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Identifying a Limit Reference Point for Striped Shrimp (*Pandalus montagui*) in Shrimp Fishing Area 4

K.D. Baker, S.C. Anderson, W. Coffey, D.R.J. Mullowney, W. Walkusz, and K.R. Skanes

Northwest Atlantic Fisheries Centre
Fisheries and Oceans Canada
80 East Whitehills Road, P.O. Box 5667
St. John's, Newfoundland and Labrador, 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

Off Atlantic Canada, Striped Shrimp (*Pandalus montagui*) are fished in Eastern Assessment Zone (EAZ), Western Assessment Zone (WAZ), and Shrimp Fishing Area (SFA) 4. Although there is assumed to be strong mixing and movement of the population throughout these areas, each of the three zones are assessed independently. To counteract this spatial-scale mismatch, and in accordance with Fisheries and Oceans Canada (DFO) Precautionary Approach (PA) framework, a limit reference point (LRP) for Striped Shrimp based on the combined survey data time series (2005–22) of SFA 4, EAZ, and WAZ was developed from a spatiotemporal model that created a new fishable biomass index for the entire region (FB_{pop}) to determine the stock status in SFA 4. The LRP was based on FB_{pop} and was calculated as the average of three methods:

1. the lowest fishable biomass at which the stock increased and remained above the geometric mean for a period of at least three years,
2. 40% of the geometric mean of the fishable biomass index throughout the time series, and
3. the lowest observed fishable biomass in the time series.

An LRP based on methodology, rather than an estimate of biomass, and a consistent reference period (2005–22) will allow for adjustments as model refinements are made and additional data are collected. In recognizing FB_{pop} as an index, the status of SFA 4 Striped Shrimp will be provided based on its relatively position in relation to the LRP. In addition to an LRP, three additional indicators of stock health were identified as important metrics for monitoring and reporting to highlight any concerning trends (“red flags”): potential predator index (ecological outlook), total egg production index (reproductive health), and SFA 4-specific fishable biomass index (local population health). In 2022, FB_{pop} was estimated to be five times the LRP with high certainty. Other indices of stock health (the potential predator index, total egg production index, and SFA 4-specific fishable biomass index) showed no cause for concern.

1. INTRODUCTION

1.1. GENERAL ECOLOGY

Striped Shrimp (*Pandalus montagui*) are found in the Northwest Atlantic from Davis Strait south to Rhode Island (Squires 1996). They are assumed to form one genetic population throughout their northern range, including within our study area (i.e., Davis Strait, Ungava Bay, and northern Labrador Sea), where the population is thought to be most abundant (Figure 1). Within this area there are strong and dynamic currents that likely cause a high degree of transfer and mixing of shrimp and their larvae (Le Corre et al. 2020). Hudson Strait, in particular, is considered a highly dynamic system with strong currents and mixing (Le Corre et al. 2020).

Compared to the more commonly recognized Northern Shrimp (*Pandalus borealis*), Striped Shrimp tend to prefer cooler (-0.3 to 2.7°C) and shallower (200 to 300 m) waters (Baker et al. 2021). Striped Shrimp complete diel vertical migrations in the pursuit of prey (Hudon et al. 1992). During the daytime, shrimp rest and feed on or near the ocean floor, while at night a substantial proportion of the population (particularly males) migrate vertically in the water column feeding on zooplankton (Hudon et al. 1992). Catches of males during daylight are approximately 1.5 times those made at night (Baker et al. 2021).

In general, pandalid shrimp are known to be important prey for a variety of fishes. Striped Shrimp have been documented in the stomachs of Greenland Halibut (*Reinhardtius hippoglossoides*) (Tremblay-Gagnon 2022), Redfish (*Sebastes* spp.), Roughhead Grenadier (*Macrourus berglax*), American Plaice (*Hippoglossoides platessoides*), and skates (Rajidae) caught during summer surveys (Polaczek et al. 2023). Predators, such as Atlantic Cod (*Gadus morhua*) and squid, are significant drivers of biomass and population dynamics in other pandalid shrimp stocks (e.g., Pedersen et al. 2022; Richards and Hunter 2021).

Striped Shrimp are protandrous hermaphrodites; they are born and mature as males and mate as males for one or more years, then usually transition to mature females. The carapace length (CL) of transition in the study area is a function of reproductive competition (average CL of females in the previous year) and large-scale environmental conditions (the areal extent of preferred habitat temperatures in the previous year) (Baker et al. 2021). Striped Shrimp throughout the study area transition at larger sizes and generally grow to larger sizes compared to those in their more southernly range (Baker et al. 2021). The average CL of transitional shrimp were above 20 mm in the study area in recent years (Baker et al. 2021). Striped Shrimp are recruited to the fishery at approximately 3–4 years of age or older.

The degree of adult and larval Striped Shrimp movement throughout the area has not been quantified and is assumed to vary through time. Larval studies in West Greenland waters concluded that Striped Shrimp likely have an earlier hatch and slower development time than Northern Shrimp based on sizes of the different larvae sampled (Pedersen et al. 2002). Given this information, recent larval drift modelling of Northern Shrimp (Le Corre et al. 2019; Le Corre et al. 2020) is unlikely to apply to Striped Shrimp on the same scale.

Several epidemiological conditions that influence overall health and/or reproductive health have been documented in Striped Shrimp (e.g., black gill, black shell, microsporidian, and bopyrid isopod), with black shell being the most prevalent (~2.5% of individuals sampled during surveys). Although the overall influence of these conditions on population health remains unknown, a number of the documented conditions can directly impact Striped Shrimp reproductive health and fecundity. For example, female shrimp parasitized by a microsporidian have poorly developed ovaries and reduced mating capacities, while bopyrid isopod infections lead to a significant reduction in the number of eggs. The prevalence of the various epidemiological conditions are generally influenced by environmental conditions (e.g., temperature) and population density (Baker et al. 2021). Overall, the annual prevalence of any condition has consistently remained low throughout the population (Baker et al. 2021).

1.2. FISHERY

In Canadian waters, commercial landings of Striped Shrimp are recorded in SFA 4, EAZ, and WAZ (Figure 1) and were valued at nearly $59 million CAD in 2019 (DFO, unpublished data). Within WAZ, the Striped Shrimp fishery is generally targeted, whereas within SFA 4 and EAZ, Striped Shrimp are considered a bycatch product within the larger Northern Shrimp fishery. However, at-sea observer records have recorded consistent targeting of Striped Shrimp within SFA 4 and EAZ since the mid-2000s (DFO, unpublished data).

The fishery is managed annually from April 1 to March 31. In SFA 4, Striped Shrimp are primarily managed based on a bycatch quota. A bycatch quota of 4,033 tonnes (t) was established in 2013/14; however, documented Striped Shrimp catch has only exceeded that amount once, in 2012. In WAZ, the total allowable catch (TAC) has steadily increased since 2010 (DFO 2021) to 12,096 t in 2022/23. In EAZ, the quota increased from below 1,000 t in 2014–21 to 1,400 t in 2022/23. The exploitation rates based on reported catches have generally been below 20% in WAZ, and below 25% in EAZ and SFA 4 (DFO 2021, 2022).

The fishery occurs during ice-free conditions and uses factory freezer trawlers (>33 m) and smaller inshore trawlers (DFO 2018). Although there is no minimum legal size for Striped Shrimp, the minimum mesh size of 40 mm is thought to exclude individuals with CLs less than 17 mm (DFO 2018). This size was originally thought to allow most shrimp to transition to females before becoming vulnerable to the fishery, but Baker et al. (2021) showed that this measure was likely ineffective at protecting males and transitioning individuals as Striped Shrimp in the fished areas transition at significantly larger sizes.

Nordmore grates (i.e., sorting grates in the trawl) are mandatory on all trawlers to reduce bycatch of marine mammals, turtles, and groundfish (DFO 2018). In 2007, the Hatton Basin Conservation Area zone was voluntarily closed to bottom-contact fishing to protect vulnerable corals and sponges as part of an industry-led initiative (Figure 1). In 2018, the Hatton Basin closure was expanded and was formally designated a marine refuge (DFO 2018). This 42,459 km^2 area remains closed to bottom-contact fishing. In 2018, Davis Strait Conservation Area (17,298 km^2) was also formally deemed a marine refuge and closed to all bottom-contact fishing activities to protect corals, sea pens, and sponges.

1.3. RESOURCE ASSESSMENTS

While known to be an open system (Le Corre et al. 2020), Striped Shrimp stocks are assessed separately in SFA 4, EAZ, and WAZ every two years and treated as closed systems, thereby creating a scale-mismatch between the assessment units and the larger population dynamics (DFO 2023a). Fishery scale-mismatches between assessment units, management units, and biological processes can cause unintended consequences, including fishery mismanagement. For example, changes in distribution can be misunderstood as changes in population abundance in one or more the assessment areas (Baker et al. 2024). The assessment areas are the basis by which Fisheries and Oceans Canada (DFO) Fisheries Resource Management (FRM) manage the setting and allocation of quotas after consideration of DFO Science advice and consultations with stakeholders (DFO 2018).

The assessments focus on a variety of stock indicators including biomass indices of various Striped Shrimp maturity stages, length frequencies, distribution, and fishery catch statistics (e.g., DFO 2021). In SFA 4, biomass indices are estimated using ogive mapping methodology, commonly termed OGMAP (Skanes and Evans 2005), from survey data spanning 2005 to present. In EAZ and WAZ, biomass indices are calculated using a stratified-based spatial expansion method (STRAP) from survey data spanning 2009 to present in EAZ and 2014 to present in WAZ (Siferd 2015). STRAP was discontinued in SFA 4 shrimp assessments due to its reliance on strata specifically developed for groundfish species, along with its large/negative confidence intervals (Skanes and Evans 2005).

The fishable and female spawning stock biomass indices within the three management areas have generally varied without strong trends throughout their respective time series. Movement across the management areas is suspected to contribute to interannual variability in stock size measurements (DFO 2021), however the extent of this has not been quantified. The largest biomass estimates tend to occur in WAZ, although SFA 4 estimates can occasionally record annual estimates of approximately the same magnitude (DFO 2021, 2022). Within the last few (~3) years, there has been little concern for the stock health in any area based on survey and assessment results (DFO 2021; 2022).

1.4. PRECAUTIONARY APPROACH FRAMEWORKS

Currently, there is no PA framework for Striped Shrimp in SFA 4. A limit reference point (LRP) and upper stock reference point (USR) are required for SFA 4 Striped Shrimp under DFO's Fishery Decision-making Framework, incorporating the PA framework. The LRP is defined as the stock status below which serious harm is being done to the stock. Serious harm is "an undesirable state that may be irreversible or only slowly reversible over the long term" (DFO 2023b). The harm does not need to be caused by fishing or other anthropogenic impacts and can be the result of natural dynamics in the system (DFO 2023b). The LRP is based on best available information and identified by DFO Science through a peer-review process (DFO 2009).

In 2021, a recovery-based LRP for SFA 4 Striped Shrimp was proposed and peer reviewed. The LRP was proposed at 13,900 t of fishable biomass and represented the lowest estimate of fishable biomass from which the fishable biomass was able to recover to above the time-series average three years later (DFO 2023a). This LRP was not accepted during the peer-review process with the reasoning that this method had not been previously used for Canadian shrimp stocks (DFO 2023a). In 2021, the methods used in other shrimp stocks (i.e., 0.4 or 0.3 of the proxy of spawning stock biomass associated with maximum stainable yield) would have placed the LRP below the minimum observed historical biomass. In such cases, this method is not advised (DFO 2023b). In addition to the criticism that the method was not used in other Canadian shrimp stocks, other participants felt that the proposed level did not represent prolonged recovery because the recovery point was a single point above the population mean after which the biomass index fell back below the mean (DFO 2023a). There was general agreement that fishable biomass was an appropriate indicator of stock health (DFO 2023a).

In 2020, LRPs were established separately for Striped Shrimp stocks within EAZ and WAZ (DFO 2020). The LRP was set at 40% of the geometric mean of spawning stock biomass index (all female shrimp regardless of size) between 2009 and 2019 in EAZ and 2014 to 2019 in WAZ (DFO 2020). The methods used to identify the LRPs generally followed those used in Northern Shrimp stocks, although slightly more conservative, adopting 40% (rather than 30%) of the geometric mean of female spawning stock biomass. This method followed the DFO PA policy suggesting an LRP of 40% for data deficient stocks and accounted for uncertainty in biomass variability (DFO 2009, 2020). During the 2021 Striped Shrimp assessment, spawning stock biomass indices in both WAZ and EAZ were estimated to be well above the LRP (DFO 2021). The Striped Shrimp stock in EAZ was never in the critical zone throughout the survey time series, while the WAZ stock was considered *Critical* in 2013/14 (DFO 2020).

The lack of clear stock-recruitment relationships, as well as the lack of strong trends or consistent fluctuations in biomass and catch indices and short survey time series has meant that popular methods for establishing references points in data-limited stocks (e.g., Surplus production model in continuous time - SPiCT) have remained unfeasible for Striped Shrimp. The use of multi-indicator approaches to establish PA frameworks have been used in similar situations (DFO 2023b; Mullowney et al. 2018). While conventional PA methodologies focus on a single indicator (usually biomass), multi-indicator approaches tend to more holistic, considering the whole health of the stock. They can more readily incorporate ecosystem considerations – a requirement of the updated *Fisheries Act* (R.S.C. 1985, c. F-14), species-level and population-level health indicators, as well as fishery dynamics (Mullowney and Baker 2023). In fact, during the early development of PA management systems on an international scale, the intent of the Food and Agriculture Organization (FAO) of the United Nations was to establish multivariate, multi-sectoral, cooperative PA systems (FAO 1996).

1.5. OBJECTIVES

As previously indicated Striped Shrimp stock dynamics within SFA 4 are assumed to be heavily influenced by not only SFA 4 conditions, but also the conditions in more northern assessment areas (i.e., EAZ and WAZ), where the population is thought to readily mix. Therefore, in the context of this scale mismatch between the biological and assessment units, the proposed LRP in SFA 4 should not be based solely on SFA 4 conditions, but should consider the conditions/dynamics of the larger population (i.e., SFA 4, EAZ, and WAZ combined). However, the LRP is intended only for providing advice on SFA 4 stock and does not negate the previously established reference points for EAZ and WAZ Striped Shrimp stocks.

Within this document, we provide details on three indicators of Striped Shrimp stock health, encompassing population health, reproductive health, and ecosystem outlook pertaining to the study area (i.e., SFA 4, EAZ, and WAZ combined), and one indicator of SFA 4-specific population health. An LRP for SFA 4 Striped Shrimp based on the fishable biomass index (population health) of the study area is estimated using three methods. The other three indicators are presented and will be used as stock health “red flags” to ensure any concerning trends in these metrics are flagged during stock assessment processes.

2. METHODS

2.1. DATA SOURCES

2.1.1. Northern Shrimp Research Foundation Survey

The Northern Shrimp Research Foundation (NSRF) survey was initially formed by seventeen offshore shrimp license holders to address a gap in shrimp research and data in SFA 4 and EAZ. The annual survey of these areas commenced in 2005, funded through special funding from 2005 to 2021 and from an allocation of Northern Shrimp in SFA 4, authorized under Section 10 of the *Fisheries Act* since 2013. In 2014, an agreement was struck between the NSRF and regional organizations to fund the survey extension into WAZ, which commenced in that same year. This resulted in the three areas being surveyed in the same timeframe utilizing the same vessel, as well as the same survey and sampling protocols.

The NSRF stratified random trawl survey occurred in the summer months utilizing a commercial shrimp trawler with similar survey protocols in place as the DFO spring and autumn multispecies surveys (Walsh and McCallum 1997). In most years the survey occurred from July through August using the Ocean Choice International (OCI) vessel *Aqvik*. However, operational issues sometimes resulted in alternate OCI vessels being utilized or delays/breaks/extensions in survey timing. The effects of these adjustments have not been quantified, but are generally deemed to be comparable given the similarity in vessels.

The survey used a standard Campelen 1800 shrimp trawl (0.36 m rockhopper footgear) in SFA 4 and modified Campelen 1800 shrimp trawl (0.53 m rockhopper footgear) in EAZ and WAZ. The modified trawl was adopted to reduce tear-ups, but catchability was considered to be equal between the two trawl types (Siferd and Legge 2014). A trawl-mounted conductivity-temperature-depth (CTD) instrument recorded bottom temperature, salinity, and depth.

Shrimp were subsampled during each tow and sorted to species, counted, and weighed. Maturity/sex, overall condition (e.g., presence of parasites), shell condition, and carapace length were recorded for both Northern Shrimp and Striped Shrimp (Siferd 2015). Fish and invertebrates were sorted to species-level, then counted and weighed. All weights and numbers were standardized to 1 km^2. Catches were further standardized to account for male Striped Shrimp diel migrations (Baker et al. 2021; DFO 2022).

2.2. LIMIT REFERENCE POINT

2.2.1. Fishable Biomass Index (FB_{pop})

Fishable shrimp are Striped Shrimp >17 mm CL and assumed to be vulnerable to the fishery. Since Striped Shrimp in northern areas transition at larger sizes, fishable shrimp in Arctic waters are represented by males (pre-transition), transitioning individuals, and females (post-transition); very few primary females or non-transitioning males are known to occur in northern waters (Baker et al. 2021; Bergström 2000). In the study area, Striped Shrimp generally transition to females at approximately 20 mm CL, but transitional individuals have been found in surveys ranging from 10 to 28 mm CL (Baker et al. 2021). Fishable Striped Shrimp are an appropriate indicator of population health because they represent the portion of the population vulnerable to the fisheries and represent relatively large shrimp that are currently reproducing as females, and males and transitioning individuals that will become reproducing females in the future.

Since the time series of the NSRF survey and biomass estimation methods differ between the SFAs, a model-based estimate of fishable biomass was needed to develop a full time-series biomass index for the entire study area (SFA 4, EAZ, and WAZ combined).

A spatiotemporal model was developed to estimate fishable Striped Shrimp biomass within the study area (FB_{pop}) throughout the time series (2005 to 2022) using the R package *sdmTMB* (Anderson et al. 2022). *sdmTMB* was inspired by the Vector Autoregressive Spatio-Temporal (*VAST*) package (Thorson 2019). The basic functional form of the models within each methodology are equivalent, thereby providing identical results if configured the same (Anderson et al. 2022). *sdmTMB* was accepted by the International Council for the Exploration of the Sea (ICES) and Northwest Atlantic Fisheries Organization (NAFO) as a technique to estimate biomass for populations where survey coverage was inconsistent, and is currently used to assess Northern Shrimp biomass in Skagerrak-Norwegian Deep stocks (ICES 2022; NAFO 2022). In addition, the NAFO's Standing Committee on Research Coordination (STACREC) recommended *sdmTMB* be further explored for use in stocks within the NAFO Regulatory Area (NAFO 2022). *sdmTMB* was also accepted by the National Oceanic and Atmospheric Administration (NOAA) Northwest Fisheries Science Center Scientific Statistical

Committee (SSC) for use in assessments and is regularly used in Pacific Region DFO stock assessments (e.g., Grandin et al. in press[1]; Haggarty et al. 2022; Huynh et al. in press[2]).

Here, we provide a summary of the biomass estimation model, but details on the methodologies, results, and discussion points can be found in Baker et al. (2024).

The fishable biomass index (FB_{pop}) model can be described as:

Eq. 1

$$\begin{aligned} \mathbb{E}[y_{\mathbf{s},t}] &= \mu_{\mathbf{s},t}, \\ \mu_{\mathbf{s},t} &= f^{-1}(\alpha_t + g(D_{\mathbf{s},t}) + \omega_{\mathbf{s}} + \epsilon_{\mathbf{s},t}), \end{aligned}$$

where $y_{\mathbf{s},t}$ represents the density (kg/km^2) of fishable Striped Shrimp caught in a set during the trawl survey at spatial point $\mathbf{s}$ and time t (year) and $\mathbb{E}[y_{\mathbf{s},t}]$ indicates its expected value. The symbol μ represents the mean of fishable Striped Shrimp density, f represents a link function (logit or log), and f^{-1} represents its inverse. The symbol α_t represents an independent intercept for each year and $g(D_{\mathbf{s},t})$ represents a penalized smoother function for bottom depth (m) of the trawl set. The symbol $\omega_{\mathbf{s}}$ represents a spatial random effect component (a random field), $\omega_{\mathbf{s}} \sim \mathrm{MVN}(\mathbf{0}, \mathbf{\Sigma}_\omega)$; and $\epsilon_{\mathbf{s},t}$ represents a spatiotemporal random effect component (random fields), $\epsilon_{\mathbf{s},t} \sim \mathrm{MVN}(\mathbf{0}, \mathbf{\Sigma}_\epsilon)$. The spatiotemporal random fields were assumed to be independent across years; the spatial and spatiotemporal random fields account for how unmeasured or latent habitat suitability metrics change through space and by year. The model uses a delta-lognormal family (a binomial distribution with a logit link for encounter–non-encounter and lognormal distribution with a log link conditional on encounters). Spatial and spatiotemporal correlation within the random fields is constrained by an anisotropic Matérn function with separate spatial ranges (distance at which correlation is approximately 0.1) for the spatial and spatiotemporal fields and binomial/lognormal components but with the degree of anisotropy shared across fields and model components to ease estimation.

For interpretation ease, model formulations herein are shown using pseudo-R code following an *mgcv* (Wood 2017) syntax, so that Eq. 1 is equivalent to Eq. 2.

Eq. 2

Density = s(Depth)+Year

Where, *Density* was the density (kg/km^2) of fishable Striped Shrimp caught in a set during the trawl survey. *Depth* was the bottom depth (m) of the trawl set and *Year* was the year that the trawl set occurred and represented as a factor. The basis dimensions (i.e., complexity) of the thin plate regression splines (*s*) used in the smooth relationship between *Depth* and *Density* is represented by k.

Annual density was predicted throughout the study area on a 5 km^2 gridded surface of depth (IOC et al. 2022). Then, an area-weighted annual FB_{pop} was calculated within the study area using the predicted density surface by summing the predicted density per grid cell multiped by the cell area. Standard errors of the annual estimates were calculated using the generalized delta method in TMB (Kristensen et al. 2016) and mean values were bias-adjusted to account for the non-linear transformation of the random effects (Thorson & Kristensen 2016).

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[1]Grandin, C.J., Anderson, S.C., and English, P.A. In press. Arrowtooth Flounder (*Atheresthes stomias*) Stock Assessment for the West Coast of British Columbia in 2021. DFO Can. Sci. Advis. Sec. Res. Doc.

[2]Huynh, Q.C., Siegle, M.R., and Haggarty, D.R. In press. Application of the Management Procedure Framework for Inside Quillback Rockfish (*Sebastes majiger*) in British Columbia in 2021. DFO Can. Sci. Advis. Sec. Res. Doc.

Numerous efforts were taken to create an accurate and precise forecasting model for Striped Shrimp, but this was not possible given the relatively short survey time series. Efforts to create an effective forecasting model will continue as the survey time series lengthens.

2.2.2. Reference Point Identification

The identification of a single value below (or above) which stock health indicators become "*Critical*" is dependent on different methodologies indicating different values and always subject to caveats and a healthy level of criticism. Each method to identify a reference point makes explicit or implicit assumptions regarding population dynamics, ecosystem variability, etc. (e.g., the underlying ecosystem drivers of population dynamics remain constant). Striped Shrimp is a data-deficient stock; therefore, we used several comparative approaches to identify these values. This approach has been successfully used to identify LRPs for other Newfoundland and Labrador (NL) shellfish stocks (e.g., snow crab – *Chionoecetes opilio*) (Mullowney et al. 2018).

Three methods were used to identify potential value of the LRP related to fishable Striped Shrimp population health using the indicator FB_{pop}.:

1. A limit point (LP) was estimated based on $B_{recovery}$ (DFO 2023a). $B_{recovery}$, as well as B_{loss} (lowest observed stock size) are commonly used methods to identify LRPs when stocks lack stock-recruitment relationships (Silvar-Viladomiu et al. 2022). $B_{recovery}$ was defined as the lowest FB_{pop} at which the stock increased and exhibited prolonged recovery, so that three years later it remained above the geometric biomass mean of the time series (2005–22) for a period of at least three years. Three years to recovery was chosen because it represents the very minimum time a larval Striped Shrimp may take to reach fishable size.
2. An LP was identified based on similar methodology peer-reviewed and accepted for *Pandalus* spp. in WAZ and EAZ (DFO 2020). The LP represented 40% of the geometric mean of the FB_{pop} throughout the time series (2005–22). This method follows that identified in DFO's PA policy (DFO 2009).
3. An LP was identified based on B_{loss} (DFO 2023b). B_{loss} was defined as the lowest observed FBpop in the time series (2005–22). B_{loss} is a commonly used method for identifying LRP when there is no obvious stock-recruitment relationship and no known recruitment issues throughout the history of the stocks (Silvar-Viladomiu et al. 2022).

The average of the three LP estimates was used as the final LP related to FB_{pop}.

In this study, the FB_{pop} index will be reported as a scaled value in reference to the LRP (FB_{pop} / LRP), so that the LRP is equivalent to 1 (e.g., in 2021 FB_{pop} is three times larger than the LRP).

Using a methodology-based LRP also ensures that as annual refinements are made to the model (e.g., more years of data are included and/or incorporation of additional covariates) that lead to modified estimates of FB_{pop}, the LRP can and will be updated accordingly using the established methodologies and refined model-derived estimates for the reference period (2005 –22).

2.3. STOCK HEALTH RED FLAGS

2.3.1. Reproductive Health

Striped Shrimp potential fecundity is proportional to the body length of the female (Shumway et al. 1985), and as such, the size of females in combination with their abundance (i.e., numbers) can provide insights into the reproductive potential of the population. Therefore, total egg production directly takes into consideration both the abundance and size distribution of females. As such, we developed a study-area wide metric of total egg production using spatiotemporal modelling, similar to the modelling used to develop FB_{pop}.

There were no known size (CL) to fecundity relationships available for Striped Shrimp in the study area, so the relationship identified by Parsons and Tucker (1986) was used to estimate the potential fecundity of each female caught within a trawl set during the NSRF survey. This relationship is based on Northern Shrimp caught in the Northern Labrador Sea (off Cape Chidley) in 1982 (Parsons and Tucker 1986). Northern Shrimp and Striped Shrimp tend to have similar life history characteristics (Squires 1996), so this relationship was considered the best available.

Eq. 3

$$\text{Log}_{10}(\text{fecundity}_F) = 3.2715 * \log_{10}(\text{CL}) - 1.4550$$

Where, $fecundity_F$ is the predicted number of eggs carried by a female and *CL* is the female's carapace length (mm).

A spatiotemporal model was developed within the package *sdmTMB* (Anderson et al. 2022) to estimate egg production, using the summed potential fecundity from individual fecundity (calculated in Eq. 2) at each set location.

Total egg production index (TEPI) model:

Eq. 4

$$\text{EggProduction}_{set} = \text{s(Depth, k = 5) + as.factor(Year)}$$

Where, $EggProduction_{set}$ was the standardized predicted number of eggs (1,000s of eggs/km^2). *Year* was the year that the trawl set occurred and represented as a factor and *Depth* is the average depth where the trawl set occurred (m). The basis dimensions (i.e., complexity) of the thin plate regression splines used in the smooth relationship between *Depth* and *EggProduction* is represented by *k*. Spatial and spatiotemporal autocorrelation were included as Gaussian random fields, thereby accounting for unmeasured or latent habitat suitability metrics change through space and by year. The spatiotemporal random fields were assumed to be independent across years. The model used a delta log-normal distribution and incorporated anisotropy.

Using the results from Eq. 4, the egg production index was predicted throughout the study area on a 5 km^2 gridded depth surface. Then, an area-weighted annual TEPI was calculated from 2005 to 2022 within the study area using the predicted density surface and the same methods described for FB_{pop}.

The TEPI was meant to act as a "red flag" metric associated with reproductive health and what is expected to be influencing the fishable Striped Shrimp abundance three (or likely more) years into the future. Since it is unclear how many years it takes Striped Shrimp to grow from eggs to fishable size (but is likely slower than more southerly *Pandalus* spp. populations) (Baker et al. 2021), and it is unknown if a single poor year of TEPI would lead to significantly poor future outcomes for the population, we used a three-year moving average of TEPI as the indicator.

2.3.2. Ecosystem Outlook

Stomach analyses of potential predators throughout the study area have found Striped Shrimp within the stomachs of Redfish, Greenland Halibut, skates, grenadiers (Polaczek et al. 2023), and Atlantic Cod (DFO, unpublished data). The overall influence of these predators on Striped Shrimp biomass trends and population dynamics remains unquantified. However, *Pandalus* spp.

population dynamics are commonly influenced by top-down drivers, such as predators. For example, in the Gulf of Maine longfin squid (*Doryteuthis pealeii*) populations were deemed a significant factor in the collapse of the Northern Shrimp (Richards and Hunter 2021). Off of NL, Northern Shrimp productivity was negatively related to Atlantic Cod, Redfish, and Greenland Halibut biomass in the previous year (Pedersen et al. 2022). In West Greenland waters, Greenland Halibut hindered Northern Shrimp population growth, despite favorable environmental conditions for Northern Shrimp population growth (Wieland et al. 2007). Incorporating predators as a stock health “red flag” will formally incorporate ecosystem factors into SFA 4 Striped Shrimp stock assessments and provide insights into current and anticipated issues that may arise for the Striped Shrimp population from top-down forcing.

The study area had a large population explosion of Redfish in recent years (Baker et al. in prep[1]), but this increase has been dominated by small individuals (i.e., too small to prey upon fishable shrimp). Since Redfish tend to be caught within cohorts of similar sizes within single survey sets (i.e., there is very little variation of Redfish sizes within a set), the total weight/number recorded during sets was used as rough indication of the size of Redfish within each set. Redfish larger than approximately 15 cm, corresponding to approximately 44 g (Perreault et al. 2022) were considered potential predators of fishable Striped Shrimp (DFO, unpublished data); herein referred to as large Redfish. All sets with average Redfish weight less than 0.044 kg were set to zero to calculate an estimate of only Redfish deemed to be potential predators of fishable Striped Shrimp.

A total potential predator index (PPI) was calculated using available data from the NSRF survey. The biomass of large Redfish, Greenland Halibut, skates, and grenadiers were estimated individually in R using the package *sdmTMB* and similar techniques as described in Eq. 1 and within Baker et al. (in prep[1]).

PPI model (taxa-specific):

Eq. 5

$$\text{Density}_{\text{Fish}} = \text{s}(\text{Depth}, k = 5) + \text{as.factor}(\text{Year})$$

Where, $\text{Density}_{\text{Fish}}$ was the predicted density (kg/km^2) of each fish taxa at a given set. *Depth* was the bottom depth (m) of the trawl set and *Year* was the year that the trawl set occurred and represented as a factor. The basis dimensions (i.e., complexity) of the thin plate regression splines used in the smooth relationship between *Depth* and *Density* is represented by *k*. Spatial and spatiotemporal autocorrelation were included as Gaussian random fields, thereby accounting for unmeasured or latent habitat suitability metrics change through space and by year. The spatiotemporal random fields were assumed to be independent across years. The family used for the modelling was dependent on fish taxa (decided by Akaike information criterion - AIC): Greenland Halibut – Tweedie, large Redfish – delta log-normal, skates – delta log-normal, grenadiers – delta log-normal.

Density of each fish taxa was predicted throughout the study area on a 5 km^2 gridded surface (IOC et al. 2022). Then, annual biomass indices were calculated within the study area using the predicted density surface and the same methods used in calculated FB_{pop}. The biomass indices for each taxon were summed to create a PPI for the study area.

Similar to TEPI, single-year spikes in the biomass indices of predators were considered unlikely to have long-lasting effects on the future fishable biomass. Instead, a three-year moving average of PPI was used as the red-flag metric.

2.3.3. SFA 4 - Specific Population Health

A fishable biomass estimate of SFA 4 (only) was used as an indicator of SFA 4-specific Striped Shrimp population health. This metric was included to identify signs of localized depletion within SFA 4. To ensure consistency with the SFA 4 Striped Shrimp stock assessment, Ogmap-derived estimates were used to examine trends in this metric (see Le Corre et al. In prep[3] for details).

3. RESULTS

3.1. LIMIT REFERENCE POINT - POPULATION HEALTH

The distribution of fishable Striped Shrimp throughout the study area showed a general pattern of particularly large, consistent densities near the WAZ/EAZ border, along the shelf edge of SFA 4, and into Hudson Strait (Figure 2). The model-derived FB_{pop} was low in 2005 and 2006, then remained variable throughout the time series (Figure 3). FB_{pop} was the highest in the time series in 2022.

The year 2010 represented the lowest fishable biomass from which the fishable biomass was able to recover to beyond the long-term average three years later and remain recovered for three years - $B_{recovery}$ (Figure 3). B_{loss} corresponded to the FB_{pop} in 2005. Based on initial modelling results, the FB_{pop} LRP was estimated to be at a value between 2006 and 2007 levels (Figure 4).

In 2022, FB_{pop} was estimated to be five times the LRP with high certainty (Figure 4).

3.2. STOCK HEALTH RED FLAGS

3.2.1. Reproductive Health

Females ranged in size from 8 mm to 32.9 mm CL, with an average of 22.3 mm CL through the time series. Set-specific egg production ranged from 0 to 55 million eggs, with an average of 936,681 eggs. The three-year moving average of TEPI throughout the study area increased from 2007 to 2016, then declined to 2021, but remained above the long-term mean (Figure 5). TEPI remains high in 2022 and shows no cause for concern.

3.2.2. Ecosystem Outlook

The three-year moving average of PPI increased during 2007–13, generally declined from 2013–21 (Figure 6). The 2022 value is slightly above the time-series average. The trend was heavily influenced by the biomass of Greenland halibut and large Redfish, whereas other potential predator biomass indices remained a low proportion of the overall PPI throughout the time series (Figure 6). In 2022, PPI showed no cause for concern.

3.2.3. SFA 4 - Specific Population Health

The SFA 4-specific fishable biomass index, with the exception of 2008, was relatively low from 2005 to 2012. Since 2013, it has remained above the average value of the 2005–13 time series.

[3] Le Corre, N., Skanes, K.R., Baker, K.D., Sullivan, D., Coffey, W., Cyr, F., Belanger, D., and Morrissey, K. In prep. An Assessment of Northern Shrimp (*Pandalus borealis*) and Striped Shrimp (*Pandalus montagui*) in Shrimp Fishing Area 4 in 2022. DFO Can. Sci. Advis. Sec. Res. Doc.

In 2022, the index was above the long-term mean, was on an increasing trend since 2020, and showed no cause for concern (Figure 7).

4. DISCUSSSION

4.1. MODEL-BASED & MULTI-INDICATOR APPROACHES

The development of spatiotemporal models for estimating biomass indices throughout the study area is an important step in a more thorough understanding of the population dynamics and moves one step closer to assessing the population as a whole (Hilborn 2002), thereby reducing scale mismatch. Model-based methodologies can account for inconsistent data collection and inevitable incomplete survey coverage (Evans et al. 2021), account for random effects, incorporate spatial-varying factors, and make predictions in areas smaller or larger than the area surveyed (Barnett et al. 2021).

Pandalid shrimp are known to have patchy distributions and patterns in abundance. OGMAP, and particularly STRAP can be highly influenced by a single large catch in a given strata that can in turn easily skew biomass estimates for the entire stratum and result in disproportionally large confidence intervals, as witnessed in SFA 4 Northern Shrimp biomass estimates in 2022 (DFO 2023c).

Conventional methods for developing a PA framework and identifying reference points have resulted in indicators rarely swaying from simple biomass/abundance indicators (Hilborn 2002). However, the formal adoption of red-flag metrics allow for a more holistic approach focussed on overall stock health. In addition, using multiple methods to help pinpoint when a stock may be considered reaching the point of “serious harm”, particularly in data deficient stocks or stocks with short data time series (DFO 2023a), highlights the variability in methods and allows for the incorporation of different assumptions and objectives to be considered in their identification.

4.2. STOCK STATUS RESULTS

Throughout the history of the NSRF survey time series Striped Shrimp FB_{pop} has, for the most part, remained above the LRP. As a result, the overall stock status was identified as being above the LRP for all but two years: 2005 and 2006 were deemed *Critical*.

The three-stock health red flag indicators showed no cause for concern in recent years. In 2022, TEPI and the SFA 4-specific fishable biomass index remained above their time series averages, while PPI was slightly above the time series average.

Although Striped Shrimp are not considered a target fishery within SFA 4, records of targeted fishing activities have increased in prevalence in recent years and exploitation rate indices can be quite high through the available time series (e.g., >15% in 2011/12 and 2012/13). Care should be taken to not underestimate the potential for fishing pressure (both inside and outside of SFA 4) to influence population dynamics because Striped Shrimp are caught as bycatch.

4.3. MOVING FORWARD

Efforts to predict future Striped Shrimp biomass should continue. Because of the relatively short time series of survey data available, preliminary analyses (not presented here) were ineffective at creating a reliable forecast model to predict Striped Shrimp biomass. Once developed, a forecasting model could easily be integrated into the PA framework by using the forecasted FB_{pop}, rather than the last available estimate from the survey, to help promote real-time management of resource use. In addition, efforts to refine model-derived FB_{pop} estimates will continue, as more data are obtained and additional covariates identified.

There is an extremely large cohort of small Redfish within the study area (Baker et al. in prep[1]). Juvenile Redfish are expected to have a competitive role over food resources until they reach a size where predation of shrimp is possible (DFO, unpublished data). As these individuals grow, they could have an increasing influence over the ecosystem, both as predators and competitors for resources. The rate of shrimp consumption by Redfish and its potential influence on Striped Shrimp population dynamics remains unknown. It is imperative that more dedicated research on Redfish dynamics and shrimp consumption be initiated to more fully understand the influence of Redfish on *Pandalus* spp. population dynamics. In addition, efforts should be taken to explore collaborations with researchers in areas where large changes in Redfish populations have influenced *Pandalus* spp. population trends to help predict the future repercussions of such a large Redfish cohort.

There was no CL to fecundity relationship available for Striped Shrimp, so that Northern Shrimp was used as a proxy. The TEPI of the SFA 4 Striped Shrimp population currently assumes a constant CL to fecundity relationship through the time series, but in the case of Northern Shrimp this relationship is known to vary spatially and temporally, resulting from environmental and ecological changes, including parasites in the egg masses and changes in water temperature (Beita Jiménez 2021; Parsons and Tucker 1986; Shumway et al. 1985). To ensure changes with TEPI are accurately documented within the population, NSRF sampling should extend to size-based stratified random sampling of female Striped Shrimp for estimating CL-fecundity relationships annually, allowing the calculations of set-specific and annual egg production to be adjusted based on these findings. This will provide a more accurate estimate of TEPI moving forward, while also ensuring variations in CL to fecundity relationships are noted and investigated further, particularly in relation to potential epidemiological conditions in the population.

Although EAZ, WAZ, and SFA 4 will continue to be assessed separately within different DFO administrative regions, we strongly encourage that whole-area analyses (e.g., biomass estimates and L50) be incorporated into future assessments of SFA 4 Striped Shrimp for a more comprehensive picture of population dynamics throughout the northern Canada populations. This will allow assessment scientists, industry, and FRM to view the SFA 4 stock dynamics in the larger context of the northern population. This is particularly important in SFA 4 because SFA 4 is located downstream of EAZ and WAZ and will be directly influenced by changes within those assessment areas, and unlike more southerly stocks of Northern Shrimp, the timing of the survey in relation to the fishery of Striped Shrimp in SFA 4 does not permit calculations of exploitation rate indices in the following year.

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6. FIGURES

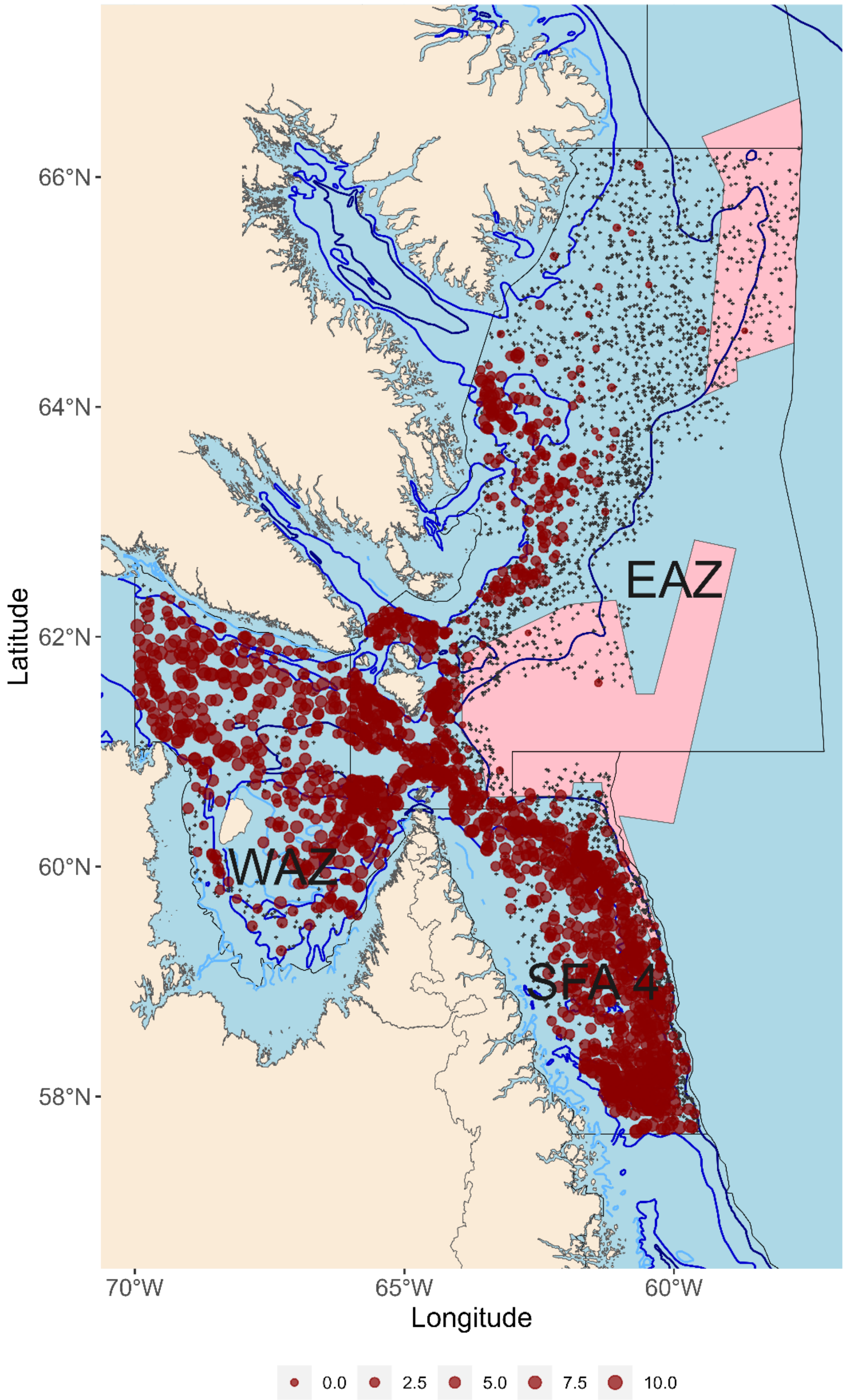

Figure 1. Map depicting the study area and shrimp assessment areas Western Assessment Zone (WAZ), Eastern Assessment Zone (EAZ) and shrimp fishing area (SFA) 4. Red circles denote logged catches (kg/km^2) of Striped Shrimp (Pandalus montagui) from the Northern Shrimp Research Foundation (NSRF) survey, 2005 to 2022. The pink polygons are Hatton Basin Conservation Area (south) and Davis Strait Conservation Area (north). Depth contours (100 m, 200 m, and 500 m) are depicted by blue solid lines.

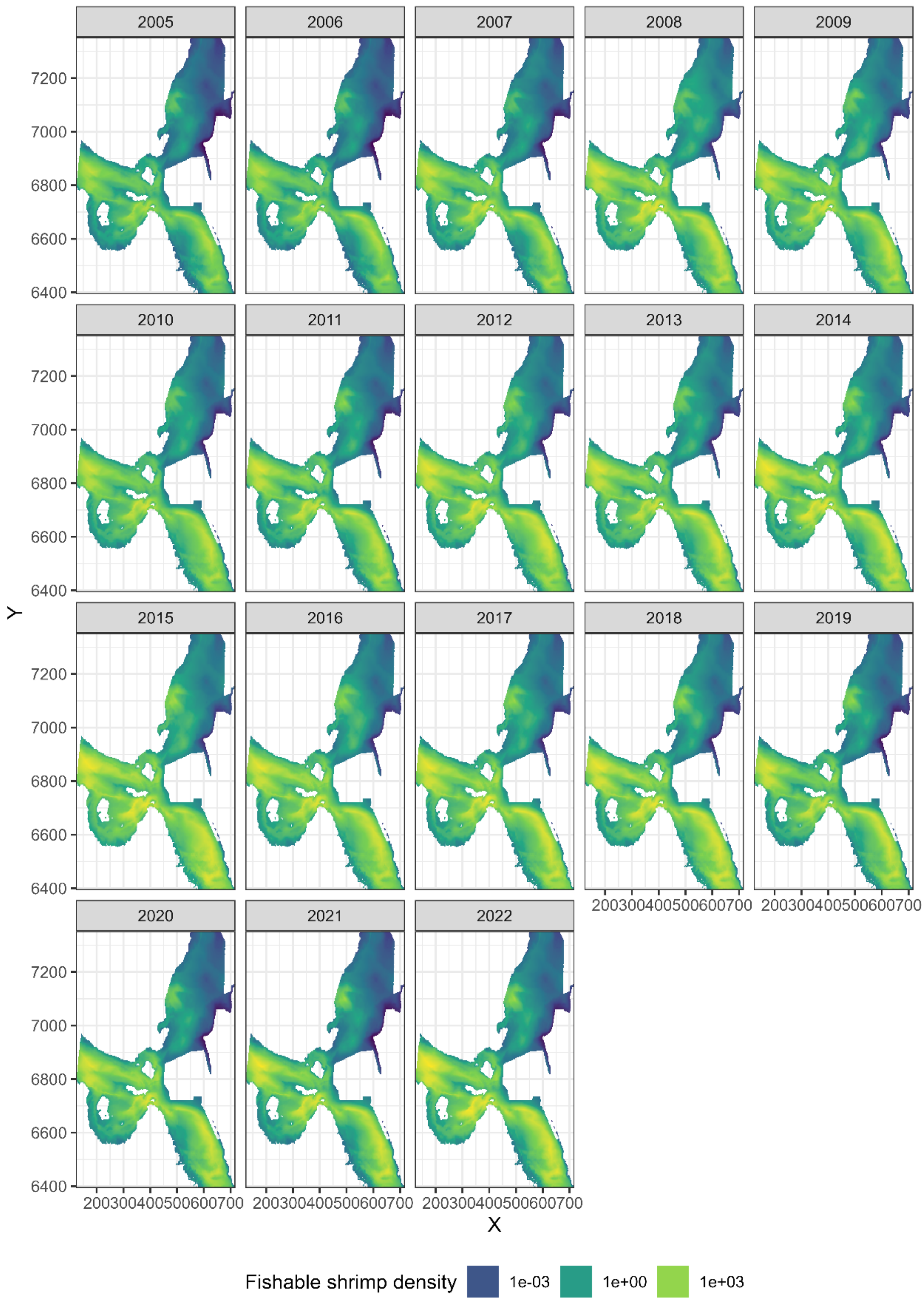

Figure 2. Spatiotemporal modelling results of fishable Striped Shrimp density, based on Northern Shrimp Research Foundation (NSRF) surveys, 2005 to 2022.

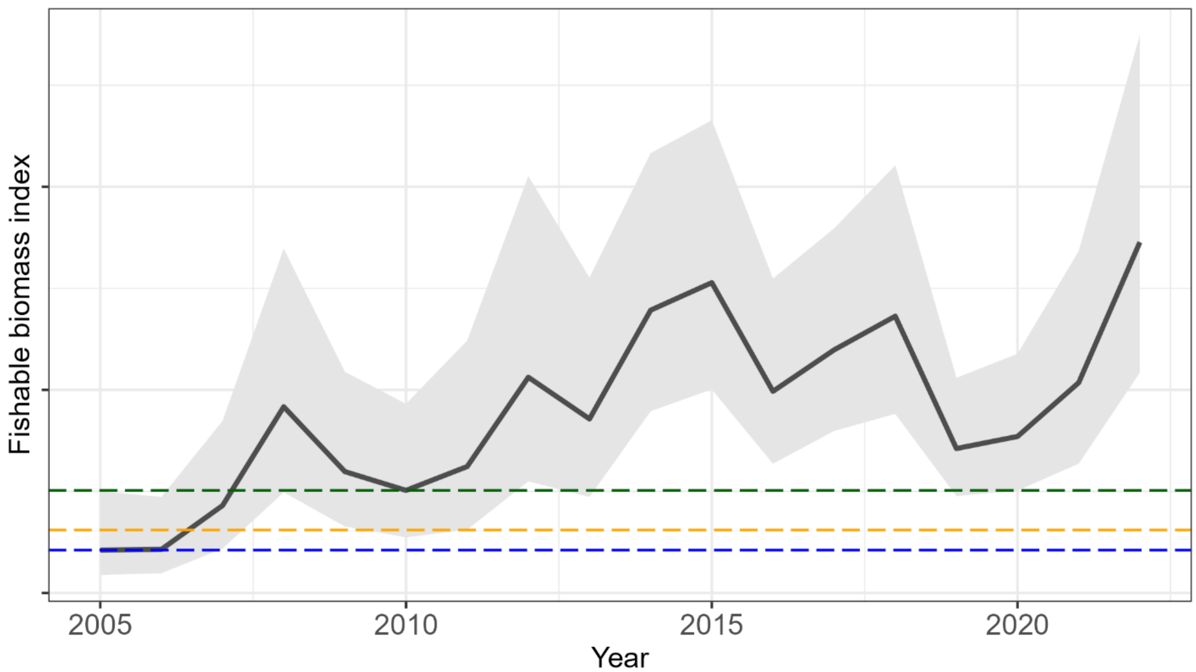

Figure 3. Modelled Striped Shrimp fishable biomass index in the Western Assessment Zone (WAZ), Eastern Assessment Zone (EAZ), and shrimp fishing area (SFA) 4 combined (solid line) based on Northern Shrimp Research Foundation (NSRF) surveys, 2005 to 2022. Shaded ribbon represents confidence interval of estimates from model. Dashed lines represent estimates of the LRP based on different methodologies: $B_{recovery}$ (green), 40% of the time-series geometric mean (orange), and B_{loss} (blue). The y-axis begins at 0.

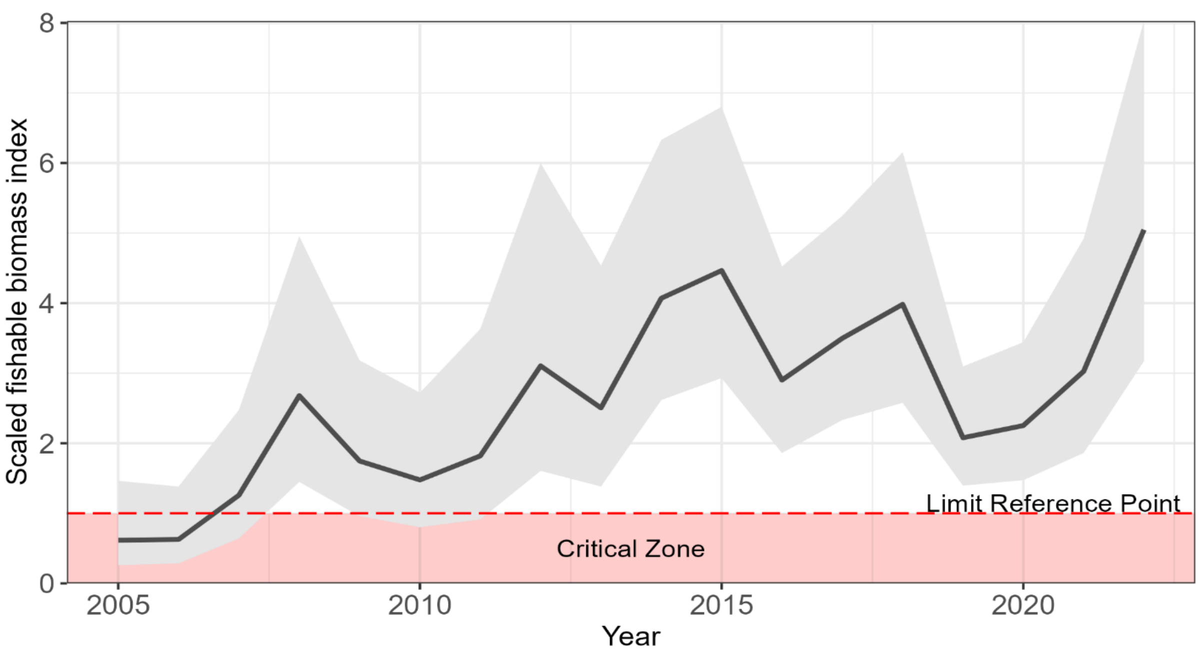

Figure 4. SFA 4 Striped Shrimp Precautionary Approach (PA) Framework: modelled Striped Shrimp fishable biomass index in the Western Assessment Zone (WAZ), Eastern Assessment Zone (EAZ), and shrimp fishing area (SFA) 4 combined (solid line) based on Northern Shrimp Research Foundation (NSRF) surveys, 2005 to 2022 with 95% confidence limits (values scaled to LRP).

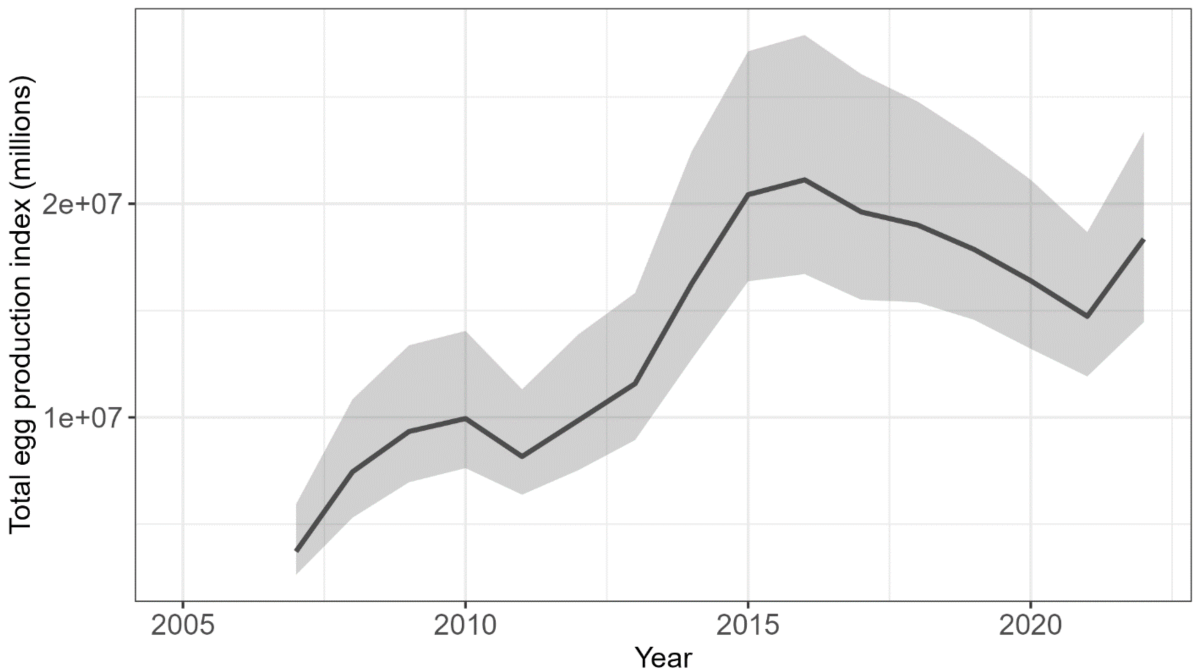

Figure 5. Three-year moving average of modelled total egg production index (millions) of Striped Shrimp in the Western Assessment Zone (WAZ), Eastern Assessment Zone (EAZ), and shrimp fishing area (SFA) 4 combined, based on Northern Shrimp Research Foundation (NSRF) surveys, 2005 to 2022.

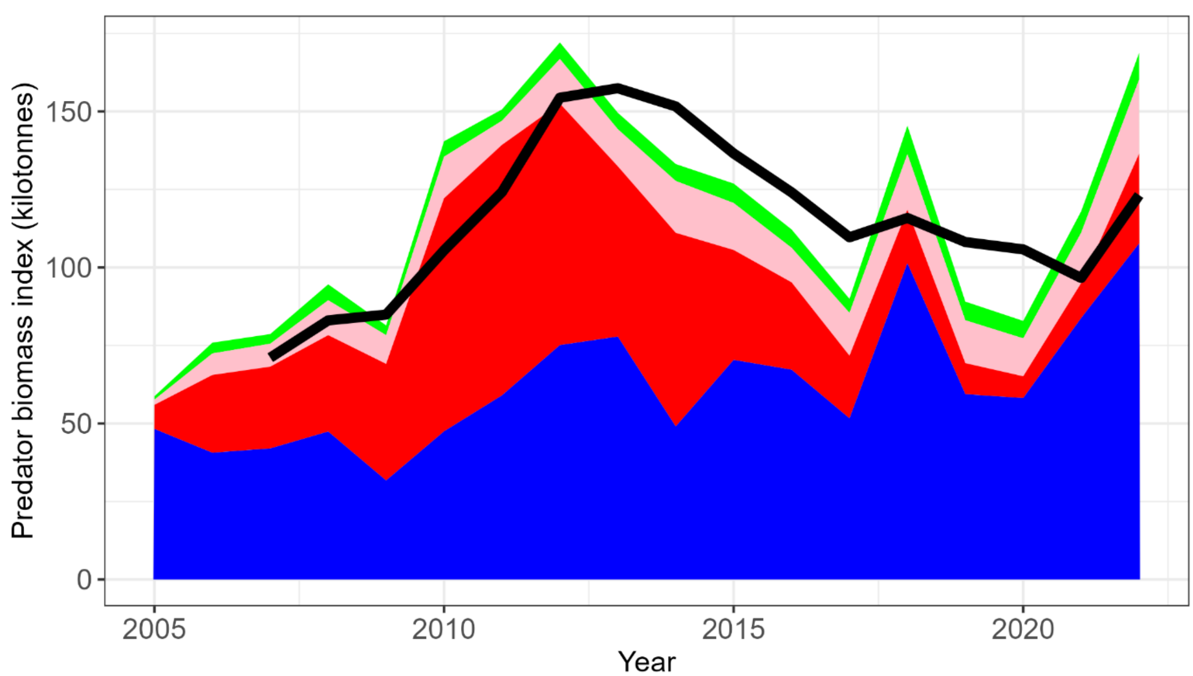

Figure 6. Modelled annual biomass indices (stacked shaded areas) and three-year moving average (black solid line) of potential predator indices (kilotonnes). Blue area – annual Greenland Halibut biomass index, red area – annual large Redfish biomass index, pink – annual skate biomass index, green – annual grenadier biomass index.

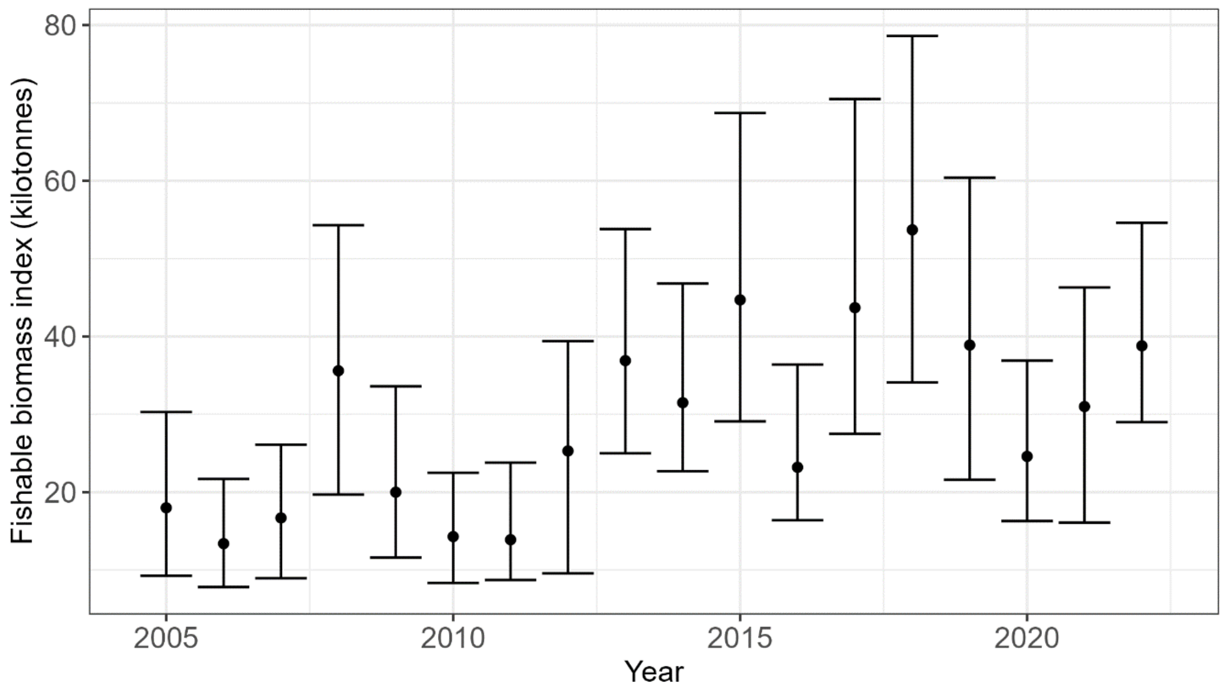

Figure 7. Ogmap-derived Striped Shrimp fishable biomass index in shrimp fishing area (SFA) 4 (points) based on Northern Shrimp Research Foundation (NSRF) surveys, 2005 to 2022. Error bars represent confidence interval of estimates.

7. APPENDIX – SUPPLEMENTAL FIGURES

Total Egg Production Index

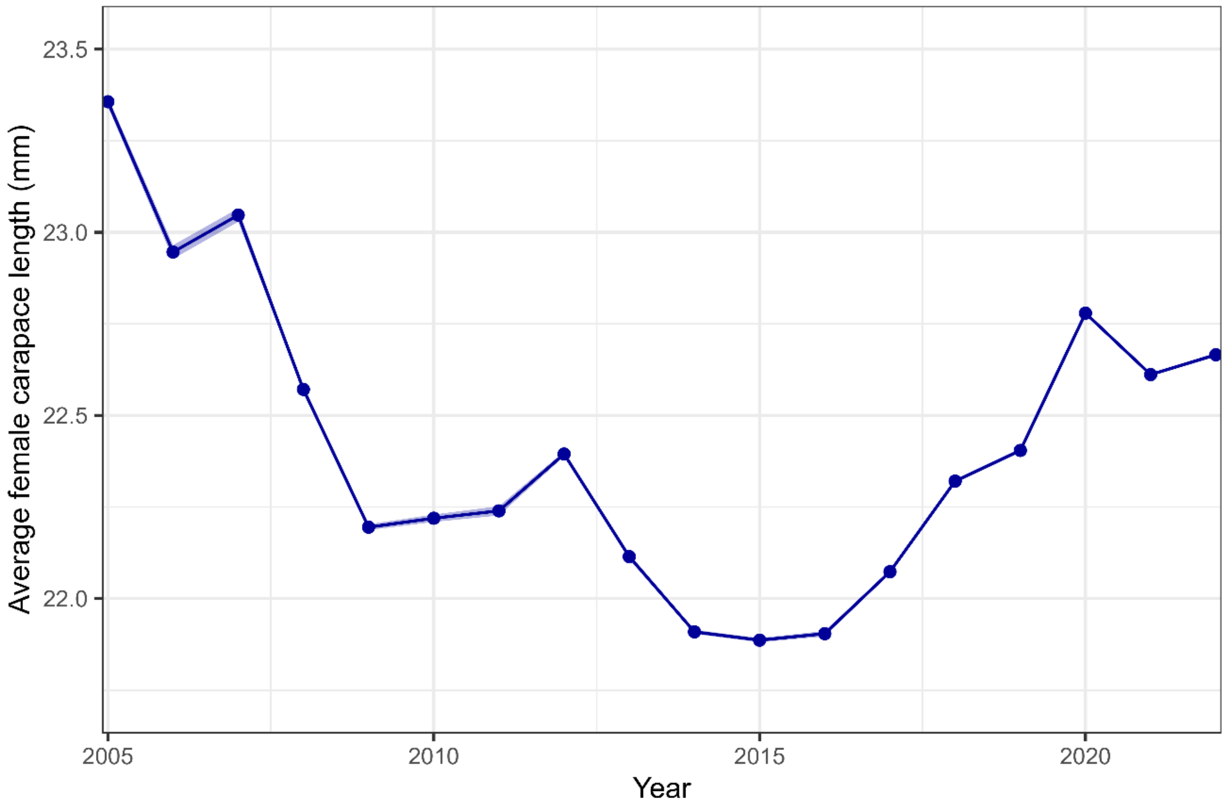

Figure S.1. The average carapace lengths (mm) of Striped Shrimp females from the Northern Shrimp Research Foundation (NSRF) surveys, 2005–22.

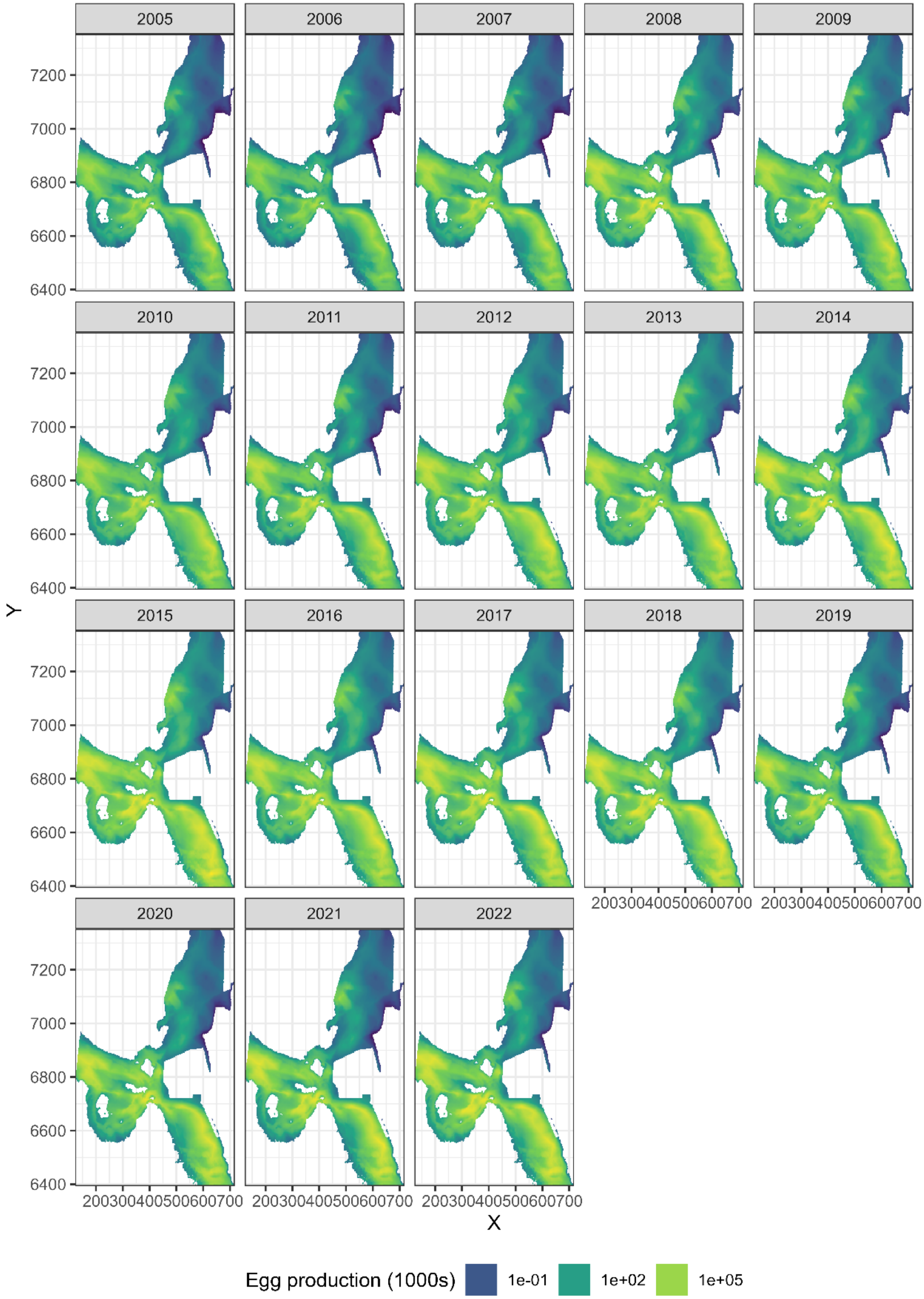

Figure S.2. Spatiotemporal modelling results of predicted egg production of Striped Shrimp, based on Northern Shrimp Research Foundation (NSRF) surveys, 2005–22.

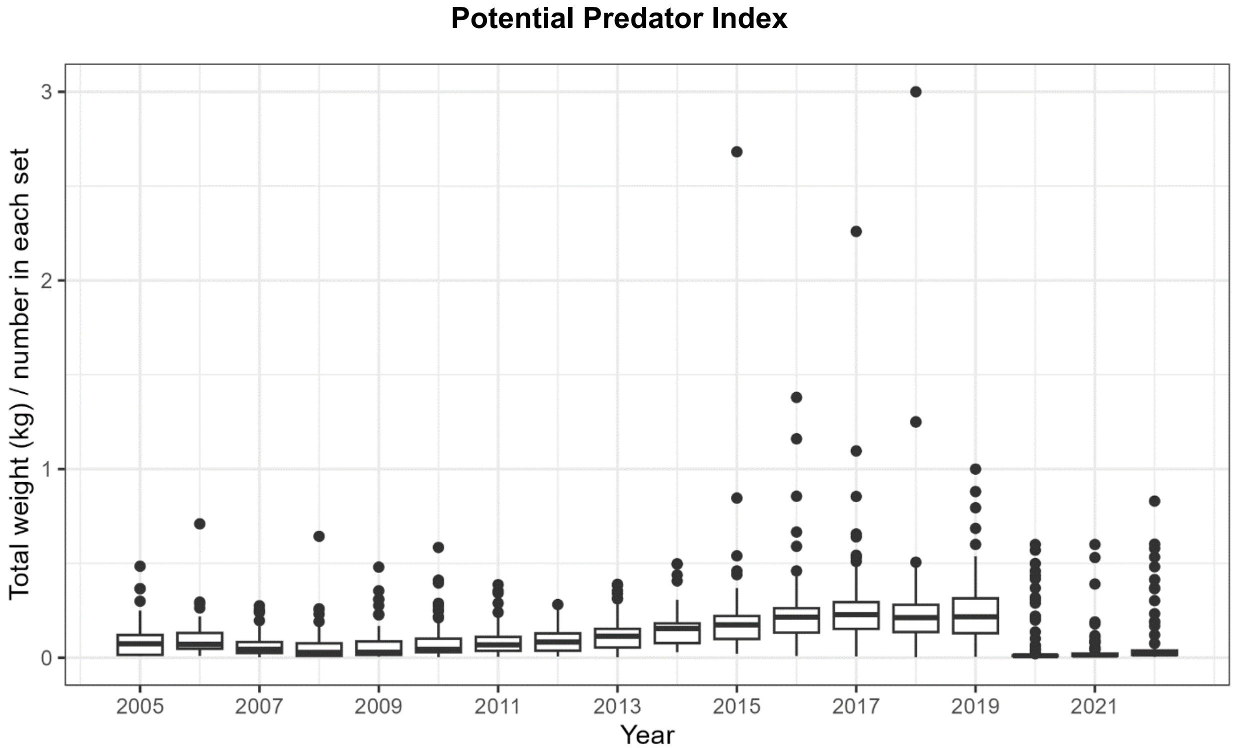

Figure S.3. The total weight / number of Redfish from trawl sets with Redfish in the Northern Shrimp Research Foundation (NSRF) surveys, 2005–22.

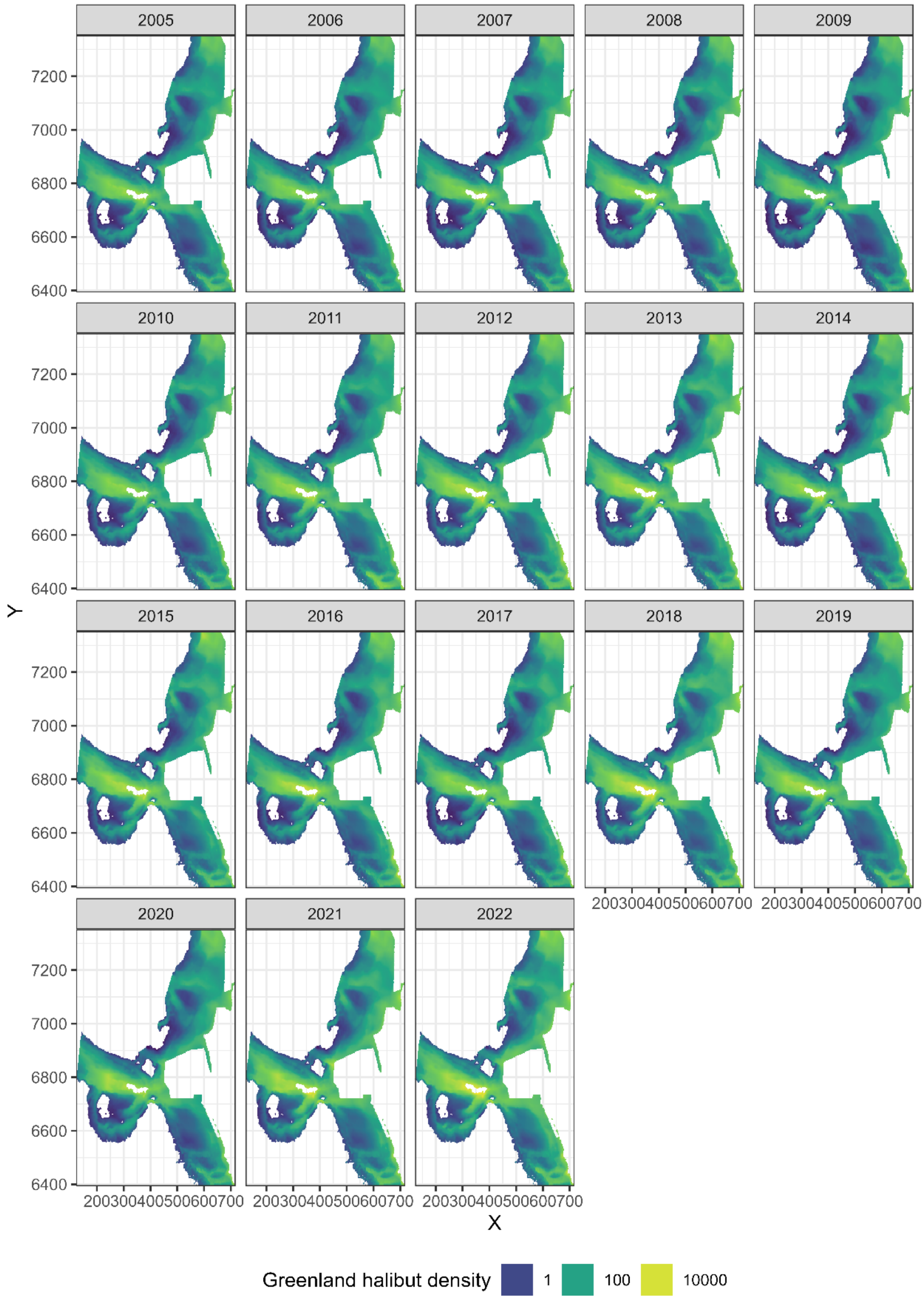

Figure S.4. Spatiotemporal modelling results of Greenland Halibut (kg/km²), based on Northern Shrimp Research Foundation (NSRF) surveys, 2005–22.

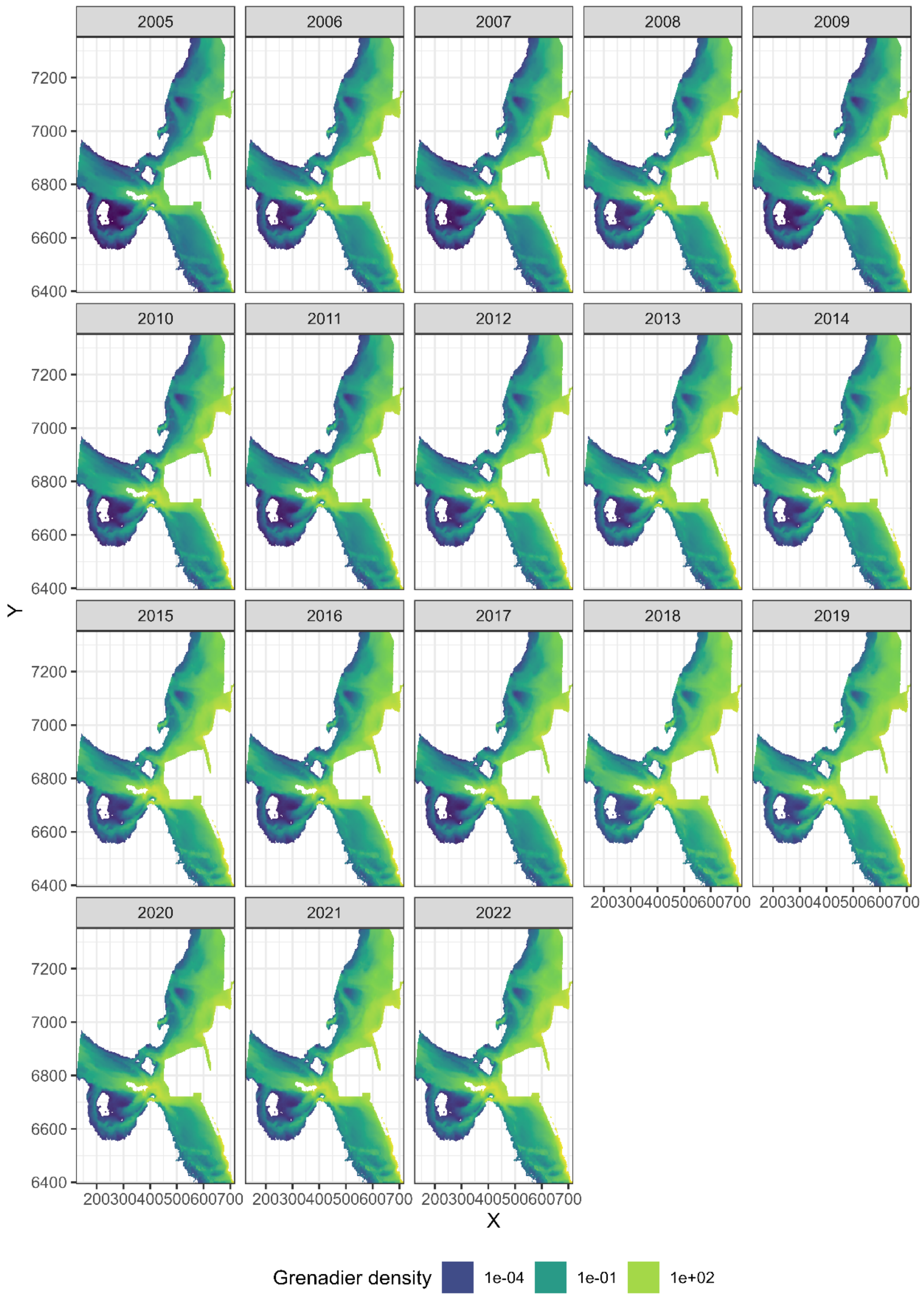

Figure S.5. Spatiotemporal modelling results of grenadiers (kg/km²), based on Northern Shrimp Research Foundation (NSRF) surveys, 2005–22.

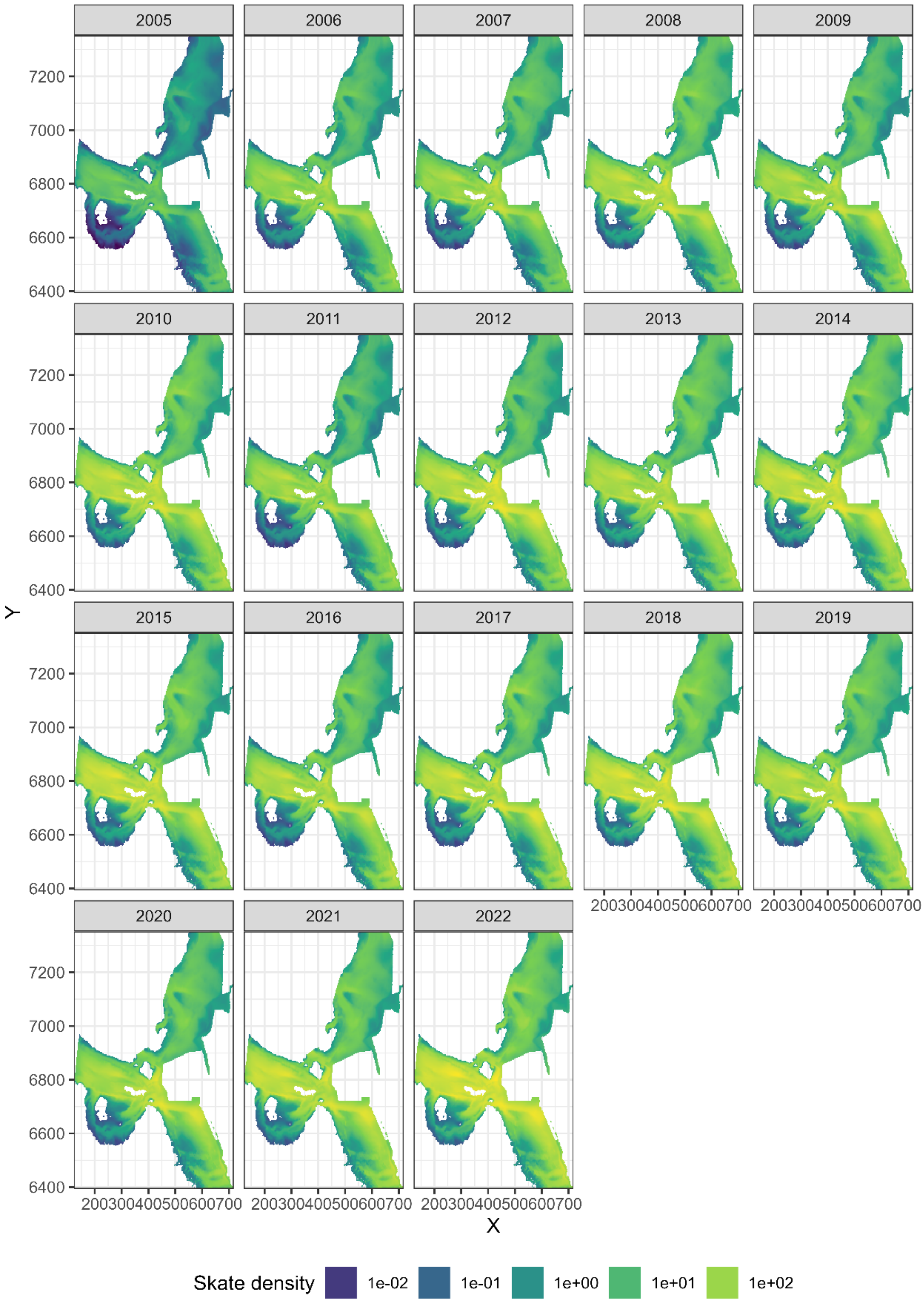

Figure S.6. Spatiotemporal modelling results of skates (kg/km²), based on Northern Shrimp Research Foundation (NSRF) surveys, 2005–22.

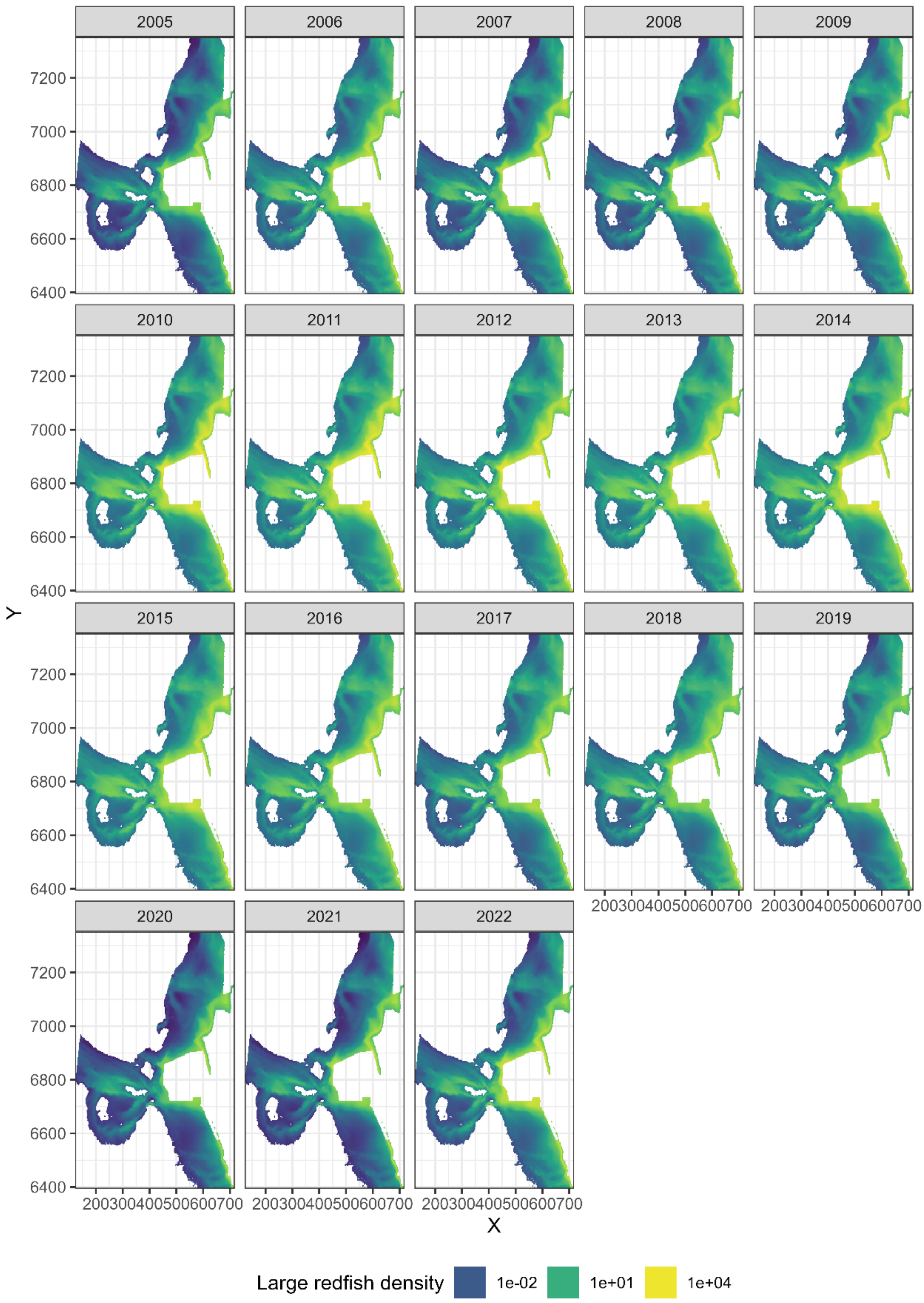

Figure S.7. Spatiotemporal modelling results of large Redfish density (kg/km^2), based on Northern Shrimp Research Foundation (NSRF) surveys, 2005–22.