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Reference points for assessing significant adverse impacts on deep sea vulnerable marine ecosystems

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ABSTRACT

Biodiversity loss due to human activities is a critical issue, particularly in the High Seas where bottom-contact fishing poses a significant threat to Vulnerable Marine Ecosystems (VMEs). Deep sea VMEs, tend to be composed of slow-growing, long-lived benthic organisms such as deep-sea corals and sponges. The United Nations Food and Agriculture Organization (FAO) has developed guidelines to protect these ecosystems from Significant Adverse Impacts (SAI) caused by bottom trawling activities.

This study focuses on the Northwest Atlantic Fisheries Organization (NAFO) Regulatory Area, utilizing fishery-independent surveys and fishing Vessel Monitoring System (VMS) data to map fishing intensity and VME functional type biomass. Seven VME types have been assessed, e.g., large-sized sponges, sea pens, sea-squirts, bryozoans, black corals, large and small gorgonian corals, to determine the risk of impact. Results indicate that sponges, black corals, and large gorgonians are the most sensitive VME types to bottom trawling activities, with significant biomass loss occurring at very low fishing intensities. The study defines bottom trawling biomass impact thresholds for each VME type in the range of 0.12–9.43 km·km^{-2}·yr^{-1} and 0.01–0.11 km·km^{-2}·yr^{-1} for upper and lower impact thresholds, respectively. The study determines that rapid losses in VME biomass occurs at bottom trawling intensities of about 0.10 km·km^{-2}·y^{-1} for fisheries operating in the NAFO Regulatory Area. The study concludes that modest reductions in fishing effort in sensitive areas could substantially mitigate SAI whilst having little or no impact on fishing opportunities. The findings also support the target of protecting at least 60 % to 70 % of VME biomass to likely ensure good seabed status; and the importance of implementing spatial fisheries management measures, such as defining a fishing footprint and establishing fishery closed areas, to protect VMEs.

1. Introduction

Biodiversity loss caused by environmental change brought about by human activities is fast becoming one of the most serious ecological challenges facing humanity (Clausen and York, 2008; Danovaro et al., 2008). In this respect, bottom contact fishing activities in the High Seas pose a significant threat to vulnerable marine ecosystems (VMEs) that host diverse and fragile communities typically composed of slow-growing, long-lived and fragile benthic organisms, such as deep-sea corals and sponges (Fuller et al., 2008; Beazley et al., 2013; Beazley et al., 2015; Murillo et al., 2016; Murillo et al., 2020a; Murillo et al., 2020b). Such VMEs are often associated with geomorphological

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features, for example; seamounts, canyons, ridges, spurs, steep slopes, and knolls (FAO, 2009).

In 2003, the protection of deep-sea VMEs in the high-seas was raised as a standing issue for the Consultative Process of the United Nations General Assembly (UNGA, 2003). Accordingly, the Food and Agriculture Organization of the United Nations (FAO) developed non-legally binding "International Guidelines for the Management of Deep-sea Fisheries in the High Seas" (FAO, 2009) which remains the foundation for global actions to identify and protect VMEs from significant adverse impacts (SAI) caused primarily by bottom-contact fishing gears (FAO, 2016). The guidance provides an interpretation of the scope of the analysis that is required for an assessment of SAI, e.g. "when determining the scale and significance of fishing impacts on VMEs, the following six criteria should be considered: (i) the intensity or severity of the impact at the specific site being affected; (ii) the spatial extent of the impact relative to the availability of the habitat type affected; and (iii) the sensitivity/vulnerability of the ecosystem to the impact, (iv) the ability of an ecosystem to recover from harm, and the rate of such recovery, (v) the extent to which ecosystem functions may be altered by the impact; and (vi) the timing and duration of the impact relative to the period in which a species needs the habitat during one or more of its life-history stages." Therefore, an assessment of the location and extent of the risk of SAI to VMEs requires knowledge of the distribution of biomass for each of the VME indicator taxa of interest, delineation of their significant concentration, an understanding of how sensitive each taxon is to bottom fishing impacts, and the distribution of bottom fishing intensity, both temporally and spatially.

To date, Coastal States and Regional Fishery Management Organisations (RFMOs) have focussed on identifying areas where VMEs are known or likely to occur and on implementing spatial closures to protect them (FAO, 2016). Less work has been done to assess SAI which could allow fishing to proceed in areas of VME under certain conditions. However, of the six criteria listed in the FAO guidelines, the focus has been to assess the spatial extent of the impact relative to the availability of the habitat type affected (criteria ii and iii), from data which are more commonly available, and to determine the expected vulnerability of the ecosystem to fishing disturbance based on either trawling impact literature or through scientific (fishery independent) surveys.

Among RFMOs globally, the Northwest Atlantic Fisheries Organization (NAFO) benefits from a long history of fishery-independent surveys, thereby offering access to considerable quantitative data on the abundance and distribution of VME indicator species within the NAFO Regulatory Area (NRA). For other RFMOs, this remains an aspiration for a variety of reasons (Bell et al., 2019) and precautionary management approaches rightly continue to dominate measures for the mitigation or avoidance of SAI for all RFMOs. However, in data-limited cases, the extent to which management organisations apply the precautionary approach to avoid SAI is largely informed by expert judgement. Therefore, a key challenge is knowing how to determine quantitatively whether SAI has occurred, or is likely to occur, in a given area; essentially to determine the first SAI criterion of the FAO guidelines (FAO, 2009), especially when the availability of data is poor. Historically, this has led to the development of risk-based frameworks (Martin-Smith, 2009; Kenny et al., 2018) that consider the degree of spatial overlaps between fisheries and VMEs, and the application of a precautionary approach, but more integrated assessments and data-driven approaches are required to underpin the effective implementation of ecosystem and fisheries sustainability objectives. Balancing these objectives requires an assessment and quantification of how fishing activity pressures result in an impact or risk of impact in areas of VME and occurrence of VME indicators. Given that NAFO is not the only RFMO aiming to evaluate, manage and mitigate the impacts of bottom trawl fisheries on VMEs (e.g., see Martin-Smith, 2009; Penney & Guinotte, 2013), the approach presented here may offer some utility in supporting environmental impact assessments undertaken by other RFMOs and States, possibly in more data-limited situations, and thus achieve greater coherence in the global management of VMEs.

We present a novel empirical framework to quantitatively determine thresholds for the intensity or severity of bottom trawling impacts in specific VME habitats, and so determine whether or not SAI has occurred or is likely to occur in VMEs within the NAFO Regulatory Area.

2. Materials and methods

2.1. Study area and analytical framework

NAFO delineated a fishing footprint (where bottom fishing is permitted) within the NRA in 2009 based upon bottom documented fishing activity during a 20-year period (1988–2007) from information submitted by fishing vessel flag States (NAFO, 2009c). The western extent of the fishing footprint overlaps the eastern part of the Canadian Grand Banks Continental Shelf (Fig. 1), whilst the remaining parts of the fishing footprint are mostly restricted to depths less than 2000 m, which corresponds approximately to the maximum depth at which commercial bottom trawls in NAFO normally operate.

Although the seaward extent of the NAFO fishing footprint limits trawling to depths of less than 2000 m, in practice the vast majority of the active fishing areas, are concentrated in three depth bands, e.g. 50–100 m, 200–500 m, and 800–1200 m as determined by an analysis of fishing vessel monitoring system (VMS) data between 2010 and 2019. Bottom trawl fisheries in this area also typically follow isobaths rather than fixed headings, especially around the Flemish Cap, the Nose of the Grand Bank, and within the Flemish Pass (Fig. 2). There is also a high degree of spatial patchiness in fishing activity, with very large areas of the fishing footprint having little, or no fishing activity recorded (Fig. 2). For example, about 28 % of the fishing footprint had no fishing activity

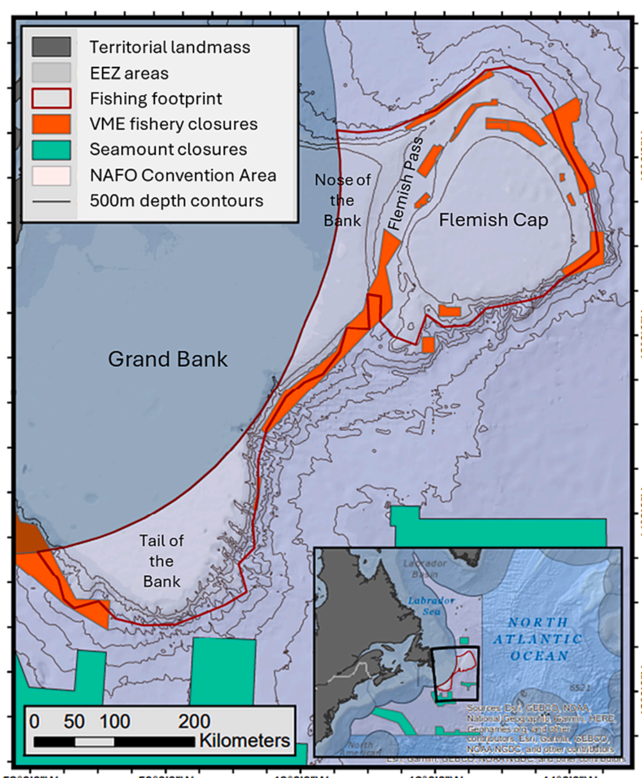

Fig. 1. Northwest Atlantic Fisheries Organization (NAFO) Regulatory Area (NRA) showing seamount fishery closures (light green) and VME coral and sponge fishery closures (orange) established to protect biodiversity hotspots in the High Seas, and the fishing footprint (outlined in red). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

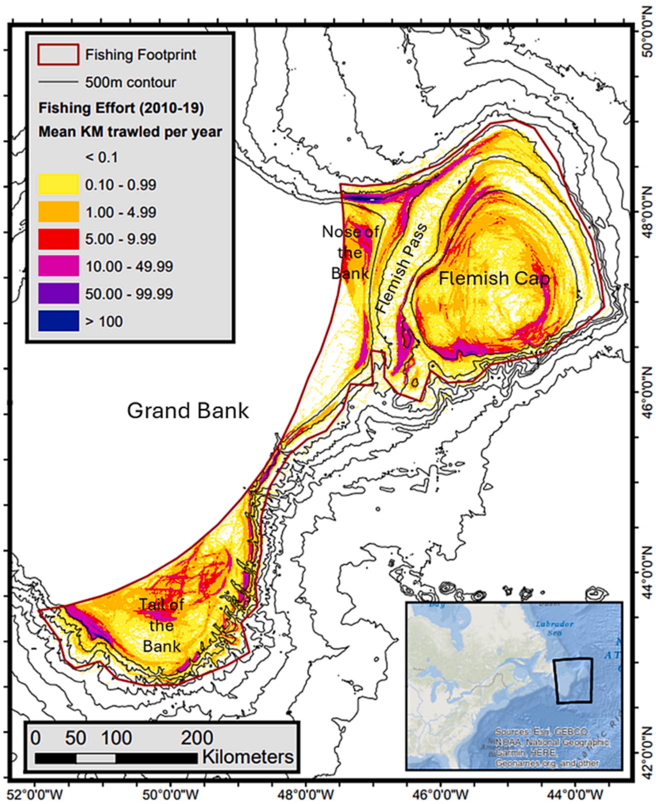

Fig. 2. Distribution of fishing activity (VMS records, 2010–2019) in the NAFO fishing footprint of the Regulatory Area, showing fine scale details of fishing corridors on top of the Tail of the Grand Bank and a number of areas of high fishing effort.

recorded between 2010 and 2019, and a further 16 % had been fished only once or twice in the assessed period.

In January 2010 NAFO established 11 coral and sponge protection zones (NAFO, 2009a; NAFO, 2009b), which were subsequently extended and augmented in number to protect significant concentrations of large sponges and corals (NAFO, 2011) (Fig. 1). Other VME closed areas have been established outside of the fishing footprint for the protection of VME elements (see NAFO, 2023), notably seamounts, bringing the total number of individual VME fishery closures to 27 as of 2024 (NAFO, 2023).

Our hierarchical framework and approach for the assessment of risk of SAI, as applied in the present study, is depicted in Fig. 3, which involves: (i) identification and mapping of VMEs (Section 2.2), (ii) mapping and estimation of fishing effort (Section 2.3), (iii) linking VME surveys with fishing effort (Section 2.4), and (iv) assessment of VME sensitivity and risk of SAI (section 2.5). Together these elements yield a dataset of VME functional type biomass (kg), used to define fishing effort impact thresholds for each VME type, which was generated by selecting scientific survey trawl samples that were within areas of high VME concentration and had some level of associated commercial fishing activity (Lirette et al., 2021), corresponding to the mean annual fishing effort (km·km^{-2}·y^{-1}) between 2010 and 2019 (see Table 1).

2.2. Identification and mapping of VMEs

Following a review of over 500 benthic invertebrate taxa known to occur in the NRA against the characteristics of VMEs outlined in the FAO guidelines (Murillo et al., 2011), a number of VME indicator species were identified and assigned to higher order VME categories (or VME functional types) for the purpose of mapping VMEs and assessing the risk of SAI. The assigned VME functional types are: (i) large-sized sponges (Porifera), (ii) sea pens (Pennatuloidea), (iii) sea-squirts (Ascidiacea), (iv) erect bryozoans (Bryozoa), (v) black corals (Antipatharia), and (vi) large and (vii) small gorgonian corals (Octocorallia), (viii) tube-dwelling anemones (Cerianthids) and (ix) sea lilies (Crinoids). For a full list of the specific VME indicator taxa assigned to each of the VME functional types see NAFO (2023) and associated Supplementary Material.

Biomass data for seven of the VME functional types; large-size sponges, sea pens, bryozoans, sea-squirts (*Boltenia ovifera*), black corals, large gorgonian corals, small gorgonian corals, were obtained

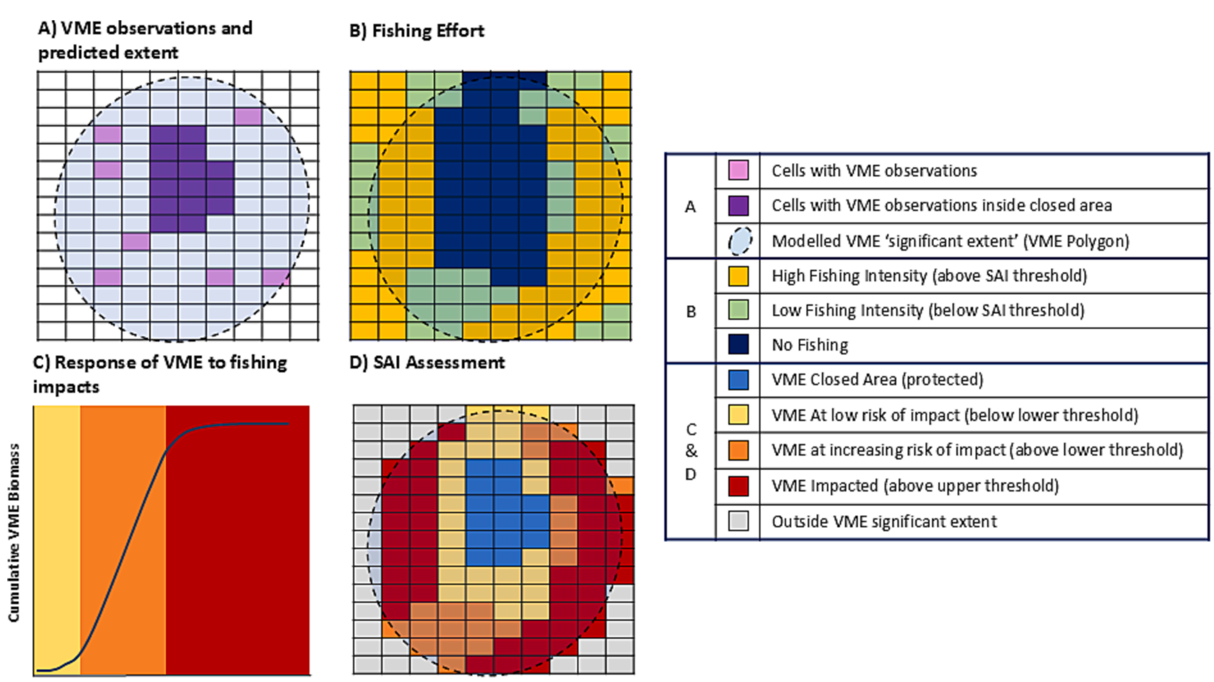

Fig. 3. Schematic representation of the approach taken to assess VME significant adverse impacts (SAI), including the identification of VME (e.g., modelled VME 'significant extent' using KDE analysis to define VME polygons).

Table 1
Number of scientific survey trawls obtained between 2010 and 2019 (inclusive) within each VME polygon used in the present study. (a) the total number of scientific survey trawls in the VME polygons associated with zero fishing effort, (b) the total number of scientific survey trawls with non-zero VME indicator species biomass and associated with at least one VMS track over the ten-year study period, (c) the total number of scientific survey trawls used in the analysis of impact thresholds, excluding unrepresentative scientific survey trawls due to associated uneven distribution of fishing effort, and (d) the total number of scientific survey trawls associated with any fishing effort but having zero VME indicator species biomass.

	Number of Scientific Survey Trawls				
VME type	a) having biomass with zero fishing effort	b) having biomass associated with fishing effort	c) after filtering for uneven distribution of fishing effort	d) associated with fishing effort but zero biomass	e) included in the final analysis
Black Coral	8	20	20	61	85
Boltenia sp. (Sea Squirt)	9	141	137	146	290
Bryozoa	6	55	55	34	94
Large Gorgonians	12	17	17	121	141
Sea Pens	26	234	229	32	286
Small Gorgonians	12	99	95	131	141
Sponges	37	256	249	52	333

from over 3500 scientific trawls collected in the NRA from annual fishery independent surveys, undertaken by the European Union (Spain and Portugal), and Canada (Fisheries and Oceans Canada) between 2011 and 2019. Mapping of VMEs was achieved using kernel density estimation (KDE), which utilises spatially explicit data to model the distribution of a variable of interest and has been applied in this study to the VME functional type biomass data (Kenchington et al., 2014; Kenchington et al., 2016; Kenchington et al., 2019; Kenchington et al., 2020). This non-parametric neighbour-based smoothing function relies on few assumptions about the structure of the observed data and has been widely used in ecology to identify species abundance/biomass hotspots. Accordingly, this serves to identify thresholds in significant biomass, above which the taxon of interest is considered as aggregated, and thus defined as representing a significant concentration of that taxon (Murillo et al., 2010; Kenchington et al., 2014; Kenchington et al., 2019). Such areas, in the present analysis, are termed VME polygons (Fig. 4), and are used to help identify and designate closed areas to bottom fishing by NAFO, as they equate to VMEs (NAFO, 2020). Within the fishing footprint, the current network of VME closures (Fig. 4) accounts for about 38 % of the total area of VME identified within the fishing footprint.

A high spatial resolution VME biomass layer was generated for the study region using ArcGIS Spatial Analyst tool (ArcGIS 10.5) applied to the KDE modelled VME biomass layer to create a raster with a 1 km^2 cell size that was aligned to the same grid used to map the commercial fishing effort.

2.3. Fishing effort estimation

Hourly fishing vessel position VMS data were obtained between 2010 and 2019, inclusive. In order to establish the track of each vessel, data were filtered to exclude records of vessels with speeds <0.5 knots and >5 knots, based on known fishing vessel speeds derived from log-book data, and converted into individual vessel tracks by the NAFO Secretariat using standardized methods (NAFO, 2020). The filtered tracks are therefore assumed to represent paths travelled by vessels during fishing. In addition, each track was attributed with the type of fishing gear used, by reference to the fishing vessel log-book data. The main impact to the seafloor is considered to come from bottom-trawl fisheries (McConnaughey et al., 2020; Hiddink et al., 2019), therefore only bottom trawl fishing effort data were used in the present study, although bottom long-line fisheries also occur in some parts of the NRA (NAFO, 2020). Each track is assumed to represent the extent of the potential impact for a commercial bottom trawl, operating with a 150 m swath width as measured between the otter boards, which is a trawling configuration commonly used by all trawl-vessels operating in the NAFO Regulatory Area.

The benefit of using VMS tracks, as opposed to using gridded fishing

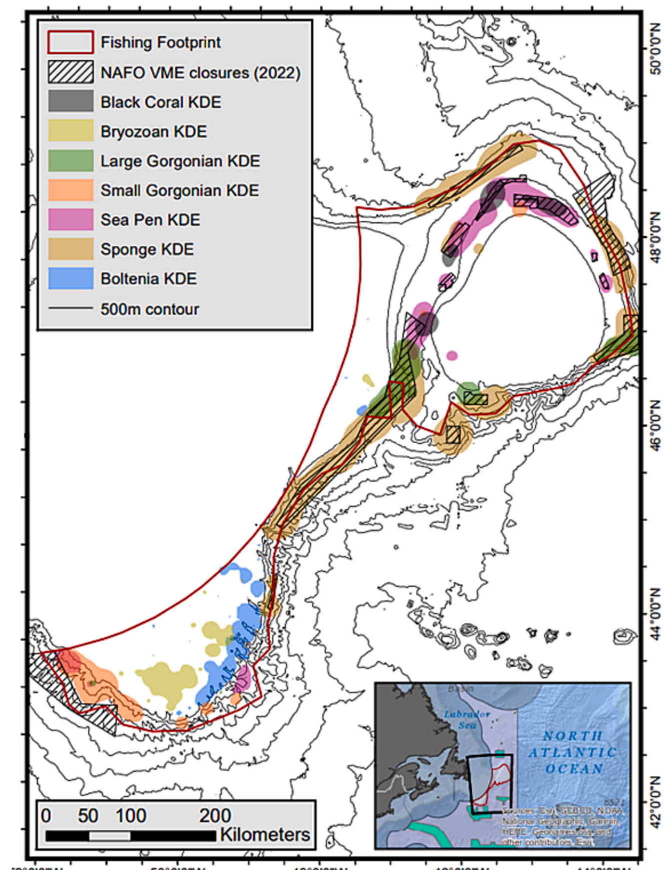

Fig. 4. Combined extent of all VME polygons in the NRA (as of 2021), defined by KDE analyses (Kenchington et al., 2014). The location and extent of VME fishery closures is also shown (Note; the current VME fishery closures were implemented as management measures in 2022 when the last review of VME fishery closures and VMEs was undertaken; the next review of VME fishery closures and VMEs is due in 2027).

effort data, is it describes the ship's direction of travel and passage over ground, which allows for a more spatially resolved assessment of effort to be linked to VME indicator species biomass records from scientific trawl surveys. This is especially important when determining the impact of bottom trawling on VME biomass.

In addition, a high spatial resolution fishing effort raster layer for the study region was produced to determine the effectiveness of area-based management measures (such as fishery closures to protect VMEs). This was achieved using a moving window approach, whereby the total length of VMS tracks within a specified circular neighbourhood was estimated using ArcGIS Spatial Analyst 'Line Statistics' tool (ArcGIS 10.5). The radius of the circular neighbourhood was set at 565 m, which corresponds to an area of 1 km^2. The cell size for the output raster layer was specified as 1000 m and was aligned to the same grid created for the regional VME biomass layer used in the assessment of SAI. The corresponding bottom trawl fishing effort (F_c) within the specified neighbourhood for each raster cell was calculated as:

$$F_c = \frac{D}{A \bullet T} \tag{1}$$

Where the total distance trawled by all vessels (D – km) within each km^2 grid cell (A) per year (T) (km·km^{-2}·y^{-1}), and using the calculated distance travelled and dividing the total track length by the number of years of data (10 years) included in the VMS track line feature. The total tow length in a given grid cell per year was used as a metric of fishing effort as typically the trawl fisheries all use the same type of gear. This value was then converted, for illustrative purposes only in Table 2, to a single estimate of swept area (km^2. yr^{-1}) using a conversion factor of 0.15, specific to the gear dimensions in the present study.

2.4. Linking VME distributions with fishing effort data

Scientific survey trawls, start and end coordinates, were represented as linear tracks in a geographic information system (GIS). Owing to the short duration of survey trawls (15 – 30 min), tracks in excess of 10 km in length were excluded from the dataset to eliminate observations with likely incorrect coordinates. Scientific trawls acquired before 2011 were also excluded from the analysis to allow for at least one year of VMS data to precede the survey trawls used in the present study. Commercial fishing effort was estimated in a 500 m buffer area positioned around each scientific trawl creating a rectangle corresponding to the VME indicator biomass sampled from scientific survey trawls (Fig. 5).

With the scientific survey trawls covering an average distance of between 2 and 3 km, it is possible that some scientific trawls will traverse areas of both high and low VMS track density (as shown in Fig. 5), resulting in only part of a scientific trawl sample corresponding to high or low fishing effort. To take account of potentially large gradients in commercial fishing effort in sampled areas, any scientific trawl sample coinciding with commercial fishing effort above 12.58 km·km^{-2}·y^{-1}, and which had less than 90 % of their area overlapping with commercial trawls, were excluded from further analysis. We found that a fishing effort of 12.58 km·km^{-2}·y^{-1}, derived from fitting a LOESS spline to the survey sample area/commercial fishing effort data, corresponds to more than 90 % of the scientific trawl sample area impacted by commercial trawls. Most scientific survey trawl samples were observed to have an even distribution of commercial fishing effort (based on VMS track data) and therefore relatively few (≤ 4 %) scientific survey trawls were excluded from the final dataset (Table 1).

Fishing effort was calculated by summing the length (km) of VMS tracks between 2010 and 2019 falling inside each scientific survey trawl

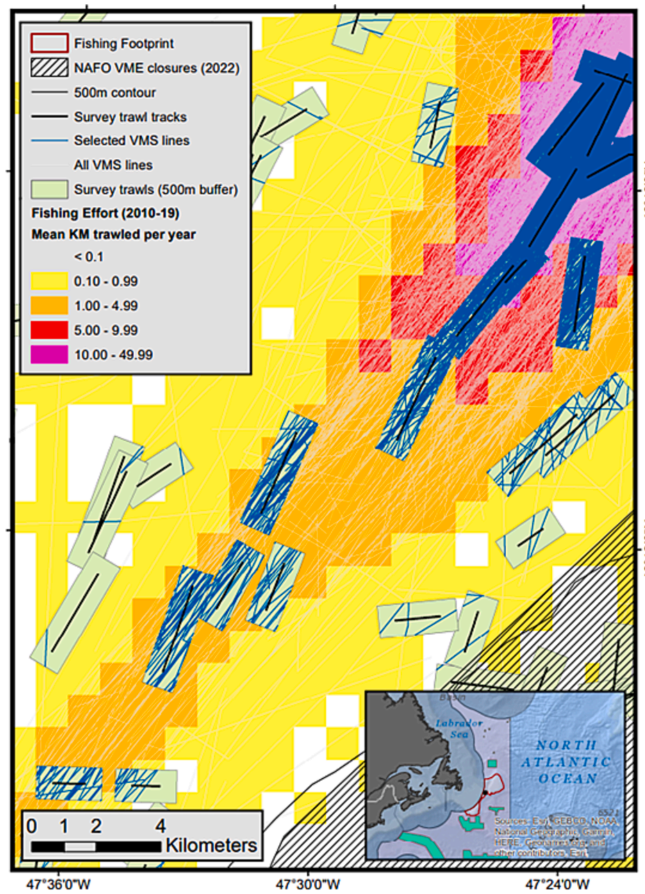

Fig. 5. An example of recorded fishing vessel VMS data showing the area fished as VMS trawl tracks (in grey) and sampled VMS trawl tracks (blue) intersecting the scientific survey trawl sample buffer areas highlighted in green. A corresponding grid of fishing effort (1 km^2) is also illustrated. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 2
Parameter estimates of the fitted logistic model of the proportional cumulative VME biomass in relation to fishing effort, including model fit, estimated lower and upper impact thresholds, along with the corresponding fishing effort (km·km^{-2}·y^{-1}) and Swept Area Ratio (SAR).

	Parameter estimates				Model fit		Estimated		Fishing	Estimated		Fishing
VME Taxon	a	b	x_0	y_0	Standard error	Adjusted r^2	Floor	Lower Threshold	Effort (SAR)	Ceiling	Upper Threshold	Effort (SAR)
Black coral	0.857	−4.409	0.095	0.087	0.071	0.965	0.0872	0.229	0.065 (0.009)	0.944	0.803	0.137 (0.021)
Boltenia	0.96	−2.056	−0.282	0.024	0.047	0.979	0.0236	0.118	0.096 (0.014)	0.984	0.890	0.830 (0.124)
Bryozoa	1	−0.827	1.157	0.021	0.064	0.950	0.0213	0.150	0.114 (0.017)	1	0.871	9.433 (1.414)
Large Gorgonians	0.870	−10.63	0.089	0.050	0.082	0.959	0.0503	0.214	0.077 (0.011)	0.921	0.757	0.102 (0.015)
Sea Pens	0.948	−0.891	0.193	0.049	0.034	0.988	0.0485	0.117	0.011 (0.002)	0.996	0.928	3.386 (0.507)
Small Gorgonians	0.963	−1.536	−0.393	0.026	0.0445	0.985	0.0262	0.115	0.089 (0.013)	0.989	0.900	1.738 (0.261)
Sponge	0.555	−2.45	−0.0506	0.434	0.027	0.939	0.434	0.489	0.020 (0.003)	0.989	0.935	0.125 (0.018)

area (including the buffer) and dividing by the surface area of the sampled area in km^2. Finally, the km·km^{-2} (total VMS track length by buffer area) was divided by the number of years in the track dataset (10 years) to derive the average fishing pressure in km·km^{-2}·y^{-1} corresponding to the sampled VME indicator species biomass from each scientific survey trawl sample.

The dataset for each VME type includes observations in which scientific trawl samples come from within protected areas (i.e., zero current fishing effort), from within VME polygons which have an estimate of fishing effort, but at which the VME type was not observed (i.e., zero biomass in the trawl from within the VME polygon), and all non-zero biomass observations of the VME taxon with associated fishing effort estimates (Table 1). Scientific trawl samples outside the fishing footprint and outside the VME polygons were excluded from the analyses.

2.5. VME sensitivity and SAI assessment

We identified 84 VME polygons within the fishing footprint in the NAFO Regulatory Area. Of these, only a few are completely protected by closed areas (e.g. a sponge VME on Beothuk Knoll, sea pen VME polygons to the east of the Flemish Cap). Therefore, evaluation of significant adverse impacts (SAI) resulting from bottom contact fishing requires an assessment of where unprotected biomass of VME can continue to exist in relation to fishing effort, based on empirical observations.

Accordingly, it may be argued that the current biomass distribution of VME indicator taxa will vary, at least in part, as a function of both the availability of suitable habitat, the spatial–temporal patterns in bottom fishing intensity, and the sensitivity of each VME type to the impact of commercial trawling. Further, catchability issues will heavily influence the risk of SAI. For the KDE analyses identifying VMEs, catchability is not such a large issue as long as it is similar across the habitat, as it identifies relative hot spots of biomass. Here, catchability is a factor especially when equating commercial catches of VME biomass with those from survey trawls to the extent the present assessment of impact may be underestimating the true extent of VME biomass removal caused by commercial trawling. The balance of these factors operating over decades of fishing results in the present-day state and distribution of VME (i.e., significant aggregations of VME indicator species) as determined by KDE analysis.

The interaction between fishing intensity and VME biomass was assessed by ranking every survey trawl sample biomass within the area of impact on a gradient of corresponding increasing fishing intensity and plotting the observed cumulative sampled VME biomass along the fishing effort gradient based on all available observations within a VME polygon, as illustrated in Fig. 6. The cumulative distribution is derived by comparing the biomass of VME from all sites below a specified level of fishing effort relative to the sum of biomass from all scientific trawls within the VME polygons. For each VME type, an assessment of the level of fishing effort at which VME is considered as at *low risk of impact*, at *increasing risk of impact*, and *impacted* by bottom trawl fisheries based on estimates derived by fitting a four-parameter logistic function to the proportional cumulative biomass of VME in relation to fishing effort:

$$y = y_0 + \frac{a}{1 + \left(\frac{x}{x_0}\right)^b} \tag{2}$$

where y is the cumulative proportion of VME biomass, x is fishing effort (km·km^{-2}·y^{-1}), and a, b, x_0, and y_0 are parameters estimated using iterative least squares. The lower (y_0) and upper ($y_0 + a$) asymptotes reflect the proportion of the VME taxon protected by closures, and our estimate of the maximum VME loss that can be detected considering the

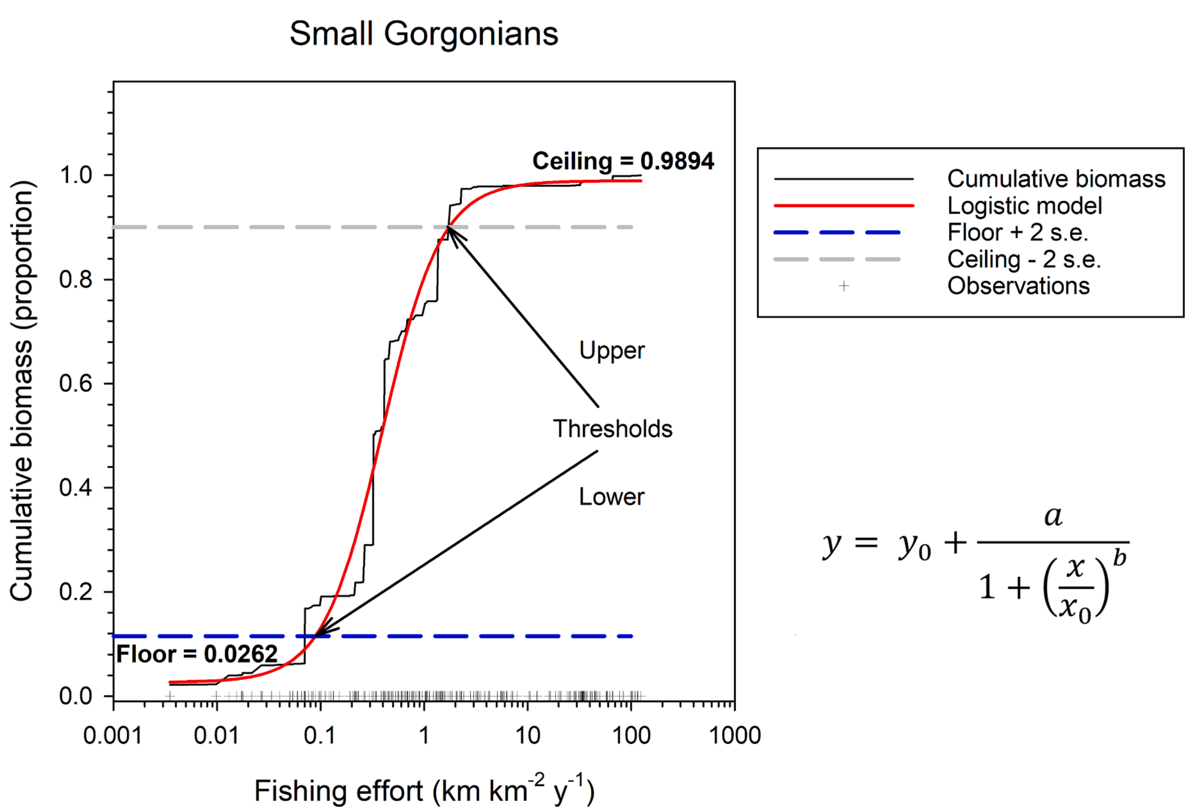

Fig. 6. Illustrative example of the relationship between cumulative VME biomass in relation to fishing effort. The black line represents the proportional cumulative biomass of small gorgonian in relation to associated fishing effort using sampled biomass. The red line represents a fitted four-parameter logistic function; the dashed blue and grey lines represent the upper and lower estimates of the confidence intervals (+2 s.e.) for the 'floor' and 'ceiling' of the functional relationship. Crossed tick marks along the x-axis represent the distribution of observations from which the cumulative biomass and functional relationship was derived. The logistic equation fit to the data is provided for reference. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

uncertainty in our data, respectively.

Estimates derived from equation (2) allow the identification of the 'floor' and 'ceiling' of VME biomass for each VME type at which the rates of accumulation (or loss) of VME biomass in relation to fishing effort are low (Fig. 6). The upper and lower impact thresholds are determined by adding (lower) and subtracting (upper), twice the standard error of the logistic model fit to the floor and ceiling values of the cumulative distribution of VME biomass, respectively. Twice the standard error of estimates of the floor and ceiling represent the upper and lower 95th confidence intervals of the estimates and therefore provides an objective approach to defining the lower and upper impact thresholds based on the quality of the data from which we estimate the functional relationship between the occurrence of fishing activity and areas of high VME concentration. The lower threshold represents the reference point below which VME are essentially unimpacted by current fishing effort, the upper threshold represents the reference point at which VMEs are impacted by bottom trawling activities. The interval of fishing effort between the lower and upper impact thresholds represents the level of fishing effort at which VMEs are at increasing risk of impact (SAI). Estimates of the fishing effort associated with lower and upper thresholds are determined by solving equation (2) for x using the parameter estimates for each VME.[2]

Each 1 km^2 cell of the gridded biomass layer within the VME polygons from the KDE analyses was assessed in relation to fishing effort to one of four impact assessment categories namely: (i) ***protected***, either in fishery closures or outside the fishing footprint (FF) where fishing is prohibited by virtue of the fishing footprint and/or by VME fishery closures; (ii) ***low risk of impact***; in areas where fishing is permitted (within the fishing footprint and inside VME polygons), but where fishing has been limited or did not occur between 2010 and 2019 and is below the lower impact threshold of fishing effort; (iii) at ***increasing risk of impact***: in any area where fishing has occurred between 2010 and 2019 within the fishing footprint that overlaps with VME polygons at levels between the lower and upper impact thresholds; and (iv) ***impacted***: in any area where fishing has occurred between 2010 and 2019 within the fishing footprint and VME polygons, at levels of fishing effort greater than the upper impact threshold.

3. Results

3.1. Linking VME distributions and fishing effort

Plots of cumulative VME biomass against ranked fishing effort are shown for small gorgonian corals (Fig. 6), large-size sponges, sea pens, sea-squirts (*Boltenia* sp.), bryozoans, black corals, and large gorgonian corals (Fig. 7). A logistic relationship fit to all observations provides a very good representation of the data for 5 of the 7 VME types, with only large-size sponge and bryozoan VMEs requiring adaptations of the functional model. The high proportion of large-size sponge VME scientific trawl samples in areas protected by closures required that we exclude the observations from within the sponge fishery closures to accurately fit the logistic model in relation to changing fishing effort. The biomass observations from within the closures were nevertheless used in the estimation of cumulative relative biomass to estimate the lower fishing effort threshold. In the case of bryozoans, the asymptote (a) was fixed to a value of 1 rather than estimated because the limited number of observations at the higher levels of fishing effort at which the VME occurs resulted in an unrealistic estimate of the upper asymptote. For all VMEs the fit to the logistic model is highly significant ($p < 0.001$), and the parameters of equation (2), estimated floor, ceiling, and impact thresholds are provided in Table 2. Model uncertainty, represented by the standard error of the estimate, has a strong influence on impact threshold estimates, with the lower thresholds increasing with increasing uncertainty ($r = 0.89$, excluding sponges, $p < 0.05$) while the upper thresholds decline with increasing uncertainty ($r = -0.96$, $p < 0.05$). These dependencies imply that data quality may have important consequences for the application of precautionary principles in the designation of VMEs at risk or impact.

3.2. VME sensitivity

The shape of the response curves in Figs. 6 and 7 indicates that decreasing the impact thresholds (in terms of fishing effort) by only a small amount could substantially mitigate bottom trawling impacts whilst minimising potential losses in fishing opportunities by the fisheries. For instance, the difference in fishing intensity between the lower and upper impact thresholds for large-size sponges, black corals and large gorgonians, equates to an increase in the trawl fishing intensity of just 0.10, 0.07 and 0.02 km·km^{-2}·y^{-1}, respectively. These values are the nominal equivalents of 1 trawl per km^2 in the entire 2010–2019 period or an average trawling frequency ($\sim<0.1$ y^{-1}), which therefore represent areas of little importance to the fishery, but represent potentially significant reductions in VME impact and risk of impact.

The shape of the pressure-biomass response curves are deemed to represent a measure of VME sensitivity to capture, such that inflexion points of increasing VME impact corresponding to relatively low levels of fishing effort is indicative of increased VME sensitivity (or catchability) to bottom trawling (Fig. 8). In this case, the analyses reveal that large-size sponges, black coral and large gorgonians are the most sensitive VMEs, compared to small gorgonians, sea pens and sea squirts (*Boltenia* sp.), followed by the bryozoan VME which is the least sensitive to bottom trawling activities (Fig. 8). This makes sense as the larger corals and sponges are more likely to be caught and retained by the trawl gear used by fisheries in NAFO.

3.3. SAI assessment

Based on the proposed lower and upper impact thresholds for each VME functional type (Table 2), VME loss (% areal extent and % biomass) were estimated (Table 3a and b). We estimate that between about 1 % and 39 % of the extent of the different VME functional types in the NRA are considered to have been impacted (>upper impact threshold) between 2010 and 2019 (Table 3a). By contrast, areas subject to any level of fishing activity (including areas fished at intensities between the lower and upper impact thresholds) raises this to between about 25 % and 86 % of the extent of the different VME types, with small gorgonians, bryozoans, sea pens and sea-squirts (*Boltenia sp.*) all having had their extent impacted substantially (77 %, 76 %, 54 % and 86 %, respectively). Large-size sponges, large gorgonians and black corals have the largest proportion of their biomass protected in areas that are closed to bottom fishing (93 %, 89 % and 72 %, respectively; Table 3b), with other taxa having between about <1 % and 57 % of their biomass in areas closed to bottom fishing. An example of the spatial distribution for each of the assessed impact-risk categories for the large sponge VME is presented in Fig. 9. Fig. 9 shows that much of the large sponge biomass occurrence outside the fishery closures and within the fishing footprint is impacted by bottom fishing. It also highlights that some areas of large-size sponge VME (below the lower impact threshold) appear to have limited fishing effort and could therefore be added to adjacent closures to avoid the possibility of further losses. Maps of impact-risk for the other 6 VMEs types assessed are provided in the Supplementary Material.

Crucially, this analysis suggests that given a very modest reduction in the area actively fished at the lowest levels of fishing effort, a substantial reduction in the risk of impact could be achieved, especially for the black coral, sea-squirt (*Boltenia sp.*), large gorgonian, small gorgonian, and sponge VMEs. For example, excluding bottom trawling from areas with a historic fishing intensity of less than 0.10 km·km^{-2}·y^{-1} (2010–2019)

[2] Note: if ($b < 0$, y_0, y_0+a), $.f = y_0 + a|x/x_0|^{|b|}/\left(1+|x/x_0|^{|b|}\right)$

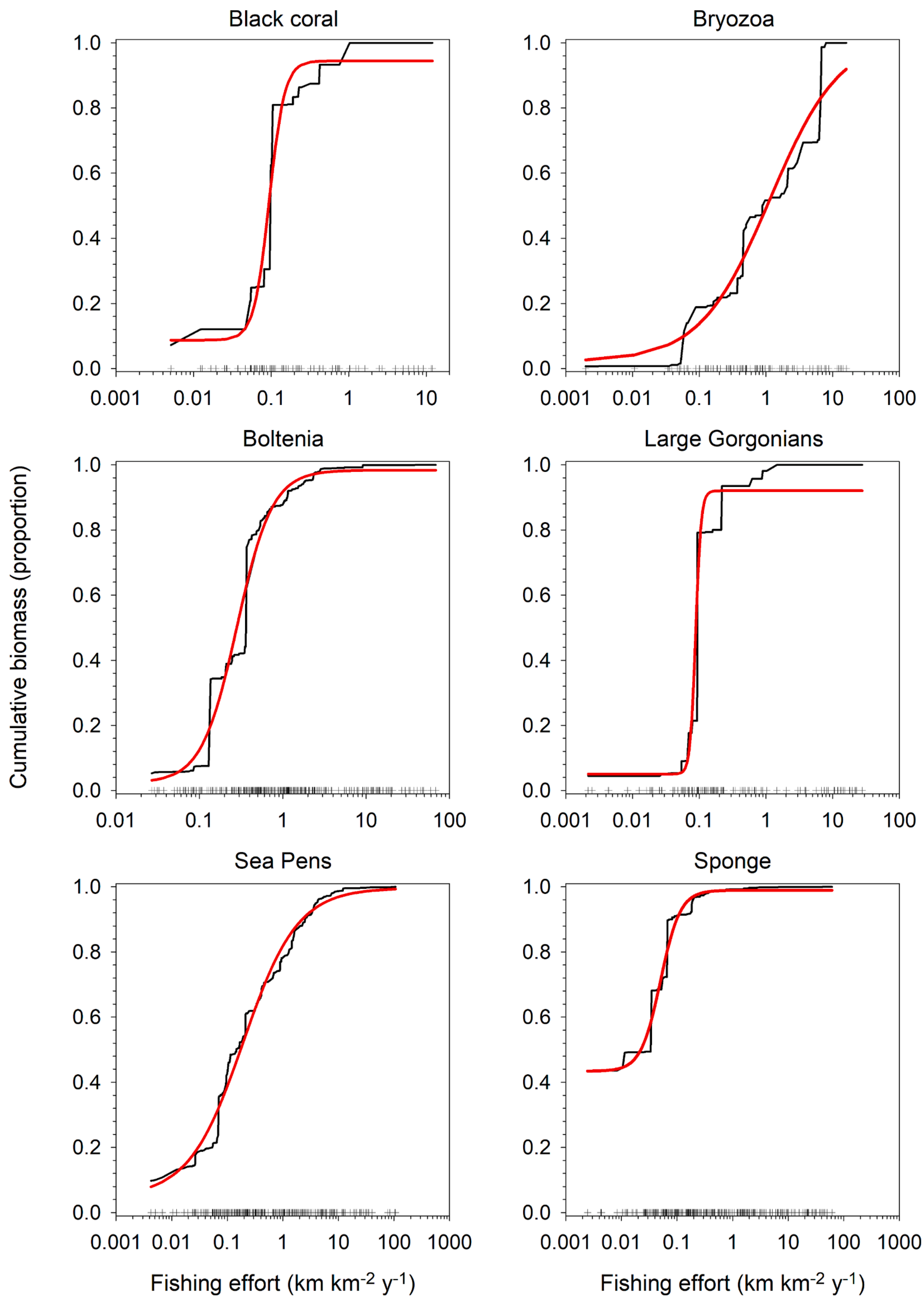

Fig. 7. Relationship between proportional cumulative VME biomass in relation to fishing effort. The black line represents the proportional cumulative biomass of small gorgonian in relation to associated fishing effort based on our observations; the red line represents the fitted four-parameter logistic function. Crosses along the x-axis represent the distribution of observations. Data to recreate these plots is given in the supplementary material. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

would increase the overall protected proportion of VME biomass in the NRA by an average of 20 %.

4. Discussion

Our investigation has mapped and quantified fishing intensity and VME biomass within a significant part of the northwest Atlantic. In doing so, we have developed a hierarchical analytical approach to identify VMEs likely to be at risk of impact from bottom trawling activities and VMEs that have been impacted.

An ecosystem-based approach to fisheries management (EAFM) requires (*inter alia*) robust estimates of the risks of VME impact by fishing activities, at meaningful ecological and fishery spatial scales. Quantitative risk assessments that link spatially explicit information on the

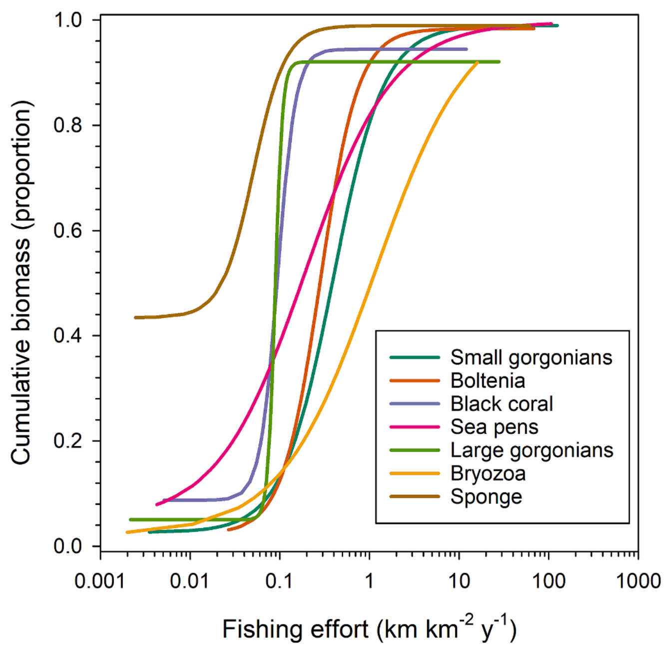

Fig. 8. Comparison of the estimated sensitivity of the assessed seven VME types to bottom contact fishing effort.

vulnerability of ecosystem components with the occurrence and magnitude of pressures are also necessary for the successful implementation of EAFM (Stelzenmüller et al., 2015). In this respect, there are some important considerations that must be addressed when assessing the impact-risk of bottom fishing on VMEs; namely: (i) identifying and mapping the ecologically and biologically significant components of the ecosystem, (ii) mapping the extent and intensity of human activities or pressures likely to cause impact, and (iii) defining the sensitivity of the ecologically and biologically significant components to activities that overlap with their distribution.

For the majority of the VMEs assessed in the present study, the first point of rapid loss in biomass in a VME polygon, typically occurs at a bottom trawling intensity of about 0.10 km·km^{-2}·y^{-1} (which represents a trawling frequency of about once per decade) at which point between 10 % and 20 % of the biomass is removed. Black coral and large gorgonians demonstrate an almost binary response to increasing fishing effort above the lower impact threshold, with a difference between the lower and upper impact thresholds being defined by less than 0.1 km·km^{-2}·y^{-1} difference in fishing effort. In contrast, the more gradual depletion of biomass in response to increasing fishing effort observed for some other VME types (e.g. Bryozoa, sea-squirts and sea pens) possibly reflects differences in their relative catchability and sensitivity to the impacts of bottom trawling.

It is noteworthy, that our results contrast with a comprehensive *meta*-analysis of trawling impacts conducted on shallower continental shelve benthic assemblages, which shows that trawling frequencies typically about 1 y^{-1} cause an average decline of about 15 % in the biomass of benthos (Hiddink et al., 2017). This compares to declines in VME biomass observed in the present study of between 10 and 20 % at an average trawling frequency of 0.1 y^{-1}, suggesting that some deep-sea habitats (especially black corals, large gorgonians and large sponges) are 10 times more sensitive to the effects of bottom trawling than some shallower continental shelf benthic habitats. Accordingly, identifying areas which are fished at a precautionary fishing effort limit of 0.10 km·km^{-2}·y^{-1}, below which fishing would be prohibited, would in most cases mitigate VME impacts by potentially reducing VME cumulative biomass loss by up to 20 % (Fig. 10).

However, the guidelines for the management of deep-sea fisheries (FAO, 2009) do not stipulate a level (or quantitative definition) of SAI, only that SAI should be avoided or mitigated wherever possible. In any area where bottom contacting activities such as trawling are coincident with significant concentrations of VME indicator taxa, some level of impact (as locally assessed) is arguably unavoidable, but determining what proportion of the overall spatial extent (or biomass) of VME can be impacted without significant loss of ecosystem function, relative to what is available within a region, is a challenge and in many instances remains unknown. Mapping of ecosystem functions has been undertaken in the NAFO Regulatory Area (Murillo et al., 2020a; Murillo et al., 2020b) and the areas where fishing is likely to have SAI (increasing risk of current impact and impacted) could be incorporated into future assessments of SAI on ecosystem function, potentially as a covariate in a random forest or GAM.

Assigning overall limits of impact, determined by the loss of VME biomass, or areal extent, in a regional context largely remains a subjective exercise, with overall results likely to be dependent on the specific functional characteristics of each VME type under consideration. Indeed, given the uncertainty in determining the actual extent of impacted seabed in areas of increasing risk of bottom trawling, it may be preferential to assess SAI from the perspective of what proportion of VME habitat is protected, rather than how much VME is impacted. In this respect, NAFO is working towards protecting at least 60 % of the biomass, for different VME types, in the NRA to maintain the health and resilience of the benthic ecosystem (NAFO, 2020) and the South Pacific Regional Fisheries Management Organisation (SPRFMO) considers 70 % protection a suitable target to sustain deep-sea benthic VME diversity and function (SPRFMO, 2023). Furthermore, in a recent review of approaches setting thresholds for good ecosystem state of the seabed, it was concluded that thresholds of between 54 and 79 % of the undisturbed seabed community biomass, would typically represent good status (Hiddink, et al 2023), values which are consistent with the overall targets for protecting VMEs in NAFO and SPRFMO.

Another important consideration in determining SAI, in addition to assessing the overall loss of biomass, is how spatially fragmented the VME habitat becomes after impact (Wang et al., 2020; Wang et al., 2024). For example, fishing impacts on VME in one location may have different or significant downstream ecological consequences on other VMEs in a regional context (Wang et al., 2020; Wang et al., 2024) and therefore amplify the SAI of the fishing activity. Furthermore, habitat degradation in the suitable habitat surrounding the VMEs may negatively impact VME indicator taxa recruitment through reducing larval subsidies from the habitat matrix. Therefore, a combination of the proportion of VME biomass protected and the extent of VME fragmentation could provide a more accurate estimate of SAI in a regional context, especially when assessing the spatial extent of the impact relative to the availability of the habitat type affected, as suggested in the FAO guidance (FAO, 2009) and assessed by Wang et al. (2020).

The biomass surfaces used in the present study were derived from research vessel trawl survey catch data (Lirette et al., 2021). Wang et al. (2024) were interested in identifying the suitable habitat matrix for each of the VME taxa under consideration. They used habitat suitability models, which incorporate environmental data to predict distributions, allowing for the probability of occurrence to be interpolated between observations, and extrapolated to unsampled areas. They then estimated the degree of habitat degradation by calculating the percentage of fishing activity occurring within the suitable habitat, the VME patches, and areas of suitable habitat in 20 km buffer zones surrounding the VMEs for each taxon group. Despite the different approach, they also identified the sea squirts (*Boltenia ovifera*), erect bryozoans and small gorgonian corals as having the greatest percentage of fishing activity over their available habitat, and therefore potentially most at risk of SAI from bottom contact fishing.

The estimation of VME specific upper and lower bottom trawling impact thresholds (as determined in the present study) provides a relatively simple measure of quantifying the relative sensitivity of different types of VMEs. However, the method requires considerable

Table 3

3a and 3b. Summary of proposed SAI reference points and corresponding bottom trawl fishing intensity values for the assessed VME types. Summary of area (a) and biomass (b) calculations estimated for each SAI category are given in Table 3a and b, respectively.

(3a)

VME type	Proposed Lower SAI Reference Point (percent biomass)	Proposed Upper SAI Reference Point (percent biomass)	Fishing effort at 40 % cumulative biomass (km·km^{-2}·y^{-1})	Difference in fishing effort between upper and lower threshold (km·km^{-2}·y^{-1})	Area within each category using assigned SAI Reference Point values (% of cells, and km^2)			
					Protected/ Outside Fishing Footprint	At Low Risk of impact (no fishing, or <lower impact threshold)	At Increasing Risk of impact (<upper and > lower impact thresholds)	Impacted (>upper impact threshold)
Black Corals	23	80	0.085	0.071	44.9 % 1181 km^2	16.5 % 434 km^2	8.5 % 223 km^2	30.2 % 795 km^2
Boltenia	12	89	0.205	0.734	0.7 % 27 km^2	13.0 % 533 km^2	47.4 % 1937 km^2	38.9 % 1593 km^2
Bryozoa	15	87	0.452	9.319	0.1 % 5 km^2	23.8 % 832 km^2	75.2 % 2630 km^2	0.9 % 31 km^2
Large Gorgonians	21	76	0.085	0.024	67.6 % 3407 km^2	6.4 % 321 km^2	1.3 % 65 km^2	24.8 % 1250 km^2
Sea Pens	12	93	0.120	3.375	32.9 % 2795 km^2	13.3 % 1133 km^2	43.2 % 3674 km^2	10.5 % 896 km^2
Small Gorgonians	12	90	0.259	1.650	4.1 % 188 km^2	19.2 % 873 km^2	47.9 % 2175 km^2	28.8 % 1306 km^2
Sponges	49	93	0.042	0.104	66.5 % 16425 km^2	8.1 % 2003 km^2	4.8 % 1187 km^2	20.6 % 5099 km^2

(3b)

VME type	Proposed Lower SAI Reference Point (percent biomass)	Proposed Upper SAI Reference Point (percent biomass)	Fishing effort at 40 % cumulative biomass (km·km^{-2}·y^{-1})	Difference in fishing effort between upper and lower threshold (km·km^{-2}·y^{-1})	Biomass within each category using assigned SAI Reference Point values (% of total, and tonnes)			
					Protected/ Outside Fishing Footprint	At Low Risk of impact (no fishing, or <lower cut-off)	At Increasing Risk of impact (<upper and >lower cut-offs)	Impacted (>upper cut-off)
Black Corals	23	80	0.085	0.071	71.6 % 7.5 t	8.7 % 0.9 t	4.2 % 0.4 t	15.6 % 1.6 t
Boltenia	12	89	0.205	0.734	0.5 % 0.2 t	13.6 % 5.6 t	54.9 % 22.8 t	31.0 % 12.9 t
Bryozoa	15	87	0.452	9.319	< 0.1 % < 0.1 t	62.1 % 40.7 t	37.9 % 24.8 t	< 0.1 % < 0.1 t
Large Gorgonians	21	76	0.085	0.024	89.4 % 120.3 t	3.6 % 4.8 t	1.1 % 1.4 t	5.9 % 7.9 t
Sea Pens	12	93	0.120	3.375	56.8 % 56.9 t	10.7 % 10.8 t	29.8 % 29.9 t	2.7 % 2.6 t
Small Gorgonians	12	90	0.259	1.650	3.2 % 0.1 t	22.4 % 0.8 t	58.9 % 2.0 t	15.5 % 0.5 t
Sponges	49	93	0.042	0.104	93.2 % 258 106.8 t	4.7 % 13 090.2 t	1.0 % 2 844.4 t	1.1 % 2 944.1 t

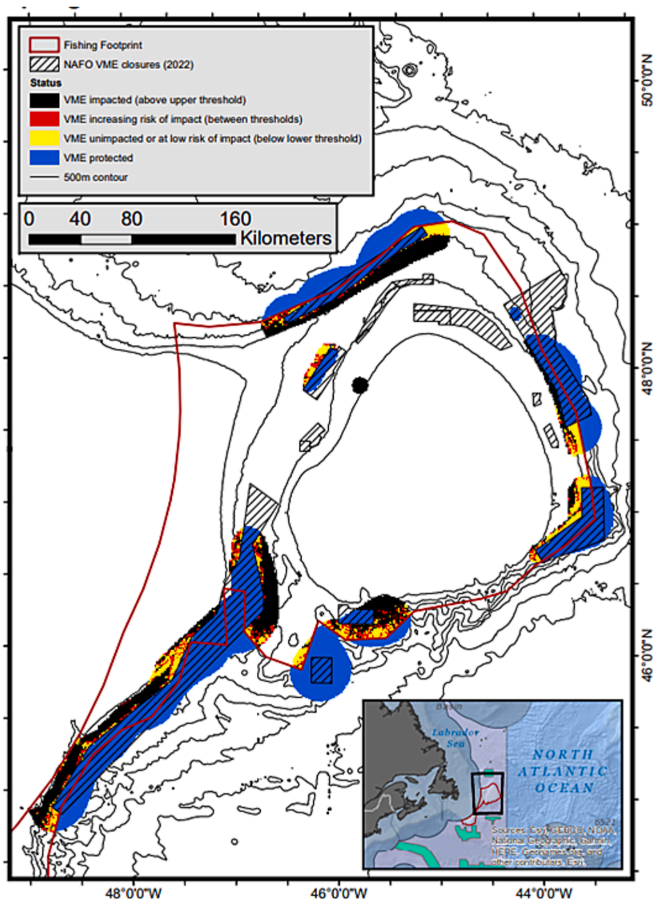

Fig. 9. Current status of the large sponge VME in the NAFO Regulatory Area using the defined assessment categories, e.g. blue polygons are areas which are protected by either fishery closures or the fishing footprint, brown polygons are areas of sponge VME which have either been impacted or are subject to increasing risk of impact (at or above the lower impact threshold), yellow polygons are areas of sponge VME which are at low risk of impact (below lower impact threshold). Tabulated biomass and areal extent values are given in Tables 3a and b, respectively. Figures for the other assessed VME types are provided in the supplementary material. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

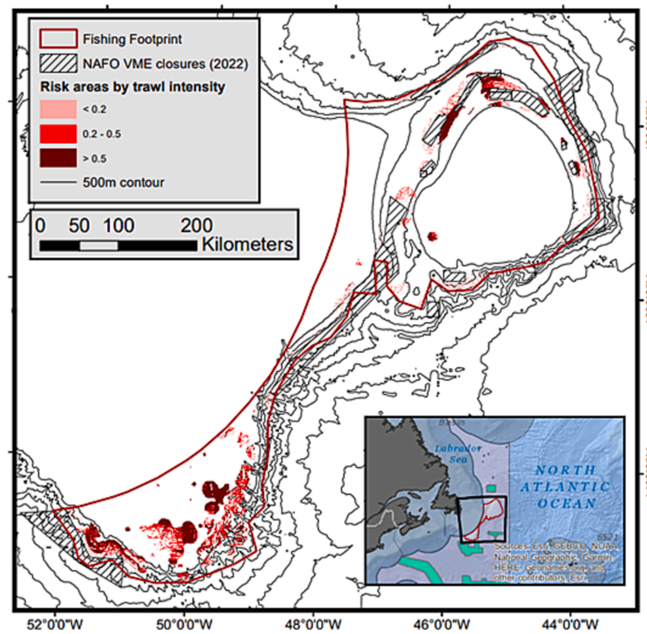

Fig. 10. Total combined VME polygon of "increasing risk of impact" (defined by lower and upper impact thresholds outside of protected areas) exposed to different levels of fishing effort (km km^{-2} yr^{-1}). Fishing effort at 0.2 km km^{-2} yr^{-1} and 0.5 km km^{-2} yr^{-1} correspond approximately to SAR values of 0.03 km^2 yr^{-1} and 0.08 km^2 yr^{-1}, respectively.

amounts of empirical data and does not consider the potential changes in ecosystem function across a gradient of biomass loss. For example, it is assumed that such highly fished areas represent degraded ecosystems, but it will remain challenging to determine to what degree this equates to loss of key ecosystem services and functions provided by these VMEs at wider spatial scales, such as habitat provision or their contribution to secondary production. To address fishing effects on ecosystem function, the SAI approach detailed here could be applied to functional relationships as opposed to VME indicator taxon biomass relationships, as shown for biodiversity functions of cold-water corals (Rowden et al., 2020). For example, Pham et al. (2019) translated the biomass of the deep-sea sponges in the NRA into filtration and nutrient-cycling capacity using physiological data from the scientific literature. They then conferred impacts on those functions through an overlay of fishing effort and concluded that fishing removals for their study period were unlikely to have caused SAI, largely because most of the sponge biomass was either in protected areas or in deeper waters outside of the fishing footprint, which concurs with the findings of the present study, (e.g., >90 % of the sponge biomass is now protected by fishery closures in the NRA).

Furthermore, despite uncertainty in the accuracy of the present impact assessment approach, the results do confirm that present-day patterns in observed VME distribution are, to some extent, a product of historic and present-day bottom trawling activities, an assertion further supported by habitat suitability modelling undertaken by Downie et al. (2021) for sponges, and by Murillo et al. (2020b) for benthic species diversity (measured as species density). Nevertheless, it is acknowledged that the method to identify VME extent using habitat suitability models and KDE analysis is beset with unavoidable assumptions and concessions, but at the same time, the assessed areal extent and biomass of VME in the present study represents the best available empirical evidence generated by extensive fishery independent surveys of VME indicator taxa biomass.

The authors also recognise the importance of assessing the potential indirect impacts on VMEs in closed areas from the re-suspension of fine sediment caused by nearby fishing activities (Boutillier et al., 2013), although some VME indicator species (e.g., sponges) may be tolerant of temporary high sediment loads (Wurz et al., 2021). Such considerations are partly addressed in the present study by the inclusion of a 500 m buffer area around each scientific survey trawl samples and should therefore not be a major factor affecting our assessment.

The implementation of spatial fisheries management measures, such as defining a fishing footprint (Jennings et al., 2012; Campbell et al., 2014) and establishing closed areas to bottom fishing, are typically employed by RFMOs as part of an integrated ecosystem management approach to fishing in the high seas (Ardron et al., 2008; Katsanevakis et al., 2011; Bell et al., 2019). Such fishery area-based management measures can complement more traditional (i.e., non-spatial) fishery management practices, such as setting total allowable catch limits or reducing fishing effort, especially in situations where more traditional stock assessments and monitoring, compliance and enforcement of regulations can be difficult to implement (Large et al., 2013). Measures designed to ensure sustainability of a single target species also overlook the wider ecosystem-level implications of the activity being controlled.

The present assessment partially fulfils the requirements of UNGA Resolution 61/105 (UNGA, 2006) on sustainable fisheries and, crucially, is the first study to define and apply empirically derived quantitative estimates of impact, rather than rely purely upon expert judgement and the precautionary approach. The results of this data-driven assessment may also be applied in support of more qualitative risk-based fisheries management, especially in data limited situations, where RFMOs may not have access to regionally derived VME specific impact reference points (van Denderen et al., 2022). For example, by identifying potentially high-risk impact fishing areas where the effort of mobile bottom-contact gears is below the least sensitive VME impact threshold, would enable fishery management measures (e.g. closed areas) to be targeted in areas which are potentially at highest risk of impact but with limited fishery socio-economic consequences (van Denderen et al., 2022). Indeed, the transferability and application of the VME impact thresholds to other regions (where the same or similar type of VME and bottom trawl fisheries occur) in combination with precautionary and risk-based approaches to mitigate the potential impacts of bottom trawling on VMEs (Pitcher et al., 2017; Kenny et al., 2018), may provide a cost-effective way for data-limited RFMOs to fulfil the requirements of the relevant UN General Assembly Resolutions on this topic (e.g. UNGA, 2006).

Finally, demersal fishing is not the only human activity impacting VMEs in the deep sea. Other activities, such as hydrocarbon and mineral extraction are increasingly being explored and developed in the deep-sea. These, in combination with environmental regime shifts brought about by global climate change and the increased sensitivity of deep-sea ecosystems to such pressures, makes deep sea research an important priority to ensure the sustainability of deep-sea VME resources and functions.

5. Conclusions

The hierarchical analytical framework developed in this study provides a quantitative approach to the assessment of risk for deep-sea VMEs, based on a logistic model of the relationship between VME occurrence and estimated fishing effort, which can serve to support more qualitative risk-based fisheries management in data limited situations. Our application of this framework across numerous deep-sea VMEs yielded consistent outcomes that provide important insights into their sensitivity to the impact of bottom contact fishing. Our observations and analyses provide a substantive basis for the establishment of policies and procedures by RFMOs aimed at avoiding and mitigating potential loss of VMEs as a result of the impact of bottom fishing. The first point of rapid loss in biomass in a VME polygon (10–20 % of virgin biomass), typically occurs at a bottom trawling intensity of about 0.10 $km{\cdot}km^2{\cdot}y^{-1}$. Parameter uncertainty indicates that data quality may have important consequences for the application of precautionary principles in the designation of VMEs at risk or impact. Our results demonstrate that deep-sea habitats are potentially 10 times more susceptible to the adverse effects of bottom fishing compared to typical soft sediment continental shelve habitats. However, until there are peer reviewed assessments of the potential losses of ecosystem function caused by bottom fishing, RFMOs and States should adopt highly precautionary approaches, such as ones based on the lower impact thresholds identified in this study, in order to avoid biodiversity losses that can result in long-term reductions in ecosystem productivity.

CRediT authorship contribution statement

Andrew J. Kenny: Writing – original draft, Project administration, Formal analysis, Conceptualization. **Pierre Pepin:** Writing – original draft, Supervision, Formal analysis. **James Bell:** Writing – review & editing, Formal analysis. **Anna Downie:** Writing – review & editing, Formal analysis. **Ellen Kenchington:** Writing – review & editing, Supervision, Formal analysis. **Mariano Koen-Alonso:** Investigation, Conceptualization. **Camille Lirette:** Formal analysis, Data curation. **Christopher Barrio Froján:** Writing – original draft, Visualization, Investigation. **Neil Ollerhead:** Formal analysis, Data curation. **F. Javier Murillo:** Methodology, Formal analysis. **Mar Sacau:** Formal analysis, Data curation. **Susanna Fuller:** Methodology. **Daniela Diz:** Writing – review & editing, Methodology.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2025.113296.

Data availability

I have included a data file as Supplementary Material.

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