b; Veettil et al., 2020).

Irish coastal waters and nearshore habitats host a variety of key ecosystems, including saltmarshes, seagrasses, maërl, oyster reefs, kelp forests, and seaweed meadows. Many of these are highly sensitive, requiring conservation efforts to ensure their survival and continued ecological functioning in the face of increasing environmental pressures (Gibson et al., 2007; Cott et al., 2021). In Ireland, seagrass meadows are formed by *Zostera marina* in subtidal and *Z. noltei* in intertidal areas, with the occasional occurrence of the ecotype *Z. marina* angustifolia; additionally, smaller meadows consist of *Ruppia* spp. (i.e. NPWS, 2011a, 2011b, 2011c, 2011d, 2011e, 2011f, 2014a, 2014b, 2014c, 2015). Overall, spatial information on Irish seagrasses has remained incomplete and requires updating. Previous efforts to map the distribution of both intertidal and subtidal populations as part of general seabed mapping efforts were led by the National Parks and Wildlife Service (NPWS), the MESH Atlantic project (http://www.emodnet-seabedhabitats.eu/map), the Site-Specific Conservation Objectives Marine Community Types project (https://data.gov.ie), and the OSPAR Habitats project (http://www.ospar.org/). These studies commenced in 1997 as part of the BioMar program and were later continued by a Marine Institute survey in 2010–2011 (Tully and Clarke, 2012). More recently, Wilkes et al. (2017) collected a comprehensive inventory of intertidal seagrass extent around Ireland, accounting for 19.1 km^2, mostly represented by *Z. noltei,* and to a lesser degree *Z. marina* angustifolia. However, recent studies of Irish seagrass meadows suggested that their actual distribution is significantly wider than currently documented (Beca-Carretero et al., 2020b; Cott et al., 2021; Hastings et al., 2020).

Notably, recent investigations have revealed extensive subtidal *Z. marina* meadows along the west coast, which remain largely undisturbed and exposed to low anthropogenic pressure (Beca-Carretero et al., 2019, 2020b). Wilkes et al. (2017) reported an overall adequate health status of the intertidal seagrass environments, particularly of *Z. noltei* meadows, but also identified certain areas that are significantly impacted by anthropogenic pressures, including nutrient loadings and mechanical disturbances. It has also been noted that some areas have experienced the depletion of seagrass meadows in recent years, for example, Dungarvan (Co. Waterford) or the wider Dublin Bay area including Malahide and Baldoyle (Madden et al., 1993; Wilkes et al., 2017). These losses were linked to anthropogenic impacts such as nutrient runoff and algae blooms. Historically, in the early 1930s, seagrass habitats on the east coast of Ireland, especially in Dublin Bay and surrounding areas, were affected by the 'wasting disease', primarily associated with the presence of the microbe *Labyrinthula zosterae* (Whelan and Cullinane, 1987). This disease resulted in substantial seagrass loss in these areas, and in other Atlantic regions of Europe (Sullivan et al., 2013) although its specific impacts in Irish waters are not well established.

In European waters, the Water Framework Directive (WFD) aims to monitor and manage water quality in marine and freshwater environments (https://environment.ec.europa.eu/topics/water/water-framework-directive_en). This tool implements various key criteria, which include assessing the chemical status by comparing pollutant concentrations against established standards, such as nutrient content or heavy metals in the water columns. It also involves evaluating various biological quality elements, such as phytoplankton, macrophytes, and invertebrates, and monitoring groundwater quality (Reyjol et al., 2014; Carvalho et al., 2019). This tool has been applied to nearshore ecosystems, including seagrasses and seaweeds (i.e. Brito et al., 2010; Pavlidou et al., 2015; Wilkes et al., 2017).

The primary objective of this study was to generate an updated distribution map of seagrasses in Ireland and evaluate the water quality to which documented meadows are exposed, thereby addressing priority questions identified for advancing seagrass conservation in Europe (Nordlund et al., 2024). First, we created a comprehensive map of seagrass distribution, focusing on *Z. marina* and *Z. noltei*, by (i) merging available data on the spatial distribution of intertidal and subtidal seagrass meadows in Ireland. Subsequently (ii), we employed a mapping approach based on a species distribution model (SDM) and satellite-derived images to gather spatial information on seagrasses around the Irish coast, further validated through snorkelling field assessments. Additionally, we determined water quality in Irish seagrass meadows using the quality index provided by the WFD.

We hypothesized that the distribution of Irish seagrass is significantly larger than currently reported in the literature, partly due to the limited attention that seagrass has received until recently. This applies particularly to subtidal meadows because of the specific difficulty associated with documenting and mapping such habitats. Additionally, we expected that a significant proportion of Irish seagrass meadows are situated in environments characterized by high or good water quality.

2. Methodology

2.1. Updated maps of Irish seagrass meadows

To create updated distribution maps of seagrasses in Ireland, we compiled, evaluated, and integrated fragmentary available records of seagrass meadows of the literature (Table 1). Subsequently, we conducted an integrated mapping approach to document novel seagrass meadows along shallow coastal waters. The spatial information derived from both approaches was then combined to produce a final distribution map (Fig. 1).

2.1.1. Sources of published seagrass distribution data

The spatial information for Irish seagrasses was categorized into two groups: one comprising specific location data (polypoint or polyline shapefiles), and another group encompassing the extent of seagrass meadows (polygon shapefiles). Based on each category, we created two separate maps.

Regarding specific location data, we gathered information from various sources, including the Global Biodiversity Information Facility (GBIF, https://www.gbif.org/), Biodiversitymapping (https://biodiversitymapping.org), Global Seagrass Watch (GSW, https://www.seagrasswatch.org/), Seagrassspotter (https://seagrassspotter.org), and citizen science projects aiming at mapping Irish seagrass meadows, such as the "Coastwatch Project of Seagrasses in Ireland" or "Searching for Seagrasses" (Beca-Carretero, 2019). Additionally, we reviewed and integrated spatial information provided by previous scientific articles (i.e.

Table 1
Data sources containing the presence and/or distribution of *Zostera marina* and *Z. noltei* from the coast of Ireland. GBIF (Global Biodiversity Information Facility), OBIS (Ocean Biogeographic Information System), NPWS (National Parks and Wildlife Service), MERC (Marine and Freshwater Research Centre).

Spatial information	Species	Region	Source	Type of sources	Year
Point	*Zostera marina*	Co Galway	Breen et al., 2024	Scientific article	2024
Points	*Zostera marina and Z. noltei*	All Ireland	GBIF	Geospatial data platforms	2024
Points	*Zostera marina and Z. noltei*	All Ireland	OBIS	Geospatial data platforms	2024
Points	*Zostera marina and Z. noltei*	All Ireland	SeagrassSpotter	Geospatial data platforms	2024
Points	*Zostera marina*	Co. Clare	Jones et al., 2018	Scientific article	2022
Points	*Zostera marina and Z. noltei*	Co Galway, Co Clare,	Azcárate-García et al., 2022	Scientific article	2022
Points and transects	*Zostera marina and Z. noltei*	Co. Waterford	Alghamdi and Young, 2022	Scientific article	2022
Points	*Zostera marina and Z. noltei*	All Ireland	Coastwatch	Report	2019
Points/ coordinates	*Zostera marina and Z. noltei*	All Ireland	Tully and Clarke, 2012	Scientific article	2012
Transects	*Zostera noltei*	All Ireland	NPWS, 2007	Report	2007
Transects	*Zostera noltei*	Co. Dublin	NPWS, 1997	Report	1997
Points	*Zostera marina and Z. noltei*	Co. Dublin	Madden et al., 1993	Scientific article	1993
Coordinates	*Zostera marina and Z. noltei*	Co. Galway, Co. Kerry	Dawes and Guiry, 1992	Scientific article	1992
Points	*Zostera marina and Z. noltei*	Co. Dublin	Whelan and Cullinane, 1987	Scientific article	1987
Points	*Zostera marina and Z. noltei*	Co. Kerry	Whelan and Cullinane, 1985	Scientific article	1985
Points	*Zostera marina and Z. noltei*	Co. Waterford	Guiry et al., 1972	Scientific article	1972
Points	*Zostera marina and Z. noltei*	Co. Waterford	Scannell and Ferguson, 1969	Scientific article	1969
Polygons and points	*Zostera marina and Z. noltei*	All Ireland	EMODNET	Geospatial data platforms	2024
Polygons and points	*Zostera marina and Z. noltei*	All Ireland	DATA.GOV.IE	Geospatial data platforms	2024
Polygons	*Zostera marina and Z. noltei*	All Ireland	OSPAR	Geospatial data platforms	2024
Polygons	*Zostera marina and Z. noltei*	Co. Kerry	NPWS, 2022	Report	2022
Polygons	*Zostera marina*	Co Galway	Beca-Carretero et al., 2024	Scientific article	2024
Polygons	*Zostera marina*	Co Galway	Beca-Carretero et al., 2021	Scientific article	2021
Polygons and points	*Zostera marina*	Co Galway	Beca-Carretero et al., 2020b	Scientific article	2020
Polygons	*Zostera marina*	Co Galway	Beca-Carretero et al., 2020a	Scientific article	2020
Polygons and points	*Zostera marina*	All Ireland	Beca-Carretero et al., 2019	PhD thesis	2019
Polygons	*Zostera marina*	Co Galway	Beca-Carretero et al., 2019	Scientific article	2019
Polygons	*Zostera noltei and Z. marina*	All Ireland	Wilkes et al., 2017	Scientific article	2017
Polygons	*Zostera marina*	Co. Galway	NPWS, 2015	Report	2015
Polygons	*Zostera marina*	Co. Galway	NPWS, 2014a	Report	2014
Polygons	*Zostera marina*	Co. Kerry	NPWS, 2014b	Report	2014
Polygons	*Zostera marina*	Co. Galway	NPWS, 2013a	Report	2013
Polygons	*Zostera marina*	Co. Cork	NPWS, 2013b	Report	2013
Polygons	*Zostera marina*	Co. Cork	NPWS, 2013c	Report	2013
Polygons	*Zostera marina*	Co. Dublin	NPWS, 2013d	Report	2013
Polygons	*Zostera marina*	Co. Waterford	NPWS, 2013e	Report	2013
Polygons	*Zostera marina*	Co. Kerry	NPWS, 2013d	Report	2013
Polygons	*Zostera marina*	Co. Wexford	NPWS, 2012a	Report	2012
Polygons	*Zostera marina*	Co. Kerry	NPWS, 2012b	Report	2012
Polygons	*Zostera marina*	Co. Kerry	NPWS, 2011a	Report	2011
Polygons	*Zostera marina*	Co. Mayo	NPWS, 2011b	Report	2011
Polygons	*Zostera marina*	Co. Cork	NPWS, 2011c	Report	2011
Polygons	*Zostera marina*	Co. Kerry	NPWS, 2011d	Report	2011
Polygons	*Zostera marina*	Co. Mayo	NPWS, 2011e	Report	2011
Polygons	*Zostera marina*	Co. Kerry	MERC, 2009	Report	2009
Polygons	*Zostera marina*	Co. Mayo, Co. Donegal	MERC, 2008	Report	2008
Polygons	*Zostera marina*	Co. Cork	Dale et al., 2007	Master thesis	2007
Polygons	*Zostera marina*	Co. Kerry	MERC, 2007a	Report	2007
Polygons	*Zostera marina*	Co Cork, Co. Mayo, Co. Kerry	MERC, 2007b	Report	2007
Polygons	*Zostera marina*	Co Galway, Co. Mayo	MERC, 2006	Report	2006

Whelan and Cullinane, 1987; Madden et al., 1993; Dale et al., 2007; Alghamdi and Young, 2022) and reports, such as MERC or NPWS (NPWS, 2007, 2015). These datasets were merged into one shapefile (ArcGIS 10.6 software [ESRI®]).

For data on *Zostera* spp. meadow characteristics including meadow extent (polygon shapefiles), we collected data from four main sources: (i) the MESH Atlantic project (http://www.emodnet-seabedhabitats.eu/map); (ii) the Site-Specific Conservation Objectives Marine Community Types project (https://data.gov.ie); (iii) the OSPAR Habitats project (http://www.ospar.org/); and (iv) published spatial information regarding Irish subtidal (Beca-Carretero et al., 2019) and intertidal (Wilkes et al., 2017) meadows. These datasets were merged and dissolved into one polygon shapefile (ArcGIS 10.6 software [ESRI®]). The extent of each meadow was calculated in square kilometers (km^2) under the Irish Transverse Mercator (IRENET 95) projection.

2.2. Integrated method for mapping seagrasses

To document novel seagrass meadows along the Irish coast, based on the proposed method by Beca-Carretero et al. (2020b), we employed an integrated mapping approach based on a Species Distribution Model (SDM) and satellite-derived images, further validated through snorkelling field assessments.

2.2.1. Seagrass occurrences

First, to perform the SDM for *Zostera* spp. in Ireland, we combined data of the spatial extent (polygon shapefiles) for both *Z. marina* (combined common ecotype and the ecotype *Z. marina* var. angustifolia [Beca-Carretero et al., 2024]) and *Z. noltei* meadows, for the following reasons: in Ireland, both species can be found in intertidal and low subtidal areas, forming mixed-species meadows (Wilkes et al., 2017; Azcárate-García et al., 2022; Beca-Carretero et al., 2024). Additionally, we detected likely species identification errors in previously published seagrass records along the coast of Ireland, particularly regarding

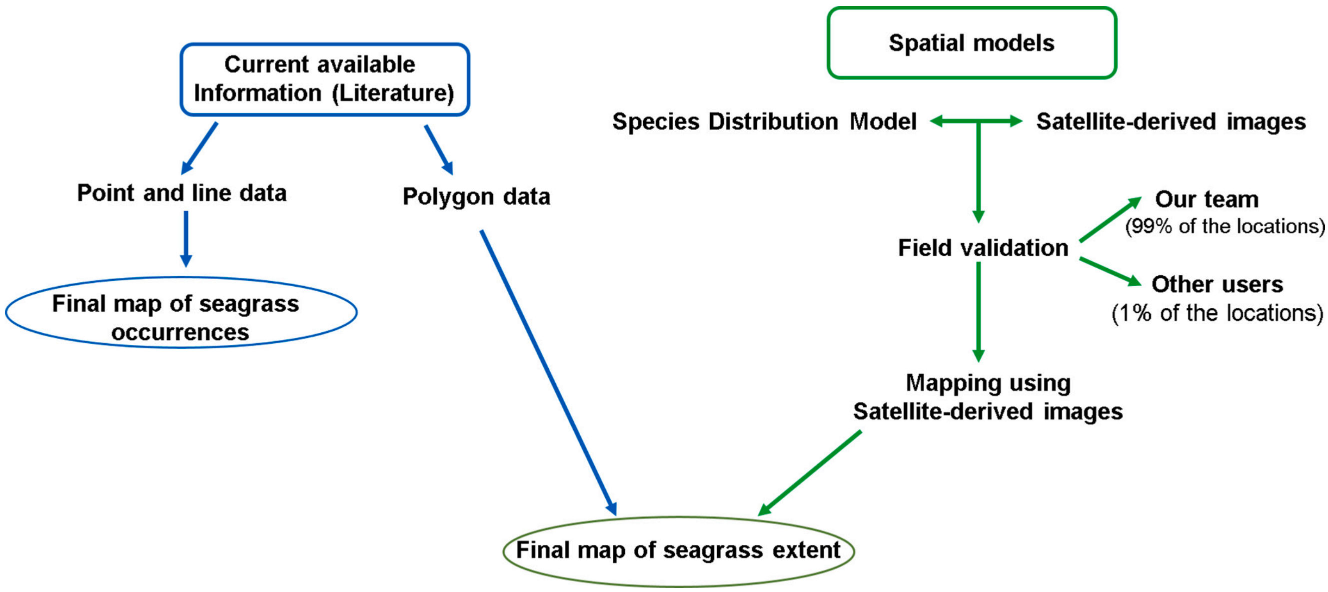

Fig. 1. Work-flow used to document and map the seagrass habitat distribution in Ireland integrating diverse approaches.

differentiation between *Z. noltei* and *Z. marina* angustifolia. Therefore, the combined information of *Zostera* spp. was merged and transformed into a polypoint shapefile, utilizing a 200-m cell grid. This resulted in a total of 155 records, of which 116 were *Z. marina* and 39 *Z. noltei*.

2.2.2. Predictor variables and pre-processing the GIS layers

To perform the SDM, a set of ten environmental variables were utilized, seven of which were continuous variables, including annual mean temperature, current energy, fetch, depth, slope, orientation, and distance from the coast, and three sedimentological layers were designated as categorical (Fig. S3). Temperature data (°C) was derived from the bioclimatic layers of the WorldClim - Global Climate Data (http://www.worldclim.org/bioclim), specifically the BIO = Annual Mean Temperature with a resolution of 0.5°. Depth (m) data were obtained from the European Marine Observation and Data Network (http://portal.emodnet-bathymetry.eu/) with a resolution of 0.2°, and from this layer, the orientation (°) and the slope (°) layers were created using the aspect and slope tools of the Spatial Analyst extension from ArcGIS 10.6 software (ESRI®), respectively. The distance from the coast (m) was calculated using the Euclidean distance tool of the Spatial Analyst extension. The raster layer of tidal current energy (m s^{-1}) was derived from the National Oceanographic Centre (NOC) as part of the EMODnet Seabed Habitats project (2010) (http://www.emodnetseabedhabitats.eu/default.aspx). This layer was created using hydrodynamic NOC models developed at 1 m above the seabed in the Celtic Sea and expressed in terms of peak kinetic energy (J m^{-3}). The fetch (m) layer was created using a method described in Finlayson (2005) designed for ArcGIS 10.6 software (ESRI®). This tool calculates effective fetch for multiple wind directions based on a text file listing individual compass directions, applying the recommended procedure of the Shore Protection Manual (https://www.umesc.usgs.gov) (USACE 1984). Finally, sedimentological data were sourced from the EUNIS seabed habitat map for the North Sea and Celtic Sea (http://www.emodnet-seabedhabitats.eu/), which is categorized following the EUNIS classification system (Galparsoro et al., 2012). Three sedimentological layers were created: (i) soft sediment, including mud, muddy–sand, and sandy–mud; (ii) mixed sediment, comprising sand, and mixed and coarse sediment; and (iii) hard sediment, consisting only of rock and reef. Data of sediment types were collected from three different sources: (i) the MESH Atlantic project (http://www.emodnet-seabedhabitats.eu/map); (ii) the Site-Specific Conservation Objectives Marine Community Types project (https://wwww.data.gov.ie); and (iii) the OSPAR Habitats project (http://www.ospar.org). All predictor variables were transformed into raster files to ensure the same resolution extent and projection (IRENET 95). The environmental variables were specifically selected based on their significant influence on seagrass habitat requirements. For instance, seagrass presence can be limited by exposure to high water currents or wave velocities. Additionally, changes in water depth and orientation impact the quality of light available for photosynthesis which, in turn, affects the vertical distribution of seagrasses. The type of sediment and the slope of the sediment is another important factor, as seagrasses generally prefer sandy and muddy areas with relatively steady slopes on the seafloor.

2.2.3. SDM and model evaluation

The MAXENT model was used to (i) identify the environmental factors that best explained the distribution of seagrasses, and (ii) generate a map of seagrass habitat suitability. Therefore, the objective of the SDM was not to predict the potential extent of seagrass meadows in Ireland, but rather to identify areas with suitable environmental conditions for seagrass presence, to guide the next steps in the proposed mapping methods. The MAXENT model was run with the default response settings (Phillips et al., 2006). For this, we assumed that (i) the depth distribution of seagrasses must be equal to or below 0 m and (ii) the seagrass distribution has remained constant since the first records in 1996. MAXENT generated a continuous raster file with pixel values ranging from 0 to 1, with 1 representing the highest probability of potential habitat suitability and 0 representing the absence of the target species. Subsequently, we created a binary map indicating the presence or absence of potential seagrass habitat. To assume the potential habitat suitability of seagrasses, a logistic threshold was set to 0.33 (Table S2). We calibrated the model using a random sample of 70 % (109 records) of the presence data of the target species along the Irish coast and validated it by selecting a random 30 % (46 records) of the distribution data of the target species. The calibration and validation were conducted ten times using different random distributions of seagrasses in both cases. The final habitat suitability model was obtained based on the average of the 10 independent predictions.

Two different evaluation measurements were used to assess the performance of the SDM, as was previously applied in similar seagrass studies in Ireland (Beca-Carretero et al., 2020b). The first evaluation method used was the area under the Receiver Operating Characteristic curve (commonly abbreviated as ROC) and its corresponding area metric, the area under the curve (AUC), which assesses the model's ability to distinguish between the presence and absence of a species. This is a standard method to evaluate the performance of a model that aims to split into two categories, which allow us to give a general value for the performance of the model independently of the threshold used to transform the continuous output into a binomial map The ROC curve plots the true positive rate against the false positive rate, and the AUC quantifies the overall performance of the model, with a value of 1 indicating perfect discrimination and a value of 0.5 representing random chance. An AUC value between 0.5 and 0.7 indicates poor model performance, while values between 0.7 and 0.9 are considered to have moderate discriminatory ability. Models with AUC values higher than 0.9 are considered to perform excellently. To test the significance of the AUC, a cross-validation procedure was performed with 100 iterations. The second evaluation method was the sensitivity parameter, which is the proportion of correctly predicted presence of the target species by the SDM. This approach was chosen based on the nature of the data and the SDM used (Allouche et al., 2006).

2.2.4. Satellite-derived images

To visually identify potential seagrass meadows in areas where the SDM predicted its habitat suitability, we downloaded high-resolution satellite images from World Imagery in ArcGIS 10.6 software (ESRI®) for different months between 2014 and 2019. To ensure optimal accuracy in identifying seagrass meadows using satellite images, we prioritize images generated in days with low tides and clear skies. This multi-season and multi-year approach provided additional information on the seasonality of seagrass meadows and allowed selection of those days that could enable visual differentiation of seagrass presence.

2.2.5. Field-survey seagrass documentation and spatial assessment

To document and assess the spatial extent of new seagrass meadows, we conducted snorkelling-based surveys between December 2015 and March 2019, based on spatial information obtained from the SDM and satellite-derived images. The methodology was adapted from Beca-Carretero et al. (2020b); specifically, we did not use GPS devices to map

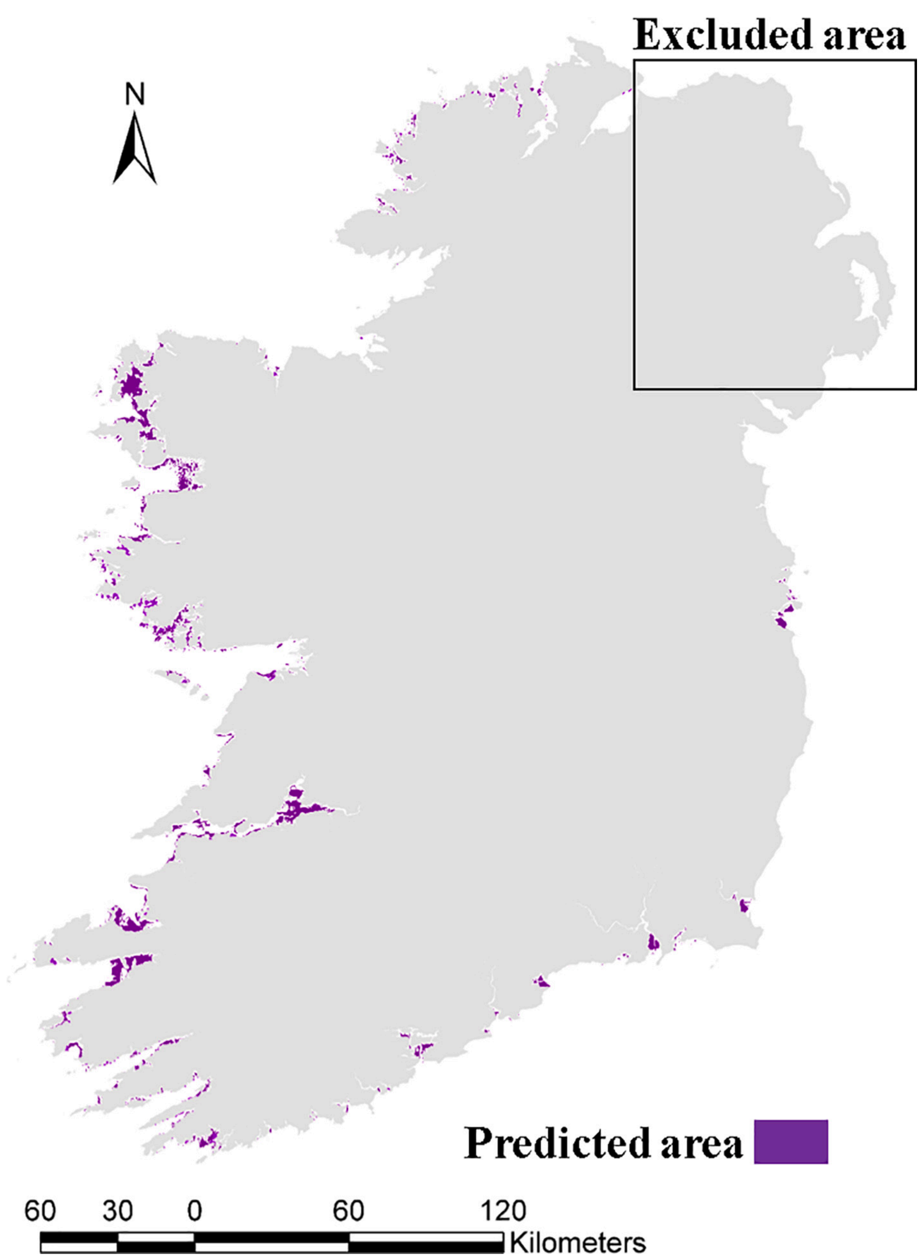

Fig. 2. Map of habitat suitability of seagrass meadows (*Zostera* spp.) predicted by the maximum entropy (MAXENT) model along the coast of Ireland under present conditions. The SDM outcome is based on the average result of 10 model simulations.

the extent or edges of the seagrass meadows. Instead, we used high-resolution satellite images to delineate the meadow edges. We manually drew the potential extent of the meadows using ArcGIS 10.6 software (ESRI®) and high-resolution satellite images (Fig. S5).

2.3. Production of final seagrass distribution maps

To generate the final seagrass distribution maps for the coast of Ireland, we developed the following maps: (i) Combined known and new areas map: we merged the documented extent of seagrass meadows along the coast using available and published distribution data labelled as "known areas" (Table 1 and Fig. 2). Additionally, we included newly documented spatial information categorized as "new areas," obtained through our integrated mapping approach (Fig. 3). During this process, we also redefined the extent of certain previously documented meadows where inaccuracies in their edges were identified. (ii) Species-specific map: Based on the spatial information provided in Fig. 3, we created an additional map showing the distribution specifically for *Zostera marina* and *Zostera noltei* (Fig. 4). (iii) Point and line shapefiles map: A map encompassing seagrass records compiled in the literature as point and line shapefiles is included in the supplementary material (Fig. S1).

2.4. Determining the environmental quality of Irish seagrass meadows

To evaluate the water quality in areas where Irish seagrass meadows were present, we conducted an analysis to assess their exposure to different levels of anthropogenic pressures. To accomplish this, the water quality index provided by the Water Framework Directive (WFD) of the European Environment Agency (EEA) [https://www.eea.europa.eu/] was applied to classify water quality as HIGH, GOOD, MODERATE, POOR, or VERY POOR. We then transformed the final polygon shapefile of the seagrass distribution map, encompassing both

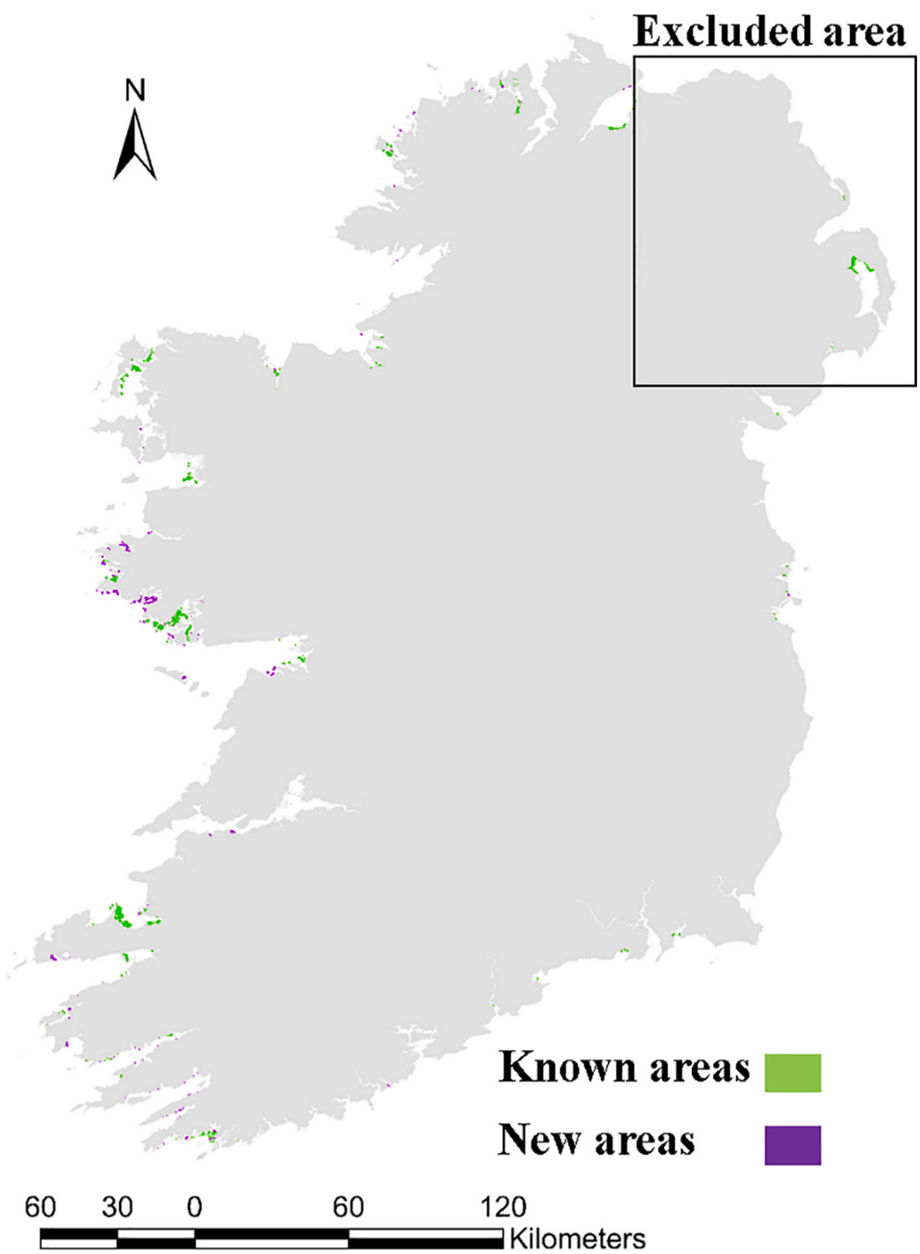

Fig. 3. Updated map of seagrass distribution in Ireland based on previously published records (green) and newly discovered (purple) seagrass meadows based on the spatial data obtained from implementing the described mapping approach. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Fig. 4. Final map of the distribution of *Zostera marina* (dark brown) and *Z. noltei* (orange) around the coast of Ireland, based on both literature records and the newly mapped seagrass meadows. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

previously documented and newly discovered meadows (Fig. 4), into a polypoint shapefile, utilizing a 200-m cell grid. This yielded a total of 204 records, comprising 158 records of *Z. marina* and 46 of *Z. noltei.* We superimposed the distribution points of marine seagrasses onto the water quality map (Fig. S7), and by examining the number of seagrass distribution points within each category, determined the percentage of seagrass meadows exposed to different water quality levels.

3. Results

3.1. Literature review

We compiled data from 48 sources to create an updated map of seagrass distribution, including meadow extents of "known areas" (Table 1 and Fig. 3) based on records from the literature. We incorporated spatial data from 37 sources, resulting in a total area covered by seagrass of 39.96 km^2, of which 31.15 km^2 is attributed to *Zostera marina* and 8.81 km^2 to *Z. noltei*.

For the map with point and line shapefile datasets, we integrated spatial information from 12 additionally sources, accounting for a total 412 seagrass occurrences (Table 1).

3.2. Integrated mapping approach

3.2.1. SDM

The performance of the SDM built for *Zostera* spp. reported a high discriminatory capacity within an AUC value of 0.993 and a sensitivity of 71 %. (Table S2). Model results indicate that, among the environmental descriptors, fetch (39.5 %) and depth (35.7 %) were the most important parameters explaining the distribution of the combined *Zostera* spp., followed by distance from the coast (19.0 %) and mean temperature (4.2 %). On the contrary, other environmental variables, such as tidal velocity, slope, orientation, and sediment type, did not have a significant importance in explaining the seagrass presence (Fig. S5). The SDM predicted a habitat suitability of seagrass meadows of 365.6 km^2 along the coast of Ireland (Fig. 2).

3.2.2. Field validations

Through in-situ snorkelling validations, we assessed 209 potential seagrass locations identified from the implementation of the SDM and satellite-derived images. Among these sites, seagrass presence was confirmed in 185 locations, yielding a validation success rate of 88.5 %. The newly documented seagrass meadows covered a total area of 14.88 km^2, representing a 37.03 % increase in habitat distribution compared to the previously 39.96 km^2 of meadows reported in the literature. The newly documented meadows were predominantly represented by submerged *Z. marina* meadows and, to a lesser extent, intertidal *Z. marina* meadows belonging to the ecotype *Z. marina* angustifolia. Three new *Z. noltei* meadows were verified (Figs. 3 and 4). Notably, our assessment also incorporates two additional locations of subtidal *Z. marina* meadows, one in the north of Ireland at Island Roy, Co. Donegal (decimal coordinates: 55.196071, −7.792812) and the other in the southeast at Kilkilleen Co. Cork (decimal coordinates: 51.519929, −9.421983), where professional divers reported the presence and extent of the meadow, albeit without our verification. These sites were included in the final map of seagrass distribution. Additionally, we recorded a substantial intertidal meadow of *Ruppia* sp. in Dunfanaghy Bay (0.02 km^2; decimal coordinates: 55.188, −7.975). It should be noted that *Ruppia* spp. were not the particular focus of this study and only this location was added.

3.2.3. Final updated map of Irish seagrasses

By merging spatial information of seagrass ecosystems from previous records (of various sources, as outlined above) and the newly reported meadows (confirmed by field surveys), we recorded an updated extent of 54.85 km^2 along the Irish coast. Of this, 10.2 km^2 correspond to intertidal *Z. noltei* beds and 44.63 km^2 to subtidal *Z. marina* meadows.

3.3. Environmental quality of Irish seagrass meadows

Our results indicate that the majority of *Z. marina* meadows occurred in environments categorized as ‘HIGH’ (61 %) or ‘GOOD’ (34 %) status based on the Water Framework Directive-compliant assessment tool. Only 5 % of the meadows are situated in environments categorized as ‘MODERATE’ (Fig. 5). *Zostera noltei*, predominantly situated in intertidal areas within estuaries or the inner regions of bays, are located in environments classified as ‘HIGH’ (4 %), ‘GOOD’ (26 %), ‘MODERATE’ (59 %), and ‘POOR’ (11 %). (Fig. 5).

4. Discussion

This study contributes towards addressing important knowledge gaps regarding Irish seagrass ecosystems by creating an updated distribution map of seagrasses, and by evaluating the environmental

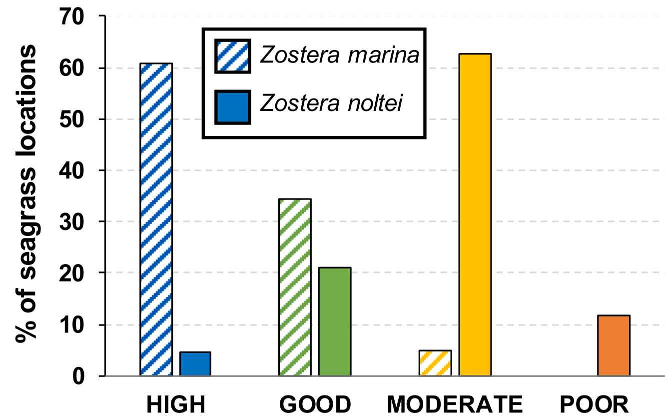

Fig. 5. Percentages of *Zostera marina* and *Z. noltei* distribution exposed to distinct environmental conditions I based on the criteria outlined in the Water Framework Directive (WFD) (https://environment.ec.europa.eu).

conditions, including anthropogenic pressures, in which meadows occur. Our analysis has revealed extensive seagrass meadows along the coast of Ireland comprising a significant proportion that were previously undocumented, mostly represented by subtidal *Z. marina* meadows. Most meadows occur in environments characterized by HIGH or GOOD water quality. These new data support European and global efforts in seagrass mapping and conservation (Unsworth et al., 2019; Griffiths et al., 2020; Nordlund et al., 2024).

4.1. Documentation and mapping of seagrass habitats along the coast of Ireland

Wilkes et al. (2017) published a comprehensive assessment of Irish intertidal seagrass meadows (8.81 km^2 in Republic of Ireland), detailing extent and annual distribution changes. However, a significant knowledge gap remained regarding the overall spatial information on Irish seagrasses, and in particular on subtidal meadows. To address this gap, we implemented an integrated mapping approach based on the method developed by Beca-Carretero et al. (2020a, 2020b). The first map we created was based on previously fragmented records of seagrasses in Ireland and includes reported spatial extent of seagrass meadows, encompassing 39.96 km^2, with 31.15 km^2, corresponding to *Z. marina* and 8.81 km^2 to *Z. noltei*. The compiled spatial information in polygons highlighted the dispersed nature of the available sources, as several existing maps overlapped, however without providing the total meadow extent. It is noteworthy that although most records were gathered over the past two decades (Table 1), some spatial information previously published may have changed since first data were collected in 1969. The second map integrates information from specific locations (polypoint and polyline shapefiles), comprising 368 points of *Zostera* spp. records (Table 2).

As part of the integrated mapping approach, the SDM demonstrated a high predictive capacity for identifying suitable habitats for seagrasses at a regional scale in Ireland, with a high discriminatory ability reflected in AUC values of 0.993 and a sensitivity of 71 %. Fetch, defined as the length of the sea surface over which a given wind has blown, represented the most important factor explaining seagrass presence distribution (39.5 %), as was previously documented for seagrasses ecosystems elsewhere (Downie et al., 2013; Valle et al., 2014). This can be explained by the fact that high hydrodynamic forces, such as fetch or wave exposure, can reduce seagrass anchoring capacity to the sediment, leading to unsuitable conditions for their presence (Fonseca et al., 2019). Depth was the second most important variable (35.7 %) in determining seagrass habitat suitability, which can be expected as light energy is a key factor controlling photosynthetic processes, productivity, growth, and population structure, and thus partially defines the vertical

Table 2
Summary of the environmental descriptors including depth (m), orientation (°), slope (°), distance to coast (m), tidal velocity (m s^{-1}), fetch (m), mean temperature (°C), soft sediment, hard sediment and mixed sediment of *Zostera marina* and *Z. noltei* meadows in Ireland.

Zostera marina				
	Depth (m)	**Orientation (°)**	**Slope (°)**	**Distance to coast (m)**
Mean	−2.6	190.3	0.6	10
Maximum	0	358.2	2.2	301
Minimum	−12.2	0	0.05	0
	Tidal velocity (m s^{-1})	**Fetch (m)**	**Mean temperature**	
Mean	15.9	467.6	11.1	
Maximum	49.6	5068.7	12.1	
Minimum	0.7	50.2	10.3	
	Soft sediment	**Mixed sediment**	**Hard sediment**	
Mean	0.8	0.1	0	
Maximum	1	1	0	
Minimum	0	0	0	
Zostera noltei				
	Depth (m)	**Orientation (°)**	**Slope (°)**	**Distance to coast (m)**
Mean	−0.8	195.2	0.35	3.2
Maximum	0	348.7	3.5	75.1
Minimum	−5.6	0	0.03	0
	Tidal velocity (m s^{-1})	**Fetch (m)**	**Mean temperature**	
Mean	4.2	1552.6	10.8	
Maximum	23.1	3069	11.8	
Minimum	0.4	406	9.9	
	Soft sediment	**Mixed sediment**	**Hard sediment**	
Mean	0.9	0.1	0	
Maximum	1	1	0	
Minimum	0	0	0	

distribution limits of seagrasses (Schubert et al., 2015). In Ireland, *Z. marina* meadows are commonly located at an average depth of 2.6 m, although observations reveal depths of up to 12–13 m in Ventry Bay (Co. Kerry) and the Connemara area (Co. Galway), placing them among the deepest *Z. marina* populations in Europe (Beca-Carretero et al., 2020b; Whelan and Cullinane, 1985). Some variables, such as sedimentological parameters, were less significant in explaining the habitat suitability for *Zostera* spp. than expected. This is likely because, for some areas data were obtained through simulation, resulting in a somewhat higher degree of uncertainty. Additionally, sediment composition can vary at finer spatial scales than those captured by our data resolution, potentially leading to a less accurate representation of its influence.

Our SDM indicated a potential habitat suitability of 365.6 km^2 for seagrasses, which is higher than the estimates from recent studies based on spatial models which suggested a potential Irish seagrass habitat suitability of 165–255 km^2 (Beca-Carretero et al., 2020b; Hastings et al., 2020). The area predicted by the SDM was also larger than the actual seagrass distribution, likely because it did not account for limiting factors such as human impacts, species competition, or other environmental, biological, or biochemical conditions. Thus, in our study, the SDM serves as a broad indicator of potential habitat rather than an exact map of current seagrass extent. Indeed, the SDM's primary strength is predicting potential habitat suitability across a broad landscape, offering valuable guidance for prioritizing field assessments and refining seagrass distribution knowledge. It helped optimize efforts by identifying key areas of interest, providing crucial insights for field assessments.

In the next step of our approach, we refined our spatial seagrass predictions by comparing the SDM results with satellite-derived images. This visual comparison allowed identification and potential exclusion of areas where the model predicted seagrass presence but the satellite images did not, reducing the number of required field surveys. This procedure was successfully employed to document and map new seagrass meadows at a local scale (Beca-Carretero et al., 2020b). Through field surveys, we then identified and assessed over 200 new potential meadow locations, achieving a success rate of 88.5 %. These newly documented seagrass meadows covered an area of 14.88 km^2, increasing the documented seagrass distribution in Ireland by 37.03 %. Notably, we anticipate that the actual distribution of seagrasses is probably significantly more extensive, due to the remoteness and limited coastal infrastructure available for accessing several areas where seagrass could potentially thrive. The majority of the recently discovered locations corresponded to subtidal *Z. marina* meadows (> 95 %), and to a lesser extent of intertidal *Z. marina* and *Z. noltei* populations (4 locations). Regarding the latter species, we documented and mapped two new *Zostera noltei* meadows in Shannon Bay, in western Ireland. One of these is among the largest *Z. noltei* meadows documented to date in Ireland, with an extent of 1.03 km^2 (decimal coordinates: 52.576, −9.361). Our mapping approach suggests that this bay has significant potential to host larger seagrass meadows, adding to its potential ecological and conservation value. Whilst outside the objectives of this study, we also denoted one large intertidal meadow of *Ruppia* sp. in Dunfanaghy Bay, Co. Galway (0.02 km^2; decimal coordinates: 55.188, −7.975). We included this particular location because of its unusual characteristics forming a large monospecific meadow in an open, sandy bay directly exposed to seawater flow without significant freshwater influence.

Most field surveys were conducted from March to October when temperatures exceed 10 °C, and plant descriptors likely reach their peak annual values (Wilkes et al., 2017; Beca-Carretero et al., 2019, 2024). Consequently, there may be potential changes in meadow edges and extension throughout the year, as temperate seagrass populations exhibit slight seasonal variations in their structure (Dale et al., 2007).

By merging both the previously documented (based on published literature), and the newly reported spatial information on seagrass meadows, we were able to document a total seagrass distribution of 58.8 km^2 along the Irish coast. *Z. marina* was the most abundant species, accounting for approximately 83 % (44.63 km^2) of the mapped seagrass meadows, and *Z. noltei* 17 % (10.2 km^2). The extent of these seagrass patches or meadows varies greatly, ranging from 1 m^2 to approximately 5 km^2 of *Z. marina* in Horse Island (decimal coordinates: 52.256, −9.972) and approximately 3 km^2 of *Z. noltei* in Tralee Bay (decimal coordinates: 52.248, −9.811) (Fig. 6). Across many regions, intertidal *Z. marina* meadows are present, likely represented by the ecotype *Z. marina* var. angustifolia which forms monospecific or mixed meadows with *Z. noltei* (Wilkes et al., 2017; Azcárate-García et al., 2022; Beca-Carretero et al., 2024). The majority of Irish seagrass meadows are located in the western, northern and southern regions of Ireland where the presence of bays, estuaries, or inlets creates favourable conditions for them to thrive. By contrast, the Irish east coast exhibits a relatively lower presence of seagrass meadows compared to other regions, likely due to the prevalence of open and straight coastlines that are directly exposed to high hydrodynamic forces. Specifically, this region is characterized by intertidal *Z. noltei* or low intertidal to shallow subtidal *Z. marina* angustifolia meadows in estuaries or bays such as in Dublin Bay or the Boyne Estuary.

Our study demonstrates that a moderately rapid method can be implemented to document and map large areas of seagrass at a regional scale. It is important to note that implementing the proposed approach requires generating maps of the potential habitat suitability of the target species using spatial models such as SDMs and identifying the potential presence of the target ecosystem using satellite images. This requires relevant knowledge to interpret the characteristics of the nearshore ecosystem in the region of interest.

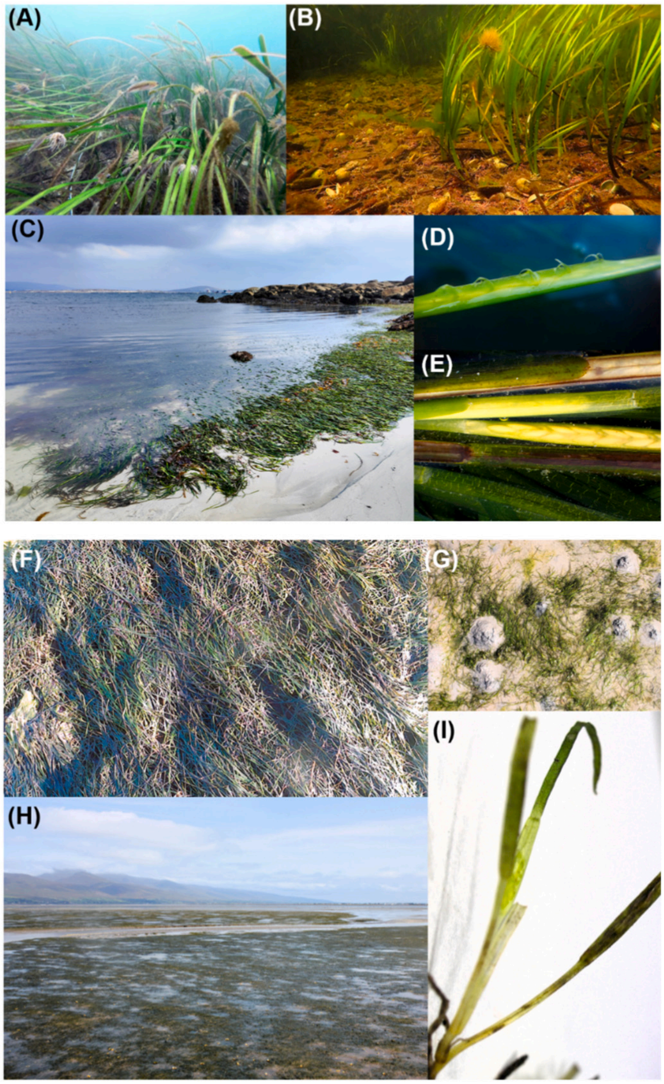

Fig. 6. Images of *Zostera marina* and *Z. noltei* from Irish locations. **A** *Z. marina* meadow in Kilkieran Bay, western Ireland; **B** *Z. marina* in interaction with maërl in Bertraghboy Bay; **C** *Z. marina* meadow in Kilkieran Bay; **D** and **E** Reproductive shoots of *Z. marina*; **F** *Z. noltei* meadow at Fenit Island; **G** and **H** *Z. noltei* meadow in Cromane and Bannow Bay; **H** reproductive shoot of *Z. noltei*.

4.2. State of conservation and vulnerability of Irish seagrass meadows

The outputs from this study are particularly significant as they allow the capture of the areal extent of seagrass habitats, and the water quality where seagrass drive, aiding the targeting of more critical meadows for protection and creating a conservation strategy plan in a regional context. This research represents one of the largest efforts to document and map seagrasses in Europe, comparable to studies conducted in Spain and the UK (Ruiz et al., 2015; Green et al., 2021). The latter study reported a catastrophic loss of seagrass habitats over the last decades, which was likely due to industrial and urban coastal development (Green et al., 2021).

Our results indicate that most of the subtidal *Z. marina* meadows are located in environments categorized as 'HIGH' (61 %) or 'GOOD' (34 %) according to the Water Framework Directive-compliant assessment tool. Only 5 % of these meadows are in environments categorized as 'MODERATE'. The positive correlation between *Z. marina* occurrence and the WFD index suggests a healthy state for subtidal seagrass environments, likely due to reduced anthropogenic pressures, land erosion, and minimal nutrient or chemical runoff (Grilo et al., 2012; Bertelli et al., 2021; Beca-Carretero et al., 2019). By contrast, *Z. noltei* and some *Z. marina* angustifolia meadows, primarily found in intertidal areas within estuaries or inner bays, show a broader distribution across environments classified as 'HIGH' (4 %), 'GOOD' (26 %), 'MODERATE' (59 %), and 'POOR' (11 %). These outcomes align with previous observations of intertidal Irish *Zostera* meadows (Wilkes et al., 2017). Some intertidal seagrass meadows, located in estuarine waters along the eastern and southern coasts of Ireland, are located in areas with 'POOR' environmental conditions (EPA, 2022). This degradation is generally attributed to agricultural activities and nutrient runoff, which lead to the overgrowth of opportunistic macroalgae and the potential deterioration of these transitional habitats (EPA, 2022; Bermejo et al., 2019).

Across Europe, there are signs that seagrass recovery can occur locally while in some areas substantial losses have been recorded (de los Santos et al., 2019). In the absence of a robust dataset on historical Irish seagrass distribution is it not possible to ascertain the extent of losses. However, more recent losses are thought to have occurred, for example, in Dungarvan, Co. Waterford, and Dublin Bay, mainly driven by physical disturbance, nutrient run-off and blanketing by opportunistic green algae (Madden et al., 1993; Wilkes et al., 2017). Other potential threats to Irish seagrasses are invasive macroalgae *Sargassum muticum* or *Gracilaria vermiculophylla* which can outcompete seagrasses for light, space and resources (Tweedley et al., 2008; Höffle et al., 2011; Mendoza-Segura et al., 2023). Concerning the current scenario of climate change, recent studies indicate some potential positive aspects for Irish seagrass meadows, suggesting that predicted higher temperatures may increase *Z. marina* productivity and an increased contribution to carbon fixation (Beca-Carretero et al., 2021).

Seagrass conservation must be based on scientific evidence to effectively support local management and societal needs. This study provides valuable insights that enhance the ecological significance of key areas along the Irish coast, which could significantly impact conservation and management efforts in these regions. This study aligns with EU policies such as the Water Framework Directive and Biodiversity Strategies, offering insights to support these frameworks and global initiatives like the UN Convention on Biological Diversity (European Commission, 2021; UN, 2021). Our models and updated spatial information have the potential for various applications, supporting the identification of areas for seagrass restoration or rehabilitation and thus their implementation as nature-based solutions (NbS) (Kumar et al., 2021). NbS can play a pivotal role in enhancing ecosystem services of coastal ecosystems specifically since seagrass systems are essential for carbon sequestration, promoting biodiversity, aiding in the restoration of degraded habitats, and mitigating the effects of climatic change (Kumar et al., 2021).

In conclusion, by updating records, establishing new distribution maps for seagrasses in Ireland, alongside examining the degree of anthropogenic influence to which seagrass meadows are exposed, this study has addressed critical gaps in our knowledge of Irish seagrass ecology (Wilkes et al., 2017; Beca-Carretero et al., 2020b; Cott et al., 2021) and European (Nordlund et al., 2024). The updated spatial information reported in this study serves as a baseline for national and international comparatives evaluations and assessments. Importantly, mapping efforts to document undiscovered meadows and monitoring potential changes in distribution (including losses) must continue in the future. With these considerations in mind, a future goal should be to develop a user-friendly map that is publically accessible and can be updated by organizations, institutions, and citizens alike. This map will serve as a valuable platform for integrating new spatial information regarding seagrass meadows along the coast of Ireland.

CRediT authorship contribution statement

Pedro Beca-Carretero: Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Sara Varela:** Writing

– review & editing, Supervision, Methodology, Formal analysis, Data curation, Conceptualization. **Tom Rossiter:** Writing – review & editing, Methodology. **Robert Wilkes:** Writing – review & editing, Methodology. **Marc Julia-Miralles:** Writing – review & editing, Methodology. **Dagmar B. Stengel:** Writing – review & editing, Visualization, Validation, Supervision, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: This project was supported by a College of Science of the National University of Ireland (NUI Galway) PhD Scholarship to Pedro Beca-Carretero. Pedro Beca-Carretero was also financed by a research grant from the Alexander von Humboldt Foundation. Additionally, this research was in part supported by the project 'BlueC-Investigating Ireland's Blue Carbon Potential Through a Plants 2024, 13, 396 16 of 19 Scientific, Socio-economic and Legislative approach (PBA/CC/21/03), funded by the Marine Institute and Environmental Protection Agency.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpolbul.2024.117082.

References

Adams, M.P., Saunders, M.I., Maxwell, P.S., Tuazon, D., Roelfsema, C.M., Callaghan, D. P., et al., 2016. Prioritizing localized management actions for seagrass conservation and restoration using a species distribution model. Aquat. Conserv. Mar. Freshwat. Ecosyst. 26 (4), 639–659.

Allouche, O., Tsoar, A., Kadmon, R., 2006. Assessing the accuracy of species distribution models: prevalence, kappa and the true skill statistic (TSS). J. Appl. Ecol. 43 (6), 1223–1232.

Aswani, S., Lauer, M., 2006. Benthic mapping using local aerial photo interpretation and resident taxa inventories for designing marine protected areas. Environ. Conserv. 33 (3), 263–273.

Alghamdi, M.A.A., Young, B.C., 2022. The influence of macroalgal mats on seagrass beds in Dungarvan Bay, County Waterford, Ireland. Aquac., Aquar. Conserv. Legis. 15 (5), 2452–2459.

Azcárate-García, T., Beca-Carretero, P., Cara, C.L., Villamayor, B., Cosnett, E., Bermejo, R., Hernandez, I., Brun, F., Stengel, D.B., 2022. Seasonal plant development and meadow structure of Irish and southern Spanish seagrass populations. Aquatic Botany 183, 103569.

Barbier, E.B., Hacker, S.D., Kennedy, C., Koch, E.W., Stier, A.C., Silliman, B.R., 2011. The value of estuarine and coastal ecosystem services. Ecological monographs 81 (2), 169–193.

Beca-Carretero, P., 2019. Irish Seagrass Ecology and Habitat Mapping in the Context of Climate Change. PhD Thesis,. National University of Ireland Galway.

Beca-Carretero, P., Stanschewski, C.S., Julia-Miralles, M., Sanchez-Gallego, A., Stengel, D.B., 2019. Temporal and depth-associated changes in the structure, morphometry and production of near-pristine *Zostera marina* meadows in western Ireland. Aquatic Botany 155, 5–17.

Beca-Carretero, P., Teichberg, M., Winters, G., Procaccini, G., Reuter, H., 2020a. Projected rapid habitat expansion of tropical seagrass species in the Mediterranean Sea as climate change progresses. Front. Plant Sci. 11, 555376.

Beca-Carretero, P., Varela, S., Stengel, D.B., 2020b. A novel method combining species distribution models, remote sensing, and field surveys for detecting and mapping subtidal seagrass meadows. Aquatic Conservation: Marine and Freshwater Ecosystems 30 (6), 1098–1110.

Beca-Carretero, P., Azcárate-García, T., Julia-Miralles, M., Stanschewski, C.S., Guihéneuf, F., Stengel, D.B., 2021. Seasonal acclimation modulates the impacts of simulated warming and light reduction on temperate seagrass productivity and biochemical composition. Front. Mar. Sci. 8, 731152.

Beca-Carretero, P., Marín, C., Azcárate-García, T., Cara, C.L., Brun, F., Stengel, D.B., 2024. Ecotype-specific and correlated seasonal responses of biomass production, non-structural carbohydrates, and fatty acids in *Zostera marina*. Plants 13 (3), 396.

Beltran, R., Beca-Carretero, P., Marbà, N., Jiménez, M.A., Traveset, A., 2020. Spatio-temporal variation in macrofauna community structure in Mediterranean seagrass wrack. Food Webs 25, e00178.

Bermejo, R., Heesch, S., Mac Monagail, M., O'Donnell, M., Daly, E., Wilkes, R.J., Morrison, L., 2019. Spatial and temporal variability of biomass and composition of green tides in Ireland. Harmful Algae 81, 94–105.

Bertelli, C.M., Bull, J.C., Cullen-Unsworth, L.C., Unsworth, R.K.F., 2021. Unravelling the spatial and temporal plasticity of eelgrass meadows. Front. Plant Sci. 12, 664523.

Breen, P., Ó Cuaig, M., Guilfoyle, F., Hannon, C., Tully, O., 2024. A before after control impact experiment on a historically fished seagrass (Zostera marina) bed. Conserv. Sci. Pract., e13218

Brito, A., Newton, A., Tett, P., Fernandes, T.F., 2010. Sediment and water nutrients and microalgae in a coastal shallow lagoon, Ria Formosa (Portugal): implications for the Water Framework Directive. J. Environ. Monit. 12 (1), 318–328.

Carvalho, L., Mackay, E.B., Cardoso, A.C., Baattrup-Pedersen, A., Birk, S., Blackstock, K. L., Borics, G., Borja, A., Feld, C.K., Ferreira, M.T., Globevnik, L., Grizzetti, B., Hendry, S., Hering, D., Kelly, M., Langaas, S., Meissner, K., Panagopoulos, Y., Penning, E., Rouillard, J., Solheim, A.L., 2019. Protecting and restoring Europe's waters: an analysis of the future development needs of the Water Framework Directive. Sci. Total Environ. 658, 1228–1238.

Chefaoui, R.M., Duarte, C.M., Serrão, E.A., 2018. Dramatic loss of seagrass habitat under projected climate change in the Mediterranean Sea. Glob. Chang. Biol. 24 (10), 4919–4928.

Cott, G., Beca-Carretero, P., Stengel, D.B., 2021. Blue carbon and marine carbon sequestration in Irish waters and coastal habitats. In: Marine Institute. Technical Report. 2021-05-20T11:59:44Z.

Crespo, D., Faião, R., Freitas, V., Oliveira, V.H., Sousa, A.I., Coelho, J.P., Dolbeth, M., 2023. Using seagrass as a nature-based solution: Short-term effects of *Zostera noltei* transplant in benthic communities of a European Atlantic coastal lagoon. Mar. Pollut. Bull. 197, 115762.

Dale, A.L., McAllen, R., Whelan, P., 2007. Management Considerations for Subtidal *Zostera marina* Beds in Ireland. Irish Wildlife Manuals, No. 28. National Parks and Wildlife Service, Department of Environment, Heritage and Local Government, Dublin, Ireland.

Dawes, C.J., Guiry, M.D., 1992. Proximate constituents in the sea-grasses *Zostera marina* and *Z. Noltii* in Ireland: seasonal changes and the effect of blade removal. Mar. Ecol. 13 (4), 307–315.

Downie, A.L., von Numers, M., Boström, C., 2013. Influence of model selection on the predicted distribution of the seagrass *Zostera marina*. Estuar. Coast. Shelf Sci. 121, 8–19.

Dunic, J.C., Brown, C.J., Connolly, R.M., Turschwell, M.P., Côté, I.M., 2021. Long-term declines and recovery of meadow area across the world's seagrass bioregions. Glob. Chang. Biol. 27 (17), 4096–4109.

Egoh, B., Drakou, E.G., Dunbar, M.B., Maes, J., Willemen, L., 2012. Indicators for Mapping Ecosystem Services: A Review. European Commission, Joint Research Centre (JRC), Ispra, Italy, p. 111.

Environmental Protection Agency (EPA), 2022. Water Quality in 2022: An Indicators Report. Environmental Protection Agency. ISBN: 978-1-80009-104-7.

European Commission, 2021. Guidance Document on the Implementation of the EU Biodiversity Strategy to 2020. Publications Office of the European Union.

European Environment Agency (EEA). https://www.eea.europa.eu/.

Finlayson, D., 2005. Puget Sound Fetch. School of Oceanography. University of Washington, Seattle, WA. Accessed October 16, 2007, from. http://david.p.finlayson.googlepages.com/pugetsoundfetch.

Fonseca, M.S., Fourqurean, J.W., Koehl, M.A.R., 2019. Effect of seagrass on current speed: importance of flexibility vs. shoot density. Frontiers in Marine Science 6, 376.

Fourqurean, J.W., Duarte, C.M., Kennedy, H., Marbà, N., Holmer, M., Mateo, M.A., Apostolaki, E.T., Kendrick, G.A., Krause-Jensen, D., McGlathery, K.J., Serrano, O., 2012. Seagrass ecosystems as a globally significant carbon stock. Nat. Geosci. 5 (7), 505–509.

Galparsoro, I., Connor, D.W., Borja, Á., Aish, A., Amorim, P., Bajjouk, T., Chambers, C., Coggan, R., Dirberg, G., Ellwood, H., 2012. Archimer using EUNIS habitat

classification for benthic mapping in European seas: present concerns and future needs. Mar. Pollut. Bull. 64, 2630–2638.
Gibson, R., Atkinson, R., Gordon, J., 2007. Loss, status and trends for coastal marine habitats of Europe. Oceanogr. Mar. Biol. Annu. Rev. 45, 345–405.
Green, A.E., Unsworth, R.K., Chadwick, M.A., Jones, P.J., 2021. Historical analysis exposes catastrophic seagrass loss for the United Kingdom. Front. Plant Sci. 12, 261.
Griffiths, L.L., Connolly, R.M., Brown, C.J., 2020. Critical gaps in seagrass protection reveal the need to address multiple pressures and cumulative impacts. Ocean Coast. Manag. 183, 104946.
Grilo, T.F., Cardoso, P.G., Pardal, M.A., 2012. Implications of *Zostera noltii* recolonization on *Hydrobia ulvae* population structure success. Mar. Environ. Res. 73, 78–84.
Hastings, R., Cummins, V., Holloway, P., 2020. Assessing the impact of physical and anthropogenic environmental factors in determining the habitat suitability of seagrass ecosystems. Sustainability 12 (20), 8302.
Höffle, H., Thomsen, M.S., Holmer, M., 2011. High mortality of *Zostera marina* under high temperature regimes but minor effects of the invasive macroalgae *Gracilaria vermiculophylla*. Estuar. Coast. Shelf Sci. 92 (1), 35–46.
Hossain, M.S., Bujang, J.S., Zakaria, M.H., Hashim, M., 2015. The application of remote sensing to seagrass ecosystems: an overview and future research prospects. Int. J. Remote Sens. 36 (1), 61–114.
Jayathilake, D.R., Costello, M.J., 2018. A modelled global distribution of the seagrass biome. Biol. Conserv. 226, 120–126.
Jones, B.L., Cullen-Unsworth, L.C., Unsworth, R.K., 2018. Tracking nitrogen source using δ15N reveals human and agricultural drivers of seagrass degradation across the British Isles. Front. Plant Sci. 9, 133.
Kennedy, H., Beggins, J., Duarte, C.M., Fourqurean, J.W., Holmer, M., Marbà, N., Middelburg, J.J., 2010. Seagrass sediments as a global carbon sink: isotopic constraints. Global Biogeochem. Cycles 24 (4).
Komatsu, T., Igarashi, C., Tatsukawa, K., Sultana, S., Matsuoka, Y., Harada, S., 2003. Use of multi-beam sonar to map seagrass meadows in Otsuchi Bay on the Sanriku Coast of Japan. Aquat. Living Resour. 16 (3), 223–230.
Kumar, P., Debele, S.E., Sahani, J., Rawat, N., Marti-Cardona, B., Alfieri, S.M., Basu, B., Sarkar Basu, A., Bowyer, P., Charizopoulos, N., Gallotti, G., Jaakko, J., Leo, L.S., Loupis, M., Menenti, M., Mickovski, S.B., Mun, S.-J., Gonzalez-Ollauri, A., Pfeiffer, J., Pilla, F., Zieher, T., 2021. Nature-based solutions efficiency evaluation against natural hazards: modelling methods, advantages and limitations. Sci. Total Environ. 784, 147058.
Lavery, P.S., Mateo, M.Á., Serrano, O., Rozaimi, M., 2013. Variability in the carbon storage of seagrass habitats and its implications for global estimates of blue carbon ecosystem service. PloS One 8 (9), e73748.
de Los Santos, C.B., Krause-Jensen, D., Alcoverro, T., Marbà, N., Duarte, C.M., Van Katwijk, M.M., et al., 2019. Recent trend reversal for declining European seagrass meadows. Nat. Commun. 10 (1), 3356.
Madden, B., Jennings, E., Jeffrey, D.W., 1993. Distribution and ecology of *Zostera* in Co. Dublin. The Irish Naturalists' Journal 24 (8), 303–310.
Mendoza-Segura, C., Fernández, E., Beca-Carretero, P., 2023. Predicted changes in the biogeographical range of *Gracilaria vermiculophylla* under present and future climate scenarios. Journal of Marine Science and Engineering 11 (2), 367.
MERC, 2006. Surveys of Sensitive Subtidal Benthic Communities in Slyne Head Peninsula SAC, Clew Bay Complex SAC, and Galway Bay Complex SAC.
MERC, 2007a. Survey of the distribution of the anemone Edwardsia delapiae (Carlgren and Stephenson, 1928) in Valentia Harbour and Portmagee Channel SAC, Co Kerry.
MERC, 2007b. Surveys of sensitive sublittoral benthic communities in Kenmare River SAC 002158, Tralee Bay & Maharee Islands West to Cloghane SAC 002070.
MERC, 2008. Surveys of Sensitive Sublittoral Benthic Communities in Blacksod Bay, Rutland Island, Mulroy Bay SACs.
MERC, 2009. Surveys of Sensitive Subtidal Benthic Communities in Maharees Tralee Bay Kenmare River.
MESH Atlantic project. http://www.emodnet-seabedhabitats.eu/map.
National Parks and Wildlife Service (NPWS), 1997. Conservation Objectives: Survey of Intertidal Sediment Biotopes in Estuaries in Ireland. Department of Arts, Heritage and the Gaeltacht, Dublin, Ireland. https://www.npws.ie.
National Parks and Wildlife Service (NPWS), 2007. Conservation Objectives: A Survey of Mudflats and Sandflats in Ireland. Department of Arts, Heritage and the Gaeltacht, Dublin, Ireland. https://www.npws.ie.
National Parks and Wildlife Service (NPWS), 2011a. Conservation Objectives: Castlemaine Harbour SAC 00343. Department of Arts, Heritage and the Gaeltacht. https://www.npws.ie.
National Parks and Wildlife Service (NPWS), 2011b. Conservation Objectives: Clew Bay Complex SAC 001482. Department of Arts, Heritage and the Gaeltacht. https://www.npws.ie.
National Parks and Wildlife Service (NPWS), 2011c. Conservation Objectives: Roaringwater Bay and Islands SAC 000101. https://www.npws.ie.
National Parks and Wildlife Service (NPWS), 2011d. Castlemaine Harbour SAC 00343. Department of Arts, Heritage and the Gaeltacht. https://www.npws.ie.
National Parks and Wildlife Service (NPWS), 2011e. Conservation Objectives: Clew Bay Complex SAC 001482. Department of Arts, Heritage and the Gaeltacht. https://www.npws.ie.
National Parks and Wildlife Service (NPWS), 2011f. Conservation Objectives: Roaringwater Bay and Islands SAC 000101. Department of Arts, Heritage and the Gaeltacht. Retrieved from. https://www.npws.ie.
National Parks and Wildlife Service (NPWS), 2012a. Conservation Objectives: Bannow Bay SAC 000697. Department of Arts, Heritage and the Gaeltacht. https://www.npws.ie.
National Parks and Wildlife Service (NPWS), 2012b. Conservation Objectives: Valencia Harbour/Portmagee Channel SAC 002262. Department of Arts, Heritage and the Gaeltacht. https://www.npws.ie.
National Parks and Wildlife Service (NPWS), 2013a. Conservation Objectives: Galway Bay Complex SAC 00268. Department of Arts, Heritage and the Gaeltacht. https://www.npws.ie.
National Parks and Wildlife Service (NPWS), 2013b. Conservation Objectives: Kenmare River SAC 002158. Department of Arts, Heritage and the Gaeltacht. https://www.npws.ie.
National Parks and Wildlife Service (NPWS), 2013c. Conservation Objectives: Lough Hyne Nature Reserve and Environs SAC 000097. Department of Arts, Heritage and the Gaeltacht. https://www.npws.ie.
National Parks and Wildlife Service (NPWS), 2013d. Conservation Objectives: South Dublin Bay SAC 000210. Department of Arts, Heritage and the Gaeltacht. https://www.npws.ie.
National Parks and Wildlife Service (NPWS), 2013e. Conservation Objectives: Tramore Dunes and Backstrand SAC 000671. Department of Arts, Heritage and the Gaeltacht. https://www.npws.ie.
National Parks and Wildlife Service (NPWS), 2014a. Conservation Objectives: Tralee Bay and Magharees Peninsula, West to Cloghane SAC 002070. Department of Arts, Heritage and the Gaeltacht. https://www.npws.ie.
National Parks and Wildlife Service (NPWS), 2014b. Conservation Objectives: Kilkieran Bay and Islands SAC 002111. Department of Arts, Heritage and the Gaeltacht. https://www.npws.ie.
National Parks and Wildlife Service (NPWS), 2014c. Conservation Objectives: Lough Hyne Nature Reserve and Environs SAC 000097. Department of Arts, Heritage and the Gaeltacht. https://www.npws.ie.
National Parks and Wildlife Service (NPWS), 2015. Conservation Objectives: Slyne Head Peninsula SAC 002074. Department of Arts, Heritage and the Gaeltacht. https://www.npws.ie.
National Parks and Wildlife Service (NPWS), 2022. Conservation Objectives: *Zostera* Seagrass Beds of Kerry. Department of Arts, Heritage and the Gaeltacht. https://www.npws.ie.
Nordlund, L.M., Jackson, E.L., Nakaoka, M., Samper-Villarreal, J., Beca-Carretero, P., Creed, J.C., 2018. Seagrass ecosystem services–What's next? Mar. Pollut. Bull. 134, 145–151.
Nordlund, L.M., Unsworth, R.K.F., Wallner-Hahn, S., Ratnarajah, L., Beca-Carretero, P., Boikova, E., Bull, J.C., Chefaoui, R.M., de los Santos, C.B., Gagnon, K., Garmendia, J. M., Gizzi, F., Govers, L.L., Gustafsson, C., Hineva, E., Infantes, E., Canning-Clode, J., Jahnke, M., Kleitou, P., Kennedy, H., Klayn, S., Moller, T., Monteiro, J., Piñeiro-Juncal, N., Ponis, E., Papathanasiou, V., Poursanidis, D., Pieraccini, R., Serrano, O., Sousa, A.I., Schäfer, S., Rossi, F., Storey, D.S., van Katwijk, M.M., Wall, D., Ward, E. A., Wilkes, R., 2024. One hundred priority questions for advancing seagrass conservation in Europe. Plants, People, Planet. 6 (3), 587–603.
Orth, R.J., Carruthers, T.J.B., Dennison, W.C., Duarte, C.M., Fourqurean, J.W., Heck, K. L., Hughes, A.R., Kendrick, G.A., Kenworthy, W.J., Olyarnik, S., Short, F.T., Waycott, M., Williams, S.L., 2006. A global crisis for seagrass ecosystems. Bioscience 56 (12), 987–996.
Pavlidou, A., Simboura, N., Rousselaki, E., Tsapakis, M., Pagou, K., Drakopoulou, P., Assimakopoulou, G., Kontoyiannis, H., Panayotidis, P., 2015. Methods of eutrophication assessment in the context of the water framework directive: examples from the eastern Mediterranean coastal areas. Cont. Shelf Res. 108, 156–168.
Phillips, S.J., Anderson, R.P., Schapire, R.E., 2006. Maximum entropy modeling of species geographic distributions. Ecol. Model. 190 (3–4), 231–259.
Reyjol, Y., Argillier, C., Bonne, W., Borja, A., Buijse, A.D., Cardoso, A.C., van de Bund, W., 2014. Assessing the ecological status in the context of the European water framework directive: where do we go now? Sci. Total Environ. 497, 332–344.
Roelfsema, C., Kovacs, E.M., Saunders, M.I., Phinn, S., Lyons, M., Maxwell, P., 2013. Challenges of remote sensing for quantifying changes in large complex seagrass environments. Estuar. Coast. Shelf Sci. 133, 161–171.
Rossiter, T., Furey, T., McCarthy, T., Stengel, D.B., 2020. UAV-mounted hyperspectral mapping of intertidal macroalgae. Estuar. Coast. Shelf Sci. 242, 106789.
Ruiz, J.M., Guillén, J.E., Ramos Segura, A., Otero, M.M. (Eds.), 2015. Atlas de las praderas marinas de España. IEO/IEL/ UICN, Murcia-Alicante-Málaga, p. 681.
Scannell, M.J.P., Ferguson, I.K., 1969. *Zostera* in Co. Waterford. Irish Nat. J. 16, 176–177.
Schubert, P.R., Hukriede, W., Karez, R., Reusch, T.B., 2015. Mapping and modeling eelgrass *Zostera marina* distribution in the western Baltic Sea. Mar. Ecol. Prog. Ser. 522, 79–95.
Sullivan, B.K., Sherman, T.D., Damare, V.S., Lilje, O., Gleason, F.H., 2013. Potential roles of *Labyrinthula* spp. in global seagrass population declines. Fungal Ecol. 6 (5), 328–338.
Traganos, D., Lee, C.B., Blume, A., Poursanidis, D., Čižmek, H., Deter, J., Mačić, V., Montefalcone, M., Pergent, G., Pergent-Martini, C., Ricart, A.M., Reinartz, P., 2022. Spatially explicit seagrass extent mapping across the entire Mediterranean. Frontiers in Marine Science 9.
Tully, O., Clarke, S., 2012. The status and management of oyster (*Ostrea edulis*) in Ireland. Irish Investigations of Marine Fisheries and Environment Series 24, 1–22.
Tweedley, J.R., Jackson, E.L., Attrill, M.J., 2008. *Zostera marina* seagrass meadows enhance the attachment of the invasive alga *Sargassum muticum* in soft sediments. Mar. Ecol. Prog. Ser. 354, 305–309.
United Nations, 2021. Convention on Biological Diversity. https://www.cbd.int.
Unsworth, R.K., McKenzie, L.J., Collier, C.J., Cullen-Unsworth, L.C., Duarte, C.M., Eklöf, J.S., Jarvis, J.C., Jones, B., Nordlund, L.M., 2019. Global challenges for seagrass conservation. Ambio 48, 801–815.
Unsworth, R.K., Cullen-Unsworth, L.C., Jones, B.L., Lilley, R.J., 2022. The planetary role of seagrass conservation. Science 377 (6606), 609–613.

Valle, M., Chust, G., del Campo, A., Wisz, M.S., Olsen, S.M., Garmendia, J.M., Borja, Á., 2014. Projecting future distribution of the seagrass *Zostera noltii* under global warming and sea level rise. Biol. Conserv. 170, 74–85.

Veettil, B.K., Ward, R.D., Lima, M.D.A.C., Stankovic, M., Hoai, P.N., Quang, N.X., 2020. Opportunities for seagrass research derived from remote sensing: a review of current methods. Ecol. Indic. 117, 106560.

Waycott, M., Duarte, C.M., Carruthers, T.J.B., Orth, R.J., Dennison, W.C., Olyarnik, S., Calladine, A., Fourqurean, J.W., Heck Jr., K.L., Hughes, A.R., Kendrick, G.A., Kenworthy, W.J., Short, F.T., Williams, S.L., 2009. Accelerating loss of seagrasses across the globe threatens coastal ecosystems. Proc. Natl. Acad. Sci. 106 (30), 12377–12381.

Whelan, P.M., Cullinane, J.P., 1985. The algal flora of a subtidal *Zostera* bed in Ventry Bay, Southwest Ireland. Aquatic Botany 23 (1), 41–51.

Whelan, P.W., Cullinane, J.P., 1987. The occurrence of "wasting disease" of *Zostera* in Ireland in the 1930's. Aquat. Bot. 27 (3), 285–289.

Wilkes, R., Bennion, M., McQuaid, N., Beer, C., McCullough-Annett, G., Colhoun, K., Inger, R., Morrison, L., 2017. Intertidal seagrass in Ireland: pressures, WFD status and an assessment of trace element contamination in intertidal habitats using *Zostera noltei*. Ecol. Indic. 82, 117–130.

Winters, G., Edelist, D., Shem-Tov, R., Beer, S., Rilov, G., 2017. A low cost field-survey method for mapping seagrasses and their potential threats: an example from the northern Gulf of Aqaba, Red Sea. Aquat. Conserv. Mar. Freshwat. Ecosyst. 27 (2), 324–339.

Worldclim - Global Climate Data. http://www.worldclim.org/bioclim.