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The Relative Risk of Significant Adverse Impacts to Vulnerable Marine Ecosystems in the northeast part of the NPFC's Convention Area

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Abstract

In 2006, the United Nations General Assembly (UNGA) adopted resolution 61/105 to address growing concerns about the impacts to benthic ecosystems by fisheries whose gears contact the seafloor. The Food and Agriculture Organization (FAO) outlined criteria to identify vulnerable marine ecosystems (VMEs), undertake impact assessments, and assess for significant adverse impacts (SAIs) to VMEs in its *International Guidelines for the Management of Deep-Sea Fisheries in the High Seas* (FAO 2009). VMEs are (1) unique or rare, (2) functionally significant habitat, (3) fragile, (4) structurally complex and/or (5) have species with life history traits that make recovery difficult (FAO 2009). The NPFC's Scientific Committee and its subsidiary groups have taken an active role in addressing the *Convention on the Conservation and Management of High Sea Fisheries Resources in the North Pacific Ocean*'s mandates related to VMEs and SAIs. The NPFC has not yet developed measurable objectives for determining the occurrence of SAI, and Canada has insufficient data to evaluate the impacts of its bottom fisheries for sablefish. The longline trap and longline hook gear used to harvest sablefish in the NPFC Convention Area (CA) can damage sensitive benthic areas. But a lack of data, including baseline data, to assess the impacts to VMEs by Canada's sablefish fishery, as well as the timing and magnitude of VME recovery, means that Canada is unable to assess if SAIs have taken place or are likely to take place in the northeastern part of the NPFC's CA where Canada fishes for sablefish. In this working paper we quantify the relative risk of SAIs on VMEs and areas likely to be VMEs in the Northeastern part of the NPFC's CA. We focus our assessment specifically along part of the Cobb-Eickelberg seamount chain where most of Canada's fishing effort for sablefish in the NPFC CA has taken place. Our approach draws on the fishing footprint of Canada's sablefish fishery and its overlap with the distribution of VMEs and areas likely to be VMEs. We describe the occurrence, spatial scale, and footprint of cumulative fishing activities for sablefish in the NPFC CA. We also describe how these data were used with the distribution of VMEs and areas likely to be VMEs to assess the relative risk of SAIs. We categorize 1 km x 1 km grid cells in our study area into areas at high, medium, or low relative risk of SAI. To fall into the highest relative risk category, both the cumulative fishing footprint and the VME indicator occurrence probability had to have values above the highest thresholds. Most (94%) of the grid cells are in the medium-risk category and 5% are in the high-risk category. High-risk areas are found on Brown Bear, Cobb, and Warwick Seamounts, where cumulative (i.e. summed over time) fishing is greater. Our assessment can be used to inform precautionary management decisions, including spatial closures, to protect VMEs and areas likely to be VMEs from SAIs.

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Introduction

Vulnerable marine ecosystems (VMEs) and significant adverse impacts (SAIs)

In 2006, the United Nations General Assembly (UNGA) adopted resolution 61/105 (paragraphs 80-91) to address growing concerns about the impacts to benthic ecosystems by fisheries whose gears contact the seafloor. By adopting UNGA resolution 61/105, states agreed to identify areas where vulnerable marine ecosystems (VMEs) are known or likely to occur, assess if a bottom fishery in the high seas would put those areas at risk, and to close them to bottom fishing unless fishing could be managed to prevent significant adverse impacts (SAIs). States also agreed that common criteria for identifying VMEs (paragraph 42), undertaking impact assessments (paragraph 47), and assessing for SAIs (paragraphs 16-20) were needed for consistent implementation of UNGA resolution 61/105. These criteria were developed by the United Nations Food and Agriculture Organization (FAO), outlined in the FAO's *International Guidelines for the Management of Deep-Sea Fisheries in the High Seas* (FAO 2009, hereafter referred to as the FAO Guidelines), and adopted in UNGA resolution 64/72.

The FAO Guidelines (FAO 2009) were developed for fisheries that capture species that can only sustain low exploitation rates with fishing gear that is likely to contact the seafloor in areas beyond national jurisdiction (ABNJ). Such fisheries typically occur at bottom depths between 400-2000 m on seamounts and ridges and target benthic or benthopelagic species using gear such as bottom and mid-water trawls, pots and longlines (Bell et al. 2019). Fished species in deep-sea ecosystems are characterized in part by low fecundity and can only sustain low exploitation rates. The FAO Guidelines describe the most vulnerable ecosystems as "those that are both easily disturbed and take a long time to recover, or may never recover" (FAO 2009). The preamble to FAO's Guidelines (FAO 2009) identifies the prevention of SAIs on VMEs as a key activity to achieve responsible management of deep-sea fisheries that provide economic opportunities while conserving and protecting biodiversity.

SAIs compromise ecosystem structure or functions by impairing the reproduction of affected populations, degrading long-term productivity of affected habitats, or causing, on more than a temporary basis, significant loss of the richness of species, habitats, or communities (FAO 2009). Commercial fishing activities that employ fishing gears that contact the seabed have been associated with damage to the seabed and associated ecosystems that may cause SAIs (Bell et al. 2019; Brewin et al. 2021 and references therein; DOSI 2022). For example, visual surveys of the Emperor Seamounts, where bottom contact fishing has occurred for decades, suggest that VMEs are likely to be widespread and SAIs have occurred (Baco et al. 2019, 2020; USA 2020).

The FAO recommended that both the duration and frequency of a repeated disturbance be considered when determining if an impact is temporary (FAO 2009). The FAO explained that a disturbance was more than temporary if the interval between the disturbance of a habitat is shorter than the recovery time. It also defined temporary impacts as those that are limited in duration and allow the ecosystem to recover over an acceptable period of time (on the order of 5-20 years). The FAO Guidelines identified six factors to consider when determining the scale and significance of an impact (DOSI 2022):

- *the intensity or severity of the impact at the specific site being affected,*
- *the spatial extent of the impact relative to the availability of the habitat type affected,*
- *the sensitivity/vulnerability of the ecosystem to the impact,*
- *the ability of an ecosystem to recover from harm, and the rate of such recovery,*
- *the extent to which ecosystem functions may be altered by the impact, and*
- *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.*

The FAO also suggested that States and regional fisheries management organizations or arrangements (RFMO/As) apply the precautionary approach when determining the nature and duration of impacts in accordance with Article 6 of the *1995 UN Fish Stock Agreement* (United Nations 1995) and Articles 6.5 and 7.5 of the *1995 FAO Code of Conduct for Responsible Fisheries* (FAO 1995).

The FAO Guidelines (FAO 2009) outline seven key steps of an assessment to establish if deep-sea fishing activities are likely to produce SAIs in a given area:

> i) description of type(s) of fishing conducted or contemplated, including vessels and gear types, fishing areas, target and potential bycatch species, fishing effort levels and duration of fishing (harvesting plan),
>
> ii) collation of best available scientific and technical information on the current state of fishery resources and baseline information on the ecosystems, habitats and communities in the fishing area, against which future changes are to be compared,
>
> iii) identification, description and mapping of VMEs known or likely to occur in the fishing area,

iv) description of data and methods used to identify, describe and assess the impacts of the activity, the identification of gaps in knowledge, and an evaluation of uncertainties in the information presented in the assessment,

v) identification, description and evaluation of the occurrence, scale and duration of likely impacts, including cumulative impacts of activities covered by the assessment on VMEs and low productivity fishery resources in the fishing area,

vi) risk assessment of likely impacts by the fishing operations to determine which impacts are likely to be SAIs, particularly impacts on VMEs and low-productivity fishery resources, and

vii) proposal of mitigation and management measures to be used to prevent SAIs on VMEs and ensure long-term conservation and sustainable utilization of low-productivity fishery resources, and the measures to be used to monitor effects of the fishing operations.

Annex 2 of the North Pacific Fisheries Commission's (NPFC) Conservation and Management Measure (CMM) 2021-05 and CMM 2019-06 states that "Each member of the Commission is to conduct assessments to establish if bottom fishing activities are likely to produce SAIs in a given seamount or other VMEs. Such an impact assessment is to address" these seven key steps outlined in the FAO Guidelines (FAO 2009).

The North Pacific Fisheries Commission (NPFC) and SAIs

Article 3 of the *Convention on the Conservation and Management of High Sea Fisheries Resources in the North Pacific Ocean* (hereafter The Convention, available here: NPFC Convention | npfc) specifies that Contracting Parties of the NPFC should prevent SAIs on VMEs and take into account relevant international guidelines, including those by FAO.
Article 7 specifies that the Commission adopt conservation and management measures (CMMs) to prevent SAIs on VMEs in the NPFC's Convention Area (CA). Those CMMs should include measures for conducting and reviewing impact assessments to determine if bottom fishing activities would cause SAIs on VMEs and, if appropriate, close the corresponding areas to fishing. Annex 2 of the NPFC's CMM 2021-05 and 2019-06 are *Science-Based Standards and Criteria for Identification of VMEs and Assessment of [SAIs] on VMEs and Marine Species*.
The Convention's Article 10 addresses activities by the NPFC's Scientific Committee (SC), which include developing a process to identify VMEs and areas likely to be VMEs, identifying the location of bottom fisheries in relation to those areas, and establishing science-based standards and criteria to determine if bottom fishing activities are likely to produce SAIs on VMEs, and recommend measures to avoid such impacts.

The NPFC's SC and its subsidiary groups have taken an active role in addressing the Convention's mandates related to VMEs and SAIs. In 2018, the Small Scientific Committee on VMEs recommended that the SC develop measurable objectives for determining the occurrence of SAIs and a standardized approach and metrics to assess the cumulative impact of all Members' bottom fisheries on VMEs over time (Small Scientific Committee on VMEs 2018). Also in 2018, Russia undertook an assessment of SAIs on VMEs potentially associated with their bottom trawl, bottom gillnet, and bottom longline fisheries, as well with their pots. Russia concluded that based on their catches, there was no evidence of SAIs where VMEs occur, although they did note insufficient catch statistics were available for assessment of SAIs in their gillnet fishery (Russian Federation 2018).

The following year, Japan presented an assessment of the impact of Japanese bottom fisheries on potential VMEs, also in the Emperor Seamounts (Miyamoto and Yonezaki 2019; and see Miyamoto and Kiyota 2018). Japan's approach characterized benthic communities with visual surveys, mapped the overlap in distributions of fishing data and densities of potential VME indicator taxa, used categorical variables to identify areas at potential risk of SAI, and used a qualitative approach to visually evaluate areas at risk using the VME criteria specified in Annex 2 of CMM 2016-05 and in the FAO Guidelines. Japan did not find evidence of VMEs in their fishing grounds, although they suggested that potential VMEs outside of the fishing grounds could be spatially protected from SAIs (Miyamoto and Kiyota 2018).

Other RFMOs and SAIs

Other RFMOs have undertaken assessments to determine if there are or may be SAIs on VMEs in their respective CAs. The South Pacific Regional Fisheries Management Organization (SPRFMO) conducted a review of approaches used by RFMOs to avoid SAIs on VMEs (Cryer and Soeffker 2019). The approaches used by RFMOs are broad and variable in relation to assessing SAIs, defining the fishing footprint, applying predictive habitat models of VME indicator taxa, and quantifying the risk of VME impacts (Bell et al. 2019). Although most RFMO/As have adopted spatial management measures to protect VMEs, the assessment of SAIs is far less advanced, including for the NPFC (Bell et al. 2019). When SAI methods have been developed, they usually do not address all the criteria published in the FAO Guidelines. As noted by SPRFMO, most RFMOs have area closures and other measures that protect VMEs (Cryer and Soeffker 2019).

SPRFMO minimizes SAIs on VMEs by restricting bottom fishing to defined areas within the historical fishing footprint (SPRFMO 2019, see CMM-03-2019). SPRFMO has developed a Bottom Fishery Impact Assessment Standard (BFIAS), in part to assess the cumulative impacts of bottom fishing activities on VMEs. The Southern Indian Ocean Fisheries Agreement (SIOFA) also developed a BFIAS to assess impacts of bottom fisheries on VMEs. The Northeast Atlantic Fisheries Commission's (NEAFC) analyses of the impacts of bottom fishing on VMEs are undertaken by the International Council for the Exploration of the Seas (ICES).

The Deep Ocean Stewardship Initiative (DOSI) recently undertook a review of impact assessments for deep-sea fisheries in the high seas (DOSI 2022). In their review, DOSI compared the contents of those assessments to FAO's Guidelines (FAO 2009) and outlined ways for RFMO/As and individual states to improve future impact assessments to comply with the UNGA resolutions on deep-sea fishing. DOSI identified several key shortcomings of impact assessments with respect to the FAO Guidelines, including limited availability of quality data on VMEs, inadequate assessment of uncertainties and their implications for management decisions, inadequate monitoring of impacts and recovery from cumulative effects including climate change, and limited recognition of the dynamic nature of habitats, marine resources, and fisheries during risk assessments. DOSI (2022) also found that risk assessments are either completely missing or the methods are inadequately described.

Conceptual approach and Canada's assessment of the relative risk of SAIs on VMEs

Risk assessments are increasingly used to account for uncertainties related to environmental impacts and to inform optimal management decisions under those uncertainties (reviewed in DOSI 2022). Key steps in a risk assessment are risk identification, risk analysis (i.e., the quantification of risk) and consideration of measures to reduce the risk (DOSI 2022). Paragraph 48 of the FAO Guidelines recommended that risk assessments should consider spatial variability in fishing intensities (FAO 2009). Although quantitative risk assessments are ideal, a qualitative risk assessment may be the most cost-effective approach when there is limited knowledge of the ecological impacts associated with a risk (DOSI 2022). The risk of impacts should be evaluated individually, in combination and cumulatively. Gros et al. (2022) recommended overlaying the predicted distribution of VME taxa with the fishing footprint as in Brewin et al. (2021). They also recommended that RFMO/As develop modelling approaches that consider the whole ecosystem rather than individual indicator taxa.

Overview of Canada's Approach

As with other assessments of the risk of SAIs on VMEs (e.g., Brewin et al. 2021), our approach in the northeast part of the NPFC CA draws on the fishing footprint of Canada's sablefish (*Anoplopoma fimbria*) fishery and its overlap with the distribution of VMEs and the predicted distribution of VME indicators. Because of data limitations, our approach does not explicitly refer to impacts to benthic ecosystems, but it provides a quantitative and repeatable measure of the spatially-explicit relative risk of SAIs.

Canada fishes for sablefish on seamounts in the northeast part of the NPFC CA. This fishery predominantly uses longline trap gear, but also uses longline hook gear (see Figure 2 in Doherty et al. 2018 for a description of fishing gear and vessels). Because these gears are relatively stationary on the seabed (but see Doherty et al. 2018; Gauthier 2017, 2018), they have lower impacts on benthic ecosystems relative to mobile fishing gears such as bottom trawls (Heifetz et al. 2009; Brewin et al. 2021), which have a larger footprint and contact greater areas of the seafloor. However, they still have potential to produce negative impacts on structure-forming invertebrates (Sampaio et al. 2012). Under normal use in Canada, bottom longline trap sets are frequently dragged, rolled, and bounced on the seafloor (see Gauthier 2017, 2018). Similarly, in the Aleutian Islands damage to cold-water corals and sponges has been well-documented, including in untrawled areas where gear types similar to the sablefish fishery were deployed (Stone 2006; Heifetz et al. 2009). Further, derelict fishing gear is known to damage underwater habitats such as corals and other benthic fauna (NOAA Marine Debris Program 2015). The cumulative impacts of repeated use of these sablefish fishing gears on VMEs and areas likely to be VMEs is unknown.

Assessing Vulnerability

In the context of SAIs, vulnerability refers to the risk that a VME will be altered irreversibly or over the long term (>20 years) by disturbance caused by bottom-contact fishing. Vulnerability is both relative and qualitative (Gros et al. 2022). Annex 2 of the NPFC's Small Scientific Committee on VME's fourth meeting report (SSC VME 2019) states that "Vulnerability is related to the likelihood that a population, community or habitat will experience substantial alteration by fishing activities and how much time will be required for its recovery from such alteration. The most vulnerable ecosystems are those that are both easily disturbed and are very slow to recover, or may never recover. The vulnerabilities of populations, communities and habitats are to be assessed relative to specific threats […] The risks to a marine ecosystem are determined by its vulnerability, the probability of a threat occurring and the mitigation means applied to the threat."

Corals may be particularly vulnerable to the impacts of bottom-contact fishing gear (Brewin et al. 2021). The NPFC VME indicator taxa are long-lived: age estimates range from ten to hundreds of years for scleractinians and octocorals (Andrews et al. 2002) and from hundreds to thousands of years for antipatharians and soft corals (Roark et al. 2009; Watling et al. 2011; Prouty et al. 2015; Etnoyer et al. 2018), and scleractinian reefs form over thousands of years (e.g. Fallon et al. 2014). They also tend to have slow rates of recruitment and growth (Aranha et al. 2014; Doughty et al. 2014). Baco et al. (2020) found evidence of SAIs on the Northwestern Hawaiian Ridge seamounts with little evidence of recovery in octocoral communities. Trawling impacts on seamount scleractinian reef have also been observed, with little recovery in the habitat or associated megafauna over a decade since fishing ceased (Althuas et al. 2009). Coral communities provide three-dimensional habitat for fish and invertebrate populations (Bulh-Mortensen et al. 2010; Gros et al. 2022). As the abundance of faunal associates in these habitats is positively correlated with the biocomplexity of structure-forming VME taxa (Price et al. 2019), reductions in the abundance and/or diversity of these organisms are likely to have negative downstream effects on communities and ecosystems.

Overlap between VMEs and intensity of fishing: data needs and resolution

At the NPFC's Small Scientific Committee on VMEs meeting in 2017, Members recognized that the identification of fished and unfished areas forms the foundation of assessing for SAIs and developing appropriate conservation measures, including encounter protocols and VME closures. At the same meeting in 2017, Japan presented its analysis of the spatial overlap of fishing activities and the distribution of potential VME indicator taxa to identify potential VME risk sites in the Emperor Seamounts (Miyamoto and Kyota 2017). More recently, the NPFC's Members have prepared a combined map footprint of fishing activities to better identify fishing grounds (NPFC 2021). Because Canada is the only NPFC Member that practices bottom-contact fishing in the northeast part of the NPFC's CA, Canada is using its own fisheries data to assess the relative risk of SAIs on VMEs there.

The FAO Guidelines specify that the management of deep-sea fisheries be based on the best scientific and technical information available. SPRFMO's BFIAS requires mapping of the distribution of fishing effort be prepared with available tow-by-tow or set-by-set data, noting the importance of maintaining data confidentiality. As with SPRFMO, we employ a 1 km x 1 km resolution in our assessment. We undertake our analyses of the relative risk of SAIs with Canada's sablefish fishery data in the NPFC CA, noting that assessing impacts of fisheries on VMEs in the deep-sea is operationally challenging (Brewin et al. 2021), not least because of the dearth of data on the structure and distribution of VMEs.

NPFC VME Indicator taxa and VMEs in the North Pacific Ocean

When undertaking risk assessments, most RFMOs focus on assessing impacts to VME indicator taxa rather than VMEs, and they do not clarify how well the distribution or abundance of VME indicator taxa reflect the distribution of VMEs (DOSI 2022, but see Rowden et al. 2020). Many quantitative approaches to identify VMEs focus on predicting the distribution of VME indicator taxa, however, the presence of one or more VME indicator taxa does not necessarily mean that a VME is present (Rowden et al. 2020; Gros et al. 2022). VMEs have not yet been identified in the northeast part of the NPFC's CA (but see Warawa et al. 2021 and Warawa et al. 2022a for a proposed quantitative approach), thus we are using predictive habitat suitability models (HSMs; also known as "ecological niche" or "species distribution" models) of the NPFC's VME indicator taxa to assess the relative risk of SAIs. Our method assumes that higher habitat suitability index (HSI) scores for VME indicator taxa (see Warawa et al. 2021, 2022a), indicating greater occurrence probability, correlate with higher likelihood of VME presence. We focus our analyses on the four groups of corals recognized by the NPFC (NPFC 2019, 2021a) as VME indicator taxa: Alcyonacea (excluding Gorgonians), Antipatharia, Gorgonacea (now within the order Alcyonacea), and Scleractinia. We recognize the value of assessing the risk of SAIs on other potential NPFC VME indicator taxa in the future, including sponges (NPFC 2022). Warawa et al. (2022a) use visual data to define VME density and occurrence thresholds above which an area is a VME or likely to be a VME, and show that the epibenthic megafaunal community structure of areas identified as VMEs or areas likely being VMEs differs from areas with lesser likelihoods of VME occurrence. Areas identified as VMEs or likely to be VMEs have higher likelihood of VME indicator taxa presence and are thus also correlated with higher associated species richness.

Objectives

In this working paper we quantify the relative risk of SAIs on VMEs and areas likely to be VMEs (see Warawa et al. 2021, 2022a) in the northeast part of the NPFC's CA. The NPFC has not yet developed measurable objectives for determining the occurrence of SAI, and Canada has insufficient data to evaluate the impacts of its bottom fisheries for sablefish.
Although we recognize that there probably is a long history of bottom-contact fishing in the northeast part of the NPFC CA (e.g., historical bottom fishing on Cobb Seamount; Curtis et al. 2015), we focus our assessment specifically along part of the Cobb-Eickelberg seamount chain where most of Canada's fishing effort for sablefish in the NPFC CA has taken place, while also taking into account the broader ecosystem (NPFC/FAO VME Workshop 2018).

Methods

Study Area – Cobb-Eickleberg Seamount Chain

The Cobb-Eickelberg seamount chain was formed by the movement of tectonic plates over the Cobb hotspot and ranges from approximately 1800 km from Axial Seamount, which is almost 500 km west of Oregon, USA, to Patton Seamount in the northwest part of the Gulf of Alaska (Desonie and Duncan 1990; West et al. 2003).

In this study, we focus our assessment of the relative risk of SAIs on part of the Cobb-Eickelberg seamount chain from Eickelberg Seamount southeast to Brown Bear Seamount, seamounts where Canada fishes outside of Canadian and USA exclusive economic zones (Figure 1). These seamounts include Brown Bear, Corn, Cobb, Warwick, and Eickelberg Seamounts, as well as Eickelberg Ridge. The summit depths of seamounts in this part of the chain range from approximately 30 m on Cobb Seamount to more than 850 m on Eickelberg Seamount (Harris et al. 2018; Chu et al. 2019).

As a consequence of the range of pinnacle depths and the expansive oxygen minimum zone (OMZ) in this region (OMZ depth range: 600-1200 m, Helly and Levin, 2004), waters overlying each seamount can span a range of conditions that have a strong influence on the depth distribution of VME indicator taxa in this region (Chu et al. 2019). Calcite and aragonite can be undersaturated in the OMZ ($\Omega < 1$) suggesting potentially unfavorable conditions for the skeleton growth of multiple VME indicator taxa (Table 1). Similarly, dissolved oxygen concentrations can be severely hypoxic within the OMZ (minimum of 14.78 µmol/kg) which is inhospitable for many species of fish and invertebrates (Chu and Gale, 2017). The full range of environmental conditions at this seamount chain are shown in Table 1.

Brown Bear, Cobb and Warwick Seamounts have been surveyed to assess their fisheries, geology, oceanography, ecology and/or biodiversity (Birkeland 1971; Curtis et al. 2015; Douglas 2011; Dower et al. 1992; Parker and Tunnicliffe 1994, Hill et al. 2011). Most biological studies have focused on Cobb Seamount, which is an unusual and biologically significant feature in the northeast Pacific Ocean because it extends from the abyssal plain at almost 3000 m depth well into the photic zone and supports productive, diverse and unusual communities of organisms (Birkeland 1971; Dower et al. 1992; Parker and Tunnicliffe 1994, Du Preez et al. 2015; Du Preez et al. 2016). Despite these studies, considerable data deficiency means that there is inadequate baseline information on the habitats, communities, and ecosystems in this seamount chain to monitor and assess future changes.

In a 2012 visual survey of Cobb Seamount, 144 demersal, benthic and infaunal taxa were observed from 19 remotely operated vehicle (ROV) and autonomous underwater vehicle (AUV) transects carried out at depths from 34 to 1154 m (Curtis et al. 2015; Du Preez et al. 2015). NPFC VME indicator taxa were found on all 19 survey transects. Populations of rockfishes (*Sebastes* spp.) were observed on the plateau (<225 m depth), as were dense populations of two corals: the cup coral (*Desmophyllum dianthus*) and colonies of an unidentified hydrocoral *Stylaster* spp. At greater depths on the AUV transects, dense corals included a bamboo coral (*Lepidisis* sp.), the antipatharian corals *Bathypathes* sp. and *Lillipathes* cf *lillei*, an unknown antipatharian species (Antipatharia sp. 1, as described in Du Preez et al. 2015), and the nongorgonian soft coral *Heteropolypus ritteri*. Seventeen coral taxa observed were on the NPFC's list of indicators of potential VMEs. Overall, 267 benthic and mid-water taxa from 14 phyla are known to occur on Cobb Seamount (Du Preez et al. 2015). Most species identified are known from the Northeast Pacific continental slope (Du Preez et al. 2016). Sand, boulders and creviced rock habitats were more prevalent on Cobb Seamount's plateau, but at greater depths (>435 m), creviced bedrock was more commonly observed (Curtis et al. 2015). Du Preez et al. (2016) described the structure and distribution of benthic communities on Cobb Seamount at a finer spatial scale, resolving nine distinctive assemblages over the 35-1200m depth range with primarily cold-water coral and sponge taxa driving the distinctions between assemblages. From 1996 to 2017, the depths with the greatest fishing effort on Cobb Seamount were approximately 600-700 m (Canada 2018).

Warawa et al. (2021, 2022a) identify areas that are VMEs based on a quantitative definition that draws on visual data. In the northeast Pacific Ocean, only Cobb Seamount has visual data available to identify VMEs but less than 0.01% of Cobb Seamount has been visually surveyed to date (Curtis et al. 2015). Areas likely to be VMEs have also been identified in our study area using a quantitative definition that has been proposed for application in the NPFC CA (Warawa et al. 2021, 2022a). This definition draws on predictive HSMs for NPFC's four VME indicator taxa, but areas likely to be VMEs have not yet been validated with visual surveys or fisheries catches. These proposed methods and results for identifying VMEs and areas likely to be VMEs have been reviewed by NPFC Members as well as the broader scientific community. Areas likely to be VMEs were identified on named seamounts where fishing occurs (red in Figure 4), seamounts where fishing does not occur (Foster, Hoh, Vance, and Gluttony Seamounts), and unnamed seamount features (Harris et al. 2014; Warawa et al. 2022a). On Cobb Seamount VMEs were identified on 22% of the area surveyed which occurred on three out of four AUV transects and falls within 5 of the 1km^2 grid cells (Figure 6).

Sablefish fishery data and its fishing footprint in the NPFC Convention Area

Canada uses long-line hook and long-line trap bottom-fishing gear to catch primarily sablefish on seamounts in the NPFC CA (Doherty et al. 2018), although there are also landing limits for other demersal fishes, including Rougheye/Blackspotted Rockfish (*Sebastes aleutianus*/*Sebastes melanostictus*) (Canada 2018). This fishery's bycatch is described in Canada (2018). Canada's fishery for sablefish in international waters began in the 1970s.

The abundance of sablefish in the NPFC CA is maintained by connectivity with coastal sablefish and the fishery does not pose any known conservation concern to sablefish in the NPFC CA. Thus, SAIs to sablefish by the fishery are unlikely (Canada 2018).

Fishing effort for sablefish in the NPFC CA is in part limited by a seasonal closure, the number of vessels that can fish, and the gear that can be used. The length of fishing vessels averages 25 m (Canada 2018). At-sea electronic monitoring retains details about each fishing set, including the date, time, latitude, and longitude. Between 2006 and 2021, the sablefish fishery was active in the NPFC CA with a total of 409 fishing days among 43 seamount trips made there.

Canada's sablefish fishery has set its gear at depths from 73 to 1600 m between 2006 and 2021, in our study area. The focus of fishing on Cobb Seamount has historically ranged from approximately 700 to 900 m Canada 2018), but there is evidence that fishing for sablefish became more prevalent at shallower depths from 2012 to 2017 (Canada 2018; Du Preez et al. 2020), and also reached depths of 1600 m in 2019.

Compared to the impacts of trawling, relatively little is known about the potential impacts of bottom longline fisheries, even though these are more common and set over a wider range of benthic habitats. Long-line gear can damage NPFC's VME indicator taxa, through crushing and entanglement. Moreover, long-line gear can become mobile with scouring effects if traps are dragged across the bottom during deployment or retrieval, or while grappling for the retrieval of lost gear (DFO 2010; Doherty et al. 2018). Cameras mounted on longlines have captured evidence of damage associated with hauling (Brewin et al. 2021).

Gauthier (2018) used cameras deployed on sablefish longline trap gear on SGaan Kinghlas-Bowie Seamount to annotate habitat, fisheries-related impacts, and soft corals. They found evidence of these traps dragging, rolling, or bouncing on the seafloor on 59% of sampled gear sets and observed impacts to habitat-forming organisms. The visual data from the trap cameras also showed evidence of damage to benthic invertebrates, including corals. Using video from the same camera study, Doherty et al. (2018) reported that cold-water corals or sponges were present at 28% of the sites sampled by their gear. Their analysis suggests that sablefish traps are typically stationary once the gear has been set, but interact with the seafloor and associated fauna during gear retrieval. Neither Gauthier (2018) nor Doherty et al. (2018) reported indirect impacts of the sablefish longline trap gear on nearby areas or impacts on pelagic organisms.

The longline gear used in this fishery generally does not retain sessile organisms (DFO 2010; Boutillier et al. 2011), so any VME indicator bycatch is likely to under-represent the impacts to VMEs or areas likely to be VMEs. However, damage caused by longline fishing gear (Gauthier 2017, 2018; Doherty et al. 2018) suggests VMEs and areas likely to be VMEs are at risk of SAIs. Canada (2018) reported that a small percentage of the area on Cobb Seamount was potentially impacted by the sablefish fishery (as much as 7%, depending on the depth stratum).

Habitat suitability models of VME indicator taxa in the NPFC Convention Area

Ideally, direct observations of VME indicator taxa and VMEs should be used to assess SAIs, but the availability of visual or other types of data on the occurrence of VMEs or VME indicator taxa in an area of interest is usually lacking. In our case, the majority of occurrence records used to train the HSMs come from the adjacent continental shelf areas of the northeast Pacific Ocean and not specifically from the seamount chain of interest (Warawa et al. 2021). The fisheries-independent records used to project predicted occurrences in the Cobb-Eickelberg seamount chain were compiled from several DFO databases, the NOAA deep-sea coral data portal, the Ocean Biogeographic Information System (OBIS), and the Global Biodiversity Information Facility. Absence records were also generated from synoptic, research bottom trawl surveys carried out by NOAA and DFO covering the same biogeographic extent and depth range of the compiled presence records (Warawa et al. 2021). A 'trawl-absence' record was the coordinates of a single trawl event that yielded no records of any of the VME indicator taxa used in our models. The maximum depth of the model predictions was restricted to 1600 m which was the limit of the presence and absence records.

HSMs were fit to create continuous surfaces predicting the probability of occurrence for each of the four VME indicator taxa. Warawa et al. (2021) previously provided details on the data synthesis and data layer sources used to create the HSMs used in this working paper. In brief, input data for the models included a suite of both terrain and oceanographic variables developed by the North Pacific Marine Science Organization's Working Group on Biodiversity of Biogenic Habitats (PICES WG32) and were used previously to predict the occurrence of these taxa in the study area (Chu et al. 2019). For this study, the environmental data were updated to include the most recent data from the World Ocean Atlas (WOA 2021). These data layers were combined using an azimuthal equidistant spatial projection centered on our study area (-180 central meridian), and have the same grid dimensions. For our case study at the Cobb-Eickelberg seamount chain, we use a 1 km x 1 km grid cell dimension which aligns with the resolution of our HSM predictions of areas likely to be VMEs. A 1 km^2 resolution balances (1) a spatial scale that is finer than the general footprint of individual seamounts in this region (~ 100 km^2) and (2) the best available data for generating data layers for HSMs and fisheries footprint data.

As with the updated environmental data layers, we also updated the predictions from our HSMs by using an ensemble approach that averaged predictions among several HSM algorithms. Random Forest (RF), Boosted Regression Trees (BRT), and Generalized Additive Models (GAM) were included in an ensemble model to reduce biases from any individual approach (Hao et al. 2020). These algorithms were chosen to include both tree-based (RF, BRT) and continuous regression approaches (GAM) effective in predicting cold-water coral distributions (e.g. Rowden et al. 2017, Georgian et al. 2019, Morato et al. 2020, Wang et al. 2022). The models were evaluated with True Skill Statistic (TSS), area under the receiving operator curve (ROC), and Kappa metrics using a repeated ten-fold cross-validation procedure with 30% of data withheld for each training-testing split (Table 2). Ensemble models were calculated for each taxon using a ROC-weighted average of habitat suitability predictions the mean probability of occurrence across models weighted by their respective ROC scores. The relative importance of each variable per taxon was also calculated (Table 3).

Quantification of the relative risk of SAI

Calculation of the index of relative risk of SAIs in our study area requires spatially explicit data layers of VMEs or areas likely to be VMEs, as well as the footprint of the sablefish fishery. We created a spatial data layer of the cumulative impact of fishing events from the Canadian sablefish fishery using georeferenced commercial catch records from 2006-2021. This fishery only operates at seamounts in the northeast side of the NPFC CA; data from other countries and/or historical data are not available. Records were queried by Devon Warawa in April 2022 from the Fisheries and Oceans Canada (DFO) groundfish view of the Fishery Operations System (GFFOS). These data are a collation of fisher logbook, observer, dockside monitoring, and electronic monitoring data and provides a set-by-set enumeration of the location and quantity of catch. Position data and 100% monitoring was only mandated by DFO in 2006, which determined the timeframe of data in our study. All hook and line trips also have mandatory electronic monitoring.

Queries were restricted to fishing events targeting sablefish and recorded from the years 2006-2021. Queried data for individual fishing events included (1) start and end coordinates, (2) fishing gear type, and (3) number of traps for fishing events associated with trap gear types (i.e. trap-events). For trap-events where the number of traps were not reported, we used the average number of traps deployed among all trap-events where the number of traps was reported (mean=54 traps).

We spatialized the fishing event data for each gear type by standardizing the catch records to the same 1 km x 1 km grid used by our HSMs. For fishing events that used longline gear, we assumed the deployment was a straight line between the start and end coordinates. We then created area polygons using a width of 6.2 m to account for the average lateral movement documented for this gear type (Welsford et al. 2014). For fishing events that used trap gear, we also assumed the deployment was done in a straight line between the start and end coordinates. Doherty et al. (2018) assessed the general bottom-contact footprint of a standard sablefish trap deployment using traps with an approximate 1.47 m^2 footprint. Following Doherty et al. (2018), we assumed the bottom contact of a sablefish trap set to occur primarily from the traps themselves and, with movement from deployment and recovery, each trap to have a bottom contact footprint of 53 m^2. We created 53 m^2 circular polygons around the coordinates of each trap which we assumed to be spaced between the start and end coordinates of each trap fishing event. The cumulative fishing impact for each 1 km^2 grid cell in the study area was calculated as the sum of all fishing event polygons occurring in that cell (Figure 3). These data were then normalized without transformation of their relative values to match the 0-1 scale of the ensemble HSM outputs.

Calculating the Relative Risk of SAIs

To calculate the relative risk of SAIs to areas likely to be VMEs, the probability of VME indicator occurrence and the cumulative fishing impact area were used to group grid cells into categories. Conversion of continuous data into categorical data is common among studies that aim to quantify risks of fishing operations (e.g. Brewin et al. 2021; Miyamota & Kiyota 2018). The optimal number of clusters for each data type was found by the ‘elbow method’ in the R package ‘factoextra’ (Kassambara & Mundt 2020), which involves visually assessing the within-group sum of squares error calculated when splitting the data into 1-10 clusters. For both the fishing footprint data and the VME indicator occurrence, four clusters was optimal (i.e., balanced simplicity with low within-group sum of squares). Rather than use arbitrary values to split the data into the four categories, breakpoints were found via k-means clustering, an unsupervised machine learning method commonly used to find subgroupings within datasets. We note that for the VME indicator occurrence probability, the highest of the four clusters was set to 0.78 based on the threshold calculated in Warawa et al. (2022a) that is used to identify areas that are likely to be VMEs. Thus, k-means clustering was used to find three clusters within the subset of data with occurrence probability < 0.78, and areas with HSI > 0.78 were placed within the highest cluster. We note that the three VME areas on Cobb Seamount identified with visual data by Warawa et al. (2022a) were also assessed for the relative risk of SAI using the above HSM and cumulative fishing footprint categorization and are shown in Figure 6. However, the known presence of VMEs within these grid cells may warrant additional consideration in spatial management plans, as fishing within these grid cells could reasonably affect the dense coral communities observed there.

The 4 groupings (Figure 4) for each of the VME indicator occurrence and fishing footprint data were used to assess the relative risk of SAIs to areas likely to be VMEs. Grid cells with both a fishing footprint and a VME indicator occurrence probability within their respective highest clusters (> 0.53 and 0.78, respectively) were assessed to be at 'high' risk of SAI. Grid cells with a fishing footprint and VME indicator probability within the lowest two clusters (< 0.3 and 0.34, respectively) were deemed 'low' risk, and all other cells 'medium' risk (Table 5).

Results and Discussion

In this paper, we assess the relative risk of SAIs in the Northeastern part of the NPFC CA by examining the overlap between the footprint of Canada's sablefish fishery and VMEs. The NPFC and most other RFMOs do not define SAIs or outline a quantitative and repeatable methodology for assessing SAIs (DOSI 2022). Moreover, Canada lacks the data to assess if its fishery in the NPFC CA has caused or can cause SAIs to VMEs. We therefore focus on assessing the relative risk of SAIs to VMEs and areas likely to be VMEs. We recognize that the relative risk of SAIs to VMEs is rarely zero because the probability of there being a VME cannot be zero without thorough visual data and assessment. With a grid size of 1 km^2 in our analysis, we are currently unable to identify grid cells with a confirmed absence of VMEs as visual data do not cover that spatial scale (see Curtis et al. 2015 who surveyed a fraction of Cobb Seamount with ROVs and an AUV). We are also unable to identify areas with zero risk of SAIs because we cannot predict the future distribution of the Sablefish fishery's footprint in the northeast part of the NPFC's CA.

Cross-validation of HSMs reveals satisfactory performance across model types, with all three algorithm types performing similarly (Table 2). The ensemble model, which averages the models run with each algorithm type based on their ROC scores, shows that the seamounts in the Cobb-Eickelberg chain likely harbor VME indicator taxa (Figure 2). The average HSI value, which quantifies the occurrence probability, is greater for gorgonians and antipatharians than it is for stony or soft corals (Table 4). Relatively steep seamounts also have higher HSI values, whereas those with large flanks or low slope areas have lesser average HSI values despite high HSI grid cells concentrated around the peak (e.g. Brown Bear). With higher resolution (e.g. multi-beam) bathymetry, classification of the seafloor into different geomorphologies may aid in predicting VME indicator distributions (Masetti et al. 2018), but despite the 1 km^2 resolution of our analysis, multiple bathymetry-derived variables are important in predicting VME indicator distributions (Table 3). Eastness and slope are particularly important for gorgonian models, while roughness and BPI are important in predicting soft corals. Oceanographic variables including chlorophyll-A (for all groups except black corals), surface temperature (stony corals), horizontal (stony corals) and vertical (stony and gorgonian corals) regional current velocities, surface POC flux (black corals), and photosynthetically active radiation (soft and black corals) are among the top 3 variables in at least one taxon-algorithm combination (Table 3). Notably, dissolved oxygen and the saturation of skeleton-forming minerals (i.e. Ωaragonite and Ωcalcite) are only among the top three variables for black corals, and the latter only in the black coral GAMs.

We provide maps of a cumulative fishing footprint, represented by the cumulative area of impact for both longline hook and longline trap gears for each 1 km^2 grid cell from 2006-2021 at each seamount in the study area (Figure 3). Fishing is concentrated on the slopes/peaks of the seamounts and tends to decrease towards the flanks. However, the fishing footprint varies both within and among the seamounts. Eickelberg Seamount, for example, has a relatively small fishing footprint concentrated within 11 km^2 at the seamount peak while Warwick, Cobb and Brown Bear Seamounts have greater fishing footprints with a larger areal extent (Table 3). There were no sablefish fishing records on the relatively shallow and flat plateau of Cobb Seamount (Figure 3), although evidence of bottom-contact fisheries (e.g. trawl, gillnets) have been documented there (Curtis et al. 2015).

Summary statistics

K-means clusters of both HSI and fishing footprint data were used to determine areas at high, medium, and low relative risk of SAIs (Table 5, Figures 5 and 6). The spatial footprint of the relative risk index is primarily driven by fishing effort among seamounts rather than the HSM predictions. While all seamounts in the study area have areas likely to be VMEs based on the 0.78 HSI threshold from Warawa et al. (2022a) (Figure 4), there are only 790 km^2 where both HSM predictions and fishing footprint data co-occur. Approximately 5% (42 km^2) of this area has a high relative risk of SAIs which contrasts with the 94% (746 km^2) and <1% (2 km^2) that are at medium and low relative SAI risk, respectively (Figure 5). Areas at high relative risk occur at Warwick (12 km^2), Cobb (9 km^2) and Brown Bear (21 km^2) Seamounts (Figure 6). The average relative risk is thus highest at Warwick, Cobb, and Brown Bear Seamounts where there is the most fishing. At seamounts without high relative risk areas (e.g. Eickelberg, Corn, and Pipe Seamounts) the risk tends to be lower but some areas of Corn Seamount approach the high risk category (Figure 5c). The mean and standard deviation of both HSI and fishing footprint are presented for each seamount in Table 3.

Uncertainty

Canada (2018) outlined key uncertainties in its preliminary assessment of VMEs and SAIs in the NPFC CA but excluded quantitative evidence of:

- Structure and function of benthic habitats, communities, and ecosystems in the Cobb-Eickelberg seamount chain,
- The susceptibility of VMEs and areas likely to be VMEs to SAIs caused by the sablefish fishery, or their rate of recovery,

- Indirect impacts of the sablefish fishery (e.g., smothering or scouring from resuspended sediment), and
- Cumulative stressors associated with oceanographic changes (e.g., ocean acidification, hypoxia, alterations to patterns of primary production).

In their review of impact assessments, DOSI (2022) noted that uncertainty was poorly addressed in all reviewed assessments, but that uncertainty associated with models used to predict the distribution of VME indicators was the best described source of uncertainty. Data-deficiency was noted by all impact assessments. The location of potential VMEs was the most common data gap. The location of areas likely to be VMEs is also a key source of uncertainty in our assessment. Impact assessments reviewed by DOSI (2022) identified sources of uncertainty associated with cumulative impacts, including those associated with climate change, although these were not explicitly addressed.

Uncertainty associated with sablefish data and fishing footprint

As in other studies (e.g. Miyamoto and Kiyota 2018), we assumed that the longlines were set as straight lines between the start and end coordinates reported in the DFO database. This may not be the case given the varied topography of the area, which would cause vessels to deviate from linear tracks. Another source of uncertainty is the estimated sablefish trap footprint (53 m^2), because this estimate was based on three commercial fishing trips on a single seamount within Canada's domestic waters (SG̲aan-K̲inghlas Bowie Seamount); the trap footprint may differ among fishing areas (Doherty et al. 2018). There is also uncertainty associated with summing fishing records across multiple years where older records may be less relevant to the current (or future) fishery and recovery from their adverse effects may have progressed to some degree.

Uncertainties associated with predictions of suitable habitat of VME indicators

Effective protection of VMEs relies on knowledge of their structure, distribution, environmental requirements, and vulnerabilities (Gros et al. 2022). We draw on predictions of the distribution of suitable habitat for VME indicator taxa to identify areas that are likely to be VMEs throughout the Cobb-Eickelberg seamount chain (Warawa et al. 2021, 2022a) because most of this region has not been surveyed with image-based sampling using submersibles (Curtis et al. 2015; Canada 2018).

There is considerable uncertainty in the HSM predictions of VME indicator taxa. Despite the satisfactory performance of the predictive models assessed through cross-validation (Table 2), preliminary ground-truthing (unpublished data and analyses) suggests performance at the Cobb-Eickelberg seamount chain may be diminished due to the bias of presence/absence input data records coming from the continental shelf where environment-taxon relationships may be different.

Prediction resolutions < 1 km^2 are difficult to achieve with this paucity of visual data, which contributes to uncertainty because these taxa often respond to variations in terrain at relatively high (< 100 m) resolutions (Rengstorf et al. 2013, Rowden et al. 2017). Model resolution and the resolution of predictor variables can also affect predictions of the extent of suitable habitat

(Brewin et al. 2021; Gros et al. 2022). For example, Ross and Howell (2013) suggested that the coarse resolution of their study's bathymetry data may have led to overestimates of the distribution of VMEs in the northeast Atlantic Ocean.

Although our ensemble modeling approach minimizes bias and weighs the models based on their performance, there is still inter-model variance in addition to the variance between VME indicator taxa shown in Figure 2. The broad taxonomic resolution also leads to imprecision in the predictions. By pooling the many families within the taxa modelled here, we may be modelling a wider niche for each broad taxon than the niche of the subset of that taxon that is actually present within a given area. Wider niches of modeled taxa do tend to decrease model performance, usually by overpredicting (Segurado & Arujao 2004; Georgian et al. 2019). Another source of uncertainty associated with our predictive models include sampling artefacts associated with presence and absence data caused by differences in catchability among taxa; fishing gears generally have low catchability for small, fragile, and brittle VME indicator taxa (Gros et al. 2022).

Other sources of uncertainty – e.g. distribution of VME indicator taxa vs VMEs and areas likely to be VMEs

Assessment and conservation of VMEs is hampered because the location of most VMEs is unknown, even though VME indicator taxa are often reported as bycatch in fisheries gear or in visual surveys (Curtis et al. 2015; Gros et al. 2022). Many studies predict the distribution of VME indicator taxa to identify areas that are likely to be VMEs (e.g. Chu et al. 2019; Warawa et al. 2021, 2022a), but, the distribution of VMEs and areas likely to be VMEs do not necessarily coincide with the predicted distribution of VME indicator taxa or presence of VME indicator taxa in bycatch or visual surveys. The occurrence of the NPFC's VME indicator taxa, however, was positively associated with greater richness and diversity of associated benthic taxa in visual surveys on Cobb Seamount (Warawa et al. 2021, 2022a), supporting the assumption that VME indicator taxa provide structural complexity, one of the five VME criteria outlined by the FAO (2009; see also Rowden et al. 2020). Lack of data to map the spatial distribution of VMEs impedes comprehensive assessments of the impacts of bottom contact fisheries (DOSI 2022). In such cases, models to predict the distribution of suitable habitat of VME indicator taxa can be valuable to rank the relative vulnerability of areas to fishing (Gros et al. 2022). Other structure-forming taxa such as sponges may also constitute VMEs in our study area and may have notably different distributions and environmental tolerances (e.g. to low-oxygen conditions; Chu et al. 2019; Micaroni et al. 2022). Thus, their inclusion as a VME indicator taxon in future analyses may increase the known extent of VMEs and the predicted areas likely to be VMEs in the region.

Data deficiency

Deep-sea environments support unique ecosystems but remain poorly understood (Ramirez-Llodra et al. 2010). A dearth in data on VMEs impedes comprehensive assessments of the potential impacts of bottom contact fishing to vulnerable areas (Doherty et al. 2018; DOSI 2022). Precautionary management to prevent SAIs to VMEs where there is uncertainty in the spatial distribution of VMEs in the deep sea at fishable depths is warranted (Bell et al. 2019).

The spatial distribution of areas likely to be VMEs has been identified for the Cobb-Eickelberg seamount chain (Warawa et al. 2021, 2022a), but we are missing information from visual surveys to identify the location of VMEs in most areas that are fished by Canada's sablefish fishery. Only a total of 0.01 km² on Cobb seamount has been assessed for VMEs using visual data, of which 0.002 km² was identified as such by Warawa et al. (2022a; Figure 6). Although we have catch and effort data from Canada's sablefish fishery in the NPFC CA from 2006-2021, we do not have reliable data on this fishery from the 1970s to 2005. We are also missing data from other historical bottom-contact fisheries, including trawling, that took place on the Cobb-Eickelberg seamount chain (see Curtis et al. 2015). Given the slow growth rate and long lifespan of VME indicator taxa, it is possible SAIs have occurred on VMEs during historical fishing by Canada and other nations and the VMEs have not yet recovered. In addition, we are unable to assess the cumulative impacts of these historical fisheries on VMEs and areas likely to be VMEs in that part of the NPFC CA (Warawa et al. 2022a).

Direct and indirect impacts of Canada's sablefish fishery

The current Canadian sablefish fishery does not pose conservation concern to sablefish populations in the Cobb-Eickerberg seamount chain (Canada 2018). Potential impacts of this fishery on VMEs and areas likely to be VMEs, however, are considered likely due to its bottom contact gear (Gauthier 2017, 2018; Doherty et al. 2018). Because of its small footprint and low effort (up to a maximum of six vessels can fish in this part of the NPFC CA from April to September each year), however, the risk is considered relatively small (Canada 2018). The risk of SAI is also less than if the sablefish fishery used mobile gears, such as otter trawls (see Bell et al. 2019).

However, because impacts from the sablefish fishery occur throughout the Cobb-Eickelberg seamount chain and an estimated 100% of VMEs and 46% of areas likely to be VMEs in the region overlap with its fishing footprint (based on Warawa et al 2022a), this fishery has the potential to have significant ecological consequences (Kaiser et al. 2006) or SAIs. This is on the same order of magnitude as the 33–62% overlap Brewin et al. (2021) found between VME indicators and a Patagonian toothfish fishery in international waters. Widespread chronic impacts of fishing with sablefish trap and hook longlines may be difficult to distinguish from natural variations observed in visual surveys. Therefore, the severity of such chronic impacts may be challenging to evaluate until it is too late to prevent loss of biodiversity or ecosystem function (Kaiser et al. 2006).

The FAO Guidelines (FAO 2009) call for a description of the likely impacts, including cumulative impacts of activities on VMEs. In this assessment, we focus primarily on assessing the relative risk of SAIs caused by the direct impacts of Canada's sablefish fishery. But we recognize that this fishery may also cause direct impacts to target and incidentally captured species and indirect impacts to the seafloor or water column in the fished or adjacent areas.

Cumulative impacts

Our detailed analysis of gear types, effort, and line-by-line positional data allowed us to calculate the sablefish fishery's recent footprint in the northeast part of the NPFC's CA (Figure

3). Because of a lack of data to assess the impacts of these gears on the structure and ecological function, we are unable to calculate the cumulative impacts of fishing on VMEs and areas likely to be VMEs. Although cumulative impacts are explicitly required in impact assessments (FAO 2009), most impact assessments reviewed by DOSI (2022) did not address cumulative impacts. The few that did considered the cumulative impacts of past fishing activities only. Although cumulative impacts from other sectors or the environment were acknowledged in some impact assessments, they were not further assessed.

Our analysis does not incorporate the potential impacts related to connectivity and climate change that may also affect the distribution, structure, and ecological function of VMEs in the northeast part of the NPFC's CA. However, numerous climate-affected oceanographic variables are important to the modeled VME indicator taxa (Table 2), suggesting that changes in climate will likely affect their distributions. The oceanography of the northeast Pacific Ocean puts VMEs at risk of stress from the accumulating stressors of deoxygenation, warming, and acidification (Somero et al. 2016). Thus, predictive models of climate-driven shifts in both VME indicator and fished taxa are needed to determine how climate may affect the relative risk of SAIs. Numerous studies have modeled climate-related distribution shifts in cold-water coral and exploited fish taxa (Morato et al. 2020; Anderson et al. 2022; Cheung et al. 2022; Gasbarro et al. 2022; Wang et al. 2022), but to date none have done so in the northeast Pacific Ocean.

The connectivity among populations of VME indicator taxa in this study area has not been assessed with genetic tools but coral metacommunities (i.e., communities linked by dispersal) are assumed to be maintained by metacommunity processes (e.g., patch source-sink dynamics; Leibold et al. 2004; Morrison et al. 2011; Henry et al. 2014). Because they are distributed on discontinuous features in this seamount chain, the impacts of fishing may negatively affect coral communities on seamounts through disruptions to these processes (Lima et al. 2020; Brewin et al. 2021). 3-D particle tracking simulations (e.g. Wang et al. 2020) characterizing the potential connectivity of seamount populations of VME indicators in this region would augment predictions of potential climate refugia.

Monitoring and Mitigation

Monitoring the response and recovery of VMEs impacted by the sablefish fishery would improve our ability to assess the risk of SAIs in the northeastern part of the NPFC's CA. Greater uncertainties in the impacts of fisheries should be reflected in more precautionary mitigation and management decisions (DOSI 2022). Precautionary management to prevent SAIs to VMEs where there is uncertainty in the spatial distribution of VMEs in the deep sea at fishable depths is warranted (Bell et al. 2019).

In their review of impact assessments, DOSI (2022) noted that move-on rules and observer systems on boats for bycatch monitoring were the main mitigation measures to prevent SAI on VMEs. The NPFC has an encounter protocol in place for its VME indicator taxa and requires 100% observer coverage in all of its bottom fisheries, including Canada's sablefish fishery in the northeastern part of the NPFC CA. The NPFC currently has a move-on encounter threshold of 50 kg of corals, which is unlikely to ever be met by bottom-contact fishing gears other than trawls

(NPFC 2022). Several RFMO-related impact assessments considered mitigation measures as unnecessary because the risk of SAIs on VMEs was low (DOSI 2022).

In its preamble, the FAO Guidelines (FAO 2009) encourage RFMO/As to prevent SAIs to VMEs and protect the marine biodiversity of VMEs. Paragraph 71 identifies conservation and management measures to protect VMEs and prevent SAIs that include effort controls, gear changes, and spatial closures. In its comprehensive review of RFMO impact assessments and management of deep-sea fisheries, Bell et al. (2019) ranked closing areas to fishing as the most effective management measure to prevent SAIs, followed by gear prohibitions, gear modifications, exploratory fishing rules and finally encounter protocols.

Despite a culture of hostility towards fishery observers that may lead to under-reporting of VME encounters (Bell et al. 2019), encounter protocols have been used for almost three decades (Shotton and Patchell 2008 as in DOSI 2022). Encounter protocols are reactive measures aimed to prevent further damage to VMEs that have already been impacted by bottom-contact fishing. In their review of impact assessments, DOSI (2022) noted that move-on rules within encounter protocols were often the only measures to protect potential VMEs.

Encounter protocols, which for the NPFC includes a move-on rule, are not precautionary and are deemed inadequate to prevent SAIs impacts because they still allow damage to occur which will gradually degrade VMEs over time (ICES 2010). The NPFC's Small Scientific Committee on VMEs recognized that the NPFC's exploratory fishing protocol can also potentially cause SAIs to VMEs (Small Scientific Committee on Vulnerable Marine Ecosystems (SSC VME) 2018). Closing VME areas has the greatest potential to reduce SAIs, but it can also reduce the fishable area, redistribute fishing effort, and lead to a risk of serial depletions (Bell et al. 2019).

One potential mitigation measure for Canada's bottom fishery would be to prohibit the use of sablefish longline trap gear in VMEs and areas likely to be VMEs. The area potentially impacted by a sablefish trap (53 m^2) is greater than the area presumably affected by hook and line gear while setting, soaking, and hauling the gear.

Another potential mitigation measure would be to reduce the amount of allowable fishing effort in areas with a higher probability of suitable habitat for VME indicator taxa. VMEs and areas likely to be VMEs that are at a high relative risk of SAI could be protected through closures to all bottom-contact fisheries.

The NPFC now has a vessel monitoring system (VMS) in place and Canada's sablefish vessels and their activities can be monitored by enforcement officials. VMS could be used to evaluate whether or not a mitigation measure is having the intended effect. VMS and logbook data could also be used to evaluate the effect of spatial closures or other mitigation measures on the anticipated re-distribution of fishing effort (Doherty et al. 2018). Bell et al. (2019) underscore the value of monitoring VMEs to evaluate the performance of spatial management measures to minimize and mitigate SAIs.

VME closures - Preventing SAIs by protecting VMEs and areas likely to be VMEs

The NPFC's CMMs on Bottom Fisheries and Protection of Vulnerable Marine Ecosystems (CMM 2021-05 for the Northwestern Pacific Ocean and CMM 2019-06 for the northeastern Pacific Ocean) do not currently specify gear-specific encounter thresholds: a single threshold of 50 kg of cold-water corals applies to all bottom-fishing gears including trawls, gillnets, pots, and longlines. If more than 50 kg of cold-water corals are captured in a single gear retrieval, the fishing vessel shall move at least 2 nautical miles before resuming fishing to avoid further impacts to potential VMEs. In its second meeting in 2022, The NPFC's Small Working Group on VMEs (SWG on VME) noted that the current encounter threshold of 50 kg of corals per tow may only to apply to trawl gear (NPFC 2022).

With few exceptions, all RFMOs have adopted a combination of VME fishery area closures, VME encounter protocols, and exploratory fishing rules to protect VMEs from SAIs (Bell et al. 2019). For example, SPRFMO's encounter protocol is used to complement spatial management measures rather than being used as a primary tool (Bell et al. 2019).

Closing VMEs and areas likely to be VMEs to bottom contact fishing is the most effective and precautionary management tool for preventing SAIs on VMEs (Bell al. 2019). The FAO Guidelines (FAO 2009) advocate the closure of areas with known or likely VMEs until conservation and management measures have been established to prevent SAIs.

Recovery

The NPFC's Small Scientific Committee on Bottom Fish and Marine Ecosystems (SSC BFME) recognized during its first meeting in 2020 that because recovery is possible for VME indicator taxa, both VMEs and areas likely to be VMEs should be closed to bottom contact gear in both fished and unfished areas to allow them time to recover (Small Scientific Committee on Bottom Fish and Marine Ecosystems (SSC BFME) 2020)). Recovery time could take decades (see references cited in Doherty et al. 2018, including Rooper et al. 2011), so it is worthwhile to assess and protect both pristine and recovering VMEs (NPFC/FAO VME Workshop. 2018).

Conclusions

In this paper, we draw on Canada's sablefish fishery data from 2006-2021 as well as preliminary VMEs and areas likely to be VMEs (Warawa et al. 2021, 2022a) to assess the relative risk of SAIs in the northeastern part of the NPFC's CA. We describe the occurrence, spatial scale, and footprint of cumulative fishing activities for sablefish in the NPFC CA (Figure 3, Table 4). We also describe how these data were used with the distribution of (a) VME indicators (Figure 2), (b) VMEs and (c) areas likely to be VMEs (Warawa et al. 2021, 2022a) to assess the relative risk of SAIs.

A lack of data, including baseline data, to assess the impacts to VMEs by Canada's sablefish fishery, as well as the timing and magnitude of VME recovery means that Canada is unable to assess if SAIs have taken place or are likely to take place in the northeastern part of the NPFC's CA, where Canada fishes for sablefish. Like most bottom fishing RFMOs (with the exception of NAFO, DOSI 2022), the NPFC has not defined an SAI, and neither have any of its Members.

Although the gear used to harvest sablefish in the NPFC CA can damage sensitive benthic areas (Doherty et al. 2018), Canada cannot evaluate such damage and thus it is unable to effectively implement the UNGA resolutions related to VMEs and SAIs (UNGA 61/105, UNGA 64/72, UNGA 71/123).

To fall into the highest relative risk category, (red areas in figure 5), both the cumulative fishing footprint and the VME indicator occurrence probability (HSI) had to have values above the highest cluster thresholds (Table 5). For occurrence probability, this was based on the visual threshold for areas likely to be VMEs by Warawa et al. (2022a). All other clusters (four in the fishing footprint and three more in the HSI data) were defined by k-means clustering. We defined the combination of the two lowest clusters in each data set to represent 'low' relative SAI risk. Although this categorization is subjective, it was made due to the low occurrence probability of VME indicator taxa in these clusters (Figure 4). Most (~94%) of the grid cells are in the medium risk category (Figure 5). In fact, the entire fished areas on Eickelberg Ridge, Eickelberg and Corn Seamounts are at medium relative risk. We note that this medium risk category contains areas with high occurrence probability but a lower fishing footprint, and vice versa; more research is needed to understand how these two scenarios may produce different SAI risk. High relative risk areas are found on Brown Bear, Cobb, and Warwick Seamounts (Figure 6), where cumulative fishing is greater than on other seamounts. One of the five grid cells that overlap with areas identified as VMEs on Cobb Seamount by Warawa et al. (2022a) is categorized as high relative risk (Figure 6).

Data deficiency is challenging when providing scientific advice; both assessment and management of deep-sea fisheries can be very costly and subject to greater degrees of uncertainty (FAO 2009). In their review, DOSI (2022) concluded that the reviewed impact assessments were unable to demonstrate that fisheries in the high sea could be managed to prevent SAIs.

In this paper, we outline some sources of uncertainty associated with fishery data and the predictive models of the distribution of areas likely to be VMEs. Because of a lack of sufficient data, we were unable to assess if Canada's sablefish fishery has caused or could cause SAIs. Nevertheless, our assessment can be used to inform precautionary management decisions to protect VMEs and areas likely to be VMEs from SAIs.

The spatial management measures used in the south Pacific by SPRFMO are based on HSMs (Georgian et al. 2019). Japan suggested that it was possible to avoid SAIs on fished seamounts by spatially protecting VMEs and improving the NPFC's encounter protocol (NPFC/FAO VME Workshop. 2018). Spatial closures are widely recognized as the most effective conservation and management measure to avoid SAIs (Bell et al. 2019).

Next steps for analysis in NE part of the NPFC CA

Ideally, the NPFC and other RFMO/As develop quantitative definitions of SAIs that consider whole ecosystems rather than simply the VME indicator taxa, and focus on modelling vulnerability of benthic resources, habitats, communities and ecosystems to SAIs (Gros et al. 2022). Those definitions should also complement measurable objectives for assessing the occurrence of SAIs (NPFC/FAO VME Workshop. 2018) and the confidence in assessment should be measurable (DOSI 2022). Research to measure the impacts of bottom contact fishing on the persistence of habitats, communities and ecosystems as well as the timing and magnitude of recovery from such impacts are essential to identify and assess SAIs (see Doherty et al. 2018).

In the meantime, we aim to do the following:

- Consider impacts of climate change on the distribution of VMEs and areas likely to be VMEs, their connectivity, and as well as on the distribution and status of target resources.
- Improve environmental baseline data, particularly related to the occurrence of VMEs and species associated with VMEs.
- Undertake spatial optimization analysis to identify VME areas to protect from SAIs while minimizing impacts to the sablefish fishery (Warawa et al. 2022b)
- Periodically review our analyses to including new information, including the addition of new NPFC VME indicator taxa.

The value of periodically reviewing the risk and occurrence of SAIs is widely recognized, especially when there is new information relevant to the assessment (see UNGA resolution 71/123 and FAO 2009). New information could relate to changes in the distribution of fishing effort or changes in the distribution of target resources or VMEs. New information and model products on regional oceanography may also contribute to future iterations of SAI risk assessments. NEAFC, in collaboration with ICES, reviews all available data every year. Similarly, NAFO reviews its VME CMMs every 5 years (Bell et al. 2019). The NPFC also recognizes the value of periodic review in Annex 2 of its CMM 2019-06 and CMM 2021-05. The framework we present in this study for assessing the relative risk of SAIs may be used for future iterations of SAI risk assessments as new information becomes available.

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Figure and Tables

Table 1. Summary of oceanographic and bathymetry-derived variables (separated by dashed line) within the Cobb-Eickelberg seamount chain. Shortened variable names are listed in brackets.

Variable	Mean	SD	Min	Max
ΩAragonite [*Ωarag*]	1.23	0.14	0.94	1.87
ΩCalcite [*Ωcalc*]	1.93	0.23	1.46	2.94
Chlorophyll-A (mg m^{-3}) [*chla*]	0.3	0.05	0.24	0.46
Current velocity – regional (m s^{-1}) [*regfl*]	2.70E-03	2.40E-03	6.90E-10	2.60E-02

Current velocity – vertical (m s^{-1}) [*vertfl*]	-9.70E-07	8.60E-06	-1.60E-04	3.60E-07
Current direction – relative to aspect (º) [*curasp*]	82.77	50.97	0.08	179.9
Dissolved oxygen (µmol kg^{-1}) [*DO*]	31.12	33.27	14.78	281.3
Photosynthetically active radiation (W m^{-2}) [*par*]	25.14	0.95	23.24	26.76
Surface particulate oganic carbon flux [*pocs*]	80.25	6.32	70.33	99.16
Sea surface temperature (ºC) [*sst*]	12.26	0.45	11.11	13.27
Aspect – east-facing (º) [*eastness*]	0.01	0.7	-1	1
Aspect – north-facing (º) [*northness*]	0.07	0.71	-1	1
Bathymetric position index – 20000m [*bpi_20000*]	1025.09	393.64	239.72	1866.63
Curvature – cross-sectional [*crosscurv*]	0.01	0.02	-0.14	0.17
Curvature direction [*curdir*]	-32.9	62.8	-154.88	94.24
Depth*	-1142.25	352.1	-1598	-18
Roughness	1.02	0.03	1	1.68
Slope (º)	9.16	5.5	0.03	51.79

* Not included in habitat suitability models

Table 2. Habitat suitability model evaluation metrics (TSS, ROC) for each model type (RF, BRT, & GAM) assessed via a ten-fold cross-validation procedure withholding a random 30% of training data in each fold for testing.

Taxa	**Model**	**TSS**	**ROC**	**Kappa**
Black	RF	0.49±0.04	0.81±0.02	0.14±0.02
	BRT	0.59±0.03	0.86±0.02	0.23±0.02
	GAM	0.6±0.04	0.86±0.02	0.23±0.02
Stony	RF	0.54±0.06	0.8±0.03	0.44±0.05
	BRT	0.54±0.05	0.87±0.02	0.45±0.06
	GAM	0.53±0.03	0.84±0.02	0.41±0.06
Gorgonian	RF	0.55±0.02	0.85±0.01	0.41±0.02
	BRT	0.56±0.02	0.86±0.01	0.43±0.02
	GAM	0.52±0.02	0.83±0.01	0.35±0.02
Soft	RF	0.54±0.04	0.8±0.02	0.49±0.04
	BRT	0.66±0.03	0.8±0.02	0.5±0.04
	GAM	0.6±0.03	0.89±0.01	0.47±0.03

Table 3. Variable importance for each algorithm and VME indicator taxon combination used in habitat suitability modeling. The values for the three most important variables are bolded in each column. Full variable names are listed in Table 1.

	Stony			**Gorgonian**			**Soft**			**Black**		
Variable	**RF**	**BRT**	**GAM**	**RF**	**BRT**	**GAM**	**RF**	**BRT**	**GAM**	**RF**	**BRT**	**GAM**
Ω**arag/calc***	1.9	1.8	0.8	6.1	8.6	10.5	4.1	0.9	9.7	7.7	1.8	**11.5**
chla	**16.2**	**13.3†**	**9.4**	**11.8**	**10.7**	5.1	**20.9**	**11.7**	**24.7**	9.7	13.0	0.0
crosscurv	4.7	2.3	1.3	0.0	0.0	0.5	3.5	5.6	3.0	1.6	2.0	0.5
curangle	0.0	0.1	0.4	1.3	1.7	2.3	0.6	0.0	1.4	1.4	0.1	0.5
curasp	0.5	0.1	1.0	11.1	7.4	2.0	0.0	0.0	1.3	0.6	0.0	1.0
curdir	2.5	6.7	2.3	0.7	2.8	8.8	0.3	0.0	2.1	2.3	1.3	1.0
DO	0.5	0.2	2.0	0.1	0.4	6.1	2.8	5.1	4.6	**19.8**	**27.2**	**39.6**
eastness	0.8	1.1	2.4	**30.4**	**35.2**	**13.7**	0.3	0.4	2.1	1.7	0.2	0.1
northness	12.1	8.0	7.9	2.8	1.1	4.7	0.0	0.0	0.6	1.6	0.2	0.0
par	2.5	0.5	2.4	0.9	1.3	2.9	8.2	**11.4**	**10.5**	**19.9**	**22.3**	**22.0**
pocs	0.5	0.1	0.3	5.1	4.0	6.3	8.2	3.1	3.2	**10.4**	**16.8**	1.2
regfl	**27.2**	**31.3**	0.7	1.5	0.0	1.0	0.0	0.2	0.5	2.0	0.2	4.0
roughnes	13.7	0.1	**30.6**	8.9	0.9	9.9	**26.9**	**48.2**	2.8	3.8	0.8	1.7
slope	2.2	0.2	3.3	**17.3**	**25.0**	**24.2**	7.9	0.0	6.7	3.1	0.5	0.1
sst	14.6	**34.1**	**35.2**	1.8	0.8	1.8	3.5	2.2	9.1	8.4	0.5	4.4
bpi_20000	1.9	1.8	0.8	0.2	0.1	0.2	**12.3**	**11.4**	**17.1**	2.8	9.7	10.2
vertfl	**16.2**	**13.3†**	**9.4**	6.1	8.6	**10.5**	0.3	0.0	0.6	3.3	3.4	2.1

* ΩAragonite used in stony coral models only

† indicates variables tied for 3rd in relative importance

Table 4. Summary (Mean ± SD) of habitat suitability index (HSI) scores and fishing data (normalized fishing footprint and the number of 1 km^2 grid cells with fishing records) used to calculate the relative risk of SAIs.

Seamount	Stony HSI	Soft HSI	Gorg HSI	Black HSI	Fishing Footprint	Fishing Cells
Eickelberg	0.66 ± 0.05	0.7 ± 0.09	0.91 ± 0.02	0.87 ± 0.02	0.13 ± 0.1	11
Eickelberg Ridge†	0.65 ± 0.05	0.74 ± 0.07	0.9 ± 0.01	0.86 ± 0.03	0.07 ± 0.09	35
Warwick	0.63 ± 0.06	0.66 ± 0.08	0.89 ± 0.02	0.81 ± 0.06	0.17 ± 0.2	154
Corn	0.54 ± 0.13	0.65 ± 0.1	0.85 ± 0.07	0.76 ± 0.1	0.08 ± 0.11	137
Cobb	0.46 ± 0.19	0.55 ± 0.12	0.76 ± 0.11	0.65 ± 0.13	0.14 ± 0.18	227
Brown Bear	0.29 ± 0.29	0.52 ± 0.16	0.62 ± 0.19	0.55 ± 0.16	0.23 ± 0.22	185
Pipe	0.5 ± 0.14	0.68 ± 0.1	0.84 ± 0.08	0.74 ± 0.12	NA	0

Table 5. Summary of k-means clusters used to categorize fishing footprint and occurrence probability (HSI) into SAI relative risk categories and the colors used to represent them in Figure 4. The 'Risk' column denotes the SAI relative risk category for a given grid cell if both HSI and fishing footprint are within the range of that cluster (see Figure 5).

Cluster	HSI	Fishing Footprint	Color	Relative Risk
1	< 0.1	< 0.1	Blue	Low
2	0.1 - 0.34	0.1 - 0.3	Yellow	Low
3	0.34 - 0.78*	0.3 - 0.53	Purple	Medium
4	> 0.78*	> 0.53	Red	High

* denotes threshold from Warawa et al. (2022a) rather than k-means clustering

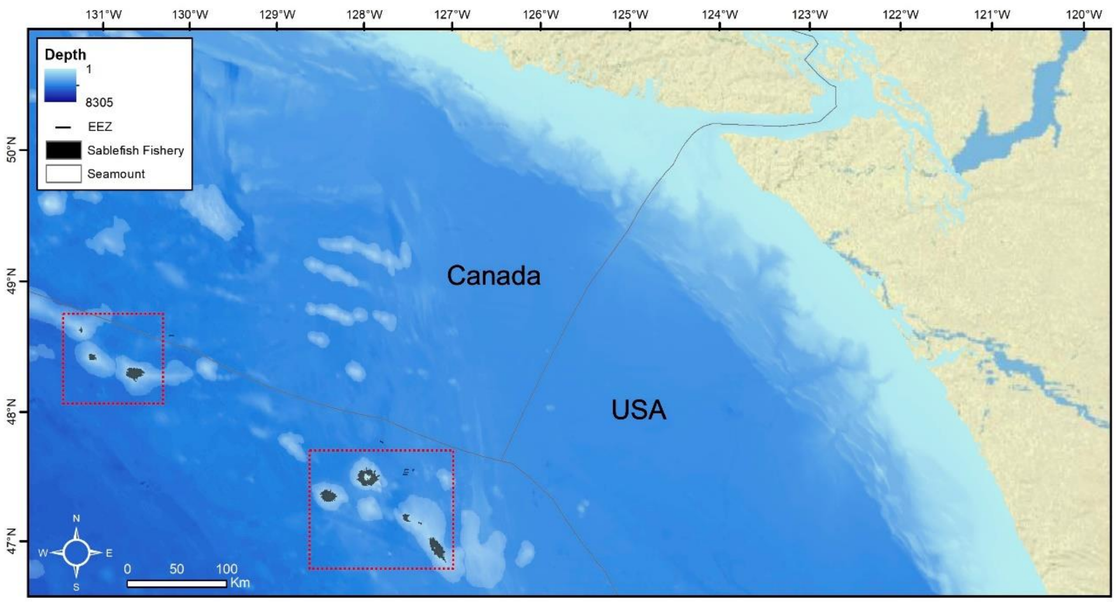

Figure 1. Map of study area. Cobb-Eickelberg seamount chain areas shown in Figures 2 and 3 are outlined with red boxes. Seamounts (Harris et al. 2014) and areas with a sablefish fishing footprint are shaded in white and black, respectively.

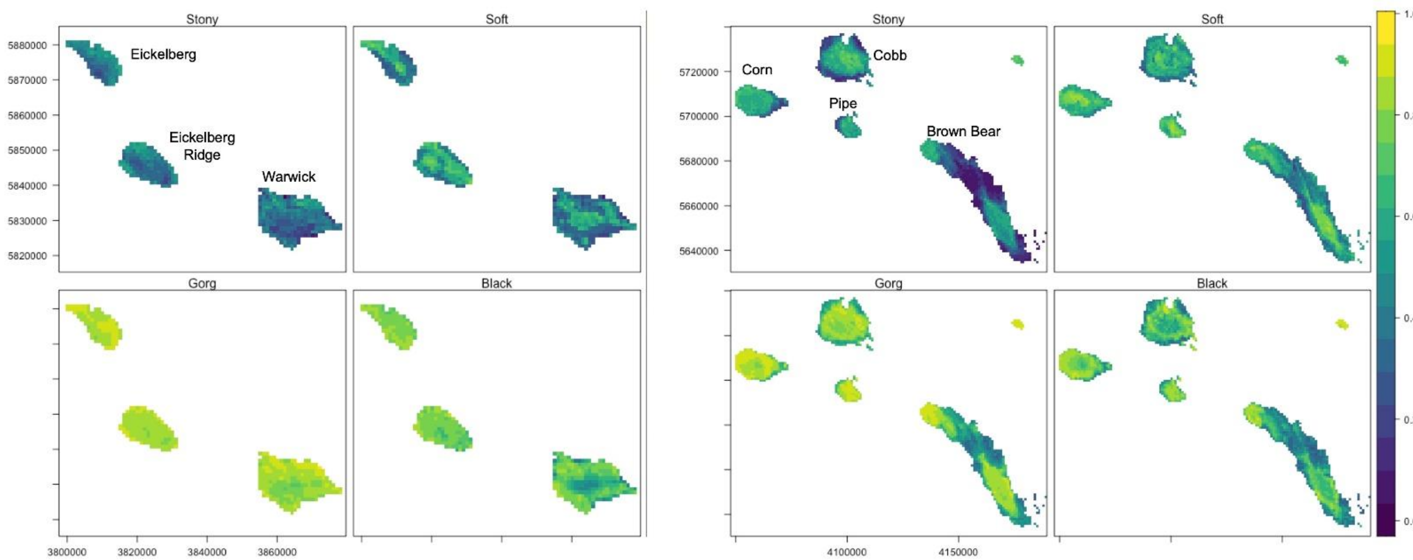

Figure 2. VME indicator occurrence probability at Eickelberg and Warwick Seamounts (left) and Corn, Cobb, Pipe, and Brown Bear Seamounts (right).

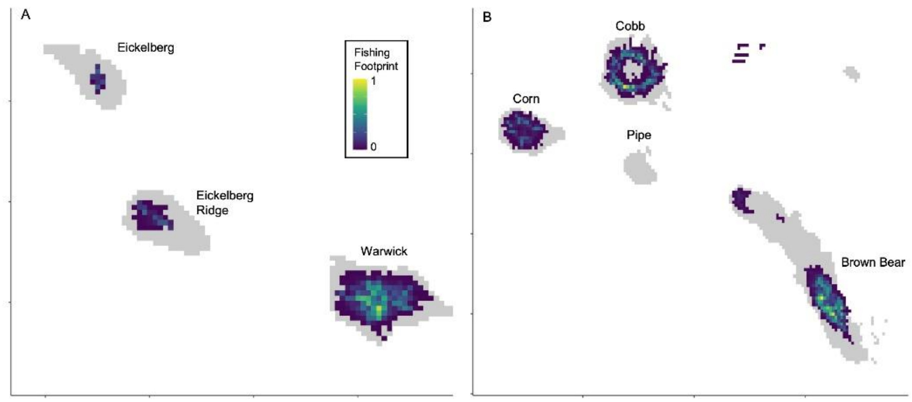

Figure 3. Normalized (0-1) fishing footprint at (A) Eickelberg and Warwick Seamounts and (B) Corn, Cobb, Pipe, and Brown Bear Seamounts. Grey cells denote seamount areas with no fishing footprint from 2006-2021.

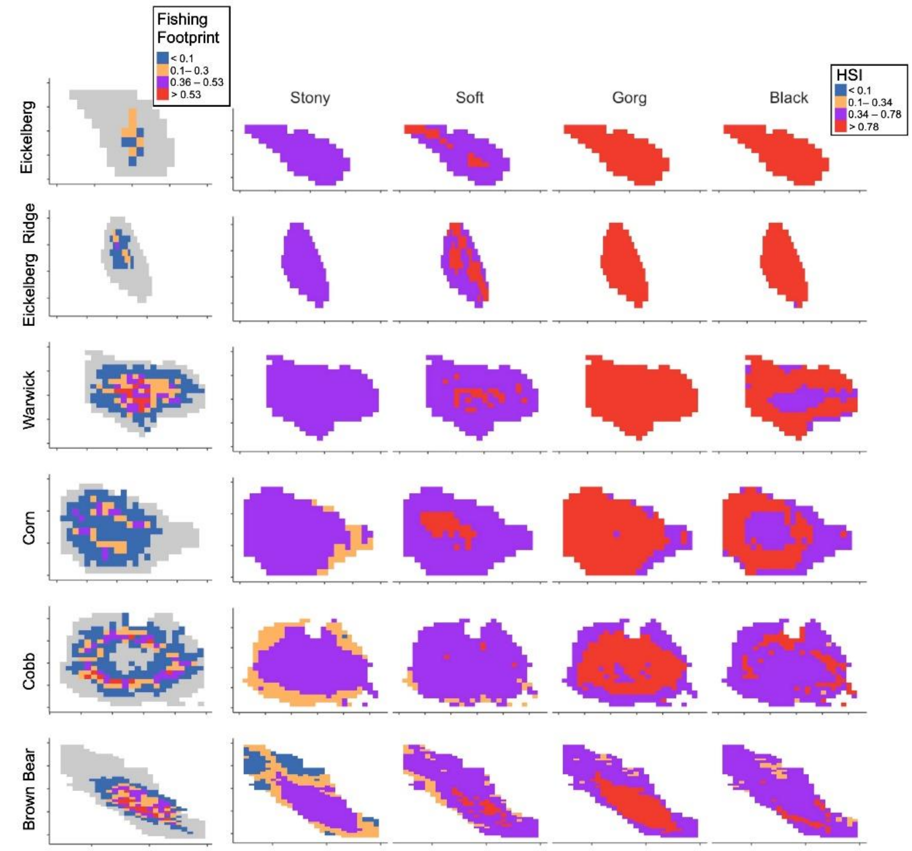

Figure 4. Normalized (0-1) cumulative fishing footprint (leftmost column) and probability of occurrence (HSI) for each VME indicator taxon and normalized (0-1) cumulative fishing footprint categorized by k-means clustering at each seamount. Red cells for HSI plots are areas likely to be VMEs (Warawa et al. 2022a). Grey cells denote seamount areas with no fishing footprint from 2006-2021.

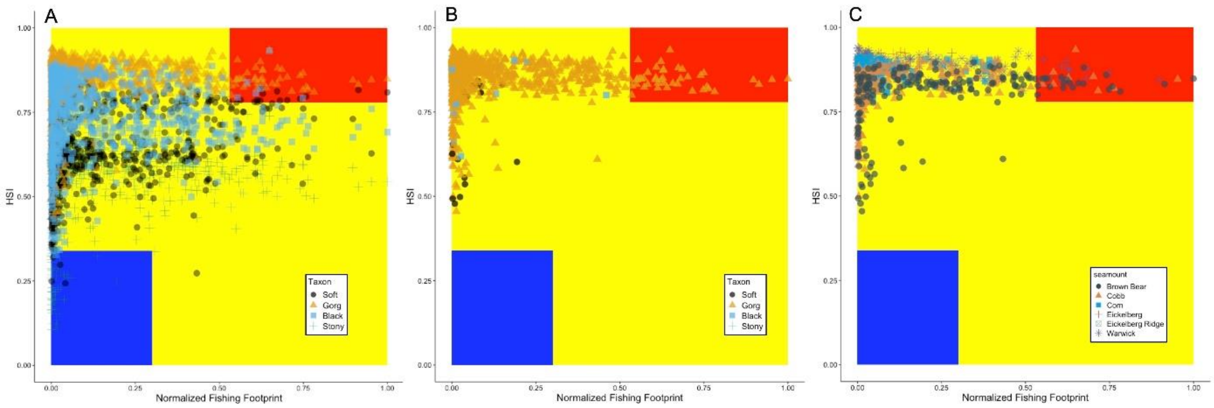

Figure 5. Kobe plots showing the categorical relative risk (shaded areas) at each grid cell for (A) all taxa (B) the taxon with the highest HSI in each respective grid cell by taxon and (C) seamount. Red, yellow, and blue areas represent high, medium, and low relative risk categories, respectively.

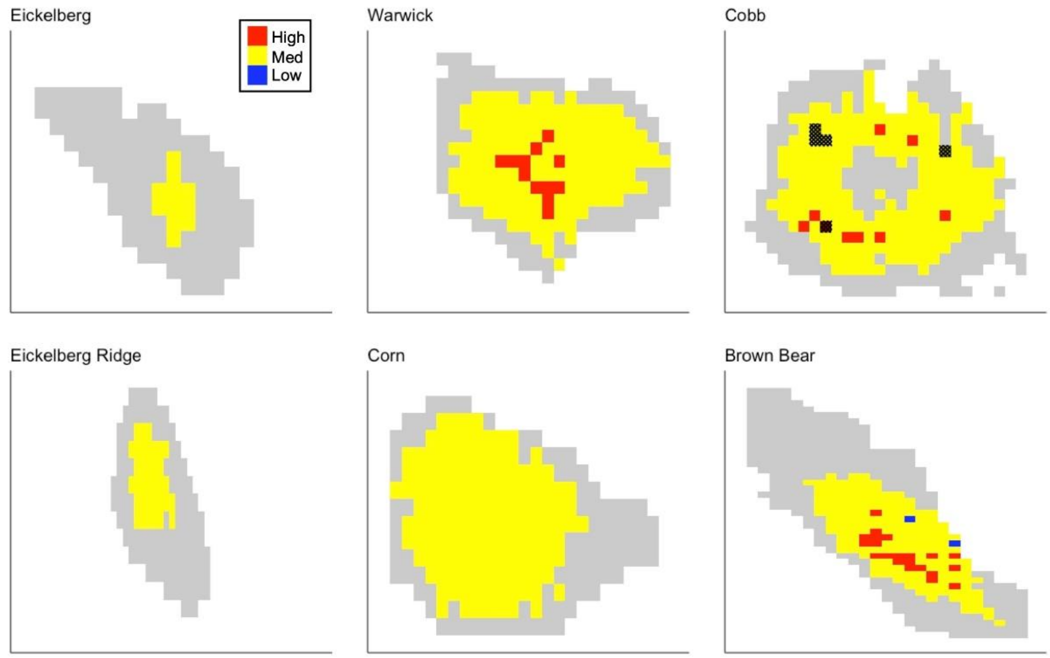

Figure 6. Relative risk of SAIs at **s**eamounts within the study area. Red, yellow, and blue areas represent high, medium, and low relative risk categories, respectively. Grey cells denote seamount areas with no fishing footprint from 2006-2021 while hatched cells on Cobb seamount show grid cells with VMEs identified by Warawa et al. (2022a).