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Working Group on Marine Habitat Mapping (WGMHM)

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WORKING GROUP ON MARINE HABITAT MAPPING (WGMHM)

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Contents

i Executive summary

The 2019 meeting of the Working Group on Marine Habitat Mapping (WGMHM) was held jointly with the Working Group on Deepwater Ecology (WGDEC). The primary objective for the WGMHM was to provide information and guidance on how Predictive Habitat Model (PHM) techniques can support the work of ICES, and specially the WGDEC, on the estimation of where Vulnerable Marine Ecosystems (VMEs) are likely to occur in the North Atlantic (see WGMHM work plan for year 2).

The main recommendations and outputs from WGMHM to WGDEC are: (i) the use of carefully-executed PHMs represents the best possible evidence for assessing the likely distribution of these features when compared with the current methods for plotting point observations of VMEs (which are generally grossly under-sampled); (ii) a WGMHM report describes the background, use and caveats of using PHM for estimations of VME distribution; (iii) detailed advice on the extraction and use of predictor variables that are likely to be relevant for VME prediction; and (iv) a 'roadmap' for implementing the PHM. The guidance produced represents a significant step forward towards the adoption of PHM for estimating the distribution of VMEs and providing more robust evidence for assessing the overlap between VMEs and other human activities.

Having highlighted the value of predictive habitat modelling, the roadmap clearly defines the steps required for the implementation of these techniques. These steps include: (i) generating a specification for the modelled outputs so that clear thresholds of resolution and accuracy constrain the modelling process; (ii) both WGDEC and WGMHM work together again in 2020 to produce a method for modelling VMEs (i.e. agreeing on sources of data for both response and predictor variables, PHM techniques and required validation steps for the modelled outputs); (iii) conduct a trial run for a small number of models to ensure that both the approach and outputs are fit-for-purpose; and (iv) a period of review to ensure the compatibility of the outputs with subsequent advice drafting analyses.

ii Expert group information

Expert group name	Working Group on Marine Habitat Mapping (WGMHM)
Expert group cycle	Multiannual fixed term
Year cycle started	2018
Reporting year in cycle	2/3
Chair	James Asa Strong (UK)
Meeting venue(s) and dates	3–7 June 2019, Esporles, Mallorca, Spain (4 participants plus additional input from WGDEC members)

1 Using species and habitat distribution modelling to support the management of vulnerable marine ecosystems (VMEs)

Background

In 2018, the WGDEC was asked to prepare spatial layers and a list of areas where VMEs occur, or are likely to occur, in the Northeast Atlantic. This work was requested to support ICES advice to the European Commission with respect to implementation of the deep-sea access regulations (EU 2016/2336). Products delivered by WGDEC include maps of known VME occurrences using data from the ICES VME database[1], supplemented with data from peer reviewed literature and the OSPAR 2015 database[2]. To identify areas where VMEs are likely to occur, WGDEC used the outputs of the VME weighting algorithm, according to the VME Index (ICES, 2018).

Following a review of the evidence provided by WGDEC by the Review Group on Vulnerable Marine Ecosystems (RGVME), it was noted that the VME Index and habitat observations within the maps presented were very scattered and sparse, meaning an overlap with the fisheries footprint data would be challenging. The RGVME recommended that Predictive Habitat Modelling (PHM) (i.e. geo-statistical modelling techniques that produce predicted probability surfaces for VMEs) should be investigated by WGDEC to support their future deliverables. Furthermore, the RGVME proposed that PHM could also be used to provide a fuller representation of 'suitable habitat' or potential VME distribution in EU waters, to support the European Commission MoU request to provide new data on habitats sensitive to particular fishing activities within EU waters.

To implement these recommendations, WGDEC 2019 was organised as a joint meeting with the WGMHM – the latter also having necessary expertise to support habitat mapping and modelling work. The joint 2019 meeting aimed to examine the implementation of PHM to estimate the potential distribution of VMEs in the North Atlantic. The use of PHM has also been highlighted by WGDEC before. In their 2009 report, WGDEC recommended that in the absence of reliable widespread biological sampling, to approximate species distributions, the use of PHMs should be explored. However, the group stopped short of adopting use of these models in their advice-making process. In 2014 WGDEC revisited this subject, and reviewed the state-of-the-art in high resolution 'terrain-based models' for predicting VME distribution. The WGDEC report concluded the following:

1. Published (and therefore peer reviewed) predictive models of the distribution of VMEs or VME indicator species should be taken into consideration in management decisions regarding human use of the deep-sea ecosystem.
2. Predictive models based on high resolution multibeam bathymetry data offer finer resolution predictive models (maps of VME suitable areas) that can be used to inform the provision of advice on spatial use of the deep-sea ecosystem.

[1] https://www.ices.dk/marine-data/data-portals/Pages/vulnerable-marine-ecosystems.aspx

[2] https://www.ospar.org/work-areas/bdc/species-habitats/mapping-habitats-on-the-ospar-list-of-threatened-or-declining-species-and-habitats

3. In regions where published predictive models indicate a high likelihood of VME presence WGDEC suggest survey effort is required to discount presence in order to implement a bottom contact fishery.

Despite these conclusions, WGDEC have not used PHMs (also called habitat suitability models) in their advice drafting process to-date. This year the WGMHM discussed how PHM might be bought into the decision-making process and providing document to support this implementation.

2 Advice to WGDEC on the use of predictive modelling of species and habitat to support the management of vulnerable marine ecosystems

Purpose

The purpose of this document is to provide information and guidance on how predictive habitat model (PHM) techniques can support the work of ICES and its working groups (specifically WGDEC) on the estimation of 'where VMEs are likely to occur' in the North Atlantic. The document will highlight:

(i) why predictive habitat modelling techniques were recommended for representing where VMEs are likely to occur;
(ii) a brief review of suitable modelling techniques for VMEs including examples of peer-reviewed case studies;
(iii) a clear statement of the limitations of predictive habitat modelling;
(iv) advice on the use of modelled outputs for the management of VME;
(v) recommendations on how to improve the outputs from predictive habitat models used for VME management.

Introduction to Predictive Habitat Models (PHM)

Predictive habitat models (PHMs, also known as habitat suitability models, species distribution models or environmental niche models) are models that predict the likely distribution of a species or habitat using environmental variables as predictors. PHMs are widely used in conservation ecology and environmental management, but their application to deep-sea environment is relatively new (e.g. (Vierod *et al.*, 2014)). Given the wide distribution and the lack of extensive biological data on deep-sea communities, the potential for PHMs to 'fill the data gap' in this poorly-sampled ecosystem has obvious appeal. PHMs are increasingly recognised as an effective way to obtain knowledge on the likely distribution of VMEs or VME indicator taxa (Vierod *et al.*, 2014; Clark *et al.*, 2015) which maximises the use of available data and provides a defensible method for producing complete coverage distribution maps on which to base management decisions (ICES, 2014). Several studies have used PHMs to predict the distribution of VMEs (Howell *et al.*, 2011, 2016) and of VME indicator taxa (e.g. Davies and Guinotte, 2011; Yesson *et al.*, 2012; Rengstorf *et al.*, 2013; Ross and Howell, 2013; Guinotte and Davies, 2014; Anderson *et al.*, 2016a; Buhl-Mortensen *et al.*, 2019). PHMs are increasingly being used for designing management tools to protect VMEs from fishing impacts (Ardron *et al.*, 2014; Vierod *et al.*, 2014), including for evaluating the risk of fishing impacts (Penney and Guinotte, 2013) and selecting spatial closures (Lagasse *et al.*, 2015; Rowden *et al.*, 2019).

It is highly likely that full coverage products provide the most effective evidence base on which to conduct management-orientated analyses of VME distribution and pressure overlap. Nevertheless, PHMs are not a replacement for dedicated field studies using underwater images and other methods. Instead, they should be considered as an integral part of an iterative process where the models are used to summarise and aggregate present data on ocean conditions and distribution of VMEs and VME indicator taxa, to inform management decision taking into account the uncertainty of the model output, and to guide new exploration and scientific efforts that in turn provide data for updated models.

Why use predictive modelling techniques for estimating where VMEs are likely to occur?

The process for the protection of VMEs involves: (i) the identification of areas containing or likely to contain VMEs; (ii) an overlap analysis of the VME footprint with fishing effort (from vessel monitoring system (VMS) data); (iii) exclusion of areas in the 'reference area'; and (iv) recommendation of closed areas for fished VMEs not already covered by an exclusion.

The current method for representing the presence of VMEs relies on the use of point observations (so called *bona fide* habitat records). The current method for representing where VMEs are highly likely to occur is provided by indicator points (observations not qualifying as presence values but attaining a certain threshold within the ICES 'weighted algorithm'). WGDEC use VME indicators to calculate a vulnerability index (Morato *et al.*, 2018), which is ultimately classified in low, medium and high vulnerability index classes.

The indicator values are provided as point observations that are subsequently gridded into c-squares (0.05 x 0.05 degree). In many areas, the coverage of VME indicator points is extremely sparse, which hampers the interpretation of where VMEs are likely to occur. A recent assessment of the WGDEC VME database by the Review Group Vulnerable Marine Ecosystems, suggested that use of VME indicator points, gridded into a c-square grid, did not lend itself to the interpretation of where VMEs are likely to occur. This in turn compromises the efficacy of the protection process. It was clear to the Review Group that the VMEs were often associated with bathymetric and geomorphological features. As such, the Review Group recommended the used of PHM techniques to extrapolate VME indicator information and get full coverage predictions for where VMEs are likely to occur. The Review Group emphasised that PHMs identify suitable or potential habitat rather than VME presence – this important point indicates that these modelling techniques are only suitable for supporting the estimation of where VMEs are likely to occur.

It is the opinion of both WGMHM and WGDEC that PHM, which meet specific quality thresholds (the 'ICES VME PHM Specification'), represents the best available evidence for estimating where VMEs are likely to occur at a broad scale. The existing method that is based on grid point observations fails to fully exploit the data and overlooks established and trusted methods for spatial extrapolation supported by geo-statistical methods. Consequently, existing management advice is biased towards observed (the very small number of areas surveyed annual) or fished areas (via the reporting of trawl bycatch). This bias fails to adequately represent the distribution of VMEs (diminishing the conservation advice for these features) and may unfairly impact on fished areas.

Strategies for VME modelling using predictive habitat modelling

Most deep-sea VME models published to this date have used "presence-only" approaches, because much of the available data on VMEs and VME indicator taxa consists only on records of presence or occurrence, often from different sources and sampling techniques. The most popular modelling algorithm is MaxEnt (maximum entropy) (Davies and Guinotte, 2011; Rengstorf *et al.*, 2012; Georgian *et al.*, 2014), which is considered to outperform other presence-only methods (Elith *et al.*, 2006). Other methods include ENFA (Ecological-Niche Factor Analysis, (Davies *et al.*, 2008)) and GARP (Genetic Algorithm for Rule Set Production modelling (Guinan *et al.*, 2009)). If reliable absence data is available (usually from standardised bottom trawl surveys or underwater image surveys), it is possible to use "presence-absence" approaches that tend to produce more accurate predictions. These approaches include Random Forests (Kenchington *et al.*, 2014;

Beazley *et al.*, 2015; Anderson *et al.*, 2016b), Boosted Regression Trees (Tracey *et al.*, 2011), Generalised Linear Models (GLMs, (Woodby *et al.*, 2009; Huff *et al.*, 2013)) Generalised Additive Models (GAMs, e.g. (Ross and Howell, 2013; Sigler *et al.*, 2015; Rooper *et al.*, 2016)). In addition, models that incorporate a quantitative measure of abundance or density (e.g. by-catch weight, or estimated density of organism from underwater images) can be used more directly to predict the distribution of high concentrations of VME indicator taxa. This latter approach is used in the NAFO area where bottom trawl surveys provide data on the by-catch of VME indicator taxa (Froján *et al.*, 2015).

Predictive modelling of VMEs can be achieved following different strategies (Howell *et al.*, 2016). If the habitat is dominated by a single species (e.g. *Lophelia pertusa* reefs), two approaches have been used. First, it is possible to model the distribution of the species itself (Davies *et al.*, 2008; Georgian *et al.*, 2014; Etnoyer *et al.*, 2018) using all occurrence records. Secondly, it is possible to model the presence of the habitat (Howell *et al.*, 2011; Ross *et al.*, 2015). This latter approach is usually done in cases where the presence of the habitat has been identified either from underwater images or from trawl catches. In some cases, when both approaches have been compared, the predicted distribution of the VME itself is a subset of the distribution of the species (Howell *et al.*, 2011, 2016; Rengstorf *et al.*, 2013). This is the case if the presence of the VME is defined by a set of environmental factors more restrictive than for the entire species. However, this is not always the case. One illustrating example are the seapen field models produced by Knudby *et al.* (2013), which did not predict occurrences of VME to exist outside of the known locations. Knudby *et al.* (2013) suggested that the distribution of these significant concentrations of seapens are not determined by the environmental variables included in the model, and could arise from stochastic biological processes related to recruitment.

If the VME is defined by the presence of a biotope or community (e.g. coral gardens), an array of different modelling strategies are available to model their distribution (D'Amen *et al.*, 2017). When modelling VMEs, a commonly used approach is first to identify the presence of the biotope through the ordination analysis of data derived from underwater images, and then model the distribution of the biotope. This is the approach followed by the MAREANO project in Norway (Gonzalez-Mirelis and Buhl-Mortensen, 2015), and follows the "assemble first, predict later" strategy (D'Amen *et al.*, 2017).

An alternative approach is to model the distribution of the individual species that characterise the biotope, and then combine the predictions to highlight areas of overlap that could indicate the potential distribution of the assemblage (Ferrier and Guisan, 2006; Howell *et al.*, 2016). This is an example of the "predict first, assemble later" strategy (D'Amen *et al.*, 2017), and has been used occasionally to model the distribution of VMEs (Howell *et al.*, 2016). It is also possible to predict the distribution of a biotope by including in a single model occurrence records of multiple indicator taxa (Buhl-Mortensen *et al.*, 2019). Modelling the distribution of individual species has the advantage that allows for each species to have distinct responses to environmental predictors, and has the potential ability to combine species distribution models derived from different survey dataset (Ferrier and Guisan, 2006). It also has the key advantage that it does not requires that all the observations of species from the same biotope are concurrent. The latter is important when modelling deep-sea benthic megafauna in areas where the majority of records originated from fisheries bycatch and from scientific surveys using gear with relatively low sampling efficiency like dredges or bottom trawls (as opposed to underwater video surveys, which provide a more complete description of the benthic megafauna in a particular location).

3 Limitations, assumptions and common issues associated with predictive habitat modelling

An introductory warning about modelled map products

It is effectively impossible to produce a map that is completely accurate and satisfies the needs of all (Brown *et al.*, 1999). Due to the high quality of terrestrial maps, map users have become accustomed to assuming that maps (modelled surfaces) show the location and thematic properties of objects accurately. As such, maps are often ingested without concern for their quality or accuracy. However, shortcomings in the collection of seabed observations (training data and predictor variables) as well as the approximation of relationships between predictor and response variables act to significantly reduce the accuracy of modelled seabed species and habitats. Despite this, modelled surfaces may still appear superficially convincing but it must be remembered that model quality cannot be assessed visually. Only through assessments of model accuracy (uncertainty assessments such as cross-validation) can the quality, and hence fitness for purpose, of a modelled output be assessed.

Check that spatial autocorrelation has be effectively addressed

Spatial autocorrelation is the tendency for a variable to be correlated with itself through space (i.e. things that are near tend to be similar), and is a common property in geographic data sets (Vierod *et al.*, 2014). The presence of spatial autocorrelation within a data set diminishes the independence of individual observations and therefore violates the statistical assumptions underpinning most modelling methods. Although spatial autocorrelation is typically present in most data sets, many modelled maps often fail to tackle or completely reduce its influence (Dormann, 2007). This can be particularly relevant in the case of deep-sea modelling studies that often rely on seabed observations that are heavily clustered. When this is not accounted for, the explanatory power of predictor variables may be distorted (Lennon, 2000), predictions biased (Dormann, 2007; Segurado *et al.*, 2006) and the statistics that are commonly used to measure model performance can be artificially inflated (Araújo *et al.*, 2005; Hijmans, 2012; Seguradoetal.,2006; Veloz, 2009). As such, it is critical that assurances are sought, from the method or model producer, that spatial autocorrelation has been tracked adequately within the production of the map.

The prediction of potential rather than realised habitat

The vast majority of models predict potential habitat (also termed suitable habitat) and not presence (aka occupied or realised habitat). Seabed observations of species or biotopes are only provided by point (e.g., grab or photographic still) or line (e.g., video transect) sampling. The continuous distribution of these features is then predicted using PHM, meaning that the resulting distribution is an extrapolated product not fully supported by direct observation. Furthermore, the predictor variables typically used to model the distribution of these biotopes also fail to represent all of the influential factors including biological processes such as competition, predation, and dispersal (Brown *et al.*, 2011). As such, one is modelling 'potential' habitat for that species, which may or may not be occupied by the species.

Broad-scale model outputs are prone to bias and are harder to validate accurately

Modelling large geographic areas results in the inclusion of a wide range of environmental values. Depending on the modelling approach used, this breath of variable ranges can result in more generalised predictions (VanDerWal *et al.*, 2009) and less informative outputs (Vierod *et al.*, 2014). Equally, the combination of poorer geo-referencing of seabed observations in deep water and coarse resolution of predicted surfaces can hamper the validation process. The potential for the over-prediction of features within certain broad-scale models and uncertainty within the validation process should be carefully considered when interpreting broad-scale VME models.

Model accuracy will generally be lower for deep-water and broad-scale spatial models

It is generally accepted that the deep sea is a data-poor environment. The cost and effort required to collect seabed observations in deep water is great and this results in both a poor distribution of observations (and spatially correlated data) and a very low density of observations across the area of interest. Furthermore, observation errors, which are the product of shortfalls in data collection for both the predictor and response variables, will be more prevalent in deep-water and broad-scale models (Vierod *et al.*, 2014). Once again, the precision of geo-referencing of seabed observations in deep water environments is likely to be poor, which may have an effect on the model prediction (Moudry and Šímová, 2012). The error inherent in the interpolations used to convert low density point observations into surfaces of predictor variables is also great. Expectations of modelled accuracy for deep-water species and habitats modelled over large distances must be realistic yet sufficient for them to be fit for purpose and confidently applied.

Low resolution models alter the reporting of habitat units

A decrease in resolution will refer to an increase in the dimensions of individual units, hence increasing the coarseness and graininess of representation. Resolution has a profound influence on the ability to represent the modelled extent of a species or habitat. The resolution used during sampling dictates the size of the habitat unit that can be detected. As resolution decreases, a greater proportion of the spatial heterogeneity is contained within a sampled unit and is therefore lost to the sampling resolution, whilst variance within map units increases. Analysis of the influence of spatial resolution reveals some other basic trends. As the resolution decreases (fine to coarse), individual predicted patches that are smaller than the resolution fail to be identified. If there is some consistency to the size of habitat patches within the modelling domain, a degradation in modelling resolution can result in the sudden loss of predicted areas from a map at certain resolution thresholds (specific to individual species and habitats). This results in unpredictable or step-change inaccuracies within the representation of modelled features and poor landscape metrics (Wu *et al.*, 2002). Analysis of these issues using real data confirmed that the values used to characterise landscape pattern, such as the number, total extent and spatial pattern of different habitat patches, will change when resolution and/or survey coverage is altered (Wu *et al.*, 2002).

Connectivity between habitat patches also enlarges with increasing sampling resolution, i.e. patches aggregate artificially as the resolution is decreased. This loss of information is greatest for complex landscapes and those with small average patch sizes, hence the landscape metrics are influenced by both the underlying complexity of the landscape and the sampling resolution. Recent studies from the deep-sea environment have highlighted an overall trend toward better model performance with increasing environmental data resolution, with significant differences in performance found between models of different resolution (Marshall, 2010; Rengstorf *et al.*, 2012). Interpreters of modelled outputs must consider the relationship between the inherent patch size of the modelled species or habitat and the resolution used for the modelling exercise. It is the responsibility of the interpreter to ensure the resolution of the modelled outputs are fit for purpose.

VME models tend to be presence-only models, which are typically poorer than presence and absence and quantitative models used in data rich environments

Verified absence data for deep-water species and habitat (e.g. VMEs) is typically not recorded or generated, i.e. the locations where an appropriate amount of survey effort has not found specific species of interest. Absence information can be reconstructed from survey metadata but this has not been undertaken for enough data sets to allow the modeller to use presence and absence modelling techniques for VME species, assemblages or habitats. Consequently, modelling approaches for VMEs typically use a presence & pseudo-absence or presence & background approaches. There are several methods for generating pseudo-absence and background data, such as designating absence status to other species records that are known not to co-occur with the modelled species, or to use randomly placed points through the modelled domain (but often buffered away from presence observations). In these situations, it is difficult to ensure that pseudo-absence and background points truly represent absences. This assumption is further complicated by the fact that models predict potential habitat and therefore artificial absence points that fall within areas lacking the species of interest cannot be assumed to also be outside the envelop of suitable habitat. As such, models relying on pseudo-absence and background data are more uncertain than those using observed absence data. It has been demonstrated that deep-water models relying on randomly distributed background points can artificially inflate the 'area under the curve' value (Vierod *et al.*, 2014) and the predicted distribution (VanDerWal *et al.*, 2009). The relative proportion of presence to pseudo-absence or background observations is also important. It is important that the model producer states: (i) how absence data were generated; (ii) how many absence points were included in comparison to the number of presence points; and (iii) any implications of the absence data method on overlap map accuracy and interpretability.

Interpreting modelled predictions for the distribution of VMEs

Before starting the interpretation, the user must: (i) understand the caveats and assumptions inherent in the modelling method; (ii) possess both the modelled outputs and the uncertainty information (summary statistics for the whole model and spatial assessments of agreement/accuracy); and (iii) have clearly defined the purpose of the interpretation exercise and therefore model accuracy required for the inputs to be 'fit for purpose'.

The need for transparency, transferability, and repeatability

PHMs are relatively complex. During the development of a PHM, several decisions have to be taken including the selection of modelling framework, occurrence data, environmental predictors, model resolution, tuning parameters, etc. In this way, PHMs are analogous to stock assessment models. It is necessary then that the modelling process is documented in such a way that the model is transparent, transferable and repeatable (Borregaard and Hart, 2016). Recently ICES has developed the Transparent Assessment Framework (TAF) to achieve this goal with the stock assessment models used in fishery management. We recommend that PHMs are also developed within this framework, potentially in conjunction with existing tools for reproducible PHMs (e.g. (Naimi and Araújo, 2016; Golding *et al.*, 2017; Kass *et al.*, 2018)). Environmental predictors should also be available in repositories.

4 Extracting predictor variables from spatially-explicit dynamic models

Among the several PHMs that have been created for deep sea habitats and species, there is a notable lack of potentially-useful predictor variables that can be extracted from spatially-explicit dynamic models (SEDMs). This section describes (i) what are SEDMs and why they are relevant to VMEs, (ii) variables that may be extracted from SEDMs, (iii) linking variables in time and space, (iv) limitations and (v) recommendations for the use of SEDMs for PHM.

What is spatially-explicit dynamic modelling and what is the relevance?

Examples of SEDMs include 2D or 3D hydrodynamic models mimicking ocean current speed and directions (horizontal and vertical), water temperature and salinity, and ecosystem models that are built on top of hydro-dynamic models to simulate ecological and biological processes in the water column. While water temperature, salinity and water currents may directly affect the VMEs in deep sea habitats, the focus of ecosystem models is typically the ecological and biological processes in the most upper parts of the water column including the photic zone and its vicinity. Nevertheless, biological processes such as primary production in the photic zone eventually contribute to the flux of organic carbon to the seafloor and hence supporting the presence, production and abundance of benthic organisms and communities in deeper part of the ocean (e.g. Loubere and Fariduddin, 1999; Anderson *et al.*, 2016). Carbon flux quality and quantity integrated over time along the sea floor can be highly variable in space and time and are dependent on often complex hydrographic and ecological condition which can be described using SEDMs in various scales. Figure 1below, shows an example of a modelling study of the vertical current velocities and carbon concentrations during the tidal cycles in an area with cold water corals in the North Atlantic (Soetaert *et al.*, 2016).

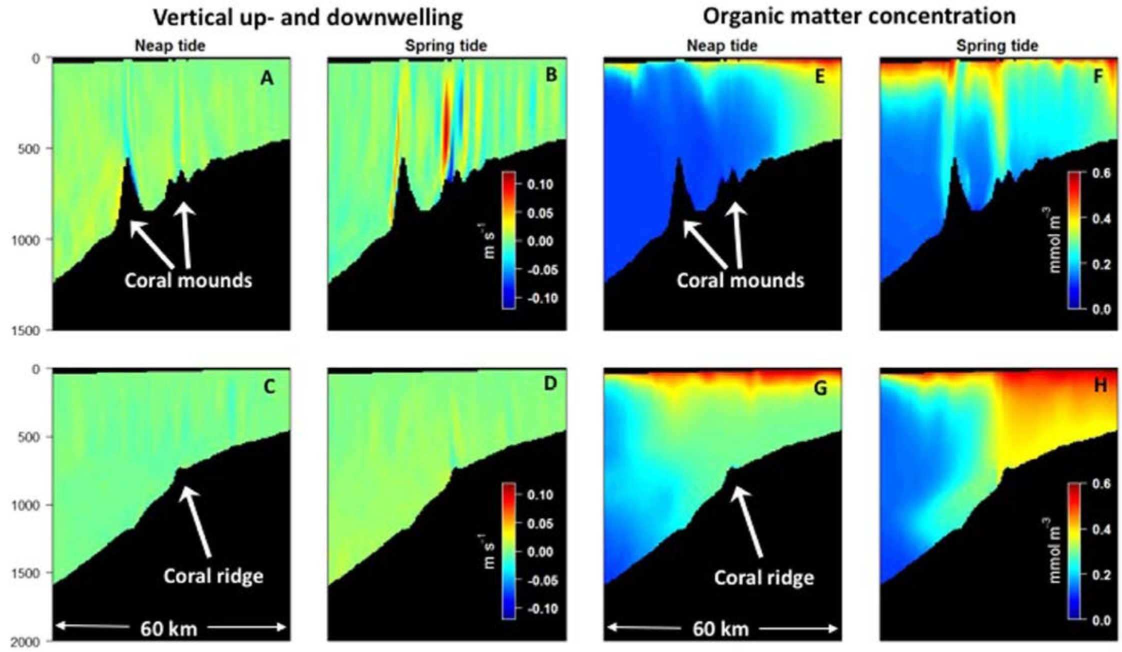

Figure 1. Reference: Figure 3 in Soetart *et al.* 2016. "Model output of vertical current velocities (A–D) and organic matter concentration in the water column (E–H) along the coral mound (A,B,E,F) and coral ridge transect (C,D,G,H) during neap and springtide."

Hydrodynamic processes driving the flux of organic matter produced in the photic zone to the seabed sustaining the presence and production of VMEs, such as cold water corals (CWCs), have been suggested by several studies.(e.g. Kiriakolulakis *et al.* 2005, 2007, White *et al.* 2005, Knudby *et al.* 2013, Mohn *et al.* 2014, Soetart *et al.* 2016). White *et al.* 2005 presented a conceptual model suggesting deep sea water motion around seabed ridges and coral mounds may increase turbulence and mixing of the water column above and along these seabed structures. As a result, nutrient rich water may be forced towards the surface sustaining an increase in photic zone productivity and at the same time increasing the vertical downward transport of organic material produced in the photic zone to the seabed elevating the food source flux to CWCs. These processes have been supported by other studies. As an example Kiriakolulakis *et al.* (2005, 2007) found elevated fluxes of fresh lipid rich organic matter originating from photic zone to the deep locations of CWCs using analysis of molecular components of suspended organic matter. In deep sea habitats the hydrodynamic processes involved are predominantly driven by tidal water movements in terms of internal tidal waves interacting with sea bed topography, or by oceanographic disturbances such as fronts or storms creating "inertial" water motions (van Haren and Gostiaux 2012). Internal tidal wave heights of e.g. 10–100 m (with low frequency and long periods) can induce strong turbulence when interacting with seabed topography and support both vertical mixing events as well as sediment resuspension. Mohn *et al.* (2014) extracted explanatory variables from a high resolution hydrodynamic models (250–750 m horizontal resolution) of 3 sites in the North East Atlantic comprising CWCs habitats ranging from 500–1000 m depths. They found a clear coupling between the presence of CWCs and the energetic near bottom flow dynamics largely controlled by tide-topography interaction generating and enhancing periodic motions such as trapped waves, freely propagating internal tides and internal hydraulic jumps. Elevated energy levels found at locations of CWCs presence compared to location with no presence, suggests that flow interaction with topography supports vertical mixing locally and is likely an important food supply mechanisms to CWCs. Outputs from global and regional SEDMs have been made available through the EU Copernicus Marine Environmental Monitoring Service[3] and simulated variables are typically stored as daily means. These models are calibrated and validated. Explanatory variables for PHM predicting VMEs in deeper parts of the ocean may be extracted from this type of dynamic models potentially improving the predictive ability of PHMs. The use of explanatory variables extracted from dynamic models as input to PHMs is not new and have been included in many PHMs of marine species such as marine benthos, fish, marine mammals and seabirds (e.g. Skov and Thomsen, 2008; Reiss *et al.*, 2011; Reiss *et al.*, 2014; Skov *et al.*, 2014; Gilles *et al.*, 2016; Heinänen *et al.*, 2018), but most of these studies have been conducted in shallow water systems.

Although data derived from SEDMs may potentially improve the predictability of PHM in general and specifically for VMEs, the task is not trivial and requires insight into a number of issues in relation to quality, accuracy and potential biases of the data, and the original scope of the dynamic model including resolution, parameterisation and calibration of the model. In general dynamic models are calibrated to meet some calibration criterion that are tightly linked to the application of the model, e.g. a hydrodynamic model can be calibrated to describe and predict water level (when used for flood risk assessment) or it can be calibrated to describe the vertical stratification in order to support an ecosystem model predicting primary production and the timing of algae blooms. Sometimes, there is a trade-off between such calibration criteria and one calibration supporting one criteria with high performance e.g. prediction of water level, may fail to perform well in general or in parts of the model domain when validated on vertical stratification and vice versa. Model resolution of the computational grid are also often tightly linked to the original application of the model and may impose limitations on the quality of the data with respect to providing explanatory variables for models predicting VMEs.

While the extraction of explanatory variables from SEDMs can be done relatively easy from data available from e.g. the Copernicus website, these data are typically only available at coarse scales (~ 10 km grid resolution or more) and considerations on scaling issues as described in the earlier section in this document on low resolution PHM equally apply to SEDM derived explanatory variables. SEDMs customised specifically for the purpose of providing high resolution and more accurate predictor variables for PHM of VMEs (like Mohn *et al.* 2014), can add considerable predictive power to these models, however this is not very often done. Although it will require collaboration with physical and/or biological oceanographers as part of the research projects it may be worthwhile considering. Rescaling, adjusting and calibrating a part of a regional model (available from Copernicus or another data provider) to reflect e.g. a higher resolution for a study area is not a major task for an experienced modeller.

[3] marine.copernicus.eu

Types of variables that can be considered

Examples of types of variables that can be extracted from a 3D hydrodynamic model and that may be relevant for deep sea VMEs include:

- Water temperature Salinity Currents (speed and direction)
  - Horizontal current speed (mean, max)
  - Current stability ("mean velocity"/"mean current speed")
  - Current gradients/fronts (vorticity)
  - Vertical currents (mean, downwelling)
- Internal wave reflection on bottom topography
  - Maximum resonance frequency
  - Internal tide slope parameter
  - Tidal excursion inverse froude number
  - Vertical displacement scale

While current speed, temperature and salinity can be easily extracted from SEDMs, Horizontal and or vertical fronts which are often associated with high productive areas in the photic zone can be retrieved by computing the gradients of current speed (i.e. vorticity), temperature and/or salinity. In absence of data from an ecosystem model vorticity may serve as a good proxy for high productive areas as well as areas with an elevated carbon flux to the seabed.

The internal wave reflection on seabed topography particularly relevant for VMEs associated with sloping and complex bathymetry of deep sea habitats, can be represented by a number of derived variables, and can be calculated and mapped from the hydrodynamic models as described in Mohn *et al.* (2014).

Having access to data from ecosystem models, simulated data such as carbon flux to and along the seabed in both shallow and deeper parts of the oceans can be extracted. Some models may provide additional information on the quality of the carbon flux such as decomposition stages, lipid content, and/or the N, P and Si contents.

Examples of VME explanatory variables that may be extracted from ecosystem models include:

- Dissolved oxygen
- pH
- Inorganic nitrogen (NO_3 NO_4)
- Dissolved inorganic phosphorus
- Particulate inorganic phosphorous
- Dissolved and particulate organic matter (C, N, P)
- Particulate inorganic matter and particle size distribution
- Calcium carbonates

In the absence of ecosystem model data, explanatory variables such as carbon flux to the deeper ocean may be roughly estimated by combining satellite derived chlorophyll-a concentrations and hydrodynamic model results, and applying a simple sedimentation/decomposition model. However, since satellite-derived chlorophyll concentrations do not include subsurface primary production located in the boundary layer of a stratified water column, the use of such data caution must be taken depending on the ecosystem considered. Linking observations in time and space to dynamic modelling output

In some PHMs, environmental variables may be represented in a somewhat simplistic manner, e.g. by representing bottom temperatures as monthly, quarterly or annual averages or other statistics and in a gridded aggregation. The use of this type of statistics assume some sort of steady state of the monitored response variables such as presence-only, presence/absence or abundance which may be reasonable for reef building species and for species and communities in relatively stable or repetitive fluctuating environments. For some deep sea species or habitats, however, both presence-only, presence/absence and abundance (density and biomass) may vary considerably in time (within and between years) due to e.g. varying and irregular event based supply of organic matter, oxygen depletion and physical disturbances (e.g. Gooday and Rathburne 1999, Kahn *et al.* 2012). In such cases a more meaningful representation of explanatory variables may be achieved by extracting the explanatory variables from the SEDM at the exact location and time of each VME observation (ideally observations of both presence/absence, and abundance). For each such location, statistics of the explanatory variables can be extracted for selected periods prior to the time of observations (days, months or years) and examples of such statistics include temperature days, cumulated carbon flux (or carbon flux exceedance triggering reproductive events and recruitment), frequency and duration of exceedances of chemical or physical thresholds (e.g. oxygen, pH, temperature) etc. Ideally, such statistics should be extracted in such a way that it supports general or species specific hypothesis or knowledge.

Uncertainties associated with predictor variables extracted from SEDMs

Like any other models, SEDMs are a simple representation of complex systems, and thus, both model algorithms, model calibration/validation (and data available for calibration/validation) and data forcing the model (i.e. meteorological data, boundary conditions) are all associated with uncertainties and/or biases. For deep sea habitats, that is, habitats below 4–500 m, information on how well the models perform are typically not available. Although hydro-dynamic variables often lack performance indications, this doesn't necessarily mean that the predicted ocean currents are entirely wrong or highly uncertain. In fact, ocean currents for instance at the global or oceanic regions scales (used in e.g. climate modelling) are typically good at representing the known broad-scale ocean current patterns including large eddies, subduction and upwelling zones, vertical mixing etc. and the deep sea circulation processes are tightly linked to these. Large, contiguous and uniform deep ocean areas may be considered as relatively well-represented by SEDMs from a hydrodynamic perspective. By contrast, VMEs located at or near areas where different large-scale water masses meet, and where seabed topography are complex and not resolved in the model resolution, the uncertainty on a number of SEDM derived exploratory variables may be significant and affect the outcome the PHMs.

The level of performance of hydrodynamic data from SEDMs can be assessed through validation by comparison of monitoring data with model outputs. While monitoring of hydrographic variables during VME surveys are useful, in a modelling calibration/validation perspective such data is typically not covering a sufficiently long period to reflect the variability in hydrographic conditions over time which is necessary for model calibration/validation. Repetitive monitoring over time is more important than spatial coverage, although having both would be ideal.

In general when working with SEDMs in areas where data for model calibration are limited, sensitivity analysis can be used for evaluating the sensitivity of model outputs (= predictor variables to be extracted) to changes in individual model input parameters. Many model parameters (e.g. model constants) of a SEDM refer to concrete physical or biological processes such as sinking velocity of POM, decomposition rate of POM, critical threshold for resuspension of POM, etc. and most of these constants can be associated with expected (realistic) range found in the literature. By running a SEDM numerous times changing each model constant from min to max of its range and evaluate the output of the explanatory variable, the modeller will get an indication of the likely range, and thus the constraints, of the explanatory variable and be able to communicate this to others using the model outputs.

Recommendations

These recommendations are primarily targeting future scientific studies that apply PHMs to predict the distribution species or habitats in relation to VMEs, and where the extraction of explanatory variables from SEDMs may improve predictive powers of the models.

- Identify biological meaningful statistics to be extracted from SEDMs as explanatory variables for PHMs.
- Understand what the SEDM was originally designed for and which, if any, implications this may have for the explanatory variables to be extracted.
- Consider rescaling of the SEDM for the study area to increase model resolution by involving physical and/or ecological oceanographers in research projects.

5 'Roadmap' for using predictive habitat modelling for the management of VMEs in the North Atlantic

Recommended actions for the adoption of predictive habitat modelling by WGDEC

WGMHM recommends that PHM should be adopted by WGDEC to enhance their package of evidence provided to ICES for VME management. The ICES WGMHM have outlined the required steps to facilitate this adoption below. It should be noted that the completion of all steps is likely to take several years and may require the input of other groups and the ICES data centre.

1. WGDEC to generate a specification for the modelled outputs, to be called the 'ICES VME Predictive Habitat Modelling Specification'. The specification needs to include;

   (i) what species, biotopes and habitats should be modelled (also define how the response variable is structured – this can be complex for VMEs that are defined as biotopes or habitat-forming species);
   (ii) the spatial extent of the modelled domain for each VME feature;
   (iii) the minimum mapping resolution for each model;
   (iv) a minimum level of map quality (e.g. quantitative thresholds of map accuracy, specificity/sensitivity, kappa etc.) sufficient to deliver a robust evidence base; and
   (v) how often the model should to be rerun/refreshed (e.g. annually before advice drafting sessions).

   Based on the amount of work required for the adoption of PHM, it is recommended that WGDEC prioritise the VME features for a phased development of models. Only one or two species or habitats should be selected for the first phase of model production. The specification should be circulated to other expert groups or stakeholders to validate the values and thresholds contained in the specification.

2. Jointly, WGDEC and WGMHM need to define the modelling method for each VME feature of interest. A review of existing peer-reviewed PHM studies, of which there are several, will inform the working groups on effective modelling approaches. Based on the review, a modelling method should be generated for each VME feature of interest. Each method should specify:

   (i) the **source data** for the response variable and any initial processing of the observations required e.g. the exclusion of poor-quality observations based on geo-referencing, age or source;
   (ii) the **predictor variables** to be include in each model and their source data;
   (iii) how to **prepare the predictor variable data**, including methods used for the selection of working scales for each predictor variables, methods for the regridding of predictor variables (either up or down scaling), and the calculation methods for each derived variable;
   (iv) the **model approach**, e.g. regression approaches and/or machine learning and whether a single model or ensemble approaches are required. A case study

will aid the selection of a modelling methods – Hatton Bank has been highlighted as a suitable case study where both broad and fine scale approaches can be trialled (K Howell, pers. comms., 2019);

(v) any **final actions** required to merge 'stacked' predictions or weight specific outputs; and

(vi) the **model validation** steps required to ensure that the model outputs abide by the requirements of the 'ICES VME Predictive Habitat Modelling Specification'.

3. With help from the ICES data centre and other working groups, conduct a trial run and optimise the modelled approaches for a subset of VME features. Each model method, prediction and validation results should be circulated for independent peer-review. WGDEC and WGMHM should make changes to the method according to recommendations of the review. The finalised methods should be published as well-commented scripts and uploaded to the ICES 'Transparent Assessment Framework'.

4. Advice Drafting Group or WGDEC to trial the annual VME x VMS overlap analysis using both the existing gridded-point method and the modelled method. The exercise should examine the potential for significant step-changes in the levels of receptor / pressure overlap and, consequently, substantial changes in management advice. If significant changes do occur, a validation report should explain why it has occurred and if it reflects a satisfactory assessment. Additional recommendations should be drafted for the refinement of both the 'ICES VME Advice Drafting Group Specification' and the individual methods used for each VME. This should be a separate exercise and not be part of an advice drafting session.

5. Advice Drafting Group to conduct the VME x VMS overlap analysis as part of the standing advice draft meeting. The group should create recommendations directed at WGDEC on the further implementation of VME models – this can include reprioritisation of VMEs and the frequency of model updates.

WGMHM have committed to a second joint meeting with WGDEC in 2020. The objective of another joint meeting is to progress the development of both the modelling specification and the preferred modelling method.

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Annex 1: List of participants

Name	Institute	Country (of institute)	Email
James Strong (chair)	National Oceanography Centre Southampton	UK	jamstr@noc.ac.uk
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Annex 2: WGMHM Resolution

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

	Meeting dates	Venue	Reporting details	Comments (change in Chair, etc.)
Year 2018	22-24 May	Hamburg, Germany	Interim report by 1 August	
Year 2019	3-7 June	Palma de Mallorca, Spain	Interim report by 1 August	Meeting in association with WGDEC
Year 2020	TBC	Denmark or UK (TBC)	Final report by DATE	Meeting in association with WGDEC

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 importance 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.	3.4	3 years	Annual updates and final report
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. 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.	3.4	3 years	Annual updates and final report. Submission of of survey metatdata to ICES Data Center
C	Summarise recent advances in marine	This ToR provides the main avenue for mappers to coomunicate new or improved	3.3	3 years	Annual updates and final report.

	habitat mapping and modelling techniques, including field work methodology, and data analysis and interpretation.	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.			The 2018 intersessional work will be directed towards producing our first marine habitat mapping best practice document (1–2 methodological topics only)
D	Review practise about the use of habitat maps, for example mapping for the MSFD, marine spatial planning, and management of MPAs; and assess the ability 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.	6.2	3 years	Annual updates and final report. The WGMHM also made a substantial contribution to the ICES Special Request Advice 'EU request for guidance on how pressure maps of fishing intensity contribute to an assessment of the state of seabed habitats' Published 4 July 2016
E	The identification of 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.	3.2	Year 1	An annually updated database listing important data sources suitable for marine habitat mapping
F	Identify and advance theoretical aspects of habitat mapping (e.g. landscape ecology, supply-side ecology, implications of scale etc.).	This ToR is to provide an opportunity for EG members to address the theoretical aspects of marine habitat mapping. As a science in its infancy, it is important that underpinning concepts are challenged and re-evaluated.	4.1	Years 1 and 2	Important presentations and discusses summarised in annual reports. Scientific publication assessing the influence of classification schemes on marine habitat mapping (to be submitted in md December 2017 to ICES Journal of Marine Science)

Summary of the Work Plan

Year 1	Draft and finalise the “Recommended Operating Guidelines for Assessing and Communicating Confidence in Marine Habitat Mapping
Year 2	Conduct a joint meeting with the working group on deep-water ecology (WGDEC) and collaborate a significant joint output, e.g., geo-spatial modeling of the distribution of Atlantic Vulnerable Marine Ecosystems”.
Year 3	Annual reporting for remaining ToRs and comissioning of new intersessional papers and database.

Supporting information

Priority	These ToRs are essential for maintaining the WG as a focused and relavent group for marine habitat mapping. The ToRs also contribute to the disemination of innovative ideas and best practice. This in turn improves the quality and quantity of marine habitat maps.
Resource requirements	The only resouces required will be the occassional use of ICES HQ meeting rooms.
Participants	The Group is normally attended by some 10 - 15 members and guests.
Secretariat facilities	None.
Financial	No financial implications.
Linkages to ACOM and groups under ACOM	There are no obvious direct linkages.
Linkages to other committees or groups	There is a very close working relationship with Working Groups on Benthic Ecology, Deep-Water Ecology, Marine Planning and Coastal Zone Management and Spatial Fisheries Data.
Linkages to other organizations	EMODnet bathymetry and EMODnet seabed habitats.

Annex 3: Update on EMODnet Seabed Habitats

The EMODnet Seabed Habitats portal provides a 'one-stop shop' for seabed habitat data from across Europe. From 2017–2019, JNCC has led a consortium of 12 partners from around Europe to deliver this on behalf of the European Commission.

Seabed Habitats is one of seven themes under the wider European Marine Observation and Data Network (EMODnet). EMODnet consists of more than 150 organisations assembling marine data, products and metadata to make these fragmented resources more available to public and private users relying on quality-assured, standardised and harmonised marine data, which are interoperable and free of restrictions on use.

What habitat data is there?

The EMODnet Seabed Habitats portal holds collections of habitat data from across Europe, with separate collations of approximately 300 000 habitat sample points, over 800 habitat maps from survey and more than 80 single predictive habitat models available to view, access via web services and download (Figure 2).

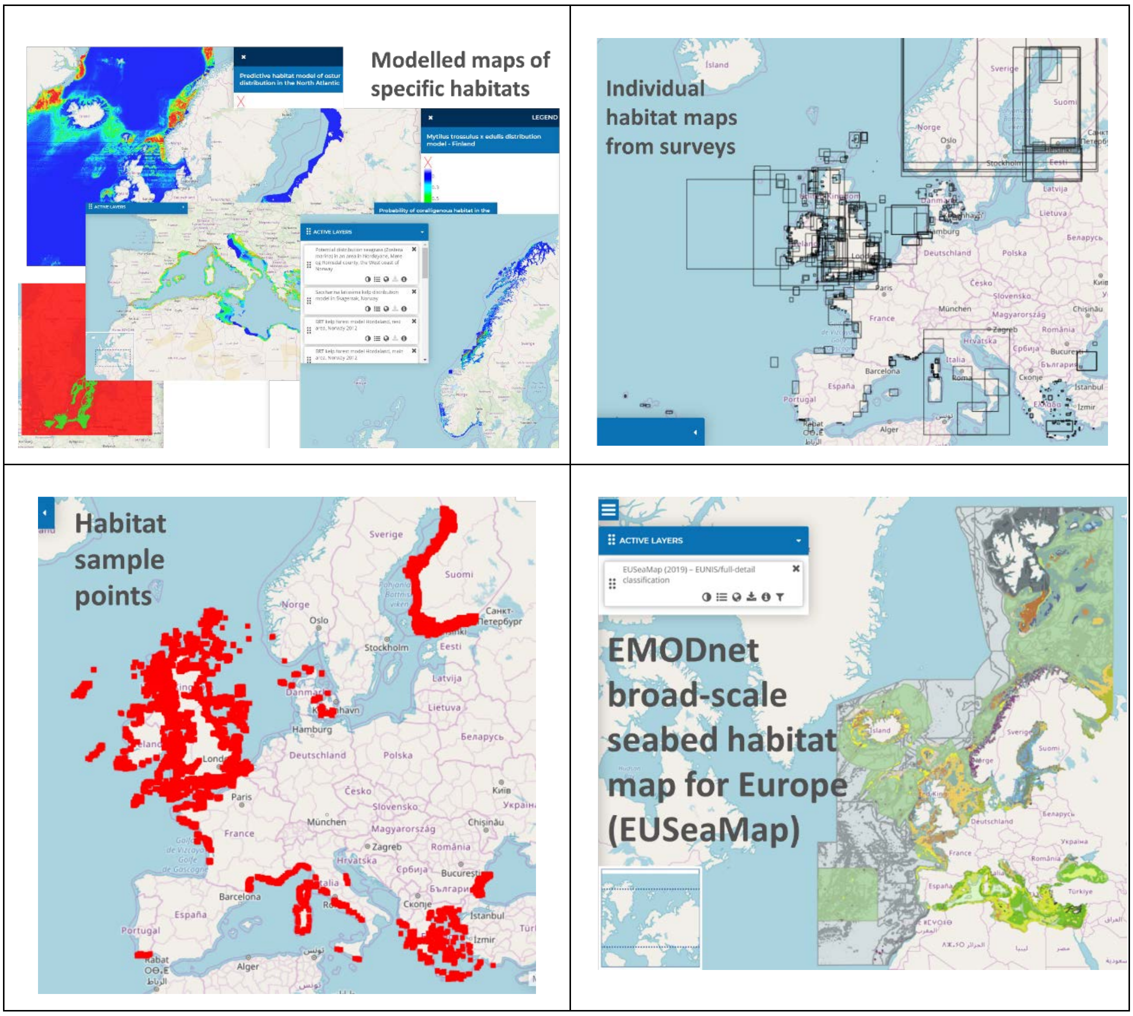

Figure 2. Key products of EMODnet Seabed Habitats. All are freely available through the portal.

In addition to providing access to existing data and products, EMODnet Seabed Habitats creates new products. The flagship, EUSeaMap, is a full-coverage broad-scale habitat map for the whole of Europe's seas. New for 2019, this model has extended further north and now covers the Barents, North-East Atlantic, Baltic, Mediterranean and Black Seas. EUSeaMap has already been used extensively across the policy, research and industry sectors on projects ranging from offshore windfarm environmental impact assessments to Europe-wide Marine Protected Area network evaluations.

For the first time, by plugging into other international initiatives, the extensive collection of habitat maps has been used to create composite maps for habitats of particular conservation importance. This initial work has focussed on three of the Global Ocean Observing System Essential Ocean Variables – seagrass cover, macroalgal canopy cover and hard coral cover. These assembled Europe-wide products showing the current best knowledge on the extent of these important habitats. The portal also plays host to the official product showing the current best knowledge on the extent and distribution of the habitats listed on the OSPAR list of threatened and/or declining habitats.

What about environmental variables?

The production of EUSeaMap required full-coverage surfaces of biologically-relevant environmental variables. Where they did not already exist, new ones were created. They are now freely available for anybody to use via the portal (go straight to map layers). Newly published datasets include:

- Light availability at the seabed for all of Europe
- Energy at the seabed due to waves and currents for large areas of the Mediterranean, Black Sea, Iberian Peninsula and Macaronesia
- Temperature and oxygen at the seabed for the Black Sea