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A policy-based framework for the determination of management options to protect vulnerable marine ecosystems under the EU deep-sea access regulations

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Abstract :

Vulnerable marine ecosystems (VMEs) are particularly susceptible to bottom-fishing activity as they are easily disturbed and slow to recover. A data-driven approach was developed to provide management options for the protection of VMEs under the European Union “deep-sea access regulations.” A total of two options within two scenarios were developed. The first scenario defined VME closure areas without consideration of fishing activity. Option 1 proposed closures for the protection of VME habitats and likely habitat, while Option 2 also included areas where four types of VME geophysical elements were present. The second scenario additionally considered fishing. This scenario used VME biomass—fishing intensity relationships to identify a threshold where effort of mobile bottom-contact gears was low and unlikely to have caused significant adverse impacts. Achieving a high level of VME protection requires the creation of many closures (> 100), made up of many small (~50 km2) and fewer larger closures (> 1000 km2). The greatest protection of VMEs will affect approximately 9% of the mobile fleet fishing effort, while closure scenarios that avoid highly fished areas reduce this to around 4–6%. The framework allows managers to choose the level of risk-aversion they wish to apply in protecting VMEs by comparing alternative strategies.

Keywords : bottom fishing, ecosystem-basedmanagement, fishing activity, marine protected area, protection, significant adverse impacts, vessel monitoring systems, vulnerable marine ecosystem

Introduction

Certain habitats and species of deep-sea bottom-living organisms such as cold-water coral reefs and aggregations of deep-sea sponges, are defined as vulnerable marine ecosystems (VMEs) (FAO, 2009). VMEs are often associated with topographic features including seamounts, hydrothermal vents, and canyons. VMEs can be extremely long lived and are particularly vulnerable to bottom-fishing activity as they are easily disturbed and slow to recover. The United Nations General Assembly (UNGA) Sustainable Fisheries Resolutions, particularly Resolutions 61/105 (UNGA, 2006) and 64/72 (UNGA, 2009), call for adoption of conservation and management measures to prevent significant adverse impacts (SAI) by bottom-contact fishing gears on VMEs where they are known or likely to occur. An essential step towards the prevention of SAI on VMEs is to assess the identity and distribution of VMEs relative to bottom fishing activity (Ardron *et al.*, 2014).

Data records that suggest the presence of a VME frequently have varying degrees of uncertainty due to limited spatial and temporal sampling effort in the deep-sea regions where they are most found, e.g. Morato *et al.* (2018). Moreover, absence data, i.e. samples where no VMEs have been identified, are less regularly collated in databases of deep-sea biodiversity. These limitations have important consequences and implications for managers designing protective measures to achieve the objectives of the above UNGA resolutions (Figure 1). Managers may choose a high level of precaution and close all areas to bottom-contact fishing where VMEs are known or likely to occur, based on the best available scientific information. Yet, some of these areas, or parts thereof, may not host an actual VME (Type 1 error) and this may cause unnecessary fisheries restrictions with resultant socio-economic impacts. Instead, risk-averse managers may prioritize socio-economic developments and only close areas where VMEs are unequivocally present or highly likely to occur, opting for other management measures to prevent SAI in fished areas. This option will limit impacts to fisheries but increases the risk of SAI on VMEs that have not yet been detected (Type 2 error).

Managers designing protective measures will hence need to decide on the desired level of risk-aversion or precaution in protecting areas where VMEs are known or likely to occur, and on the importance of avoiding excessive socio-economic restrictions, i.e. trading off false positives and negatives and their relative costs. Such a trade-off evaluation requires a quantitative assessment of the costs and benefits associated with decisions (Penney and Guinotte, 2013).

In this study, we present a transparent and consistent framework, which uses quality-controlled information on VME and fishing effort distribution within European Union and United Kingdom waters, to identify closed area options that vary in the level of risk-aversion for the protection of VMEs. The approach allows managers to choose the risk-aversion level they wish to apply. We examine the consequences of these management options in two ecoregions: the Celtic Seas ecoregion and the Bay of Biscay and the Iberian Coast ecoregion. These ecoregions are based on biogeographic and oceanographic features and existing political, social, economic, and management divisions (ICES, 2020a). The two ecoregions constitute most of the EU waters in the North Atlantic between 400-800 m depth.

Background and material

Policy Context

Under Regulation (EU) 2016/2336 (hereafter termed the "deep-sea access regulations"), bottom trawling below 800 m depth is banned, whilst bottom contact fishing between 400 and 800 m depth conducted by EU vessels within EU waters will be confined to the existing bottom-fishing footprint. This footprint is calculated based on bottom contact fishing (static and mobile gears) location data between 2009 and 2011 [Article 7 and Article 8(2)]. Within that existing footprint, the European Commission, in consultation with Member States, will list, and periodically review, areas where VMEs are known or are likely to occur [Article 9(6)]. The Commission will adopt implementing acts for the closure of selected areas between 400-800 m depth in order to protect the VMEs found there. The United Kingdom has retained the deep-sea access regulation in national legislation following exit from the EU, and the obligations in the regulation have transferred to national fisheries administrations. As of yet, the science-policy interface still needs to reconcile how to link the protection of deep-sea VMEs (the focus of this paper) with the management of habitats and communities that are not classified as VMEs in deep-sea regions (see further Kazanidis *et al*., 2020; Orejas *et al*., 2020).

Data on Vulnerable Marine Ecosystems

A central database holding information on the distribution and abundance of habitats and species considered to be indicators of VMEs across the North Atlantic, is maintained by the ICES Data Centre, in collaboration with the Joint ICES/NAFO Working Group on Deep-water Ecology (WGDEC) (ICES, 2020b). This database aims to store and make available all known VME habitat and indicator records in the North Atlantic, covering deep water areas inside and outside national jurisdiction. For the development of closed area options, only data from this database (Accessed

May 2020) were used directly in the identification of VMEs, to ensure comparability between regions and same quality assumptions.

The definition of VMEs for submission to the database are based on the five criteria defined by the FAO International Guidelines for the Management of Deep-sea Fisheries in the High Seas (FAO, 2009): 1) uniqueness or rarity, 2) functional significance of the habitat, 3) fragility, 4) life history traits of the component species that make recovery difficult, and 5) structural complexity. Each year, a data call is sent out to ICES member states requesting any new data on VMEs to be submitted to the VME database. The data call provides a list of habitats that are currently recognized as VMEs, as well as their representative taxa, i.e. VME indicator taxa (ICES, 2020c). VME data submissions can take three forms: 1) VME habitats – records for which there is unequivocal evidence for a VME, e.g., Remotely Operated Vehicle observations of a cold-water coral reef; 2) VME indicators - records that suggest the presence of a VME with varying degrees of positional uncertainty, e.g., bycatch of gorgonian corals from a fishing vessel; 3) absence data – samples where neither a VME nor a VME indicator have been identified. Absence data is rarely available in the VME database and thus not used in the current analysis.

In the VME database, VME habitat records are considered unequivocal VMEs whereas VME indicator records represent data from multiple sources, collected at different times through different survey methods, including older data from scientific literature. VME indicator data are therefore not standardized and cannot easily be compared against each other. To use these data for understanding VME distribution in North Atlantic waters, while taking into account standardization issues, a multi-criterion assessment system was developed by WGDEC (ICES, 2015) and further refined by Morato *et al.* (2018). A series of transparent steps are followed to produce a VME 'likelihood' score and a confidence score. This method produces the "VME index", which indicates the likelihood of an area containing a VME, based on the underlying VME indicator data.

The index combines a ranked VME indicator 'vulnerability score', based on expert knowledge of each indicator species considered against the five FAO criteria for VMEs (FAO, 2009), with available data on the abundance of VME indicator species records, where provided in the database. These two parameters are combined and the VME index scores overall VME likelihood as either High, Medium or Low. The index is mapped on a spatial C-square grid scale (Rees, 2003) of 0.05° x 0.05° (approximately 3 km by 5 km at 62° latitude, hereafter termed C-square). Records of VME habitat submitted to the database are assigned to a 'VME habitat' category, and therefore do not sit on the 'likelihood' scale. Full details on the method for the VME index are provided in Morato *et al.* (2018). The distribution of VME habitats and the VME index is illustrated in Supplementary Figure 1. Although the VME data are used at the C-square resolution to identify VME likelihood, the database holds records as point or line coordinates. Therefore, to assess how the different closure scenarios and options captured these records, we evaluated the closure both at the C-square and individual record level. Where the record geometry was recorded as a line, that is, if it arose from a trawl or a camera tow, the mid-point of the line was taken and treated as a point record.

Caveats and Limitations of the VME Database

During the development of this work some important data gaps in VME locations (known but not submitted to the ICES database) were identified and have been partially corrected (ICES 2021a) although not in time to be included in this work, which is based on data availability in May 2020. Key gaps in VME locations in this work are mostly found in the Bay of Biscay and the Iberian Coast ecoregion and include: coral reefs, coral gardens and sponge aggregations associated with the Avilés canyon system (Louzao *et al.*, 2010; Sánchez *et al.*, 2014) and the Galicia Bank (Somoza *et al.* 2014; Altuna *et al.* 2017; Serrano *et al.*, 2017); sponges and stony corals from Nazaré submarine canyon on the Portuguese margin (Huvenne *et al.*, 2012) as well as sea pen presence records (Ruiz-Pico *et al.,* 2017), and numerous mud volcanoes in the Gulf of Cádiz (Díaz del Río *et al.*, 2014, Urra *et al.*, 2021). There are also several improvements that could be made to the VME index to support further use for the identification of VME closure proposals (ICES, 2018). The VME index is based on a mix of information on the presence of VME indicator groups, the characteristics of these species and measures of their abundance (where available), and the contribution of each of these elements is not detailed in the final index value. This means that it is difficult to infer what an index value within a specific location is likely to represent in terms of indicator type(s) and abundance.

VME Geophysical Elements

VME geophysical elements were used to identify areas where VMEs are likely to occur. VME geophysical elements are defined by the FAO (2009) as topographical, hydrophysical or geological features, including fragile geological structures, that potentially support VMEs. Elements include: 1) submerged edges and slopes, hosting e.g. corals and sponges; 2) summits and flanks of seamounts, guyots, banks, knolls, and hills, hosting e.g. corals, sponges, xenophyophores; 3) canyons and trenches, e.g. burrowed clay outcrops, corals; 4) hydrothermal vents, e.g. microbial communities and endemic invertebrates; and 5) cold seeps, e.g. mud volcanoes for microbes, hard substrates for sessile invertebrates.

The EMODnet seafloor geology data layers were used to identify VME geophysical elements in the two ecoregions. These data layers are publicly available through the EMODnet Geology portal. The portal provides georeferenced data layers of geological and biogenic structures such as banks, coral mounds, mud volcanoes and seamounts at a higher spatial resolution than other global sources of information. For hydrothermal vents, point data were extracted from the InterRidge Vents Database (Beaulieu and Szafranski, 2020) for active submarine hydrothermal vent fields.

Four types of VME geophysical elements present in the two ecoregions were included in the assessment: seamounts, banks, coral mounds, and mud volcanoes (Supplementary Figure 2). Canyons were not included in the VME elements data layer as both EMODnet Geology as well as a global seafloor geomorphic features map (Harris *et al.*, 2014) provide data layers that consist of large dendritic canyon systems. In these canyon complexes, multiple canyon heads on the upper slope are connected by a single fan on the lower slope. As a consequence, the occurrence of a VME in one canyon head would result in a large closure including all interconnected canyons (see further "*Closed Area Scenarios*" section). The exclusion of these canyon complexes as a VME geophysical element has a large impact on our results as there are numerous canyons throughout both regions (Supplementary Figure 2).

Data on fishing activity

The fishing distribution in both ecoregions was estimated for mobile bottom-contacting gears (bottom otter trawls, bottom seines, dredges, and beam trawls) and static bottom-contacting gears (pots and traps, gillnets and longlines). The fishing distribution was described by coupling vessel monitoring systems (VMS) data with logbook data via an annual ICES data call, see further ICES (2019). Vessel Monitoring System data products produced through the VMS and logbook data call are currently aggregated on a spatial grid scale of 0.05° x 0.05° (i.e. C-square), matching the resolution of the VME data. The C-square cell size used for this aggregation is chosen as it represents an optimum solution given the current time interval between the polling frequency seen in the available VMS data (typically one hour, but ranging between 15 minutes and 2 hours) and the distance a vessel travelling at speeds consistent with fishing will cover during this period. This minimizes the probability of a vessel fishing in a cell without being observed. In all analyses, we included fishing activity data from both EU and non-EU countries; the fishing data is only available as a combined output.

Criteria Used to Delineate the Fishing Footprint

The deep-sea access regulation defines the footprint based on the activity of vessels that had deep-sea fishing authorizations during the period 2009 – 2011. The legislation prohibits trawl fishing below 800 m depth, which is the lower boundary considered in this work. An upper bound of 400 m has been used, which is a practical decision; fishing activity by vessels with and without a deep-sea fishing authorization may occur in waters shallower than 400 m but a distinction between these cannot be made as the license condition is not specified within the available fishing activity data. While the upper bound of 400 m may not represent all activity of vessels with a deep-sea fishing authorization, it does align with the deep-sea access regulation, which aims to implement specific requirements for the protection of VMEs in waters below this depth.

To establish rules for how the footprint could be established, a set of footprint scenarios were explored (Supplementary Table 1, Supplementary Figure 3). All scenarios presented use C-squares as the basic unit; this will result in a marginally larger footprint than is actually fished as the fished area will be defined in C-squares rather than actual ground covered by fishing tracks. C-squares were considered to be fished where there was a presence of fishing activity for mobile bottom-contacting gears and/or static gears. To examine the distribution of different fisheries types within the fishing footprint, VMS data products for mobile gears were disaggregated into four different gear groupings (hereafter termed métiers); otter, beam, seine and dredge. For the ‘Otter’ métier, fisheries types were further disaggregated to six sub-gear métiers of otter trawl for *Nephrops* or shrimp, cod or plaice, mixed fish species, sprat or sandeel, mixed benthic fish, and *Nephrops* and mixed fish, following Eigaard *et al*. (2015). Static gears were disaggregated into pots and traps, gillnets and longlines.

Based on the outcome of the different footprint scenarios (Supplementary Table 1, Supplementary Figure 3), we estimated the footprint by removing all isolated C-squares that do not share any boundaries by edge or vertex with another fished C-square (Figure 2). These less contiguous C-squares are more likely to represent artefacts in the VMS data and could represent VMS points classified as fishing based on speed profiles, where in fact the vessels may have been transiting at low speeds due to poor weather conditions, or low frequencies of fishing pings at the edge of fishing grounds.

Caveats and Limitations of the Fishing Footprint

There are two primary quality assurance issues relating to the fishery footprint as defined using the aggregated data provided. Firstly, the level of correctly assigning effort (using VMS) to logbook landings, known as matching, is variable across métiers and regions (ICES, 2016). The matching of Spanish effort and catch data is believed to be quite low particularly for the reference period (2009-2011). A low percentage of matching means that the effort mapped is likely to underestimate the fishery footprint, which may not reflect the full extent of the fishing activity. This caveat has been recently identified for the Spanish data and a new approach for merging the data that allows much higher percentages of matching for some specific gears, e.g. from < 45% to > 90% for bottom otter trawl, can be used in a future update. A second issue related to the fishery footprint is that VMS data are available from 2009 for vessels over 15 m and from 2012 for vessels over 12 m. The proximity in some areas of the deep sea to the coast, especially in the southern part of the Bay of Biscay and Iberian Coast, means that the deep sea is also accessible to smaller vessels.

Therefore, the fishery footprint could potentially be underestimated. This issue mainly affects static gears which can operate in these depths despite small vessel lengths.

Fishing Intensity

The fishing footprint (Figure 2) describes the presence at any intensity of any gears that touch or have the potential to touch the bottom. A complementary way to describe the intensity of “areas fished with mobile bottom gear” is based on the Swept-Area-Ratio (SAR) value. The Swept-Area is calculated as hours fished x average fishing speed x gear width. The Swept-Area is a useful fishing intensity metric when considering the impact of trawl fisheries on benthic communities given that it accounts for gear contact with the seabed (Hiddink *et al.*, 2017). The gear width, which is expressed as surface bottom contact to derive SAR, is estimated based on relationships between average gear widths and average vessel length or engine power (kW) in Eigaard *et al.* (2015) and using expert input (ICES, 2019). SAR is the sum of the swept area divided by the area of each grid cell per year. Therefore, the C-square SAR indicates the theoretical number of times the entire grid cell has been swept if effort were evenly distributed within the cell. In reality, fishing in a C-square is often spatially aggregated. These spatially aggregated patterns may either shift over time so that the long-term distribution becomes spatially random, or they remain consistent over time since part of the grid cell is untrawlable (Ellis *et al.* 2014). The uncertainty in the spatial distribution of fishing within a C-square has important implications for VME – fishing interactions as VMEs within a C-square may or may not spatially overlap with fishing (and this cannot be resolved with the spatial resolution of the data provided to ICES by member states). Where there is a significant overlap between VME and fishing, there may be limited benefit to be gained from closing these C-squares based on the current state (not considering potential recolonization/ recovery of VMEs in the area over long time scales), whereas, where there is little or no overlap (even if intensively fished), closure to prevent fishing in hitherto unfished parts of the C-square also containing VMEs could result in a significant benefit to VME protection. This highlights that designing protective measures for VMEs at the C-square resolution will result in a high likelihood of Type 1 and/or Type 2 errors (see further "*Closed Area Scenarios*" section). One option for such areas is to provide conditional protection until more information can be obtained to refine the boundaries of the C-square, e. g. through targeted *in situ* camera surveys and analysis of individual VMS records by member states.

More than 99% of all SAR intensity in the two ecoregions in the 400-800 m depth range is from otter trawls. For these otter trawls, the distribution of SAR intensity shows that 90% of their total SAR intensity, hereafter termed the "core fishing area", occurs in < 50% of the C-squares that are fished (Figure 3). The remaining C-squares are fished with low intensities and only contribute to 10% of total SAR. We use fishing effort as a proxy for the economic importance of a fished area. For a proper assessment of the economic value of a fished area, there is a need to calculate marginal costs, representing the value of landings minus the variable cost, e.g. labor and fuel cost of fishing in an area. An estimate of the value of landings is available in the VMS data call for each C-square but no estimate of variable cost is available. Since fishing effort and value of landings are correlated at large spatial scales (Pearson-product correlation coefficient is 0.83 for the Celtic Sea ecoregion in the 400-800 depth range; no information on value is available for the Iberian Peninsula), we assumed they might equally well represent contribution margin. Nonetheless, some low fishing intensity areas may be associated with a high contribution margin and suggested closures in these areas may disproportionally impact local fisheries.

While it is possible to quantify the intensity of mobile bottom-contacting gears using VMS data, issues still surround the use of VMS data to quantify intensity for vessels using static gears. VMS coverage is low for static gears both in relation to effort and landing weight. Where VMS data are available, there are often other key parameters needed to estimate static gear fishing effort that are missing. At present, it is therefore only possible to reliably infer presence/absence of static gears.

Relationship Between VME Biomass and Fishing Intensity

Structure-forming VMEs are subject to physical damage from bottom-contact fishing gears, resulting in immediate declines through injuries and removal (Braga-Henriques et al., 2013; Aguilar *et al.*, 2017; Hiddink *et al.*, 2018; Dias *et al.*, 2020). Further reductions in population densities may occur due to indirect impacts by fishing gear such as increase in sediment load resuspended by the fishing gear, increased predation and declines in population viability due to the removal of large and mature specimens (Pierdomenico *et al.*, 2018; Vieira *et al.*, 2020; Buhl-Mortensen *et al*., 2021). SAI are defined by FAO (2009) as those that compromise ecosystem integrity, i.e. ecosystem structure or function, in a manner that (i) impairs the ability of affected populations to replace themselves, (ii) degrades the long-term natural productivity of habitats, or (iii) causes, on more than a temporary basis, significant loss of species richness, habitat or community types.

The Northwest Atlantic Fisheries Organization (NAFO) has developed an approach for identifying SAI based on the biomass of VME species in the catch with increased fishing intensity, thus contributing to a qualitative risk assessment and management framework to avoid SAI on VME (NAFO, 2015) (Figure 4). The NAFO used the characteristics of cumulative VME biomass - fishing effort relationships to enable identification of the level of fishing effort above which there is little biomass observed for each of three VME indicator groups (sponges, large gorgonians, sea pens) and, therefore, no further SAI of fishing on VMEs can be expected. This threshold was defined as the fishing effort below which 95% of VME biomass was recorded when fishing effort is ranked from low to high (NAFO, 2016). The work revealed that of the three VME taxon groups studied, sea pens are the least sensitive to bottom trawling disturbance with the highest threshold of 0.5 hrs trawling km^{-2} $year^{-1}$.

Any potential areas of VME subject to fishing effort lower than this threshold would be expected to have VME biomass present (of any VME type with the same or greater resilience than sea pens) and therefore be at risk of impact from fishing. Consequently, identifying the level of fishing effort associated with a reduction of 95% of the VME biomass for the most resilient (least sensitive) VME can be used to define an area of fishing activity where the fishing effort is so high that the likelihood of observing any VME (even that associated with the least sensitive VME) would be very low. Although some VME species differ on both sides of the Atlantic, they share similar life-histories and morphologies within functional groups – often belonging to the same genera or families, e.g., for sponges see Cárdenas *et al.*, (2013) and for corals see Braga-Henriques *et al.*, (2013). Considering the shared response curve shapes of the three disparate taxa (NAFO, 2016), the similar fishing gears used and the absence of similar biomass and effort data in EU waters, we adopted the NAFO fishing intensity threshold of 0.5 hrs km^{-2} $year^{-1}$ as an ecologically-relevant threshold for providing management options.

To apply the NAFO threshold, we converted the fishing effort cut-off value to a SAR, so that a SAR minimum threshold could be applied to the fisheries data in both ecoregions. This value, using fishing gear dimensions for the halibut trawl fishery (NAFO, 2016), equates to 0.43 SAR per year. Therefore, in the present study, a SAR cut-off value of 0.43 has been applied to define an area of fishing activity where the risk of future VME impact is very high (≤ 0.43 SAR) and conversely, to areas which are greater than 0.43 SAR and therefore are at potentially relatively low risk of further VME impact as it is assumed that the ecosystem is already degraded. To determine whether a C-square was above or below the SAR threshold of 0.43, we used average SAR per year for 2009-2018.

Methods

Closed Area Scenarios

We developed a framework for the selection of closed areas to protect VMEs from SAI by bottom trawling, with two options within two scenarios. The first scenario defined VME closure areas without consideration of fishing activity. Option 1 proposed fishing closures for the protection of VME habitats and likely VME habitat, while Option 2 also included areas where four types of VME geophysical elements were present. The second scenario additionally considered fishing. This scenario used VME biomass - fishing intensity relationships to identify a threshold where effort of mobile bottom-contact gears is low and unlikely to have caused significant adverse impacts (see previous section). The two options per scenario are presented with management implications of each option summarized (Table 1). Detailed steps for operationalizing these options are found in Supplementary Text 1. The scenario rules were used to create closure areas for the whole ecoregion, irrespective of the depth and the boundary of the ecoregion. Afterwards, the closure area boundaries were clipped to the 400-800 m depth range. The reason we created closures for the entire area is to make sure that VMEs one C-square outside of the 400-800 m depth range have a buffer within the depth range (see Buffer zones below), and that VMEs outside the depth range may be associated with a VME geophysical element that extends into the 400-800 m depth range. Apart from these effects, similar closure areas would have been obtained by clipping to the 400-800 m depth range before creating the closures.

The two options presented for Scenario 1 prioritize protection of VMEs, irrespective of the fishing activity (Table 1). These are consistent with the UNGA resolutions, specifically UNGA 61/105, paragraph 83: *"(c) In respect of areas where vulnerable marine ecosystems, including seamounts, hydrothermal vents and cold water corals, are known to occur or are likely to occur based on the best available scientific information, to close such areas to bottom fishing and ensure that such activities do not proceed unless conservation and management measures have been established to prevent significant adverse impacts on vulnerable marine ecosystems"* (UNGA, 2006). The two options presented for Scenario 2 prioritize protection of VMEs but incorporate a threshold for the level of fishing activity that is linked to significant adverse impacts (Table 1). These are consistent with the UNGA resolutions, specifically UNGA 61/105, paragraph 83: *"(a) To assess, on the basis of the best available scientific information, whether individual bottom fishing activities would have significant adverse impacts on vulnerable marine ecosystems, and to ensure that if it is assessed that these activities would have significant adverse impacts, they are managed to prevent such impacts, or not authorized to proceed"* (UNGA, 2006). Scenario 2 therefore avoids unnecessary restrictions on fishing activities where VMEs are unlikely to persist given current levels of fishing effort. Note that Scenario 2 does not consider potential recolonization/ recovery of VMEs in the area over long time scales if left undisturbed by fishing.

The selected scenarios/options vary in their level of risk-aversion. Scenario 1 Option 1 prioritizes protection of VMEs where they are known to occur. Scenario 1 Option 1 therefore has a high risk of Type 2 errors (VME present when assumed it is not) when data availability is low and many VMEs are unlikely to be mapped (see Figure 1). The chance of Type 2 errors is lower in Scenario 1 Option 2 by adding VME geophysical elements of which VME designation is uncertain. Scenario 2 Option 1 also lowers the risk of Type 2 errors by closing all cells with Low VME index and low fishing activity. Lastly, Scenario 2 Option 2 limits the chance of Type 1 errors (VME not present when assumed it is) and lowers socio-economic impacts by not protecting areas that have experienced fishing pressures above an evidence-based threshold beyond which VMEs are unlikely to persist. The different scenarios/options result in different spatial extents and numbers of closures in the 400-800 m depth range. These are compared for each ecoregion in the results section and the consequences of the closures for protecting VMEs and their potential impact on the fisheries are tabulated and discussed.

Buffer Zones

Modern navigation systems provide very accurate locations of fishing vessels at sea. However, trawl gears are towed behind a vessel on wires several times the depth on location, as a result, the location of the actual mobile bottom contacting gear at depths between 400-800 m is much less accurately defined. We considered that a ½ C-square buffer around each C-square to be closed to mobile bottom-contacting gears would be an appropriate buffer to ensure the protection of VME habitats distributed along the edge of the C-square. The choice of ½ a C-square, rather than another distance, was primarily for the ease of implementation given the lack of empirical evidence for applying a buffer over such diverse habitats. Earlier work has suggested using a depth-dependent buffer (3x the water depth) to account for the fishing gear location in relation to the position of the ship (ICES 2013). This option has an empirical basis and could be implemented in a future update.

Results

Celtic Seas ecoregion

In the Celtic Seas ecoregion, the ICES VME database contains 3,091 records for VME habitats and 9,278 records for VME indicators (as of May 2020). This information, from across the ecoregion, has been collected through various gear types and survey methods. Most records come from the northwest of Scotland and west of Ireland (Supplementary Figure 1).

The fishing footprint is extensive and covers 85% of the 400-800 m depth in the Celtic Seas ecoregion (Table 2). Along the continental slope, unfished C-squares are commonly found on the deeper edge of the bathymetric range (Figure 2). This is most apparent on the northern edge of the United Kingdom EEZ north of the Wyville-Thomson Ridge where just over half of the depth range appears to be fished moving from shallow into deeper waters. Unfished C-squares on the deeper edge are to a lesser extent visible around the Porcupine Bank. There appears to be slightly differing distributions of fishing presence on the isolated banks and seamounts. There is a perimeter of unfished C-squares at George Bligh Bank, whereas a small aggregation of unfished C-squares can be seen in the centre of the Anton Dohrn Seamount and no deep-sea waters at Rosemary Bank are unfished (Figure 2).

The areas of the fishing footprint that are fished by most sub-gears and, therefore, likely important for multiple fisheries (see Table 3 for list), are the shelf edge south of Wyville-Thomson Ridge stopping north of the Porcupine Bank, to the south of the shelf edge surrounding Porcupine Seabight and in the Hatton-Rockall Basin. The C-squares with the fewest sub-gears present include the isolated banks and seamounts and appear to reflect the areas where unfished C-squares are more frequently observed.

The EEZs of the UK and Ireland have the greatest number of C-squares within the 400-800 m depth range (Table 2). In this depth range, the percentage of fished C-squares in each EEZ ranges from 77% in the UK to 96% in France (Table 2). The majority of C-squares experience fishing pressure from multiple gears, with only 19% fished by only one gear type (Table 3). Most of the C-squares fished in the reference period (2009-2011) are also fished in the period 2012-2018 (Supplementary Figure 4). Fishing in the 400-800 m depth contour accounts for 11% (UK), 18% (Ireland) and 5% (France) of the total fished C-squares in each EEZ, illustrating different potential socio-economic impacts.

Overlap between VME and fishing data shows that fishing occurs in 92% of C-squares with known VME occurrence or likely occurrence, i.e. VME habitat and all three index levels (Table 2). Overlap is most pronounced in France (100%), however, very few VME occurrences (7) are within the French EEZ in this ecoregion. VMEs are most numerous within the Irish EEZ (243) where 96% are fished, followed by the United Kingdom with 142 known or likely VMEs (83% fished). The overlap is estimated using data on all gear types but is mostly coming from otter trawl gears that are the dominant fishing gear operating in the 400-800 m depth range. These trawls predominantly target gadoids, and benthic fish species, and are primarily active within the Irish EEZ (highest overlap of gears). However, static gears are also important; pots overlap with 5% of the C-squares with known or likely VME occurrence, longlines overlap with 50% and gillnets 62%.

Analysis of Trade-offs Between Closures and Impact on Fisheries

The different closure scenarios result in a different spatial extent and number of closures in the 400-800 m depth range. Scenario 2 Option 1 has most closed areas (n= 89), which are predominantly small in spatial extent (Figure 5). Scenario 1 Option 2 has fewest closures (n= 69) but covers a larger area due to the closing of the Anton Dohrn Seamount as well as the Rosemary and the George Bligh Banks.

The consequences of the closures for protecting VMEs and their potential impact on the fisheries are shown in Table 4. Scenario 1 Option 1 and Scenario 1 Option 2 protect the same number of VME habitats and index cells, with Scenario 1 Option 2 affecting more fishing activity and particularly so when evaluated as the footprint area rather than as SAR. Scenario 2 Option 1 closures capture many more Low VME index cells at a low additional impact on fishing activities, while Scenario 2 Option 2 strongly reduces the impact on fishing activities at the expense of not closing some VME habitats, High and Medium index cells (83% of VME habitats, 88% High and 67% Medium index cells are closed in those categories).

Approximately, 7-9% of total SAR intensity is in C-squares that are closed in Scenario 1 (both options) and Scenario 2 Option 1, whereas 4% of total SAR intensity is closed in Scenario 2 Option 2 (Table 4). The number of C-squares that are closed in Scenario 2 Option 2 is not much lower than for the other scenarios. This illustrates that fishing activity is concentrated in high effort C-squares and that there are a lot of C-squares with minimal effort levels. Effects of the different scenarios on static and mobile fishing activities appear very similar.

The number of records of VME indicator and habitat groups inside each of the closure scenarios is evaluated in Table 5. The evaluation counts all records per group, including multiple records inside a single C-square. For most groups, Scenario 2 Option 2 protects a smaller number of records than the other scenarios. The main deviation from this pattern are sea pens. Because sea pens rarely classify above ‘Low VME index’, inclusion of lightly fished Low index cells in

Scenario 2 Option 1 and Scenario 2 Option 2 increases the number of sea pen records included in the closures.

Bay of Biscay and the Iberian Coast ecoregion

The Bay of Biscay and the Iberian Coast ecoregion covers the southeastern shelf seas of the EU. It includes all or parts of the EEZs of France, Spain and Portugal, and a small proportion of the High Seas. In total, the ICES VME database holds 3,834 records for VME habitats and indicators within this ecoregion (as of May 2020). The VME indicators are all ranked as Medium or Low VME index (Supplementary Figure 1). These records are unevenly distributed across the EEZs of France, Spain and Portugal, and are mainly associated with a few VME geophysical elements, including: the Mériadzek Terrace, submarine canyons of the Bay of Biscay and Portuguese margins, El Cachucho (Le Danois Bank), the Gorringe Bank, as well as two mud volcano fields in the Gulf of Cádiz. As noted in the section "*Caveats and Limitations of the VME Database*", the VME database is known to be missing VME data in this ecoregion.

The fishing footprint is extensive and covers 83% of the 400-800 m depth in the ecoregion (Figure 2 and Table 6). Most of the unfished areas seem to be concentrated in Spanish waters (25% of C-squares unfished) followed by Portuguese waters (18% of C-squares unfished), whereas there are very few unfished areas in French waters (3%). Most of the unfished C-squares are concentrated in three areas: El Cachucho where fishing has been strictly limited, Galicia Bank and the Gulf of Cádiz, including both Spanish and Portuguese waters. However, caution is advised in assuming that all the unfished C-squares in this region are really unfished due to the omission of a large proportion of fishing effort of the Spanish fleet and the proximity of some of these deep-water areas to the coast, where they are accessible to smaller vessels without VMS.

A fairly well-defined north-south gradient is identified in terms of the diversity in gear type used, with the northern Bay of Biscay waters accounting for the highest diversity of gear used, ranging from an average of 3 to 5 gears per C-square (reaching 6 and even 7 in some cases, see list in Table 7) to the southernmost stretches of the ecoregion where the lowest diversity are reported, with 1 gear per C-square in the Spanish Gulf of Cádiz. The southern Bay of Biscay and western Iberian Shelf display intermediate values, with 2 to 4 gear types per C-square. Most of the C-squares fished in the reference period (2009-2011) are also fished in the period 2012-2018 (Supplementary Figure 5). Fishing in the 400-800 m depth range accounts for 28% (Portugal), 23% (Spain) and 10% (France) of the total fished C-squares in each EEZ, illustrating different potential socio-economic impacts.

Overlap between VME and fishing data shows that fishing occurs in 78% of C-squares with known VME occurrence or likely occurrence, i.e. VME habitat and all index levels (Table 6). Similar to the Celtic Seas, overlap is most pronounced in France (100%), which is also the country whose EEZ hosts the larger number of VME C-squares (26). The EEZs of Spain and Portugal have similar numbers of C-squares with VME occurrence (18, 20, respectively) and similar percentages of overlap between VME and fishing in those C-squares (61%, 65%). The overlap is estimated using data on all gear types but is mostly coming from otter trawl gears, followed by static gears, in particular longlines and gillnets. Gillnets and longlines are roughly equally present in C-squares in the EEZs of France and Spain, while in the EEZ of Portugal gillnets are considerably less present. Pots and traps are far less present compared with the other static gears across the ecoregion.

Analysis of Trade-offs Between Closures and Impact on Fisheries

The different scenarios result in a different spatial extent and number of closures in the 400-800 m depth range. Scenario 2 Option 1 has most closed areas (n= 47), which are predominantly small in spatial extent (Figure 6). Scenario 1 has the fewest closures (n= 37 to 39, for options 2 and 1 respectively) but Option 2 covers a larger area due to the closing of the two seamounts on the Gorringe Bank as well as El Cachucho.

The consequences of the closures for protecting VMEs and their potential impact on the fisheries are shown in Table 8. The results show that the number of C-squares with VME habitats and index records is the same for Scenario 1 Option 1 and Scenario 1 Option 2. Yet, in the second option, two VME geophysical elements are included in the closures: El Cachucho in the southern Bay of Biscay and two seamounts of the Gorringe Bank (Ormonde and Gettysburg) off southern Portugal. Scenario 1 Option 2 thus increases the likelihood that VMEs not yet recorded are included in closures. The additional impact on fishing activities of Scenario 1 Option 2 compared with Scenario 1 Option 1 is small, presumably because the closure areas with VME geophysical elements are fished with a low intensity. Scenario 2 Option 1 closures capture more Low VME index cells at a low additional impact on fishing activities, while Scenario 2 Option 2 slightly reduces the impact on fishing activities at the expense of not closing some VME habitats and Medium index cells.

The different closures result in a moderately different impact on fishing activities. For the 2015-2018 period, Scenario 2 Option 2 closes 6% of the total SAR of the mobile fleet, whereas the other scenarios 8-9%. The number of C-squares that is closed in Scenario 2 Option 2 is not much lower than for the other scenarios. This illustrates that fishing activity is concentrated in high effort C-squares and that there are a lot of C-squares with minimal effort levels. Effects of the different scenarios on static and mobile fishing activities appear very similar (Table 8).

A closer look at the VME records shows that within the 400-800 m depth band, the different scenarios have no influence on the level of protection of VME habitats (Table 9). In each case, all records of VME habitats are included in the closure areas. The different scenarios have slightly different outcomes on the level of protection of VME indicators (Table 9). Except for lace corals (stylasterids), all VME indicators are less protected by Scenario 2 Option 2. This is because in Scenario 2 Option 2 C-squares that have already been heavily fished (SAR > 0.43) are excluded from closure areas on the assumption that fishing has caused SAI to these VMEs. However, considering the size of a C-square relative to the clumped distribution of both fishing footprint and VME patches, C-squares with high SAR and VME records are to be expected. This is exemplified in the Bay of Biscay by canyon heads. While the occurrence of VMEs on heads of submarine canyons lead to C-square closure within the 400-800 m depth band, fisheries may solely target the flat interfluves at the periphery of canyon heads in the same C-square (van den Beld *et al*. 2017).

The soft coral, whose vulnerability is low according to the multi-criteria assessment method, is less protected in Scenario 1 than Scenario 2. Sea pen, another ‘low vulnerability’ indicator taxon, is most protected in Scenario 2 Option 1. Both these VME indicator taxa are also the only two that are not fully protected by any of the scenarios.

Conclusion

We have presented a transparent framework for consistently identifying management options in support of European Union deep-sea access regulations for the protection of VMEs. The results show that the approach and outcome will depend on the desired level of risk-aversion in protecting VMEs and on the importance of avoiding socio-economic restrictions, i.e., trading off Type 1 versus Type 2 errors and their relative costs (Figure 1). Achieving a high level of VME protection in closures requires the creation of many closures (> 100) with many small (~ 50 km^2) and fewer larger closures (> 1000 km^2). Full protection of all areas with a high probability of containing VMEs within the 400-800 m depth band will maximally affect 24% of the fishing footprint in the Celtic Seas ecoregion and 16% in the Bay of Biscay and the Iberian Coast ecoregion, while closure scenarios that avoid highly fished areas, which are therefore less likely to support viable VMEs, would reduce this to around 16% and 14% respectively. For both ecoregions, the total intensity of the mobile fleet will be less affected within the 400-800 m depth band; 4-9% in the Celtic Seas and 6-9% in the Bay of Biscay and the Iberian Coast ecoregion.

VME protection leads, in all management options, to many small closures and a mosaic of open and closed areas. This may raise concern that the suggested area closures will be difficult to implement. An initial evaluation of the closure options presented to fisheries managers suggested that this mosaic can be implemented (and enforced) using modern vessel navigation systems (ICES 2020d). Fishing vessels are also known to operate and select locations at much finer spatial resolutions than C-squares (NAFO 2020). Ultimately it is for managers to make the final decision of VME closure locations, including how large the closure area should be. Such decisions go beyond the scope of our paper that offers a framework for consistently identifying management options for consideration as potential VME fishery closures. If larger areas need to be implemented, an aspect of science that could help in this situation is the use of predictive habitat models to justify joining some of the VME closure areas together (see e.g. ICES 2021b).

This framework establishes a transparent approach for managers to follow for the protection of vulnerable marine ecosystems. To our knowledge this is the first time that such a framework has been made public. With the EU anticipating periodic updates of the scientific advice, it will be possible to learn from the application of this approach and build in improvements in the future. The framework allows managers to choose the risk-aversion level they wish to apply in protecting VMEs and supports the decision-making process by comparing alternative management options. The language of the UNGA resolutions acknowledges uncertainty in the presence of VMEs by calling for protection of areas where VMEs "are known or likely to occur". This means that full knowledge of the spatial distribution of the VMEs is not a pre-requisite for management action and that there is an expectation to accept Type 1 error over Type 2 error. The scenarios tested can be combined in other combinations to produce alternative options e.g. the C-squares identified under Scenario 1 option 2, which includes the VME geophysical elements, could be combined with those identified under Scenario 2 option 2, which includes all known VME data from the VME database, to further reduce Type 1 error. The scenarios tested can be updated when new information on VMEs and fishing activity becomes available.

Data Availability

The R-scripts which produced the closed area options and data summaries, including closure .shp files, are available on an open-source platform (WKEUVME GitHub site). For each ecoregion/Management Option/Closed Area, there is a table of the coordinates available on GitHub that indicates the VME habitat, VME indicator and VME geophysical element data present. The GitHub also includes spatial information on the static, mobile and combined fishing footprints. VME habitat and indicator records that are publicly available can be downloaded from the ICES VME data portal.

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References

Aguilar, R., Perry, A.L., and López, J. 2017. Conservation and management of vulnerable marine benthic ecosystems. *In* Marine Animal Forests (Rossi, S., Bramanti, L., Gori, A., and Orejas, C. eds.), chapter 41, pp 1165–1207.

Altuna, A. 2017. Deep-water scleractinian corals (Cnidaria: Anthozoa) from 2010 - 2011 INDEMARES expeditions to the Galicia Bank (Spain, northeast Atlantic). Zootaxa, 4353: 257–293.

Ardron, J. A., Clark, M. R., Penney, A. J., Hourigan, T. F., Rowden, A. A., Dunstan, P. K., Watling, L., *et al.* 2014. A systematic approach towards the identification and protection of vulnerable marine ecosystems. Marine Policy, 49: 146–154.

Beaulieu, S., and Szafranski, K. 2020. InterRidge Global database of active submarine hydrothermal vent fields, Version 3.4. World Wide Web electronic publication available from http://vents-data.interridge.org Accessed Spring 2020.

Braga-Henriques, A., Porteiro, F. M., Ribeiro, P. A., de Matos, V., Sampaio, I., Ocaña, O., Santos, R. S. 2013. Diversity, distribution and spatial structure of the cold-water coral fauna of the Azores (NE Atlantic). Biogeosciences, 10: 4009–4036.

Buhl-Mortensen, P., Braga-Henriques, A., and Stevenson, A. 2021. Polyp loss and mass occurrence of sea urchins on bamboo corals in the deep sea: an indirect effect of fishing impact? Ecology, 10.1002/ecy.3564

Cárdenas, P., Rapp, H. T., Klitgaard, A. B., Best, M., Thollesson, M., and Tendal, O. S. 2013. Taxonomy, biogeography and DNA barcodes of Geodia species (Porifera, Demospongiae, Tetractinellida) in the Atlantic boreo-arctic region. Zoological Journal of the Linnean Society, 169: 251–311.

Dias, V., Oliveira, F., Boavida, J., Serrão, E. A., Gonçalves, J. M. S., and Coelho, M. A. G. 2020. High coral bycatch in bottom-set gillnet coastal fisheries reveals rich coral habitats in Southern Portugal. Frontiers in Marine Science, 7: 603438.

Díaz del Río, V., Bruque, G., Fernández-Salas, L. M., Rueda, J., González, E., López, N., Palomino, D., *et al.* 2014. Volcanes de fango del Golfo de Cádiz - Áreas de estudio del proyecto LIFE+ INDEMARES. Ed. Fundación Biodiversidad del Ministerio de Agricultura, Alimentación y Medio Ambiente.

Eigaard, O. R., Bastardie, F., Breen, M., Dinesen, G. E., Hintzen, N. T., Laffargue, P., Mortensen, L. O., *et al.* 2015. Estimating seabed pressure from demersal trawls, seines, and dredges based on gear design and dimensions. ICES Journal of Marine Science, 73: i27–i43.

Ellis, N., Pantus, F., and Pitcher, C. R. 2014. Scaling up experimental trawl impact results to fishery management scales - a modelling approach for a "hot time." Canadian Journal of Fisheries and Aquatic Sciences, 71: 733–746.

EU. 2016. Regulation (EU) 2016/2336 of the European Parliament and of the Council. *In* Official Journal of the European Union, pp. 1–19.

FAO. 2009. International Guidelines for the Management of Deep-sea Fisheries in the High Seas. Rome/Roma, FAO. 2009. 73p.

Harris, P. T., Macmillan-Lawler, M., Rupp, J., and Baker, E. K. 2014. Geomorphology of the oceans. Marine Geology, 352: 4–24.

Hiddink, J. G., Jennings, S., Sciberras, M., Szostek, C. L., Hughes, K. M., Ellis, N., Rijnsdorp, A. D., *et al.* 2017. Global analysis of depletion and recovery of seabed biota after bottom trawling disturbance. Proceedings of the National Academy of Sciences, 114: 8301–8306.

Hiddink, J. G., Jennings, S., Sciberras, M., Bolam, S. G., Cambiè, G., McConnaughey, R. A., Mazor, T., *et al.* 2018. Assessing bottom-trawling impacts based on the longevity of benthic invertebrates. Journal of Applied Ecology, 56: 1075–1084.

Huvenne, V. A. I., Pattenden, A. D. C., Masson, D. G., and Tyler, P. A. 2012. Habitat heterogeneity in the Nazare deep-sea canyon offshore Portugal. *In* Seafloor Geomorphology as Benthic Habitat: Geohab Atlas of Seafloor Geomorphic Features and Benthic Habitats (Harris, P.T., and Baker, E.K. eds.), Elsevier, Amsterdam, pp. 691-701

ICES. 2013. Evaluation of the appropriateness of buffer zones ICES Advice 2013, Book 1

ICES. 2015. Report of the ICES/NAFO Joint Working Group on Deep-water Ecology (WGDEC), 16–20 February 2015, Horta, Azores, Portugal. ICES CM 2015/ACOM:27. 113 pp.

ICES. 2016. OSPAR request for further development of fishing intensity and pressure mapping. *In* Report of the ICES Advisory Committee, 2016. ICES Advice 2016, Book 1, Section 1.6.6.4. 27 pp.

ICES. 2018. Report of the ICES/NAFO Joint Working Group on Deep-water Ecology (WGDEC), 5–9 March 2018, Dartmouth, Nova Scotia, Canada. ICES CM 2018/ACOM:26. 126 pp.

ICES. 2019. Working Group on Spatial Fisheries Data (WGSFD). ICES Scientific Reports, 1:52. 144 pp. http://doi.org/10.17895/ices.pub.5648.

ICES. 2020a. Definition and rationale for ICES ecoregions. *In* Report of the ICES Advisory Committee, 2020. ICES Advice 2020, Section 1.4. https://doi.org/10.17895/ices.advice.6014.

ICES. 2020b. Vulnerable Marine Ecosystems, Data Portal. Accessed Spring 2020.

ICES. 2020c. A suggestive list of deep-water VMEs and their characteristic taxa – updated Jan 2020.

ICES. 2020d. Chapter 5. *In* Workshop on EU regulatory area options for VME protection (WKEUVME). ICES Scientific Reports. 2:114. 237 pp. https://doi.org/10.17895/ices.pub.7618

ICES. 2021a. New information regarding the impact of fisheries on other components of the ecosystem. In Report of the ICES Advisory Committee, 2021. ICES Advice 2021, vme.eu. https://doi.org/10.17895/ices.advice.8316

ICES. 2021b. Workshop on the Use of Predictive Habitat Models in ICES Advice (WKPHM). ICES Scientific Reports. 3:67. 100 pp. http://doi.org/10.17895/ices.pub.8213

Kazanidis, G., Orejas, C., Borja, A., Kenchington, E., Henry, L-A., Callery, O., Carreiro-Silva, M., Egilsdottir, H., Giacomello, E., Grehan, A., Menot, L., Morato, T., Ragnarsson, S.A., Rueda, J.L., Stirling, D., Stratmann, T., van Oevelen, D., Palialexis, A., Johnson, D., Roberts, .J.M. 2020. Assessing the environmental status of selected North Atlantic deep-sea ecosystems. Ecological Indicators 119:106624.

Louzao, M., Anadon, N., Arrontes, J., Alvarez-Claudio, C., Fuente, D. M., Ocharan, F., Anadon, A., and Acuna, J. L. 2010. Historical macrobenthic community assemblages in the Avilés Canyon, N Iberian Shelf: Baseline biodiversity information for a marine protected area. Journal of Marine Systems 80:47-56.

Morato, T., Pham, C. K., Pinto, C., Golding, N., Ardron, J. A., Durán Muñoz, P., and Neat, F. 2018. A multi criteria assessment method for identifying vulnerable marine ecosystems in the North-East Atlantic. Frontiers in Marine Science, 5: 460

NAFO. 2015. Report of the 8th Meeting of the NAFO Scientific Council (SC) Working Group on Ecosystem Science and Assessment (WGESA). NAFO SCS Doc. 15/19, Serial No. N6549.

NAFO. 2016. Report of the Scientific Council Meeting. 03-16 June 2016, Halifax, Nova Scotia. NAFO SCS Doc. 16-14 Rev., Serial No. N6587.

NAFO. 2020. Report of the Scientific Council Working Group on Ecosystem Science and Assessment, 17 - 26 November 2020, Dartmouth, Nova Scotia, Canada. NAFO SCS Doc. 19/23.

Orejas, C., Kenchington, E., Rice, J., Kazanidis, G., Palialexis, A., Johnson, D., Gianni, M., Danovaro, R., Roberts, J.M. 2020. Towards a common approach to the assessment of the environmental status of deep-sea ecosystems in areas beyond national jurisdiction. Marine Policy 121:104182.

Penney, A. J., and Guinotte, J. M. 2013. Evaluation of New Zealand's High-Seas bottom trawl closures using predictive habitat models and quantitative risk assessment. PLOS ONE, 8: e82273.

Pierdomenico, M., Russo, T., Ambroso, S., Gori, A., Martorelli, E., D'Andrea, L., Gili, J.-M., *et al.* 2018. Effects of trawling activity on the bamboo-coral *Isidella elongata* and the sea pen *Funiculina quadrangularis* along the Gioia Canyon (Western Mediterranean, southern Tyrrhenian Sea). Progress in Oceanography, 169: 214–226.

Rees, T. 2003. "C-squares", a new spatial indexing system and its applicability to the description of oceanographic datasets. Oceanography, 16: 11–19.

Sánchez, F., González-Pola, C., Druet, M., García-Alegre, A., Acosta, J., Cristobo, J., Parra, S., *et al.* 2014. Habitat characterization of deep-water coral reefs in La Gaviera Canyon (Avilés Canyon System, Cantabrian Sea). Deep Sea Research Part II: Topical Studies in Oceanography, 106: 118–140.

Serrano, A., González-Irusta, J. M., Punzón, A., García-Alegre, A., Lourido, A., Ríos, P., Blanco, M., *et al.* 2017. Deep-sea benthic habitats modeling and mapping in a NE Atlantic seamount (Galicia Bank). Deep Sea Research Part I: Oceanographic Research Papers, 126: 115–127.

Somoza, L., Ercilla, G., Urgorri, V., León, R., Medialdea, T., Paredes, M., Gonzalez, F. J., and Nombela, M. A. 2014. Detection and mapping of cold-water coral mounds and living Lophelia reefs in the Galicia Bank, Atlantic NW Iberia margin. Marine Geology 349:73-90.

UNGA. 2006. United Nations General Assembly Resolution: A/RES/61/105. 21 pp.

UNGA. 2009. United Nations General Assembly Resolution: A/RES/64/72. 26 pp.

Urra, J., Palomino, D., Lozano, P., González-García, E., Farias, C., Mateo-Ramírez, Á., Fernández-Salas, L. M., López-González, N., *et al*. 2021. Deep-sea habitat characterization using acoustic data and underwater imagery in Gazul mud volcano (Gulf of Cádiz, NE Atlantic). Deep Sea Research Part I: Oceanographic Research Papers 169: 103458

van den Beld, I.M., Bourillet, J.F., Arnaud-Haond, S., De Chambure, L., Davies, J.S., Guillaumont, B., Olu, K. and Menot, L. 2017. Cold-water coral habitats in submarine canyons of the Bay of Biscay. Frontiers in Marine Science, 4: 118.

Vieira, R. P., Bett, B. J., Jones, D. O. B., Durden, J. M., Morris, K. J., Cunha, M. R., Trueman, C. N., *et al.* 2020. Deep-sea sponge aggregations (*Pheronema carpenteri*) in the Porcupine Seabight (NE Atlantic) potentially degraded by demersal fishing. Progress in Oceanography, 183: 102189.

Tables

Table 1. Description of management scenarios and options presented with associated management implications for the protection of VMEs and general impacts to fisheries.

Scenario	**Option**	**Description**	**Management Implication**
Scenario 1	Option 1	Close C-squares between 400-800 m depth that contain VME habitats and VME index Medium to High ‘likelihood’ of occurrence, regardless of fishing activity in the 2009-11 period. C-squares with Low VME index are only included when adjacent to VME index Medium to High C-squares.	Prioritizes protection of VMEs where they are *known* to occur, regardless of fishing activity.
Scenario 1	Option 2	Close Scenario 1 Option 1 + C-squares that contain selected VME physical elements (banks, seamounts, coral mounds, mud volcanoes) associated with any VME records.	Prioritizes protection of VMEs where they are *known* and *where they are likely to occur*, regardless of fishing activity.
Scenario 2	Option 1	As for Scenario 1 Option 1 but includes Low VME index C-squares if mobile bottom-contacting gear fishing pressure is also low (≤ 0.43 SAR).	Prioritizes protection of VMEs where they are *known* or *likely to occur*, and includes areas where the ‘likelihood’ of occurrence of VME presence is lower but where fishing activity is also low and therefore any VMEs present are less likely to have been heavily damaged by trawl fishing. Gives highest protection of VMEs in the fishing footprint.
Scenario 2	Option 2	Close C-squares between 400-800 m depth including all VME habitats, High, Medium and Low VME index C-squares but excluding C-squares with high mobile bottom-contacting gear fishing pressure (SAR > 0.43).	Prioritizes protection of VMEs where they are *known* or *likely to occur*, but excludes areas that have been heavily fished (core fishing areas) and where VMEs are therefore likely to have been heavily damaged by past trawl fishing.

Table 2. Total numbers of C-squares, numbers (and percentage in brackets) of C-squares fished (mobile + static), numbers of C-squares with a VME habitat or index (all three index levels) and the percentage of VME habitat and index C-squares with fishing in the Celtic Seas ecoregion and per EEZ within 400-800 m depth range.

EEZ	**C-sq. within 400-800 m depth**	**C-sq. fished within 400-800 m depth (with % in brackets)**	**C-sq. with a VME habitat or index within 400-800 m depth**	**% of VME habitat or index C-sq. fished within 400-800 m depth**
United Kingdom	2442	1872 (77)	142	83
Ireland	2306	2164 (94)	243	96
France	75	72 (96)	7	100
Total	4823	4108 (85)	392	92

Table 3. Total numbers of C-squares fished by multiple sub-gears (mobile + static) in the Celtic Seas ecoregion and per EEZ within 400-800 m depth range.

Number of sub-gears fishing in C-square	France EEZ	Ireland EEZ	United Kingdom EEZ	Total
1	0	472	552	1024
2	2	660	788	1450
3	18	459	381	858
4	31	478	128	637
5	20	85	23	128
6	1	10	0	11

Table 4. Table evaluating each of the 4 closure scenarios/options by impact on fishery and protection of VME habitat and index as a percentage of the total in the 400-800 m depth range in the Celtic Seas ecoregion.

	Total number in 400-800 m	**Scenario 1 Option 1 (as a %)**	**Scenario 1 Option 2 (as a %)**	**Scenario 2 Option 1 (as a %)**	**Scenario 2 Option 2 (as a %)**
VME protection					
C-squares with VME habitat	78	100	100	100	83
C-squares with VME index High	41	100	100	100	88
C-squares with VME index Medium	30	100	100	100	67
C-squares with VME index Low	246	11	11	36	25
Fisheries footprint in 2009-2011					
C-squares part of fishing footprint	4108	19	24	23	17
Fisheries consequences (2015-2018)					
C-squares with static bottom fishing present in footprint	2994	19	22	23	17
C-squares with mobile bottom fishing (SAR > 0) in footprint	2874	16	16	20	12
C-squares that form core fishing area based on SAR in footprint	1222	10	10	12	4
Sum of SAR per year in footprint	6790.4	7	7	9	4

Table 5. Protection of VME habitat and indicator records for each of the 4 closure scenarios/options as a percentage of the total number in the 400-800 m depth range in the Celtic Seas ecoregion.

	Total number in 400-800m	**Scenario 1 Option 1 (as a %)**	**Scenario 1 Option 2 (as a %)**	**Scenario 2 Option 1 (as a %)**	**Scenario 2 Option 2 (as a %)**
VME indicator					
Anemones	531	97	97	97	78
Black coral	194	100	100	100	93
Cup coral	130	89	89	89	50
Gorgonian	96	100	100	100	73
Sea pen	810	45	45	57	48
Soft coral	71	77	77	94	82
Sponge	1332	87	87	91	45
Stony coral	743	100	100	100	87
Lace coral	14	100	100	100	86
VME habitat					
Cold-water coral reef	230	100	100	100	91
Coral garden	1042	100	100	100	86
Deep-sea sponge aggregations	635	100	100	100	80
Sea pen fields	374	100	100	100	95
Tube-dwelling anemone aggregations	21	100	100	100	86
Xenophyophore aggregations	7	100	100	100	57
Anemone aggregations	22	100	100	100	23

Table 6. Total numbers of C-squares, numbers (and percentage in brackets) of C-squares fished (mobile + static), numbers of C-squares with a VME habitat or index (all three index levels) and the percentage of VME habitat and index C-squares with fishing in the Bay of Biscay and Iberian Coast ecoregion and per EEZ within 400-800 m depth range.

EEZ	**C-sq. within 400-800 m depth**	**C-sq. fished within 400-800 m depth (with % in brackets)**	**C-sq. with a VME habitat or index within 400-800 m depth**	**% of VME habitat or index C-sq. fished within 400-800 m depth**
Spain	866	649 (75)	18	61
Portugal	696	568 (82)	20	65
France	501	487 (97)	26	100
Total	2063	1704 (83)	64	78

Table 7. Total numbers of C-squares fished by multiple sub-gears (mobile + static) in the Bay of Biscay and Iberian Coast ecoregion and per EEZ within 400-800 m depth range.

Number of Sub-gears fishing in C-square	France EEZ	Portugal EEZ	Spain EEZ	Total
1	14	224	163	401
2	64	167	209	440
3	172	157	248	577
4	128	20	16	164
5	85	0	11	96
6	23	0	1	24
7	1	0	0	1

Table 8. Table evaluating each of the 4 closure scenarios/options by impact on fishery and protection of VME habitat and index as a percentage of the total in the 400-800 m depth range in the Bay of Biscay and Iberian Coast ecoregion.

	Total number in 400-800 m	**Scenario 1 Option 1 (as a %)**	**Scenario 1 Option 2 (as a %)**	**Scenario 2 Option 1 (as a %)**	**Scenario 2 Option 2 (as a %)**
VME protection					
C-squares with VME habitat	25	100	100	100	100
C-squares with VME index High	0	-	-	-	-
C-squares with VME index Medium	18	100	100	100	83
C-squares with VME index Low	21	29	29	62	62
Fisheries footprint (2009-2011)					
C-squares part of fishing footprint	1704	15	16	16	14
Fisheries consequences (2015-2018)					
C-squares with static bottom fishing (present in footprint)	1370	16	18	17	16
C-squares with mobile bottom fishing (SAR > 0 in footprint)	1295	14	14	15	13
C-squares that form core fishing area based on SAR in footprint	485	9	9	10	7
Total SAR per year in footprint	2111.3	8	8	9	6

Table 9. Protection of VME habitat and indicator records for each of the 4 closure scenarios/options as a percentage of the total number in the 400-800 m depth range in the Bay of Biscay and Iberian Coast ecoregion.

	Total in 400-800 m	**Scenario 1 Option 1 (as a %)**	**Scenario 1 Option 2 (as a %)**	**Scenario 2 Option 1 (as a %)**	**Scenario 2 Option 2 (as a %)**
VME Indicator					
Anemones	928	100	100	100	95
Black coral	438	100	100	100	99
Cup coral	51	100	100	100	98
Gorgonian	528	100	100	100	99
Sea pen	490	96	96	98	82
Soft coral	26	81	81	85	85
Sponge	171	100	100	100	98
Stony coral	871	100	100	100	99.7
Lace coral	1	100	100	100	100
VME Habitat					
Cold-water coral reef	988	100	100	100	99.6
Cold seeps	1	100	100	100	100
Coral garden	1944	100	100	100	98
Deep-sea sponge aggregations	7	100	100	100	100
Mud and sand emergent fauna	4	100	100	100	100

Figures

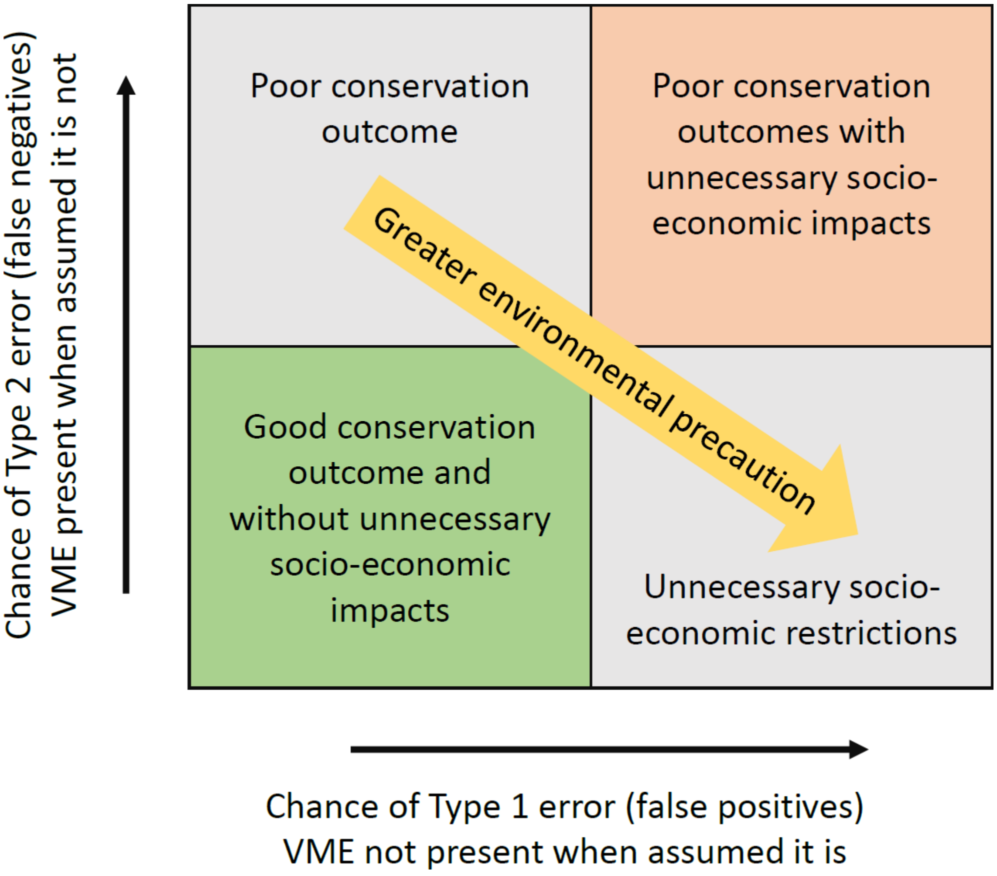


Figure 1. Conceptual overview of the consequences of Type 1 and 2 errors when designing protective measures for Vulnerable Marine Ecosystems (VMEs) to achieve the objectives of the United Nations General Assembly resolutions 61/105 (UNGA, 2006) and 64/72 (UNGA, 2009).

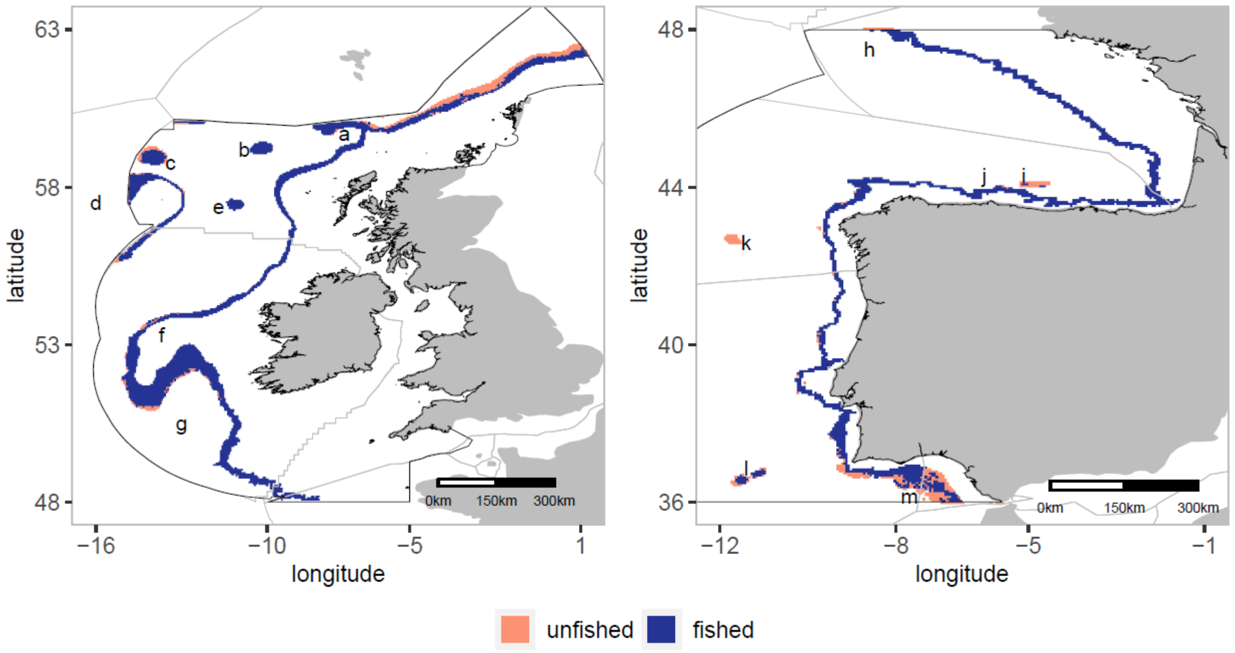


Figure 2. Fishing footprint (blue area) between 400-800 m depth of all bottom-contacting fishing gears (mobile and static) in 2009-2011. Left panel: Celtic Seas ecoregion; Right panel: Bay of Biscay and the Iberian Coast ecoregion. The letters show the approximate location of: Wyville-Thomson ridge (a), Rosemary Bank (b), George Bligh Bank (c), Hatton-Rockall Basin (d), Anton Dohrn Seamount (e), Porcupine Bank (f), Porcupine Seabight (g), Mériadzek Terrace (h), El Cachucho (Le Danois) (i), Avilés canyon system (j), Galicia Bank (k), Gorringe Bank (l), Gulf of Cádiz (m).

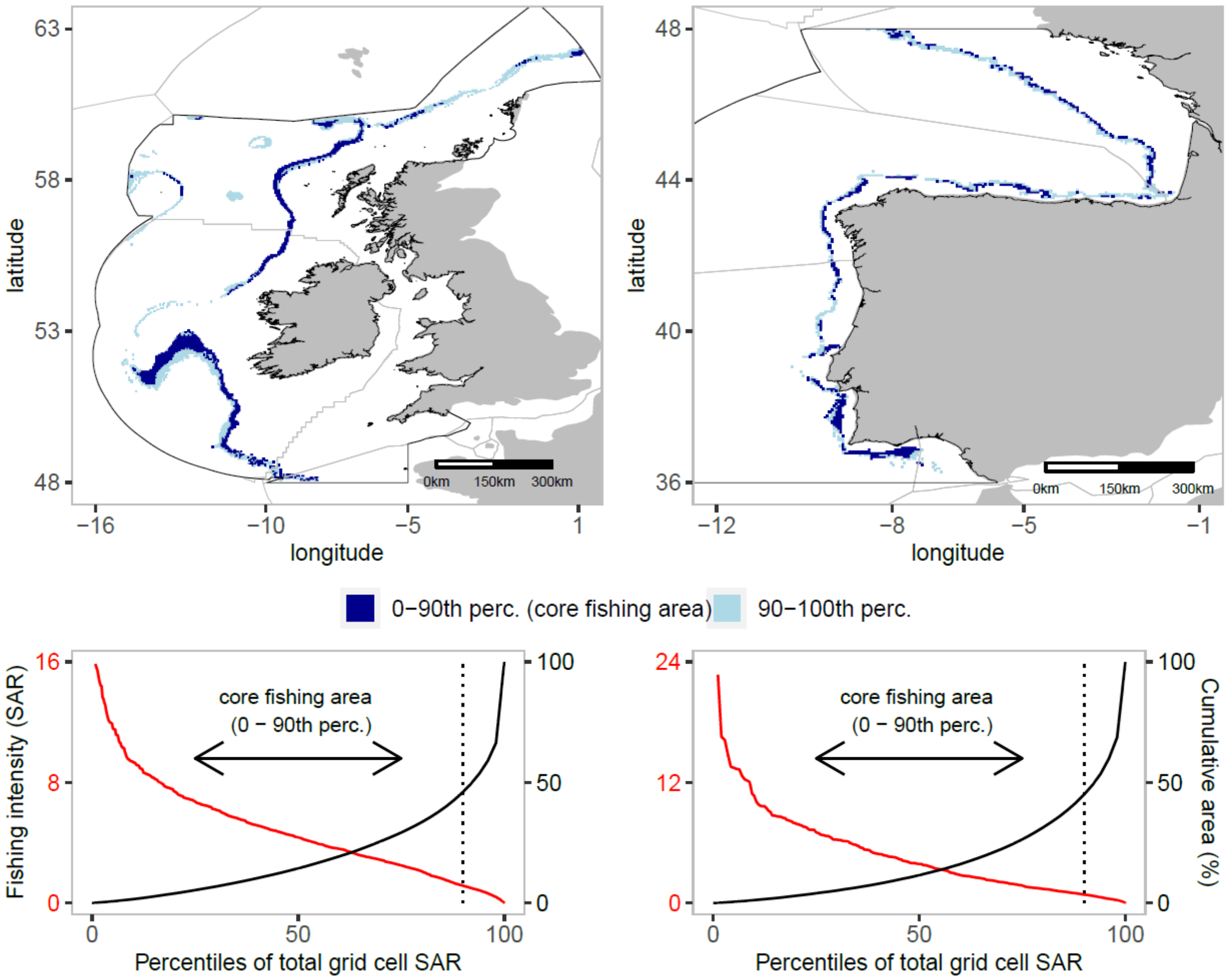


Figure 3. Upper panel shows maps of the core fishing area (dark blue area) for otter trawl gears (the dominant mobile gear grouping) within the fishing footprint based on average SAR per year for 2009-2011. The lower panel shows all C-squares within the fishing footprint sorted from high to low SAR (red lines) and the cumulative area of these C-squares (solid black lines) as a function of the percentiles of total SAR intensity in the footprint. Left panel: Celtic Seas ecoregion; Right panel: Bay of Biscay and the Iberian Coast ecoregion. In both ecoregions, the lower panel plots show that 90% of total SAR intensity occurs in less than 50% of the C-squares that are fished (the vertical dashed line intersects the solid black line below 50%). Note that the estimation of the core fishing area is affected by the VMS merging issue described for Spanish vessels in the “Caveats

and Limitations of the Fishing Footprint” section, so caution is needed in areas where this fleet is responsible for an important part of the total fishing pressure.

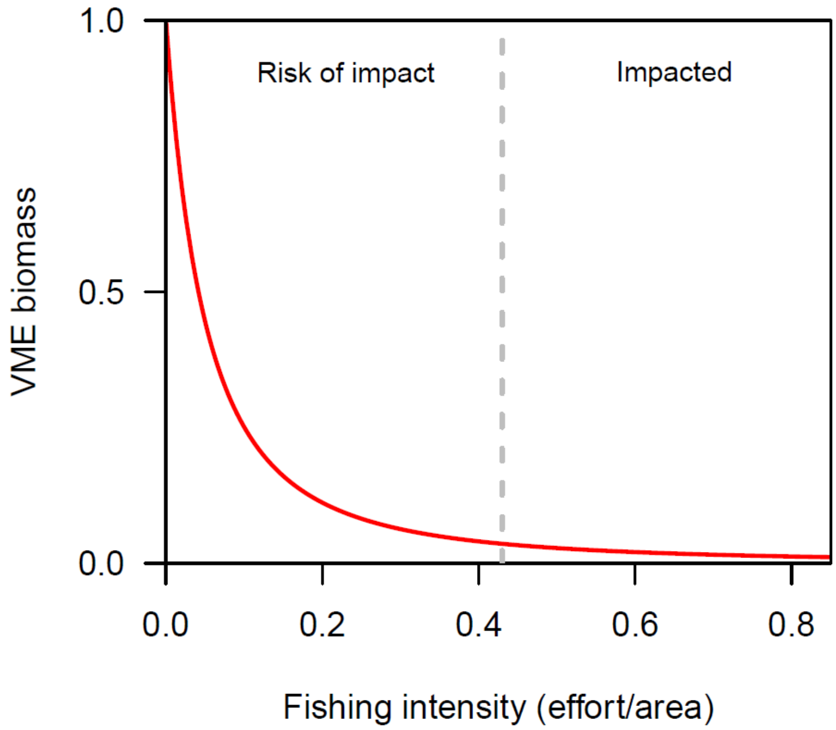
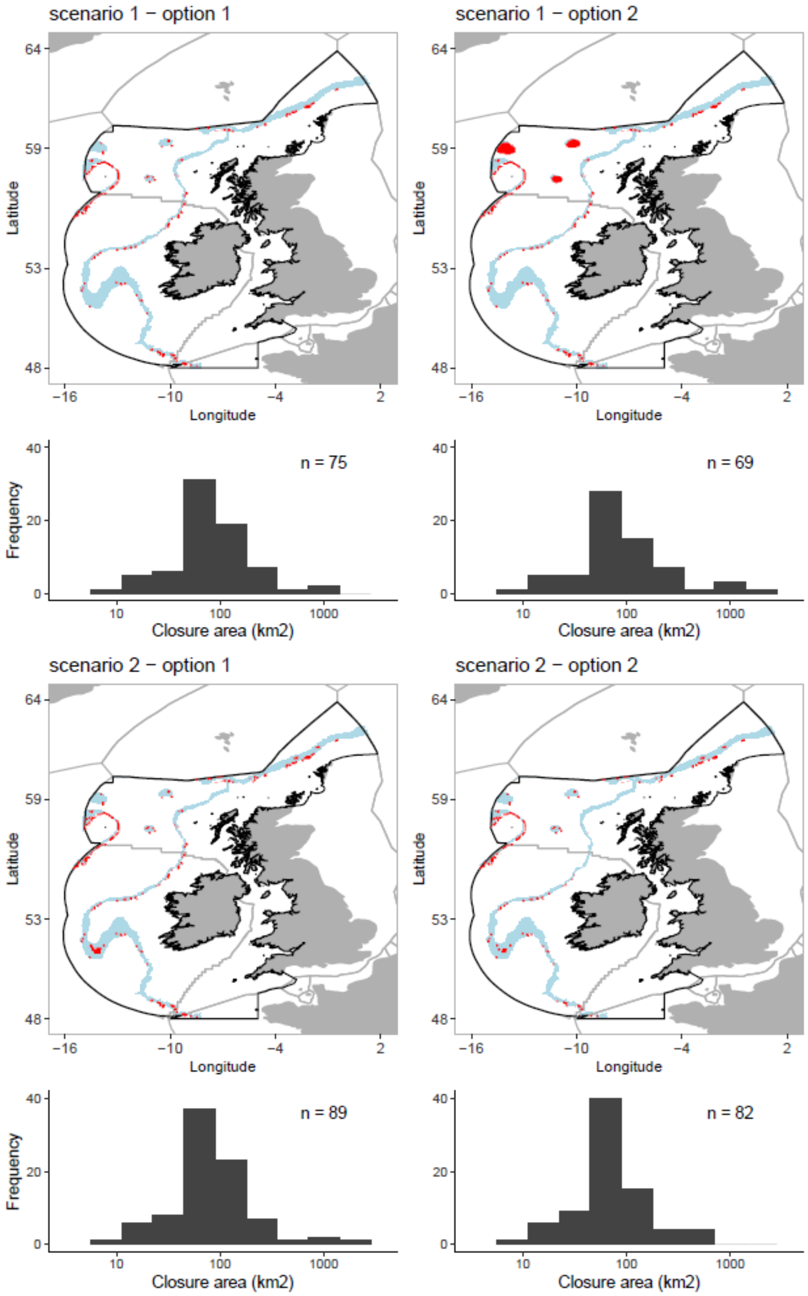


Figure 4. Example showing the hypothetical relationship between biomass of VME species in the catch with increased fishing intensity. The dashed line indicates the threshold below which fishing intensity still negatively impacts VMEs. Above this threshold fishing intensity is so high that > 95% of VME biomass is removed and it is unlikely that further fishing results in SAI.


scenario 1 − option 1

scenario 1 − option 2

scenario 2 − option 1

scenario 2 − option 2

Figure 5. Maps of closures (red) within the 400-800 m depth range (light blue) and histograms of the size of the closed areas following the two different Scenarios, each with two options for the Celtic Seas ecoregion. The total number of closure areas is in the upper right of each histogram and ranges from 69 to 89.

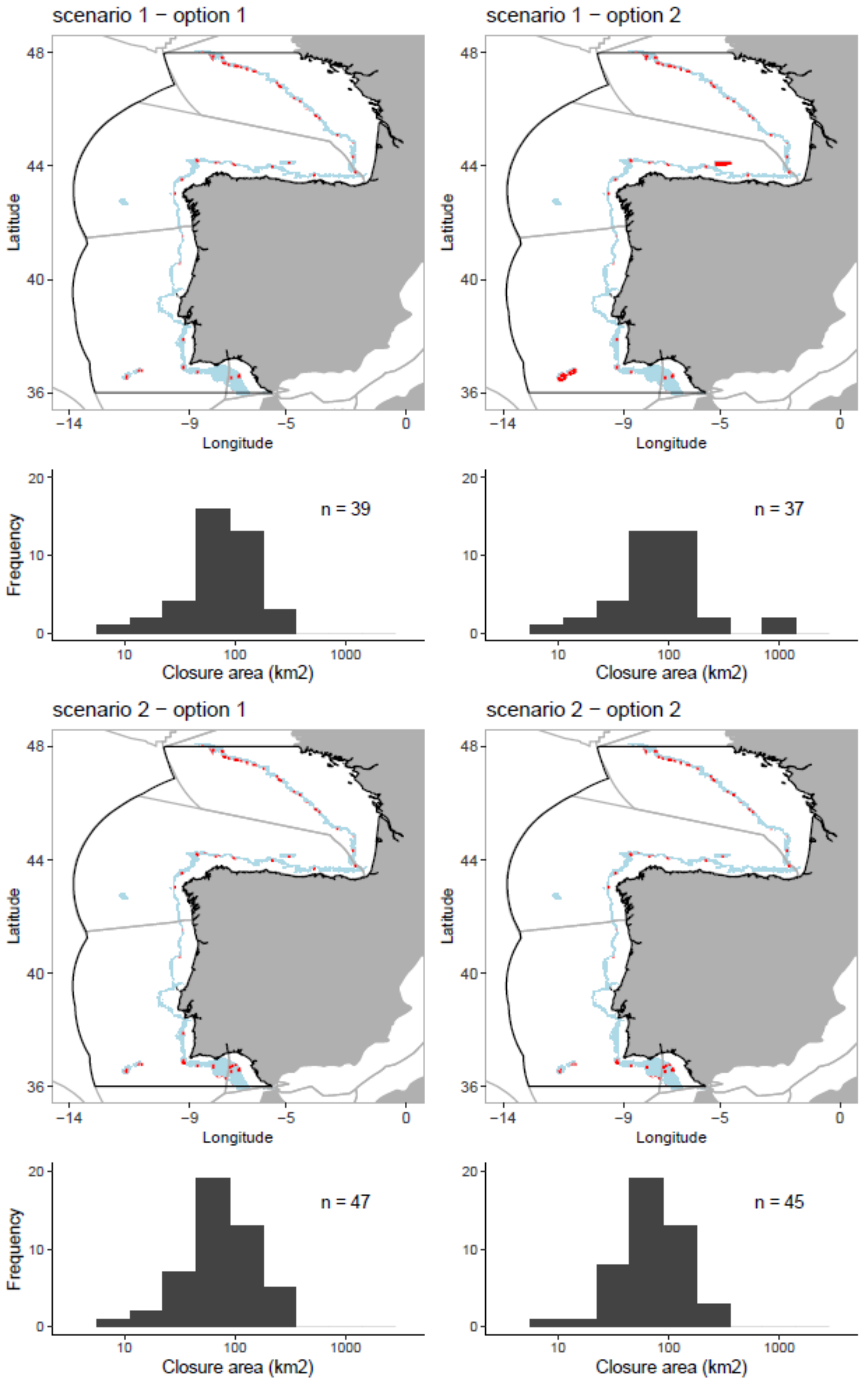


Figure 6. Maps of closures (red) within the 400-800 m depth range (light blue) and histograms of the size of the closed areas following the two different Scenarios, each with two options, for the Bay of Biscay and Iberian Coast ecoregions. The total number of closure areas is in the upper right of each histogram and ranges from 37 to 47.