WORKING GROUP ON MARINE HABITAT MAPPING (WGMHM; outputs from 2023 meeting)

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Contents

i Executive summary

The Working Group on Marine Habitat Mapping (WGMHM) coordinates the review of habitat classification and mapping activities in the ICES area and promotes the standardization of approaches and techniques.

The current report summarises the activities of the group between 2021 and 2023. In this period much of the activities related to supporting the development of the use of Predicted Habitat Models (PHMs) into the ICES advice process regarding Vulnerable Marine Ecosystems (VMEs). Specifically, the WGMHM applied the criteria developed during the Workshop on the Use of Predictive Habitat Models in ICES Advice (WKPHM) to evaluate the quality of 33 published VME models. The results indicated significant differences in the quality of the models, with the proportion of criteria scored as "desired" or "required" ranging between 23 and 98% (median = 73%). During the review process some limitations of the criteria become evident, and modifications were proposed to facilitate future reviews. In addition, WGMHM produced a data product (shapefile) of VME elements, defined as geomorphological features that provide habitat for VMEs. These were used in two scenarios (scenarios B and E) used during the VME advice process to delineate areas where VMEs exist or are likely to exist.

This report also includes a review of recent advances in marine habitat mapping methods including hyperspectral imagery, multifrequency acoustics, and photogrammetry, as well as a review of the uses of habitat maps.

ii Expert group information

Expert group name	Working Group on Marine Habitat Mapping (WGMHM)
Expert group cycle	Multiannual
Year cycle started	2021
Reporting year in cycle	3/3
Chair	Julian Mariano Burgos, Iceland
Meeting venue(s) and dates	24–28 May 2021. Remote meeting
	30 August – 4 September 2022; Hafnarfjörður, Iceland
	6–10 November 2023; Santander, Spain

1 WGMHM Terms of Reference

WGMHM terms of reference addressed in the report:

a) Report on progress in international mapping programmes (including OSPAR and HELCOM Conventions, EMODnet, EC and EEA initiatives, CHARM, Mesh-Atlantic and other projects).

b) Review and synthesise key results from national habitat mapping during the preceding year, as well as new on-going and planned projects focusing on particular issues of relevance to the rest of the meeting. Provide National Status Report updates in geographic format in the ICES webGIS.

c) Review recent advances in marine habitat mapping and modelling techniques, including field work methodology, and data analysis and interpretation.

d) Review use of habitat maps, for example mapping for the MSFD, marine spatial planning, and management of MPAs; and assess the ability (e.g. through the monitoring of the MSFD indictor 'extent') to use habitat maps for monitoring of the environment.

e) Identify sources of information (e.g. bathymetry, oceanography, fisheries or socio-economic) that can be used for the production and enrichment of marine habitat maps.

f) Identify and advance theoretical aspects of habitat mapping (e.g. landscape ecology, supplyside ecology, implications of scale etc.).

2 VME model evaluation

2.1 Background

The term Vulnerable Marine Ecosystem (VME) refers to benthic ecosystems dominated by epibenthic organisms which are likely to experience substantial alterations and recover slowly after being affected by bottom trawling. After the recognition of their vulnerability, the United Nations General Assembly (UNGA) adopted resolutions 59/25, 61/105, and 71/105 calling member states and regional fisheries management organisations (RFMOs) to prevent significant adverse impacts on Vulnerable Marine Ecosystems (VMEs). The UNGA resolutions, as well as the FAO Guidelines (FAO, 2009) established the need to identify, describe and map areas where VMEs are "known or likely to occur". These provisions have been incorporated into bottom fisheries regulations by the North East Atlantic Commission (NEAFC) and the Northwest Atlantic Fisheries Organization (NAFO), as well as into the EU regulation for the management of deep-sea fisheries in EU waters (EU Regulation 2016/2336).

ICES has provided scientific advice about where VMEs are known or are likely to occur, following requests from the EU and NEAFC. To this date the advice is based on records from the ICES VME database, compiled by the WGDEC. This data consists of direct observations of VMEs (e.g. obtained from ROV surveys), and of records of indicator taxa that suggest the presence of a VME (e.g. from trawl bycatch). The information in the database is summarised into a VME index which estimates the likelihood of the presence of VMEs (ICES, 2018; Morato *et al.*, 2018). The VME index, and its associated confidence index, are created on a c-square grid of 0.05 x 0.05 degrees. The records in the VME database, and therefore the index values, are spatially sparse.

The use of Predictive Habitat Models (PHMs), also known as Species Distribution Models or Habitat Suitability Models, has been suggested as a methodology to "fill the gaps", helping to identify areas where VMEs are likely to occur (Clark *et al.*, 2015; Hourigan, 2014; Vierod *et al.*, 2014). PHMs use environmental parameters (e.g. depth, temperature, sediment type) to predict the potential distribution of a species or a group of species in an area. PHMs have been used in multiple studies to predict the distribution of VMEs (e.g. Howell *et al.* 2016) and of VME indicator species (e.g. Anderson *et al.* 2016). In 2018, the Review Group on Vulnerable Marine Ecosystems (RGVME) recommended that modelling techniques like these should be considered advice on the likely distribution of VMEs.

Following these recommendations, WGDEC and WGMHM held joint meetings in 2019 and 2020 to explore the use of PHMs for providing advice on VMEs. WGMHM developed a 'roadmap' setting out proposed steps to facilitate the adoption of PHMs in ICES advice (ICES, 2019). The 'roadmap' highlighted the need to generate a standard set of model outputs, identifying with habitats or species to model, the spatial extent of the model, minimum mapping resolution, and how often the model should be re-run. In addition, during the 2020 meeting, WGDEC identified the need for set of criteria against which new and existing PHMs could be reviewed (ICES, 2020). These criteria could be used for a benchmarking process, this is to generate consensus on the best modelling approach for the use of these models for scientific advice.

The Workshop on the Use of Predictive Habitat Models in ICES Advice (WKPHM) was carried out with the objective of developing standards for data and modelling approaches that could be used to select models to be used in ICES advice (ICES, 2021). The terms of reference (ToR) for the workshop were:

a) Based on existing approaches, identify the methods for modelling vulnerable marine ecosystems (VMEs) that would be the most appropriate for use within ICES advice, detailing "required" and "desirable" criteria, with emphasis on the deep-sea environment greater than 200 m (considering bias of preferential sampling), PHM techniques (including spatial display of uncertainty) and required validation steps for the modelling outputs.

b) Develop clear standards for recording the caveats and assumptions inherent in the modelling method, for future use.

c) Conduct a trial run for a small number of existing models to ensure that both the approach and outputs are fit-for purpose.

d) Review and recommend a set of criteria, similar to the existing ICES benchmarking system for regional fish stock assessment, under which new and existing predictive habitat models can be uses for ICES scientific advice related to the distribution of VMEs.

During the workshop, a set of 48 criteria were defined to qualify different attributes of the modelling process including independent and dependent data used for modelling, modelling methods, uncertainty and model validation, and model outputs. Each of the criteria had three levels: "unacceptable", "required", and "desired". "Unacceptable" attributes indicate that the model output should be interpreted with caution or not considered for management, "required" attributes are the agreed standard, and "desired" attributes are the best practices in the literature that may be difficult to achieve in many cases.

During WKPHM it was recognised that the next steps in the process of incorporating PHM into ICES advice would be two-fold. First, published VME models should be reviewed to assess whether they meet the standards for use in ICES advice. This would involve a literature review to identify existing models, followed by a ranking against the criteria developed in WKPHM to judge whether the models could be used. The second step would be to develop new models to predict the distribution of VMEs where gaps in existing PHMs are found. During the 2021 meeting of the WGMHM we carried out the first step, by doing a literature review of peer-reviewed models for VMEs and VME indicator taxa in the North Atlantic and Mediterranean Sea.

2.2 Compilation of published PHMs

The group carried out a search of peer-reviewed predictive habitat models of VMEs or VME indicator taxa in the North Atlantic and the Mediterranean Sea. We focused on models where the presence or abundance of VMEs was modelled as function of environmental covariates. The search did not include purely spatial approaches (e.g. kernel density estimations, Kenchington *et al.*, 2014), nor approaches based on segmentation and supervised classification of the seabed (e.g. Savini *et al.*, 2014). The search resulted in a total of 33 models, from which 28 were in the North Atlantic and 5 in the Mediterranean Sea (Table 1). The models were published between 2009 and 2021.

Table 1. List of models compiled for review. Columns indicate model number, reference, regions (NA=North Atlantic, ME=Mediterranean), model target (IT=individual taxa, SA=species assemblages, VME=vulnerable marine ecosystems), type of data (Pr=Presence only, P/A=presence/absence, A=Abundance, D=density, pro=proportion), bathymetry source (MB=multi beam echosounder, EMODnet= European Marine Observation and Data Network, GEBCO=General Bathymetric Chart of the Oceans), resolution (i.e. cell size), source of observation (UI=Underwater imagery, trawl=bycatch from bottom trawling, Comp=compilation of multiple sources), and algorithm used (GAM=Generalised Additive Model, RF=Random Forest, MaxEnt=Maximum Entropy, CIF=Conditional Inference Forests, GLM=Generalised Linear Models).

Model	Reference	Region	Target	Data	Bathymetry	Resolution	Source	Algorithm
1	Bastari *et al.* 2018	ME	IT	P/A	EMODnet	2 km	Comp	GAM
2	Beazley *et al.* 2018	NA	IT	P/A	Other	1km	Comp	RF
3	Beazley *et al.* 2021	NA	IT	Pr	GEBCO	7.5 km	Comp	GAM, RF
4	Burgos *et al.* 2020	NA	IT	Pr	GEBCO	500 m	Comp	MaxEnt, SSDM
5	De Clippele *et al.* 2017	NA	Other	Other	MB	2 m	UI	RF
6	Downie *et al.* 2021	NA	IT	D/A	MB	75 m	Trawl	RF
7	García-Alegre *et al.* 2014	NA	IT	Pr	MB	75 m	Trawl, UI	MaxEnt
8	Gonzales-Mirelis *et al.* 2015	NA	SA	P/A	MB	?	UI	CIF
9	Gonzales-Mirelis *et al.* 2020	NA	IT	P/A and D	EMODnet	500 m	UI	CIF
10	Greathead *et al.* 2014	NA	IT	Pr	MB	5 m	UI, trawl, diver	MaxEnt
11	Gullage *et al.* 2017	NA	SA	Pr	GEBCO	30 arc sec	Trawl	MaxEnt
12	Howell *et al.* 2011	NA	IT/ VME	Pr	MB	200 m	UI	MaxEnt
13	Howell *et al.* 2016	NA	IT/ VME	Pr	GEBCO	1 km	Comp	MaxEnt
14	Iacono *et al.* 2018	ME	IT	Pr, P/A	MB	5 m	UI	MaxEnt, RF, GAM
15	Kinlan *et al.* 2020	NA	SA	Pr	Other	92 m	Comp	MaxEnt
16	Knudby *et al.* 2013	NA	IT/ VME	P/A	GEBCO	1 km	Comp	RF

17	Lauria *et al.* 2017	ME	IT	P/A, D	Other	900 m	Trawl	GAM
18	Lauria *et al.* 2021	ME	IT	Pr	EMODnet	200 m	Comp	MaxEnt
19	Morato *et al.* 2020	NA	IT	Pr, P/A	EMODnet	3 km	Comp	MaxEnt, RF, GAM
20	Moritz *et al.* 2013	NA	SA	P/A	Other	?	Trawl	GLM
21	Pearman *et al.* 2020	NA	IT	P/A	MB	50 m	UI	GAM, RF, BRT
22	Piechaud *et al.* 2015	NA	SA	P/A	MB	25 m	UI	MaxEnt, RF
23	Ramiro-Sánchez *et al.* 2019	NA	IT	P/A	MB	50 m	UI	MaxEnt, RF, GAM
24	Rengstorf *et al.* 2013	NA	VME	Pr	MB	0.002 o	UI	MaxEnt
25	Rengstorf *et al.* 2014	NA	VME	P/A, pro	MB	50 m	UI	GLM
26	Robert *et al.* 2015	NA	IT/ VME	P/A, A	MB	50 m	UI	GAM
27	Rodríguez-Basalo *et al.* 2021	NA	IT	Pr, D	MB	32 m	UI, trawl	MaxEnt, GAM
28	Ross *et al.* 2013	NA	VME	Pr	GEBCO	0.0083 o	UI	MaxEnt
29	Ross *et al.* 2015	NA	VME	Pr	MB	200 m	UI	MaxEnt
30	Sánchez *et al.* 2017	NA	IT	Pr	MB	32 m	UI	MaxEnt, SSDM
31	Serrano *et al.* 2017	NA	SA	P/A	MB	75 m	Trawl, dredges	GAM
32	Sundahl *et al.* 2020	NA	IT	Pr	EMODnet	176 m	UI	MaxEnt
33	De la Torriente *et al.* 2019	ME	SA	P/A	MB	15 m	UI	GAM

The target of the models differed. Most models predicted the distribution of individual VME indicator taxa, either as presence-only or presence-absence data. A smaller number of models predicted the abundance or density of VME indicator taxa (Rodríguez-Basalo *et al.*, 2021). In addition, some models predicted the distribution of VMEs directly (i.e. the presence of the habitat, Howell *et al.* 2016), where VMEs were identified from the analysis of seabed imagery. Several models predicted the distribution of species assemblages or biotopes identified through multivariate analysis of species composition data, in which one of more of the assemblages are considered VMEs or are comprised by VME indicator taxa (e.g. Piechaud *et al.*, 2015). Other approaches to approximate the distribution of VMEs included the simultaneous modelling of multiple taxa indicators of a particular VME (Gonzalez-Mirelis *et al.*, 2020) or the use of stacked species distribution models (Burgos *et al.*, 2020). Most published models used data from underwater video surveys as the sole or main data source (n=19), while the remainder studies used aggregated data from multiple sources, or data from bottom trawl surveys.

The models used a range of statistical methods. The most used was MaxEnt (Phillips & Dudík, 2008), followed by Generalised Additive Models (GAMs) (Wood, 2006) and Random Forest (Breiman, 2001). Other machine learning approaches were less common, including Boosted Regression Trees (De'ath, 2007) and Conditional Inference Forests (Hothorn *et al.*, 2006). Used methods also included Generalised Linear Models (GLMs) and GARP (Stockwell, 1999).

Most models were based on high-resolution bathymetry collected using multibeam echosounders. In most cases, resolutions ranging between 50 and 200m although there were cases with higher resolutions. Some of the models (n=15) were based on aggregated bathymetry datasets (e.g. GEBCO, EMODnet) and had relatively coarse resolutions (500 m – 7.5 km).

2.3 Model review methodology

To facilitate discussion, the criteria were numbered, from 1 to 48, according to their position in table A.2.1. in (ICES, 2021). Each of the 33 models obtained from the literature search was assigned to one of the participants of the 2021 WGMHM meeting. In addition, ten of the models were assigned to a second reviewer, with the objective of exploring the differences in the evaluation results between reviewers. Reviewers were requested to evaluate, as far as possible, each of the models in each of the criterion.

In some of the criteria the requirements for the "Required" and "Desired" levels are the same (e.g. criteria 2, 3 and 5). In those cases, models that fulfilled those requirements were classified as "Desired". Reviewers were also instructed to mark those criteria that could not be evaluated based on the information available on the publication, and to add any comments deemed necessary. In some of the articles, details on the data sources or methods were not included explicitly but included bibliographic references to other publications with that information. In those cases, reviewers were instructed not to review those references, to complete the review in a timely manner. The review process was discussed among the participants during the meeting.

2.4 Results of the model review

A total of 43 reviews were carried out by the group. These include reviews of the 33 models identified in the literature search, plus a second review for models 1, 2, 5, 8, 13, 22, 24, 25, 29 and 31. Results are shown in Annex 3.

To evaluate the models, we tabulated the number of criteria for which the reviewer assigned the categories of "Desired" or "Required", as a proportion of the total number of criteria. This value ranged between 23 and 98%, with a median value of 73%. The models ranked highest by at least one reviewer were Pearman *et al.* (2020), Beazley *et al.* (2018), Beazley *et al.* (2021), Sundahl *et al.* (2020) and Piechaud *et al.* (2015).

There was a variable degree of agreement between the evaluations in the models that received two reviews. In some cases, the proportions were very similar (or equal, in one case), but in others the differences in the evaluation where substantial. In three of the ten paired evaluations the agreements differ for more than 20%, which highlights the subjectivity in the application of the criteria.

The application of the criteria defined during the WKPHM to evaluate models from the peer-review literature presented some challenges. In some cases, the information necessary to evaluate the criteria was not provided in the article describing the model. In a subset of these studies, authors make references to surveys and/or databases where the observations came from, but for purposes of this report we did not trace the sources to verify if the information was available in those sources.

2.5 Difficulties in the application of the criteria

Additional difficulties arose from the criteria definitions. In some cases, the wording of the requirements was somewhat confusing, or were written to evaluate model output provided with a complete set of metadata, and not necessarily models as published in the peer-reviewed literature. This caused some inconsistency among how the criteria were evaluated by the reviewers. This was evident in the differences when a model was examined by two reviewers. For example, for the first criteria the first reviewer raked the model by Bastari *et al.* (2018) as "required", because it provided a clear description of the sampling method, but the second ranked it as "unacceptable" because it lacks an explicit description of the quality standards.

Criteria 1-3

The first set of seven criteria (table 2.3.1 in PHM) define the agreed standards for describing the dependent data used in the development of PHMs. Among these, criteria 1, 2 and 3 were difficult to evaluate because they combine different attributes of the dependent data. Therefore, it is not clear how to rate models that satisfied one of the conditions. Criteria 1 refers both to sampling design and the inclusion of available data on the model. Criteria 2 refers to the documentation of quality control, but also includes a consideration about combining data from multiple sources. Criteria 3 refers about the documentation of data sources and pre-processing of the data.

Criterion 1 is particularly problematic, as it is very difficult to receive a "Required" or "Desired" score. First, in many cases models (Burgos *et al.*, 2020; e.g. Greathead *et al.*, 2007; Lauria *et al.*, 2021) are fitted using aggregations of data from different sources, or from existing databases (e.g. OBIS) for which there is not a specific sampling design. All these models would receive an "unacceptable" score in this criterion. In addition, it is difficult to evaluate if all the available data that meet QC standards was used in the model. Finally, the requirement that the biological and environmental data should be sampled with the same design is too strict, as PHMs in the deep sea are fitted to environmental data products data that are obtained independently from the biological data.

We recommend that the criteria should highlight the need for a clear description of the sampling methodology, giving preference to data collected with a systematic sampling design. The requirement for the use of QC standards should be a separate criterion. Therefore, we propose that criteria 1-3 are replaced by the following five criteria addressing the presence of metadata, quality control, data sources and sampling design, the use of multiple data sources, and data pre-processing:

Unacceptable	No metadata provided on data sources or the treatment of data.
Required	Metadata are reported following the standard in Annex 4.
Desired	Same as required.

Unacceptable	Data have no quality control, or quality control of data is not described
Required	Quality control meets the minimum standards of the ICES VME database, following national and/or international best practice guidelines. Details of which guidelines where followed are provided.
Desired	Same as required.

Unacceptable	Data sources and/or sampling methods are not clearly described.
Required	Sampling design(s) and/or data sources clearly described.
Desired	Data obtained from a systematic sampling design.

Unacceptable	If multiple data sources are combined, there is no description of consideration of the differences among the sources.
Required	When multiple data sources are combined, each source is described. Potential limitations of each data source are discussed.
Desired	Same as required.

Unacceptable	Pre-processing of data (of the lack of thereof) is not clearly described.
Required	Data pre-processing, including, spatial thinning or bias correction is clearly described.
Desired	Same as required.

Criterion 8

The "desired" level requires that the same sampling design is used for biological and environmental data. This is unrealistic for marine PHMs. We recommend that the description of the "desired" level removes the phrase "same for biological and environmental data".

Criterion 9

This criterion was difficult to apply to models published in the peer-reviewed literature, as they rarely report the independent data sources with the amount of detail required in Annex 4.

Criterion 10

Uncertainty in predictors is very rarely reported in marine PHMs, particularly because the methods commonly used for modelling assume that the predictors are measured without error.

Criterion 12

The requirement for reaching the “desired” levels is a subset of the requirements for the “required” level. We recommend that the “required” level is as following:

“Predictor variables and their ranges are inferred from those evidenced and documented for ‘proxy’ taxa with expert evaluation approval for their use.”

Criteria 21 and 22

Both criteria refer to the rationale of the model selection. Criteria 21 is difficult to apply. The “unacceptable” level is assigned when model selection is made a priori without considering the available data characteristics, while the “required” and “desired” levels require that a review of pros and cons of each model type is carried out. Very often published models justify the selection of a single modelling approach, but without explicitly comparing multiple modelling approaches. For example (Lauria *et al.*, 2021) used MaxEnt because is a well-established method to model presence-only data. In cases like this is not clear which score should be assigned. Criteria 22 on the other hand makes a clear distinction. We recommend that both criteria are replaced with the following:

Unacceptable	No rationale is given for choice of modelling method.
Required	A single modelling method used. The rationale for the choice is well justified. Methods are appropriate for the study objective and available data.
Desired	Multiple modelling methods evaluated during model development. Methods are appropriate for the study objective and available data.

Criterion 29

In criterion 29 the difference between the “required” and “desired” levels is not clear. We recommend that the “desired” level is as following:

“Model outputs have been validated by comparison to independent data or established references.”

Criterion 31

The difference between the “required” and “desired” levels is the phrase “Data and code are provided” in the later. This phrase has to do with reproducibility and not with goodness-of-fit. We recommend making the text in “desired” the same as in “required”.

Criterion 32

In this criterion the "unacceptable" score is assigned when model performance is not reported, while the "required" level is assigned when "multiple measures of model performance reported". It is unclear what to do if a single measure of model performance is reported. We recommend rewording the "unacceptable" level to "model performance is not reported or is reported with a single metric".

2.6 Conclusions

The use of the criteria established by the WKPHM to evaluate the output of predictive habitat models (ICES, 2020) presented some challenges, but it proved a useful tool to compare in a qualitative and semi-quantitative way the quality of the models. The criteria also served to highlight weakness in the modelling procedure or on the reporting of the output of individual models.

It is recommended that the output of PHMs that will be uses for ICES advise should we collected through a data call in which model authors are requested to provide the model predictions in standard file formats (e.g. ASCII or GeoTIFF files for rasters, and GeoPackages for polygons). The corresponding metadata should be provided by the authors using the template in Annex 3 (ICES, 2020), or by following the ODMAP protocol (Fitzpatrick *et al.*, 2021; Zurell *et al.*, 2020). This information will facilitate the application of the criteria.

3 Review recent advances in marine habitat mapping and modelling techniques

3.1 Hyperspectral imagery

Optical methods are key for delivering observational data (ground-truthing) to support interpretation of continuous spatial data within a classification typology. Traditionally, underwater imagery (video & still images) is collected with adapted RGB cameras, i.e. off the shelf camera lens and sensor repackaged into a waterproof housing. These optical data can be interpreted in various ways:

i. Direct visual interpretation & classification as is employed when identifying taxa and substrata present in the image frame.
ii. Image analysis techniques which enhance certain signatures or identify homogeneity/heterogeneity to aid classification such as Gray Level Co-Occurrence Matrix (GLCM), Object-Based Image Analysis (OBIA), etc.
iii. AI/Machine learning techniques whereby training datasets are provided to a system such as a convoluted neural network to enable automated identification of taxa and features of interest e.g. Nephrops norvegicus burrows.

In part, all these techniques rely on the interpretation of shape, texture and colour. One way in which the discrimination of entities can be enhanced is by increasing the number of spectra available for analysis. In satellite imagery, this is achieved by exploiting near infrared or ultraviolet bandwidths of light to complement the visible red, blue, and green spectra of visible light. In marine environments, the use of NIR and UV is less common but the availability of hyperspectral devices exploiting the visible light range is becoming more commonplace and being applied in various scenarios (Chennu *et al.*, 2017; Foglini *et al.*, 2019; Montes-Herrera *et al.*, 2021). Hyperspectral imaging converts traditional three band imagery into hundreds of bands – some implementations can resolve ~800 bands within the RGB visible spectrum.

This increase in available information can assist in improving the discrimination and delineation of seabed features over analysis of RGB imagery because those features that might all be pink (e.g. coralline algae) in standard imagery, can be assigned to specific wavelengths (Figure 1) and as such can be defined as separate features from hyperspectral data alone (Foglini *et al.*, 2019; Montes-Herrera *et al.*, 2021). These spectral categories can then be compared against morphology and texture to describe different entities and train classification algorithms.

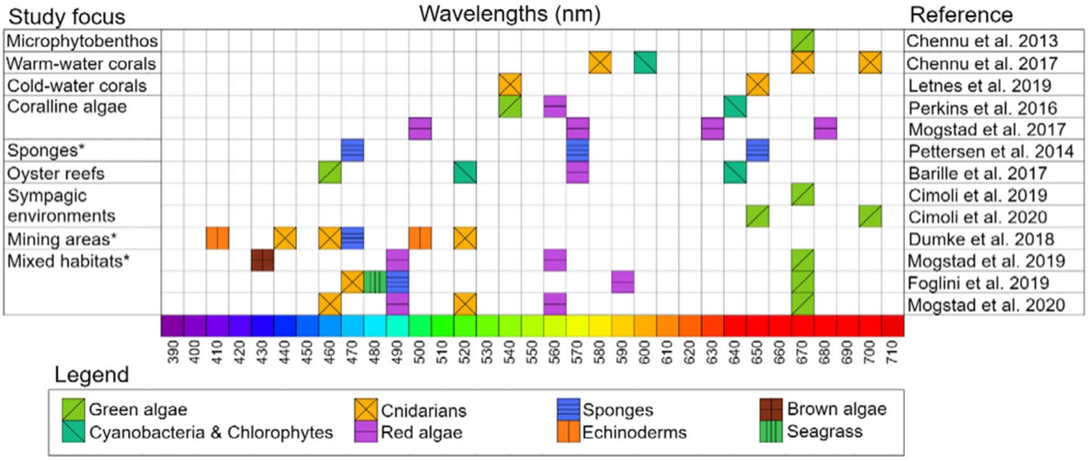


Figure 1. Examples of taxa and corresponding hyperspectral wavelength (Montes-Herrera *et al.*, 2021).

Underwater hyperspectral imagers (UHI) facilitate the classification of seabed areas alongside standard underwater imagery techniques (Foglini *et al.*, 2019). These classified images can then be used alongside telemetry data to give accurate measurements of density/seafloor coverage of features of interest (Foglini *et al.*, 2019); (Figure 2) rather than relying on estimated densities (e.g. SACFOR, averaging abundance values across distance/time). This capability should improve the assessment of features in support of fisheries assessment and aid comparison of ground-truthing data with high-resolution acoustic data. This is more poignant with the increasing adoption of multifrequency multibeam echosounders over those that emit a single frequency.

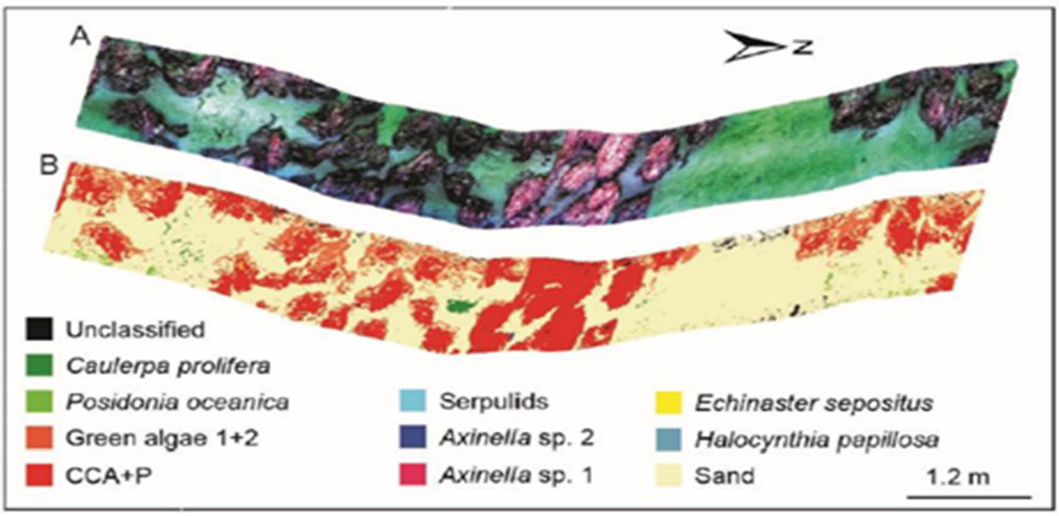


Figure 2. Application of UHI in seabed mapping (Foglini *et al.*, 2019).

3.2 Multifrequency acoustics

Multibeam echosounders (MBES) have become the tool of choice for seabed mapping. They were developed initially for hydrographic purposes, increasing efficiency and accuracy of navigational surveys and are now near ubiquitous in their application for seabed classification mapping from shelf- to deep sea environments (Misiuk and Brown, 2023; Mitchell *et al.*, 2018). Traditionally, MBES data are collected at a single frequency based upon the survey requirements. Shallow-water surveys requiring high-density information would use a high frequency (≥400kHz), while a mid-depth survey would likely use frequencies in the range 100-400 kHz, and deep-sea surveys would use systems that emit at low frequencies (<30 kHz). Some studies have combined multiple data sources collected at different frequencies, highlighting the advantages of multi-frequency investigation (Runya *et al.*, 2021). This method can introduce artefacts to results due to orientation of survey, temporal differences in the oceanographic and substrata properties along with prevailing conditions which can compromise study aims. It is now possible for MBES systems to emit and receive multiple frequencies in such short pulse rates that it can be considered near-simultaneous. This advent enables acoustic data to be acquired at multiple frequencies in a single pass and considered for use in a similar way to multiband data, most associated with earth observation platforms (satellite imagery) (Brown *et al.*, 2019; Schulze *et al.*, 2022); (Figure 3).

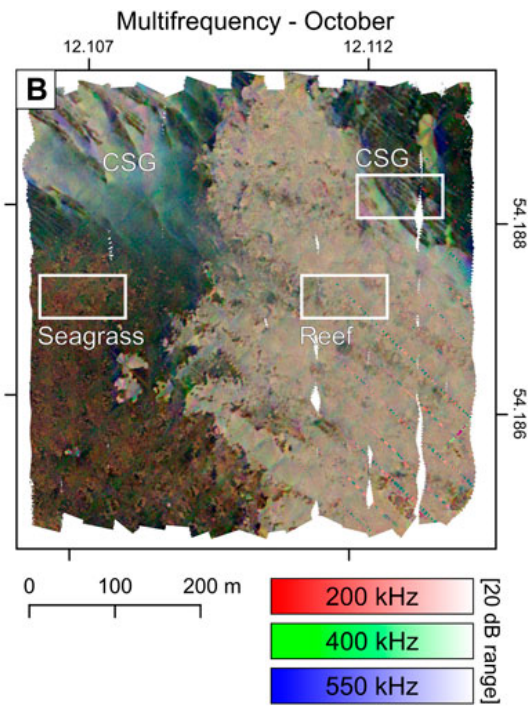


Figure 3. False colour multifrequency backscatter image (Schulze, 2022).

These multifrequency data enable different sedimentological properties to be displayed enhancing the ability to define sediments into a greater number of classes than would be possible from a single frequency. This is because of the behaviour of different frequencies when they interact with the seabed. Higher frequencies will be reflected at or near surface whilst lower frequencies can penetrate beyond the surface (Brown *et al.*, 2019) which reveals additional information on the substrata and can improve classification capability when analysed alongside appropriate ground-truthing data.

These latest developments in data acquisition should provide enhanced capability for those undertaking seabed mapping to exploit analysis techniques employed in terrestrial remote sensing or create analogous methods with reduced reworking of the original principle.

3.3 Photogrammetry

Photogrammetry, also known as structure-from-motion, is a technique to reconstruct an object or a scene in three dimensions, from overlapping images taken from multiple perspectives (Figueira 2015). First developed in the 1970s (Pollio, 1968) for use in the terrestrial environment, it is now increasingly used to study and monitor the 3D characteristics of marine habitats. Mapping in three dimensions, means that it is possible to measure lengths, area and volumes, which can be difficult to ascertain using traditional underwater video methods. 3D photogrammetric imagery can be generated at a range of spatial scales from centimetres to tens of metres. Although these areas are small compared to maps generated from backscatter, they provide an immense amount of detailed 3D imagery rather than simple allocation of classes.

When coupled with accurate georeferencing, the method can provide a permanent record of the state of a feature at a given time. By repeating monitoring over the same area, the method can be used for estimating temporal change in features. Recent uses of photogrammetry in the marine environment are in measuring structural integrity of coral reef ecosystems (Figuera 2015), measuring effects of disturbance events such as coral bleaching (Shephard *et al.*, 2017), measuring success of habitat restoration (Ventura at al., 2022) and for estimating the marine growth on artificial structures such as oil and gas platforms and offshore wind foundations (3D-Marg project, https://www.sams.ac.uk/science/projects/3d-marg/).

The Scottish Environment Protection Agency is currently working with Tritonia on a SAIC funded project to develop 3D photogrammetry methods to use in the regulation of Marine Pen Fish farms when located on or protected hard substrata. Traditionally photogrammetry has been carried out using diver held cameras due to the high quality of the imagery that can be obtained compared to ROVs or towed cameras. Tritonia is specifically working to demonstrate that georeferenced ROVs can be used to create photogrammetric imagery over multiple spatial scales (20 x 20 m, 10 x 10 m or 5 x 5 m). Use of ROVs is generally a more feasible method for fish farm operators than divers. The imagery is being assessed for various metrics from which temporal and spatial variation can be measured, such as extent of a feature, volume of smothering, percentage of live maerl and presence of bacterial mats. Automation or semi-automation of the ROVs is increasing the speed at which data can be obtained and analysed, enabling larger areas to be mapped. In favourable conditions (water clarity, weather, tides) Tritonia can currently survey areas of seabed of up to 1000 m^2 in an hour.

It is anticipated that these advances in the field of 3D photogrammetry will provide an innovative, non-invasive method in which fine-scale ecological processes can be detected and monitored. The visual nature of the tool makes it a particularly valuable technique to demonstrate impacts of anthropogenic pressures or success of habitat restoration programmes to a wide audience.

3.4 Multispecies/community models

Habitat mapping is a broad term which refers to different things depending on what type of habitat is being modelled. The current MSFD-defined broad habitat types, for instance, are the result of crossing two different information sources; depth and sediment type (e.g. circalittoral rock). However, habitat maps can also refer to complex concepts which enclose specific biological communities, such as vulnerable marine ecosystems (VMEs). These communities usually include more than one species that can positively modify biodiversity by enhancing complexity, after reaching a certain density threshold. These types of habitats, also called biological, special or listed habitats are usually mapped by applying distribution models, although the way how these models are build is highly variable.

In the past, these habitats were mapped by modelling the distribution of a selected number of species, often the indicator or habitat forming species, as a proxy for the distribution of a wider habitat type, such as their associated community or a VME. However, these approaches have often been criticised by overpredicting the distribution of the habitat since the distribution of the species is usually broader than the distribution of the habitat they form (it is easier to find one sea pen than a group of sea pens with a large enough density to form a field). To solve this problem, there has been growing interest in the past three years, on the application of community models to map the distribution of listed habitats. According to Ferrier and Guisan (2006) community models can be divided in 3 groups: predict first-assemble later, assemble first-predict later, and aassemble and predict together.

Predict first-assemble later

In these models the distributions of indicator species (e.g. habitat forming species) are modelled in a first step using presence-only or presence-absence models. In the second step the assemblages are computed using the prediction maps of these models. The analysis provides the predicted distribution of stacked species. In marine ecosystems this approach has been used by Burgos *et al.* (2020) who used MAXENT and presence-only data to model the distribution of 44 VME indicator species, analyzing in a second step the co-occurrence of these species using a cluster analysis of the predicted maps.

Assemble first-predict later

In contrast to the previous approach, assemblages are first defined here by using multivariate techniques (e.g. cluster analysis) to analyze the biological samples. In a second step, the distribution of these assemblages is modelled using a presence/absence approach. The analysis provided the distribution of biological communities (assemblages) previously defined using multivariate techniques. In marine ecosystems this technique was first used by Moritz *et al.*, (2013) to model the distribution of epibenthic communities in the Gulf of St Lawrence (Canada). This approach has later been applied to model deep-sea biogenic habitats in the Galicia and Seco de los Olivos Banks (Spain, Serrano *et al.*, 2017; Torriente *et al.*, 2019) and to determine endobenthos, epifaunal, and demersal fish assemblage distributions in the North Sea (van der Reijden *et al.*, 2021).

Assemble and predict together

Both processes, which describe the assemblages and predict their distribution, are made within the same model framework. Although relatively new in marine ecosystems, these models have been extensively used in terrestrial ecosystems (Ferrier & Guisan, 2006). The output type differs slightly depending on the type of model used. Joint Species Distribution Models (Ovaskainen *et al.*, 2016, 2017), for instance, includes co-occurrence matrices as latent variables and offers very powerful tools to model community data (already used in the marine ecosystems, Murillo *et al.*, 2020). Region Common Profile (RCP) models enable the delineation of geographic areas where the probabilities of observing a group of species remains approximately constant (Foster *et al.*, 2013; Hill *et al.*, 2017).

4 Marine habitat maps: uses, data sources and methodologies

4.1 Overview of habitat map types

EMODnet Central Portal provides a single access point to European seabed habitat data to aid marine spatial planning and marine habitat assessments. It is used here to illustrate the different types of marine habitat mapping products that are publicly available. Maps are grouped into the following categories:

- Individual habitat maps from surveys.

Detailed habitat maps that characterise the habitats present at a particular time, based on survey data such as acoustics and ground truth records. These maps usually cover a small area and have a high spatial and thematic resolution.

- Broad-scale habitat maps

Environmental variables known to influence benthic communities are classified into biologically meaningful classes. These data together with seabed substrate data can be combined by ‘layering’ in a GIS to create a map of benthic broad habitats. EUSeaMap is the first modelled, broad-scale marine habitat map for Europe. The current iteration, EUSeaMap 2023 (Vasquez *et al.* 2023) contains detailed substrate data interpreted from MBES where available. Where detailed substrate data are sparse, data on bathymetry and other environmental variables are used to predict the extent of habitats.

- Composite maps

The plethora of habitat maps and point data currently available provides the opportunity to create other data products from the existing data that show the best-known extent and distribution of important habitats.

- Models

Predictive Habitat Models (PHM) are models are used to predict the distribution of a certain species/habitat/community, based on its correlation with explanatory variables. Most often, environmental parameters that reflect the physical environment are selected as explanatory variables, such as depth, shear stress, and sediment type. Within ICES, these models are usually applied for VMEs and species of high importance.

Table 2. Summary of Map Types published by EMODnet Central Portal.

EMODnet Data:	Individual maps from surveys	Broad-scale habitat maps	Composite	Predictive Habitat Models
Format	Polygon	Polygon	Polygon, points	Raster
Res. (spatial)	Medium - high	Multi- resolution	High-low	Low
Res. (thematic)	High	Low	High	High
Extent	Local, regional	Sea basin	Regional, sea basin	Regional
Original Purpose	Habitat distribution	Baseline reference	Best available data	Habitat distribution
Theme	Habitats, biotopes	Broad habitat types	Habitats, Species, EOVs	Species, habitat
Classification	EUNIS, Folk, Annex I HD, other	EUNIS, MSFD	EUNIS, OSPAR T&D, other	VME, other
Application	Monitoring	MSFD D6 Reporting	Monitoring	Monitoring, advice

Broadscale International or National classified habitat maps (e.g. EUSeaMap or UKSeaMap) provide useful regional overviews of habitats distributions at very broad spatial scales which are impossible to achieve using direct survey methods. Such maps may be the best option for assessing regional MPA networks (Agnesi *et al.*, 2017). However, when site-specific habitat maps created from acoustics and ground-truthing surveys are available, they often suggest the presence of additional habitats and provide a more detailed picture of their extent and distribution (e.g. Eggleton & Downie, 2017). This indicates that regional habitat maps are less suitable for providing specific advice at a site level. The process of creating the habitat maps from survey requires collection of biological ground truthing records that improve confidence in the habitat maps and their use in advice (JNCC, 2013).

Are there issues around using maps with "hard delineations between habitat types/maps that are deceptively precise" we might want to go into here.

Similar to regional habitat maps, predicted distribution models are a useful method of creating maps of biogenic habitats (or other species/indicators) for large spatial areas when direct surveys are unavailable/unfeasible. However, usage of these maps in advice or management decisions is currently limited, as the level of confidence is often assessed to low by managers or stakeholders, which rather would have direct evidence that the species/habitats are present at the predicted locations. Yet, the predictive power of these models may provide evidence to support management decisions, whereas surveys only allow to map the status quo. As such, predictive models could be useful to determine recovery potential, or optimal restoration sites (Elsäßer *et al.* 2013, Bertelli *et al.*, 2022).

Broadscale habitat type (e.g. EUNIS level 3 habitats), are generally defined by physical characteristics of the seabed (ref. EUNIS Level 3 descriptions). For EUSeaMap these are predicted based on variables such as seabed depth, substrate type and light penetration. Such variables are unlikely to change in response to human activities and as a result are more stable over time and can be useful for some MSFD D6 indicators. However, because broadscale habitats do not include biological information and each broadscale habitat can support a range of different communities, broadscale habitat maps cannot be used to make biodiversity assessments without complementary information on the biological component.

The use of maps in marine management decisions (i.e. Marine Protected Area (MPA) designation, industrial licensing & fisheries management) has varying thresholds of need in the confidence/uncertainty of the data. Whilst maps produced should be of the highest quality, accuracy, and specificity possible, the threshold for rejection against use for a particular purpose differs. For example, the designation of MPAs in Northern Ireland has been carried out using manually drawn maps (Red Bay SAC) and unsupervised classification (The Maidens SAC, Murlough SAC and Strangford Lough MCZ). These maps constitute a small component within the evidence considered by the responsible department, meaning the consequences of map inaccuracy (usually using broadscale classes) underpinning designation is reduced. It is likely that activities will be permitted to continue in the MPA, until a deleterious effect is observed meaning the conflict resulting from any inaccuracies are initially reduced.

Following designation, these seabed classification maps should be considered as nothing more than a baseline assessment of the MPA site. This could be used for assessment against MSFD descriptor D6 by giving an indication of the potential feature extent. However, no further assessment against alternative interests, such as licensing of the industry, should be made because the reporting requirement against MSFD/UKMS is at a level where prescribed thresholds of change will not be observed. This is because most maps for the designation of MPAs in the UK are classified using EUNIS Level 3 criteria. The initial impact of carrying out an activity, whether licensed or unlicensed, will not affect change in the seabed classification, i.e. areas classified as 'offshore circalittoral mud' will likely remain as 'offshore circalittoral mud' following activities such as cable burying, wind farm installation, or ongoing fishing activity.

The impact here would be upon the biological component of the system and will vary depending on the type of activity undertaken. It is evident that a map which provides a cursory assessment of D6 would be of no use for the assessment of indicator D1 (biodiversity) because the map has not been created to describe or illustrate biodiversity. Thus, use of a EUNIS Level 3 map to assess biodiversity would be negligent use of the product.

4.2 Data accessibility

Web mapping viewers and data portals facilitate easy access to marine habitat mapping data products. Unfortunately, not all data are published due to commercial issues, data sensitivity and a lack of awareness of projects like EMODnet that will ingest and publish data without any additional costs. Habitat maps may be produced under restricted used licences, with data only available upon request, or published as image files. Most habitat mapping exercises begin with a data collation exercise to ascertain what data exists. This usually involves searching online portals and metadata catalogues and conducting a literature search. The latter usually unearths data that have not yet been published, and in some instances, data that are better than the existing published habitat maps. These data, with the author's permission, can be ingested into project like EMODnet either by direct contact or by georeferencing the data with the author's permission.

EMODnet Seabed Habitats has been successful in collating marine habitat data according to international standards and making that information freely available as interoperable data layers and data products. Countries that have embarked on large scale national mapping programmes, such as INFOMAR in Ireland and MAREANO in Norway, have also developed online viewers and portals. Although the data from these projects feed into EMODnet products, it might be more beneficial to access the data from the original source. National data centres/mapping programmes aggregate data at a national level, whereas EMODnet aggregates and standardises these data into a standardised European aggregation. The full suite of data products at the highest resolution are available from the national data sources.

INFOMAR publish all bathymetry and backscatter acquired by MBES. The data can be viewed and downloaded as a WMS or as individual grids. In addition, interpretations of these data have produced sediment classification and geomorphology layers which are also published online and are free to download. The advantages of publishing all outputs in digital format is the increase in the uptake of the data to generate new products different to the outputs generated by the original project.

4.3 Temporal resolution

Habitat maps can refer to a wide range of different concepts because of the many meanings of the term habitat (Elliott *et al.*, 2016). All these terms are eventually affected by temporal resolution, but the importance of this factor is not the same for broadscale habitats such as the MSFD broadscale habitats (e.g. offshore circalittoral sand) as it is for biogenic habitats (e.g. sea pen fields). Therefore, whilst human impacts can in theory completely modify broadscale habitats (e.g. heavy trawling disturbance sustained over time can eventually alter sediment type and therefore the broadscale habitat observed), this is a relatively slow process at the scale of the broadscale habitat. Temporal resolution is especially important when the habitat map includes a biological component because biological assemblages show natural interannual variation as well as being very sensitive to human activities such as trawling impact (Thrush & Dayton, 2002). Trawling disturbance is one of the most wide-spread pressures in European waters (Amoroso *et al.*, 2018; Eigaard *et al.*, 2016) and it has the capacity to severely modify benthic communities (e.g. González-Irusta *et al.*, 2018), with the potential to completely change the distribution of habitat forming species (e.g. Downie *et al.*, 2021; González-Irusta *et al.*, 2022; Stirling *et al.*, 2016, Harrald *et al.* 2018) in relatively short timescales. Broadscale habitat maps offer an advantage over biogenic habitat map for studies focused on trawling impacts because the extent of a broadscale habitat will remain relatively unchanged with time. This allows the calculation of percentages of the area adversely affected whilst the total extent of the assessment unit is not modified by the evaluated pressure. Using broadscale habitats this way also enables the assessment of complete pressure gradients even in the highest levels of pressure. Conversely, for biogenic habitats sensitive to human pressures, extent computations may be biased by habitat loss, producing a lack of overlap between the pressure and the habitat which can be confused with a lack of impact (González-Irusta *et al.*, 2022) and confound the ability to obtain data on high levels of pressure.

Therefore, temporal resolution is a key factor to consider before using habitat maps. The data collection date needs to be consulted, and the relevance of these data put into the context of its specific application and the current knowledge on historical pressures (if relevant).

4.4 Spatial resolution

Spatial resolution is a key feature of any map and habitat maps are not an exception. Regardless of whether the habitat map is a broadscale habitat map or a high-resolution map, the map users need to consider if the scale is adequate for its purpose and if better resolution information is available. Recent work demonstrates that high resolution models based on multibeam data outperform low-resolution GEBCO based models for the same area (Howell *et al.*, In press). Unfortunately, high-resolution multibeam data is often not widely available and therefore habitat maps with a large extent (e.g. all Europe) are usually based on other information sources of poorest resolution. One option that should be explored further is the use of two stage processes, by combining maps of different scale, always keeping the information of high-resolution models for the areas they cover and using the low-resolution maps for the other areas. Finally, it is important to highlight that resolution is only one of the many aspects that need to be considered before deciding which map fits the intended purpose (see below).

There are many seabed classification maps created using input data with high spatial resolution. These data tend to comprise multibeam echosounder (MBES) bathymetry and backscatter at very high resolution (0.25 < 5 m) alongside high density ground-truthing (100 < 500 m spacing). Such maps are often produced using other inputs available at lower resolutions (5 > 0.2 km), from earth observation platforms or modelling frameworks, but have intrinsic value for the system being mapped, e.g. bed shear stress; light penetration and fishing effort (VMS; Swept area ratio). Whilst the disparity in resolution can impact on the mapped output, it is necessary to make use of the best available data, where appropriate, to train/constrain models

High-resolution seabed classification maps can be generated through a variety of methods. Expert interpretation (e.g. geological facies) is a manual process where areas of homogeneity within continuous spatial data are delineated before being classified according to ground-truth information. Unsupervised classification automates the process of identifying homogeneous areas through an algorithm of choice and a classification is assigned to the clusters or objects produced. Supervised classification directly classifies continuous data based upon a training dataset derived from ground-truthing data.

4.5 Using other type of maps from models (e.g. maps of ecological indices)

In the current context of implementation of the ecosystem approach to the management of the marine ecosystems there is a growing need for reliable and informative maps (include references). This need exceeds habitat maps and there are many examples where other response variables (different to the probability of presence of one species or biological community) have been modelled. In recent years there are some examples where indices of benthic status have been mapped in a distribution model framework (Jac *et al.*, 2020; Preciado *et al.*, 2019; Serrano *et al.*, 2022) as well as other features of benthic communities such as biological traits (include references). Furthermore, Gros *et al.* (2022) have suggested modelling the vulnerability of an area, rather than its suitability to harbour an indicator taxon and proposed to use the "VME index" (Morato *et al.*, 2018). The ICES working group on marine habitat mapping (WGMHM) are in agreement that these are promising fields of research which have the potential to be useful in providing improved advice to facilitate better management of marine ecosystems. Whilst supporting the exploration of the above methods further, WGMHM acknowledges that such model outputs should be subject to the same assessment requirements and identification of limitations in use that any other distribution model would be (see ICES 2021 for recommendations).

When multiple maps exist for an area of interest it will be beneficial to consider the information together. It is, however, important to weigh the relevance to the question being addressed, the spatial resolution, the reported accuracy, and the weight of evidence behind each map when combining evidence from co-located maps. The question being addressed is the main determining factor for the appropriate spatial scale of a map product. In general, maps with the highest resolution should be given priority. However, this needs to be balanced against the weight of evidence i.e., the source and method of collection of input layers and data, as well as the number of observations used to produce the map. In some cases, the higher resolution maps may cover a smaller area and be based on less observational data. Cross-validation, or ideally external validation, of the maps will give guidance on the relative accuracy of each map product but, especially where validation data is collected before the map is produced, spatial and thematic bias in the data should be considered. Where multiple maps of comparable resolution, accuracy and weight of evidence, produced using different mapping or statistical methods, overlap the variation can be used to infer uncertainty resulting from the choice of method and areas of agreement given more confidence.

4.6 Marine connectivity to inform recoverability

The fragmentation and deterioration of marine benthic habitats may disrupt dispersal pathways between habitats and patches increasing the vulnerability of meta-populations by reducing recruitment, decreasing the ability of population recovery and limiting gene transfer that may affect population resilience in time. This dispersal of marine organisms between seascape units are referred to as marine functional connectivity, MFC (Darnaude *et al.* 2022), and MFC are typically inferred from studies using biophysical modelling (~modelling of the dispersal of pelagic life stages) that links predicted currents from oceanographic modelling with information on larval traits.

While the importance of ocean currents for species dispersal has been generally accepted (e.g. Cowen *et al.* 2006) recent years have provided a growing number of studies linking outcome of biophysical models with empirical data emphasizing the importance of MFC in both an evolutionary and demographic context. The former operating on multiple generational and long-term time scales and the latter operating on year-to-year or ecological time scales (Lowe & Allendorf 2010, Marandel *et al.* 2018). A recent meta-study on coral reef fish found clear correlation between predicted connectivity metrics from biophysical modelling studies and empirical indices on biodiversity and species abundances (Fontoura *et al.* 2022). Numerous other studies have found coincidence between empirical population genetic gradients and dispersal barriers inferred from biophysical modelling (e.g. see Mertens *et al.* 2018), implying that MFC may contribute in shaping the structure and hence potentially also the functioning of many marine populations and biogenic habitats. Dispersal of pelagic life stages, however, are only rarely considered as part of management efforts to protect marine populations (Darnaude *et al.* 2022).

In relation to the use of SDM's for management purposes the maps produced could be supplemented by maps that describe the connectivity between the predicted habitats or predicted species distributions, for supporting an optimal configuration of habitat protections or MPA's. Or even better, connectivity metrics could be included explicitly as predictor variables (Cecino *et al.* 2021). Examples of different types of information as maps that can be produced from connectivity analysis and their relevance are listed below.

- Sink-Source dynamics: A habitat may serve primarily as a source exporting propagules to other habitats, or as a sink, receiving propagules from other habitats. Pure source areas may be particularly vulnerable to habitat quality degradation due to limited recovery potential, and pure sink areas will not contribute to maintenance or recovery of other habitats. To optimize the configuration of habitats to meet quality thresholds of selected indicators, the fraction of habitats that serve as both sinks and sources should be maximized.
- Betweenness centrality: This is a metric in graph theory that identifies habitats which serve both as a source and as a sink, and that are particularly important as a link, via stepping stone dispersal, connecting different parts of a network which are otherwise less connected.
- Closeness centrality: This is somewhat supplementary to betweeness centrality a metric for detecting habitats that can spread propagules very efficiently, via stepping stone dispersal, through a habitat network
- Transitivity: This metric is also called "Cluster coefficient" and is a measure for how well the habitats in the neighbourhood of a given habitat are connected. Transitivity can be calculated for individual habitats (or patches) and for the whole network of habitats.
- Clustering: Clustering algorithms are often used when analysing MFC network graphs to detect communities of habitats or patches, and particularly for detecting dispersal boundaries between otherwise well-connected habitats. Dispersal boundaries from

biophysical modelling are often found to coincide with population genetic gradients from empirical data.

The connectivity metrics can be analyzed for both potential habitats as well as for predicted species distribution, and iteration routines (e.g. bootstrapping) can be used to identify how sensitivity or robust the calculated metrics are to changes in habitat configurations and this way identify the most optimal (Depending on the criteria) configuration of an MPA network etc. (e.g. Kininmonth et. al 2011). Similarly, this way uncertainty in outputs from SDM's can be incorporated into the connectivity metrics.

As for other predictive models, the biophysical model outputs and the connectivity metrics extracted are subject to uncertainties and limitations. In most larval dispersal and marine connectivity studies connectivity is evaluated based on relative terms, e.g. as strong or weak. However, a relatively low demographic connectivity may not necessarily imply that habitats are not connected, and vice versa (Treml *et al.* 2012), and this remains one of the major challenges in MFC. The temporal and spatial scale of the underlying hydrographic data set is another issue to consider. While coarse resolutions of predicted currents may be adequate for prediction of dispersal of pelagic life stages in large homogeneous seabed topologies, finer resolution of hydrographic data may be required in more complex seabed topologies to resolve eddies that may affect local dispersal processes. Other uncertainties relating to both the hydrographic data as well the various pelagic traits used in the biophysical model may have to be considered. In general, all major identified uncertainties that may eventually affect the produced connectivity metrics should be analyzed systematically to inform decision makers.

4.7 Model information content

Species distribution models (SDMs) can be built with different types of data. In the case of VMEs, most observations are a) records of indicator taxa from scientific surveys or b) fisheries bycatch, and direct observation of habitats using underwater imagery. The type of data used to fit the model strongly determines how the output of the model should be interpreted (Gros *et al.*, 2022).

Presence-only (or rather, presence-background) models can only provide a ranked suitability value, which is not proportional to the actual probability of occurrence. These outputs can be used to discriminate which areas are more or less likely to harbor the modelled taxa. When true absence data is available, presence-absence models can provide a probability of occurrence. The highest information content is provided by models fitted to abundance or coverage data.

4.8 Uncertainty

Every predictive modelling process is related to a certain degree of uncertainty which can be assessed both globally (e.g. through performance measures and / or cross-validation/validation procedures) or locally (e.g. through the mapping of local errors / misclassification rates per raster cell). Ideally, corresponding uncertainty score and / or maps should be made available for each mapping output. Together with metadata on mapping resolution and scale these uncertainty measures can help to assess the usability of habitat maps for defined management actions. Maps with high global uncertainty tend to be not fit for purpose. Maps of local modelling uncertainty could be used to prioritise areas for monitoring and management measures (e.g. to plan benthic HD or MSFD monitoring, reintroduction of species, to identify areas for fisheries closure). As an example, multicriteria decision analyses (MCDA) were applied in Germany to identify suitable areas for the reintroduction of the European Oyster within the Natura 2000 sites Sylter Outer Reef and Borkum Reefground (Pogoda *et al.* 2022). MCDA primarily relies on expert opinion for weighted averaging of relevant input maps (e.g. on sediments, bathymetry, anthropogenic pressures) to derive local suitability scores for a defined raster. In this study, information on the uncertainty of the input maps were communicated to the experts and therefore accounted for in the analysis.

4.9 How maps can be presented to support clarity and value to managers

An essential element of management of marine ecosystems is understanding their components. The seabed habitats are the principal component of the seabed. Maps of substrate type and biotope are important; however maps of habitat sensitivity, ecological function and anthropogenic pressures can also assist managers in decision making. There are several policy drivers for which habitat maps are key. One is the commitment to achieve Good Environmental Status under the Marine Strategy Framework Directive, which includes a descriptor that states, 'The sea floor integrity ensures functioning of the ecosystem'. Another driver stems from the increasing use of the marine environment by multiple industries. This competition for marine space requires marine spatial planning and consideration of potentially multiple use of the marine space. In the past fishing and oil and gas were the principal large-scale users of our seas, but now managers are required to plan for development of many industries, such as offshore wind and other marine renewables, aggregate extraction, carbon capture and storage, deep sea mining, shipping, aquaculture, mariculture, telecommunications cables and harvesting of marine resources and more. Habitat maps also contribute an important component of Environmental Impact Assessments to enable managers to assess impact of a development on a habitat or ecosystem. Management of seabed features requires understanding of both the distribution and sensitivity of the habitats at a local level where they may be directly impacted by a development, and at a wider scale to ensure that there are still thriving and connected populations of the habitat throughout the species range.

Another important driver for habitat mapping is the commitment by EU Member States and the United Kingdom to development of an ecologically coherent network of Marine Protected Areas (MPAs). Up to date maps of the biological or geological features, depending on the focus of the MPA, are essential to inform these protected areas. Detailed, fine-scale maps may be derived from actual species or habitat records, which when combined with geophysical data (backscatter or side-scan) can inform the extent of a given habitat. This type of map is useful for ensuring protection of sensitive and long-lived features such as biogenic reefs. Mapping a given species or habitat at a broader scale may require predictive mapping as it is not possible to collect sufficient sampling data throughout the species range. In this case species distribution models can be useful to define where a species or habitat is likely to be present given environmental characteristics and anthropogenic pressures. Another approach to selection of areas for designation within MPAs is to consider the ecosystem services of a particular habitat together with their marine natural capital. The natural capital approach considers quantity, quality, function and value of environmental assets, and the derived ecosystem services and benefits. Habitats can be assigned an index of natural capital which can be illustrated as a map to aid in decision making.

AFBI (2015) produced a high-resolution seabed classification map for Strangford Lough using MBES data and derivatives plus historic ground-truthing spanning 35 years to create a map which used MNCR (then EUNIS equivalent) level 4 classes. Due to the nature of using biotope classes there was conflicting information for many ground-truth stations. For mapping, observation records were assigned a mosaic classification due to the heterogeneity of the area confounding the minimum biotope recording area of 25 m2 (AFBI, 2015). This resulted in one map class comprising six biotope classes (SS.SMX.CMx, CR.HCR.XFa, CR.HCR.FaT, IR.MIR.KR, IR.HIR.KSed, CR.MCR.EcCr, SS.SBR.SMus) encompassing sublittoral mud, moderate- and high energy infralittoral rock, moderate- and high energy circalittoral rock and sublittoral biogenic reef. It is unclear in the map how the temporal disparity in the records affected the seabed classification map. The confidence assessment (MESH, 2007) suggested an overall map confidence score of 77 but the ground-truthing component scored 62. It was reported that information on substrata was not universally available nor at a resolution to best inform seabed classification mapping which resulted in deriving substrata from biotope classes. The authors also highlight disparity in the level of information afforded by the biotope classes with some level four classes containing biological information and others not (AFBI, 2015). In spite of these limitations the map is still fit for purpose when used for MPA designation and onward assessment. Managers can have some confidence that the list of features are present (or were present in historical records so could recover if proven to be now absent – this would inform the setting of conservation objectives), they have an idea of the distribution of features enabling targeted monitoring to verify presence and refine the map in future iterations.

Conversely, the lack of well-defined areas of biological components (assemblages/biotopes/communities) means the map is not fit for purpose if the intent is to assess potential ecological impact of an activity. There is inadequate information to determine the condition of the assemblage or Priority Marine Feature (e.g. *Modiolus modiolus* beds). Similarly, biodiversity (D1) cannot be assessed and as such the map cannot be used to limit fishing activity, advise on licensable activities such as aggregate extraction, or siting of offshore renewable energy developments. For assessment pertaining to management of industry, such a map can only be used to advise on areas for further survey to develop an Environmental Impact Assessment or fishery assessment.

The advantage of using automated algorithms to cluster or delineate areas of homogeneity is that it can be carried out across multiple inputs simultaneously. Likewise, the ease of access, through open access platforms, to modelling environments enabling supervised classification using a variety of input data mean that it is now commonplace to produce maps for use in marine management using predictive means.

It is unclear whether mapping to higher levels of biotope class will provide better management capability/information. There have been efforts to map to higher EUNIS classification levels which illustrate other potential issues with map use.

4.10 Sediment predictions

Standard seabed mapping using multibeam echosounder (MBES) or sidescan sonar systems produce high resolution grids of bathymetry and backscatter data with 100% coverage. When complemented with seabed samples, either photographic or physical, these acoustic data products form the basis for the creation of detailed seabed maps (Diesing *et al.*, 2020). Classification approaches including rule-based classification, geostatistics, machine learning, and object-based image analysis (OBIA) are commonly employed but detailed methodologies and guidelines on how to conduct such analyses are limited. Despite using the same input data, numerous different approaches to sediment classification are described in literature. Such choices are frequently based on the type of seabed features present, availability of specific software, user expertise, processing time and the specific application of the final map.

Fully automated, image-based classification is one approach to classifying MBES data into substrate types. In most cases, the backscatter data are clustered into similar acoustic classes (pixel-based) or segmented into spatial units (object-based) where pixels in proximity and having similar backscatter values are grouped together into a segment. Segments exhibiting certain shapes and acoustic signatures can be further grouped into objects representing seabed features. The next step in interpreting the imagery depends on the availability of sediment samples or camera footage to "groundtruth" the acoustic classes or image segments generated. This is known as supervised classification and there are a variety of algorithms that can be used for this purpose. Maximum Likelihood Classification and Random Forest are examples of image classification algorithms. They use a subset of sample data as a training set to derive relationships between a substrate/habitat type and predictor variables (e.g. backscatter, bathymetry). The classifier then uses this information to classify the entire area. A small proportion of the groundtruth data are set aside to be used in an accuracy assessment which provides a measure of confidence to the interpretation. One of the advantages of this image-based approach is that the number of input predictor variables is unlimited. Bathymetric derivatives (e.g. slope, rugosity) can be used to extract rocky areas and oceanographic variables (energy) can be incorporated into the classification process to aid prediction of sediment types.

Despite recent advances in fully automated approaches to the classification of sediments, semi-automated methods are still used by many seabed mappers. The first step in most semi-automated workflows is to separate rocky areas from the softer, sediment data. Bathymetry data, viewed with shaded relief effects, highlight the hard, rough textured features that are quite evidently rock. The use of automated tools or a manual digitising approach will extract the rock outcrops as a distinct feature. Backscatter is the primary dataset used in the classification of seabed sediments. The grey scale features correspond to the different signal strengths recorded from the returning echo. These features can be clustered into acoustic classes using automated tools. The acoustic classes are classified using overlying sediment sample data classified according to Folk. Sample data are analysed in a laboratory where they undergo a quantitative, classification process based on the percentage of mud/sand/gravel present in the sample.

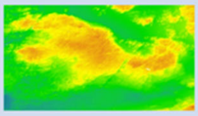
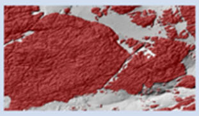
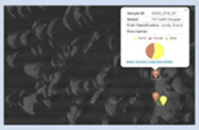
Data	Analysis	Product
MBES **bathymetry** grid 	Manual/automated extraction of rock outcrops	Rock class 
MBES **backscatter** mosaic 	Auto-clustering of data (unsupervised classification)	Acoustic classes 
Sediment **samples** 	Groundtruthing of acoustic classes (supervised classification)	Sediment classes 

Figure 4. How MBES data can be interpreted in a semi-automated approach to making a benthic substrate map.

Backscatter mosaics are the most used MBES output for sediment classification purposes (Figure 4). These images display backscatter intensity, which is a measure of the strength of the returning echo after it has interacted with the seafloor. Some of the energy is absorbed by the seabed, the amount reflected or "scattered" is indicative of the type of sediment present. Rough surfaces scatter a greater portion of the acoustic signal back to the receiver compared to smooth surfaces, which scatter much less signal. The backscatter intensity is also impacted by the incidence angle, with increasingly weaker returns as the incidence angle increases (Lurton *et al.*, 2015). Some studies suggest using this angular response, often represented as a mean angular curve, to derive further variables such as the mean, slope, kurtosis and skewness of the curves which can be used as additional variables for the classification process (Hasan *et al.*, 2014).

4.11 Use of fisheries data

Although fishermen do not collect data in a scientific way, they have obtained extensive knowledge of the system by being at sea. Knowing their fishing grounds and in particular which places to avoid is essential for them to earn a living. As such, fisheries data holds valuable information that potentially could be used in marine habitat mapping.

It has been observed that different mobile bottom-towed fisheries have very distinct fishing grounds that represent environmental conditions preferred by the (main) target species (van der Reijden *et al.*, 2018). As such, the fishing footprint of specific fisheries could potentially serve as a proxy of certain habitat types (van der Reijden *et al.*, 2023). Such habitat-fishery interactions are likely strongest for specialized fisheries that target species with strong habitat preferences, such as the sandeel or Nephrops fisheries. The absence of any fishing activity, on the other hand, could indicate the presence of specific, unfishable habitats, like rocky outcrop or stony areas (van der Reijden *et al.*, 2023). The best methodology for extracting indirect environmental information from fishing data for habitat mapping purposes is yet to be explored. For instance, high-resolution fishing footprints could be included as explanatory variable(s) in predictive habitat modelling (van der Reijden *et al.*, 2023), although this approach is not yet optimal. Alternative ways of using the fishing footprint would be i) to 'validate' habitat mapping results against fishing distributions, to see if the habitat distributions make sense, or ii) to 'prioritize' areas for scientific habitat mapping, based on crude assumptions of prevailing habitat types from fishing footprints. An important notification is that mobile bottom-towed gears themselves also alter the prevailing substrate, as chronic, intense fishing removes the smaller grain sizes because of repeated sediment resuspension (shown by e.g. Brown *et al.*, 2005).

In addition to the use of fishing footprints, fisheries data could provide more species-specific information. Fisheries data contain registered catches (total or species specific), which pose a new and massive source of abundance data for habitat mapping purposes when linked to the fishing footprint. These data have important limitations with the geolocation error being the most important, but this is often compensated for by the impressive number of records and the large spatiotemporal coverage of the data. Figure 5 shows the spatiotemporal distribution of mackerel (*Scomber scombrus*) Catch per Unit Effort (CPUE) in the Spanish hand line fishery for the period 2007–2009, which is used as a proxy for its abundance and distribution to determine the environmental parameters that affect mackerel migration (Rodriguez-Basalo *et al.*, 2022).

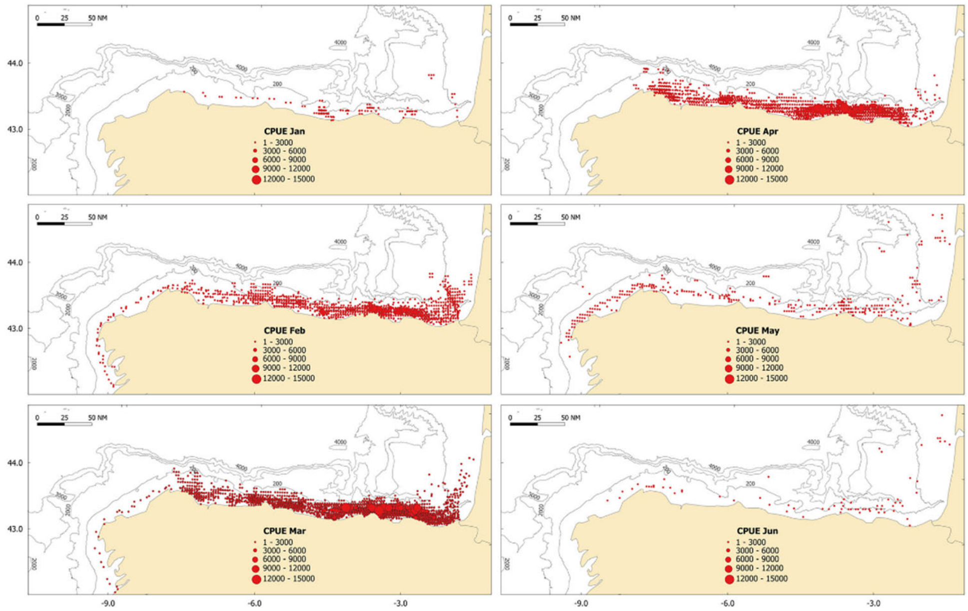


Figure 5. Monthly Catch per Unit Effort (CPUE) of mackerel along the northwestern Iberian Peninsula and Cantabrian Sea, estimated from the hand line fishery during the half part of the year (January – June) for the period 2007–2009 (taken from Rodriguez-Basalo *et al.*, 2022).

4.12 Coastal modelling and spatial mismatch in large-scale environmental model coverage

In the past few years, members of the group have been developing predictive habitat models for a range of species. These have tended to be in offshore or deep-water locations, such as models for vulnerable marine ecosystems. Predictive modelling work is now beginning in shallower, more coastal locations. There are various drivers for modelling these habitats such as conservation, sustainable use or restoration. The current extent of habitat in near coast locations could be directly mapped through field surveys or remote sensing. However, it may not be possible to undertake these over a large area with the time and resources available. In addition, questions relating to restoration require predictions of suitable locations beyond the current extent. Therefore, predicting suitable habitat based on the distribution of environmental conditions is still required.

There seems to be a persistent challenge in obtaining environmental parameter estimates in the coastal areas, which are required for predictive habitat modelling. Most large-scale physical models, like the outputs from the Atlantic-European Northwest Shelf - Ocean Wave Analysis and Forecast model available in Copernicus or the various data layers available in BIO-ORACLE, do not stretch all the way to the coastline, or provide very distorted estimates for these regions (Figure 6). A similar phenomenon can be observed for the EMODnet EUSeaMap that is often widely used amongst others in marine management, where inland waters are often not (completely) covered by the habitat map. This also hampers habitat impact assessments based on these habitat maps under the Water Framework Direction. As a result, most coastal modelling studies rely on regional hydrodynamic model outputs, or (restricted) in-situ measurements (see e.g. McLaverty *et al.*, 2023 and Meijer *et al.*, 2023). Some environmental layers such as those relating to light availability (e.g. turbidity, diffuse attenuation coefficient) and temperature are often derived from satellite data (Downie *et al.* 2013; Neiva *et al.* 2014; Martin *et al.* 2014; Chefaoui *et al.* 2015; Beca-Carretero *et al.*, 2020). Parameters derived from bathymetry layers and the shape of the coastline also feature in some coastal models (e.g. Martin *et al.* 2014; Chefaoui *et al.*, 2015). A review of the parameters used in some recent models of coastal species and habitats is shown in Table 3.

Table 3. Parameters used as predictor in predictive habitat models in coastal areas.

Reference	Variable	Source
Martinez et al. 2023	Wave exposure	Odin module of the Coastline Modelling System software smc 2.0
	Air Temperature	Digital climate atlas of Iberian Penninsula and Worldclim
	Substratum	Personal observation, topographic maps, aerial photography
Folmer et al. 2017	Hydrodynamic variables	Simuated from the General Esturine Transport Model
	Wave forcing	From wave model SWAN version 40.91 AB
	Mud fraction	Sediment samples collected at 500 m grid intervals
Neiva et al. 2014	salinity	NOAA/OAR/ESRL PSD, http://www.esrl.noaa.gov/psd/
	Sea surface temperature	NOAA/OAR/ESRL PSD, http://www.esrl.noaa.gov/psd/
	Air Temperature	NOAA/OAR/ESRL PSD, http://www.esrl.noaa.gov/psd/
	Relative air humidity	NOAA/OAR/ESRL PSD, http://www.esrl.noaa.gov/psd/
	Tidal amplitude	?
	Intertidal availability	?
Grech and Coles, 2010.	Bathymetry	Great barrier reef depth and elevation model
	Substrate	Geoscience Australia 2007
	Sea surface temperature	Australian Commonwealth Scientific and Research Organisation 2007
	Tidal range	Hopley et al 2007. The geomorphology of the great barrier reef
	Spatial extent of flood plumes	Delvin et al 2001 Flood plumes of the great barrier reef
	Relative wave exposure	Santana Garcon et al. 2010
Adams et al. 2016	Significant wave height	SWAN model
	Benthic light availability	Estimated from bathymetry, global solar exposure, and secchi depth
	Sediment size distribution	40 sediment samples
Downie et al. 2013	Depth	Finnish Maritime Administration digital 1:50000 nautical chart
	Slope	Derived from DEM
	Wave exposure index	Calculated from Simplified Wave Model
	Distance to sandy shore	National Land survey of Finland and CORNIE land cover data
	Turbidity	EOS-Terra-MODIS images
Chefaoui et al. 2015	Diffuse attenuation coefficient	Satellite data - SeaWiFS satellite radiance and MODIS
	Sea surface temperature	Satellite data - infrared and microwave data OSTIA system
	Significant wave height	Satellite data - AVISO altimeter data
	Dissolved oxygen, nitrate, phosphate, pH, PAR and salinity	Bio-ORACLE
	Coastal shape parameters	derived from coastline
Beca-Carretero et al. 2020	Bottom temperature	Regional Ocean Modelling System Models
	Bottom velocity	Regional Ocean Modelling System Models
	Bathymetry	High resolution LIDAR
	Slope	Derived from bathymetry
	Orientation	Derived from bathymetry
	Distance to shore	Derived from coastline
	Sediment size distribution	EUNIS habitat maps and maërl presence
Martin et al. 2014	Bathymetry	EMODnet Hydrography portal
	Slope	EMODnet Hydrography portal
	Bottom salinity	World Ocean Database
	Bottom temperature	World Ocean Database
	Bottom type	Halpern et al. 2008
	Distance to ports	World port index
	Distance to major river mouth	River mouth location from ESRI data
	Euphotic depth	Prepared from satellite telemetry - Ocean Color Web
	Nutrient input	Based on annual use of fertilisers (Halpern et al. 2008)
	Phosphate concentration	In situ surface observations - Bio-ORACLE
	Sea surface current	Prepared from satellite telemetry - Aviso SSALTO/DUACS
	Silicate concentration	In situ surface observations - Bio-ORACLE
Simon-Nutbrown et al. 2020	Bathymetry	MARSPEC via Bio-ORACLE
	pH	Bio-ORACLE
	Diffuse attenuation coefficient	Bio-ORACLE
	Nitrate concentration	Bio-ORACLE
	Benthic temperature	Bio-ORACLE
	Benthic salinity	Bio-ORACLE
	Benthic current velocity	Bio-ORACLE

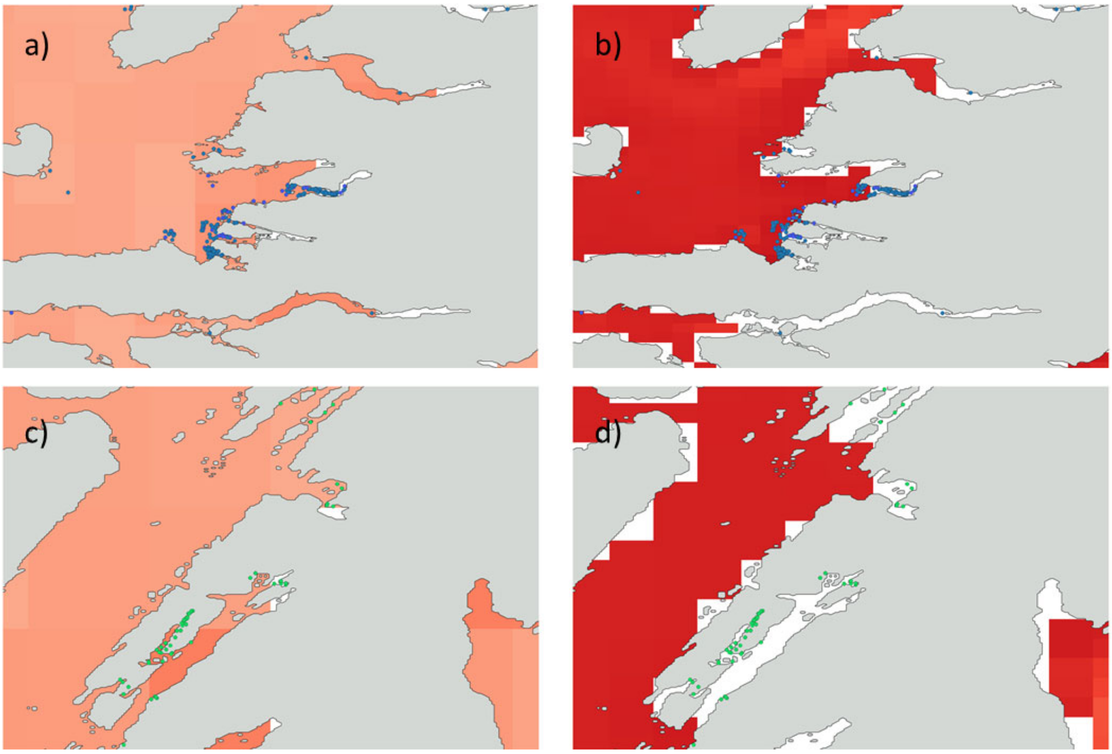


Figure 6. The observational records of a & b) maerl beds/maerl beds or coarse shell gravel with burrowing cucumbers and c & d) seagrass beds alongside bottom temperature layer a & c) Bio-ORACLE (Assis *et al.*, 2018) and b & d) Atlantic-European North West Shelf Forecast. The Bio-ORACLE layer has a larger spatial coverage but low-resolution c. 0.08°, the North West Shelf Forecast has a higher resolution (c. 0.03° by 0.01°) but overlaps with fewer records near the coast. The habitat records are taken from the Geodatabase of Marine Features Adjacent to Scotland (GeMS version 26).

Some models of coastal habitats do use the relatively coarse global environmental data sets e.g. bio-ORACLE and either resample or make predictions at a coarse resolution (Simon-Nutbrown *et al.* 2020), particularly if the predictions were being made at national or international scales.

4.13 Using data from *Nephrops* surveys for habitat mapping

The management of Norway lobster (*Nephrops norvegicus*) is based on the estimation on the density of burrows from videos collected during Under-Water TV surveys (UWTV). In the videos, trawl marks and other organisms, particularly sea pens, are often visible, and therefore can provide useful information for habitat mapping purposes. Indeed, previous work has shown that *Nephrops* surveys could be used to assess sea pen distributions and their habitat preferences (see e.g. Greathead *et al.*, 2007, 2014, Harrald *et al.*, 2018), and for comprehensive community analysis at *Nephrops* fishing grounds (Le Joncour *et al.*, 2023). Videos from UWTV surveys have the potential of complementing large-scale marine habitat mapping programmes, as is the case in Icelandic waters (Figure 7).

Data from *Nephrops* surveys is therefore particularly valuable when including abundance estimations of sea pens and other organisms, yet given financial and time constraints, it is often not possible to register all organisms present in videos obtained in UWTV surveys. One possibility is to carry out full analyses only in a subsample of the videos. Estimates of classified abundances (preferably classified in levels with enough detail, e.g.: not high, medium, low, but 0, 5, 10, 20, 50, 100 per m2) could also be useful. Another option is the use of machine learning algorithms trained to identify the sea pens, which may already have been initiated with the University of Plymouth, CEFAS and the Marine Directorate (Downie *et al.* 2022).

The use of these videos could even be wider than *Nephrops* or sea pen abundance estimation alone, by including presence/abundance of marine litter and other species. Moreover, the spatial configuration of sea pen abundance would be interesting to investigate as well. Sea pen distribution is often patchy, while the dimensions and dynamics of these patches are currently not understood. Since video observations could provide exact information of the spatial distribution of sea pen abundances, information on sea pen patches could be obtained. In addition, since annual surveys are performed for quite some years, these *Nephrops* video surveys could provide long-term information on species abundances. As such, it would be able to study temporal trends in abundances. Especially for those monitoring stations that are subjected to changing fishing restrictions (for instance within MPAs), such time trends would allow for recovery studies, that are currently very limited.

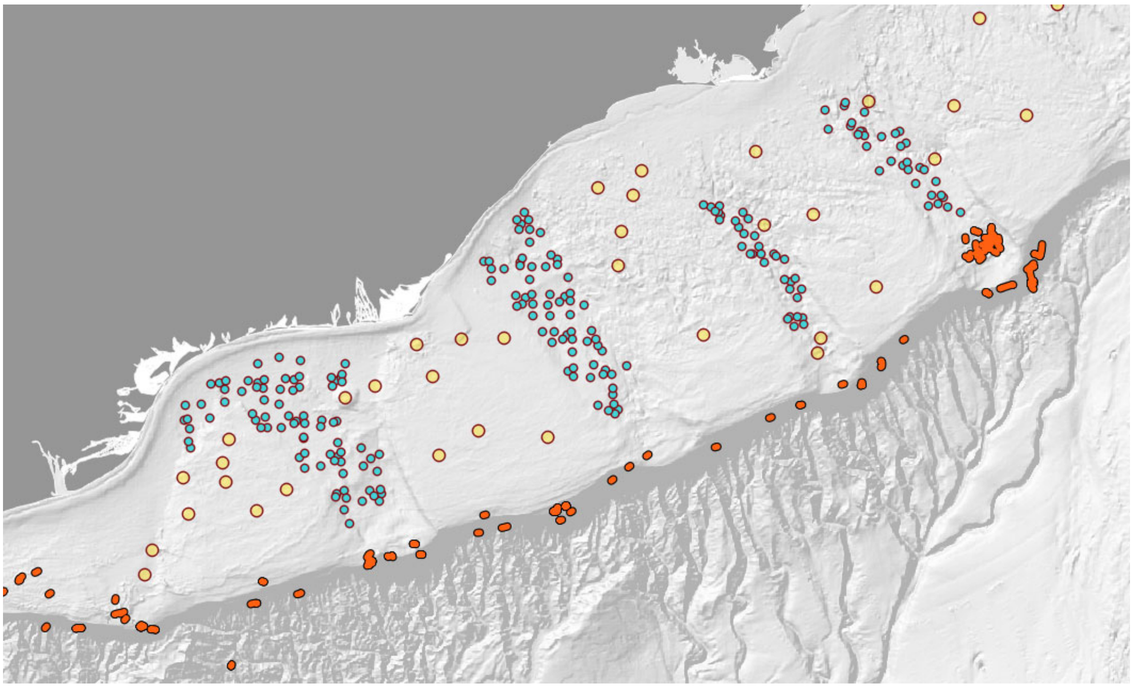


Figure 7. Video observations off southeastern Iceland. Blue dots indicate the position of video observations from Nephrops surveys in the southeastern Iceland shelf (2016–2023). Orange lines indicate video transects carried out for habitat mapping focusing on VME areas in the shelf and break (2004–2019). Yellow dots indicate new video transects carried out during the 2024 habitat mapping survey.

5 VME elements for WKVMEBM

5.1 Background

VME elements refers to geomorphological features on the seabed that are known to provide suitable habitats for VME indicator taxa. The concept of VME elements stem from the UNGA resolutions 59/25 and 61/105 that call for the protection of VMEs (United Nations General Assembly, 2004, 2006) and specifically mention seamounts. The FAO guidelines, which operationalise the UNGA resolutions, also list additional elements (FAO, 2009):

1. submerged edges and slopes (e.g. corals and sponges);
2. summits and flanks of seamounts, guyots, banks, knolls, and hills (e.g. corals, sponges, xenophyophores);
3. canyons and trenches (e.g. burrowed clay outcrops, corals);
4. hydrothermal vents (e.g. microbial communities and endemic invertebrates); and
5. cold seeps (e.g. mud volcanoes for microbes, hard substrates for sessile invertebrates).

During the ICES Workshop on the Occurrence and Protection of VMEs (Vulnerable Marine Ecosystems) (WKVMEBM) (ICES, 2022), data for mapping VME elements was obtained from EMODnet seafloor geology (https://emodnet.ec.europa.eu/en/geology). The elements used in the workshop were limited to topographic highs (seamounts and banks) as well as small, spatially well-constrained elements (coral mounds, mud volcanoes, cold seeps and hydrothermal vents). (ICES, 2022) recommended the incorporation of other elements, namely canyons, ridges and steep slopes even in the case when the spatial resolution of these elements is coarse. Nevertheless, following the review by the ICES Working Group on Marine Habitat Mapping (ICES, 2020), it was decided not to use these elements to avoid the incorporation of these relatively large areas until there is a better methodology to delineate the potential habitat of VME indicator taxa.

An examination of the EMODnet geology dataset revealed that:

- In most cases the EMODnet data is restricted to EU waters. There are very few objects in the NEAFC area.
- Some of the objects classified as seamounts in the EMODnet database, particularly Spain and Portugal, are large structures (>200km) that do not seem to be seamounts according to the IHO definition (rising >1000m above the seafloor, characteristically of conical form"); (Figure 8).

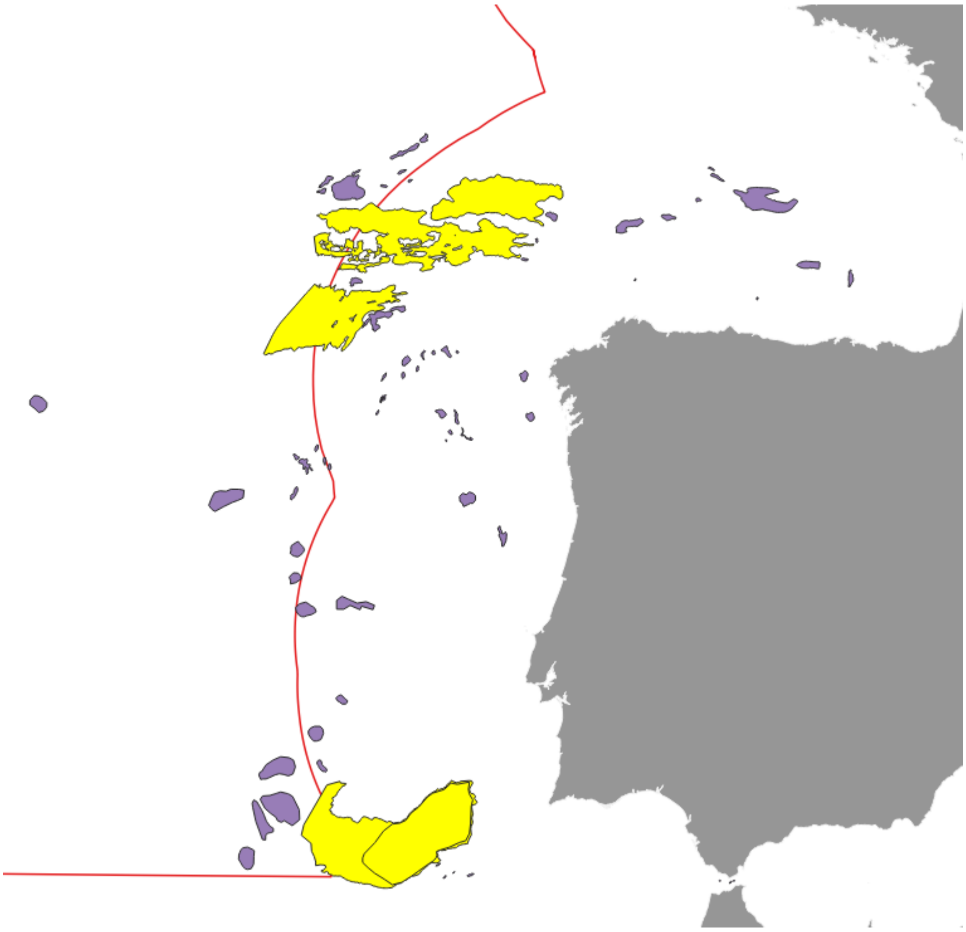


Figure 8. EMODnet seamounts off Spain and Portugal. Very large seamounts are shown in yellow. The red line indicates the limit of the NEAFC area.

Therefore, it was necessary to include additional information sources to map the distribution of VME elements in the NEAFC area, particularly seamounts, and to better delineate the elements from EMODnet geology.

Following Kutti *et al.* (2019) we distinguished between charted and modelled seamounts. Information on charted seamounts from the digital gazetteer of names and geographic position of generic features of the seafloor (IHO_IOC GEBCO Gazetteer of Undersea Feature Names) from the sub-committee of Undersea Feature Names (SCUFN) of the General Bathymetric Chart of the Oceans (GEBCO, https://www.gebco.net). From the gazetteer we extracted the positions of features labelled as "Bank", "Hill", "Hills", "Knoll", "Seamount", or "Seamounts". Within the ICES area the gazetteer included 68 seamounts, 54 banks, and 23 hills or knolls.

Modelled seamounts are identified from the analysis of bathymetric data using semi-automatic algorithms. We utilized two sets of modelled seamounts. First, we used the work by Harris *et al.* (2014), who used a modified version the SRTM30 PLUS global bathymetry grid (Becker *et al.*, 2009) to map the distribution of 29 categories of geomorphic features. Shapefiles are available at (https://bluehabitats.org/). Seamounts were detected following a two-step process. The first step was to apply two algorithms to detect peaks that raised 1000m above the surrounding seafloor, and that had a conical form (length/with ratio <2). Next, seamount bases were delineated using topographic position index (TPI) values and smoothing the resulting polygon. The feature elongation is used to distinguish between seamounts and ridges. Within the ICES area this database included 188 seamounts and 144 ridges.

We also utilized the work by (Yesson *et al.*, 2021), which is an update of their previous analysis (Yesson *et al.*, 2011) using version 11 of SRTM30 Plus bathymetry. The methodology used is different than the one used by Harris *et al.* (2014) and consisted of first detecting peaks using flow direction and sink algorithms, and then applying a set of five conditions to identify seamounts based on their height and shape. Shapefiles are available at https://doi.pangaea.de/10.1594/PANGAEA.921688%20. Within the ICES area this dataset included 1679 seamounts. The number is considerable larger than the estimated by Harris *et al.* (2014), in part because features classified as ridges by Harris *et al.* (2014) appear as chains of seamounts in the Yesson *et al.* (2021) dataset.

A comparison of the seamounts from EMODnet, the GEBCO Gazetteer, and the predictions by Harris *et al.* (2014) and Yesson *et al.* (2021) revealed that:

- Some EMODnet seamounts are labelled as banks in the GEBCO Gazetteer (e.g. Rosemary and George Bligh, off the UK), so it is not clear how consistent the terminology used by EMODnet and/or the GEBCO Gazetteer is.
- Some seamounts named in the GEBCO Gazetteer are not in EMODnet but are predicted in the Harris *et al.* (2014) and/or the Yesson *et al.* (2021) datasets.
- Some seamounts that are named in the GEBCO Gazetteer are not present in any of the datasets.
- Some seamounts listed in the Gazetteer are not seamounts according to Harris, but ridges.

5.2 Strategy

We decided to be rather conservative in the selection of seamounts for the VME advice. Within EU waters, we only used EMODnet seamounts. EMODnet polygons were not modified, except for five large polygons off Spain and Portugal which appear not to be seamounts according to the IHO definition (polygon fid = 49, 59, 61, 91, and 92). These polygons were cropped using modelled seamounts and/or ridges from the Harris *et al.* (2014) dataset.

Within the NEAFC area, we complemented the EMODnet seamounts with modelled seamounts from Harris *et al.* (2014) and/or Yesson *et al.* (2021) datasets. We included only polygons that overlapped a named location from the GEBCO Gazetteer (including seamounts, banks, and hills). In this way we included only seabed features for which there is a reported location to the IHO. These included:

- Seamounts from Harris *et al.* (2014) that overlapped with a Gazetteer records.
- Ridges from Harris *et al.* (2014) that overlapped with a Gazetteer records, cropped with seamounts from Yesson *et al.* (2021) that overlapped the same locations.
- Seamounts from Yesson *et al.* (2021) that overlapped the remaining Gazetteer records.

In addition to seamounts, the following features were included from the EMODnet database: coral mounds, banks, mud volcanoes, and mounds.

The resulting dataset contained 3224 polygons, including 112 seamounts, 3085 coral mounds, 14 mud volcanoes and 13 banks (Figure 9).

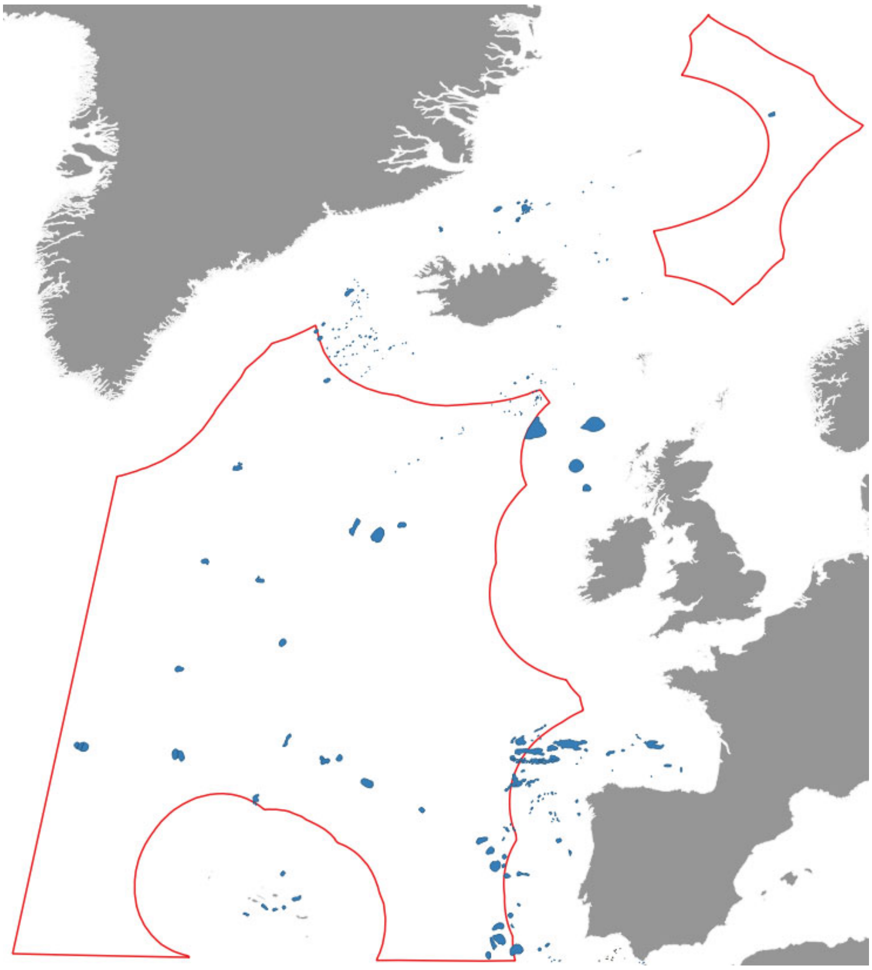


Figure 9. Location of VME elements resulting from the combination of information from EMODnet, the GEBCO Gazetteer, and the predictions by Harris *et al.* (2014) and Yesson *et al.* (2021).

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Annex 1: List of participants

WGMHM 2021 meeting

Name	Institute	Country	Emai
Julian Mariano Burgos	Marine and Freshwater Research Institute	Iceland	julian.burgos@hafogvatn.is
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James Strong	National Oceanography Centre Southampton	UK	jamstr@noc.ac.uk
Oscar Tornqvist	Geological Survey of Sweden	Sweden	Oscar.Tornqvist@sgu.se

WGMHM 2022 meeting

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WGMHM 2023 meeting

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Annex 2: WGMHM Resolution

The **Working Group on Marine Habitat Mapping (WGMHM)**, chaired by Julian Burgos, Iceland, will work on ToRs and generate deliverables as listed in the Table below.

	Meeting dates	Venue	Reporting details	Comments (change in Chair, etc.)
Year 2021	24–28 May	Online meeting		
Year 2022	29 August - 2 September	Hafnarfjordur, Iceland		
Year 2023	6–10 November	Santander, Spain	Final report by 15 December to SCICOM	

ToR descriptors

ToR	Description	Background	Science Plan Codes	Duration	Expected Deliverables
a	Report on progress in international mapping programmes (including OSPAR and HELCOM Conventions, EMODnet, EC and EEA initiatives, CHARM, Mesh-Atlantic and other projects).	Capturing the presence and work of large international mapping projects is important because (i) the WGMHM report becomes a useful 'state of the art' summary of marine habitat mapping activity, (ii) the presentations from these projects helps spread best-practice, standardisation and collaborative working within the group, and (iii) other presentations highlight relevant mapping work that may benefit the large international programmes.	1.3, 1.4, 1.5 3.2, 3.4	Years 1–3	Meeting reports
b	Review and synthesise key results from national habitat mapping during the preceding year, as well as new on-going and planned projects focusing on particular issues of relevance to the rest of the meeting. Provide National Status Report updates in geographic format in the ICES webGIS.	The current extent of marine habitat mapping and modelling means that maps are meeting at international boundaries. It is important that maps are joined internationally and in a standardised manner. This requires an understanding of the extent and distribution of habitat mapping within nation states. Equally, WGMHM are often interested in specific habitats and wish to be kept informed of specific mapping exercises on these habitats, e.g. deepwater habitats or cold water corals.	1.3, 1.4, 1.5, 3.2, 3.4	Years 1–3	Meeting reports

		The reporting of national mapping is also the primary mechanism for encouraging WG members to submit survey metadata files to the various data archiving centres. The National Progress reports also states whether member countries have purchased significant survey items, such as ships, AUVs and sonars. This provides a good opportunity for others to identify useful resources for international colloboration.			
c	Review recent advances in marine habitat mapping and modelling techniques, including field work methodology, and data analysis and interpretation	This ToR provides the main avenue for mappers to communicate new or improved techniques to the other scientists present (and captured in the report). As such, this ToR is essential for spreading best practice and developing new methods.	1.3, 1.4, 1.5, 3.2, 3.4	Years 1–3	Meeting reports
d	Review use of habitat maps, for example mapping for the MSFD, marine spatial planning, and management of MPAs; and assess the ability (e.g. through the monitoring of the MSFD indictor 'extent') to use habitat maps for monitoring of the environment.	To encourage the diversification of the WGMHM, the group also consider how marine habitat maps are used for scientific and management purposes. Members of the group are often the creators of these maps and have important insights into how the maps can be used. Equally, it gives marine managers an opportunity to suggest how maps are best presented to support clarity and value for management purposes.	1.3, 1.4, 1.5, 3.2, 3.4	Years 1–3	Meeting reports
e	Identify sources of information (e.g. bathymetry, oceanography, fisheries or socio-economic) that can be used for the production and enrichment of marine habitat maps.	Many of the remotely sensed and modelled outputs that are of value to marine habitat mappers is available online. Although much of this information is centralised in large data archives, other information remains dispersed on the web. This ToR seeks to collate the important data soueces that are of value for marine habitat mapping into one database.	1.3, 1.4, 1.5, 3.2, 3.4	Years 1–3	Meeting reports
f	Identify and advance theoretical aspects of habitat mapping (e.g.	This ToR is to provide an opportunity for EG members to address the theoretical	1.3, 1.4, 1.5, 3.2, 3.4	Years 1–3	Meeting reports and scientific papers

	landscape ecology, supplyside ecology, implications of scale etc.).	aspects of marine habitat mapping. As a science in its infancy, it is important that underpinning concepts are challenged and re-evaluated.

Summary of the Work Plan

Year 1	Cover ToRs A-E. Support the 'Benchmark Workshop on the Use of Predictive Habitat Models in ICES Advice (WKPHM)' workshop to be held jointly by Working Group on Deep-water Ecology (WGDEC) and WGMHM.
Year 2	Focus on a specific ToR for in-depth analysis
Year 3	Focus on a specific ToR for in-depth analysis

Supporting information

Priority	Supporting the Benchmark Workshop on the Use of Predictive Habitat Models in ICES Advice (WKPHM). The WGMHM may choose to address some of the topics that are highlighted as necessities for further work in 2021 and 2022. Much of the initial work will feed into the work of WGDEC. Further work will also provide support for the species and habitat predictive models that are required for WGDEC advice.
Resource requirements	Other than the support for the Benthmarking Workshop, WGMHM do not need additional resource at this moment.
Participants	The Group is normally attended by some 10–15 members and guests.
Secretariat facilities	Standard support.
Financial	No financial implications.
Linkages to ACOM and groups under ACOM	Linkage to WGDEC (advice legacy group).
Linkages to other committees or groups	There is a very close working relationship with WGDEC. It is also very relevant to the Benthos Ecology Working Group (BEWG).
Linkages to other organizations	

Annex 3: Evaluation of predictive habitat models

	Bastari et al. 2018	Bastari et al. 2018	Beazley et al. 2018	Beazley et al. 2018	Beazley et al. 2021	Burgos et al. 2020	De Clippele et al. 2017
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Sheet4

De Clippele et al. 2017	Downie et al. 2021	García-Alegre et al. 2014	González-Mirelis and Buhl-Mortensen. 2015	González-Mirelis and Buhl-Mortensen. 2015	González-Mirelis et al. 2020	Greathead et al. 2014	Gullage et al. 2017
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Sheet4

Howell et al. 2011 12	Howell et al. 2016 13	Howell et al. 2016 13	Iacono et al. 2018 14	Kinlan et al. 2020 15	Knudby et al. 2013 16	Lauria et al. 2017 17	Lauria et al. 2021 18
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Sheet4

Morato et al. 2020 19	Moritz et al. 2013 20	Pearman et al. 2020 21	Piechaud et al. 2015 22	Piechaud et al. 2015 22	Ramiro-Sánchez et al. 2019 23	Rengstorf et al. 2013 24	Rengstorf et al. 2013 24
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4	0	0	2	1	3	0	4
48	48	48	48	48	48	48	48

Rengstorf et al. 2014 25	Rengstorf et al. 2014 25	Robert et al. 2015 26	Rodríguez-Basalo et al. 2021 27	Ross et al. 2013 28	Ross et al. 2015 29	Ross et al. 2015 29	Sánchez et al. 2017 30
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Desired	Desired	Unacceptable	Desired	Desired	Desired	Unacceptable	Desired
Not evaluated	Required	Required	Not evaluated	Unacceptable	Not evaluated	Required	Required
Desired	Desired	Desired	Required	Required	Required	Required	Required
Unacceptable	Required	Unacceptable	Unacceptable	Unacceptable	Unacceptable	Unacceptable	Unacceptable
Required	Required	Unacceptable	Required	Required	Required	Required	Desired
Required	Required	Required	Unacceptable	Required	Required	Required	Required
Desired	Required	Desired	Required	Required	Required	Unacceptable	Desired
Required	Required	Required	Required	Required	Required	Required	Not evaluated
Desired	Desired	Desired	Not evaluated	Required	Desired	Desired	Desired
Required	Required	Unacceptable	Not evaluated	Required	Required	Unacceptable	Required
Required	Required	Unacceptable	Not evaluated	Required	Required	Unacceptable	Required
Required	Required	Required	Not evaluated	Required	Unacceptable	Unacceptable	Required
Required	Required	Required	Not evaluated	Unacceptable	Required	Required	Required
Required	Required	Required	Not evaluated	Required	Required	Required	Required
Required	Desired	Desired	Desired	Unacceptable	Desired	Desired	Desired
Desired	Required	Required	Not evaluated	Required	Required	Required	Required
Desired	Desired	Desired	Not evaluated	Required	Required	Required	Desired
Required	Required	Required	Not evaluated	Unacceptable	Required	Required	Unacceptable
Required	Required	Required	Not evaluated	Unacceptable	Required	Required	Unacceptable
Required	Required	Unacceptable	Unacceptable	Required	Unacceptable	Unacceptable	Unacceptable
Desired	Desired	Desired	Not evaluated	Required	Unacceptable	Unacceptable	Unacceptable
Required	Required	Unacceptable	Unacceptable	Unacceptable	Required	Required	Required
Required	Required	Unacceptable	Unacceptable	Required	Required	Required	Required
Desired	Desired	Desired	Unacceptable	Required	Required	Required	Desired
Required	Required	Required	Unacceptable	Required	Required	Required	Unacceptable
Unacceptable	Desired	Desired	Unacceptable	Required	Required	Required	Unacceptable
Unacceptable	Required	Desired	Not evaluated	Required	Required	Required	Required
Unacceptable	Required	Desired	Not evaluated	Required	Required	Unacceptable	Unacceptable
Required	Required	Required	Not evaluated	Unacceptable	Required	Unacceptable	Unacceptable
Unacceptable	Required	Required	Not evaluated	Unacceptable	Unacceptable	Unacceptable	Unacceptable

Sheet4

Unacceptable	Required	Required	Not evaluated	Required	Unacceptable	Required	Unacceptable
Required	Required	Required	Unacceptable	Required	Unacceptable	Required	Unacceptable
Desired	Desired	Desired	Required	Required	Required	Required	Required
Required	Required	Unacceptable	Not evaluated	Required	Not evaluated	Unacceptable	Unacceptable
Desired	Required	Unacceptable	Not evaluated	Desired	Required	Unacceptable	Desired
Desired	Desired	Desired	Not evaluated	Unacceptable	Required	Required	Desired
Unacceptable	Unacceptable	Required	Unacceptable	Required	Required	Unacceptable	Unacceptable
Not evaluated	Unacceptable	Desired	Not evaluated	Unacceptable	Required	Desired	Unacceptable
Not evaluated	Not evaluated	Desired	Not evaluated	Required	Desired	Desired	Desired
Required	Required	Unacceptable	Not evaluated	Required	Required	Unacceptable	Required
Desired	Required	Required	Not evaluated	Desired	Required	Required	Not evaluated
Required	Unacceptable	Required	Desired	Desired	Required	Required	Desired

14	12	16	4	4	4	4	13
23	29	20	7	31	33	29	15
7	3	12	11	13	8	15	16
4	4	0	26	0	3	0	4
48	48	48	48	48	48	48	48

Sheet4

Serrano et al. 2017 31	Serrano et al. 2017 31	Sundahl et al. 2020 32	Torriente et al. 2019 33
Not evaluated	Not evaluated	Desired	Required
Not evaluated	Not evaluated	Required	Not evaluated
Required	Not evaluated	Required	Not evaluated
Desired	Desired	Desired	Desired
Unacceptable	Desired	Required	Unacceptable
Required	Required	Required	Unacceptable
Required	Required	Required	Required
Not evaluated	Required	Not evaluated	Required
Required	Required	Desired	Required
Unacceptable	Required	Required	Unacceptable
Unacceptable	Required	Required	Desired
Unacceptable	Required	Required	Not evaluated
Required	Required	Required	Desired
Required	Required	Required	Not evaluated
Unacceptable	Desired	Desired	Desired
Required	Desired	Required	Desired
Required	Desired	Required	Desired
Required	Required	Required	Required
Required	Unacceptable	Unacceptable	Unacceptable
Required	Required	Required	Required
Desired	Desired	Desired	Unacceptable
Required	Required	Required	Unacceptable
Required	Required	Required	Desired
Not evaluated	Required	Required	Unacceptable
Not evaluated	Required	Not evaluated	Unacceptable
Required	Required	Required	Required
Required	Required	Required	Unacceptable
Not evaluated	Required	Required	Required
Required	Required	Required	Required
Unacceptable	Required	Required	Desired
Required	Required	Required	Required
Required	Required	Required	Desired
Required	Required	Required	Required
Unacceptable	Required	Unacceptable	Unacceptable
Unacceptable	Unacceptable	Required	Unacceptable
Required	Desired	Required	Required

Not evaluated	Required	Required	Required
Required	Required	Required	Unacceptable
Required	Required	Required	Desired
Required	Required	Required	Unacceptable
Required	Desired	Required	Required
Required	Desired	Required	Desired
Unacceptable	Unacceptable	Required	Unacceptable
Desired	Unacceptable	Required	Unacceptable
Desired	Not evaluated	Desired	Desired
Required	Required	Required	Required
Required	Required	Not evaluated	Not evaluated
Required	Required	Required	Desired

4	9	6	13
28	31	37	15
9	4	2	15
7	4	3	5
48	48	48	48

Annex 4: National Progress Reports

ICES Working Group Marine Habitat Mapping: National Progress Report (2020-2021)

Table 1. National progress report (NRP) source and uploads.

Country:	United kingdom
Organisation completing NPR:	JNCC,
Map metadata uploaded into the ICES Geo-portal[1]:	YES
Cruise Summary Reports (CSR) uploaded[2]:	NO

Comments
The following map metadata records have been uploaded into the ICES Geo-portal, and the maps added to the EMODnet Seabed Habitats portal:

Core reef approach to Sabellaria spinulosa reef management in The Wash and North Norfolk Coast SAC and The Wash approaches	View map GB100440
Pobie Bank Reef (East of Shetland) Annex I Reef Type	View map GB001083
East Coast REC Sabellaria spinosa in Haisborough, Hammond & Winterton	View map GB100355

[1] http://geo.ices.dk/geonetwork/srv/en/main.home

[2] Via either ICES or SeaDataNet

Assessment of the Torbay Biogenic Reef within the Lyme Bay and Torbay cSAC	View map GB100299
North Norfolk Sandbanks and Saturn Reef CEND 22/13 Annex I Reef survey	View map GB001517
2014 WFO Mussel Stock Assessment - Eastern IFCA	View map GB100361
2015 WFO Mussel Stock Assessment - Eastern IFCA	View map GB100397
2016 WFO Mussel Stock Assessment - Eastern IFCA	View map GB100398
2017 WFO Mussel Stock Assessment - Eastern IFCA	View map GB100399
2015 Natural England (NE) Shell Flat and Lune Deep Site of Community Importance (SCI) - Drop-Down Video Survey	View map GB100362
2012 Natural England (NE) The Wash and North Norfolk Coast SAC - Baseline Monitoring Survey of Large Shallow Inlet and Bay	View map GB100249
2010 Natural England (NE) Flamborough Head SAC - Biotope Mapping of Intertidal Reef	View map GB100250
2012 Natural England (NE) Solent Maritime SAC - Intertidal Survey	View map GB100244
Welsh Marine Article 17 Reporting Habitat Features - Reef (2018)	View map GB001553

Table 2. New mapping infrastructure (significant items such as ships, sonars, ROVs etc.)

Item	Organisation/Location

Table 3. Marine habitat mapping or modelling programmes.

Mapping programme	Purpose[3]	Location(s)[4]	Progress[5]	Comments	Reference or link
MAREMAP	To bring together Natural Environment Research Council (NERC) organisations with common geoscience objectives to integrate their research and inform practical applications such as marine planning, conservation and industry.	All UK	Funding has ended, but partnership continues		www.maremap.ac.uk
Updating UK priority habitat compilations	To compile the best available data for OSPAR threatened and/or declining habitats, Habitats Directive Annex I habitats and nationally listed priority habitats.	All UK/ OSPAR	Ongoing	Work carried out by JNCC, Natural England, NRW, NatureScot, DAERA. The following datasets were updated in 2020/21: UK EUNIS Level 3 composite product OSPAR T&D habitats database Scottish Priority Marine Features offshore layer Habitat of Conservation Importance layer in English offshore waters	https://jncc.gov.uk/our-work/marine-habitat-mapping/

[3] Habitats, physical seabed features, pressures etc.
[4] Sea area only.
[5] About to start, ongoing or complete.

Table 4. Additional projects and products of interest.

Project name	Purpose[6]	Comments	Reference or link
Marine Habitat Classification for Britain and Ireland update	A national-scale reanalysis of thousands of seafloor samples to identify new biotopes to insert into the comprehensive classification system for the UK seabed.	Ongoing work - Led by JNCC, in conjunction with NE, NRW, SNH, DAERI, AFBNI, Cefas and EA	JNCC Marine Habitat Classification
EUNIS v2019 marine habitat classification	EEA published the marine section of the new EUNIS classification in 2019 with major restructuring at the higher levels. The crosswalks spreadsheet that they published is available to download from their website and outlines the relationship between the new EUNIS habitats and the old EUNIS habitats. JNCC have been working to create a version of the spreadsheet (for Atlantic waters) which converts from the old EUNIS	Work in progress led by JNCC with Support from EMODnet Seabed Habitats and UK country agencies	Link to EEA crosswalk spreadsheet EUNIS marine habitat classification 2019 — European Environment Agency (europa.eu)

[6] Technical development, mapping methods, data management, novel map products etc.

	habitats to the new ones to allow us to update our existing EUNIS products to the new classification.		
Habitat suitability modelling at national scale	UK wide suitablity models for Zostera marina beds, Sabellaria spinulosa reef, Modiolus beds. Habitat suitability models for Maerl bed and, Kelp forest in English inshore waters	Work in progress led by JNCC as part of Marine Stategy indicator development work , funded by DEFRA.	

ICES Working Group Marine Habitat Mapping: National Progress Report (2020-2021)

Table 1. National progress report (NRP) source and uploads.

Country:	Ireland
Organisation completing NPR:	Marine Institute (MI)
Map metadata uploaded into the ICES Geo-portal[7]:	NO
Cruise Summary Reports (CSR) uploaded[8]:	NO

Comments

16,000 km^2 of seabed in the Celtic Sea have been classified into habitat maps over the past year and are due for upload onto INFOMAR and EMODnet Geology webmapping viewers. All maps are INSPIRE-compliant and classified to EUNIS Level 3, Folk (modified) and MSFD BBHT.

Table 2. New mapping infrastructure (significant items such as ships, sonars, ROVs etc.)

Item	Organisation/Location
DJi Matrice 600 Pro Drone	Marine Institute
Resonon Hyperspectral remote sensor camera	Marine Institute

[7] http://geo.ices.dk/geonetwork/srv/en/main.home

[8] Via either ICES or SeaDataNet

RV Celtic Explorer Kongsberg EM2040 MBES system upgrade	Marine Institute

Table 3. Marine habitat mapping or modelling programmes.

Mapping programme	Purpose[9]	Location(s)[10]	Progress[11]	Comments	Reference or link
INFOMAR	Hydrographic mapping of Irish waters to produce high resolution bathymetric and seabed classification charts.	Irish EEZ	Phase 1 (Priority Bays & Areas) complete. 77,000 km^2 coverage delivered to end 2020. 39,000 km^2 remaining. Area classified (up to 200 m contour) = 58,754 km^2.	Phase 2, focusing on Celtic Sea and remaining shallow shelf and inshore areas, is ongoing and due to be complete in 2026.	INFOMAR benthic broad habitat map
Natura 2000	Biotope mapping of Natura 2000 sites to produce baseline maps for conservation and monitoring.	Special Areas of Conservation in Irish Coastal Waters	Ongoing	Maps used in the Appropriate Assessment of Aquaculture sites and the Risk Assessment of Inshore Fishing activity.	www.npws.ie

[9] Habitats, physical seabed features, pressures etc.
[10] Sea area only.
[11] About to start, ongoing or complete.

Table 4. Additional projects and products of interest.

Project name	Purpose[12]	Comments	Reference or link
EMFF Project – Synthesis and Development of Advisory Products: SeaRover Phase 3	Synthesise the output of SeaRover surveys and map out how the data should be disseminated, analysed and developed into products and tools used for policy support. Synthesis Report - Synopsis and synthesis of the three SeaRover mapping survey reports (2017, 2018 and 2019). Delivered Q4 2020.	The EMFF Offshore Reef project, SeaRover (Sensitive ecosystem Assessment & ROV Exploration of Reef) was a three year project (2017-2019) to map offshore reef habitats with a view to protecting them from deterioration due to fishing pressures. 'Best Practice' review, SOP & Guidelines, Data Flow (for policy support) to commence Q3 2021.	
EMFF Project – National Sediment Sampling and Seabed Imagery Catalogue	Develop an integrated national sediment sampling and seabed imagery catalogue to facilitate increased re-use of data, increased resolution for EIAs, and recomendations for future developments. 'Best Practice' review complete Q4 2019. Initial Data Collation, Video Processing (File size reduction/SOP) and Georeferencing ongoing to Q2 2021.	Catalogue Hosting (ERDDAP / Marine Atlas), SOPS (Ingestion, Standardisation), Sectoral Prioritisation to commence Q3 2021.	

[12] Technical development, mapping methods, data management, novel map products etc.

EMFF Project – Biological and Physical Characterisation of Reef Habitats inhabited by Crayfish *(Palinurus elephas)*	Explore the relationship between species richness and terrain variability on reef habitats	Survey and analysis complete, report currently being finalised for publication on EMFF website.	N/A
H2020 Project - Mission Atlantic: WP4	Mapping and assessing present and future status of Atlantic marine ecosystems under multiple stressors (climate change and exploitation). This porject commenced in Q4 2020 and will run until 2024.	WP 4 will deliver a Strategic framework for Atlantic Bathymetry & Benthic Habitat Mapping for IEA. Mapping and modelling benthic communities and seafloor habitats across the Atlantic and in Case Study Areas will be carried out, along with modelling future distribution of benthic communities and biodiversity.	
EMFF Project - Development of Methodologies for Assessment of Ireland's Seaweed Resource	Conduct a biomass assessment for certain types of seaweed.	Methodology Assesment studies are in progress with data acquisition to commence in Q3 2021	N/A

Additional points of interest (optional):

The following scholarships are approved in order to support elements of the projects listed above:

- Cullen Scholarship (PhD): "Celtic Sea acoustic data analytics for improved habitat mapping & ecosystem assessment"(MI)
- Cullen Scholarship (Post Doc) - Celtic Sea Geomorphology "NoMansTiff" (UCC/USP/MI)

ICES Working Group Marine Habitat Mapping: National Progress Report (2020-2021)

Table 1. National progress report (NRP) source and uploads.

Country:	Belgium
Organisation completing NPR:	Giacomo Montereale Gavazzi (Royal Belgian Institute of Natural Sciences, Brussels, Rue Vautier, 29, 1000)
Map metadata uploaded into the ICES Geo-portal[13]:	YES/NO (not yet)
Cruise Summary Reports (CSR) uploaded[14]:	YES/NO (see comments)

Comments

Our summary reports and metadata are accessible via the vessels campaign yearly schedule website and by consulting the research programme e.g., https://odnature.naturalsciences.be/belgica/en/programmes/2021

Table 2. New mapping infrastructure (significant items such as ships, sonars, ROVs etc.)

[13] http://geo.ices.dk/geonetwork/srv/en/main.home
[14] Via either ICES or SeaDataNet

Item	Organisation/Location
RV Belgica 2 (https://www.eurofleets.eu/vessel/rv-belgica-ii/) expected to be operative by September 2021 (with campaign schedule booked already for habitat mapping and monitoring purposes)	RBINS OD NATURE/Belgian Navy/Belgian Scientific Policy office (Belspo)/Brussels/Oostende/BELGIUM (EU)

Comments

We are progressing towards the construction of a video frame for the purpose of seafloor modeling and ground truthing with underwater imagery (UI) + enable quantitate seafloor modeling (tree based machine learning approaches) by means of numerical parametrisation of the UI.

Table 3. Marine habitat mapping or modelling programmes.

Mapping programme	Purpose[15]	Location(s)[16]	Progress[17]	Comments	Reference or link
https://odnature.naturalsciences.be/msfd/nl/monitoring/2020/#ANSBE-P9-Benthos-4-hard-substrate	Habitat/substrate (stony reef)	Belgian part of the North Sea (BPNS)	Ongoing	I am in the process of re-designing and running an MSFD monitoring programe deictae to map and monitor natural hard substrate	See link to project name

[15] Habitats, physical seabed features, pressures etc.
[16] Sea area only.
[17] About to start, ongoing or complete.

				communities (e.g., stony reefs sensu JNCC).	

Table 4. Additional projects and products of interest.

Project name	Purpose[18]	Comments	Reference or link
https://odnature.naturalsciences.be/msfd/nl/monitoring/2020/#ANSBE-P9-Benthos-4-hard-substrate	National obligations (MFSD) + mapping methods & technical developments	As above	See link to project name

[18] Technical development, mapping methods, data management, novel map products etc.

Additional points of interest (optional): Please note comments in the previous boxes The MSFD monitoring programme I referred to above is strictly linked t that of Van Lancker et al. Focused specifically on seafloor integrity (D6) (https://odnature.naturalsciences.be/msfd/nl/monitoring/2020/#ANSBE-P5-Seabed-physical) – we work closely, attempting our best at synergy @ sea of the sedimentology and ecology research groups (needed toward seafloor modeling and habitat mapping).

ICES Working Group Marine Habitat Mapping: National Progress Report (2022-2023)

Table 1. National progress report (NRP) source and uploads.

Country:	Denmark
Organisation completing NPR:	DTU Aqua and GEUS
Map metadata uploaded into the ICES Geo-portal[19]:	NO
Cruise Summary Reports (CSR) uploaded[20]:	NO

Comments

[19] http://geo.ices.dk/geonetwork/srv/en/main.home
[20] Via either ICES or SeaDataNet

DTU Aqua and the Geological Institute of Greenland and Denmark (GEUS) are currently involved in a large habitat mapping project, called JAMBAY. This project is focussed on the Jammerbugt area in the Skagerrak, where intensive data collection and mapping of bathymetry, morphology, substrate types and habitat types; and modelling of broad-scale habitat types will form the basis of a broad-scale assessment of human impacts such as fisheries.

Table 2. New mapping infrastructure (significant items such as ships, sonars, ROVs etc.)

Item	Organisation/Location
EdgeTech 4205 Tri-Frequency / Motion Tolerant Side Scan Sonar System (120/410 kHz)	GEUS
BleuROV2	GEUS

Comments

Unknown

Table 3. Marine habitat mapping or modelling programmes.

Mapping programme	Purpose[21]	Location(s)[22]	Progress[23]	Comments	Reference or link
JAMBAY project	Habitat mapping and impact assessment	Jammerbugt Area, Skagerrak	Project ongoing	Mapping of bathymetry, morphology, substrate types and habitat types; and modelling of broad-scale habitat types.	Project leader: Grete Dinesen.
VELUX project 'Sustainability in Danish Waters'	Habitat mapping and impact assessment	Jammerbugt Area, Skagerrak	Project ongoing	Video recordings of substrate types and habitat types, and sampling of sediment and benthic fauna	Project leader: Ole Eigaard
National seabed mapping project (Danish EPA)	Seabed mapping for MSFD and MSPD	Four areas around Bornholm in the Baltic Sea	Project completed	Mapping of bathymetry, morphology, substrate types and habitat types; and modelling of broad-scale habitat types.	Project lead: Verner Brandbyge Ernstsen, GEUS
Coastal Life	Seabed	Løgstør Bredning	Project ongoing	Mapping of bathymetry,	Project lead: Verner

[21] Habitats, physical seabed features, pressures etc.
[22] Sea area only.
[23] About to start, ongoing or complete.

research project (EU-LIFE)	mapping for nature restoration	in Limfjorden		morphology, substrate types and habitat types; and modelling of broad-scale habitat types.	Brandbyge Ernstsen, GEUS

Table 4. Additional projects and products of interest.

Project name	Purpose[24]	Comments	Reference or link

Additional points of interest (optional):

ICES Working Group Marine Habitat Mapping: National Progress Report (2022-2023)

Table 1. National progress report (NRP) source and uploads.

[24] Technical development, mapping methods, data management, novel map products etc.

Country:	United Kingdom
Organisation completing NPR:	JNCC
Map metadata uploaded into the ICES Geo-portal[25]:	YES
Cruise Summary Reports (CSR) uploaded[26]:	NO

Comments

The following map metadata records have been uploaded into the ICES Geo-portal, and the maps added to the EMODnet Seabed Habitats data infrastructure and available via the EMODnet central portal

South West Strategic Regional Coastal Monitoring Programme EMSW01 - Portland Bill to Rame Head

South West Strategic Regional Coastal Monitoring Programme EMSW02 - Rame Head to Lands End

South West Strategic Regional Coastal Monitoring Programme EMSW03 - Lands End to Hartland Point

South West Strategic Regional Coastal Monitoring Programme EMSW04 - Hartland Point to Gloucester City

South West Strategic Regional Coastal Monitoring Programme EMSW05 - Isles of Scilly

North West Regional Monitoring Programme - Phase 1 Habitats

South East Regional Coastal Monitoring Programme Provision of Terrestrial Ecological Mapping Service. Work Package ESE01, Isle of Grain to Portland Bill

[25] http://geo.ices.dk/geonetwork/srv/en/main.home
[26] Via either ICES or SeaDataNet

North East Coastal Monitoring Programme 1940

2012 Cefas/EA MCZ Subtidal Verification Survey - Dover to Folkestone

Braemar Annex I Associated pockmark features

Scanner Annex I Associated pockmark features

Wight-Barfleur Reef BSH map

Wight-Barfleur Reef Annex I

Fladen Ground BSH

2013 Cefas Subtidal Verification Survey South Dorset MCZ

2013 Cefas Chesil Beach and Stennis Ledges MCZ Subtidal Verification Survey

Offshore Foreland rMCZ 2014 Survey Report Map

Cefas 2014 Continuation of baseline monitoring of reef features in the Wash and North Norfolk Coast SAC RP0785

2012 Cefas Subtidal Verification Survey Utopia rMCZ

South of Celtic Deep BSH

2014 Environment Agency EA Subtidal Verification Survey Coquet to St Marys rMCZ

Broadscale habitat (EUNIS level 3) for Skerries Bank and Surrounds designated Marine Conservation Zone (dMCZ)

South of the Isles of Scilly BSH

2012 North of Celtic Deep rMCZ Survey Habitat Map

Morte Platform BSH map

2011 Isles of Scilly Seagrass Mapping

South Wight SAC: Rocky Intertidal and Sea Cave Condition Assessment 2012 habitat map

2007 Marine Benthic Biotope Mapping of Sedimentary Environments, Lundy Marine Protected Area

2011 Natural England North West Region European Marine Sites Condition Monitoring of Littoral Features

Walney Channel AGDS and DDV Survey

2013 Tweed Estuary SAC Intertidal Biotope Survey

2013 Distribution and Extent of Zostera beds Roa Island and Foulney Island

Severn estuary intertidal biotope mapping baseline phase I study 2006 EMU ltd

2000 Cook Coral Cay Conservation Survey of the Fal Estuary

2014 Baseline habitat mapping of the Alde, Ore and Butley SAC

IECS North West Condition Assessment of Intertidal Mud and Sand Features

2015 Solent Maritime SAC subtidal sandbanks mapping and condition assessment MESL

2009 University of Brighton Intertidal IoW Sediment survey for the purpose of SSSI condition assessment

Solent Maritime SAC 2013 Vegetated Shingle

Table 2. New mapping infrastructure (significant items such as ships, sonars, ROVs etc.)

Item	Organisation/Location

Comments

Table 3. Marine habitat mapping or modelling programmes.

Mapping programme	Purpose[27]	Location(s)[28]	Progress[29]	Comments	Reference or link
Updating UK priority habitat compilations	To compile the best available data for OSPAR threatened and/or declining habitats, Habitats Directive Annex I habitats and nationally listed priority habitats.	All UK/ OSPAR	Ongoing	Work carried out by JNCC, Natural England, NRW, NatureScot, DAERA. The following datasets were updated in 2022/23: OSPAR T&D habitats database Updates to the following are in progress UK EUNIS Level 3 composite product Habitat of Conservation Importance layer in English offshore waters Habitats Directive Annex I Reefs layer	https://jncc.gov.uk/our-work/marine-habitat-mapping/
Marine Habitat Classification for Britain and Ireland	A national-scale reanalysis of thousands of seafloor samples to identify new biotopes to insert into the comprehensive classification system for the UK seabed.	All UK	Ongoing	The sublittoral sediment section of MHCBI was updated in 2022 and a new version of the classification published (22.04) with five new sublittoral sediment biotopes and several updates to the definitions of existing sublittoral sediment biotopes. Work is ongoing to review littoral sediment biotopes.	JNCC Marine Habitat Classification

Table 4. Additional projects and products of interest.

Project name	Purpose[30]	Comments	Reference or link
Habitat suitability modelling at national scale	Update to UK wide suitability models for Modiolus	Updated model has been produced and will be	

[27] Habitats, physical seabed features, pressures etc.
[28] Sea area only.
[29] About to start, ongoing or complete.
[30] Technical development, mapping methods, data management, novel map products etc.

	beds.	published shortly.	
Marine Restoration Potential project (MaRePo)	Proof-of-concept study which explores the habitat restoration potential of some key OSPAR threatened and declining (subtidal) marine habitats in English waters	Work lead by NE in conjunction with JNCC, Cefas and EA. Further work planed for 2023-24.	https://publications.naturalengland.org.uk/publication/6296202682040320
Marine Natural Capital Ecosystem Assessment project: Asset Service Matrix	Online tool that links ecosystem services to standardised list of marine habitats and species using EUNIS and OSPAR Threatened and declining species.	Tool works at various hierarchical levels using EUNIS and CICES as standard translation format.	https://www.marlin.ac.uk/asm
Marine Natural Capital Ecosystem Assessment project: UKSeaMap	Update to the UK's predictive seabed habitat map utilising recent developments to EUSeaMap and update to sediment mapping.	Updated model is in production due for release in April 2024.	

ICES Working Group Marine Habitat Mapping: National Progress Report (2022-2023)

Table 1. National progress report (NRP) source and uploads.

Country:	UK
Organisation completing NPR:	SEPA
Map metadata uploaded into the ICES Geo-portal[31]:	YES/NO
Cruise Summary Reports (CSR) uploaded[32]:	YES/NO

Comments

SEPA has been working in collaboration with the Scottish Government Marine Directorate on carrying out seabed mapping and habitat mapping work in the north of Orkney, in September 2023, where no previous multibeam has been carried out before. The habitat mapping will be used for marine planning primarily of Marine Pen Fish Farm developments. We carried out Multibeam Echo Sounding (MBES) at two sites in the Orkney Isles: off the north of Shapinsay (8.1 km^2) and in Pierowall Road and North Sound between Westray and Papa Westray (7.9 km^2). Bathymetry and backscatter data were collected from a hull mounted multibeam (Teledyne Reson Seabat T50-P single head system) on board

[31] http://geo.ices.dk/geonetwork/srv/en/main.home

[32] Via either ICES or SeaDataNet

the Alba na Mara. Drop frame video tows were completed throughout each site and were specifically placed to cover the variety of habitat types found at each site that were at a workable depth and distance to shore.

The bathymetry and backscatter data wil be post-processed using industry standard software and the video data will be analysed to as a high a level as possible given the quality of the data. We will develop habitat maps in due course using a manual method and will overlay the biotopes allocated to each photograph.

The bathymetry data will be supplied to the UK Centre for Seabed Mapping once processed and likewise, the analysis of the videos will be sent to DASSH or put directly onto Marine Recorder and the habitat map to EMODnet. SEPA can also supply the map metadata to the ICES Geo-portal and can upload the cruise summary report.

Table 2. New mapping infrastructure (significant items such as ships, sonars, ROVs etc.)

Item	Organisation/Location

Table 3. Marine habitat mapping or modelling programmes.

Mapping programme	Purpose[33]	Location(s)[34]	Progress[35]	Comments	Reference or link

Table 4. Additional projects and products of interest.

Project name	Purpose[36]	Comments	Reference or link

Additional points of interest (optional):

[33] Habitats, physical seabed features, pressures etc.
[34] Sea area only.
[35] About to start, ongoing or complete.
[36] Technical development, mapping methods, data management, novel map products etc.

ICES Working Group Marine Habitat Mapping: National Progress Report (2022-2023)

Table 1. National progress report (NRP) source and uploads.

Country: Spain	
Organisation completing NPR: IEO-CSIC	
Map metadata uploaded into the ICES Geo-portal[37]:	NO
Cruise Summary Reports (CSR) uploaded[38]:	No

Comments

Spain is developping an intense effort to increase the mapping of marine habitats in its EEZ. This effort involves several institutions (e.g. Instituto hidrográfico de la marina, Instituto Geológico Minero, Secretaría General de Pesca, Instituto Español de Oceanografía) but unfortunately this effort is not centralize and the different data product are usually spread across different respositories with different level of acces. Because of this is very difficult to really have a clear image on the progress done during the last year o years.

[37] http://geo.ices.dk/geonetwork/srv/en/main.home
[38] Via either ICES or SeaDataNet

Table 2. New mapping infrastructure (significant items such as ships, sonars, ROVs etc.)

Item	Organisation/Location

<u>Comments</u>

Table 3. Marine habitat mapping or modelling programmes.

Mapping programme	Purpose[39]	Location(s)[40]	Progress[41]	Comments	Reference or link

Table 4. Additional projects and products of interest.

Project name	Purpose[42]	Comments	Reference or link

Additional points of interest (optional):

[39] Habitats, physical seabed features, pressures etc.
[40] Sea area only.
[41] About to start, ongoing or complete.
[42] Technical development, mapping methods, data management, novel map products etc.

ICES Working Group Marine Habitat Mapping: National Progress Report (2022-2023)

Table 1. National progress report (NRP) source and uploads.

Country:	Iceland
Organisation completing NPR:	MFRI
Map metadata uploaded into the ICES Geo-portal[43]:	Partially
Cruise Summary Reports (CSR) uploaded[44]:	Partially

Comments

Table 2. New mapping infrastructure (significant items such as ships, sonars, ROVs etc.)

Item	Organisation/Location

[43] http://geo.ices.dk/geonetwork/srv/en/main.home
[44] Via either ICES or SeaDataNet

Comments

Table 3. Marine habitat mapping or modelling programmes.

Mapping programme	Purpose[45]	Location(s)[46]	Progress[47]	Comments	Reference or link
Iceland multibeam mapping programme	Bathymetry and backscatter maps	Iceland EEZ	2000 – 2021: 39.000 km2 (40,5% of EEZ) 2000 – 2022: 28.000 km2 (44,3% of EEZ) 2000 – 2023: 13.000 km2 (46,0% of EEZ)		https://www.hafogvatn.is/is/rannsoknir/kortlagning-hafsbotnsins

Table 4. Additional projects and products of interest.

Project name	Purpose[48]	Comments	Reference or link

Additional points of interest (optional):

[45] Habitats, physical seabed features, pressures etc.
[46] Sea area only.
[47] About to start, ongoing or complete.
[48] Technical development, mapping methods, data management, novel map products etc.