Estimating quantitative gear and taxa specific encounter thresholds for commercial fisheries bycatch of vulnerable marine ecosystem indicator taxa

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Abstract: Corals and sponges are often a component of vulnerable marine ecosystems (VMEs) in the deep sea. These taxa can be impacted and removed by bottom contacting fishing gear and protecting VMEs is an important component of managing ecosystems. One of the tools that is routinely used to manage VME impacts from fishing gear is move-on rules triggered by bycatch thresholds (encounter thresholds) of VME. Usually, these bycatch thresholds are set with little information regarding the level of impact on the benthic habitat. The objective of this analysis was to develop and apply methods for quantifying threshold catches of VME indicator taxa by gear type and VME indicator taxa grouping. Three previously used methods based on cumulative bycatch distributions and one novel method based on percentile regression of fishery bycatch and density from underwater camera surveys were applied to data from the northeast Pacific Ocean to determine data-based encounter thresholds that could trigger spatial fishery closures. The percentile regression method suggested encounter thresholds of ~40 - 65 kg of Antipatharia, < 20 kg of gorgonians and 78 - 131 kg of Porifera would equate to a density of 0.2 VME indicator taxa per m^2 for bottom trawl bycatch. Threshold values were lower for longline and pot gear (generally < 10 kg per set). Using the percentile regression method allowed for the definition of VME encounter thresholds to be expressed in terms of density of the taxa of interest, an improvement over examination of break points in the cumulative bycatch data alone. This improvement allows the ecological importance (e.g. density of VME) to be defined and used to estimate encounter thresholds, rather than assuming that the natural break points in cumulative bycatch represent an ecological break point.

Keywords: vulnerable marine ecosystems, move-on rules, bycatch thresholds, deep-sea coral and sponge, fisheries bycatch

Introduction

Deep-sea corals and sponges have been identified as ecosystem components that need protection from bottom-contact fishing activity, and in 2006, resolution 61/105 was adopted by the UN General Assembly to prevent impacts on vulnerable ecosystems by deep-sea fisheries (FAO 2009). Vulnerable marine ecosystems (VMEs) have further been defined as areas where fishing activities are likely to have significant and adverse impacts on the benthic community (FAO 2009). Deep-sea corals and sponges are widely recognized as important components of VMEs and these taxa can increase seafloor biodiversity and contribute to fisheries production by providing complex structure on the seafloor (Buhl-Mortensen et al. 2010, Watling et al. 2011, Linley et al. 2017). In general, deep-sea corals and sponges are long-lived, mature after an extended period (years to decades), have low capacity for recruitment and recovery and are structurally fragile making them vulnerable to damage from mobile or fixed fishing gears (Koslow et al. 2001, Freese 2001, Clark and Rowden 2009, Heifetz et al. 2009). Spatial management of the impacts of fishing activity on VMEs is difficult due to the paucity of data on the distribution of deep sea VMEs and the poor or unknown distribution and spatial resolution of fishing activity.

Encounter protocols with subsequent spatial closures is a tool often used in managing fisheries and VME impacts (Hourigan 2009, Auster et al. 2011, Ardron et al. 2014, Wallace et al. 2015). Typical implementation of an encounter protocol to protect VME involves defining a threshold bycatch weight of benthic invertebrates that indicate the potential presence of a VME on the seafloor. Bycatch at or above this threshold weight then triggers a move-on rule where the fishing activity is forced to move away from the location where the encounter threshold was exceeded. In some cases, either a permanent or temporary spatial closure is adopted around the encounter event. The move-on rule and spatial closure can apply to only the vessel or gear type that triggered the encounter (Wallace et al. 2015, SPRFMO 2023) or it can apply to all fisheries operating in the area with bottom contacting gear (NPFC 2023). Indicator taxa are typically used to indicate the presence of a VME. So for example, in international waters of the Northeast Pacific Ocean, bycatch of > 50 kg of corals (any combination of Alcyonacea, gorgonian, Antipatharian or Scleractinian corals) or > 500 kg of sponges (any combination of Hexactinellida or Demospongiae) by a commercial fishing event (e.g. a bottom trawl haul) triggers a temporary spatial closure within 1 nm of the trawl path and forces the vessel (and other vessels fishing the same gear type) to avoid the closed area (NPFC 2023). Although there is substantial debate over the effectiveness of encounter protocols with move-on rules as a mechanism to protect VME (e.g. Auster et al. 2011), these protocols are a commonly used tool, especially for fisheries in international waters (FAO 2016). The goal of the analyses presented here is to improve the use of these tools.

Setting thresholds for VME indicator taxa is difficult because of the unquantified link between VME indicator taxa abundance, the observed bycatch on commercial fishing gear, and the degree of impact on the indicator taxa. An effective threshold is dependent on knowledge of the catch efficiency of the gear (e.g. what does the weight of VME indicator taxa in a trawl haul equate to in terms of abundance of the VME indicator taxa on the seafloor?). Patch size for VME can be determined from underwater imagery, and can guide the placement and size of spatial closures (Kenchington et al. 2014, Rowden et al. 2017, SPRFMO 2021, Piechaud and Howell 2022). However, bycatch thresholds have historically been put in place based on limited information (Ardron et al. 2014). Thresholds that have been picked using bycatch data may not have an ecological basis for the value (Geange et al. 2020). Only a handful of studies have examined the efficiency of fishing gear in capturing VME indicator taxa (e.g. Freese 2001). Most of these studies have examined bottom trawl gear and have found that the catch efficiency is typically less than 5% for VME indicator taxa (Kenchington et al. 2011, SPRFMO 2022). Assessing catch efficiency of VME indicator taxa in fishing gear would allow for more data-based methods to identify when bycatch values indicate the presence of a VME.

The objective of this analysis was to develop and apply methods for quantifying threshold catches of VME indicator taxa by gear type and VME indicator taxa grouping. Geange et al. (2020) developed three methods to estimate VME indicator taxa encounter thresholds and applied them to New Zealand bottom trawl fishery bycatch data from seamount systems in the South Pacific Regional Fishery Management Organization (SPRFMO) Convention Area. Here we apply these three methods (Geange et al. 2020) to fishery bycatch data only and develop and apply a new method that relates fishery bycatch data to density data independently collected during stereo-camera surveys. Threshold catches are then proposed that would indicate the presence of a VME based on fishery observer data and observed density data. These threshold catches could then be used to trigger move-on rules and spatial closures for bottom contacting fishing gears.

Methods

A variety of benthic invertebrates have been defined as vulnerable marine ecosystem indicator taxa by management bodies (Baco-Taylor et al. 2023). In this analysis we used VME indicator taxa groupings as defined by the Regional Fisheries Management Organization (RFMO) for international waters of the North Pacific, the North Pacific Fisheries Commission (NPFC; NPFC 2023) with two additions. The VME indicator taxa groupings used here are

Alcyonacea (soft corals, excepting those species defined as gorgonian corals), gorgonian corals (upright, complex and branching corals from the families Primnoidae, Plexauridae, Keratoisididae, Coralliidae, and Acanthogorgiidae), Antipatharia (black corals), Scleractinia (stony corals), Hexactinellida (glass sponges) and Demospongiae in the phylum Porifera. The two additional groups that were included in the analyses were pennatulaceans (Pennatuloidea) and hydrocorals (Stylasteridae). These two taxonomic groups have been considered in the past for inclusion in the NPFC indicator taxa list and are included as VME indicator taxa by some other regional fisheries management organizations. Although we use these definitions of VME indicator taxa here to be consistent with the current RFMO definition for the North Pacific, the definitions are clearly not consistent with the currently accepted taxonomic definitions for coral species (McFadden et al. 2022). The parentheses above and Table 1 contain the family level names that can be used to cross-walk between the VME indicator taxa (NPFC definition) and the currently accepted taxonomy (McFadden et al. 2022).

Fisheries data

Information collected by fisheries monitoring programs in Alaska, British Columbia and the contiguous west coast of the United States of America (US) from 2002-2022 were the primary data used in this analysis. For each fisheries monitoring program the bycatch of deep-sea coral and sponge taxa are recorded from subsamples of the total catch collected from individual hauls as the weight of each taxa. These weights are then expanded to the total haul catch using the total weight of the bycatch. The proportion of the catch sampled for each fishing event is highly variable depending on the gear type, fishery, region and species targeted. All of these data are subject to privacy restrictions in Canada and the US, so the data from individual hauls were provided for analyses without potentially identifying characteristics or other confidential information (e.g. latitude, longitude, depth, vessel name, etc.). The data were identified by year of catch and one of 5 regions; eastern Bering Sea, Aleutian Islands, Gulf of Alaska, British Columbia and the US west coast which roughly follow the existing definitions of large marine ecosystems for the marine waters of North America (Figure 1). The data were also identified as coming from one of three fishing gear types; bottom trawl, hook and line (primarily longline gear), or trap gear (pot). All of these fishing gear types have been used to target benthic fish and invertebrates in commercial fisheries in each area since the early 20th century. Typical species targeted by bottom trawls are rockfishes, flatfishes and gadids in all 5 regions (NPFMC 2020a, NPFMC 2020b, PFMC 2023, DFO 2024). These bottom trawl fisheries, although usually targeting a single species or species complex (e.g. rockfishes), can have significant bycatch of both VME indicator taxa and other fishes and invertebrates (NOAA 2011). Hook and line gear is typically used to target single species most commonly Pacific halibut (*Hippoglossus stenolepis*), sablefish (*Anoplopoma fimbria*) or Pacific cod (*Gadus macrocephalus*) in all five regions (NPFMC 2020a, NPFMC 2020b, PFMC 2023, DFO 2024). Bycatch in these longline fisheries tends to be less (but can comprise significant portions of the catch) and because of the stationary nature of the fishing configuration and the active capture method (baited hooks), less VME indicator taxa are retained on the gear than for mobile fishing methods (NOAA 2011). Similarly, pot gear is stationary and requires active capture by the target fish or invertebrates, so the amount of retained VME indicator taxa is less (NOAA 2011). Pot gear is used in all five regions primarily to capture Pacific cod, sablefish and multiple crab species (NPFMC 2020a, NPFMC 2020b, PFMC 2023, DFO 2024). Observer coverage strategies vary by region and fishery. In Canada, there has been 100% observer coverage on the groundfish fleet since 1997 through either electronic monitoring or human observers combined with dockside monitoring (Turris 2000). In Alaska coverage rates depend on the fishery and typically range from ~20-100% of fishing events for bottom trawl fisheries and 15-100% for pot and longline fisheries. On the U.S. west coast coverage rates are ~5-100% of fishing events for pot and longline fisheries and ~20% from 2002 to 2010 and 100% from 2011 to 2022 for trawl fisheries. Further details on observer protocols, coverage rates and data collection can be found in NWFSC (2023), AFSC (2023), AMR (2005), NMFS (2023) and Somers et al. (2024).

The individual observations used in the analysis of fishery data were the bycatch in kg of benthic taxa for each haul or set of a gear type. Zero catches were not used in this analysis since they would not be relevant to setting a taxa specific threshold. Effort data from the commercial fishery (e.g. hours towed by each bottom trawl) was also not used in this analysis. This was primarily due to the fishery data being collected over many different gear types and target fisheries, so comparisons of effort between, for example, longline gear and trawl gear were impossible, without strong assumptions regarding the seafloor area contacted by the gear and the impact of that contact. Even within gear types, such as bottom trawl gear, the gear types were not comparable as the relative effort and catchability of benthic taxa in rockfish gear with large rollers on the footrope was different than for flatfish gear with less robust footrope construction. Thus standardizing the catches among gear types, fisheries and VME indicator taxa was not possible. Instead, here we assumed that within a broad gear type (e.g. bottom trawl), the bycatch of VME indicator taxa would reflect their relative abundance on the seafloor.

Observers typically identified benthic invertebrate taxa to the lowest possible taxonomic resolution. In some cases this was species, but more often it was a higher taxonomic level (e.g. class or higher for sponges). The taxonomic groups used for reporting also varied somewhat over time and among regions, for example in Alaska sponges were lumped into a single taxonomic grouping (Porifera), while in British Columbia sponges were split into Demospongiae, Hexactinellida and Calcarea (Table 1). Similarly, observers in Alaska sometimes identified observations of gorgonian, stony coral, black coral, and soft coral groups only as a single coral group (corals and bryozoans). The majority of the occurrence records were from bottom trawls (particularly in the Aleutian Islands), while longline gear and pot gear had fewer observations of benthic invertebrate bycatch (Table 1). Porifera tend to be the most abundant VME indicator taxa overall across all the regions studied here (Hourigan et al. 2017, Stone et al. 2011). Of these, Demospongiae at shallower depths in Alaska and Hexactinellida across all depths in the more southern regions are dominant, with Calcarea being relatively rare across all regions. The dominant coral taxa on hard substrate in continental shelf waters of the northeast Pacific are typically Primnoidae, with Keratoisididae and Antipatharia dominating in deeper slope waters (Hourigan et al. 2017, Wilborn et al. 2021, Stone et al. 2023). In soft-bottom substrates sea whips (pennatulaceans) tend to be the most common VME indicator taxa (Hourigan et al. 2017, Wilborn et al. 2021, Stone et al. 2023).

Camera survey data

The other source of data used in these analyses were obtained from underwater camera transects conducted in Alaska from 2012-2019 (Table 2). These data were collected using a stereo-camera system in the Aleutian Islands (n = 216, Rooper et al. 2018), eastern Bering Sea outer shelf and slope (n = 250, Rooper et al. 2016) and Gulf of Alaska (n = 338, Sigler et al. 2023) as a part of a series of species distribution model validation studies and were only available for these three regions. The stereo-camera surveys followed roughly the same sampling protocol in each of the regions, with stations chosen using a stratified random sampling design

(Aleutian Islands and eastern Bering Sea) or a haphazardly stratified sampling design (Gulf of Alaska). Stratification in the Aleutian Islands and the eastern Bering Sea was by depth and were designed to collect data that would represent each of the regions to depths of 900 m. Transects targeting 15 minutes of on-bottom time were visually surveyed at each selected location (~350 – 420 m in length). Fish and benthic invertebrates (primarily corals and sponges) were enumerated to their lowest possible taxonomic level (sub-family in most cases) and all or a subsample were measured for total height using stereo-image analysis (Williams et al. 2010). The area observed by the camera was calculated using the distance traveled during transect observations and the median target distance for each transect, assuming 100% detection at a swath width equivalent to the viewing width, typically 2 - 5 m (Rooper et al. 2016). Density was then calculated as the number of each taxa observed on a transect divided by the area observed on that transect in $no./m^2$. Densities of individual taxa were summed by transect into the VME indicator taxa groups used for analysis (Table 2). In this analysis only transects with density greater than zero were utilized (n = 196 in the Aleutian Islands, n = 183 in the eastern Bering Sea and n = 196 in the Gulf of Alaska).

Data analysis - Fishery bycatch frequency

Bycatch data from all five regions were examined across the various VME indicator taxa to determine the general trends and data characteristics. Mean, median, histograms and cumulative frequency of bycatch were summarized and compared among regions (see Supplemental Material). Naturally occurring breakpoints (Jenks breaks) and quantiles were also computed and compared for each of the regions.

Geange et al. (2020) used three methods to estimate potential encounter thresholds using only the shape of the cumulative bycatch curve. We applied these cumulative bycatch curve threshold methods to data from the Northeast Pacific and compared among regions and across taxa where the number of bycatch records within the grouping was ≥ 300. The first of the three methods used by Geange et al. (2020) fits a 3-parameter segmented regression to the cumulative frequency distribution of the bycatch and was applied here to each gear type, region and VME indicator taxa indicator individually. The final breakpoint of the segmented regression is used to calculate the cumulative bycatch threshold. Fitting of segmented regressions for the VME indicator data from fishery bycatch was completed using the segmented package in R (Muggeo 2008, R Core Team 2022). In the second method, the point on the cumulative frequency distribution that is closest to the top-left corner (point closest to x = 0 and y = 1) was calculated as

$$q_1 = \min_{i=1}^{n} \sqrt{(1 - y_i)^2 + (0 - x_i)^2},$$

referred to hereafter as the minimum distance method (Tilbury et al. 2000). The final method applied to the fishery bycatch data was to calculate the Youden Index (Youden 1950, Ruopp et al. 2008), which is the point on the cumulative distribution that is the maximum of the linear distance between the extreme points on the curve. The Youden Index is calculated as

$$q_2 = \max_{i=1}^{n} (y_i + x_i - 1).$$

Variance estimates for the cumulative bycatch threshold generated using the segmented regression were taken directly from the model fit, whereas for the q_1 and q_2 variance was estimated by the bootstrap method where the bycatch data was resampled 1000 times with replacement and the variance calculated from the 1000 replicated estimates (Efron and Tibshirani 1993).

Data analysis - Fishery-camera percentile estimation

An alternative and potentially improved taxa and gear specific method to estimate a threshold is to compare the cumulative distribution of densities of VME indicator species from camera surveys to the cumulative distribution of bycatch of the same VME indicator taxa groups. The goal of this comparison was to estimate an equivalent density of VME indicator species to a weight of bycatch of that taxonomic grouping. To accomplish this comparison, 20 percentiles (5th, 10th, 15th, 20th,…) from the cumulative distribution function of the observed density of VME indicator taxa in stereo-camera surveys were used to predict the corresponding 20 percentiles (5th, 10th, 15th, 20th,…) from the cumulative distribution function of fisheries bycatch data within each region and within each gear type in Alaska. The stereo-camera data and the bycatch data were not collected at the exact same location or through the same process, so a number of assumptions were required: 1) we assumed the true distribution of the density of VME indicator taxa was known for each region from the stereo-camera survey, 2) we assumed that the bycatch of VME indicator taxa by each gear type for each fishing event was proportional to the density of VME indicator taxa at that site, 3) we assumed that the fishery events sampled from the full distribution of potential densities of VME indicator taxa in a region, and 4) from this we assumed that the distribution of bycatch of VME indicator taxa by a gear type in a region was proportional to the distribution of density of VME indicator taxa in the region.

A linear model was fit to the percentiles of bycatch weights (dependent variable) and the percentiles of stereo-camera survey densities (independent covariate). Both the fisheries bycatch weights and the stereo-camera survey densities were log-transformed prior to analyses to meet assumptions of normality. The log-transformed density and the log-transformed weight of bycatch of VME indicator taxa were ordered and the density and weight at each 5^{th} percentile calculated (exploratory analyses were conducted using the 10^{th} and 1^{st} percentiles, but the effect on the results was negligible). The percentiles for the log-transformed weight of bycatch ($w_{t,r,g}$) were the density dependent variable in an analysis of covariance so that;

$$w_{t,r,g} = \beta * d_{t,r} + g + r + t + d_{t,r} * g + d_{t,r} * r + d_{t,r} * t + g * r + \epsilon$$

where g is gear type (bottom trawl, longline or pot), r is region (eastern Bering Sea, Aleutian Islands or Gulf of Alaska), t is the VME indicator taxa found in Alaska (Alcyonacea, Antipatharia, gorgonian, hydrocoral, pennatulacean, or Porifera), ϵ are normally distributed errors. The second order interactions between gear and taxa and region and taxa could not be included, since some taxa did not occur in all regions or gear types. The model was simplified by removing insignificant variables in a backwards stepwise fashion until all remaining variables in the model were significant ($p < 0.05$).

Once the best-fitting model was determined, the equation was used to generate predictions of a potential encounter threshold based on the percentile regressions. Currently there is no definition of a vulnerable marine ecosystem based on the density of deep-sea corals or sponges. For demonstration purposes in this analysis, we defined a VME as a density of 1 individual coral colony or sponge per 5 m^2. Using this definition and the best fitting model, thresholds were generated using a $d_{t,r} = log(0.2)$ for each specific gear, taxon and region combination. Confidence intervals were also estimated for the prediction. It is important to note that the choice of example density was somewhat arbitrary, reflecting a sensible estimate of what a relatively high density VME area might be. This example value could be easily updated if a regional or commonly held density-based definition of a VME was determined (e.g. Rowden et al. 2020). Percentile regression-based threshold bycatch weights were then compared among regions, gears and VME indicator groupings.

Results

In the eastern Bering Sea there have been over 430,000 fishing events observed from 2002 to 2022 (58.5% of these observed events were bottom trawl hauls, 36.5% were longline sets and 5% were pot sets). Sponges (unidentified Porifera, Hexactinellida, Calcarea and Demospongiae combined) were the most commonly occurring taxa, but only occurred in 3% of bottom trawl hauls and longline survey sets, and 2% of pot sets (Figure 2, Supplementary Material). Coral taxa (Alcyonacea, Antipatharia, unidentified corals, gorgonians or Scleractinia) occurred in < 1% of bottom trawl hauls and pot sets, while they occurred in ~2% of longline sets. Pennatulaceans were more common in the eastern Bering Sea, occurring in > 5% of longline sets and less than 1% of bottom trawl hauls and pot sets. Pennatulaceans also had the highest weight of bycatch in longline gear compared to other gear types (361 mt, Figure 2). The weight of sponge bycatch was highest in the eastern Bering Sea, with 1.3 mt observed in pot sets and 1,584 mt observed in bottom trawls. Coral bycatch although relatively infrequently caught had a combined bycatch weight of 80 mt for bottom trawl hauls, 40 mt for longline sets and 0.1 mt for pot sets. Hydrocorals were rarely observed to be caught both in terms of frequency of occurrence and total bycatch weight (< 0.03% frequency of occurrence and ~0.1 mt combined across all gear types). In the eastern Bering Sea, the time series of bycatch indicates bycatch of VME indicator taxa peaked from 2008-2015, but has been relatively low in the last 7 years (Figure 3). The pattern in peak bycatch for the eastern Bering Sea was primarily driven by an increase in the observed bycatch of sponges during 2008-2015.

In the Aleutian Islands there were ~81,000 observed fishing events from 2002 – 2022, mostly bottom trawling events (73%) and longline events (22%). Sponges occurred in 24% of observed bottom trawl and longline events, while corals occurred in 16% of bottom trawl hauls, but 27% of longline sets (Figure 2). Pot gear had low rates of occurrence for both coral 3.3% and sponge 5.6% in observed sets. Hydrocorals and pennatulaceans occurred infrequently in Aleutian Islands fishing, with frequency of occurrence in observed hauls ~1% for all gear types. Total bycatch weight of VME indicator taxa in the Aleutian Islands was high (Figure 2), with observed sponge bycatch over the 21 years of data exceeding 3,400 mt across all fisheries. Coral bycatch was also relatively high in both the longline and bottom trawl fisheries with 69 mt and 579 mt respectively. Pot gear retained less VME indicator taxa in the Aleutian Islands, with a total of 1.2 mt observed (Figure 2). In the Aleutian Islands, the total observed bycatch of VME indicator taxa has remained relatively steady, except for Porifera, which has been higher since 2013, than in the earlier half of the time series (Figure 3).

Forty-eight and 43% of the observed fishing events (n = 105,115) from 2002-2022 in the Gulf of Alaska were bottom trawl hauls and longline sets respectively. The remainder (9%) were pot sets. Sponges occurred in 4% of observed bottom trawl hauls, 2.5% of observed longline sets and 1% of pot sets (Figure 2). Corals occurred in 1.7% of bottom trawl hauls, 2.7% of longline sets and 0.5% of pot sets. Pennatulaceans were more frequently caught in longline sets (2.7%) than in bottom trawl hauls (0.5%) or pot sets (0.2%). Hydrocorals occurred in < 0.2 % of all observed fishing events in the Gulf of Alaska. Total observed weight of VME indicator taxa bycatch in the Gulf of Alaska was lower than the other regions of Alaska, only 77 mt of sponge was observed in bottom trawl hauls, 10 mt in longline sets and 0.1 mt in pot sets (Figure 2). For corals, 29 mt was observed in bottom trawl hauls, 9 mt in longline sets and 34 kg in pot sets. Almost 10 mt of pennatulaceans were observed in longline sets, but only around 1 mt in the bottom trawl hauls and pot sets combined. Combined hydrocoral bycatch across all gears was 1.2 mt. Over time the Gulf of Alaska has seen no trend, but highly variable bycatch weight of VME indicator taxa (Figure 3).

Since 1997 Canada has had 100% observer coverage, so the number of observed fishing events from 2002-2022 was 625,129. Of these, 49% were bottom trawl hauls, 43% were longline sets and 8% were pot sets. The frequency of occurrence of corals, pennatulaceans and hydrocorals in bottom trawl hauls, longline sets and pot sets in Canada was < 1% from 2002-2022 (Figure 2). Only sponge bycatch occurred at a higher frequency 1.5% in bottom trawl hauls, while in longline sets and pot sets the frequency of sponge bycatch was < 1%. The weight of observed corals and sponges captured in bottom trawl hauls was 13 mt and 62 mt respectively when combined over the 11 years (Figure 2). In longline sets and pot sets coral bycatch was 0.4 mt and 0.2 mt, while sponge catches were 0.1 mt and 0.04 mt. Hydrocorals only occurred in the bottom trawl fishery and in total 15 kg of these were observed from 2002-2022 in Canada (Figure 2). Combined VME indicator taxa bycatch decreased in Canada from 2002-2011 and has remained at very low levels since then (Figure 3).

West Coast data was primarily from bottom trawl hauls (78%), while observed longline sets (13%) and pot sets (9%) comprise the remainder of the 193,158 observed fishing events. Similar to Canada, the frequency of occurrence of corals in observed fishing events was low (~1% for bottom trawls, longline sets and pot sets, Figure 2). Pennatulaceans were caught in 2.1% of bottom trawl hauls, 0.8% of longline sets, and 2.1% of pot sets, while sponge was captured in 2.6% of bottom trawl hauls, 0.9% of pot sets. Hydrocoral frequency of occurrence was < 0.03% across all gear types (Figure 2). Sponge was the most abundant VME indicator taxa in the bycatch of bottom trawls (67.5 mt), longline sets (1.0 mt) and pot sets (0.1 mt). Coral bycatch was 8.5 mt in bottom trawls and 94 kg in longline sets and 54 kg in pot sets. Pennatulacean catches were 1.8 mt in bottom trawls, 50 kg in longline sets and 34 kg in pot sets (Figure 2). Also similar to Canada, bycatch weight on the west coast peaked in 2009 and has been at low levels since then (Figure 3).

Overall, the mean bycatch when they were observed was higher for sponges (Porifera, Hexactinellida and Demospongiae) in the Aleutian Islands than the other regions (Figure 4). This pattern was also apparent for most upright and branching corals (e.g. gorgonians), and some of the other coral groups (stony corals and Alcyonacea as a grouped taxa). Pennatulacean bycatch was higher in the eastern Bering Sea than any of the other regions across all gear types (Figure 4). Across all regions, the gear type with the highest bycatch overall of VME indicator taxa were bottom trawls followed by longline gear and pot gear. Longline gear in the eastern Bering Sea were particularly notable in having higher bycatch on average than even bottom trawls in the eastern Bering Sea (mean = 42 kg, SE = 0.70 for longline gear and mean = 8 kg SE = 1.0 for bottom trawls), this pattern was also true in the Gulf of Alaska and Aleutian Islands. Although the range of bycatch weights generally overlapped among regions for a gear type and VME indicator taxa group, there were significant differences ($p < 0.05$) in the mean values across all regions for all gear types for each indicator taxa (Figure 4) as indicated by analysis of variance and Tukey’s post-hoc comparisons.

Fishery cumulative bycatch thresholds

The distributions of bycatch of VME indicator taxa for almost all gear types, regions and taxa were heavily right-hand skewed. This was true for taxa with very few observations (e.g. Alcyonacea in the west coast longline fishery with n = 100 observed catches, Figure 5) and large numbers of observations (e.g. gorgonians in the Aleutian Islands bottom trawl fisheries, Figure 5). See the supplemental information for the full array of bycatch from all combinations of VME indicator taxa, gear type and region. The skewness of the bycatch data resulted in distributions where the median was often at least an order of magnitude lower than the mean (Figure 5). So for example, the mean bycatch of Demospongiae in bottom trawls in Canada was 16 kg, while the median bycatch (meaning 50% of the catches were above and below) was 0.9 kg.

For the most part, the cumulative bycatch-based thresholds suggested by the Youden Index and the minimum distance metrics were similar, if not exactly the same within taxonomic group-region-gear type combinations (Figure 6 and Supplemental Figures and Tables). Where the Youden Index and minimum distance metrics were slightly different, their standard error bars overlapped indicating that the difference was not statistically significant (Figure 7). The segmented regression tended to estimate a cumulative bycatch-based threshold (third break point) that was lower (and almost always significantly lower) than the two other methods. Reflecting the relative catches in each of the regions, the cumulative bycatch-based thresholds were generally highest in the Aleutians and lowest on the US west coast (Figure 7). When averaged across regions and break points, Porifera had the highest cumulative bycatch-based threshold of any of the taxonomic groups. Pennatulaceans stood out in the longline gear, with high cumulative bycatch-based thresholds (> 75 kg) in the eastern Bering Sea only (Figure 7). There were not enough occurrences of any VME indicator taxa bycatch in the pot fishery to estimate cumulative bycatch-based thresholds (see supplemental material for cumulative bycatch curves for the pot fishery). There were also not enough occurrences of Scleractinians in any of the fisheries to estimate cumulative bycatch-based thresholds.

Percentile regression thresholds based on image data

The regression of percentiles of log-transformed observed VME indicator taxa density against percentiles of log-transformed VME indicator bycatch in Alaskan fisheries resulted in consistent patterns among gear types and regions for most fishing gears (Figure 8). The full model included all possible interaction terms. Two could not be included due to the unbalanced design (Gear-VME_taxa and Region-VME_taxa). The density-region term was insignificant ($p = 0.48$) and was removed from the best-fitting model. In the best fitting model all main effects (gear type, VME indicator taxa and region) were significant, as well as the covariate interactions between log-transformed VME density observed in the camera and VME indicator taxa and region. The gear type-region interaction term was also significant (Table 3).

The predicted percentile regression thresholds were highest in the Bering Sea for bottom trawl gear across most VME indicator taxa (Figure 9). The predicted percentile regression thresholds were lower for longline gear, but also tended to also be slightly higher in the eastern Bering Sea. For pot gear, predicted percentile regression thresholds were uniformly low across all taxonomic groups and regions. For gorgonians, the estimated threshold ranged from 11.52 kg in the Gulf of Alaska to 19.15 kg in eastern Bering Sea for bottom trawls (predicted at a camera density of 0.5 colonies*m^{-2}, Supplemental Table S2). For Porifera, the values were larger ranging from 79 kg in the Gulf of Alaska to 131 kg in the eastern Bering Sea. The threshold values determined by regressing percentiles of observed density against percentiles of bycatch were uniformly lower than the threshold values estimated by the minimum distance, Youden Index or segmented regression for the same regions and gear types in Alaska.

Discussion

Unsurprisingly, bycatch of VME indicator taxa in bottom trawls was higher than for other gears across multiple taxa and all of the observed regions. Sponges were the most frequently captured VME indicator taxa and accounted for the most bycatch weight of any of the VME indicator taxa across all regions, generally due to their broader distribution, larger size and heavier body than most coral species. Hydrocorals were generally the least common bycatch species in all regions by frequency of occurrence and weight, but coral taxa and pennatulaceans were fairly common although with regional differences (e.g. the high abundance of pennatulaceans in eastern Bering Sea catches relative to other areas). Total bycatch frequency and weight was highest in the Aleutian Islands and lowest in Canada and the U.S. west coast.

Fishery bycatch of VME indicator taxa generally agreed with the observed density where underwater image data were available. Areas with high density in the images (e.g. sponges in the Aleutian Islands or pennatulaceans in the eastern Bering Sea) yielded high bycatch in fisheries. The shape of the distribution of both the fishery bycatch data and the camera survey density data were similarly highly skewed with large right-handed tails. These general characteristics of the two data sources and their agreement provides some comfort that the patterns and relationships developed in the analysis are complementary. Of the two methods (bycatch data only or percentile regression), the percentile regressions tended to generate lower bycatch thresholds across all taxa. However, these comparisons could only be made for data in Alaska, as camera surveys for density were not available for the other regions.

Temporal trends in bycatch

Time trends were evident in coral and sponge bycatch over the regional time series. In part this may have been due to changes in fishing regulations that were designed to protect benthic habitat in all three jurisdictions. In British Columbia an individual transferable quota (ITQ) system was put in place to manage bycatch of corals and sponges in 2007 (Wallace et al. 2015). This catch accounting system succeeded in reducing the amount of bycatch overall in the fishery and also caused a shift in fishing effort away from coral and sponge hotspots (Gale et al. 2022). In the Aleutian Islands of Alaska and on the U.S. west coast, spatial closures to protect known or suspected concentrations of sponge and coral and to protect essential fish habitat were implemented in 2005 and 2006 respectively. In the Aleutian Islands, these closures were focused on areas outside of those historically fished, essentially freezing the fishing footprint at that moment. The resulting consistency of spatial patterns in fishing effort did not, at least initially, result in clear declines of coral and sponge bycatch, as was observed in British Columbia. West coast closures excluded fishing in some areas that were actively fished at the time of closure, but bycatch continued to increase until a peak in 2009, after which it has declined to relatively low levels. This initial increase may have been caused by an increase in fishing effort along the continental slope (PFMC 2023), that could have more closely overlapped the distribution of VME indicator taxa (Poti et al. 2020). However the west coast bottom trawl effort also peaked in 2009, so it also appears likely that the decrease in bycatch of VME on the west coast was a result of implementation of the groundfish ITQ program in 2011. This implementation has resulted in fleetwide reductions of bottom trawl fishing effort by more than ½ since 2010 and also resulted in some changes to fisher behavior, such as avoidance of prohibited species (Somers et al. 2023). On the U.S. west coast footrope restrictions were also implemented in 2001 that were demonstrated to have moved the trawl fishery away from hard-bottom substrates, potentially making the response to spatial closures somewhat more complex (Bellman et al. 2005). All of these changes in regulation resulted in behavioral changes that may have also significantly reduced VME indicator taxa bycatch directly or indirectly. It is also likely that in areas that have been continually fished, reductions in VME indicator taxa bycatch are the result of direct removals and mortality due to historic damage from fishing gear that has resulted in reduced biomass of these taxa on the seafloor.

Catch efficiency

Few if any studies have measured the efficiency of different gear types in capturing benthic invertebrates. The most comprehensive review of catchability of VME indicator taxa is for bottom trawls and can be found in SPRFMO (2022). The authors examined published and unpublished data sets from a variety of regions and substrate types and found that the catchability estimates by bottom trawls were generally < 5%, but could range as high as 27% for some taxa. However, SPRFMO (2022) also noted that many of these estimates were both highly variable and based on very small sample sizes. Studies in Alaska have shown that a single pass of a bottom trawl can remove a substantial biomass of corals and detach a high proportion (~27%) of the colonies in its path (Krieger 2001). A single study that examined density of sponges along experimental bottom trawl tow paths found that the densities for two types of upright sponges were 16% and 31% lower in an experimentally trawled area versus background densities (Freese 2001). The rate of damaged sponges remaining in the trawl path was 67% (Freese 2001), and the overall density of sponges in the trawled transects had not recovered 13 years post-trawling (Malecha and Heifetz 2017). Moran and Stevenson (2000) estimated a standard demersal trawl reduced benthic invertebrate density by ~16%, with only 4% of the removed organisms retained in the net. Removals of 13.8% of sponges and 3% of gorgonians by a bottom trawl in Australia was observed by Wassenberg et al. (2002), however the removals varied by both organism height (with those higher than 50 cm most likely to be impacted) and morphotype (with broad-based sponges more likely to be impacted). Sainsbury et al. (1997) looked at the catchability of sponges >15 cm in height and found that 89% were removed by a trawl. Catchability from longline, trap gear or longlined pots has not been well studied, but a study by Pham et al. (2014) estimated very low removal rates for longline gear of 0.058% for branched corals and 0.011% for unbranched corals. They observed impacts (ranging from minor damage to non-survivable damage) on 47% of the corals located near lost fishing gear. These catch efficiencies and removal rates are much lower than have been estimated for bottom trawls, which explains in large part the smaller thresholds for most VME indicator taxa for longline and pot gear estimated by this study (e.g. a lower catchability means that a small bycatch of VME indicator taxa would indicate a comparatively large density of that taxa on the seafloor).

Caveats for the camera density-fishery bycatch comparisons

The analysis comparing the stereo-camera data and the fishery bycatch data required strong assumptions regarding the validity of the density estimates from the underwater camera and the proportionality of the bycatch data to that density. These assumptions could not be tested during the analyses, so the results should be viewed in that context. There were no indications that the density of VME indicator taxa were biased, as the estimates were collected via random stratified sampling and should estimate the density accurately across space. However, the fishing activity in Alaska was likely spatially biased. The fisheries operating in the different regions of

Alaska target different species that may not fully represent available habitats. For example, the majority of bottom trawls in the eastern Bering Sea were targeting Walleye Pollock or flatfish assemblages. As such, they were more likely to occur in flat-soft sediment areas where structure forming invertebrates, except pennatulaceans, were absent. In contrast, the majority of bottom trawls in the Aleutian Islands targeted rockfish species or Atka mackerel that are more likely to occur in hard-bottom areas where corals and sponges are more likely to be present. This is reflected in the low overall frequency of occurrence of VME indicator taxa (except pennatulaceans) for the eastern Bering Sea and the high frequency of occurrence in the Aleutian Islands. The impact of spatial bias and potential bias in the habitats sampled by the fishery may have been mitigated somewhat in this analysis by using only those bottom trawl hauls that captured benthic invertebrates. Catchability of VME indicator taxa within a gear type likely also varied (e.g. footropes with tire gear may be used for rockfish trawling on hard substrate while footropes with rubber disks for flatfish trawling in soft sediments). This likely had some impact on the results of this study, especially for Porifera which are known to occur in both soft and hard substrates in Alaska (Rooper et al. 2016). However, for the VME indicator taxa that have specific substrate associations, such as gorgonians found predominantly on hard bottom, similar types of trawls and thus similar types of catchabilities would be expected. So the encounter thresholds resulting from this study should be considered a generic result representing the mix of broad gear types used for fishing on the west coast of North America.

Although the observer programs adhere to rigorous statistical designs for observer deployment and subsampling of the catch resulting in high quality bycatch data, the taxonomic resolution of the fishery data used in Alaska is also a source of uncertainty. Similar species identification resources are available and used across the different regions, but these have changed over time (e.g. Stone 2011, Wilborn et al. 2021). In some cases, the taxonomic resolution of Alcyonaceans (coral or bryozoan) recorded by observer programs in Alaska is less specific than the taxonomic resolution of the camera data and includes a taxa (bryozoan) that is not in fact a coral. However, given the small size and lack of hard skeletal structure in bryozoans their contribution to the overall weight of bycatch may have been minimal. The broader category Alcyonacean certainly included some members of the gorgonian families as well. At-sea observers primarily assess and sample targeted fish and invertebrate catches in order to support fisheries stock assessments. The extensive training needed to more successfully identify corals to lower taxonomic levels has generally not been prioritized (Stone et al. 2015). These characteristics of the bycatch data (poor taxonomic resolution, potential misidentification issues and inclusion of bryozoans) made the comparisons with camera data less certain.

The spatial distribution of historical fishing was not considered in the random stratified design for the stereo camera surveys in Alaska. This has implications for the results of this study in that it is likely that some or many (depending on the region in Alaska) of the image transects occurred in areas that may have been previously fished by one of the gear types. The impact of using densities from previously fished areas on the results would have been to reduce the densities of VME indicator taxa relative to pristine condition and thus increase the frequency of lower densities in the cumulative frequency distribution. This in turn may have reduced the percentile values for the observed density distribution resulting in a decrease in the corresponding fisheries bycatch threshold. Similarly, if the cumulative distribution of VME indicator taxa in fisheries bycatch was truncated or reduced by historical fishing, the impact on the analysis would be a reduction in estimated encounter threshold. As such, these data and results are indicative of the current nature of VME indicator taxa abundance in Alaska, rather than reflecting what might be found in a pristine ecosystem. Comparisons of the density distributions of VME indicator taxa from unfished areas/times to densities after fishing has occurred would be useful in teasing out the impacts of historical fishing on the results. However, the spatially-explicit fishing effort data from these gears and regions date at earliest from late in the 20th century and so cannot be used to identify unfished areas at the necessary time scales.

This analysis uses the best available data to determine thresholds for bycatch in the North Pacific. Specifically this data-informed method could set gear and VME indicator taxa specific thresholds for bycatch that would trigger implementation of a spatial closure and a move-on rule. The analysis indirectly attempts to measure relative catchability of VME indicator taxa using the distributions of catches. Ideally, data would be collected that could directly measure catchability and damage rates of benthic organisms in the deep-sea. Selectivity for fishes in fishing gear has long been studied to support stock assessment analysis (e.g. MacLennan 1992). However, these data are not easily attained for non-motile VME indicator taxa. In part this is due to their tendency to break apart when contacted by the gear (Freese 1999), which makes it difficult to judge the original size of the organism based on the catch. Another difficulty is that the individuals may not be entirely removed or even removed at all by the fishing gear, yet can still experience mortality or damage (NRC 2002, Stone 2014, Malecha and Heifetz 2017). This has necessitated either correlative assessments, such as the remote camera study described here, or experimental studies, such as those where underwater imagery is used to look for mortality and damage after known trawling events (Freese 1999, Wassenberg 2002). More of these types of studies with larger sample sizes, fishing gears that include non-mobile gears, and varying densities of benthic invertebrates are needed.

Comparisons to other work

As has been observed in other studies attempting to set data-based encounter thresholds, it is difficult to estimate a threshold that is applicable across wide regions. Most previous attempts to set thresholds have in part utilized some version of fisheries bycatch data (e.g. Kenchington et al. 2009, Parker et al. 2009 and Geange et al. 2020 for the North Atlantic Fisheries Organisation, NAFO, and SPRFMO). However, fisheries management organizations have generally taken their own approach to setting thresholds, including less quantifiable methods such as expert opinion (Ardron et al. 2014), an arbitrarily chosen percentile of the historical bycatch (Wallace et al. 2015), or adopted encounter thresholds put forward by other RFMOs (FAO 2016). The NAFO put into place encounter thresholds that were based on a kernel density analysis (Kenchington et al. 2009, Kenchington et al. 2014) that examined bycatch in research survey trawls scaled up to account for the differences in commercial trawling techniques and gear (Kenchington et al. 2011). SPRFMO analyzed bycatch of VME indicator taxa by New Zealand fishers both domestically and in international waters to develop a threshold that was based both on the 50th percentile of the cumulative weight frequency distribution of bycatch and on the VME indicator taxa richness in the bycatch (Parker et al. 2009). Geange et al. (2020) called for using area specific thresholds, but also recognized that data paucity forced them to combine data across areas and taxa. In the absence of known VME indicator taxa densities from underwater camera footage for British Columbia and the U.S. West Coast, the current study averages across Alaska regions to provide an estimated threshold that can be applied coast-wide. However, this estimate is very sensitive to the data from the Aleutian Islands. Removing the Aleutian Islands from the analysis reduces the percentile-based threshold by over 50% for both Porifera and the other coral taxa (gorgonians, Antipatharia, and Alcyonacea). This is due to the high density of VME indicator taxa in the Aleutian Islands which has been shown to be related to the high abundance of suitable hard substrates for VME indicator taxa and the relatively high current speeds that deliver production to benthic invertebrates in the ecosystem (Rooper et al. 2016). The naturally occurring densities of some of the VME indicator taxa examined here also vary substantially. For example, sea whip densities in the eastern Bering Sea have been estimated as high as 8.4 individuals * m^{-2}, whereas corals only ranged to 0.28 individuals * m^{-2} (Rooper et al. 2016). The differences in naturally occurring densities among VME indicator taxa also have implications for encounter thresholds, as a lower density (than the 0.2 * m^{-2} example used here for all taxa) might be preferred for taxa that are naturally less dense. So it is clear that bycatch and visual survey data collected from a region should be used to set a data-derived threshold for that region for each VME indicator taxa. However, the lack of available image-based density data that fully represents regions and substrate conditions limits development of more region specific relationships for British Columbia and the U.S. West coast. There are likely both published and unpublished data available from these regions that could be compiled and used in future analyses.

Conclusions and Recommendation

The percentile regression thresholding method allowed the development of linear relationships between density percentiles of VME indicator taxa observed on the seafloor and observed bycatch in that same region. This method allows density on the seafloor to be easily converted to VME indicator taxa bycatch. For example, if managers wished to protect gorgonians at densities above a density of 5 individuals per 100 m^2 from bottom trawling, a bycatch weight of 15.7 kg would be used to trigger an encounter based closure using the average regression coefficients developed for this taxa. In contrast, encounter thresholds based on cumulative catch from bycatch data only were able to distinguish break points, but with no biological basis for these breakpoints being meaningful or relating to a specific VME prevalence (Ardron et al. 2014, Geange et al. 2020). In the absence of better available data, we recommend using the percentile regression approach for setting VME encounter thresholds even across regions. This method is repeatable, quantifiable and easily updateable when new data become available, an improvement over expert opinion or an arbitrarily chosen thresholds based on historical bycatch.

One of the most important conclusions from this analysis is that regional-specific data (bycatch and visual survey data) should be used derive encounter thresholds for that region. Future studies should collect data that would allow the development of regional and gear specific percentile regressions that represent the regional distribution of VME indicator taxa densities and quantify the relationship between actual VME density and bycatch amounts. Ideally, this work would include experiments that documented the density of VME indicator taxa along transects before and after fishing and documented the amount of retained VME indicator taxa and damaged VME indicator taxa after fishing. These experiments could likely be done with co-located (overlapping) visual surveys and fishing activity (e.g. Freese 2001, Malecha and Heifetz 2017) or with camera systems that are mounted on the fishing gear (e.g. headrope mounted cameras, McCarthy et al. 2023) so that the data on density and catch are collected on the same tow path. A series of such experiments could collect data that would allow direct estimation of VME indicator taxa catchability by gear type across a wide range of seafloor substrates and VME densities. These improved datasets could better inform ecosystem-based fisheries management by utilizing recent methods such as Rowden et al. (2020), which identified densities of VME indicator taxa using visual imagery that are associated with thresholds in diversity, or

Baco et al. (2023), which used individual images of the benthos to define a vulnerable marine ecosystem. These datasets combined could be used to support ecologically-relevant encounter thresholds that would protect the important characteristics of vulnerable marine species and the ecosystem services that they provide.

Deep sea corals and sponges are long-lived, reproduce slowly and are known to have episodic recruitment. Primnoid corals and Hexactinellida are known to live for over 100 years, Antipatharians have been documented to live for thousands of years, and scleractinian and hexactinellid sponge reefs accumulating for tens of thousands of years (Conway et al. 1991, Leys and Lauzon 1998, Andrews et al. 2002, Fallon et al. 2010, Fallon et al. 2014, Hitt et al. 2020). In our current analysis we have developed a method that can be used to identify high density areas of VME indicator taxa. The thresholds identified by this regression method are lower than those estimated by cumulated catch curves and are generally lower than the thresholds currently in use by most RFMOs (FAO 2016). This would imply that these thresholds would be more effective at protecting aggregations of deep-sea corals and sponges. Given the long lifespan of these taxa and the time needed for recovery it is still unclear that encounter thresholds combined with move-on rules are an effective way to minimize significant and adverse impacts to VME (Auster et al. 2011). It has been pointed out that a more precautionary approach might be to enforce move-on rules and implement closures upon any encounter of VME indicator taxa (Auster et al. 2011). However, the risk in implementing move-on rules guided by any encounter threshold is that it will effectively move fishing activity into new areas, spreading any significant and adverse impacts across a wider area since it has been found that the majority of damage to corals and sponges is caused by the first pass of fishing gear (Moran and Stevenson 2002, Wassenburg et al. 2002). Ultimately, alternative management tools might lead to better outcomes for VME protection than simple use of move-on rules that trigger small spatial closures. For example, combining comprehensive surveys of VME indicator taxa, species distribution modeling and mapping of fishing effort by gear type would allow areas of high risk to be identified and protected. The approach used in Canada's groundfish trawl fisheries (Wallace et al. 2015) to require 100% observer coverage, set an ITQ for vessels limiting the amount of VME indicator taxa that can be captured, freezing the existing footprint and implementing encounter thresholds with move-on rules triggering closures has been very effective at reducing the VME indicator bycatch by these fisheries (Gale et al. 2022). These approaches, although likely better for protection of VME, require more high quality data collections than are currently available for most areas of the world's oceans, particularly those areas managed by regional fisheries management organizations.

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Tables

Table 1. Taxonomic grouping of data collected from commercial fisheries 2002-2022 by gear type in the northeast Pacific Ocean within the five study regions (Aleutian Islands, eastern Bering Sea, Gulf of Alaska, British Columbia and the US west coast) and number of observations (hauls) where each taxonomic grouping was recorded.

Observer classification	VME indicator taxa	Gear type	eastern Bering Sea	Aleutian Islands	Gulf of Alaska
Alcyonacea	Alcyonacea	Bottom trawl	296	852	31
		Longline	354	30	69
		Pot	2	--	1
CoralsBryozoans	Alcyonacea	Bottom trawl	1664	7557	526
		Longline	3984	5481	1559
		Pot	120	100	39
Antipatharia	Antipatharia	Bottom trawl	23	451	23

		Longline	2	103	39
		Pot	1	1	1
Gorgonian	Gorgonian	Bottom trawl	253	6379	295
		Longline	349	869	244
		Pot	8	23	3
Hydrocoral	Hydrocoral	Bottom trawl	12	710	58
		Longline	38	688	74
		Pot	1	23	1
Pennatulacean	Pennatulacean	Bottom trawl	1479	213	228
		Longline	15452	291	1608
		Pot	13	--	22
Calcarea	Porifera	Bottom trawl	--	--	--
		Longline	--	--	--
		Pot	--	--	--
Demospongiae	Porifera	Bottom trawl	--	--	--
		Longline	--	--	--
		Pot	--	--	--
Hexactinellida	Porifera	Bottom trawl	--	--	--
		Longline	--	--	--
		Pot	--	--	--
Porifera	Porifera	Bottom trawl	11243	26984	2251
		Longline	7296	4830	1349
		Pot	566	220	100
Scleractinia	Scleractinia	Bottom trawl	1	82	4
		Longline	1	2	33
		Pot	--	--	3

Table 2. Summary of number of transects with observations of vulnerable marine ecosystem indicator taxa by region from stereo-camera surveys from Alaska in 2012-2019.

VME indicator grouping	Aleutian Islands	Gulf of Alaska	eastern Bering Sea
Alcyonacea	2		
Antipatharia	54	5	
Calcarea	9	3	4
Demospongiae	177	141	107
Hexactinellida	88	95	56
Gorgonian	137	64	32
Hydrocoral	102	54	
Pennatulacean	81	99	105
Porifera		1	9

Table 3. Results of analysis of covariance relating the percentiles of bycatch weight in the commercial fisheries to the percentiles of density for stereo-camera surveys in regions of Alaska by gear type. Df are the degrees of freedom, Sum Sq are the sum of squares, Mean Sq is the mean squared error and p is the probability of the outcome (significance was indicated at p < 0.05).

Term	Df	Sum Sq	Mean Sq	F value	p
Density percentile (camera)	1	1,818.5	1,818.5	1,750.1	0
Gear type	2	864.0	432.0	415.7	0
Region	2	105.3	52.6	50.7	0
VME indicator taxa	4	377.3	94.3	90.8	0
Density percentile (camera) * Gear type	2	146.2	73.1	70.4	0
Density percentile (camera) * VME indicator taxa	4	43.3	10.8	10.4	0
Gear type * Region	4	42.8	10.7	10.3	0
Residuals	737	765.8	1.0		

Figures

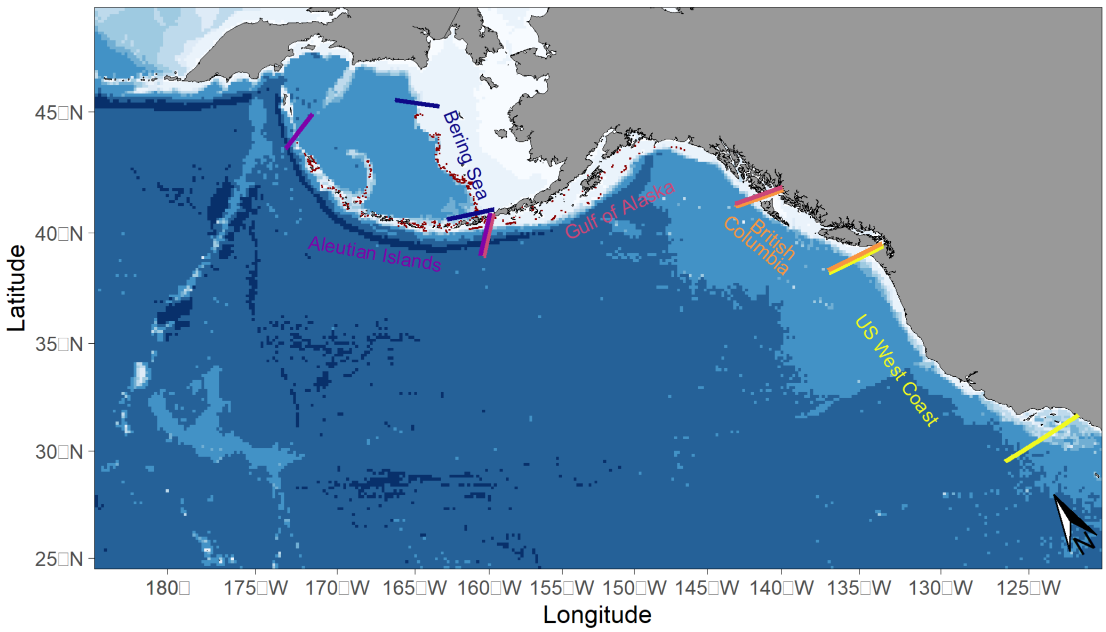

Figure 1. Map of the northeast Pacific Ocean and the five study regions: Aleutian Islands, eastern Bering Sea, Gulf of Alaska, British Columbia and the U.S west coast. Also shown are the locations of stereo-camera transects conducted in Alaska ecosystems from 2012-2019 indicated by red points.

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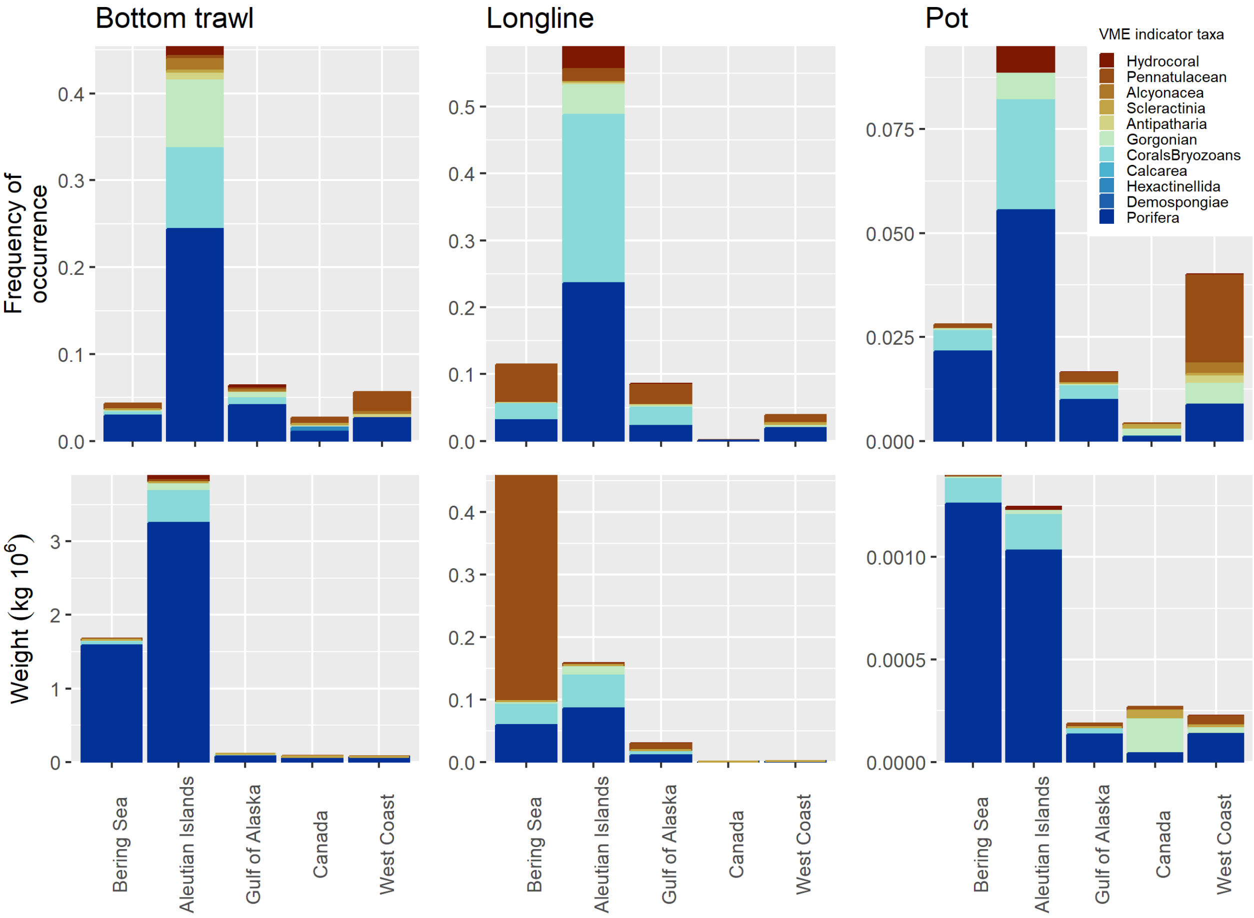

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932 *Figure 2. Frequency of occurrence calculated as the number of observed occurrences divided by*

933 *the number of observed hauls (top panels) and total weight of bycatch aggregated across all*

934 *observed hauls (bottom panels) of each VME indicator taxa captured by gear type and region.*

935 *The data used in this figure can be found in Table S1 in the supplementary material.*

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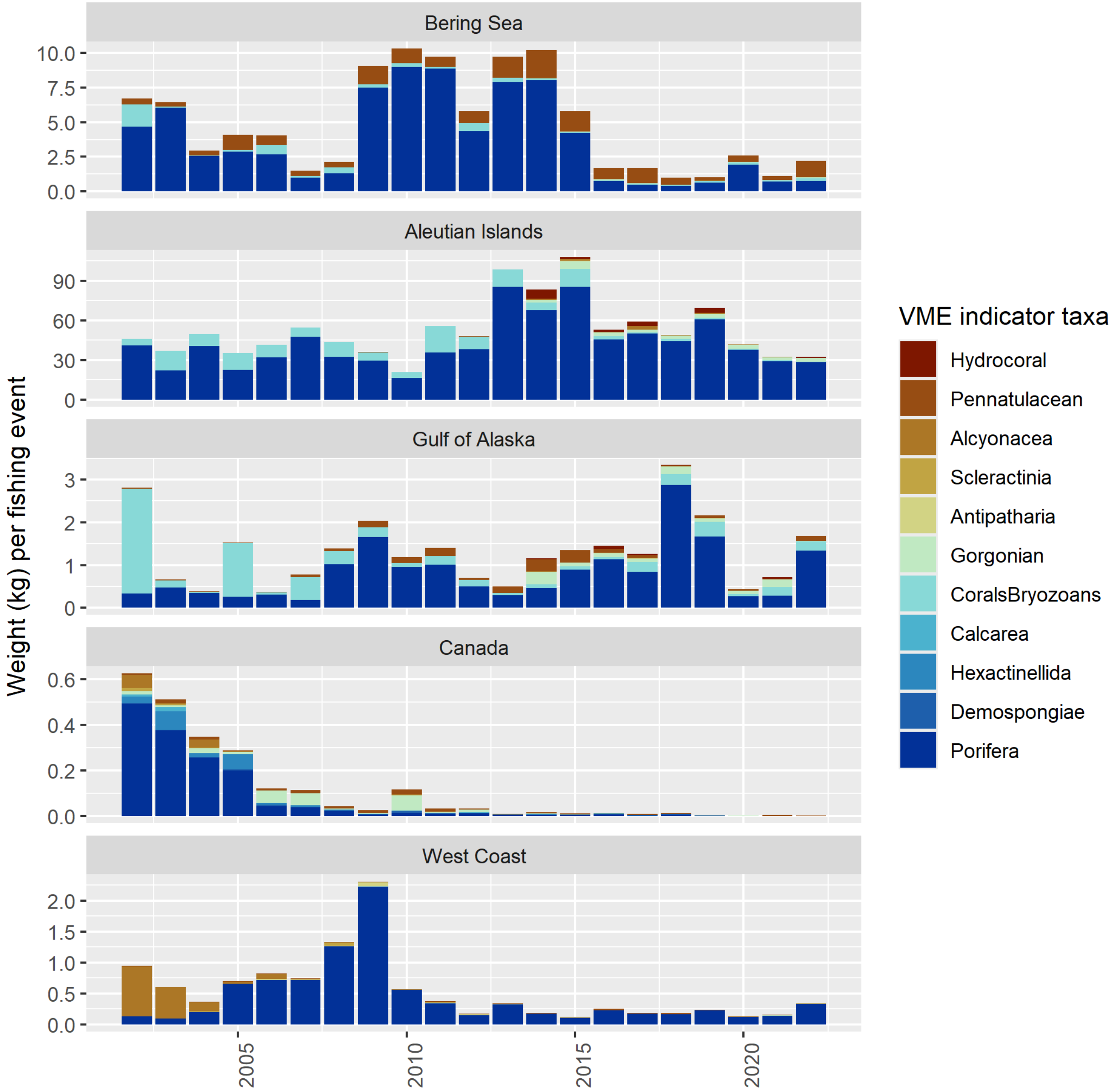

Figure 3. Time series of total annual bycatch of vulnerable marine ecosystem indicator taxa in each of the five regions of the NE Pacific Ocean from 2002-2022. The sum of the weight of the bycatch (in kg) for each year has been standardized by the number of fishing events (bottom trawl hauls, longline sets and pot sets) observed in each year combined across gear types.

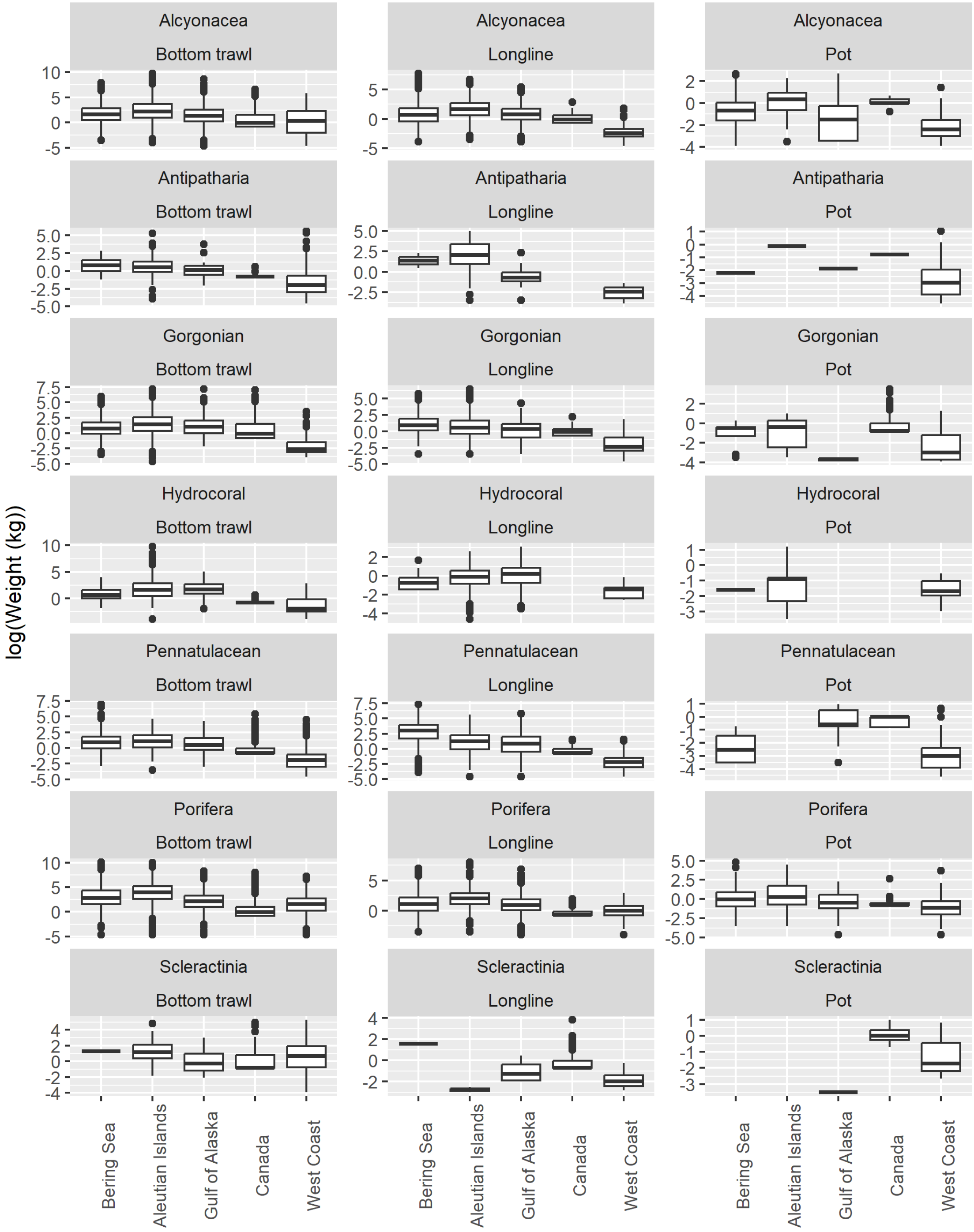

Figure 4. Mean bycatch weight of VME indicator taxa by gear type and region in instances where there was positive bycatch in commercial fishing gear. Data are combined across all

years (2002-2022) and values are plotted on a log-scale. In this figure Porifera includes unidentified Porifera, Hexactinellida, Demospongiae and Calcarea combined.

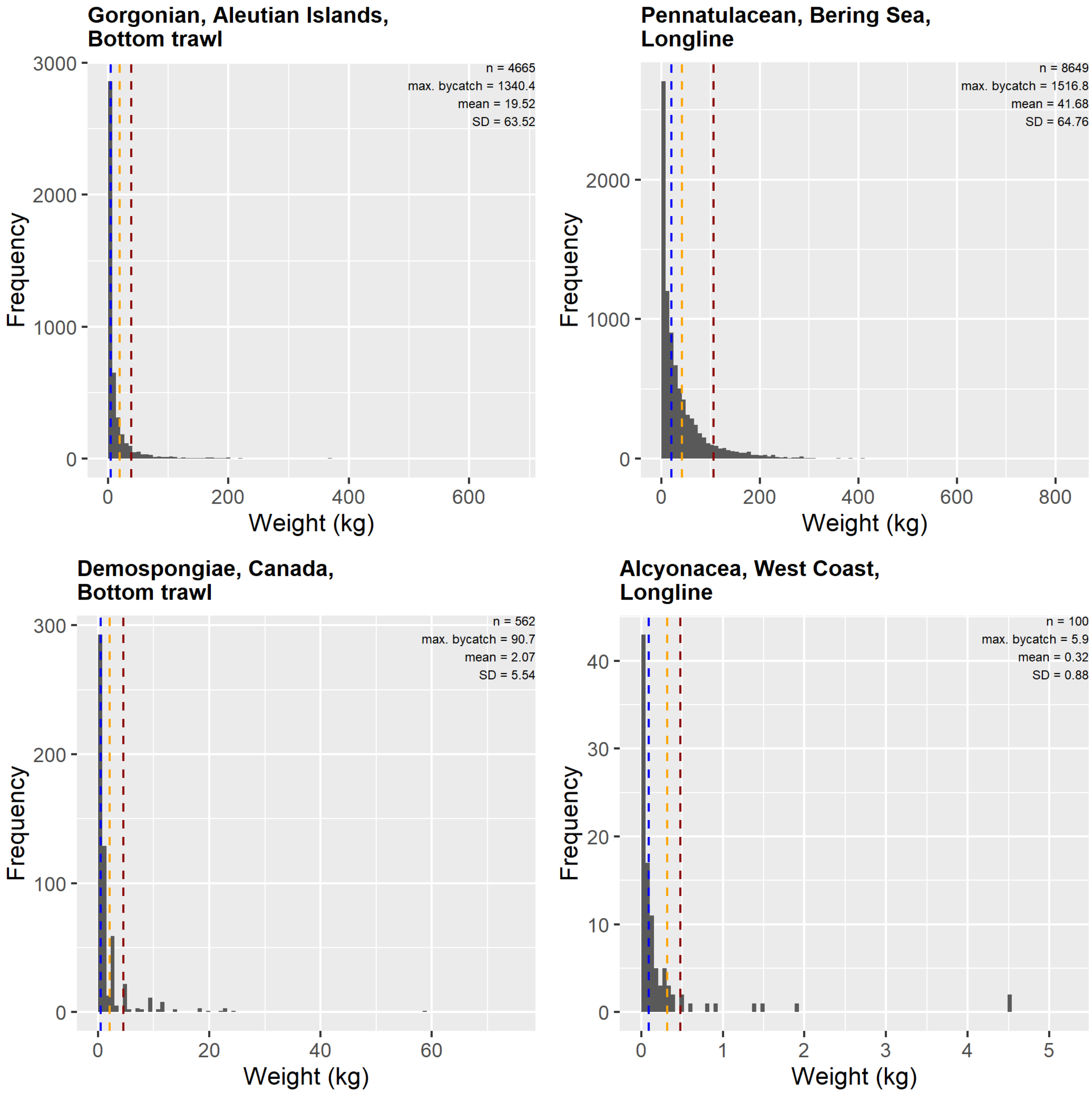

Figure 5. Histograms of bycatch data for example VME indicator taxa by gear type in four example regions of the NE Pacific Ocean from 2002-2022. Dashed lines indicate the 90% quantile (red), the mean bycatch (orange) and the median bycatch (blue). Additional combinations of taxa and gear type by region can be found in the supplemental material (Figure S1).

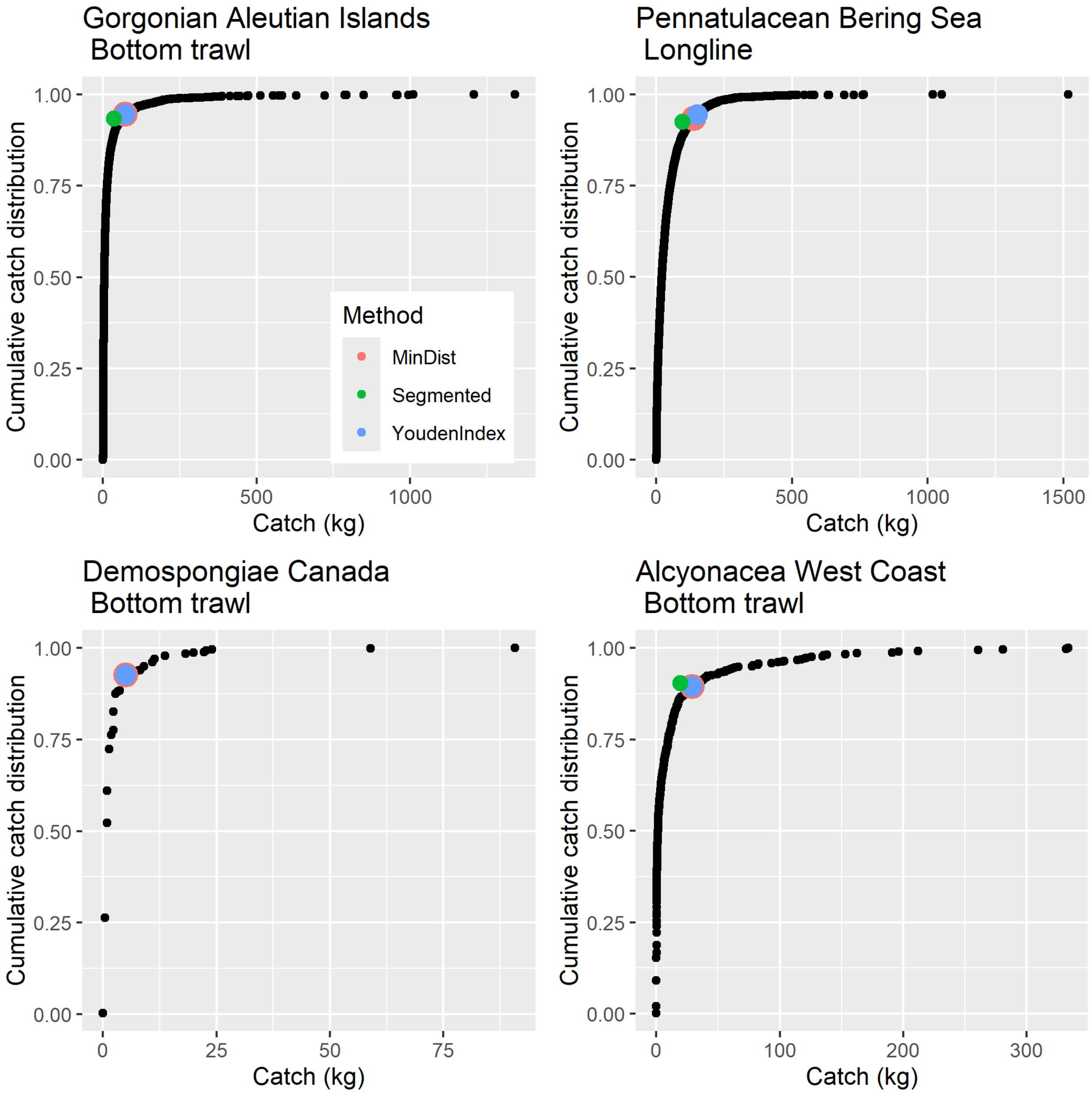

Figure 6. Cumulative frequency distributions of bycatch in commercial fisheries from 2002-2022 for four example vulnerable marine ecosystem indicator taxa by gear type in four example regions of the NE Pacific Ocean. The full set of combinations of taxa and gear type by region can be found in the supplemental material (Figure S2).

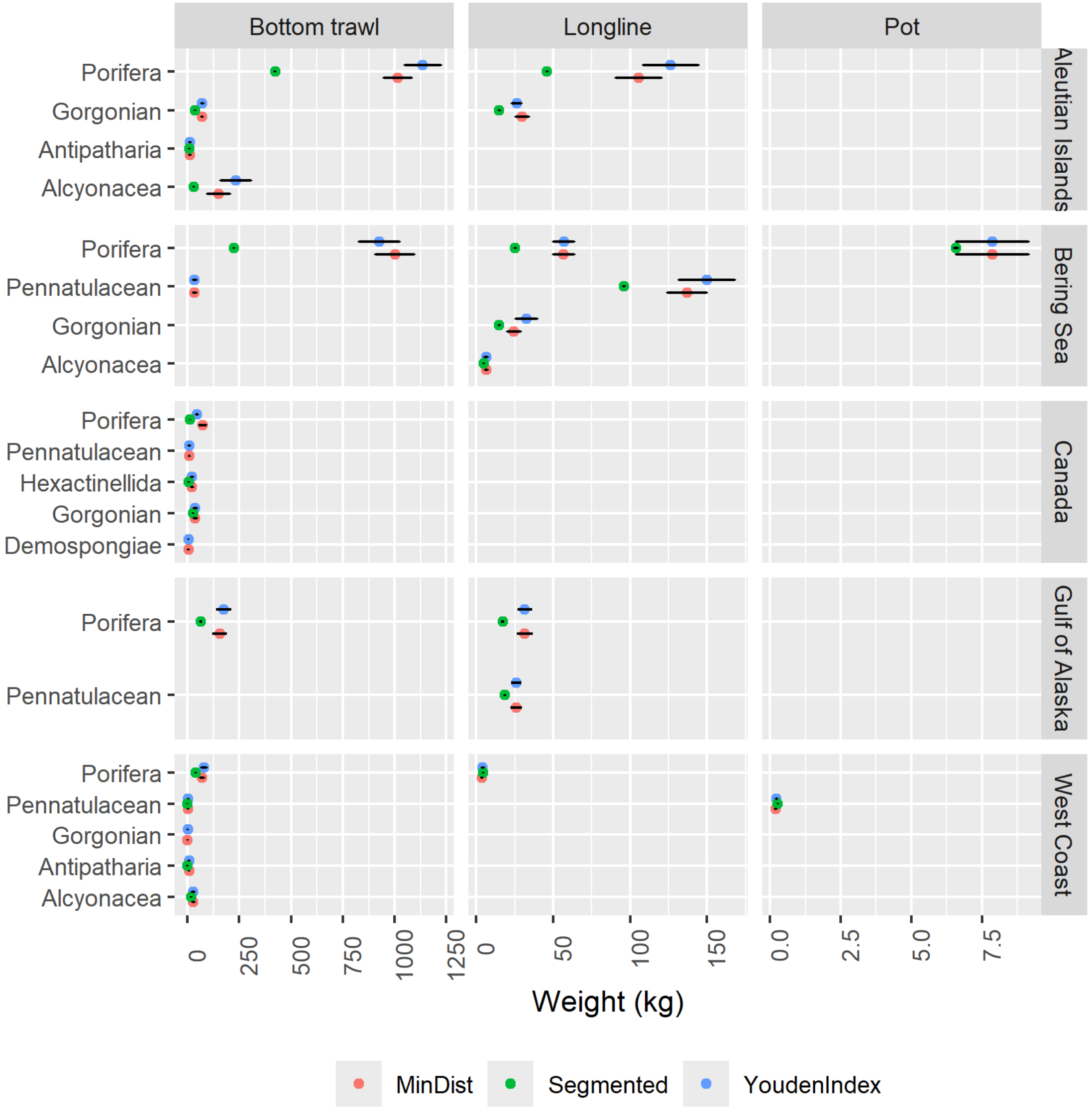

Figure 7. Vulnerable marine ecosystem indicator taxa bycatch thresholds estimated from the cumulative frequency of bycatch data in each region and gear type in 2002-2022. Where the number of data points were < 300 a threshold value was not calculated. Threshold values used for this plot are shown in Table S2.

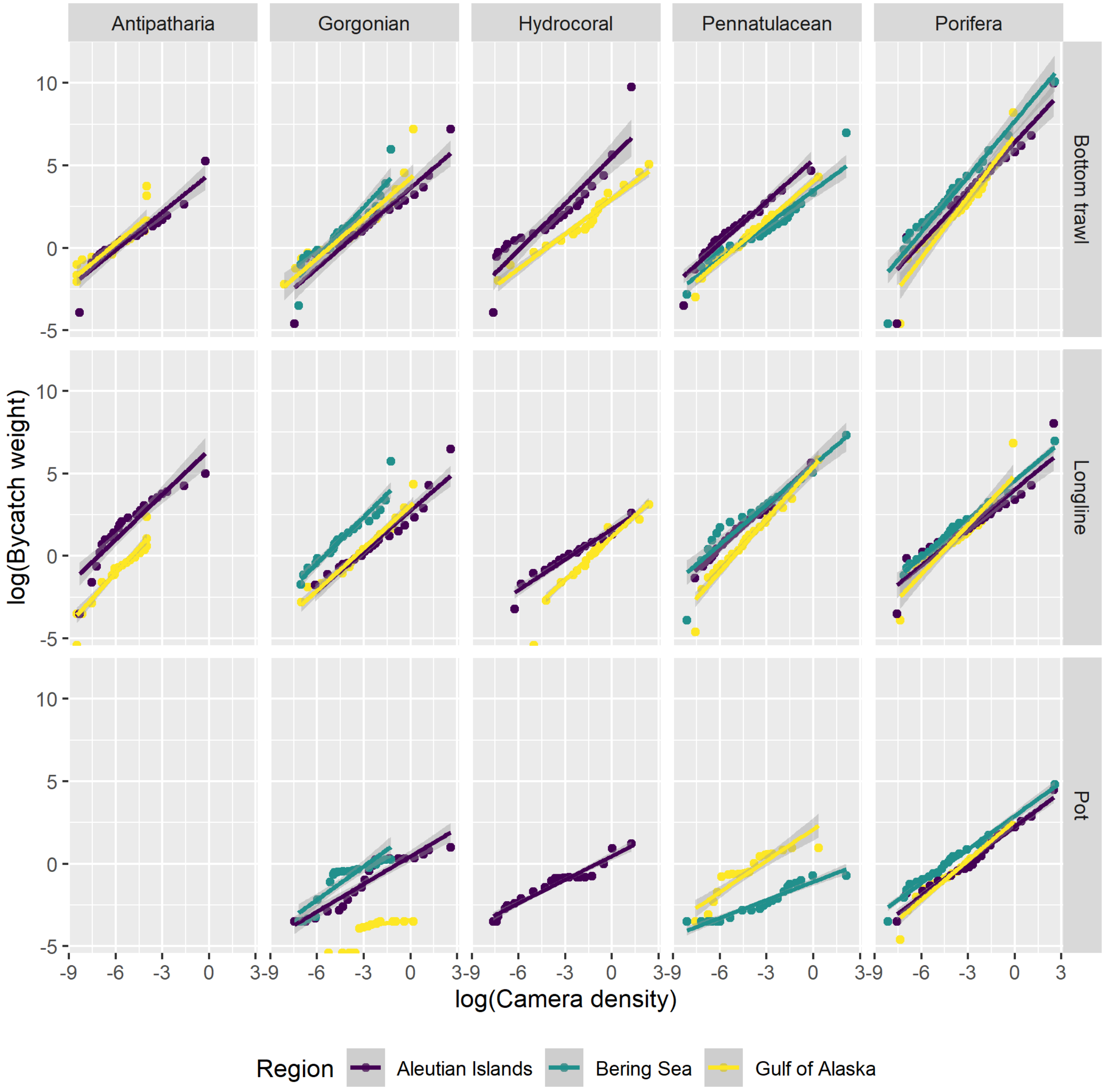

Figure 8. Linear regressions of percentile-percentile plots of log commercial fishery bycatch and log density from stereo-camera surveys of vulnerable marine ecosystem indicator taxa by gear type in each of the three regions of Alaska. Gray shaded areas indicate 95% confidence intervals.

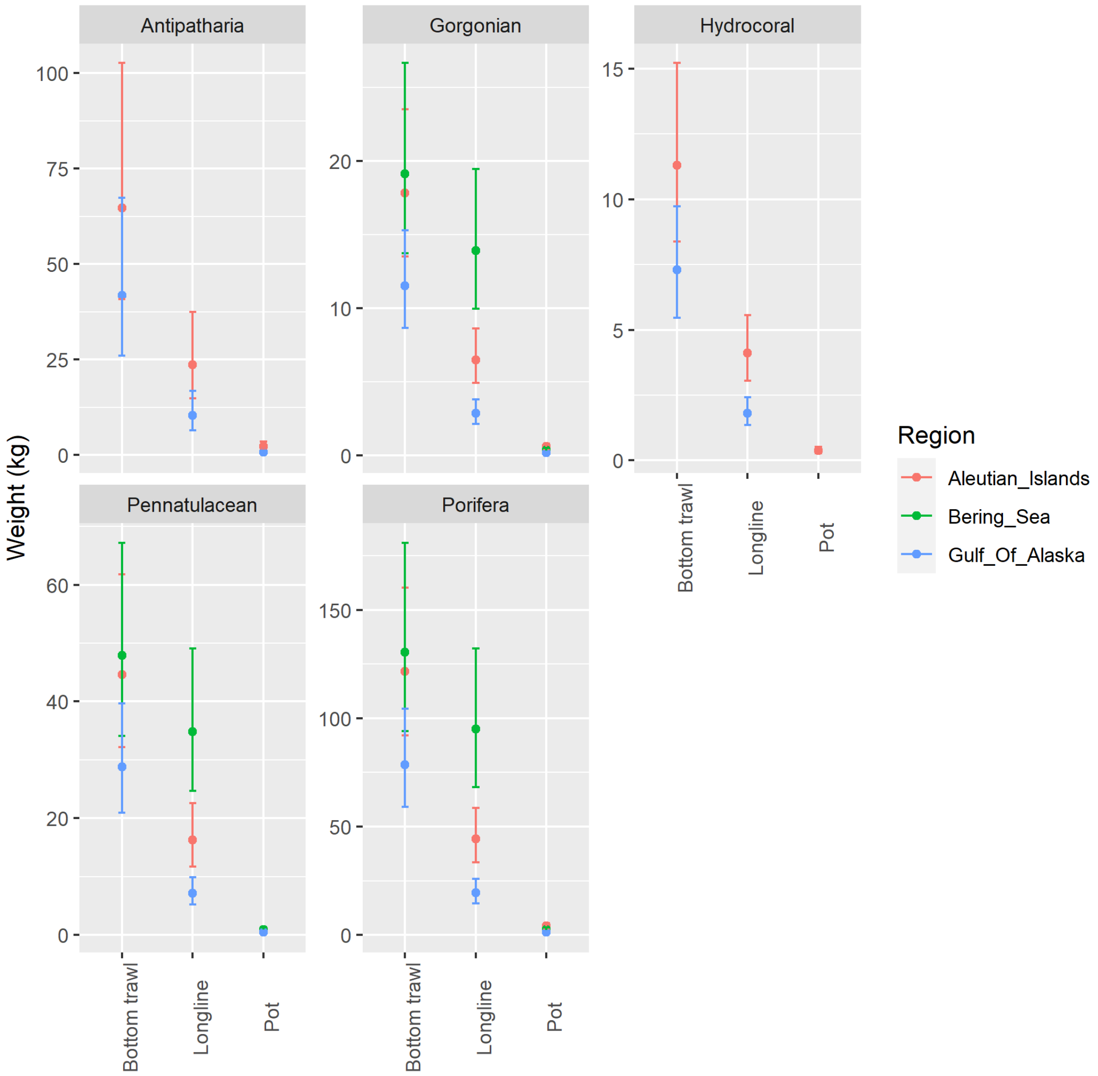

Figure 9. Predicted thresholds by gear type, region in Alaska and taxonomic grouping of VME using the percentile regression method. Error bars indicate 95% confidence intervals. Values used for this plot are shown in Table S2.

Supplemental Material

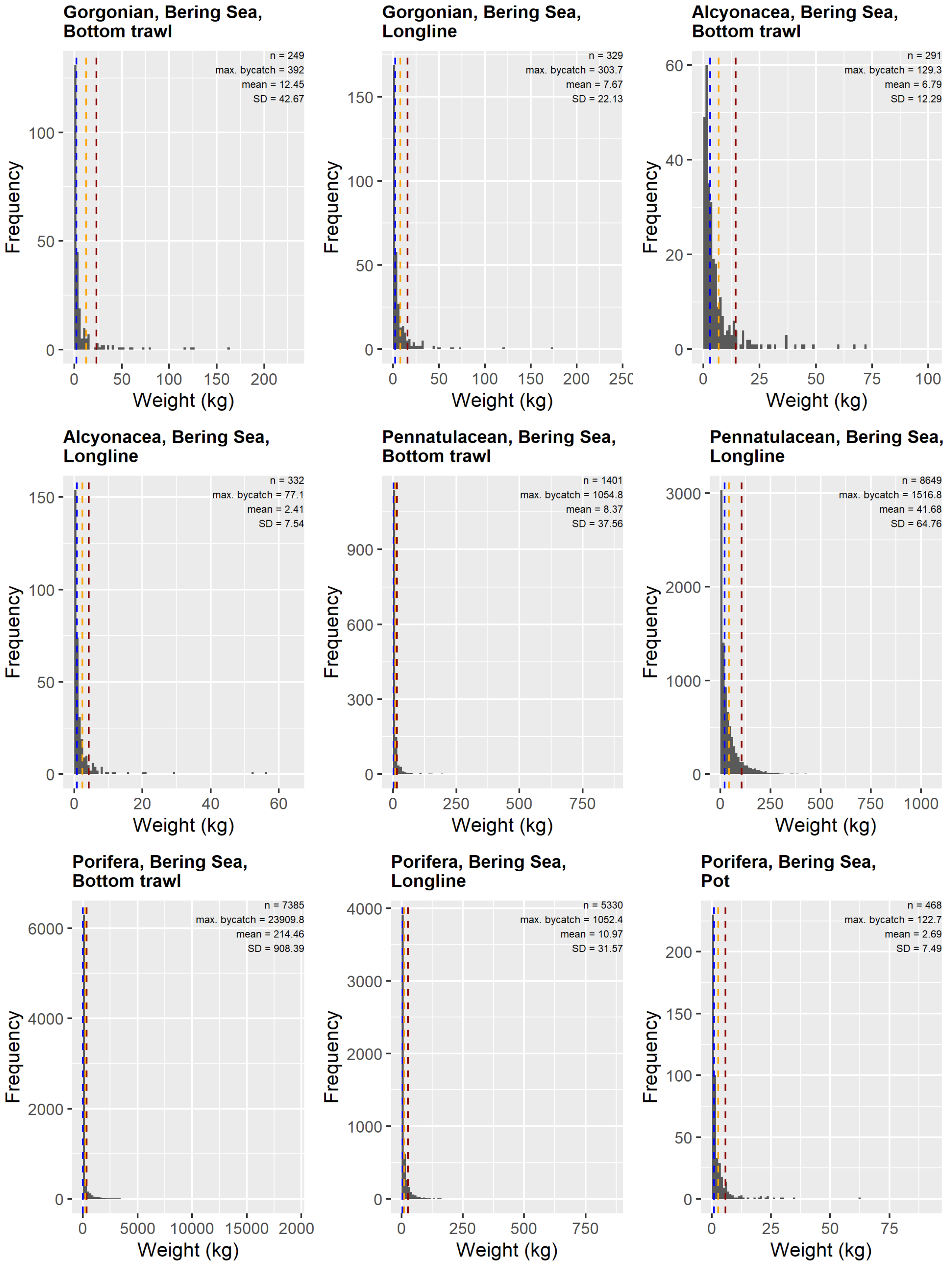

Figure S1. Histograms of bycatch data from the eastern Bering Sea from 2002-2022. Dashed lines indicate the 90% quantile (red), the mean bycatch (orange) and the median bycatch (blue).

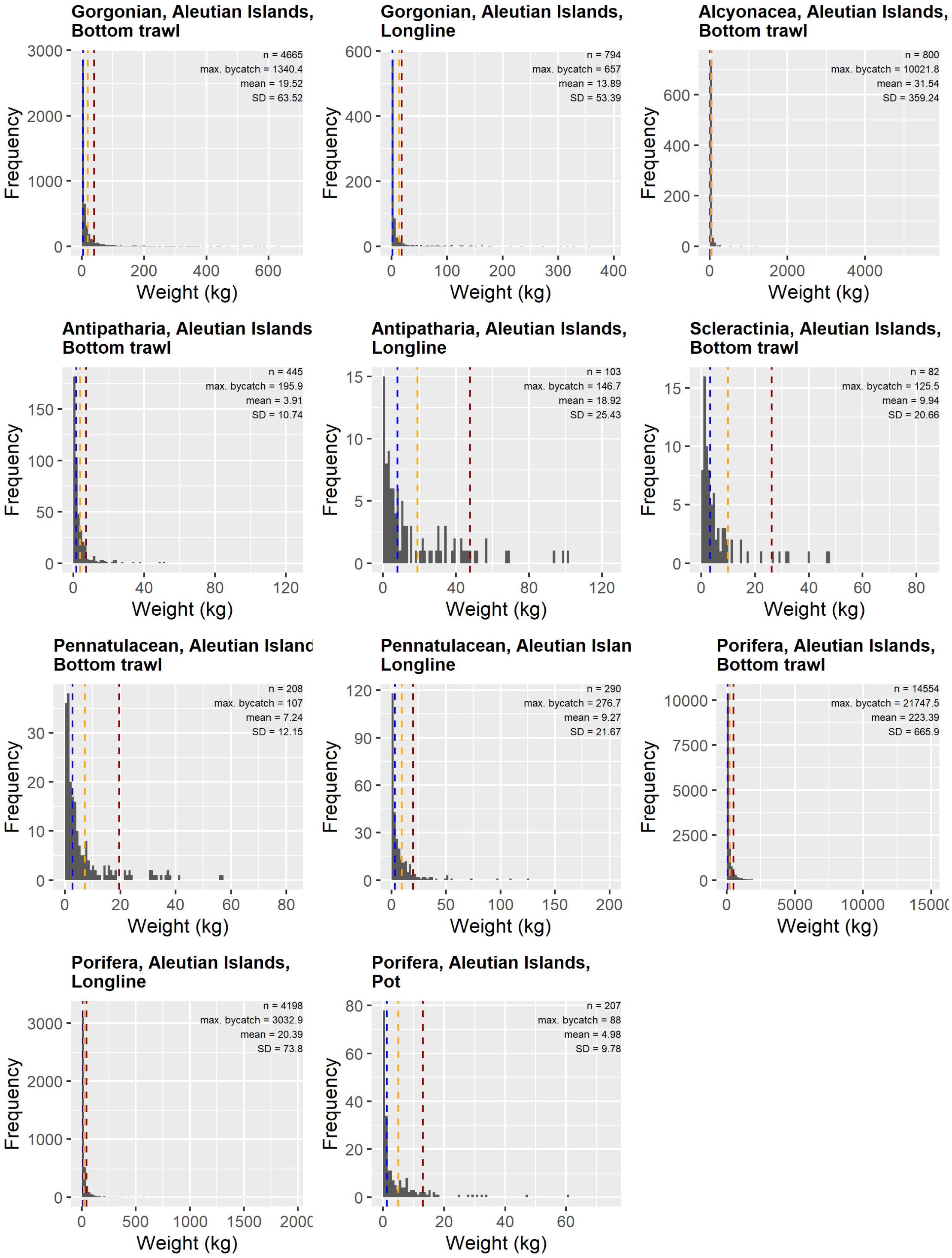

Figure S1 (cont.). Histograms of bycatch data from the Aleutian Islands from 2002-2022. Dashed lines indicate the 90% quantile (red), the mean bycatch (orange) and the median bycatch (blue).

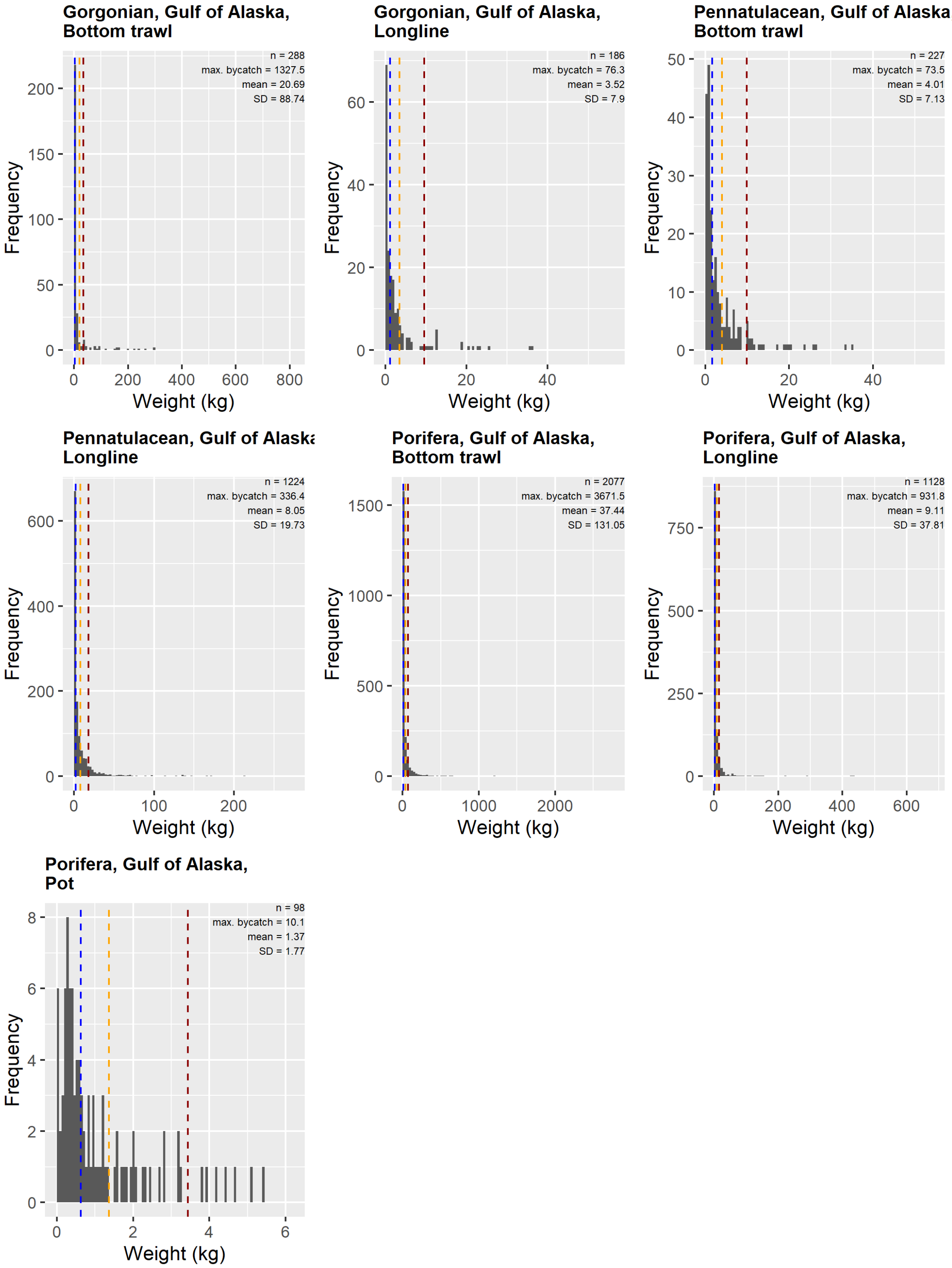

Figure S1 (cont.). Histograms of bycatch data from the Gulf of Alaska from 2002-2022. Dashed lines indicate the 90% quantile (red), the mean bycatch (orange) and the median bycatch (blue).

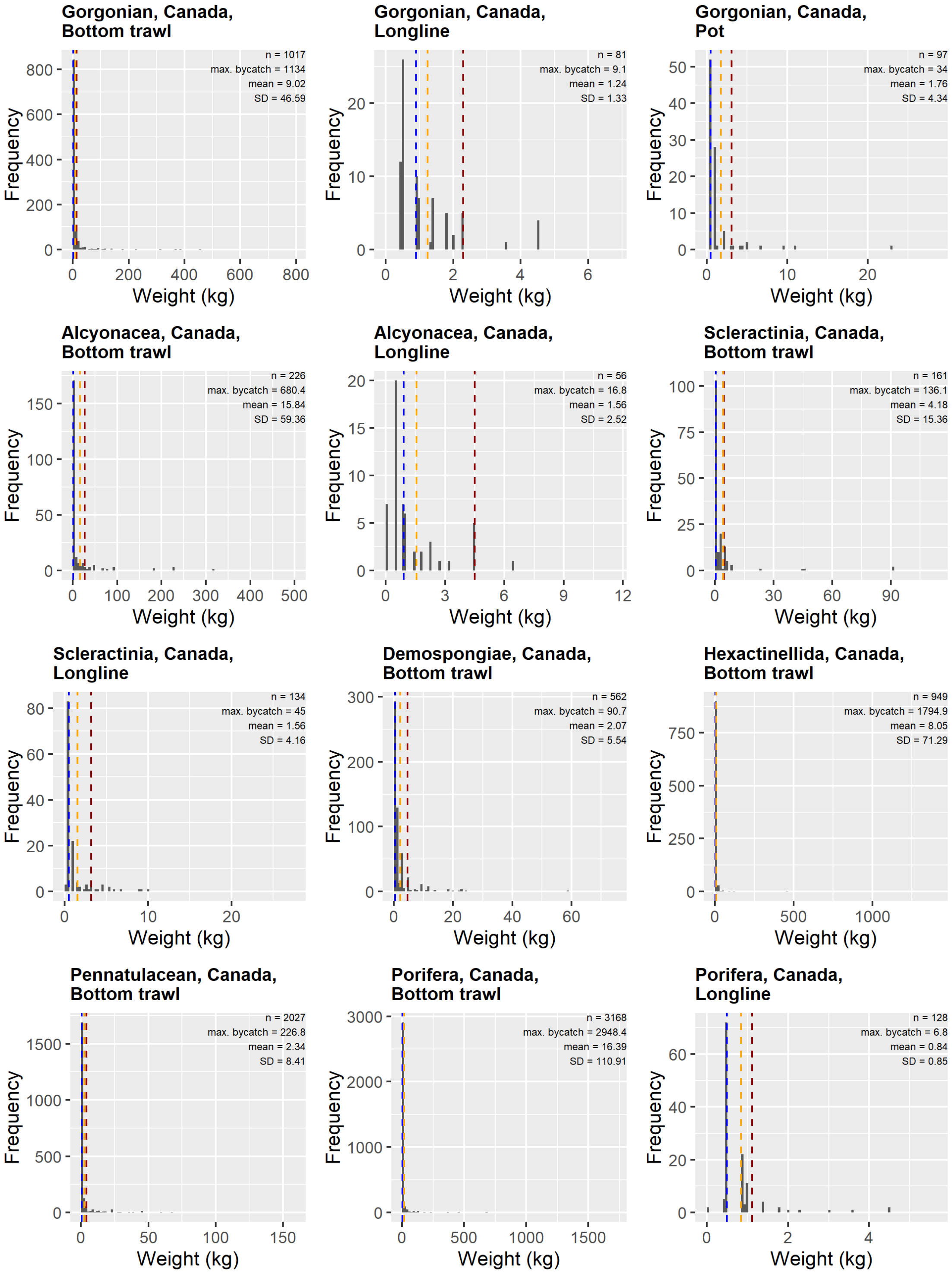

Figure S1 (cont.). Histograms of bycatch data from Canada from 2002-2022. Dashed lines indicate the 90% quantile (red), the mean bycatch (orange) and the median bycatch (blue).

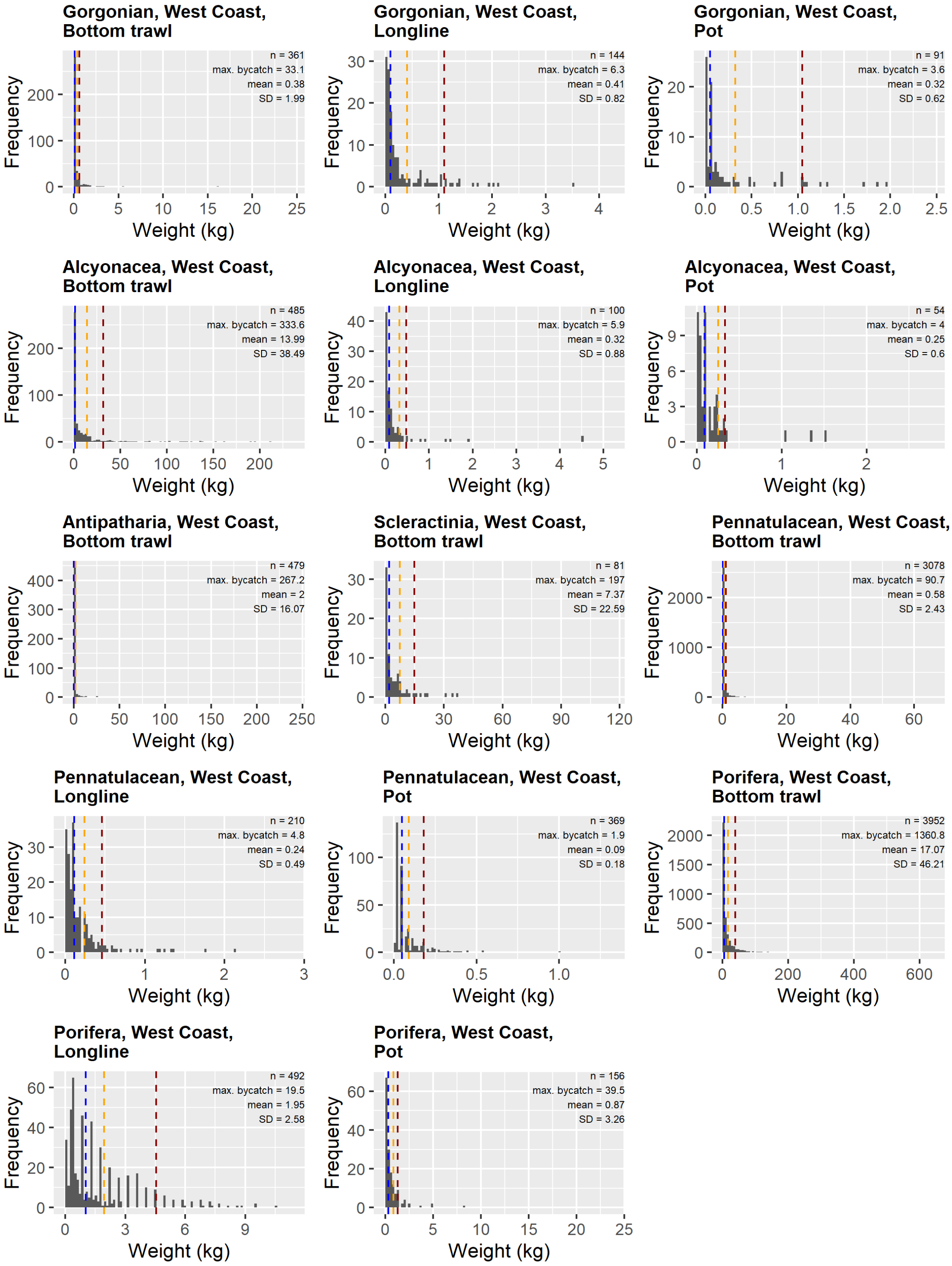

Figure S1 (cont.). Histograms of bycatch data from the U.S. West Coast from 2002-2022. Dashed lines indicate the 90% quantile (red), the mean bycatch (orange) and the median bycatch (blue).

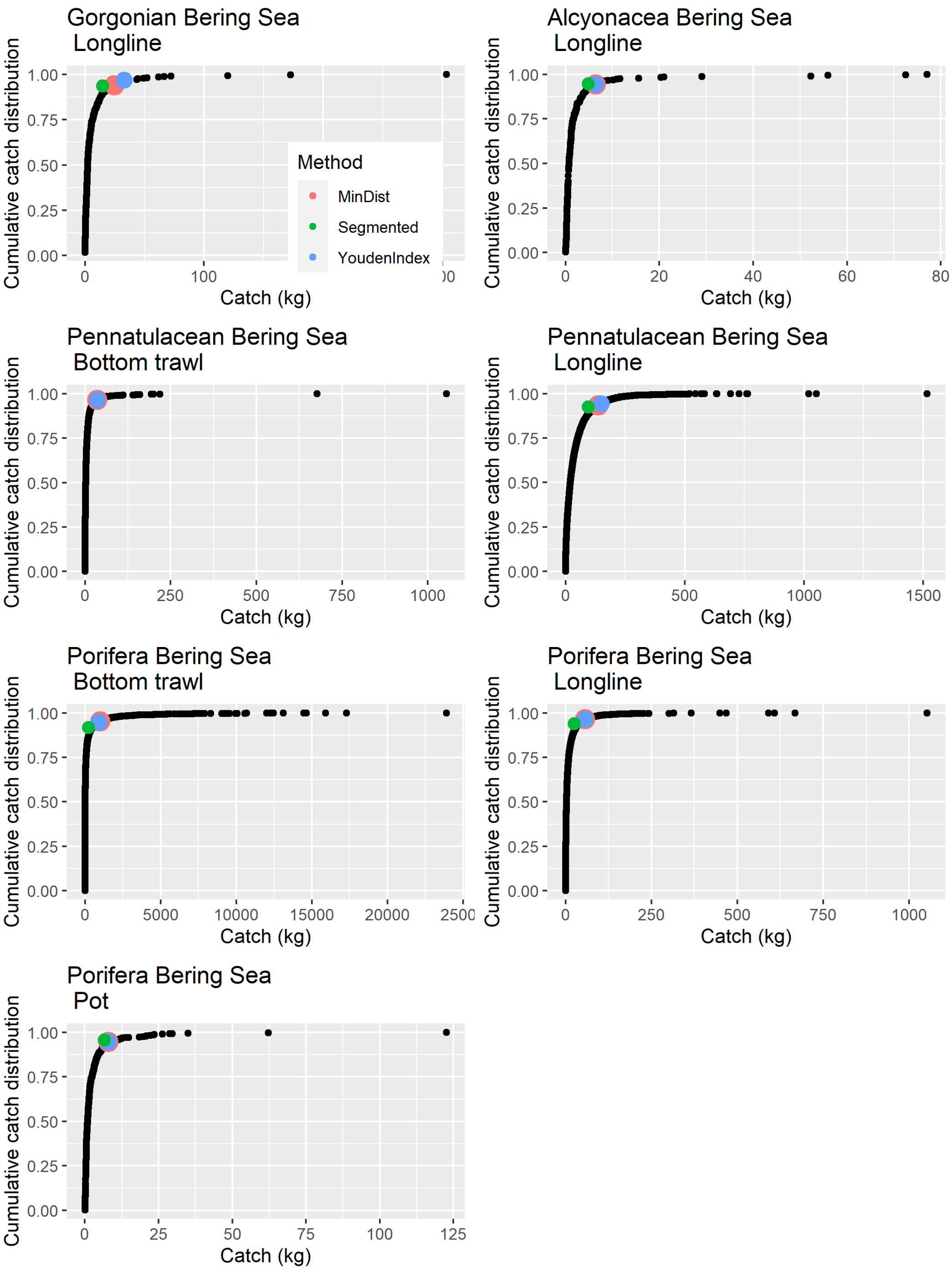

Figure S2. Cumulative frequency distributions of bycatch of VME indicator taxa by gear type in the eastern Bering Sea from 2002-2022. Points indicate the fit threshold values (where n > 300) for the minimum distance (MinDist), segmented regression (Segmented) and Youden Index (YoudenIndex) methods.

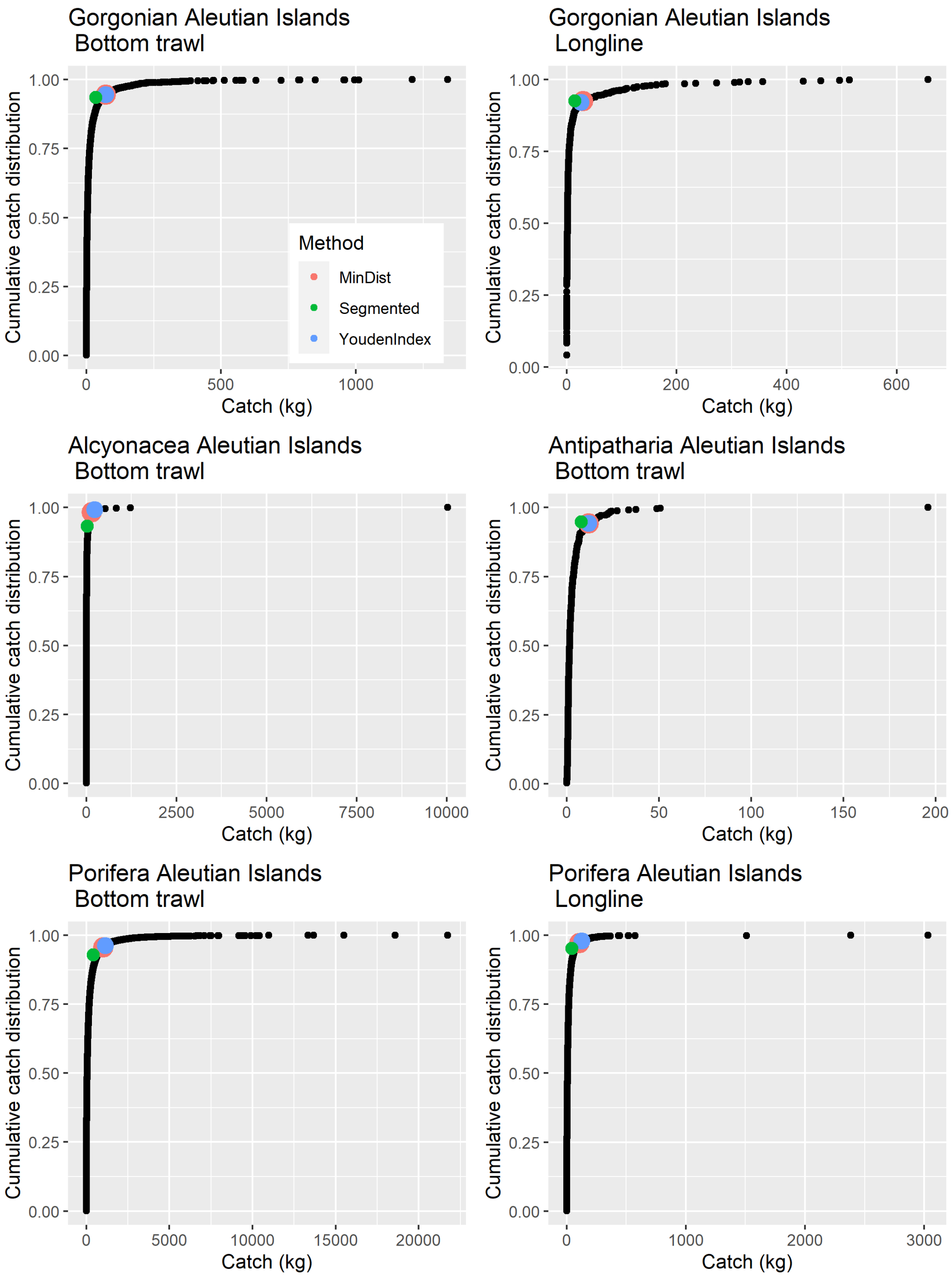

Figure S2 (cont.). Cumulative frequency distributions of bycatch of vulnerable marine ecosystem indicator taxa by gear type in the Aleutian Islands from 2002-2022. Points indicate the fit threshold values (where n > 300) for the minimum distance (MinDist), segmented regression (Segmented) and Youden Index (YoudenIndex) methods.

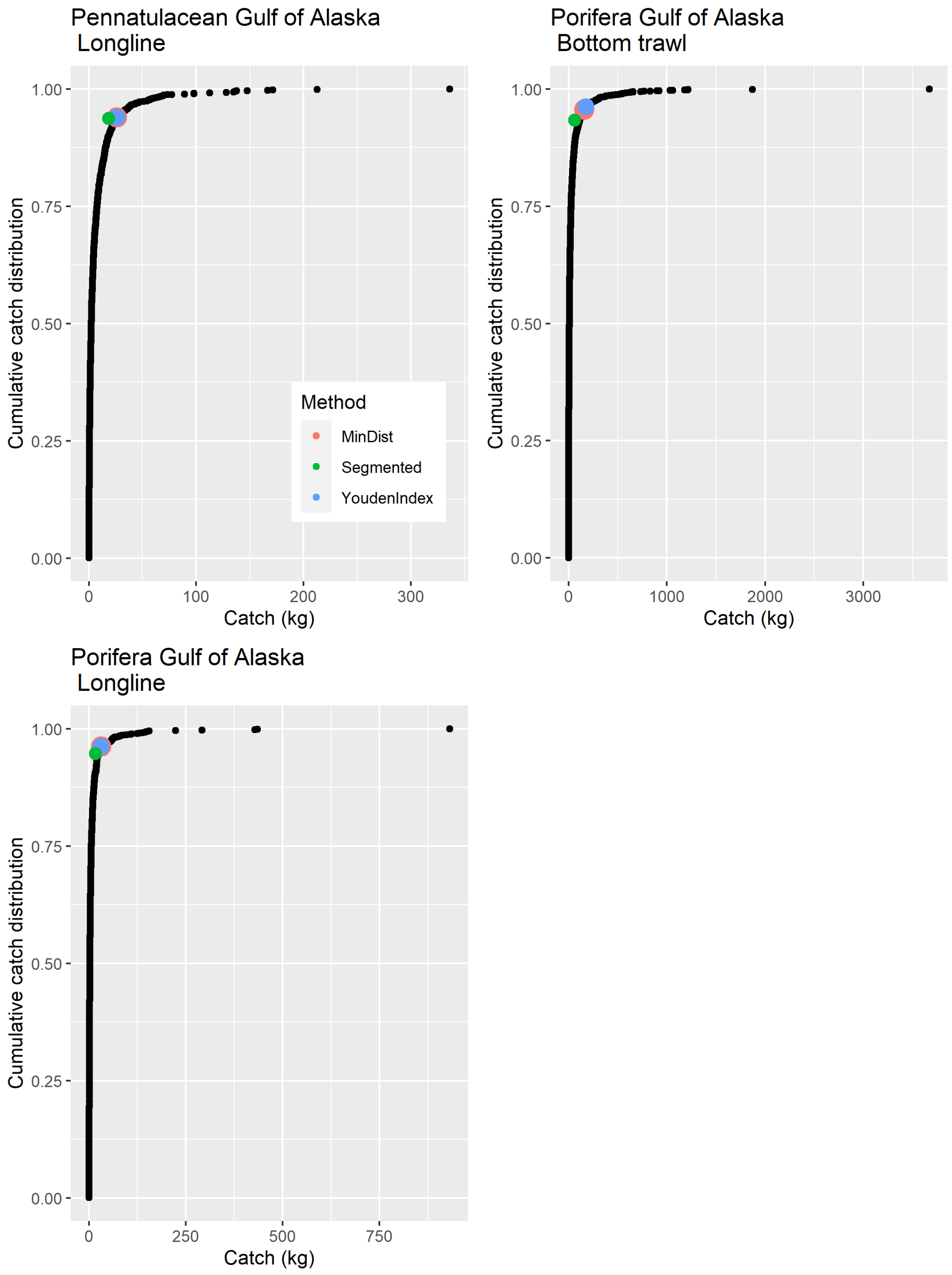

Figure S2 (cont.). Cumulative frequency distributions of bycatch of vulnerable marine ecosystem indicator taxa by gear type in the Gulf of Alaska from 2002-2022. Points indicate the fit threshold values (where n > 300) for the minimum distance (MinDist), segmented regression (Segmented) and Youden Index (YoudenIndex) methods.

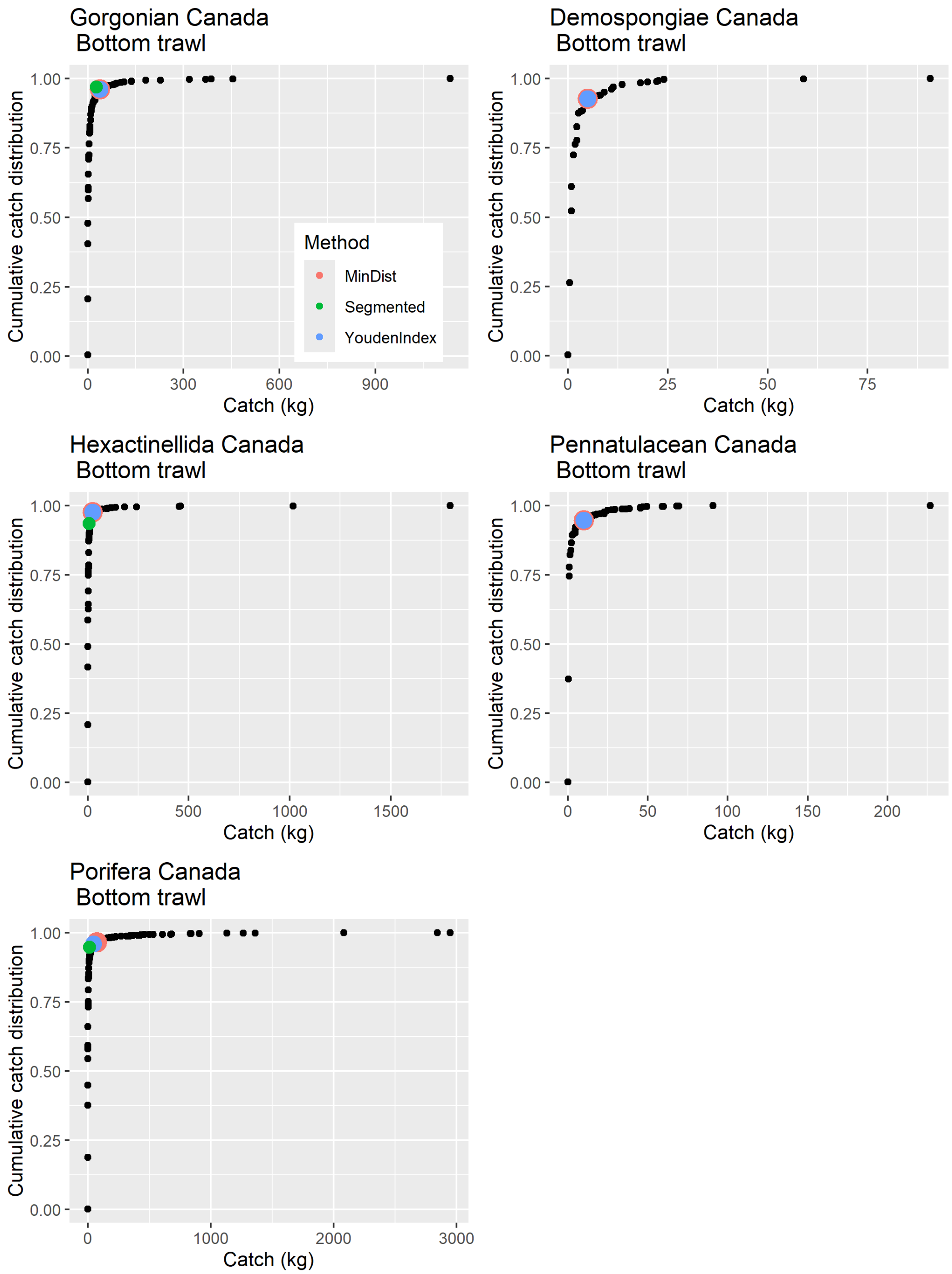

Figure S2 (cont.). Cumulative frequency distributions of bycatch of vulnerable marine ecosystem indicator taxa by gear type in Canada from . Points indicate the fit threshold values (where n > 300) for the minimum distance (MinDist), segmented regression (Segmented) and Youden Index (YoudenIndex) methods.

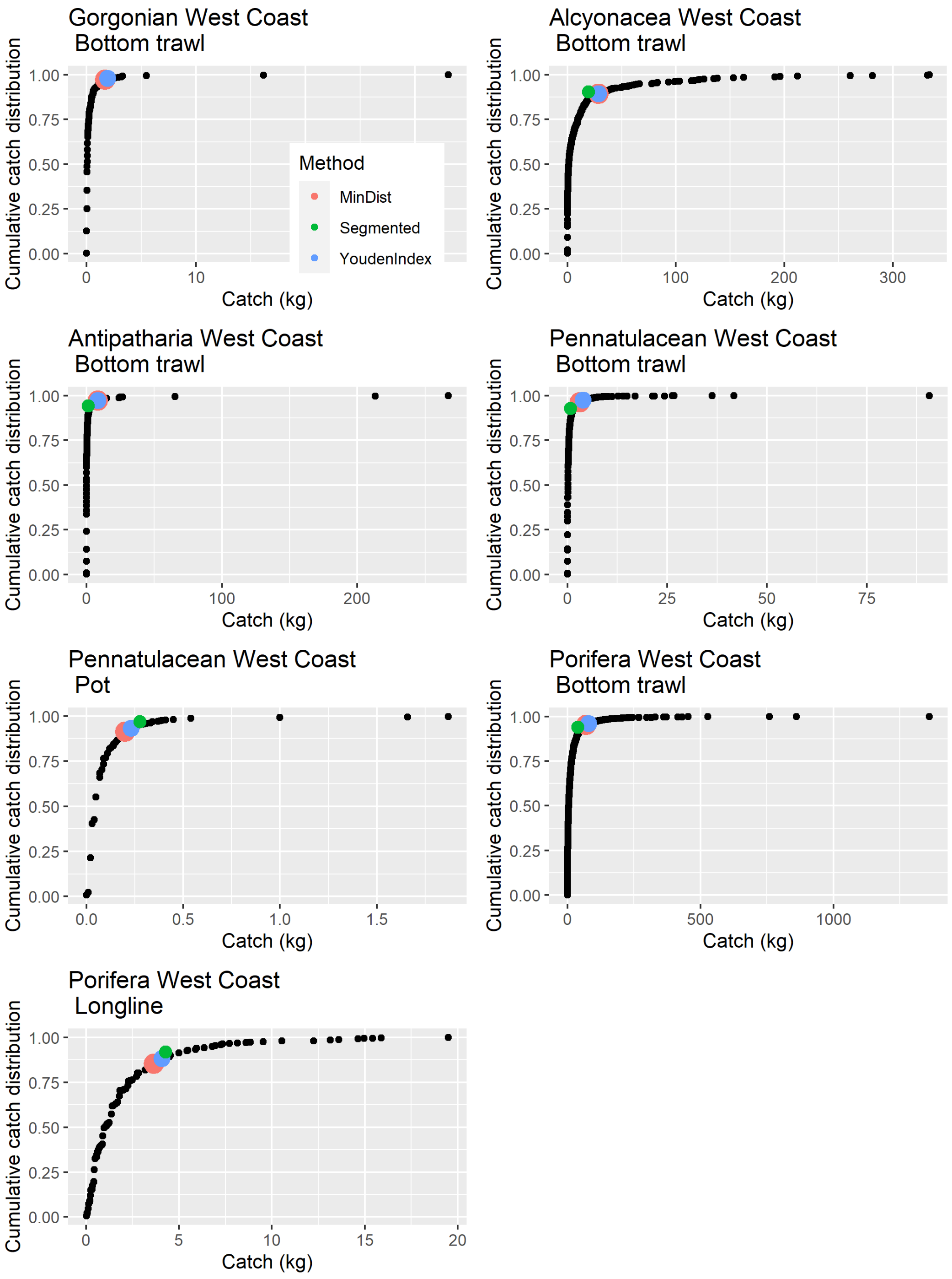

Figure S2 (cont.). Cumulative frequency distributions of bycatch of vulnerable marine ecosystem indicator taxa by gear type on the U.S. West Coast from 2002 - 2022. Points indicate the fit threshold values (where n > 300) for the minimum distance (MinDist), segmented regression (Segmented) and Youden Index (YoudenIndex) methods.

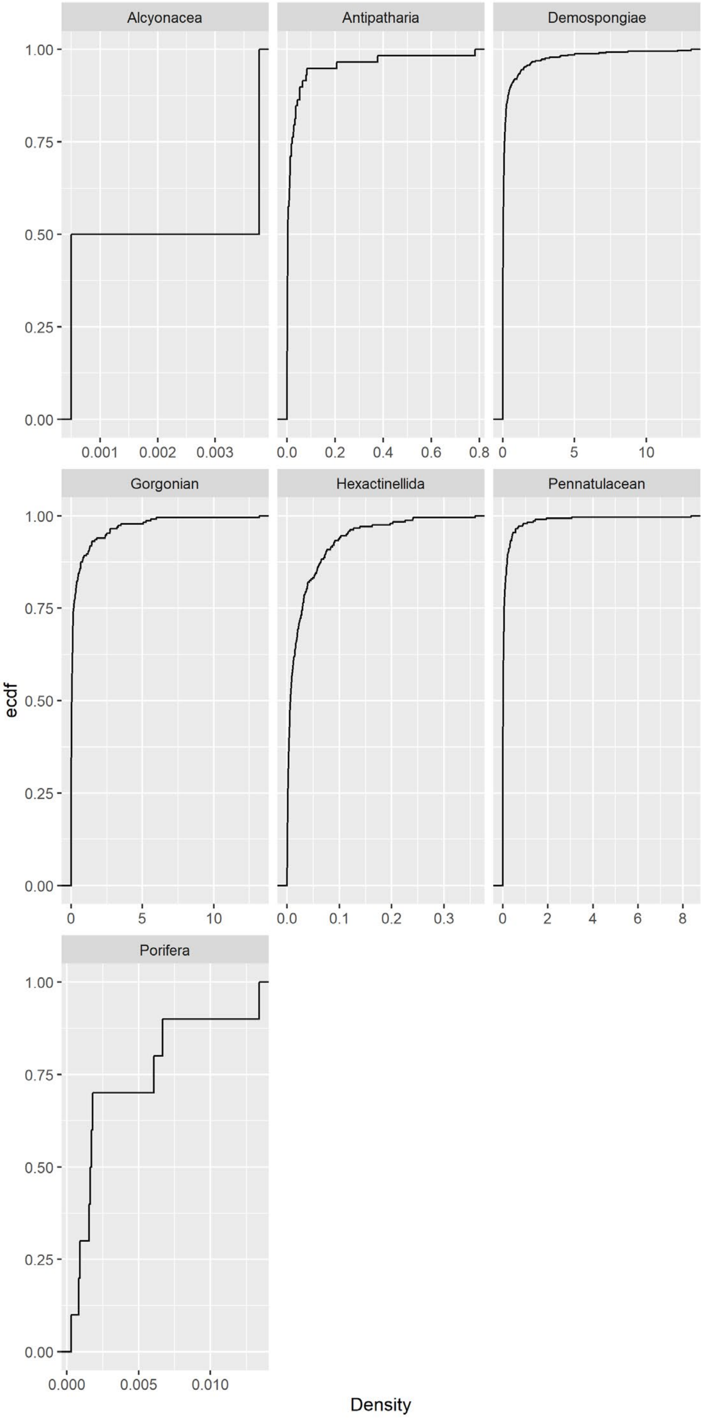

Figure S3. Cumulative frequency distributions of density of VME indicator taxa in camera surveys of Alaska regions from 2012 - 2019 .

*Table S1. Frequency of occurrence calculated as the number of observed occurrences divided by the number of observed hauls and total weight (kg * 10^{-3}) of catch aggregated across all observed hauls of each VME indicator taxa captured by gear type and region.*

Gear type	Region	VME indicator taxa	Weight (kg * 10^{-3})	Frequency of occurrence
Bottom trawl	Bering Sea	Alcyonacea	1.9770	0.001150
		Antipatharia	0.1007	0.000091
		CoralsBryozoans	75.1722	0.006270
		Gorgonian	3.0996	0.000984
		Hydrocoral	0.0962	0.000047
		Pennatulacean	11.7234	0.005535
		Porifera	1583.7927	0.029177
		Scleractinia	0.0037	0.000004
	Aleutian Islands	Alcyonacea	25.2340	0.013399
		Antipatharia	1.7419	0.007453
		CoralsBryozoans	460.1901	0.095516
		Gorgonian	91.0732	0.078132
		Hydrocoral	68.2431	0.011322
		Pennatulacean	1.5069	0.003484
		Porifera	3251.2513	0.243757
		Scleractinia	0.8151	0.001373
	Gulf of Alaska	Alcyonacea	0.1669	0.000617
		Antipatharia	0.0822	0.000458
		CoralsBryozoans	22.9991	0.010188
		Gorgonian	5.9575	0.005731
		Hydrocoral	1.0328	0.001154
		Pennatulacean	0.9107	0.004517
		Porifera	77.7599	0.041331
		Scleractinia	0.0222	0.000080
	Canada	Alcyonacea	3.5789	0.000737
		Antipatharia	0.0135	0.000082
		Calcarea	1.0895	0.000333
		Demospongiae	1.1641	0.001833
		Hexactinellida	7.6375	0.003096
		Gorgonian	9.1735	0.003318
		Hydrocoral	0.0153	0.000088
		Pennatulacean	4.7493	0.006613
		Porifera	51.9082	0.010335
		Scleractinia	0.6733	0.000525
	West Coast	Alcyonacea	6.7832	0.003231
		Antipatharia	0.9594	0.003191

		Gorgonian	0.1385	0.002405
		Hydrocoral	0.0186	0.000053
		Pennatulacean	1.7874	0.020504
		Porifera	67.4655	0.026327
		Scleractinia	0.5967	0.000540
Longline	Bering Sea	Alcyonacea	0.8002	0.002102
		Antipatharia	0.0116	0.000013
		CoralsBryozoans	36.3506	0.021688
		Gorgonian	2.5242	0.002083
		Hydrocoral	0.0249	0.000234
		Pennatulacean	360.5305	0.054751
		Porifera	58.4796	0.033740
		Scleractinia	0.0047	0.000006
	Aleutian Islands	Alcyonacea	0.0235	0.001683
		Antipatharia	1.9492	0.005778
		CoralsBryozoans	55.7987	0.251977
		Gorgonian	11.0263	0.044539
		Hydrocoral	0.6854	0.034723
		Pennatulacean	2.6882	0.016267
		Porifera	85.6134	0.235486
		Scleractinia	0.0001	0.000112
	Gulf of Alaska	Alcyonacea	0.0982	0.001381
		Antipatharia	0.0327	0.000780
		CoralsBryozoans	8.1752	0.024687
		Gorgonian	0.6547	0.004144
		Hydrocoral	0.1555	0.001515
		Pennatulacean	9.8567	0.027272
		Porifera	10.2809	0.025133
		Scleractinia	0.0024	0.000668
	Canada	Alcyonacea	0.0872	0.000206
		Calcarea	0.0024	0.000011
		Demospongiae	0.0068	0.000026
		Hexactinellida	0.0106	0.000018
		Gorgonian	0.1008	0.000299
		Pennatulacean	0.0317	0.000125
		Porifera	0.1077	0.000472
		Scleractinia	0.2088	0.000494
	West Coast	Alcyonacea	0.0321	0.003982
		Antipatharia	0.0008	0.000319
		Gorgonian	0.0588	0.005734
		Hydrocoral	0.0016	0.000199
		Pennatulacean	0.0503	0.008362
		Porifera	0.9585	0.019591
		Scleractinia	0.0022	0.000358
Pot	Bering Sea	Alcyonacea	0.0015	0.000092

	Antipatharia	0.0001	0.000046
	CoralsBryozoans	0.1304	0.005386
	Gorgonian	0.0045	0.000368
	Hydrocoral	0.0002	0.000046
	Pennatulacean	0.0019	0.000598
	Porifera	1.2600	0.021543
Aleutian Islands	Antipatharia	0.0009	0.000268
	CoralsBryozoans	0.1831	0.026831
	Gorgonian	0.0186	0.006171
	Hydrocoral	0.0114	0.006171
	Porifera	1.0314	0.055541
Gulf of Alaska	Alcyonacea	0.0000	0.000100
	Antipatharia	0.0002	0.000100
	CoralsBryozoans	0.0345	0.003808
	Gorgonian	0.0001	0.000301
	Hydrocoral	0.0000	0.000100
	Pennatulacean	0.0188	0.002004
	Porifera	0.1342	0.009820
	Scleractinia	0.0001	0.000301
Canada	Alcyonacea	0.0085	0.000148
	Antipatharia	0.0009	0.000042
	Calcarea	0.0005	0.000021
	Hexactinellida	0.0014	0.000063
	Gorgonian	0.1709	0.002051
	Pennatulacean	0.0093	0.000254
	Porifera	0.0430	0.001015
	Scleractinia	0.0344	0.000677
West Coast	Alcyonacea	0.0137	0.003012
	Antipatharia	0.0084	0.002231
	Gorgonian	0.0292	0.005075
	Hydrocoral	0.0013	0.000279
	Pennatulacean	0.0336	0.020579
	Porifera	0.1355	0.008700
	Scleractinia	0.0025	0.000167

Table S3. Threshold results from using fishery data only (no stereo-camera) to develop the Youden Index, minimum distance and segmented regression points. The bycatch weight threshold values in this table correspond to the points in Figure S2.

Method	Bycatch weight threshold	VME_taxa	Region	Gear
MinDist	72	Gorgonian	Aleutian_Islands	Bottom trawl
YoudenIndex	72	Gorgonian	Aleutian_Islands	Bottom trawl
Segmented	36	Gorgonian	Aleutian_Islands	Bottom trawl
MinDist	30	Gorgonian	Aleutian_Islands	Longline
YoudenIndex	26	Gorgonian	Aleutian_Islands	Longline
Segmented	15	Gorgonian	Aleutian_Islands	Longline
MinDist	38	Gorgonian	BC	Bottom trawl
YoudenIndex	38	Gorgonian	BC	Bottom trawl
Segmented	27	Gorgonian	BC	Bottom trawl
MinDist	2	Gorgonian	West Coast	Bottom trawl
YoudenIndex	2	Gorgonian	West Coast	Bottom trawl
Segmented		Gorgonian	West Coast	Bottom trawl
MinDist	151	Alcyonacea	Aleutian_Islands	Bottom trawl
YoudenIndex	234	Alcyonacea	Aleutian_Islands	Bottom trawl

Method	Bycatch weight threshold	VME_taxa	Region	Gear
Segmented	30	Alcyonacea	Aleutian_Islands	Bottom trawl
MinDist	29	Alcyonacea	West Coast	Bottom trawl
YoudenIndex	29	Alcyonacea	West Coast	Bottom trawl
Segmented	19	Alcyonacea	West Coast	Bottom trawl
MinDist	12	Antipatharia	Aleutian_Islands	Bottom trawl
YoudenIndex	12	Antipatharia	Aleutian_Islands	Bottom trawl
Segmented	8	Antipatharia	Aleutian_Islands	Bottom trawl
MinDist	8	Antipatharia	West Coast	Bottom trawl
YoudenIndex	8	Antipatharia	West Coast	Bottom trawl
Segmented	1	Antipatharia	West Coast	Bottom trawl
MinDist	5	Demospongiae	BC	Bottom trawl
YoudenIndex	5	Demospongiae	BC	Bottom trawl
Segmented		Demospongiae	BC	Bottom trawl
MinDist	23	Hexactinellida	BC	Bottom trawl
YoudenIndex	23	Hexactinellida	BC	Bottom trawl
Segmented	6	Hexactinellida	BC	Bottom trawl

Method	Bycatch weight threshold	VME_taxa	Region	Gear
MinDist	35	Pennatulacean	Bering_Sea	Bottom trawl
YoudenIndex	35	Pennatulacean	Bering_Sea	Bottom trawl
Segmented	15	Pennatulacean	Bering_Sea	Bottom trawl
MinDist	137	Pennatulacean	Bering_Sea	Longline
YoudenIndex	150	Pennatulacean	Bering_Sea	Longline
Segmented	96	Pennatulacean	Bering_Sea	Longline
MinDist	10	Pennatulacean	BC	Bottom trawl
YoudenIndex	10	Pennatulacean	BC	Bottom trawl
Segmented		Pennatulacean	BC	Bottom trawl
MinDist	3	Pennatulacean	West Coast	Bottom trawl
YoudenIndex	4	Pennatulacean	West Coast	Bottom trawl
Segmented	1	Pennatulacean	West Coast	Bottom trawl
MinDist	1,015	Porifera	Aleutian_Islands	Bottom trawl
YoudenIndex	1,136	Porifera	Aleutian_Islands	Bottom trawl
Segmented	423	Porifera	Aleutian_Islands	Bottom trawl
MinDist	105	Porifera	Aleutian_Islands	Longline

Method	Bycatch weight threshold	VME_taxa	Region	Gear
YoudenIndex	126	Porifera	Aleutian_Islands	Longline
Segmented	46	Porifera	Aleutian_Islands	Longline
MinDist	1,002	Porifera	Bering_Sea	Bottom trawl
YoudenIndex	927	Porifera	Bering_Sea	Bottom trawl
Segmented	224	Porifera	Bering_Sea	Bottom trawl
MinDist	57	Porifera	Bering_Sea	Longline
YoudenIndex	57	Porifera	Bering_Sea	Longline
Segmented	25	Porifera	Bering_Sea	Longline
MinDist	8	Porifera	Bering_Sea	Pot
YoudenIndex	8	Porifera	Bering_Sea	Pot
Segmented	7	Porifera	Bering_Sea	Pot
MinDist	156	Porifera	Gulf_Of_Alaska	Bottom trawl
YoudenIndex	176	Porifera	Gulf_Of_Alaska	Bottom trawl
Segmented	64	Porifera	Gulf_Of_Alaska	Bottom trawl
MinDist	32	Porifera	Gulf_Of_Alaska	Longline
YoudenIndex	32	Porifera	Gulf_Of_Alaska	Longline

Method	Bycatch weight threshold	VME_taxa	Region	Gear
Segmented	17	Porifera	Gulf_Of_Alaska	Longline
MinDist	74	Porifera	BC	Bottom trawl
YoudenIndex	46	Porifera	BC	Bottom trawl
Segmented	13	Porifera	BC	Bottom trawl
MinDist	70	Porifera	West Coast	Bottom trawl
YoudenIndex	80	Porifera	West Coast	Bottom trawl
Segmented	39	Porifera	West Coast	Bottom trawl
MinDist	4	Porifera	West Coast	Longline
YoudenIndex	4	Porifera	West Coast	Longline
Segmented	4	Porifera	West Coast	Longline

*Table S2. Predicted thresholds encounter weights (and confidence intervals) for VME indicator taxa in the regions of Alaska by gear type using percentile regression method. Threshold weights use the average regression parameters from relationships in Figure 8 and a density of log(0.5 individuals * m*$^{-2}$*) (x axis) to predict the associated bycatch weight (y axis), which is then exponentiated to calculate a bycatch weight for the threshold.*

Region	Gear	Antipatharia	Gorgonian	Hydrocoral	Pennatulacean	Porifera
Aleutian_Islands	Bottom trawl	64.75 (40.86 - 102.62)	17.83 (13.5 - 23.55)	11.29 (8.38 - 15.21)	44.57 (32.15 - 61.78)	121.58 (92.15 - 160.42)
Aleutian_Islands	Longline	23.62 (14.88 - 37.51)	6.5 (4.91 - 8.61)	4.12 (3.05 - 5.57)	16.26 (11.71 - 22.58)	44.36 (33.54 - 58.66)
Aleutian_Islands	Pot	2.18 (1.37 - 3.47)	0.6 (0.45 - 0.8)	0.38 (0.28 - 0.53)		4.09 (3.06 - 5.47)
Bering_Sea	Bottom trawl		19.15 (13.75 - 26.67)		47.86 (34.07 - 67.24)	130.57 (94.13 - 181.11)
Bering_Sea	Longline		13.94 (9.97 - 19.48)		34.84 (24.72 - 49.1)	95.04 (68.33 - 132.19)
Bering_Sea	Pot		0.36 (0.26 - 0.51)		0.91 (0.64 - 1.29)	2.48 (1.78 - 3.46)
Gulf_Of_Alaska	Bottom trawl	41.82 (25.95 - 67.4)	11.52 (8.66 - 15.31)	7.29 (5.46 - 9.74)	28.79 (20.89 - 39.66)	78.53 (59.06 - 104.41)
Gulf_Of_Alaska	Longline	10.36 (6.42 - 16.71)	2.85 (2.14 - 3.8)	1.81 (1.35 - 2.41)	7.13 (5.16 - 9.85)	19.44 (14.58 - 25.92)
Gulf_Of_Alaska	Pot	0.7 (0.43 - 1.16)	0.19 (0.14 - 0.26)		0.48 (0.34 - 0.68)	1.32 (0.97 - 1.81)