Fisheries and Oceans Canada / Pêches et Océans Canada
Ecosystems and Oceans Science / Sciences des écosystèmes et des océans

Canadian Science Advisory Secretariat (CSAS)

Research Document 2025/014

Pacific Region

Identification of Vulnerable Marine Ecosystems on Seamounts in the North Pacific Fisheries Commission Convention Area using Visual Surveys and Distribution Models

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July 2025

Foreword

This series documents the scientific basis for the evaluation of aquatic resources and ecosystems in Canada. As such, it addresses the issues of the day in the time frames required and the documents it contains are not intended as definitive statements on the subjects addressed but rather as progress reports on ongoing investigations.

Published by:

Fisheries and Oceans Canada
Canadian Science Advisory Secretariat
200 Kent Street
Ottawa ON K1A 0E6

http://www.dfo-mpo.gc.ca/csas-sccs/
csas-sccs@dfo-mpo.gc.ca

ISSN 1919-5044
ISBN 978-0-660-75816-9 Cat. No. Fs70-5/2025-014E-PDF

Correct citation for this publication:

Warawa, D., Curtis, J., Rooper, C., Nephin, J., Georgian, S., Chu, J.W.F., Dudas, S., and Knudby, A. 2025. Identification of Vulnerable Marine Ecosystems on Seamounts in the North Pacific Fisheries Commission Convention Area using Visual Surveys and Distribution Models. DFO Can. Sci. Advis. Sec. Res. Doc. 2025/014. vi + 42 p.

Aussi disponible en français :

Warawa, D., Curtis, J., Rooper, C., Nephin, J., Georgian, S., Chu, J.W.F., Dudas, S. et Knudby, A. 2025. Recensement des écosystèmes marins vulnérables des monts sous-marins dans la zone de la Convention de la Commission des pêches du Pacifique Nord au moyen de relevés visuels et de modèles de répartition. Secr. can. des avis sci. du MPO. Doc. de rech. 2025/014. viii + 46 p.

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ABSTRACT

The United Nations General Assembly called upon States to manage fisheries sustainably and protect vulnerable marine ecosystems (VMEs) from destructive fishing practices when they adopted Resolution 61/105 in 2006. The Convention on the Conservation and Management of High Seas Fisheries Resources in the North Pacific Ocean requires North Pacific Fisheries Commission (NPFC) Members, including Canada, to develop a process to identify VMEs and areas where they are likely to occur (i.e., likely VMEs) using the best scientific information available. As of January 2024, the NPFC included four groups of corals and two classes of sponges as VME indicator taxa and recently adopted a quantitative methodology that can be used to identify VMEs based on visual surveys (NPFC-SSC BFME 2022, NPFC-SC 2022a; NPFC-COM 2023). This quantitative approach was originally developed by Rowden et al. (2020) for the South Pacific Regional Fisheries Management Organization and applied by Warawa et al. (2022, 2023a, 2023b) to the eastern NPFC Convention Area (CA). The NPFC also adopted a framework that identifies predictive models as one means to identify likely VMEs (NPFC 2023a; NPFC 2023b). As a Contracting Party to the NPFC, and the only Member operating a bottom fishery in the northeast (NE) part of the NPFC's Convention Area, Canada has the responsibility to identify VMEs and likely VMEs in this region. As of January 2024, Canada has identified five VME areas on Cobb Seamount, which were endorsed by the NPFC's Scientific Committee in December 2023. These were adopted by the Commission in April 2024. We describe how these five VMEs were identified using Rowden et al.'s (2020) approach (see Warawa et al. 2022, 2023a). We used visual data collected in 2012 (Curtis et al. 2015) to estimate a regional VME indicator density threshold to identify the five VMEs on Cobb Seamount by applying our threshold to these visual data. The five VMEs ranged from approximately 50 – 200 m^2 in size and 500 – 1,200 m in depth. We also identify likely VMEs in the Cobb-Eickelberg seamount chain by applying the regional VME indicator density threshold to model predictions of the density of VME indicator taxa (Warawa et al. 2023b). Likely VMEs are probably present on all seamounts in the Cobb-Eickelberg seamount chain. Cobb Seamount had the largest total area identified as likely VME (27.55 km^2, 15.39% of modeled area on Cobb Seamount), followed by Brown Bear North (20.4 km^2, 19.88% of modeled area on Brown Bear North), Brown Bear South (13.74 km^2, 4.40% modeled area on Brown Bear South) and Eickelberg Ridge (10.95 km^2, 22.71% of modeled area on Eickelberg Ridge).

1. INTRODUCTION

1.1. INTERNATIONAL VME POLICY AND MANAGEMENT MEASURES

In 2006, the United Nations General Assembly (UNGA) Resolution 61/105 called upon “States to take action immediately, individually and through fisheries management organizations and arrangements, and consistent with the precautionary and ecosystem approaches, to sustainably manage fish stocks and protect vulnerable marine ecosystems (VMEs), including seamounts, hydrothermal vents and cold water corals, from destructive fishing practices, recognizing the immense importance and value of deep-sea ecosystems and the biodiversity they contain” (UNGA 2006). The Food and Agriculture Organization (FAO) subsequently published guidelines for the management of deep-sea fisheries in international waters (FAO 2009). Those guidelines outlined five criteria of areas, habitats, or ecosystems that should be used individually or in combination to identify VMEs, including:

1. uniqueness or rarity
2. functional significance of the habitat
3. fragility
4. life-history traits of component species that make recovery difficult
5. structural complexity

The FAO also recommended the development of case-specific operational definitions of VMEs for their application (see examples in Kenchington et al. 2014, Morato et al. 2018, Miyamoto and Yonezaki 2019, Rowden et al. 2020). The process and method used for applying this recommendation is purposefully left open for Regional Fisheries Management Organizations (RFMOs) to implement.

The North Pacific Fisheries Commission (NPFC) RFMO came into force in 2015 and its convention requires the NPFC to develop a process to identify VMEs using the best scientific information available. Specifically, Article 10(4) of the Convention on the Conservation and Management of High Seas Fisheries Resources in the North Pacific Ocean (henceforth: the Convention) asserts that the NPFC’s Scientific Committee shall “develop a process to identify vulnerable marine ecosystems, including relevant criteria for doing so, and identify, based on the best scientific information available, areas or features where these ecosystems are known to occur, or are likely to occur...” For the purpose of this research document, “likely VMEs” are synonymous with NPFC’s “areas where VMEs are likely to occur.” The NPFC Scientific Committee’s Research Plan (NPFC-SC 2022b) explicitly aims to “develop consensus on criteria used to identify VMEs and how this might be applied in the NPFC.” Annex 2 of the NPFC’s Conservation and Management Measures (CMMs) 2023-05 (NPFC 2023a) and 2023-06 (NPFC 2023b) provides science-based standards and criteria for identification of VMEs and states: “The purpose of the standards and criteria is to provide guidelines for each member of the Commission in identifying VMEs and assessing SAIs [significant adverse impacts] of individual bottom fishing activities on VMEs or marine species in the Convention Area (CA).”

As a contracting Party to the NPFC, Canada is mandated to protect biodiversity in the marine environment, including by preventing significant adverse impacts (SAIs) on VMEs and likely VMEs. Canada identified VMEs in the northeast part of the NPFC CA (Figure 1) in December 2023 and proposed two areas to close to bottom fishing to prevent SAIs to those VMEs (Warawa et al. 2023a; NPFC-SSC BFME 2023; NPFC-SC 2023), but likely VMEs have not yet been identified in this area. To date, Canada has only presented a methodology for identification of likely VMEs (Warawa et al. 2023a) and this was endorsed by the NPFC's scientific committee in December 2023 (NPFC-SSC BFME 2023; NPFC-SC 2023). Canada is the only NPFC Contracting Party who currently fishes with bottom-contact gear in the northeast (NE) part of the NPFC CA. Therefore, Canada has a responsibility to identify both VMEs and likely VMEs in this area, and to protect them from SAIs.

1.2. APPROACHES FOR IDENTIFYING VMES

Some approaches to identifying VMEs rely on using qualitative information and expert judgement, which can be inconsistent and lack transparency (Morato et al. 2018). Morato et al. (2018) emphasize that it would be advantageous for analysts to develop robust and repeatable quantitative methods to identify VMEs.

The examples of existing quantitative approaches below draw on catch data from extractive scientific sampling methods, historical observational data of VME indicator taxa, and/or visual data from non-extractive scientific surveys of benthic organisms. However, the sparse visual data currently available on VME indicator taxa from the eastern NPFC CA limits the ability to quantitatively identify VMEs on Cobb Seamount only. Thus we use spatial modelling to predict the distribution of likely VMEs throughout the Cobb-Eickelberg seamount chain, where Canada fishes for sablefish (*Anoplopoma fimbria*).

1.2.1. Kernel density estimation

Based on FAO's criterion of structural complexity created by significant concentrations of biotic features for identifying VMEs (FAO 2009), Kenchington et al. (2014) used a kernel density estimation (KDE) approach to analyze research trawl survey data and identify areas of relatively high biomass of four VME indicator taxa (large-sized sponges, sea pens, and small and large gorgonians) in the Northwest Atlantic Fisheries Organization (NAFO) Regulatory Area. Using KDE, NAFO identified significant concentrations of the biomass of VME indicator taxa, which they interpreted as VMEs. They also independently assessed the high concentrations of VME indicators they observed with images, benthic sampling, and/or predictive models. KDE is a method for producing a smooth data surface from point observations; it is thus strongly affected by incomplete sampling of the VME in question and is only suited for use in densely sampled areas.

1.2.2. ICES multi-criteria assessment

In the northeast Atlantic Ocean, the International Council for the Exploration of the Sea (ICES) has adopted a multi-criteria assessment method to identify VMEs (Morato et al. 2018). This multi-criteria assessment aggregates data from different sources and with different attributes. The method evaluates how likely it is that a VME occurs, and accounts for both the quantity and quality of input data. The multi-criteria approach combined a list of 13 VME indicator groups that were present in the ICES VME database and developed a scoring rubric to relate the FAO VME criteria for each of these groups. In general, score values ranged from 1 (poorest fit) to 5 (best fit) and were assigned after discussions among a panel of expert deep-sea scientists. The single VME index metric combined scores for each group using the geometric mean and also included additional quantitative information such as abundance data levels (if that existed for a VME group), uncertainty, and data quality issues.

1.2.3. Structural complexity density threshold

Rowden et al. (2020) noted that many quantitative approaches to identifying VMEs focused on predicting the distribution of VME indicator taxa, however, they also recognized that the presence of one or more VME indicator taxa does not necessarily mean that a VME is present. They drew on the FAO's VME criterion of structural complexity (FAO 2009) and developed a quantitative approach to determine a density threshold of VME indicator taxa above which a VME was determined to be present in the South Pacific Regional Fisheries Management Organization (SPRFMO) CA. Their method is based on a theoretical relationship where the amount of associated species richness increases as the amount of structurally-complex habitat increases (Figure 2). They found a significant relationship between the density of *Solenosmilia variabilis* and the richness of associated epifauna organisms, and suggested that a density threshold could be used in combination with predictive models to map areas where the predicted density of VME indicators was equal to or greater than that threshold. They developed predictive models of *Solenosmilia variabilis* density and then applied the density threshold to identify VMEs. Areas where predicted densities of *Solenosmilia variabilis* are equal to or greater than the density threshold are assumed to meet the FAO VME criterion of structural complexity (FAO 2009) and are identified as VMEs. Rowden et al. (2020) emphasized the value of such quantitative thresholds to make the identification of VMEs less subjective. The predictive coral density models developed by Rowden et al. (2020) provide improved information for identifying VMEs compared to models that predict occurrence, because the distribution of VME indicator taxa doesn't necessarily align with the actual VME area (Howell et al. 2011 as described in Rowden et al. 2020).

1.3. SELECTING APPROPRIATE METHODS FOR THE NORTHEAST PACIFIC OCEAN

There are few sources of available data on the distribution and abundance of the NPFC's VME indicator taxa and other epifauna or benthic organisms in the study area. These sources of data include visual surveys of epifauna, but the images from only one survey have been systematically annotated (see Curtis et al. 2015).

In 1982 and 1983 the crewed submersible Pisces IV completed seven dives on Cobb Seamount, where it collected physical specimens as well as still-camera photographs. However, image annotations are not available.

In 2002, the USA National Oceanic and Atmospheric Administration (NOAA) undertook a visual survey of Warwick Seamount and observations of corals, sponges, and other taxa are freely available. The accuracy of coordinates associated with annotations of a subset of the observed epifauna, however, means that they are less reliable for identifying the location of VMEs and likely VMEs.

In 2012, a scientific survey to characterize the benthic community structure on Cobb Seamount was completed using a remotely operated vehicle (ROV) to a maximum depth of about 220 m and an autonomous underwater vehicle (AUV) to collect still photos below 400 m along four transects (see Figure 3; Curtis et al. 2015). The location of these four AUV transects was haphazardly selected from a suite of random transect starting points and directions to ensure that each AUV transect fell within each of the northwest, northeast, southwest and southeast quadrants of Cobb Seamount (Janelle Curtis, personal observation). A fully annotated dataset of AUV photos was produced by NOAA. By contrast, the ROV video images were not annotated and only a small quadrat area (0.16 m^2) of photos collected every 15 seconds along each ROV transect was annotated. This made it difficult to reliably identify VME indicator taxa and other associated epifauna with the ROV.

A more recent visual survey conducted in the study area was a joint Canada-USA International Seamount Survey in 2022 (Rooper et al. 2023). It was designed to estimate the distribution, abundance and size-structure of deep-sea corals and sponges and their associated taxa using a random stratified survey design. Paired still images were collected using an underwater stereo camera system at five seamounts in the Cobb-Eickelberg seamount chain. Preliminary analysis of the 77 transects indicates that the occurrence of VME indicator taxa is widespread on these seamounts at depths surveyed from 400 to 850 m. Analysis of the images collected during this survey is ongoing and annotations are not yet available.

Most coral and sponge data in the northeast Pacific Ocean were collected with fishing gears in coastal areas or on the continental shelf within domestic waters of Canada and the United States. These data are therefore not representative of the seamounts further offshore in international waters. The only bottom fishery in the northeast part of the NPFC CA is Canada's sablefish fishery, which operates primarily on a subset of seamounts along the Cobb-Eickelberg seamount chain (Brown Bear, Cobb, Corn, Eickelberg, and Warwick Seamounts). Canada's sablefish fishery is conducted with long-lined traps or hook and line gear, which typically do not retain VME indicator taxa. As a result, there are insufficient incidental catch records of coral and sponge taxa available for this region that might support an analysis with the KDE approach developed and applied by Kenchington et al. (2014).

Conducting a multi-criteria assessment similar to ICES (see Morato et al. 2018) also requires large databases that are not available in the eastern NPFC CA. The ICES database comprises approximately 15,000 records of VME indicator taxa that were pooled from various sources. Although a similarly large number of records exist in domestic waters of Canada's North Pacific Ocean, there are limited data on coral and sponge taxa in international waters. Further, there is not currently a consensus panel of experts or a scoring rubric to undertake a similar multi-criteria assessment.

The most suitable VME identification method for application to the eastern NPFC CA currently is the approach based on structural complexity outlined by Rowden et al. (2020), because it can be applied using the single annotated visual survey dataset by Curtis et al. (2015). With this approach and visual survey data from Cobb Seamount, we are able to calculate a regional VME density threshold and use density modelling to develop predictions of the locations of likely VMEs. Drawing on NPFC's framework for VME identification (NPFC 2023a; NPFC 2023b) and Rowden et al.'s (2020) VME indicator taxa threshold method, Warawa et al. (2023a) use the limited visual data available on Cobb Seamount to identify VMEs. Warawa et al. (2023b) then propose to use Rowden et al.'s (2020) method of applying a regional VME indicator density threshold in combination with modelled VME indicator taxa density to predict the location of likely VMEs along the Cobb-Eickelberg seamount chain.

1.4. FRAMEWORK TO IDENTIFY VMES IN THE NPFC CA

We have adapted the methods developed by Rowden et al. (2020) to the eastern NPFC CA (Figure 2), with minor modifications, to ensure it is ecologically appropriate and follows the NPFC's science standards, research plan, and conservation and management measures. First, Rowden et al. (2020) hypothesized that the thresholds used to identify VMEs would likely vary among regions. Therefore, we used our survey data to develop a regional VME indicator density threshold that is ecologically relevant to the northeast Pacific Ocean. Second, VME indicator taxa also vary among RFMOs. Rowden et al. (2020) focused on *Solenosmilia variabilis*, a reef-forming species of stony coral occurring in the South Pacific Ocean and listed as a SPRFMO VME indicator taxon. By contrast, our application of this approach utilizes the VME indicator taxa currently recognized by the NPFC, which as of January 2024, included four higher-level groups of cold-water corals occurring in the northeast Pacific Ocean – *Alcyonacea* (historically non-gorgonian soft-corals), *Antipatharia* (black corals), *Gorgonacea* (historically gorgonian corals), and *Scleractinia* (stony corals) – as well as two classes of sponges: *Demospongiae* (demosponges) and *Hexactinellida* (glass sponges) (NPFC-SC 2022a;

NPFC-COM 2023). Finally, we incorporated the NPFC-specific conservation and management measures, which distinguish between identifying areas that are VMEs and identifying areas that are likely VMEs. Within the NPFC CA, VMEs are identified using visual data and, for areas where visual data are not currently available, likely VMEs are identified using modelling or other approaches (see Annex 2.3 of NPFC 2023a and NPFC 2023b). Likely VMEs then become high priority areas for undertaking visual surveys to ground-truth predictions. Therefore, we adapt steps 2 and 3 of Rowden et al.'s (2020) approach according to our identification of VMEs or likely VMEs, and the data used (see Figure 4).

The NPFC endorsed this method to identify VMEs (NPFC-COM 2023). Our general approach and adaptation of Rowden et al.'s (2020) methodology in the eastern NPFC CA using visual data from Cobb Seamount is described in Warawa et al. (2021, 2022, 2023a). Canada's adaptation of this method was reviewed by NPFC Members and observers during the Small Scientific Committee on Bottom Fish and Marine Ecosystem (SSC BF-ME) meetings in 2021 (NPFC-SSC BFME 2021) and 2022 (NPFC-SSC BFME 2022). It was also endorsed by the NPFC's Scientific Committee (NPFC-SC 2022a) and adopted by the Commission (NPFC-COM 2023) in March 2023. The NPFC's Small Scientific Committee on Bottom Fish and Marine Ecosystem and Scientific Committee also endorsed Canada's methodology to predict the distribution of likely VMEs throughout the Cobb-Eickelberg seamount chain (NPFC-SSC BFME 2023; NPFC-SC 2023).

1.5. OBJECTIVES

The objectives of this research document are to:

1. Identify areas that are VMEs in the Cobb-Eickelberg seamount chain.
2. Review methodology that could be used to identify areas that are likely VMEs in the NPFC Convention Area.
3. Provide advice on the location of VMEs and likely VMEs in the Cobb-Eickelberg seamount chain.
4. Identify uncertainties in the data and methodology used to identify likely VMEs.

2. METHODS AND APPLICATION

2.1. STUDY AREA

Our study area, the Cobb-Eickelberg seamount chain, is in the eastern part of the NPFC CA just outside of Canada's exclusive economic zone (EEZ), approximately 450 km offshore Vancouver Island (Figure 5). This seamount chain includes 11 named seamounts and one ridge (Eickelberg Ridge), with Cobb Seamount having the shallowest pinnacle depth of 24 m (Parker & Tunnicliffe 1994). The Canadian commercial fishery for sablefish has been active in the area since the 1980s using mainly longline trap and some longline hook and line gear. From 2006 – 2020, this fishery set their gear at a median depth of 727 m (n = 1263).The 25th and 75th percentiles of depth were 621 m and 822 m, respectively. Canada's sablefish fishery is currently the only fishery operating in the eastern part of the NPFC CA.

2.2. DATA

The annotated data collected during a scientific survey to characterize benthic community structure with an autonomous underwater vehicle (AUV) on Cobb Seamount in 2012 (Curtis et al. 2015) was used in our analyses (see transects in Figure 3). NOAA's fully annotated dataset of AUV photos included data on at least 56 morphotypes or species. Of these, 12 were structure-forming coral and sponge VME indicator taxa and three were non-structuring forming corals (Table 1). Although demosponges were on the list of NPFC's VME indicator taxa as of January 2024, there was only one upright demosponge observed on the four AUV transects; the rest were encrusting sponges. There were at least 14 sedentary morphotypes associated with the structure-forming VME indicator taxa (Table 2), including sea pens, hydrocorals, non-structure-forming corals, and encrusting sponges. Although pennatulaceans (sea pens) can provide structural complexity to habitats, they were not endorsed by the NPFC's Commission as VME indicator taxa until April 2024. NOAA's annotated AUV dataset included at least 30 mobile species associated with the NPFC's structure-forming VME indicator taxa, including crinoids, nudibranchs, sea stars, sea cucumbers, crabs, squat lobsters, fishes, sharks, and an octopus species (Table 3).

2.3. IDENTIFYING VMES

The steps we use to identify VMEs and likely VMEs in the eastern NPFC CA are outlined in Figure 4. Each of those steps is described in more detail below.

2.3.1. Step 1: Identify a regional density threshold

Following Rowden et al.'s (2020) theoretical approach and assertion that the density of VME indicator taxa within VMEs will differ according to region, we adapted their method to calculate a regionally-specific VME indicator density threshold for our study area in the eastern NPFC CA. This is step 1 for Canada's application of the NPFC's methodology for identifying VMEs and likely VMEs in Figure 4 (see Warawa et al. 2022; NPFC-SC 2022a; NPFC-COM 2023).

2.3.1.1. Model the density of VME indicator taxa and associated species richness

To calculate a regional VME indicator density threshold in the NE Pacific, we started by plotting species richness of epifaunal taxa against the density of NPFC's VME indicator taxa. Those data came from the fully annotated AUV dataset created by NOAA (Curtis et al. 2015). This dataset consists of data extracted from 2,614 AUV photos. Photos were taken from four AUV transects with an average length of 1,805 m ranging from 435 – 1,154 m in depth (Figure 3). Discernible taxa, including corals, sponges, other invertebrates (but not brittle stars or snails), and fishes were identified and counted (Curtis et al. 2015; Du Preez et al. 2015). We limited our identification of VMEs and likely VMEs to the AUV photo annotations, which is the more complete and relevant dataset of the two collected by Curtis et al. (2015).

Overall, NOAA identified 25 sedentary taxa and 31 mobile taxa. There were sedentary species from three of the NPFC's VME indicator taxa: gorgonians, black corals, and glass sponges (see Table 1). These taxa were not counted as associated species. Associated sedentary taxa included anemones, hydrocorals, and pennatulaceans (see Table 2), which were recently endorsed as NPFC VME indicator taxa in April 2024. The associated mobile taxa identified by NOAA included one nudibranch, one crinoid, eight sea stars, four sea cucumbers, four crabs, squat lobsters, octopus, ten species of fish, and one shark (see Table 3).

To process the AUV annotated data for analysis, we divided transects into area-standardized segments of 50 m^2 by grouping adjacent photos until a combined area of 50 m^2 was reached. Rowden et al. (2020) suggest that observations made at spatial scales between 25 m^2 and 50 m^2 result in more stable and reliable density estimates because they are more likely to capture whole coral reef patches. While VME indicator taxa in our study region do not form reefs, we used this same patch size so the studies are comparable. We treated each 50 m^2 as the minimum unit to identify as a VME, and adjacent segments that meet our definition of a VME would be combined into a larger VME area. The area of each photo varied depending on the distance between the AUV and the seafloor when the photo was captured. We omitted transect segments from our analysis if they were 10 % smaller or larger than our target area (50 m^2) to prevent a large variation in the final segment size. This resulted in the removal of 5.6 % (13 out of a total of 234) of the 50 m^2 transect segments. Each 50 m^2 transect segment group comprised 5 – 12 AUV photos, depending on the area covered by each photo in the grouping.

Within each transect segment, the total number of NPFC VME indicator taxa was summed and divided by the area to obtain density of VME indicator taxa individuals (e.g. colonies of corals, or individual sponges) per square meter. Because our method is based on the assumption that VME indicator taxa provide structurally-complex habitat, VME indicator taxa that we included in the threshold calculation were filtered to exclude taxa that do not contribute to the formation of structurally-complex areas (see Table 1). Our criterion for taxa that contribute to the formation of structurally-complex habitat is that it is known to grow in our study area to be greater than 10 cm in height. As a result three taxa were excluded from our VME indicator taxa density dataset and analyses: *Gersemia* spp. (soft coral), *Heteropolypus ritteri* (soft coral) and *Desmophyllum dianthus* (stony coral). Due to limited visual data available, we combined all groups of retained structurally-complex VME indicators to calculate a single regional VME density threshold. Species- or taxon-specific thresholds may exist, but our limited visual dataset means that we have insufficient data to calculate these.

The density of structurally-complex VME indicator taxa was calculated for n = 221 segments of the AUV transects on Cobb Seamount. The number of associated species (richness) ranged from 2 to 16 per 50 m^2 transect segment, with a mean of 7.4 (SD = 2.5). The density of VME indicators ranged from 0 to 1.16 individuals m^{-2}, with a mean of 0.15 individuals m^{-2} (SD = 0.19).

Generalized additive models (GAMs) fitting the species richness of all discernable epifaunal taxa identified by NOAA on the four AUV transects in Curtis et al. (2015) except NPFC VME indicators (henceforth associated species richness and dependent variable) to the density of NPFC VME indicators (independent variable) were used to estimate the VME density threshold as in Rowden et al. (2020). Final GAM selection was based on the lowest Akaike’s Information Criterion (AIC) score. The GAMs were fit using a Gaussian distribution and an identity link function.

Depth and AUV transect were considered as explanator variables when selecting the GAM. Depth was included as a predictor variable to account for any differences in taxonomic diversity related solely to the changes in depth (e.g. decreases in overall diversity at deeper depths as observed by other studies and meta-analysis (Costello and Chaudhary 2017; Davies and Guinotte 2011; Georgian et al. 2014). Transect was included as a random effect in the model to account for the potential dependence of observations taken from the same transect (see Figure 3). No additional explanatory variables were considered, although information about the dominant type of substratum might have improved model fit.

The number of basis functions or inflection points in the smooth terms (k) was assessed to ensure dimension choices were adequate. Model accuracy was estimated using the adjusted R^2 values and model fit was compared using the AIC score. Assessment of GAM fit showed the model performed well (Figure A1) with an adjusted R^2 of 0.46 (Table 4).

The effect of VME indicator density on associated species richness is not significant with a p-value of 0.14. We note however that the p-value associated with independent variables in a GAM is only approximate and does not have the same interpretation as in a linear model. Multiple criteria need to be used to assess the model’s fit (see Wood 2017). We assessed GAM fit by comparing the restricted maximum likelihood (or REML), the Akaike Information Criterion (AIC), and deviance explained with and without the variable. When we compare this GAM to one without this variable, the AIC decreases from 919.58 to 917.95, but the REML increases from 463.85 to 464.74, and the explained model deviance decreases from 48.6% to 47.8%. VME indicator density is also the key explanatory variable of interest in this study and therefore it was retained in the GAM.

The final model formula is shown below (see marginal effects plots in Figure A2), where *bs='re'* indicates the variable treated as a random effect and *s* indicates a cubic spline smoother:

Species richness ~ s(VME indicator density) + s(depth) + s(transect, bs='re')

2.3.1.2. Calculate threshold

We calculated the VME indicator density threshold from the GAM using the same four methods outlined in Rowden et al. (2020) and used the mean as the final threshold value. The four methods include:

1. the point of intersection of linear regressions using the initial and final 5% of data,
2. the point of intersection between a linear regression using the initial 5% of data and the maximum cumulative species richness value,
3. the point on the curve that is closest to the top right corner (0,1), and
4. the point on the curve that maximizes the distance between the curve and the line between extreme points (Youden Index).

See Figure S2 in Rowden et al. (2020) for a visual explanation of these four methods and Figure 6 for plots of their application using our data.

The final mean regional VME indicator density threshold in the NE Pacific is 0.6 individuals of VME indicator taxa m^{-2} (SD = 0.1, lower 95% CI = 0.5 and upper 95% CI = 0.7) (Table 5).

2.3.2. Step 2: Calculate VME taxa density from visual data

We calculate the density of VME indicator taxa on the four AUV transects as described above in section 2.3.1(a). Only one visual dataset is currently available in our study area, therefore, we used it to calculate the regional VME indicator density threshold and to identify VMEs.

2.3.3. Step 3: Apply the regional VME density threshold

We use the VME indicator density values in each 50 m^2 transect segment and the threshold estimated in step 1 to identify VMEs along the four AUV transects on Cobb Seamount. We identified VMEs as transect segments where the VME indicator taxa densities were equal to or greater than our regional VME density threshold (0.6 individuals m^{-2}). Adjacent transect segments that were above the threshold were grouped and considered a single VME.

Using these methods, we identified five VME areas on Cobb Seamount consisting of 1-4 adjacent transect segments (Table 6). VMEs ranged in size from approximately 50 - 200 m^2 and ranged in depth from approximately 500 - 1,150 m. VMEs were identified on two out of the four AUV transects on Cobb Seamount (Figure 7). The largest VME areas occurred in the deepest areas of transect AUV 4. VMEs on transect AUV 4 included 290 gorgonian corals, 45 black corals, and 13 individual glass sponges, while the VME on transect AUV 2 consisted of mainly 30 colonies of black corals and only one gorgonian and one glass sponge. The total area assessed for VMEs using AUV data in this study was 0.011 km^2 and the total area identified as VMEs was 0.0005 km^2.

2.4. IDENTIFYING LIKELY VMES

We identify likely VMEs on seamounts within our modelling depth range with the same predictive modelling approach used by Rowden et al. (2020) to predict the location of VMEs (see Figure 4 and section 1.2.3).

2.4.1. Step 1: Identify a regional density threshold

We use the same regional VME indicator density threshold of 0.6 VME indicator taxa m^{-2} that was identified and used to identify VMEs on Cobb Seamount (see section 2.3.1).

2.4.2. Step 2: Predictive models of VME indicator density

2.4.2.1. Dependent data

We use the combined densities of VME indicator taxa from 50 m^2 transect segments (n=221, Warawa et al. 2023a) of the 2012 Cobb Seamount Survey (Curtis et al. 2015) AUV data as the dependent data in models of likely VME density in the Cobb-Eickelberg seamount chain. Abundances of structure forming NPFC VME indicator taxa densities were summed. This approach assumes that the environmental variables measured along the four AUV transects on Cobb Seamount (see Warawa et al. 2023a) influence VME indicator density and were representative of environmental conditions associated with VME indicator densities throughout the Cobb Eickelberg seamount chain. Our approach also assumes that Cobb Seamount is representative of other seamounts in that seamount chain.

We created training and testing datasets from the AUV transect segments by grouping them into five roughly equal folds for cross-validation (44 or 45 AUV transect segments in each fold). The folds were spatially aggregated along each transect to reduce the amount of spatial autocorrelation between training and testing data (Figure B1).

2.4.2.2. Environmental data

Our independent data were environmental variables known or assumed to be correlated with the distribution and density of corals and sponges. We considered the following environmental raster layers from Chu et al. (2019) for modelling VME indicator density based on prior knowledge of environmental conditions that strongly influence the density and distribution of corals and sponges: depth, calcite, dissolved oxygen, percent organic carbon, eastness, northness, silicate, slope, bottom temperature, topographic position index (TPI) at spatial scales of 1,000, 500, and 100 meters, and sea surface temperature. We considered eastness and northness as proxies for other variables that were not available or were not well resolved over the seamounts along the Cobb-Eickelberg seamount chain, such as current velocity and shear stress. Environmental raster layers were World Ocean Atlas layers (Boyer et al. 2018) downscaled to 100 m x 100 m. The bathymetry layer was NOAA multibeam mosaic data which was mosaiced with NOAA’s digital elevation model (DEM) to fill in data gaps where necessary. The bathymetry layer was used to derive terrain layers including slope, northness, eastness, and TPI. We extracted model covariates from the environmental raster layers at the centroid locations of the AUV segments, using the terra R package (Hijmans 2022). We checked for high collinearity among the model covariates using Pearson’s correlations and Variance Inflation Factor (VIF) with the *usdm* R package (Naimi et al. 2014). We removed silicate, bottom temperature, calcite, sea surface temperature, TPI 100, and TPI 1000 covariates to limit VIF values to less than 10.

2.4.2.3. Model fitting and selection

We fit a generalized additive model (GAM) using the *mgcv* R package (Wood 2011). We modelled the density of VME indicator taxa using the Tweedie distribution with a log link function, setting the power parameter p to 1.5. The power parameter was fit to the model and chosen based on lowest AIC value. P can range between 1 and 2, where 1 would represent a Poisson and 2 would represent a gamma distribution. P of 1.5 represents the standard compound Poisson (called non-central gamma) and can be expressed as a mixture of a Poisson density function with an incomplete gamma function (de Oliveira et al. 2013). We limited complexity by modelling all covariates using a low basis dimension (k=3) to avoid biologically unrealistic response curves.

We completed a backwards model selection, starting with the full model and removing covariates based on model out-of-sample predictive performance and marginal response curves. We favoured models with higher R^2 calculated by comparing test observations and predictions. We calculated marginal response curves following the evaluation strip method (Elith et al. 2005). During model selection, we removed the covariates dissolved oxygen, percent organic carbon, eastness, and TPI 500. The final model structure included only the covariates depth, northness and slope to give the final model formula (*s* indicates a cubic spline smoother):

VME indicator density ~ s(depth) + s(northness) + s(slope)

Model validation was completed using the gam.check function from the *mgcv* R package to examine residuals. Residual plots showed that model assumptions were met (Figure B2). Marginal effects plots showed a positive relationship of VME density with both depth and northness and a negative relationship with slope (Figure B3).

VME density was predicted using a 100 by 100 m^2 resolution. Predictions were limited to areas between 400 m and 1,200 m depth to avoid extrapolating beyond the depth range of the observations of VME density (dependent data, Figures 8 and 9). Seamounts Anger, Sloth, Lust, and Gluttony have peak depths below 1,200 m, therefore, we did not complete VME density modelling and identify likely VMEs on them.

2.4.2.4. Model evaluation

For each cross validation (CV) model, we made predictions at the test (hold-out) data locations. We pooled the test predictions from the CV models to calculate R^2 as the squared Pearson's correlation between all test observation and test predictions. We opted to pool test predictions to calculate a single R^2 because of our small sample size and a high proportion of zero observations in one fold. Training data R^2 was 0.51 and testing data R^2 was 0.44. The standard error of the model estimate was obtained using the *terra* R package, which ranged from 0.00078 - 0.42 (Figure 10).

2.4.3. Step 3: Apply the regional VME density threshold

We converted the predictions of VME indicator taxa density to binary predictions of likely VME presence and absence areas using the regional VME indicator density threshold of 0.6 individuals of VME indicator taxa m^{-2} described in section 2.3. We applied the mean threshold (0.6 individuals of indicator taxa m^{-2}) as well as the lower (0.5 individuals of indicator taxa m^{-2}) and upper (0.7 individuals of indicator taxa m^{-2}) 95% confidence interval threshold values to obtain lower and upper bounds of likely VME area predictions in the region (Figure 9).

Likely VMEs were identified on all seamounts in the analysis study area. The total area of likely VMEs identified per seamount ranged from 2.11 km^2 to 27.55 km^2 (Table 7). The largest area of likely VMEs was identified on Cobb Seamount (27.55 km^2). Eickelberg, Hoh, and Pipe

Seamounts had the lowest total areas of likely VMEs at around 2 km^2 each. Within the 400-1,200 m depth range Hoh Seamount, Eickelberg Ridge and Brown Bear Seamount North had the highest proportion of area identified as likely VMEs. The total area of likely VMEs identified over the entire seamount chain is 99 km^2, which covers about 10% of the seamount area in the depth range of 400-1,200 m.

3. DISCUSSION

3.1. AREAS THAT ARE VMES IN THE COBB-EICKELBERG SEAMOUNT CHAIN

We identify five areas as VMEs on Cobb Seamount ranging in size from approximately 50 m^2 to 200 m^2 with a combined total area of 508 m^2 using a method based on the FAO VME criterion of structural complexity by Rowden et al (2020) (See Figure 7). A very small proportion of the total seamount area in the eastern NPFC CA was assessed for the presence of VMEs due to the limited amount of visual data that are currently available, leaving additional areas of VMEs likely undetected.

We are limited to only one visual data set currently available in our study area which meant we had to use the same VME indicator taxa density values for identifying the regional VME density threshold (Step 1) and for calculating density from visual data that the threshold is applied to (Step 2).

While the FAO guidelines for identifying VMEs (FAO 2009) point to seamounts as examples of geographical features that potentially support VMEs (Annex of FAO 2009), there is no guidance on the spatial extent to which VMEs should be identified. It is suggested that the natural range of VME patch size is dependent on the dominant taxa and location (Baco et al. 2023). The minimum size of a VME in our study was bounded by the 50 m^2 transect segments on which we calculated VME taxa density. In some cases, however, adjacent transect segments met our criterion of a VME and were aggregated into VME patch sizes up to approximately 200 m^2.

Using the same dataset from Cobb Seamount, Du Preez et al. (2020) calculated the density of VME indicator taxa and categorized VME density using the following thresholds: no VME indicators (0 m^{-2}), sparse VME indicators (>0 and <1 m^{-2}), and dense VME indicators (>1 m^{-2}). With this definition, the only AUV transect they identified as having dense VME indicators was on 11.4% of transect AUV 4. This aligns with our results, using a quantitatively derived threshold, where we also identified the most VME area on transect AUV 4. This deeper transect was most abundant with gorgonian corals, black corals, and individual glass sponges. Because our VME density threshold is slightly lower than Du Preez et al.'s (2020) threshold for distinguishing between areas with sparse and dense VME indicators, we also identified a VME on transect AUV 2; Du Preez et al. (2020) describe transect AUV 2 as having either sparse VME indicators or no VME indicators.

Du Preez et al. (2020) also highlight that Cobb Seamount has been subjected to a half-century of bottom-contact fishing. Historical fishing in the seamount chain has undoubtedly affected the distribution and abundance of structure-forming VME indicator taxa, which have low resilience to bottom trawling gear (Rowden et al. 2010). Thus fisheries may have influenced the calculation of our VME indicator density threshold as well as predictions of where likely VMEs occur.

Fishing-related impacts could have affected our calculation of a VME indicator density threshold, because damage to or loss of some of the NPFC's VME indicators would reduce the number of data points at higher densities in the plot we used to calculate the threshold. Thus, where fishing-related impacts have had the most damage, there would be fewer segments of

AUV transects identified as VMEs. And consequently, the environmental niche space used to predict the location of likely VMEs could be smaller. If that is the case, the distribution of likely VMEs may very well be more widespread on the seamount chain than what we predicted with our GAM.

3.2. METHODOLOGY USED TO IDENTIFY AREAS THAT ARE LIKELY VMES

The method we used to identify areas that are likely VMEs is based on structural complexity (see Rowden et al. 2020), which is one of the five FAO VME criteria (FAO 2009). In the SPRFMO area, corals are the dominant structure-forming taxa. However, while we were able to model the relationship between species richness and VME indicator taxa density for our region, our results show that there are likely other factors influencing species richness. Indeed, only 48.6% of the model deviance was explained by a combination of VME indicator density, depth, and transect (Table 4). For example, substrate type may also be contributing to structure and habitat for species as well as other taxa not recognized as of January 2024 by the NPFC as VME indicator taxa (e.g. sea pens and stylasterids). Moreover, noise around our fitted model, including higher species richness at lower densities of VME indicator taxa, may be an artefact of our small dataset.

We also note that this approach assumes that the distributions of structure-forming corals and sponges are similar among different seamounts, but there is uncertainty associated with assuming seamounts are similar along the Cobb-Eickelberg seamount chain. Cobb Seamount, where VMEs were identified and used to predict the location of likely VMEs throughout the seamount chain, is an unusual seamount. Specifically, Cobb Seamount stands out among approximately 100 seamounts in the northeast Pacific Ocean as an unusual and biologically significant feature because it extends from the abyssal plain at almost 3,000 m depth to well into the photic zone and supports productive, diverse and unusual communities of organisms (Birkeland 1971; Dower et al. 1992; Parker and Tunnicliffe 1994). However, Lundsen et al. (2009a) found no evidence of endemism among species at three seamounts further south in the Northeast Pacific Ocean and Lundsen et al. (2009b) found that taxa were similar at similar depths. Nevertheless this uncertainty underscores the importance of managers taking a precautionary approach to preventing SAIs to VMEs and likely VMEs.

Relatively few studies have attempted to calculate a threshold of either habitat suitability or abundance that qualifies a site as a VME. This presents a significant challenge for generating effective VME spatial management from modeling results. As noted above, our data were too limited to calculate taxa-specific thresholds. However we expect that taxa-specific thresholds in our region would be lower, and more similar to the Rowden et al. (2020) threshold, than the threshold of 0.6 individuals m^{-2} calculated with data from all six NPFC VME taxa aggregated because VME indicator taxa in our visual data tend to co-occur and share habitat.

The use of density models in our likely VME identification methods follows current guidance for making distribution models relevant and impactful for managing VMEs. Much effort for identifying VMEs has been through the development of species distribution modelling of VME indicator taxa (e.g. Baco et al. 2020; Burgos et al. 2020; Chu et al. 2019; Georgian et al. 2019). Species distribution models play an important role in guiding further scientific surveys, however there is a push towards using abundance or density based models in the literature, especially because of their usefulness when informing management decisions (Howard et al. 2014; Dallas and Hastings, 2018; Gonzalez-Mirelis et al. 2021; Gros et al. 2022). For example, Gonzalez-Mirelis et al. (2021) compare a density-based model to a presence/absence-based model of deep-sea habitat forming sponges. They find the density-based modelling is better at detecting and identifying specific locations of conservation interest as well as delineating the size and boundaries of areas that are of interest to managers.

We chose to focus on structural complexity as it is one of the criteria that can be quantitatively assessed, however, it should also be noted that this method does not capture all likely VMEs that may be identified based on the other four FAO VME criteria. Baco et al. (2023) present a flow chart for assessing if images collected during visual surveys represent a VME. Their flow chart leads to a more comprehensive assessment of areas as VMEs using one or more of FAO's five VME criteria. The method outlined in Baco et al. (2023) is not quantitative nor easily repeatable, which is important for transparency and transferability (Morato et al. 2018; Gros et al. 2022). The FAO guidelines (FAO 2009) specify that "Merely detecting the presence of an element itself is not sufficient to identify a VME" (see Annex of FAO 2009), therefore, we focused on adapting Rowden et al.'s (2020) quantitative approach to identify both VMEs and likely VMEs in the eastern NPFC CA.

We note that although we do not have sufficient bycatch data in the northeast Pacific Ocean to undertake the kernel density estimation (KDE) approach to identifying VMEs as in Kenchington et al. (2014), we can plot the percent change in observed VME area as we vary the threshold value to identify natural breaks as an alternative means to identify thresholds. In Figure 8, we can see that the largest percent change in identified VME area occurs when we increase the VME indicator density threshold from 0.5 to 0.6 VME indicators m^{-2}. This jump in area of observed VMEs can be interpreted as a threshold density of VME indicator taxa that separates high concentration areas and background densities. Although both methods coincidentally identify 0.6 VME indicators m^{-2} as a threshold, the KDE plot in Figure 11 is a much simpler application of the robust KDE analysis completed by NAFO (see Kenchington et al. 2014).

3.3. ADVICE ON THE LOCATION OF LIKELY VMES IN THE COBB-EICKELBERG SEAMOUNT CHAIN

Based on our predictive model of VME indicator taxa density, our results suggest that there could be areas with high VME indicator taxa density occurring on all seamounts in the Cobb-Eickelberg seamount chain. Likely VMEs were predicted on all seamounts in the study area based on application of our VME indicator taxa density threshold of 0.6 individuals of VME indicator taxa m^{-2} to our predicted densities (Figure 9). The total likely VME area identified per seamount ranged from 2.11 km^2 to 27.55 km^2 (Table 7). Cobb Seamount had the largest total area identified as likely VMEs as well as the largest percent coverage of total seamount area. Eickelberg, Hoh and Pipe Seamounts had the smallest total area identified as likely VMEs, at about 2 km^2 each. They also had the smallest areas over which predictions of VME indicator density were made.

The patchy distributions of likely VMEs on all seamounts in our study area is comparable to other studies in the northeast Pacific Ocean and elsewhere. Similar work by Rowden et al. (2017, 2020) on the Louisville seamount chain in the South Pacific also predicted VME habitat on all seven seamounts in the chain. They found that coral density was also generally low with a patchy distribution. In the eastern NPFC CA, Chu et al. (2019) used different data than in our analyses (i.e. coral and sponge records from the continental shelf), as well as a different model algorithm (MaxEnt), subset of environmental data layers, modelled response result (i.e., habitat suitability index ranging from 0 to 1), and a different approach to combining the coral and sponge groups to identify likely VMEs. Yet, Chu et al. (2019) also concluded that likely VMEs occur on the same seamounts where we predicted likely VMEs to occur. Here, the main difference (and improvement) is that our study refines the area of likely VME occurrence to within-seamount areas (compared to Chu et al. 2019, who focused mostly on differences among whole seamounts). Moreover, data used in Chu et al (2019) were primarily from shelf and coastal ecosystems and there was concern about uncertainties associated with extrapolating into the high seas. An abundance-data driven GAM is an improvement over presence-only models used by Chu et al. (2019) which have a tendency to over-predict areas of suitable habitat (Vierod et al. 2014).

3.4. UNCERTAINTIES IN DATA AND METHODS FOR IDENTIFYING LIKELY VMES

The main uncertainties with the methods for identifying likely VMEs are those associated with predictive modelling, current data limitations, and uncertainties carried over from calculation of the regional VME indicator density threshold. Moreover there is the fact that Cobb Seamount may not be representative of other seamounts in the seamount chain. There is also a dearth of annotated visual data currently available the Cobb-Eickelberg seamount chain and potential impacts of bottom-contact fishing on the distribution and abundance of epifauna. While we acknowledge uncertainties exist in this study, we note that many of these uncertainties are ubiquitous in deep-sea studies and remain challenges that the greater scientific community has yet to overcome.

As noted above, Cobb Seamount is unusual in the northeast part of the Pacific Ocean, including along the Cobb-Eickelberg seamount chain, because it has the shallowest summit (24 m deep, Parker and Tunnicliffe 1994) and a high intensity of fishing by Canada's sablefish fishery that may have affected the distribution and abundance of structure-forming VME indicator taxa (Du Preez et al. 2020). There are few published studies of ocean circulation, connectivity, structure and topographies from the Cobb-Eickelberg seamount chain, but see studies related to ocean circulation on or near Cobb Seamount (e.g. Dower et al. 1992 and Dower and Mackas 1996). Thus, it is hard to assess if the strong influence of northness in the GAM used to predict the distribution of likely VMEs is real or an artefact of data limitations. Likely VMEs may be distributed on the southern part of seamounts in the Cobb-Eickelberg seamount chain.

Although only one visual dataset was available to adapt Rowden et al.'s (2020) approach to identify VMEs and likely VMEs on the Cobb-Eickelberg seamount chain (see AUV data from Curtis et al. 2015), there are other visual survey data collected by NOAA on Warwick Seamount within our study area and on Murray and Pratt Seamounts further north in the Gulf of Alaska that may provide informative qualitative data for identifying VMEs and likely VMEs.

Where possible, we followed the accepted standards for predictive habitat modeling developed by the ICES Workshop on the use of Predictive Habitat Models (ICES 2021) to improve the application of our model, report uncertainty, and increase transparency.

Even though we followed these accepted standards, our estimate of the VME indicator taxa density threshold and our predictions of likely VMEs throughout the Cobb-Eickelberg seamount chain may be influenced by the impacts of historical bottom-contact fishing on the distribution and abundance of epifauna observed with the AUV on Cobb Seamount in 2012 (see Curtis et al. 2015). Cobb Seamount has experienced disturbance by the use of bottom-contact fishing gears since the 1970s (see references cited in Curtis et al. 2015) and the distribution and intensity of bottom-contact fishing is a source of uncertainty in calculating the VME density indicator taxa threshold as well as predicting the distribution of likely VMEs.

Although there are no data to assess impacts caused by the use of those fishing gears during the four decades leading up to the AUV survey in 2012 (Curtis et al. 2015), bottom-contact fishing may very well have influenced the abundance and distribution of NPFC VME indicators used to identify VMEs on Cobb Seamount and predict the location of likely VMEs throughout the Cobb-Eickelberg seamount chain.

In their 2012 survey, Curtis et al. (2015) observed evidence of fishing-related impacts. On the shallow plateau of Cobb Seamount (less than approximately 200 m), most instances of entangled fishing gear involved *Stylaster* spp and the gear included trawl nets, gillnets, and longline gear. In deeper waters surveyed with the AUV, only trap or longline groundlines were observed entangled in coral. In some cases, the groundlines appeared to have toppled or killed whole colonies and in other cases, entangled groundlines were associated with partial damage to coral colonies.

Most of the longline and trap gear used by Canada to catch Sablefish on Cobb Seamount from 1996 to 2017 was set at depths that ranged from 625 to 875 m (corresponding to the 1st and 3rd quantiles, respectively) with a mean depth of 736 ± 1.39 m (Du Preez et al. 2020).

Given the distribution of fishing effort for Sablefish and the potential for this gear to damage or kill NPFC VME indicators, the distribution of fishing effort may have influenced the identification of VMEs in Cobb Seamount which were identified with the NPFC's VME indicator taxa density threshold. Indeed, the two larger VMEs identified by Warawa et al. (2023a,) were deeper (Table 6) than where Sablefish is usually fished on Cobb Seamount.

If the distribution of VMEs on Cobb Seamount have been affected by fishing-related impacts, Cobb Seamount may not be representative of other seamounts in the Cobb-Eickelberg seamount chain and this could in turn have affected predicted locations of likely VMEs throughout the seamount chain. This is of particular concern because depth is used in our GAM to predict the distribution of likely VMEs.

All of these sources of uncertainty have implications for the application of a precautionary approach to the protection of likely VMEs from SAIs in the NPFC CA. The NPFC does not currently define a precautionary approach to fisheries management, but when this is defined, it could potentially draw on measures of uncertainty associated with the models used to identify the distribution of likely VMEs in the NPFC's CA as well as maps of the relative risk of SAI in the eastern part of its CA.

3.4.1. Uncertainties in the statistical model (GAM) estimating VME density along the Cobb-Eickelberg seamount chain

The environmental data layers used as independent data in the likely VME density GAM were modeled layers which could influence the ability to resolve likely VMEs. Original modelling environmental data layers were created at an ocean-basin scale and are unlikely to capture the fine-scale features and microhabitats of individual seamounts. The data layers themselves were originally created as outputs of models with varying levels of spatial interpolation (Davies and Guinotte 2011). Given the grain size of our modelled environmental data layers (10,000 m^2) there is a limitation in identifying areas of likely VMEs that are smaller than what our current models can resolve. Currently, fine-scale data do not exist for most of the key niche parameters that influence the niche space of corals and sponges occurring over the entire study area of interest. The variables selected for our final VME density model did not include any modeled environmental data layers so uncertainty associated with the modeled and interpolated environmental data was not ultimately directly carried into the density predictions.

There was incomplete coverage of higher resolution bathymetry data over some seamounts which results in some density predictions associated with higher uncertainty. Stitching of bathymetry datasets to achieve complete coverage resulted in artifacts at some seamounts, mostly on Corn and Eickelberg Seamounts. These artifacts are a result of varying resolutions of multibeam layers composited into one layer and are associated with higher uncertainty.

It is possible that our suite of independent data layers was incomplete and didn't fully represent all factors important to predicting VME indicator density. For example, substrate was not available to include in our model, but is an important habitat predictor for coral and sponges (Guinotte and Davies 2014; Masuda and Stone 2015). There may also be other structure forming organisms that were not NPFC VME indicator taxa and thus excluded in our threshold analysis. For example, pennatulacean species (sea pens) were present on the AUV transects and can be tall, structure forming organisms. However, they were not included in calculations of the density of structure forming organisms because they were not recognized as VME indicators by the NPFC as of January 2024, although the NPFC endorsed their inclusion on the list of VME indicator taxa in April 2024 (NPFC-COM 2024).

The VME indicator density model extrapolated a small degree into unsurveyed areas. Dependent VME density data came from one of the seven seamounts modeled. To limit the amount of extrapolation outside the environmental variable range sampled, we restricted the model output to the same depth range as the dependent observations of VME density.

We attempted to asses uncertainties in the VME density GAM by validating the models using cross-validation.

3.4.2. Uncertainty in the density threshold method that estimates VME presence

Observations of VME indicator taxa density from visual data used as dependent data in density modelling are limited. Given the small sample size of 4 visual transects that VME density values were calculated from and the haphazard, non-random sampling design associated with these four AUV transects (Curtis et al. 2015), there is potential for spatial bias.

Not all VME indicator groups used by other RFMOs were represented in the threshold analysis. By only using the NPFC's VME indicator taxa, we did not include some corals that contribute to structural complexity, including pennatulaceans and hydrocorals.

Pennatulacean species (sea pens) were present on the AUV transects and can be tall, structure-forming organisms. However, they were not included in calculations of the density of VME indicator taxa because they were not recognized as VME indicators by the NPFC at the time of writing this research document. The NPFC Commission endorsed the recommendation to list these corals as VME indicator taxa in April 2024 (NPFC-COM 2024). In anticipation that these taxa would be recognized as VME indicator taxa by the NPFC after this January 2024 regional peer review, we recalculated our regional VME indicator density threshold with pennatulaceans included as structure-forming VME indicators. Sea pens account for 0.5% of organisms that were identified on the four AUV transects (n = 40) and when they are included as VME indicators in our threshold calculation, the average threshold is 0.41 VME indicator taxa per square metre with a 95% confidence interval of 0.37 - 0.45 (see Table 8). This value falls outside the 95% confidence interval calculated when pennatulaceans were excluded as VME indicators. Periodic review of methods and data is a key step of the NPFC's framework for identifying VMEs and likely VMEs (Warawa et al. 2022) and future iterations of analyses to calculate the threshold can include these structure-forming taxa and other VME indicator taxa that are listed by the NPFC in the future.

By removing non-structure forming taxa from our dataset of VME indicator taxa, we also excluded one scleractinian (*Desmophyllum dianthus*) and two soft corals (historically Alcyonacea) (*Heteropolypus ritteri* and *Gersemia* spp) even though they are on the list of NPFC's VME indicators. However, by doing so we reduced some uncertainty by ensuring all NPFC VME indicator taxa used to calculate our regional VME indicator density threshold were in fact providing structural complexity. Thus, our analyses were more closely aligned to the FAO's criterion of structural complexity.

To show uncertainty in the distribution of likely VMEs, we also show maps of where these are predicted to be when we use the lower and upper 95% confidence interval values of the regional VME indicator density threshold (Figure 9).

3.5. FUTURE WORK

An important implication of these sources of uncertainty is that the identified VMEs and likely VME areas are expected to be a subset of the full VME extent in this seamount range within the depths considered, while VMEs and likely VMEs outside this depth range have yet to be evaluated. Further analyses with more data will likely lead to more observed and likely VMEs being identified, especially if the FAO VME criteria, other than structural complexity, are used during assessments. Periodic review of methods and data is a key step of the NPFC's framework for identifying VMEs and likely VMEs (Warawa et al. 2022). With periodic review analysts can:

1. Use new visual data obtained from nearby seamounts in the eastern NPFC CA to evaluate the variability of the regional VME indicator density threshold across seamounts and depths.
2. Use causal inference modelling to calculate a regional VME indicator density threshold.
3. Repeat our analysis to calculate a regional VME indicator density threshold that includes sea pens and any other VME indicator taxa recognized by the NPFC.
4. Repeat our analysis when new visual survey data become available to identify other VMEs.
5. Improve our predictions of the location of likely VMEs when new visual data become available.
6. Use the location of likely VMEs to select areas for future visual surveys to validate our model predictions.
7. Use Welches ANOVA to test for differences between VME and non-VME communities as in Rowden et al. (2020).
8. Model species diversity rather than species richness when calculating a regional density VME indicator threshold.
9. Consider using a negative binomial or poisson error distribution that would be suitable for count data when calculating a regional density VME indicator threshold.

4. TABLES

Table 1. NPFC VME indicator taxa represented in the autonomous underwater vehicle (AUV) annotated data from the Cobb Seamount 2012 survey (Curtis et al. 2015). Structurally-complex taxa are indicated with an asterix (*) and total count is from all four AUV transects.

VME Group	Scientific Name	Total Count
Black Coral	Bathypathes*	373
	Lillipathes*	281
	Stichopathes*	61
Glass Sponge	Euretidae*	27
	Farrea omniclavata*	39
	Rossellidae*	128
	Staurocalyptus*	8
Gorgonian	Callistephanus simplex*	29
	Keratoisididae*	570
	Primnoidae*	188
Soft Coral	Gersemia	40
	Heteropolypus ritteri	245
Stony Coral	Desmophyllum dianthus	8

Table 2. Sedentary taxa associated with the NPFC's VME indicator taxa identified by NOAA on the four autonomous Underwater vehicle (AUV) transects surveyed in 2012 on Cobb Seamount (see Curtis et al. 2015).

Taxonomic group	***Morphotype Name***	***Scientific Name***	***Rank***	***Phylum***
anemone	*Unidentified anemone*	*Anthozoa*	*Sub-phylum*	*Cnidaria*
anemone	*Liponema brevicorne*	*Liponema brevicorne*	*Species*	*Cnidaria*
anemone	*Actinostola faeculenta*	*Actinostola faeculenta*	*Species*	*Cnidaria*
anemone	*Unidentified anemone*	*Anthozoa*	*Sub-phylum*	*Cnidaria*
anemone	*Hormathiidae*	*Hormathiidae*	*Family*	*Cnidaria*
hydrocoral	*Stylaster sp*	*Stylaster*	*Genus*	*Cnidaria*
pennatulacean	*Anthoptilum sp*	*Anthoptilum*	*Genus*	*Cnidaria*
pennatulacean	*Umbellula lindahli*	*Umbellula lindahli*	*Species*	*Cnidaria*
pennatulacean	*Pennatuloidea*	*Pennatuloidea*	*Order*	*Cnidaria*
pennatulacean	*Balticina willemoesi*	*Balticina willemoesi*	*Species*	*Cnidaria*
Soft coral	*Gersemia spp.*	*Gersemia spp.*	*Genus*	*Cnidaria*
Soft coral	*Heteropolypus ritteri*	*Heteropolypus ritteri*	*Species*	*Cnidaria*
Stony coral	*Desmophyllum dianthus*	*Desmophyllum dianthus*	*Species*	*Cnidaria*
sponge	*Unidentified sponge*	*Porifera*	*Phylum*	*Porifera*

Table 3. Mobile taxa associated with the NPFC's VME indicator taxa identified by NOAA on the four autonomous Underwater vehicle (AUV) transects surveyed in 2012 on Cobb Seamount (see Curtis et al. 2015).

Taxonomic group	**Morphotype Name**	**Scientific Name**	**Rank**	**Phylum**
Crinoid	*Florometra serratissima*	*Florometra serratissima*	*Species*	*Echinodermata*
Nudibranch	*Tritoniidae*	*Tritoniidae*	*Family*	*Mollusca*
Sea star	*Ampheraster marianus*	*Ampheraster marianus*	*Species*	*Echinodermata*
Sea star	*Brisingidae*	*Brisingidae*	*Family*	*Echinodermata*
Sea star	*Hippasteria phrygiana*	*Hippasteria phrygiana*	*Species*	*Echinodermata*
Sea star	*Pseudarchaster sp*	*Pseudarchaster*	*Genus*	*Echinodermata*
Sea star	*Pteraster sp*	*Pteraster*	*Genus*	*Echinodermata*
Sea star	*Rathbunaster californicus*	*Rathbunaster californicus*	*Species*	*Echinodermata*
Sea star	*Thrissacanthias sp*	*Thrissacanthias*	*Genus*	*Echinodermata*
Sea star	*Unidentified sea star*	*Asteroidea*	*Class*	*Echinodermata*
Sea cucumber	*Molpadia intermedia*	*Molpadia intermedia*	*Species*	*Echinodermata*
Sea cucumber	*Pannychia moseleyi*	*Pannychia moseleyi*	*Species*	*Echinodermata*
Sea cucumber	*Psolus squamatus*	*Psolus squamatus*	*Species*	*Echinodermata*
Sea cucumber	*Unidentified sea cucumber*	*Holothuroidea*	*Class*	*Echinodermata*
Crab	*Chionoecetes tanneri*	*Chionoecetes tanneri*	*Species*	*Arthropoda*
Crab	*Chorilia longipes*	*Chorilia longipes*	*Species*	*Arthropoda*
Crab	*Lithodes couesi*	*Lithodes couesi*	*Species*	*Arthropoda*
Crab	*Unidentified crab*	*Decapoda*	*Order*	*Arthropoda*

Taxonomic group	***Morphotype Name***	***Scientific Name***	***Rank***	***Phylum***
Squat lobster	*Chirostylidae*	*Chirostylidae*	*Family*	*Arthropoda*
Fish	*Anoplopoma fimbria*	*Anoplopoma fimbria*	*Species*	*Chordata*
Fish	*Antimora microlepis*	*Antimora microlepis*	*Species*	*Chordata*
Fish	*Coryphaenoides acrolepis*	*Coryphaenoides acrolepis*	*Species*	*Chordata*
Fish	*Glyptocephalus zachirus*	*Glyptocephalus zachirus*	*Species*	*Chordata*
Fish	*Microstomus bathybius*	*Microstomus bathybius*	*Species*	*Chordata*
Fish	*Microstomus pacificus*	*Microstomus pacificus*	*Species*	*Chordata*
Fish	*Sebastes sp*	*Sebastes*	*Genus*	*Chordata*
Fish	*Sebastolobus alascanus*	*Sebastolobus alascanus*	*Species*	*Chordata*
Fish	*Sebastolobus sp*	*Sebastolobus*	*Genus*	*Chordata*
Fish	*Unidentified fish*	*Chordata*	*Phylum*	*Chordata*
Shark	*Scyliorhinidae*	*Scyliorhinidae*	*Family*	*Chordata*
Octopus	*Octopus sp*	*Octopus*	*Genus*	*Mollusca*

Table 4. Results of GAM used for identifying the regional VME indicator density threshold with Cobb Seamount NOAA's annotated autonomous underwater vehicle (AUV) data (see Curtis et al. 2015 for survey details). Estimated degrees of freedom (edf), F statistic and p-value are given for each model term.

Term	***edf***	***F***	***p-value***
VME density	*1.41*	*1.61*	*0.14*
Depth	*5.19*	*12.72*	*<0.001*
Transect	*2.78*	*3.00*	*<0.001*
Adjusted R^2	*0.46*	*-*	*-*
Deviance explained	*48.6%*	*-*	*-*
AIC	*919.58*	*-*	*-*

Table 5. Calculations of VME indicator density thresholds for the Cobb-Eickelberg regional threshold using the four methods Rowden et al. (2020) used to estimate a VME indicator density threshold in the SPRFMO CA (in number of VME indicator taxa m-2). The mean and standard deviation are also calculated.

Threshold Method		*Threshold Value*
1)	*the point of intersection of linear regressions using the initial and final 5% of data*	*0.53*
2)	*the point of intersection between a linear regression using the initial 5% of data and the maximum cumulative species richness value*	*0.74*
3)	*the point on the curve that is closest to the top right corner (0,1)*	*0.61*
4)	*the point on the curve that maximizes the distance between the curve and the line between extreme points (Youden Index)*	*0.52*
	Mean	*0.60 (SD = 0.1)*

Table 6. Summary of five areas identified as VMEs on Cobb Seamount.

VME ID	Latitude	Longitude	Area (m^2)	Approx width (m)	Approx length (m)	Depth (m)	VME indicator density (VME individuals/m^2)	Black coral abundance	Gorgonian abundance	Glass sponge abundance
COBB_VME-A	46.80567	-130.845	201	2.3	87.5	1,138	0.9	10	165	4
COBB_VME-B	46.80434	-130.844	152	2.3	66	1,112	0.71	8	93	5
COBB_VME-C	46.79705	-130.842	51	2.3	22.4	802	0.66	27	2	4
COBB_VME-D	46.79162	-130.841	52	2.3	22.8	508	0.6	0	30	0
COBB_VME-E	46.75812	-130.724	52	2.3	22.7	689	0.64	30	1	1

Table 7. Characteristics of areas identified as likely VMEs by seamount in the Cobb-Eickelberg seamount chain. Seamount peak depth is from Harris et al (2014).

Seamount	***Peak depth (m)***	***Total likely VME area (km²)***	***Seamount area within the 400-1,200 m depth range (km²)***	***Percent of seamount area within 400-1,200 m depth range identified as likely VME***
Brown Bear North	*655*	*20.4*	*102.60*	*19.88%*
Brown Bear South	*575*	*13.74*	*312.27*	*4.40%*
Cobb	*2*	*27.55*	*179.01*	*15.39%*
Corn	*380*	*6.91*	*121.17*	*5.70%*
Eickelberg	*786*	*2.12*	*30.64*	*6.92%*
Eickelberg Ridge	*739*	*10.95*	*48.21*	*22.71%*
Hoh	*1199*	*2.11*	*7.16*	*29.47%*
Pipe	*NA*	*2.13*	*16.33*	*13.04%*
Warwick	*510*	*13.3*	*134.84*	*9.86%*
Total		*99.21*	*952.95*	*10.42%*

Table 8. GAM results used for recalculating the regional VME indicator density threshold when sea pens are included as VME indicator taxa. Estimated degrees of freedom (edf), F statistic and p-value are given for each model term.

Term	***edf***	***F***	***p-value***
VME density	*1.87*	*2.49*	*0.0735*
Depth	*4.86*	*9.81*	*<0.001*
Transect	*2.68*	*7.56*	*<0.001*
Adjusted R^2	*0.41*	-	-
Deviance explained	*43.20%*	-	-
AIC	*864.26*	-	-

5. FIGURES

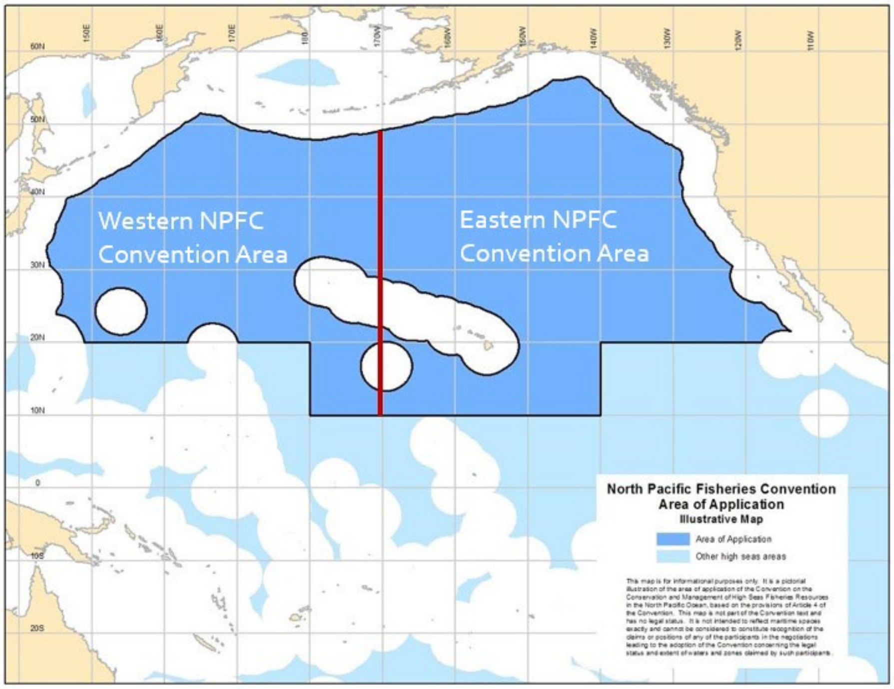

Figure 1. The North Pacific Fisheries Commission's (NPFC) Convention Area, which spans the international waters of the Northern Pacific Ocean. All NPFC Conservation and Management Measures apply to the western, eastern, or both parts of its Convention Area.

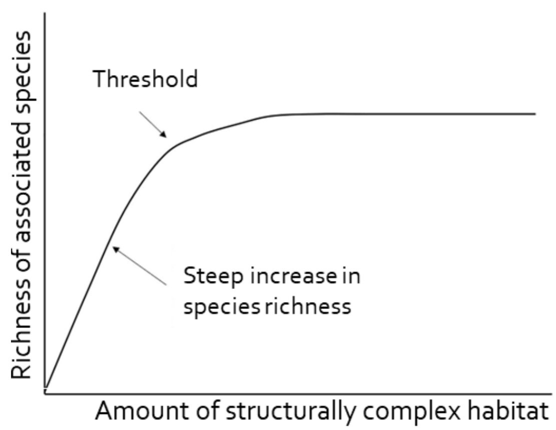

Figure 2. Theoretical curve that describes the relationship between the amount of structurally-complex habitat and the amount of associated species richness (after Figure 4 in Rowden et al. 2020).

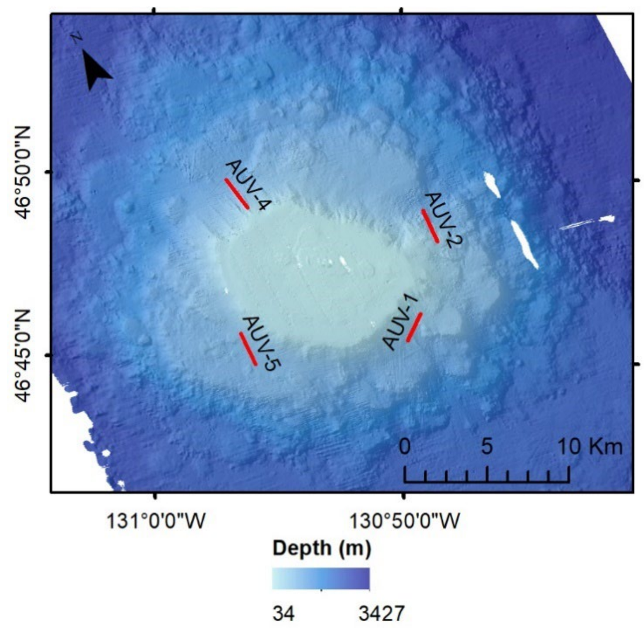

Figure 3. Bathymetry map of Cobb Seamount showing the locations of four autonomous underwater vehicle (AUV) transects (red) from the survey of Cobb Seamount in 2012 (see Curtis et al. 2015 for more details).

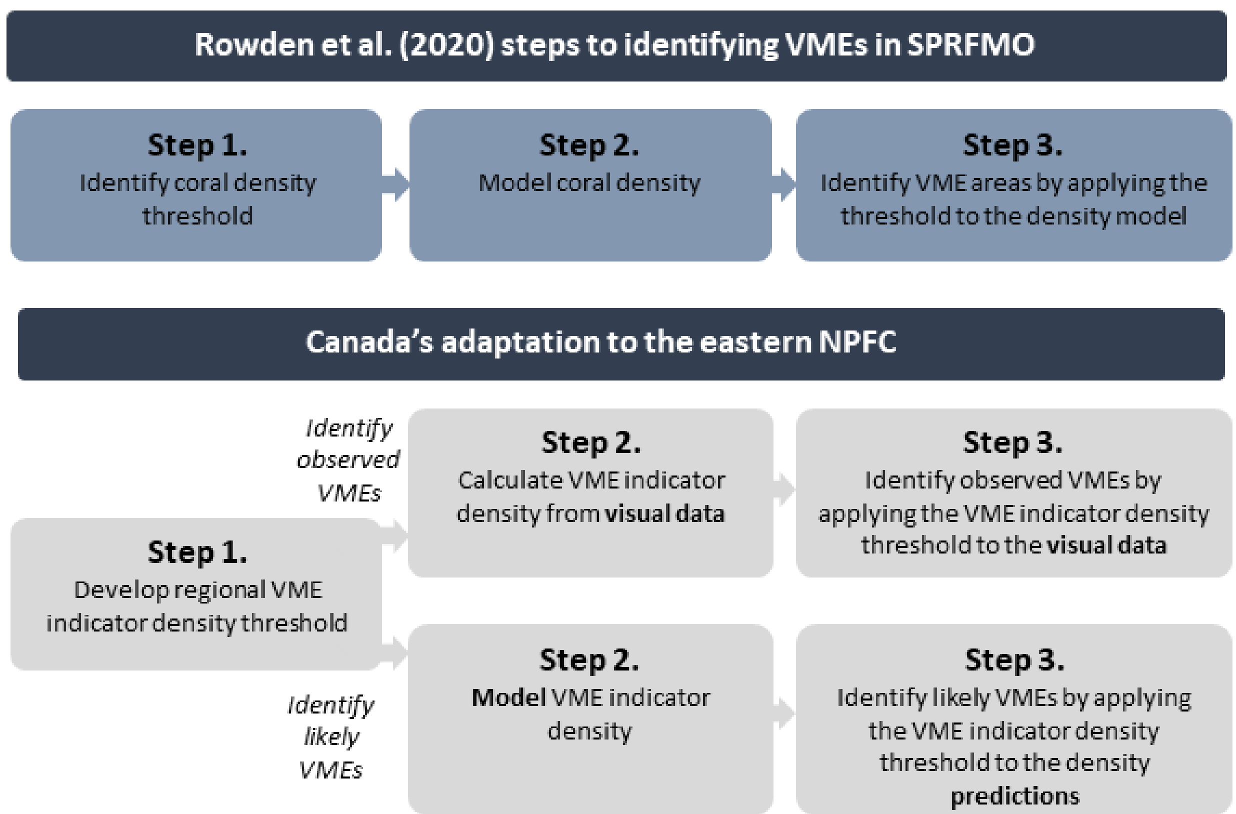

Figure 4. Canada's adaptation of the methods used in Rowden et al. (2017; 2020) in the eastern NPFC CA.

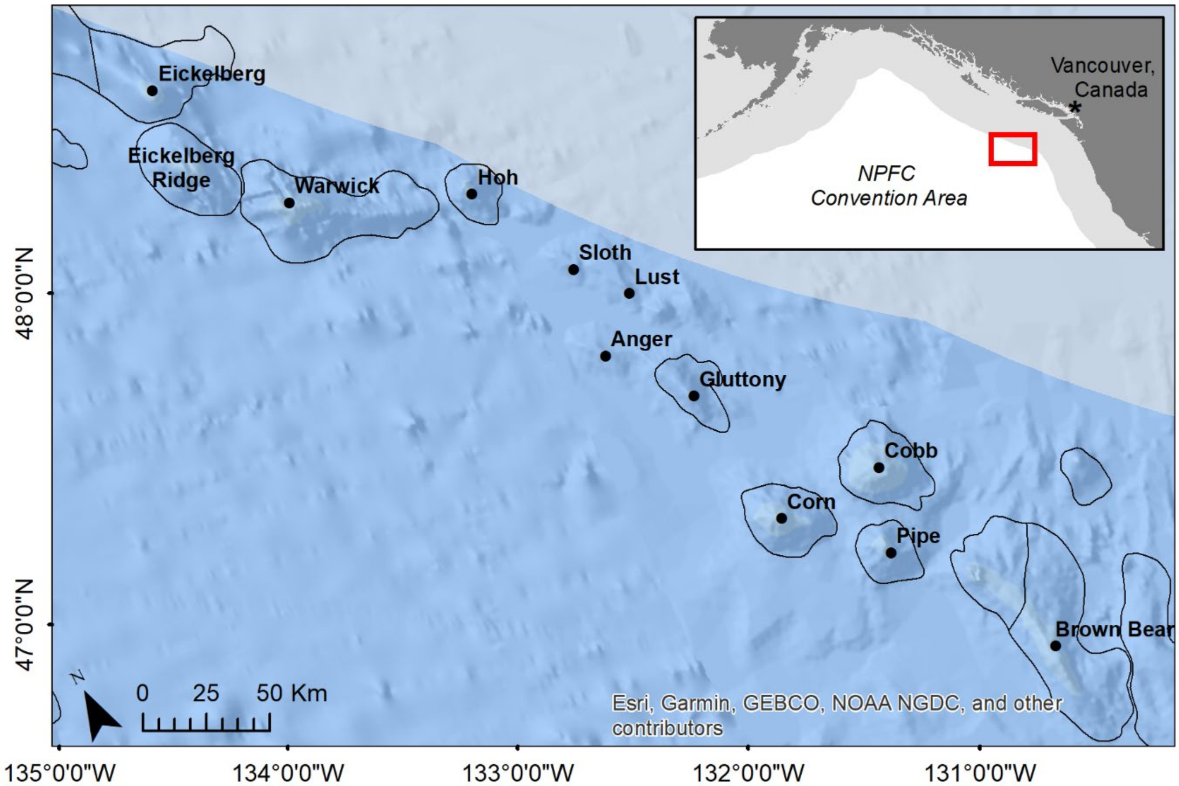

Figure 5. The Cobb-Eickelberg seamount chain study area in the eastern NPFC Convention Area, next to the Canadian EEZ (light grey). Black dots represent named seamounts and black outlines represent seamounts identified from geomorphic features in Harris et al. (2014).

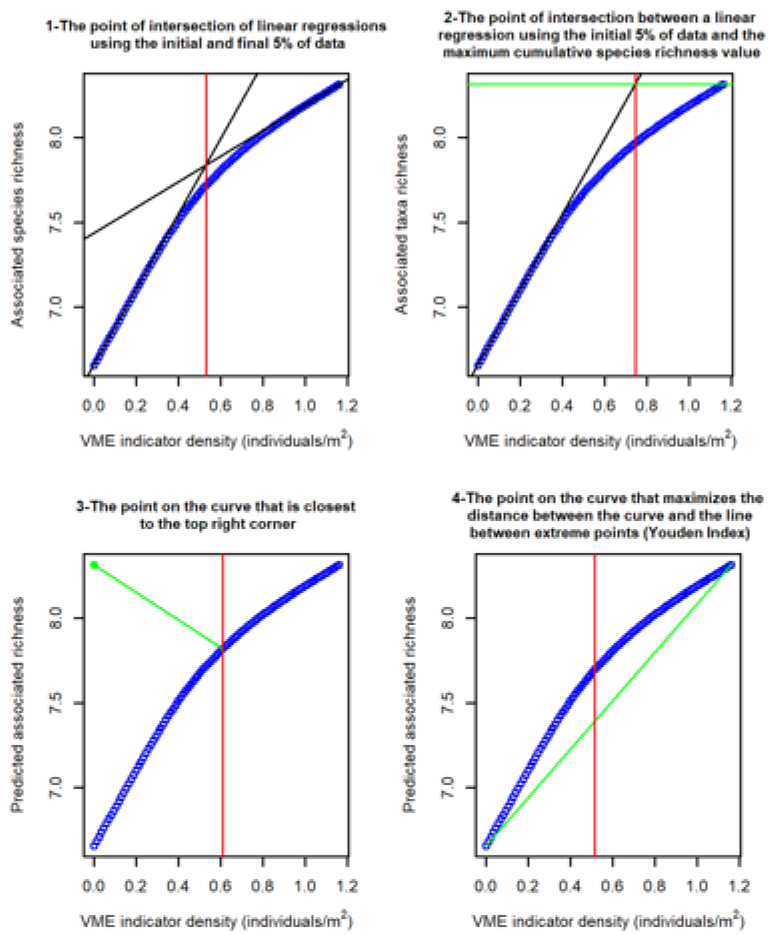

Figure 6. The four methods described in Rowden et al. (2020) we used to calculate our regional VME indicator density threshold.

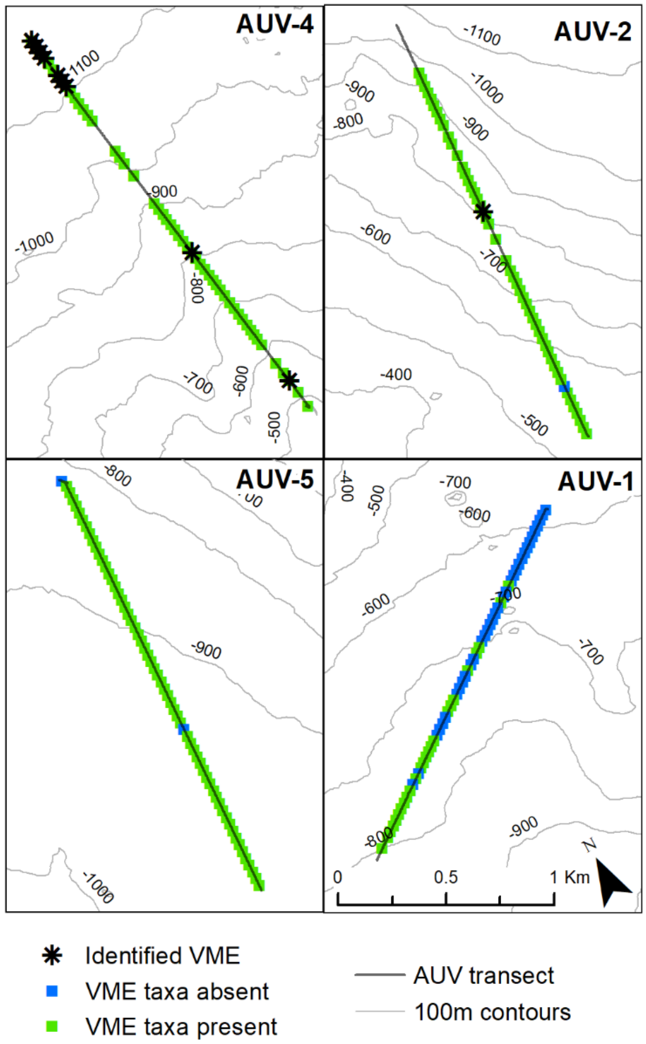

Figure 7. AUV transect segments with VMEs identified on Cobb Seamount are marked with black stars on transect AUV 4 and AUV 2.Transect segments with observed densities of VME indicator taxa below the regional VME indicator density threshold of 0.6 m^{-2} are in green. Transects with no observed VME indicator taxa are marked in blue. Grey lines are 100-m depth contour lines (see Curtis et al. 2015).

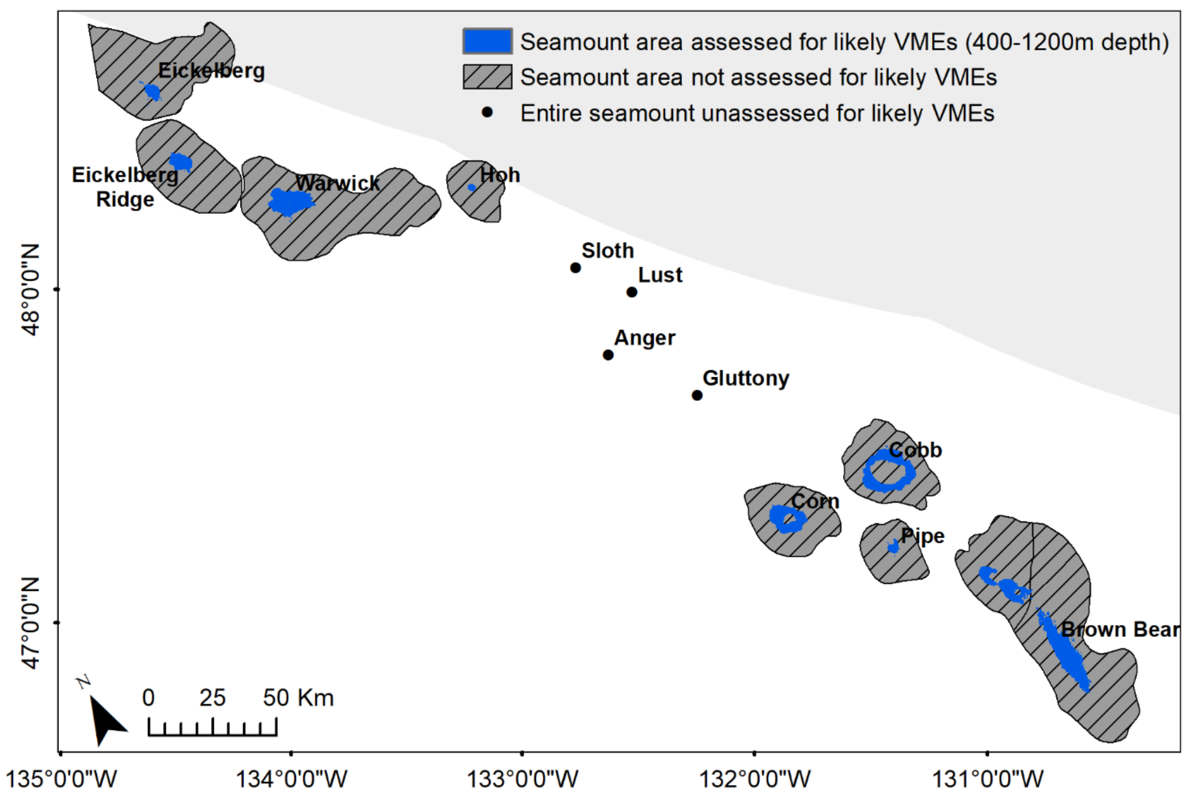

Figure 8. Parts of the Cobb-Eickelberg seamount chain that were assessed for the presence of likely VMEs (blue areas) and not assessed for the presence of VMEs or likely VMEs (hatched grey areas shallower than 400 m and deeper than 1,200 m).

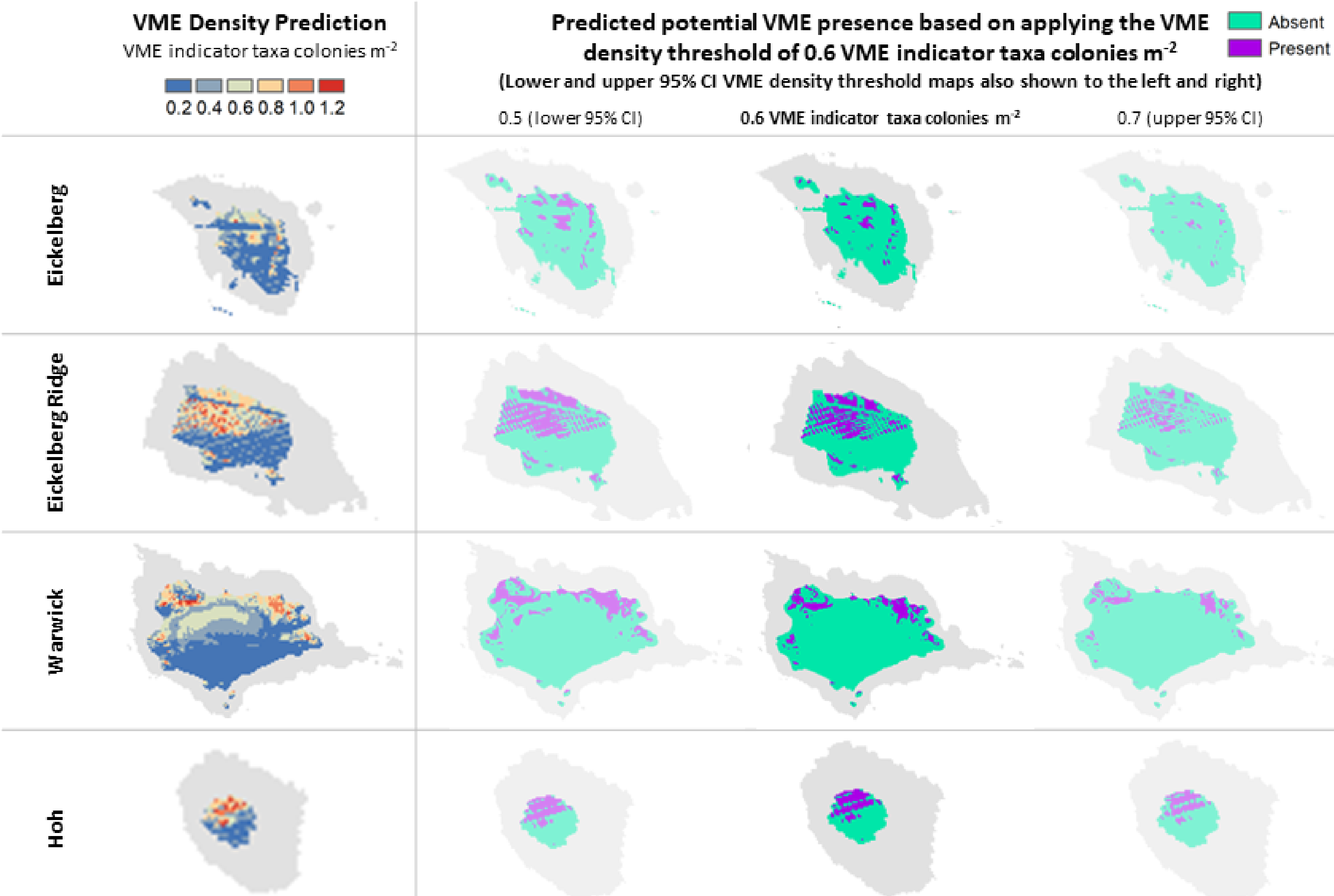

Figure 9. VME indicator taxa density model prediction maps and likely VME presence by seamount (not to scale). Likely VME presence (purple) is determined by applying the VME density threshold (see Warawa et al. 2023a) to the VME density prediction model output. Likely VME presence maps using the lower and upper 95% confidence interval of the VME density threshold (0.5 and 0.7, respectfully) is shown for comparison. The grey shaded areas represent depths outside of the prediction area, which was limited to 400-1,200 m.

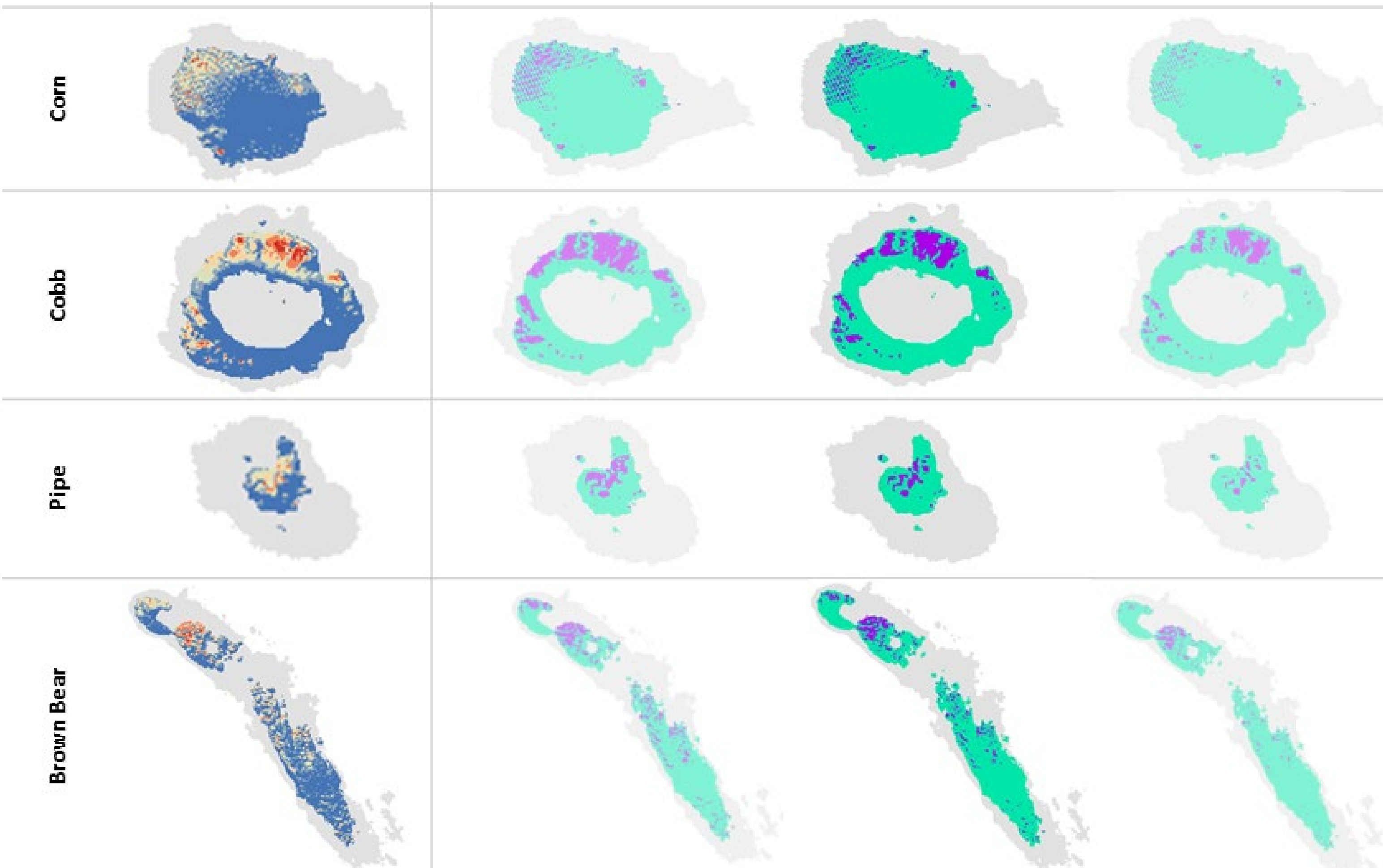

Figure 9.Continued.

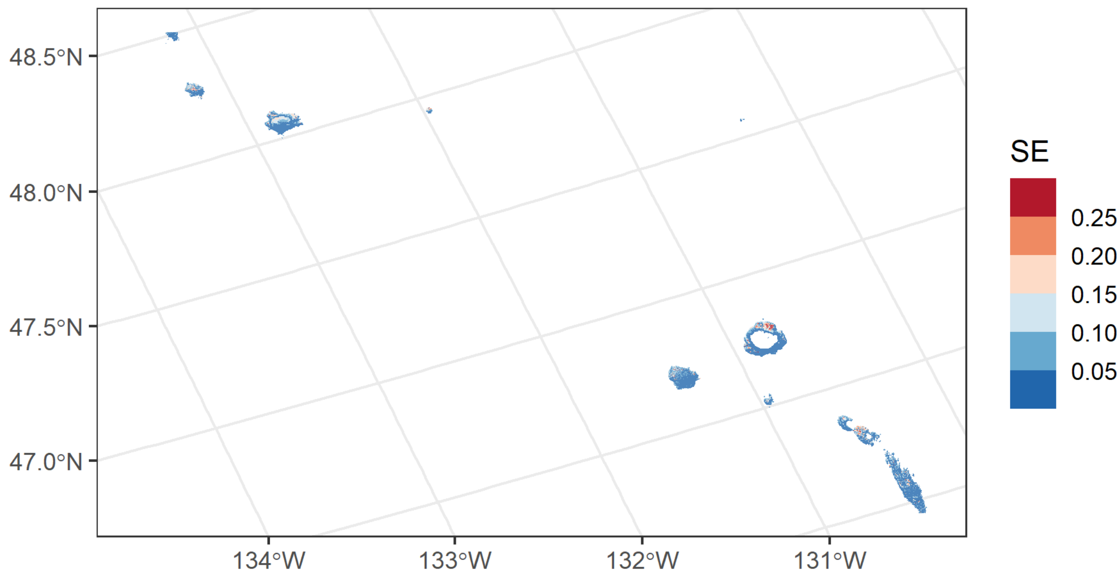

Figure 10. The standard error of the GAM VME density model estimate. Smaller standard error values indicate a better fit of the regression model to the data and are associated with smaller uncertainty in the prediction.

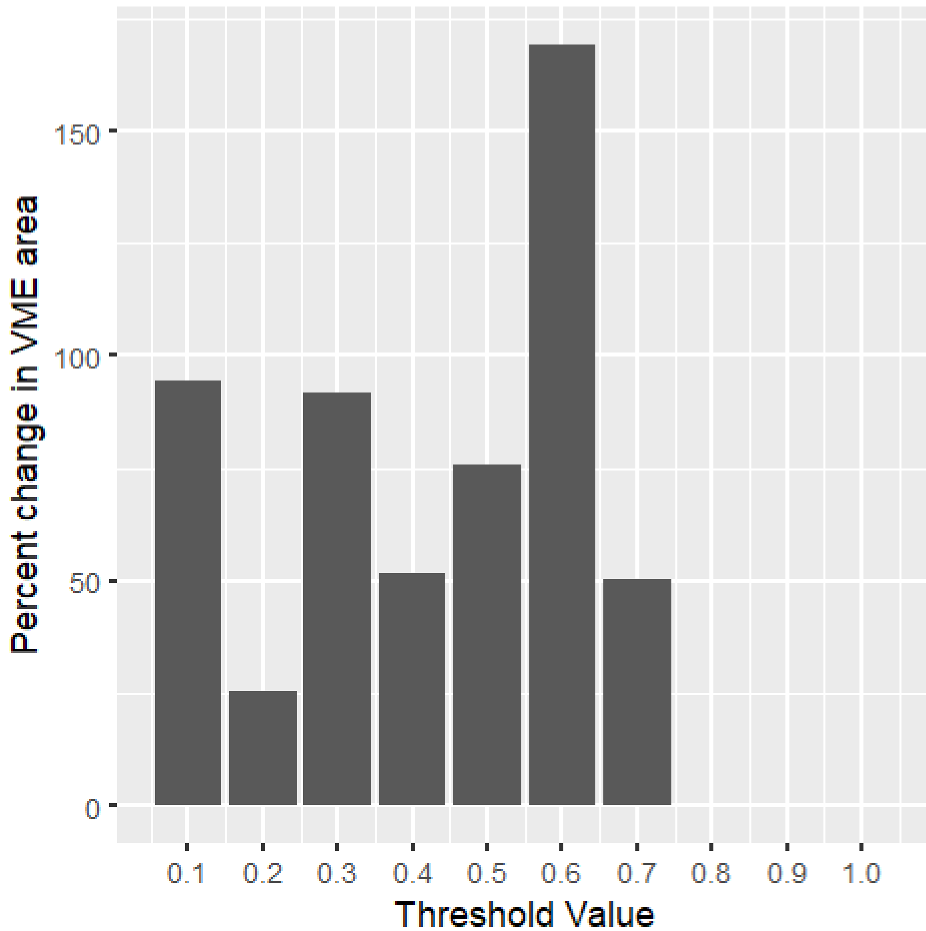

Figure 11. A simplified version of the kernel density estimation (KDE) analysis used by Kenchington et al. (2014): a plot of the percent change in area of observed VMEs as the threshold value is increased by increments of 0.1 as an alternative means to use natural breaks to identify thresholds. The largest percent change in identified VME area occurs when we increase the VME indicator density threshold from 0.5 to 0.6 VME indicators per m^2.

6. ACKNOWLEDGMENTS

We gratefully thank participants of the NPFC's Small Working Group on VMEs (SWG VME), Small Scientific Committee on Bottom Fish and Marine Ecosystems (SSC BFME), and Scientific Committee (SC) for sharing their thoughtful and insightful comments, questions, and suggestions with us as we progressed through development of our methods, communication of preliminary results, and revision of our methods and analyses based on their feedback. These participants included members of nine NPFC Contracting Parties as well as observers from the Deep Sea Conservation Coalition, including Amy Baco-Taylor and Matthew Gianni. We appreciate externals reviews of our work by Ashley Rowden, Ellen Kenchington, Chris Yesson, and a representative of the UN Food and Agriculture Organization, Tony Thompson. The NPFC Secretariat supported our work logistically, including hosting meetings of the SWG VME, SSC BFME, and SC, and preparing invaluable meeting summaries and reports. Development of our methods, data analyses, and writing were financially supported by DFO's Competitive Science Research Fund. Tom Hourigan and Mariano Koen-Alonso provided constructive and perceptive reviews of our research document and we appreciated the comments, questions, and suggestions from participants of the January 23-25, 2024, regional peer review process. The Centre for Science Advice in Pacific Region facilitated the reviews of our research document.

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APPENDIX A. VME INDICATOR DENSITY THRESHOLD MODEL

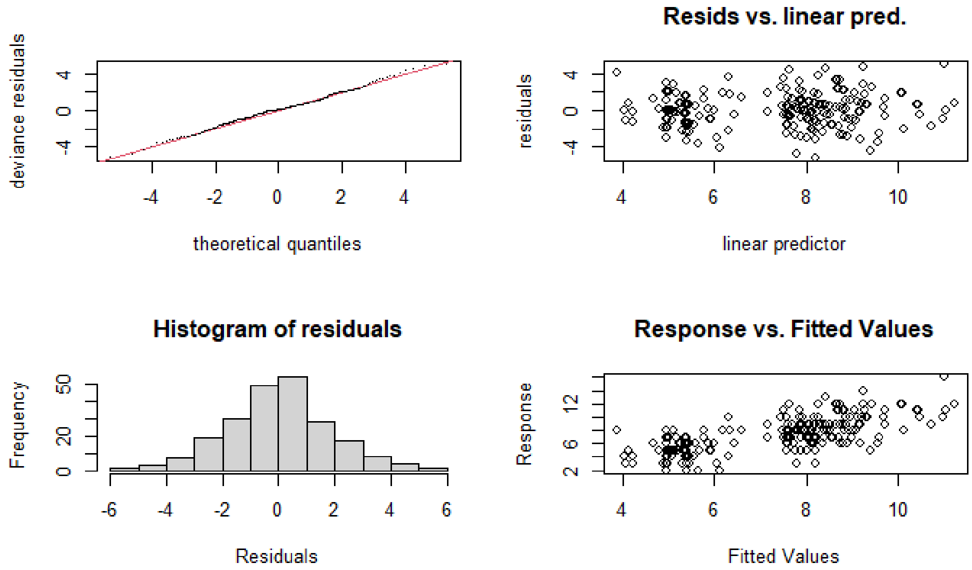

Figure A1. Model evaluation plots for VME indicator density threshold GAM using gam.check() to examine residuals.

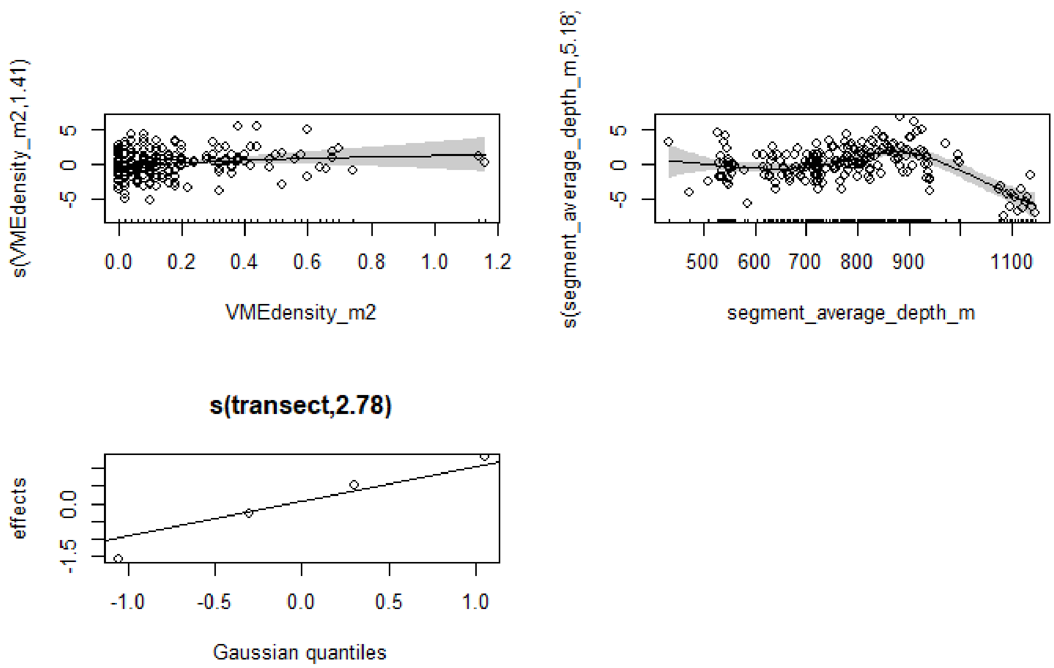

Figure A2. Marginal effects plots for VME indicator density threshold GAM.

APPENDIX B. VME DENSITY MODEL

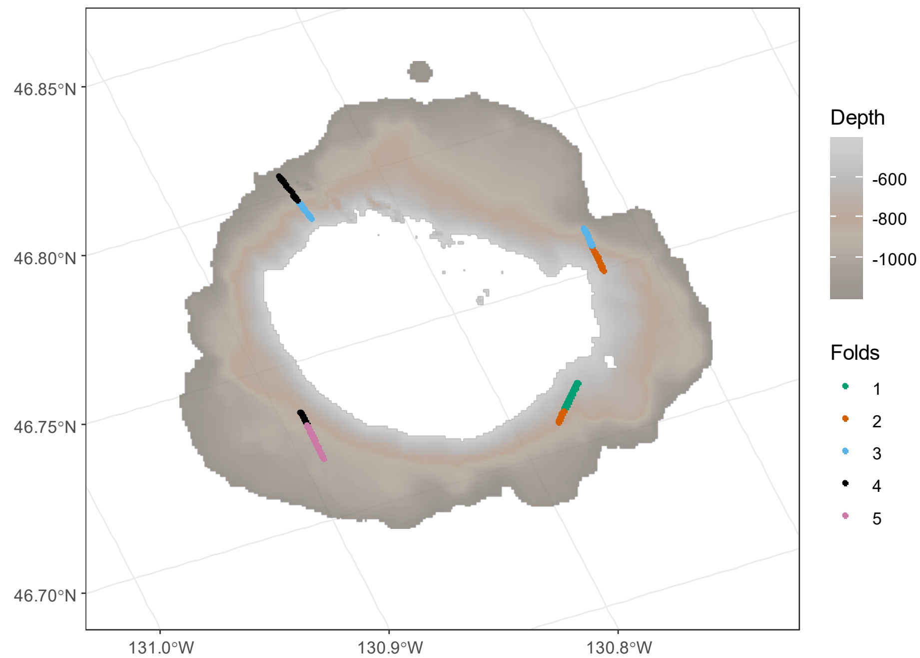

Figure B1. 5 folds used for testing data.

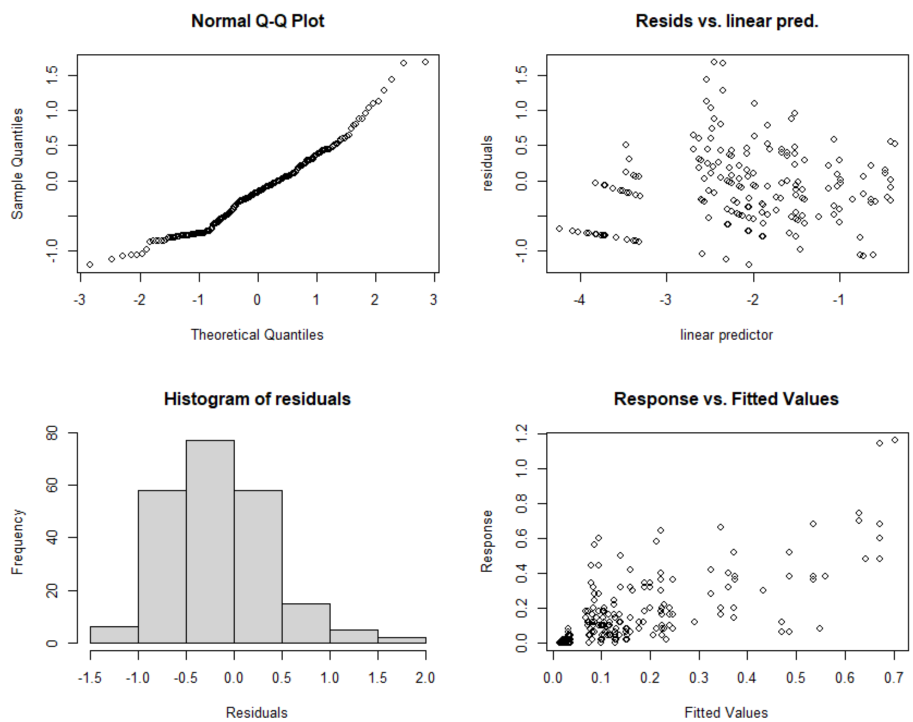

Figure B2. Model evaluation plots for VME density model using gam.check() to examine residuals.

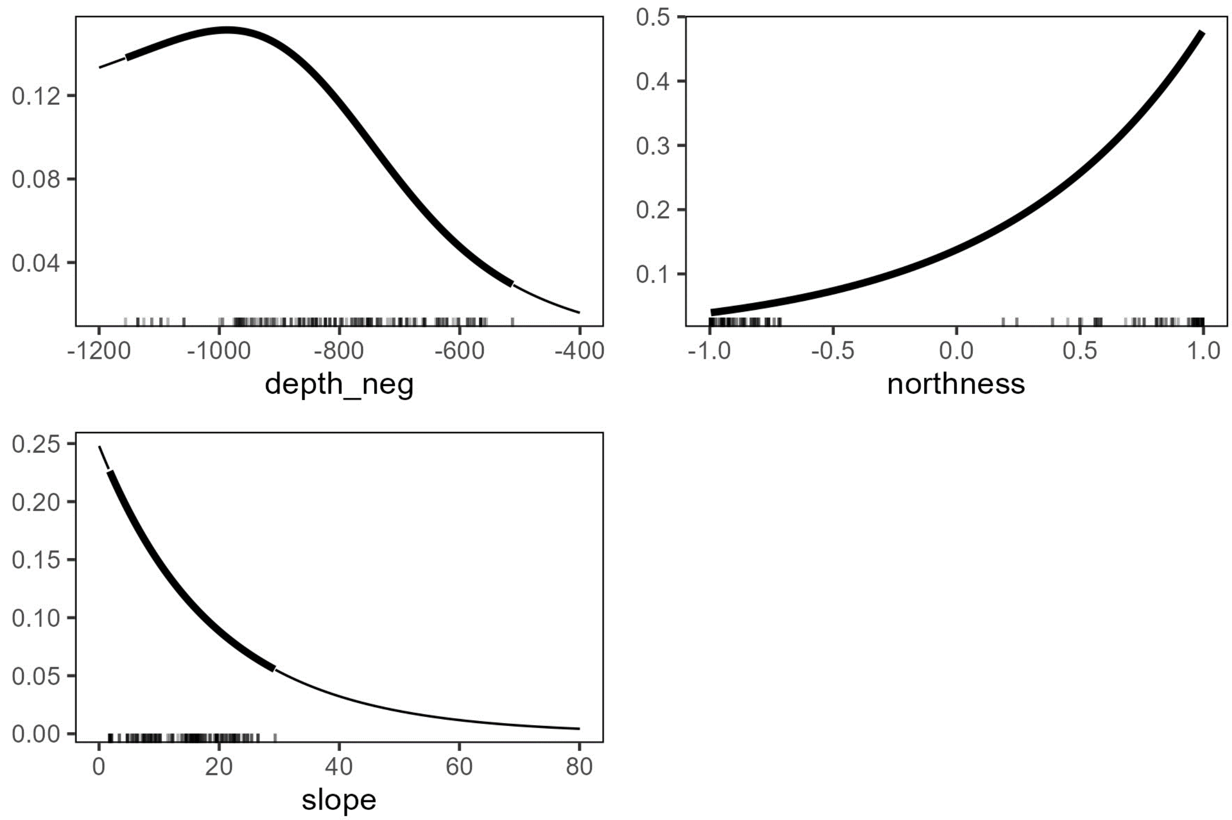

Figure B3. Marginal effects plots for VME density GAM.