Deliverable 3.4 - Conservation Management Issues in ATLAS

Basin-scale systematic conservation planning: identifying suitable networks for VMEs protection

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D3.4 Conservation Management Issues in ATLAS. Basin-scale systematic conservation planning: identifying suitable networks for VMEs protection

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Executive summary

The last two decades have witnessed a complete shift in our perception of the deep sea, from a homogeneous, mostly muddy and unspoiled seafloor to a vast patchwork of diverse and fragile habitats as well as a reservoir of living resources, both energy and mineral. Growing and concomitant awareness of the potential for blue growth and vulnerability of deep-sea ecosystems triggered the implementation of management measures and Marine Spatial Planning (MSP) at national, regional and international levels, which are now cumulating in the UN Decade of Ocean Science for Sustainable Development and the International Conference on Marine Biodiversity of Areas Beyond National Jurisdiction (ABNJ). Based on the best available knowledge collated and produced in the framework of ATLAS, the objective of the present deliverable was to integrate all available data into a common analytical framework for systematic conservation planning at the scale of the North Atlantic.

Regional-scale MSP in the deep sea unfortunately suffers from a lack of knowledge on the distribution of species and habitats. Such large-scale endeavours to date have thus been mainly relying on biogeochemical and physiographic proxies to design networks of marine protected areas. In just three years, ATLAS has taken an unprecedented step forward in synthesising the data available for the North Atlantic on the distribution of the most vulnerable deep-sea habitats where fragile and long-lived engineering species, such as corals and sponges, are aggregating. Such a synthesis has been enabled through trans-Atlantic collaboration. The 13 case studies (CS), evenly distributed from north to south and east to west of the northern Atlantic, provided new discoveries of deep-sea vulnerable habitats off Greenland, in the Alboran Sea and the Gulf of Cádiz, as well as on Formigas and Tropic seamounts. Beyond new discoveries, ATLAS CS confirmed and improved knowledge on the distribution, ecology and functionality of those vulnerable habitats in the North Atlantic. **For Case Study 1** – LoVe Observatory, 1417 records of *Lophelia pertusa* coral reefs along the Norwegian coast are included. **For Case Study 6** - Bay of Biscay, a total of 450 records of 12 different VME types, including coral reefs, coral rubbles, scleractinians, Antipatharians, gorgonians, seapens or pennatulids, mixed corals, aggregation of actiniarians, sponge community and Xenophyophores, are reported. **For Case Study 7**, VMEs are reported for two areas: 1) for Seco de los Olivos, in the Alboran Sea, 17 VMEs that include sea pen fields, deep-sea sponge aggregations and diverse coral gardens are reported, and 2) for the Volcano of Gazul, in the Gulf of Cádiz, 16 VMEs are reported, that include diverse coral gardens, mud and sand emergent fauna, cold-water coral reef of *Lophelia pertusa / Madrepora oculata* and deep-sea sponge aggregations. **For Case Study 8**, VMEs from different areas of the Azores are included: in the Formigas Seamount, 18 VMEs including diverse coral gardens and deep-sea sponge aggregations are reported. Cavalo Seamount, a ridge on the Mid-Atlantic Ridge, Gigante Seamount, Condor Seamount, Dom João de Castro Seamount, and Mar de Prata Seamount also host various coral gardens; the South of Pico Island hosts a deep-sea sponge aggregation of *Pheronema carpenteri*. The newly discovered Hydrothermal Vent Luso is also reported as a VME for the Azores. **For Case Study 10** – Davis Strait, Eastern Arctic, 8 VME areas of deep-sea sponges, 5 VME areas of large gorgonian corals, 4 of small gorgonian corals and 13 of sea pens are reported. Under Case Study 10, the only known *Lophelia pertusa* reef in Greenland waters is also reported. **For Case Study 11** – Flemish Cap, three VME types were identified by the Northwest Atlantic Fisheries Organization (NAFO) and for each, several VME areas are reported: 13 VME areas for sponges, 6 for sea pens and 7 for large gorgonians. **For Case Study 12** - Mid-Atlantic Canyons and SE USA, four VMEs are included: 1) Cape Lookout Coral Banks, dominated by large bioherms built by *Lophelia pertusa*, 2) Hatteras Middle Slope, a physically and biologically unique area of rugged mini-canyons (composed of consolidated muds), 3) Norfolk Canyon, and 4) Baltimore Canyon and vicinities, two rugged submarine canyons that contain extensive cold-water corals. **For Case Study 13** - Tropic Seamount is host to multiple VMEs, including dense patches of reef framework-forming scleractinian, dense aggregations of coral gardens, dense monospecific sponge ground of *Poliopogon amadou*, mixed deep-sea sponge aggregations, Xenophyophore field, and dense crinoid fields.

Knowledge gained from ATLAS CS significantly increases the database of vulnerable marine ecosystem (VME) occurrences in the northern Atlantic but the species that define VMEs have been known about for over a century. In order to get an overview of the distribution of VMEs, data coming from sources as various as historical cruises, by-catch of fisheries surveys and Remotely Operated Vehicle (ROV) surveys must be compiled. The reliability of these data however varies and a confidence index has thus been developed in order to objectively and quantitatively rank the reliability of VME records according to the source of records. The ranking ranges from low, for inferred records, to high, for visually assessed records. In addition, not all VMEs equally meet the criteria of rarity, functional significance, fragility and recovery, which vary according to taxa and the abundance of indicator taxa. A VME index has thus been developed to quantitatively and objectively score the vulnerability of VME records. The VME index and the confidence index have been applied to the records of the VME database created and curated by the joint ICES/NAFO Working Group on Deep-water Ecology (WGDEC). This spatial grid of VME likelihood was completed with the unequivocal VMEs mapped in the ATLAS CS.

In general, the VME index provides a simplified, spatially aggregated and weighted estimate of the degree to which an area could be considered to contain VMEs under the Food and Agriculture Organisation of the UN (FAO) definition. The VME index clearly highlights areas where a VME is more likely to occur while the associated estimate of confidence gives an indication of how (un)certain that assessment is. The methodology is transparent, science based and data driven, and the aggregate cells can be explored in greater detail to reveal the individual data points that have contributed to the assessment. It integrates far more information than previous methods and as such, better captures the underlying reasoning for identifying VME areas or benthic deep-sea Ecologically or Biologically Significant Marine Areas (EBSAs). The VME index is expected to be updated each year as new data are submitted and will therefore provide an up to date, repeatable and defensible source upon which to base advice as new information is received. The VME index appears to capture most of the important elements of the VME database. This methodology may be considered as a first step towards a systematic approach for the identification and protection of VMEs and EBSAs in the North Atlantic. Our methodology clearly considered several of the steps proposed by Ardron et al. (2014), namely step 1 on assessing potential VME indicator taxa and habitats in a region, step 3 on considering areas already known for their ecological importance, step 4 on compiling information on the distributions of likely VME indicator species and habitats, step 6 on considering fishing impacts, and step 8 on identify ecologically important areas. However, at least one important aspect of the Ardron et al. (2014) framework is missing in the current VME index which refers to understanding the natural distribution of VMEs before significant impacts occurred. This aspect could be considered in future improvements of the VME index to encompass predicted distribution of VME as discussed in Vierod et al. (2014) and Anderson et al. (2016b).

Systematic conservation planning is an explicit, objective-based and quantitative approach for allocating areas for biodiversity conservation, for instance used in Marine Protected Area (MPA) networks design process. It aims to identify priority areas answering specific conservation objectives for each considered species or habitat, whilst minimising the socioeconomic costs of conservation over the study area. For the purpose of systematic conservation planning, data on known or inferred VMEs are still too sparse at the scale of the northern Atlantic. The spatial prioritisation developed here aimed to identify zones of conservation importance for seabed species and habitats associated with VMEs in a comprehensive approach, by complementing the **records of unequivocal VMEs** and the **VME likelihood over the basin** resulting from the VME index with supplementary information targeting deep-sea species and habitats. ATLAS modelled the present and future **distributions of six coral species indicators** of VMEs as well as **six exploited fish species** (D3.3). Through a collaboration with the H2020 Blue Growth SponGES project, the present and future distribution of **one sponge species** have also been modelled to provide maps of the distribution of key VME indicator taxa with different environmental requirements, life-history strategies and functional significance. The overlap between the present and future distribution of these species under climate change scenarios further allowed the mapping of their future **climate refugia**, constituting resilient areas that were given a high conservation target in simulations. Although the primary focus of ATLAS is on cold-water corals, there is more at stake in terms of conversation in the northern Atlantic. In order to increase the scope of this systematic conservation planning exercise, **chemosynthetic ecosystems** that qualify as VMEs as well as large physiographic features known to be functional hotspots such as **canyons**, **seamounts** and **fracture zones** have also been considered. Conservation scenarios integrated current management and human activities aspects over the basin, to combine the conservation and socioeconomic stakes during the prioritisation process. While areas already profiting from conservation designations such as **fishing closures, MPAs and EBSAs** were favoured, areas situated in major **bottom-fishing grounds** or within **deep-sea mining contracts** were penalised. In order to suggest a geographically balanced protection network, conservation objectives were replicated within **13 provinces**, which considered the main biogeographic and geographical boundaries over the basin as well as a dissociation between broad shallow (<800m) and deep (>800m) habitats. This regionalisation approach ensured a regional replication and representativity of each conservation feature within the main deep-sea biotopes. Finally, this work addressed benthic connectivity aspects, by using the results of **larvae drift models** to favour connected networks of conservation as best as possible.

Emerging from an incremental scenario complexification process, the final simulation ("all management", Figure 1) resulted in an ecologically coherent conservation network that gave insight into spatial planning possibilities to better protect seabed vulnerable habitats and species. In particular, continental margin slopes, the Mid-Atlantic Ridge, and shelf areas comporting fishing grounds appeared as crucial zones for preserving deep-sea biodiversity (Figure 1). These identified areas comprised of specific habitats (e.g. canyons, ridges, seamounts), concentrating diverse substrates and representing key areas for nutrient circulation, that sustain VMEs and deep-water fish. Even if their depth range is larger, most of the VME indicator taxa used in this study largely occur between 500 and 2500m depths, which were prioritised here. For some species, including gorgonians (*Acanella arbuscula*, *Acanthogorgia armata*), scleratinian coral (*Lophelia pertusa*) and the sponge species (*Geodia barretti*), future climate refugia are almost exclusively predicted along margin slopes (ATLAS D3.3), that appeared as the most prioritised areas in conservation scenarios. In addition, the Mid-Atlantic Ridge concentrates sites of hydrothermal activity, giving rise to unique chemosynthetic ecosystems. As all known hydrothermal vents south of the Azores Exclusive Economic Zone (EEZ), but also several other VMEs, are located in areas already pre-empted for massive sulphide exploration, these latter contained substantial conservation potential. Identified conservation areas situated within the International Seabed Authority (ISA) contracts could inform the regional management plan to be implemented for preserving the Mid-Atlantic Ridge biodiversity from adverse mining impacts. Finally, the prioritisation results suggest that conservation objectives, especially for demersal fish species, could not be achieved without including large fished areas situated on shelves. This result may promote the development of conservation measures on fishing grounds, from full closures for the most efficient, to species-based catch limitation or minimum fish size. The implementation of such restrictions in EEZs or Regional Fisheries Management Organisations (RFMOs) regulatory areas in Areas Beyond National Jurisdictions (ABNJs) would also contribute to fisheries' sustainability objectives.

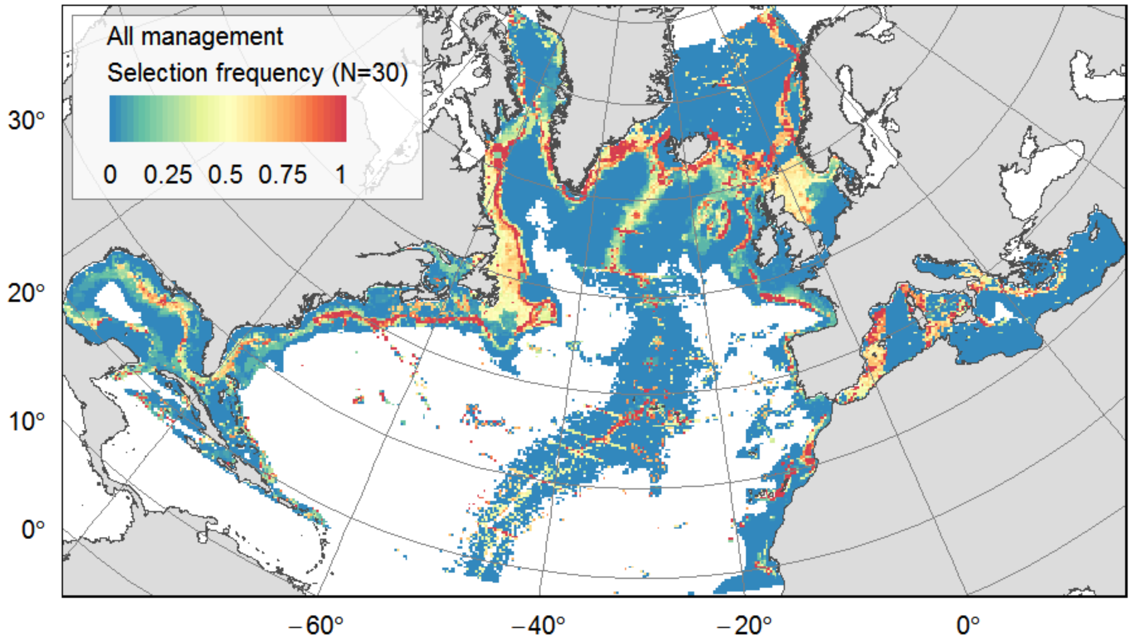

*Figure 1. Map displaying the output of the final scenario "all management". The conservation scenario was implemented from coasts to bathyal depths (3500m), in a gridded study area consisting of 25*25km planning units. The 30 solutions displaying the lower cost among the 100 runs implemented were selected to map the results. The selection frequency of planning units within the 30 selected solutions ranges from 0 (in blue), representing the planning units of the study area that were never selected and thus, do not contribute to conservation solutions, to 1 (in red), representing the PUs that were systematically selected in the 30 solutions.*

Selecting the most prioritised planning units allowed delineation of the main priority areas for deep-sea conservation (*Figure* 2). Covering approximatively 17% of the study area, these priority areas would answer a relatively high conservation goal for the deep sea, nonetheless they suffer from poor conservation at the moment (Figure 2). Less than 1% of the study area falls into fishing closures and marine reserves that already protect the priority areas for benthic deep-sea ecosystems. For instance, only a few unequivocal VMEs, species climate refugia or canyons currently benefit from some form of protection. In that respect, our systematic planning exercise has shown that, as important as they are, the sum of all Area-Based Management Tools (ABMTs) of the northern Atlantic still suffer from a lack of conservation efficiency, representativity and viability. Moreover, our results highlighted that a more continuous conservation network, displaying corridors or shorter distances between conservation areas, would lead to a more connected and thus more resilient benthic conservation framework. Ultimately, climate change pressures are likely to largely affect deep-sea oceanography and biodiversity, and the ability of current ABMTs to preserve them. Protecting the priority areas herein identified, which hold substantial resilience potential to future environmental changes through the central place of climate refugia in scenarios, could promote the long-term viability of the deep-sea conservation for the North Atlantic.

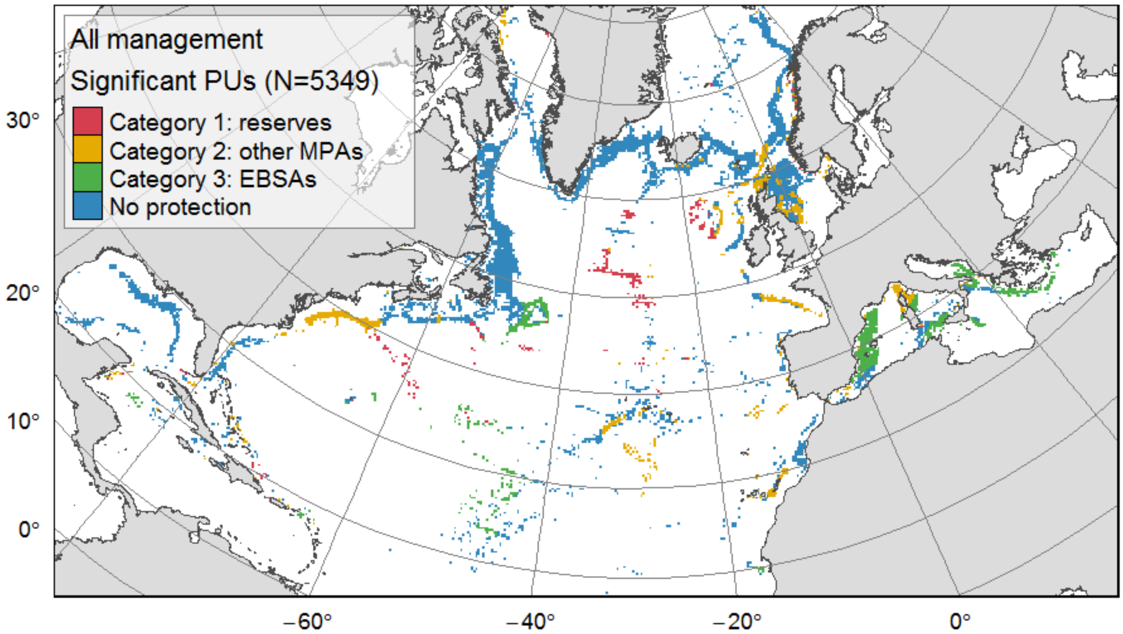

Figure 2. Map of the priority areas delineated with the significant planning units (PUs) selection (i.e. the PUs that were selected at least in 50% of selection frequency) for the "all management" scenario. The 4 colour categories display the presence of current protection designations: fishing closures and marine reserves (category 1), other MPAs with lower protection level (category 2), EBSAs (category 3), and no protection. The 3 ABMT categories (red, orange, green) represent 24.7% of this selection.

To our knowledge, this study is the first in systematic conservation planning to address the conservation of deep-sea benthic and demersal biodiversity across a whole oceanic basin. These results contribute to the development of systematic approaches for large scale MSP, such as the conservation management of ABNJs currently the object of ongoing international discussions. Lacking of a coordinated framework as well as efficient, permanent and recognised protection measures, the North-Atlantic high seas conservation network could benefit from the suggestions provided by our scientific evaluation. Finally, this basin scale prioritisation will provide general material for local conservation, through a transfer to the MSP work implemented for ATLAS case studies in ATLAS Work Package 6.

1 General Introduction

Deep-sea ecosystems are under increasing pressures from human activities (Ramirez-Llodra et al., 2011). As resources decrease on land and on shore, exploitation intensifies further offshore, and deeper. Deep-sea fishing has been shown to induce the depletion of deep-water fishes, and the fishing gears impact can adversely wipe out entire habitats, such as cold-water coral reefs, that may never recover (Bailey et al., 2009; Koslow et al., 2000; Roberts, 2002). Along with the progress of fishing further deep, the recent advances in technology opened the way for biotechnology industry to exploit the high potential of deep-sea biochemical compounds hold by benthic species. The oil and gas industry went deep two decades ago (LaBelle, 2001), soon followed by the mining industry (Sharma, 2017). Deep-sea mining exploration targets deep-sea minerals that are often found in areas supporting high biodiversity, such as hydrothermal vents (Van Dover, 2011). Facing these growing exploitation threats, the future of deep-sea species and habitats is also largely concerned by climate change consequences. Increasing water temperature and acidity will widely affect deep-sea ecosystem structure and function (Sweetman et al., 2017).

The environmental consequences of the many risks posed by human activities on deep-sea ecosystems, including cumulative impacts, remain highly uncertain and challenge the sustainable exploitation of deep-water resources (Armstrong et al., 2019; Levin, Mengerink, et al., 2016). “Experience from terrestrial and coastal areas indicates that a systematic approach to conservation planning and management can help to maintain ecosystem health and productivity while enabling sustainable use” (Ban et al., 2014). A number of regional or international agreements, conventions and laws may contribute to the management of deep-sea ecosystems (Ardron et al., 2014). Each has dedicated spatial planning instruments such as Vulnerable Marine Ecosystem designation by the FAO and fisheries closures by RFMOs to regulate fishing, Areas of Particular Environmental Interest by the International Seabed Authority to regulate seabed mining, Ecologically and Biologically Significant Areas by the Convention on Biological Diversity (CBD) to highlight biodiversity or the OSPAR designation of marine protected areas as well as threatened species or habitats. Most of these management measures pertain only to Areas Beyond National Jurisdiction. Yet, with less than 2% of coverage, ABNJ protection is largely underrepresented compared to EEZ protection (17%) and protection objectives (10% goal of the CBD Aichi target 11, CBD/COP10)(UNEP-WCMC & IUCN, 2019). Moreover, even though management measures in ABNJ all share the same overarching goal of protecting and preserving the marine environment as required by the United Nation Convention on the Law of the Sea (UNCLOS), spatial planning is implemented for sectorial purposes at regional scale. This is an obstacle to the design of an integrated, ecologically coherent, representative, and comprehensive network of MPAs (Ardron et al., 2014). While such a governance impediment is tackled by ongoing discussions to develop a new legally-binding instrument for the conservation and sustainable use of marine biological diversity of ABNJ (Wright et al., 2019), designing an ecologically coherent network of MPAs presents is challenging (Johnson et al., 2014) and requires the development and use of systematic conservation planning (Ban & Klein, 2009; Wright et al., 2019). Climate change makes it even more challenging as it is likely to severely limit the effectiveness of currently existing protection measures (Johnson, Ferreira, & Kenchington, 2018).

A major constraint on the development of systematic conservation planning in the deep sea, and particularly in ABNJ, is the lack of baseline data on the distribution, biogeography and connectivity of both vulnerable and exploited species (Wright et al., 2019). ATLAS made significant progress filling those gaps for the North Atlantic by gathering new information on Vulnerable Marine Ecosystems (VMEs), developing a framework for the identification and ranking of VMEs from records of VME indicators taxa, as well as modelling the current and future distribution of key vulnerable and exploited species.

The objective of the ATLAS Deliverable 3.4 is to integrate all of these data into a common analytical framework for systematic conservation planning at the scale of the North Atlantic.

In particular, ATLAS Deliverable D3.4 aimed to:

1. Summarise the information on VMEs in each ATLAS case study and about the new VMEs discoveries made through ATLAS.

2. Achieve Ecosystem Evaluation Framework (EEF) designation of portfolio conservation categories and contribution of existing conservation initiatives to ensure Good Environmental Status (GES).

3. Delineate areas of management importance including potential EBSAs (EEF designations) for seabed biodiversity and inform the importance of each ATLAS case study for the North Atlantic basin conservation

2 Bona fide Vulnerable Marine Ecosystems (VME) identified in ATLAS case studies

2.1 Introduction

Recognising the vulnerability of deep-sea biodiversity, the United Nations General Assembly (UNGA) called upon States and Regional Fisheries Management Organisations (RFMOs) to identify areas beyond national jurisdiction (ABNJ) where vulnerable marine ecosystems occur, or are likely to occur, and to prevent significant adverse impacts (UNGA, 2006). The Food and Agricultural Organization (FAO) of the United Nations subsequently developed guidelines for the management of deep-sea fisheries in the high seas (FAO, 2009). This included criteria for defining what constitutes a VME:

1. Uniqueness or rarity - an area or ecosystem that is unique or that contains rare species whose loss could not be compensated for by similar areas or ecosystems. These include: habitats that contain endemic species habitats of rare, threatened or endangered species that occur only in discrete areas nurseries or discrete feeding, breeding, or spawning areas;

2. Functional significance of the habitat - discrete areas or habitats that are necessary for the survival, function, spawning/reproduction or recovery of fish stocks, particular life history stages (e.g. nursery grounds or rearing areas), or of rare, threatened or endangered marine species;

3. Fragility - an ecosystem that is highly susceptible to degradation by anthropogenic activities;

4. Life-history traits of component species that make recovery difficult - ecosystems that are characterised by populations or assemblages of species with one or more of the following characteristics: slow growth rates, late age of maturity, low or unpredictable recruitment, and/or long-lived;

5. Structural complexity - an ecosystem that is characterised by complex physical structures created by significant concentrations of biotic and abiotic features. In these ecosystems, ecological processes are usually highly dependent on these structured systems. Further, such ecosystems often have high diversity, which is dependent on the structuring organisms.

These criteria may apply to a wide variety of habitats and ecosystems of the deep sea (e.g. hydrothermal vents, seamounts or cold seeps). Generally, VMEs have been identified based on the occurrence of indicator taxa such as stony or gorgonian corals, or sponges. However, these taxa can occur in varying spatial densities, and the FAO guidelines do not provide threshold values for defining what constitutes ‘‘significant concentrations’’ of VME indicator records that would constitute an actual VME (Auster et al., 2011).

VMEs are best identified using high quality underwater imagery (Remotely Operated Vehicles - ROV, towed camera, etc.), allowing accurate and quantitative description of community composition and associated fauna (e.g. Fabri et al., 2014). A major component of the ATLAS project has been the collection of new data on biodiversity and benthic communities through dedicated cruises using different technological means including ROV video surveys, submersibles and drop-down camera systems, and the collection of biological samples (see Deliverable 3.3). During these cruises, many areas that may fit the FAO criteria for defining vulnerable marine ecosystems have been found. In this section, we provide a summary description of bona fide VMEs identified in several of the ATLAS case studies.

2.2 Case Study 1 – LoVe Observatory

2.2.1 Name of the VME

Lophelia pertusa reefs

2.2.2 Latitude / longitude of the centre of the VME

The distribution of 1417 records of *Lophelia pertusa* reefs collected from historical data and oceanographic survey programs along the Norwegian coast in Case Study #1 is displayed in Figure 3.

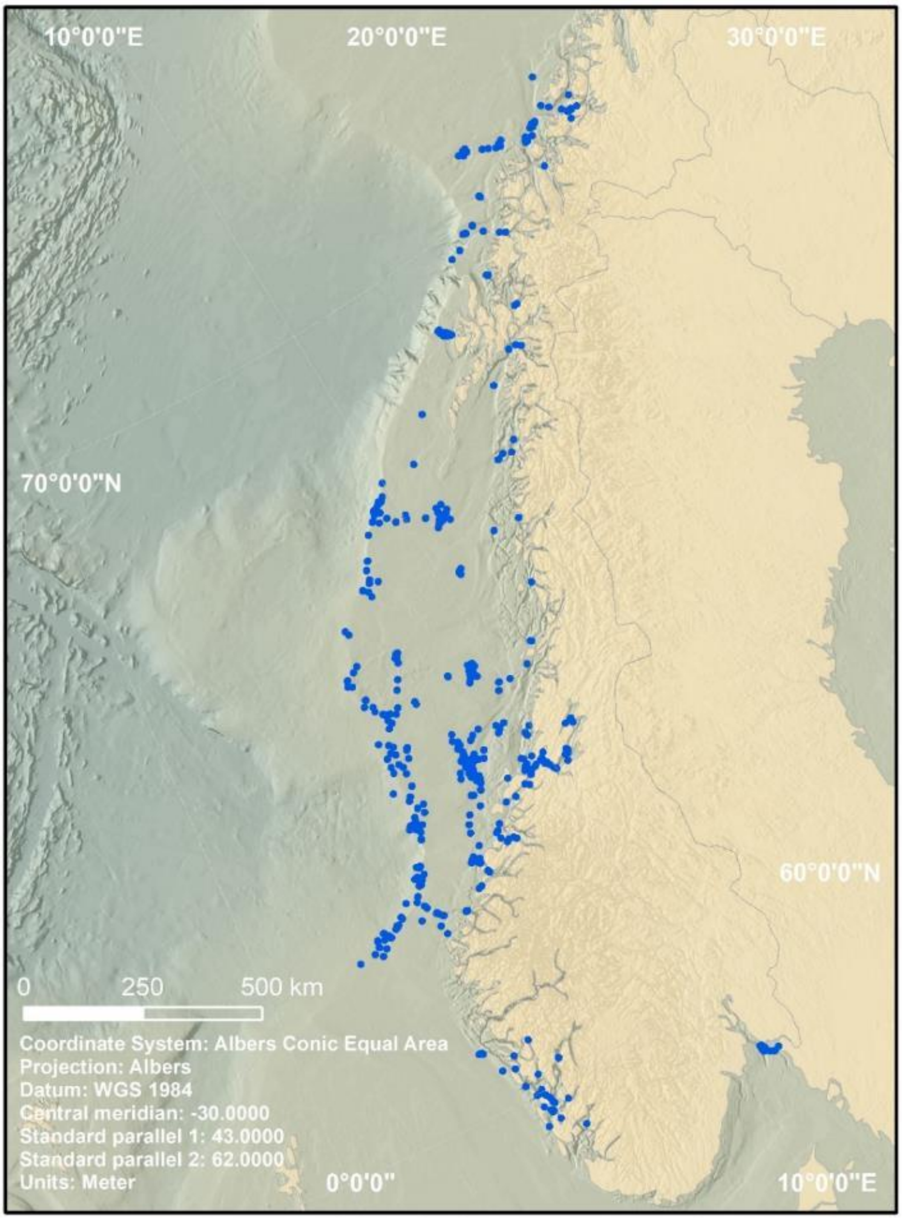

Figure 3 Distribution of Lophelia pertusa *reefs for Case Study #1 LoVe Observatory*

2.2.3 Features description

Identified coral areas available on the MAREANO website (http://www.mareano.no) were included.

2.2.4 Supporting citations

MAREANO - Cold water coral reefs V1.0 (2014). Institute of Marine Research. http://www.mareano.no

2.3 Case Study 3 – Rockall Bank / Faroe-Shetland Channel

Given that all the areas visited by the case study partners over the last two years had already been visited before, any VMEs had already been identified. All the relevant data from within the Scottish sea area (Rockall Bank, Faroe-Shetland Channel, Mingulay) required for the purpose of this study had already been submitted to ICES. The species data (VME indicator species) submitted to ICES underpins the identification of VME areas.

2.4 Case Study 6 – Bay of Biscay

2.4.1 Name of the VME

Table 1. VMEs identified in Case Study #6 – Bay of Biscay and number of records per VME type.

VME	Number of records
Coral reef	96
Coral rubble	124
Colonial scleractinians on soft substrates	59
Colonial scleractinians on hard substrates	31
Antipatharians or gorgonians on hard substrates	16
Mixed corals on hard substrates	28
Solitary scleractinians on soft substrates	6
Gorgonians on soft substrates	9
Seapens or pennatulids on soft substrates	46
Mixed corals on soft substrates	3
Aggregation of actiniarians	16
Sponge community	7
Xenophyophores on soft substrates	9
Total	**450**

NB. Segments of habitats with a length lower than 8 m (an area of ca. 25 m^2), which is the lower size limit to define a habitat, were not included.

2.4.2 Latitude / longitude of the centre of the VME

The distribution of the VMEs reported for Case Study #6 Bay of Biscay is displayed in Figure 4.

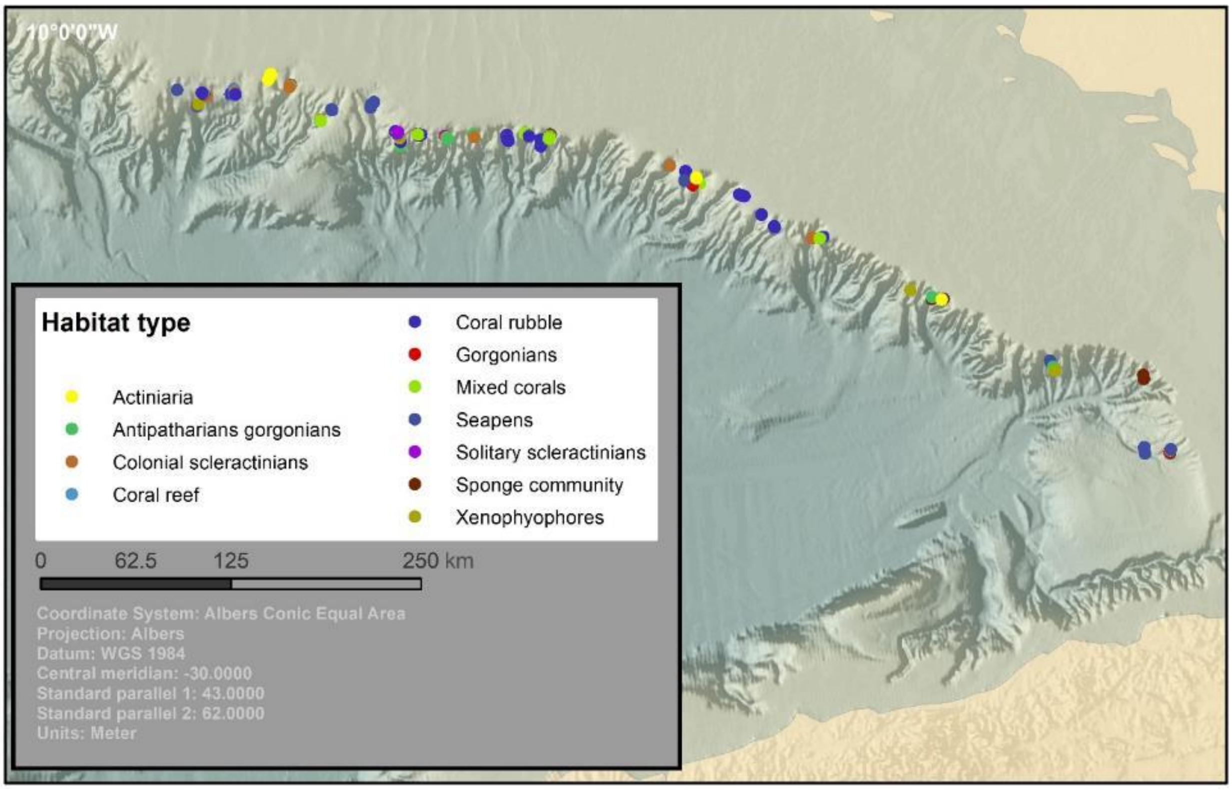

Figure 4. Distribution of the different VMEs by habitat types in the Bay of Biscay

2.4.3 Features description

The operational definition of VMEs in the Bay of Biscay:

The known distribution of VMEs in the Bay of Biscay comes from the image analysis of 46 dives of the ROV Victor 6000 and the towed camera Scampi, carried out during 7 oceanographic cruises between 2009 and 2013 (van den Beld et al., 2017). The video transects aimed to describe and map the cold-water coral habitats of the Bay of Biscay. They cover a bathymetric range of between 185 m and 2665 m, in or near 24 submarine canyons. Each image has been assigned a habitat characterising the substrate (soft or hard) and aggregations of fauna, following a methodology and a typology developed in the framework of the European project CoralFish (Davies et al., 2017). The operational definition of a habitat is an area that shows similar dominant species compositions in multiple seafloor photos along a video footage stretch representing an area ≥ 25 m². Since it was not possible to accurately assess the footprint of videos and images from our dataset, we instead assigned a threshold of footage stretch ≥ 8 m. The aggregations of VME indicator taxa (ICES, 2016) were then used to match the CoralFish habitat classification with the typology of VME habitats proposed by the ICES Working Group on Deep-water Ecology (Table 2).

Table 2. List of benthic habitats with aggregations of VME indicator taxa according to CoralFish and ICES/WDGDEC typologies.

Extended CoralFish classification	VME typology (ICES/WGDEC)
Coral reef	*Lophelia pertusa*/*Madrepora oculata* reef
Coral rubble	Hard-bottom coral garden
Colonial scleractinians on soft substrates	Hard-bottom coral garden
Colonial scleractinians on hard substrates	Colonial scleractinians on rocky out-crops
Antipatharians and gorgonians on hard substrates	Hard-bottom gorgonian and black coral gardens
Mixed corals on hard substrates	Hard-bottom coral garden
Solitary scleractinians on soft substrates	Cup-coral fields
Gorgonians on soft substrates	Soft-bottom gorgonian and black coral gardens
Seapens on soft substrates	Sea-pen fields
Mixed corals on soft substrates	Soft-bottom coral garden
Aggregations of Actiniaria	Anemone aggregations
Sponge community on hard substrates	Hard-bottom sponge aggregations
Sponge community on soft substrates	Soft-bottom sponge aggregations
Xenophyophores on soft substrates	Xenophyophores

Description of VMEs in the Bay of Biscay

Each VME in the Bay of Biscay is described below:

Coral reefs in the Bay of Biscay are built by the two scleractinian species *Madrepora oculata* and *Lophelia pertusa*, growing on dead framework and/or rubble. Coral reefs were observed on twelve dives, from ten canyons, and at depth ranging from 655 m to 1239 m. The cumulated length of dive transects where coral reefs were observed total 10.8 km. The length of single habitat ranged from 8 to 1180 m, with a median at 65 m. A total of 3208 individual corals were observed in this habitat belonging to 32 morphotypes. The three most abundant taxa were *Leiopathes* spp. (1923 colonies), *Stichopathes gravieri* (293 colonies) and *Narella versluysi* (238 colonies). The main traits qualifying coral reefs as VME are their functional significance, fragility, life history traits that limit recovery and the structural complexity they provide.

Coral rubbles are remains of scleractinian corals. This habitat was observed on 25 dives in 21 canyons, .and at depth ranging from 228 m to 1783 m. The cumulated length of dive transects where coral rubbles were observed total 18.1 km. The length of single habitat ranged from 8 to 1026 m, with a median length at 55 m. A total of 672 individual corals were observed associated with coral rubbles, belonging to 26 morphotypes. The main traits qualifying coral rubbles as VME are their functional significance and the structural complexity they provide.

Colonial scleractinians on soft substrate refers to isolated colonies of *M. oculata* and *L. pertusa* on sandy or muddy substrates. In some cases, the seabed showed sediment-ripples. This habitat was observed on 13 dives in 11 canyons, and at depth ranging from 655 m to 1229 m. The cumulated length of dive transects where this habitat was observed total 4.2 km. The length of single habitat ranged from 8 to 266 m, with a median length at 36 m. A total of 249 individual corals were observed, belonging to 19 morphotypes. The main traits qualifying colonial scleractinians on soft substrate as

VMEs are their fragility, life history traits that limit recovery and the structural complexity they provide.

Colonial scleractinians on hard substrate refers to isolated colonies of the colonial scleractinians *M. oculata*, *L. pertusa*, *Solenosmilia variabilis, Enallopsammia rostrata* and/or *Dendrophyllia cornigera*, emerging on hard substrate. The habitat is usually mono-specific, except in the case of *M. oculata* and *L. pertusa* that occur together. *S. variabilis* and *E. rostrata* have been observed on vertical walls or other vertical features, such as steps. A single occurrence of *D. cornigera* was observed. This habitat was observed on 13 dives in 12 canyons, and at depth ranging from 556 and 1819 m. The cumulated length of dive transects where coral rubbles were observed totalize 3.4 km. The length of single habitat ranged from 8 to 415 m, with a median length at 37 m. A total of 199 individual corals were observed associated with colonial scleractinians on hard substrate, belonging to 27 morphotypes. The main traits qualifying colonial scleractinians on hard substrate as VMEs are their fragility, life history traits that limit recovery and the structural complexity they provide.

Antipatharians or gorgonians on hard substrate refers to aggregations of corals dominated by either isidid gorgonians (e.g. *Acanella* cf. *arbuscula*) or antipathid black corals (*Antipathes dichotoma* and *A. viminalis*). This habitat was observed on 11 dives in 9 canyons, and at depth ranging from 580 m to 2348 m. The cumulated length of dive transects where aggregations of antipatharians or gorgonians were observed totalize 804 m. The length of single habitat ranged from 8 to 120 m, with a median length at 25 m. A total of 205 individual corals were observed associated with colonial scleractinians on hard substrate, belonging to 21 morphotypes. The main traits qualifying antipatharians or gorgonians on hard substrates as VMEs are their rarity, fragility and life history traits that limit recovery.

Mixed corals on hard substrate refers to aggregations of antipatharians, gorgonians and/or scleractinians, usually found in similar abundances. Examples of species forming this habitat are the antipatharians *A. viminalis*, *A. dichotoma*, *Stichopathes gravieri, Parantipathes* sp. 1, *Leiopathes* spp., the gorgonian *Narella versluysi*, solitary scleractinians, or the colonial scleractinians *M. oculata/L. pertusa*. This habitat was observed on 15 dives in 12 canyons, and at depth ranging from 678 m to 1816 m. The cumulated length of dive transects where this habitat was observed totalize 2.2 km. The length of single habitat ranged from 8 to 220 m, with a median length at 28 m. A total of 718 individual corals were observed, belonging to 30 morphotypes. The main traits qualifying mixed corals on hard substrate as VMEs are their rarity, fragility and life history traits that limit recovery.

Solitary scleractinians on soft substrate refers to aggregations of cup corals belonging to the Flabellidae family. This habitat was observed on 5 dives in 5 canyons, and at depth ranging from 752 m to 1085 m. The cumulated length of dive transects where this habitat was observed totalize 457 m. The length of a single habitat ranged from 29 to 138 m, with a median length at 62 m. A total of 75 individual corals were observed, belonging to four morphotypes. The main traits qualifying solitary scleractinians on soft substrate as VMEs are their rarity, fragility and life history traits that limit recovery.

Gorgonians on soft substrate refers to aggregations of the bamboo coral *Acanella* cf. *arbuscula*. This habitat was observed on 6 dives in 5 canyons, and at depth ranging from 763 m to 1847 m. The cumulated length of dive transects where this habitat was observed totalize 1.1 km. The length of a single habitat ranged from 29 to 438 m, with a median length at 43 m. A total of 68 individual corals were observed, belonging to four morphotypes. The main traits qualifying Gorgonians on soft substrate as VMEs are their fragility and life history traits that limit recovery.

Seapens or pennatulids on soft substrate refers to monospecific aggregations of *Kophobelemnon* cf. *stelliferum, Pennatula* spp., *Funiculina quadrangularis* or *Distichoptilum gracile*. This habitat was observed on 11 dives in 9 canyons, and at depth ranging from 234 m to 2305 m. The cumulated length of dive transects where this habitat was observed totalize 6.7 km. The length of a single habitat ranged from 8 to 783 m, with a median length at 64 m. A total of 877 individual corals were observed, belonging to 12 morphotypes. The main traits qualifying seapens on soft substrate as VMEs are their fragility and life history traits that limit recovery.

Mixed corals on soft substrate refers to aggregations of the gorgonian *Acanella* cf. *arbuscula* and the seapen *Kophobelemnon* cf. *stelliferum*. The associations of these two species were rare. This habitat was observed on 3 dives in 3 canyons, and at depth ranging from 788 m to 1799 m. The cumulated length of dive transects where this habitat was observed totalize 365 m. The length of a single habitat ranged from 9 to 236 m, with a median length at 38 m. In total, 16 colonies of the two species *Kophobelemnon* cf. *stelliferum and Acanella* cf. *arbuscula* were observed. The main traits qualifying mixed corals on soft substrate as VMEs are their fragility and life history traits that limit recovery.

Aggregations of actiniarians refer to the aggregations of two hormatiid anemone likely belonging to the genus *Phelliactis* and *Hormathia*. The former has been observed on cobbles and pebbles while the latter was found on soft substrates. Aggregations of actiniarians were observed on 4 dives, in 3 canyons, at depth ranging from 192 to 700 m. The cumulated length of dive transects where these aggregations were observed totalize 1.7 km. The length of a single habitat ranged from 9 to 521 m, with a median length at 86 m. The main traits qualifying aggregations of anemone as VMEs are their fragility and life history traits that limit recovery.

Aggregations of sponges were rare and mostly found on soft sediments where they consist in monospecific aggregations of either *Pheronema carpenteri* or *Hyalonema* sp. Sponge aggregations were observed on 6 dives, in 5 canyons, at depth ranging from 524 to 1363 m. The cumulated length of dive transects where these aggregations were observed totalize 835 m. The length of a single habitat ranged from 26 to 360 m, with a median length at 96 m. The main traits qualifying aggregations of sponges as VMEs are their fragility, life history traits that limit recovery and the structural complexity they provide.

Aggregations of xenophyophores on soft substrates were observed on 5 dives, in 5 canyons, at depth ranging from 1068 to 258 m. The cumulated length of dive transects where aggregations of xenophyophores were observed totalize 2.4 km. The length of a single habitat ranged from 13 to 336 m, with a median length at 104 m. The main traits qualifying aggregations of xenophyophorses as VMEs are their functional role and fragility.

2.4.4 Supporting citations

Davies, J. S., Guillaumont, B., Tempera, F., Vertino, A., Beuck, L., Ólafsdóttir, S. H., Smith, C. J., Fosså, J. H., van den Beld, I. M. J., Savini, A., Rengstorf, A., Bayle, C., Bourillet, J. F., Arnaud-Haond, S., & Grehan, A. (2017). A new classification scheme of European cold-water coral habitats: Implications for ecosystem-based management of the deep sea. *Deep Sea Research Part II: Topical Studies in Oceanography*, 145, 102-109, https://doi.org/10.1016/j.dsr2.2017.04.014.

ICES (2016). Report of the Workshop on Vulnerable Marine Ecosystem Database (WKVME), 10–11 December 2015, Peterborough, UK., ICES CM 2015/ACOM:62, 42.

Van den Beld, I. M. J., Bourillet, J.-F., Arnaud-Haond, S., de Chambure, L., Davies, J. S., Guillaumont, B., Olu, K., & Menot, L. (2017). Cold-Water Coral Habitats in Submarine Canyons of the Bay of Biscay. *Frontiers in Marine Science*, 4, 10.3389/fmars.2017.00118.

2.5 Case Study 7 – Seco de los Olivos, Alborán Sea

2.5.1 Name of the VME and latitude / longitude of the centre of the VME

Table 3 includes the VME described during the MEDWAVES cruise in the Seco de los Olivos, a guyot located in Alborán Sea.

These data have not been submitted to ICES as this area is located in the Mediterranean and the ICES database does not include the Mediterranean.

Table 3. VMEs included for Case Study #7, Seco de los Olivos, Alborán Sea

ID	VME Indicator	VME Habitat Type	Taxon	Latitude	Longitude
1	Sea pen	Sea pen fields	*Kophobelemnon* sp. and Pennatulacea	36,4836692	-2,8901017
2	Gorgonian		*Callogorgia verticillata*	36,4959771	-2,8899862
3	Sponge	Deep-sea sponge aggregations		36,4938643	-2,8899374
4	Gorgonian	Coral garden	*Acanthogorgia* spp.	36,5406813	-2,8202423
5	Black coral	Coral garden	*Parantipathes* sp.	36,5409209	-2,8200549
6	Sponge	Deep-sea sponge aggregations		36,5414181	-2,8200929
7	Gorgonian	Coral garden	*Acanthogorgia* spp	36,5380034	-2,8207333
8	Stony coral	Cold-water coral reef	*Dendrophyllia cornigera*	36,5380034	-2,8207333
9	Black coral	Coral garden	*Parantipathes* sp	36,5389911	-2,8211175
10	Black coral	Coral garden	*Parantipathes* sp and Alcyonacea	36,5371733	-2,8205016
11	Gorgonian		*Callogorgia verticillata*	36,5367067	-2,8202846
12	Stony coral	Cold-water coral reef	*Lophelia pertusa/Madrepora oculata*	36,5373242	-2,8206526
13	Sponge	Deep-sea sponge aggregations		36,5380523	-2,8207283
14	Sponge	Deep-sea sponge aggregations		36,5180741	-2,8013402
15	Gorgonian	Coral garden	*Acanthogorgia* spp	36,5160531	-2,8187626
16	Stony coral	Cold-water coral reef	*Dendrophyllia cornigera*	36,5161031	-2,8187827
17	Sponge	Deep-sea sponge aggregations		36,5152854	-2,8186584

2.5.2 Features description

For each VME listed in the table above (the first column refers to VME ID number), a short description is provided below.

Sea pen field with presence of *Kophobelemnon* sp. and other sea pen species (VME 1): This habitat is considered a VME due to the functional significance, structural role and fragility of component species. Further, as they grow in a soft sediment area, they are very vulnerable to bottom contact fishing gears.

Deep-sea sponge aggregations (VMEs 3, 6, 13, 14 and 17): These habitats are considered a VME due to the uniqueness or rarity, functional significance, fragility, and the life history traits of component species that make recovery difficult. Moreover they show a structural complexity, providing an habitat for other species.

Coral gardens with *Callogorgia verticilata* (VMEs 2, 11): Although the species occur frequently as isolated specimens, the large sizes displayed by these gorgonians makes them important VME indicators. A single colony can harbor a high associated biodiversity, playing an important structural role, therefore having a functional significance. These colonies are also fragile, and probably have slow growth rates, making recovery of the species after disturbances, difficult or even impossible.

Coral gardens with *Acanthogorgia* spp. in soft bottoms (VMEs 4, 7 and 15): This habitat is considered a VME due to the functional significance and fragility of component species, further, as they grow in a soft sediment area, they are very vulnerable to bottom contact fishing gears.

Coral gardens with black coral spp. (*Paranthipates* sp. and Alcyonacea; VMEs 5, 9 and 10): This habitat is considered a VME due to the structural role and functional significance and fragility of component species.

Cold-water coral "garden" with *Dendrophyllia cornigera (*VMEs 8, 16): This habitat is considered a VME due to the structural role and functional significance and fragility of component species. We use the term coral garden although the species is a scleractinian coral, as the species occur in a patched way with single isolated colonies that do not form a framework nor a reef.

Cold-water coral reef *Lophelia pertusa / Madrepora oculata (*VME 12)*:* This habitat is considered a VME due to the uniqueness or rarity, functional significance, fragility, and the life history traits of component species that make recovery difficult. Moreover they show a structural complexity, providing an habitat for other species.

2.5.3 Supporting citations

Abad, E., Preciado, I., Serrano, A., & Baro, J. (2007). Demersal and epibenthic assemblages of trawlable grounds in the northern Alboran Sea (western Mediterranean). *Scientia Marina,* 71, 513-524.

De la Torriente, A., Serrano, A., Fernandez-Salas, L.M., Garcia, M., & Aguilar, R. (2018). Identifying epibenthic habitats on the Seco de los Olivos Seamount: Species assemblages and environmental characteristics. *Deep-Sea Research Part I-Oceanographic Research Papers,* 135, 9-22.

Lo Iacono, C., Gracia, E., Diez, S., Bozzano, G., Moreno, X., Danobeitia, J., & Alonso, B. (2008). Seafloor characterization and backscatter variability of the Almeria Margin (Alboran Sea, SW Mediterranean) based on high-resolution acoustic data. *Marine Geology*, 250, 1-18.

Lo Iacono, C., Gracia, E., Bartolome, R., Coiras, E., Dañobeitia, J.J., & Acosta, J. (2012). Habitats of the Chella Bank, Eastern Moran Sea (Western Mediterranean). In: Seafloor geomorphology as benthic habitat: geohab atlas of seafloor geomorphic features and benthic habitats. (Harris PT, Baker EK, eds) Elsevier Insights, p 681-690.

2.6 Case Study 7 – Volcano of Gazul, Gulf of Cádiz

2.6.1 Name of the VME and latitude / longitude of the centre of the VME

Table 4 includes the VME described during the MEDWAVES cruise in the Mud Volcano of Gazul in the Gulf of Cádiz. These data have been submitted this year to the ICES database, therefore they are currently under review.

Table 4. VMEs included for Case Study #7, Volcano of Gazul, Gulf of Cádiz

ID	VME Indicator	VME Habitat Type	Taxon	Latitude	Longitude
1	Gorgonian	Coral garden	*Acanthogorgia* spp	36,5675518	-6,931666985
2	Gorgonian	Coral garden	*Acanthogorgia* spp	36,5618353	-6,9308629
3	Gorgonian	Coral garden	*Acanthogorgia* spp	36,5597763	-6,931372375
4	Gorgonian	Coral garden	*Callogorgia verticillata*	36,5663615	-6,931106875
5	Gorgonian	Coral garden	Plexauridae	36,5604991	-6,931206185
6	Stony coral	Mud and sand emergent fauna	*Flabellum chunii*	36,5648719	-6,9307401
7	Stony coral	Mud and sand emergent fauna	*Flabellum chunii*	36,5599483	-6,931336455
8	Stony coral	Cold-water coral reef	*Lophelia pertusa / Madrepora oculata*	36,5629896	-6,93103885
9	Sponge	Deep-sea sponge aggregations		36,5651003	-6,931999125
10	Sponge	Deep-sea sponge aggregations	*Asconema setubalense*	36,5668635	-6,9313975
11	Sponge	Deep-sea sponge aggregations	*Leiodermatium* sp	36,5680044	-6,9316813
12	Gorgonian	Coral garden	*Acanthogorgia* spp	36,5585583	-6,9478762
13	Gorgonian	Coral garden	*Acanthogorgia* spp	36,5566955	-6,93579095
14	Gorgonian	Coral garden	Plexauridae	36,5567293	-6,93551089
15	Sponge	Deep-sea sponge aggregations		36,5574341	-6,9469489
16	Sponge	Deep-sea sponge aggregations		36,5566712	-6,935646615

2.6.2 Features description

For each VME listed in the table above (the first column refers to VME ID number), a short description is provided below. A map with images representing the VMEs is also displayed in Figure 5.

Coral gardens:

- Coral gardens dominated by *Acanthogorgia* sp. (VMEs 1, 2, 3, 12 and 13)
- Coral gardens with *Callogorgia verticilata (*VME 4)
- Coral gardens with Plexauridae (VMEs 5, 14)

These habitats are considered a VME due to their functional significance, fragility, and the life history traits of component species that make recovery difficult. Moreover they show a structural complexity, providing an habitat for other species.

Mud and sand emergent fauna *Flabellum chunii* (VMEs 6, 7)*:* This habitat is considered a VME due to the functional significance, fragility and life history traits of component species that make recovery difficult and the structural complexity the organisms add to a soft sediment area.

Cold-water coral reef *Lophelia pertusa / Madrepora oculata (*VME 8): This habitat is considered a VME due to the uniqueness or rarity, functional significance, fragility, and the life history traits of component species that make recovery difficult. Moreover they show a structural complexity, providing an habitat for other species.

Deep-sea sponge aggregations:

- Deep-sea sponge aggregations (VMEs 9, 15, 16)
- Deep-sea sponge aggregations with *Asconema setubalense (*VME 10)
- Deep-sea sponge aggregations with *Leiodermatium* sp. *(*VME 11)

These habitats are considered a VME due to the uniqueness or rarity, functional significance, fragility, and the life history traits of component species that make recovery difficult. Moreover they show a structural complexity, providing an habitat for other species.

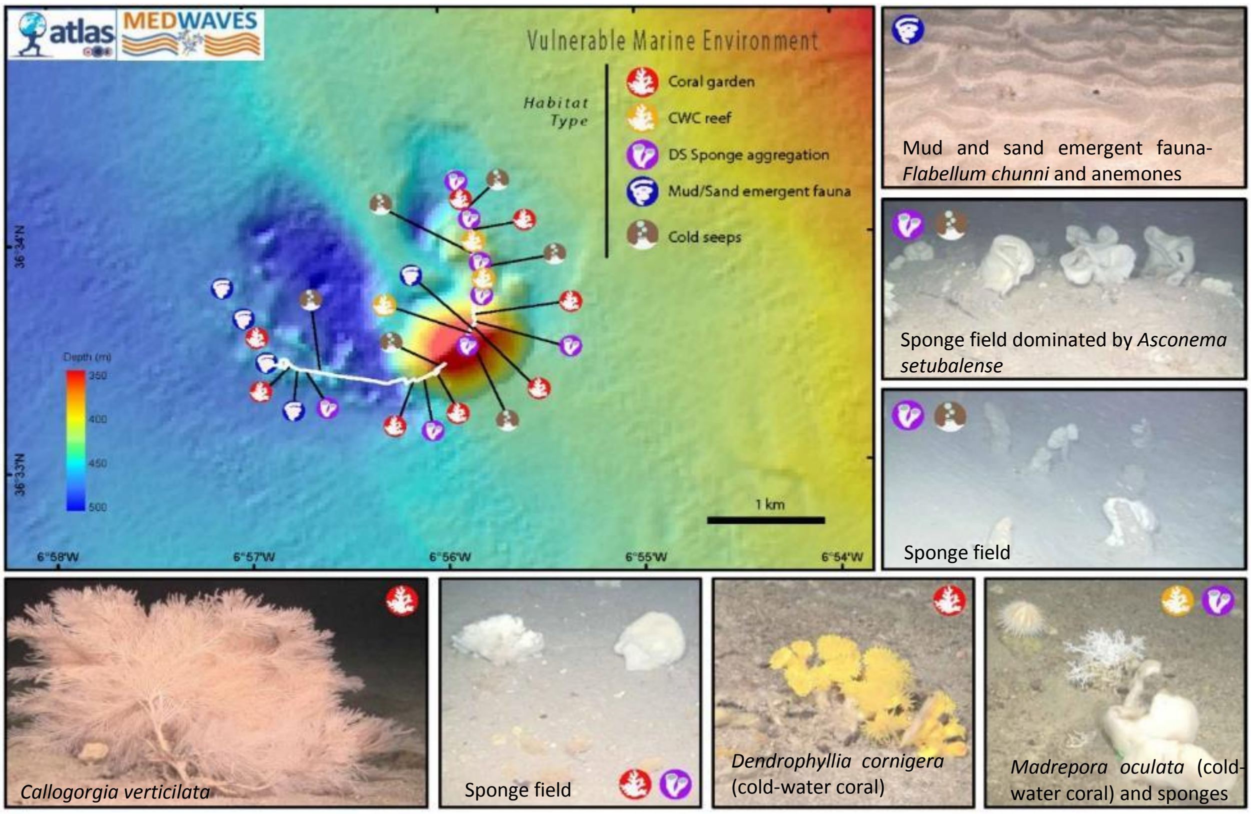

Figure 5. Map of the volcano of Gazul with images representing the different VMEs it hosts.

2.6.3 Supporting citations

Rueda, J.L., Gonzalez-Garcia, E., Krutzky, C., Lopez-Rodriguez, F.J., Bruque, G., Lopez-Gonzalez, N., Palomino, D., Sanchez, R.F., Vazquez, J.T., Fernandez-Salas, L.M., et al. (2016). From chemosynthesis-based communities to cold-water corals: Vulnerable deep-sea habitats of the Gulf of Cadiz. *Marine Biodiversity*, 46, 473-482.

2.7 Case Study 8 – Azores – Formigas Seamount

2.7.1 Name of the VME and latitude / longitude of the centre of the VME

Table 5 includes the VMEs described during the MEDWAVES cruise in the Formigas Seamount. These data have been submitted this year to the ICES database[1], therefore they are currently under review.

Table 5. VMEs included for Case Study #8, Formigas Seamount

ID	VME Indicator	VME Habitat Type	Taxon	Latitude	Longitude
1	Gorgonian	Coral garden	*Acanella arbuscula*	37,1883951	-24,6303977
2	Sponge	Deep-sea sponge aggregations	*Stylocordia pellita*	37,18813	-24,6286
3	Sponge	Deep-sea sponge aggregations		37,18813	-24,6286
4	Sponge	Deep-sea sponge aggregations	*Stylocordia pellita*	37,1887925	-24,6284035
5	Sponge	Deep-sea sponge aggregations		37,1887925	-24,6284035
6	Gorgonian	Coral garden	*Acanella arbuscula*	37,1945355	-24,6257173
7	Gorgonian	Coral garden	*Candidella imbricata*	37,197951	-24,6240973
8	Gorgonian	Coral garden	*Narella versluysi*	37,197951	-24,6240973
9	Gorgonian	Coral garden	*Leiopathes expansa*	37,197951	-24,6240973
10	Gorgonian	Coral garden	*Poecillastra compressa*	37,197951	-24,6240973
11	Gorgonian	Coral garden	*Narella bellissima*	37,2065251	-24,6201673
12	Gorgonian	Coral garden	*Narella versluysi*	37,2065251	-24,6201673
13	Gorgonian	Coral garden	*Acanthogorgia armata*	37,2065251	-24,6201673
14	Sponge	Deep-sea sponge aggregations	*Pheronema carpenteri*	37,2065251	-24,6201673
15	Gorgonian	Coral garden	*Narella versluysi*	37,2106066	-24,6615558
16	Gorgonian	Coral garden	*Narella bellissima*	37,2106066	-24,6615558
17	Gorgonian	Coral garden	*Nicella granifera*	37,210966	-24,658077
18	Gorgonian	Coral garden	*Leptopsamnia formosa*	37,210966	-24,658077

[1] Some mistakes in the excel template submitted to ICES were detected and corrected in the table included here.

2.7.2 Features description

For each VME listed in the table above (the first column refers to VME ID number), a short description is provided below. A map with images representing the different VMEs is displayed in Figure 6.

Coral gardens:

- Coral gardens dominated by the bamboo coral *Acanella arbuscula (*VMEs 1, and 6)
- Coral gardens with *Narella verluysi (*VME 8, 12 and 15)
- Coral gardens with *Narella bellisima (*VMEs 11 and 16);
- Coral gardens with *Candidella imbricate (*VME 7)
- Coral gardens with black coral *Leiopathes glaberrima (*VME 9);
- Coral gardens with *Poecillastra compressa (*VME 10);
- Coral gardens with *Acanthogorgia armata (*VME 13)
- Coral gardens with *Nicella granifera (*VME 17)
- Coral gardens with *Leptosamnia formosa (*VME 18)

These habitats are considered a VME due to the functional significance, fragility, and the life history traits of component species that make recovery difficult. Moreover they show a structural complexity, providing an habitat for other species.

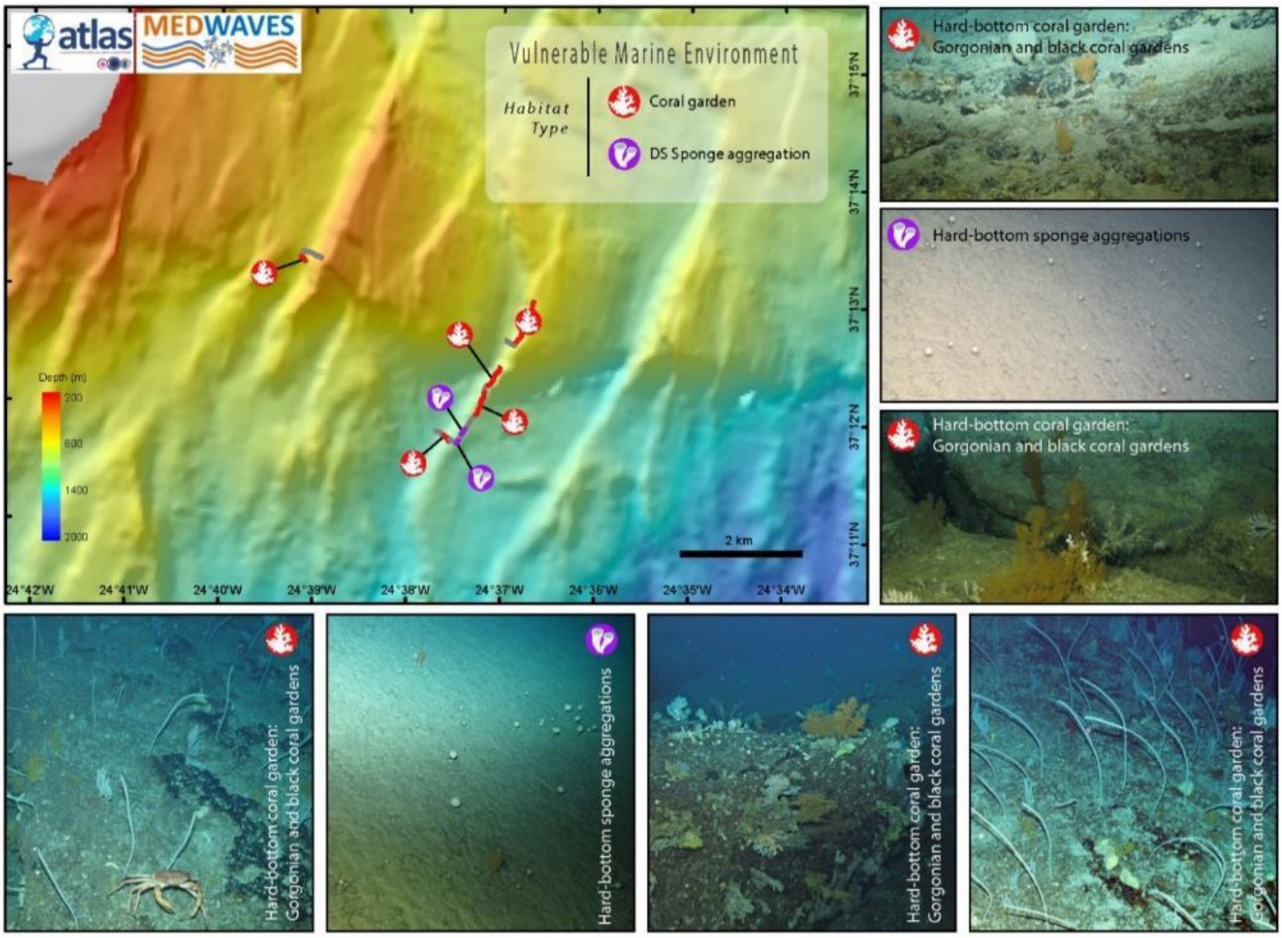

Figure 6. Map of Formigas Seamount with images representing the different VMEs it hosts.

Deep-sea sponge aggregations:

- Deep-sea sponge aggregations with *Stylocordia pellita (*VMEs 2 and 4)
- Deep-sea sponge aggregations (VMEs 3 and 5)
- Deep-sea sponge aggregations with *Pheronema carpentieri (*VME 14*)*

These habitats are considered a VME due to the uniqueness or rarity, functional significance, fragility, and the life history traits of component species that make recovery difficult. Moreover they show a structural complexity, providing an habitat for other species.

2.7.3 Supporting citations

Braga-Henriques, A., Porteiro, F., Ribeiro, P., Matos, V.D., Sampaio, Í., Ocaña, O., & Santos, R. (2013). Diversity, distribution and spatial structure of the cold-water coral fauna of the Azores (NE Atlantic). *Biogeosciences Discussions*, 10, 529-590.

Sampaio, Í., Freiwald, A., Porteiro, F., Menezes, G. & Carreiro-Silva, M. (2019). Census of Octocorallia (Cnidaria: Anthozoa) of the Azores (NE Atlantic) with a nomenclature update. *Zootaxa*, 4550 (4), 451–498.

2.8 Case Study 8 – Azores – other areas

2.8.1 Name of the VME and latitude / longitude of the centre of the VME

Table 6 includes the most relevant VMEs identified in the Azores region during the cruises carried out during the past three years.

Table 6. VMEs included for Case Study #8 – Azores, other areas

ID	Location	VME Indicator	VME Habitat Type	Taxon	Latitude	Longitude
1	Cavalo Seamount	Gorgonian	Coral garden	*Narella bellissima, Narella versluysi*	36.80854	-32.5527
2	Ridge on MAR	Gorgonian	Coral garden	*Paragorgia* spp.	38.70778	-30.2224
3	Gigante Seamount	Gorgonian	Coral garden	*Viminella flagellum, Dentomuricea* aff. *meteor* and *Acanthogorgia* cf. *hirsuta*	39.0001	-29.9214
4	Condor Seamount	Gorgonian	Coral garden	*Viminella flagellum, Dentomuricea* aff. *meteor* and *Callogorgia verticillata*	38.5415	-29.0347
5	South of Pico	Sponge	Deep-sea sponge aggregations	*Pheronema carpenteri*	38.3492	-28.2671
6	Dom João de Castro	Gorgonian	Coral garden	*Callogorgia verticilata*	38,2112	-26,5712
7	Mar da Prata	Gorgonian	Coral garden	*Dentomuricea* cf. *meteor*	37,1462	-25,6438
8	Gigante Seamount	n/a	Hydrothermal vent	n/a		

2.8.2 Features description

For each VME listed in the table above (the first column refers to VME ID number), a short description is provided below. A map showing the location of the different VMEs is displayed in Figure 7, together with images of each VME in Figure 8.

VME 1. Cavalo Seamount: The hard substrates on the flanks of this seamount, at depths of 600-700 metres, are dominated by the Primnoidae species *Narella bellissima* and *Narella versluysi*, both found in very high densities along a considerably large area. Those two species were accompanied by a wide range of other large coral species, such as the gorgonians *Paragorgia johnsoni*, *Corallium* cf. *johnsoni* and *Callogorgia verticillate,* as well as some laminate sponges. The main traits qualifying gorgonians on hard substrates as VMEs are the structural complexity they provide, their rarity, fragility and life history traits that limit their recovery.

VME 2. Ridge on the Mid-Atlantic Ridge: The elongated ridge found close to the Mid-Atlantic Ridge hosts a cold-water coral assemblage dominated by the Scleraxonia species *Paragorgia arborea* and *P. johnsoni*, with large colonies reaching sizes above 1 metre. Although some colonies on the summit showed signs of fishing impact, a large number of colonies on the flanks remain in a very good conservation status, with all their branches still intact. The main traits qualifying gorgonians on hard substrates as VMEs are the structural complexity they provide, their rarity, fragility and life history traits that limit their recovery.

VME 3. Gigante Seamount: The summit of Gigante Seamount hosts a diverse coral garden, characterised by the whip coral *Viminella flagellum* and the sea fans *Dentomuricea* aff. *meteor* and *Acanthogorgia* cf. *hirsuta*, together with a large number of sponge species of considerable sizes. The main traits qualifying gorgonians on hard substrates as VMEs are the structural complexity they provide, their rarity, fragility and life history traits that limit their recovery.

VME 4. Summit of Condor Seamount: Coral gardens formed by the octocorals *Viminella flagellum*, *Dentomuricea* aff. *meteor* and *Callogorgia verticillata*, together with the large hydrozoan cf. *Lytocarpia myriophyllum* dominate the summit of Condor Seamount. The three gorgonian species are found forming a mixed assemblage both in consolidated and unconsolidated substrates, with the dominance of one species over the others changing throughout the summit. The main traits qualifying gorgonians on mixed substrates as VMEs are their fragility and life history traits that limit their recovery.

VME 5. Southern slopes of Pico Island: The sedimentary slopes of the southern flank of Pico Island host dense aggregations of the hexactinellid sponge *Pheronema carpenteri*, with highest recorded densities at around 900 m depth. The main traits qualifying aggregations of sponges as VMEs are their fragility, and the life history traits of component species that make recovery difficult. Moreover they show a structural complexity, providing an habitat for other species.

VME 6. Dom João de Castro Seamount: The benthic community identified was dominated by the primnoid *Callorgorgia verticillata*, found forming relatively dense aggregations, with some very large colonies. Not many colonies showed signs of fishing impacts, although there was a considerable number of small fishing lines lying over the seabed or entangled around rocks. The main traits qualifying gorgonians on mixed substrates as VMEs are their fragility and life history traits that limit their recovery.

VME 7. Mar da Prata Seamount: A large monospecific patch of the yellow sea fan *Dentomuricea* cf. *meteor* was found on hard substrates of the southern tip of Mar da Prata Seamount, with the highest densities recorded for this species in the Azores so far. The main traits qualifying gorgonians on mixed substrates as VMEs are their fragility and life history traits that limit their recovery.

VME 8. Luso hydrothermal vent field: The newly discovered Luso hydrothermal vent field occupies an area of about 400 m^2 on the slopes of Gigante Seamount. It is composed of at least 26 chimney-like structures of different sizes, with orifices up to about 30 cm in diameter. The active chimneys expel transparent but well noticeable hydrothermal fluids, with a maximum temperature of 62°C inside the outer rim of the main chimney conduit. Fluids are moderately acidic (pH 5.6-5.7), iron-rich (from 226.3 to 336.7 µM total HNO3-leachable iron), CO_2 rich, hydrogen rich (up to 357 µM), with moderate methane contents (up to 4.9), but they do not contain sulphides.

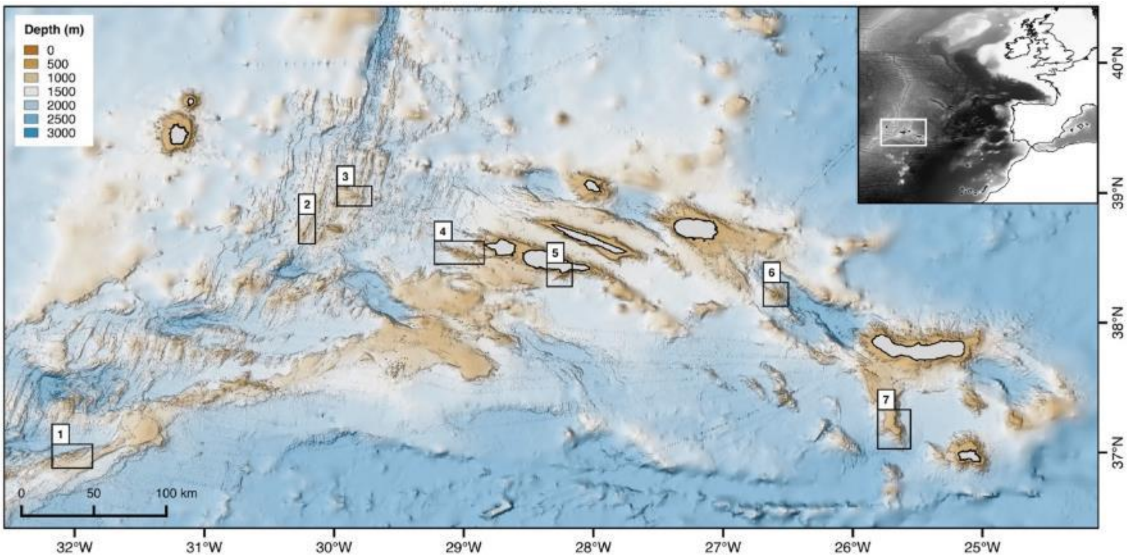

Figure 7. Location of the different VMEs described for Case Study #8, Azores, all areas except Formigas Seamount.

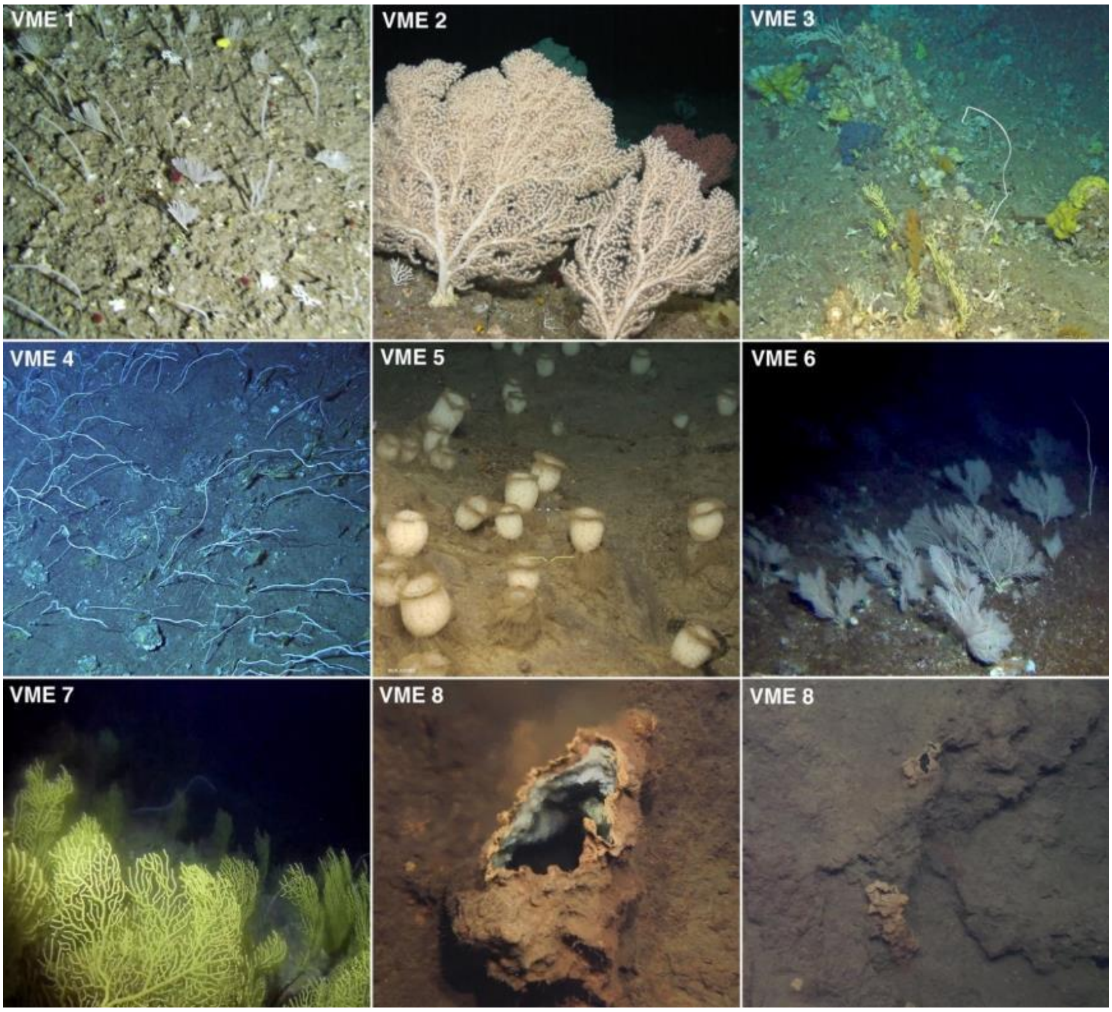

Figure 8. Images of the different VMEs identified in the deep-sea areas of the Azores region.

2.8.3 Supporting citations

Braga-Henriques, A., Porteiro, F., Ribeiro, P., Matos, V.D., Sampaio, Í., Ocaña, O., & Santos, R. (2013). Diversity, distribution and spatial structure of the cold-water coral fauna of the Azores (NE Atlantic). *Biogeosciences Discussions*, 10, 529-590.

Sampaio, Í., Freiwald, A., Porteiro, F., Menezes, G. & Carreiro-Silva, M. (2019). Census of Octocorallia (Cnidaria: Anthozoa) of the Azores (NE Atlantic) with a nomenclature update. *Zootaxa*, 4550 (4), 451–498.

2.9 Case Study 9 – Reykjanes Ridge

The contribution from CS9 was not included in this section as this information was already present in the databases (InterRidge, ICES).

2.10 Case Study 10 – Davis Strait – Eastern Arctic

2.10.1 Name of the VME

Deep-sea sponges, large gorgonian corals, small gorgonian corals and sea pens in sensitive benthic areas (SBA) in the Eastern Arctic.

VMEs are a term used for the ABNJ and Canada has adopted SBA (sensitive benthic area) for the equivalent in Canadian waters.

A peer-review process was undergone to identify SBA and kernel density analyses combined with Species Distribution Models were used to identify the SBA/VME. The primary advisory publication is found at http://waves-vagues.dfo-mpo.gc.ca/Library/40577806.pdf (Kenchington et al., 2016a), along with the original polygons http://dx.doi.org/10.17632/hnp4xr2sy3.1 (Kenchington et al., 2018).

2.10.2 Latitude / longitude of the centre of the VME

The centroids for the larger polygons were determined using the “Feature to Point” tool in ArcGIS 10.2.2 using the inside polygon calculations. Their positions for large Gorgonians, sea pens, Small Gorgonians and Sponges are displayed in Table 7, Table 8, Table 9, and Table 10 respectively.

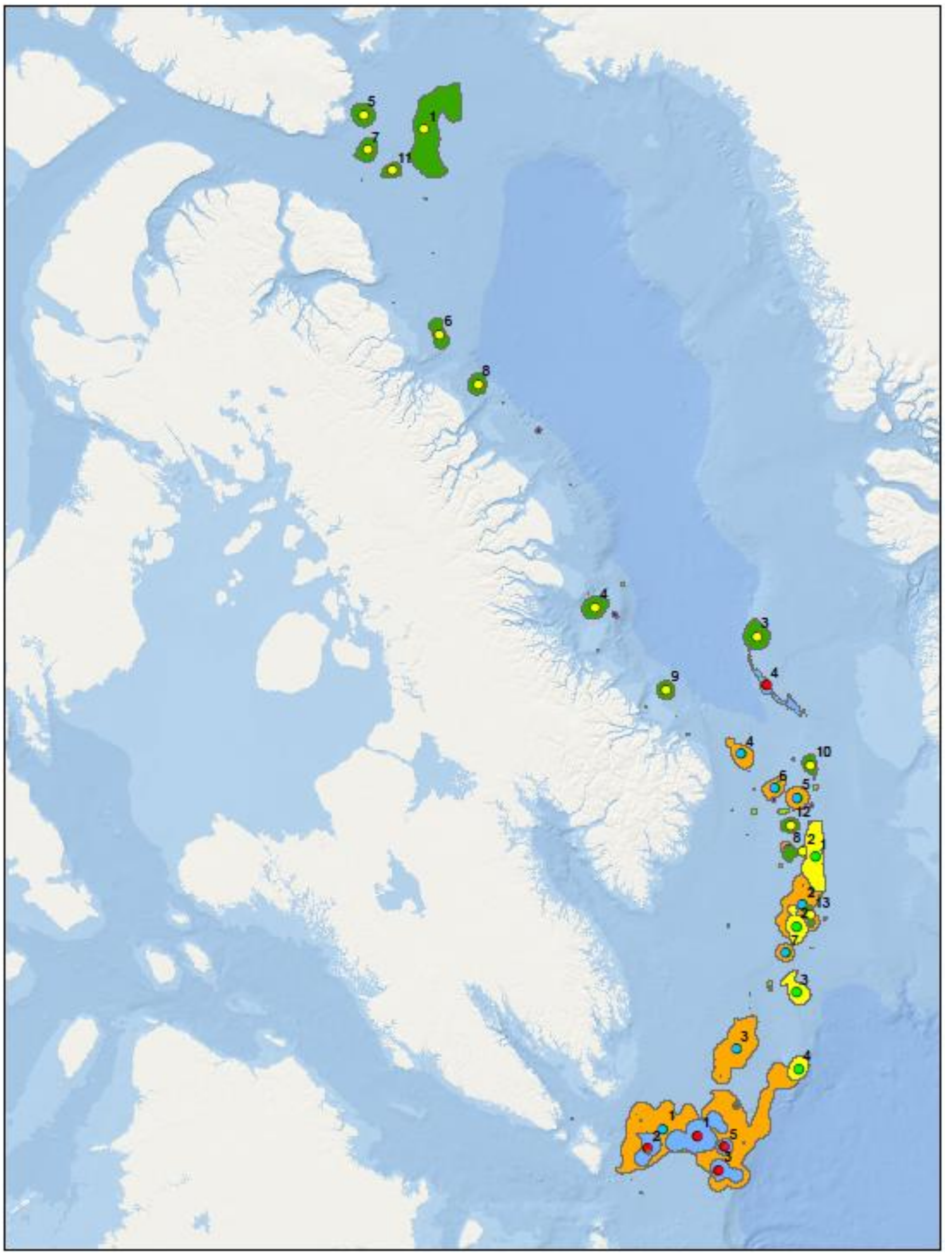

Figure 9. Map of SBA polygons, VME polygons and VME centroids for Eastern Arctic Sponge (areas in orange, blue circles for centroids), Sea Pens (areas in green, yellow circles for centroids), Large Gorgonians (areas in blue, red circles for centroids) and Small Gorgonians (areas in yellow, green circles for centroids).

Table 7. ***Small Gorgonian Significant Benthic Areas in the Eastern Arctic*** *centroids attribute table with latitude and longitude for each centroid. Each VME polygon and associated centroid has an ID code which starts at 1 (largest polygon).*

ID	Longitude	Latitude	Area (km^2)
1	-58.01090788	65.48786878	2761.2408
2	-58.76494059	64.58401024	1267.386495
3	-58.89847554	63.68861637	1238.392986
4	-58.97137755	62.67470367	871.9879964

Table 8. ***Sea Pen Significant Benthic Areas in the Eastern Arctic*** *centroids attribute table with latitude and longitude for each centroid. Each VME polygon and associated centroid has an ID code which starts at 1 (largest polygon).*

ID	Longitude	Latitude	Area (km^2)
1	-75.31465444	74.99235531	6141.116131
2	-58.38898365	65.56653975	1362.277218
3	-59.48921128	68.50041144	1321.871106
4	-65.42688825	68.90244222	1031.691168
5	-78.53243703	74.99859255	962.7702542
6	-72.80101456	72.34483352	883.3727698
7	-77.87916758	74.55125936	872.0854671
8	-70.82370297	71.75327176	711.4880845
9	-62.79961319	67.80942071	596.1888957
10	-57.90736806	66.72790219	549.7388832
11	-76.42139453	74.36413378	548.0091693
12	-58.73124301	65.93847078	490.2132121
13	-58.30705239	64.7190929	362.7572153

Table 9. ***Sponge Significant Benthic Areas in the Eastern Arctic*** *centroids attribute table with latitude and longitude for each centroid. Each VME polygon and associated centroid has an ID code which starts at 1 (largest polygon).*

ID	Longitude	Latitude	Area (km^2)
1	-62.93203269	61.91911103	21507.19483
2	-58.52511125	64.86715495	6149.42542
3	-60.77897195	62.97774014	4137.779998
4	-60.24337044	66.92555302	1123.056443
5	-58.43337581	66.29493386	949.9298664
6	-59.16805826	66.4540041	854.4525543
7	-59.14343487	64.23590793	593.9801398
8	-58.85592509	65.61094466	447.5408353

Table 10. ***Large Gorgonian Significant Benthic Areas in the Eastern Arctic*** *centroids attribute table with latitude and longitude for each centroid. Each VME polygon and associated centroid has an ID code which starts at 1 (largest polygon).*

ID	Longitude	Latitude	Area (km^2)
1	-61.94318154	61.83463963	3375.59329
2	-63.35195142	61.65675053	1312.998451
3	-61.35892349	61.35796524	1079.224978
4	-59.24117052	67.82188243	823.4273597
5	-61.18388541	61.6687019	479.5214374

Other data which complement this are found at http://dx.doi.org/10.17632/dtk86rjm86.1 (Kenchington et al., 2018).

2.10.3 Features description

Deep-sea sponges, large gorgonian corals, small gorgonian corals and sea pens are all considered VME indicators by the Northwest Atlantic Fisheries Organization (NAFO), who reviewed the species found in the Northwest Atlantic against the FAO criteria for VME indicators (Fuller et al., 2008). Specifically, VME indicators were determined as those with one or more of the following characteristics: uniqueness or rarity; functional significance of the habitat; fragility, life history traits and structural complexity (FAO, 2009). All of the above-listed VME met all of the criteria except for uniqueness or rarity. At the time no unique or rare species were identified although black corals (Antipatharia) were at first thought to be rare but were later determined to be widespread species occurring naturally at low density.

Significant concentrations of VME indicators, that is VMEs, have been formally accepted by NAFO as equating to areas identified through kernel density estimation of trawl catch and assessment of area occupied (Kenchington et al., 2014). Canada has independently reviewed this process and has adopted it for identification of significant benthic areas (VME equivalents) in its national waters. In both cases VME areas were ground-truthed with selected *in situ* sampling and supported by SDM prediction models.

2.10.4 Existing citations

FAO (2009). *International Guidelines for the Management of Deep-Sea Fisheries in the High Seas*. Food and Agriculture Organization of the United Nations, Rome, 2009.

Fuller, S.D., Murillo Perez, F.J., Wareham, V. & Kenchington, E. (2008). *Vulnerable Marine Ecosystems Dominated by Deep-Water Corals and Sponges in the NAFO Convention Area*. Serial No. N5524. NAFO Scientific Council Research Document 08/22, 24pp.

Kenchington, E., Murillo, F.J., Lirette, C., Sacau, M., Koen-Alonso, M., Kenny, A., Ollerhead, N., Wareham, V. & Beazley, L. (2014). Kernel density surface modelling as a means to identify significant concentrations of vulnerable marine ecosystem indicators. *PLoS ONE*, 9(10), e109365. doi:10.1371/journal.pone.0109365.

Kenchington, E., Beazley, L., Lirette, C., Murillo, F.J., Guijarro, J., Wareham, V., Gilkinson, K., Koen-Alonso, M., Benoît, H., Bourdages, H., Sainte-Marie, B., Treble, M., & Siferd, T. (2016a). Delineation of Coral and Sponge Significant Benthic Areas in Eastern Canada Using Kernel Density Analyses and

Species Distribution Models. Canadian Science Advisory Secretariat (CSAS) Research Document 2016/093, 184 p.

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Kenchington, E., Beazley, L., Lirette, C., Murillo-Perez, J., Guijarro-Sabaniel, J., Wareham, V., Gilkinson, K., Koen-Alonso, M., Benoit, H., Bourdages, H., Sainte-Marie, B., Treble, M., & Siferd, T. (2018). Delineation of Coral and Sponge Significant Benthic Areas in Eastern Canada Using Kernel Density Analyses and Species Distribution Models [Data set]. https://doi.org/10.17632/hnp4xr2sy3.1.

Kenchington, E., Lirette, C., Murillo-Perez, J., Beazley, L., Guijarro-Sabaniel, J., Wareham, V., Gilkinson, K., et al. (2018). Kernel Density Analyses of Coral and Sponge Catches from Research Vessel Survey Data for Use in Identification of Significant Benthic Areas. Mendeley. https://doi.org/10.17632/dtk86rjm86.1.

2.11 Case Study 10 – Davis Strait – Greenland waters

2.11.1 Name of the VME

Lophelia pertusa reef

2.11.2 Latitude / longitude of the centre of the VME

Here is reported the only known *Lophelia pertusa* reef that was discovered in the Greenland side, at 60.3675°, -48.45528°.

2.11.3 Features description

This new reef fits the FAO VME criteria both for the qualities of the VME but also for its uniqueness/rarity as it is the only known reef of *Lophelia pertusa* in that region. Its exact size remains unknown, but it is more than a few metres. It is in a difficult place to sample but others found it last summer so it is extensive enough that it can be relocated from the co-ordinates.

Further details can be found in Kenchington et al. (2017).

2.11.4 Supporting citations

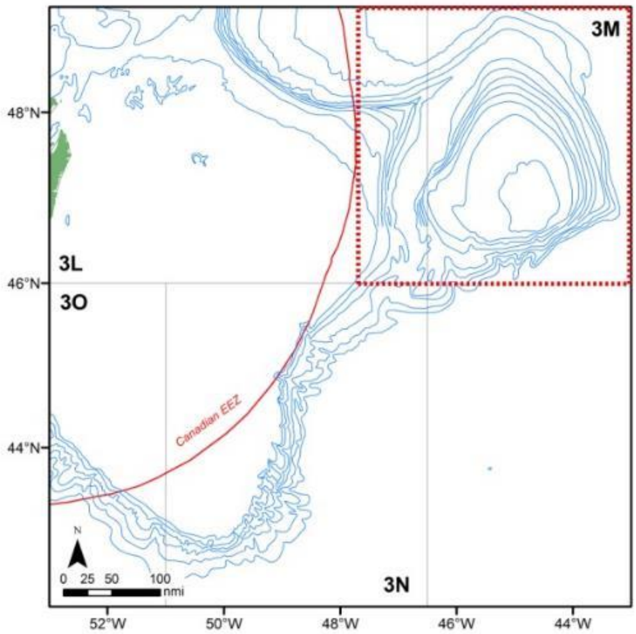
Kenchington, E., Yashayaev, I., Tendal, O. S., & Jørgensbye, H. (2017). Water mass characteristics and associated fauna of a recently discovered *Lophelia pertusa* (Scleractinia: Anthozoa) reef in Greenlandic waters. *Polar Biology*, *40*(2), 321-337.

2.12 Case Study 11 – Flemish Cap

2.12.1 Name of the VME

Three VMEs types were identified by NAFO (2016) within Case Study #11 area (see boundaries of Case Study in Figure 10):

- Sponge VME extent,
- Sea pen VME extent,
- Large gorgonian VME extent.



Red dotted square coordinates	
Lon (Max)	4743W
Lon (Min)	4300W
Lat (Max)	4910N
Lat (Min)	4600N

Figure 10. Case Study #11 Flemish Cap region boundaries

2.12.2 Latitude / longitude of the centre of the VME

VMEs identified by NAFO within Case study #11 area, are polygons with irregular shapes (see maps in Figure 11, Figure 12, Figure 13). Centroids of such polygons are presented in Table 11.

Table 11. Centroids of VME polygons within Case Study #11, Flemish Cap (WGS84)

VME Type (within CS11)	Longitude	Latitude
Large Gorgonians	-45.94215	46.33286
Large Gorgonians	-43.94822	46.7183
Large Gorgonians	-43.75639	46.85886
Large Gorgonians	-46.59765	46.88575
Large Gorgonians	-43.42973	46.87654
Large Gorgonians	-47.04374	46.48801
Large Gorgonians	-46.96569	47.91339

VME Type (within CS11)	Longitude	Latitude
Sea Pens	-46.25143	46.74296
Sea Pens	-46.75976	47.01468
Sea Pens	-43.84988	47.52291
Sea Pens	-46.36242	47.53087
Sea Pens	-44.0229	47.82558
Sea Pens	-45.43025	48.50000
Sponges	-46.00479	46.05225
Sponges	-44.34811	46.59322
Sponges	-47.68109	45.83314
Sponges	-43.54869	46.96461
Sponges	-43.69578	47.65872
Sponges	-46.40778	47.86279
Sponges	-45.8452	47.89391
Sponges	-43.85364	48.00792
Sponges	-46.13065	48.1794
Sponges	-46.56977	48.34365
Sponges	-44.23769	48.40456
Sponges	-46.18921	48.47869
Sponges	-45.40928	48.86092

2.12.3 Features description

VMEs were defined by NAFO (2013) as “under the structure-forming criterion" (FAO, 2009). Under this criterion, a VME is a regional habitat that contains VME indicator species at or above significant concentration levels. These habitats are structurally complex, characterised by higher diversities and/or different benthic communities, and provide a platform for ecosystem functions/processes closely linked to these characteristics.

VME categories were selected by NAFO (2008; 2011) after a review of all invertebrate by-catch species taken in research vessel surveys, according the FAO (2009) guidelines. They are characterised by populations or assemblages of species with one or more of the following characteristics: slow growth rates, late age of maturity, low or unpredictable recruitment, or long-lived.

Since 2009 the kernel density estimation (Kenchington et al., 2014) is being used by NAFO as a primary quantitative method to determine the distribution and extent of cold-water corals and deep-sea sponges vulnerable ecosystems (VMEs polygons). This method identifies “hotspots” in the biomass distribution derived from groundfish survey catch data, by looking at natural breaks in the spatial distribution related with changes in local density. These natural breaks allow defining of significant VMEs polygons with irregular shapes (NAFO, 2016):

- Sponge polygons encompassing catches $\geq$ 75 kg
- Sea pen polygons encompassing catches $\geq$ 1.4 kg
- Large gorgonian polygons encompassing catches $\geq$ 0.6 kg.

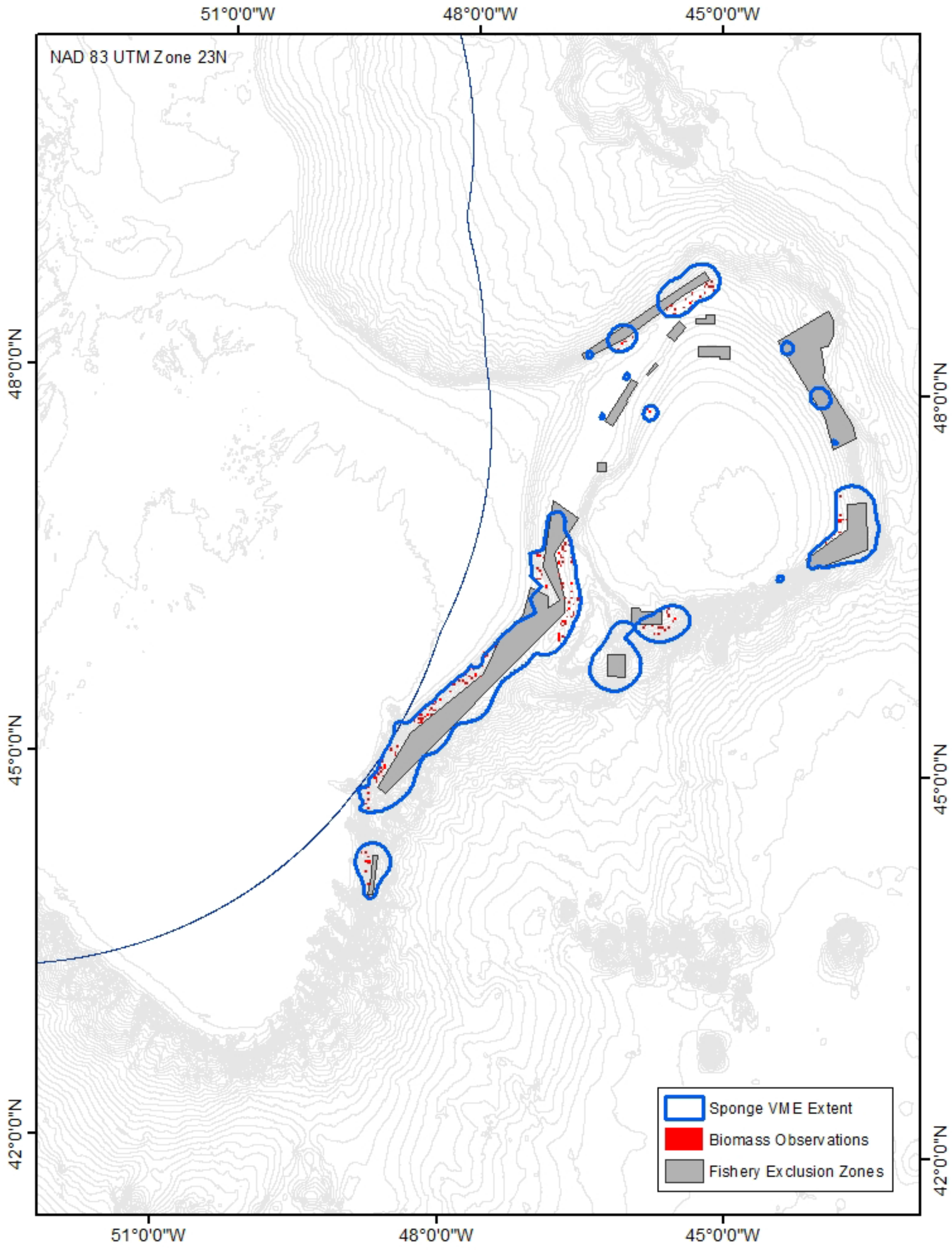


Figure 11. Maps of VMEs extent polygons for Sponges. Source: NAFO, 2016.

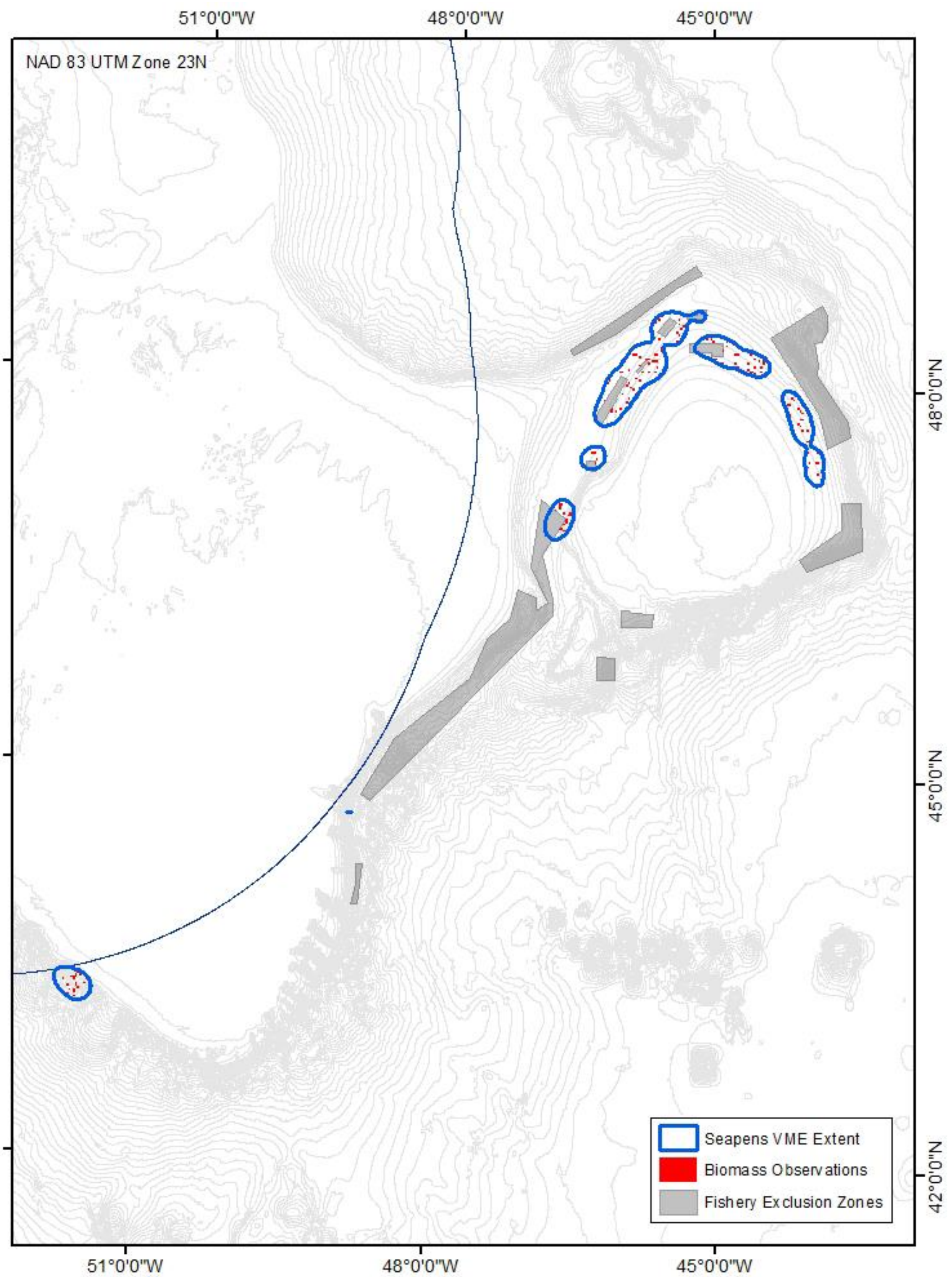


Figure 12. Maps of VMEs extent polygons for Sea pens. Source: NAFO, 2016.

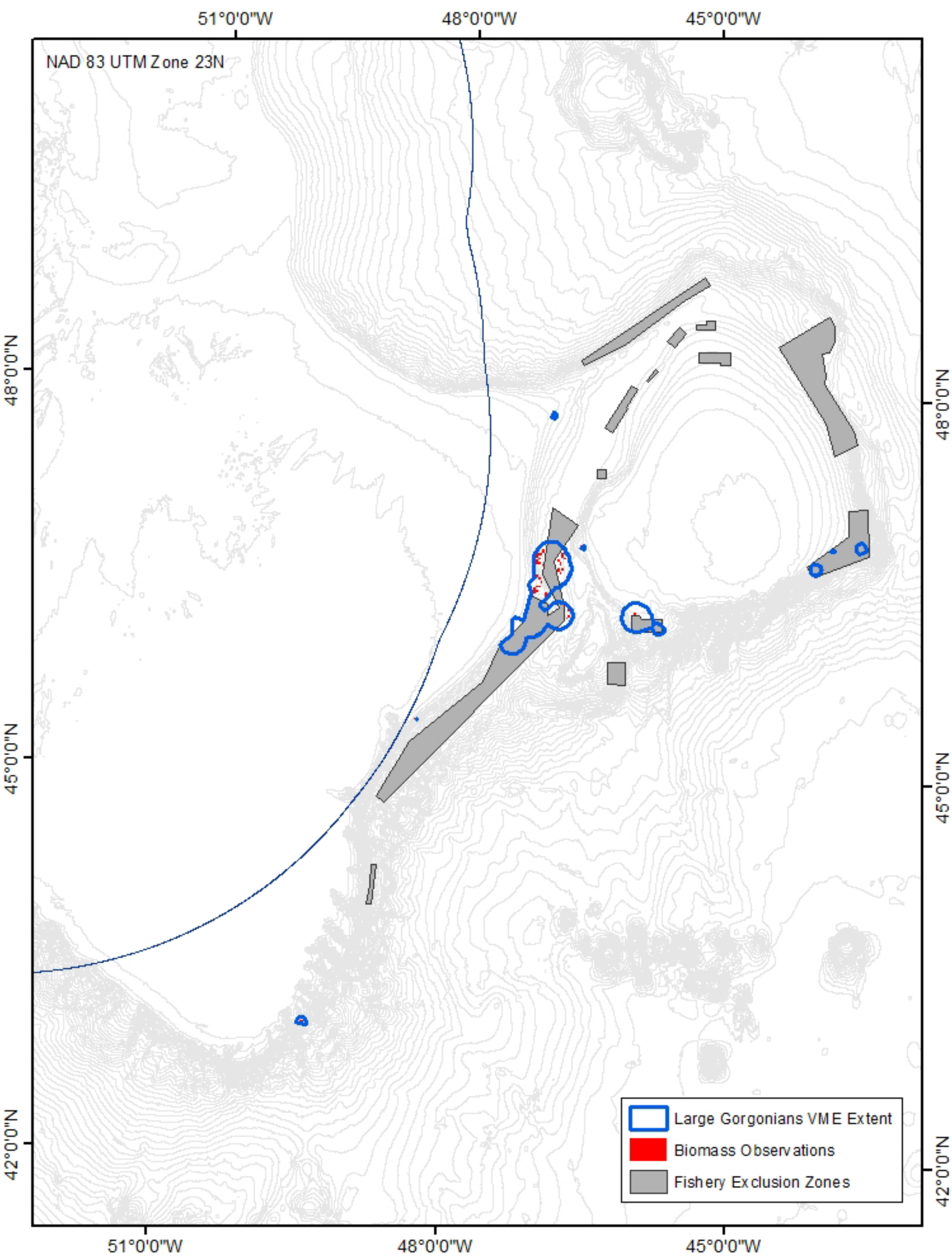


Figure 13. Maps of VMEs extent polygons for Large gorgonians. Source: NAFO, 2016.

2.12.4 Supporting citations

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Kenchington, E., Murillo, F.J., Lirette, C., Sacau, M., Koen-Alonso, M., Kenny, A., Ollerhead, N., Wareham, V., & Beazley, L. (2014). Kernel density surface modelling as a means to identify significant concentrations of vulnerable marine ecosystem indicators. *PLoS ONE*, 9(10), e109365. doi:10.1371/journal.pone.0109365.

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2.13 Case Study 12 – Mid-Atlantic Canyons (and SE USA)

2.13.1 Name of the VME

Four VMEs were included for CS#12, Mid-Atlantic Canyons and SE USA:

- Cape Lookout Coral Banks
- Hatteras Middle Slope
- Norfolk Canyon and vicinity
- Baltimore Canyon and vicinity

2.13.2 Latitude / longitude of the centre of the VME

Table 12 displays the positions of the centre of the VMEs.

Table 12. Location of the centres of the VMEs for Case Study #12, Mid-Atlantic Canyons and SE USA

VME	Longitude	Latitude
Cape Lookout Coral Banks	-75.87527778	34.2194444
Hatteras Middle Slope	-74.83333333	35.5
Norfolk Canyon and vicinity	-74.65333333	37.0744444
Baltimore Canyon and vicinity	-73.79333333	38.085

2.13.3 Features description

Cape Lookout Coral Banks: This is a large area of extensive cold-water coral habitat, dominated by large bioherms built by *Lophelia pertusa*. This deep coral ecosystem ranges in depth from about 370 to 600 m. Biodiversity is quite high. The area was protected by the South Atlantic Fishery Management Council from fishery impacts (only) as a Habitat Area of Particular Concern.

Further details can be found in Ross & Nizinski (2007), Ross & Quattrini (2007, 2009), Hourigan et al. (2017).

Hatteras Middle Slope: This area of rugged mini-canyons (composed of consolidated muds) is physically and biologically unique. It exhibits some of the most productive benthic and water column habitats along the US east coast. The area was considered Essential Fish Habitat by the South Atlantic Fishery Management Council.

Further details can be found in Schaff et al. (1992), Diaz et al. (1994), Sulak & Ross (1996), Ross et al. (2001), Bauer et al. (2002), Gartner et al. (2008).

Norfolk Canyon and vicinity: This is a very rugged submarine canyon that contains extensive cold-water corals (dominated by octocorals) and high biodiversity. Cold methane seeps and historical shipwrecks occur in this vicinity, adding to structural and trophic complexity. Commercial and recreational fisheries use the area. Corals and benthic habitats have been protected by the Mid-Atlantic Fishery Management Council. This canyon has been the subject of intensive recent multidisciplinary studies.

Further details can be found in Obelcz et al. (2014), Skarke et al. (2014), Ross et al. (2015), Prouty et al. (2016), Brooke et al. (2017), CSA et al. (2017).

Baltimore Canyon and vicinity: This is a rugged submarine canyon that contains extensive cold-water corals (dominated by octocorals) and high biodiversity. Cold methane seeps occur in this vicinity, adding to structural and trophic complexity. Commercial and recreational fisheries use the area. Corals and benthic habitats have been protected by the Mid-Atlantic Fishery Management Council. This canyon has been the subject of intensive recent multidisciplinary studies.

Further details can be found in Hecker & Blechschmidt (1980), Obelcz et al. (2014), Skarke et al. (2014), Ross et al. (2015), Prouty et al. (2016), Brooke et al. (2017), CSA et al. (2017).

2.13.4 Supporting citations

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2.14 Case Study 13 – Tropic Seamount

2.14.1 Name of the VME

Tropic Seamount

2.14.2 Latitude / longitude of the centre of the VME

The centre of this VME is located at a longitude of -20.75°, and a latitude of 23.916667°.

2.14.3 Features description

The Tropic Seamount hosts multiple VMEs:

(a) Dense patches of the reef framework-forming scleractinian *Solenosmilia variabilis* (Duncan, 1873) occurred on ledges at depths from ~1,000 to 1,800 m.

(b) Dense aggregations of coral gardens formed by *Acanella arbuscula* (Johnson, 1862), *Metallogorgia melanotrichos* (Wright & Studer, 1889), *Corallium tricolor* (Johnson, 1899), *Chrysogorgia* (Duchassaing & Michelotti, 1864), *Iridogorgia* (Verrill, 1883), and *Thouarella* (Gray, 1870) occurred at depths of ~ 1010 to 3000 m on rocky substrata, while dense coral gardens formed by *Narella bellissima* (Kükenthal, 1915), *Acanthogorgia armata* (Verrill, 1878) and *cf. Swiftia* (Duchassaing & Michelotti, 1864) occurred at depths up to 3600 m and were associated with volcanic substrata. A third type of coral gardens was formed by dense aggregations of bamboo corals (Familiy Isididae) tentatively assigned to the genus *Keratoisis* (Wright, 1869) and *Lepidisis* (Verrill, 1883) occurring at 2,500-3,500 m depth. This third type of coral gardens also hosted deep-sea squid eggs, indicating a potential spawning and/or nursery ground.

(c) Dense monospecific sponge ground formed by the hexactinellid sponge *Poliopogon amadou* (Thomson, 1878) occurred on steeply sided ridges of the seamount from 2,500-3,000 m.

Mixed deep-sea sponge aggregations also occurred, formed by other hexactinellids including *Pheronema carpenteri* (Thomson, 1869), *Stylocordyla pellita* (Topsent, 1904), *Hertwigia falcifera* (Schmidt, 1880), *Aphrocallistes beatrix* (Gray, 1858), and species from the genus *Euplectella* (Owen, 1841); *Hyalonema* (Gray, 1832); *Caulophacus* (Schulze, 1886); *Asconema* (Kent, 1870); and *Phakellia* (Bowerbank, 1862). Demosponges and other undetermined massive and encrusting sponges were also observed.

(d) Xenophyophore field were also observed, likely *Syringammina* sp.

(e) Dense crinoid fields were also observed, including stalked *Endoxocrinus (Diplocrinus) wyvillethomsoni* (Thomson, 1872) (Isselicrinidae), and two thalassometrid feather stars, *Koehlermetra porrecta* (Carpenter, 1888), and perhaps *Thalassometra lusitanica* (Carpenter, 1884).

The Tropic Seamount has VMEs that meet all five FAO criteria: i) uniqueness or rarity (e.g., the biogeographically restricted sponge grounds formed by *Poliopogon amadou*); ii) functional significance (e.g., coral gardens formed by octocorals, likely primnoids, host deep-sea squid eggs so are part of an egg-laying ground); iii) fragility (most of the VME indicator taxa we recorded would be damaged or killed by bottom trawling at depths that are fishable, whereas both the summit and deeper water VMEs would be susceptible to damage from seabed mining plumes), iv) life history traits that make recovery difficult (species like the reef framework-forming coral *Solenosmilia variabilis* are long lived and likely mature slowly); v) structural complexity (most of the VME indicator taxa are megafaunal erect species that branch, including corals such as *S. variabilis* which are associated with higher species richness than non-coral bearing areas).

2.14.4 Supporting citations

Ramiro-Sánchez, B., González-Irusta, J.M., Henry, L.-A.H., Cleland, J., Yeo, I., Xavier, J.R., Carreiro-Silva, M., Sampaio, Í., Spearman, J., Victorero, L., Messing, C.G., Kazanidis, G., Roberts, J.M. & Murton, B. (2019). Characterization and mapping of a deep-sea sponge ground on the Tropic Seamount (Northeast tropical Atlantic): implications for spatial management in the High Seas. *Frontiers in Marine Science*, *6*(278).

3 Adjust EEF Portfolio – VME index

3.1 Introduction

In the last twenty years, several global agreements on biological conservation and sustainable development have proposed to set aside for protection 10–30% of all the marine biomes by the year 2012, 2020 and 2030. In order to speed up deep sea and open ocean conservation and achieve the proposed targets, the parties to the Convention on Biological Diversity (CBD) have adopted seven scientific criteria for identifying ecologically or biologically significant areas (EBSA) in need of protection in open-ocean waters and deep-sea habitats (COP decision IX/20 paragraph 14). These criteria are (CBD, 2009): uniqueness or rarity; special importance for life-history stages of species; importance for threatened, endangered or declining species and/or habitats; vulnerability, fragility, sensitivity or slow recovery; biological productivity; biological diversity; and naturalness. The application of the CBD EBSA criteria should ultimately allow the establishment of representative marine protected area networks in the high seas and help the implementation of ecosystem- based managements. CBD also defined five criteria for the definition of representative networks of Marine Protected Areas (MPAs): identification of ecologically or biologically significant areas, representativity, connectivity, selection of replicated ecological features and selection of viable and adequate sites (CBD, 2009). The identification of ecologically and biologically significant areas more suitable for conservation may represent an important first step in the creation of such networks.

Taranto et al. (2012) proposed a framework for applying the CBD EBSA criteria (CBD, 2009) to locate potential ecologically or biologically significant seamount areas, based on the best available information available. In particular, Taranto et al. (2012) developed methods for applying the EBSA criteria to individual seamounts and methods to assess the impact of different fishing gears and mining activities on the various components of individual seamounts such as pelagic, benthopelagic and benthic environments. This framework could allow managers to identify EBSAs and to prioritise their choices or policies in terms of protecting undisturbed areas, protecting disturbed areas for recovery of habitats and species, or both. CDB prioritise areas having low levels of disturbance relative to their surroundings. However, where no natural areas remain, areas with high possibilities of recovery after the cessation of anthropogenic-related activities should be considered (Roberts et al., 2003; CBD, 2009). Thus, measuring major human activities is of paramount importance in deep-sea conservation. The Ecosystem Evaluation Framework (EEF) could be redesigned for other habitats to enhance a systematic approach to deep-sea and open-ocean management. The outcomes of these evaluations should serve as a powerful tool for identifying sites of particular importance for conservation which can then be integrated in MPA networks following the set of principles and criteria guiding design and implementation of MPA networks (IUCN-WCPA; 2008; Gilman et al., 2011).

3.1.1 Adjust the EEF Portfolio to the deep sea – VME index

ATLAS adapted the EEF to identify ecologically and biologically significant areas (EBSAs) in the deep sea and assign each area to conservation categories as a precursor to the development of a North Atlantic wide MPA network. In this context, the protocols were adapted to the deep sea by focusing on identifying areas where VMEs are more likely to occur and compiling fisheries data that may directly impact VMEs.

Whilst significant steps have been made to map and protect VMEs in the high-seas areas in general (e.g. Portela et al., 2010) and in the high-seas areas regulated by RFMOs (e.g. Durán-Muñoz et al., 2012a), progress has been inconsistent or incomplete (Durán-Muñoz and Sayago-Gil, 2011; Wright et al., 2014; FAO, 2016). In part, limited knowledge about their spatial distribution has impeded the application of effective protective measures in many areas (Weaver et al., 2011). Although dedicated field surveys and species distribution models of some individual VME indicator taxa are increasingly being made available (Rengstorf et al., 2013, 2014; Fabri et al., 2014; Vierod et al., 2014; Anderson et al., 2016a), there is little information on the spatial distribution of species assemblages in concentrations that might constitute a VME and therefore what is needed to trigger management actions (Ardron et al., 2014).

Currently, larger amounts of data on VME indicator taxa occurrences across large spatial scales may be available from bycatch records from fisheries surveys (e.g. Murillo et al., 2011, 2012; Portela et al. 2012), cooperative surveys (Durán-Muñoz et al., 2011, 2012b) and commercial fishing operations. The problem in using bycatch data to inform on the presence of VMEs lies in the fact that bottom fishing gear are poor sampling tools for VME indicator organisms and that bycatch data may not represent the true benthic community composition and densities (Auster et al., 2011). Although better than no data, there is a large amount of uncertainty associated with bycatch data.

In the Northwest Atlantic Fisheries Organization (NAFO) Regulatory Area, a geospatial methodology was developed to identify VMEs using data from research trawl surveys (Kenchington et al., 2014). However, this approach requires comprehensive fisheries survey programmes (Murillo et al., 2011, 2012) and standardised datasets that are generally not available for most areas beyond national jurisdiction. Generally, data on VME indicator presence are derived from a wide variety of sources (commercial trawl and longline operations, ROV surveys, towed camera surveys or research surveys), which are challenging to integrate and interpret as a whole. For example, some records are bona fide VME habitat types such as those identified through recent ROV video footage of large *Lophelia* reefs while others are scientific trawl survey bycatch records and anecdotal information from commercial fishing operations. As a result, VME-related data are generally qualitatively assessed using expert judgement (ICES, 2013). Expert judgement is a common component of resource management and conservation decision-making, but comes with known limitations and inconsistencies, many of which concern how disparate information is contextualised, and a poor characterisation of uncertainty (Burgman et al., 2011; Martin et al., 2012). To aid decision-making concerning the protection of VMEs, we have developed methods that are capable of integrating the wide range of existing VME data, while taking into account some of the uncertainties associated with sampling methods and reported taxonomy.

Taking advantage of existing institutional databases of partners participating in this work as well as from public databases such as the Ocean Biogeographic Information System portal (OBIS), the NOAA Deep Sea Coral Data Portal, and the ICES Vulnerable Marine Ecosystems data portal, we developed a multi-criterion assessment (MCA) method to adapt the EEF to the deep sea, and namely to evaluate how likely an area represents a VME at two different spatial scales (regional and ocean-basin scale). Some of these datasets were built to facilitate more scientifically robust advice on the distribution of VMEs and to aid the development of possible management recommendations such as bottom fishing closures to protect VMEs. The outcomes of these analyses will be put forward to develop systematic conservation planning approaches as candidate areas that warrant further investigation as potential MPAs with management options that reduce threats.

3.2 Material and methods

The term Vulnerable Marine Ecosystem is used here in the context of the FAO international guidelines (FAO, 2009) and reviewed by ICES (ICES, 2016a). The ATLAS VME database is currently comprised of approximately 455,000 records (Table 13) distributed in both sides of the North Atlantic (Figure 14).

Table 13. Sources of VME indicator compiled in this study.

Database	Number of records
ATLAS data call	38401
ICES VME database	30169
InterRidge	106
NOAA	71497
OBIS	314354
Total	**454527**

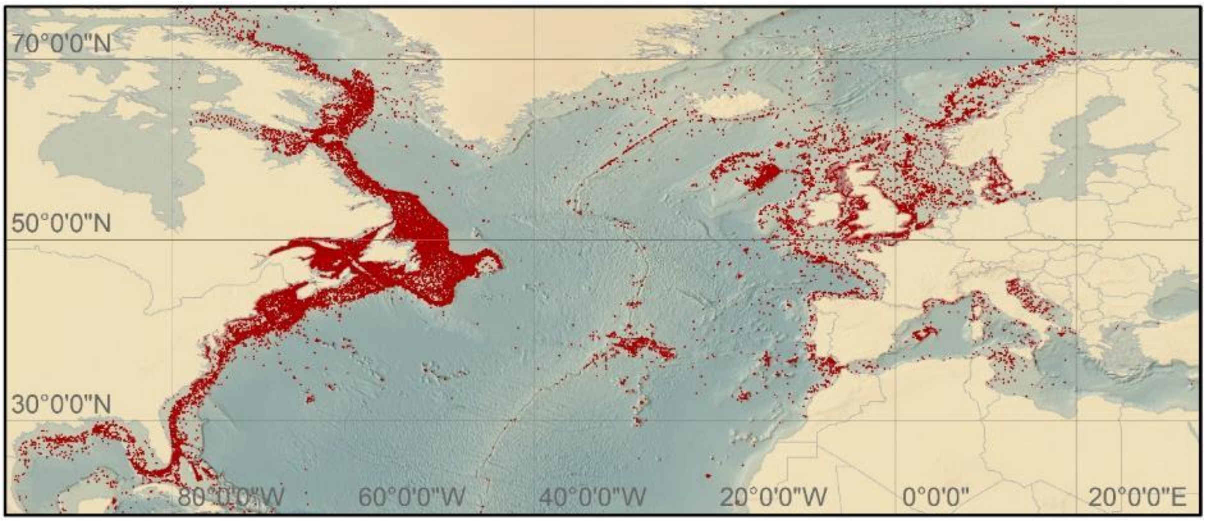

Figure 14. The distribution of VME indicator records throughout the North Atlantic contained within the VME database.

Multi-criteria assessment (MCA) is a method of aggregating data based on different criteria or attributes that contain information relevant to the decision and weighting these to provide a single metric that captures all this information. The essential feature of MCA is the development of a matrix in which the performance of the data are weighted against each criterion (e.g. the survey method) and from which an aggregate value is derived. The MCA was based on spatially-gridded data format, i.e. multiple individual points or records contributed to the assessment of a single grid cell containing a VME. A C-square spatial grid methodology (Rees, 2003) composed of grid cell size of 0.225x 0.225 degrees, similar to that used in the systematic conservation planning approach (Section 4). As described below, the MCA captures the fact that not all VME indicators have the same vulnerability to human impacts, and thus should be weighted differently. Therefore, the MCA is a taxa-dependent spatial method. Additionally, to account for data quality issues a measure of the confidence associated with each VME record was developed.

For each c-square grid cell, two values were calculated:

- A 'VME index' which combines how intrinsically vulnerable to human impacts the VME indicator is deemed to be, and how abundant the VME indicator is (for example, an aggregation representing a cold-water coral reef as opposed to a record of a single individual or taxon).

- A 'Confidence index' associated with the 'VME index'. This is a confidence (or uncertainty) estimate based upon a) the numbers of samples available within the grid cell, b) the provenance of the records in that cell (e.g. visual survey, fisheries data, or inferred from other methods), c) the time span of the data (i.e. time between the first and last record), and d) the age of the most recent survey.

3.2.1 'VME index' scoring procedure

Because the ATLAS VME database includes both records of known VME habitats (Section 2) as well as VME indicators, these former bona fide records were treated separately from the latter. Bona fide records included high quality underwater imagery from ROV surveys of anemone aggregations, cold seeps, cold-water coral reefs, coral gardens, deep-sea sponge aggregations, hydrothermal vents, and sea pen fields (Section 2). Non-VME habitat grid cells (i.e. not containing bona fide records) were evaluated by assigning a VME indicator score to each VME indicators present, based on their taxonomy and their abundance as explained below.

3.2.2 Assigning a VME indicator score to VME indicators

Twelve VME indicator types were agreed for inclusion in the ATLAS database and followed the ICES advice (ICES, 2016a), reflecting the main taxonomic groups of VME indicators occurring in the North Atlantic (Table 14). Naturally, there are some interspecific inconsistencies, for example, not all species of 'Gorgonian' will be equally vulnerable. However, these categories were considered to be a reasonable compromise between a manageable list and a range of vulnerabilities that was not excessive (ICES, 2016b). The category 'sponges' was found to be particularly problematic because it includes all sponges, from small encrusting species to the massive, aggregation forming species (e.g. Geodiids). The reason a generic 'sponges' category was created in the past was because there is often much uncertainty in species identification and many records in the VME database are simply identified to the Phylum level of 'Porifera'. Nevertheless, the VME database contains sponge records identified to the lowest possible taxonomical level, which is of value for use in the MCA. When a sponge record was identified to the genus level, literature sources (e.g. Hogg et al., 2010; Murillo et al., 2012; McIntyre et al., 2016) and expert opinion was used to decide on those genera of sponges containing species that can be described as 'massive' and forming aggregations. All species belonging to the following genera were classified as the type 'Large Sponge' and as such would receive a different 'VME' score than all other sponges: *Asconema*, *Craniella*, *Chonelasma*, *Geodia*, *Pheronema*, *Polymastia*, *Stryphnus*, *Tetilla*, *Thenea*, and *Vazella*. All others species of sponges and records for which no information of Genus were provided were ranked according to the scores in the type 'Generic Sponges'. Following this assessment of sponge types, thirteen VME indicator types were considered in the next phase (Table 14). The distribution of occurrences of each VME indicator records throughout the North Atlantic contained within the ATLAS VME database is shown in Figure 15.

Table 14. Number of records compiled for each VME indicator.

VME Indicator	**Number of records**
Stony coral	38553
Black coral	13536
Chemosynthetic species (seeps and vents)	53
Large Sponge	22920
Gorgonian	47236
Xenophyophore	179
Stylasterids	4502
Stalked Crinoid	150
Generic sponge	184536
Sea pen	16846
Cup coral	20087
Soft coral	26659
Anemone	78445
NA or to revise	*825*
Total	**454527**

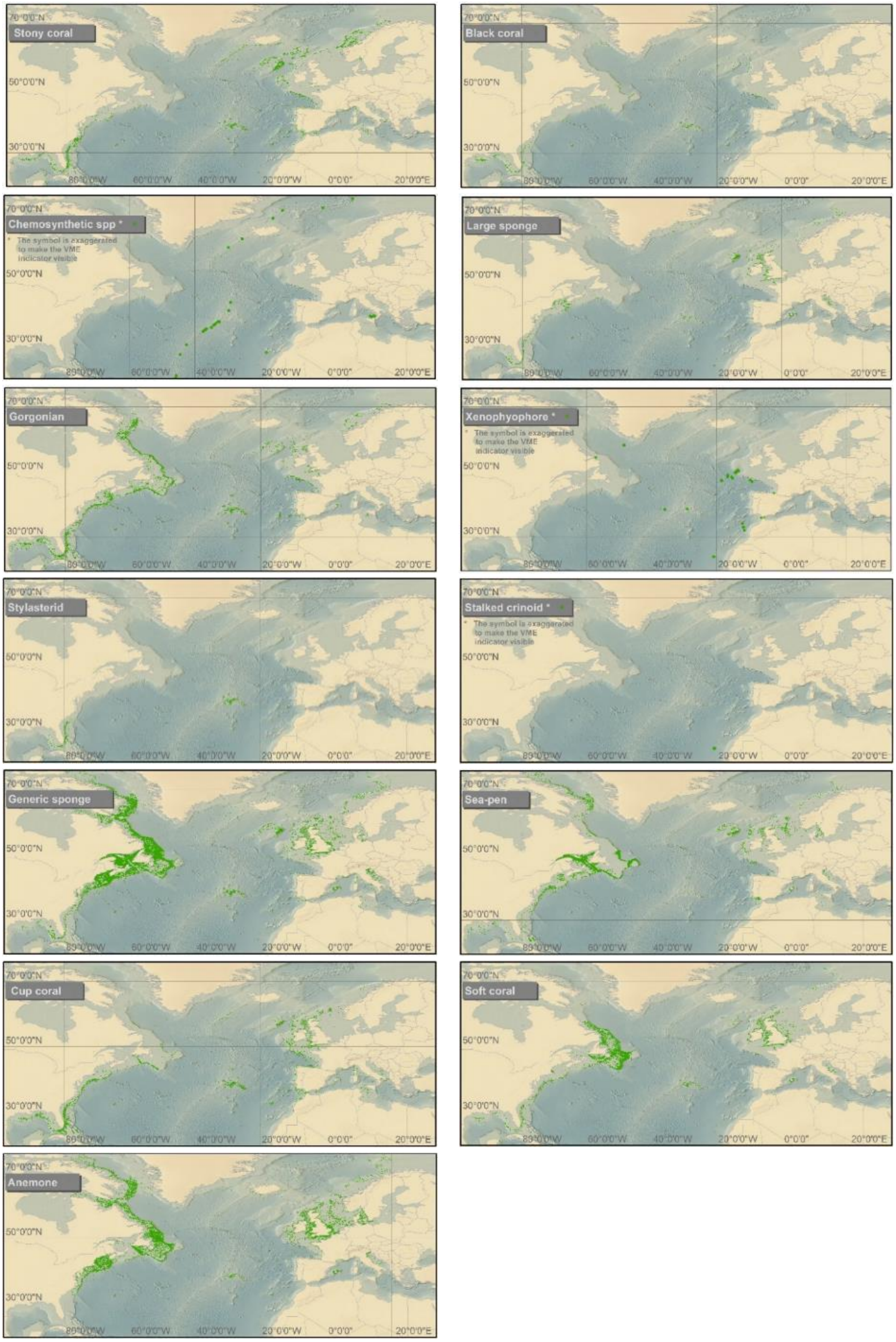

Figure 15. The distribution of occurrences of each VME indicator records throughout the North Atlantic contained within the VME database.

VME indicator types included in the ATLAS VME database were assessed against each of the five FAO criteria for defining what constitute a VME. The FAO list of characteristics used as criteria in the identification of VMEs are (FAO, 2009):

- Uniqueness or rareness: An area or ecosystem that is unique or that contains rare species whose loss could not be compensated for by similar areas or ecosystems.
- Functional significance of the habitat: Discrete areas or habitats that are necessary for the survival, function, spawning/reproduction or recovery of fish stocks, particular life-history stages (e.g. nursery grounds or rearing areas), or of rare, threatened or endangered marine species.
- Fragility: An ecosystem that is highly susceptible to degradation by anthropogenic activities
- Life history of species makes recovery difficult: Ecosystems that are characterised by populations or assemblages of species with one or more of the following characteristics: slow growth rates, late age of maturity, low or unpredictable recruitment, or long-lived.
- Structural complexity: An ecosystem that is characterised by complex physical structures created by significant concentrations of biotic and abiotic features.

The degree to which each VME indicator group (not the individual taxa contained) fit each of the five FAO criteria was scored from 1 (low) through 5 (high). The scoring procedure was discussed and agreed by a group of deep-sea scientists through an ICES Expert Group using existing informed expert judgement, and the following specific guidelines:

- Rarity: was scored according to presence on the IUCN red list, and if the indicator was known to be endemic, rare, threatened or declining.
- Functionality: was scored by evaluating if the indicators were known to create nursery areas for other species, or known for having higher level ecosystem role, such as nutrient cycling and water filtration.
- Fragility: was scored according to the fragility of the indicator against physical contact, the height and complexity of its structure, and the capacity for retraction, retention or re-growth or if being naturally protected in some way.
- Life-history: was scored against the longevity, fecundity, age at maturity, growth rate, and known frequency of recruitment success.
- Structural complexity: was scored based on structural habitat created, frame-building, and presence of commensal or closely associated species.

These ratings resulted in VME indicator scores for each VME indicator type (Table 15) where, for example, stony corals were considered the most susceptible to degradation by anthropogenic activities and with life-history characteristics that make recovery more difficult. It should however be noted that these scores could change if new data were to become available and when the taxonomic resolution of the indicators present in the database is improved. As the five FAO criteria were seen as being approximately orthogonal, the final VME indicator score for each of the thirteen VME indicators was calculated using the quadratic mean, i.e. the square root of the mean of the squares.

Table 15- Scores for VME indicators occurring in deep sea of the North Atlantic basin based on the degree to which each VME indicator fits each of the five FAO criteria (FAO, 2009). Scores range from 1 (low) to 5 (high). The final VME indicator score was calculated using the quadratic mean, i.e. the square root of the mean of the squares, across the five FAO criteria being assessed. Chemosynthetic species. (seeps and vents) refers to megabenthos species as described in ICES (2016a).

	FAO criteria for defining what constitutes a VME					VME
VME indicator	**Unique.**	**Functional.**	**Fragility**	**Life History**	**Structural**	**Indicator score**
Stony coral	3	4	5	5	5	4.47
Black coral	5	2	4	5	2.5	3.91
Chemosynthetic spp. (seeps and vents)	5	5	1	4	3	3.90
Large Sponge	2	5	4	4	3	3.74
Gorgonian	4	3	3	5	2.5	3.61
Xenophyophore	2	3	5	2	2	3.03
Stylasterid	4	1	4	2.5	2	2.94
Stalked crinoid	4	1	2	4	1	2.76
Generic Sponge	2	3	3	3	2	2.65
Sea-pen	2	3	3	2	2	2.45
Cup coral	2	1	2	4	1	2.28
Soft coral	1	1	2	2	2	1.67
Anemone	1	1	2	2	1	1.48

3.2.3 Assigning abundance score to VME indicator records

For each record with weight data in the database, the abundance recorded was evaluated against the NEAFC (Recommendation 19 2014: Protection of VMEs in NEAFC Regulatory Areas as Amended by Recommendation 09:2015) and EU (Regulation 2016/2336) VME encounter thresholds for live corals (30 kg) or live sponges (400 kg). If the abundance was over the encounter threshold, a value of 5 was assigned. If the abundance was below the encounter threshold we used Jenks natural breaks classification method (Jenks, 1967) to identify an intermediate encounter threshold. Therefore, a value of 3 was assigned if abundance was above 1kg (for corals) or 60kg (for sponges) and otherwise a value of 1 was assigned. If no data for abundance were available, a score of 0 was allocated to the "abundance score" and thus had no effect on the final 'VME index'. As there are no agreed thresholds for VME indicators that are not "corals" or "sponges" (e.g. anemones) we used the encounter thresholds values defined for corals. Although the NEAFC thresholds are considered to be too high and not based on robust scientific data (Ardron et al., 2014), without agreed thresholds this was considered the most appropriate option, so as to be relevant for current (albeit imperfect) management practices.

3.2.4 Defining the final 'VME index'

VME bona fide habitats identified in the ATLAS VME database received the maximum 'VME index' of 5. The final 'VME index' for each remaining records was calculated based on the VME indicator score and the abundance score. In the current version of the MCA we gave 90% weight to the 'VME indicator score' and 10% weight to the abundance score. A low weighting was assigned to the abundance score because of the limited number of records where such information is available, and because there is much uncertainty regarding encounter thresholds when little is known about how VMEs abundances and vulnerabilities have been estimated (ICES, 2012).

After assigning a VME index to each VME indicator record, the results were then aggregated to grid cell of sizes 0.225x 0.225 degrees. For each cell, the maximum VME index value was retained as the overall value for that cell. This was to prevent down-weighting of important records by less important records as would happen if, for example, the median or the mean value of a cell was used. It was therefore acknowledged that some cells would have high scores due to a single high scoring record even when other records in that cell might have a low score. This approach was viewed as consistent with the precautionary approach.

The final outcome was presented as VME habitat for these grid cells containing bona fide records and as three nominal categories of 'VME index' scores, indicating the likelihood of encountering a VME in the assessed grid cells. Thresholds were computed using the Jenks natural breaks classification method (Jenks, 1967). The categories were: low 'VME index', for total scores <2.7; medium, for total scores between 2.7 and 3.7; and high, for total scores >3.7. The breaks produced suggested that the high 'VME index' scores would pick out stony corals at any abundance, and black corals, large sponges and chemosynthetic species when above the NEAFC VME threshold. The medium 'VME index' scores would pick out black corals, sponges and chemosynthetic species when below the NEAFC VME threshold, and gorgonians, stylasterids, sea pens, sponges, xenophyophores and stalked crinoids when above the threshold.

3.2.5 'Confidence index' scoring procedure

To account for data uncertainty such as data quality issues and the varying degree of knowledge regarding each cell (i.e. how well it has been surveyed), we developed a data confidence index similar to the ones elaborated by Wallace et al. (2010). This index served as a measure of confidence in the 'VME index' scores assigned to individual grid cells and was calculated independently of the 'VME index'. The 'Confidence Index' was not calculated for bona fide VME habitats where a confidence index of 1 was allocated.

Two measures are usually incorporated in such indices (Wallace et al., 2010; Taranto et al. 2012): data quality and data deficiency. We considered using a measure of data deficiency for each grid cell but did not implement that measure as data deficiency is being partially covered in the data quality measure. Therefore, data quality here reflects the origin and nature of the collected data and was divided into three categories: low (scored as 0), medium (scored as 0.5), and high (scored as 1) data quality. The high data quality category highlights cells with information derived from scientific visual surveys, sampled by many independent surveys (>5 surveys), over a long time period (>10 years), and where the most recent record is recent (<10 years) and thus giving an idea if the VME is still present. Low quality data refers to a VME index derived from a poorly sampled grid cell (< 3 surveys), where the presence of a VME had been somehow inferred, sampled for only a short period (<5 years) and a long time ago (>30 years). Consequently, four distinct criteria were used for estimating the data 'Confidence Index' (Table 16).

Table 16. Criteria used to score different components of the 'Confidence Index' for each grid cell.

	Confidence		
Criteria	**Low (score = 0)**	**Medium (score = 0.5)**	**High (score = 1)**
Survey method	If inferred from other survey methods or indirect methods scores, e.g. acoustic methods	Record from commercial fisheries or scientific surveys without visual information	Record originated from visual surveys
Number of surveys	<3 surveys	3-5 surveys	>5 surveys
Time span or range in years	<5 years	5-10 years	>10 years
Age of the last survey	>30 years	10-30 years	<10 years

The resulting data 'Confidence index' for each grid cell was calculated as the quadratic mean (i.e. the square root of the mean of the squares) of the scores associated with the records producing the highest 'VME index', and had a minimum value of 0 (few factors scored or low data quality) and a maximum value approaching 1 (all factors scored with high data quality). As in the 'VME Index', the final outcome was presented by grid cell containing no uncertainty (i.e. Confidence Index of 1) or VME bona fide habitat, and as three nominal categories of 'Confidence index' computed using the Jenks natural breaks classification method (Jenks, 1967): low confidence, for scores smaller than 0.32; medium confidence, for scores between 0.32 and 0.77; and high confidence for scores greater than 0.77.

3.2.6 Implementation of the MCA to the VME database

The implementation of the MCA can be illustrated schematically by generating maps of the VME and Confidence indices (Figure 16). By combining these maps, cells with high 'VME index' scores and different confidences can be highlighted. In the top panel of Figure 16, VME bona fide habitats with total confidence are highlighted. In the second panel of Figure 16, we highlighted those grid cells scoring high in the 'VME index' with all confidence categories. In the third panel, grid cells scoring high in the 'VME index' but excluding those cells with a low confidence index were highlighted. In the bottom panel of Figure 16, we highlighted only those grid cells scoring high in the VME index and high confidence. It should be noted that cells with low confidence are not unimportant, but rather the degree of uncertainty means that additional sampling is required to produce a more reliable 'VME index' value.

Prior to the application of the procedure, a detailed quality check of the ATLAS VME database was performed. This included: 1) standardisation and correction of the information contained in all fields; 2) filling missing mandatory fields or correcting detected errors by contacting original data providers, by thorough searches, or ultimately deleting records for which validation was not possible; 3) correction and validation of all species identifications using World Register of Marine Species database (WoRMS, 2016); and 4) deleting duplicated records.

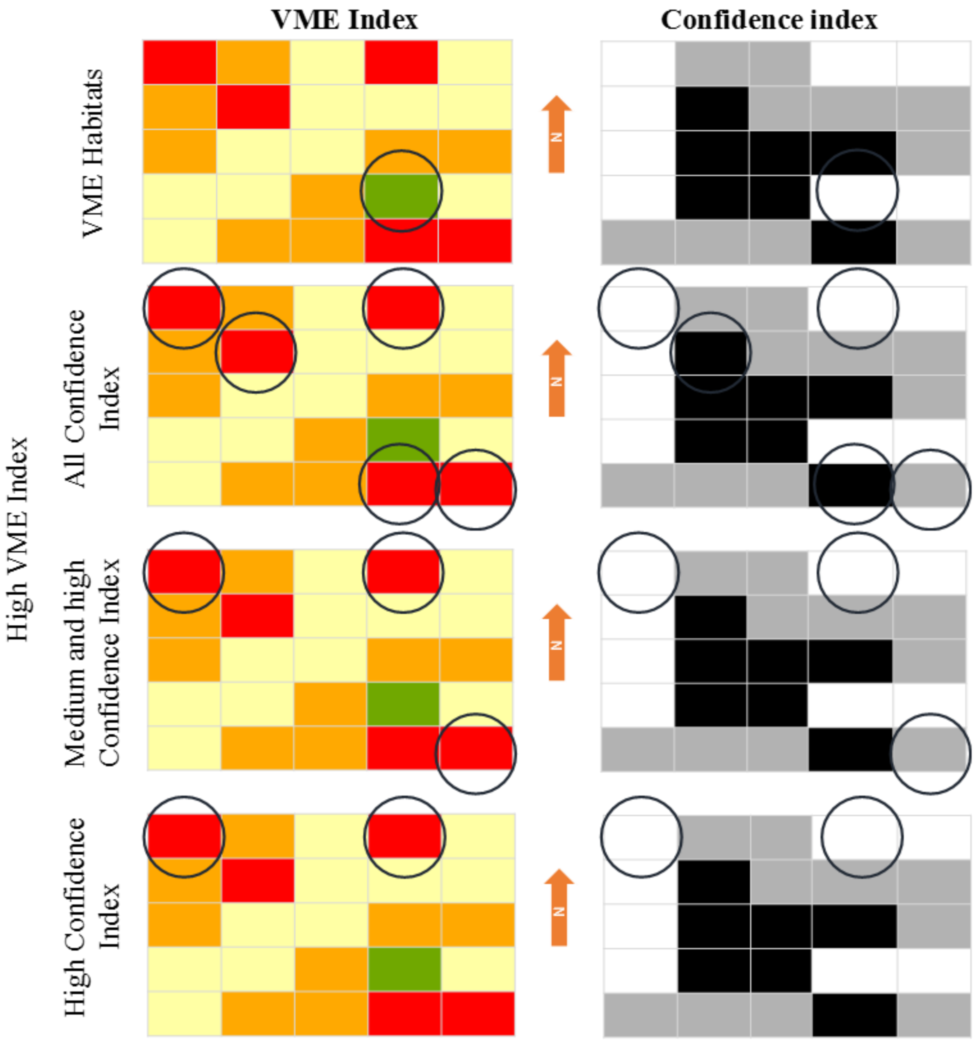

Figure 16. Representation of the usefulness of the VME and Confidence indices maps. The 'VME index' hypothetical map contains VME habitats in green, cells with high 'VME index' scores in red, medium in orange, and low in yellow. The 'Confidence index' map contained cells with high confidence score in white, medium in grey, and low confidence in black. Circles indicate those cells in the hypothetical map that meet the criteria described on the left of the panel.

3.2.7 VME and Fishing Effort portfolio categories

One of the main advantages of deriving a gridded 'VME index' is that it can be directly compared to other gridded data with the same grid size, as for example fishing effort. Fishing intensity data can therefore be used to account for the anthropogenic activities occurring within each cell. We suggest an approach that combines the 'VME index' and the level of fishing activity, measured as the fishing catch rate (average 2010-2015 of annual tonnage per square km) of bottom contact gears (dredges, bottom trawls, and Danish seines) throughout the North Atlantic (Watson & Tidd, 2018; Figure 17). The average annual tonnage per km^2 was log-transformed and re-scaled between 1 and 5.

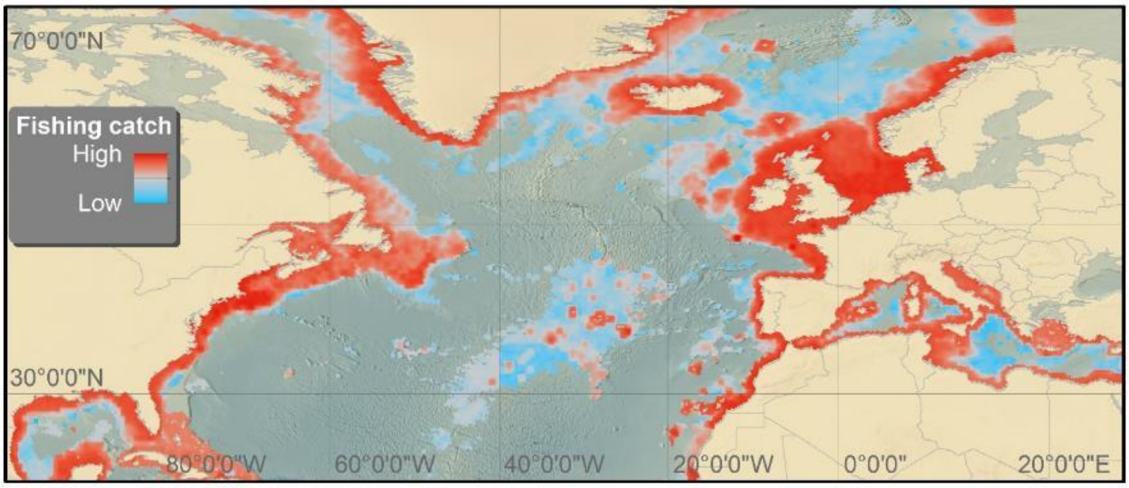

Figure 17. Map of fishing catch rate (average 2010-2015 of annual tonnage per square km, displayed at a 30-min spatial resolution, log-transformed and re-scaled between 1 and 5) of dredges, bottom trawls, and Danish seines throughout the North Atlantic. Source: Watson & Tidd, 2018.

This methodology allows the classification of individual cells into four main categories, which can help in optimising management efforts toward spatial management: Low VME index-Low fishing; Low VME index–High fishing; High VME index-Low fishing; High VME index-High fishing. 'VME index' and fishing intensity for individual cells can therefore be easily summarised and graphically compared (Figure 18).

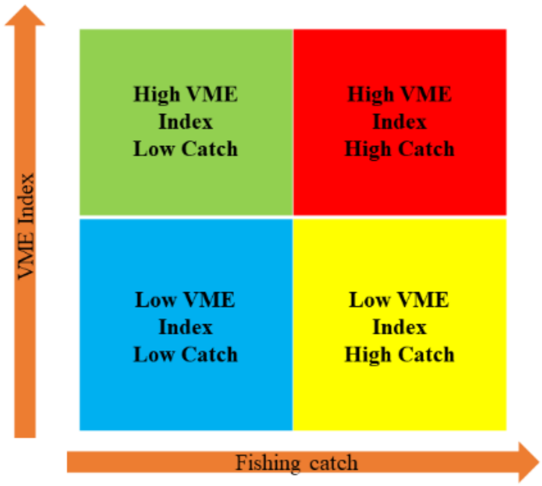

Figure 18. Representation of the application of the portfolio categories concept.

3.3 Implementation of the MCA to the VME database

When applying the MCA to the VME database, the VME index ranged from 1.51 to 4.52. A score of 5.0 was reserved for records of bona fide VME habitats. The observed frequency of the VME index showed a unimodal distribution with most cells being between 2 and 4 (Figure 19). The output appears to capture the main features of the database despite the paucity of life-history data for many of the VME indicator taxa (e.g. Ramirez-Llodra et al., 2010). The results remain to some extent dependent on the expert judgment on scoring how each VME indicator fits the FAO VME criteria. This source of variability, however, was minimal as scores were thoroughly discussed and agreed by a group of approximately 20 deep-sea experts. We recognise that knowledge gaps for some taxon are a major limitation for appropriately scoring some VME indicators (e.g. anemones or sponges). As more scientific information is gathered, this 'inter-VME' weighting may be revised by the Working Group on Deep-water Ecology (WGDEC).

The VME index is also dependent on the encounter thresholds adopted by NEAFC. There is currently a recommendation to reduce these to 15 kg of live corals and 200 kg of live sponges (ICES, 2012). If new encounter thresholds are adopted, the MCA methodology should be updated accordingly.

The confidence index ranged from 0.0 to 0.75. Again a score of 1 was reserved for those records of bona fide VME habitats (Figure 19). Most of the cells showed a confidence index lower than 0.6, most of the ocean-basin scale approach even lower than 0.2, highlighting a reduced sampling effort, with records often falling into the lowest category.

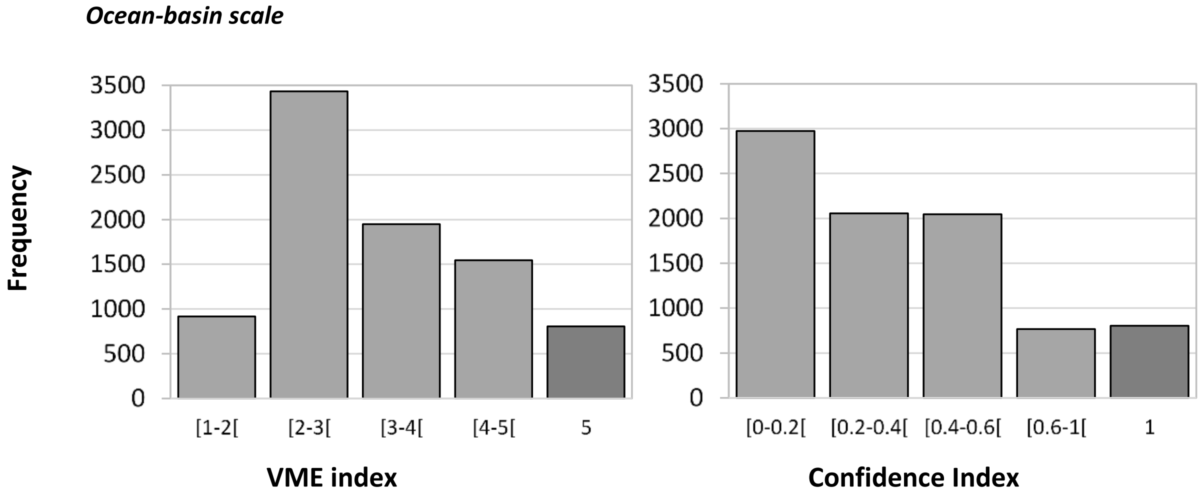

Figure 19. Resulting distribution of the VME index (left) and the Confidence Index (right) when applied to the VME database, including certain VME habitats (VME index of 5 and Confidence index of 1).

3.3.1 North Atlantic ocean-basin scale

This study focuses on the deep waters of the North Atlantic basin, from 18°N to 76°N and 36°E to 98°W. This area was selected for the present study because it is one of the best-studied deep-water regions in the world with respect to both VMEs and fishing effort. Additionally, the North Atlantic Ocean contains well-established Regional Fisheries Management Organisation making this analysis extremely relevant for deep-sea VMEs management purposes.

High numbers of VME habitats (bona fide) are present in the Northeastern Canadian coast, Gulf of Saint Lawrence and Northeast American coasts (Figure 20). A high density of bona fide areas is also reported around Rockall Bank and along the Norwegian coast. Those areas have been extensively sampled and hold lengthy records of historical data (Figure 20).

The MCA identified areas with high values of VME index are mostly located around the Florida-Hatteras slope, the Azores, Reykjanes Ridge and southern Iceland, around the Strait of Gibraltar, in the Bay of Biscay, the Rockall and Hatton Banks, Faroe Islands, and along the Norwegian coast (Figure 20). While a high number of low VME index areas were found in the North Sea and English Channel, in the Irish Sea and along the Canadian coast, and off the northern American coast (Figure 20).

Most of the VMEs are associated with low confidence index (Figure 20). Records with medium confidence were found inside the Gulf of St Lawrence, around the Flemish Cap and Grand Banks, and along most of the Canadian coast, and also around UK and Rockall Bank (Figure 20b, c). With few exceptions, high confidence areas are restricted to bona fide areas (Figure 20b, d) and to small areas in the Gulf of Mexico and around Florida, around the Azores and in the Bay of Biscay.

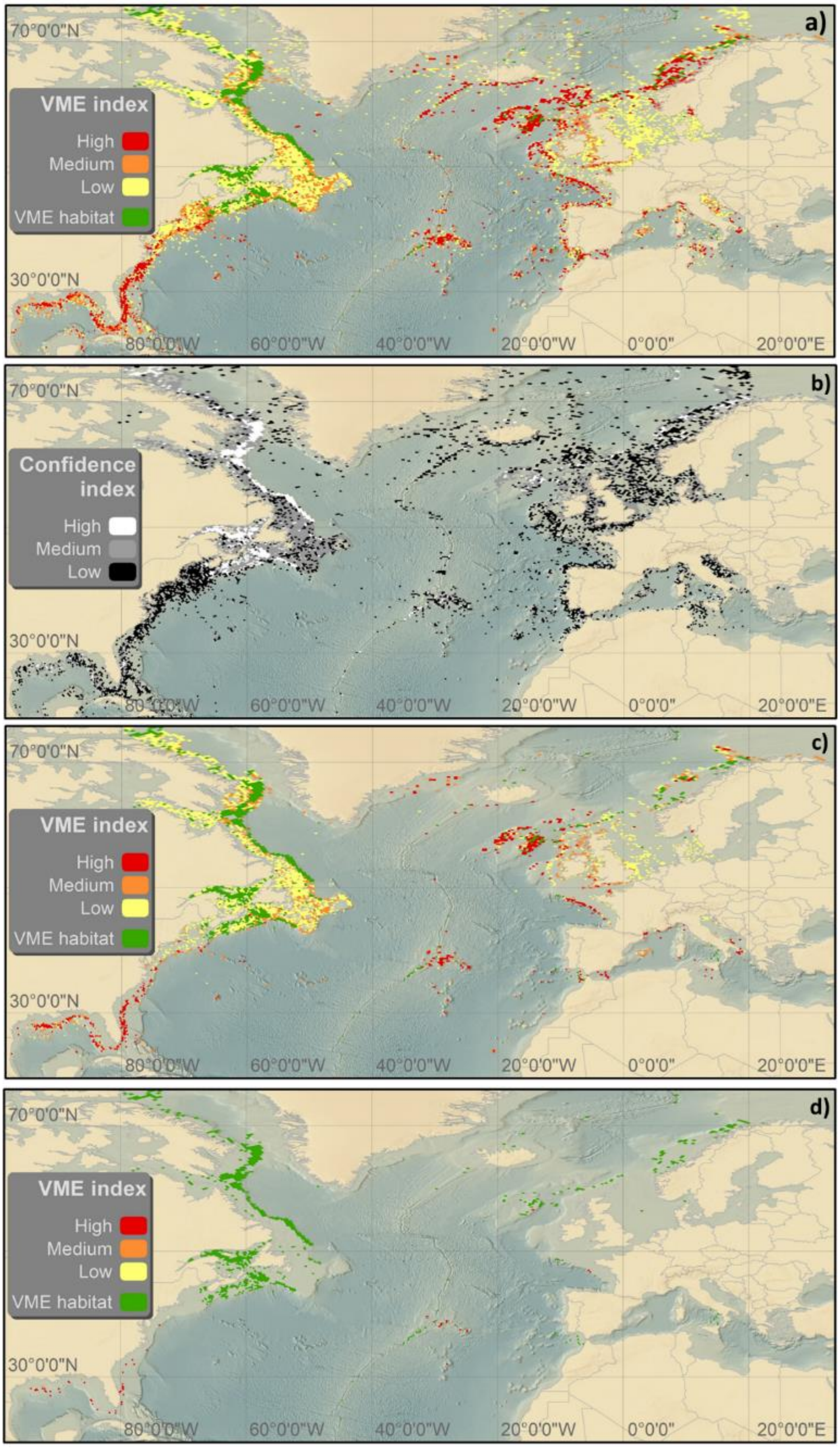

Figure 20. Applying the VME Index and Confidence Index to the VME database for the whole North Atlantic. a) VME index for all cells with data in the VME database; b) Confidence Index for all cells with data in the VME database; c) VME index for cells with medium and high confidence; and d) VME index for cells with high confidence.

3.3.2 Hatton-Rockall Bank

The Hatton-Rockall Bank area in the NE Atlantic provides a model case study to illustrate the application of the MCA approach. Scientific data on the presence of coral at Rockall dates back to the 1970s (Wilson, 1979) and a spate of recent surveys have revealed the occurrence of coral mounds (Wienberg et al., 2008; Durán Muñoz et al., 2009), cold seep ecosystems (Neat et al., 2018), and other important geomorphological features throughout the area (Roberts et al., 2008; Sayago-Gil et al., 2010). In addition, several VME indicator species including cold-water corals and sponges have been identified in recent years through collaboration with commercial trawl and longline fisheries (Durán Muñoz et al., 2011, 2012). Thus the variable amount of information for this area and the range in quality of that information (e.g. fishing records v's scientific observations), serve as a good case study to illustrate the approach.

The data outputs for the Hatton-Rockall Bank area illustrate several important aspects of the MCA (Figure 21). First, there were some bona fide VME habitats identified in the Rockall Bank which are clearly highlighted by the method (Figure 21a). Second, the areas identified by the MCA as high values of 'VME index' often fell within existing NEAFC closures for example NW Rockall and SW Rockall. This suggests the method is useful for identifying areas that need protection. Third, it identified areas of medium and high value of 'VME index' situated outside closed areas thereby suggesting such areas should be carefully assessed and possibly protected. Finally, in Figure 21b, it is apparent that the intensive sampling on the Rockall plateau yields high confidence, whereas the less-well sampled Reykjanes Ridge, southern Iceland and Faroe Islands yield lower overall confidence. This can then be seen particularly clearly where only the cells with medium and high confidence are plotted (Figure 21c, d). This does not mean Rockall Bank is more important from a VME perspective; rather, only that we are more confident that Rockall Bank is an important VME area. There is good evidence that VMEs are present at Hatton Bank and in Reykjanes Ridge, southern Iceland and Faroe Islands, but the confidence of these records is not as high as it is at the Rockall Bank.

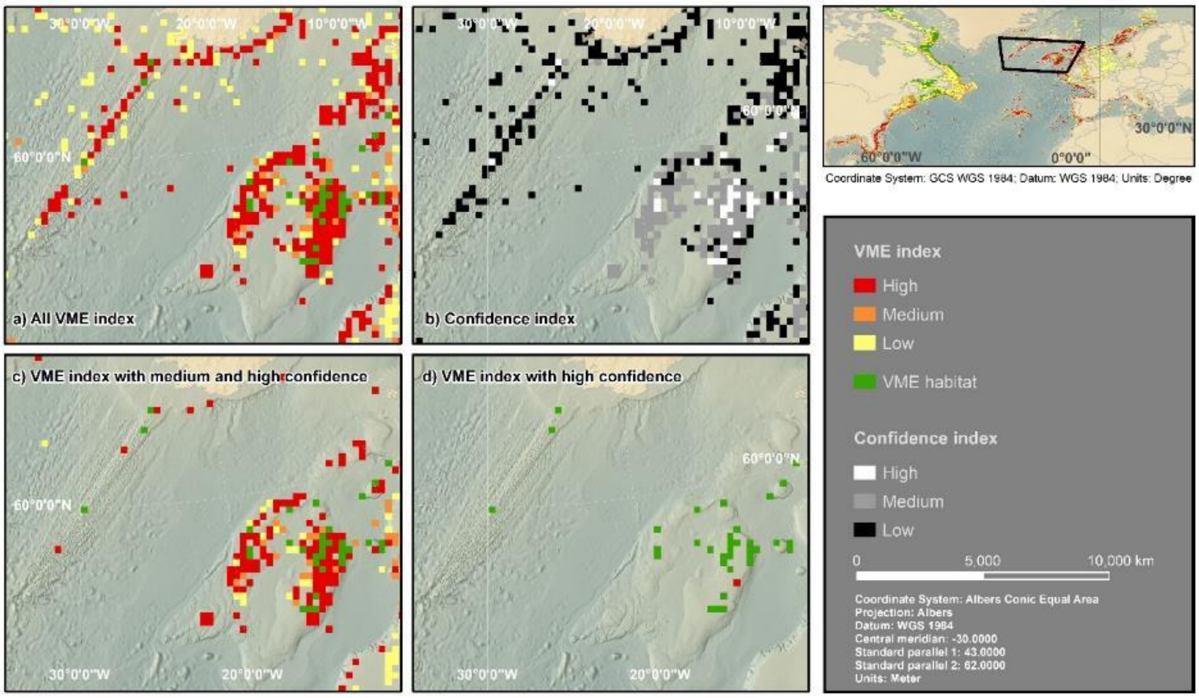

Figure 21. Applying the VME Index and Confidence Index to the VME database: Hatton-Rockall Bank and southern Iceland. a) VME index for all cells with data in the VME database; b) Confidence Index for all cells with data in the VME database; c) VME index for cells with medium and high confidence; and d) VME index for cells with high confidence.

3.3.3 Bay of Biscay

The known distribution of Vulnerable Marine Ecosystems (VME) in the Bay of Biscay comes from the image analysis of 46 dives of the ROV Victor 6000 and the towed camera Scampi, carried out during 7 oceanographic cruises between 2009 and 2013 (van den Beld et al., 2017). The video transects aimed to describe and map the cold-water coral habitats of the Bay of Biscay. They cover a bathymetric range of between 185 m and 2665 m, in or near 24 submarine canyons.

In the Bay of Biscay only few bona fide VME habitats were identified in the northern part, they are the only records holding high confidence (Figure 22a,d). VMEs classified with high values of VME Index were found mainly in the northern coast of Spain, and along the margin of the Bay of the Biscay, while VMEs classified with low values were mostly located closer to the Spanish and French coasts and in the Celtic Sea (Figure 22a). Yet, most VMEs in the area yield low confidence, with medium confidence records found in the canyons of the Bay of Biscay and in the coastal areas, likely reflecting areas with higher sampling effort (Figure 22b). When only considering medium and high confidence records, many areas along the margin of the Bay of Biscay, especially in the North, were identified as high values of VME index (Figure 22c).

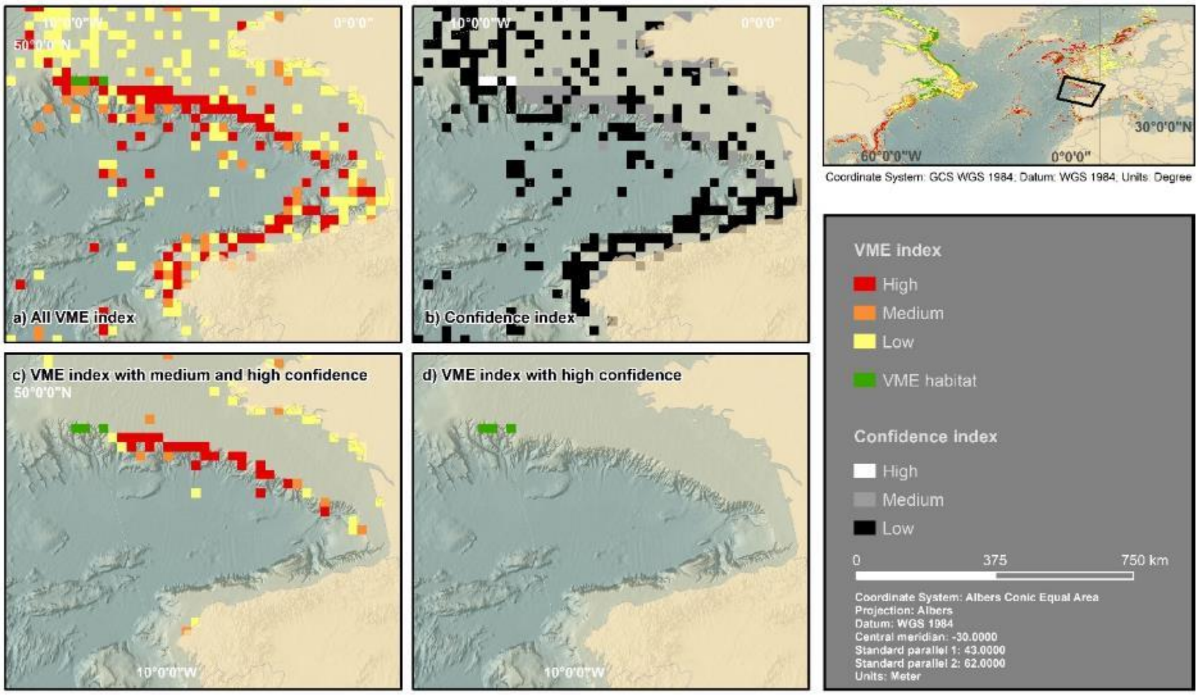

Figure 22. Applying the VME Index and Confidence Index to the VME database: Bay of Biscay. A and b) VME index for all cells with data in the VME database; c and d) Confidence Index for all cells with data in the VME database.

3.3.4 Azores

Spanning some of the most remote areas of the northern Mid-Atlantic Ridge, the Azores region (~1 million km^2) hosts a range of seascapes unique to European waters. Harsh bathymetric variations over short distances shape volcanic geomorphologies rising from plains well below 5000 m deep and provide a great heterogeneity of deep-sea habitats. Such concentrations of habitat diversity have been suggested to constitute priority targets for global conservation actions (Costello & Chaudhary, 2017). The seafloor that surrounds the archipelago comprises a variety of open ocean deep-sea habitats, from island slopes and numerous seamounts to hydrothermal vents at various depths and abyssal plains exceeding 5,000m depth (Tempera et al., 2012). Among the organisms inhabiting the seafloor, the Azores region may represent a hotspot of cold-water coral (CWC) diversity (Braga-Henriques et al., 2013) especially within the subclass *Octocorallia* (Sampaio et al., 2019).

Several bona fide VMEs areas have been identified along the Mid-Atlantic Ridge, mostly in its southern part (Figure 23a, d). Many VMEs identified in the area were found to hold high values of VME index (Figure 23a), including among the VMEs only associated with medium and high confidence index (Figure 23c, d). Confidence Index is high for a few areas, medium for the half of the remaining records and low for the other half, suggesting an area rather well but heterogeneously sampled (Figure 23b).

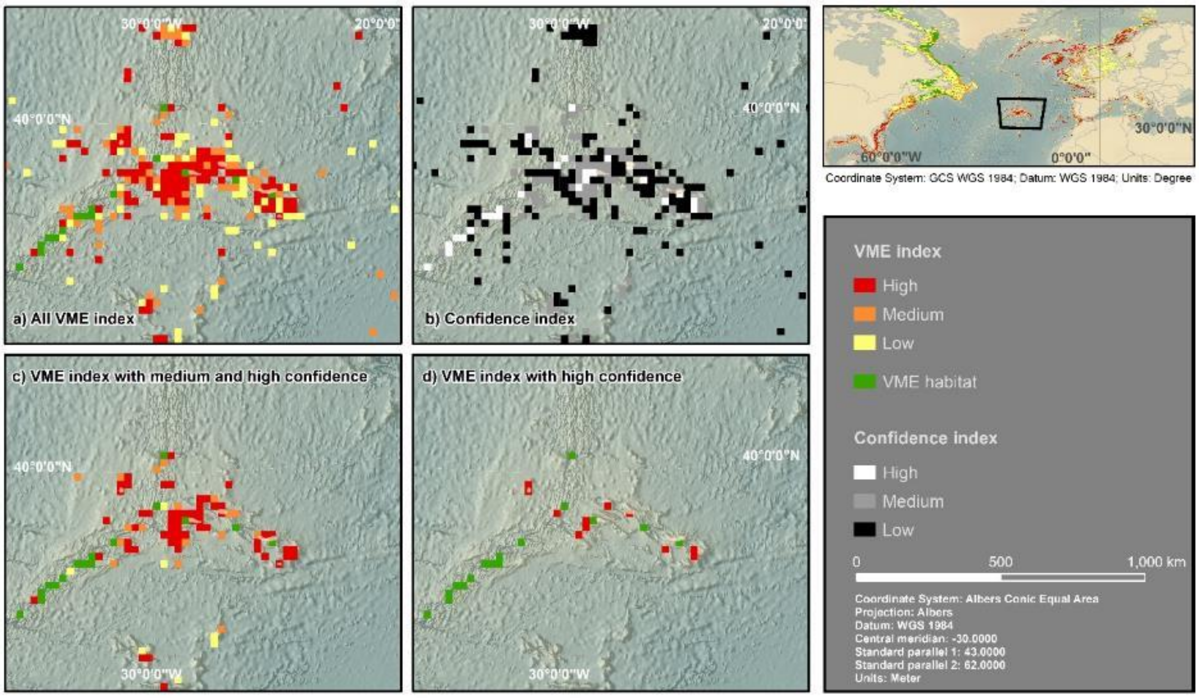

Figure 23. Applying the VME Index and Confidence Index to the VME database: Azores. A and b) VME index for all cells with data in the VME database; c and d) Confidence Index for all cells with data in the VME database.

3.3.5 Davis Strait

Davis Strait joins two basins, Baffin Bay and the Labrador Sea, and separates western Greenland and Baffin Island. It connects to the Arctic Ocean in the north via Baffin Bay and to the Atlantic Ocean in the south via the Labrador Sea. It is considered the world's largest strait and is renowned for exceptionally strong tides, ranging from 9 to 18 m, and complex hydrography. The shelves extending from both Canada and Greenland typically range between 20 and 100 m in depth and are traversed by deep troughs. At its narrowest point, a ridge or sill up to approximately 600 m depth extends between Greenland (at Holsteinborg, Sisimiut) and Baffin Island (at Cape Dyer). The slopes along the Labrador Sea flank of this ridge and farther south along the Labrador and West Greenland shelves drop to 2500 m or more. On these slopes coral and sponge have been found, including the only known *Lophelia pertusa* reef in Greenlandic waters (Kenchington et al., 2017). South of Davis Strait the waters off west Greenland support intense phytoplankton blooms in April, which progress northward into Baffin Bay in May as the seasonal ice-cover retreats. These blooms are characterised by high phytoplankton biomass and a community of grazers dominated by large copepods, i.e. *Calanus*. Within the study region *Calanus* provide an important food source for higher trophic levels (e.g., fish, seabirds, whales). In addition, however, they play a key ecological role in supplying the benthic communities with high quality food via the production of large and fast-sinking faecal pellets. Baffin Bay and Davis Strait have the only large-scale commercial fisheries in Canada's Arctic.

The Western part of the Davis Strait holds a high number of bona fide VMEs habitats, the only records holding high confidence in this area (Figure 24a, d). The MCA approach identified most other VMEs as low values, especially in the Hudson Strait and Hudson Bay, in the Western Baffin Bay and the areas of the Davis Strait closest to the Canadian coast (Figure 24a). Most records, outside of the bona fide, hold medium confidence, likely due to intense sampling effort in this area (Figure 24b, c). VME areas holding low confidence are mostly located in the eastern and northern parts of the Davis Strait and in the southern part of the Hudson Bay, probably resulting from lower sampling effort (Figure 24b).

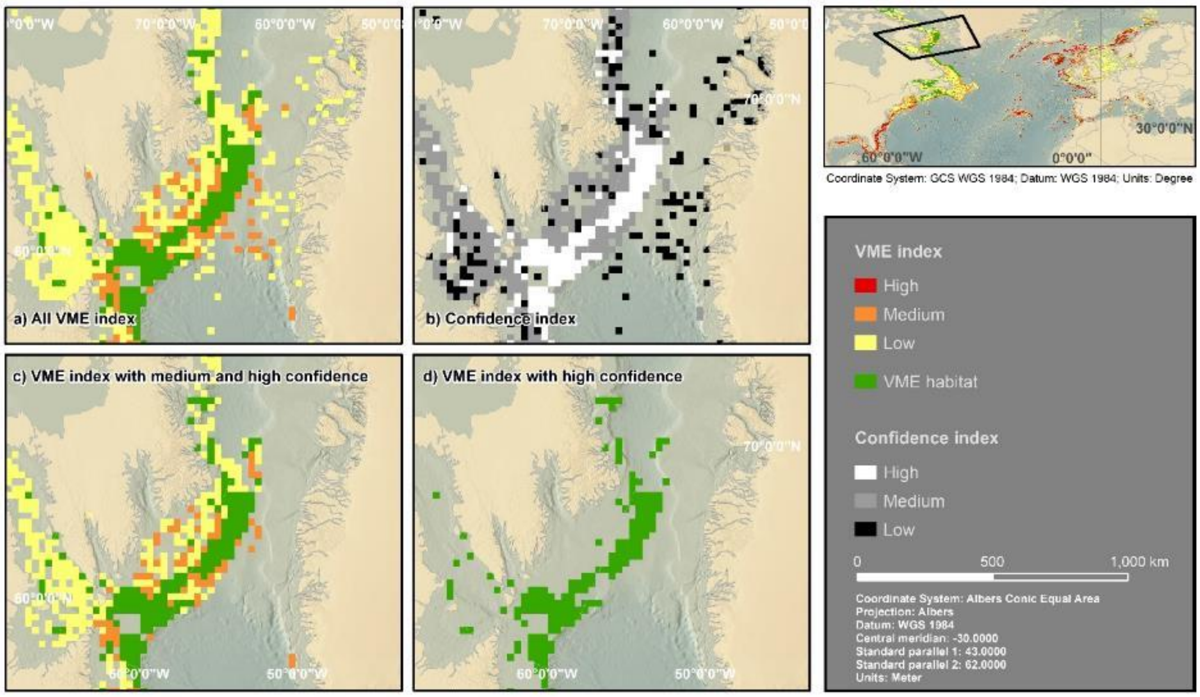

Figure 24. Applying the VME Index and Confidence Index to the VME database: Davis Strait. A and b) VME index for all cells with data in the VME database; c and d) Confidence Index for all cells with data in the VME database.

3.3.6 Flemish Cap

This study area is located in the NW Atlantic, in an Area Beyond National Jurisdiction (ABNJ), within the Northwest Atlantic Fisheries Organization (NAFO) Regulatory Area. It is characterised by the Flemish Pass, the Flemish Cap and the NE part of the Grand Bank of Newfoundland including the "nose". The Flemish Pass is a channel of ~1,200 m deep which separates Flemish Cap, an isolated plateau of approximately 200 km, and the Grand Banks of Newfoundland. The Cap has a minimum depth of 120m situated in the southeastern part and a maximum of 730 m in the north. This area is on the Canadian continental shelf and stretches beyond 200 nautical miles (Canadian EEZ) off the coastline. It is within a transition zone between cold subpolar waters, influenced by fluctuations in the Labrador Current and in the North Atlantic Current (Gil et al., 2004). The Grand Banks shelf is separated from the Flemish Cap by the cold southward flow of the Labrador Current (Colbourne & Footek, 2000). Most of the Flemish Cap substrata is constituted by unconsolidated substrata as muddy sand and sandy mud although in its centre a patch of sand is found, while stones are scattered in the entire area (Murillo et al., 2011).

A large number of bona fide VME habitats have been identified in the Gulf of St. Lawrence and in the SW and NE parts of the Grand Banks (Figure 25a). They are the only records holding high confidence (Figure 25d). Most other VMEs identified in the area were classified with low or medium value of VME Index (Figure 25a), most of which were associated with medium confidence (Figure 25b). Yet, all over the Grand Banks and Flemish Cap VME areas with low confidence were identified (Figure 25b), likely reflecting heterogeneous sampling effort in the area.

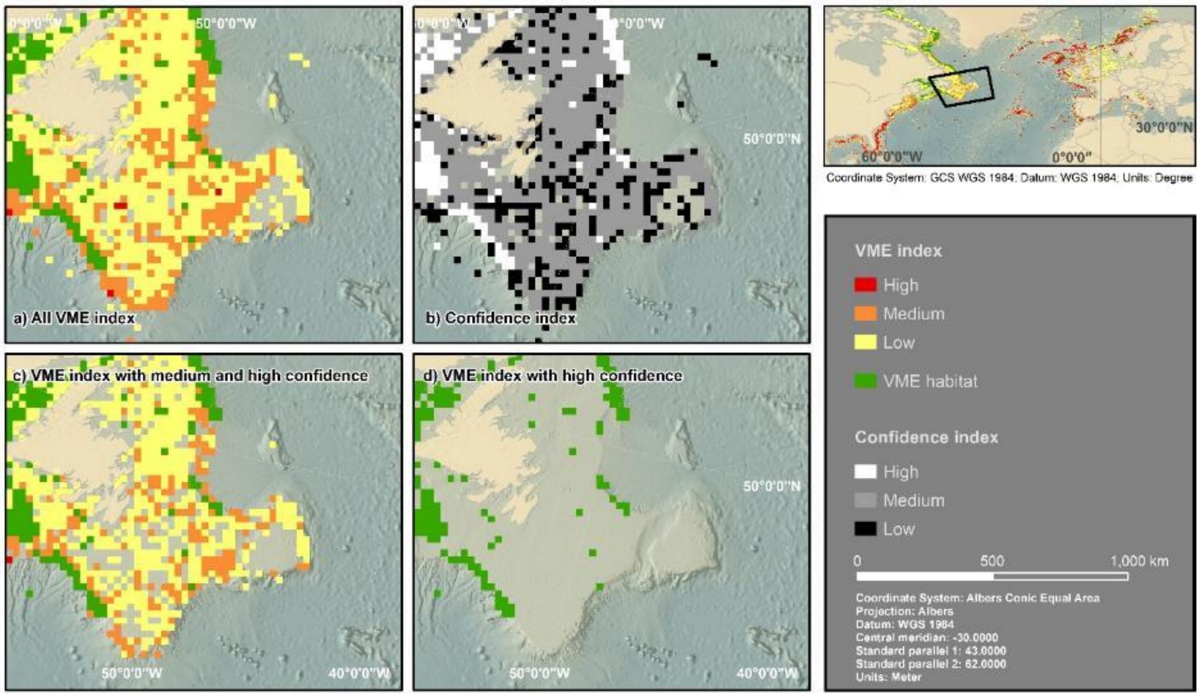

Figure 25. Applying the VME Index and Confidence Index to the VME database: Flemish Cap. A and b) VME index for all cells with data in the VME database; c and d) Confidence Index for all cells with data in the VME database.

3.4 Implementation of the VME and Fishing Effort portfolio categories

The data was assigned to all four portfolio categories (Figure 26). The method we used (Jenks breaks) identified a threshold of fishing catch of 3.31, on a scale going from 1 (catch = 0) to 5. For the VME Index the threshold we used was the same as previously, with results from 3.7 to 5 belonging to the "High value" category. The outcomes of the framework can be visualised for comparing different areas, allowing managers to prioritise their choices or policies in terms of closing pristine VME areas, closing disturbed areas for recovery of VMEs, or both (Figure 26). A large portion of the cells were revealed as low VME and high catch (58.8%) or high VME and high catch (23.8%) (Figure 26). Only a small portion of the cells fell in the category high VME and low catch (7.2%) (Figure 26).

However, the high number of cells with high fishing catch should be considered with caution because some catch might have been wrongly attributed to bottom trawling, as appears to be the case around the Azores, where bottom trawling has been prohibited since 2005. On the other hand, some areas were closed to fishing in recent years but may have experienced higher impacts previously.

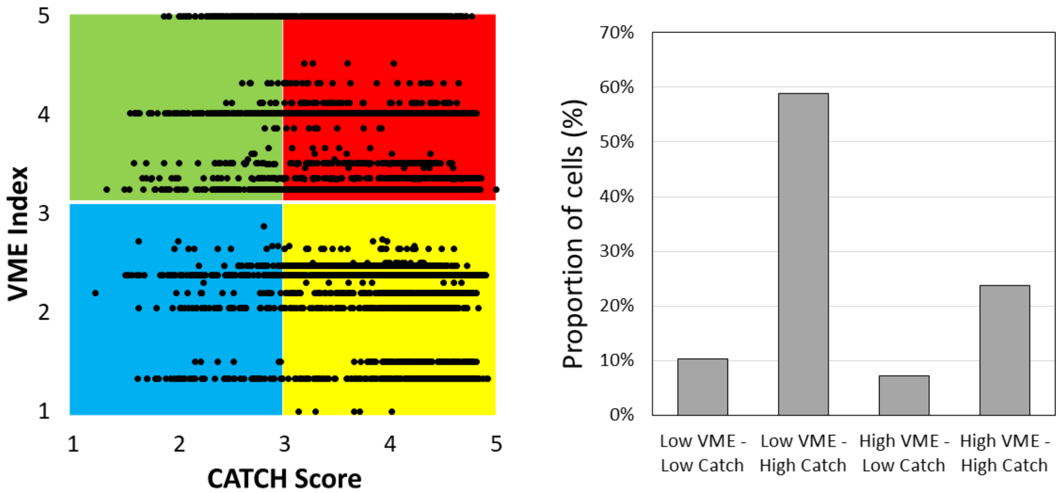

Figure 26. Application of the portfolio categories concept to the ICES database. In the left panel, the different colours represent four portfolio categories: blue is low VME - low catch, yellow is low VME – high catch, green is high VME - low catch, and red is high VME - high catch. In the right panel, proportions of cells falling into those categories are shown.

Mapping the outcomes of the framework can be another way to visualise areas falling in different portfolio categories. It results in the characterisation of most of the coastal areas of the North Atlantic as high catch values, with the exceptions of the central part of the Davis Strait, the north of Flemish Cap, most of the Azores, the Denmark Strait, the southern part of the Reykjanes Ridge, the Hutton Bank and offshore areas of the Norwegian Sea (Figure 27). The areas where those high catch overlap with high values VMEs are essentially located around Florida and Hatteras Slope, in the NE US coast, in the Gulf of St Lawrence and in the southern part of the Davis Strait, some around the Azores, the northern part of Reykjanes Ridge and southern Iceland, along the coast of Norway, around the Faroe, Rockall Bank and the margin of the Rochebonne Plateau and Gibraltar Strait.

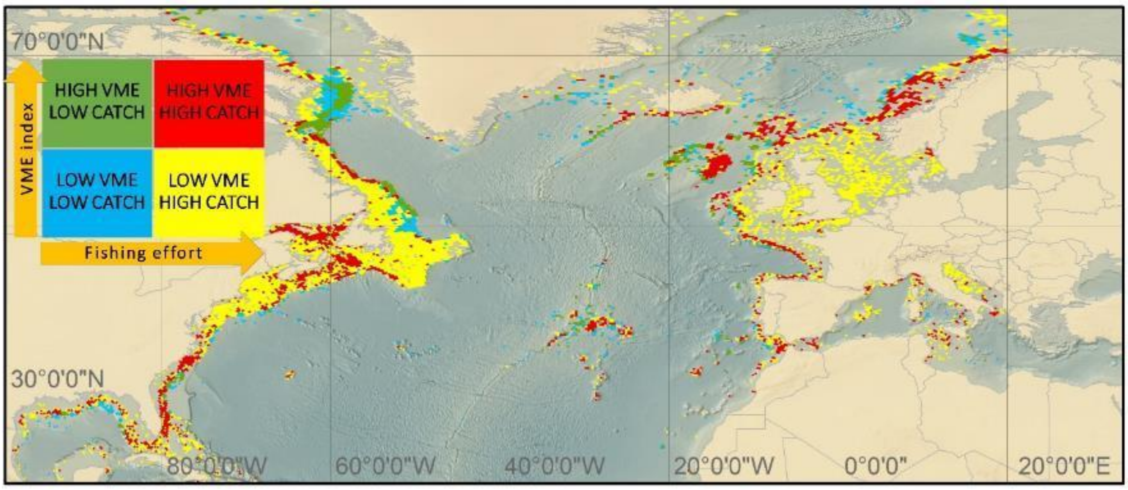

Figure 27. Application of the portfolio categories concept to the whole North Atlantic. Blue cells are low VME - low catch, yellow cells are low VME – high catch, green cells are high VME - low catch, and red cells are high VME - high catch.

In the Hatton-Rockall area, a high fishing effort/catch occurs in most of the area (Figure 28). Many of those areas overlap with VMEs holding high values of VME index, in particular along the southern coast of Iceland, around the Faroe Islands, and in the Rockall Bank. High fishing effort but low values of VME index were also found in many areas, in particular in the southern part of the Reykjanes Ridge and in the Hatton Bank. The Bay of Biscay is also characterised by high fishing effort values, with overlap with high values of VME Index mostly along the margin of the continental plain / Rochebonne plateau, and along the northern coast of Spain (Figure 28). The Azores are characterised by a mix of areas with high and low catch and high and low values of VME Index (Figure 28). High catch values are mostly located around the islands of the archipelago, which is surprising because bottom trawling has been prohibited in most of this area since 2005, and suggests that local fishing vessels which mostly deployed hooks-and-lines fishing gear could have been wrongly assigned as bottom trawlers. In the Davis Strait, high fishing effort is mainly concentrated in the areas closest to the coast, where there is little overlap with high value VMEs, only limited to a few areas in the southern part and northern parts of the strait. Most high value VMEs are located in areas with low catch (Figure 28). The area around Flemish Cap is also characterised by high fishing effort/catch, that overlaps with high value VMEs mostly in the Gulf of St. Lawrence, and in the southern part. Low fishing effort occurs in the northern part, but only a few of those areas overlap with high value VMEs (Figure 28).

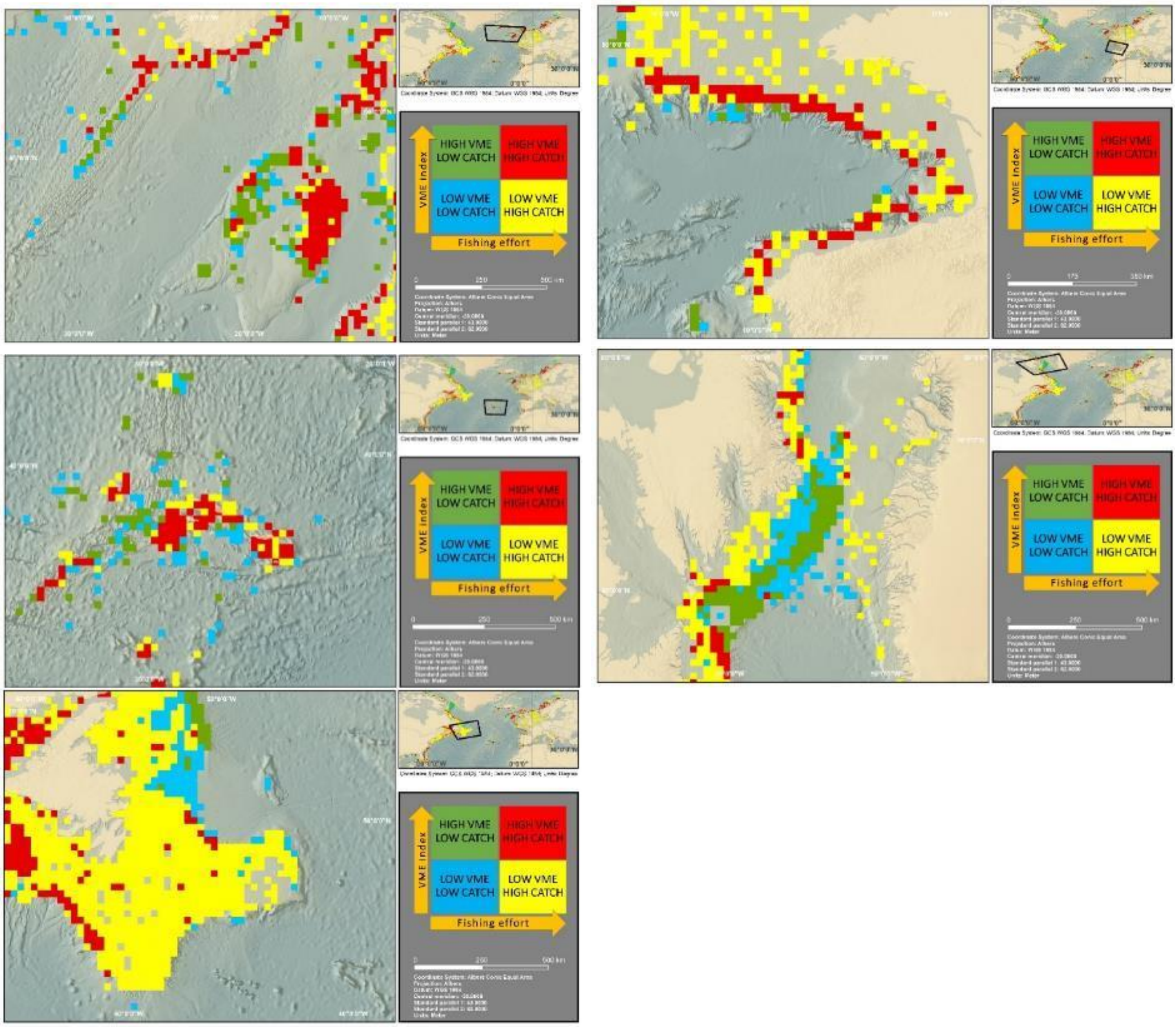

Figure 28. Application of the portfolio categories concept to (top-left) the Rockall-Hatton Bank and southern Iceland, (top right) the Bay of Biscay, (mid-left) the Azores, (mid right) Davis Strait, and (bottom-left) the Flemish Cap. Blue cells are low VME - low catch, yellow cells are low VME – high catch, green cells are high VME - low catch, and red cells are high VME - high catch.

3.5 Conclusion

Portions of this work have been published by Morato et al. (2018). This study at the scale of the North Atlantic shows that in general, the MCA provides a simplified, spatially aggregated and weighted estimate of the degree an area could be considered to contain VMEs under the FAO definition. The VME index clearly highlights areas where a VME is more likely to occur while the associated estimate of confidence gives an indication of how (un)certain that assessment is. The methodology is transparent, science-based and data-driven, and the aggregate cells can be explored in greater detail to reveal the individual data points that have contributed to the assessment. It integrates far more information than previous methods and as such, better captures the underlying reasoning for identifying VME areas or benthic deep-sea EBSAs. The MCA can be expected to be updated each year as new data are submitted and thus provide an up-to-date, repeatable and defensible source upon which to base advice as new information is received.

The MCA approach achieved three main aims. (1) To develop a system which could provide a measure of the likelihood of a cell constituting a VME and the associated level of fishing activity. The choice of the VME scoring criteria and the definition of the most relevant fishing activities were based on the existing information but should be revisited when more information is made available; as for example on the life history of VME indicator taxa. Using quadratic means to estimate the VME indicator score was chosen to avoid several low scores adding up to a misleadingly high score; but it could still underestimate the value of abundant VME indicators that rank high in only few criteria as compared to less abundant indicators with several high scores. This problem may be overcome by increasing the weight assigned to the abundance score; however, this should only be done when more abundance data in weight are reported in the VME database. (2) To design a system compatible with, and making use of, all the data currently available. The major constraint faced by this analysis is the general scarcity of information, mostly related to the lack of abundance data (weight or numbers) for each VME indicator record present in the VME database. Additionally, some work has to be done to develop a methodology to standardise information that has originated from very different sampling methods, as for example fisheries, trawls and ROV transects. (3) To deliver an output that is simple to visualise and understand, in order to facilitate its implementation in management deliberations.

The UN General Assembly resolution that committed to protecting VMEs from destructive fishing practices also calls upon States to do so, “consistent with the precautionary approach” (UNGA, 2006, paras. 80 & 83). The inclusion of the confidence index in the MCA allows for decision-making concerning possible fisheries closures (and other management measures) to determine explicitly what level of uncertainty may still warrant precautionary actions.

Overall the MCA appears to capture most of the important elements of the VME database. This methodology may be considered as a first step towards a systematic approach for the identification and protection of VME and EBSAs in the North Atlantic. Our methodology clearly considered several of the steps proposed by Ardron et al. (2014), namely step 1 on assessing potential VME indicator taxa and habitats in a region, step 3 on considering areas already known for their ecological importance, step 4 on compiling information on the distributions of likely VME indicator species and habitats, step 6 on considering fishing impacts, and step 8 on identify ecologically important areas. However, at least one important aspect of the Ardron et al. (2014) framework is missing in the current MCA which refers to understanding the natural distribution of VMEs before significant impacts occurred. This aspect could be considered in future improvements of the MCA to encompass predicted distribution of VME as discussed in Vierod et al. (2014) and Anderson et al. (2016b).

By providing an indication of uncertainty alongside predicted occurrence, the MCA allows for management decisions to be openly discussed, logically weighed, and documented. In the future, with better recognition technology becoming available, these methods could be automated and applied to survey data as they are collected, or soon thereafter, thus avoiding delays that could leave newly identified VME areas at risk. The ability to readily incorporate new data also makes the MCA approach appropriate for adaptive management frameworks.

4 Designation of priority areas through a conservation planning approach

4.1 Goal

This basin-wide conservation planning approach was implemented to inform about priority areas for North Atlantic deep-sea conservation, that could be preserved through spatial management.

The approach developed here focuses on conservation goals for the deep sea, whether in ABNJ or EEZs, whilst integrating current management and human activities aspects, to combine the conservation and socioeconomic stakes during the prioritisation process. In order to suggest conservation possibilities distributed in the whole ocean basin, and in the main broad types of habitats, a balanced geographical allocation of conservation units was employed.

This prioritisation approach aimed to identify zones of conservation importance for seabed species and habitats associated with VMEs, focusing on: VME indicator species, known or predicted VMEs, and geomorphological features supporting VMEs. Moreover, an emphasis was given to climate change concerns, by setting high conservation goals for resilient areas housing VME indicators and demersal fishes. Although fishes are not the predominant focus of this exercise, identifying habitats with a general climate resilience capability, including demersal fauna associated with economic and conservation stakes, appeared as a more comprehensive approach. Finally, this work addressed benthic connectivity aspects, by using the results of larval drift models to favour connected networks of conservation as best as possible.

Beyond their practical conservation objective, the implemented conservation scenarios depict a summary of the information of VMEs biodiversity distribution across the basin, in view of the state of knowledge about the deep-sea ecosystems and the findings from the EU ATLAS project (especially work packages 3 and 4).

Finally, this basin scale prioritisation will provide general material for local conservation, through a transfer to the marine spatial planning for ATLAS case studies implemented in ATLAS Work Package 6.

4.2 Spatial conservation planning

Systematic conservation planning is an explicit, objective-based and quantitative approach for allocating areas for biodiversity conservation (Margules & Pressey, 2000). It aims to identify priority areas answering specific conservation targets whilst minimising the socioeconomic costs of conservation. Spatial planning is implemented on a gridded region where each grid square represents a planning unit (PU) that can be either selected or excluded from the conservation solution, i.e. the set of planning units answering the conservation objective. The solutions of planning simulations emerging primarily from the distribution of biodiversity in the planning region, they are therefore highly dependent on the choice of biodiversity features and conservation goals set by the user. Key-terms about spatial conservation planning are explicated in box 1.

Among other conservation planning tools, the Marxan approach is widely used, and is based on the "minimum set" objective function whose goal is to minimise the cost of the solution whilst ensuring that all targets (and other constraints, if any) are met (Ball, Possingham, & Watts, 2009).

Box 1. Key-terms about spatial planning problems

Key terms about "minimum set" problem setting and solving outputs are defined below, from Daigle et al. (2018), Hanson et al. (2019) :

- **Planning region**: the study area over which the spatial planning exercise is taking place.
- **Planning unit (PU)**: a spatial unit resulting from the subdivision of the planning region.
- **Conservation feature**: the features of interest for conservation, e.g. species or habitats. In simulations, a feature's distribution can be split into several pseudo-features according to a criterion (e.g. temporal, spatial, categorisation of an index). This allows balancing the selection of PUs considering the criteria, or assigning different targets to the pseudo-features (e.g. in this deliverable, the VMEs feature is split in four pseudo-features with four different targets, varying according to VME likelihood within each PU).
- **Conservation target**: the minimum amount or proportion of a feature's distribution in the study area that has to be included in solutions.
- **Cost**: a relative measure of the socioeconomic cost of protecting a planning unit, e.g. acquisition cost, foregone value of economic activity (opportunity cost), or easiness-to-implement management. The use of socioeconomic costs is discussed in Ban and Klein (2009). When no socioeconomic costs are included in the problem, an area-based uniform cost is used.
- **Penalties**: a penalty associated to a specific metric which will act as a trade-off on the cost of planning units. The "boundary penalty", called "blm" (boundary length modifier) in Marxan, increases the cost of more spatially fragmented solutions, whereas the "connectivity penalty" decreases the cost of solutions with higher connectivity.
- **Constraints**: spatial requirements applied on the conservation solution, e.g. exclude or include certain planning units.
- **Solution**: a binary output resulting from problem solving and displaying the selected (1) and not selected (0) planning units for the conservation plan
- **Selection Frequency**: the summed solutions from a number of runs of the same problem, reflecting how often a planning unit was selected

4.3 Study area and data used in simulations

Datasets used for the prioritisation approach were developed within ATLAS work packages or obtained from ATLAS partners and public databases. All data sources are detailed in the Appendix 1, with mention of the use of this data within the scenarios (features, costs, constraints and penalties).

4.3.1 Study area

The study area covered the Atlantic Ocean from 18°N to 76°N and 36°E to 98°W, including adjacent seas: the Mediterranean Sea, the Gulf of Mexico and the north of the Caribbean Sea. Only depths between 1 and 3500m were selected within this area, using a 3km resolution depth layer resulting from the EMODnet Digital Bathymetry portal (EMODnet Bathymetry Consortium, 2016) and the General Bathymetric Chart of the Oceans (GEBCO 2014; Weatherall et al. 2015) as explained in ATLAS Deliverable 3.3 (Chapter 3.2.4). While abyssal and hadal depths (>3500 m) were excluded from the analysis, continental shelf depths (0 to 500m) were kept. Indeed, cold-water corals are often found at shallow depths in high latitudes (e.g. reefs at 25m in Norway), and several conservation scenarios of this exercise included demersal fish species that are exploited on continental shelves.

Spatial prioritisation and mapping were done on an Albers equal-area conic projection centred on the Atlantic ocean (latitude 30°N; longitude 30°W). The study zone was divided in 25km-side squares, each one representing a spatial planning unit (PU). All PUs containing depths shallower or equal to 3500m were kept, even if they could also contain deeper areas locally. PUs with more than 20% of continent cover were excluded, leading to a final number of 31 518 PUs on a 19 698 750 km² area (Figure 29).

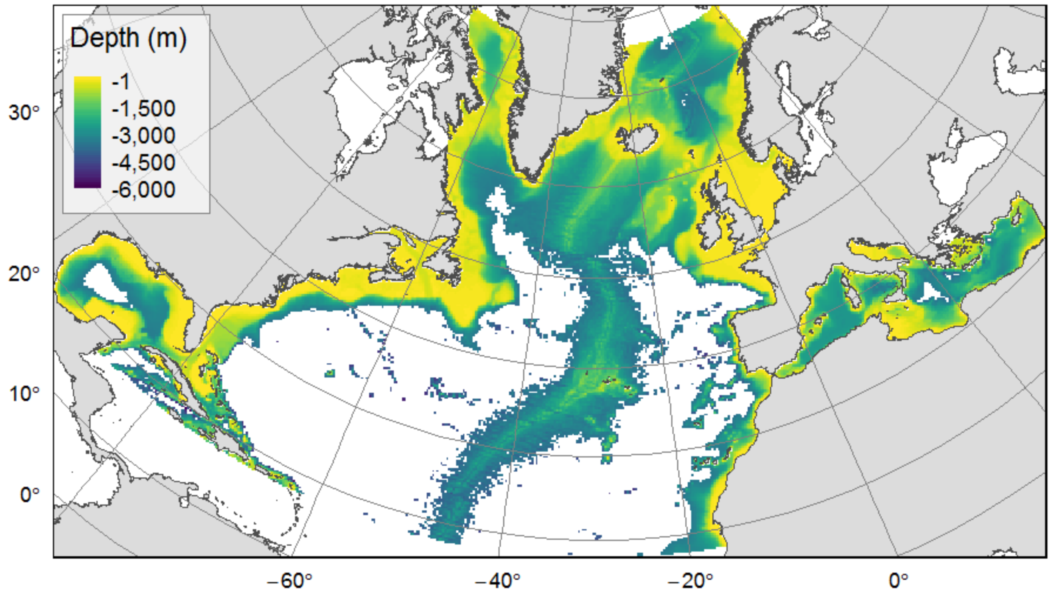

Figure 29. Delimitation of the study area outlying PUs (resolution) and corresponding depth (colour range).

4.3.2 Data used for features

Species

Within ATLAS work package 3, Habitats Suitability Models were developed for six fish and six coral species to assess the patterns of deep-sea species distribution and forecast their change under future climate change scenarios (ATLAS Deliverable 3.3 chapter 3.2). The outputs of these models were used as species features, and complemented by a last model for a sponge species, *Geodia barretti*, thanks to a collaboration with the H2020 Blue Growth SponGES project “Deep-sea Sponge Grounds Ecosystems of the North Atlantic - an integrated approach towards their preservation and sustainable exploitation”. This model was developed using the same methodology applied for the other species but with the presence records supplied by the SponGES project.

Habitat suitability models were developed using a set of terrain (static in time) and environmental (dynamic in time) variables to predict present-day (1951-2000) distribution and to forecast future (2081-2100) changes. The climate refugia represent the habitats that are predicted suitable for both the present and the future conditions (ATLAS Deliverable 3.3 chapter 4.3). Binary outputs defined with the Maximum Sensitivity and Specificity threshold (MSS) for present conditions and climate refugia were used in the prioritisation scenarios. These two kinds of features were selected with the aim of protecting current suitable habitat and securing future climate refugia for the 13 species. The presence of suitable habitat in 3km*3km cells for the present conditions was used to calculate the relative cover of present suitable habitat for each PU. Regarding future climate refugia, the presence of refugia in the PUs, rather than their relative cover, was chosen as a precautionary approach given the uncertainty of future predictions.

The six coral species and the sponge species (*Geodia barretti*) selected are all classified as VME indicator taxa. The corals included three scleractinian corals forming aragonitic skeletons (the reef building colonial species *Lophelia pertusa*, *Madrepora oculata*, and the solitary coral *Desmophyllum dianthus*), and three gorgonians forming calcitic skeletons (*Acanella arbuscula*, *Acanthogorgia armata*, and *Paragorgia arborea*). These two groups are expected to respond differently to future conditions of water mass properties (ATLAS Deliverable 3.3 chapter 4). The deep-sea fish species selected were the roundnose grenadier (*Coryphaenoides rupestris*), the Atlantic cod (*Gadus morhua*), the bluemouth rockfish (*Helicolenus dactylopterus*), the American plaice (*Hippoglossoides platessoides*), the Greenland halibut (*Reinhardtius hippoglossoides*), and the beaked redfish (*Sebastes mentella*). These species were selected based on their ecological significance or fisheries catch relevance, but also on the availability and wide spatial coverage of existing occurrence records.

For fishes, only the climate refugia outputs were considered in the simulations, whereas for VME indicators both present and climate refugia outputs were used. This choice was made to emphasize the prioritisation on the VMEs features, while also considering important areas for demersal fishes in the future.

All relative cover values for species features, ranging from less than 0.01% to 21.5% of the study zone, are displayed in Appendix 2.

Vulnerable Marine Ecosystems

The attribution of Vulnerable Marine Ecosystems (VMEs) likelihood to planning units was based on the occurrence of VME indicator taxa and VME habitat types listed by the ICES Working Group on Deep-water Ecology (WGDEC) (ICES, 2015).

Georeferenced data on VMEs originated from four different sources:

(1) The InterRidge Global Database of Active Submarine Hydrothermal Vent Fields (Beaulieu & Szafranski, 2018) was mined to extract all known hydrothermal systems in the North Atlantic. Among 68 hydrothermal vents documented in the study zone, 90% are active or inferred as active, and 10% are inactive. While active hydrothermal vents support chemosynthetic communities, inactive vents provide substratum for suspension feeders such as sponges and cnidarians (Boschen et al., 2016; Levin et al., 2016). Hence, all types of hydrothermal vents were kept, distributed on 0.18% of the study zone.

(2) The literature was mined (Appendix 1) to list all known cold seep ecosystems in the North Atlantic. One cold seep location, from the Gazul mud volcano in the Gulf of Cadiz (ATLAS CS 7, see Section 2.6), complemented the bibliographic survey. A total of 41 cold seeps and mud volcanoes were located in the study zone, and covered 0.11% of the study area.

(3) The VMEs dataset collected through a call to ATLAS case studies leaders represents the VMEs that have been identified within the ATLAS case studies and through ATLAS research activities (Section 2). Several of these VMEs have been discovered recently, and although those records have been described in publications or submitted to databases as ICES, they are not yet mentioned in VME databases. The 1980 VMEs were often gathered in close groups (up to 442 points in a 25*25km cell), and parts of the records were situated out of the study zones (i.e. in Norwegian fjords), overall this layer covered 0.63% of the study zone.

(4) The ICES VME database (http://vme.ices.dk). The database is comprised of: 1) 'VME habitats' that are records for which there is unequivocal evidence for a VME and 2) 'VME indicators' which are records that suggest the presence of a VME with varying degrees of uncertainty. The VME habitats were present on 2.30% of the study zone. For VME indicators the weighting

system of vulnerability and uncertainty (Morato et al., 2018) was implemented on the prioritisation grid to assign VME likelihood levels to planning units as detailed in Section 3, and subsequently adapt conservation targets and costs as explained in the following (Parts 4.4.2 and 4.4.3). The values of the two indices were divided in categories of VME likelihood and confidence levels (low, medium and high; Table 17), with the use of the Jenks natural breaks classification method (Jenks 1967).

Table 17. Result of the categorisation with the Jenks breaks for the VME index on the study area

Jenks breaks levels	Index range
Confidence Index	
low	0 - 0.37
mid	0.38 - 0.79
high	0.8 – 1
VME Index	
low	1 - 2.74
mid	2.75 - 3.60
high	3.61 - 4.51
VME Habitat (Unequivocal)	5

The VME habitats supersede the VME indicators. Thus, if a PU had been attributed a VME index value but also an unequivocal VME, as determined by other datasets (hydrothermal vents, cold seeps, and ALTAS identified VMEs), the index value was deleted and the PU was categorised as an "unequivocal VME". Thus, the four resulting layers had no overlay and were considered as different levels of the same feature in scenarios, i.e., four pseudo-features of a VME likelihood feature. The "unequivocal VMEs" covered 3.02% of the study area (Appendix 2). The "high", "medium" and "low" VME index categories covered 1.85%, 3.26%, and 5.64% of the study area respectively (Appendix 2). The other 86% PUs had no unequivocal VMEs or VME index.

Geomorphological features

Three geomorphological features, i.e. seamounts, fracture zones and canyons, were added to the prioritisation, these types of structures being known to represent a physical support for VMEs.

Seamounts locations from Yesson et al. (2011) were used in the prioritisation scenarios. In the study zone, 2577 seamounts were located within the 0-3500m depth, the other ones occurring too deep in the abyssal plains. Nevertheless, several planning units between the Mid-Atlantic Ridge and the continental shelf, i.e. surrounded by abyssal plains, were included in the study area because of the presence of seamounts' tops rising above 3500m depth. Up to 14 seamounts could be found in one planning unit, but as several close peaks are likely to belong to the same structure, only the presence of seamounts in PUs was used for the following, totalling 4.95% of the study zone (Appendix 2).

The 15 fracture zones along the Mid-Atlantic Ridge, extracted from the GEBCO Gazetteer of Undersea Features Names (www.gebco.net, IHO-IOC), overlaid 0.99% of study zone (Appendix 2), and their presence in planning units was used in conservation scenarios.

Submarine canyons data was obtained from Harris & Whiteway (2011). The dataset gathered two types of canyons: the shelf-incising canyons (N=702 in the study zone), which have a shelf origin and pursue towards the margin slope; and the blind canyons (N=1085) that do not. Only the shelf-incising canyons were selected to be used as a feature in conservation scenarios, by calculating the total length of canyon in km for each planning unit on the 4.24% of the study zone containing them (Appendix 2). These length values varied from 6m to 106.4km (mean 22.5km).

Regionalisation

In order to geographically balance the distribution of solutions across the study area, each feature was divided in pseudo-features according to 13 delimited regions. The feature-associated target value was the same for all derived pseudo-features. This approach was adopted to ensure that in solutions, each feature was protected at the same proportion within each region of the North Atlantic.

Divisions of the study area were implemented using three criteria. First, lower bathyal Global Open Oceans and Deep Seabed (GOODS) provinces (UNESCO 2009, Watling et al. 2013), delimited by the 800 and 3500 isobaths, were extended to the coastline to identify three large biogeographic regions. Then, these were divided in two to four longitudinal sections following geographical cuts: the West Atlantic abyssal plain and Greenland; the East Atlantic abyssal plain; and the Atlantic-Mediterranean separation (Figure 30).

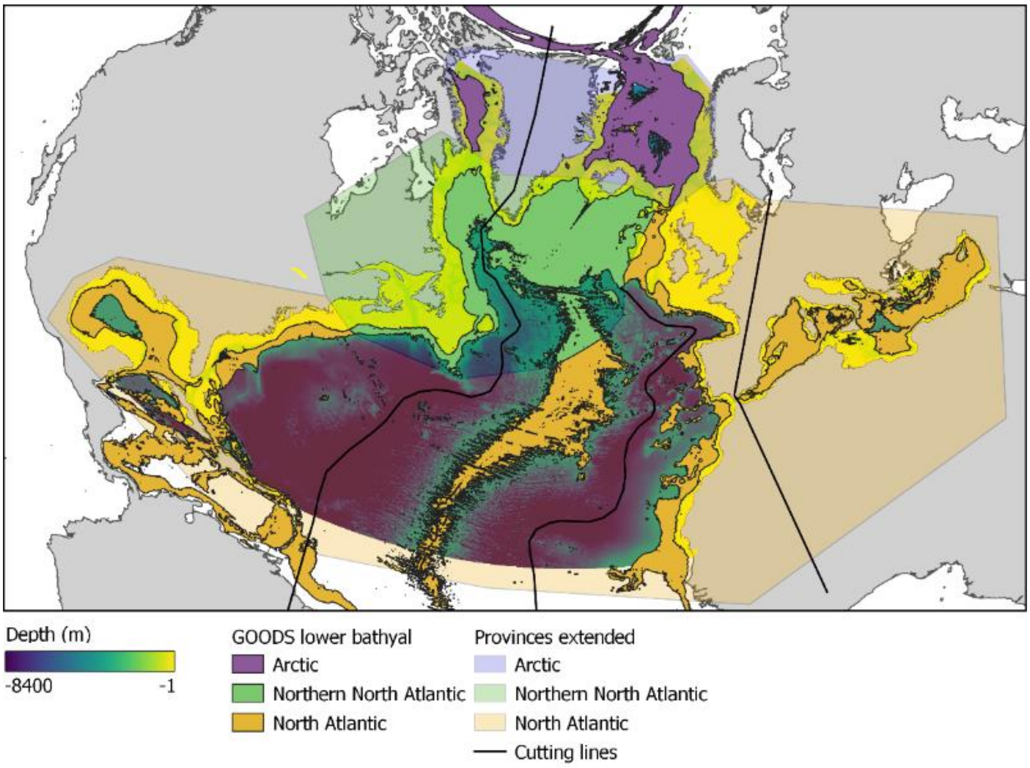

Figure 30. Creation of the regionalisation. Abyssal plains (i.e. >3500m depth), here displayed in dark purple, were used to delimit the provinces but not included in the study area.

Finally, the eight resulting regions were independently separated using the depth layer resampled at the planning unit resolution (25km*25km). Following the original GOODS regions, two depth ranges were created, shallow (<800m) and deep (>800m), leading to 16 sub-regions. Because of the small area of certain sub-regions, and of geographical contiguity, several sub-regions were merged back:

- The large South-central region had few PUs at depth between ~500 and 800m, thus the “shallow” and “deep” sub-regions were pooled (“deep 7” province, Figure 31).
- The North-West “shallow” regions, along Canada and between Canada and Greenland, were merged together because of their contiguity (“shallow 5” province, Figure 31).
- The North-East “shallow” regions North and South to Iceland, were merged together because of their contiguity (“shallow 1” province, Figure 31).

This process led to 13 provinces (Figure 31), including eigth “deep” provinces, and five “shallow” provinces, respectively covering from 1 to 15% of the study zone (Appendix 3). In the prioritisation process, such regionalisation allowed for consideration of the broad types of habitats (shallow VS deep) and also for the geographical breaks in the study zone (e.g. the Atlantic-Mediterranean separation). It also took into account the North Atlantic biogeographic zonation. The chosen longitudinal cuts, following the abyssal plains, agreed well with the results of clustering analyses for VMEs biogeography made during ATLAS (Deliverable 3 Chapter 2).

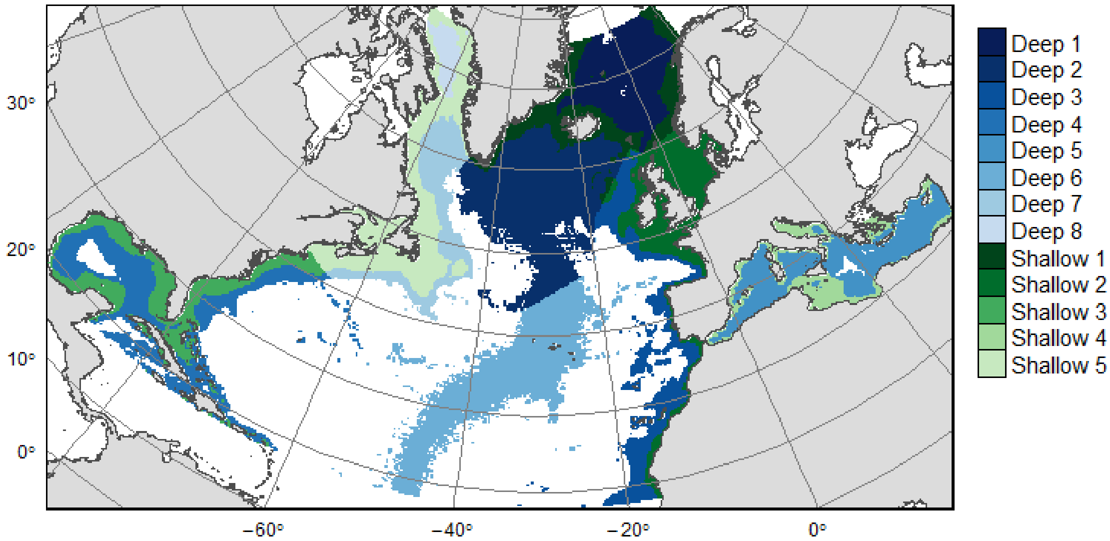

Figure 31. The 13 provinces used for regionalisation

4.3.3 Data used for costs

Three sets of data were used to vary the cost of planning units in conservation problems: the VMEs confidence index, associated to VME index features; the location of areas with a legal protection or designation; and the fishing catch rates over the ocean basin.

Confidence index for Vulnerable Marine Ecosystems

As explained in Section 3.2.5, the VME index was associated to a confidence index depending on data quality and calculated independently to the VME index. This index accounted for confidence in the “VME index” scores assigned to individual grid cells. As for the VME index, the confidence index was divided in three levels (Table 17). The confidence for unequivocal VMEs was set to 1.

Fishing restrictions by Regional fisheries management organisations

Regional Fisheries Management Organisations (RFMOs), which have the mandate to regulate fishing activities in large marine regions, implemented fishing closures following the UN General Assembly resolution 61/105 (2006) to protect VMEs from the adverse impacts of bottom fishing (Wright et al. 2015). Fishing closure areas in the regulatory areas of the Atlantic high seas are designated and controlled by two organisations: the NAFO (Northwest Atlantic Fisheries Organization) and the NEAFC (North East Atlantic Fisheries Commission). The VME bottom fishing closures were established first in 2005 for NEAFC and 2007 for NAFO and extended since (NAFO, 2019; NEAFC, 2014; Wright et al., 2015). They were delimited following identification of benthic assemblages (Barrio Froján et al., 2016). The two RFMOs total 40 fishing closures, ranging from 14 km² to 244 848km². Their cover accounted for 2.46% of the study area.

In the Mediterranean Sea, the GFCM (General Fisheries Commission for the Mediterranean) established Fishing Restricted Areas (FRAs) to protect VMEs. In 2006 three FRAs were delimited constituting full bottom fishing closures (GFCM, 2006), followed by a fourth one in 2009, in which bottom fishing is restricted but not forbidden (GFCM, 2009). These areas range from 1005 km² to 10306 km², and cover 0.1% of the study area.

Marine Protected Areas

The World Database on Protected Areas (WDPA, www.protectedplanet.net) is a global database on protected areas, updated monthly and managed by the United Nations Environment World Conservation Monitoring Centre (UNEP-WCMC) with support from IUCN and its World Commission on Protected Areas (WCPA). Its marine subset gathers delimitation together with protection and management information about MPAs worldwide (UNEP-WCMC, 2017).

The database was extracted for the study area extent (N= 3174 MPAs). MPAs categorisation was tested using several sources of information describing each MPA: the last updated status; the environment type (“marine” field); the designation in English; the IUCN category; the existence and area of no-take zones. The designation field being open for filling by providers, it contained a high number of categories but also some typing errors. Moreover, the information displayed a large variability in precision, from very specific designations to very undefined ones. Hence, it was not possible to use this criterion to categorise the types of MPAs.

The other fields, presented in Table 18, were used to first eliminate certain areas, and then delimit two large categories of MPAs: marine reserves with important protection measures, and other MPAs with either a lower protection or a lack of information. First, the MPAs with a “Proposed” status were deleted since they are not yet approved by the authorities. Then, the MPAs with a “terrestrial” value in the “marine” field were also excluded from the dataset. Since numerous MPAs with a “coastal” value encompassed large marine areas, comparable to the extent of those with a “marine” value, these two types were conserved in the dataset. This filtering process eliminated 2.52% of the MPAs (N=80). Then, the marine reserve category was defined as MPAs with a presence of no-take zones (“no take” field with “all” or “part” value), or with a restrictive IUCN category (“IUCN” field with a “cat Ia” or “cat Ib” value). The remaining MPAs, likely under weaker protection regimes, were pooled in the second category. The “marine reserves” and “other MPAs” categories gathered 282 and 2815 MPAs for a study area cover of 0.52% and 9.15% respectively.

Table 18. Attributes of MPAs used for categorisation

Attribute field	Description	Allowed values	Selection process
STATUS	The legal status of the MPA, from proposed to designated	Proposed, Inscribed, Adopted, Designated, Established	"proposed" MPAs excluded
MARINE	The type of environment that the MPA is covering	0 (100% Terrestrial PA), 1 (Coastal: marine and terrestrial PA), and 2 (100% marine PA)	"terrestrial" MPAs excluded
IUCN_CAT	The IUCN category assigned to the MPA	Ia, Ib, II, III, IV, V, VI, Not Applicable, Not Assigned, Not Reported	"Ia" and "Ib" as marine reserves
NO_TAKE	The presence and relative importance of no-take zones in the MPA	All, Part, None, Not Reported, Not Applicable (if MARINE field = 0)	"all" and "part" as marine reserves

Ecologically or Biologically Significant Areas (EBSAs)

The scientific criteria for identifying ecologically or biologically significant areas were adopted in 2008 and further developed in 2010 during the meetings of Conference of the Parties to the Convention on Biological Diversity (COP 9 and COP 10) (Dunn et al., 2014). EBSAs are recognised as important by their uniqueness, naturalness, and role for species, habitats and ecosystem functioning. The identification of EBSAs in the North Atlantic, done through regional workshops, was completed for the North-West, Caribbean, and Mediterranean regions. The study zone was covered at 8.54% by these existing EBSAs. The North-East Atlantic regional workshop has not yet reached an agreement, thus EBSAs are absent on this part of the basin.

The CBD encourages the adoption of conservation and management measures within identified EBSAs, such as the development of MPAs networks (Dunn et al., 2014). However, EBSAs are not associated with any legislation, thus they were considered to have a low protection level in the following.

Global fishing catch

The fishing catch for industrial and non-industrial fishing described in Watson (2017), was downloaded for the 2010-2015 period. Available for the period 1950-2015, this dataset compiles global fisheries landings from several sources and spatializes it using the distribution of the reported taxa and the fishing fleets involved. Recently, AIS data was also included to improve mapping procedures for years back to 2010 (Watson & Tidd, 2018). The mapped results are expressed in annual catch rates (tonnes per square km of ocean) in each 30-min spatial cell, for each fishing nation and fished taxa. These catch rate records were further disaggregated using auxiliary data, by assessing the contribution of the different fishing gears used, the different types of catch (illegal, unregulated and unreported, discards), and the scale of the fishing operations (industrial vs non-industrial) (Watson, 2017; Watson & Tidd, 2018). The fishing catch dataset was filtered to select only the fishing gears that have an impact on large areas of the seafloor: dredges, bottom trawls, and Danish seines which act very similarly to bottom trawls. For each record, the three catch values "Reported", "IUU" and "Discards" were summed to get the total catch rate. All taxa and all nations total catch rates, for industrial and non-industrial fishing, were summed to get the yearly value of each spatial cell. The six yearly values by cell were then averaged. One outlier point was deleted, which had a very high value compared to all others. This yearly catch rate (annual tonnage per square km), displayed at a 30-min spatial resolution, was finally resampled at the planning unit resolution.

Bottom trawling footprint in European waters was also available through OSPAR for the 2009-2015 period and was computed following the methodology detailed in ICES (2018) and Eigaard et al. (2017). This dataset has a high spatial resolution and more accurately describes the abrasion impact of bottom fishing on seabed (expressed as yearly swept area ratio), despite its incomplete coverage of the study zone. Several statistical regression tests were attempted to predict abrasion from the fishing catch value over the ocean basin, and use the available abrasion value in cells where it was present. These were unsuccessful as the relationship between the two was too weak statistically. Although this result raised questions on the overall representativity of fishing catch rates in term of seabed impact, only these were used in the following as they covered the whole study area. It is therefore considered here that despite some potential inaccuracies, fishing catch may still be used as an acceptable *proxy* to fishery-induced seabed alteration.

4.3.4 Data used for constraints

Deep-sea mining licences

The International Seabed Authority (ISA) is an autonomous international organisation, gathering 168 member states, which organises and controls activities of mineral resource use on the ocean floor beyond the limits of national jurisdiction, i.e. the Area. ISA has granted three contracts for exploration for polymetallic sulphides on the Mid-Atlantic Ridge to Poland (2018 to 2033), France (2014 to 2029) and Russia (2012 to 2027). These contracts give the exclusive right to explore an initial area of 10 000 km² of the Area (ISA, 2010). Over the first 10 years of the contract, 75% of this area is to be relinquished to the Area, leading to a maximum area of 2 500km² area that can be retained for exploitation by the contractor (ISA, 2010).

Each of the three contract areas of the Mid-Atlantic Ridge is divided into 100 squares of 10km by 10km. The Russian contract had 68 squares located south of the study area, thus only 232 squares were used for the spatial prioritisation, accounting for 0.34% of the study area with mining presence.

4.3.5 Data used for penalties

Lagrangian connectivity

Modelling water mass and realistic larval dispersal and connectivity is part of ATLAS WP1 and WP4, in which Langrangian dispersion models were developed to model benthic larvae drift across the ocean basin (ATLAS Deliverable 1.1 and Deliverable 1.6). These models consisted in particle release and tracking and were based on the VIKING20 ocean circulation model, designed on the North Atlantic from 30°N to 85°N and from 81°W to 21°E in the Arctic and to 8°E in the Mediterranean with a 0.05° spatial and 2016s temporal resolution (Böning et al., 2016), and the ARIANE Lagrangian particle tracking model. For the present deliverable, particles were released in each planning unit of the study zone within the coverage of the VIKING20 model. Particles were released four times a year and over 50 years of current circulation and at various depths in the water column from surface to bed. A total of almost 500 million particles were tracked. Two simulations were implemented, for a 20 days pelagic larval duration (PLD) and for an 80 days PLD, in which drifting was possible on all the water column. Connectivity strength between all source/target pairs of planning units of the considered extent was calculated as the proportion of particles released from each source planning unit which pass through each target unit within the relevant PLD.

4.4 Implementation plan and parametrisation

4.4.1 Approach and implementation scheme

The spatial prioritisation approach was implemented on the Prioritizr package (Hanson et al., 2019) on R (R Core Team, 2018), interacting with the Gurobi optimisation software (Gurobi Optimization LLC, 2018). Prioritizr is a recent package that uses integer linear programming (ILP) instead of conventionally used heuristics or simulated annealing algorithms (e.g. in Marxan, Ball et al. 2009). ILP has been shown to present several advantages compared to other methods, such as the measure of solutions' optimality (Beyer et al., 2016; Rodrigues & Gaston, 2002) and provided results to inform practical conservation planning (Schuster et al., 2019; Tack et al., 2019).

A "minimum set" problem was used. It consists in an integer linear programming (ILP) problem and can be expressed in matrix notation (Hanson, et al., 2019) as:

$$minimize\ cx\ subject\ to\ Ax\ \geq b$$

Here x is a vector of decision variables (here, whether to select or not a planning unit), c and b are vectors of known coefficients, and A is the constraint matrix. In the "minimum set" problem, c represents a vector of costs for each planning unit, A stores the amount of each feature in each planning unit, b is a vector of targets for each conservation feature, the ≥ symbol indicates that the total amount of each feature in the solution must exceed the quantities in b. This means that the most basic conservation problem will consider the distribution of conservation features, their respective conservation target, and the cost associated to planning units. A conservation problem can be further complicated by adding penalties acting on c, or constraints acting on A.

The conservation scenarios were implemented sequentially, by adding features, and then penalties or costs, until reaching the final, more complex, scenario. In this way, the simple scenarios would allow focus on the priority areas for specific features, the scenarios pooling all the features would identify areas by considering all the biodiversity aspects, and the last scenarios involving costs would finally add management and human use constraints to the solutions.

The sequential procedure is displayed in the implementation scheme below (Figure 32), together with description of scenarios. Detailed information about conservation targets, costs, penalties and solving parameters, is found in the following part.

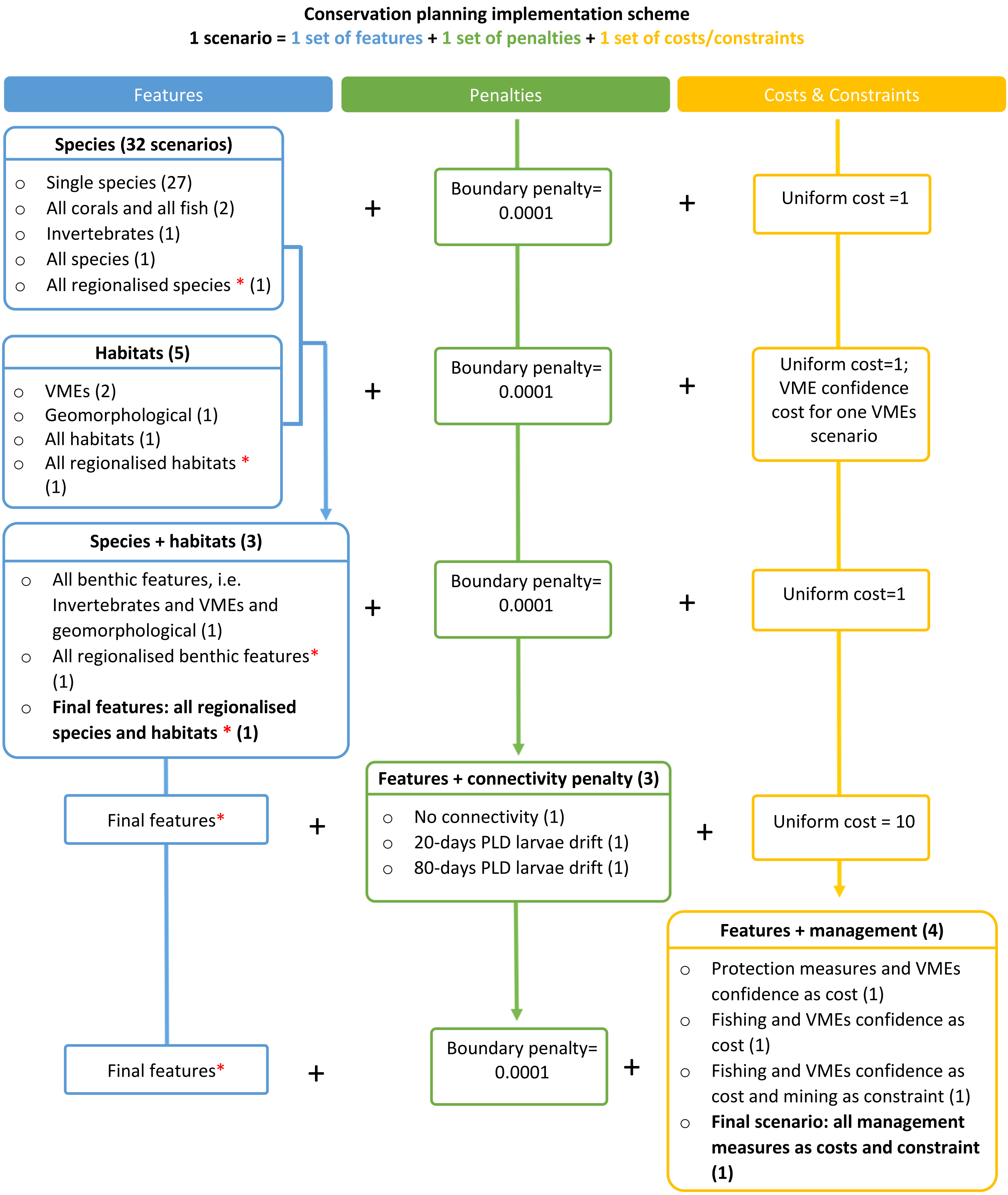

Figure 32. Conservation planning implementation scheme. The number of simulations for each scenario is mentioned in brackets. Each scenario contains the 3 components: features, penalties, and costs/constraints. The first scenarios used different features (blue), then the connectivity was changed (green), and finally varying costs and constraints were implemented (orange).
**: use of regionalisation by division of features in pseudo-features according to the 13 provinces.*

Species scenarios

The “single species” scenarios aimed at identifying important conservation areas for each of the coral, fish and sponge species, independently of other features (Table 19). One conservation target was set for each climate refugia, varying from 30% to 80%, and three targets were tested on present-day habitat layers (15, 30 or 50%; see following part 4.4.2 for conservation targets attribution).

Table 19. Description of single species scenarios

Species (n)	Features in scenario (target)	Goal	N scenarios
Fishes (6)	Climate refugia (1 specific target)	Secure future climate refugia	6
Corals (6)	Climate refugia (1 specific target); Present-day suitable habitat (15, 30 or 50%)	Secure current habitat and future climate refugia	18
Sponge (1)	Climate refugia (1 specific target); Present-day suitable habitat (15, 30 or 50%)	Secure current habitat and future climate refugia	3

Two scenarios, “all corals” and “all fish” were implemented, pooling features for fish or coral species. For corals, the target for present-day suitable habitat depended this time on the relative cover of the layer, as for all the following scenarios (part 4.4.2).

The “invertebrates” scenario gathered the corals and the sponge, aiming to identify conservation areas for VME engineer species especially.
The last species scenario, “all species”, pooled all species (including fishes) and their associated features and targets. The “all species regional” scenario used the same features, but each one was divided into 13 pseudo-features according to the created provinces. This ensured allocation of species conservation units in the same proportion for each province in order to reach a geographically balanced network of protection.

Habitats scenarios

The “VMEs” scenario aimed at identifying conservation areas for VMEs, by considering all ICES indicator species but also georeferenced VME habitats. The VME feature consisted in four levels of the same information (i.e. the VME likelihood) thus four pseudo-features: the unequivocal VMEs and the three levels of VME index, which each had a specific target according to their VME likelihood (part 4.4.2). This scenario was implemented twice: with a uniform cost of 1, and a cost associated to the confidence index for VMEs varying from 2 to 10 (see following part 4.4.3 for cost attribution).
The “geomorphological” scenario aimed at identifying conservation areas for VME-supporting geomorphological features: fracture zones, canyons and seamounts.
The final “all habitats” scenario pooled the VMEs and geomorphological features, with the goal of identifying important benthic habitats for biodiversity: biologically and functionally important as displayed by VME features (hydrothermal vents, cold seeps, sponge grounds, coral reefs, etc.); and physically important as displayed by geomorphological features (likely hard substrate and high range of depths because of slope, also providing physical protection against human activities).
As previously, all habitats features were divided into 13 pseudo-features, one for each province, to geographically balance the solutions in the “all habitats regional” scenario.

Pooling species and habitats: final features scenarios

Species and habitats features were then gathered in three scenarios. The “all benthic” and “all benthic regional” scenarios used all the features except the fish species, aiming at identifying conservation areas for seabed ecosystems in a large approach. The third one, “final features”, comprised also the six climate refugia layers for demersal fish. This later scenario was then used as a basis for the following connectivity and cost simulations.

Connectivity scenarios

Connectivity across the study area was addressed by comparing the effect of the boundary penalty, influencing the clumping of planning units in the solution, to a connectivity matrix and calibrated penalty (see following part 4.4.4 for the penalties implementation). Scenarios were run on a smaller area matching the extent of larvae dispersal models (part 4.3.6), with 22347 PUs (70.9% of the study zone). The connectivity matrices contained probabilities of connection between planning units, calculated from 20 days and 80 days PLD larvae dispersal models. The goal of these scenarios was to consider the benthic larvae connectivity to achieve a connected and thus more resilient network of conservation units. The 20-days PLD and 80-days PLD scenarios were built to take into consideration two possible coral larval dispersal patterns, using two PLD that induced a lower (20-days) and a larger (80-days) connection potential. The 80-days PLD scenario was more representative of *Lophelia pertusa*, the only deep-sea species for which the reproduction and larval behaviour are well known (Larsson et al., 2014). The 20-day PLD scenario represents the shorter end of the range of deep-sea PLDs reported in the review of Hilário et al. (2015), allowing a more conservative choice where only one connectivity matrix can be used to represent the whole ecosystem.

Management scenarios

All the above scenarios, except one of the VMEs scenarios, used a uniform cost. Therefore, the cost of the solution only depended on the extent of area selected by the MARXAN solution (the more conservation units, the more costly).

Four additional spatial management scenarios were investigated using varying costs of planning units and spatial constraints (part 4.4.3). Cost variation depended on protection measures (lowering the cost) and fishing activity (increasing the cost). The VMEs cost was also included, but its importance was low given the small proportion of features impacted by this cost. A spatial constraint was also added to take into account the deep-sea mining activities in the North Atlantic.

The first scenario, “protection”, took account of the spatial protection measures in high seas and EEZs: fishing closures (RFMO and MPAs), MPAs without fishing closure, and EBSAs. It aimed to prioritise zones that already have protection measures and acknowledge the management efforts in place.

The second scenario, “fishing”, used the bottom fishing catch as a supplementary cost, proportional to the catch value. The third scenario, “fishing and mining”, consisted in adding deep-sea mining exploration zones as an exclusion constraint. These zones are under contract with the International seabed authority and the environmental management plan for the region is not mature enough to be incorporated in this framework for systematic conservation planning. Therefore, planning units in which mining was present were excluded from the conservation problem and thus were not displayed in solutions. These two scenarios considered that the implementation of protection on planning units supporting human activities would be costlier, because of the economic loss involved or the need to restore impacted habitats. Hence, solutions favoured zones that were either not impacted or less impacted by human activities.

The fourth and last scenario "all management" combined all the management costs and constraints. This was the most complete scenario in the context of an integrated prioritisation approach.

4.4.2 Conservation targets for features

Each feature in the simulation was associated with a relative conservation target, corresponding to a proportion of the feature cover that is required to be protected in the study area, and thus varying from 0 to 1 (0 to 100% of protection in the prioritisation solution, Table 20). The decision rules that have resulted in the attribution of these protection targets are detailed below.

Table 20. Summary table of conservation target attribution. The three criteria for target attribution, which can interact, are exposed in the first and second column.

% cover rule (basis target)	Other decision rule	Effect on target	Final target	Features
Cover <=5% (60%)	-	-	60%	Unequivocal VMEs; fracture zones; seamounts; canyons
	Refugia reduction >=70%	+20%	80%	*Acanthogorgia a.* refugia; *Paragorgia a.* refugia; *Geodia b.* refugia
Cover 5-10% (50%)	-	-	50%	*Acanthogorgia a.* present; *Paragorgia a.* present; *Geodia b.* present
	Refugia reduction >=70%	+20%	70%	*Acanella a.* refugia; *Lophelia p.* refugia
	Refugia reduction <70%	0	50%	*Coryphaenoides r.* refugia; *Hippoglossoides p.* refugia ; *Gadus m.* refugia; *Reinhardtius h.* refugia; *Sebastes m.* refugia
Cover 10-25% (30%)	-	-	30%	*Acanella a.* present; *Desmophyllum d.* present; *Lophelia p.* present; *Madrepora o.* present
	Refugia reduction <70%	0	30%	*Desmophyllum d.* refugia ; *Madrepora o.* refugia; *Helicolenus d.* refugia
-	Levels of VME likelihood	50%	50%	High VME index
		30%	30%	Medium VME index
		15%	15%	Low VME index

General target decision criteria

In most instances, conservation targets were defined as a function of the commonness of the features at the scale of the study zone (Figure 33). The most common features had lower conservation targets than the rare ones. Three conservation targets were defined according to the relative cover of features:

- Conservation target of 60% for features covering less than 5% of the study zone
- Conservation target of 50% for features covering between 5% and 10% of the study zone
- Conservation target of 30% for features covering between 10% and 25% of the study zone

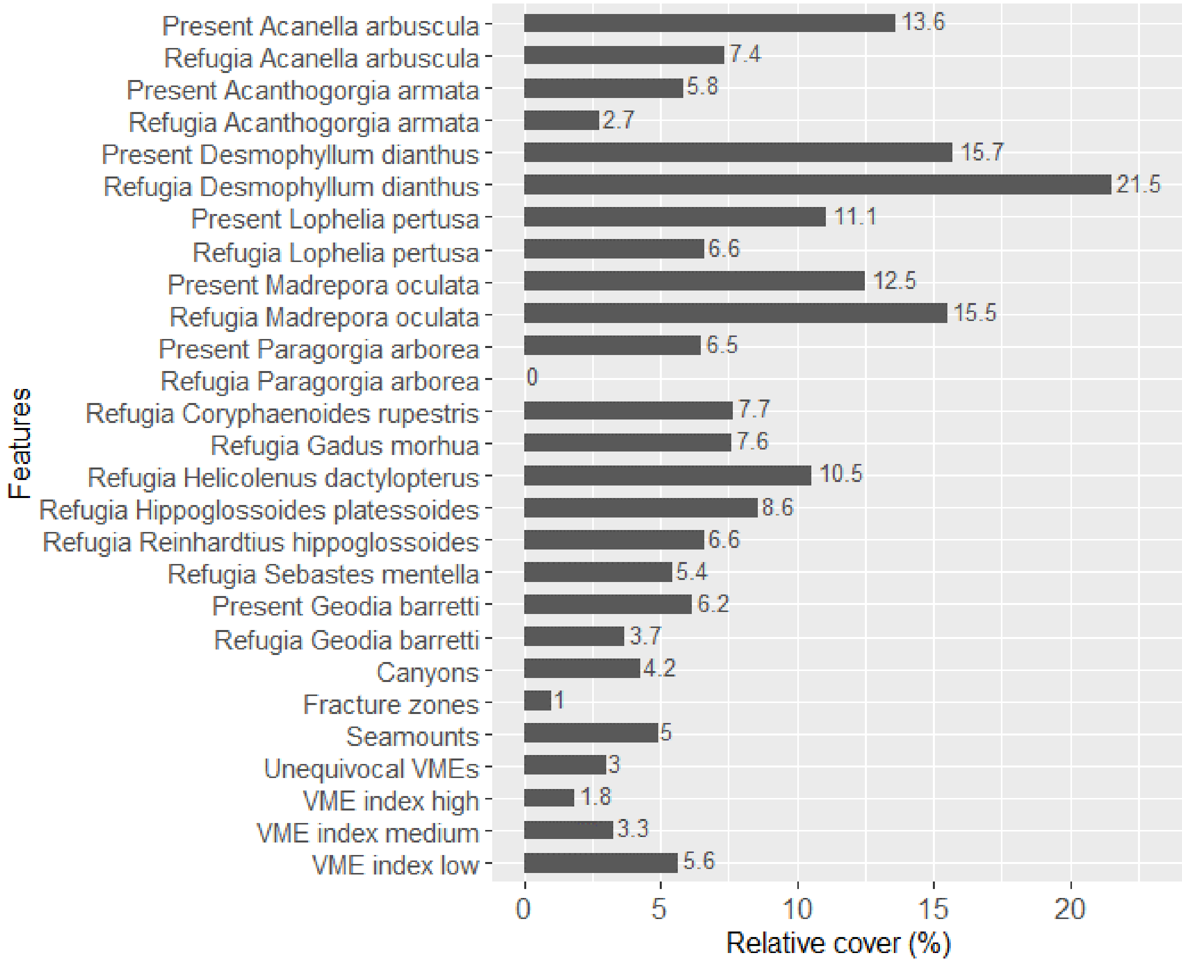

Figure 33. Relative cover of the study area by each feature.

Conservation targets for climate refugia

Climate refugia represent the overlap between present and predicted future species distribution. As such they do not reflect the full extent of future suitable habitat as species may (or may not) colonise new areas where the environment conditions may become favourable. Also, they do not consider the ability of species for phenotypic plasticity or genomic adaptation that may enhance their tolerance to the forecasted climatic conditions. As such, they are a relatively conservative representation of the predicted future species distribution. Conservation targets for species' climate refugia were defined as a function of the extent of reduction in the size of PUs supporting suitable habitat. The habitat reduction was calculated as the difference between present predictions and future climate refugia (Figure 34). Two groups appeared in the data exploration: species with a moderate reduction (mostly 35%-50%) and species with a high reduction (>=70%, Figure 34). For those five species with high predicted reduction (the three gorgonian corals, one scleractinian coral and the sponge), climate refugia were regarded as crucial areas for the viability of species and thus were prioritised by increasing the general conservation targets described above by another 20%.

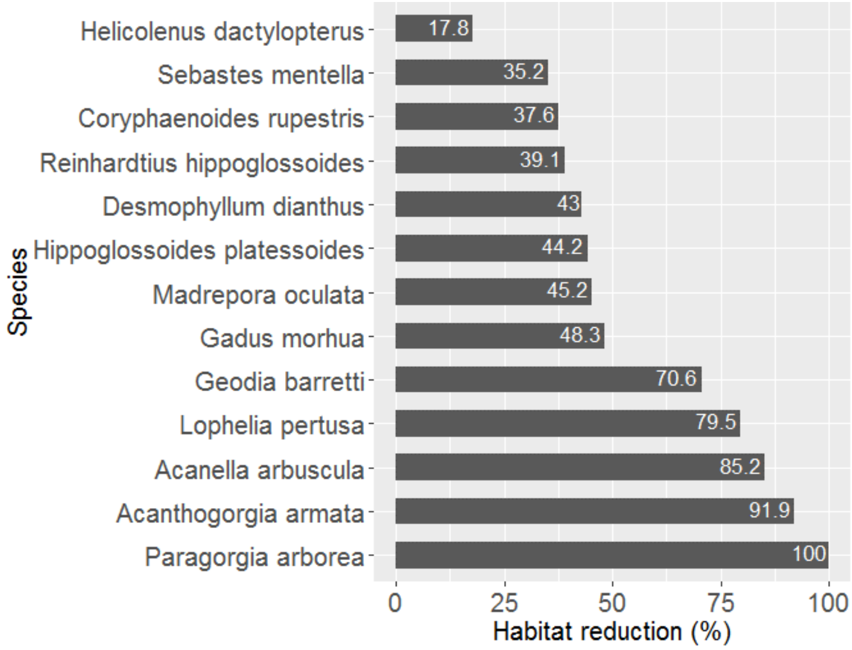

Figure 34. Relative habitat reduction between present and climate refugia.

Conservation targets for single species scenarios

Within coral and sponge single species scenarios, three conservation targets were tested for the present-day distribution of suitable habitat, independently of the relative cover of the layers:

- 15%: usual international protection goals (that vary between 10 and 20% in function of organisations/spatial scales)
- 30%: compromise
- 50 %: scientific recommendation to insure a large protection and buffer the uncertainties associated to habitat models and climate predictions

For the scenarios in which species were pooled together, conservation targets were set as a function of feature percent cover under present-day conditions as described above.

Conservation targets for VME index

The likelihood of presence of VMEs quantified by the VME index was divided in three levels (part 4.3.2), thus a different conservation target was assigned to each level:

- 15% for low VME likelihood
- 30% for medium VME likelihood
- 50% for high VME likelihood

4.4.3 Planning unit cost classification

Several area-based costs for PUs were tested (1, 10, 100, 1000), showing that higher costs highly impacted the number of PUs in solutions. For 39 of the species and/or habitats scenarios, the cost of PUs was set to 1 uniformly, so this cost had little influence on the number of PUs selected. In the three connectivity scenarios, the cost was set to 10, to give more weight to the connectivity penalty that is acting on the cost, but also because it reduced the solving time needed to process the scenario.

Five scenarios included specific costs indexed on the VME confidence index, existing protection measures and fishing catches. For those scenarios, the PUs cost baseline (b) was set to 10 to increase constraints on PUs selection and costs were defined from this base cost following the formula:

$$Cost\ layer\ = b\ (1 - \frac{f1}{n} * c1 - \frac{f2}{n} * c2 + \frac{f3}{n} * c3)$$

With
b: PUs raster layer with base cost of 10
n: number of features in the scenario
$f1$, $f2$, $f3$: number of features affected by VME confidence index (f1), protection measures (f2) or fishing (f3)
$c1$, $c2$, $c3$: raster layers with VME confidence (c1), protection (c2) or fishing (c3) cost indices rescaled within [0,0.8]

Following parametrisation tests, a maximum cost variation was set to 80% to strengthen its effects on scenarios outputs. The cost indices were structured either in categories or along a continuous gradient between 0 and 0.8, depending on the source data. These indices were then weighted, for each scenario, depending on the proportion of features likely affected by each kind of cost.

VME confidence index

PUs cost was negatively indexed to the VME confidence index in order to favour conservation of PUs in the presence of VMEs. The VME cost index was set to 0.8 for high confidence and for unequivocal VMEs, corresponding to an 80% cost decrease; and to 0.5 for medium VME confidence (50% cost decrease), Figure 35). The cost was unchanged for PUs with low VME confidence (index value =0).

One feature was affected by this cost ($f1$=1): the distribution of VMEs, divided in four pseudo-features (unequivocal VMEs, high VME index, medium VME index, low VME index).

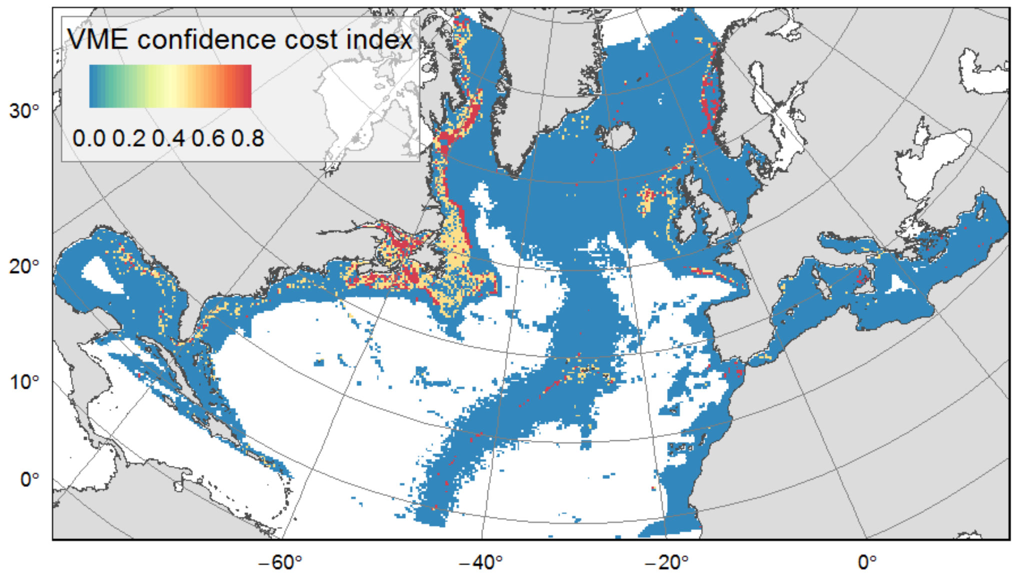

Figure 35. Distribution of the VME confidence cost index in planning units. Red: 80% of PU cost decrease for unequivocal VMEs and VME index with high confidence; yellow: 50% of PU cost decrease for medium VME confidence; blue: PUs with a low VME confidence index or without index value

Protection cost

PUs cost was negatively indexed to levels of protections provided by management efforts already in place in ABMTs. The three protection levels and their associated costs were defined for RFMOs' fishing closures, MPAs, and EBSAs (Figure 36):

(1) A 0.8 index value (i.e. 80% cost decrease) for high protection level offered by NAFO and NEAFC fishing closures and the marine reserves (MPAs with no-take zones or IUCN Cat I) totalizing 2.99 % of the study area (Appendix 4);
(2) A 0.5 index value (i.e. 50% cost decrease) for a medium protection level offered by the GFCM fishing restricted area of the Gulf of Lion and the other MPAs (with lower protection) totalizing 7.57 % of the study area (Appendix 4);
(3) A 0.25 index value (i.e. 25% cost decrease) for a low protection level attributed to EBSAs totalizing 7.14 % of the study area (Appendix 4).

In case of overlapping protection measures in a same planning unit, the higher protection category was kept. It was considered that all the features were affected by protection, thus $f2$ was equal to n (=24 for the final feature scenario).

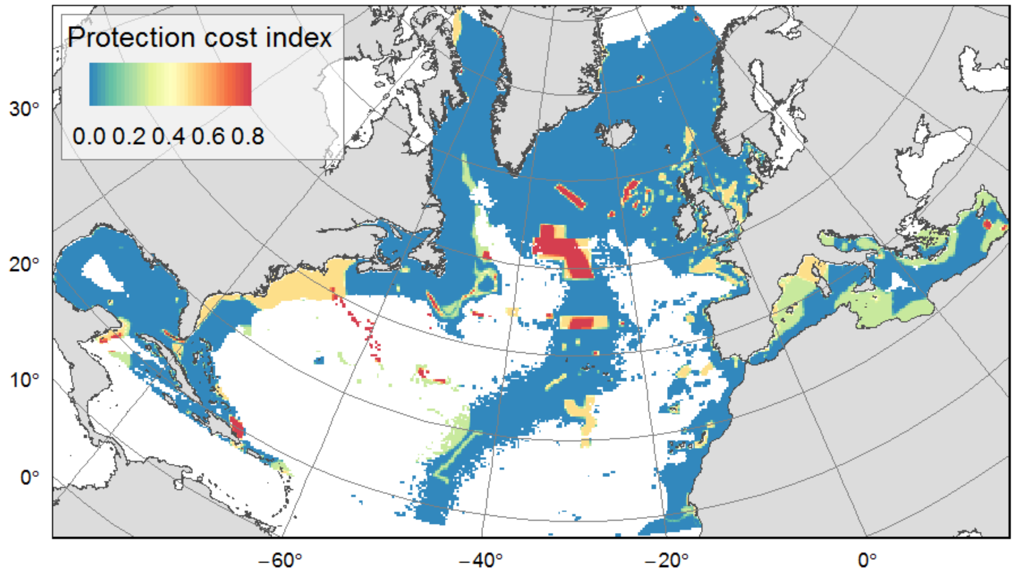

Figure 36. Distribution of the protection cost index in planning units. Red: 80% of PU cost decrease for fishing closures and marine reserves; yellow: 50% of PU cost decrease for other MPAs; green: 25% of PU cost decrease for EBSAs; blue: PUs with no protection designation.

Fishing cost

PUs cost was positively indexed to fish catches. The cost of protecting fishing grounds was increased in order to favour solutions that limit the economic loss due to fishing restrictions on selected conservation units (fishing is defined here as an opportunity cost, see Ban and Klein, 2009). This cost increase could be also interpreted as a cost accounting for already existing ecological impact of human activities.

The fishing catch was log transformed as $log(\ catch\ + 1)$ to lower the weight of high catch values. Log values were then rescaled as an index between 0 and 0.8; 0 corresponding to a null catch (likely to no fishing) and 0.8 to the maximum catch on the study zone (Figure 37). Therefore, the cost of planning units was increased of up to 80% for the higher catch value.

Fishing catch was considered to have a potential impact on species and on VMEs, but not on the three geomorphological structures. Therefore, $f3$ was equal to $n-3$ (thus 21 for the final features).

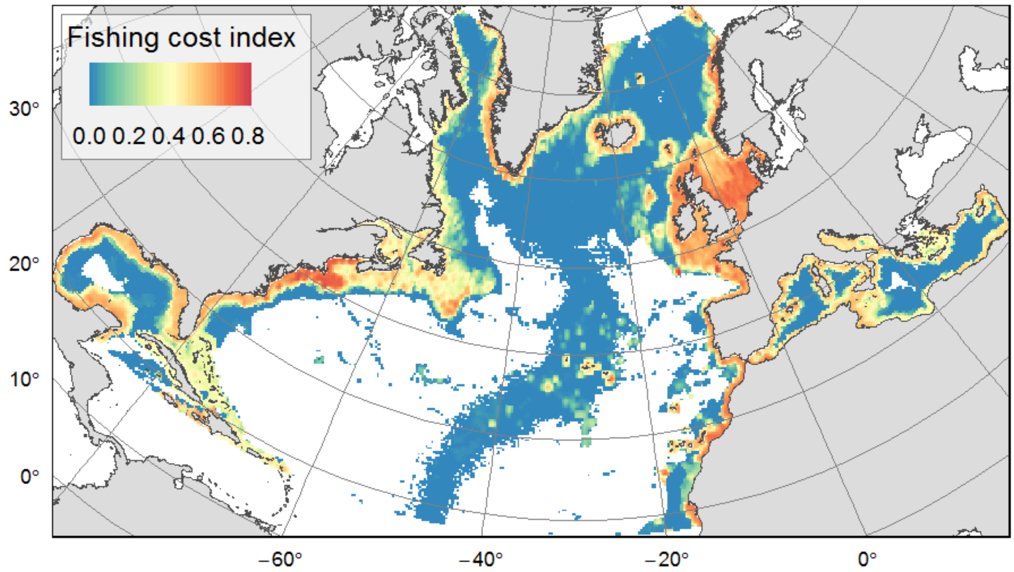

Figure 37. Distribution of the fishing cost index in planning units, from a null fishing catch (blue) to the maximum fishing catch associated to an 80% PU cost increase (red).

4.4.4 Boundary and connectivity penalties

Boundary

The boundary penalty penalises fragmented solutions by using a matrix of shared boundary length between different planning units (Hanson et al., 2019). Increasing the boundary penalty reduces the number but increases the size of each individual conservation areas, ultimately leading to a single large and contiguous area. The boundary penalty was calibrated on one scenario, to reach a compromise between very scattered solutions and clumped solutions. The value of 0.0001 was selected and applied to all scenarios without connectivity.

Connectivity

For scenarios with connectivity, the boundary penalty was replaced by a connectivity penalty, favouring solutions depending on their degree of connectivity (Hanson et al., 2019). The values in connectivity matrices, displaying all pairs of planning units, ranged from 0 to 1, i.e. no connectivity to maximum connectivity.

Two connectivity matrices originated from larval dispersal models for a 20 days and 80 days PLD. The number of connections between each pair of planning units, from sources (release of virtual larvae) to targets (location of larvae after the PLD), were displayed in an asymmetric matrix as probabilities of connection. Probabilities were calculated as the proportion of particles released over the 50 years of simulation in gridsquare A which entered gridsquare B before reaching the PLD. The numerous very low connectivity values (under 0.01 for the 20-days PLD and 0.1 for the 80-days PLD) were set to 0 to allow a realistic time for calculations.

As for the boundary penalty, the connectivity penalty was calibrated in test scenarios: it was set to 1 for the 20-days PLD matrix, and to 0.5 for the 80-days PLD matrix.

4.4.5 Common parameters and solving specifications

The Gurobi solver (Gurobi Optimization LLC, 2018) was used to solve prioritisation problems with a 0.1 gap to optimality. For each scenario, 100 runs were required using the cuts portfolio method (Hanson et al., 2019), and the 30 best solutions, i.e. the less costly solutions, were picked among the 100. If less than 30 solutions were returned by the solver, all the achieved solutions were displayed.

When solving time was very long (more than 48h for individual species, more than four days for complex scenarios), the gap parameter was increased to 0.2, and if not sufficient, a time limit for solutions was set to 1000 seconds (individual species) or 2000s (complex scenarios, Appendix 5). It was possible to see for which solutions (generally the last ones of the 100) the time limit was reached, interrupting the solving. These solutions were excluded from the list to select the final set of 30. Connectivity problems were particularly long to solve, thus a specific parametrisation was set (30 or 15 runs only, gap of 0.3, time limit of 10000 or 15000s, *see* Appendix 5).

4.4.6 Delineation of priority areas and post-hoc evaluation

Post-hoc analyses were implemented on the two final scenarios “final features” and “all management”. These aimed first to delineate suggestions of conservation priority areas by operating PUs selection, and then, to assess the representativity of the prioritisation elements (features, provinces, protection designations and fishing catch) and of three terrain variables (depth, slope and Bathymetric Position Index or BPI) in those priority areas. The slope and BPI indices were calculated using the depth layer at 3km resolution (Deliverable 3.3 Chapter 3.2.4), and averaged within each 25km*25km PU. Finally, comparisons allowed to evaluate how integrating the management aspect changed this representativity.

Three set of PUs were delineated in the final scenarios, representing three levels of PUs importance towards achievement of the conservation objectives, and based on thresholds of the selection frequency within the 30 selected solutions:

- The “contributing” PUs, selected at least once in the 30 solutions
- The “significant” PUs delineating large priority areas, selected in at least 50% of solutions
- The “essential” PUs delineating core priority areas, selected in at least 75% of solutions

4.4.7 Data management and access

All the scenarios input layers created (features and costs), at the 25km*25km resolution, will be available with a DOI on the Ifremer Sextant catalogue for spatial data (https://sextant.ifremer.fr/). The final scenarios outputs together with the corresponding code will be provided on the ATLAS GEOnode portal.

4.5 Results and discussion

4.5.1 Solving outputs

The 47 scenarios solving parameters are detailed in the Appendix 5.

For several single species scenarios, less than 100 solutions were returned after solving because the cost of solutions reached the optimality limit, automatically interrupting the solving. This happened for species with a small distribution when the present-day targets were low (15% and 30%) and thus were already included within the refugia units (*Geodia barretti*, *Acanthogorgia armata*, Appendix 5).

All scenarios displayed the same pattern of cost increase throughout the 100 solving iterations: the cost was the lower for the firstly solved solution (the more optimal one), and increased until stabilisation between solutions 20 to 60 (Figure 38). Thus, the 20 first solutions were almost always selected, complemented by other solutions usually among the 50 first ones.

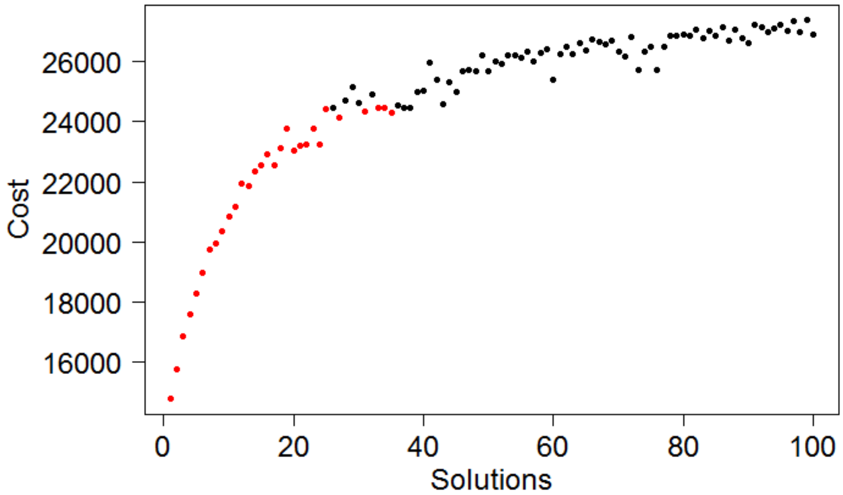

Figure 38. Cost of the 100 solutions for the scenario "all features regional". The 30 selected solutions, with the lower cost, are displayed in red.

The base cost of planning units (1 or 10) changed the aspect of solutions. The low cost (1) provided flexibility in planning unit selection: adding more PUs did not increase much the total cost, and allowed to connect close areas to reduce the total boundary of the solution. The high cost (10) constrained more the choice of planning units, and minimised the total number of units in solutions as far as possible even if it increased the boundary length of solutions. For example, this difference is easily seen in the VMEs scenarios, for which the output selection became more scattered when using the VME cost, focusing on planning units with high conservation value and high confidence in the VME likelihood even if they were isolated from others (Appendix 6 Figures 33 and 34).

All scenarios outputs are displayed in the Appendix 6. The main results are displayed and discussed below. Scenarios outputs presentation contains a map and two boxplots. The map displays the scenario name and the selection frequency of PUs within the N selected solutions. The selection frequency ranges from 0, in blue, representing the PUs of the study area that were never selected and thus, do not contribute to conservation solutions, to 1, in red, representing the PUs that were systematically selected in the N solutions. The two boxplots display the dispersion: (top) of the number of planning units selected across the N solutions; and (bottom) of the total cost of the N solutions.

4.5.2 Species

Single species scenarios

For corals and sponge species, the refugia, defined as the overlapping areas between the present and future distribution of species imposed a strong constrain on solutions, up to a point where only refugia were selected when their conservation targets were high (*Acanella arbuscula*, *Acanthogorgia armata*, *Lophelia pertusa*, *Geodia barretti*, Appendix 6 Figures 1 to 21).

Fish scenarios provided flexibility as only one feature (the climate refugia) was used for each species. Hence, the maximum selection frequency was 0.75 approximatively for fish species, giving less contrasted results than for corals (Appendix 6 Figures 22 to 27).

Invertebrates

The identified conservation areas for the six coral species were mainly distributed along the slopes of continental margins and of the north Mid-Atlantic Ridge, those areas supporting the majority of the climate refugia (Appendix 6 Figure 28). Priority areas were exclusively allocated to these slopes for several species (e.g. *Acanella arbuscula* and *Acanthogorgia armata*). Shelf zones (Canada, northeast Atlantic and Mediterranean) complemented the selection to a smaller extent. *Paragorgia arborea* was the only species for which conservation areas were mainly selected on shelf areas, although suitable predicted habitat also occurred elsewhere (Appendix 6 Figures 16 to 18). Adding the sponge species, for which predicted habitat was mainly situated between 50°N and 70°N, increased the selection of priority areas in the sub-arctic region (Figure 39).

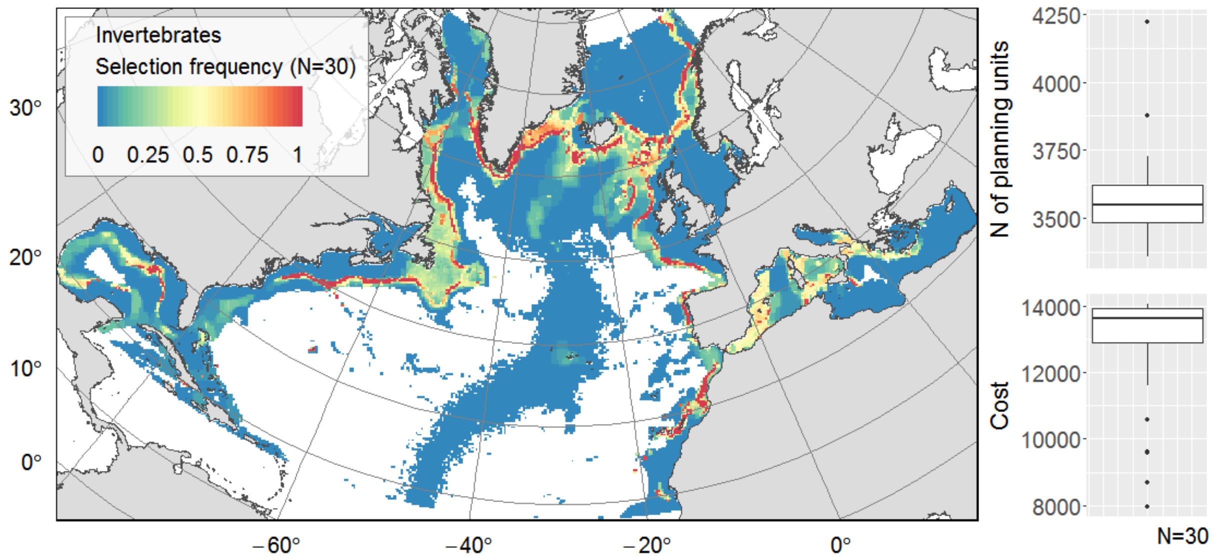

Figure 39. Output of the Invertebrates scenario. Left: map of PUs' selection frequency; upper right: boxplot of the number of PUs in all solutions; bottom right: boxplot of the total cost of all solutions.

Fish

As most of fishes refugia were situated in the northern part of the study zone (Appendix 6 Figures 22 to 27), the "all fish" output focused on this zone from 40°N to 80°N (Figure 40). In general, species' climate refugia and identified conservation areas were situated on continental shelf above 500m depth, except for *Coryphaenoides rupestris* for which they were found deeper (Appendix 6 Figure 22). Some species refugia were only found in cold waters up to arctic areas (*Reinhardtius hippoglossoides* and *Sebastes mentella*, Appendix 6 Figures 26 and 27), whereas others were in more temperate waters (*Helicolenus dactylopterus*, Appendix 6 Figure 24).

After gathering all fishes, the priority areas followed a continuous distribution from the Canadian shelf offshore Newfoundland to the North Sea and Bay of Biscay. Both shallow zones on shelves and upper slopes were selected (Figure 40).

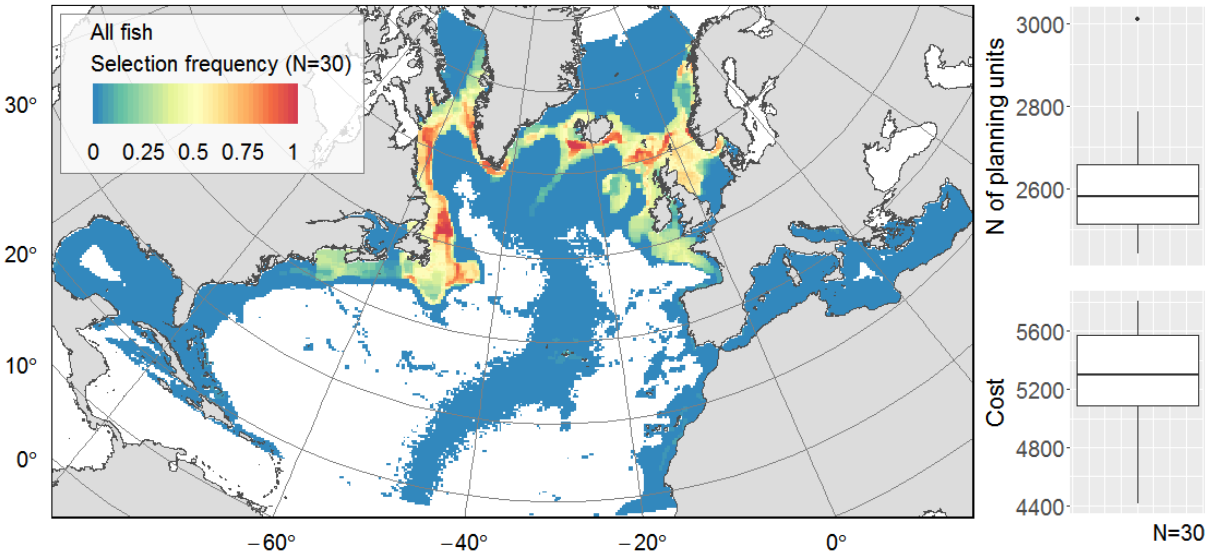

Figure 40. Output of the All fish scenario. Left: map of PUs' selection frequency; upper right: boxplot of the number of PUs in all solutions; bottom right: boxplot of the total cost of all solutions.

All species & All regionalised species

As fish conservation areas were predominantly situated on continental shelves of the northern part of the basin, (Figure 40), this scenario complemented the "invertebrates" output with several shallower areas: principally the northern part of the North Sea, around British Isles, along the St Lawrence Gulf and Newfoundland, and within the Baffin Bay (Figure 41).

The use of regionalisation allowed to balance the allocation of solutions and to identify priority areas in central and southern parts of the North Atlantic: the Mid-Atlantic Ridge around Azores, the Gulf of Mexico and the Caribbean (Figure 42). Because less species features overlap in these regions, they were sparsely or not represented in the previous scenario. In addition, selection frequencies were also slightly homogenised, ranging mostly between 0.5 and 0.75 and with less extreme values (PUs rarely or systematically included), leading for instance to an increased selection of areas in the Mediterranean.

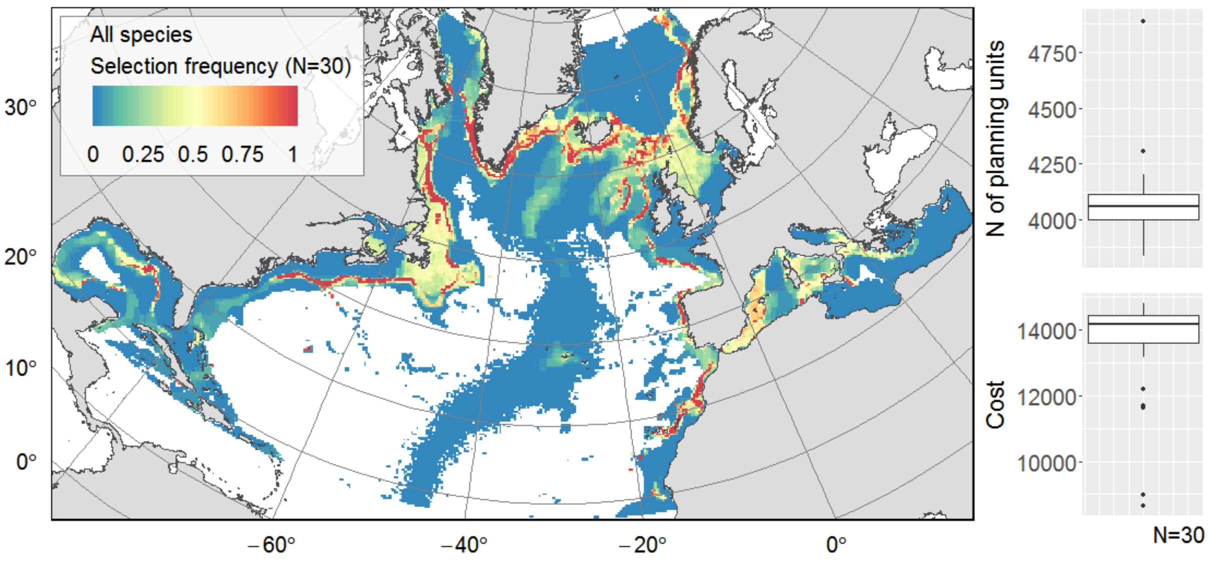

Figure 41. Output of the All species scenario. Left: map of PUs' selection frequency; upper right: boxplot of the number of PUs in all solutions; bottom right: boxplot of the total cost of all solutions.

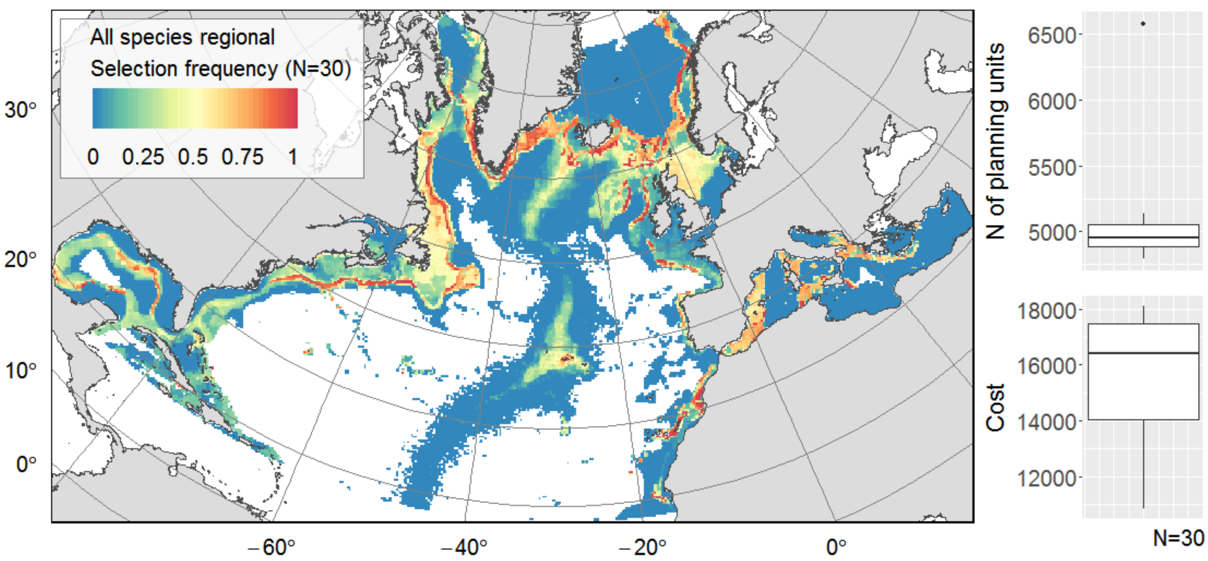

Figure 42. Output of the All species regional scenario. Left: map of PUs' selection frequency; upper right: boxplot of the number of PUs in all solutions; bottom right: boxplot of the total cost of all solutions.

4.5.3 Habitats

The principal priority areas for the VMEs' scenario were situated in areas where unequivocal VMEs and high VME index were numerous and clumped together (mostly over shelves and slopes, Appendix 6 Figure 33), likely representing coral and sponge VMEs (cold-water corals reefs and gardens, sponge grounds…). As a result, the scenario omitted certain unequivocal VMEs that were more scattered as hydrothermal vents and cold seeps (e.g. along the Mid-Atlantic Ridge and in the east Mediterranean). Hence, the VMEs scenarios did not display a comprehensive conservation of the different types of VMEs, but likely focused on VMEs with a widespread distribution rather than isolated VMEs such as chemosynthetic ecosystems.

The "geomorphological" output focused on those areas with denser canyon systems along margin slopes, between 35°N and 50°N (offshore of United-States and Canada, in the Bay of Biscay and northwest Mediterranean), and with overlaying fracture zones and seamounts, on the southern part of the Mid-Atlantic Ridge and more marginally in the Arctic region (Appendix 6 Figure 35). As these features, in particular seamounts, possess a scattered distribution, this scenario also displayed a more fragmented distribution of solutions in comparison to the species and VMEs scenarios.

All habitats & All regionalised habitats

In these scenarios, priority areas were allocated mainly to PUs concentrating both VMEs and geomorphological features (western margin slopes, Bay of Biscay, Mid-Atlantic Ridge, northwest Mediterranean), and were complemented by other conservation areas previously identified for VMEs or geomorphological features (Figure 43, Appendix 6 Figure 36). In these scenarios, PUs with hydrothermal vents or cold seeps were more represented in solutions than for the VMEs scenarios (Appendix 6 Figures 33 and 34), because these features overlaid with seamounts, fracture zones and canyons.

The use of regionalisation did not change the general distribution of priority areas but balanced the selection frequencies between the most selected areas (western slopes and south of Mid-Atlantic Ridge) and other zones of the basin (e.g. the northern provinces and the east Mediterranean, Figure 43), thus partly solving the bias observed when only VMEs were taken into account. The Bay of Biscay and Northwest Mediterranean (Gulf of Lion to Tyrrhenian Sea) remained areas with high selection frequencies of conservation units.

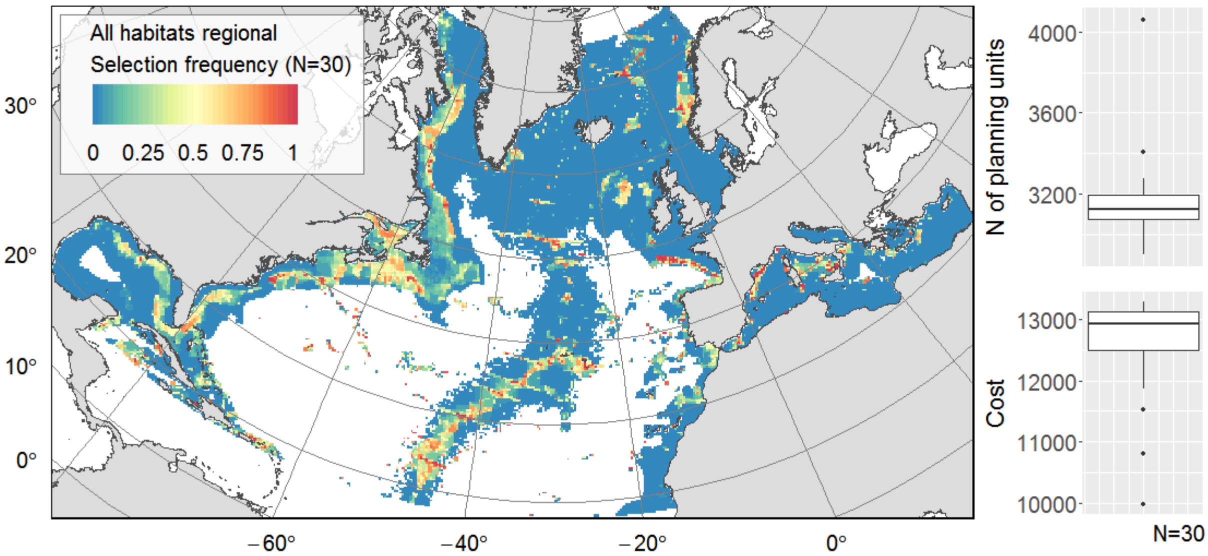

Figure 43. Output of the All habitats regional scenario. Left: map of PUs' selection frequency; upper right: boxplot of the number of PUs in all solutions; bottom right: boxplot of the total cost of all solutions.

4.5.4 Species and habitats

All benthic features & All regionalised benthic features

In scenarios combining the predicted distributions of VME indicator taxa (corals and sponge) together with the known distribution of VMEs and the geomorphological features fostering the occurrence of VMEs (e.g. seamounts, canyons), the solutions favoured the continental slopes as well as the Mid-Atlantic Ridge (Figure 44, Appendix 6 Figure 38).

Along continental slopes, canyons are hotspots for the occurrence of VMEs (De Leo et al., 2010; Fernandez-Arcaya et al., 2017), on the western side of the Atlantic (Mortensen & Buhl-Mortensen, 2005; Quattrini et al., 2015), the eastern side of the Atlantic (Morris et al., 2013; Van Den Beld et al., 2017) and the Mediterranean Sea (Fabri et al., 2014; Orejas et al., 2009). Moreover, these steep slopes are key areas for internal waves and nutrient circulation, where deep water upwellings flow up or coastal nutrient input sink, thus feeding the filtering organisms and sustaining the VMEs (Mienis et al., 2007; White et al., 2005). Even if their depth range is larger, most of the VME indicator taxa used in this study largely occur between 500 to 2500m depth (Deliverable 3.3 chapter 3 but see, for global predictions: Davies & Guinotte, 2011 and Yesson et al., 2012), and for some species, future climate refugia are almost exclusively predicted in these zones (Deliverable 3.3 chapter 4). For instance, PUs containing refugias of *Acanella arbuscula*, *Acanthogorgia armata*, *Lophelia pertusa and Geodia barretti* (Appendix 6 Figures 1 to 21), which were all small and benefited of the highest targets, formed the thin band of higher selection frequencies along slopes, present in all the final scenarios.

Whereas the Mid-Atlantic Ridge was not preeminent in species scenarios outputs, this zone was essential for habitats scenarios (Figure 43), and supports a diversity of VMEs found on the diverse substrates of the ridge (Braga-Henriques et al., 2013; Mortensen et al., 2008). Along the ridge but also all across the North Atlantic and Mediterranean Sea, seamounts are known to represent hot-spots for VMEs (Morato et al., 2013; Rogers et al., 2007) and may constitute essential refugia for species in the context of environmental change such as acidification (Tittensor et al., 2010). Moreover, the Mid-Ocean Ridges are sites of hydrothermal activity that gives rise to unique chemosynthetic ecosystems from south to north of the Azores (Schander et al., 2010; Van Dover, 1995) and up to the Arctic (Pedersen et al., 2010).

As the "benthic" scenario combined species and habitats that had various distribution patterns, more areas of the basin were therefore represented in solutions in comparison to previous scenarios. Hence, the use of regionalisation balanced the values of the PUs selection frequencies but did not bring out new conservation areas (Figure 44). As for the species and the habitat regionalised scenarios, selection frequencies were less contrasted, and for instance, previous rarely selected units (under 25% of selection frequency) were more represented in solutions: e.g. on the Canadian shelf, Gulf of Mexico and Caribbean, northern Mid-Atlantic Ridge or Hatton Bank.

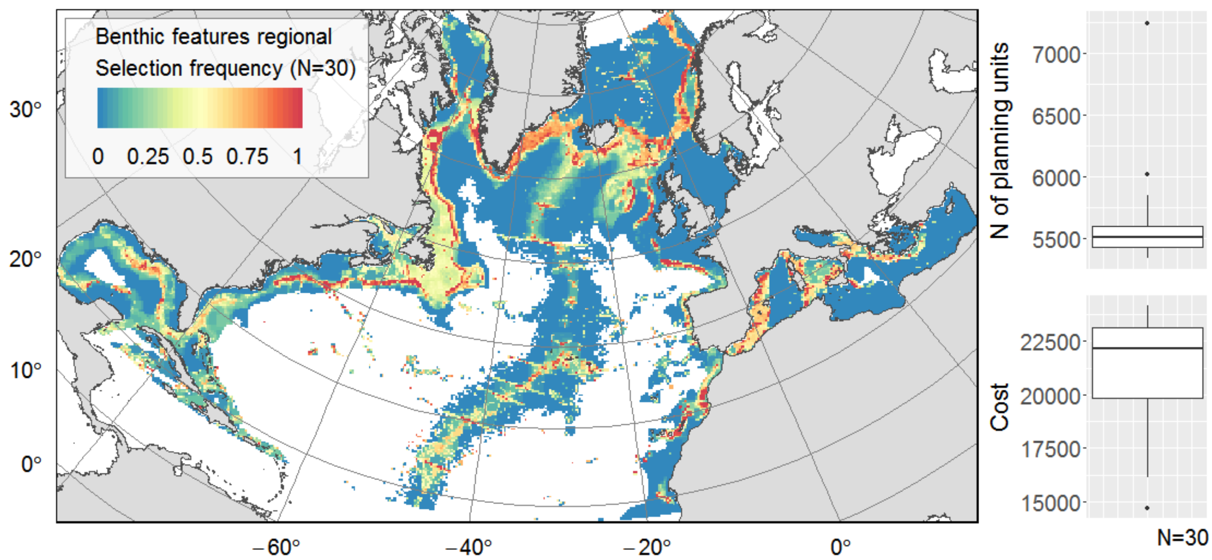

Figure 44. Output of the Benthic features regional scenario. Left: map of PUs' selection frequency; upper right: boxplot of the number of PUs in all solutions; bottom right: boxplot of the total cost of all solutions.

Final features: all regionalised species and habitats

Similarly to the "all species" scenario, adding the six fish climate refugia conducted to the selection of supplementary areas of shallower depths in the northern part of the basin (Figure 45). The pattern of PUs selection did not change in other areas, and the highly selected conservation areas remained the same.

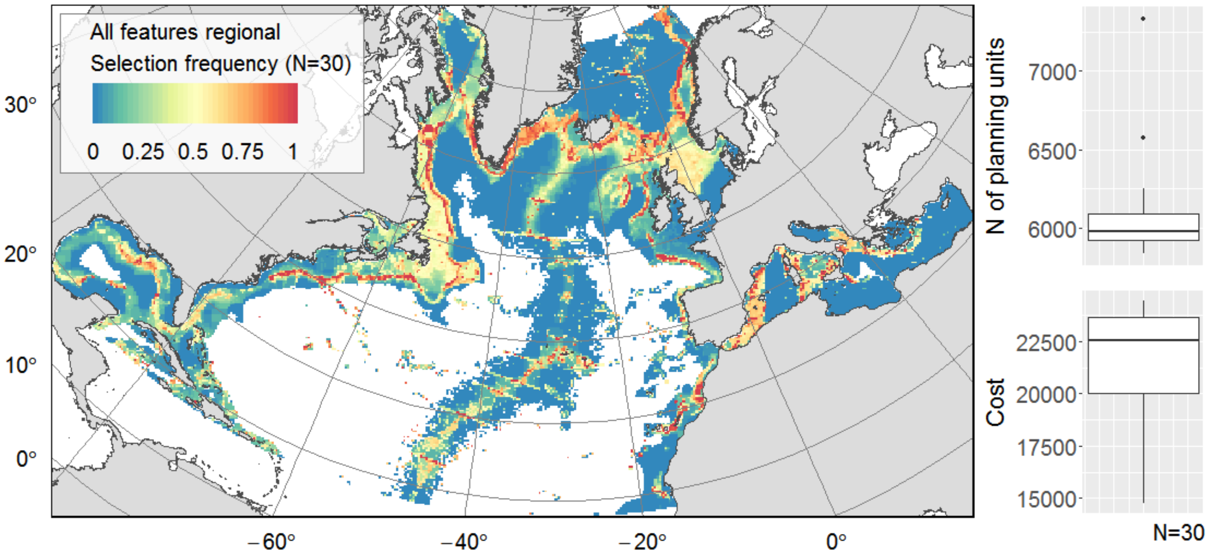

Figure 45. Output of the All features regional scenario. Left: map of PUs' selection frequency; upper right: boxplot of the number of PUs in all solutions; bottom right: boxplot of the total cost of all solutions.

Features representativity in selected priority areas

The proportions of features inclusion within the three PUs selections of the two final scenarios (see part 4.4.6) are presented in the Appendix 2. In fact, whereas each solution alone does meet the conservation target, the selection based on frequency across several solutions (here most often 30) may fail for some targets. As a result, the set of significant PUs (at least 50% of selection frequency) almost always surpassed the initial conservation targets, whereas the essential PUs (at least 75% of selection frequency) never reached the conservation targets (except for the single PU of *Paragorgia arborea* refugia), with up to a 37% deficit for the seamounts target (Figure 46). This illustrates the caution needed when selecting a set of PUs upon selection frequencies: some conservation targets may not be reached. On the other hand, the selection frequency emerging from several solutions provides more flexibility and a relative measurement of PUs importance with regards to the conservation objectives. Hence, any choice of conservation units sets based on selection frequency should be made after verifying the proportion of inclusion of the species and habitats of interest. In this deliverable, besides the chosen conservation targets, the priority areas delineated with significant or essential PUs of final scenarios contained in average from 31% to 59% of each feature (Appendix 2), proportions that represent a relatively high conservation effectiveness.

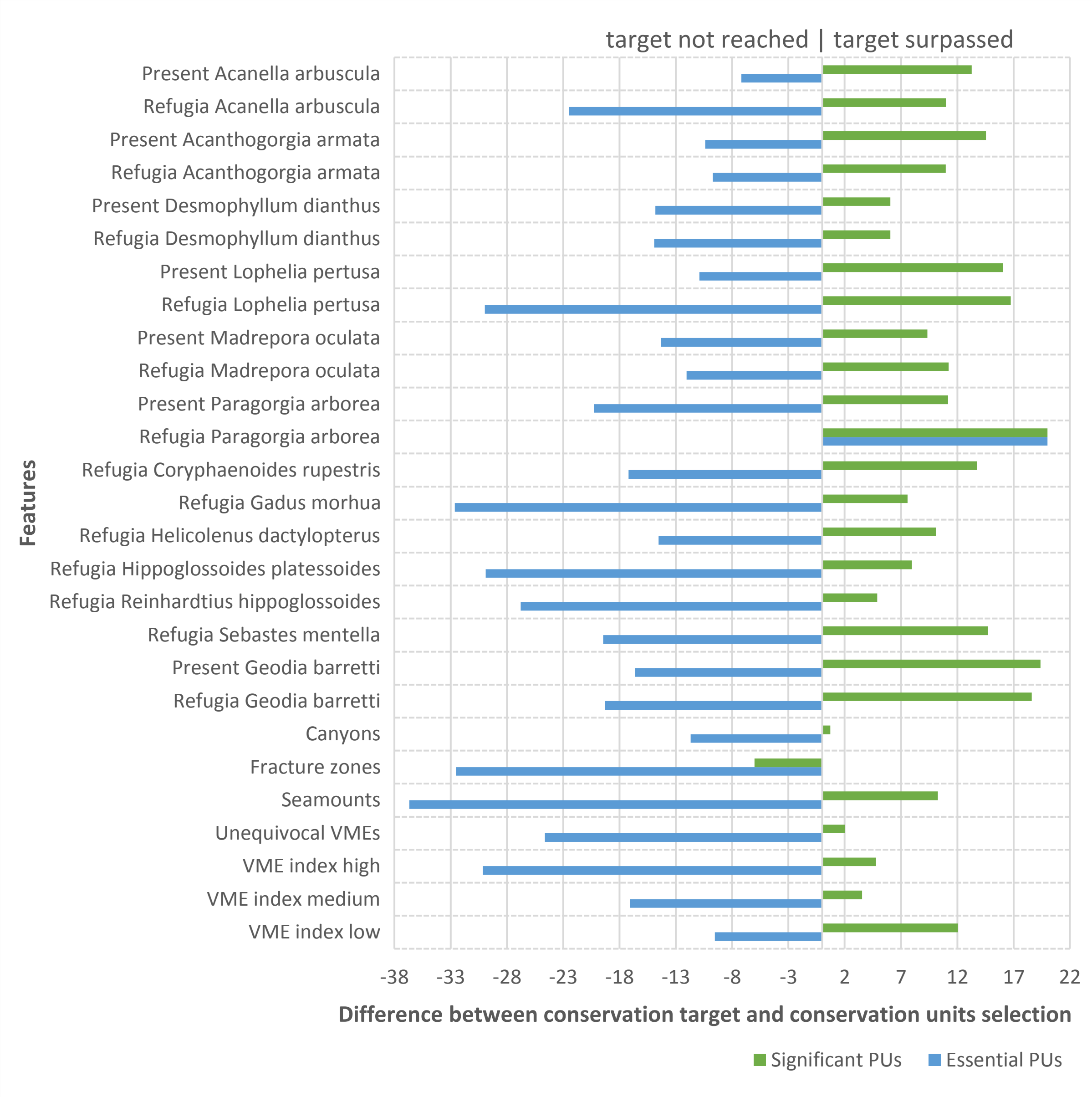

Figure 46. Completion of conservation targets within the sets of significant and essential PUs (at least 50% and 75% of selection frequency) of the "final features" scenario.

Terrain variables representativity in selected priority areas

Depth, slope and Bathymetric Position Index (BPI) are proxies for seafloor heterogeneity that drives habitat diversity. The slope indicates the steepness of depth variations: from relatively flat areas with low value (abyssal plains, shelf) to steep areas with high values typical of seamounts, canyons and the transition between continental margin and oceanic plate in general. The BPI compares the depth of each location to the mean depth of a specified neighbourhood around that location: positive BPI values are related to locally higher areas (ridges, peaks), and negative ones denote locally lower areas (valleys or troughs).

Increasing the selectivity of the PUs tended to narrow down the distribution of depth values towards shallower depths, exclude the flatter areas and exclude the most extreme BPI values (Figure 47). The median slope and BPI as well as their quartiles remained relatively unchanged (Figure 47).

These results show that prioritisation slightly favoured conservation areas comprising shallower zones, and zones displaying steep slope. This agrees with the main priority areas identified: the continental margins' slopes consisting in steep slopes and canyons, and the Mid-Atlantic Ridge comprising slopes especially on seamounts and fracture zones. These results appear more clearly when looking at the dispersion of the three terrain variables within the 13 provinces of the basin (Appendix 7). For deep provinces (depth >= 800m), shallower areas were favoured, and vice versa for shallow provinces (depth < 800m): thus the transition zones between deep and shallow habitats were favoured. Slope and BPI were generally higher within priority areas selections (Appendix 7).

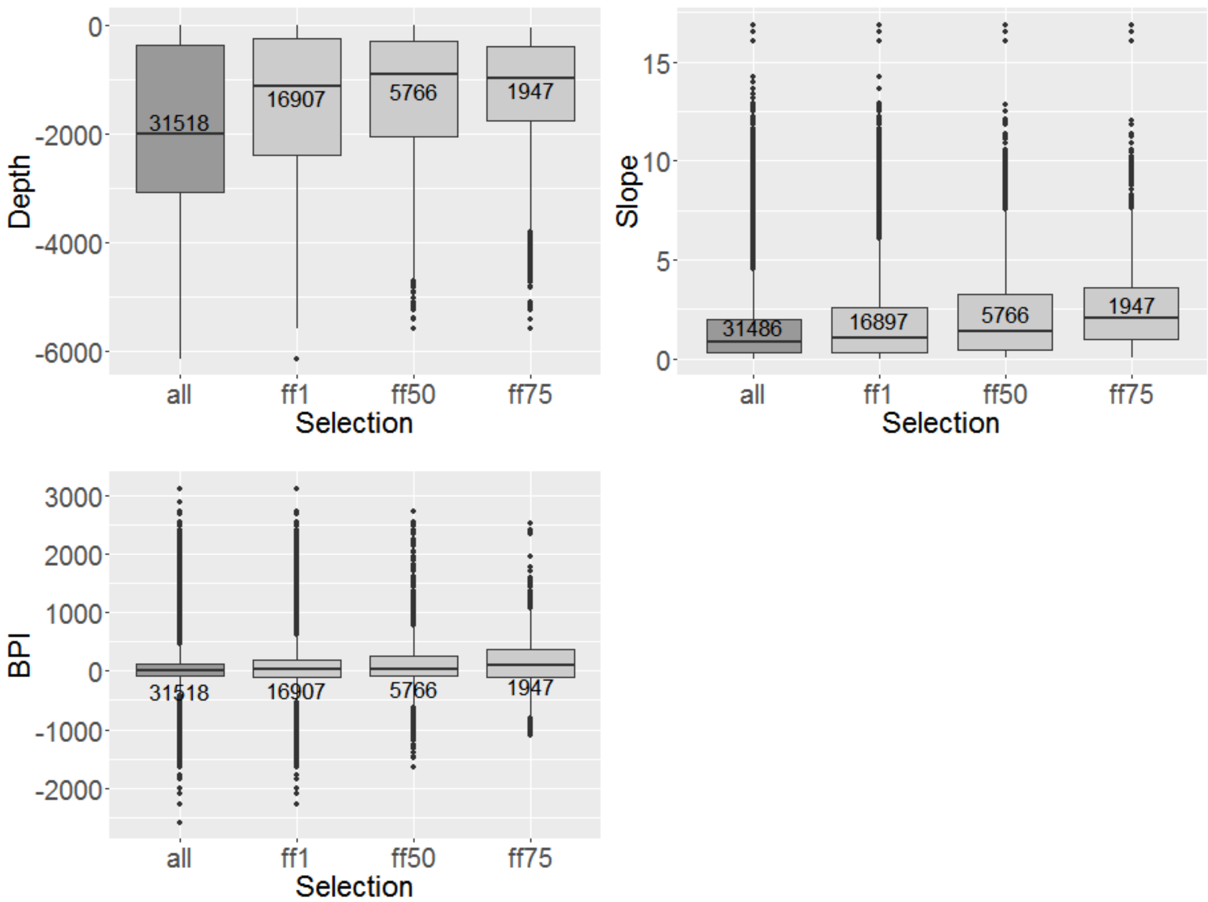

Figure 47. Dispersion of the three terrain variables according to the PUs selection. all: all planning units; ff1, ff50, ff75: selections of contributing (at least once), significant (at least 50% selection frequency) and essential (at least 75% of selection frequency) PUs in the "final features" scenario. The number of PUs in each selection is provided with the corresponding box.

4.5.5 Regionalisation

The regionalisation approach ensured that prioritisation solutions were spatially balanced across the basin. This changed the general aspect of the "all species" scenario output, by identifying priority areas in central and southern parts of the North Atlantic that were underrepresented before (Figure 42). For scenarios displaying habitats or species and habitats, the broad allocation of conservation areas was not influenced by regionalisation, because the distributions of features were already covering each province of the basin (Figure 43, Figure 44 and Figure 45). However, regionalisation balanced the selection frequencies between regions, reducing the contrast between units with high and low contribution to solutions.

Provinces representativity in selected priority areas

The importance of the different provinces for conservation was assessed by comparing, for the "final features" priority areas, their proportion of inclusion (Appendix 3) and the coverage of their contribution (Figure 20). Selection of provinces varied according to their location. Two northern shallow provinces (depth <800m) were highly selected relatively to others: the "shallow 1" along Greenland, Iceland and Norway (up to 46% of the province selected), and the "shallow 5" along Canada and Greenland (up to 32%, Appendix 3). These two provinces, which covered 15% of the study zone, contributed to almost one-third of the PUs selected within the "final features" priority areas (Figure 48). Two other northern provinces with deeper depths (>800m) were sparsely selected, always at less than 10%: the "deep 2" on the northern part of the Mid-Atlantic Ridge, and the small "deep 8" province in Baffin Bay that also contributed the least to PUs selections (Figure 48, Appendix 3). The southern shallow provinces as well provided low contribution to PUs selections ("shallow 3" along United-States and the Gulf of Mexico and "shallow 4" along the Mediterranean, Figure 48).

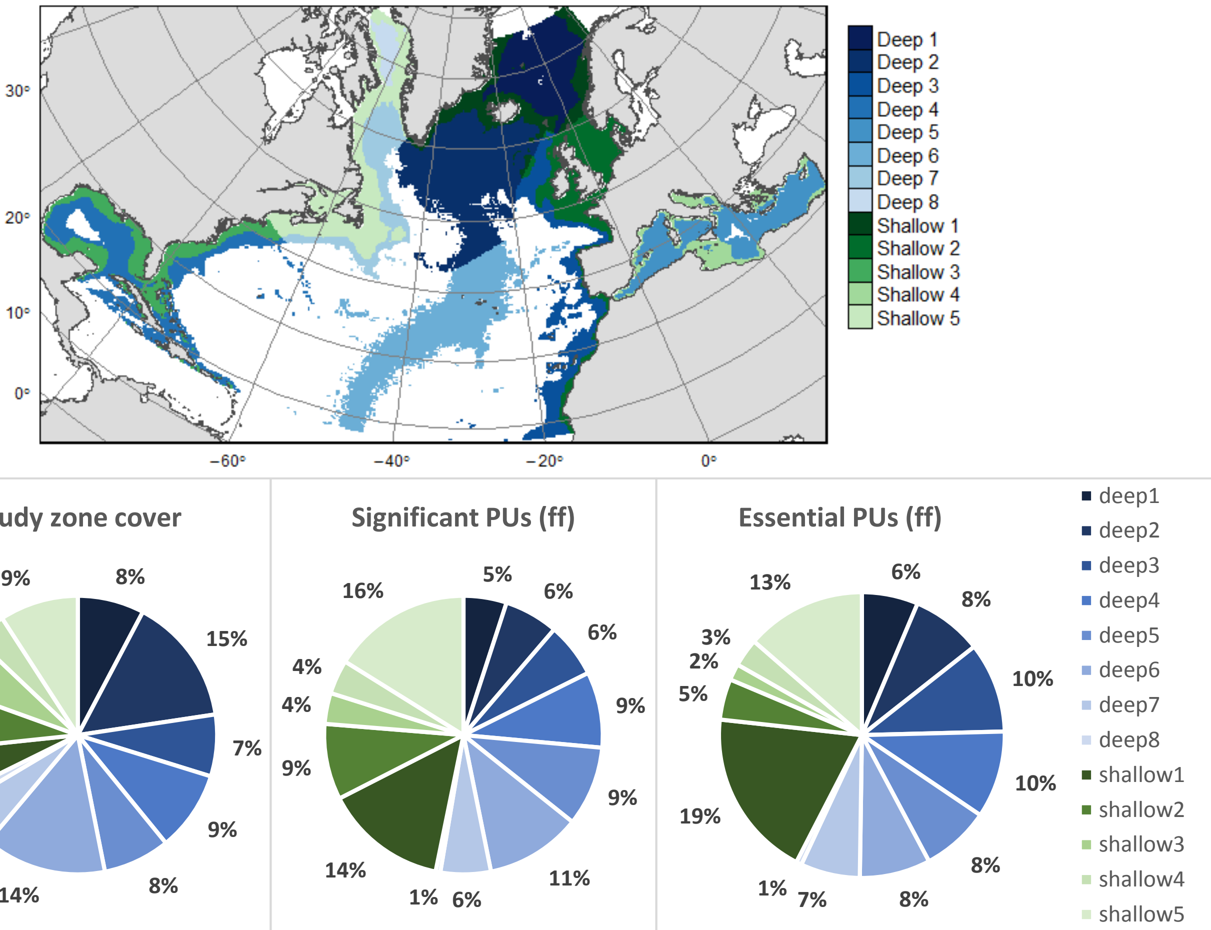

Figure 48. Map of the 13 provinces (top) and distribution of the 13 provinces within the PUs selections (bottom): on all the study area (at right), in significant PUs (at least 50% of selection frequency, in the centre) and in essential PUs (at least 75% of selection frequency, at left) for the "final features" scenario.

Scenarios including the regionalisation provided more exhaustive results, because the conservation planning was forced to cover, for each feature, the whole extent of its distribution. Such consideration can have a great importance for species conservation, because it prevents overlooking some species' phenotypes and/or genotypes, that usually are spatially structured. As such, using the regionalisation as a *proxy* of their likely distribution (although often poorly known) increases the chance that they may be represented within the selected conservation units. Intraspecific diversity aspects, such as genetic diversity and gene flow, are needed to ensure the efficiency of conservation measures and networks (Laikre et al., 2010), as this contributes to both connectivity and species adaptability (Gugerli et al., 2008; Hanson, Fuller, & Rhodes, 2019; Keller et al., 2015). As such detailed data is not available for deep-sea species at the large spatial scale targeted here, the regionalisation approach is an indirect approach desirable to account for the intraspecific diversity.

Finally, as conservation objectives were replicated according to provinces, the “regional” scenarios displayed an enhanced network replication in their conservation areas. Their geographically balanced results may prove more relevant to regional management, because they located the potential conservation areas within each region.

4.5.6 Connectivity

Connectivity was included in this work as a preliminary exercise. Very few algorithm, most of them rather recent, exist to include connectivity in prioritisation. At this large scale, such algorithm requires an extremely long computation time, resulting in fewer solutions (as most runs exceeded the time limit for computation). Moreover, the oceanographic model used has a high resolution (required for larvae trajectories), but performs on a more restricted area than the one aimed at in this work. This part is thus a preliminary exploration of the extent of change that may be expected when accounting for population connectivity in such spatial conservation exercise.

The scenario without connectivity displayed a similar output to the “all features” one, with a more scattered aspect due to the increased PUs cost (Figure 45, Figure 49). Replacing the boundary penalty by the connectivity penalty did not change the broad priority areas. Although two different larvae strategies were modelled to create the connectivity matrices of the 20-days and 80-days PLD scenarios, both scenarios displayed a similar output, in which selected areas formed a continuous and dense conservation network (Figure 50, Figure 51). However, the use of connectivity did not increase the number of PUs in solutions, ranging from 4400 to 4800 PUs for the three scenarios (Figure 49, Figure 50, Figure 51). The cost was also lower for the two scenarios with connectivity, but principally because the selection of connected PUs induced a cost reduction for those PUs. According to both scenarios, the connectivity was maximised by selecting conservation units all along margins slopes but also parts of shelf zones (northern Canada, Greenland, north of the North Sea), along the Mid-Atlantic Ridge and its Arctic prolongation, as well as in lower depth areas containing seamounts between shelves and the Mid-Atlantic Ridge (Figure 50, Figure 51).

Acknowledging that the reproduction and larval behaviour of deep-sea benthic species is largely unknown, and that oceanic models usually do not provide high resolution predictions of currents directions and velocities, larval dispersal modelling for the deep sea still lacks of precision and validation (Hilário et al., 2015). Hence, these connectivity scenarios outputs did not aim to draw a representative result for coral dispersal, but to provide insight about the most connected areas among the basin with regard to the modelled larvae PLD and oceanic circulation. According to our results, conservation units would need to be relatively close and allocated along a continuous network, deploying corridors that link the main priority areas, to optimise the conservation network connectivity. As shown here, a more connected conservation network can be achieved by prioritising PUs with high connectivity potential, without need to increase the total area of the network. Similar results have been found in the case study of Álvarez-Romero et al. (2018), in which the scenarios displaying connectivity favoured more numerous or larger reserves, in closer proximity, but with no cost increase.

Many deep-sea species are spatially fragmented and the vast majority of their dispersal relies on the pelagic larval stages (Cowen & Sponaugle, 2009; Hilário et al., 2015). Hence, using modelled larval drift trajectories in systematic conservation planning can substantially promote the viability of their populations by maintaining recruitment in the reserve network (Álvarez-Romero et al., 2018). In the North Atlantic, Kenchington et al. (2019) used a particle-tracking model to assess the performance of the NAFO's VMEs fishing closures (which design was initially performed without taking connectivity into account) to sustain benthic invertebrates populations. Their results identified possibilities of closures improvement to enhance connectivity and thus resilience of the VMEs conservation network, e.g. by extending closures or creating new closures in zones that are likely sources of recruitment for the considered species, but currently still open to fishing (Kenchington et al., 2019). Finally, prioritising highly connected networks appears crucial given the probable reduction of PLD, and thus dispersal distances, for numerous species due to global warming (Álvarez-Romero et al., 2018; Munday et al., 2009; O'Connor et al., 2007).

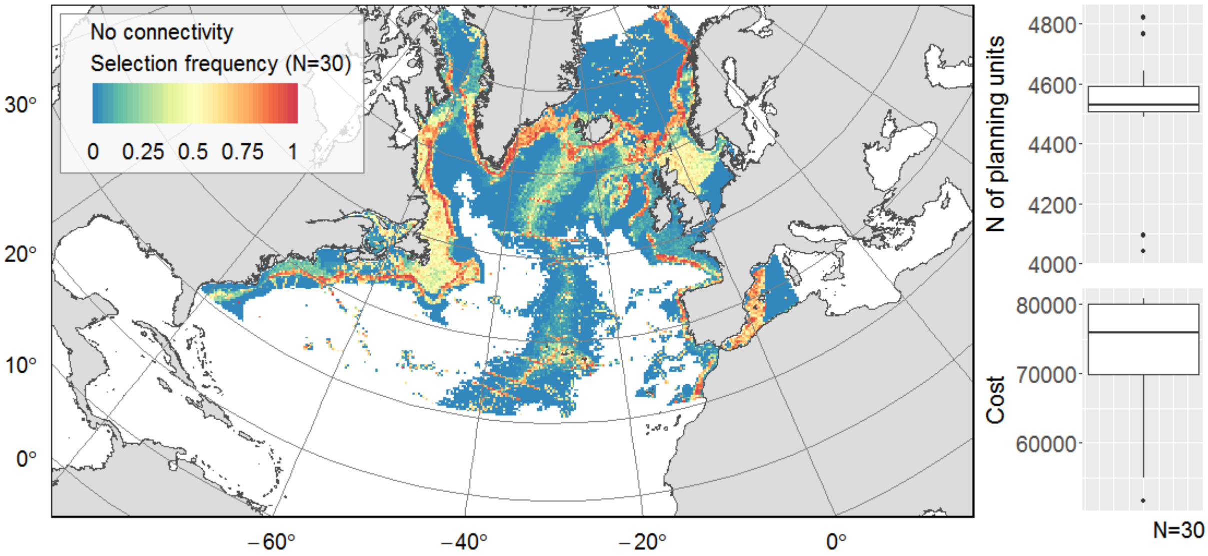

Figure 49. Output of the No connectivity scenario. Left: map of PUs' selection frequency; upper right: boxplot of the number of PUs in all solutions; bottom right: boxplot of the total cost of all solutions.

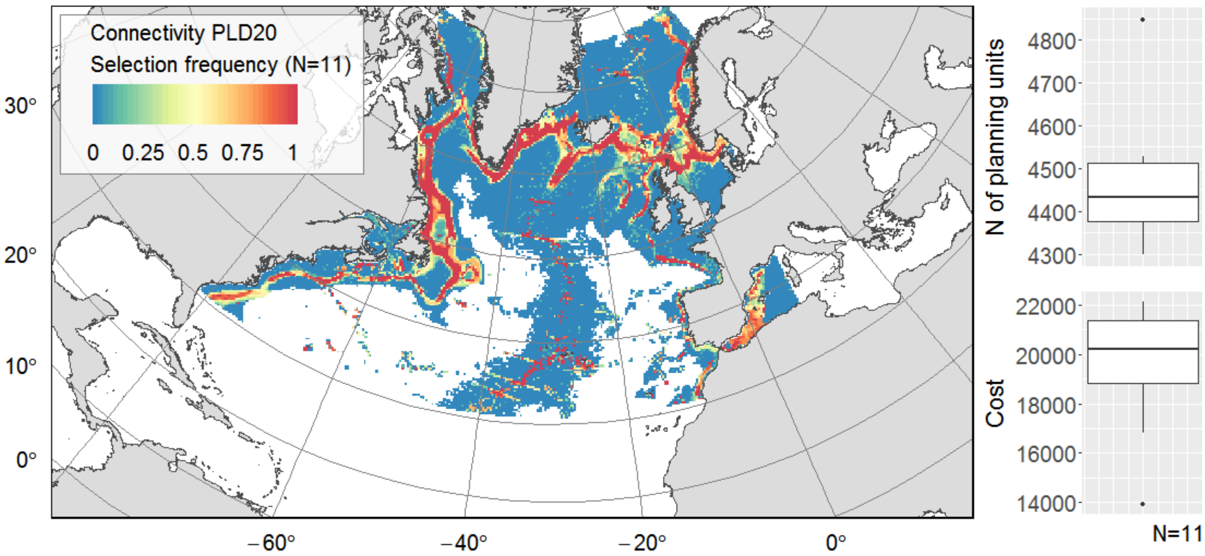

Figure 50. Output of the Connectivity PLD20 scenario. Left: map of PUs' selection frequency; upper right: boxplot of the number of PUs in all solutions; bottom right: boxplot of the total cost of all solutions.

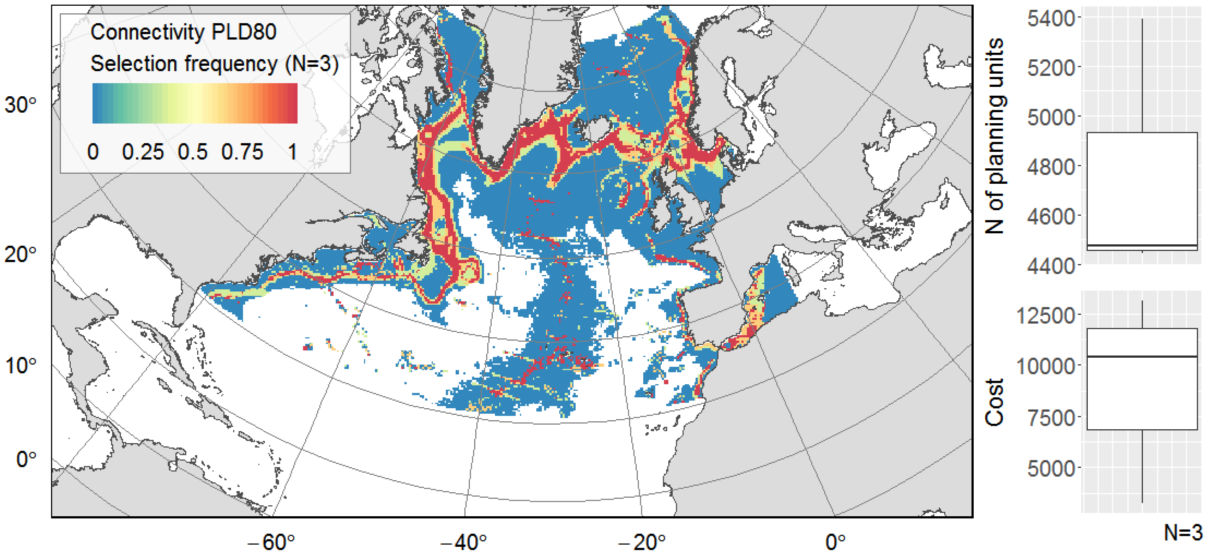

Figure 51. Output of the Connectivity PLD80 scenario. Left: map of PUs' selection frequency; upper right: boxplot of the number of PUs in all solutions; bottom right: boxplot of the total cost of all solutions.

4.5.7 Management

The "all management" scenario aimed at finding solutions for protection that minimise spatial overlap with fishing and deep-sea mining (Figure 52). Although the selection frequency varied, the broad distribution of identified priority areas remained the same than for the "final features" scenario (Figure 45, Figure 52). When using the management costs, less PUs were selected in general, but the number of highly selected units (>75% of selection frequency) increased (Table 21): solutions focused on the set of planning units that highly contributed to the conservation objective and particularly the ones that had the lower cost. Here, management costs and constraints acted as an adjustment of PUs selection, modulating selection frequencies on localised areas, whereas the features distribution and conservation targets were, and should always be, the main driver of conservation areas identification.

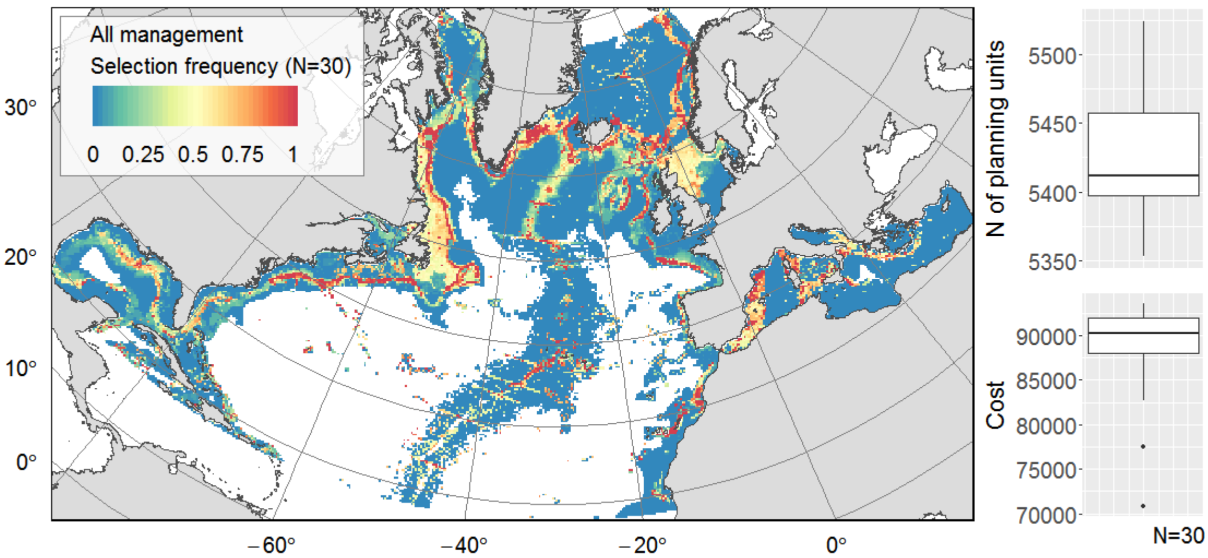

Figure 52. Output of the All management scenario. Left: map of PUs' selection frequency; upper right: boxplot of the number of PUs in all solutions; bottom right: boxplot of the total cost of all solutions.

Current protection measures VS selected priority areas

In the “final features” and “all management” scenarios, the contributing PUs (selected at least once), significant PUs (selected at least in 50% of solutions) and essential PUs (selected at least in 75% of solutions) depict priority areas for protection measures. The contributing PUs show that 37% (“all management”) to 54% (“final features”) of the study area may contribute to fulfil the conservation objective (Table 21). For both scenarios, significant PUs covered approximatively 17% of the study area (Table 21, Figure 53). This corresponds to a relatively high conservation goal for the ocean, similar to the current amount of conservation designation in EEZs (17% globally, UNEP-WCMC and IUCN 2019). When only focusing on essential PUs, the proposed priority areas covered from 6% to 8% of the study area (Table 21), slightly under the Aichi objectives of 10% (target 11, CBD/COP10), but higher than what is currently protected in ABNJ (2% globally, UNEP-WCMC and IUCN 2019).

Table 21. Number of selected planning units in function of scenario and PUs selection. Contributing; Significant; Essential PUs: selected at least once; in 50% or in 75% of selection frequency.

Scenario	Selection	N of PUs	Relative cover (%)
Final features	Contributing PUs	16907	53.64
	Significant PUs	5766	18.29
	Essential PUs	1947	6.18
All management	Contributing PUs	11756	37.3
	Significant PUs	5349	16.97
	Essential PUs	2612	8.29

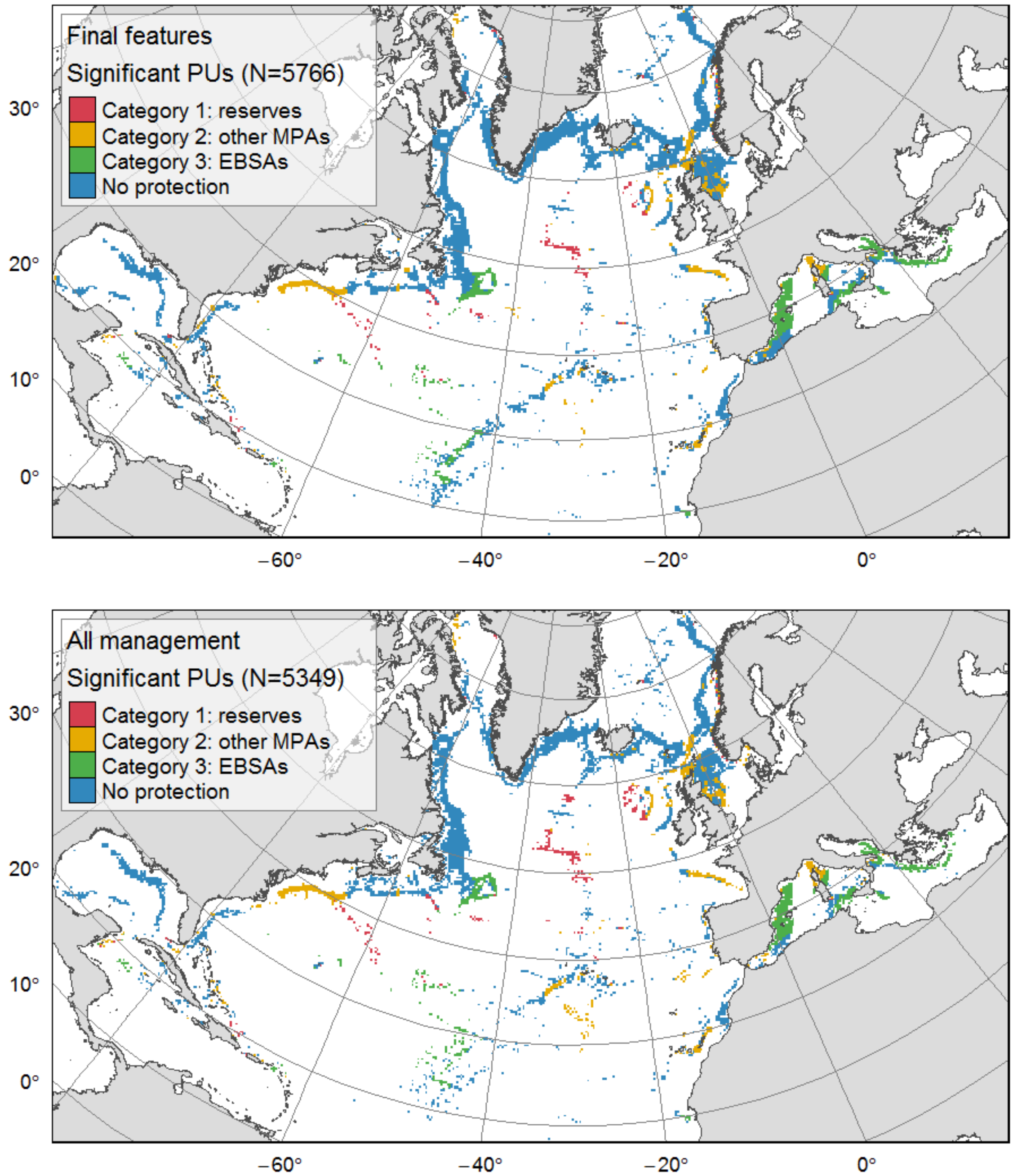

Figure 53. Maps of the priority areas delineated with the significant PUs (at least 50% of selection frequency): for the "final features" scenario (top) and the "all management" scenario (bottom). The 4 colour categories display the presence of current protection designations: fishing closures and marine reserves (category 1), other MPAs with lower protection level (category 2), EBSAs (category 3), and no protection. The 3 ABMTs categories (red, orange, green) represent respectively 20.4% and 24.7% of the "final features" (top) and the "all management" (bottom) significant PUs.

Comparing the "final features" (Figure 17, but see Figure 53 for priority areas) output to the "protection" (Appendix 6 Figure 44) and "all management" (Figure 52, but see Figure 53 for priority areas) ones allowed to assess the effects of including currently designated ABMTs as costs. A cost decrease in areas already benefiting from some form of protection mainly increased the selection of PUs in ABNJ areas relatively to other areas, especially where fishing closures were present (e.g. for NAFO regulatory area: Flemish Cap, New England and Corner seamounts; for NEAFC regulatory area: middle Mid-Atlantic Ridge in the OSPAR MPA, Northern Mid-Atlantic Ridge, Hatton bank, see Figure 36 for fishing closures locations). In EEZs, the selection frequency of already protected planning units also increased, principally around British Isles, Caribbean islands, the United-States, the Norwegian and the Northern Mediterranean coasts where MPAs were present (Figure 52, Appendix 6 Figure 44). Hence, in the "all management" scenario, the contribution of protected areas and EBSAs to solutions was enhanced: the representativity of fishing closures and reserves in essential PUs was multiplied by 3, and that of other MPAs (i.e. with lower protection) and EBSAs almost doubled (Appendix 4).

Areas already designated as priority for conservation totalised 17.7% of the study area, of which 10.6% are MPAs and 7.1% are EBSAs (Appendix 4). Between 20% and 30% of the "final features" and "all management" significant PUs (Figure 53) or essential PUs (Appendix 8) were already falling into ABMTs designations. That corresponds, when returning to the study area scale, to between 1.3% and 4.2% of the study area already targeting the priority areas for benthic deep-sea ecosystems (Figure 54). Fishing closures and marine reserves cover only 3% of the study area (Appendix 4). Significant or essential PUs overlapping with these areas, for which enforcement is in place, never exceeded 1% of the study zone (Figure 54), principally distributed in high seas fishing closures (Figure 53). When looking at specific features, the current fishing closures and reserves covered from 0% to 12% of their distribution, with an average protection of 3% (Appendix 2). For instance, less than 3% of the canyons, the unequivocal VMEs, and the climate refugia of 10 species benefit nowadays from some level of protection (Appendix 2). This proportion appears largely insufficient with regards to conservation stakes for benthic species and to global protection goals. These results agree with the previous study of Evans et al. (2015), which highlighted the lack of efficiency and representativity of the current MPA network for conserving the deep-sea habitats of the Northeast Atlantic. The study of Johnson et al. (2014) also assessed the degree of ecological coherence within the Northeast Atlantic MPA network, mainly concluding that the current MPAs in the OSPAR maritime area comported spatial gaps, for instance between Norway, Greenland and the Svalbard, and lacked of representativity with under-representation of bathyal (200–3000 m) and abyssal depths (3000–6000 m), but also of certain types of habitats. Finally, even the fishing closures designated by RFMOs may not be fully efficient at preserving benthic biodiversity, because some identified important areas have not been closed or just temporary, closures have been implemented in places considered as unfishable, and the creation of closure is generally implemented outside of the fishing footprint (i.e. the fished areas) (Wright et al., 2015). Although RFMOs closures, as well as other sectoral protected areas (e.g. from ISA), implement conservation measures, these are not legally designated as MPAs, not necessarily permanent, and less recognised than MPAs. Hence, only strongly protected MPAs (IUCN categories Ia and Ib) really ensure protection of biotopes, and less constraining or temporary measures are of little benefit in regards to the vulnerability of these habitats and the recovery time needed after harmful human impacts.

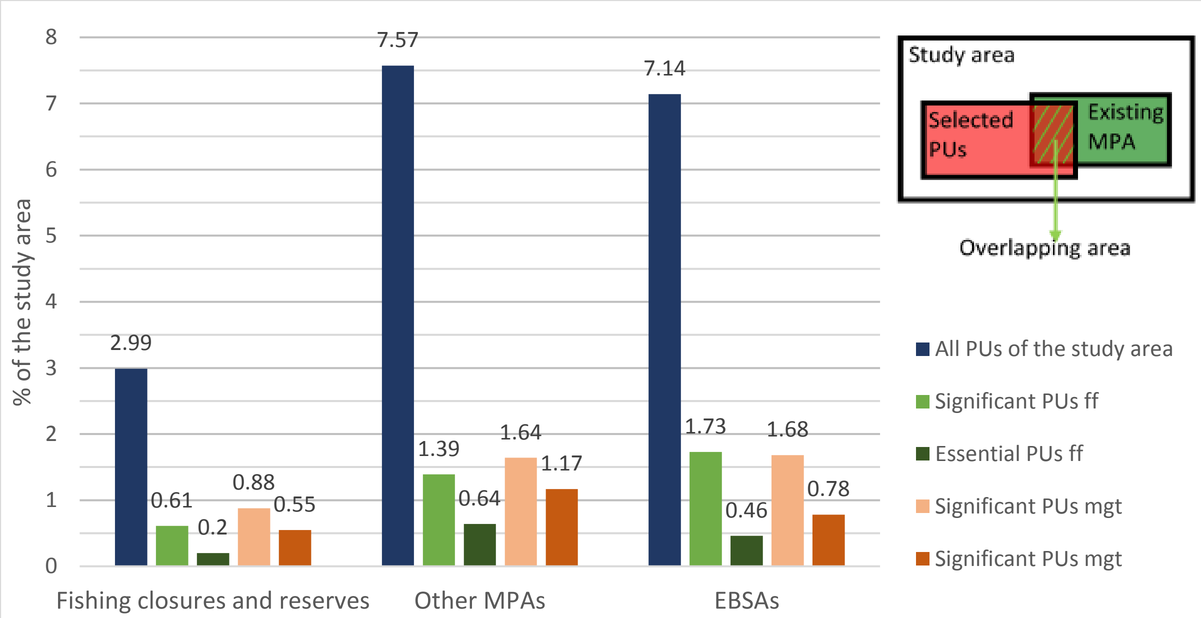

Figure 54. Proportion of the study area belonging to protected areas and included in PUs selections: in all the study area and in the significant PUs (at least 50% of selection frequency) and the essential PUs (at least 75% of selection frequency,) of the "final features" (green) and "all management" (orange) scenarios. Each bar corresponds to the area of the overlapping area (top right scheme) divided by the total study area (expressed in %).

Reconciling human activities and conservation objectives

The increase of cost indexed to fishing catch, which was generally distributed along coastal areas and mostly over large shelf areas (the North, Irish and Celtic Seas; the Newfoundland, Nova Scotia and northern United-States shelf, Figure 37), reduced the selection frequency of these zones but did not exclude them from conservation solutions because they held significant potential for demersal fish conservation (Figure 52, Appendix 6 Figure 45).

Indeed, in "final features" and "all management" solutions, median fishing catch values in selected PUs appeared to be higher than those of the whole study zone value (Figure 55). This highlighted that important fishing areas are located in irreplaceable priority areas. Using the management costs, incurring high costs for fished PUs, resulted in stabilising the fishing catch values in the solutions but around a relatively high median (Figure 55). This supports the idea that fishing grounds were needed to reach the conservation objectives and thus that fished PUs could not be left out of solutions. Further, this strongly suggests that protecting some fishing grounds may have a consequent spill over effect on areas that will not be closed to fishing, thus possibly compensating for the apparent loss of catch due to fishing closure.

Indeed, bottom fishing targets several of the species included in this prioritisation, and occurs on most of the areas where they are distributed. The prioritisation results suggest that conservation of these species could not be achieved without including fished areas. Conservation measures implemented on fishing grounds, for example by operating spatial or temporal fishing restrictions, can replenish the species' stocks and therefore support a sustainable fishery (Worm et al., 2009), process that is in place for instance in the North-East Atlantic and showed remarkable results on hake or flatfish (Baudron & Fernandes, 2015; Zimmermann & Werner, 2019). However, recovery of collapsed stocks can take considerable time even after fishing restrictions. For example, the Atlantic Cod populations, in the EEZs of the North Sea, Irish sea and also on the Canadian shelf, are likely to show a discontinuous dynamic, i.e. a more difficult and slower recovery than previously expected by recovery plans (Kelly, Codling, & Rogan, 2006; Kraak et al., 2013), in response to interacting exploitation and climatic drivers (Sguotti et al., 2019). In this configuration, strong restriction measures such as full closures of areas can play a substantial role for conservation efficiency (Kincaid & Rose, 2017). Within NEAFC and NAFO jurisdictions, several limitations for deep-sea fishes are in place, such as catch limitations (e.g. Grenadiers, Atlantic cod, American Plaice, Greenland halibut, redfish i.e. *Sebastes* genius), minimum fish size (e.g. Atlantic Cod, Greenland halibut, American Plaice, Yellowtail flounder), seasonal closure (e.g. blue Ling) (NAFO, 2019; NEAFC, 2017, 2019b, 2019a).

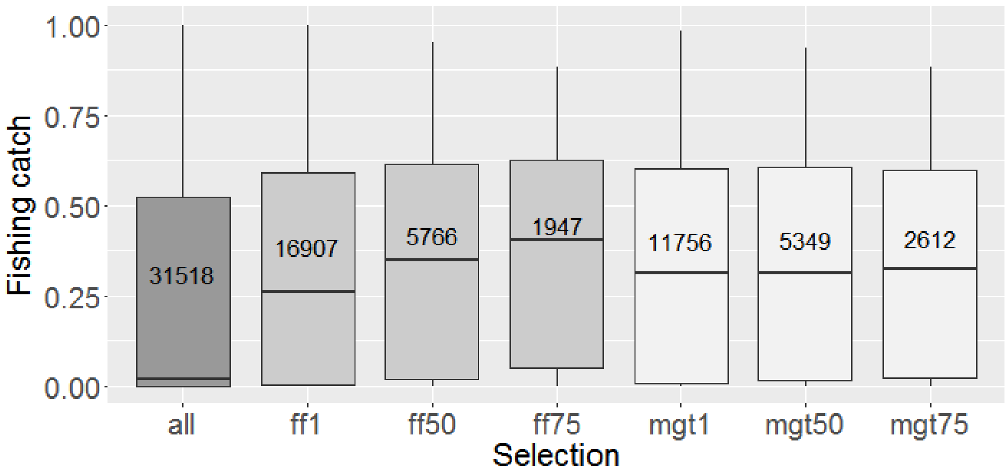

Figure 55. Dispersion of the fishing catch index (log of fishing catch +1, rescaled between 0 and 1) according to the PUs selection. all: all planning units; ff1, ff50, ff75: selections of contributing (at least once), significant (at least 50% selection frequency) and essential (at least 75% of selection frequency) PUs in the "final features" and "all management" scenarios. The number of PUs considered in each selection is provided within the corresponding box.

Removing areas already pre-empted by exploration contracts for massive sulphides from conservation solutions did not change the general output (Appendix 6 figure 46). This rather shifted fracture zones and seamounts' conservation areas northward, principally south to the Azores, to counterbalance the loss of conservation capacity in exploration contracts. The identified conservation priority areas within ISA exploration contracts could inform the regional management plan to be implemented by the ISA as well as local management plans to be proposed by mining contractors in advance of the exploitation phase. The ISA indeed has a mandate to develop regional environmental management plans for the Atlantic, Indian and western Pacific Ocean as it has already been done for polymetallic nodules in the eastern Pacific (Lodge et al., 2014; Wedding et al., 2013). A strategy for the conservation of biodiversity on the Mid-Atlantic Ridge has already been proposed (Dunn et al., 2018). Due to the paucity data, spatial planning proposed so far for the management of deep-sea mining has been mainly relying on biogeochemical and physiographic proxies. The systematic conservation planning approach we have been developing may further inform ongoing efforts to design a network of marine protected areas on the Mid-Atlantic Ridge.

In addition, conservation should be encouraged within those zones with high conservation potential that are included in exploration contracts. For instance, all known hydrothermal vents south of the Azores EEZ are located in areas already pre-empted for massive sulphide exploration, as polymetallic sulphides are formed by the precipitation of dissolved metal within hydrothermal fluids when they encounter the cold water of the ocean (Fisher, Takai, & Le Bris, 2007). Hydrothermal vent communities show high rates of endemism, symbiotic association, and extreme environmental adaptation that makes them rare. Deep-sea mining for polymetallic sulphides thus represents an important threat for them (Boschen et al., 2016; Gollner et al., 2017; Van Dover et al., 2012 and 2018). Moreover, environmental impacts of deep-sea mining and the recovery potential of hydrothermal vent communities are yet unknown (Gollner et al., 2017; Niner et al., 2018). Hydrothermal communities should hence be protected in specifically designed conservation networks like the recommended CERs

(Chemosynthetic Ecological Reserves) (Boschen et al., 2016; Van Dover et al., 2012), and deep-sea mining operated with precaution and in a step-wise manner to minimise its damage on biodiversity (Niner et al., 2018).

4.6 Limitations

The 47 conservation scenarios enabled to identify priority areas for conservation for deep-sea habitats, benthic VME indicators and demersal fishes. Moreover, the variation of input features, penalties and costs in conservation problems allowed to investigate the effects of these elements on conservation solutions. However, several limitations of this approach emerged during the implementation process and must be considered to wisely use these outputs in order to inform conservation planning.

First, the results should be interpreted with caution as they only reflect the conservation possibilities for the considered features: a set of cold-water corals and sponges, of demersal fishes and deep-sea VMEs. These results mainly stand for the temperate zone or for species with a large latitude spectrum, as no exclusively arctic or tropical species were included. For instance, most of the fish species herein included are mainly or exclusively distributed in the cold-temperate areas of the Atlantic in the present-day, in a more constrained and shallower depth range than the coral species considered. Although most of fish species, from tropical to boreal ones, are predicted to move poleward with climate change (Costa et al., 2014; Fernandes et al., 2013; Fossheim et al., 2015; Nye et al., 2009), the refugia areas included in scenarios reflect the evolution of the distribution for demersal fish of the cold-temperate zone but is not representative of species currently inhabiting other latitudes. For sponges, only *Geodia barretti* was included, and as for the fishes, this species is representative of the cold-temperate and sub-arctic regions, but other sponges species likely exhibit different environmental requirements. For cold-water corals and VME habitats, attention was given to diversify their types in order to obtain comprehensive results for North Atlantic VMEs and their cold-water engineer species (scleratinians and gorgonians VME indicators, chemosynthetic ecosystems, VMEs physical supports). This slightly larger set of species already showed by itself the large variation that can be expected in the outcome and conservation priorities. Nonetheless, the results produced here are centred and therefore biaised towards northern Atlantic temperate species.

Secondly, several scenarios outputs focused on few areas and did not provide a comprehensive conservation solution. For several species, present or climate refugia prediction encompassed one or several large patches but also smaller ones (*Desmophyllum dianthus*, *Madrepora oculata*, *Paragorgia arborea*, *Geodia barretti*, *Helicolenus dactylopterus*, Appendix 6). Similarly, the VMEs features comprised continuous and extended zones (mainly corals and sponge VMEs on continental margins) together with isolated units (mainly chemosynthetic VMEs on the Mid-Atlantic Ridge, see part 4.5.3). In those cases, conservation solutions had the tendency to focus on those larger areas rather than the smaller ones, because it minimised the boundary length of solutions. This type of result, omitting part of the distribution of features, highlights that adding spatial constraints to conservation problems would be preferable in order to identify more diverse conservation areas. For instance, by gathering all the species and habitat features, more zones of the basin were included in solutions, as each feature had a different distribution (Figure 45). Yet, the conclusive way to identify comprehensive priority areas regarding features' distribution and zones of the basin consisted here in the division of all features according to the 13 created provinces, leading to a replication of the feature's conservation objective within each individual province.

Although efforts were implemented to draw comprehensive results for seabed biodiversity, the main priority areas identified also represent the most investigated areas in the basin, and thus supporting most of the data on VMEs and the considered species. For instance, the north and west Mediterranean were often selected in conservation solutions, whereas the southern and eastern part, associated to a paucity of deep-water data (both due to imbalance in the resources dedicated to research and to geopolitical reasons), were less represented. Deep-sea exploration has always displayed a directed dimension, focusing on area of interest for resources, or associated to identifiable geomorphological “anomalies” (e.g. the relief or the existence of chemosynthetic activity or high concentration of biomass), which led to an uneven quantity and quality of information across deep-sea habitats. For species, habitat suitability models are largely employed to overcome the lack of distribution data, but their results are highly reliant on the location of known species records. Whereas the identified priority areas could secure the vulnerable biodiversity where it is currently known or suspected, no assumptions can be made in areas where exploration has been neglected so far.

Another data gap is the knowledge of intraspecific diversity (i.e. genomic and physiological data) to appraise the species capacity to adapt to forthcoming environmental change, either through phenotypic plasticity or through genetic adaptation, susceptible to modify predictions for future habitat shifts and refugia location. Also, few is known about the reproductive cycle of most species, making it difficult to predict the changes in connectivity patterns under climate change.

Concerning the parametrisation of scenarios, it should be noted that costs and boundary or connectivity penalties were calibrated in relation to the features considered, and that they influenced greatly the results. While this calibration was chosen after a testing and optimisation phase, the results remain highly dependant on these parameters which themselves are not absolute values (e.g. the costs were based on several sources of information and do not represent a fixed expenditure). Scenarios with connectivity input were particularly difficult to calibrate. The results highly relied on the penalty value, and the calculation times were extremely long, leading to few optimal solutions. Moreover, these connectivity scenarios were implemented on a smaller study area. Hence, the connectivity aspect was not included in the “all management” scenario and the connectivity outputs were interpreted with caution.

Finally, as exposed in part 4.5.4, interpretation of selection frequencies in order to select priority areas must be done cautiously, by assessing if the proportion of the features in the PUs selection is sufficient in regard to the chosen targets. Moreover, if a varying cost is applied, the total cost of a PUs selection based on several solutions can differ, and be substantially higher, than each solution’s cost.

4.7 Conclusion

To our knowledge, this study is the first in systematic conservation planning to address the conservation of deep-sea benthic and demersal biodiversity across a whole oceanic basin. The spatial prioritisation approach developed in the present deliverable allowed to identify conservation priority areas for deep-sea VMEs, their cold-water corals or sponge engineer species, and demersal fish species with conservation stakes. In particular, continental margin slopes, the Mid-Atlantic Ridge, and shelf areas comporting fishing grounds appeared as crucial zones for preserving deep-sea biodiversity. These identified areas comprised specific habitats (e.g. canyons, ridges, seamounts) that are known to represent hot-spots for deep-sea benthic and demersal species. Finally, the delineated priority areas could benefit to the conservation of species and ecosystems beyond just the seabed, as VMEs hold high functional capacities, related for instance to fish species dynamics (Baillon et al., 2012; Pham et al., 2015) or ocean functioning such as the carbon pump (Soetaert et al., 2016), all of which ultimately translate into ecosystem services for humankind (Thurber et al., 2014).

Through the use of a large range of data types and spatial constraints, the identified conservation areas present a relatively good ecological coherence following its five definition criteria: representativity, adequacy, viability, connectivity and replication (Ardron, 2008; Johnson et al., 2014).

Representativity was built upon the conservation objectives of the ATLAS project, thus focusing on benthic and demersal biodiversity, but still encompassing various species, ecosystems and habitats. Although adequacy was not assessed, the features' conservation targets were assumed as adequate because they were attributed upon the features distribution cover, increasing those of rare features, and remained high in general (above 30%). Viability was specifically addressed by the use of 13 species climate refugia among the 24 features of scenarios, enabling the solutions to select areas of high resilience towards climate change. Different approaches were used to consider connectivity: the boundary penalty which acted on the clumping of conservation solution networks, and a finer approach using modelled benthic larvae exchange rates as a *proxy* to hydrodynamic connectivity. Even if the later could not be included in final scenarios, it highlighted that a more continuous conservation network, displaying spatial corridors linking conservation areas or at least, shorter distances between those areas, would result in a more connected and thus resilient benthic conservation network. Finally, replication was systematically fulfilled over the 13 delimited provinces with the use of a regionalisation approach adjusting the conservation units' allocation across the basin. Hence, this work attempted as best as it could, to delineate an ecologically coherent conservation network, with substantial resilience potential to future environmental changes.

The results of this deliverable represent a basis for reflection on future management planning for the North Atlantic basin, and especially its high seas. Marine Spatial Planning for large marine areas such as ABNJ has been increasingly debated in international negotiations, but still lacks of a coordinated framework between the different regional authorities and sectoral bodies (Ardron et al., 2014; Ban et al., 2014; Wright et al., 2019). The present prioritisation exercise contributes to the development of systematic approaches for such MSP (Ban et al., 2014), by mapping the important areas for deep-sea biodiversity of a whole oceanic basin. While protection measures in ABNJ have generally been designed incrementally, by protecting well-known important areas, an then adding other areas to enhance conservation (Ardron et al., 2014), such systematic and evidence-based approach as the present can lead to more representative and efficient protection networks (Evans et al. 2015, Wedding et al. 2013, Johnson et al, 2014).

Our systematic planning exercise has shown that, as important as they are, the sum of all ABMTs of the northern Atlantic still suffer from a lack of efficiency, representativity and viability. Few climate refugia for example benefit from some form of protection. Our results support the conclusions of Johnson et al. (2018) that climate change pressures are likely to largely affect deep-sea oceanography and biodiversity, and thus the ability of current ABMTs to preserve them. In the case of sessile species, recommendations encourage "to reduce or eliminate other stressors (such as fishing, shipping, mining, bioprospecting, etc.) to reduce the cumulative stress on these organisms while they respond to their changing environment" (Johnson et al., 2018). The protection of the priority areas herein identified, together with a precautionary approach adopting high restrictions of human use impacts, could inform a more resilient conservation framework for the North Atlantic. Finally, these results may prove useful as they represent a scientific evaluation that may inform the designation of new fishing closures by RFMOs, of bottom MPAs by ISA, of MPAs with effective bottom protection inside EEZs but also in ABNJ where a MPA network started to emerge (O'Leary et al., 2012).

4.7.1 Link with Marine Spatial Planning of ATLAS case studies

Prioritisation results will be provided to ATLAS WP6 to inform local spatial planning within case studies.

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