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North Atlantic Basin-Scale Multi-Criteria Assessment Database to Inform Effective Management and Protection of Vulnerable Marine Ecosystems

Telmo Morato^{1,2*}, Christopher K. Pham^{1,2}, Laurence Fauconnet^{1,2}, Gerald H. Taranto^{1,2}, Giovanni Chimienti^{3,4}, Erik Cordes⁵, Carlos Dominguez-Carrió^{1,2}, Pablo Durán Muñoz⁶, Hronn Egilsdottir⁷, José-Manuel González-Irusta^{1,2,8}, Anthony Grehan⁹, Dierk Hebbeln¹⁰, Lea-Anne Henry¹¹, Georgios Kazanidis¹¹, Ellen Kenchington¹², Lenaick Menot¹³, Tina N. Molodtsova¹⁴, Covadonga Orejas¹⁵, Berta Ramiro-Sánchez^{11,16}, Manuela Ramos^{1,2}, J. Murray Roberts¹¹, Luís Rodrigues^{1,2}, Steve W. Ross¹⁷, José L. Rueda¹⁸, Mar Sacau⁶, David Stirling¹⁹ and Marina Carreiro-Silva^{1,2}

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*Correspondence:

Telmo Morato
t.morato@gmail.com

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¹ Okeanos Research Centre, Departamento de Oceanografia e Pescas, Universidade dos Açores, Horta, Portugal, ² Departamento de Oceanografia e Pescas, Instituto Do Mar, Universidade dos Açores, Horta, Portugal, ³ Department of Biology, University of Bari Aldo Moro, Bari, Italy, ⁴ Consorzio Nazionale Interuniversitario per le Scienze del Mare, Rome, Italy, ⁵ Department of Biology, Temple University, Philadelphia, PA, United States, ⁶ Centro Oceanográfico de Vigo, Instituto Español de Oceanografía, Vigo, Spain, ⁷ Marine and Freshwater Research Institute, Hafnarfjörður, Iceland, ⁸ Centro Oceanográfico de Santander, Instituto Español de Oceanografía, Santander, Spain, ⁹ Earth and Ocean Sciences, National University of Ireland Galway, Galway, Ireland, ¹⁰ MARUM - Center for Marine Environmental Sciences, University of Bremen, Bremen, Germany, ¹¹ School of GeoSciences, Grant Institute, University of Edinburgh, Edinburgh, United Kingdom, ¹² Bedford Institute of Oceanography, Fisheries and Oceans Canada, Dartmouth, NS, Canada, ¹³ L'Institut Français de Recherche pour l'Exploitation de la Mer, EEP/LEP, Centre de Bretagne, Plouzané, France, ¹⁴ P.P. Shirshov Institute of Oceanology Russian Academy of Sciences, Moscow, Russia, ¹⁵ Centro Oceanográfico de Baleares, Instituto Español de Oceanografía, Palma, Spain, ¹⁶ Lab. Biologie des Organismes et Ecosystèmes Aquatiques (BOREA), Centre National de la Recherche Scientifique, Muséum National d'Histoire Naturelle, Institut de Recherche pour le Développement, Sorbonne Université, Université de Caen Normandie, Université des Antilles, Paris, France, ¹⁷ Center for Marine Science, University of North Carolina at Wilmington, Wilmington, NC, United States, ¹⁸ Centro Oceanográfico de Málaga, Instituto Español de Oceanografía, Málaga, Spain, ¹⁹ Marine Laboratory, Marine Scotland Science, Aberdeen, United Kingdom

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INTRODUCTION

The identification of areas that fit the Food and Agriculture Organization of the United Nations (FAO) criteria to define what constitutes a Vulnerable Marine Ecosystem (VME) has been the main policy driver for the protection of deep-sea environments in Areas Beyond National Jurisdictions (United Nations General Assembly, 2006; FAO, 2009) in relation to bottom fisheries. At the same time, the Convention on Biological Diversity advocates for the implementation of representative networks of Marine Protected Areas (MPAs) in the open ocean and the deep sea, and calls for the identification of Ecologically or Biologically Significant marine Areas (EBSAs; Convention on Biological Diversity, 2008, Decision IX/20). Although VMEs and EBSAs are conceptually different, Ardron et al. (2014) argue that the designation of VMEs, EBSAs, and large open-ocean MPAs should be aligned to ensure that VMEs are incorporated within area-based management tools.

The International Council for the Exploration of the Sea (ICES) adopted a Multi-Criteria Assessment (MCA) methodology for informing the identification of VMEs in the North-East

Atlantic (ICES, 2016a,b; Morato et al., 2018). The MCA is a taxa-dependent spatial method that incorporates the fact that not all VME indicators are equally vulnerable to human impacts, and thus should not be weighted equally. By including a measure of the confidence associated with each VME record, this methodology also considers some of the uncertainties associated with the sampling methodologies, the reported taxonomy, and data quality issues. Equally important, it highlights areas in the North Atlantic that have been poorly sampled and that require further attention. Finally, this methodology also allows for the evaluation and comparison of VME index with spatial fisheries data that may directly generate significant adverse impacts on VMEs. Although the VME Index has been used since 2018 in ICES advice, several caveats and limitations have been identified (ICES, 2018, 2019, 2020). The main criticism refers to the fact that the VME index signals the presence of VME indicator taxa that are considered to be the most important rather than showing the likelihood of an area containing a spatially explicit VME. Also, concerns over the abundance scores adopted have been raised and it has been suggested that abundance thresholds should be defined for each VME indicator. It is, therefore, recognized that improvements of the VME index and the way actual VMEs are identified are still necessary.

The identification of representative areas that can form a network of MPAs in the deep sea requires ocean basin-scale approaches grounded on ocean basin-scale datasets. In this regard, the H2020 ATLAS project (GA 678760) performed a unique trans-Atlantic assessment of deep-water ecosystems to inform Atlantic Ocean basin-scale governance. The ATLAS project compiled the best available data on VME indicator taxa for the North Atlantic (Ramiro-Sánchez et al., 2020) in order to assist with the identification of locations that may constitute VMEs and EBSAs, as a precursor to the development of a North Atlantic wide network of MPAs. Here, we applied the ICES MCA method to the ATLAS VME indicator taxa database to produce and make publicly available a new “North Atlantic Ocean basin-scale VME index dataset,” facilitating further consultation and use by scientists, managers, or other relevant stakeholders.

DATA COMPILATION AND METHODS

The MCA VME assessment method described in Morato et al. (2018) was applied to the deep waters of the North Atlantic basin, from 18°N to 76°N and from 36°E to 98°W. This area is one of the best studied deep-water regions in the world with respect to both VMEs and fishing effort. ATLAS compiled the best available information on *bona fide* VMEs and VME indicator taxa for the North Atlantic Ocean from public databases such as the Ocean Biogeographic Information System portal¹ (OBIS), the NOAA Deep Sea Coral Data Portal², the ICES Vulnerable Marine Ecosystems data portal³, and the InterRidge

Vents Database⁴. The ATLAS VME indicator database (Ramiro-Sánchez et al., 2020), was complemented with records from existing institutional databases from the partners involved in the ATLAS project, and is currently comprised of ~455,000 records distributed in both sides of the North Atlantic: 38,400 records from the ATLAS partners, 315,000 from OBIS, 71,500 from NOAA, 30,000 from ICES, and 100 from InterRidge.

We applied the MCA method described in Morato et al. (2018) to the ATLAS VME database in order to assess and map the likelihood of presence of VMEs in the North Atlantic Ocean. This methodology aggregates data compiled from different sources to provide a spatially gridded index that combines how intrinsically vulnerable and abundant VME indicators are, along with the uncertainty associated with the gridded index. The MCA method comprised six main steps described below.

Assign a VME Indicator Score to VME Indicators

First, we adopted the VME indicator scores described in Morato et al. (2018) that assessed each of the thirteen VME indicator types (ICES, 2016b) against the five FAO criteria for defining what constitutes a VME (FAO, 2009); i.e., rarity, functionality, fragility, life-history, and structural complexity. The VME indicator scores represent a proxy for the intrinsic vulnerability of the VME indicator types to human impacts and range from low (1.48) to high (4.47).

Compile the Best Available Data on *bona fide* VMEs

Bona fide VMEs are spatially explicit areas that have been recently surveyed with video systems or other scientific trawl surveys and qualitatively identified as VMEs using local expert judgment. The areas containing *bona fide* VMEs were compiled from the ICES VME database and complemented by the ATLAS partners based on their best available information (Combes et al., 2019) and compiled from the list of known hydrothermal vents from the InterRidge Vents Database v.3.4. *Bona fide* VMEs have been described in multiple sources (Abad et al., 2007; Rengstorf et al., 2013; Kenchington et al., 2014, 2017, 2018a,b; NAFO, 2016; Rueda et al., 2016; Brooke et al., 2017; CSA et al., 2017; Hourigan et al., 2017; Van den Beld et al., 2017; De la Torre et al., 2018; Combes et al., 2019; Kazanidis et al., 2019; Ramiro-Sánchez et al., 2019; Durán Muñoz et al., 2020; MAREANO Cold water coral reefs; ICES VME dataset³) and included:

- (1) *Lophelia pertusa* and *Madrepora oculata* reefs in the Norwegian Sea, Porcupine, Rockall and Hatton Banks, the Bay of Biscay, the Gulf of Cádiz, the Davis Strait, and Cape Lookout;
- (2) sea pen communities in the Bay of Biscay, the Gulf of Cádiz, the Davis Strait, and the Flemish Cap;
- (3) cold-water coral gardens in the Gulf of Cádiz, the Azores, the Davis Strait, and Baltimore and Norfolk canyons;

¹<https://obis.org/>

²<https://deepseacoraldata.noaa.gov/>

³<http://www.ices.dk/marine-data/data-portals/Pages/vulnerable-marine-ecosystems.aspx>

⁴<https://vents-data.interridge.org/>

- (4) deep-sea sponge aggregations in the Faroe Shetland Channel, Gulf of Cádiz, the Azores, the Davis Strait, the Flemish Cap, and the Tropic Seamount, and
- (5) all known active hydrothermal vent fields, including the recently discovered Luso hydrothermal vent field in the Azores.

Assigning Abundance Score to VME Indicator Records

We adopted the abundance score methodology described in Morato et al. (2018), where records with abundance data were evaluated against VME encounter thresholds defined by NEAFC (Recommendation 19:2014 and 09:2015) and the EU (Regulation 2016/2336) for live corals (30 kg) and live sponges (400 kg). For other VME indicator taxa (e.g., anemones) the encounter threshold value defined for live corals was used. If the reported abundance was over the encounter threshold, the MCA assigned an abundance score of 5. When the reported abundance was below the encounter threshold, but above 1 kg of corals or 60 kg of sponges, an abundance score of 3 was assigned. Otherwise, a value of 1 was assigned. If no data for abundance were available, a score of 0 was allocated.

Assigning a Spatially Gridded VME Index

As described in Morato et al. (2018), the VME index combines the intrinsic vulnerability (VME indicator scores) and the abundance of the VME indicators (abundance score). The *bona fide* VMEs identified in the ATLAS VME database received the maximum VME index of 5. A VME index calculated from the VME indicator score (90% weight) and the abundance score (10% weight) was assigned to the remaining records. The VME index assigned to each VME indicator record was then aggregated to a grid of 25 × 25 km cells using the maximum VME index value per cell and assigned to three classes computed with the Jenks natural breaks classification method (Low “VME index”: <2.7; Medium: 2.7–3.7; High: 3.7–4.5).

Assigning a Confidence Index

A data confidence index associated with the “VME index” was estimated using the methodology described in Morato et al. (2018). Low confidence was given to confidence scores smaller than 0.32, medium confidence to scores between 0.32 and 0.77, and high confidence to scores > 0.77.

Assigning Portfolio Categories Based on the VME Index and Fishing Intensity

The VME index and fishing intensity of individual cells can be summarized and classified into four main categories: Low VME index–Low fishing; Low VME index–High fishing; High VME index–Low fishing; High VME index–High fishing (Morato et al., 2018). These categories can assist during the discussions toward the development of area-based management tools. We used a proxy of fishing intensity derived from the average annual catch per km² of bottom contact gears over the period 2010–2015, based on the catch data obtained from Watson and Tidd (2018). Values were then log-transformed, re-scaled between 1 and 5, and categorized as low fishing intensity (≤3.31) and high fishing

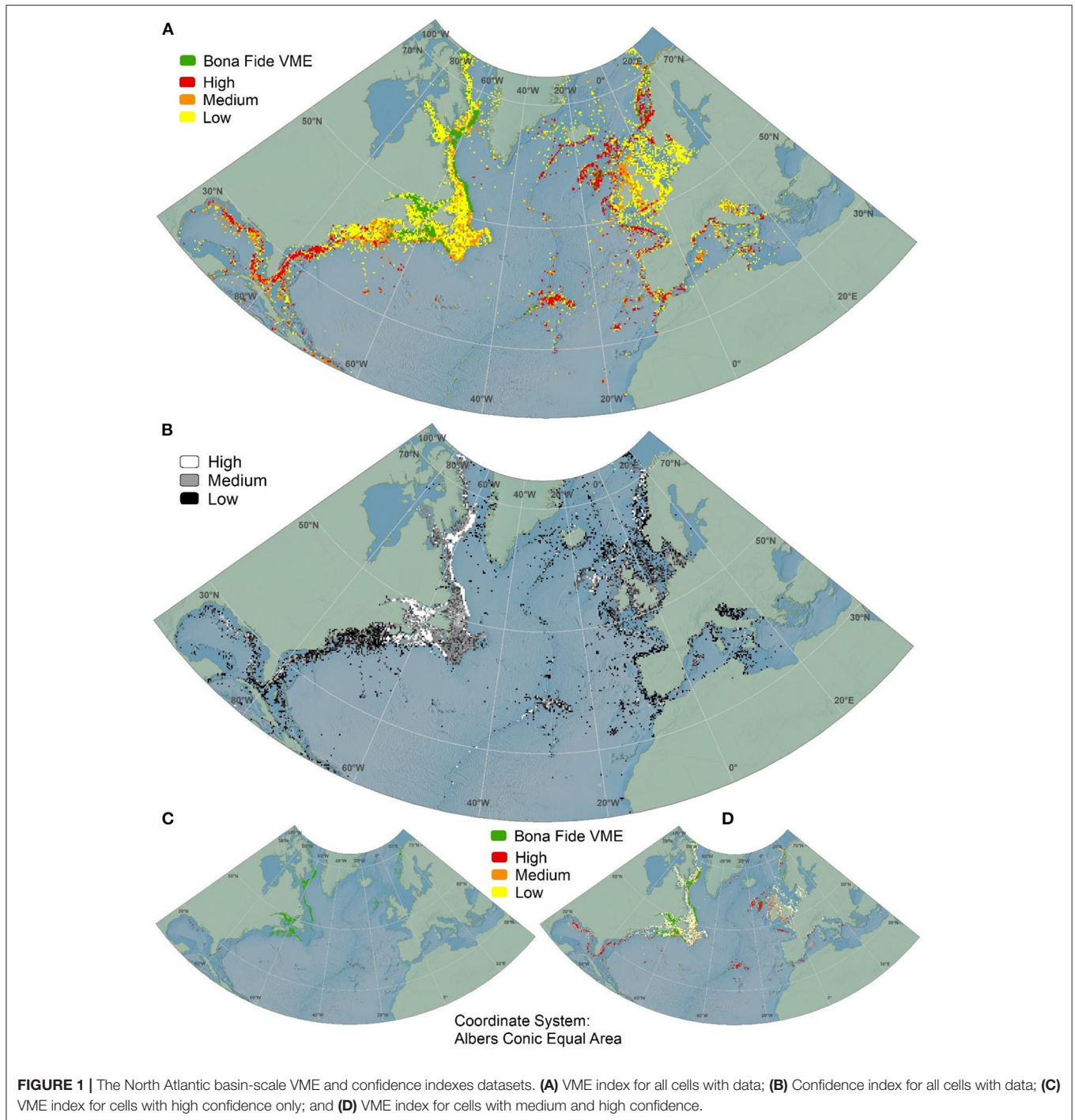
intensity (>3.31) using Jenks natural breaks. To assign portfolio categories, the adopted threshold for the VME Index was also computed with Jenks natural breaks (i.e., Low VME index ≤ 3.7 and High VME index > 3.7).

NORTH ATLANTIC BASIN-SCALE VME INDEX DATASET

The dataset presented here allowed to apply the MCA methodology developed by Morato et al. (2018) to the scale of the whole North Atlantic Ocean. The resulting basin-scale datasets of the VME Index and Confidence Index (Figure 1) and of the classification among the four portfolio categories (Figure 2) at the scale of the North Atlantic Ocean were deposited in ZENODO and are publicly available at: <http://doi.org/10.5281/zenodo.4279776>. The caveats of the MCA methodology are discussed in Morato et al. (2018). This dataset integrates the largest amount of information available on VME indicator taxa and *bona fide* VMEs for the North Atlantic. It can be used to inform deep-sea fisheries management, systematic conservation planning initiatives, or area-based management discussions, including those referred to as other effective area-based conservation measures (OECMs), at the North Atlantic basin-scale. However, this dataset also highlighted that the Eastern and Mid Atlantic are, generally, less sampled when compared to the Western Atlantic. Namely, the Mid-Atlantic Ridge beyond National Jurisdictions from Iceland down to the Azores is still one of the areas with remarked limited publicly available information. It also highlighted reduced sampling efforts in most abyssal areas. The limited coverage of the North Atlantic basin-scale VME index dataset also highlights the importance of using complementary datasets such as, for example, those produced with species distribution or habitat suitability models (e.g., Morato et al., 2020).

Although we make the North Atlantic basin-scale VME index dataset publicly available for ATLAS partners and other users, the ICES VME database should always be considered as the primary source for the VME index information since it is regularly updated with new information provided by the ICES member countries.

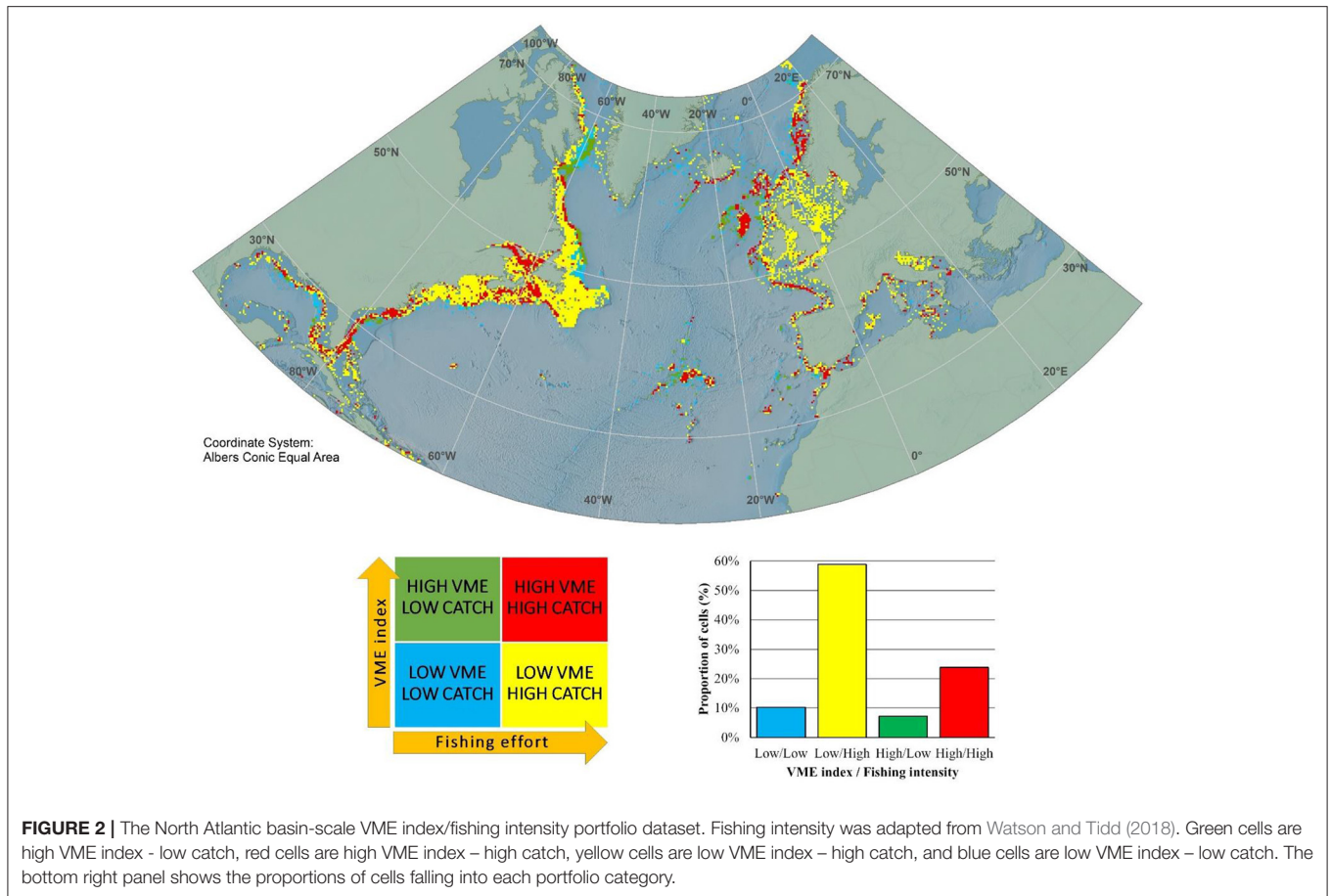
The VME index dataset (Figure 1A; Supplementary Figures 1–5) contained high numbers of VME habitats (*bona fide*) in the northeastern Canadian coast, the Gulf of Saint Lawrence and the northeastern American coast, which includes the well-known *Oculina* banks, *Lophelia pertusa* reefs, *Vazella pourtalesii* sponge grounds and sea-pen fields. The dataset also reported *bona fide* VMEs areas around Rockall Bank and along the Norwegian coast, which reflect the presence of large *Lophelia pertusa* reefs, and which have been extensively sampled. Besides the *bona fide* VMEs, the dataset also identified other areas with high values of VME index around the Florida-Hatteras slope, the Azores, the Reykjanes Ridge and southern Iceland, around the Strait of Gibraltar, in the Bay of Biscay, the Rockall and Hatton Banks, the Faroe Islands, and along the Norwegian coast. On the other hand, a high number



of low VME index areas were found in the North Sea and the English Channel, in the Irish Sea and along the shelves and slopes of the Canadian eastern coast, as well as off the northeastern American coast from the Mid-Atlantic Bight to the Gulf of Maine regions.

The VME index confidence dataset (**Figure 1B**; **Supplementary Figures 1–5**) contained mostly VME index values with low or medium confidence, highlighting a

limited sampling effort in most areas. With few exceptions, high confidence areas were restricted to *bona fide* areas (**Figures 1B,C**) and small areas in the Gulf of Mexico and around Florida, around the Azores and in the Bay of Biscay. The dataset contained medium confidence values inside the Gulf of St. Lawrence, around the Flemish Cap and the Grand Banks, along most of the Canadian coast, as well as around the UK and the Rockall Bank (**Figures 1B,D**).



The VME index/Fishing intensity portfolio dataset (Figure 2; Supplementary Figure 6) contained high catch values in most of the coastal areas of the North Atlantic, with the exceptions of the central part of the Davis Strait, north of the Flemish Cap, most of the Azores, the Denmark Strait, the southern part of the Reykjanes Ridge, the Hatton Bank and some offshore areas of the Norwegian Sea. The VME index/Fishing intensity portfolio dataset revealed a larger portion of cells categorized as Low VME index-High fishing (59%) and High VME index-High fishing (24%), with only a small portion being categorized as High VME index-Low fishing (7%). The areas where high catch overlaps with high VME index, i.e., areas of potentially significant adverse impacts, are essentially located around Florida and the Hatteras Slope, in the northeast coast of the USA, the Gulf of St. Lawrence and 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 Islands, Rockall Bank and the margin of the Bay of Biscay and the Strait of Gibraltar. However, the number of cells with high fishing catch should be considered with caution because some catch might have been incorrectly spatially allocated (Watson and Tidd, 2018), highlighting the need to make high-resolution fishing effort maps publicly available.

DATA AVAILABILITY STATEMENT

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found below: <http://doi.org/10.5281/zenodo.4279776>.

AUTHOR CONTRIBUTIONS

TMor and CP designed the work and performed the analyses. GT compiled and organized the raw data. TMor, CP, LF, and LR prepared the data report. All authors provided raw data essential for the construction of the dataset.

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SUPPLEMENTARY MATERIAL

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