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An Assessment of the Orange-Footed Sea Cucumber (*Cucumaria frondosa*) Resource on the St. Pierre Bank (NAFO Subdivision 3Ps) in 2022

K. Charmley, K.D. Baker, E. Coughlan

Science Branch
Fisheries and Oceans Canada
80 East White Hills Road
St. John’s, NL A1C 5X1

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Foreword

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

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ABSTRACT

The orange-footed sea cucumber (*Cucumaria frondosa*) is a species of holothurian widely distributed in the northern hemisphere, in both the North Atlantic and the Arctic Ocean. This species is mainly found at depths of 30 to 60 m, on hard rock, gravel, or shell substrates. There are two main sea cucumber concentrations on the Canadian portion of the St. Pierre Bank (Northwest Atlantic Fisheries Organization [NAFO] Subdivision 3Ps) - one northwest and one southeast of the French Economic Zone.

In 2003, a new sea cucumber fishery began, with eight harvesters given allocations (454 t) to explore potential commercial concentrations. As part of the emerging fisheries policy, the same eight fishers entered into a five-year Joint Project Agreement (JPA) with Fisheries and Oceans Canada (DFO) to conduct a resource assessment survey from 2004 to 2008. This fishery formally transitioned to a commercial fishery in 2013. Allocation in the northwest area increased to 2,242 t in 2013, where it remains. The southeast area opened to fishing in 2017 with temporary licenses amounting to 3,773 t. This allocation increased to 4,717 t in 2019, where it remains.

The status of NAFO subdivision 3Ps sea cucumber was last updated in 2018. The update concluded that there was no scientific basis for assessing the risk of any increase in harvest level and that sustainable exploitation rates are unknown. In 2022, this resource status was assessed based on commercial catch data, emerging fishery survey (2004–08) and DFO sea cucumber surveys (2016, 2017, and 2022).

In 2022, landings were 2,065 t in the northwest area and 4,020 t in the southeast area. The unstandardized catch per unit effort (CPUE) has increased in both beds since the beginning of the fishery. There is some evidence that sea cucumbers may be decreasing in size in both areas throughout the time series. A spatiotemporal model was used to estimate biomass and abundance indices. In 2022, the biomass index for the northwest area was near the average observed during the emerging fishery (2004–08). In 2022, the biomass index for the southeast area remains below the average biomass index observed from 2004 to 2008. The abundance index in the northwest area has a general increasing trend since the beginning of the survey. The abundance index in the southeast area varied without trend throughout the time series. Exploitation rate indices are anticipated to remain relatively stable in 2023, assuming status-quo total allowable catch. However, sustainable exploitation rates of sea cucumber on the St. Pierre Bank are unknown. Given the uncertainty with the assessment of stock status of this species, there is no scientific basis for assessing the risk of the current or any change in the harvest level.

INTRODUCTION

This document assesses the status of the orange-footed sea cucumber (*Cucumaria frondosa*; henceforth referred to as ‘sea cucumber’) in the Northwest Atlantic Fisheries Organization (NAFO) subdivision 3Ps. The information in this document was presented at a formal scientific assessment in March 2023, and a regional peer-review process was completed. The assessment focused on presenting the current scientific data on the status of the stock to aid in resource management decisions. These data and analyses will also be used in the development of the Integrated Fisheries Management Plan (IFMP).

SPECIES ECOLOGY

The sea cucumber is a species of holothurian widely distributed in the northern hemisphere, in both the North Atlantic Ocean and the Arctic Ocean (Hamel and Mercier 2008). It has a broad depth distribution of 0 to 300 m, is rarely found > 1,400 m, and is at its highest densities from 30 to 60 m (Hamel and Mercier 1996a; Ross et al. 2013; Singh et al. 1998; So et al. 2010). This species is mainly found on hard rock, gravel, or shell substrates but is also occasionally observed on softer sandy substrates (So et al. 2010). Juveniles (length < 30 mm) are typically found on the underside of hard substrates, whereas larger individuals are usually found on top of these substrates. They can grow up to 50 cm in length (Gudimova et al. 2004).

Sea cucumbers are suspension feeders consuming planktonic particles suspended in the water column. They capture these food particles by splaying out their mucus-covered tentacles, then retracting individual tentacles into their mouth, where the food particles are consumed (Singh et al. 1999). Seasonal influxes of food particles in the water column are associated with greater feeding rates and periods of growth, with greatest growth rates in the summer (So et al. 2010).

Sea cucumbers are slow-growing, with growth rates varying by maturity, diet, and location (Gianasi et al. 2017; Hamel and Mercier 1996a). Laboratory studies have shown a slower juvenile growth rate in Newfoundland than in other parts of Eastern Canada, with an estimated 25 years to reach market size (~ 15 cm) under natural conditions (So et al. 2010). On the St. Pierre Bank, male sea cucumbers begin to attain sexual maturity at 5.2 cm contracted length, with 100% reaching sexual maturity at 11.3 cm. Females begin to obtain sexual maturity at 7.0 cm contracted length, with 100% sexually mature at 11.5 cm (Grant et al. 2006). Sea cucumbers are sexually dimorphic with distinct ‘tube-shaped’ or’ heart-shaped’ gonopores under their oral tentacles for females and males, respectively (Hamel and Mercier 1996a; Montgomery et al. 2018). However, this external dimorphism was not observed on the St. Pierre Bank (Grant et al. 2006).

Sea cucumbers are ‘broadcast spawners’, meaning that both sexes chemically communicate to coordinate the release of their gametes into the water column for external fertilization. To aid in successful reproduction, adult sea cucumbers aggregate in ‘beds’, meaning sea cucumber fertilization could be negatively affected by increased sparseness. Sea cucumber fecundity increases with size (Hamel and Mercier 1996b). Spawning occurs annually and is correlated with phytoplankton concentration, light levels, and tide and lunar cycles (Gianasi et al. 2021; Hamel and Mercier 1995; Mercier and Hamel 2010). Spawning time varies slightly by latitude, with Newfoundland exhibiting the longest and earliest spawning season, which occurs annually from February to May (Coady 1973; Mercier and Hamel 2010; So et al. 2010). Large ‘yolky’ fertilized eggs develop in the water column into non-feeding larvae, where they live for four to seven weeks before settling on the seafloor (Hamel and Mercier 1996a; So et al. 2010).

Sea cucumbers are vulnerable to a variety of potential predators, including sea stars, gastropods, fish, birds, and marine mammals (e.g., seals and walruses) (Francour 1997; Gianasi et al. 2021; So et al. 2010). The purple sunstar (*Solaster endeca*) is considered their main predator at all life stages. Injured sea cucumbers are more vulnerable to predators and scavengers (So et al. 2010). Sea cucumbers use behavioural defence mechanisms; such as rippling their body, bloating, increased production of mucus, and fleeing (Gianasi et al. 2015; So et al. 2010).

Sea cucumbers move by crawling or bloating their body for active or passive (carried by the current) rolling (Sun et al. 2018). Juveniles experience a series of migrations on the scale of centimetres to metres. After settlement, they migrate to areas with higher protection, then as they grow (> 2 mm), they migrate to exposed areas with higher food availability (Hamel and Mercier 1996a). Adult sea cucumbers can migrate long distances (kilometres), with the potential to disperse up to 90 km/day when utilizing currents (Hamel et al. 2019). Adult sea cucumbers exhibit a migration downslope in autumn at sexual maturity (Hamel and Mercier 1996a). This migration is likely controlled by external environmental factors (e.g., changes to temperature or light) or intrinsic factors at maturity. Sea cucumbers are not thought to return upslope (Gianasi et al. 2021).

It is currently believed that there is no genetic difference among subpopulations of sea cucumber along the western Atlantic, suggesting one large population (So et al. 2011); however, it would be valuable to confirm this with modern genomic methodologies.

Sea cucumbers have the potential to be affected by climate change. Changing water temperatures would likely influence sea cucumber populations since temperature influences spawning, juvenile growth, oxygen uptake, and predators consumption (Gianasi et al. 2019; Hamel and Mercier 1996a; Hopcroft et al. 1985; So et al. 2010). They also have the potential to be vulnerable to ocean acidification due to their non-feeding pelagic larval stage (Verkaik et al. 2016). They ingest small microplastic fragments during suspension feeding, thus, are vulnerable to microplastic pollution (Graham and Thompson 2009).

THE FISHERY

Sea cucumbers were first commercially harvested in the eastern North Atlantic in Maine in the 1970s (Hamel and Mercier 2009). However, sea cucumber is a traditional food of Inuit and has been fished and consumed in these communities for generations (Wein et al. 1996). In Newfoundland and Labrador, sea cucumber was an abundant bycatch species in other fisheries (e.g., scallops). In 1997, exploratory sea trials began by the Canada Newfoundland Cooperation Agreement for Fishing Industry Development (CAFID 1997). In 2001, the Newfoundland and Labrador (NL) Department of Fisheries and Aquaculture (DFA) surveyed potential fishery grounds and explored potential gear types (DFA 2002). They determined that commercial levels of sea cucumber biomass existed on the St. Pierre Bank. Dive harvests were deemed uneconomical in this location, and a 6-foot modified sea urchin dredge was adopted as the standardized gear. Historical DFO and DFA surveys were used to delineate a grid of strata on the St. Pierre Bank divided into two beds, one northwest and one southeast of the French Economic Exclusion Zone (The French Corridor). The fishing season runs from June 1 to December 31 of a given year to avoid the sea cucumber spawning season in the spring.

In 2003, eight harvesters were given allocations (454 t) in the northwest bed to further explore potential commercial concentrations. Commercial concentrations were found, and quotas were caught, with most landings coming from strata 2 and 7. In 2004, a 5-year joint (DFO, DFA, Fogo Island Co-op Society Ltd., and the Fish, Food and Allied Workers Union) agreement under the DFO New Emerging Fisheries Policy was established with the same eight harvesters to conduct resource assessment surveys. Harvesters had to actively participate in the fishery for five years, submit detailed logbooks, and complete surveys. After completing the assigned survey stations, participants could take their allotted total allowable catch (TAC) while adhering to all license conditions. Participants were not permitted to take more than 25% of their landings from strata 2 and 7 (the most heavily fished strata in 2003). In 2006, the policy was revised so that participants could not take more than 30% of their landings from one stratum. This regulation remained in place until the end of the emerging fishery in 2008. Total allowable catch increased to 612 t in 2005 in an attempt to compensate fishers for the portion of their gross landings that were water, debris, or damaged/ undersized sea cucumber. Upon the completion of the emerging fishery, allocation in the northwest bed increased to 907 t, and the southeast bed was closed until more information was available regarding the potential effects of exploitation.

In 2013, the fishery formally transitioned to a commercial fishery. At this time, ten new licenses were issued, which increased the TAC in the northwest bed to 2,242 t, where it remains. In 2017, the southeast bed was open to fishing with temporary permits with a total allocation of 3,773 t, set to expire in 2022. These permits were increased to 4,717 t in 2019, where the southeast TAC remains. Currently, 6,959 t of sea cucumber are permitted to be harvested annually from the St. Pierre Bank.

METHODS

LOGBOOK DATA

Commercial catch and fishing effort (number of tows) data were collected through commercial purchase slips and vessel logbooks. During the emerging fishery (2003–08), logbooks were forwarded to DFO Science from DFO Fisheries Management, where they were processed. Since 2010, these data have been compiled by the Statistics Division of DFO Policy and Economics Branch. The most recent year of logbook data is incomplete due to the time lag associated with compiling the data from the fishery; thus, 2022's estimates include data available up to February 2023 and is considered preliminary.

Landings (t) and catch per unit effort (CPUE; kg / tow) were assessed by year and strata. Emerging fishery CPUE were standardized to 0.5 nm tows; however, logbooks since 2009 could not be standardized because tow-by-tow information is not documented. The commercial fishery documents information by trip; therefore, CPUE since 2010 was calculated by dividing the total landings by the number of tows. Tow positions from the logbooks were mapped to assess the distribution of effort annually.

EMERGING FISHERY SURVEY DATA

At the commencement of the emerging fishery in 2003, historical data from previous DFO sea cucumber surveys (i.e., scallop and multispecies surveys) and surveys initiated by DFA were used to create a grid survey design for the St. Pierre Bank. The survey area consisted of 52 10' x 10' (latitude x longitude) strata further subdivided into 1' x 1' survey units (Figure 1). The 100-m contours were used to inform the strata. In 2003, this block system was fished but not properly surveyed; therefore, no biomass estimate was calculated for this year.

In 2004, the number of survey strata was reduced to 32 based on bottom classifications of the area and sea cucumber's depth and distribution preferences. Survey stations were randomly assigned within these 32 strata. The standard survey tow used a six-foot modified sea urchin drag towed for 0.5 nm at 2.5 knots. It was a condition of the emerging fishery license to have an observer onboard for the survey duration to conduct sampling and record tow information. From 2004 to 2006, eight vessels participated in the surveys, and from 2007 to 2008, one vessel completed the survey. In 2005, gear configurations led to an unreliable biomass estimate, so this estimate was removed from analyses. In 2006, the number of survey strata was reduced to 23 by eliminating strata where no sea cucumber had been caught in previous years (2004–05). These 23 strata remained for the emerging fishery and throughout the commercial fishery (Figure 2).

Total set weights and numbers of sea cucumber were calculated by collecting individual sea cucumber weights and numbers from a single tote (the plastic container that sea cucumbers are stowed during fishing activities) and multiplying those weights and numbers by the total number of totes from the catch. In 2008, this protocol was not followed; instead, the weight of 50 or 100 sea cucumbers and the total number of totes were recorded. Therefore, to calculate total set weights and numbers for 2008, the mean weights and numbers per tote by strata and vessel from the 2007 survey were used.

DFO SEA CUCUMBER SURVEY DATA

DFO began a dedicated sea cucumber survey in 2016 using the same tow protocols used in the emerging fishery surveys. A standardized six-foot modified sea urchin dredge was towed for 0.5 nm at 2.5 knots with a warp-to-depth (m) ratio of 3:1, and sample sites were selected using a random-stratified approach in the strata grid. Total sea cucumbers weights and numbers in each set were recorded and subsequently standardized to 0.5 nm. If there were more than five baskets of sea cucumber in a catch, counts of sea cucumbers were subsampled and estimated using the total weight. Additionally, weights (kg) and numbers of all other species caught were recorded. Commercial finfish, sea stars, and scallops were also measured (mm). The percentage of 'other species' in the total catch biomass was calculated as a proxy for potential commercial bycatch.

Biometric data were collected from each set for a subset of the sea cucumber. For up to 50 sea cucumbers in each set, length (tip to tip; mm), girth (mm), and whole weight (g; to the neared 0.1) were recorded. For up to an additional 100 sea cucumbers, individual weights were recorded. These data were collected as soon as possible upon completion of the set to reduce water loss; however, some variability is expected due to the high plasticity of sea cucumbers.

The 2016 survey completed all strata in the southeast bed and 23% of the northwest bed (strata 13, 16, and 17). The northwest bed was finished in 2017 (strata 2, 3, 4, 5, 7, 8, 9, 10, 12, 13, and 14). In 2022, the southeast bed strata were sampled in full, albeit with reduced sets, due to unforeseen survey difficulties.

BIOMASS INDEX

In previous assessments, STRAP (Stratified Random Assessment Process) (Smith and Somerton 1981) was used to determine biomass and abundance indices for each bed from emerging fishery surveys and DFO sea cucumber surveys. STRAP is a spatial expansion method that uses survey catch rate data to estimate biomass and abundance indices. It uses the average weights and numbers sampled in each stratum multiplied by the area of that stratum as an estimate for the total weight or number in that stratum. STRAP requires consistent sampling of at least two sets per stratum in each year of the survey to maintain a consistent time series and trend analyses. As noted above, the spatial coverage of sea cucumber surveys has been inconsistent in recent years, with no DFO sea cucumber survey covering the entire survey area in any given year, making an area-wide biomass index throughout the time series using previous methods (i.e., STRAP) impossible.

As a result, a spatiotemporal model was created to develop biomass and abundance indices in years with available data using the R package *sdmTMB* (Anderson et al. 2022). This modelling technique has been peer-reviewed and approved for species assessment by the International Council for the Exploration of the Sea (ICES) (ICES 2022) and NAFO (NAFO 2022). In addition, NAFO's Standing Committee on Research Coordination (STACREC) recommended the model technique be explored for species within the NAFO Regulatory Area (NAFO 2022).

Using all available sea cucumber survey data, a stochastic partial differential equation (SPDE) mesh with a minimum distance edge of 5 km was constructed using integrated nested Laplace approximation (INLA). The mesh consisted of 186 vertices.

A spatiotemporal model was used to derive annual biomass (kg) and abundance (numbers) estimates (Eq. 1). Models were built and fitted using the package *sdmTMB,* which integrates a Template Model Builder (T.M.B.) model and the SPDE matrices (Anderson et al. 2022; Rue et al. 2009). Anisotropy, a depth covariate, and various families (e.g., Tweedie, delta-gamma, and delta log-normal) were considered within the model formulation. The best model was chosen based on Akaike information criterion (AIC), ability to converge, and "sanity" function checks that assure the maximum gradient log-likelihood with respect to all fixed effects was < 0.001, that the Hessian was positive definite, and that no random field marginal standard deviations were less than 0.01.

Eq. 1.

$$\text{Density} = 0 + \text{as.factor(Year)}$$

Where, *Density* was the standardized biomass (kg / km^2) or number of sea cucumber in a set during the dredge survey and *Year* is the year of the survey, represented as a factor. Spatial and spatiotemporal autocorrelation were included as Gaussian random fields to account for how unmeasured or latent habitat suitability metrics change spatially and temporally. The spatiotemporal random fields were assumed to be independent across years. The spatial random effect and the spatially varying temporal dynamics were estimated by Delaunay triangulation over the mesh, assuming Gaussian Markov random fields (GMRF) (Rue and Held 2005). The best model was fit using a delta-log normal distribution. The delta models combined a binomial GLMM with a logit link for the presence vs. absence component and a log-normal GLMM with a log link for the positive data. Anisotropy (shared and split between model components) and the inclusion of depth did not improve the model and therefore were not included.

The model was used to predict sea cucumber biomass and abundance annually across the entire survey area on a 4 km^2 gridded surface. Annual biomass and abundance were calculated within the whole area and within each bed using the predicted density surface.

Model-derived biomass and abundance estimates were compared with the estimates derived from STRAP (Smith and Somerton 1981). Since STRAP cannot manage missing data, biomass estimates could only be compared within a subset of consistently surveyed strata in each bed (Northwest bed: strata 2, 4, 5, 7, 8, 9, 10, 12, 13, 14; Southeast bed: strata 33, 34, 35, 37, 38, 39, 41, 42, 43) in the years that surveys took place.

Exploitation rates were calculated for each bed using the model-derived biomass estimates and the landings from the fishery for each bed. Exploitation rates during the emerging fishery (2004–08) were calculated using the biomass estimate and landings from the same year since surveys took place before participants fished their TAC. For exploitation rate indices calculated using biomass estimates from the DFO sea cucumber surveys (i.e., 2016, 2017, 2022), landings one year lagged from the biomass indices were used. Lagged landings were used because most commercial landings occurred earlier in the season than the DFO sea cucumber surveys (i.e., September; Figure 3).

RESULTS AND DISCUSSION

FISHERY DATA

Logbooks are used to collect information on the fishery, such as the location of landings and CPUE. The percentage of landings that are represented in returned logbooks have been variable throughout the time series ranging from 62% (northwest bed in 2014) to 100% (Figure 4). High logbook return rates are essential for monitoring fishery sustainability. The 2022 log data used in this assessment are preliminary, reflecting only logbooks received and processed by February 2023, or 61% of the landings in the northwest bed and 70% in the southeast bed.

Landings have occurred since 2003 in the northwest bed and since 2017 in the southeast bed. In the northwest bed, the TAC gradually increased from 454 t in 2003 to 2,242 t in 2013, where it remains (Figure 5). In the northwest, from 2003 to 2014, landings were at an average of 671 t, with the exception of 2007, when landings were at a time-series low (190 t) due to poor market conditions. Landings increased in 2015, two years after the increase in TAC. However, from 2015 to 2021, northwest bed landings remained relatively constant at an average of 2,239 t. In 2022, landings in the northwest bed were 2,065 t. In the southeast bed, the TAC began at 3,773 t in 2017 and increased to 4,717 t in 2019, where it remains. Landings were low in the first year of the fishery, with 1,429 t in 2017 (< 40% of TAC). Since then, southeast landings have been variable, with an average of 4,020 t (Figure 5). The 2022 landings in the southeast bed were 4,019 t. Landings in the southeast bed have not reached their TAC in any year since the fishery began.

The distribution of landings is more widespread in the southeast bed than in the northwest bed (Figure 6). Most landings in the northwest bed occurred in stratum 7 throughout the entire time series, except for in 2005, when 71% occurred in stratum 8. Landings during the emerging fishery had a wider spread over the southeast bed because of license requirements to do so, but still predominantly remained in the three most northwest strata in this bed. In 2022, 100% of the northwest bed landings that were documented in the logbooks occurred in stratum 7 (*prelim.*), which also occurred from 2016 to 2019. In the southeast bed, most landings occurred in stratum 37 until 2022, when more landings occurred in stratum 42.

Fishery CPUE has steadily increased in the northwest and southeast beds (Figure 5). In the northwest bed, CPUE reached a time-series high at 1,100 kg/tow in 2020 and has since declined and remained at 939 kg/tow. The CPUE in the southeast bed reached a time-series high in 2022 with a value of 1,169 kg/tow (*prelim.*). Due to the overall increasing CPUE trends in both beds, landings failing to reach their TAC are likely due to external factors (e.g., socio-economic reasons and market issues). However, unstandardized commercial CPUE is not a reliable metric of stock status as several other factors confound interpretations of fishery performance. CPUE is not a proportional index of abundance and can remain high when population abundances decline (i.e., CPUE trends exhibit hyperstability; Bannerot and Austin 1983; Harley et al. 2001). CPUE hyperstability is likely to occur for this stock because fishing efforts are targeted on known successful fishing grounds (i.e., not randomly distributed), and sea cucumbers on the St. Pierre Bank exhibit a highly patchy spatial distribution (So et al. 2010; MI 2006). Other species of sea cucumber in the United States provide examples of fishery CPUE remaining stable during population declines (Bradbury 1994; Schroeter et al. 2001)

Fishery CPUE has been spatially variable without a clear trend (Figure 7). Both beds show within-year depletion (decreasing CPUE) in some years (Figure 8). The southwest bed exhibited signs of depletion throughout 2019 and the northwest bed in 2019 and 2021; however, these trends have also been variable. Both beds present mid-year (between July and September) increases in CPUE in some years (e.g., 2020 and 2022). This CPUE pulse could indicate sea cucumbers migrating from shallow to deeper waters, as this movement has been documented in early autumn (Hamel and Mercier 1996a; Jordan 1974).

SURVEY DATA

Surveys in recent years have reduced in both number of sets and depth coverage (Figure 9, Figure 10). During the emerging fishery survey, there was an average of 128 sets (Standard Deviation [*SD*] = 5.6) in the northwest bed and 90 sets in the southeast bed. DFO sea cucumber surveys have visited each bed in two years, with an average of 32 sets in the northwest bed and 43 in the southeast bed. Although a reduction in survey coverage was expected with the conclusion of fisher surveys that are required for emerging fishery licenses, adequate and consistent survey coverage is important to describe patchy heterogeneous communities.

There has been minimal coverage in the deepest range of sets (> 65 m) in the northwest DFO sea cucumber surveys and the southeast 2022 DFO sea cucumber survey. Sites deeper than 65 m are also rare in the emerging fishery surveys (~1%), and survey sites are allocated using stratified random sampling. Nevertheless, sea cucumbers have a positive size relationship with depth, so a continued systematic loss of a depth class could become an issue for interpreting patterns and trends in the data.

Biometric Analyses

Individual sea cucumber length-weight and girth-weight relationships were investigated for the northwest and southeast beds. With the addition of the 2022 data, the northwest bed is still comprised of sea cucumbers that are larger and heavier than those in the southeast bed (Figure 11). This difference has been shown in previous 3Ps sea cucumber assessments (DFO 2009, Pantin et al. 2018) and by Grant et al. 2006. The mechanism behind this size difference is unknown; it could be due to substrate types (So et al. 2010) or food input (Hamel and Mercier 1996a) differences. The 2022 survey of the southeast bed trendline had a smaller magnitude, indicating that sea cucumbers may be smaller than the 2016 survey in the same area.

Individual sea cucumber size was further explored by dividing the total sea cucumber weight by the total number of sea cucumbers from each survey tow. The average individual sea cucumber weight in the northwest and southeast areas has declined since the emerging fishery (Figure 12). During the emerging fishery, the mean individual sea cucumber weight was 0.61 kg on the northwest bed and 0.42 kg on the southeast bed. During DFO sea cucumber surveys, the mean individual sea cucumber weight was 0.41 kg on the northwest bed and 0.28 kg on the southeast bed.

The reason for the observed decrease in size is unknown. It is possible that fishing has removed commercial-sized sea cucumbers from the area leading to a smaller average individual sea cucumber size. Indicators of reduced body size is believed to be a useful metric in assessing the status of sea cucumber fisheries (Anderson et al. 2010). This fishery-induced sized reduction would be evidence of over-exploitation and a source of concern since larger sea cucumbers have higher fecundity (Hamel and Mercier 1996b). Alternatively, or concurrently, it is also possible that since the DFO sea cucumber surveys occurred in September, sea cucumbers are naturally lower in weight at this time of year. Seasonal weight fluctuations have been observed for most sea cucumber size classes. They have been documented increasing in weight following the spring phytoplankton bloom and decreasing in weight during periods of low food input (So et al. 2010). Since emerging fishery surveys predominantly occurred in June and July and DFO conducted surveys in September, no years extended over multiple seasons, so we cannot distinguish these possible mechanisms. The decrease in average weight from the emerging fishery does not appear to be related to the reduced depth coverage of DFO sea cucumber surveys, as size decreases are observed at individual depths (Figure 13). The ratio of incoming recruits were not differentiated in this assessment.

‘Other’ Species

In the 2022 DFO sea cucumber survey, sea cucumbers comprised 62% of the total catch weight and 88% of the total biomass weight. Rocks made up 24% of the total catch weight. Thus, ‘other’ species (12% of the biomass weight) was lower than in the 2016 and 2017 surveys (Figure 14). However, it was not as low as in the emerging fishery when ‘other species’ (then termed bycatch) was reported as less than 2% of the total catch (DFO 2009). Sea scallops (*Placopecten magellanicus*) were the prominent non-sea cucumber species caught in 2022, comprising ~5% of the total biomass weight in the survey. This was followed by sand dollars (*Echinarachnius parma*) at 3% of the organism weight and *Solaster* sea stars (*S. endeca*), gastropods, and green sea urchins (*Strongylocentrous droebachiensis*), each at 1%. These results contrast with the 2016 and 2017 DFO sea cucumber surveys, where sea urchins comprised > 12% of the catch. The reason for these interannual changes in species caught is unknown but suggests possible changes in this ecosystem’s structure.

There was also an increase in sea cucumbers’ main predator, *S. endeca,* in the catch (1% of the biomass in 2022; Figure 15). They were found at highest densities in strata 37 in 2016 and 2022, where most of the sea cucumber landings in the southeast bed occurred prior to 2022. This coincides with previous studies on the St. Pierre Bank, where *S. endeca* occurred most often in areas with high sea cucumber densities (So et al. 2010). The 2016 survey occurred before commercial fishing began in the southeast bed, so the increase in *S. endeca* since then could be caused by the attraction of *S. endeca* to highly fished areas due to more damaged sea cucumbers and thus more food availability (So et al. 2010). It has been estimated that up to 2% of adult sea cucumbers on the St. Pierre Bank are consumed by *S. endeca* annually (So et al. 2010).

Biomass and Abundance Indices

The average biomass index for the emerging fishery surveys (pre-commercial) was 86 kt in the northwest bed and 224 kt in the southeast bed. The biomass estimate in the northwest bed has remained around this pre-commercial fishery value, with 103 kt in 2016, 61 kt in 2017, and 94 kt in 2022 (Figure 16). The southeast bed biomass index has been consistently below the pre-commercial fishery index, with 199 kt in 2016, 120 kt in 2017, and 162 kt in 2022.

The average abundance index for the emerging fishery surveys was 144 million in the northwest bed and 611 million in the southeast bed. In the northwest bed, abundance indices have been consistently higher than the average pre-commercial index (Figure 17). The highest abundance index in the northwest bed for the time series was in 2022, with an index of 287 million. In the southeast bed, the abundance indices varied without trend throughout the time series.

There is particularly high uncertainty associated with both biomass and abundance indices in recent years due to the reduced survey coverage. More frequent surveys with increased survey coverage are essential for future monitoring of this stock.

Reduced coverage biomass and abundance indices were comparable to those calculated using STRAP (Figure 18, 19). The indices differed slightly between the two methods but represented similar trends. Model-derived biomass and abundance indices in the northwest bed are mostly lower than STRAP-derived indices, and mostly higher for the southeast bed. Confidence interval ranges are frequently smaller for sdmTMB estimates. The updated indices averaged ± 10.5% of previous STRAP indices.

Spatial patterns of biomass density remained relatively unchanged throughout the time series (Figure 20). There are likely optimal environmental conditions for sea cucumbers in these high-density locations. For example, substrate type can affect sea cucumber size and density. Sea cucumber densities on the St. Pierre Bank have also been found to have higher weight with increased substrate hardness (So et al. 2010). They also have the highest densities on gravel/cobble substrates compared to sand, shell and rocky substrates (MI 2006). Other variables like topography, water current, and predator field can also impact densities (MI 2006).

There are several sources of uncertainties for the biomass and abundance indices. Though sea cucumber drags are efficient, the exact efficiency is unknown but is less than one (MI 2006). Sea cucumbers are comprised of between 6.5 and 82% water (MI 2005), but indices are calculated from fresh wet weight, with no adjustment for water loss. Indices are presented for the individual beds to match the fishery management; however, connectivity between the two beds is possible. For these reasons, biomass and abundance indices are not considered absolute estimates; instead, are intended for the observation of trends over time.

Exploitation Rate Index

Exploitation rate indices were calculated using biomass indices divided by gross annual landings. Gross landings are measured by dockside monitoring companies as they are removed from fishing vessels. Sea cucumbers remain in a vessel's hold during the fishing trip and the transit back to the wharf, which can last 2 to 3 days. Biomass estimates are predicted from DFO sea cucumber surveys, during which weights are recorded as soon the sea cucumber are removed from the water to represent the 'wet weight'. ERI is a minimum estimate due to water loss issues inherent with this species and the mismatch in methodology (i.e., time after removal) between the commercial landings and survey weight measurements. However, exploitation rates are not absolute and are only meant to observe the trends over time. The exploitation rate in the northwest bed was at a time-series high of 3.7% in 2018 (Figure 21). It is estimated to reduce to 2.4% in 2023 (with status-quo TAC). In the southeast bed, the exploitation rate is expected to reach a time-series high in 2023 of 2.9% (assuming status-quo TAC). Sustainable exploitation rates for sea cucumber on the St. Pierre Bank are unknown.

Caution should be heeded from the fate of other sea cucumber fisheries worldwide. A review in 2013 found that 58% of global sea cucumber fisheries were over-exploited or depleted (Purcell et al. 2013). The giant red sea cucumber (*Parastichopus californicus*) dive fishery in British Columbia can sustain exploitation rates of 2–4% but show density reductions at 8% and 16% (Hand et al. 2008). It was estimated that 2–4% exploitation rates could deplete some sea cucumber stocks (*Isostichopus badionotus* and *Holothuria mexicana*; Purcell et al. 2018), and catches of < 5% of the virgin biomass lead to the fishery closure of *Holothuria nobilis* due to the depleted populations (Uthicke et al. 2004).

C. frondosa is one of the slowest growing sea cucumber species, taking up to 25 years to enter the fishery. They require high population densities for chemical communication between organisms and fertilization success. The required minimum density for fertilization to occur is unknown. Therefore, conservative exploitation rates are likely important to ensure the longevity of this fishery.

CONCLUSION

There remain biological uncertainties for sea cucumbers on the St. Pierre Bank. Therefore, caution should be taken when interpreting stock status indicators for this sea cucumber fishery. Sea cucumbers exhibit a great degree of physical plasticity and can vary in weight by season or location, so collecting meaningful data on their biological parameters is difficult. Therefore, there are uncertainties regarding sea cucumber's size-age relationship and recruitment. Natural mortality rates of sea cucumbers are unknown, as is the survivability of discarded sea cucumbers in this fishery and non-sea cucumber-directed fisheries. There are also uncertainties regarding the connectivity between the northwest and the southeast beds on the St. Pierre Bank.

Interpreting the trends in stock status indicators throughout the time series is limited due to the physical plasticity of this species and the large gaps in years of data. Since the completion of the emerging fishery in 2008, there have been only three sea cucumber surveys on the St. Pierre Bank, none of which covered both the southeast and the northwest beds. Increased survey frequency and coverage is necessary to monitor trends in this stock.

There are currently no established reference points to determine stock status in relation to a Precautionary Approach Framework. Fishery data (landings and commercial CPUE) and survey data (CPUE, biomass and abundance indices, exploitation rate index, and biometric measures) are used as indicators of stock status; however, sustainable levels are unknown. Current survey indices can be compared to 'pre-commercial fishery' levels, represented by the mean estimates from the emerging fishery (2004–08). Indices do not represent absolute values and should only be used to observe trends over time.

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APPENDIX I – FIGURES

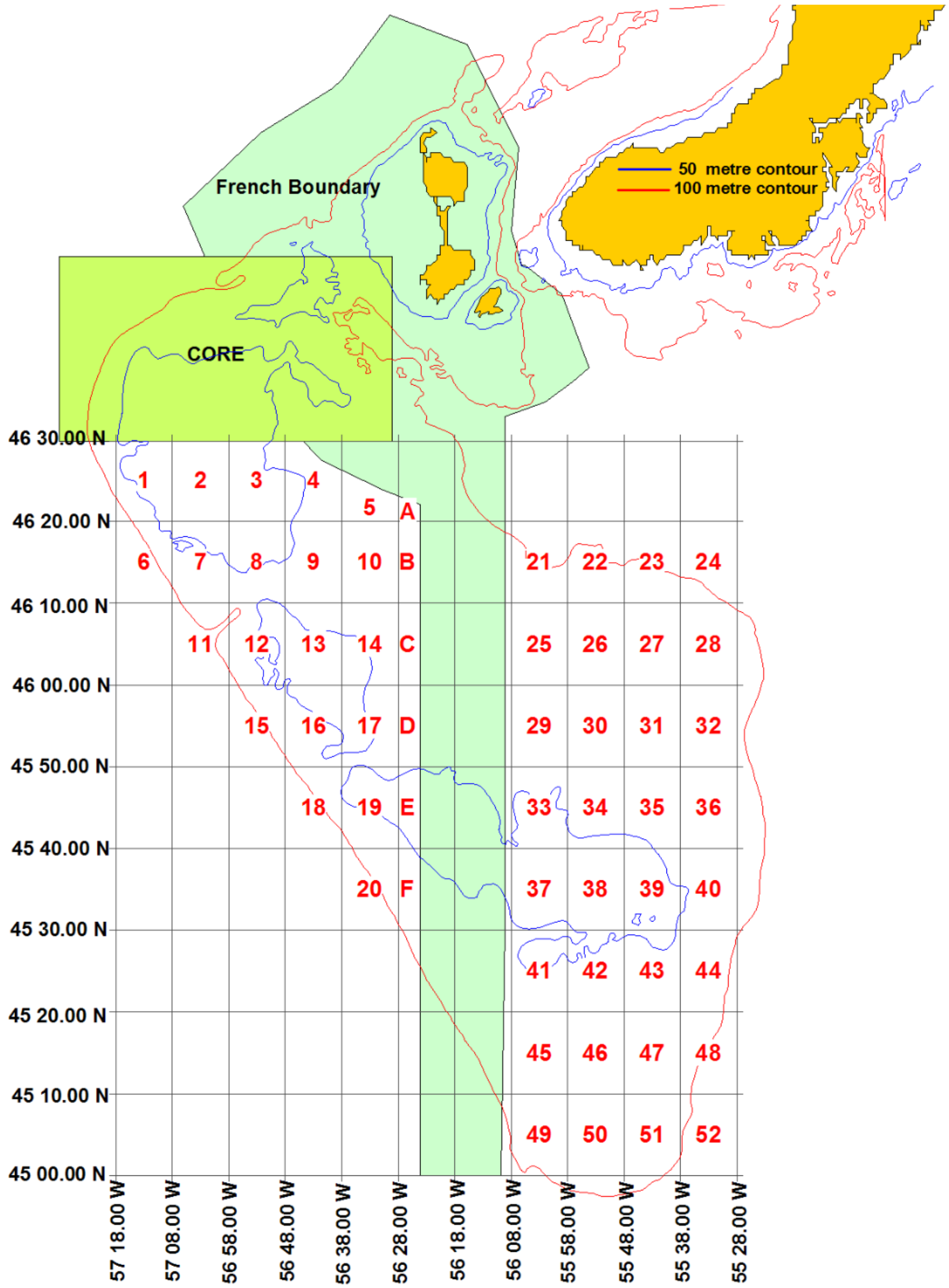

Figure 1. Map of the initial survey area for the emerging fishery sea cucumber surveys on the St. Pierre Bank. The 52 strata are divided into two areas, the 'northwest bed' and the 'southeast bed' by the French economic exclusion zone boundary (teal). The 50-m contours are in blue and the 100-m contours are in red. This is one of the original maps used in the emerging fishery (DFO 2008).

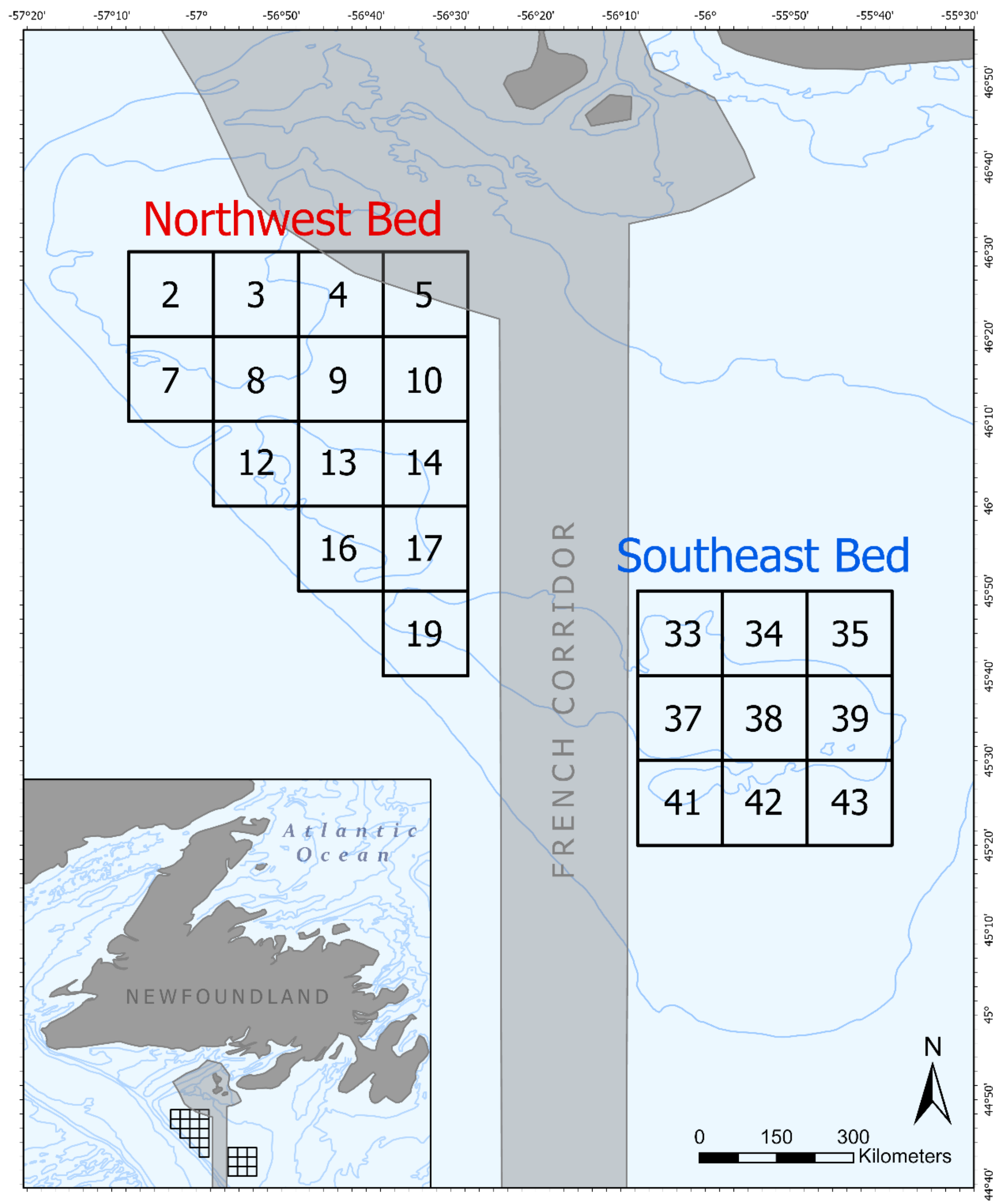

Figure 2. Map of current sea cucumber fishing grounds on the St. Pierre Bank off of Newfoundland, Canada. The area was reduced to these 23 strata in 2006. The northwest bed is comprised of strata 2, 3, 4, 5, 7, 8, 9, 10, 12, 13, 14, 16, 17, 19 and the southeast best is comprised of strata 33, 34, 35, 37, 38, 39, 41, 42, 43. These strata are used in the sea cucumber fishery and for cucumber surveys. Strata 4 and 5 have reduced area due to the interaction with the French economic exclusion zone. The contour lines are the 50-m and 100-m contour lines. The subsetted photo shows the survey area in reference to the island of Newfoundland, with blue contour lines at intervals of 100 m.

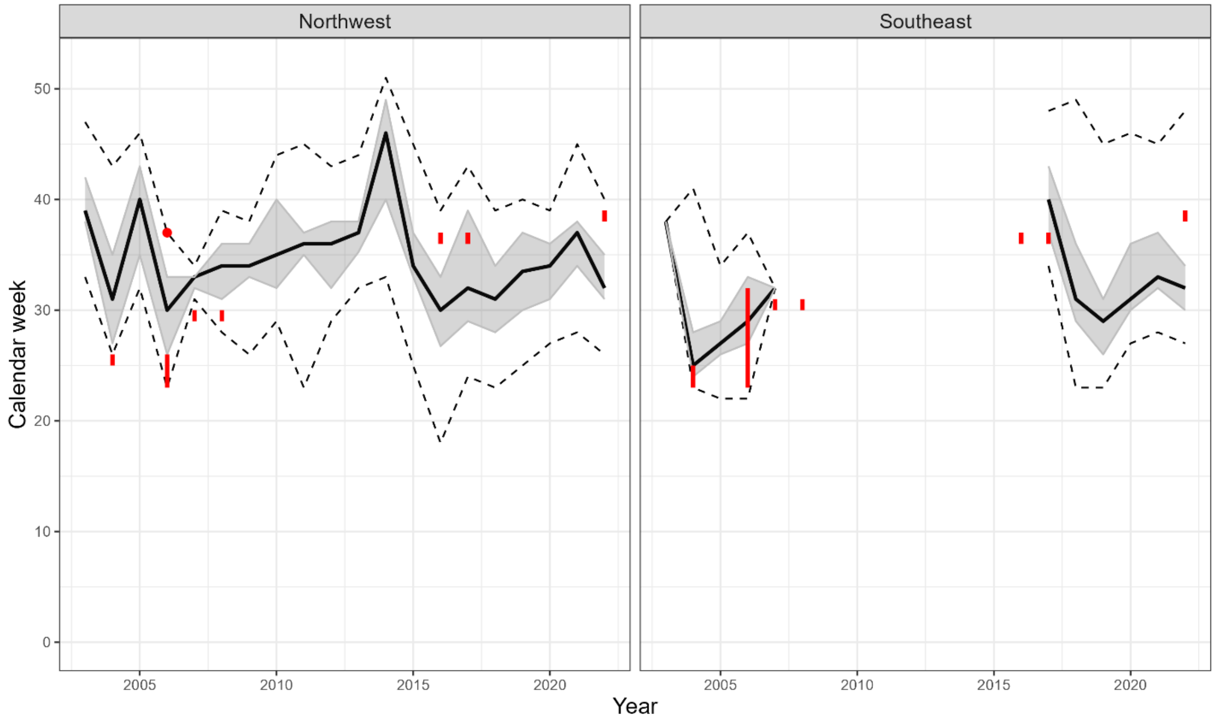

Figure 3. Timing of the sea cucumber (Cucumaria frondosa) *fishery in the northwest and southeast beds of the St. Pierre Bank (AD 3Ps) from the start of the emerging fishery (2003) to present. The black solid line represents the median fishing week, the grey shaded area represented the 1st and 3rd quartiles, and the dashed lines represent the first and last documented fishing activity for the year. Red lines denote the weeks that emerging fisheries (2004–08) and DFO sea cucumber surveys (2016, 2017, and 2022) were completed.*

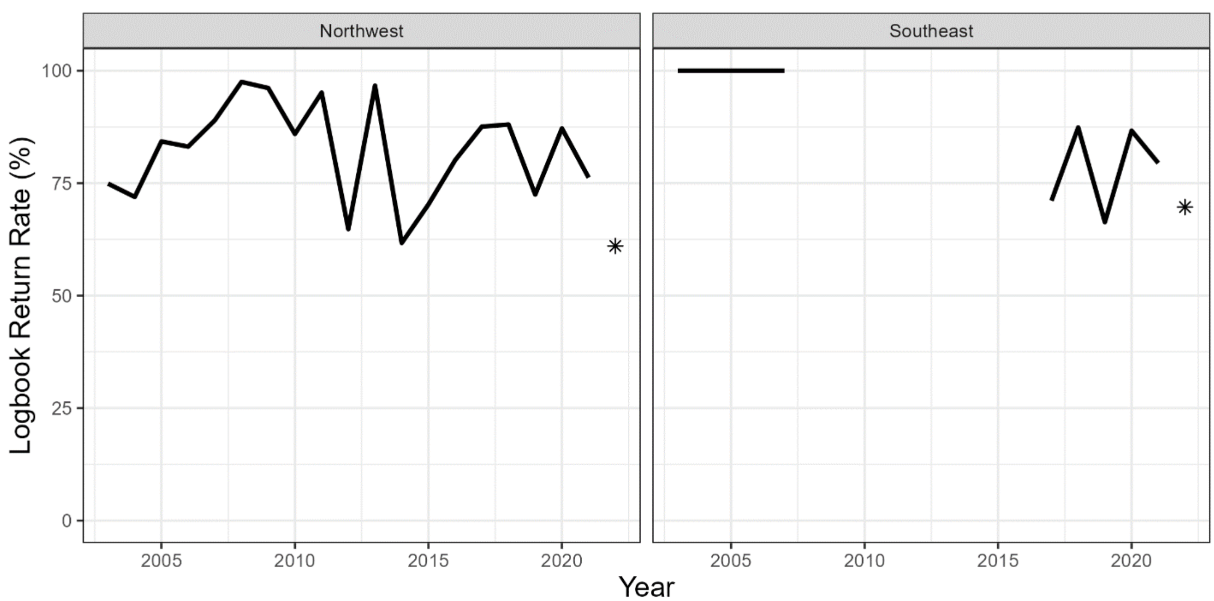

Figure 4. Sea cucumber (Cucumaria frondosa) *annual logbook return rates for the northwest and southeast beds on St. Pierre Bank (AD 3Ps) from the start of the emerging fishery in 2003. Logbook return rate was calculated as the percentage of total landings that were represented in submitted logbooks. The 2022 logbook data are preliminary and were last updated in February 2023.*

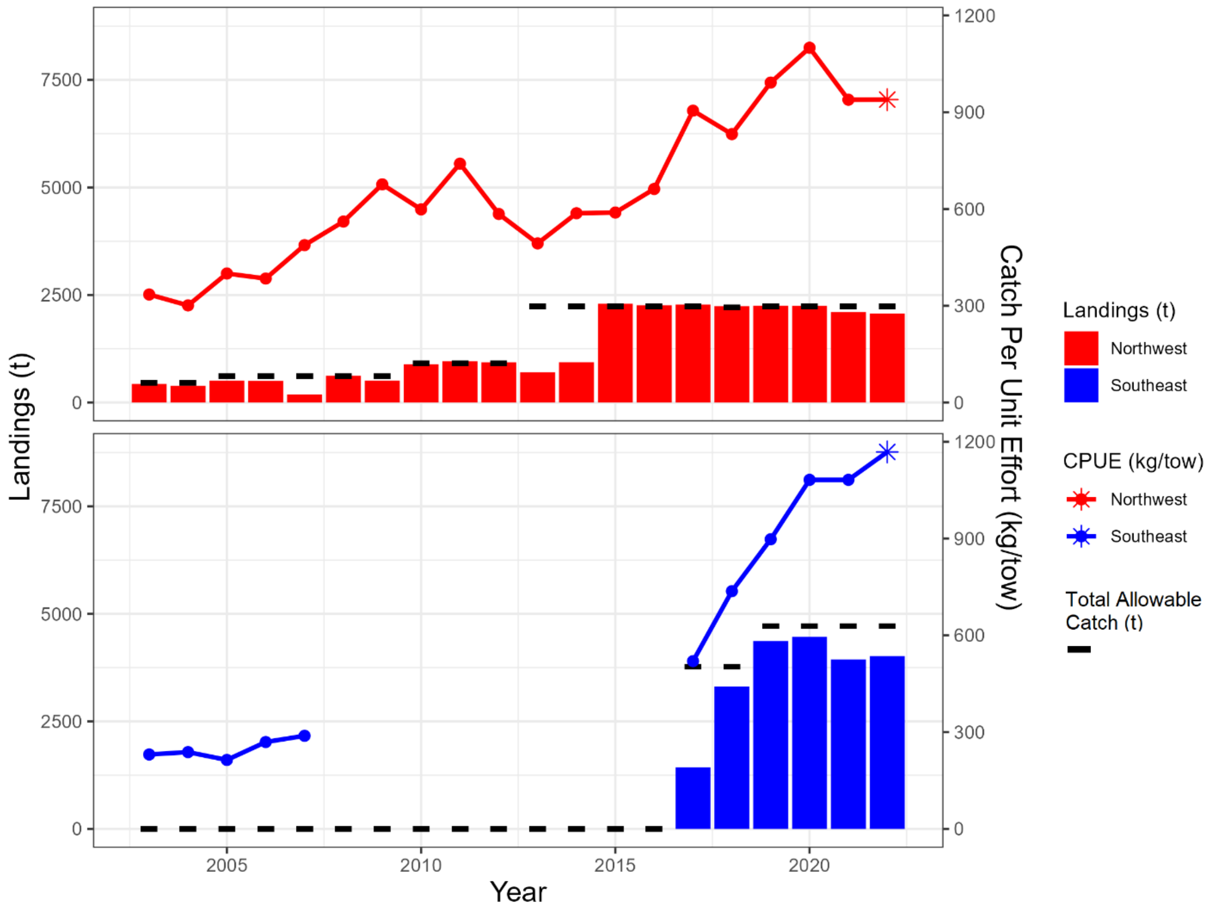

*Figure 5. Landings (Bars), Catch per Unit Effort (CPUE) (Lines), and Total Allowable Catch (black hashes) of sea cucumber (*Cucumaria frondosa*) in the northwest (top) and southeast (bottom) sea cucumber beds on the St. Pierre Bank from the start of the Emerging Fishery to present (2003–22). The 2022 logbook data are preliminary and were last updated in February 2023.*

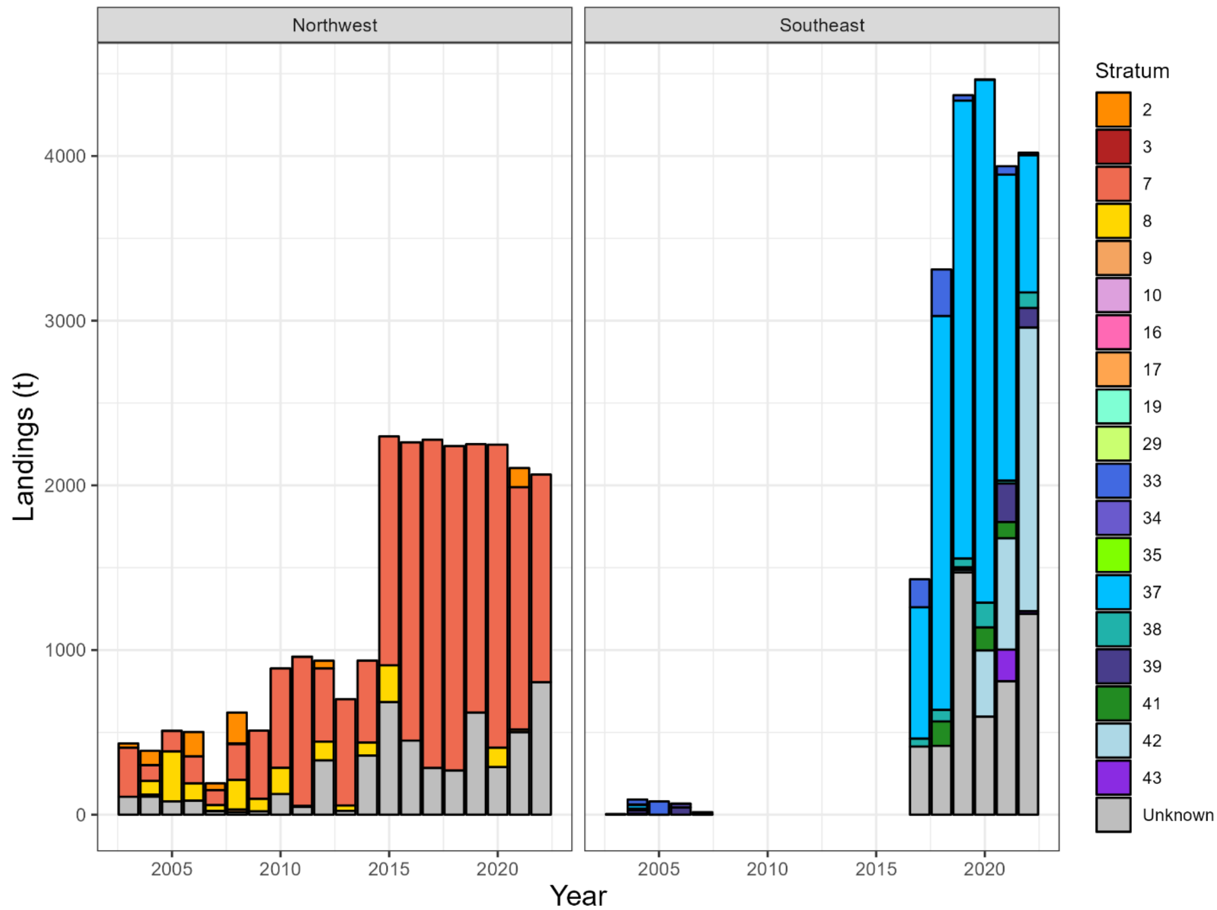

*Figure 6. Landings by strata of sea cucumber (*Cucumaria frondosa*) in the northwest (left) and southeast (right) sea cucumber beds on the St. Pierre Bank from the start of the Emerging Fishery to present (2003–22). Unknown strata are based on the difference between the total reported landings and landings represented by submitted logbooks. The 2022 logbook data are preliminary and were last updated in February 2023.*

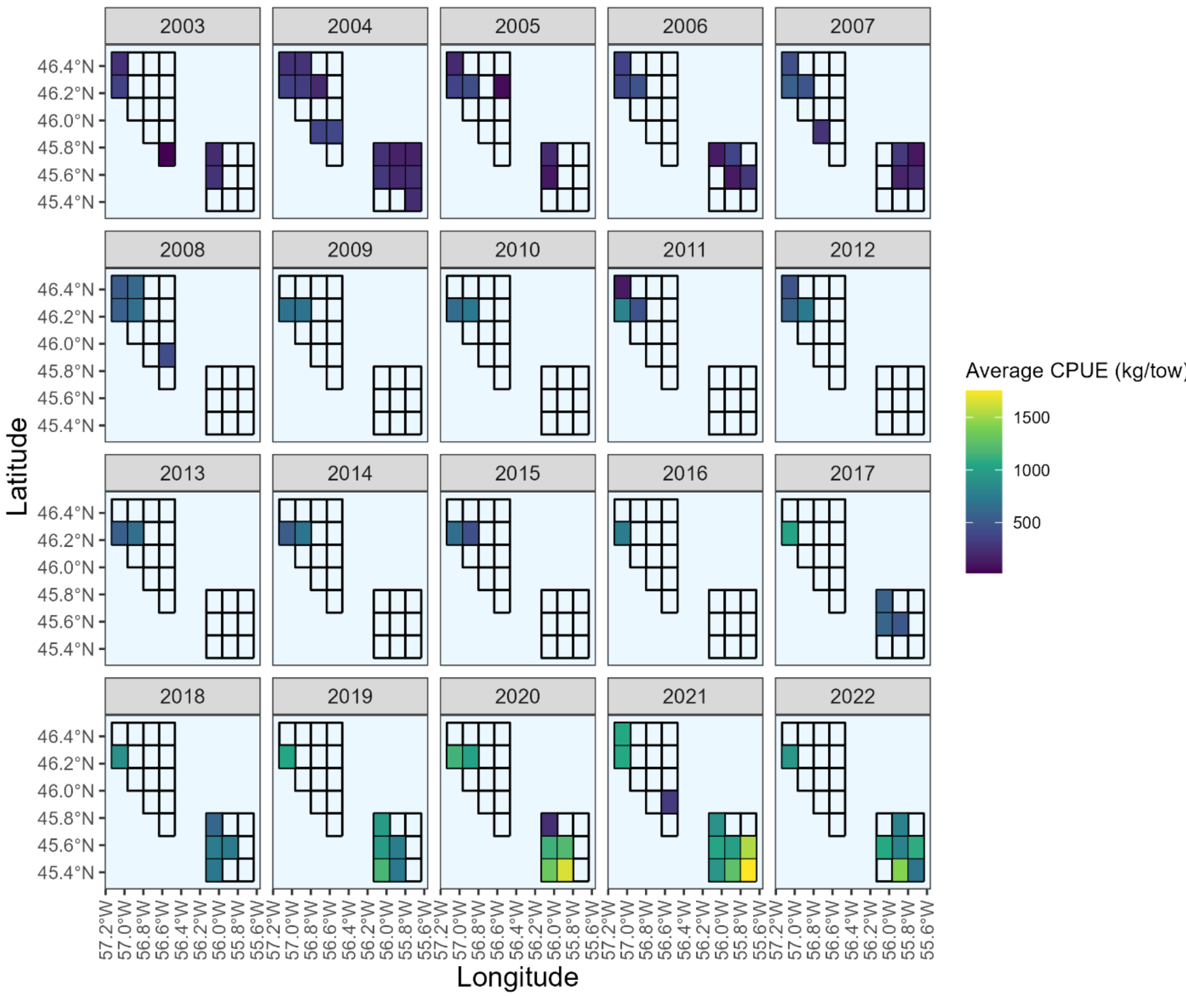

Figure 7. Heatmap of average catch per unit effort (CPUE; kg/tow) for the sea cucumber (Cucumaria frondosa) fishery in the northwest and southeast beds of the St. Pierre Bank (AD 3Ps). Emerging fishery data (2003–08) were standardized to 0.5 nm. Tow-by-tow information was no longer available after the end of the emerging fishery and thus 2009–22 data are unstandardized.

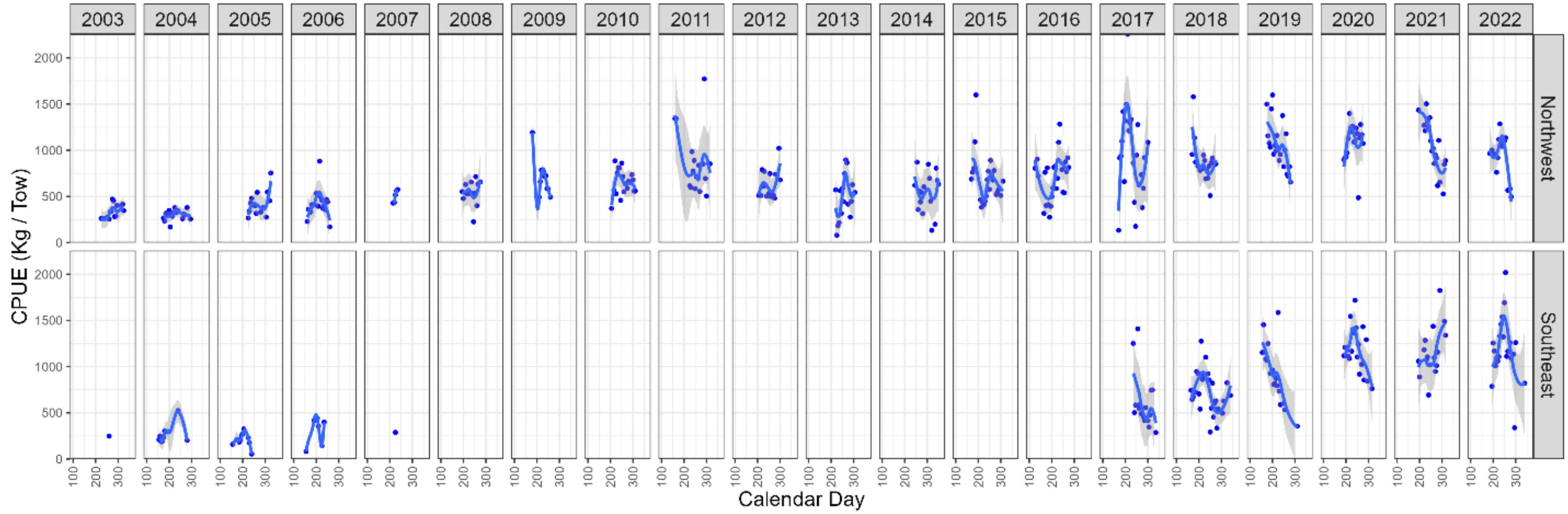

*Figure 8. Annual catch per unit effort (CPUE; kg/tow) throughout the season for the sea cucumber (*Cucumaria frondosa*) fishery on the northwest (top) and southeast (bottom) beds of the St. Pierre Bank since the start of the emerging fishery. The blue points are the five-day averages of fishery CPUE. The blue lines are loess smoother trend lines, and the grey shaded areas are the associated 95% confidence intervals.*

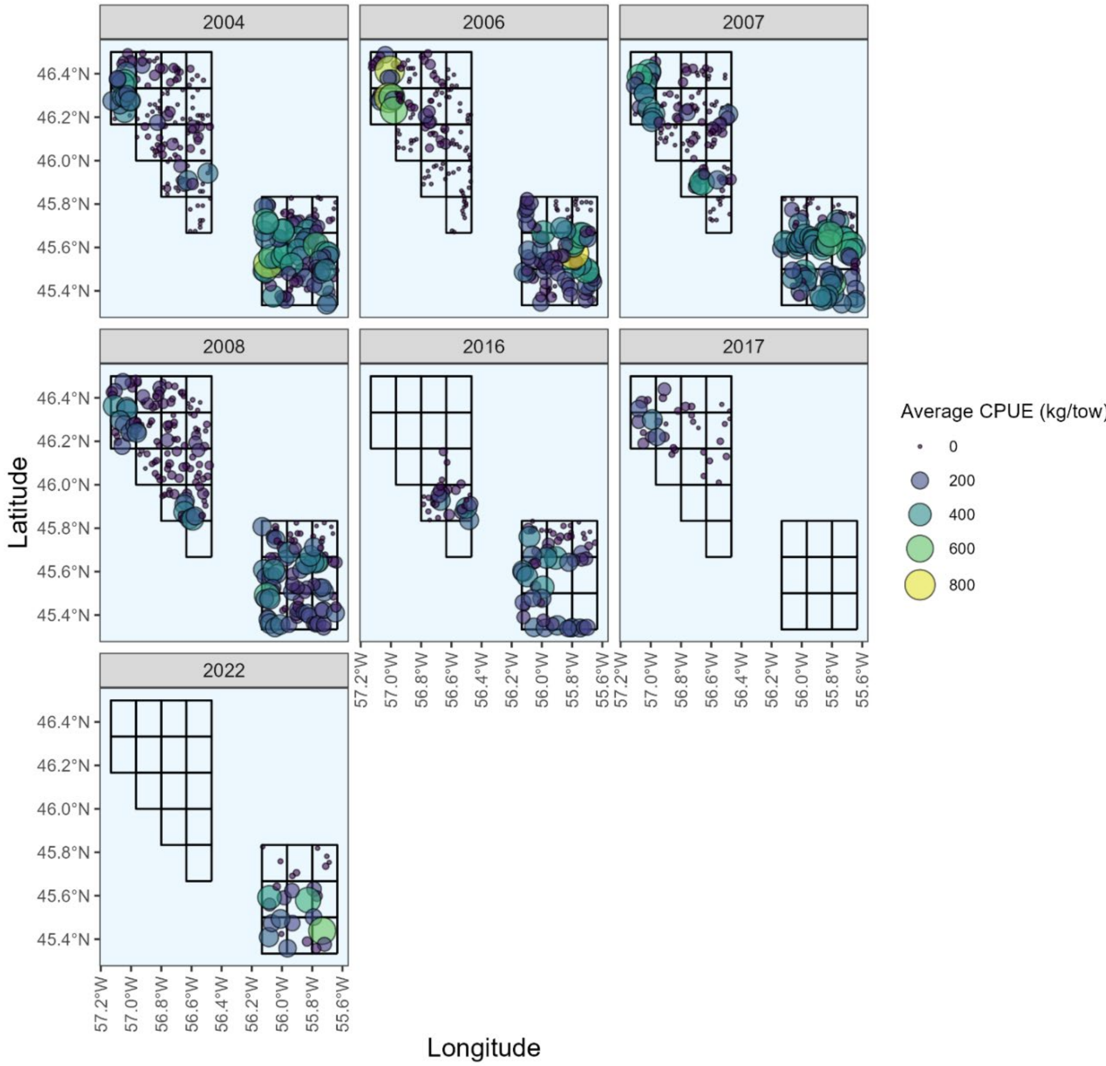

*Figure 9. Maps of survey catch rates (kg/tow) of sea cucumber (*Cucumaria frondosa*) on the St. Pierre Bank for the emerging fishery (2004–08) and the DFO sea cucumber surveys (2016, 2017, 2022). Points are survey sets, with increased size and lighter colour representing increases in sea cucumber catch rates.*

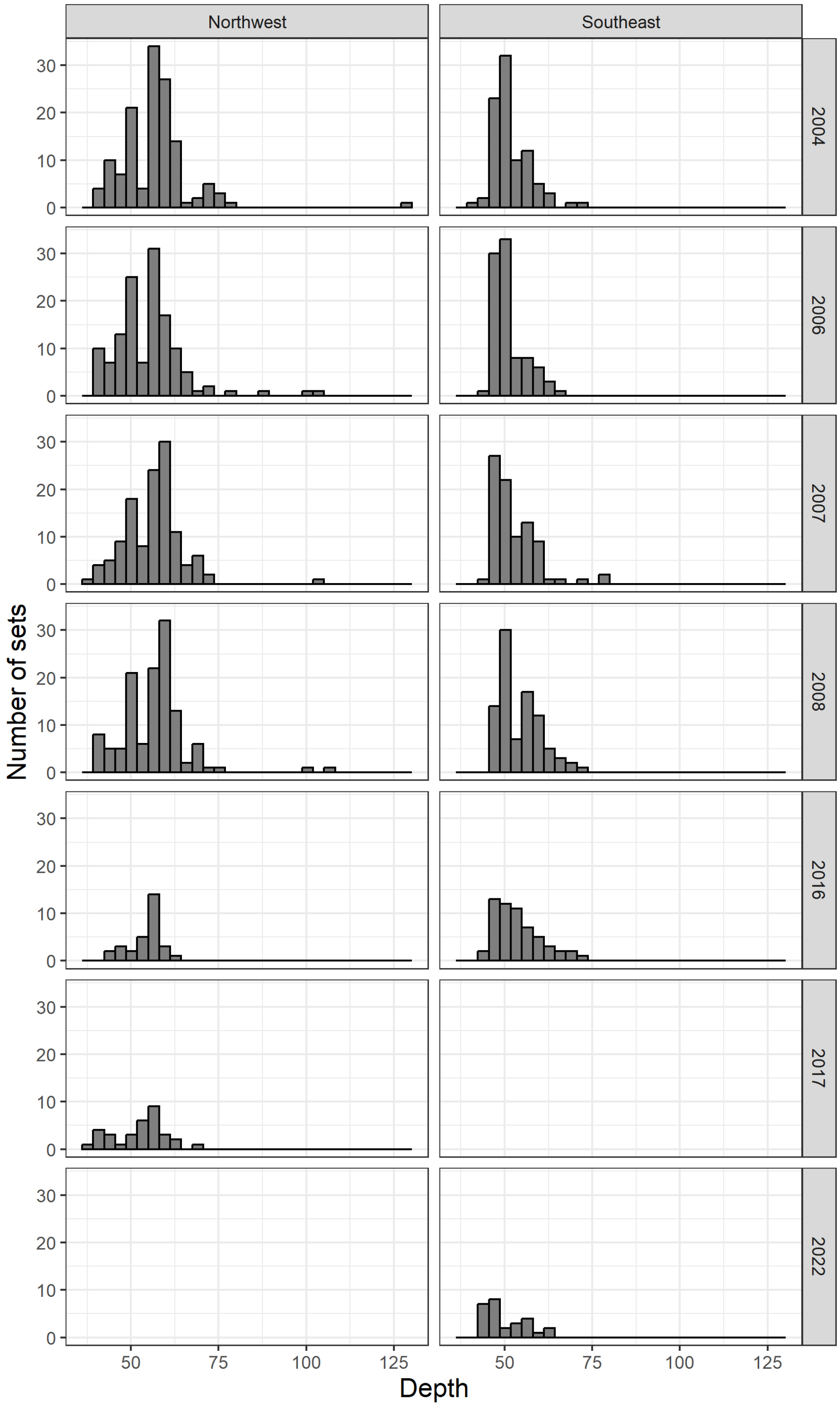

Figure 10. Depth coverage of survey sets completed in the northwest (left) and southeast (right) sea cucumber beds on the St. Pierre Bank during DFO sea cucumber surveys. Survey sets from 2004 to 2008 are from Emerging Fishery data and survey sets 2016–22 are from DFO sea cucumber surveys

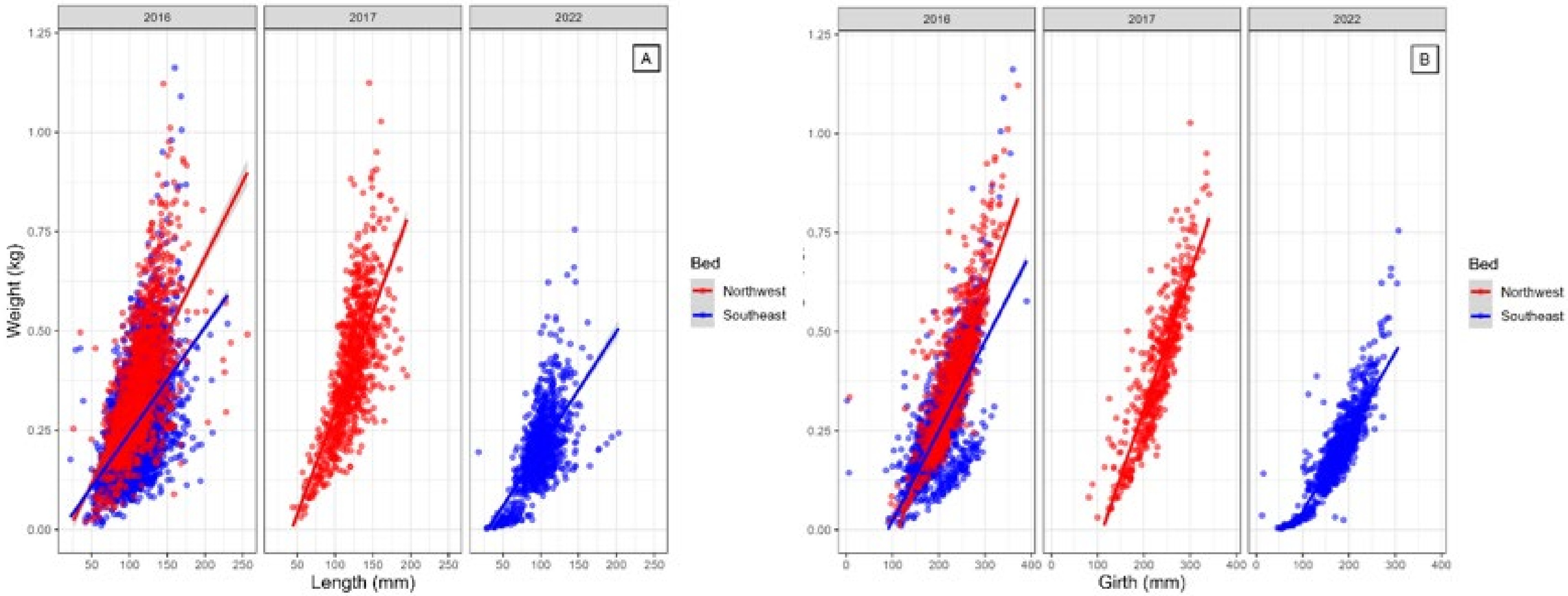

*Figure 11. (a) Length- weight and (b) girth- weight relationships fit for sea cucumber (*Cucumaria frondosa*) in the northwest and southeast sea cucumber beds on the St. Pierre Bank. Data were acquired from DFO sea cucumber surveys in 2016, 2017, and 2022.*

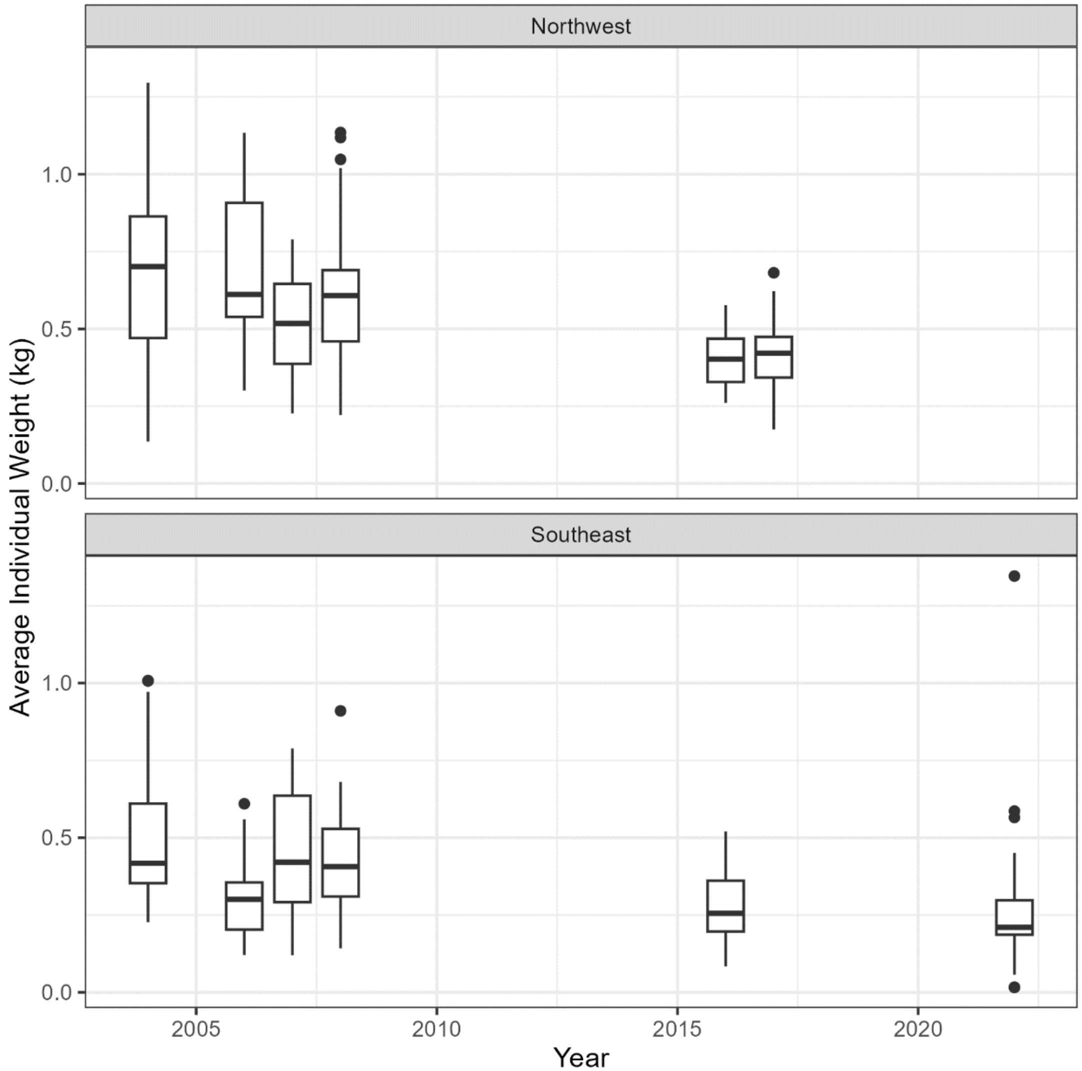

*Figure 12. Average weight of individual sea cucumbers (*Cucumaria frondosa*) in the northwest (top) and southeast (bottom) sea cucumber beds on the St. Pierre bank. The average weight was estimated from the emerging fishery and DFO sea cucumber survey data by dividing the total weight of sea cucumbers in each tow by the total number of sea cucumbers in that tow.*

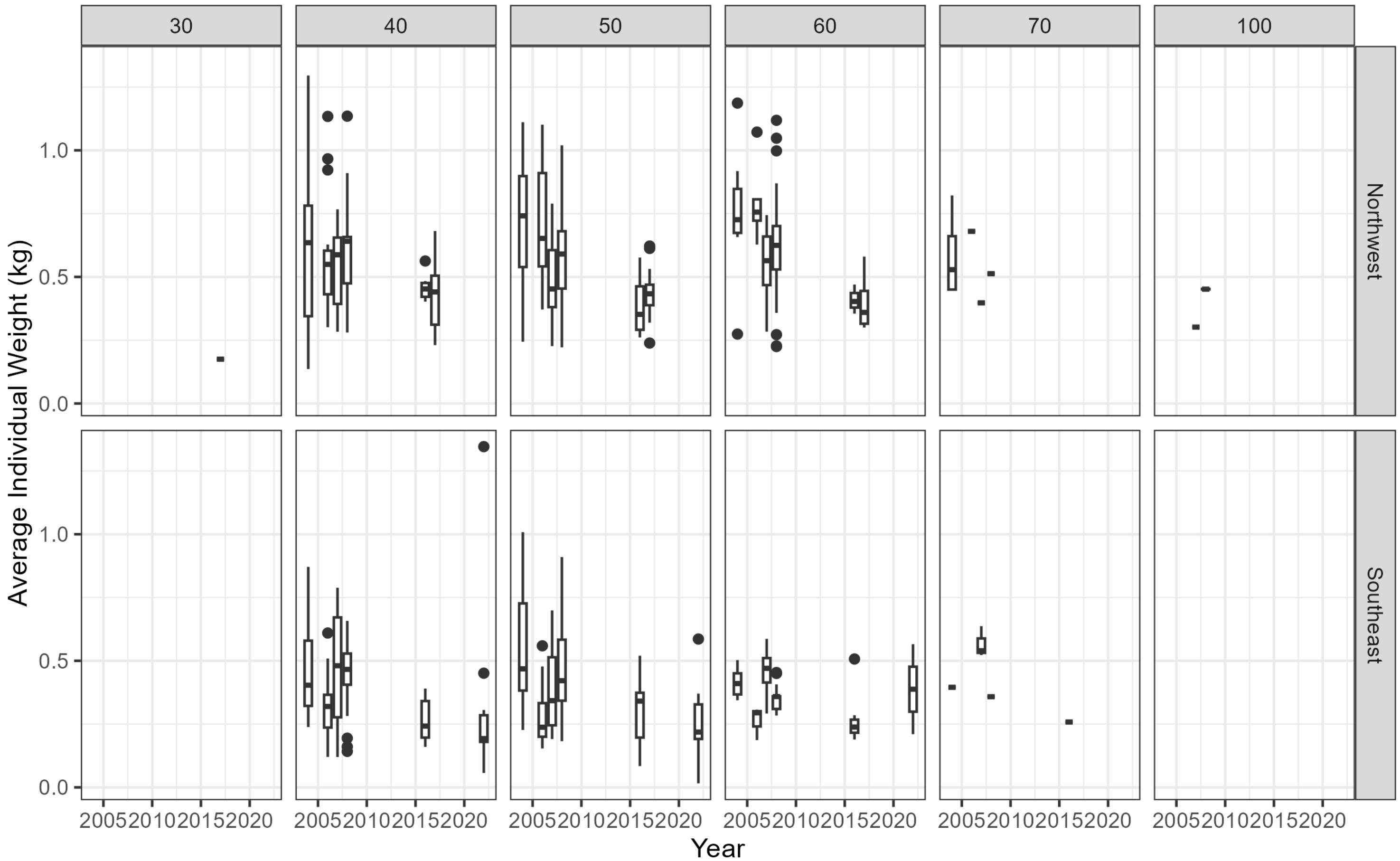

*Figure 13. Average weight of individual sea cucumber (*Cucumaria frondosa*) in the northwest (top) and southeast (bottom) sea cucumber beds on the St. Pierre bank by depth (m). Average weight is estimated from the emerging fishery and DFO sea cucumber survey data by dividing the total weight of sea cucumber in each tow by the total number or sea cucumber in that tow. Depths were binned to 10m bins (e.g., 30m–39 m).*

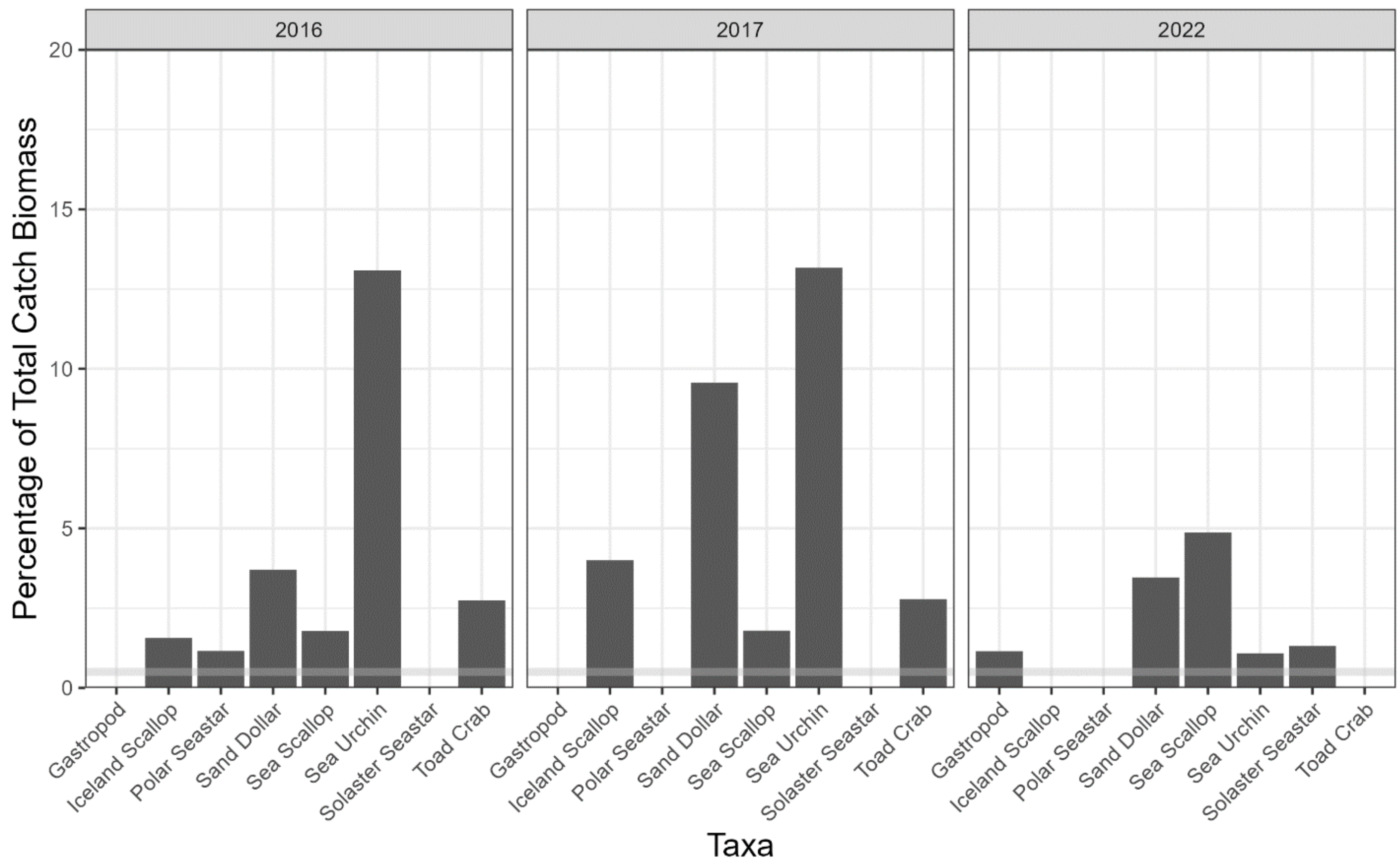

*Figure 14. The percentage of total catch biomass by weight of the most prominent non-sea cucumber ("other") species caught during the 2022 DFO sea cucumber (*Cucumaria frondosa*) survey in the southeast bed on the St. Pierre Bank. Only species that comprised >1% (light grey line) of the total biomass of the catch are displayed.*

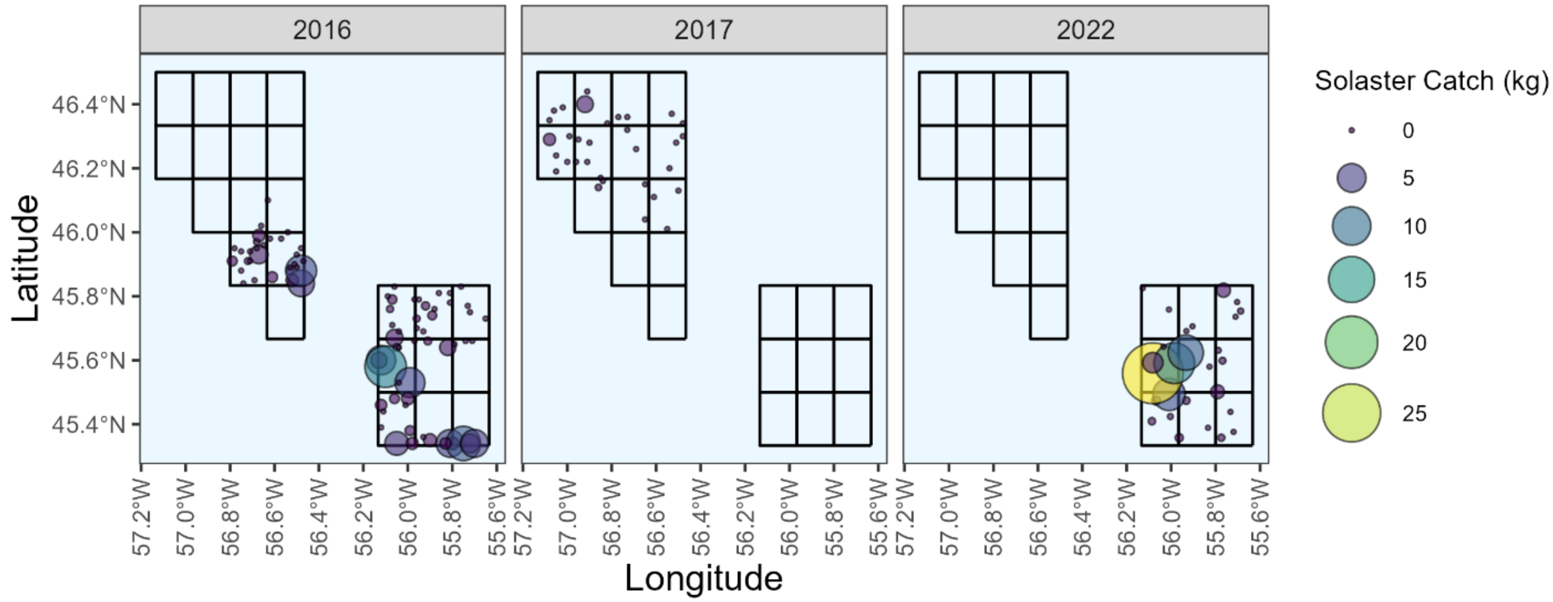

Figure 15. Maps of catch rates (kg/tow) of Solaster endeca *on sea cucumber (*Cucumaria frondosa*) fishing beds on the St. Pierre Bank. Data were collected during DFO sea cucumber surveys (2016, 2017, 2022). Points are survey sets, with increased size and lighter colour representing increases in S. endeca catch.*

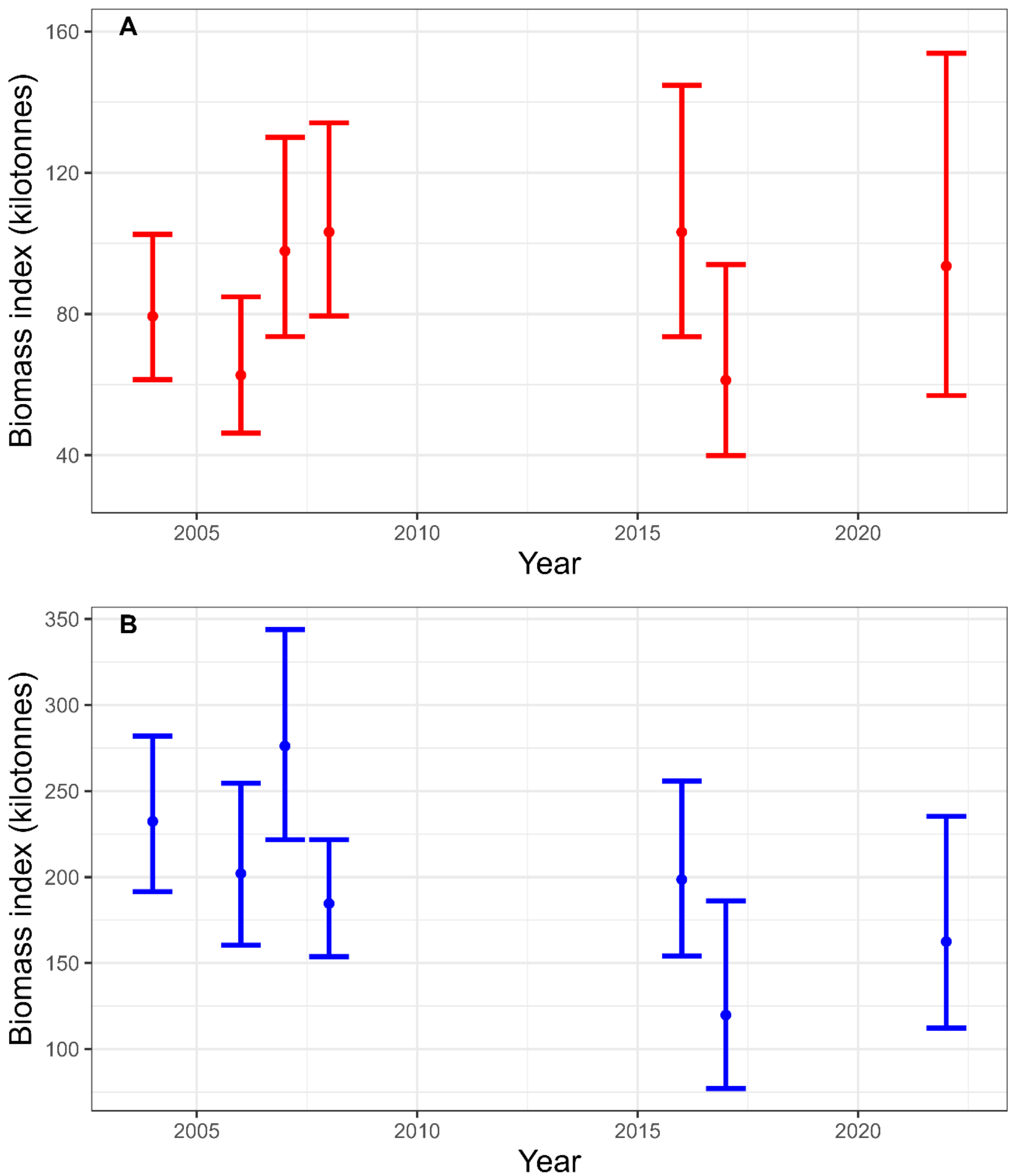

*Figure 16. Biomass indices for sea cucumber (*Cucumaria frondosa*) on the (A) northwest and (B) southeast beds on the St. Pierre bank using sdmTMB model. Bars represent 95% confidence intervals.*

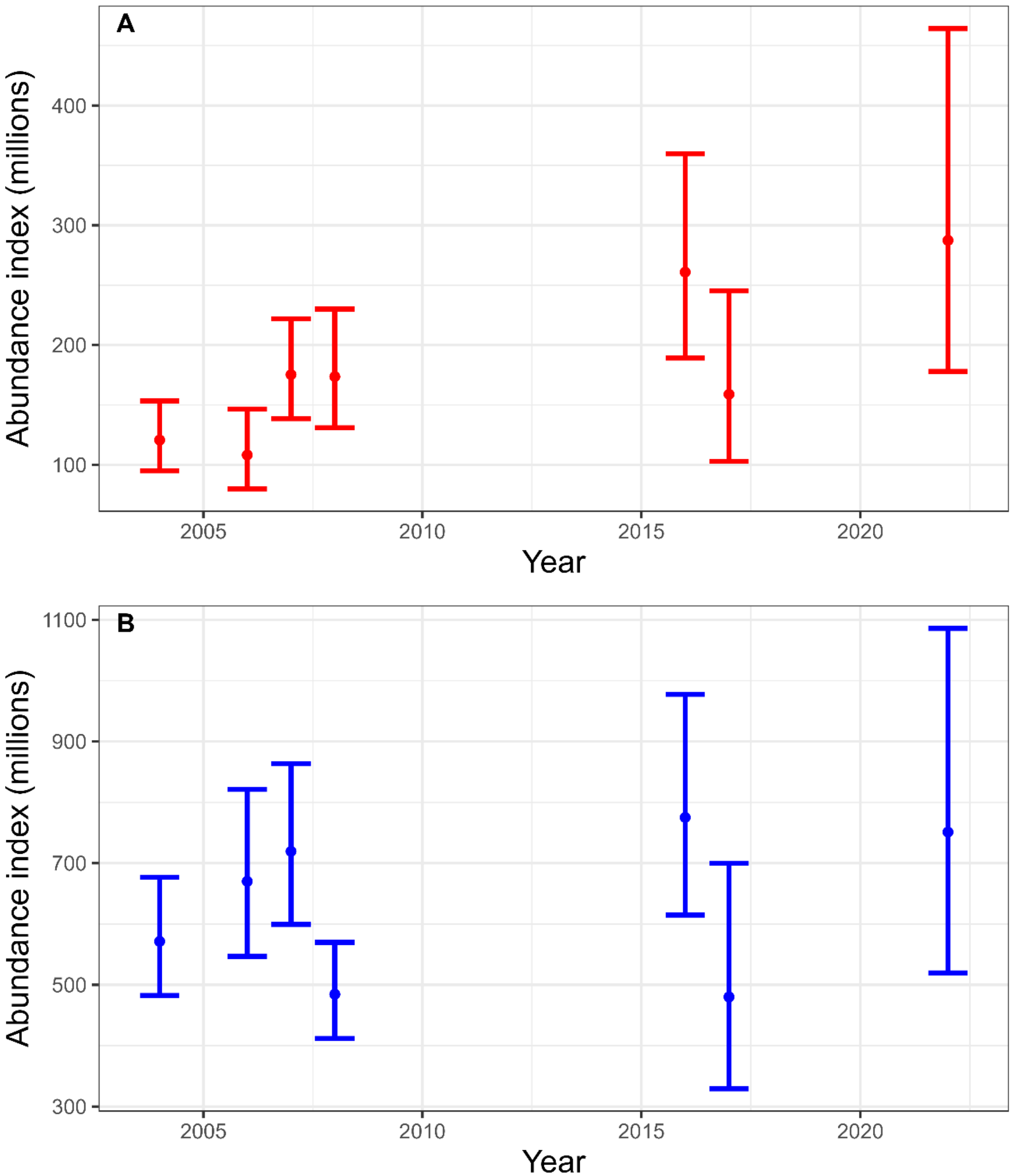

*Figure 17. Abundance indices for sea cucumber (*Cucumaria frondosa*) on the (A) northwest and (B) southeast beds on the St. Pierre bank using a sdmTMB model. Bars represent 95% confidence intervals.*

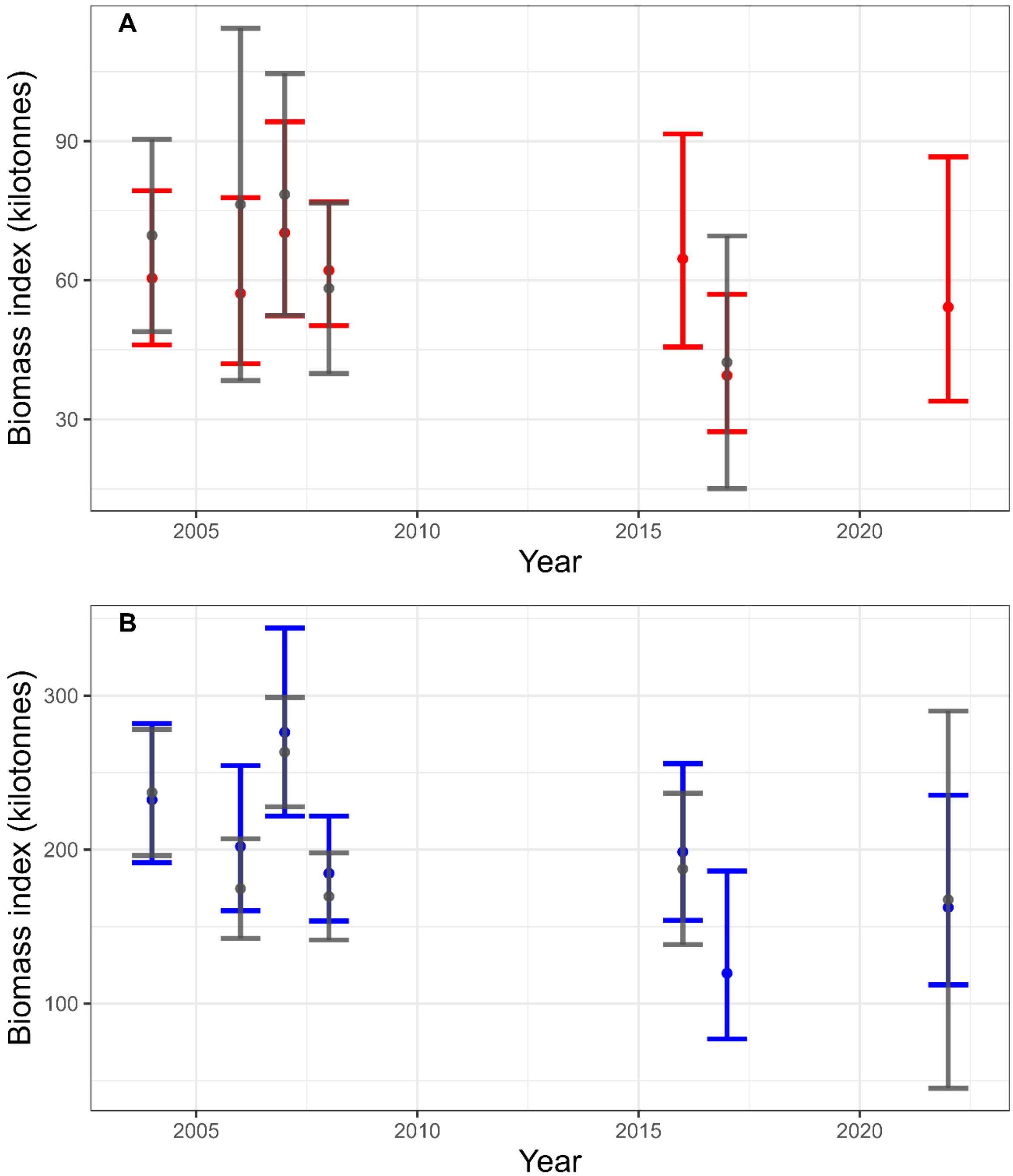

*Figure 18. Biomass indices using a subset of strata sampled in all years (Northwest bed: strata 2, 4, 5, 7, 8, 9, 10, 12, 13, 14; Southeast bed: strata 33, 34, 35, 37, 38, 39, 41, 42, 43) for sea cucumber (*Cucumaria frondosa*) on the (A) northwest and (B) southeast beds on the St. Pierre bank. Indices were calculated using a sdmTMB model (blue) and STRAP (grey). The bars represent 95% confidence intervals.*

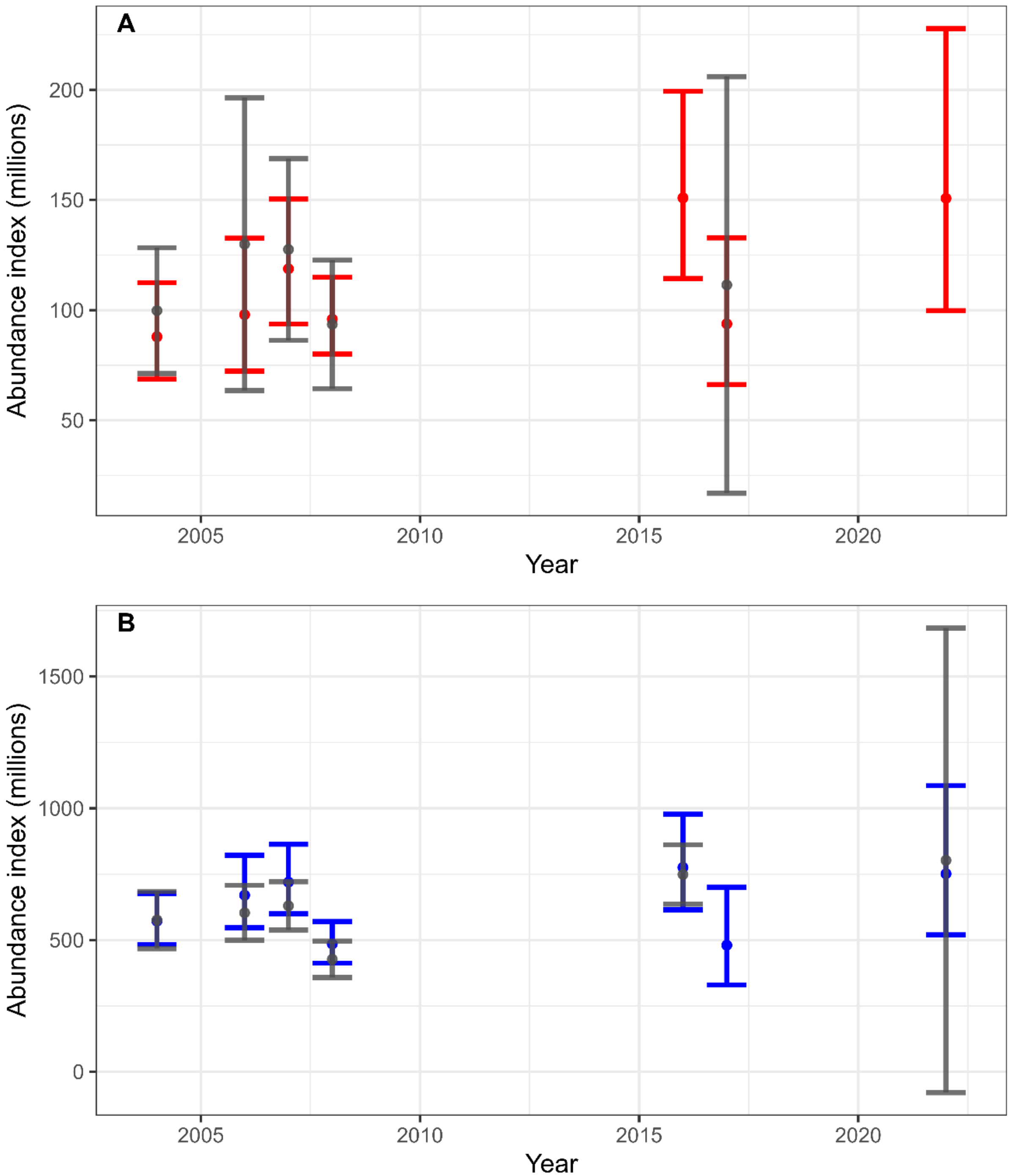

*Figure 19. Abundance indices using a subset of strata sampled in all years (Northwest bed: strata 2, 4, 5, 7, 8, 9, 10, 12, 13, 14; Southeast bed: strata 33, 34, 35, 37, 38, 39, 41, 42, 43) for sea cucumber (*Cucumaria frondosa*) on the (A) northwest and (B) southeast beds on the St. Pierre bank. Indices were calculated using a sdmTMB model (blue) and STRAP (grey). The bars represent 95% confidence intervals.*

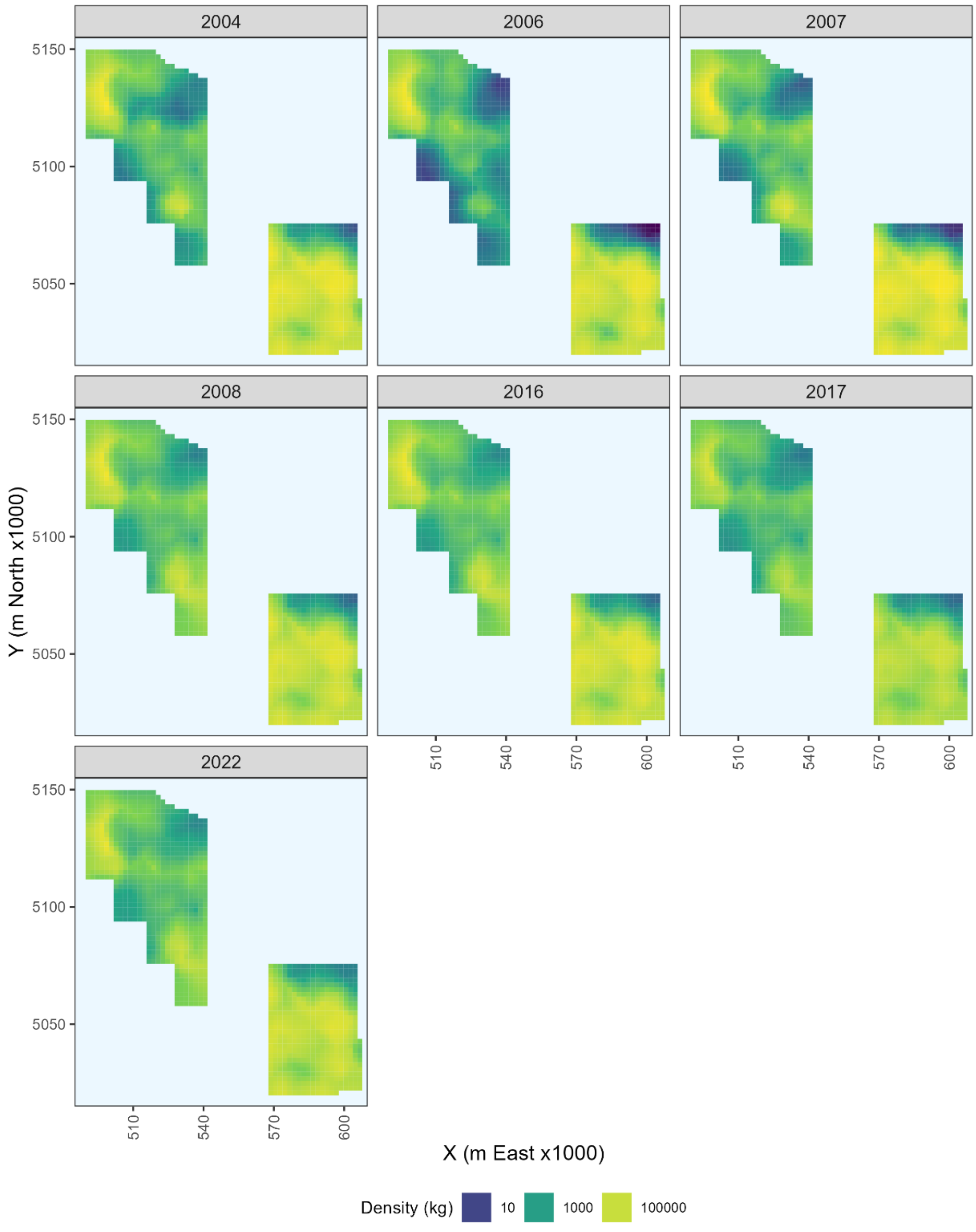

*Figure 20. Maps of model-predicted sea cucumber (*Cucumaria frondosa*) biomass density on fishing beds of the St. Pierre Bank. Coordinates are in UTM Zone 21N. Density is predicted on a 4km² grid.*

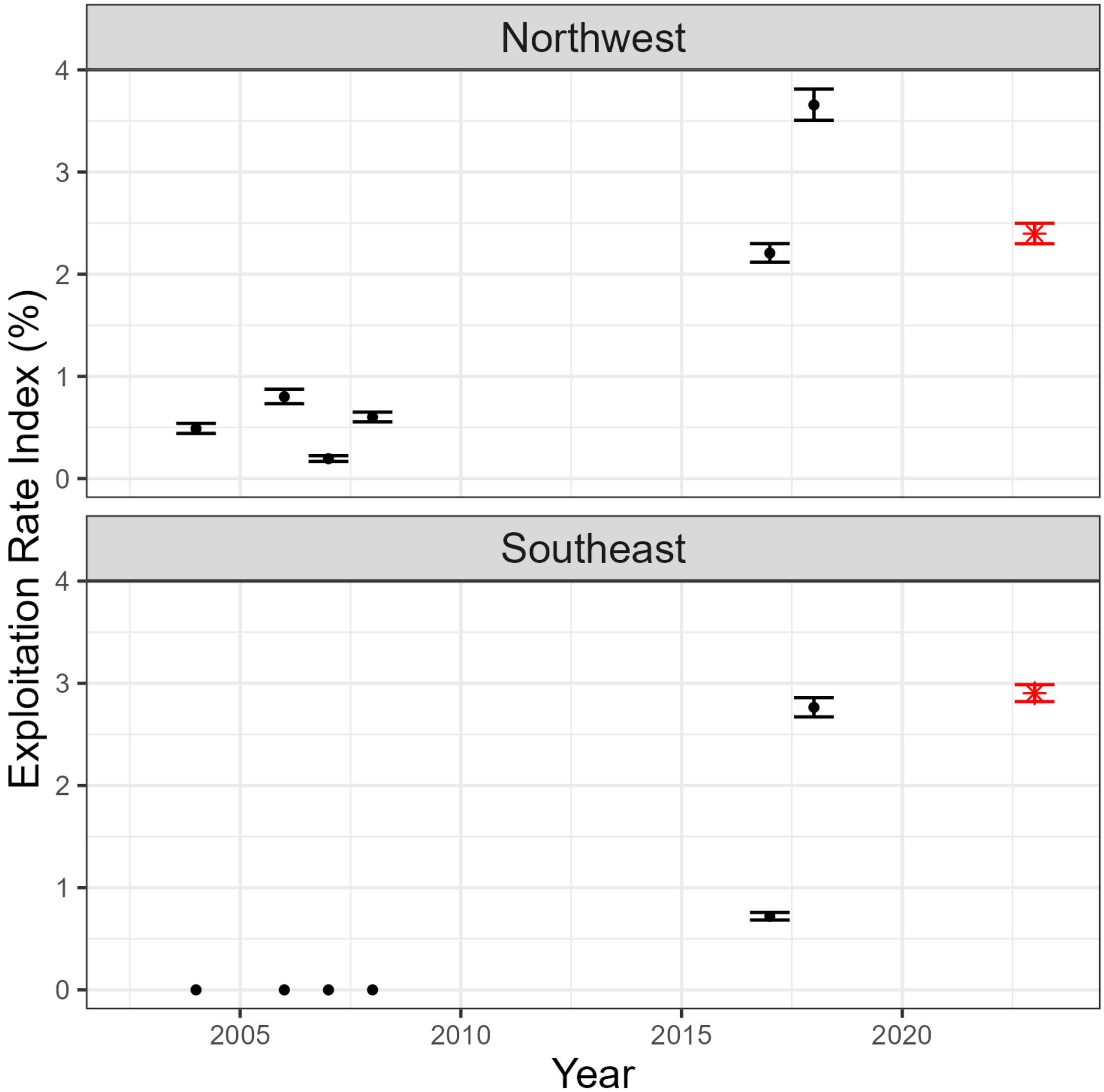

*Figure 21. Exploitation rate indices of sea cucumber (*Cucumaria frondosa*) of the northwest (top) and southeast (bottom) sea cucumber beds on the St. Pierre Bank since the start of the emerging fishery to present (2003–22). These indices were calculated using the ratio of the landings to the biomass estimates from the sdmTMB model. Indices after the emerging fishery (2008) were calculated with landings one year lagged from the biomass estimate. The 2023 (red) index is based on status quo TAC.*