

## Broad-scale mapping of seafloor habitats in the north-east Atlantic using existing environmental data

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### Abstract :

If marine management policies and actions are to achieve long-term sustainable use and management of the marine environment and its resources, they need to be informed by data giving the spatial distribution of seafloor habitats over large areas. Broad-scale seafloor habitat mapping is an approach which has the benefit of producing maps covering large extents at a reasonable cost. This approach was first investigated by Roff et al. (2003), who, acknowledging that benthic communities are strongly influenced by the physical characteristics of the seafloor, proposed overlaying mapped physical variables using a Geographic Information System (GIS) to produce an integrated map of the physical characteristics of the seafloor. In Europe the method was adapted to the marine section of EUNIS (European Nature Information System) classification of habitat types under the MESH project, and was applied at an operational level in 2011 under the EUSeaMap project. The present study compiled GIS layers for fundamental physical parameters in the northeast Atlantic, including (i) bathymetry, (ii) substrate type, (iii) light penetration depth and (iv) exposure to near-seafloor currents and wave action. Based on analyses of biological occurrences, significant thresholds were fine-tuned for each of the abiotic layers and later used in multi-criteria raster algebra for the integration of the layers into a seafloor

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habitat map. The final result was a harmonised broad-scale seafloor habitat map with a 250 m pixel size covering four extensive areas, i.e. Ireland, the Bay of Biscay, the Iberian Peninsula and the Azores. The map provided the first comprehensive perception of habitat spatial distribution for the Iberian Peninsula and the Azores, and fed into the initiative for a pan-European map initiated by the EUSeaMap project for Baltic, North, Celtic and Mediterranean seas.

### **Highlights**

► Spatial seafloor physical characteristics data for the NE Atlantic was compiled. ► Datasets were harmonised to common standards prior to input into a GIS environment. ► The inputs were overlaid via spatial analyses to derive a broad-scale habitat map. ► Habitats were described following the marine section of EUNIS habitat classification. ► Biologically-relevant thresholds were established for delineation of EUNIS categories.

**Keywords** : Habitat Mapping, EUNIS, Exposure, Biological Zones, Substrate

## 1. Introduction

The demand for accurate and reliable maps describing the seafloor habitats of Europe has increased dramatically in recent years with the implementation of legislation such as the Habitats Directive (92/43/EEC) and the Marine Strategy Framework Directive (MSFD; 2008/56/EC). Such information is crucial for the production of broad-scale maps of human impact on the marine environment (Andersen et al., 2013; Halpern et al., 2008). Marine spatial planning also demands reliable and comprehensive spatial data that includes the characteristics of coastal and ocean environments based on habitat types (e.g. Douvere et al., 2007; Gilliland and Laffoley, 2008).

Habitat mapping typically relies on the application of multiple survey techniques such as single- and multi-beam sonar, LiDAR, grab sampling and other physical ground-truthing, to derive data that can be integrated to produce a map (Brown et al., 2011). To date, numerous international protected areas programs (e.g. Natura 2000 network established under the Habitats Directive) as well as other local initiatives (e.g. Ehrhold et al., 2006; Galparsoro et al., 2013; Gorman et al., 2013; Todd and Kostylev, 2011) have used these different approaches to produce spatially explicit maps. These methods allow detailed maps to be developed: the boundaries between adjacent habitats are accurately delineated, and both the abiotic characteristics and the associated biological communities are described. Their drawback is that they are costly, resource-intensive and time-consuming, typically taking around three years from the first survey to full map completion. Therefore it is impractical to apply such an approach to all points on the seafloor in order to achieve full spatial coverage across Europe.

Broad-scale mapping represents an alternative to the piecemeal approach described above, the benefits of extended map coverage at reasonable cost. The concept relies on the assertion that benthic communities are strongly influenced by the physical characteristics of the seafloor (e.g. type of sediment, or slope) and the water column (e.g. temperature or water movement; Glémarec, 1973). Acknowledging this, Roff et al. (2003) proposed overlaying mapped physical variables using a Geographical Information System (GIS) to produce an integrated map of the physical characteristics of the seafloor, which they termed 'seascapes'. This method, which was successfully tested for the entire Canadian coastline (Roff et al. 2003), can be used to produce maps that, while less detailed, are of greater spatial extent and considerably less costly as they are based on existing information.

The capacity to rapidly augment spatial data in a very cost effective way is leading to a profound and rapid uptake of broad-scale mapping approaches. The approaches have been widely adopted, particularly in Australia (Harris et al., 2008; Huang et al., 2011) and in Europe, where it was first investigated at a continental scale as part of the INTERREG MESH project, which adapted the method to the European EUNIS (European Nature Information System) classification scheme (Coltman et al., 2008). Following on from this, the EUSeaMap project successfully put the method into practice for the western Mediterranean, Celtic, North and Baltic Seas (Cameron and Askew, 2011). Simultaneous national initiatives, in France (Hamdi et al., 2010) and in the United Kingdom (UKSeaMap 2010 project, McBreen et al., 2011), also applied this method successfully.

The present study was carried out within the framework of the MeshAtlantic project funded by the INTERREG 'Atlantic Area 2007-2013' program. A key output of the project was a broad-scale map for four extensive areas around Ireland, the Bay of Biscay, the Iberian Peninsula and the Azores islands. The goal of this output was clearly to feed into the initiative for a pan-European map initiated by the EUSeaMap project. In order to be compatible with the results of EUSeaMap, the same methodology for generating a broad-scale map was used. A particular effort was dedicated to the selection of ecologically significant thresholds for the categories considered by the EUNIS classification using groundtruthing data.

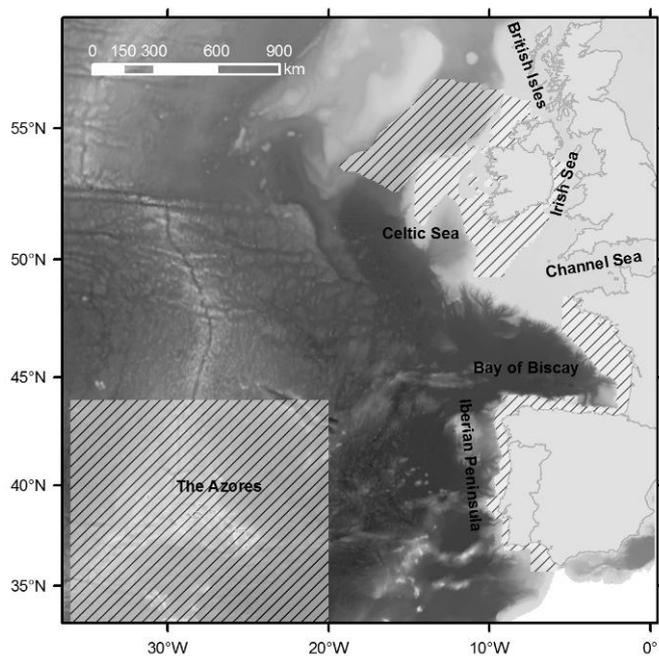
## 2. Material and methods

### 2.1. Study area

The region covered is an area of about 2 million km<sup>2</sup> which includes the Atlantic waters of continental Europe and the Portuguese archipelago of the Azores (Fig. 1). It specifically includes the Iberian Peninsula, the Bay of Biscay, the Irish Sea, the Celtic Sea, and the seas surrounding the Azores islands. Although the Western Channel Sea and western part of the Irish sea were within the geographic bounds of the EU's 'Atlantic Area 2007-2013' program (<http://www.seupb.eu/programmes2007-2013/interreg-overview/transnational/atlanticaeaprogramme.aspx>) which funded the present project, they were not specifically targeted in this project as they had already been mapped within the framework of the EUSeaMap project (Cameron and Askew, 2011), and no improvement of the data for those areas had been identified since that time.

The area includes a diverse range of environmental conditions. At the scale of the entire area sea temperature and water depth are the main features determining seafloor species geographical distribution. Dinter (2001) separates the shelf and upper slope (for depth up to 1000m) into three biogeographic zones, from North Shetlands Isles southward (i) the Boreal Lusitanian which comes down to a parallel across the English Channel, (ii) the Lusitanian Boreal extending downwards to roughly the Gironde Estuary in the Bay of Biscay and (iii) the Lusitanian extending to Gibraltar. The latter is divided into a warm subprovince covering the Aquitaine and the Basque Country in the north of Spain and an area in the south composed of the southern Portuguese coast and the Gulf of Cadiz. Due to the presence of strong upwelling, the central part of the Iberian Peninsula from Cantabria to Cape St Vincent is referred to as the cool Lusitanian subprovince. In this province, where the inshore area is dominated by rocky substrate, cold nutrient-rich water induces the presence of invertebrates and macroalgae usually found more to the north (e.g. Martins et al., 2013). Shelves and upper slopes in the Azores archipelago are put into a category of their own belonging to the Macaronesia province.

At finer scales the influence on community composition / species distribution of more specific water quality parameters along with seafloor topography, substrate and exposure to water movement become significant. Broad areas of shallow waters (light grey tones in Fig. 1) occur all around Ireland (west of the Porcupine Bank and in the southern part of the Celtic Sea) and in the western Bay of Biscay (French continental shelf), while off the coasts of northern Spain, the Iberian Peninsula and the Azores, deep-sea areas (dark grey tones in Fig. 1) are much more extensive nearshore. The Azores, a volcanic archipelago straddling the Mid-Atlantic Ridge, are noteworthy for the complexity of their geomorphology with nine islands and numerous seamounts, as well as for the prevalence of deep-sea grounds. Another deep-sea zone is the offshore Rockall Trough, which is located to the northeast of Ireland and in some places extends over 300km in width and to depths of over 3000m. From an oceanographic perspective, current-induced flows are generally weak except in the shallow, semi-enclosed Irish Sea, in local areas of the Northeastern French coast and near the Gibraltar Strait. The northeast Atlantic is known for its rough seas due to large storms that occur during the winter months.



**Fig.1.** NE Atlantic area. The hashed area shows the coverage of existing data.

## 2.2. Method overview

### 2.2.1. Classification scheme

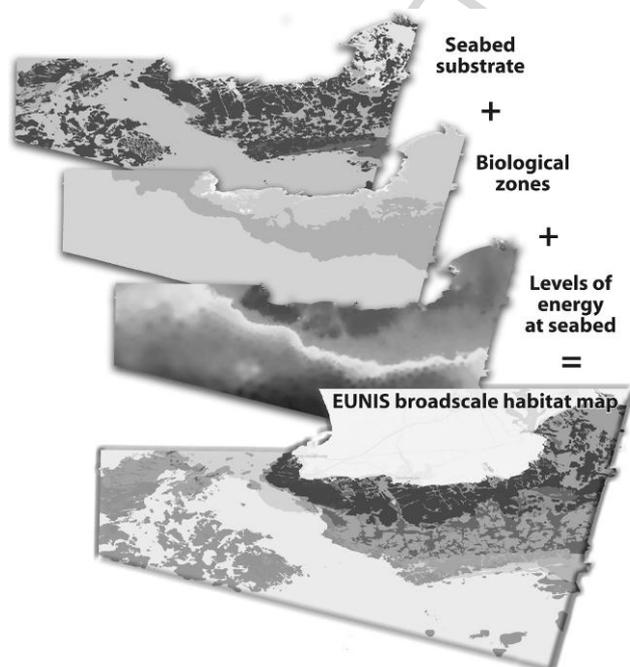
The term 'habitat' is now generally accepted to mean "a place where plants or animals normally live, characterised primarily by its physical features (topography, plant or animal physiognomy, soil characteristics, climate, water quality etc.) and secondarily by the communities of plants and animals that live there" (Davies et al., 2004). A habitat description must be based on a common habitat classification system, the function of which is to provide a common language and ensure cross-boundary consistency (i.e. particularly when spanning different countries). A number of habitat classifications schemes have been developed at regional or local scales. Most published examples of broad-scale mapping have also proposed their own classification (see e.g. Huang et al., 2011; Roff et al., 2003; Zacharias et al., 1999), but rarely were these reused by other authors.

In Europe, the EUNIS (European Nature Information System) classification, which provides a common European reference set of habitat types for terrestrial, freshwater and marine habitats (Davies et al., 2004), facilitates reporting of habitat data in a comparable manner, for use in nature conservation (e.g. inventories, monitoring and assessments), habitat mapping and environmental management. It is thus considered today as a reference tool within a European context. The current structure of the marine section of EUNIS covers a wide range of habitat types; even though it was first derived from the BioMar classification developed for Britain and Ireland (Connor et al., 1997<sup>a</sup>, 1997<sup>b</sup>, and 2004), substantial efforts have been made to include information on marine benthic habitats from different regions, aiming to provide a comprehensive geographical coverage of European seas (Galparsoro et al., 2012). It was successfully used for broad-scale mapping purpose by the MESH (Coltman et al., 2008) and EUSeaMap (Cameron and Askew, 2011) projects. For these reasons EUNIS was an obvious choice for the present study.

### 2.2.2. Mapping approach

The marine part of the EUNIS habitat classification starts from level 1, where it is named 'A: marine habitats'. The following levels (2, 3 and to some extent 4) describe the physical (or abiotic) factors of the habitat, that can be likened to the 'physical features' in the definition of the term 'habitat' given in the previous section. For example in the infralittoral zone, characterised by rocky substratum and a high degree of exposure to hydrodynamic forces the habitat is named 'A3.1: High energy infralittoral rock'. When the abiotic characteristics of the habitat are fully defined the biotic environment of the habitat, i.e. its dominant vegetal or animal communities, starts to be described in lower levels (4 or 5 to 6).

Broad-scale mapping as developed within the MESH project and as performed in our study aims to make maps at physical levels of the marine section of EUNIS, i.e. at levels 3 or 4 (Coltman et al., 2008). EUNIS uses three basic characteristics to differentiate among, and so classify, marine habitats. Firstly the 'biological zone' (e.g. infralittoral, circalittoral and deep-circalittoral zones) which is a vertical zonation reflecting changing conditions of light penetration/attenuation and disturbance of the seabed by wave action, which together influence habitat suitability for many plant and animal species. Secondly the substrate type (e.g. rock, sand, mud), which dictates habitat suitability for many organisms. Thirdly, for rock habitats only, there is also consideration of the energy regime, a qualitative indication of the relative exposure to hydrodynamic forces induced by waves and/or currents (i.e. high, moderate and low energy environments). These three characteristics can be represented in a GIS by separate data layers, and combined using simple spatial algebra to create a habitat map layer (Fig. 2), classified according to the upper levels of the EUNIS system (e.g. level 3 for rock and level 4 for sediments). The process is carried out in raster mode, because most raw datasets describing physical variables are provided in a raster format and because the cell-based map algebra language (Tomlin, 1990) is the most convenient way to overlay and perform calculations on oceanographic GIS layers. Sought pixel size for the final broad-scale habitat raster layer was 250m, which is roughly equivalent to a scale of 1:1,000,000.



**Fig. 2.** Schematic representation of the methodology, which involves the combination of three raster base-layers (i.e. the types of substrate, the biological zones and the hydrodynamics-induced energy levels at the seafloor) to produce a EUNIS habitat map describing the physical environment.

### 2.2.3. Computing climatology

Some of the variables used for modelling (i.e. light penetration and exposure to hydrodynamic forces) display considerable variation over time (e.g., seasons). Therefore, they need to be integrated over long periods in order to derive general trends. For such time-dependent variables, the choice of an appropriate metric is an important issue to consider. There is a general consensus that extreme events such as storms strongly influence the spatial distribution of habitats (because of the magnitude of destruction) and therefore the 'maximum' metric should be used to capture spatial patterns. The authors of this study argue to the contrary, recommending that this metric should not be used in the context of broad-scale habitat mapping whose purpose is to be as generalised as possible, i.e. to present where habitat boundaries are likely to be located considering the normal (i.e. not extreme) environmental conditions. Since an average value can be influenced greatly by outliers (e.g., extreme environmental events), the use of a relevant percentile (in this case the 90<sup>th</sup> percentile) was chosen as a means of filtering out such extreme events.

### 2.2.4. Defining thresholds

The marine section of EUNIS system uses qualitative descriptors for most abiotic characteristics of habitats, such as the high, moderate and low energy categories for energy regime. However, the GIS approach requires quantitative values to define thresholds/boundaries between adjacent classes, such that spatial algebra is performed in an objective, consistent and repeatable manner.

The threshold values were derived from known biology (based on the statistical analyses of field-observations of habitat type). In the optimal situation, where samples on both side of a given boundary (e.g. boundary between the infralittoral and the circalittoral biological zones) were available, the Receiver Operating Characteristic (ROC) curve (Pearce and Ferrier, 2000) from the ROCR R package (Sing et al., 2005) was used. This tool is commonly used by ecologists for validation of predictive distribution models (e.g. Dunn and Halpin, 2009; Gorman et al., 2013; Roberts et al., 2010). It can also be used, as it is widely done for medical tests (Kumar and Indrayan, 2011), for the determination of the optimal threshold value for any variable having a high discriminatory capacity to differentiate one category from another.

### 2.3. Derivation of the seafloor substrate layer

A full-coverage seafloor substrate layer, describing all the types of substratum recognised by the marine section of EUNIS classification, was an integral part of the study. In order to be EUNIS-compliant, the layer had to comprise a rock class and six sediment classes: coarse sediment, mixed sediment, sand, muddy sand, sandy mud and mud. Polygon layers were collated from a variety of sources across the study area, from historical maps derived only from extrapolation of sample point data to more recent maps produced with the help of geophysical methods that provided a higher density of information. The challenge was in integrating datasets that were quite diverse in terms of scale and sediment classification. For that purpose a classification built on that of Folk (1954) and taking into account the study area sediment characteristics was proposed (Mata Chacón et al., 2013). All datasets were translated into the aforementioned sediment classification, which sometimes necessitated the use of expert knowledge or of existing sample points for groundtruthing. In the case of the Azores, most information was available as sample point data. As a result, in a first phase a geology expert interpretation based on the substrate data points and the underlying topography was used to extrapolate point data into polygon units. This approach was later complemented by statistical modelling to cover the uninterpreted areas left by the expert.

## 2.4. Derivation of the biological zones layer

### 2.4.1. Definition

It was recognised early in the history of studies describing marine habitats that the distribution of benthic communities is strongly correlated with the environmental conditions on the seafloor (e.g. Glémarec, 1973; Pérès and Picard, 1964). This led European marine ecologists to divide the seafloor into zones, cited as 'biological zones' in the EUNIS classification.

EUNIS currently takes into account the zones occurring on the continental shelf in the following sequence with increasing depth: the infralittoral, the circalittoral, and the deep circalittoral. In contrast to this, the area from the continental slope to the abyssal plain does not have any individual zones, instead the area is grouped into a single block, termed 'deep-sea', a situation that is acknowledged to be too restrictive for a zone characterised by such a rapid change in depth (and other related parameters such as temperature), and for which faunal zones have been defined by numerous authors (for review see Carney et al., 1983). This lack of appropriate division within EUNIS for the deep sea led Howell (2010) to propose a biologically-relevant division of the deep-sea bottom for the northeast Atlantic into five zones, ranked from shallowest depth: upper slope, upper bathyal, mid-bathyal, lower bathyal, and abyssal. For the present research, this classification of deep-sea seafloor was adopted as it was considered appropriate for the study area.

### 2.4.2. The bathymetry layer

Bathymetry is a crucial data layer required for the generation of all GIS layers used as proxies for biological zones. A good quality bathymetry layer was therefore of paramount importance to the present study. The best available datasets were collated from a variety of national or local sources (i.e. sounding points or high resolution digital elevation models). In areas where detailed information was lacking, i.e. off the Azores, the Gebco 30 arc-second gridded bathymetry layer (Gebco\_08 version) was used. Data providers were requested to reference their data to local Chart Datum, which is an approximation of lowest astronomical tide (LAT), while the Gebco is referenced to mean sea level (MSL). This default of the bathymetry layer was deemed acceptable as it concerned the offshore part of the Azores only. The datasets were combined into a full-coverage raster layer covering the entire study area at a resolution of 250m (Mata Chacón et al., 2013).

### 2.4.3. Infralittoral – circalittoral boundary

The infralittoral zone extends from a boundary where the seafloor is rarely uncovered to a boundary that marks the end of favorable light conditions for the growth of seagrass and other macrophytes. The dominance of seagrass and green algae ends at the transition into the circalittoral zone, where sciaphilic algae that can tolerate low light conditions dominate. A full coverage layer describing light conditions is therefore required to accurately define the boundary between these two zones. Light attenuation, which increases with turbidity, can be quantified via the diffuse attenuation coefficient of the photosynthetically available radiation ( $k_{dPAR}$ , expressed in  $m^{-1}$ , see Saulquin et al., 2013). The advantage of this measure is that it is routinely derived from readily available ocean color satellite sensors. A 250m resolution raster layer that gave mean values for  $k_{dPAR}$  over a five-year period (2005-2009) was used in the study. The layer was derived from archives of radiance values measured by the European MERIS (Medium Resolution Imaging Spectrometer Instrument) sensor. This work was performed within the framework of EUSeaMap project for a large area of European coastal waters (Saulquin et al., 2013), and for the purpose of this study the equivalent information was computed for the Azores.

The fraction of surface light ( $F_r$ ) that reaches a given water depth,  $h$ , is estimated by a form of the Lambert-Beer law:

$$F_r = e^{-k_{dPAR} \times h}$$

Thus the fraction of surface light that reaches the seafloor is obtained by substituting into the equation the depth given by the bathymetry layer and the  $k_{dPAR}$  raster layer.

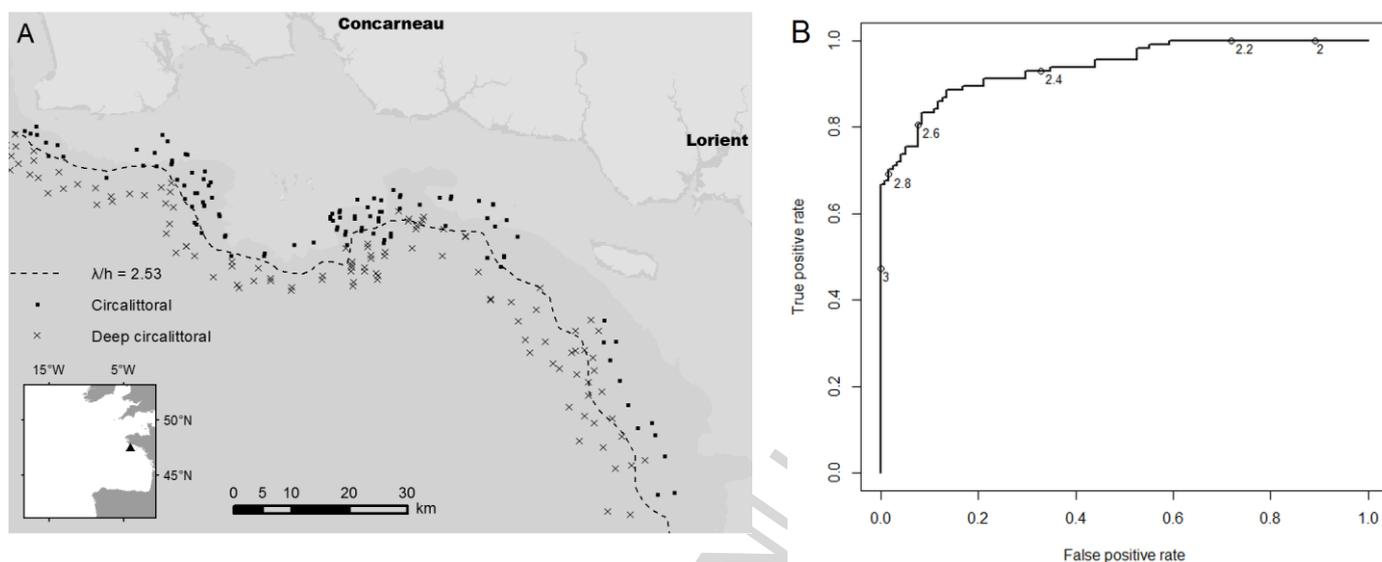
Ecologists have long acknowledged that the boundary between the infralittoral and the circalittoral relates to the threshold at which 1% of surface incident light reaches the seafloor (i.e.  $F_r=0.01$ ; Castric-Fey et al., 1973; Lüning and Dring, 1979; Pérès, 1967). Recent studies confirmed this value (Cameron and Askew, 2011; Saulquin et al., 2013). Studies on the presence of algae from sample points were conducted in both mainland Portugal and the Azores as part of the present study, the findings of which fundamentally confirmed the 1% of surface light cut-off value (see Amorim et al. for the Azores case study, in this volume).

#### 2.4.4. Circalittoral – Deep circalittoral boundary

In contrast to the circalittoral, the deep circalittoral is a zone in which variations in water motion and temperature are minimal due to the reduced exposure of the seafloor to hydrodynamic forces (Glémarec, 1973). A commonly used approach to predict the upper limit of the deep circalittoral relies on the notion of wave base, which can be defined as the depth at which the seafloor is no longer disturbed by wave action. The theory defines that depth,  $h$ , is equal to half the wave length,  $\lambda$ , of the surface waves. The boundary between the circalittoral and the deep circalittoral can therefore be defined by the formula  $\lambda/h = 2$ .

A gridded layer describing wave length was computed from peak wave period given by archived time-series data of wave prediction models developed by Ifremer (Roland and Ardhuin, 2014), the University of the Azores and the University of Lisbon. The approximation to the dispersion relation used for the derivation of wave length from peak wave period and depth was that proposed by Guo (2002). The raster layer was prepared at a spatial resolution of 4km, over a time period of three years (2010-2012) for both coasts surrounding the Iberian Peninsula and the Azores, and six years (2006-2011) for the other regions included in the study. The values of  $h$  required for the calculation of the  $\lambda/h$  raster layer were extracted from the bathymetry raster layer.

As part of the present study, the theoretical threshold  $\lambda/h = 2$  was tested with the help of observed sample data from which Glémarec (1969) had previously defined the biological zone (i.e. 114 circalittoral and 118 deep circalittoral occurrences, see Fig. 3A). For each point the value  $\lambda/h$  was extracted from the corresponding gridded layer and the resulting data set was used in a ROC curve analysis to determine the optimal  $\lambda/h$  cut-off value which would separate the circalittoral from the deep circalittoral categories (Fig. 3B). This analysis yielded an area under the curve (AUC) of 0.94, which indicates that the variable has a high capacity to differentiate between the circalittoral and the deep circalittoral. The analysis indicated an optimal threshold value of  $\lambda/h = 2.53$ , i.e. the value that least misclassified both circalittoral and deep circalittoral occurrences. This value enabled 89% of circalittoral and 86% of deep circalittoral occurrences to be classified correctly. Sample points within other parts of the study area were unavailable; therefore this value was used for the entire area. The resulting boundary was scrutinized by experts in the various regions of the study area who, based on their local knowledge, deemed it consistent with what they would expect.



**Fig. 3.** Identification of the  $\lambda/h$  threshold used to delineate the transition between the circalittoral and the deep circalittoral zones. (A) Map of the sample points used to construct the ROC analysis, and (B) ROC curve (along which  $\lambda/h$  values are displayed), which led to a decision threshold value of 2.53 ( $\lambda/h$ ). This value gives the lowest rate of misclassification for both circalittoral and deep circalittoral occurrences (resp. true positive rate and 1-false positive rate axis on the graph). The corresponding isoline is also shown on (A) as a dashed line.

#### 2.4.5. Deep-sea zones boundaries

Abrupt changes in slope were used to identify two deep-sea boundaries: i) the boundary between the deep circalittoral and the upper slope and ii) the boundary between the lower bathyal and the abyssal. Those were manually delineated by the visual interpretation of derivatives of the bathymetry layer which are i) slope, which by giving values of slope in degrees allowed for the identification of slope changes, ii) depth contours, which were extracted for every 5m of depth, with slope changes inferred where isolines were close together, and iii) vertical profiles, which were used where the two other layers were not helpful, e.g. because of local complexity in the geomorphology. This work was carried out by a geologist for the entire study area. The base of seamounts, which are characteristic features of the Azores and the western margin of mainland Portugal, were also delineated. The base of seamounts arising from the abyssal plain was considered as a slope change, and thus was interpreted as a boundary between the bathyal and the abyssal.

The three limits separating the other deep-sea zones into upper slope, the upper bathyal, the mid-bathyal and the lower bathyal were defined based on the depth contours suggested by Howell (2010), with depth values of 750m, 1100m, and 1800m respectively.

#### 2.5. Derivation of the energy layer

##### 2.5.1. Methodology

The EUNIS classification system uses relative magnitude of exposure to hydrodynamic processes (waves and currents) to differentiate three classes of rock habitat (high, moderate and low energy rock). It does not extend this to sediment habitats as it is assumed that the grain size distribution at any one location (e.g. the specific proportions of cobble, pebble, sand and mud) will

reflect the energy 'climate' (the heavier particles being prevalent in higher energy regimes and the lighter particles dominating low energy regimes). In order to prepare a gridded layer describing energy levels, the methodology developed by the EUSeaMap project (Cameron and Askew, 2011) was used. It was carried out in two steps: i) classification of a current-induced and a wave-induced energy layer into the three levels via separate thresholds (see Table 1), and ii) combining the two energy classification layers using a simple rule which states that the highest level of energy defined for each pixel by the two input layers is the level that is to be retained.

Table 1 - Kinetic energy thresholds ( $\text{N.m}^{-2}$ ) for EUNIS energy levels

Level	Currents	Waves – 4km model	Waves – 300m model
Low	> 1.16	> 0.043	> 0.13
Moderate	0.13 – 1.16	0.003 – 0.043	0.0025 – 0.13
High	< 0.13	< 0.003	< 0.0025

### 2.5.2. Compiling data for the energy layer

The base layers were climatological layers of kinetic energy at the seafloor. This one is given by the equation

$$E (\text{N.m}^{-2}) = \frac{1}{2}\rho v^2$$

where  $\rho$  is the density of the water, taken here as  $1.027 \text{ kg.m}^{-3}$ , and  $v$  is the water velocity at the seafloor, either waves orbital velocity (calculated using the peak wave period) or current speed.

The two layers were prepared by compiling a climatology computed from archived results from different models, the characteristics of which are described in Tables 2 and 3. It should be noted that the gaps were filled by a climatology computed within the framework of the UKSeaMap project (West et al., 2010).

Table 2 - Wave-induced climatological layers characteristics

Area	Resolution	Time span	Source
Bay of Biscay, including northern Spain and southern Irish sea	300m along shore 3km offshore	5 years	Ifremer, IOWAGA project hindcast archives (Roland and Arduin, 2014), WAVEWATCH III <sup>TM</sup> model (Tolman, 2009)
Iberian peninsula	4km	3 years	Maretec, WAVEWATCH III <sup>TM</sup> model (Tolman, 2009)
Azores	4km	3 years	University of the Azores, WAVEWATCH III <sup>TM</sup> model (Tolman, 2009)
Other areas	100 – 300m along shore 12.5km offshore	5 years	UKSeaMap project (West et al., 2010)

Table 3 - Current-induced climatological layers characteristics

Area	Resolution	Time span	Source
Bay of Biscay, including southern Ireland	700m	5 years	Previmer platform archives, based on Ifremer MARS2D model (Lazure et al., 2009)
Iberian peninsula and northern Spain	4km	3 years	Maretec, MOHID-PCOMS model archives (Mateus et al., 2012)
Azores	4km	3 years	University of the Azores, MOHID-PCOMS model archives
Other areas	1.8km along shore 12km offshore	5 years	UKSeaMap project (West et al., 2010)

The process led to the creation of heterogeneous layers in terms of spatial resolution. A good resolution was achieved for some coasts while for others, namely the Iberian Peninsula and the Azores, it was not possible to reach a resolution better than 4km.

### 2.5.3. Determining threshold levels

The heterogeneity of the layers in spatial resolution generated complications for the calculation of thresholds for wave-induced energy. Along the coast, values of kinetic energy derived from the 4km resolution models appeared to be considerably lower than values generated from the 250m resolution models. This can be explained by the fact that coarse resolution models are not able to capture the along-shore wave breaks (which generate high energy) whereas fine resolution models can. Therefore, the coarse resolution model significantly underestimates the kinetic energy values in shallow waters. In conclusion, because of the differences in spatial resolution within the compiled kinetic energy layer, two sets of thresholds had to be calculated, respectively for a pixel size of 300m and 4km.

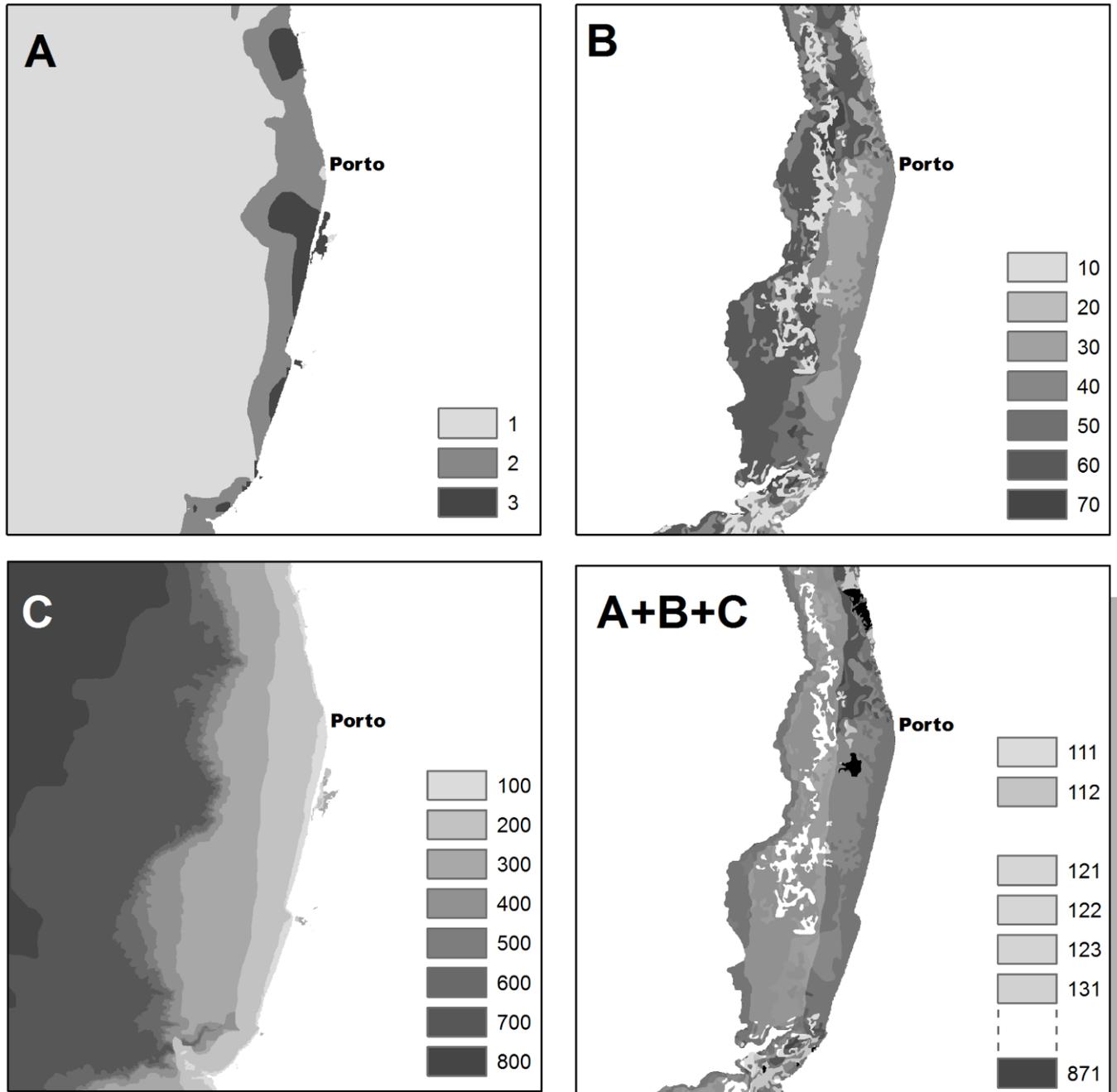
Complications due to this heterogeneity were exacerbated by the difficulties in collecting habitat-type field sample data characterising wave-induced energy levels. An observation-based approach for determining the thresholds between the different energy classes was considered but was not successful in the Bay of Biscay due to the inherent difficulties and dangers associated with making field observations in high energy environments. Therefore the thresholds were defined with the help of the boundaries calculated for the EUSeaMap project map which described wave-induced energy levels in the Channel Sea, an area that was also covered in the gridded layer generated by the present study. In areas such as the coast of mainland Portugal a statistical analysis of Kelp sample data enabled the development of a set of thresholds (Monteiro et al., in this volume). These thresholds were also applied to the Azores, which shared the same resolution (4 km). In other areas, where the layer of wave-induced kinetic energy generated by the UKSeaMap project was used, the thresholds that were computed within that framework (McBreen et al., 2011) were applied.

Currents were classified according to the thresholds defined within the framework of the UKSeaMap project (McBreen et al., 2011). The validity of these thresholds could not be tested due to the absence of habitat field data characterising the various current regimes. They were applied to the gridded layer of current-induced kinetic energy and the spatial patterns were visually verified by experts for each region during a workshop.

## 2.6. Final step: constructing the habitat map

After finalising the three primary layers the last step was to integrate them into the final habitat map. This process involved the addition of the three raster layers. As shown in Figure 4 energy levels were coded in units of one, substrate types in units of ten, and biological zones in units of hundred. Hence the sum of the 3 layers led to a three-digit coded layer, each code being representative of a unique combination of an energy level, a substrate type and a biological zone (e.g; '111' was the sum '1+10+100', which corresponded to the combination 'High energy'+ 'Rock'+ 'Infralittoral'). The resulting classification layer was then translated into EUNIS. For example the combination 'Infralittoral'+ 'Rock'+ 'Low energy' was translated into the EUNIS habitat 'A3.3: Low energy infralittoral rock'. For the deep-sea realm, as described in section 2.4.1, EUNIS was not applicable. For example the combination 'Upper bathyal'+ 'Mud'+ 'Low energy' was not translated into the overly restrictive EUNIS habitat 'A6.5: Deep-sea mud' but into the non-EUNIS habitat 'Upper bathyal mud'.

This led to a final habitat map comprising 47 habitats, from which 22 were EUNIS classes and 25 of which were new deep-sea habitat types.



**Fig. 4.** Schematic representation of method for coding the three environmental characteristics (A- energy level; B- substrate type; C- biological zone) in a GIS environment and combining them in a simple additive process to derive a habitat map (bottom right).

### 2.7. Confidence assessment

The MESH project developed a confidence assessment method for historical habitat maps based on metadata (MESH, 2008). The method involved giving a score to a habitat survey map based on criteria such as vintage, survey techniques used and interpretation techniques. This method was later adapted to substrate maps by the EMODnet Geology project (Stevenson, 2011). For the purposes of the present study, a pragmatic approach that could be easily applied by all contributors was required. The

rationale was therefore to apply a broad-scale assessment with an approach similar to the MESH method to each primary layer, namely energy, substrate type, and biological zones.

There is typically little information provided on the reliability of energy values computed from wave and current hydrodynamic models. As energy data is only used for rocky habitats it plays a minimal role in the final broad-scale map. Therefore, it was assumed that the confidence in energy layers would remain marginal in an overall assessment.

A confidence assessment of the substrate type layer was made using a modified version of the MESH confidence assessment tool (Mata Chacón et al., 2013). It was done on an individual map basis, with fourteen parameters divided into three categories collated from map metadata: five parameters describing the remote sensing surveys, five others for the collection of field data and another four accounting for the quality of the map-making process. These parameters enabled the data to be scored from 1 (lower) to 3 (higher), which were subsequently summed and expressed as a value between 0 and 100.

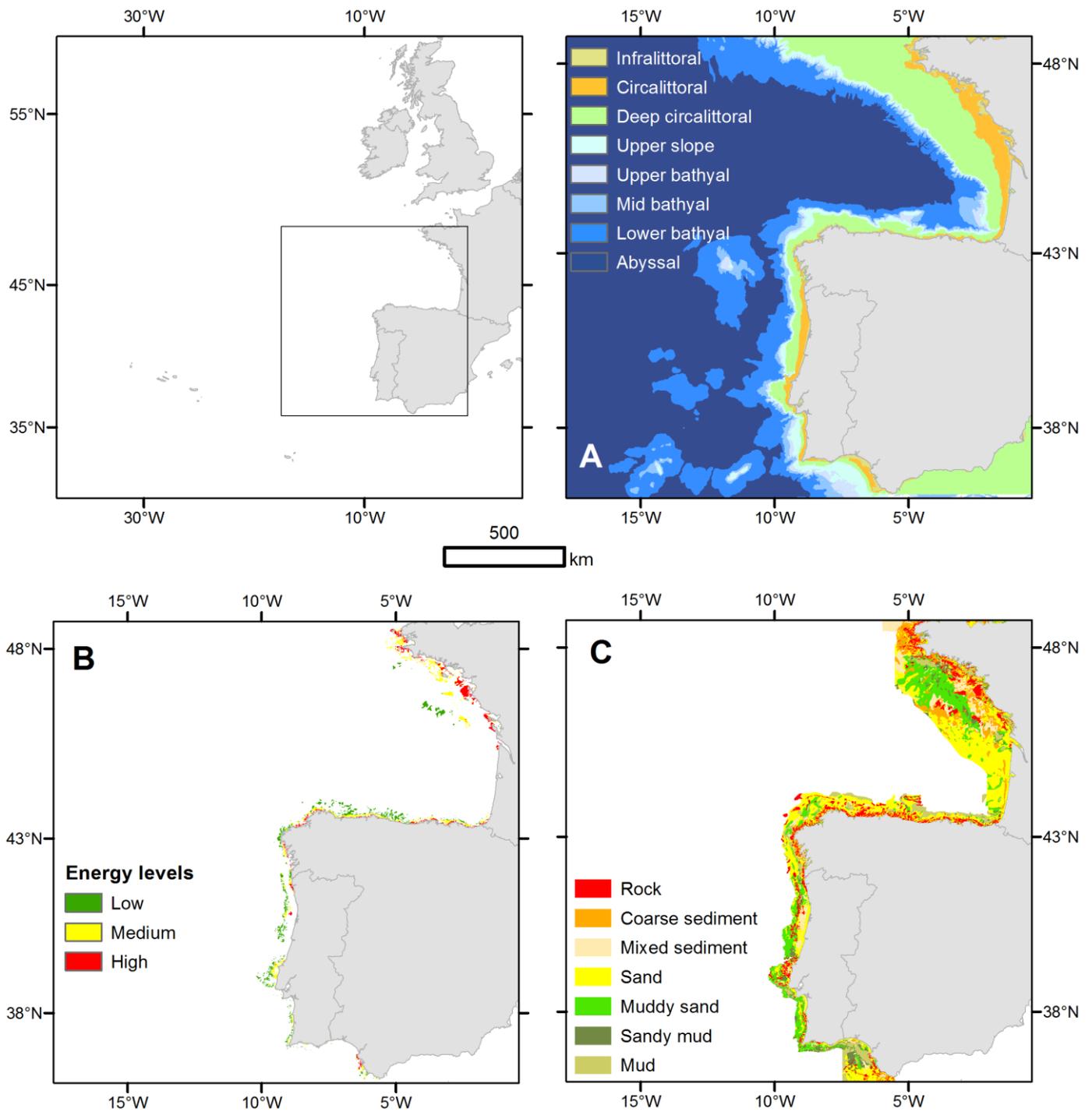
The segmentation of biological zones relies mainly on the bathymetry layer. The percentage of surface light reaching the seafloor and the  $\lambda/h$  ratio, used for defining the infralittoral and the circalittoral lower limits respectively, are a function of the depth, while the other boundaries were defined either directly by depth contours or by variation in slope delineated from depth derivatives. The spatial patterns in biological zones are therefore directly affected by the quality of the bathymetric layer, and for an initial approximation, we used a depth quality index as a proxy to confidence in those patterns. It made sense to use the same methodology as the EUSeaMap project when making the assessment of the confidence in the bathymetry layer (Cameron and Askew, 2011). The assessment of each dataset that was used to develop the bathymetry gridded layer was carried out using three criteria that were scored separately (data resolution or density, vintage, and origin). Each criterion was scored between 1 (low) and 3 (high), yielding a bathymetry confidence score between 3 and 9 (Mata Chacón et al., 2013).

In order to have comparable values between substrate and bathymetry confidence scores, the range of values of the latter (3-9) was converted into the range of confidence values of the former (0-100). Since both maps now displayed the same range of values, they could be merged via an un-weighted average.

### 3. Results

#### 3.1. Raw data and base layers

The three base layers, and the raw layers from which they are derived - such as wave-induced energy, light attenuation, or bathymetry - are not simply intermediate layers for the habitat map. They also constitute genuine products, as important as the habitat map since they provide full-coverage information for the entire study area on topics that are of interest to marine applications, both from a research and an industry perspective (e.g. extractive industries). An example of those layers are given in Figure 5.



**Fig. 5.** Primary layers for Bay Biscay and Iberian Peninsula. (A) biological zones, (B) energy levels (for rocky habitats only) and, (C) Seafloor substrate.

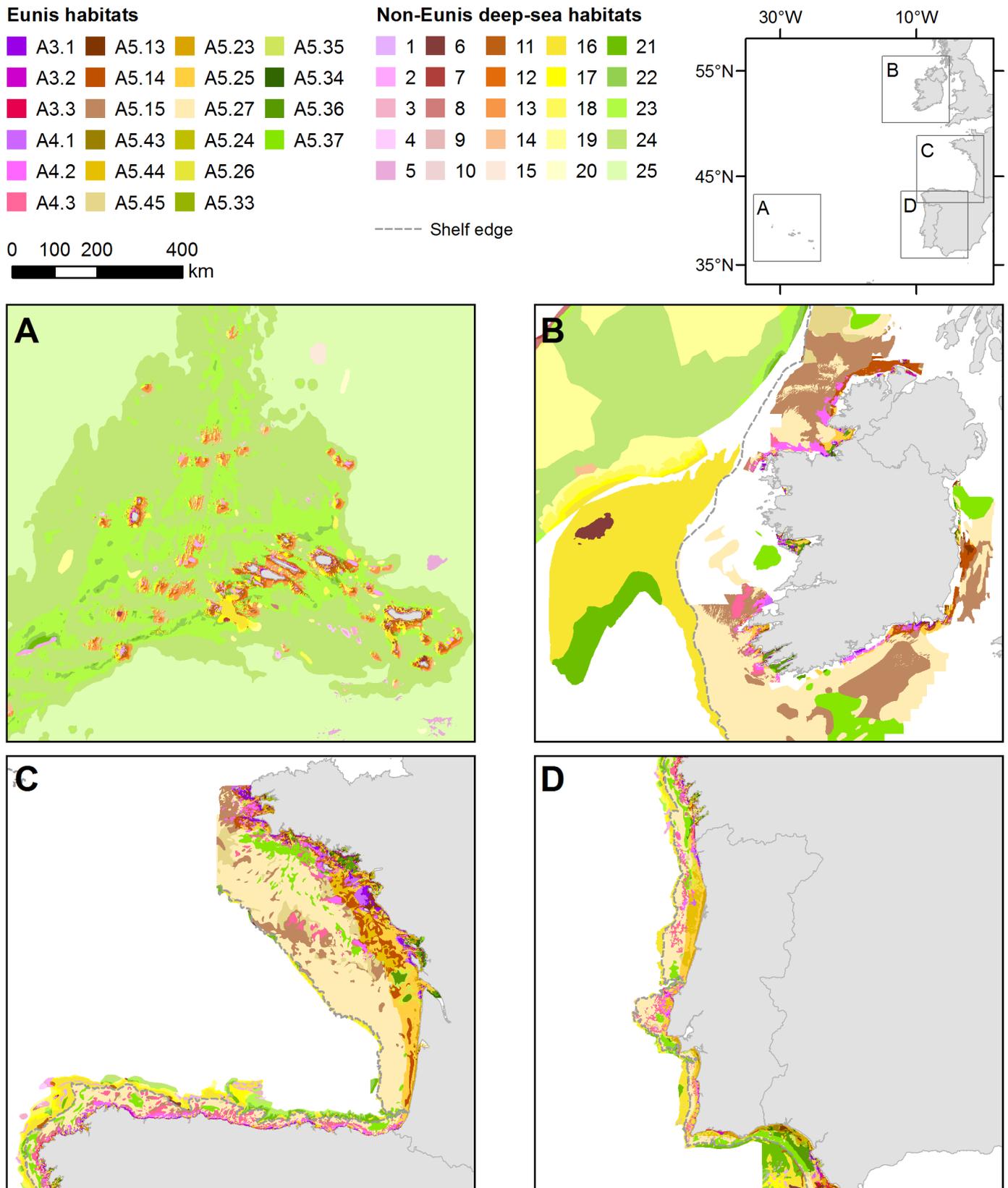
### 3.2. Habitat map

The spatial distribution of habitats is displayed in Figure 6. The area and the percentage area that are covered by each habitat are detailed in the annex and summarized as a bar graph in Figure 7. The results are split into three regions for which environmental condition were deemed comparable at a broad scale.

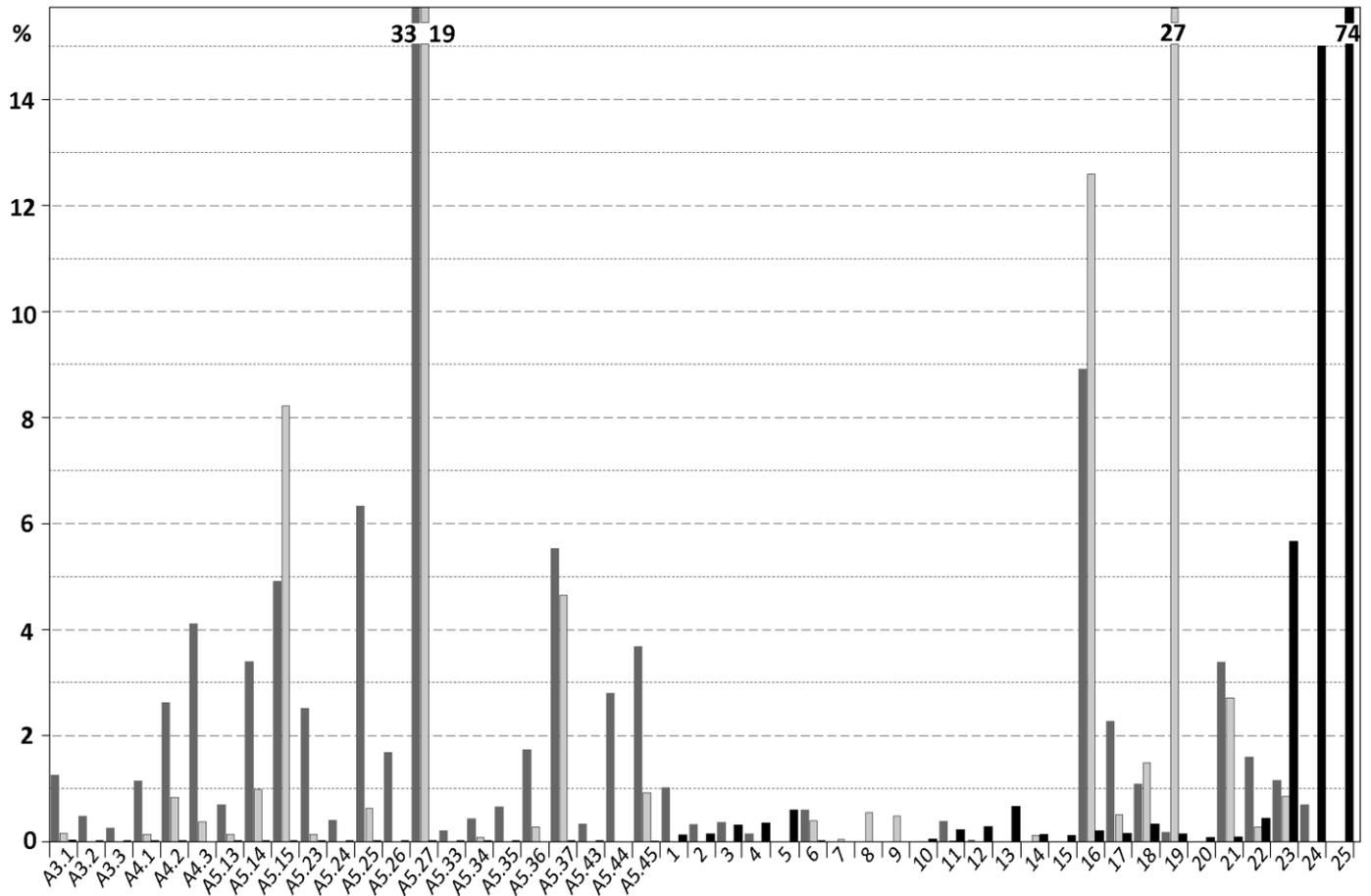
In the Bay of Biscay and the Iberian Peninsula, the area of shelf mapped is 132,000km<sup>2</sup>. In contrast to this the coverage for the deep sea in these regions is only 37,500km<sup>2</sup>. This difference is due to lack of information on substratum below the shelf, with exception of those areas along the Spanish coast where the shelf is narrower. Rocky habitat patterns are patchy but are present all along the coast and cover a large area (16,800km<sup>2</sup>). On those habitats the energy is rather high in the infralittoral zone while it is moderate to low in the circalittoral zone. Deep circalittoral sand is the habitat that covers the largest areas (55,671km<sup>2</sup>), especially off the coast of France. Other habitat types covering a large extent are circalittoral fine sand, deep circalittoral mud and upper slope sand to muddy sand. Coarse sediment is also widely distributed, especially in the circalittoral and deep circalittoral.

The areas of shelf and deep sea within the study area around Ireland were calculated as 100,000km<sup>2</sup> and 180,000km<sup>2</sup> respectively. There was not any data available for substrate type for the western and north-western areas that appear as not mapped. The figures (area and percentage area) given below, in Figure 7 and in the annex are relative to the area around Ireland that is mapped, i.e. not relative to the entire Irish seas. The deep circalittoral covers the majority of the shelf (95%). This is explained by the fact that the shelf is steep all along the coast, and thus seafloor areas not affected by wave action are very close to the shore. Rocky habitats cover 4,350km<sup>2</sup> and are essentially present along northwestern and southwestern coasts. These habitats are exposed to high energy in the infralittoral and moderate to low energy in the circalittoral. The deep circalittoral is mainly composed of sand (53,500km<sup>2</sup>), coarse sediment (23,300km<sup>2</sup>), and mud (13,200km<sup>2</sup>). In the deep sea, the most extensive habitat types are 'upper slope sand to muddy sand' (35,600km<sup>2</sup>), 'lower bathyal sand to muddy sand' (77,200km<sup>2</sup>) and 'lower bathyal mud to sandy mud' (45,700km<sup>2</sup>). The former reflects the Porcupine Bank while the latter two are found exclusively in the Rockall Trough.

An area of 1,676,000km<sup>2</sup>, which corresponds to 80% of the entire study area, was covered around the Azores. Shelves around the islands are quite narrow, and represent only an area of 1500km<sup>2</sup>, half of which is composed of rocks and one third of mixed sediment. Most of the infralittoral rocks are highly exposed to wave action. However, moderate regime is also significantly present. By contrast wave action on circalittoral rocks is fairly low. The study area covers 1,660,000km<sup>2</sup> of deep sea, of which 75% is abyssal. Hard substrate is found in each deep-sea biological zone, but most extensively in the abyssal (9,900km<sup>2</sup>). Likewise mixed sediments are present at each depth level, but the largest area is in the mid-bathyal (11,000km<sup>2</sup>). As expected, the most extensive habitat types are muddy ones, which cover 94,700km<sup>2</sup> in the mid-bathyal, 260,500km<sup>2</sup> in the lower bathyal, and 1,247,000km<sup>2</sup> in the abyssal, the latter representing 75% of the whole area covered for the Azores.



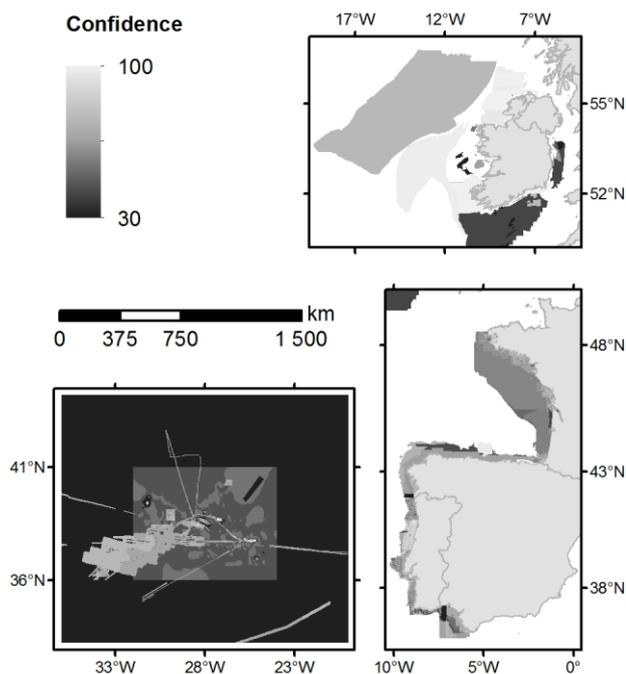
**Fig. 6.** Habitat map arbitrarily split into four regions (A: Azores; B: Ireland; C: Bay of Biscay; D: Iberian coast). The scale is identical for all regions. The shelf edge line shows the boundary between the shelf and the deep sea. The look up table between codes and class names is given in the annex.



**Fig. 7.** Percentage area covered by each habitat. Results are split into three regions: Azores (black bars); Bay of Biscay and Iberian Peninsula (dark grey bars); Ireland (light grey bars). The look up table between codes, class names, percentages and areas is given in the annex.

### 3.3. Confidence

The confidence map is presented in Figure 8. Extensive areas of minimal confidence, such as the southern part of Ireland or the deep waters of the Azores deep waters usually correspond to areas where the GEBCO dataset - pixel size of which is coarser - was widely used. Elsewhere, scores are typically in the range of 60 to 75, except where extensive mapping programs using recent techniques have been carried out, as is the case in Ireland, where two national seafloor mapping projects have been undertaken - INSS and its successor INFOMAR.



**Fig. 8.** Confidence map for Irish waters (upper right), Bay of Biscay and the Iberian Peninsula (lower right), and the Azores (lower left). Confidence is expressed as a score between 30 (low) and 100 (high)

#### 4. Discussion and conclusion

Spatial datasets describing the physical characteristics of the seafloor were combined to produce a broad-scale habitat map for four extensive areas, using a methodology that employed the best current knowledge and relies on EUNIS, a classification system widely used across Europe by managers and scientists. By integrating new datasets with improved accuracy, the quality of the broad-scale maps that had been produced for Irish and French seafloor in previous studies was enhanced. For the waters around the Azores, mainland Portugal and Spain, the study provided the first comprehensive perception of the distribution of habitats at a broad scale.

The means of assessing confidence in the final habitat map might not be the most robust, as i) it is a subjective assessment and ii) it is based solely on confidence in the bathymetry and the substrate type data. A better approach might be to compute a probability raster based on statistical validation for each underlying layer (i.e. substrate type, bathymetry, light, wave wavelength, wave- and current-induced energy). This method was tested by the UKSeaMap project (Mc Breen et al., 2011) for the wave- and the current-induced energy layers. The main obstacle to making such a meaningful confidence assessment for the present study is the fact that most layers were an amalgamation of many disparate datasets, each of which had a different provenance. The approach would have required each data provider to compute and provide a probability raster for their dataset, which is likely to be unattainable. At least the confidence map produced by the present study shows where the results are likely to be most accurate given the quality of the two key underlying layers that are the bathymetry and the substrate type. It is important to note that the score given by the confidence map at a given location does not give a percentage of chance that the mapped habitat is right, but a score expressing the confidence in the two layers.

The approach for the identification of the threshold values that define the boundaries between EUNIS categories was ecologically-driven, inasmuch as it relied on statistical analyses of observational data specific to each category. This gives an

added confidence to threshold values. Unfortunately, due to lack of readily available sample data, most of the threshold values could not be determined in this way. However, the use of the ROC curve is a recommendation of the current study to identify the optimal cutoff value that corresponds to a boundary between two categories when sample data is available for both categories.

Based on the experience gained from this research, future improvements to the resulting habitat map can be expected in the following areas: i) In the Iberian Peninsula and the Azores improved accuracy could be obtained for the definition of energy levels if models of tide or waves were of better resolution than those used for the purposes of the study (4 km). In this way the map might show more patterns of high energy thanks to e.g. the ability of fine resolution wave models to capture wave breaks. An along-shore pixel size of 250m would be optimal, but a 1km resolution would also be adequate. ii) wave- and current-induced energy layers would be greatly improved if they were based on unique models (i.e. one for waves, and another for currents). Using results from a single model would ensure coherence in the resolution and in the methodologies used for modeling. The authors of the current paper would like to encourage initiatives of high resolution (e.g. 200-300m nearshore, 3-4km offshore) modeling done at a European scale. iii) Threshold values of enhanced accuracy could be calculated, particularly for energy levels on rocky habitat. Studies to date, the present one included, have relied on limited field data specific to each wave-induced energy level, and have not validated the thresholds for current-induced energy levels suggested by McBreen et al., 2011. There would be a great potential for improvement if more sample data specific to each wave- or current-induced energy level was collated, something which was not possible during the course of this study. Likewise the threshold value for the boundary between the circalittoral and the deep circalittoral was backed up with a lot of observational data, but which was located in a relatively small French area. This value would be more reliable if it was confirmed by sample data located elsewhere. iv) The question of which variables should be used as proxies needs to be furthered. An example is the use of temperature conditions rather than the wave base for the definition of circalittoral/deep circalittoral boundary (see Glémarec, 1973). Likewise, a proxy for disturbance that would not only consider the magnitude of water movements, but also frequency, might be more relevant. v) The method used did not consider geomorphic features (e.g. seamounts, canyons). Since geomorphic features are acknowledged to host specific communities (e.g. Rogers, 1994), it is widely accepted that this information should be considered.

The main limitation to the resulting habitat map is its scale, 1:1,000,000. This makes it relatively unhelpful for local management applications. However it might be considered relevant for other applications within the study area. For example, benthic habitat maps are being used for Marine Protected Areas designation under different frameworks (e. g. Habitats Directive or OSPAR) according to different criteria such as representativity and adequacy, which should lead to the sustainable protection of relevant habitats and species. In addition to this the habitat map could be used for an assessment of the coherence of the existing MPA Networks (e.g. Natura 2000). The habitat map produced by the current study was used in that way by the Interreg IVB 'Atlantic Area 2007-2013' MAIA project (unpublished), the goal of which was to identify best practice methods for the identification, implementation and management of MPAs.

It is acknowledged the need of diverse, healthy and extensive benthic habitats areas to support the provision of important and valuable ecosystem services (i.e. food provisioning, disturbance prevention, nutrient cycling, etc.). Mapping seafloor habitats and assessing the ecosystem services they provide is a highly valuable means for understanding their current and potential benefits to society (Galparsoro et al., 2014). Habitat mapping has contributed to an improvement in the knowledge and application of several criteria and indicators used to assess environmental status in the European Marine Strategy Framework Directive (MSFD) in relation to the biological diversity descriptors, such as non-indigenous species and seafloor integrity (Borja

et al, 2011; Galparsoro et al., 2013). It might also be useful for other descriptors and for the development of sampling design for monitoring purposes. In addition to this, the MFSD requires the Member States to assess impacts due to pressure exerted by human activities. Assessing the quantity and distribution of anthropogenic impacts could be undertaken by intersecting spatial data of human pressures and seafloor habitats (Korpinen et al., 2013). Similarly, seafloor habitat maps provide a key information for present and future offshore activities placement such as fisheries, aquaculture and renewable energy installations (Douve and Ehler, 2009).

In conclusion, although broad-scale maps will never completely replace higher-quality, finer-resolution and more informative habitat maps derived from direct observations, needed for regional to local ocean management, they have the advantage of providing immediate resources to guide decision-makers involved in marine spatial planning in their search for solutions for sustainable development. The maps produced in this study, together with those compiled under the EUSeaMap project for Baltic, North, Channel, Irish and western Mediterranean sea basins, provide an improved perception of the spatial distribution of habitats across Europe than was available a few years ago.

The seafloor habitat layer is available online at <http://www.searchmesh.net>. For the other layers a specific demand should be made by email to the corresponding author.

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## Appendix

Code	EUNIS description	R1 km <sup>2</sup>	R1 %	R2 km <sup>2</sup>	R2 %	R3 km <sup>2</sup>	R4 %
A3.1	High energy infralittoral rock	2090	1.2%	462	0.2%	131	0.01%
A3.2	Moderate energy infralittoral rock	799	0.5%	70	0.0%	94	0.01%
A3.3	Low energy infralittoral rock	423	0.2%	17	0.0%	55	0.00%
A4.1	High energy circalittoral rock	1917	1.1%	383	0.1%	11	0.00%
A4.2	Moderate energy circalittoral rock	4438	2.6%	2355	0.8%	48	0.00%
A4.3	Low energy circalittoral rock	6967	4.1%	1067	0.4%	345	0.02%
A5.13	Infralittoral coarse sediment	1168	0.7%	407	0.1%	51	0.00%
A5.14	Circalittoral coarse sediment	5753	3.4%	2787	1.0%	108	0.01%
A5.15	Deep circalittoral coarse sediment	8332	4.9%	23271	8.2%	50	0.00%
A5.23	Infralittoral fine sand	4261	2.5%	394	0.1%	107	0.01%
A5.24	Infralittoral muddy sand	664	0.4%	3	0.0%	1	0.00%
A5.25	Circalittoral fine sand	10712	6.3%	1768	0.6%	103	0.01%
A5.26	Circalittoral muddy sand	2849	1.7%	56	0.0%	5	0.00%
A5.27	Deep circalittoral sand	55671	32.8%	53584	18.9%	42	0.00%
A5.33	Infralittoral sandy mud	355	0.2%	10	0.0%	0	0.00%
A5.34	Infralittoral fine mud	703	0.4%	221	0.1%	0	0.00%
A5.35	Circalittoral sandy mud	1085	0.6%	4	0.0%	0	0.00%
A5.36	Circalittoral fine mud	2920	1.7%	773	0.3%	0	0.00%
A5.37	Deep circalittoral mud	9387	5.5%	13173	4.7%	0	0.00%
A5.43	Infralittoral mixed sediments	547	0.3%	5	0.0%	104	0.01%
A5.44	Circalittoral mixed sediments	4747	2.8%	0	0.0%	252	0.02%
A5.45	Deep circalittoral mixed sediments	6230	3.7%	2618	0.9%	100	0.01%
1	Upper slope rock or reef	1725	1.0%	0	0.0%	1970	0.12%
2	Upper bathyal rock or reef	544	0.3%	0	0.0%	2344	0.14%
3	Mid bathyal rock or reef	606	0.4%	0	0.0%	5124	0.31%
4	Lower bathyal rock or reef	236	0.1%	0	0.0%	5727	0.34%
5	Abyssal rock or reef	0	0.0%	0	0.0%	9927	0.59%
6	Upper slope coarse sediment	1010	0.6%	1108	0.4%	203	0.01%
7	Upper bathyal coarse sediment	28	0.0%	110	0.0%	254	0.02%
8	Mid bathyal coarse sediment	45	0.0%	1562	0.6%	281	0.02%
9	Lower bathyal coarse sediment	3	0.0%	1367	0.5%	320	0.02%
10	Abyssal coarse sediment	0	0.0%	0	0.0%	790	0.05%
11	Upper slope mixed sediment	633	0.4%	27	0.0%	3748	0.22%
12	Upper bathyal mixed sediment	35	0.0%	0	0.0%	4636	0.28%
13	Mid bathyal mixed sediment	0	0.0%	0	0.0%	11027	0.66%
14	Lower bathyal mixed sediment	0	0.0%	349	0.1%	2144	0.13%
15	Abyssal mixed sediment	0	0.0%	0	0.0%	1860	0.11%
16	Upper slope sand to muddy sand	15101	8.9%	35599	12.6%	3347	0.20%
17	Upper bathyal sand to muddy sand	3847	2.3%	1444	0.5%	2575	0.15%
18	Mid bathyal sand to muddy sand	1830	1.1%	4221	1.5%	5544	0.33%
19	Lower bathyal sand to muddy sand	294	0.2%	77208	27.3%	2108	0.13%
20	Abyssal sand to muddy sand	0	0.0%	0	0.0%	636	0.04%
21	Upper slope mud to sandy mud	5746	3.4%	7648	2.7%	1322	0.08%
22	Upper bathyal mud to sandy mud	2699	1.6%	780	0.3%	7339	0.44%
23	Mid bathyal mud to sandy mud	1968	1.2%	2411	0.9%	94675	5.65%
24	Lower bathyal mud to sandy mud	1176	0.7%	45709	16.2%	260436	15.53%
25	Abyssal mud to sandy mud	0	0.0%	0	0.0%	1246973	74.36%
<b>Sum</b>		<b>169,544</b>	<b>100%</b>	<b>282,971</b>	<b>100%</b>	<b>1,676,922</b>	<b>100%</b>

R1: Bay of Biscay and Iberian coast; R2: Irish coast; R3: the Azores