Fisheries and Oceans Canada
Pêches et Océans Canada

Ecosystems and Oceans Science
Sciences des écosystèmes et des océans

Canadian Science Advisory Secretariat (CSAS)

Research Document 2023/089

Maritimes Region

Assessment of Scotian Shelf Snow Crab in 2019

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December 2023

Foreword

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

Published by:

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

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

ISSN 1919-5044
ISBN 978-0-660-68883-1 Cat. No. Fs70-5/2023-089E-PDF

Correct citation for this publication:

Zisserson, B.M., Cameron, B.J., Glass, A.C., and Choi, J.S. 2023. Assessment of Scotian Shelf Snow Crab in 2019. DFO Can. Sci. Advis. Sec. Res. Doc. 2023/089. v + 135 p.

Aussi disponible en français :

Zisserson, B.M., Cameron, B.J., Glass, A.C., and Choi, J.S. 2023. Évaluation du crabe des neiges du plateau néo-écossais en 2019. Secr. can. des avis sci. du MPO. Doc. de rech. 2023/089. v + 142 p.

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ABSTRACT

Landings in 2019 for North-Eastern Nova Scotia (N-ENS) and South-Eastern Nova Scotia (S-ENS) were 629 t and 6,632 t, respectively, representing a decrease of 15% (N-ENS) and an increase of 9% (S-ENS) relative to the previous year . Total Allowable Catches in 2019 were 631 t, 6,632 t, and 0 t in N-ENS, S-ENS, and 4X, respectively. Due to low commercial biomass levels, there was no allowable catch in 4X for the 2018–19 season. Non-standardized catch rates in 2019 were 87 kg/trap haul in N-ENS and 105 kg/trap haul in S-ENS—which relative to the previous year represents an increase of 40% (N-ENS) and a decrease of 9% (S-ENS). The capture of soft-shelled Snow Crab in N-ENS decreased to 5% from approximately 25% in 2018. In S-ENS, the relative occurrence of soft-shell Snow Crab was approximately 2%, consistent with 2018. Soft-shell discard rates in 4X are traditionally very low, due to season timing. Bycatch of non-target species is extremely low (< 0.4%) in all Crab Fishing Areas (CFAs). In both N-ENS and S-ENS, moderate internal recruitment to the fishery is expected for next year (and likely for 2–4 years) based on size-frequency histograms. Based on survey catches, CFA 4X shows limited potential for substantial internal recruitment to the fishery for the next 4–5 years. Movement is potentially an important source of 4X Snow Crab. In all CFAs, there was a substantial recruitment of females into the mature segment of the population from 2016–2018. Mature Snow Crab densities are now declining but small Snow Crab (< 40mm carapace width) resulting from this period of increased egg production are now observed in all areas in both sexes. These population characteristics are tempered by a number of uncertainties, including the influence of predation and rapid temperature swings (especially in CFA 4X and parts of CFA 24). Both can have direct and indirect influences upon Snow Crab, which are cold-water stenotherms. Predation from halibut is a potentially large and increasing source of natural mortality for Snow Crab on the Scotian Shelf. A new peer-reviewed assessment methodology, conditional auto-regressive spatio-temporal model (carstm), has been adopted that incorporates both survey catches and ecosystem covariates to estimate a commercial Snow Crab abundance index. This index is coupled with a population-dynamics fishery model to determine fishable biomass. The modelled post-fishery fishable biomass index of Snow Crab in N-ENS was estimated to be 4,460 t, relative to 3,299 t in 2018. In S-ENS, the post-fishery fishable biomass index was 54,408 t, relative to 44,705 t in 2018. In 4X, the pre-fishery fishable biomass was 418 t, relative to 428 t in 2018. The N-ENS fishing mortality (F) in 2019 has been estimated to have been 0.14 (exploitation rate 0.13), a decrease from 0.22 in 2018. The S-ENS fishing mortality (F) in 2019 has been estimated to have been 0.12 (exploitation rate 0.13), a decrease from .13 in 2018.The F for 4X in 2018–2019 was 0 as there was no commercial fishery. With expected increasing recruitment for both N- and S-ENS, coupled with falling F over recent years, possibilities for harvest strategy is less limited. Additional work is required to determine more applicable (than current survey-based) Harvest Control Rules and associated management measures in 4X.

MANAGEMENT

The Scotian Shelf Ecosystem (SSE) Snow Crab (*Chionoecetes opilio*) stock is managed as three main areas: North-Eastern Nova Scotia (N-ENS), South-Eastern Nova Scotia (S-ENS), and 4X (Table 1; Figure 1). S-ENS is subdivided into two fishery management areas: Crab Fishing Area (CFA) 23 and CFA 24.These areas are *ad hoc* divisions based upon political, social, economic, and historical convenience, with little biological basis.

Fishing seasons have also had a complex evolution based upon economic, safety, and conservation considerations: seasonal weather conditions; catch of soft-shell/white Snow Crab; disruption of mating periods; and overlap with other fisheries, especially American Lobster and Northern Shrimp. From 1982 to 1993, the management of the Eastern Nova Scotia (ENS) fisheries was based on effort controls (size, sex, shell-hardness, season, license, trap limits). Additional management measures were introduced from 1994 to 1999: Individual Boat Quotas (IBQs), Total Allowable Catches (TACs), 100% dockside monitoring, mandatory logbooks, and at-sea monitoring by certified observers (currently at levels of 5%, 5%, and 10% in N-ENS, S-ENS, and 4X, respectively). Vessel Monitoring Systems (VMS) have been implemented in S-ENS and 4X, and voluntary management measures requested by fishers were also introduced in some areas, such as a shortened fishing season and reduced numbers of traps. The designation of a “temporary license” holder was dropped in 2005 with a fleet rationalization that created a permanent stake in the fishery for all license holders.

In 2006, the soft-shell protocol was modified in S-ENS due to the expectation of an increased incidence of soft-shelled Snow Crab and the potential harm associated with handling mortality. Soft-shelled Snow Crab incidence observed by at-sea-observers was relayed to Fisheries and Oceans Canada (DFO) within 24 hours of landing, plotted on a two-minute grid, and re-broadcast to all members of industry on the ENS Snow Crab web location (as well as via email and fax).

Fishers are asked to voluntarily avoid fishing within 1.5 nautical miles of the locations that had greater than 20% soft Snow Crab in the observed catch. This adaptive fishing protocol allows rapid adjustment of fishing effort, shifting gear away from, or altogether avoiding, potentially problematic areas and also helping to save time, fuel, and other costs. This approach was not required in 4X due to the low incidence of soft Snow Crab in the catch and not adopted in N-ENS due to the short fishing season. However, due to high soft-shell incidence in N-ENS in 2007–2008, further direct management measures were implemented to address concerns of soft-shell handling mortality. These measures now include a spring season, in addition to the traditional summer season. This spring season was so instrumental in drastically reducing soft-shell catches that season start times were moved earlier in S-ENS as well. Finally, the voluntary return to the sea of immature, legal-sized Snow Crab (≥ 95 mm Carapace Width [CW]; pencil-clawed crab) was implemented in 2006 for all areas on the SSE, to allow these Snow Crab to complete their molting cycle and molt to maturity, thereby, simultaneously increasing the total yield per Snow Crab captured, as well as the total lifetime reproductive success of these large-sized males.

In 1996, DFO (Gulf Fisheries Centre [GFC], Moncton, New Brunswick) and Scotian Shelf Ecosystem (SSE) Snow Crab fishers initiated a Joint Project Agreement to assess SSE Snow Crab using a fisheries-independent trawl survey (Biron et al. 1997). It was officially accepted for use as an assessment tool in 1999. These surveys demonstrated the presence of unexploited Snow Crab in the south-eastern areas of the SSE, which subsequently led to large increases in TACs (Tables 2–4), fishing effort, landings, and catch rates (Figures 2–4), and the addition of new participants. Trawl surveys were formally extended to 4X in 2004.

Since 2013, research has been funded through Section 10 of the *Fisheries Act* (“fish allocation for financing purposes”). This mechanism provides additional quota to any license holder participating in a “Collaborative Agreement” (CA), which directly funds the Snow Crab scientific research program in the Maritimes Region. Since its inception in 2013, all license holders in the region have participated in the CA.

A Marine Stewardship Council (MSC) Certification was granted to the ENS fishery in September 2011. Four surveillance audits have been completed since that time. The Scotian Shelf Snow Crab fishery was re-certified under MSC Version 2 in September of 2017, without conditions. The fundamental difference between the prior standard and Version 2 is that the habitat and ecosystem considerations are much broader, taking into account cumulative impact of all certified fishery in the fishing area being assessed. Though no audits were expected to occur until late summer of 2018, an expedited audit was convened in November 2017 due to numerous interactions between Snow Crab fishing and endangered North Atlantic Right Whales (NARW) in the neighboring Snow Crab regions in the southern Gulf of St. Lawrence. Audit results maintained MSC certification for Scotian Shelf Snow Crab. Through a separate process MSC certification was suspended for the Gulf of St. Lawrence Snow Crab fishery due to negative interactions with NARW. A standard surveillance audit of the ENS Snow Crab trap fishery was convened in the fall of 2018. MSC certification (with conditions) remained intact following this surveillance audit. These conditions relate to minimizing potential impacts of the fishery on the endangered NARW. The assessors also recommend improving the fishery’s reporting of interactions with designated Species at Risk. The most recent surveillance audit occurred in March of 2020; results not yet published.

HISTORY

The Snow Crab fishery is currently the second most valuable commercial fishery (after American Lobster) in both Atlantic Canada and Nova Scotia. It has been active since the mid-1970s (Figure 2). The earliest records of landings were at levels of less than 1,000 t, mostly in the near-shore areas of ENS. By 1979, landings rose to 1,500 t, subsequent to which the fishery declined substantially in the mid-1980s and was considered a collapsed fishery. Recruitment to the fishery was observed in 1986 and, since that time, landings, effort and catch rates have increased considerably (Figures 2–4). In 1994, directed fishing for Snow Crab began in 4X, the southern-most range of distribution and continues at low harvest levels.

Annual TACs (Tables 2–4) increased to a peak in 2002–2003 at 9,113 t in S-ENS and 1,493 t in N-ENS. Approximately 10,000 t of Snow Crab were landed each year from 2000 to 2004. Thus, in S-ENS the post-1998 period was one of rapid expansion of both the economic importance of the Snow Crab fishery and also the spatial extent of the exploitation. In 2004, with persistent low levels of recruitment and a steady decline in fishable biomass estimates, since the early-2000s, precautionary exploitation strategies were adopted throughout the SSE.

In N-ENS, due to negligible recruitment, TACs declined sharply from 2004–2008. Increasing recruitment and fishable biomass estimates saw increased TACs until 2014. In 2015 and 2016, TACs were reduced due to low commercial biomass and an almost complete lack of recruitment to the fishery. These TAC declines were exacerbated by the adoption of Harvest Control Rules forcing the exploitation strategy in N-ENS to be more conservative. A new biomass estimation model, LBM (Lattice Boltzmann Method), was adopted in the 2017 assessment (2016 survey). This novel modelling approach saw a substantial increase in the biomass estimates for N-ENS, as modelled biomass estimates were used in determining a target exploitation rate rather than the previously-used survey index. In 2017, the TAC for N-ENS was the highest since 2004, in spite of continued poor recruitment to the fishery. This high TAC was essentially maintained in

2018 (5% reduction). In 2017, this LBM approach was further refined to the spatiotemporal models of variability (stmv) approach which was considered to have yielded unrealistically stable biomass estimates with limited ability to inform annual TAC decisions. In 2019, the N-ENS TAC was reduced by 20% in response to low catch rates and the TAC not being caught in 2018, coupled with minimally informative biomass estimates.

In S-ENS, TACs rose from 2005 to reach a previously unseen level in 2010, then gradually declined until 2015. The S-ENS TAC has been declining since 2016 due to decreased biomass estimates. The 2019 TAC increased by 10% given indications of increased recruitment and the highest catch rates since the expansion (number of licenses) of the S-ENS fishery.

The TACs in 4X varied between 230 t and 346 t from 2005 to 2012. Reduced biomass estimates and poor performance of the 2012–2013 fishery in 4X (< 1/2 TAC landed) resulted in drastic reductions in the 4X TAC for 2013–2014. The 4X TAC has remained low (relative to pre-2013 levels) as have commercial biomass estimates. No commercial TAC was available in 4X for the 2018–19 season due to low commercial biomass levels and catch rates. Commercial TACs were reinstated in 2019 at 55 mt.

METHODS

The primary driver of the analytical approaches developed for the assessment of Snow Crab on the SSE is the high temporal and spatial variability in spatial distributions of Snow Crab. This is likely due to the area being the southern-most extreme of the species' distributional range in the northwest Atlantic. All data analyses were implemented in the statistical computing language and environment R (R Development Core Team 2012) to allow migration and documentation of methods into the future. The complete analytical suite, coded in R, is posted to a GitHub repository website.

Conversions between cartographic and Cartesian co-ordinate systems for analytical purposes were computed with PROJ (Evenden 1995, Version 4.4.9) via the R-package rgdal (Bivand et al. 2016) onto the Universal Transverse Mercator grid system (UTM Region 20).

A number of spatial and/or temporal interpolation methods were used in this assessment. For rapid visualization of data (but not the actual assessment), thin-plate-splines were computed with the R-package fields::fastTps (Nychka et al. 2015), using a Wendland compactly supported covariance function with a range parameter of 25 km radius (theta) from every datum. This is a range comparable with that observed in the empirical variograms of many variables (Choi and Zisserson 2012).

For analytical purposes, a novel lattice-based approach (stmv) was used in 2017 and 2018. This approach was found to be so overly time and computationally expensive and not operationally feasible given the time constraints of annual stock assessments. A more operational lattice-based approach using conditional auto-regressive spatio-temporal models (carstm) has been implemented for the current assessment. (See below for details.) This methodology was formally peer-reviewed in February 2020.

FISHERIES DATA

Fishery catch rates are potentially biased indicators of Snow Crab abundance. The spatial and temporal distribution of both Snow Crab and the fishing effort are not uniform, varying strongly with season, bottom temperatures, food availability, timing of spring plankton blooms, reproductive behavior, substrate/shelter availability, relative occurrence of soft and immature Snow Crab, species composition, fisher experience, bait type, soak time, and ambient currents. Catch rates have not been adjusted for these influences and are presented here only to maintain continuity with historical records. Fishery catch rates are used as a measure of fishery performance and not necessarily stock performance/abundance.

Mandatory commercial fishing logbooks (completed onboard fishing vessels by the captain) provide information on location, effort (number of trap hauls), and landings (verified by dockside monitoring). The data are stored in the MARFIS database (DFO Maritimes Region, Policy and Economics Branch, Commercial Data Division). Data were quality checked.

At-sea-observed data provides information about the size structure and the Carapace Condition (CC) of the commercially exploited stock (Table 5; Figure 5). The data are stored in the Industry Survey Database (ISDB). At-sea observers are deployed randomly with the coverage being as evenly distributed as possible between vessels through an automated deployment system. The target coverage (as a percent of total landings) is set at 5% in S-ENS and N-ENS and 10% for 4X. At-sea-observer data is used to compute the potential bycatch of non-Snow Crab species by the Snow Crab fishery. Bycatch estimates of each species *i*, was extrapolated from the biomass of species *i*, observed in the catch and the relative observer coverage by:

$$\mathit{Bycatch}_i\ [kg] = \mathit{Observed\ catch}_i\ [kg] \times \mathit{Total\ Snow\ Crab\ landings}\ [kg] / \mathit{Observed\ catch}_{\mathit{Snow\ Crab}}\ [kg]$$

At-sea observers did not follow proper reporting protocol (only as it relates to bycatch) for the 2018 fishery in N- and S-ENS. Reliable species-specific data is not available for 2018. This issue was resolved for the 2019 fishery. Tables 10–12 include species specific bycatch levels for the past three years when proper reporting occurred by at-sea observers.

RESEARCH SURVEY DATA

Spatial coverage in the survey is (1) extensive, going well beyond all known commercial fishing grounds and (2) intensive, with a minimum of one survey station located pseudo-randomly in every 10 × 10 minute area (Figure 6). This sampling design was initially developed to facilitate geostatistical estimation techniques (Cressie 1993). Additional stations have been added adaptively based upon attempts to reduce local estimates of prediction variance, as well as identifying the spatial bounds of Snow Crab habitat. Between 2004 and present, approximately 400 stations have been sampled annually. The survey vessel *F/V The Gentle Lady* was used from 2004–2013. Due to the sinking of *F/V The Gentle Lady* in December 2013 during a commercial fishing trip, the subsequent surveys have been conducted aboard a vessel with similar characteristics; the *F/V Ms. Jessie*. Due to adverse weather conditions throughout the survey season of 2017, 32 stations did not get sampled as planned. These stations were on southern side of Banquereau Bank, on the south-east corner of the Scotian Shelf continental edge. All intended survey stations were completed in the 2018 survey. An extended survey vessel breakdown in the 2019 survey saw a later-than-normal completion, potentially affecting inter-annual comparability. To avoid a similar situation to 2017, with an entire block of stations going unsampled for the year, 7 stations were removed systematically towards the end of the 2019 survey. These were in areas where higher station density and lower inter-station variability occurred in past surveys. Total station numbers in 4X were strategically reduced from 34 to 20 since 2017 to match constricting viable habitat and reduce survey costs. The lower station count in 4X should have limited effects on modelled biomass estimates but must be considered in the interpretation of unadjusted density estimates as stations removed have had zero catches of Snow Crab for multiple years.

The extensiveness of the sampling design allows the spatial bounds of the Snow Crab population to be objectively determined. This information is essential to provide reliable estimates of biomass and population structure (e.g., size, sex, maturity). The spatial distribution of Snow Crab is dynamic and can rapidly shift to areas where they are not “traditionally” found. In addition, the distribution patterns of immature, soft-shelled, very old and females do not always correspond to those of legal size males. The former are considered to be less competitive and more susceptible to predation (Hooper 1986) and usually observed in environments or substrates with greater cover (gravel, rocks; Comeau et al. 1998). Sampling that focused upon areas where large hard-shelled males occur in high frequency would preclude the reliable estimation of the relative abundance of other segments of the Snow Crab population.

Due to the gradual evolution of the aerial extent and alterations in the intensity and timing of surveys since the mid-1990s, direct inter-annual comparisons of the data are difficult over the entire time series. Temporal trends are most reliable for the post-2004 period. In all areas, fishing grounds are left fallow for as long as possible between commercial fishing and surveying of an area. This allows Snow Crab populations to redistribute following localized removals (i.e., commercial catches). Late fishing efforts, resulting from possible fishing season extensions, can impact the redistribution of Snow Crab.

A custom *Bigouden Nephrops* trawl, a net originally designed to dig into soft sediments for a lobster species in Europe, was used to sample Snow Crab and other benthic megafauna (headline of 20 m, 27.3 m foot rope mounted with a 3.2 m long, 8 mm chain, with a mesh size of 80 mm in the wings and 60 mm in the belly and 40 mm in the cod-end). Net configuration was recorded with wireless trawl monitoring sensors; depth and temperature were recorded with Seabird SBE 39 temperature and depth recorders; and positional information was recorded with a WAAS (Wide Area Augmentation System)-enabled global positioning system. Actual duration of bottom contact was assessed from trawl monitoring and Seabird data streams. The ship speed was maintained at approximately two knots. The warp length was approximately three times the depth. Swept area of the net was computed from swept distance and monitored net width. Detailed descriptions of sampling protocols can be found in Zisserson (2015).

All Snow Crab were enumerated; measured with calipers; shell condition determined (Table 5); and weighed with motion-compensated scales. Captured Snow Crab were also visually examined for the occurrence of Bitter Crab Disease (BCD). Data entry and quality control was provided by Javitech Ltd. and migrated onto the Observer Database System, held at DFO, BIO (Bedford Institute of Oceanography, Dartmouth, Nova Scotia).

In cases where individual Snow Crab animals cannot be weighed (missing legs, excessive barnacle growth, etc.), individual weight estimates were approximated from CW measurements by applying an allometric relationship developed for SSE adult hard shelled Snow Crab (Biron et al. 1999; R2=0.98, n=750):

$$mass\ [g] = 1.543 \times 10^{-4} \times CW\ [mm]^{3.206}$$

The maturity status of males was determined from a combination of biological staging through CC and morphometric analysis. While physiological maturity is not directly coincident with the onset of morphometric maturity (Sainte-Marie 1993), the latter is more readily determined and is considered a reasonable proxy for physiological (sexual) maturity.

In the terminal molt of male Snow Crab, a disproportionate increase of Chela Height (CH) relative to CW is generally observed. Morphometrically mature males ($M_{(male)}$) can be discriminated from morphometrically immature males via the following equation (E. Wade, personal communication, GFC):

$$M_{(male)} = -25.324 \cdot \ln (CW\ [mm]) + 19.776 \cdot \ln (CH\ [mm]) + 56.650$$

where an individual is considered mature if $M_{(male)} > 0$.

The maturity status of females is assessed from visual inspection of egg presence. Where maturity status was ambiguous, maturity was determined morphometrically, as the width of abdomen (measured by the width of the fifth abdominal segment, AW) increases rapidly relative to CW at the onset of morphometric maturity, facilitating the brooding of eggs. This onset of morphometric maturity ($M_{(female)}$) can be delineated via the following equation (E. Wade, personal communication, GFC):

$$M_{(female)} = -16.423 \cdot ln\ (CW\ [mm]) + 14.756 \cdot ln\ (AW\ [mm]) + 14.900$$

where an individual is considered mature if $M_{(female)} > 0$.

Sex ratios (proportion female by number) were calculated as:

$$Sex\ ratio = N_{(female)}\ /\ (N_{(male)} + N_{(female)})$$

The BCD infections of Snow Crab were first detected on the trawl survey in 2008. From 2009–2011, laboratory analysis of haemolymph occurred to monitor actual infection rates within the Scotian Shelf Snow Crab population. This method was suggested to improve the detection rates as visual assessments are only effective in identifying late-stage infections. Upon critical comparison of the visual and laboratory results of BCD detection, visual assessment was determined to be a more robust method of detection. As such, the laboratory testing of Snow Crab haemolymph was discontinued due to high costs and unreliable results.

Size-frequency histograms were expressed as number per unit area swept in each size interval (No./km^2; therefore, the arithmetic mean numerical density per unit area). Modes and the bounds of each modal group were identified from size-frequency distributions. During development Snow Crab molt through several instar (*I*) stages. Each *I* was determined, after an analysis of size-frequency distributions, to have a lower bound of CW (mm) approximated by (see also Figure 7):

$$CW_{(I,\ male)}\ [mm] = exp(1.918 + 0.299 \cdot (I - 3))$$

$$CW_{(I,\ female)}\ [mm] = exp(2.199 + 0.315 \cdot (I - 4))$$

SPACE-TIME MODELING

Estimation of a fishable biomass index was conducted using Conditional Autoregressive models (for further details on development of this approach and model selection see Choi, 2020). The approach models Snow Crab numerical abundance with environmental (depth, substrate, temperature) and biological factors (species composition) as covariates (Figures 8–10) following a smooth process (second-order Random Walk: RW2); and random errors as a spatial autocorrelation in an Intrinsic Conditional Auto-Regressive model using a Besag York Mollié (BYM2) model grouped by year which is modelled as an AR1 (first-order autoregression) process.

Analysis was conducted on numerical counts assuming a Poisson error distribution with swept area as offsets. Fishable biomass was computed from modelled results by multiplication of average weight in each areal unit (Figure 11) and then aggregation to the relevant management units.

Parameterizations specific to the assessment can be found online.

PREDATION

Snow Crab predators were determined using data housed in the DFO Maritimes Region Food Habits Database (Cook and Bundy 2010). This database contains the stomach-contents information for more than 170,000 individuals representing 68 ground and pelagic fish species collected from various sources since 1958. There was consistent sampling of diet data in ENS between 1999 and 2016. From this data set, the predators of Snow Crab were determined, as well as the frequency with which Snow Crab have been observed as part of the predator species diet and the percent of total weight of stomach contents represented by Snow Crab . As the impact of predation relates not only to the frequency of the species consumed, but also the biomass of the predator species, the trends in biomass for the identified predators from the Snow Crab survey were examined. The biomass indices were presented as the geometric mean and bootstrapped confidence intervals of the area and were standardized weight for each tow (expressed as kg/km^2).

STOCK ASSESSMENT MODEL

A modified discrete logistic model of the fishable biomass component is used to determine the relevant biological reference points (i.e., carrying capacity and fishing mortality [F] at Maximum Sustainable Yield, or F_{MSY}) associated with the Harvest Control Rules of the Snow Crab fishery. Bayesian state-space methods are used to estimate the parameters of this model and associated Harvest Control Reference Points. See Appendix 1 for a general background to the Precautionary Approach (PA) and Sustainability as applied to this fishery.

ECOSYSTEM INDICATORS

A multivariate data simplification method known as multivariate ordination was used to describe systemic patterns in temporal data series (Koeller et al. 2000; Brodziak and Link 2002; Choi et al. 2005a; Koeller et al. 2006) from 2005 until 2014 in Scotian Shelf Snow Crab assessments. The key environmental, social, economic, and fishery-related indicators were identified and summarized annually. Indicators were made directly comparable by expression as anomalies in standard deviation units (i.e., a Z-score transformation) and then colour-coded. Missing values were coded as white. The metrics were then ordered in the sequence of the primary gradient (first eigenvector) obtained from the ordination. This allowed the visualisation of any temporal coherence in the manner in which suites of these indicators changed over time. The sequence of the indicators reflects the degree of similarity in their temporal dynamics. Specifically, a variant of Principal Components Analysis (PCA) was used that involved an eigenanalysis of the correlation matrices of the indicators, following data-normalisation of those that were not normally distributed ($\log_{10}(x+1)$ transformations were sufficient). In classical PCA, it is customary to delete all such cases (years) with missing values, but this would have eliminated much of the data series from the analysis. Instead, Pearson correlation coefficients were computed for all possible pair-wise combinations with the implicit assumption that it represents a first-order approximation of the “true” correlational structure.

In many cases, the data sources used to populate this overview have now changed (or ceased to exist completely) which has confounded the ability to keep this overview current. This approach will not be continued annually but reference herein remains to help describe the role of Snow Crab in an ever-changing ecosystem.

LIFE HISTORY

The Snow Crab is a subarctic species resident along the east coast of North America from northern Labrador to the Gulf of Maine. In the SSE, commercially fished Snow Crab are generally observed between depths of 60 m and 280 m and between temperatures of -1°C and 6 °C. Snow Crab are thought to avoid temperatures above 7°C, as metabolic costs are thought to match metabolic gains (Foyle et al. 1989); though in S-ENS Snow Crab have been observed above the “break-point” temperature. Snow Crab are generally observed on soft mud bottoms, although small-bodied and molting Snow Crab are also found on more complex (boulder, cobble) substrates (Sainte-Marie and Hazel 1992; Comeau et al. 1998).

Snow Crab eggs are brooded by their mothers for up to 2 years, depending upon ambient temperatures, food availability, and the maturity status of the mother (up to 27 months in primiparous females—first breeding event; and up to 24 months in multiparous females—second or possibly third breeding events; Sainte-Marie 1993). More rapid egg development (from 12 to 18 months) has been observed in other systems (Elner and Beninger 1995; Webb et al. 2007). Over 80% of female Snow Crab on the Scotian Shelf are estimated to follow an annual cycle, rather than the bi-annual cycle observed in most other areas (Kuhn and Choi 2011). A primiparous female of approximately 57.4 mm CW would produce between 35,000 to 46,000 eggs, which are extruded between February and April (in the Baie Sainte-Marguerite region of the northern Gulf of St. Lawrence; Sainte-Marie 1993). The observable range of fecundity is large, especially as multiparous females are thought to be more fecund with more than 100,000 eggs being produced by each female. Eggs are hatched from April to June when the pelagic larvae are released. The pelagic larval stage lasts for three to five months (zoea stages 1 and 2 and then the megalopea stage) during which Snow Crab are feeding upon plankton. The larvae settle to the bottom in autumn to winter (September to October in the Gulf area). In the SSE, pelagic stages seem to have highest abundance in October and so may begin settling as late as January. Very little is known of survival rates at these early life stages.

Once settled to the bottom (benthic phase), Snow Crab grow rapidly, molting approximately twice a year (Sainte-Marie et al. 1995; Comeau et al. 1998; Figure 12). The first inter-molt stage (instar 1) is approximately 3 mm CW. After the 5th instar (15 mm CW), the molting frequency declines to annual spring molts until they reach a terminal maturity molt. Growth is allometric, with weight increasing approximately 250% with each molt (Figure 7). Terminal molt has been observed to occur between the 9th and 13th instar in males and the 9th to 10th instar in females. Just prior to the terminal molt, male Snow Crab may skip a molt in one year to molt in the next (Conan et al. 1992; Figure 12). They generally reach legal size (≥ 95 mm CW) by the 12th instar; however, a variable fraction of instar 11 Snow Crab are also within legal size. Male instar 12 Snow Crab represent an age of approximately nine years since settlement to the bottom and 11 years since egg extrusion. Thereafter, the life expectancy of a males is approximately five to six years. Up to ten months are required for the shell to harden (CC1 and early CC2; Table 5), and up to one year for meat yields to be commercially viable. After hardening of the carapace (CC3 to CC4) the male Snow Crab is able to mate. Near the end of the lifespan of a Snow Crab (CC5), the shell decalcifies and softens and may be heavy with epibiont growth. In some warm-water environments (e.g., continental slope areas), epibiont growth occurs at an accelerated rate creating some uncertainty in the classification of CC.

Female Snow Crab reproducing for the first time (primiparous females) generally begin their molt to maturity at an average size of 60 mm CW and mate while their carapace is still soft (early spring: prior to the fishing season in ENS and during the fishing season in 4X). A second mating period later in the year (May to June) has also been observed for multiparous females(Hooper 1986). During mating, complex behavioral patterns have also been observed; the male Snow Crab helps the primiparous female molt and protects her from other males and predators (Hooper 1986). Pair formation (a mating embrace where the male holds the female) may occur up to three weeks prior to the mating event (Hooper 1986). Upon larval release, males have been seen to wave the females about to help disperse the larvae (i.e., prior to a multiparous mating). Females are selective in their mate choice, as is often the case in sexually dimorphic species, and they have been seen to die in the process of resisting mating attempts from unsolicited males (Watson 1972; Hooper 1986). Male Snow Crab compete heavily for females and often injure themselves (losing appendages) while contesting over a female. Larger males with larger chela are generally more successful in mating and protecting females from harm.

ECOSYSTEM CONTEXT

OVERVIEW

An overview of relevant social, economic, and ecological factors that have been used in previous Scotian Shelf Snow Crab assessments is summarized below (for more details, see Choi et al. 2005a). See Cook et al. 2015 for the most recent/complete table of sorted ordination of anomalies of key social, economic and ecological patterns on the Scotian Shelf relevant to Snow Crab.

The first axis of variation accounted for approximately 22% of the total variation in the data, and it was dominated by the influence of declines in mean body size of organisms in the groundfish surveys; socio-economic indicators of ocean use by humans and associated changes in their relative abundance were: landings and landed values of groundfish (declining), invertebrates (increasing), declines in sharks and large demersals and landings of pelagic fish, and oil and gas exploration and development (increasing). Nova Scotia Gross Domestic Product (GDP) and population size were also influential factors that have been increasing. Further, the physiological condition of many groups of fish has been declining as has been the number of fish harvesters in Nova Scotia. The temporal differences along this axis of variation indicates that coherent systemic changes of socio-economic and ecological indicators occurred in the early-1990s, with some return to historical states evident.

Temperature-related changes were generally orthogonal (independent) to the above axis of variation. This second (orthogonal) axis of variation, accounting for 10% of the total variation, was strongly associated with the cold intermediate-layer temperature and volume, bottom temperatures and variability in bottom temperatures, bottom oxygen concentrations, and sea ice coverage.

Anecdotal information from fishers and fishery-based catch rates (Figure 4) suggests that the abundance of Snow Crab was low in the near-shore areas of the SSE, prior to 1980. Increases in catch rates were observed throughout the shelf in the mid-1980s and 1990s in N-ENS and S-ENS, respectively. As commercially exploitable Snow Crab require at least 9 years from time of settlement to reach the legal size of 95 mm CW, their increasing numerical dominance as macroinvertebrates on the shelf must have had its origins as early as the late-1970s and 1980s (N-ENS and S-ENS, respectively). For S-ENS, these timelines are confounded by the expansion of the fishing grounds towards increasingly offshore areas and the exploitation of previously unexploited populations. Most of this expansion was observed in the post-2000 period when TACs and the closely associated landings increased up to six-fold relative to the TACs, and landings of the 1990s, and a doubling of fishing effort (Figure 2 and Figure 3). The catch-rate increases observed in the 1980s and 1990s were, therefore, likely reflecting real increases in Snow Crab abundance.

The possible causes of this change in abundance can be broken down into the following categories: connectivity (metapopulation dynamics); environment (habitat); top-down (predation); bottom-up (resource limitation); lateral (competition); and human (complex perturbations).

CONNECTIVITY

In this assessment, connectivity refers to the manner in which various populations are connected to each other via immigration and emigration, also known as metapopulation dynamics. Connectivity between Snow Crab populations exists through larval dispersion in the planktonic stages and directed movement during the benthic stages.

Larval Dispersion

The potential for hydrodynamic transport of Snow Crab larvae from the southern Gulf of St. Lawrence to the SSE and internal circulation on the SSE has been studied by J. Chassé and D. Brickman (Ocean Sciences Division, BIO, DFO; personal communication). Treating larvae as passive particles, simulations suggested that a large numbers of larvae could potentially be transported onto the SSE (especially near Sable Bank and in the shallows further west). The possibility exists that Snow Crab larvae enter the SSE from the Gulf of St. Lawrence region and the Labrador current, especially given no genetic differences are found between all Atlantic Snow Crab populations (Pubela et al. 2008). Further, planktonic organisms can maintain their position in a single location in very strong advective conditions via control of vertical migrations. Thus, the degree of larval retention on the SSE, while unknown, can be large.

The following observations also suggest that the SSE population may be acting as an autonomously reproducing system:

- The temporal dynamics of the SSE Snow Crab population is generally out-of-phase with the cycles seen thus far in the southern Gulf of St. Lawrence. If the SSE was dependent upon the larval drift from the Gulf Region, the temporal dynamics of the populations would be in-phase.
- The spatial distribution of Brachyuran larvae (Scotian Shelf Ichthyoplankton Sampling Program (SSIP) in the 1980s; see summary in Choi et al. 2005b, page 14) have been observed to be pervasive throughout the SSE with no spatial clines (i.e., no declines in abundance with distance from the Gulf of St. Lawrence area) as might occur if the source of larvae were solely from the Gulf Region.
- A pulse of larval abundance was observed from 1997 to 1999 with peak levels in 1998 (Choi et al. 2005b, Page 14). The timing of this pulse is concordant with the growth schedules of the currently expected ‘local’ recruitment. Approximately nine years would be required to grow from the zoea stages to instar 11/12, the stages in which Snow Crab begin to molt to maturity in 2007, the same timeframe between 1998 and 2007.
- The period in the late-1990s, when high larval production was observed, was the same period in which the abundance of mature male and female Snow Crab on the SSE were at their peak.

This suggests that the Snow Crab resident on the SSE may be able to function as a self-reproducing system, regardless of inputs from other systems. Even if external sources of larvae do exist, the reproductive potential of the Snow Crab resident on the SSE proper cannot be dismissed. A conservative approach to the harvest of large mature males (i.e., moderate exploitation rates) will help ensure that the earlier maturing females in a recruitment pulse are not subjected to sperm limitations. Compromised mating (such as sperm limitation) could result in potential negative population consequences 7–10 years subsequent.

Movement

Snow Crab (especially large males) have been shown to have large locomotory potential based on tagging studies within the Maritimes Region. The movement of both males and females in Newfoundland has been postulated (Mullowney et al 2018) to be divisible into two types, seasonal and ontogenetic (life cycle related). This study suggests that ontogenetic movements appear associated with a search for warm water while seasonal migrations appear associated with both mating and molting in shallow water.

Both seasonal and ontogenetic movements appear to occur on the Scotian Shelf. Commercial fishing efforts (a strong indicator of large male Snow Crab concentrations) show seasonal patterns of trending to deeper water as shallower depths warm over the course of the spring months. Longer-scale (temporally and geographically) movements of male Snow Crab appear to be related to life-history requirements such as the availability of mature females for mating.

Traditional Tagging Program

Spaghetti tags have been applied opportunistically to monitor Snow Crab movement since the early-1990s. To encourage participation, a reward program and an online alternative for submitting the tag recapture information has been developed to facilitate reporting of tag recaptures.

Movement information is primarily limited to recaptures of mature, terminally-molted male Snow Crab. The application of spaghetti tags prevents molting so only mature males are tagged and tag recaptures are from the male-only Snow Crab fishery. Results suggest that although Snow Crab movements are quite variable, the potential connectivity between regions is still high (Figure 13).

Short-term seasonal movement patterns remain unidentified and are a source of uncertainty. Long-term movement patterns are more easily observed. Two distinct patterns of movement have been identified for commercial Snow Crab, which is marked by above-average rates of movement for a segment of the population (Figure 14) and more localized movements for the majority of tagged Snow Crab. There are also two distinct periods (2–4 years each) within the time series where appreciable increases in average movement rates were observed. In both cases, the mature Snow Crab population was male dominated with mature females being low in S-ENS and almost non-existent in N-ENS. This suggests that reproduction is a key factor influencing the movement of mature male Snow Crab in the region. Substantial emigration was observed from N-ENS to the Gulf (CFAs 12 and 19) during these periods. Unfortunately, immigration into N-ENS was not observed as no Snow Crab were tagged in the Gulf for an extended period of time. The movement of immature and female Snow Crab is unknown and remains a source of uncertainty. Additional analysis of potential factors influencing patterns of short- and long-term movement patterns is required.

An unknown proportion of tag recaptures remain unreported. Anecdotal information suggests that fishers do not always report recaptures. Concern has been expressed that indication of Snow Crab movement between management areas through tag returns could influence current management practices. Such unreported recaptures negatively impact the understanding of movement patterns. Increased/complete reporting is essential to maximize this knowledge.

Since 2004, 24,967 tags have been applied and 1,813 distinct tagged-Snow Crab recaptures (7.3%) have been reported (Table 6) in 4X, N-ENS, and S-ENS. Even with potential tagging-related mortality and exploitation rates of 15–30%, a much higher (than 7.3%) proportion of tags are likely recaptured yet not reported. Since 2004, there have been 171 individuals who have reported recaptures and there have been 1958 total recaptures (Table 6) of 1,813 Snow Crab. On average, each person participating has reported ten or more different captures. Other fish harvesters, operating in close proximity to these individuals, have not reported any tag recaptures.

Of the 1,813 distinct tags recaptured, 1395 have been returned to the water and 130 of these have been captured again. Tracking tagged Snow Crab over multiple recaptures provides further insight into the movement patterns over their life cycle. When subsequent recaptures are reported, everyone who previously captured that particular Snow Crab are notified to encourage returning tagged Snow Crab to the water.

Snow Crab recaptured within 10 days of initial release are not included in analyses. This short-term movement could be directly influenced by other factors such as water currents drifting them as they settle to the bottom after release. Traditionally, the movement of tagged animals (e.g., Snow Crab) is stated as a straight line distance between release and recapture locations. This distance traveled calculation is now constrained by depth ranges of 60–280 meters. This depth range is considered to be a conservative estimate of Snow Crab habitat use as compared to previous methods ignoring habitat preferences. On average, Snow Crab tagged between 2004 and 2019 were first recaptured in the season following the tagging event (mean time to recapture was 456 days), with the longest time interval between release and initial capture being 2,278 days (approximately 6 years, 3 months; Figure 14). This Snow Crab had moved at least 132 km in that period. Very few [reported] recaptures occur two years past the tagging event. Most tagging is completed on commercial fishing vessels engaged in Snow Crab fishing operations; tags are generally applied where commercial Snow Crab concentrations and resulting harvesting is high. This high localized exploitation may explain why the majority of Snow Crab are recaptured in the same or following season after tagging. As such, higher recaptures and reporting are expected if all recaptures are reported.

The locomotory ability of Snow Crab can be very large, as the average distance traveled was 27 km, with a maximum distance traveled of 504 km (Table 6). The average rate of movement was 1.78 km/month. These distances and rates are most likely underestimates as the actual distance traveled by Snow Crab will be greater due to the topographical complexity and the meandering nature of most animal movement. On average, Snow Crab captured in S-ENS have a “shortest path” (habitat constrained) movement rate of 2.07 km/month, slightly higher than N-ENS of 1.79 km/month. In 4X, the displacement rate is slightly lower again at 1.05 km/month (Table 7, Figure 15).

From 2004–2019, movement between N-ENS and S-ENS was seldom observed. In total, 10 Snow Crab tagged in S-ENS were recaptured in N-ENS and 5 Snow Crab tagged in N-ENS were recaptured in S-ENS. These numbers may be underestimates of total movement due to non-reporting of recaptures (Figure 13).

Returns from Snow Crab tagged between 2010 and 2014 suggested significant movement from N-ENS into the southern Gulf of Saint Lawrence (“the Gulf”, Figure 13). The apparent unidirectional nature of this movement (from N-ENS to the Gulf) is confounded by the fact that there had been a period of no tagging in the Gulf region during this period of time. As such, the true degree of connectivity between the Gulf and N-ENS remains unknown, and may be substantial given the high concentrations of commercial Snow Crab in the adjacent CFA 19. It is hoped that the renewed tagging program in CFA 19 will provide further insight into the dynamics of Snow Crab movement between these regions.

The reporting rates of recaptured tags in 4X is believed to be much higher than other areas (Figure 15), due to the small fleet size (5–6 boats) and high engagement of the 4X Snow Crab fleet in the tagging program. Of the 971 tags deployed in 4X since 2008, 100 (10%) have been captured at least once. Of these, 14 (14%) were captured a second time and 5 (5%) were recaptured a third time. No movement of tagged Snow Crab between 4X and S-ENS has been reported. With high tag reporting and low emigration, a higher return rate for initial capture is expected. Higher mortality in 4X due to warming events (Zisserson and Cook 2017) and bycatch in other fisheries may be contributing factors.

It is recommended that recaptured tagged Snow Crab be released immediately with the tag still attached after relevant data are recorded (date, location, depth, condition of Snow Crab, as well as information about the vessel and the individual who recaptured the tag). To view the movement data in more detail go to ENS Snow Crab website and click on the tagging tab.

Dwindling return rates of spaghetti tags (Table 6) suggest that the substantial resources spent on this program should potentially be directed elsewhere.

Acoustic Tagging Program

Since 2013, acoustic tags have been applied to Snow Crab within and adjacent to N-ENS and proximal to the CFA 24/4X line. A methodology for the application of acoustic tags on Snow Crab has been developed (Zisserson & Cameron 2016). Acoustic receivers, both stationary and mobile, recognize and record whenever a Snow Crab with an acoustic tag approaches the receiver. To date, the majority of the acoustic tags were attached to terminally molted, mature male Snow Crab though 8 have been applied to mature female Snow Crab in Northeastern CFA 23 and 6 in CFA 19. None of the females have yet been detected. The acoustic tagging program allows for the potential discrimination of movement patterns without the need for recapture of the tag through commercial fishing activities. As such, reporting rates of tag recaptures do not bias movement data. Seasonal movement patterns into N-ENS from adjacent areas have long been hypothesized by the fishing industry in N-ENS. Acoustic receiver arrays between N-ENS and the Gulf and also N-ENS and CFA 23 may help describe these movement patterns.

In the summer of 2013, 27 acoustic tags were deployed in N-ENS. In just over a year, 10 of these tags were detected on the Cabot Strait Line (essentially separating N-ENS and the Gulf) and 3 were later detected within the Gulf Region (Figure 16). This tagging was repeated in 2015 at the same locations. To date, none of these Snow Crab have been detected within, or near, the Gulf Region. Of the 27 that were released, 23 were detected within 15 nautical miles of the release locations. This supports the episodic nature of connectivity between the Gulf and N-ENS observed in the spaghetti tag movement data. In 2015, 40 acoustic tags were released in the Glace Bay Hole area of N-ENS; 45 more tags were added over 2018 and 2019. Detections of these animals have all been from within N-ENS.

To determine if Snow Crab movement is unidirectional or bidirectional, acoustic tags have been released in the areas adjoining N-ENS. Since 2015, 57 tags were released in the Gulf Region (CFA 19) and 79 tags were released in S-ENS (CFA 23). To date, only one of these tagged Snow Crab has been detected in N-ENS—it was tagged 17 km south of the N-ENS/S-ENS line in April 2016 and was detected by a wave glider in October 2018. This detection occurred approximately 10 km north of this same dividing line, within N-ENS.

In 2017, 10 Snow Crab with acoustic tags were released near the CFA 4X and CFA 24 boundary. Four of the five that were released in CFA 4X have since been detected on the Halifax receiver line and the other was captured and re-released during the fishery. One of the five Snow Crab released on the CFA 24 side was detected by a wave glider.

If reproduction is, in fact, a main driver of movement patterns, we would expect to see increasing mobility of large male Snow Crab in the next few years as mature female abundance continues declining. Increased mean movement per month was observed in 2019 (Table 6).

ENVIRONMENTAL CONTROL (HABITAT)

Known environmental (abiotic) influences upon Snow Crab include substrate type, temperature variations, and oxygen concentrations. Altered temperature conditions over extended periods of time have been observed in the SSE. For example, prior to 1986, the Shelf was characterized by relatively warm bottom temperatures, low volume of the cold intermediate layer, and a Gulf Stream frontal position closer to the continental shelf. The post-1986 period transitioned to an environment of cold bottom temperatures, high volume of the cold-intermediate layer, and a Gulf Stream frontal position distant from the shelf. The principal cause of the cold conditions is thought to have been along-shelf advection from both the Gulf of St. Lawrence and southern Newfoundland, and local atmospherically-induced, cooling. In the southwestern areas (Emerald Basin), the offshore warm slope water kept subsurface temperatures relatively warm throughout the 1980s and 1990s, the exception being in 1997–1998, when cold Labrador Slope Water moved into the region along the shelf break and flooded the lower layers of the central and southwestern regions. While this event produced the coldest near-bottom conditions in these shelf regions since the 1960s, its duration was short, lasting about one year.

Bottom temperatures in the distributional centers of S-ENS Snow Crab have been generally increasing since the early-1990s (Figure 17). North-Eastern Nova Scotia shows a relatively more stable bottom temperature field though still exhibits a slight rising trend. In 4X, bottom temperatures continue to be generally warmer and more erratic than the other areas. Increasing temperatures can have multiple effects on Snow Crab populations. Bottom temperatures affect most instars of Snow Crab phenology though the very earliest (pelagic larvae) instars are directly affected by temperatures in the upper water column. Within acceptable temperature ranges, warmer temperatures can result in larger mature animals, hypothesized to be caused by decreased intermolt interval with warmer temperatures (Burmeister and Sainte-Marie 2010; Dawe et al. 2012). Larger mature females could also increase individual fecundity (Sainte-Marie et al. 2008). Unfortunately, these positive effects of minor temperature increases are likely mitigated or over-shadowed by more pronounced temperature changes that increase mean bottom temperatures into a range less suitable for Snow Crab. This can (and has) caused a northward shift of the overall stock’s distribution in both the Atlantic (Agnalt et al. 2010; Burmeister 2010) and Pacific (Orensanz et al. 2004). Temperature-driven biomass decreases in local Snow Crab populations have already been observed on the Scotian Shelf. Both abundance estimates and catch rates declined sharply in CFA 4X (the southernmost Snow Crab population in the Western Atlantic) following a warm water event in 2012–2013 (Zisserson and Cook 2017) and have failed to return to levels previously observed. Outside of direct biological effects on Snow Crab and their distribution, temperature changes potentially create new ecosystem regimes that affect Snow Crab’s relative role within the benthic community. These changes can manifest as changes in predation, food availability, lateral competition, invasive species, etc.

TOP-DOWN CONTROL (PREDATION)

Top-down influences refer to the role of predators in controlling a population (Paine 1966; Worm and Myers 2003). The capacity of predatory groundfish to opportunistically feed upon Snow Crab, in combination with their numerical dominance prior to the 1990s, suggests that they may have been an important regulating factor controlling the recruitment of Snow Crab. For example, Snow Crab in the size range of 5 to 30 mm CW (with a 7 mm CW mode; that is instars 2 to 7, with instar 7 being strongly selected) were targeted by Thorny Skate and Atlantic Cod (Robichaud et al. 1991). Soft-shelled males in the size range of 77 to 110 mm CW during the spring molt were also a preferred food item. The demise of these predatory groundfish in the post-1990 period, and the resultant release from predation upon the immature and soft-shelled Snow Crab, may have been an important determinant of the current rise to dominance of Snow Crab in the SSE. As the occurrence of Snow Crab (relative to other species) changes within the ecosystem, so does their potential role as both a predator and prey species (Boudreau and Worm 2012).

The known predators of Snow Crab in the SSE were, in order of importance: Atlantic Wolffish (*Anarhichas lupus*), Atlantic Halibut (*Hippoglossus hippoglossus*), skates (Smooth Skate *Malacoraja senta*, Thorny Skate *Raja radiata*, and Winter Skate *Leucoraja ocellata*), Longhorn Sculpin (*Myoxocephalus octodecimspinosus*), Sea Raven (*Hemitripterus americanus*), Atlantic

Cod (*Gadus morhua*), White Hake (*Urophycis tenuis*), American Plaice (*Hippoglossoides platessoides*), and Haddock (*Melanogrammus aeglefinus*). From this data, the overall level of predation on Snow Crab appears to be negligible on the SSE as only Atlantic Halibut and Atlantic Wolffish have Snow Crab observed in more than 1% of the stomachs sampled (Table 8). This constitutes less than 1.5% of diet by weight within each species, particularly compared to other regions where the frequency of observing Snow Crab as prey is often greater than 10% (Robichaud et al. 1989, 1991).

Atlantic Halibut biomass has increased almost exponentially (DFO 2018a), suggesting that the total number of Snow Crab consumed are likely increasing in relation to this predator (Figure 18 and Figure 19).Only Snow Crab < 65 mm CW are typically observed in fish stomachs because maximum span exceeds the predators' mouth gape (Chabot et al. 2008). A proliferation of Atlantic Halibut, particularly the largest fish with large mouth gapes, could create predation on larger Snow Crab seldom experienced previously. Anecdotal reports of large Atlantic Halibut with multiple mature female Snow Crab in their stomachs support this assertion. Increased predation of mature females will impact the reproductive potential of Scotian Shelf Snow Crab. Atlantic Halibut are likely the largest source of predation of larger Snow Crab on the Scotian Shelf. Further study of Atlantic Halibut diet focused in areas of high Snow Crab density are planned.

Atlantic Wolffish are important as a potential Snow Crab predator; however, their biomass indices suggest that they are currently at relatively low levels across all areas (Figure 20 and Figure 21). If the Snow Crab survey is more reflective of predators in Snow Crab habitat (vs. groundfish surveys), the biomass of Thorny Skate (Figure 22 and Figure 23) and Smooth Skate (Figure 24 and Figure 25) may be greater across all areas than previously thought.

In many other areas, Atlantic Cod have been shown to be an important predator of Snow Crab (Bailey 1982; Burgos et al. 2013; Chabot et al. 2008; Lilly 1984; Orensanz et al. 2004; Robichaud et al. 1989, 1991). Boudreau et al. (2011) suggest that the top-down control effect of Atlantic Cod on Atlantic Canadian Snow Crab is most prevalent on older juvenile and sub-adult Snow Crab. Conversely, diet studies on the Scotian Shelf have not demonstrated Atlantic Cod to be a prevalent predator of Snow Crab (Table 8). Moreover, the Atlantic Cod populations on the SSE are currently at reduced biomass index levels in all regions relative to historic levels (Figure 26 and Figure 27). Haddock may represent an additional increasing source of predation in localized areas of S-ENS and particularly 4X (Figure 28 and Figure 29).

The only predator species that strongly co-associated with Snow Crab based on their abundance were American Plaice, likely due to the difference in habitat preferences from the other predator species (Figure 30 and Figure 31). Due to the American Plaice's small mouth gape size and mode of feeding, they are only capable of consuming early instar Snow Crab. Reports of Snow Crab predation by squids and other crabs have been made (Bundy 2004), however, their relative impacts are not known.

Predation levels upon small, immature Snow Crab are also likely to be on the rise with the re-establishment of some groundfish populations (based on Snow Crab survey data) and changing temperature fields. High local densities of groundfish are found in areas where small immature Snow Crab are found in high densities. A change in the size structure of predator populations (towards larger body sizes) could shift predation to include larger Snow Crab as well, especially during the period immediately post-molt.

Seals are considered by fishers to be a potential predator of Snow Crab, and their continued increase in abundance (Figure 32; DFO 2017a) is a source of concern for many fishers. Diet studies of Grey Seals in the early 1990s (Bowen and Harrison 1994) found that evidence of Snow Crab species were found in < 1% of the seal scat samples examined with a diet focusing predominantly on Sand Lance, Atlantic Cod, and flatfishes. These studies were also at a time with much lower Snow Crab densities on the SSE as compared to today. While grey seals have on occasion been observed with Snow Crab in their stomachs, it should also be emphasized that some of the highest concentrations of Snow Crab are found in the immediate vicinity of Sable Island, an area where the abundance of Grey Seals is extremely high. The evidence indicating that seals have a negative influence upon the Snow Crab population, therefore, seems to be minimal. Seals and other marine mammals may have a positive influence by physically importing food and food waste (Katona and Whitehead 1988) from distant areas to the immediate vicinity of Sable Island, thereby indirectly "feeding" the Snow Crab and also removing their potential predators (in both early pelagic and benthic stages).

BOTTOM-UP CONTROL (RESOURCE LIMITATION)

Bottom-up influences refer to changes in a population due to resource (food) availability. Diet studies and field observations (Hooper 1986) indicate that the primary food items of larger (mature) Snow Crab are, in order of importance: echinoderms, polychaete worms (*Maldane* sp., *Nereis* sp.) and other worm-like invertebrates, detritus, large zooplankton, shrimps, smaller juvenile crabs (Rock Crab, *Cancer irroratus*; Toad Crab, *Hyas coarctatus*; Lesser Toad Crab, *Hyas araneus*), Ocean Quahog (*Artica islandica*), bivalve molluscs (e.g., *Mytilus edulis*, *Modiolus modiolus*), brittle stars (*Ophiura sarsi*, *Ophiopholis aculeata*) and sea anemones (*Edwardsia* sp., *Metridium senile*). Smaller Snow Crab have been observed to feed upon, in order of importance: echinoderms, polychaete worms, large zooplankton, detritus, and bivalves (e.g., *Mytilus edulis*, *Modiolus modiolus*, *Hiatella arctica*). Squires and Dawe (2003) demonstrated that male Snow Crab appear to be more capable predators than the females and consume more small fish. Studies have also demonstrated that cannibalism occurs within Snow Crab populations. Cannibalism between cohorts is size selective, with instars VIII and IX being a dominant predator on instar I individuals (Emond et al. 2015). It is also highly prevalent in intermediately-sized (morphometrically) mature female Snow Crab (Sainte-Marie and Lafrance 2002; Squires and Dawe 2003). This cannibalistic behavior can create an important source of density-dependent mortality.

Based on the proliferation of Snow Crab in the 1990s and onwards, resource competition does not appear to have been a limiting factor.

At the very base of the food web, 2018 annual chlorophyll a levels were at or below normal on the Scotian Shelf. The timing of the spring phytoplankton bloom was variable, of a lower magnitude and of normal duration on the Scotian Shelf generally. The Eastern Scotia Shelf experienced a shorter bloom than normal but it was of greater magnitude (DFO 2018b). The zookankton biomass was below normal on the Scotian Shelf in 2018. The shift in species structure of the zooplankton continues on the Scotian Shelf in 2018 with low (relative to historic mean) abundance of the energy rich *Calanus finmarchicus.* The effects of systemic changes in the plankton community will potentially echo through the higher trophic levels in the future.

The distribution of Northern Shrimp (*Pandalus borealis*) on the Scotian Shelf appears to remain broad (Figure 33); however, Snow Crab survey shrimp densities (Figure 34) and stock-specific stock assessment results (DFO 2019) suggest that the SSE stock is in a depressed but improving state compared to historical levels.

LATERAL CONTROL (COMPETITION)

Lateral (and internal) influences refer to the competitive interactions with groundfish, other crab species, cannibalism, and reproduction-induced mortality (direct and indirect). The diet of Snow Crab overlap with some groundfish species; thus, the demise of these groups in the late-1980s and early-1990s would have been doubly beneficial to Snow Crab, through the reduction in predation pressure and resource competition. The spatial distribution of Snow Crab overlaps with basket stars, sea cucumbers, Sand Lance, Capelin, and Toad Crab. Some of these species may be competitors of Snow Crab for food and habitat space. There were no strong negative relationships between Snow Crab and other bycatch species (Choi and Zisserson 2012), suggesting little competitive interaction. The potential competitors, Lesser Toad Crab (Figure 35 and Figure 36) and Jonah Crab (Figure 37 and Figure 38), remain in relatively patchy distributions and, therefore, do not currently appear to pose much threat to the overall health of the Snow Crab stock. Steady increases in near-shore Lobster populations in the past 10 years (DFO 2017b) may increase resource competition (and even predation) for juvenile Snow Crab whose habitat preferences overlap those of Lobster.

DISEASE

Bitter Crab Disease (BCD) is observed globally in crustaceans, though most-commonly in the northern hemisphere (Stentiford and Shields 2005). The name arises from the bitter (aspirin-like) taste, which infected animals exhibit once cooked, rendering them unmarketable. BCD infections in Snow Crab have been observed in Alaska, Newfoundland, Greenland, and on the Scotian Shelf (Morado et al. 2010). In Atlantic Canada, BCD infected Snow Crab were first observed in Bonavista Bay in 1990 (Taylor and Khan 1995), though the range of infection now extends from southern Labrador to the southern Grand Banks. Infected animals are rare on the southern and western coast (Dawe et al. 2010) of Newfoundland in the waters most proximal to the Eastern Scotian Shelf. Salinity levels and water temperature, as well as ocean currents (affecting the distribution of both crab larvae and the water-borne *Hematodinium*), are potential limiting factors of disease prevalence (Morado et al. 2010). Infected Snow Crab were first observed on the Scotian Shelf in the 2008 Snow Crab trawl survey, with a handful of anecdotal reports of infected Snow Crab having been seen in the commercial catch in the near-shore areas previous to 2008. The fall-survey timing is advantageous to detection as animals infected during the spring molt are expected to show visible signs of infection by the fall. Visible identification of infection can be confounded by examination of infected animals in early stages of (not yet showing visible) infection earlier in a given year.

This disease is caused by a parasitic dinoflagellate of the genus *Hematodinium*. It infects an animal's haemolymph (blood), gradually dominating the animal's haemolymph and resulting in reduced numbers of haemocytes in the blood and the ability of the organism to transport oxygen. Infection appears to occur during molting, and almost all infections appear to occur in crabs that have molted within the past year (new shell). There is a higher likelihood of infection in juvenile crabs as they molt frequently. It is not known if animals infected with *Hematodinium* will always develop the disease. BCD is considered fatal and assumed to kill the host organism within a year. Infected animals appear lethargic or lifeless, and have a more reddish ("cooked") appearance, dorsal carapace with an opaque or chalky ventral appearance, and a milky haemolymph appearance. Depending on the severity of the infection, it is readily identified visually. Polymerase Chain Reaction (PCR) laboratory assay performed on an alcohol-fixed haemolymph sample was considered by some researchers to be the definitive test of animal infection; however, the use of this laboratory approach on SSE Snow Crab appears to both costly and unreliable. Based on observational experience and seasonality of the survey, visual identification is now considered to be the most reliable method.

The number of visibly infected animals has remained constant and at low levels with prevalence rates near 0.05% (Table 9). Snow Crab of both sexes have been observed with BCD in all areas (Figure 39) across a wide range of sizes (20–100 mm CW; Choi and Zisserson 2012), though generally, in immature animals below legal commercial size (Figure 40). To date, mature, older-shelled crab infected with BCD have not been observed in the region. This suggests that infection may be linked to molting and it increases mortality rates substantially. The pulsed nature of ESS Snow Crab populations can cause apparent infection rates to climb when larger segments of the population are found in smaller size classes.

HUMAN INFLUENCE

The human influence is a relatively complex mixture of the above controlling influences, exerted both directly and indirectly upon Snow Crab. Directed fishing for Snow Crab is discussed in the next section (Fishery). Here, other forms of human influences are discussed.

Bycatch of Snow Crab in Other Fisheries

The spatial distribution of Northern Shrimp (*Pandalus borealis*) largely coincides with Snow Crab, so this fishery represents a potential source of additional Snow Crab mortality through incidental bycatch. The use of trawls by the shrimp industry is of particular concern as they can cause co-incident damage of Snow Crab, especially those susceptible to crushing, such as Snow Crab in newly molted soft-shelled stages. This is concerning since areas with high shrimp fishing activity are the same areas with the highest catch rates and landings of Snow Crab. Directed studies of the mortality and/or carapace damage caused by shrimp trawls on Snow Crab in Newfoundland concluded that the shrimp fishery did not impose substantial damage or mortality (Dawe et al. 2007).

The inshore American Lobster (*Homarus americanus*) fishery may also represent a source of juvenile and adult female Snow Crab mortality in some areas, as anecdotal reports suggest Snow Crab are captured in Lobster traps and (illegally) used as bait. This has been stated by fishers to be more prevalent in 4X, as well as some limited areas along the Eastern Shore of Nova Scotia during the early part of the Lobster season in April. The presence of Snow Crab bycatch in Lobster traps generally occurs when cold bottom-water temperatures coincide with Lobster fishing efforts in near-shore areas.

Additionally, bycatch of Snow Crab in Danish seines has been anecdotally reported from the limited flatfish fisheries on the Scotian Shelf, though this fishing method is now seldom used.

Bycatch of Other Species in the Snow Crab Fishery

At-sea-observed estimates of bycatch of other species in the commercial catch of the SSE Snow Crab fishery can be extrapolated to the entire fleet based on landings and the proportion of landings observed (Table 10 and Table 11). In 2018, at-sea observers did not follow proper reporting protocol in the N-ENS and S-ENS fisheries; therefore, reliable, species-specific bycatch estimates cannot be generated for the 2018 N-ENS and S-ENS fisheries. Proper bycatch sampling did occur during the 2017–2018 4X fishery. To best approximate total bycatch levels, the three-year mean bycatch levels for 2016, 2017, and 2019 species-specific data were used. In ENS, a total of 7,261 t of Snow Crab were landed in 2019 with associated estimates of bycatch at 3.4 t (0.05%). Bycatch rates in ENS are traditionally very low.

CFA 4X had no bycatch due to a zero TAC for the 2018–2019 season. CFA 4X traditionally shows higher (relative to ENS) bycatch rates due to lower densities of commercial Snow Crab and higher species diversity in some fishing grounds. In 2013 and 2014, 4X bycatch rates were unusually high (relative to past seasons) due to very low catch rates and increased effort to locate commercial Snow Crab. These search activities increase fishing effort in non-traditional fishing grounds with higher densities of species other than Snow Crab. The hyper-constriction of fishing effort to the eastern-most portion of 4X since 2015, likely resulted in lower bycatch levels.

The low incidence of bycatch in commercial catch of the SSE Snow Crab fishery can be attributed to:

- Trap design (top-entry conical traps) excludes many fish species.
- Passive nature of fishing gear as opposed to other gear types, such as trawl nets (also increases survival of bycatch discards).
- Large mesh-size of trap netting (at a minimum 5.25” knot-to-knot).

The majority of bycatch for all areas is generally composed of other invertebrate species (e.g., Northern Stone Crab [*Lithodes maja*] and American Lobster) for which higher survival rates after release are expected, as compared to fin-fish discards. In ENS, Northern Wolffish and Spotted Wolffish, both *Species at Risk Act* (SARA)-listed species with “Threatened” status, have been observed in the bycatch of the fishery in at least one of the three fishing seasons from 2016, 2017, and 2019 (most recent years with proper data collection). Striped Wolffish (SARA-listed species of “Special Concern”) have also been observed in each of these three seasons. The catch of all three species was at extremely low levels. Their prevalence in Snow Crab catches will continue to be monitored.

Oil and Gas Exploration and Development

Oil and gas exploration and development has occurred, and continues to occur, on the Scotian Shelf near, or upstream from, major Snow Crab fishing grounds and Snow Crab population centers in both N-ENS and S-ENS. Seismic surveys are used by the oil and gas industry to identify areas of petroleum resource potential beneath the seafloor (Breeze and Horsman 2005). The effects of offshore oil and gas seismic exploration on potentially-vulnerable components of the Snow Crab population (e.g., eggs, larvae, and soft-shelled Snow Crab), as well as on the long-term biological development and behaviour of this long-lived species remain unknown (DFO 2004; Boudreau et al. 2009; Courtenay et al. 2009). Anecdotal reports following seismic exploration that occurred in November 2005 over the Glace Bay Hole and the shallows of the Sydney Bight (i.e., Hunt Oil 2005; Husky Energy 2010), where immature and females are generally abundant, suggested that seismic activity may have negatively impacted the Snow Crab population proximal to the exploration program. The Canada-Nova Scotia Offshore Petroleum Board (CNSOPB), the regulator that oversees the petroleum industry that operates in the offshore of Nova Scotia, has issued a Call for Bids for offshore exploration in N-ENS and S-ENS in 2019–2021 (Figure 41), as part of its current three year plan (CNSOPB 2019). The potential area of exploration for 2019 is a block west of Sable Island. Potential exploration for 2020 is a large block west of The Gully encompassing Sable Island and substantial Snow Crab habitat. Two exploration blocks are open for bids for exploration in 2021. The offshore block is along the southern edge of the continental shelf east of The Gully, whereas the inshore block runs completely within S-ENS. All potential exploration areas overlap with juvenile, female, and commercial Snow Crab habitat. Future seismic exploration in offshore areas occupied by Snow Crab may need to evaluate the impacts on the species.

Undersea Cables

Undersea cables have been identified by fishers as another source of concern, in particular, the Maritime Link subsea cables in N-ENS. Two subsea High Voltage DC Cables now span approximately 180 km from Cape Ray, Newfoundland, to Point Aconi, Nova Scotia (Emera 2013), to transport electricity from the Lower Churchill Hydro-electric project. These cables were laid in the spring of 2017, directly through productive Snow Crab fishing grounds of N-ENS.The two 4’ diameter cables are spaced at least twice the water depth at a given location. Trenching to a minimum of 1 meter below the seafloor through spatially-specific jet benthic fluidizing

(20 cm path for each cable; EMERA 2016) should lower the likelihood of a physical barrier to movement being created, as opposed to more destructive and expansive methods of cable trenching. The cables may create a barrier to normal Snow Crab movement through static magnetic fields (and/or associated) induced electrical fields or increased temperature (generated by the resistance of flow through cables). These cables were energized in January 2018. Emera Newfoundland and Labrador (ENL) conducted a magnetic emissions survey in early May. Results indicate the intensity of the magnetic fields measured in-situ are lower than the emissions predicted by the models (J.-M. Nicholas, personal communication, EMERA Newfoundland and Labrador). At present, there is no information that can be presented to describe their effects upon Snow Crab.

Additional tagging effort has been undertaken in this area since 2013 (see above section: *Movement*) by both DFO and Emera. This tagging will provide additional information about the movements of Snow Crab into and out of this area prior to, and following, the installation of the undersea cable.

Socio-Economics

A coherent change in many socio-economic indicators occurred in the mid-1990s, in the same time frame as the large-scale changes in the SSE (see Figure 13, Choi and Zisserson 2012). In general, the demographics of Nova Scotia shifted toward an older and more affluent population base with the ageing of the “baby-boomers”. The total population size has also been increasing over the historical record to approximately 953,869 people in 2017, as well as a trend toward a population with higher levels of education. Nova Scotia’s GDP (Gross Domestic Product) has also been increasing along with the GDP associated with oil and gas exploitation and the number of cruise ships visiting Halifax. These demographic changes are associated with a greater biological demand for fishery resources, locally and as exports.

Amongst the more fishery-related indicators, there has been an increased importance of invertebrate fisheries with the demise of the groundfish in the early-1990s, both in terms of total landings and landed values of the fisheries. The number of shellfish closures has increased over time. However, the relative importance of fishing to the Nova Scotia GDP and the total number of fish harvesters has both been on the decline.

The fished species have changed greatly since the early-1990s in conjunction with the rapid changes in species dominance structure. Since this time, total groundfish landings have declined, falling from 281 kt in 1991 to 44 kt in 2017 for the province of Nova Scotia. Similarly, the pelagic fish landings have decreased from 125 kt in 1990 to 46 kt in 2017. In contrast, invertebrate landings have increased from 111 kt to 168 kt since the 1990s, as has the total landed value for all fisheries combined, increasing from $445 million in 1990 to $1.4 billion in 2017.

The links between the socio-economic changes observed and the changes in the SSE are complex. However, an important issue to consider is whether alterations in social and economic structure can assist in the continued evolution of precautionary and ecosystem-based management of a sustainable and viable Snow Crab fishery. Certainly, transparency in management, communication by science, and a unified voice among fishers with a long-term vision for their resource can assist, as has been the experience in S-ENS in the post-2004 period—a success that merits emphasis. Maintaining and fostering these positive determinants of stewardship is essential for the continued social, economic and ecological sustainability of this fishery.

Marine Protected Areas

St. Anns Bank area was designated as a Marine Protected Area (MPA) in 2017 pursuant to the *Oceans Act*. The MPA is subdivided into four zones (Figure 42). The majority of the MPA (Zone 1) is a core protection area. The three remaining (smaller) zones are referred to as “adaptive management zones”, which allow limited human activity to occur within their boundaries. The presence of a refuge from fishing activities serves as a fallowing area; however, if the protection is disproportionately beneficial to other organisms (i.e., Snow Crab predators or prey items), the effects upon Snow Crab can be mixed. The long-term effects of an MPA cannot be determined at this point.

The Gully MPA (Figure 42) is a 2,364 km^2 area east of Sable Island and is the largest marine canyon in the Northwest Atlantic. This area was designated as a protected area in 2004 and is comprised of three distinct management zones, each with specific allowable activities. No Snow Crab fishing is permitted in any of these zones.

The Snow Crab survey continues to occur within the St. Anns Bank and The Gully MPAs (through a designated approval process), providing data on the co-occurrence of Snow Crab and other species within these areas. Increased sampling survey catches (fish lengths, weights, and dietary analysis) occur at reference stations within and immediately outside the MPA boundaries.

FISHERY

Effort

In N-ENS, a spring season was introduced in 2008 in an effort to reduce soft and white Snow Crab capture and handling during the summer season, and now represents the majority of the fishing efforts. This season was in addition to the traditional summer season. Individual fishers were able to fish during either or both seasons. Starting in 2019, there were no longer two distinct seasons. The season ran through the spring and summer, though fishing efforts were still constrained to the two historical fishing periods within the year. This temporal gap in effort is caused by Snow Crab fishers shifting focus to Lobster fishing. The Lobster fishery (Lobster Fishing Area 27) is effort controlled; each fisher realizes their landings/profit with a set number of traps for a set time period of time. Fishing Snow Crab (TAC controlled) during an open Lobster season would likely decrease Lobster landings and overall annual profit.

After the successful trial of spring fishing in 2008, landings associated with spring fishing efforts peaked at 91% in 2010 and had remained above 65% of landings since that time, with the exception of 2014 and 2015 when sea ice conditions limited spring fishing efforts (Figure 43). Spring landings represented approximately 70% of total annual landings from 2016–2018. In 2019, 89% of the landings occurred before the shift of focus to Lobster fishing. Total effort (expressed as trap hauls) decreased in N-ENS in 2019 (Figure 2). The 2019 fishing effort (Figure 44) was again focused on the trench of deep water located along the north-eastern coast of Cape Breton (“inside”), with almost no effort in the Glace Bay Hole. Some fishing (albeit limited) occurred on the northern-most portion of N-ENS along the CFA 19 boundary line in 2019. The number of vessels active each season in N-ENS continues to slowly decline (Figure 45).

In S-ENS, fishing effort has gradually been shifting from being almost exclusively offshore (> 75km) to a mix of offshore and inshore fishing grounds (Figure 44) with higher landings from offshore areas. Much of the fishing effort in CFA 23 still continued to be focused on the holes found between Misaine and Banquereau banks. The inshore area of CFA 23 saw reduced fishing effort in 2019 as compared to 2018. In both seasons, this inshore effort occurs almost exclusively during the spring.

Crab Fishing Area 24 saw a return of fishing efforts north of Sable Island, that had been reduced in 2018, with substantial 2019 fishing effort proximal to Canso and Middle banks. Summer fishing efforts in CFA 24 occurred generally within the same areas as spring fishing efforts, though at lower levels. In 2019, almost no fishing effort occurred along the CFA 23 boundary other than south of Canso Bank. This boundary line (particularly inshore) has traditionally represented important commercial fishing grounds in CFA 24. There was limited effort in the western-most portion (along the “Eastern Shore”; west of 61.5^0 Longitude) of CFA 24 and no effort on the continental shelf edge throughout S-ENS. This lack of effort on the shelf edge is likely driven by decreased biomass (likely driven by warming bottom temperatures) coupled with increased fishing costs to operate further from shore.

In both CFAs 23 and 24, fishing patterns were affected by an overlap with spring fishing activities for shrimp as the Snow Crab fleet has limited access to some of the most productive Snow Crab fishing zones throughout the spring months, due to area closures. (These areas are known as shrimp boxes.) When these areas open to the Snow Crab fleet in the early summer, the majority of fishing effort occurs within these shrimp boxes. Prior to 2010, less than 20% of S-ENS landings occurred before July 1st, whereas now over 50% of total landings consistently occur in this spring period. In comparison to CFA 23, CFA 24 consistently shows a higher percentage of spring landings (Figure 43), possibly indicating that CFA 23 is impacted by spring “shrimp box” closures.

In S-ENS, the number of active vessels has shown a generally decreasing trend since 2009 (Figure 45). The current number of active vessels is approximately 50% lower than the pre-2010 period. This reduction is due to many licenses partnering and license holders choosing to lease their quota for the year rather than fishing it themselves. This raises concerns when hired captains and crews potentially have no long-term stake in this fishery. Such individuals may not follow proper handling protocols for discarded Snow Crab, or fish in strategic ways to avoid ones that are soft-shelled, and may not choose not to report tagged Snow Crab that are essential to proper movement studies. The vessel chosen to fish a license holder’s quota may be driven by the desire to maximize profit with little concern for experience of the captain and crew and their regard for conservation-minded harvesting.

In 2019, a total of 7,200 and 63,200 trap hauls were applied in N-ENS and S-ENS, respectively. (Tables 2–4; Figure 2).

Landings

Landings in 2019 for N-ENS and S-ENS, were 629 t and 6,632 t, respectively, representing a decrease of 15% (N-ENS) and an increase of 9% (S-ENS) relative to the previous year (Figure 3 and Figure 46; Tables 2–4). Total Allowable Catches in 2018 were 631 t, 6,632 t, and 0 t in N-ENS, S-ENS, and 4X, respectively. Due to low commercial biomass levels, there was no allowable catch in 4X for the 2018–19 season.

The majority of N-ENS landings came almost exclusively from the inner trench. S-ENS saw a general offshore migration of spatial-landings patterns from the 2018 season. (Figure 46). There were no landings on the continental slope areas of S-ENS in 2019.

Catch Rates[1]

Non-standardized catch rates in 2019 were 87 kg/trap haul in N-ENS and 105 kg/trap haul in S-ENS—relative to the previous year, represents an increase of 40% (N-ENS) and a decrease of 9% (S-ENS) (Figure 4; Tables 2–4). The effect of TACs on catch rates can confound direct comparison over time and between management areas.

In N-ENS, the 2018 catch rates were 87 kg/trap, an increase relative to 2018 (62 kg/trap). N-ENS catch rates are above the 15-year mean (76 kg/trap; Table 2; Figure 4). Catch rates were lower in the Glace Bay Hole, though higher on “inside” fishing grounds, as compared to past seasons (Figure 47). Both the spring and summer periods of the N-ENS fishery (Figure 48) showed increasing catch-rate temporal trends. In N-ENS, the increased 2019 catch rates (relative to 2018) occurred even with a drop in the mean size of animals caught (Figure 49). The N-ENS fishermen had felt that the maintenance of high catch rates from 2011–2016 indicated a much larger biomass of commercial Snow Crab than was necessarily indicated by survey-driven biomass estimation. They felt the discordant timing of the survey (fall) versus the fishery (spring-focused) causes this discrepancy. These high catch rates (> 100kg/trap) have not occurred in the last three seasons.

In S-ENS, the 2019 catch rates were 105 kg/trap, a decrease from 2018 rates (116 kg/trap) and just above the 15-year mean of 102 kg/trap (Table 3; Figure 4). Catch rates decreased from 2018 in each of the two CFAs in S-ENS, CFA 23 and CFA 24. Crab Fishing Area 23 has had higher annual catch rates since 2009 but maintains a very similar pattern of annual catch-rate changes with CFA 24. Catch rates were uniformly moderate/high throughout the majority of the exploited fishing grounds in S-ENS (Figure 47). The lack of very low localized catch rates suggests that fishers were efficiently identifying high abundance locations and, therefore, generally avoiding over-depletion of lower abundance areas. Limitations on access to all fishing grounds caused by temporal exclusions (shrimp boxes) may lead to short-term localized depletion in available fishing grounds during spring fishing activities. Examination of weekly catch rates over the course of the 2019 season (Figure 48) shows high opening catch rates in CFA 23. This is followed by a general decreasing trend until a marked resurgence in catch rates with the opening of the shrimp boxes (late June) and a declining trend after that time. CFA 24 shows a more consistent decreasing trend for catch rates over the course of the season. This would suggest that CFA 23 catch rates are more affected by the limited access to fishing grounds caused by seasonal closure of the shrimp boxes.

In all CFAs, a strong divergence in catch rate from the season trend during the final weeks of the season is common. During this time effort and landings are negligible. Some catch in traps is not retained on the final trip as individual quotas have been reached.

In 4X, the 2017–2018 catch rates were 12 kg/trap (Table 4; Figure 4), approximately half of the 14-year mean of 25 kg/trap. Catch rates were at the lowest level since 2003. These catch rates, coupled with low commercial biomass estimates, required the decisive management action to not allow any commercial fishery for the 2018–2019 season. This fishery re-opened for the 2019–2020 season with a conservative quota of 55 mt and catch rates were at the highest level on record. The relatively low TAC and no landings from previous season likely bolstered catch rates.

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[1] Please recall the caveats about catch rates being inappropriate indicators of fishable biomass, as discussed in the Methods section above.

At-sea-observer Coverage

In N-ENS, the at-sea-observer coverage was at 5.4% of landings (5% target). A total of 324 trap hauls were observed (approximately 4.5% of commercial trap hauls). In S-ENS, 5% of the landings were observed (5% target). A total of 2,891 traps (approximately 4.6% of commercial trap hauls) were observed.

Carapace Conditions of Catch and Soft-Shelled Crab

In N-ENS, CC1 and CC2 Snow Crab collectively represented approximately 3% of the total catch (Table 12; Figure 50), relative to 28% in 2018. A shift towards a predominantly spring fishery has generally lowered the catch of CC1 and CC2 Snow Crab (as they are less able to climb into traps earlier in the year due to recent molting). Observed CC1 and CC2 Snow Crab were caught mostly in the summer fishery in 2019. Higher incidence of soft-shelled Snow Crab in the summer fishery has been suggested anecdotally as being a result of localized depletion of stronger, hard-shell males, and a consequent increased catchability of new-shelled males due to the lack of competition/inhibition. The relative decrease in CC2 was accompanied by a proportional increase in CC3. CC4 levels were consistent from the previous season. CC5 levels remain negligible. There was a continued shift towards smaller-bodied animals being caught in the fishery (Figure 50), likely due to the fact that the earliest maturing animals of the current recruitment pulse mature at a smaller size.

The incidence of soft-shell catches in the N-ENS summer fishery were at the highest levels observed in ten years in 2018 (Figure 51). The causes were likely twofold: increasing pre-recruitment levels and increased summer fishing effort. Soft-shell catches returned to low levels in 2019. If one assumes no recaptures and prorates the observed landings to total landings, this amounts to an additional 31 t (approximately 5% of landings) being discarded as soft Snow Crab with potentially high handling-associated mortalities. This is a substantial decrease from 2018 soft Snow Crab incidence (approximately 25%). Maximizing spring fishing efforts, with little (or ideally no) summer fishing, will help limit this source of Snow Crab mortality incidental to the fishery removals. This is essential to protect any future increase in internal recruitment to the fishery from within the N-ENS Snow Crab population.

In S-ENS, the occurrence of CC1 Snow Crab remains at low (< 1%) levels (Table 13; Figure 50). The proportion of CC2 Snow Crab has remained constant since 2017, at approximately 6%. CC3 dominated the catch (approximately 63%). CC4 incidence rose to 31% from 8% in 2018. The summer portion of the fishery in S-ENS showed higher incidence of CC4 (41%) as compared to the spring (23%). Observed catches of high soft-shell percentage (> 20% by count) were extremely rare throughout S-ENS in 2019. When prorating observed landings to total landings in S-ENS, this amounts to a potential additional mortality of 135 t (2% of landings), consistent with 2018.

Voluntary avoidance of areas showing high incidence of soft Snow Crab must be adhered to by all members of the fleet if this mitigation is to be effective. Unfortunately, this is not always the case. There is potential miscommunication as quotas are sold through processors and other brokers and fished by individuals who do not own quota personally, and thus, have no long-term stake in this fishery. All individuals involved in every level of the fishery must realize the potential damage caused by handling soft Snow Crab.

The data from 4X are not directly comparable to ENS as their fishing season is disjunct from that of N- and S-ENS. This fall/winter, 4X fishery continues to show negligible levels of soft Snow Crab (Table 14). As such, levels of CC1 & CC2 Snow Crab/soft-shelled catches are traditionally very low. Recent warming conditions following an extreme warm-water event in 2013–2013 is hypothesized to have been very detrimental to the Snow Crab population in 4X.

Mortality (direct and incidental) caused by warming bottom temperatures likely continues to influence both stock structure and species composition in 4X.

Old Crab (CC5)

The CC5 Snow Crab represented a low proportion of the 2018 at-sea-observed catch in both legal- and sub-legal-size fractions at less than 1% in all areas (Tables 12–14). Similarly, low to undetectable proportions of CC5 were observed in the trawl surveys (Tables 15–17). Increasing levels of senescent Snow Crab (CC5) is anecdotally stated to indicate under-exploitation of the resource. No such increase has been observed in any area on the Scotian Shelf.

RESOURCE STATUS

SIZE STRUCTURE

Male

In S-ENS, the presence of small immature male Snow Crab spanning almost all size ranges (55–95 mm CW), observed by the survey, suggests that recruitment to the fishery is probable for the next 2 to 4 years (Figure 52). This may be followed by a period of decreased recruitment as there are fewer Snow Crab in the 30–55 mm size range than traditionally observed in S-ENS. Increased numerical abundance of Snow Crab < 30 mm CW, despite low trawl catchability and likely resulting from increased egg production for the past 2–3 years, suggests a positive long-term outlook. This outlook assumes reasonable survival rates of these smallest animals.

In N-ENS, the distribution of large male Snow Crab appears very similar to that of 2018 but with more animals above the 95 mm minimum legal size. Many of the Snow Crab in the 95–105 mm size range are immature and will molt again before becoming available to the fishery. Once molted, these individuals can provide substantial increases in yield per individual Snow Crab landed to the fishery. This is the leading edge of a recruitment pulse entering the fishery. Internal recruitment to the fishery is expected to continue for the next 2–4 years. The almost complete absence of Snow Crab in the 30–55 mm size range will likely result in decreased recruitment in the future; though the appearance of a relatively large cohort of Snow Crab below 30 mm, despite low trawl catchability, provides a positive longer-term outlook. High suspected natural mortality of Snow Crab in N-ENS could limit this recruitment.

The Snow Crab in Area 4X show erratic inter-annual patterns with minimal potential for internal recruitment to the fishery based on size-frequency distributions from the trawl survey. Few commercial Snow Crab were observed in the Snow Crab survey in 4X, though more than the previous two trawl surveys. As with N- and S-ENS, a strong pulse of animals < 30mm were observed in the 2019 survey.

Female

In 4X, N-ENS, and S-ENS, there was a substantial recruitment of female Snow Crab into the mature (egg-bearing) segment of the population from 2016–2018 (Figure 53) and egg/larval production is expected to be high, though decreasing. In N-ENS, densities of mature females appear to be declining faster than in S-ENS, potentially indicating high natural mortality of this segment of the population. These animals may be more susceptible to predation as they are smaller than mature males and are potentially a more energy-rich food source for predators. It is noteworthy that though mature (egg-bearing) female abundance has been relatively high (compared to previous 5 years) since 2017, it is now decreasing and peaked at lower levels than observed previous to 2009. This period of increased egg production has created progeny now captured in a pulse of Snow Crab < 30mm in both sexes in all areas.

Crab Fishing Area 4X is unique with respect to the potential for internal recruitment from egg production. Being downstream of all other Snow Crab areas increases the chance of larval settlement in 4X regardless of a resident population of mature females. Size-frequency distributions in 4X are erratic, with less inter-annual consistency as compared to N-ENS and S-ENS. Large temperature fluctuations (with associated habitat constriction), different predator fields associated with the warmer waters, and potential movements to/from CFA 24, likely result in the apparent instability in size structure. Movement of Snow Crab away from traditional locations within 4X, in reaction to such temperature and predation changes, may also confound inter-annual survey results.

High densities of mature female Snow Crab in 4X have been apparent in survey catches since 2018, relative to past 4–6 years. The appearance of small Snow Crab of both sexes in the smallest sizes classes mirrors the finding in N- and S-ENS. Interestingly, these Snow Crab appear to be larger (up to 40 mm rather than 30 mm) which might indicate increased size-at-age in the warmer water environments of 4X.

SEX RATIOS

When the relative number of mature female Snow Crab (as compared to male) is high, the possibility of reproductive limitation becomes a conservation issue. This is particularly an issue in heavily exploited areas where there is an absence of large mature males able to mate and protect the more rapidly maturing and smaller females. This is observed in the southern Gulf of St. Lawrence, where male limitation is a known issue. Conversely, with very low relative numbers of female Snow Crabs (e.g., cyclically observed circa 2003 and 2013 throughout the SSE) there is low egg and larval production. The reason for extended period(s) of poor reproductive potential in the SSE is not known. Female Snow Crab are not removed by the fishery so it is not directly a fishery-related effect. A potential explanation is differential predation pressures for males and female Snow Crab, based on varying habitat preferences for the sexes and the smaller size of mature females. Extreme sex ratios represent an unhealthy reproductive state and a long-term conservation issue. Discontinuity between temporal trends of mature male and mature female population peaks may be a driving force behind large-scale immigration or emigration patterns. Snow Crab (particularly large males) may move to find mature females. This appears to have been the case in the early 2010s with mature males emigrating from N-ENS to the neighboring Area 19.

There is a high likelihood that sex ratios will naturally fluctuate over time (Figure 54) as female Snow Crab of a given year-class will mature two to four years earlier than a male from the same year-class. Females are also believed to have a shorter mature and total life span. Such natural oscillations are particularly evident when strong year-classes dominate a population, as has been the case in the SSE. In the SSE, the sex ratios of mature Snow Crab oscillate with relatively high numbers of females in 1996, 2007, and again in 2017, with a major trough in the early 2000s and again in early 2010s (Figure 54 and Figure 55). A similar lull is anticipated in the early 2020s. In N- and S-ENS, sex ratio (% female of mature animals) have peaked in recent years and are now declining. The current declining trend is reflective of increasing mature male population and, to a larger degree, decreases in mature females. Area 4X sex ratios of mature Snow Crab have increased steadily since 2014. Female Snow Crab in 4X seem to potentially out-survive the males, a reversal of other areas on the SSE; high exploitation of males may be one cause.

The sex ratios of immature Snow Crab (Figure 56 and 57) had been decreasing in all areas since approximately 2016. This is due to females of the recent population pulse maturing before the males of the same age cohort, lowering immature sex ratios while increasing mature ratios. The decreasing trend observed in mature female densities coupled with the appearance of new immature female Snow Crab has increased immature sex ratios in 2019 in all areas.

The spatial patterns of the sex ratios are generally distinct: immature males are found in greater proportion (blue) in central areas in ENS, whereas immature females (red) are found in greater proportion in areas bordered by warm water, on the outer geographical margins of Snow Crab distributions on the Scotian Shelf. When such spatial segregation is observed, the sexes are likely exposed to differential predation effects. Immature females are likely preyed upon by fish and other macro-invertebrates (including other female Snow Crab, other crabs and Lobster) favoring warmer water habitats. This pattern would be exacerbated by the sexual dimorphism of Snow Crab, as males grow to be larger and so escape some of the size-dependent predation to which the smaller females would be exposed.

FEMALE NUMERICAL ABUNDANCE[2]

Trends in the number of immature and mature females caught in the trawl surveys has been variable across areas (Figures 58–60). In all areas, the density of immature female Snow Crab declined from 2014 to 2018. Maturation of these immature Snow Crab began in 2015 and continued into 2018, lowering the relative immature component of the female population (Figure 58), but increasing the mature component (Figure 60). This decreasing trend has reversed in 2019, with natural mortality of the mature component and the appearance of a new pulse of small, immature Snow Crab in the survey catches.

Based on population size structure, mature female abundance is expected to decline for the next 3–4 years. Increasing numbers of immature Snow Crab is expected as a result of 3+years of relatively high egg production, assuming the survival of these animals from egg to trawl-catchable sizes. This is supported by increased densities of the smallest Snow Crab in the 2019 trawl survey.

Immature females in 4X have shown a general decreasing trend since 2009 with anomalous (and unexplained) highs in both 2010 and 2014. Immature female Snow Crab numbers have increased in each of the last two years. The mature fraction of the female abundance has decreased since 2018 (Figure 60). Somewhat erratic trends in individual components (immature, mature, male, female, etc.) of the 4X Snow Crab population could potentially be explained by temperature-driven shifts in animal distribution, into or away from surveyed areas. The removal of some 4X survey stations in recent years could potentially elevate densities of all population components, as many of the stations removed had no Snow Crab in the catches for a number of years. These stations were removed to lower survey costs and increase survey efficiencies.

Most of the female Snow Crab are primarily found in shallower areas along the shore of mainland Nova Scotia and in offshore areas (Figures 59 and Figure 61). For Snow Crab, immature females appear to have a more diffuse distribution than mature females (Figure 59, Figure 61, and Figure 62).

Maturation of immature female Snow Crab in N- and S-ENS from 2016–2018 increased egg production (Figure 63). This egg production is expected to continue for 1–2 years in all areas as

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[2] Most categories of Snow Crab are likely under-estimated as catchability corrections are not applied. Their intended use is, therefore, solely to compare relative trends over time.

mature animals mate and produce broods of eggs. Larger egg clutches in aging (multiparous vs. primiparous) Snow Crab should support this egg production.

FISHABLE COMPONENT OF POPULATION

Trends of raw (unadjusted for habitat, etc.) geometric mean survey catches of commercial (male, mature ≥ 95 mm CW) Snow Crab are shown in Figure 64. The carstm approach generates area biomass estimates through aerial expansion of survey catches (Figure 65) to produce the survey biomass index. In N-ENS, the highest fishable biomass densities appeared less concentrated in 2019 compared to 2018 (Figure 66). In S-ENS, commercial Snow Crab distributions did not appear to be more aggregated but appear to be shifted generally southward in CFA 24. In 4X, the strongest concentration of fishable Snow Crab is in on the 4X/S-ENS line (Figure 66) though some expansion of commercial Snow Crab distributions slightly westward was observed in the 2019 survey. Commercial Snow Crab exist at very low densities in locations further west in 4X.

RECRUITMENT

Quantitative determination of recruitment levels into the fishable biomass is confounded by numerous factors. These include terminal molt (the timing offset of molting in spring and the survey in the fall) as well as the inability to age Snow Crab, and predict the age when males will terminally molt. Based on size-frequency histograms of the male Snow Crab population, internal recruitment to the fishery is expected for the next year in N-ENS and S-ENS (Figure 52 and Figure 67). Internal recruitment in 4X is expected to be minimal. Immigration of Snow Crab from outside a given area can represent recruitment to its fishery though it is unreliable based on its episodic nature.

In the survey, the presence of small immature male Snow Crab in N-ENS and S-ENS (Figure 52), spanning almost all size ranges (30–95 mm CW) also suggests that internal recruitment to the fishery is probable for the next 3–4 years, though potentially at decreasing rates due to the lower numeric densities of smaller animals. High numerical densities at the very smallest size range (< 30mm) in all areas are promising signs of potential long-term recruitment. The survival of these small animals is essential for the fishery to realize this recruitment. Any mortality (e.g., predation, environmental, and disease), emigration, or sub-legal size molting will impact this recruitment potential.

Based on size-frequency distributions from the trawl survey, 4X shows limited potential for internal recruitment to the fishery for the next 2–3 years. Movement is potentially an important source of Snow Crab in this area and a lack of any commercial fishing effort in the western portion of CFA 24 holds potential benefits for 4X. Erratic temperature fields in 4X create strong uncertainties for the future of commercial Snow Crab stocks.

STOCK ASSESSMENT MODEL

The logistic production model shown here is used as a heuristic to couple landings and biomass estimates from the space-time modelling (described above) in order to simplistically describe the productivity of the system and adjust the biomass scaling in relation to the landings (see Appendix 2 for more details).

Posterior distributions for carrying capacity (K), median population growth rate (r), catchability coefficient (q), and process error (bp.sd) were updated from the prior distributions suggesting the data did inform the model output (Figures 68–73). Estimates of r were 0.796 for N-ENS, 0.692 for S-ENS, and 0.722 for 4X (Figure 68), whereas K (Figure 69) for S-ENS (76.3 kt) is approximately 11 times higher than for N-ENS (6.77 kt), largely reflecting the differences in area of suitable Snow Crab habitat. There was almost no difference in q for N-ENS and S-ENS, with estimates of 1.11 and 1.1, respectively, whereas q for 4X was 0.88 (Figure 70). These estimates of q reflect the relative ability of the survey fishable-biomass index to accurately describe the stock biomass when coupled with landings. The posterior distributions for bp.sd are shown in Figure 71 and observation error (bo.sd) is shown in Figure 72.

The median estimates of F_{MSY} were 0.398 for N-ENS, 0.346 for S-ENS, and 0.361 for 4X (Figure 73).

FISHABLE BIOMASS

The modelled post-fishery fishable biomass index of Snow Crab (Figure 74) in N-ENS was estimated to be 4,460 t, relative to 3,299 t in 2018. In S-ENS, the post-fishery fishable biomass index was 54,408 t, relative to 44,705 t in 2018. In 4X, the pre-fishery fishable biomass was 418 t, relative to 428 t in 2018.

FISHING MORTALITY (F)

The N-ENS Snow Crab F value in 2019 has been estimated to have been 0.14 (exploitation rate 0.13), a decrease from 0.22 in 2018 (Figure 75).

The S-ENS Snow Crab F value in 2019 has been estimated to have been 0.12 (exploitation rate 0.13), a decrease from 0.13 in 2018 (Figure 75). Localized exploitation rates are likely higher, as not all areas where biomass estimates are provided are fished (e.g., continental slope areas and western, inshore areas of CFA 24) and reports of illegal landings remain in this area.

The 4X Snow Crab F value in 2018–2019 was 0 as there was no commercial fishery. Generally in 4X, realized exploitation rates are likely to be higher, since the computed exploitation rates incorporate biomass from throughout the 4X area and not just the fishery grounds.

NATURAL MORTALITY

Wade et al. (2003) suggested that instantaneous mortality rates for southern Gulf of St. Lawrence male Snow Crab ≥ 95 mm CW are within the range of 0.26 to 0.48. Natural mortality estimates for mature females have been estimated between 0.66 and 0.78 in the northern Gulf of St. Lawrence (Drouineau et al. 2013). For early benthic female stages (i.e., unfished Snow Crab, sex undetermined), instantaneous mortality may be near 1 (Kuhn and Choi 2011). Thus, the magnitude of fishing mortality (of males) seems to be generally smaller in magnitude than that of natural mortality and natural mortality seems to be higher for mature females than mature males. Diet studies (Bundy 2004; see section *Top-down Control: Predation*), suggest that very few natural predators seem to have existed for large Snow Crab (i.e., legal sized) in the SSE. This has been particularly the case since the demise of most large-bodied predatory groundfish from the eastern part of the SSE. The proliferation of Atlantic Halibut in the SSE poses an increasing source of natural mortality for Snow Crab of all sizes.

Other potential mortality factors include: disease (such as BCD which was found to be present in the SSE at low levels since 2008); seals (near Sable Island; although see arguments to the contrary in predation considerations above); soft-shell/handling mortality; illegal landings; bycatch in other fisheries (Lobster and other crab traps, long-lining, gill-nets, trawling); and activities associated with various other human activities, such as exploration and development of oil and gas reserves and trenching activities associated with sub-sea cable or pipe-line installation.

THE PRECAUTIONARY APPROACH

In the context of natural resource management, the Precautionary Approach (PA) identifies the importance of care in decision making by taking into account uncertainties and avoiding risky decisions. Natural ecosystems are intrinsically complex and unexpected things can and often do happen (e.g., Choi and Patten 2001). Details on the PA and caveats related to its implementation in the form of simplistic Harvest Control Rules (HCRs) can be found in Appendix 1.

The primary tools of fishery management are the control of fishing effort and removals. Generally, by reducing catch and effort, stock status and/or ecosystem context is expected to improve. Its usage in DFO has been formalized into the determination of Reference Points and HCRs (Appendix 1).

REFERENCE POINTS AND HARVEST CONTROL RULES

The ESS Snow Crab population is not at, nor near, any equilibrium state. As a result, the parameter estimates derived from the logistic model provide, at best, first order estimates of the true biological reference points (see *Methods*; Figures 68–73).

The operational reference points associated with the 4VWX Snow Crab fishery are as follows:

- Lower Stock Reference (LSR): 25% of estimated carrying capacity.
- Upper Stock Reference (USR): 50% of estimated carrying capacity.
- Removal Reference (RR): not to exceed F_{MSY} (where F is the fishing mortality of the legal sized mature male population and MSY is the theoretical Maximum Sustainable Yield).
- Target Removal Reference (TRR): 20% of the fishable biomass (F = 0.22). Secondary, contextual indicators are used to alter harvest rates between 10% and 30% of Fishable Biomass (FB; F = 0.11 to F = 0.36).

The HCRs (Figure 76 and Figure 77) are as follows:

- FB > USR: target exploitation rate of 10% to 30% be utilized, based upon contextual information provided by secondary indicators.
- LSR < FB < USR: target exploitation rate of 0% to 20%, based upon contextual information provided by secondary indicators.
- FB < LSR: fishery closure until recovery (at a minimum, until FB > LSR).

The adoption of a new approach to abundance estimation (carstm) requires that harvest strategies be considered within the context of past (back-calculated) carstm estimates of fishable biomass and fishing mortality. The harvest rates referenced within the HCRs were based on the simple assumption that approximately 1/5 of the harvestable stock will die from natural causes within a given year (based on the assumption that a male Snow Crab lives for approximately 5 years after terminally molting to maturity. The TRR of 20% followed the logic that long-term fishery removals should not exceed natural mortality over that same time period to avoid over-taxing a natural resource.

Given a longer time series of data and a more stable approach to biomass estimation, these target harvest rates can be adjusted based the performance of the stock given various harvest levels in the historical record. This should be possible over the next 2–3 years of using the carstm approach.

Current Limitations of Reference Points

Many sources of uncertainty/challenges are associated with these reference points and the underlying biological model:

- The fishery projection model is extremely simplistic and focused upon a limited fraction of the total population; intraspecific and interspecific compensatory dynamics are not considered. It is a "tactical" model for short-term projections rather than a "strategic" model for biological description and comprehension of longer-term conservation requirements associated with the PA.
- Large changes in carrying capacity have been observed in the area: pre- and post-collapse of groundfish precludes an expectation of a single K (carrying capacity) estimate with associated reference points.
- Large spatial and temporal variations in recruitment strength preclude simple r-parameter estimation.
- Large spatial and temporal variations in environmental conditions increase uncertainty in abundance indices and preclude any reasonable assumptions of fixed natural mortality/intrinsic rate of increase.
- Strong spatial and temporal variations in predator abundance, especially of pelagic and early (juvenile) benthic life stages of Snow Crab, preclude a simple assumption of fixed natural mortality/intrinsic rate of increase.
- Cannibalism, especially by mature females upon early benthic stages, results in greater dynamical instability and precludes a constant natural mortality/intrinsic rate of increase assumption.
- Anecdotal sources suggest illegal landings might be large and variable over time. This is not accounted for.
- Sampling at different points of annual biological cycles creates variable catchability/bias issues.
- Life cycle is complex.

The development of carstm was an attempt to address some of the above issues through the incorporation of ecosystem covariates into Snow Crab abundance estimation procedures.

RECOMMENDATIONS

GENERAL REMARKS

1. The capture of soft-shelled Snow Crab had been low for the past several seasons but increased substantially in N-ENS in the 2018 season. It remains an issue requiring continued diligence in all fishing areas. The timing of fishing efforts (winter and spring fisheries) can help avoid periods traditionally associated with high captures of soft Snow Crab. As some summer fishing still occurs, timely responses from industry to avoid fishing in areas showing high incidence of soft Snow Crab must continue to improve if unnecessary mortality of recruits is to be averted. Since 2010, to encourage rapid avoidance measures, soft-shell maps were implemented as interactive GoogleEarth™ maps that can be found at the ENS Snow Crab website.

2. The longevity of the fishable biomass (and, therefore, the stabilization of the fishery) can be improved by fishing solely upon morphometrically mature Snow Crab. The arguments for this approach are as follows:
    a. Fishing mature Snow Crab would allow them to mate as the fishing season is generally post-mating season (in ENS, but not 4X). This reduces Darwinian natural selection for early maturation, which is a long-term hazard for any fishery that harvests mature individuals.
    b. The capture of immature Snow Crab (pencil claws) reduces the longevity of the fishable biomass directly relative to a mature-only fishery. The time difference is two to three years as immature Snow Crab go through a soft- and white-shelled phases that exclude them from the fishery, and so extends the fishable period by this time.
    c. Specifically targeting mature (male) Snow Crab is an optimal exploitation strategy (CC3 and CC4 Snow Crab) since the fishable biomass is harvested when "ready and maximized". This is because there is a significant weight increase if immature Snow Crab are allowed to grow and mature (an increase of 250–400%; Figure 7).

    In the 2020 season, some of the ≥ 95 mm CW male Snow Crab will still be composed of immature individuals (Figure 52). Indeed, these immature Snow Crab will become the largest-sized (and heaviest) individuals in future catches if allowed to grow and reach terminal molt. They will continue to contribute towards reproduction, population-genetic fitness and represent high quality Snow Crab for the industry. Harvesting of this component of the catchable biomass is not recommended.
3. Anecdotal reports suggest that illegal fishing activities and mis-reporting of catch continues to occur, predominantly in S-ENS. Illegal/unreported landings represent an additional source of mortality for a population already pressured by external stressors such as increasing temperatures and predation. Such activities de-stabilize the "precautionary approach" to resource management and can negate the efforts made by the Snow Crab industry to help ensure the long-term stability of this fishery. This issue could be addressed through open communication, industry pressure on the offending parties, and novel approaches to fisheries regulation enforcement, such as forensic accounting and monitoring production of Snow Crab processing facilities.
4. Increasing temperature trends could be harmful to the overall health and abundance of Snow Crab on the SSE. This can create direct mortality, forced emigration in the most extreme conditions, or ecosystem regime shifts affecting prey availability, predator abundance, biological processes, etc. Changes that affect Snow Crab's relative role in the ecosystem will have population level effects. Recruitment levels in all areas seem lower than observed in the last population cycle (approximately 10 years ago), potentially as a result of these changes. This knowledge may not directly influence harvest strategies in a given year but should reinforce that fishery removals are a single component of a complex system. Limited knowledge of the entire system must be weighed when harvest strategies are considered.
5. The application of the target exploitation rate ranges, as defined by the HCRs, must be tempered by the adoption of a new biomass estimation methodology. The upper end of the target exploitation ranges are likely too high.
6. Biomass estimates are just that: estimates. Any attempt to accurately quantify something as inherently complicated as a natural population (Snow Crab in this case), let alone the effects of an ecosystem on this population, is impossible. The amount of population and ecosystem data and the associated computational power to accomplish this task is unattainable.

Acceptance of the limitations of any assessment approach stresses the further importance of using all available data sources (i.e., secondary indicators) when choosing harvest strategies.

NORTH-EASTERN NOVA SCOTIA (N-ENS)

High exploitation rates and limited recruitment, caused by handling mortality of soft-shelled Snow Crab in the past, pushed the N-ENS fishable biomass to historic lows. The capture of soft-shelled Snow Crab had been nearly eliminated, helping to protect recruitment. The 2018 fishing season saw substantial increases (potentially detrimental) in soft-shell Snow Crab catches, almost exclusively in the summer season. Spring fishing effort increased in 2019 and soft Snow Crab catches did not appear to be of concern. All efforts must be made to continue to reduce or eliminate summer fishing to protect incoming recruitment.

Large male Snow Crab must be protected to maintain habitat space and the breeding capacity of the stock. A gap in future recruitment to the fishery is expected based on the size structure of the N-ENS Snow Crab population. Both of these factors support conservative harvest strategies.

Minor decreases in TAC for the past two seasons, along with new recruitment to the fishery, appear to have helped catch rates and fishable-biomass estimates to rebound. N-ENS has moved from the cautious zone in 2018 to the healthy zone in 2019. This stock status and positive signs of increasing recruitment allow for more flexibility in harvest strategies.

SOUTH-EASTERN NOVA SCOTIA (S-ENS)

The long-term PA adopted by the S-ENS fishers since 2004 appears to have increased stability in commercial biomass levels. This stability is an important consideration given the changing ecosystems and the more volatile state of global Snow Crab populations. This stock remains in the healthy zone.

Substantial TAC reductions from 2016–2018 helped maintain stable fishery performance (catch rates) in S-ENS in spite of reduced recruitment, increased predation, and falling fishable-biomass estimates throughout that time. Based on stock structure, increased recruitment to the fishery is likely to occur for the upcoming season. Exploitation rates derived from the fishery model have been declining in recent years. Increasing recruitment and declining fishing mortality (exploitation rates) allows for flexibility in harvest strategies.

AREA 4X

CFA 4X is the southern-most extent of Snow Crab distribution in the North Atlantic, existing in more “marginal” habitats relative to the “prime” areas of S- and N-ENS. Based on a lack of coherence in inter-annual size-frequency distributions, the Snow Crab survey catches do not appear to represent the 4X Snow Crab population as effectively as the other two areas. Additionally, an increased volatility of ecosystem pressures (such as water temperature, predation, and bycatch in other fisheries) is likely to have a greater effect on Snow Crab behavior and distribution in 4X. It appears that reliance on the current HCRs and associated management practices (ultimately based on survey results) should be revisited. As this is a fall/winter fishery, additional efforts will be placed on exploring alternate harvest strategies before the upcoming season.

ACKNOWLEDGMENTS

The authors first thank W.T. Grover Fisheries Ltd., and the captain and crew of the *F/V Ms. Jessie* for the provision of a safe and hospitable environment for the conduct of the survey. The authors wish to thank Yihao Yin and David Keith of DFO Maritimes Region who provided thorough peer review. Finally, this assessment could not have been completed without the contributions of experience, time and financial aid of the Snow Crab license holders and fishers of the Scotian Shelf.

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TABLES

Table 1. Snow Crab fishing seasons on the Scotian Shelf in 2019.

Area	Season
N-ENS	April 1th–August 18th
S-ENS (CFA 23)	April 1st –August 31st
S-ENS (CFA 24)	April 1st –August 31st
4X	November 1, 2019–March 31, 2020

Table 2. Summary of Snow Crab fisheries activity of N-ENS.

Year	Licenses	TAC (t)	Landings (t)	CPUE (kg/trap haul)	Effort (x1000 trap hauls)
2005	78	566	562	31	18.4
2006	78	487	486	36	13.7
2007	78	244	233	24	9.9
2008	78	244	238	34	7.0
2009	78	576	579	76	7.6
2010	78	576	576	55	10.5
2011	78	534	536	110	4.8
2012	78	603	603	117	5.1
2013	78	783	783	106	7.4
2014	78	783	778	104	7.4
2015	78	620	619	103	6.0
2016	78	286	290	110	2.6
2017	78	825	813	90	9.0
2018	78	786	742	62	12.0
2019	78	631	629	87	7.2

Table 3. Summary of Snow Crab fisheries activity of S-ENS.

Year	Licenses	TAC (t)	Landings (t)	CPUE (kg/trap haul)	Effort (x1000 trap hauls)
2005	114	6,353	6,407	110	58.5
2006	114	4,510	4,486	91	49.4
2007	115	4,950	4,942	100	49.3
2008	115	8,316	8,253	96	85.9
2009	116	10,800	10,645	90	118.8
2010	116	13,200	13,150	103	128.3
2011	116	12,120	12,135	106	118.8
2012	116	11,707	11,733	98	120
2013	116	11,311	11,309	104	108.7
2014	116	11,311	11,267	112	100.2
2015	116	11,311	11,292	106	106.5
2016	116	9,614	9,606	106	90.6
2017	116	6,730	6,719	94	71.5
2018	116	6,057	6,064	116	52.3
2019	116	6,663	6,632	105	63.2

Table 4. Summary of Snow Crab fisheries activity of 4X. A "-" indicates no data due to 0 TAC.

Year	Licenses	TAC (t)	Landings (t)	CPUE (kg/trap haul)	Effort (x1000 trap hauls)
2005–06	9	337.6	306	29	10.8
2006–07	9	337.6	317	28	11.5
2007–08	9	230	220	18	12.1
2008–09	9	230	229	28	8.0
2009–10	9	230	229	36	6.4
2010–11	9	346	345	38	9.0
2011–12	9	346	344	29	11.8
2012–13	9	263	118	13	9.6
2013–14	9	80	79	15	5.1
2014–15	9	80	82	34	1.7
2015–16	9	150	142	31	4.6
2016–17	9	80	80	25	3.2
2017–18	9	110	55	12	4.6
2018–19*	9	0	-	-	-
2019–20**	9	55	52	51	Season ongoing

* No fishery (O TAC) due to low commercial biomass.

** As of January 6, 2020.Season ongoing.

Table 5. Snow Crab Carapace Conditions (CCs) and their description. Hardness is measured by a durometer.

Carapace Condition (CC)	Category	Hardness	Description	Age After Terminal Molt (Approximate)
1	New soft	< 68	claws easily bent, carapace soft, brightly coloured, iridescent, no epibionts	0–5 months
2	Clean	variable	claws easily bent, carapace soft, brightly coloured, iridescent, some epibionts	5 months–1 year
3	Intermediate	> 68	carapace hard, dull brown dorsally, yellow-brown ventrally, no iridescence, shell abrasion, epibionts	8 months–3 years
4	Old	> 68	carapace hard, very dirty, some decay at leg joints, some epibionts	2–5 years
5	Very old	variable	carapace soft, very dirty, extensive decay, extensive epibionts	4–6 years

Table 6. Spaghetti tagging by year since 2010 (totals since 2004). Rows represent results of all tagged Snow Crab within a single year. Average and maximum displacement represents the mean and maximum of the shortest path distance between tag release and recapture locations.

Year	Tags Applied	Tags Returned	Distinct Tags Returned	Average Displacement (km)	Max Displacement (km)	Average Days to Capture	Max Days to Capture	Average km/ month
2011	1,789	107	106	59.89	259.67	541.43	2278	3.37
2012	1,571	150	131	37.02	278.83	420.20	2219	2.68
2013	3,910	376	338	40.98	503.97	597.44	1923	2.09
2014	3,112	278	254	16.73	119.81	612.25	1550	0.83
2015	1,929	177	163	21.24	231.85	395.23	1125	1.64
2016	1,197	96	84	21.19	141.81	433.2	1089	1.49
2017	1,296	77	71	18.06	73.52	308.48	734	1.78
2018	1,216	24	24	23.68	200.7	314.5	368	2.29
2019	1,401	19	19	13.38	50.78	21.23	33	19.18
All Years/ Areas	**24,967**	**1,958**	**1,813**	**27**	**504**	**456**	**2,278**	**1.78**

Table 7. Summary of spaghetti tagging results by area since 2004.

Area	Tags Applied	Distinct Tags Returned	Average Displacement (km)	Average Days to Capture	Average km/month	Number of Fishermen Returning Tags
S-ENS	15,517	861	26.44	388.4	2.07	88
N-ENS	11,792	1,058	30.23	515.11	1.79	93
4X	833	95	8.02	231.89	1.05	17

Table 8. Predators of Snow Crab in ENS during the 1995–2016 time period. In each period, N stomachs represents the number of stomachs examined, Freq (%) is the percent of stomachs containing Snow Crab as prey, and Weight (%) is the percent of total weight represented by Snow Crab as prey. All predator species with less than 100 stomachs sampled were removed to negate potential sample size bias.

Predator Species	N Stomachs	Freq (%)	Weight (%)
Striped Wolffish	586	1.37	1.49
Halibut	673	1.34	1.18
Smooth Skate	546	0.92	1.49
Ocean Pout	149	0.67	0.65
Longhorn Sculpin	2101	0.38	0.36
Cod	6510	0.37	0.16
Thorny Skate	2789	0.32	0.60
Sea Raven	736	0.27	0.45
Winter Skate	560	0.18	0.10
White Hake	2729	0.07	0.01
American Plaice	8570	0.06	0.06
Haddock	4777	0.06	0.02

Table 9. Prevalence of Bitter Crab Disease (BCD) on the Scotian Shelf. Total Crab refers to the number of Snow Crab examined, Visible BCD Crab represents those suggested to be positive. Infection rate is the proportion of positives and %male is the proportion of BCD (+) Snow Crab that are male.

Survey Year	Total Crab	Visible BCD (+) Crab	Infection Rate (%)	% Male (BCD +)
2008	31,315	24	0.077	54
2009	29,168	33	0.113	61
2010	31,197	19	0.061	53
2011	24,852	22	0.089	59
2012	20,355	16	0.079	62
2013	21,715	16	0.074	56
2014	23,512	20	0.085	35
2015	19,749	20	0.101	55
2016	20,694	28	0.135	36
2017	15,453	13	0.084	54
2018	15, 430	7	0.045	57
2019	23,482	17	0.072	59

Table 10. Bycatch (kg) estimates of finfish and invertebrates from the ENS Snow Crab fishery. The estimates are extrapolated from at-sea-observed bycatch and at-sea-observed biomass of catch [i.e., estimated biomass of bycatch = observed biomass of bycatch species / (observed landings of Snow Crab / total landings of Snow Crab)]. The Snow Crab fishery is very species-specific as bycatch levels are extrapolated to be approximately 0.016% of Snow Crab landings for the years 2016, 2017, 2019 in ENS. ***No species specific bycatch data is available for 2018.***

Species	2016	2017	2019	3-Year Total
Rock Crab	0	0	40	40
Cod	84	353	40	477
Jonah Crab	854	0	20	874
Northern Stone Crab	670	18	337	1025
Toad Crab	84	35	278	397
Soft Coral	0	18	0	18
Basket Star	0	18	0	18
Sea Urchin	33	18	0	51
Sand Dollars	17	0	20	37
Purple Starfish	0	35	20	55
Sea Cucumbers	50	495	198	743
Whelk	17	0	20	37
Winter Flounder	0	35	0	35
Eelpout	0	35	0	35
Redfish	50	247	60	357
Sea Raven	33	0	0	33
Skate	67	18	0	85
Northern Wolffish	17	0	0	17
Spotted Wolffish	0	194	99	293
Striped Wolffish	100	371	20	491
Northern Shrimp	0	0	20	20
Mud Star	0	0	79	79
Atlantic Argentine	0	0	20	20
Flounder (unidentified)	0	0	20	20
Clam (unidentified)	0	0	20	20
Astoidea Starfish	0	0	20	20
Total Bycatch	2,076	1,890	3350	4,583
Snow Crab Landings	**9,896,000**	**7,532,000**	**7,261,000**	**29,339,000**

Table 11. Bycatch (kg) estimates from the 4X Snow Crab fishery. The estimates are extrapolated from at-sea-observed bycatch and at-sea-observer coverage, by biomass [i.e., estimated biomass of bycatch = observed biomass of bycatch species / (observed landings of Snow Crab / total landings of Snow Crab)]. Bycatch levels have been at 0.31% of total landings in the past four years. The limited spatial extent of the fishery for the past three seasons has produced lower bycatch levels than associated with a previously much larger geographical footprint. Note: no commercial fishery in 2018 due to low commercial biomass.

Species	2015	2016	2017	2018	4 Year Total
American Lobster	98	48	55	0	201
Cod	0	16	0	0	16
Jonah Crab	0	16	14	0	30
Rock Crab	0	0	14	0	14
Lumpfish	11	0	0	0	11
Northern Stone Crab	130	81	82	0	293
Redfish	0	0	14	0	14
Sea Raven	239	0	41	0	280
Total Bycatch	478	161	219	0	858
Snow Crab Landings	**142,000**	**80,000**	**55,000**	**0**	**277,000**

Table 12. Carapace Condition (CC) of Snow Crab ≥ 95 mm CW (percent by number) over time for N-ENS from at-sea-observed data.

Year	CC1	CC2	CC3	CC4	CC5
2006	3.87	9.68	71.14	13.67	1.64
2007	44.53	11.17	36.26	7.22	0.82
2008	26.84	4.21	61.33	6.86	0.75
2009	0.23	3.3	92.11	4.35	0.02
2010	1.6	1.56	92.61	3.97	0.25
2011	0	1.9	95.55	2.49	0.07
2012	0	2.99	95.68	1.33	0
2013	0	1.82	73.93	22.52	1.73
2014	0.09	25.65	72.58	1.67	0
2015	0.06	2.89	89.21	7.59	0.25
2016	0	1.26	84.96	13.66	0.11
2017	0.13	9.32	49.23	40.72	0.6
2018	0.15	34.5	45.22	19.74	0.37
2019	0	2.49	75.8	21.66	.05

Table 13. Carapace Condition (CC) of Snow Crab ≥ 95 mm CW (percent by number) over time for S-ENS from at-sea-observed data.

Year	CC1	CC2	CC3	CC4	CC5
2006	6.16	17.85	68.45	7.24	0.3
2007	7.95	15.61	58.48	16.32	1.63
2008	10.12	8.57	67.93	12.34	1.03
2009	8.41	7.4	64.77	16.9	2.52
2010	2.5	9.75	79.53	7.25	0.96
2011	0.57	9.22	85.42	4.71	0.09
2012	0.29	10.16	85.28	4.2	0.07
2013	0.25	2.78	94.14	2.81	0.02
2014	1.08	23.48	69.45	5.82	0.17
2015	0.7	8.68	83.77	6.61	0.24
2016	0.03	3.53	80.2	15.88	0.37
2017	0.02	6.3	78.67	14.75	0.26
2018	0.05	5.84	86.33	7.47	0.31
2019	0	4.91	64.1	30.76	0.22

*Table 14. Carapace Condition (CC) of Snow Crab ≥ 95 mm CW (percent by number) over time for 4X from at-sea-observed data. Year refers to the starting year of the season (i.e., 2014–15 season is shown as 2014). The * indicates no commercial fishery occurred in 2018–19 due to no TAC.*

Year	CC1	CC2	CC3	CC4	CC5
2006	0.05	0.5	98.01	1.44	0
2007	0.18	0.09	78.75	20.75	0.23
2008	0.32	0.16	56.98	42.47	0.08
2009	0.04	0.5	98.89	0.57	0
2010	0.25	1.23	54.28	44.17	0.07
2011	0.05	0.17	94.37	5.32	0.1
2012	0	0.8	81.56	17.16	0.48
2013	0	4.95	89.63	5.37	0.05
2014	0	46.99	51.98	1.04	0
2015	0.84	10.03	64.83	24.24	0.05
2016	0.95	15.54	72.3	10.68	0.54
2017	0.85	14.74	73.33	10.6	0.49
2018	*	*	*	*	*

FIGURES

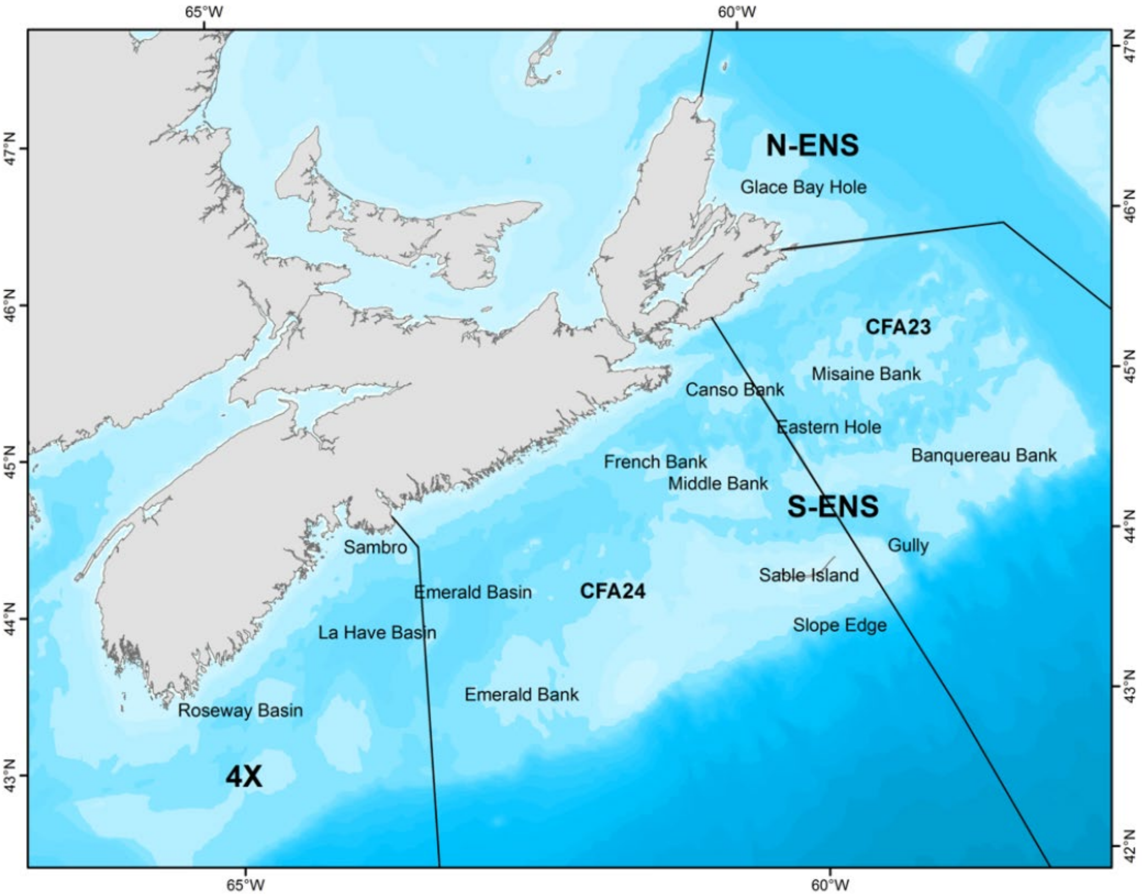


Figure 1. Location of geographic areas and the management areas for Snow Crab on the Scotian Shelf.

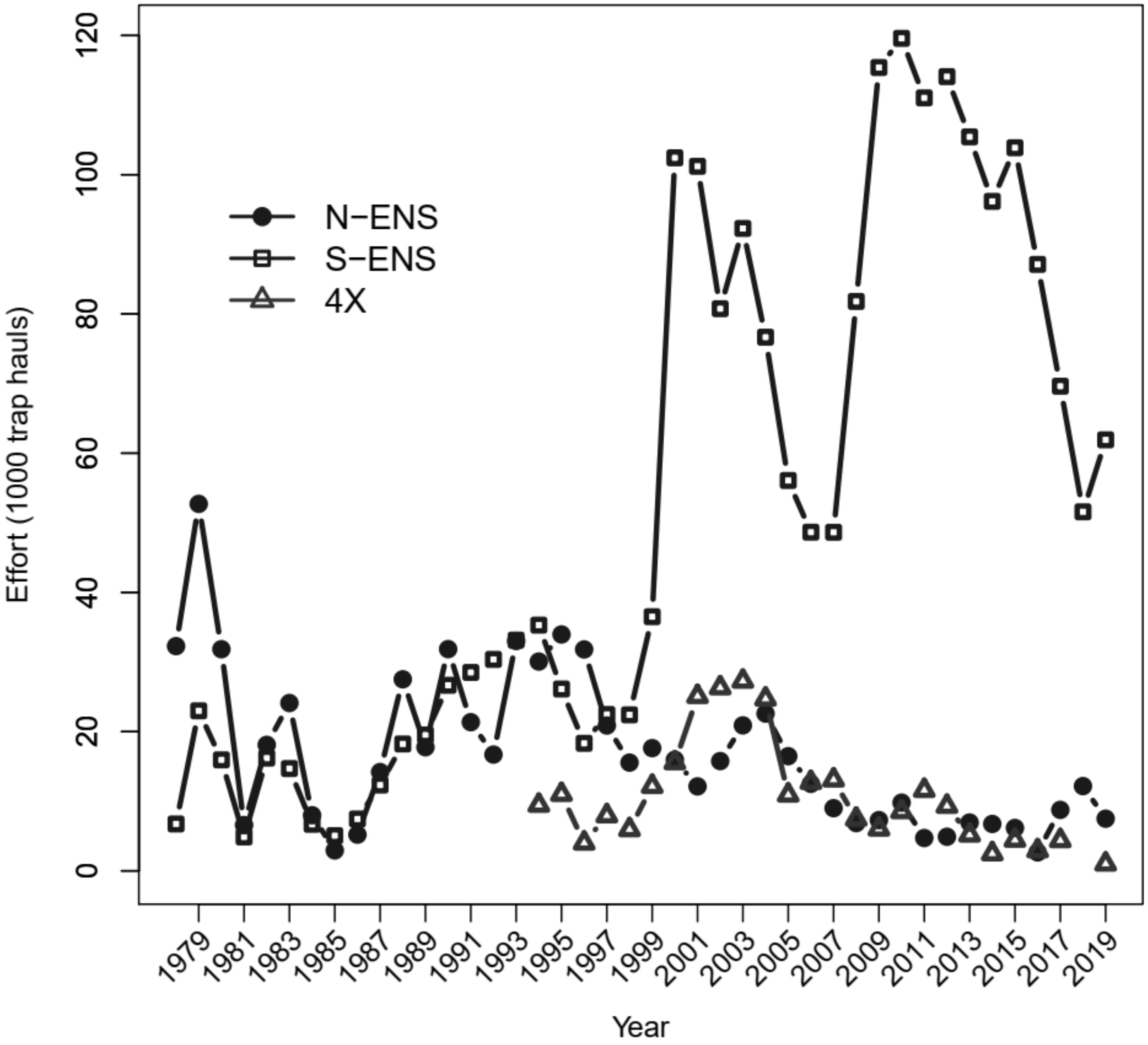


Figure 2. Temporal variations in the fishing effort for Snow Crab on the Scotian Shelf, expressed as the number of trap hauls. Year in 4X refers to the year at the start of the fishing season. No fishery occurred in 4X for the 2018 season.

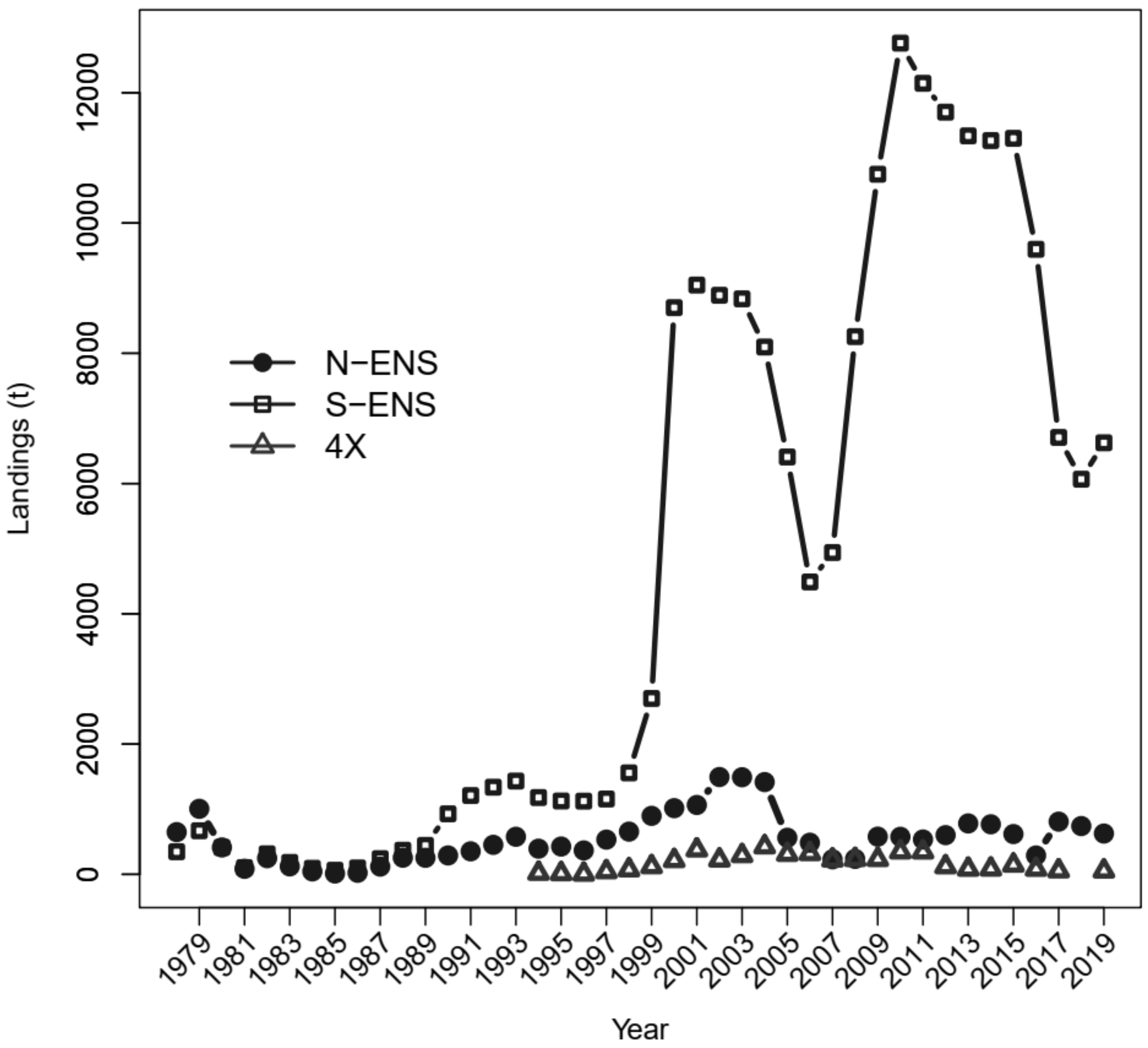


Figure 3. Temporal variations in the landings of Snow Crab on the Scotian Shelf (t). The landings follow the TACs with little deviation (Tables 2–4).

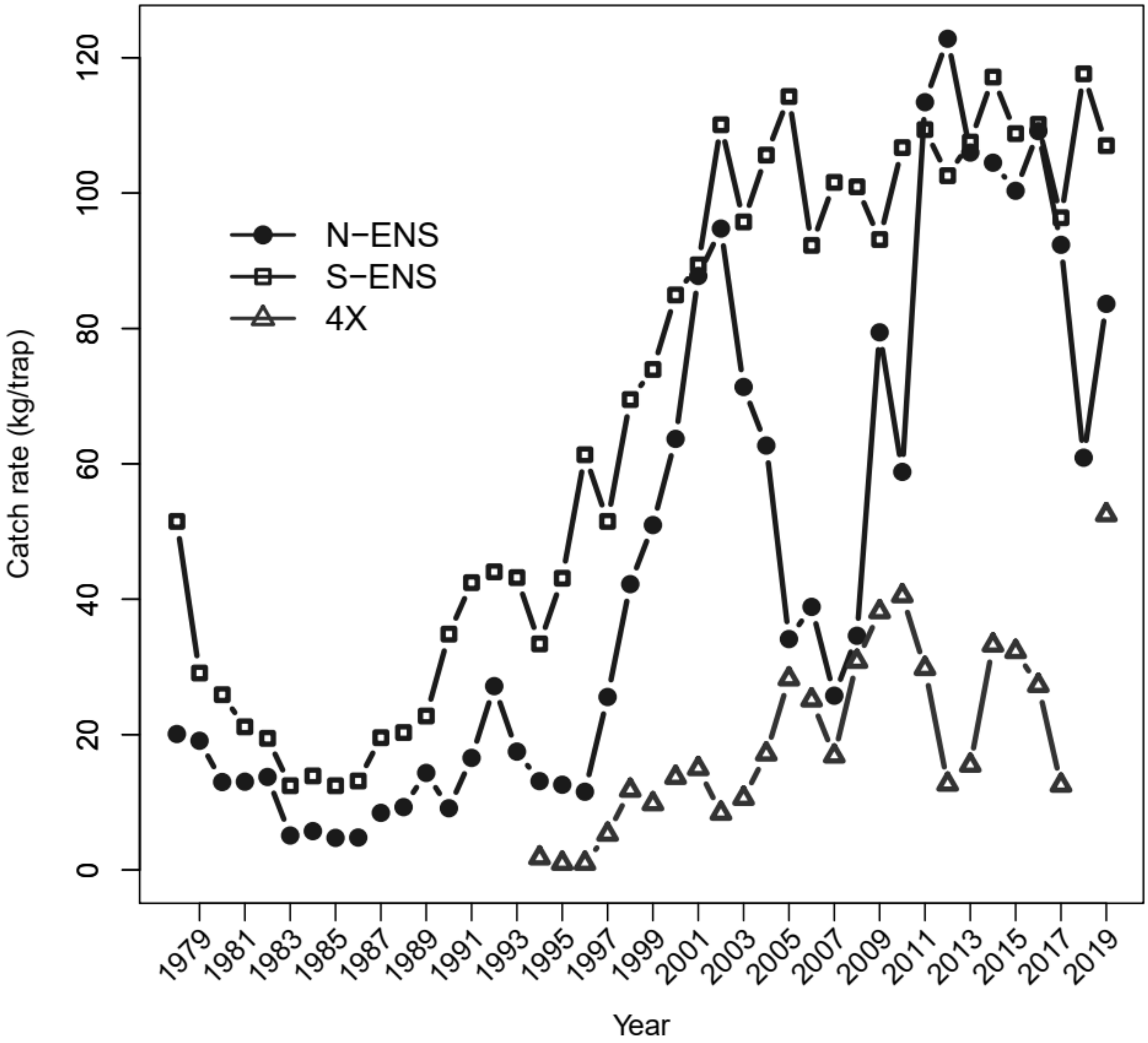
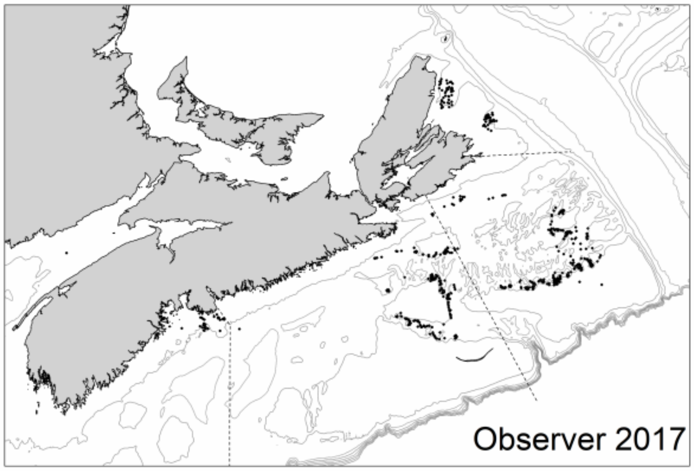
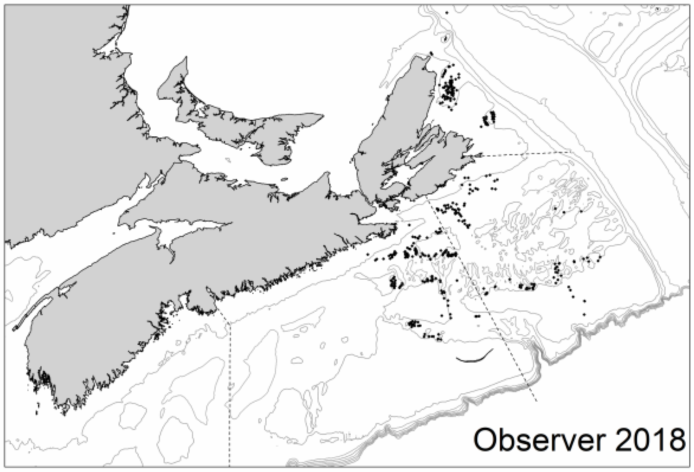


Figure 4. Temporal variations in catch rates of Snow Crab on the Scotian Shelf, expressed as kg per trap haul. Trap design and size have changed over time. No correction for these varying trap-types nor soak time and bait-type has been attempted (see Methods). Year in 4X refers to the year at the start of the fishing season.





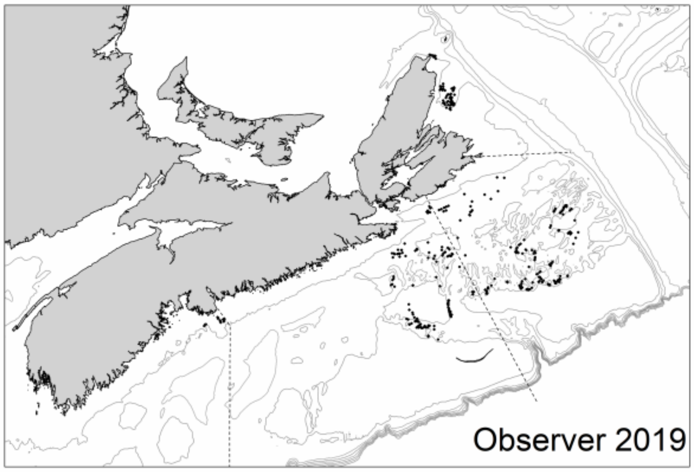


Figure 5. Snow Crab fishing locations monitored by at-sea-observers on the Scotian Shelf during each of the past three fishing seasons.

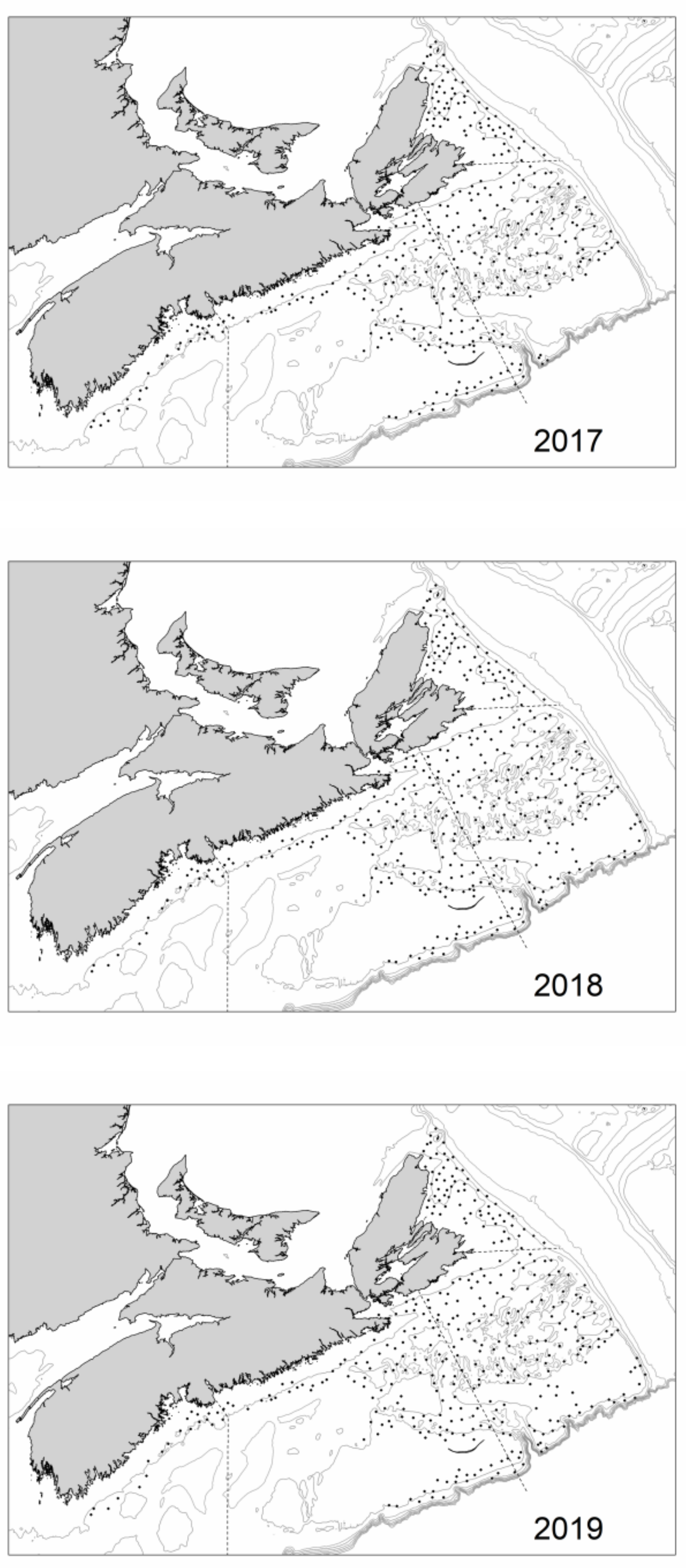


Figure 6. Locations of Snow Crab survey trawl sets on the Scotian Shelf during each of the past three years. Note stations not completed in Southeastern-most region for 2017 survey as compared to other years.

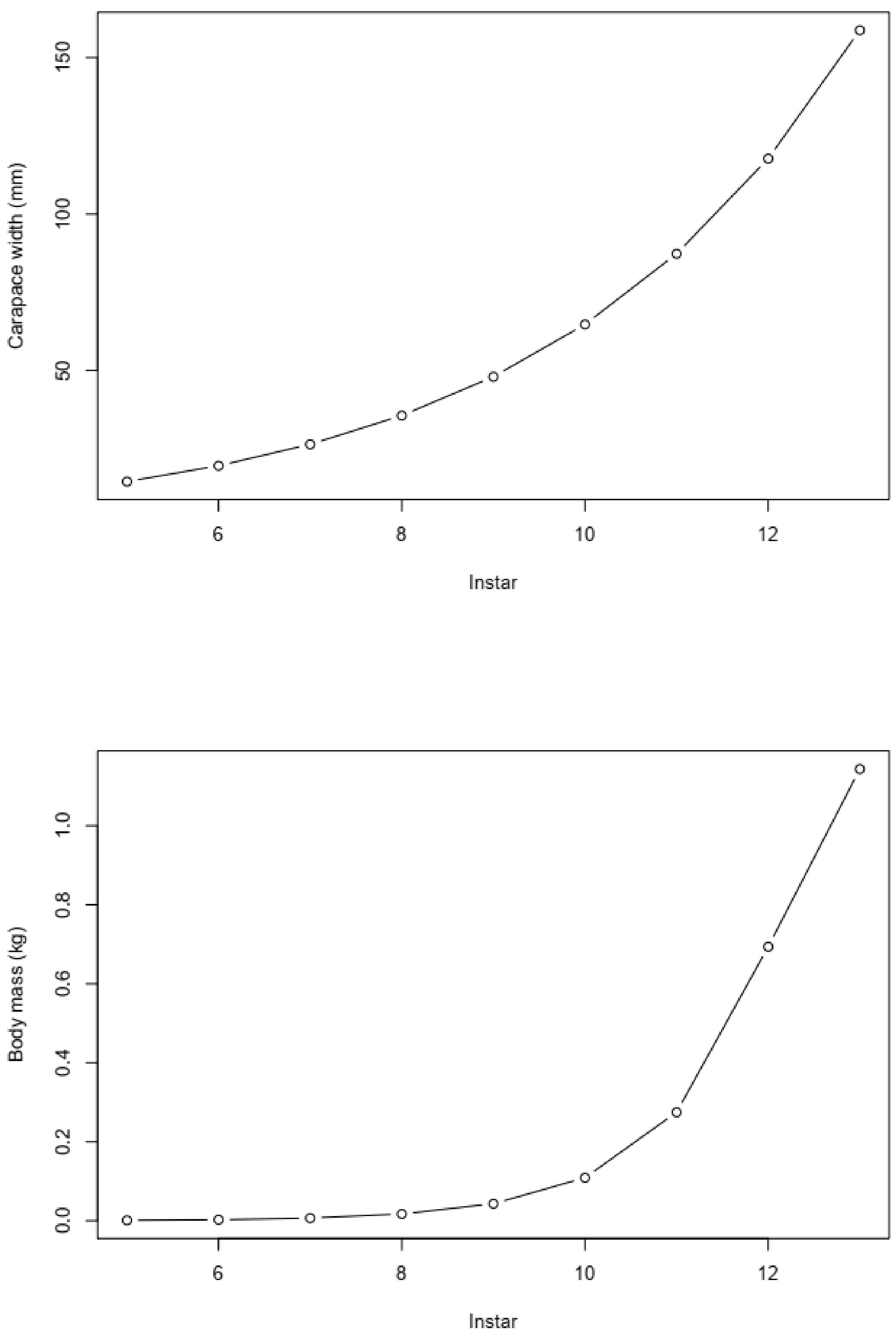
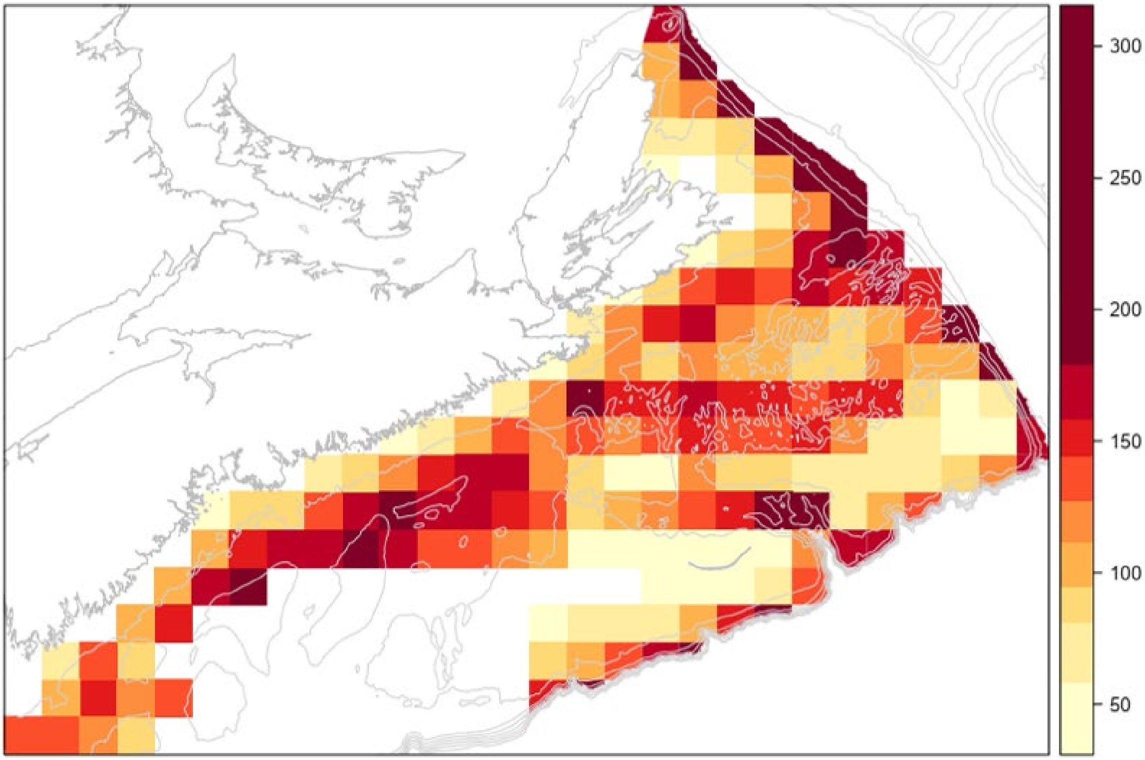


Figure 7. Growth curves determined from modal length-frequency analysis of male Snow Crab on the Scotian Shelf.



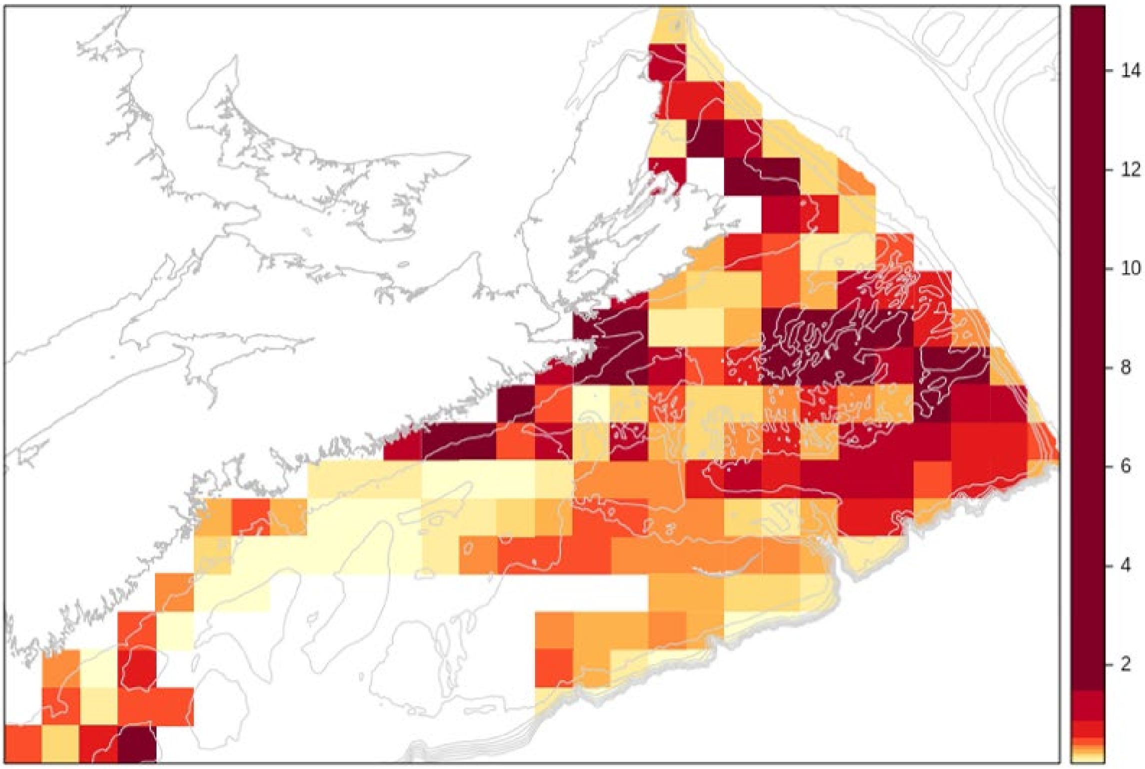
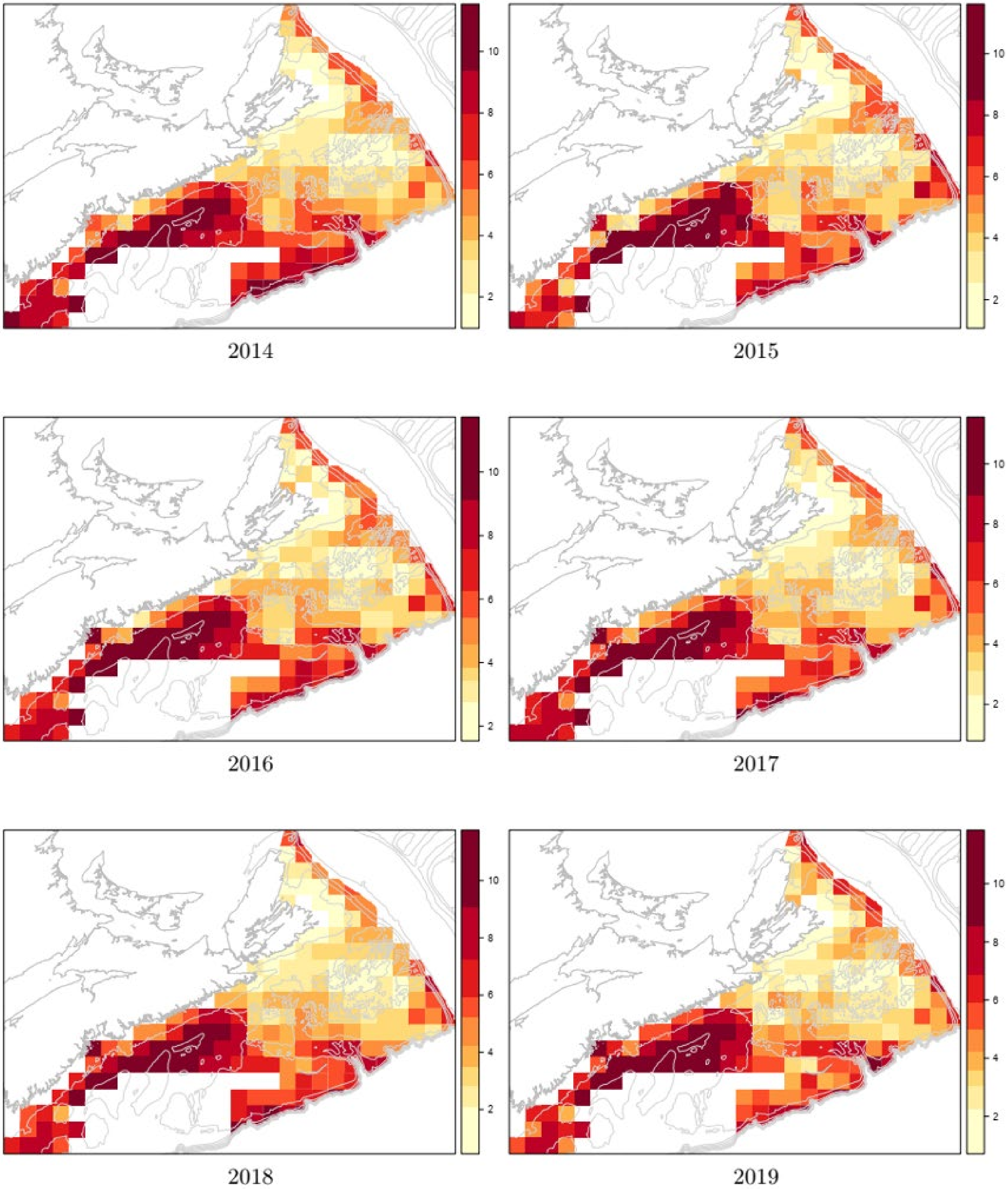


Figure 8. Predicted habitat characteristics used for Snow Crab abundance modelling. Depth (top) is in meters. Substrate (bottom) represents mean grain size in centimeters. No temporal component exists for these predictions.



2014

2015

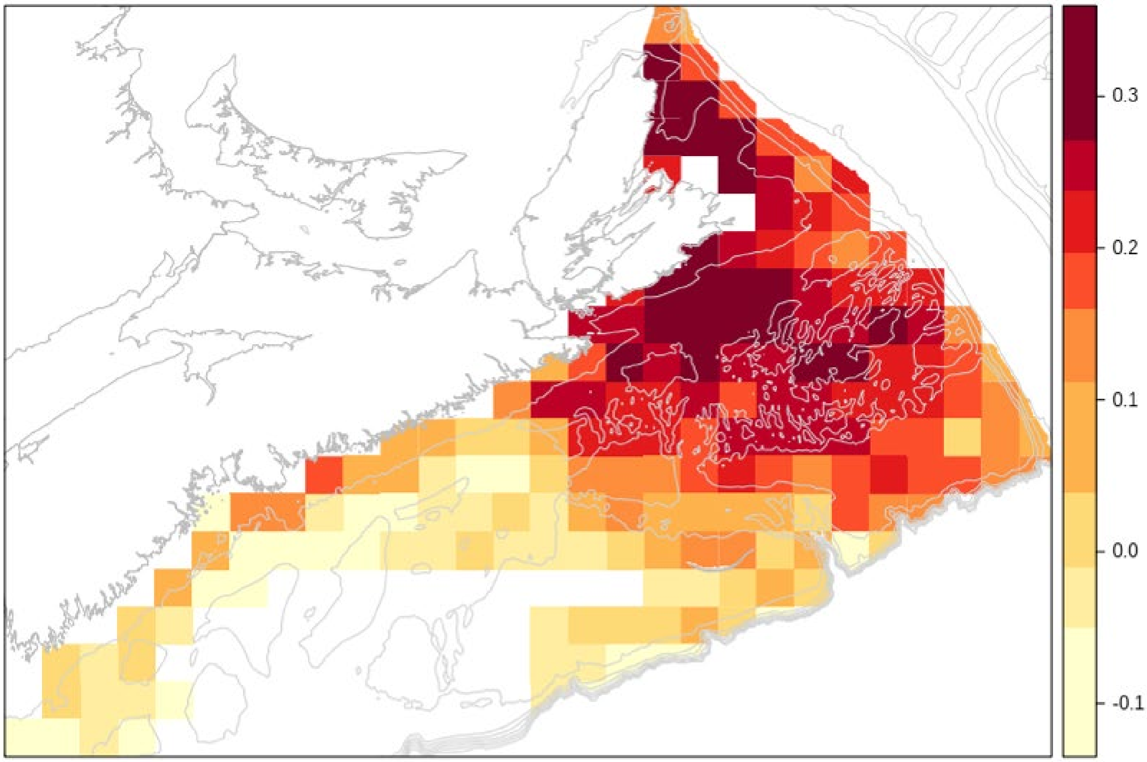
2016

2017

2018

2019

Figure 9. Annual block (25 km x 25 km) predictions of bottom temperature for early October. Spatial representations are generated with carstm modelling using various sources of temperature data.



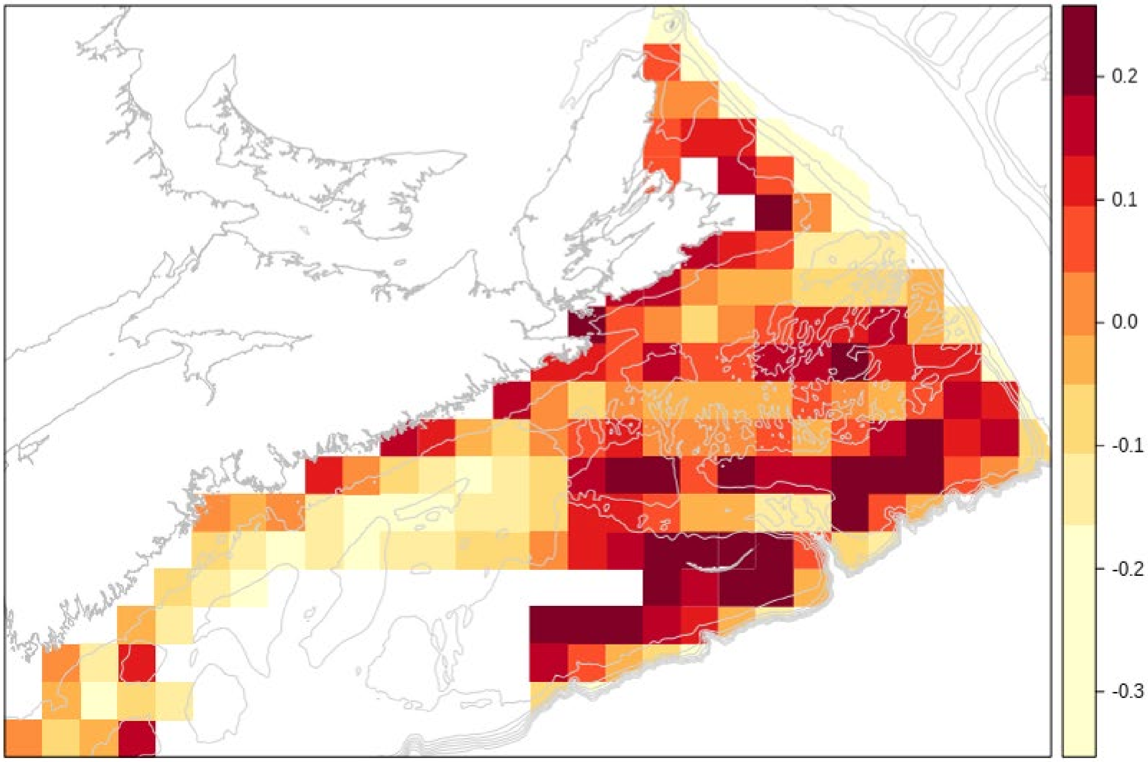


Figure 10. Block (25 km x 25 km) predictions of principal-component analysis of species composition (community) characteristics on the Scotian Shelf. Predicted for early October of 2019. Top figure is the first axis of ordination, bottom figure is second axis of ordination.

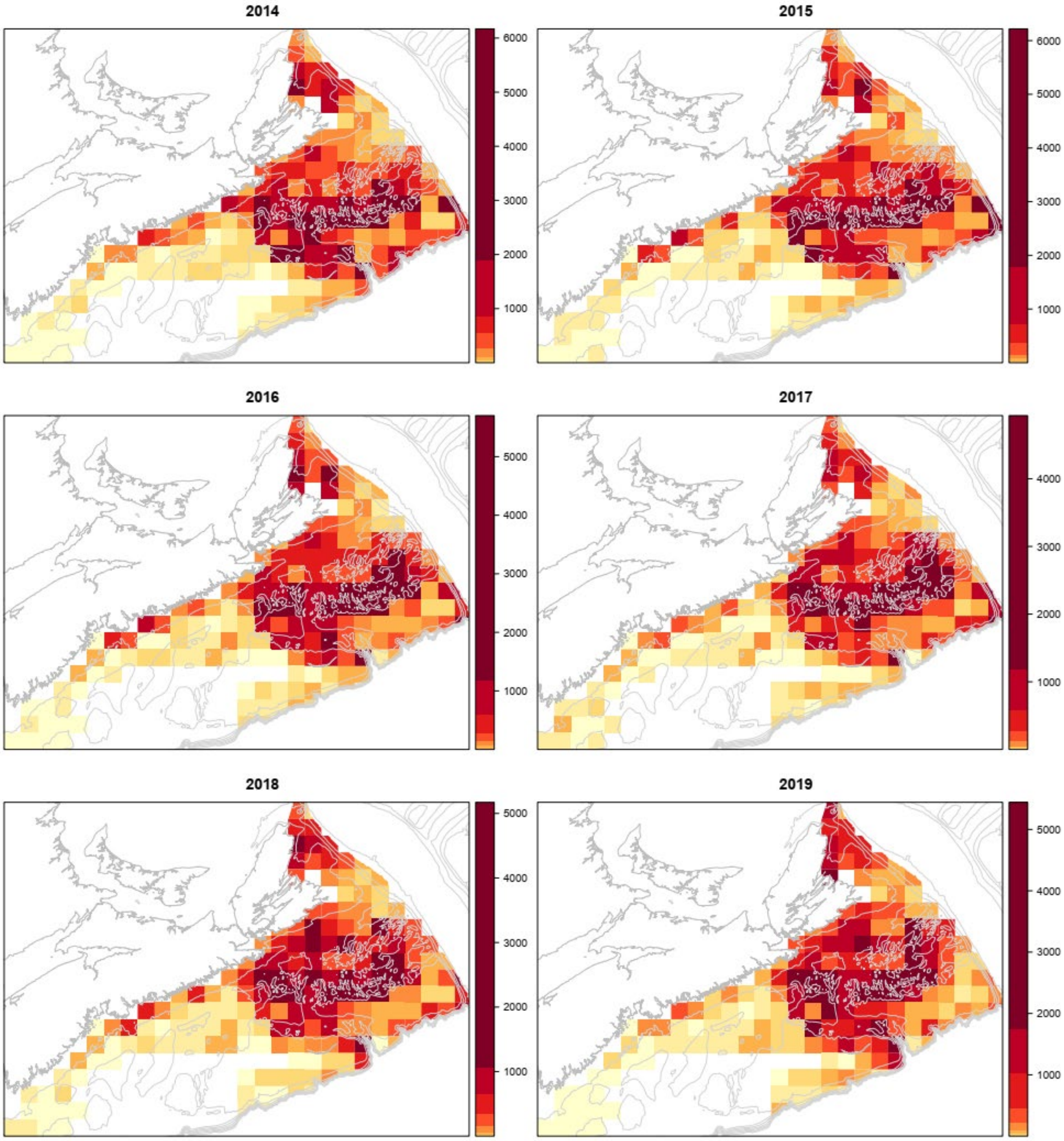


Figure 11. Annual block (25 km x 25 km) predictions of fishable Snow Crab biomass (kg/km^2). Spatial representations are generated with carstm modelling using environmental and biological variables.

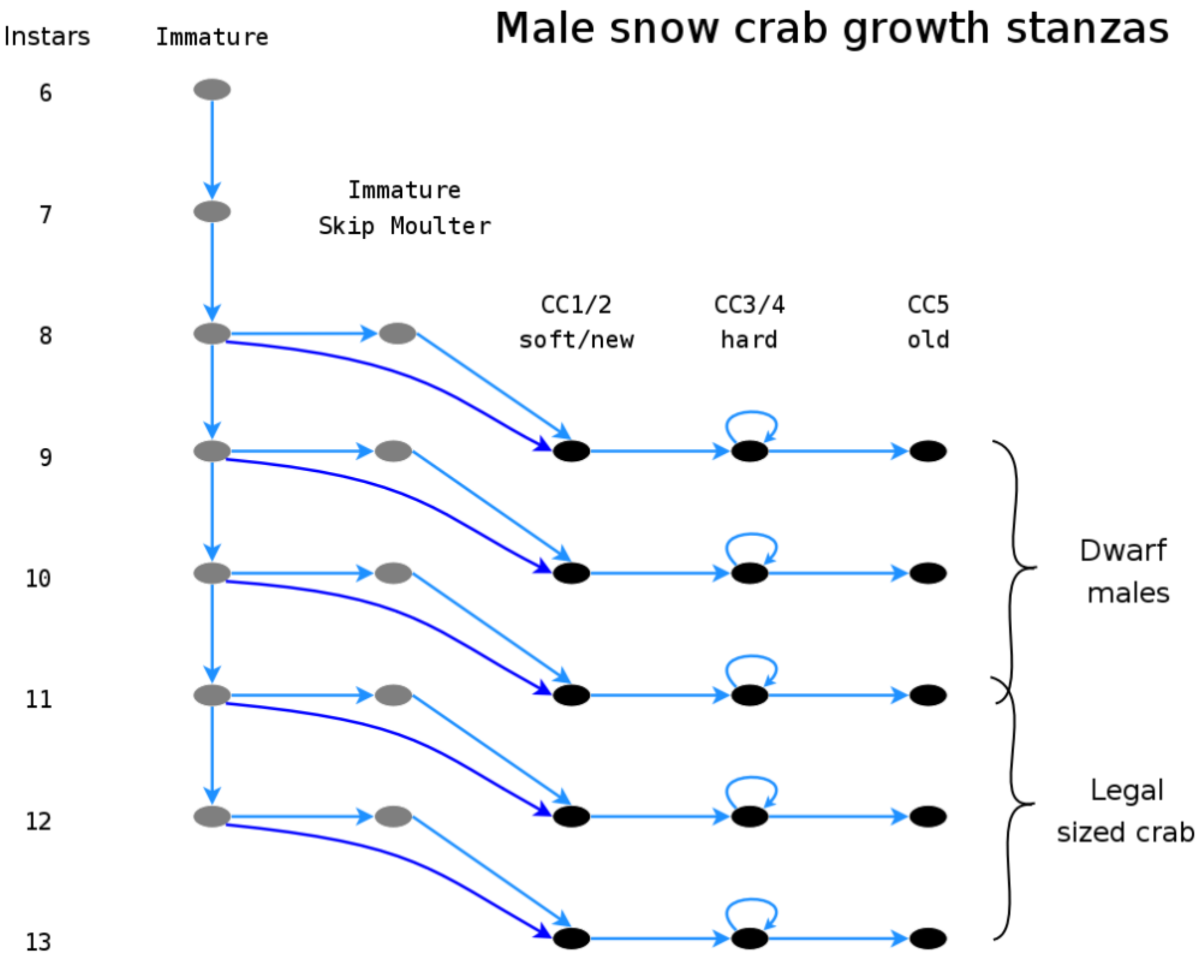


Figure 12. The growth stanzas of male Snow Crab. Each instar is determined from cw bounds obtained from modal analysis and categorized to Carapace Condition (CC) and maturity from visual inspection and/or maturity equations. Snow Crab are resident in each growth stanza for 1 year, with the exception of CC2 to CC4 which are known from mark-recapture studies to last from three to five years.

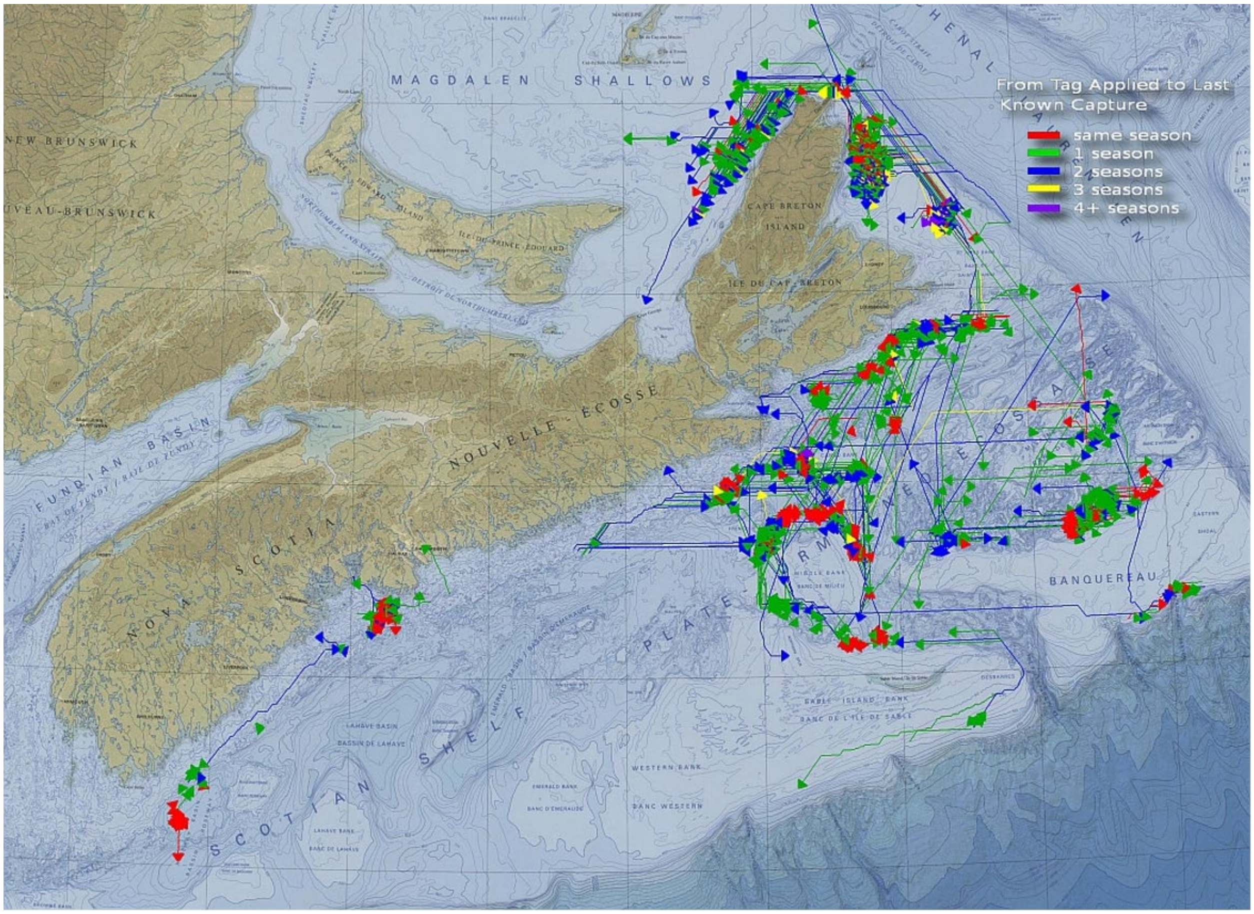


Figure 13. Movement of tagged terminally molted Snow Crab on the Scotian Shelf. Movement path between release and recapture locations constrained to the shortest path within depth contours of 60 and 280 m. Circles represent release locations and colours represent time interval in years between initial tagging and last recapture (red: < 1, green:1, blue:2, yellow:3, purple:4+).

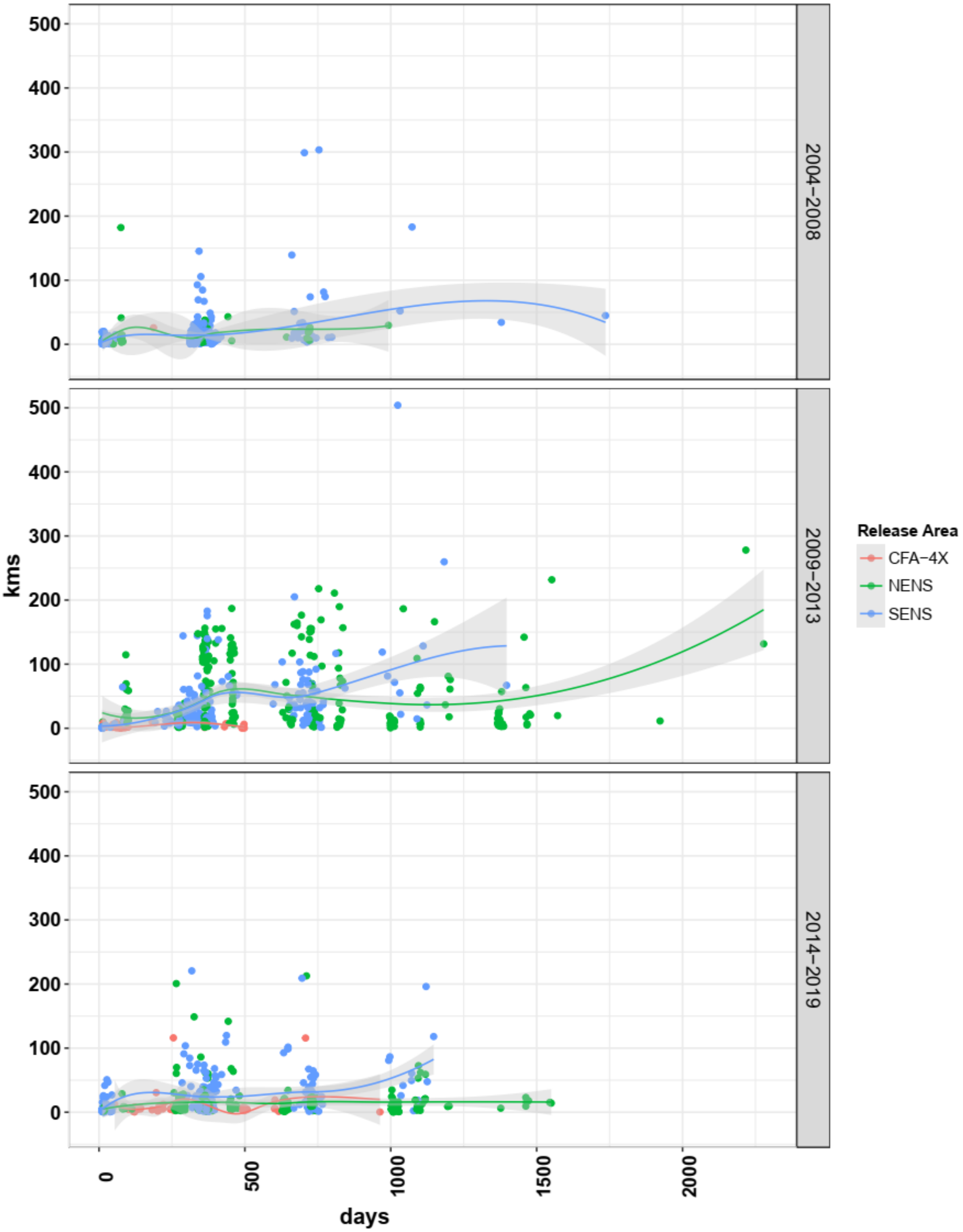
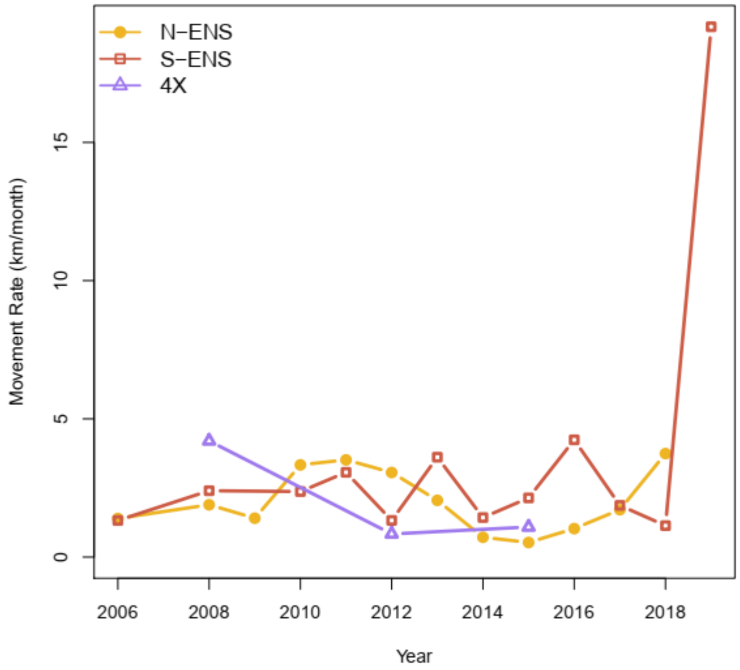


Figure 14. Distance travelled vs. time to capture for tagged Snow Crab on the Scotian Shelf since 2004. Data grouped by release year with release area distinguished by color. Periodicity in time intervals are explained by recaptures occurring during seasonal fishing operations.



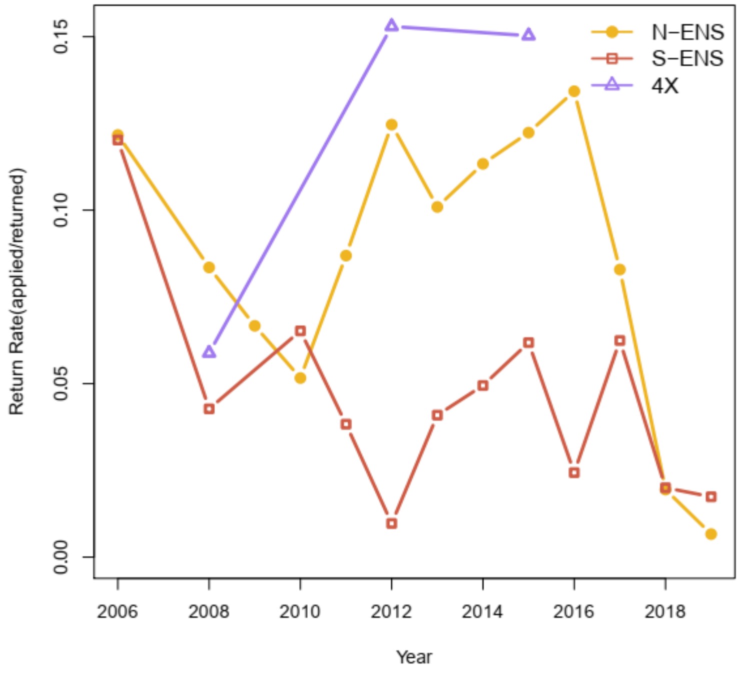


Figure 15. (Top) Mean rate of movement of Snow Crab tagged on the Scotian Shelf by area and year. Route lengths derived from calculated shortest paths as constrained by depth range of 60–280 m. Small sample size and short time between mark and potential recapture account for the higher-than-normal rates for S-ENS in 2016 and 2017. (Bottom) Tag return rate, number of returns from tags applied in given area and year.

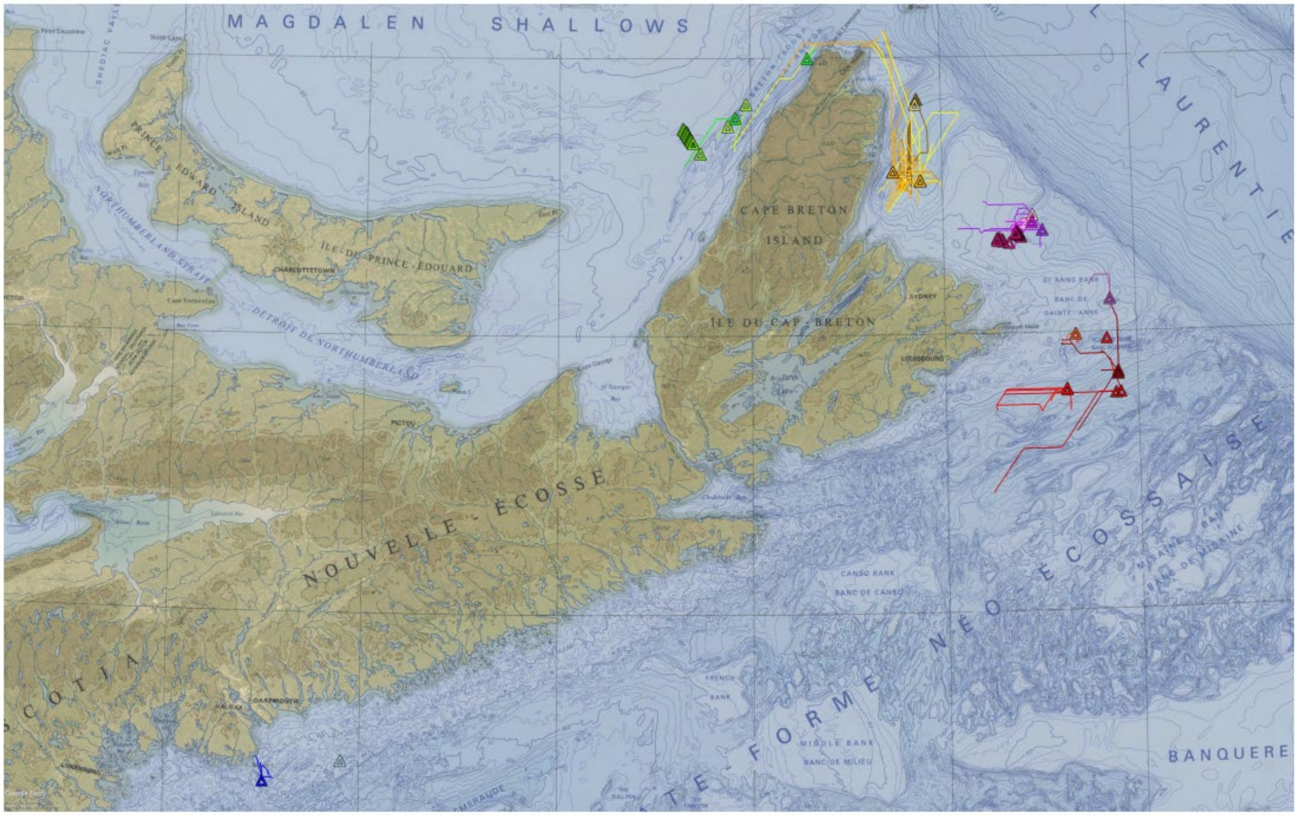


Figure 16. Movement of acoustic-tagged Snow Crab on the Scotian Shelf. Movement path between mark and detection locations is constrained to the shortest path within depth contours of 60 and 280 m. Triangles represent release locations and individual colours represent individual tagged animals.

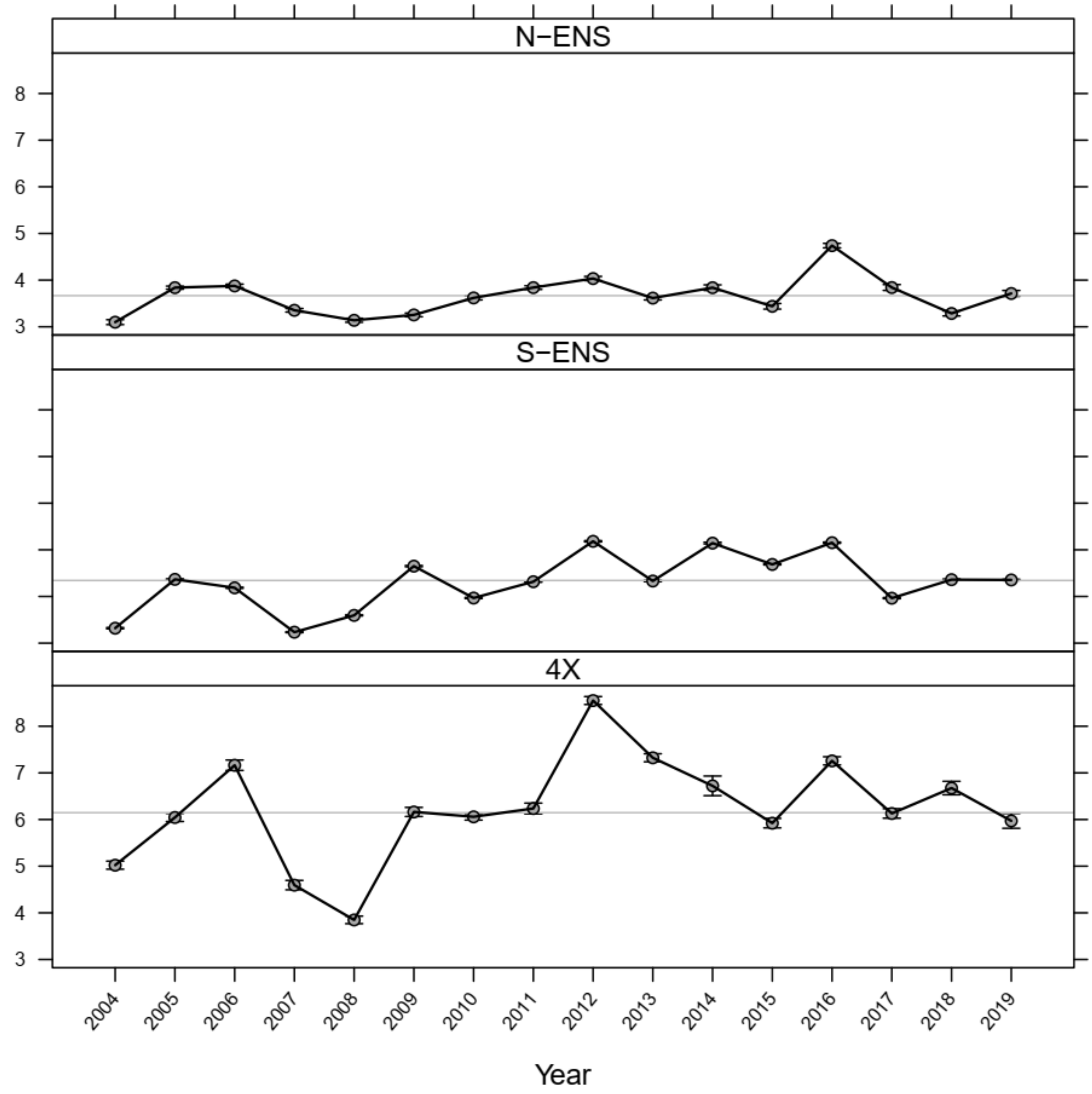


Figure 17. Annual variations in bottom temperature (°C) observed during the Eastern Nova Scotia (ENS) Snow Crab survey. The horizontal line indicates the long-term median temperature within each subarea. Error bars are 1 standard deviation.

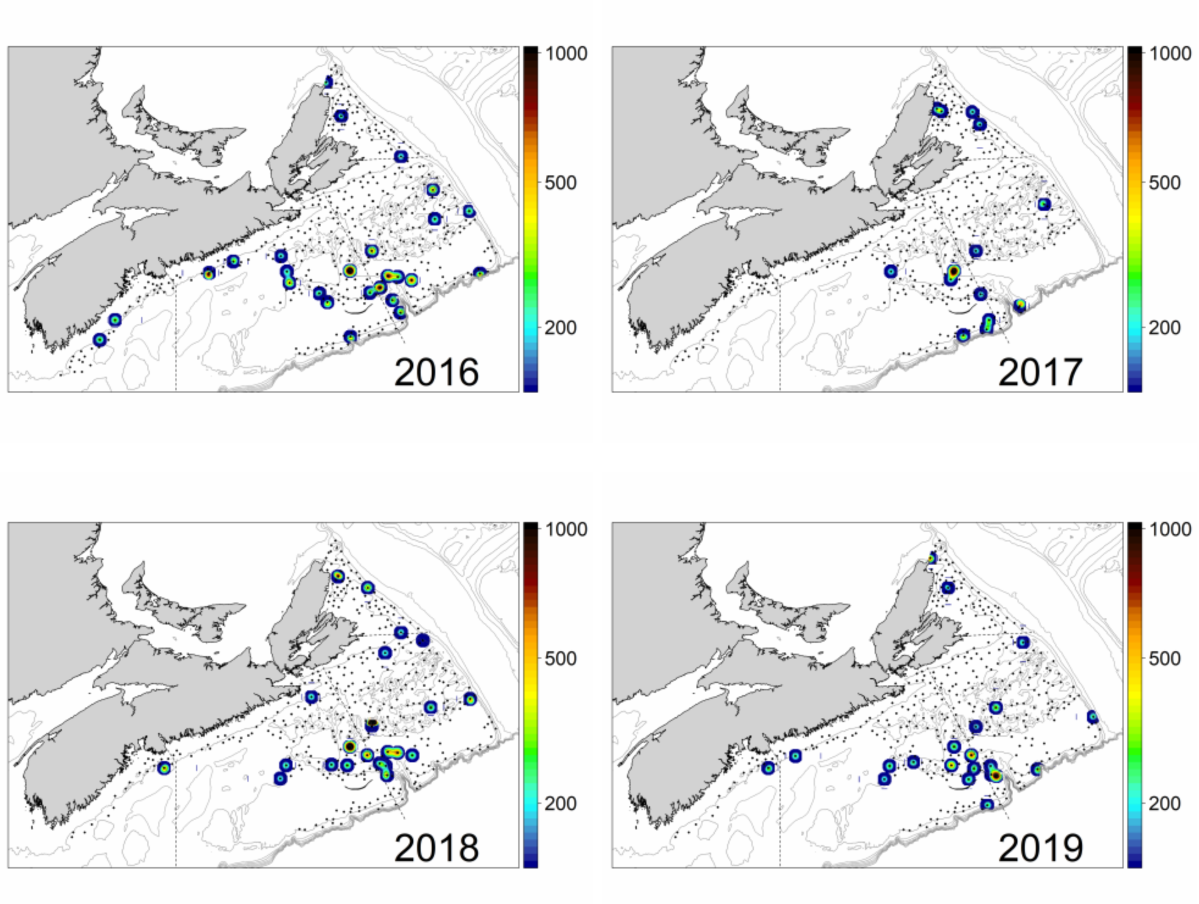


Figure 18. Locations of potential predators of Snow Crab on the Scotian Shelf from the annual Snow Crab survey. ***Atlantic Halibut****. Scale is number/km*^{2}*.*

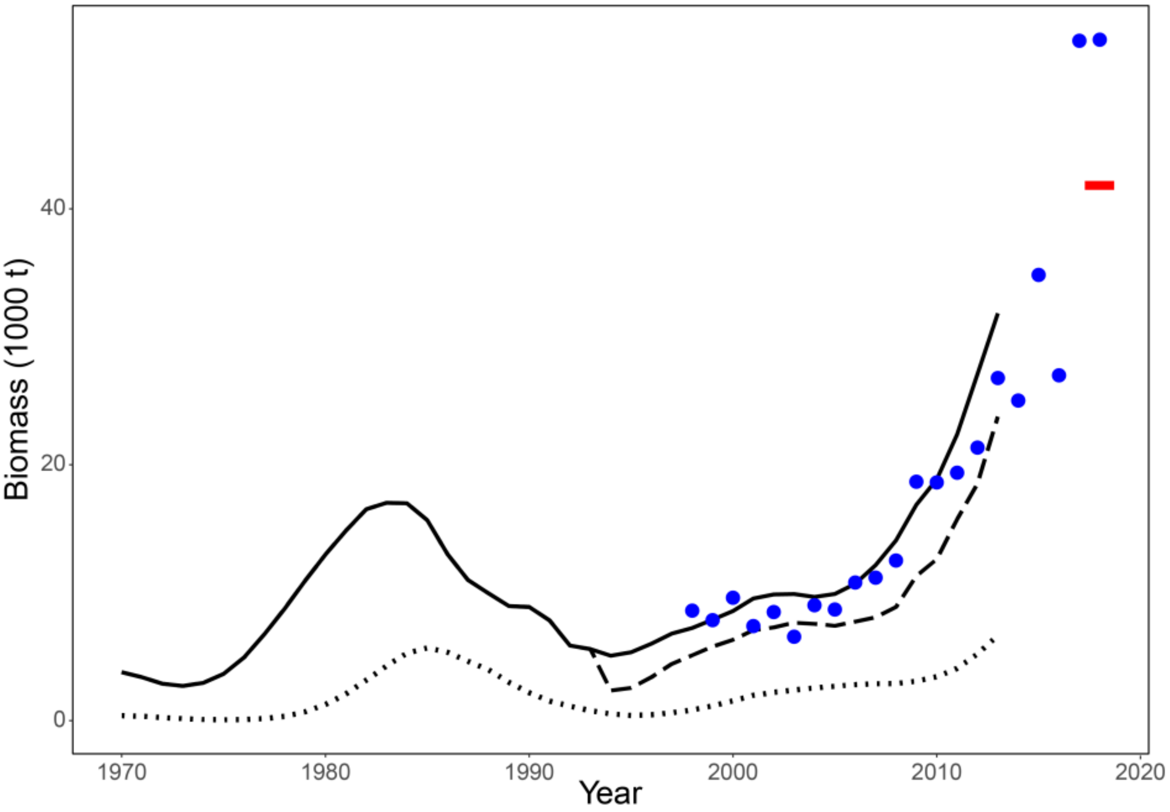


Figure 19. Atlantic Halibut biomass for Scotian Shelf and Southern Grand Banks from stock assessment model (black lines) and the Halibut Survey Index Stations (blue circles). The solid black line is total biomass, the dashed line is legal biomass, and the dotted line is spawning stock biomass. The solid red bar is the current 3-year mean of the Halibut Survey biomass index. Source: DFO 2018.

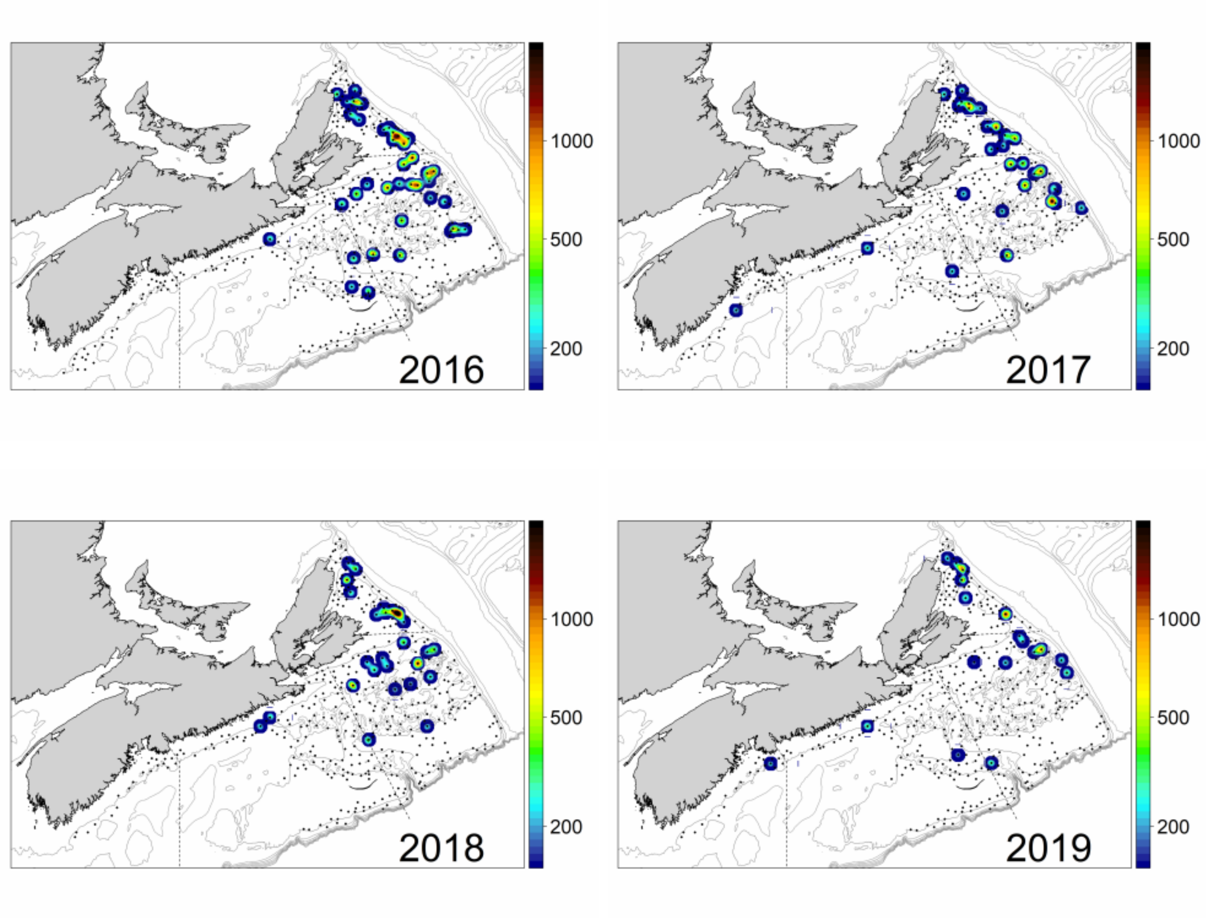


Figure 20. Locations of potential predators of Snow Crab on the Scotian Shelf from the annual Snow Crab survey: ***Atlantic Striped Wolffish****. Scale is number/km^2 .*

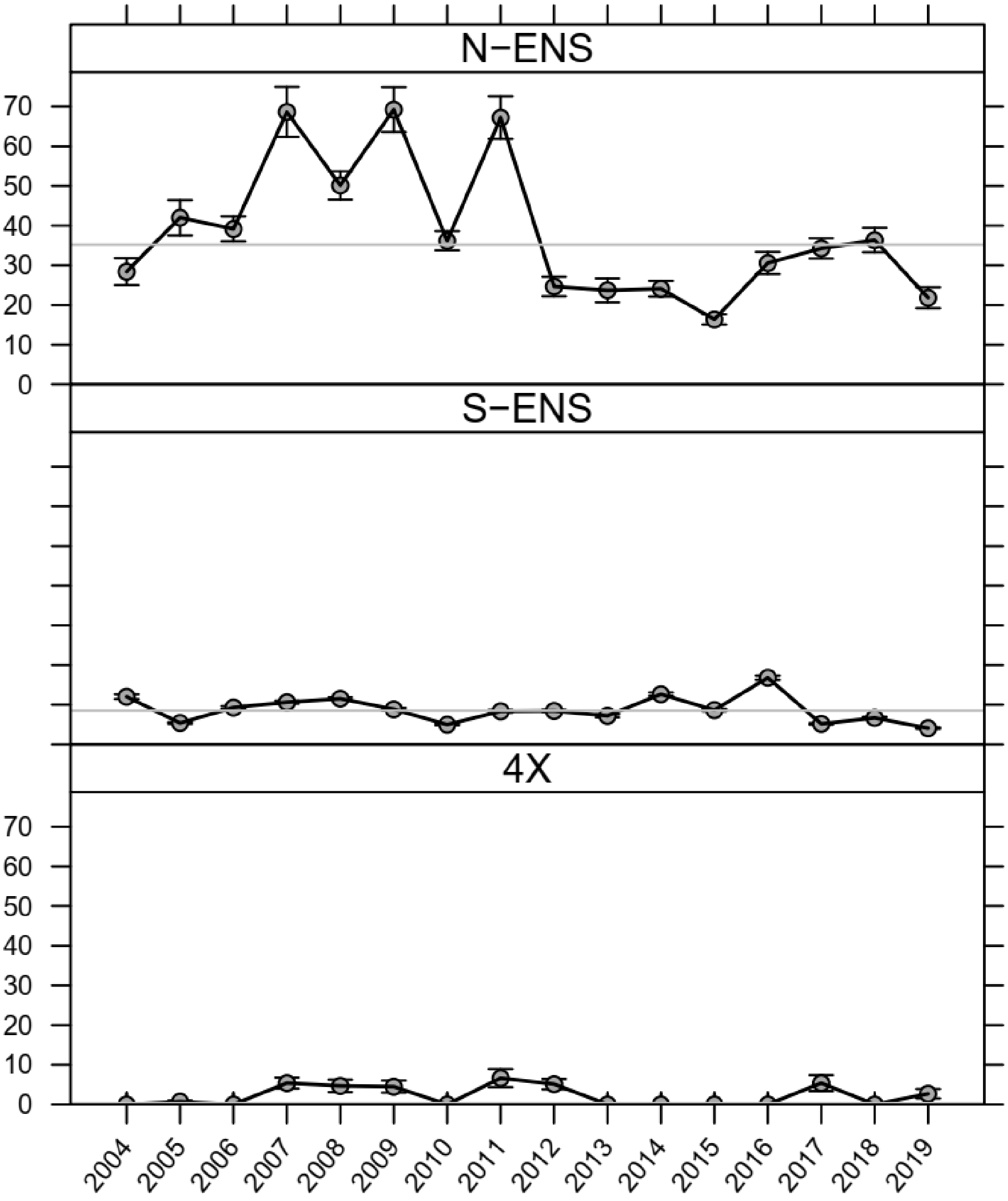


Figure 21. Trends in biomass (kg/km^2) of potential predators of Snow Crab from the annual Snow Crab survey on the Scotian Shelf: ***Atlantic Striped Wolffish****. Grey line indicates long-term mean.*

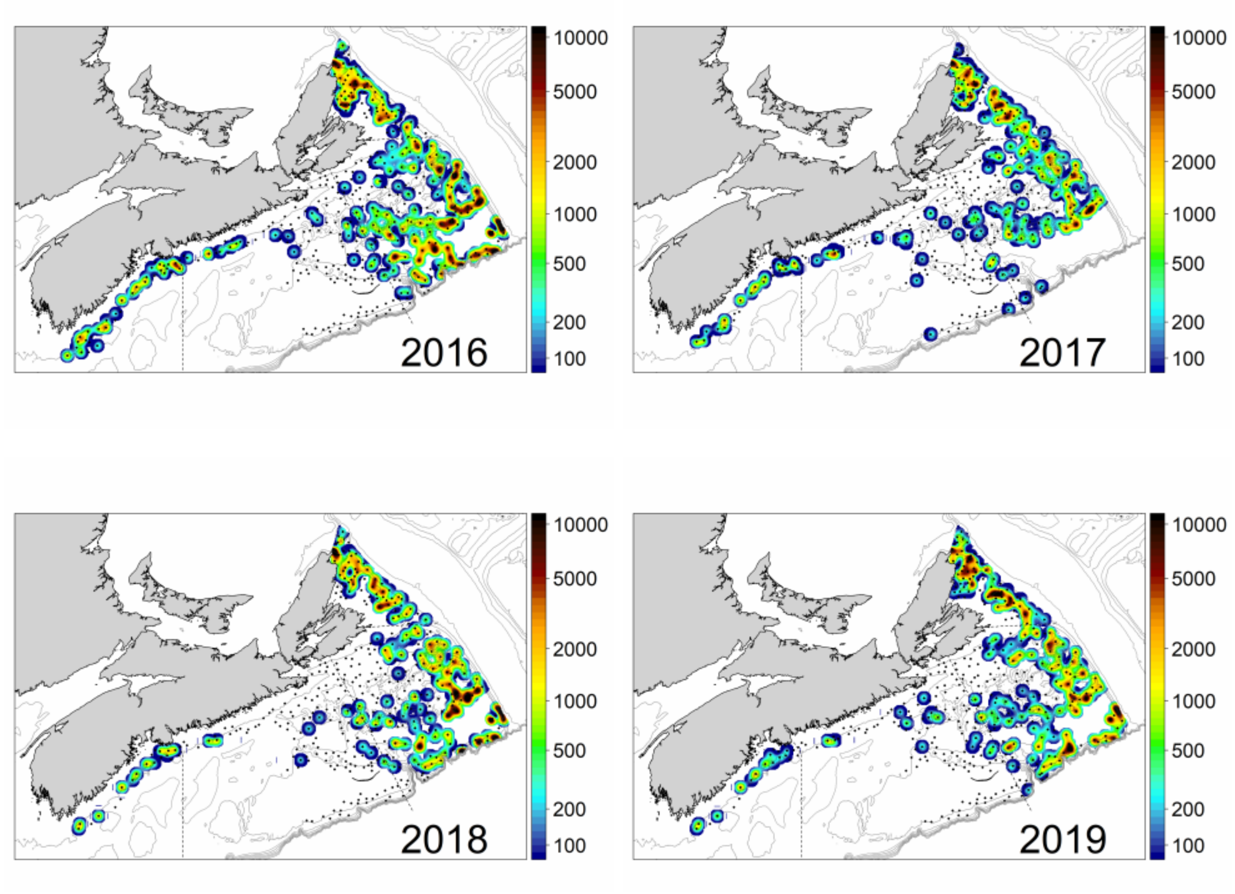


*Figure 22. Locations of potential predators of Snow Crab on the Scotian Shelf from the annual Snow Crab survey: **Thorny Skate**. Scale is number/km*^{2}*.*

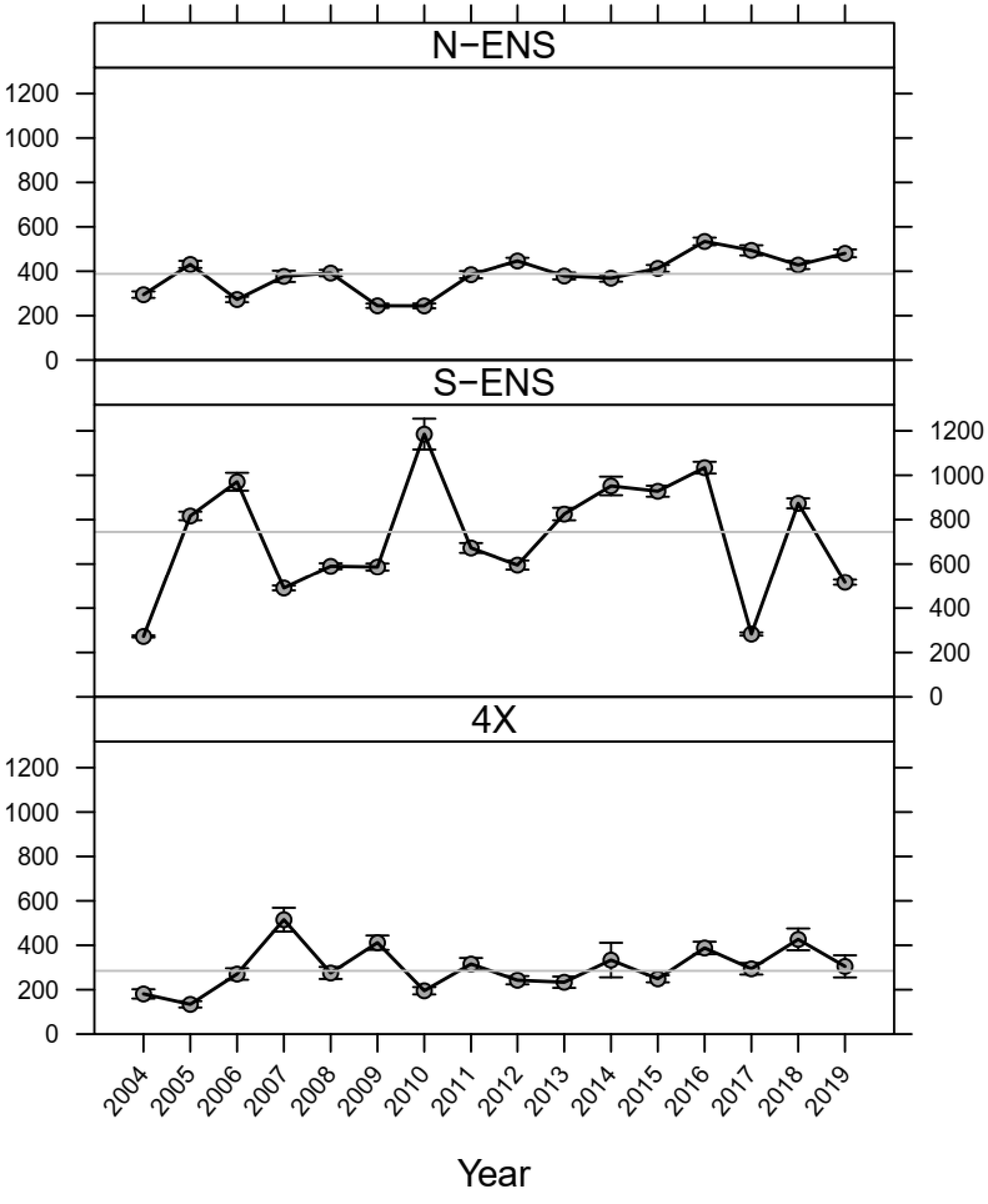


Figure 23. Trends in biomass (kg/km^2) of potential predators of Snow Crab from the annual Snow Crab survey on the Scotian Shelf: ***Thorny Skate****. Grey line indicates long-term mean.*

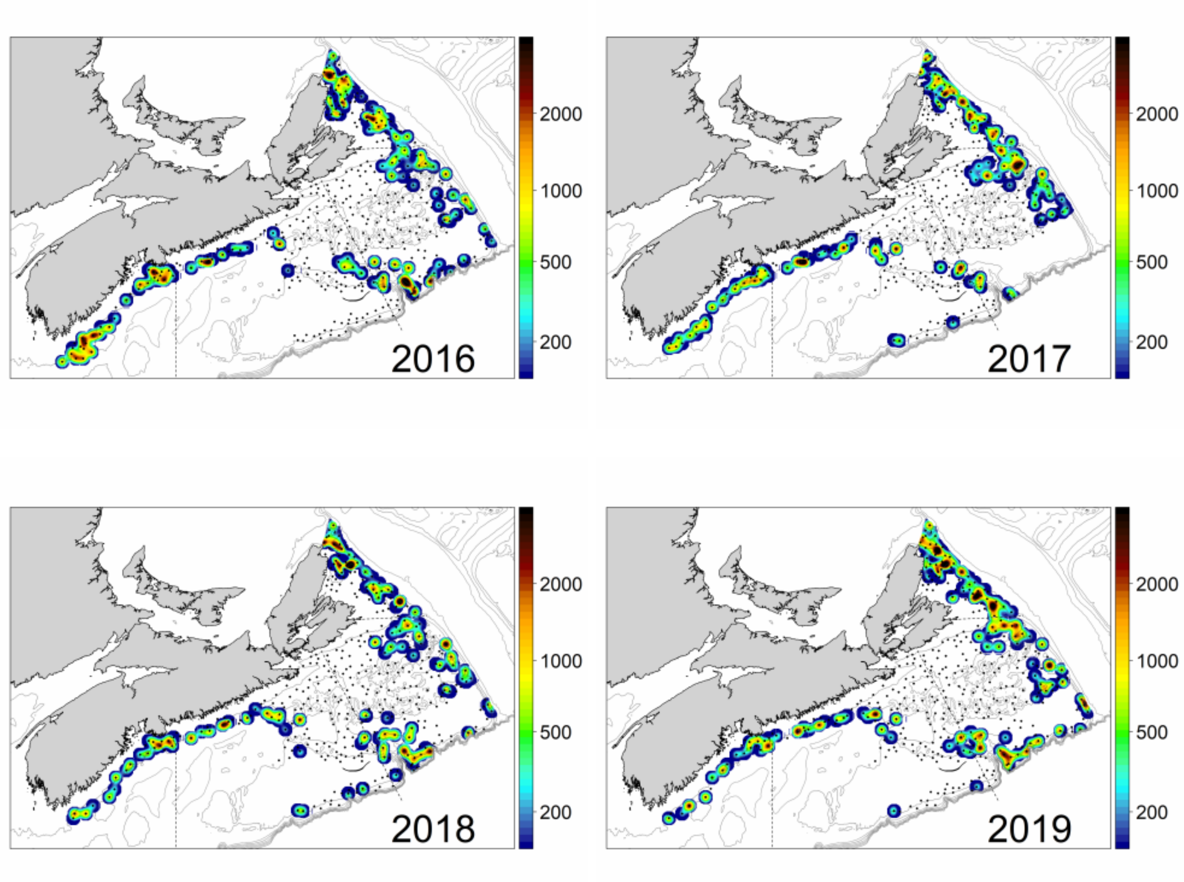


Figure 24. Locations of potential predators of Snow Crab on the Scotian Shelf from the annual Snow Crab survey: ***Smooth Skate****. Scale is number/km^2.*

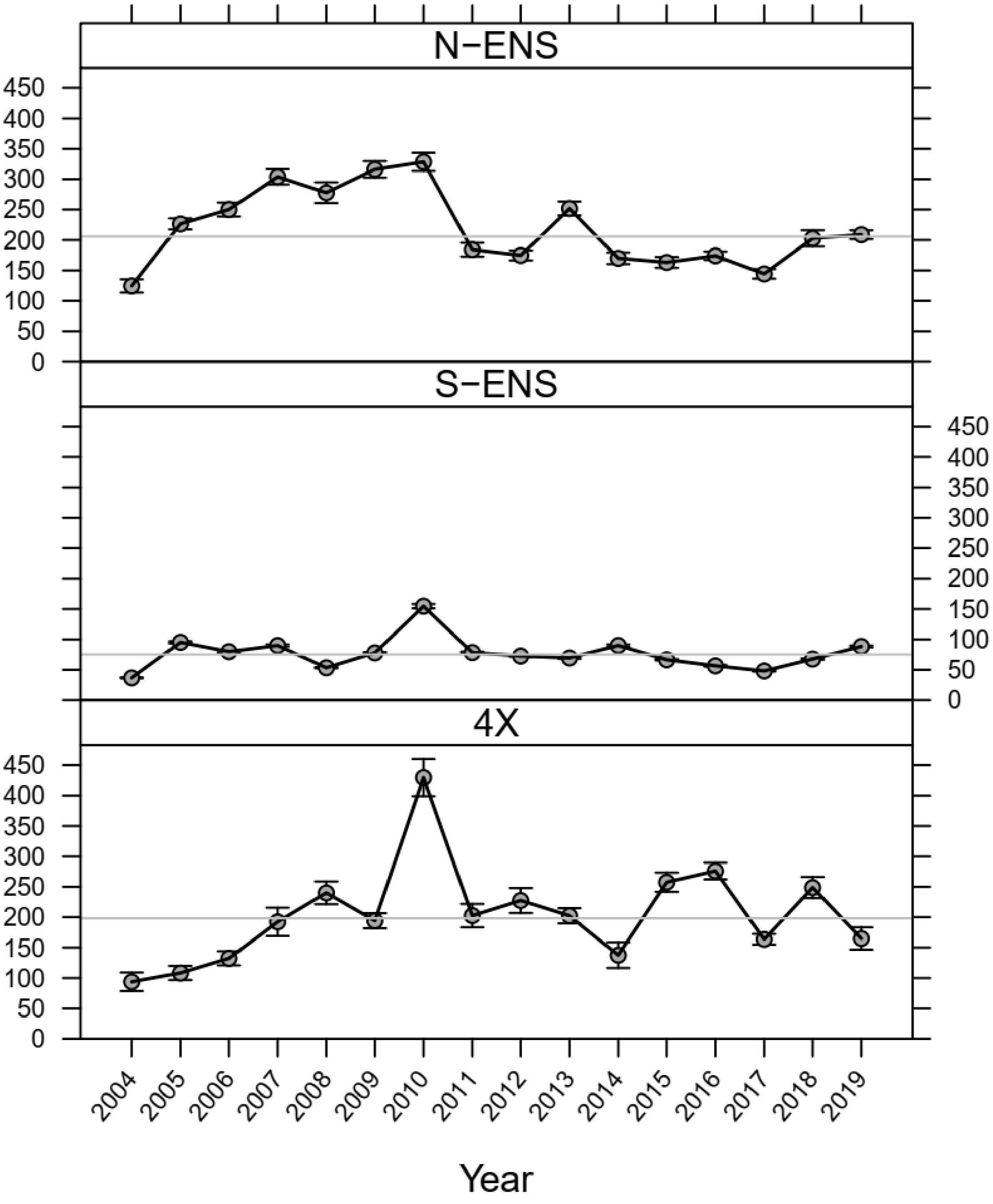


Figure 25. Trends in biomass (kg/km^2) of potential predators of Snow Crab from the annual Snow Crab survey on the Scotian Shelf: ***Smooth Skate****. Grey line indicates long-term mean.*

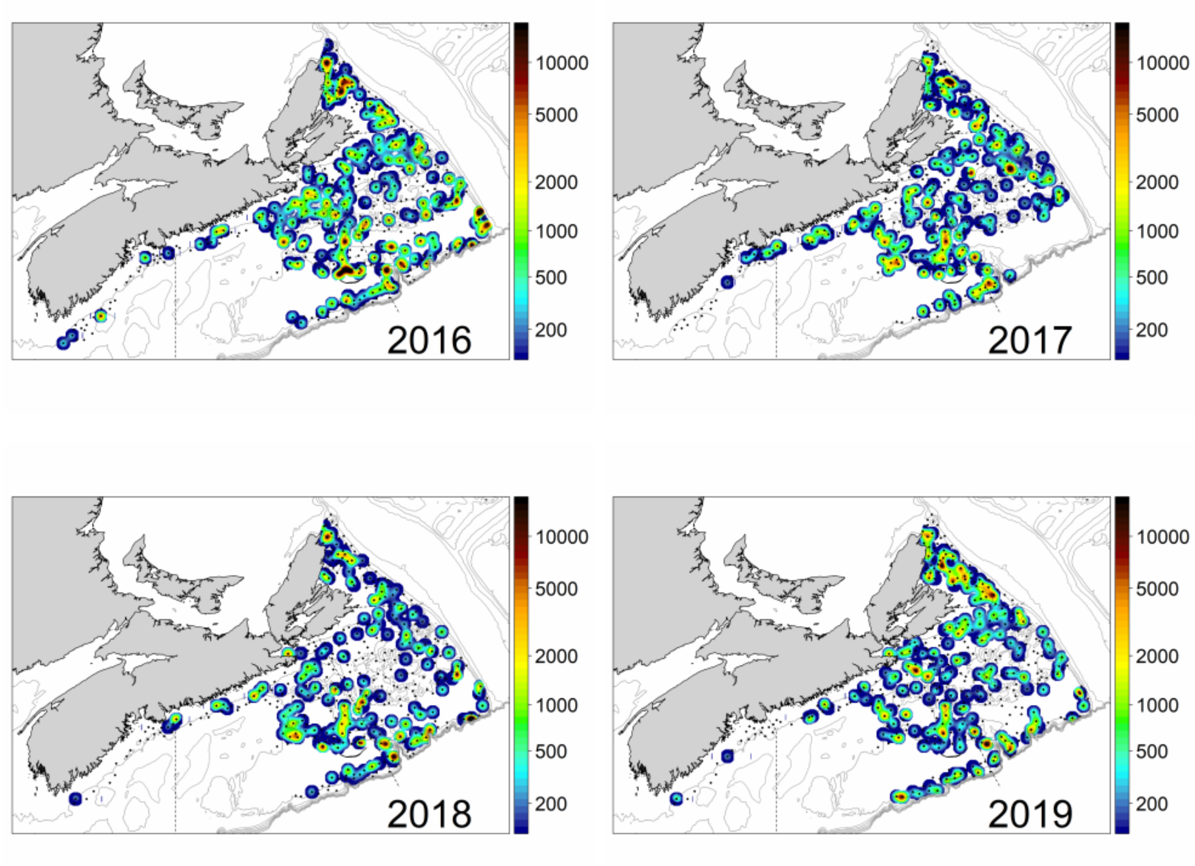


Figure 26. Locations of potential predators of Snow Crab on the Scotian Shelf from the annual Snow Crab survey: ***Atlantic Cod****. Scale is number/km^2.*

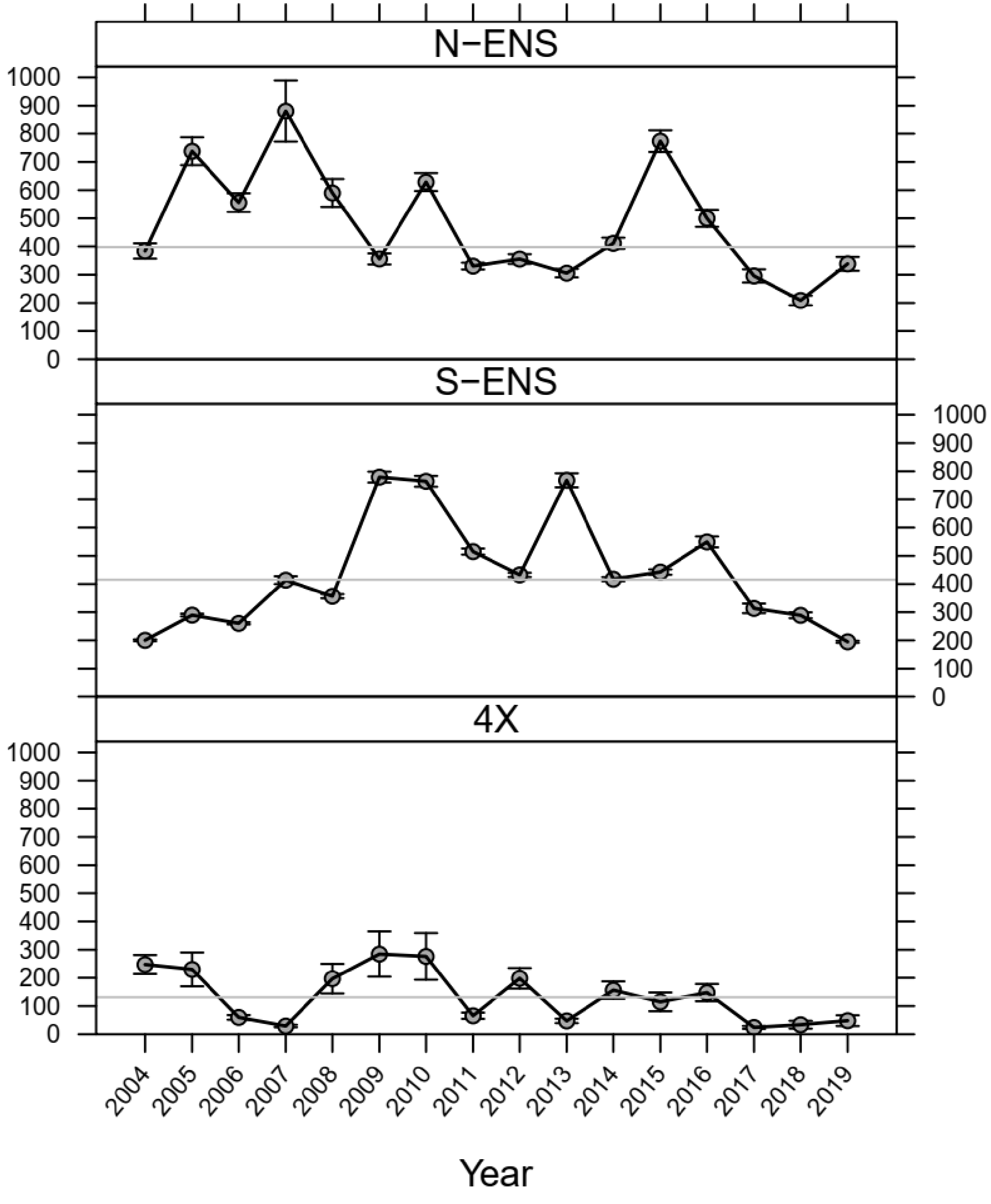


Figure 27. Trends in biomass (kg/km²) of potential predators of Snow Crab from the annual Snow Crab survey on the Scotian Shelf: ***Atlantic Cod****. Grey line indicates long-term mean.*

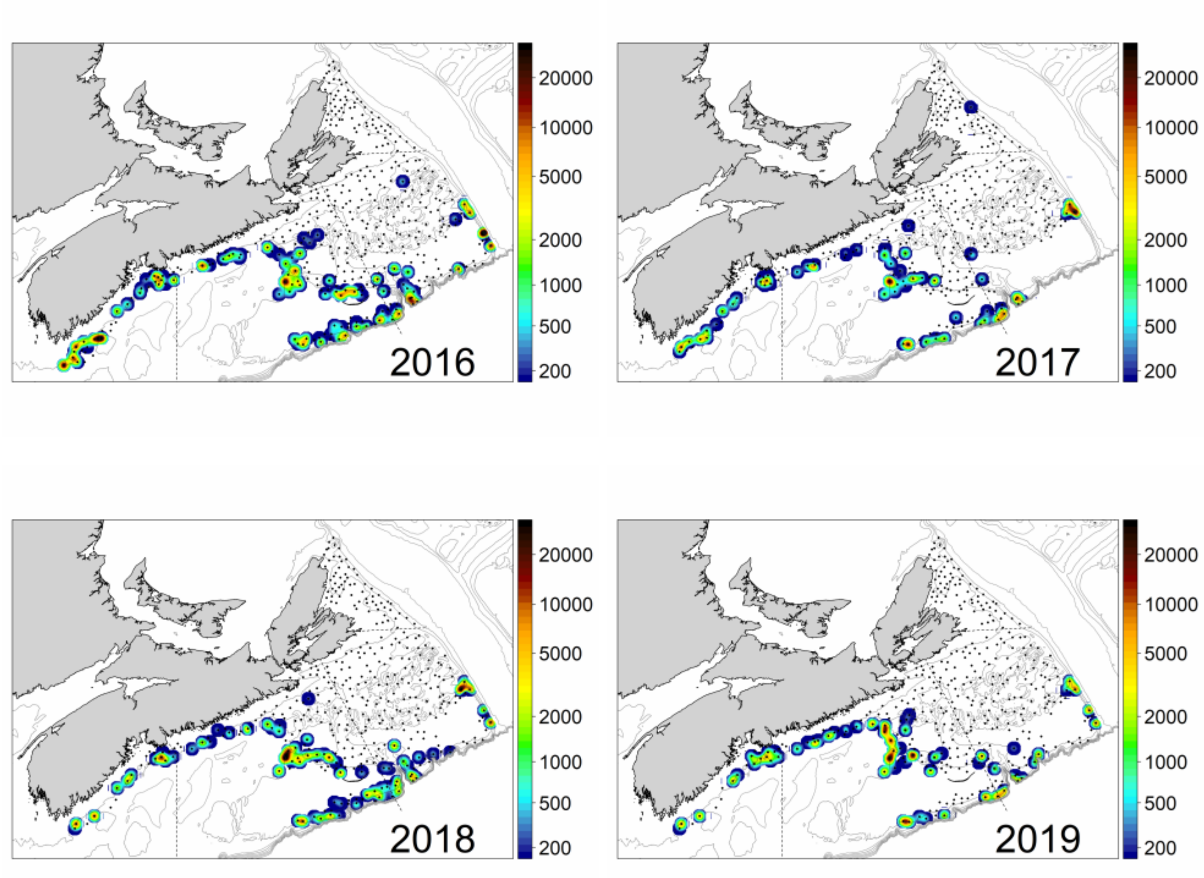


*Figure 28. Locations of potential predators of Snow Crab on the Scotian Shelf from the annual Snow Crab survey: **Haddock**. Scale is number/km^2.*

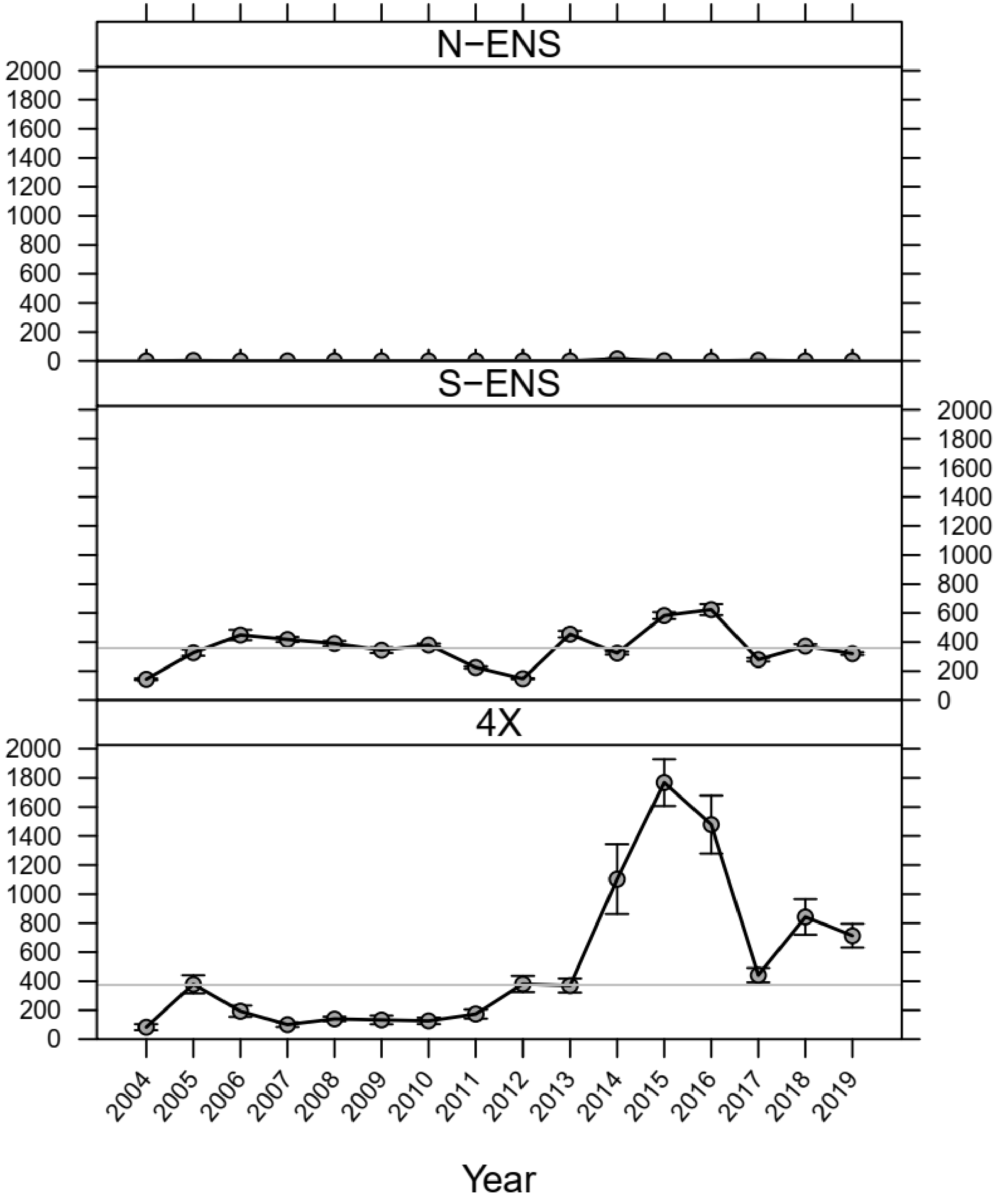


Figure 29. Trends in biomass (kg/km^2) of potential predators of Snow Crab from the annual Snow Crab survey on the Scotian Shelf: ***Haddock****. Grey line indicates long-term mean.*

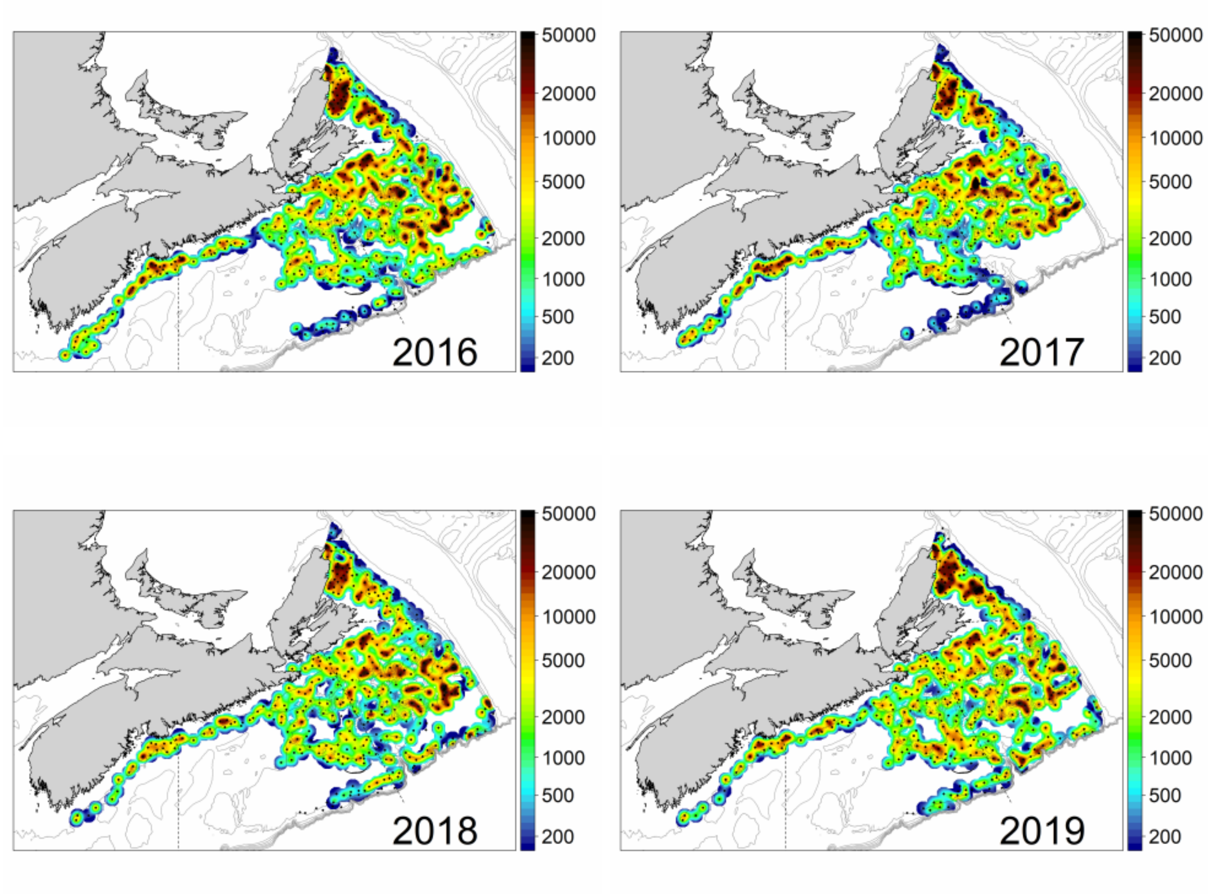


Figure 30. Locations of potential predators of Snow Crab on the Scotian Shelf from the annual Snow Crab survey: ***American Plaice****. Scale is number/km^2.*

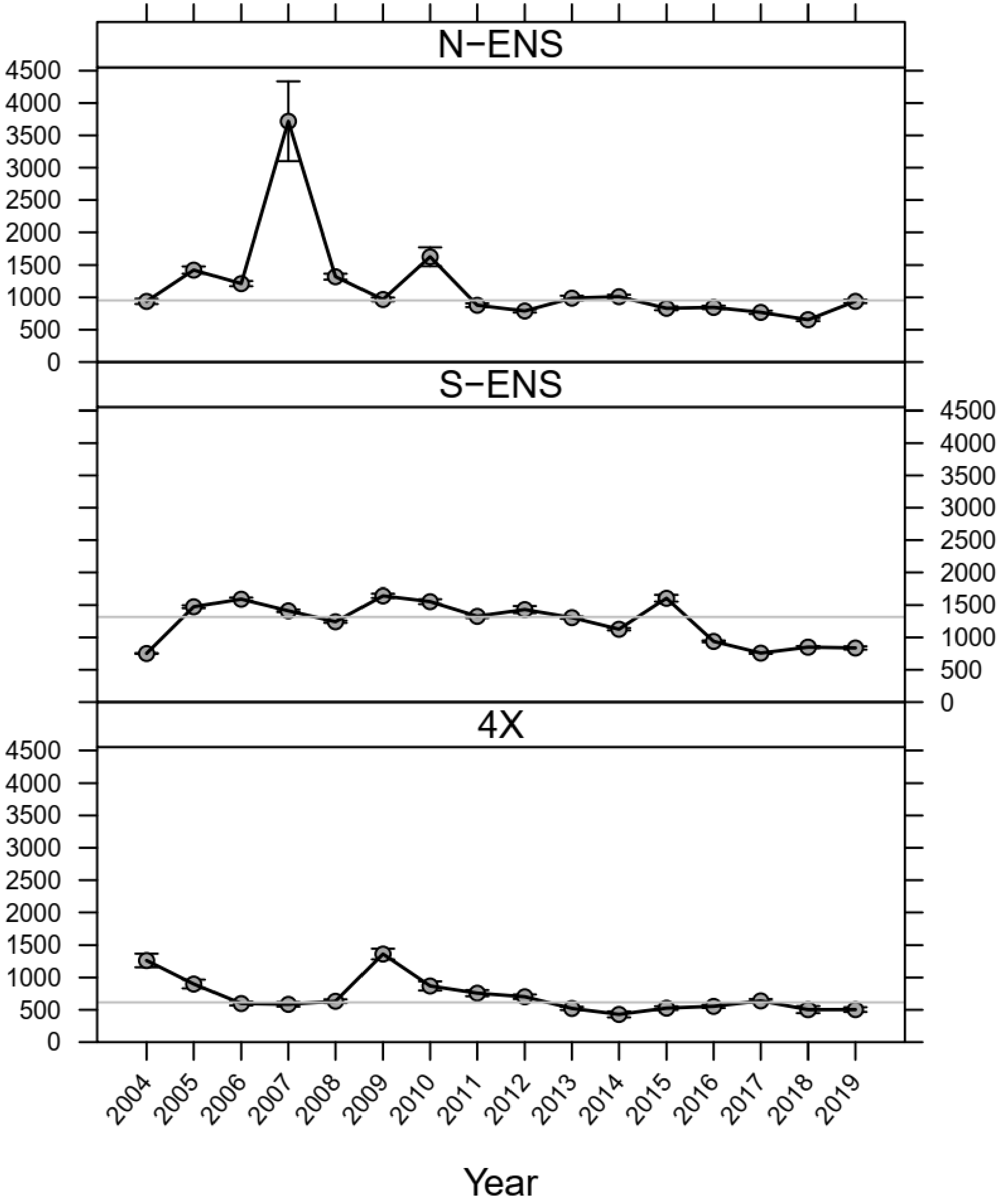


*Figure 31. Trends in biomass (kg/km^2) of potential predators of Snow Crab from the annual Snow Crab survey on the Scotian Shelf: **American Plaice**. Grey line indicates long-term mean.*

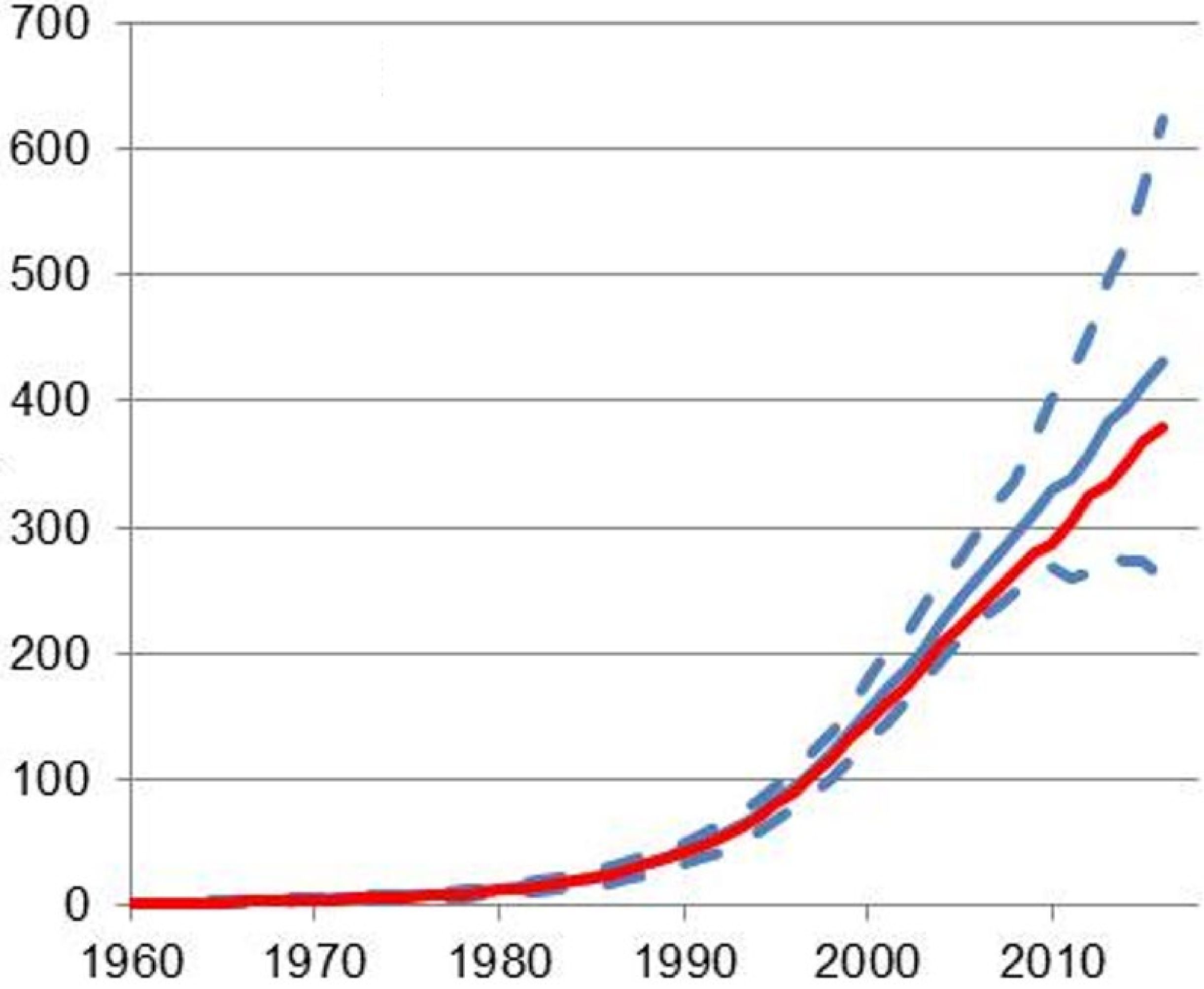


Figure 32. Trends in numerical abundance (in thousands) of Grey seals on the Scotian Shelf. The blue line is 1:1 (male:female) ratio, red line is 0.69:1. Source: DFO 2017.

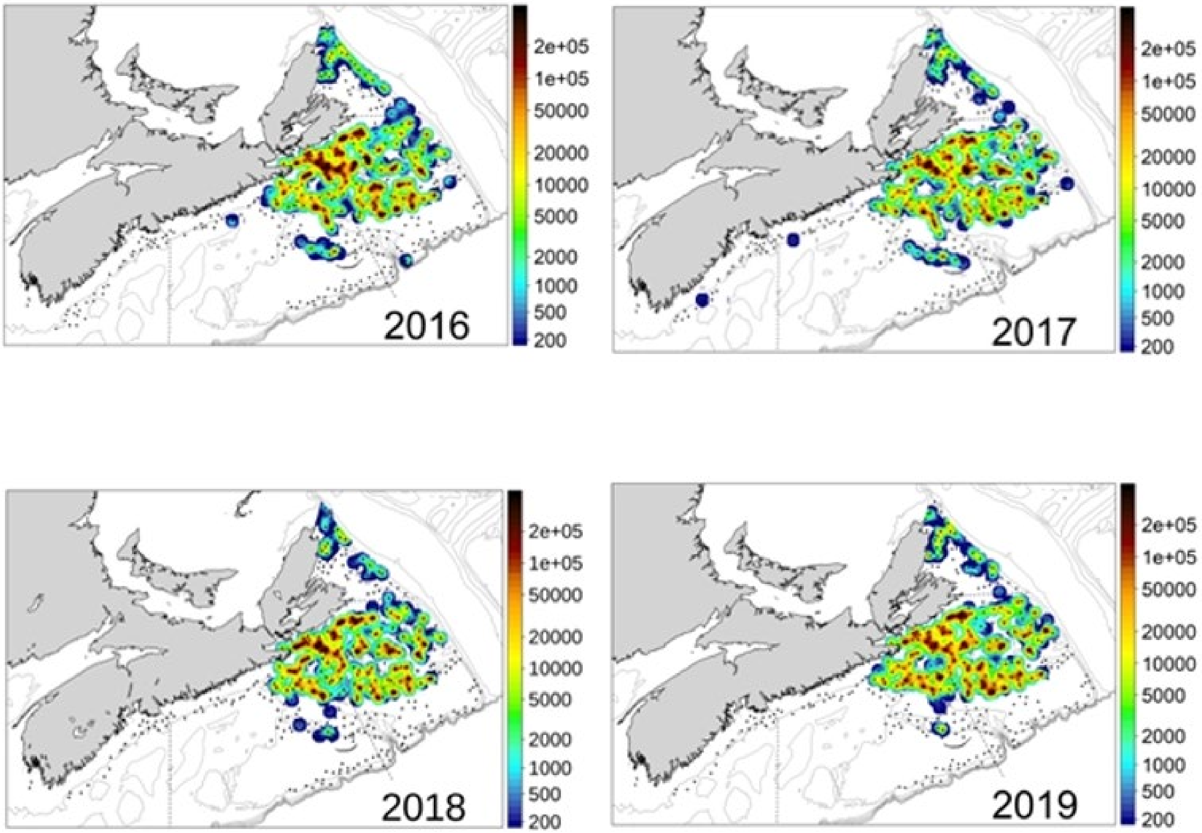


Figure 33. Locations of potential prey of Snow Crab on the Scotian Shelf from the annual Snow Crab survey: ***Northern Shrimp****. Scale is number/km^2.*

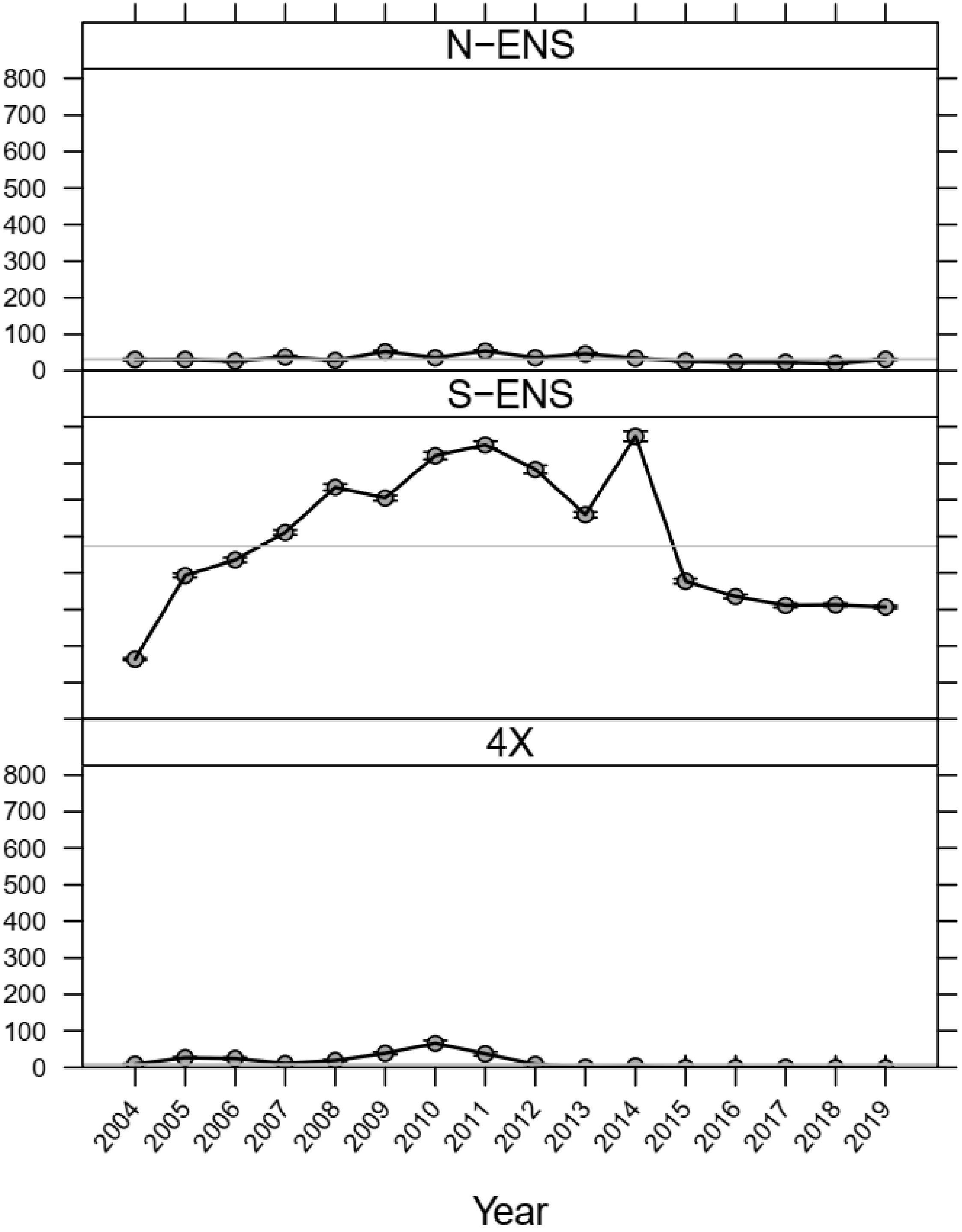


Figure 34. Trends in biomass (kg/km^2) of potential predators of Snow Crab from the annual Snow Crab survey on the Scotian Shelf: **Northern Shrimp**. Grey line indicates long-term mean.

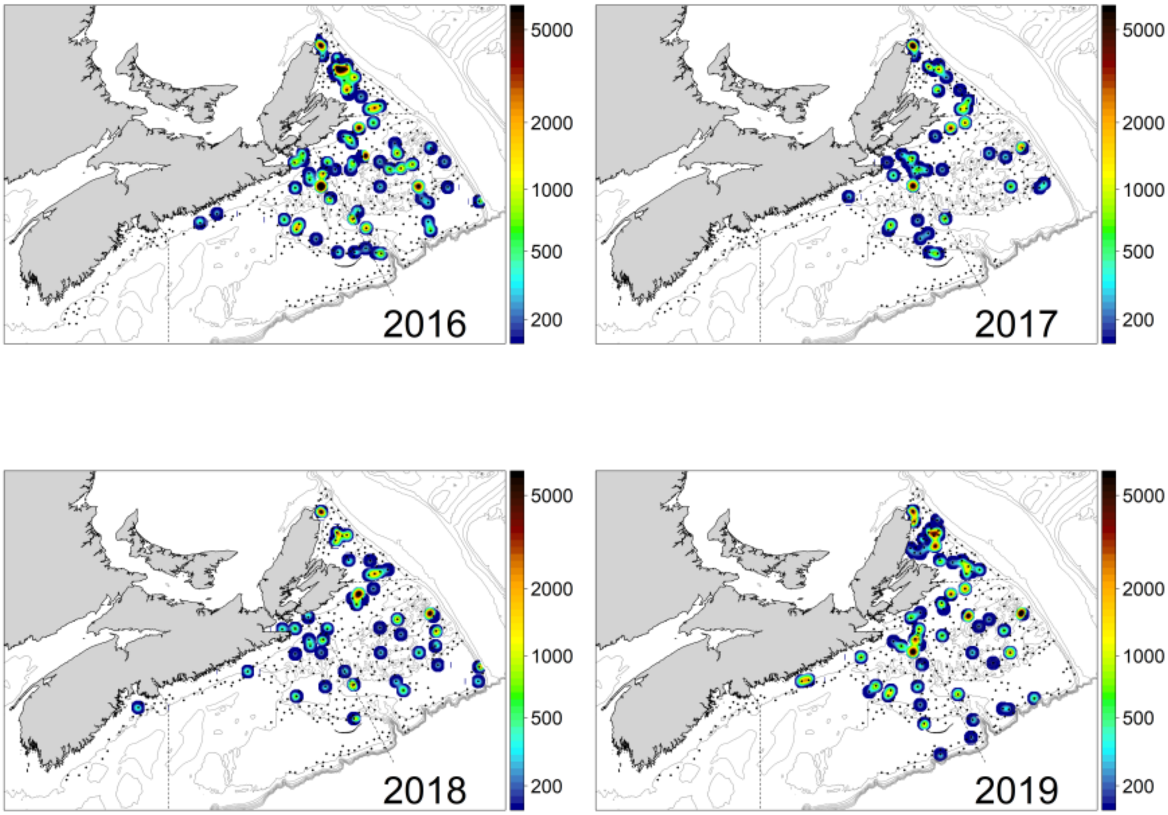


Figure 35. Locations of potential competition of Snow Crab on the Scotian Shelf from the annual Snow Crab survey: ***Lesser Toad Crab****. Scale is number/km*^{2}*.*

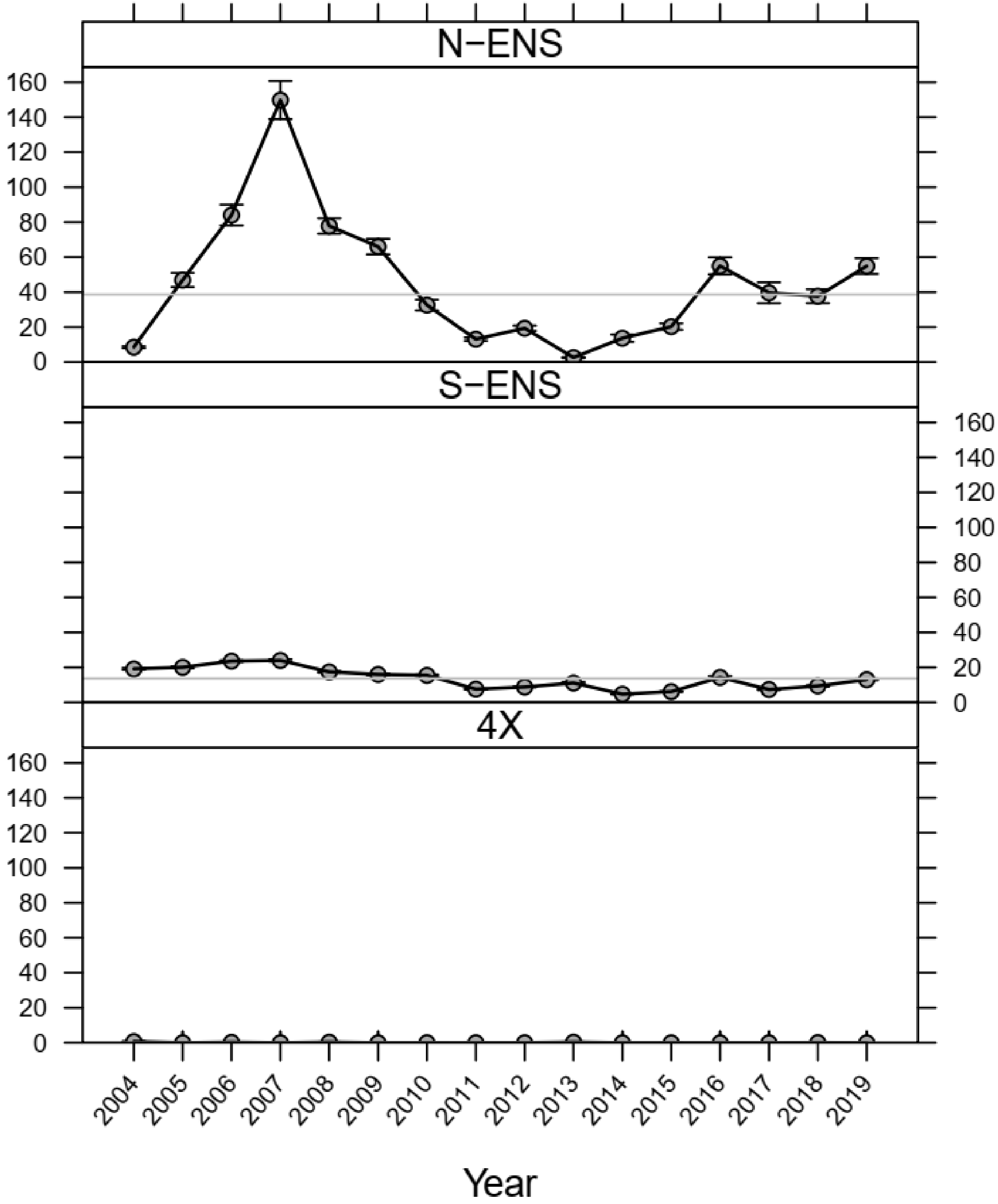


Figure 36. Trends in biomass (kg/km^2) of potential predators of Snow Crab from the annual Snow Crab survey on the Scotian Shelf: ***Lesser Toad Crab****. Grey line indicates long-term mean.*

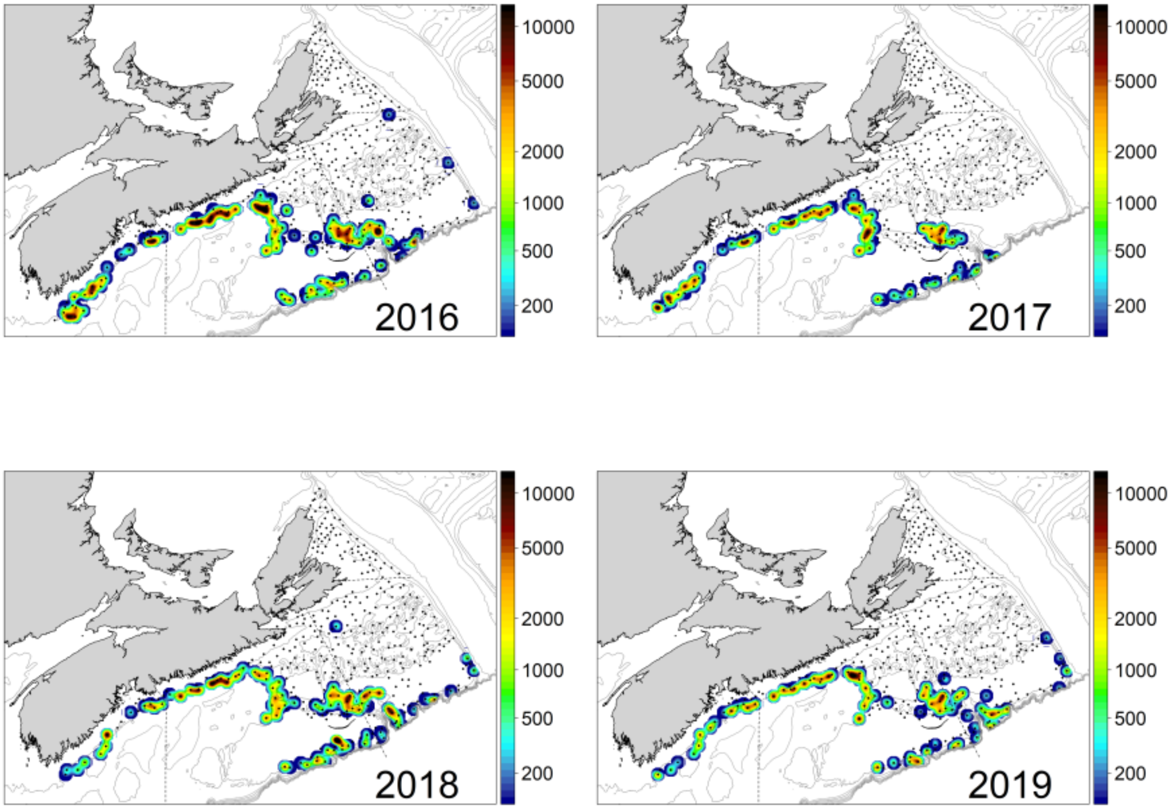


Figure 37. Locations of potential competition of Snow Crab on the Scotian Shelf from the annual Snow Crab survey: ***Jonah Crab****. Scale is number/km^2.*

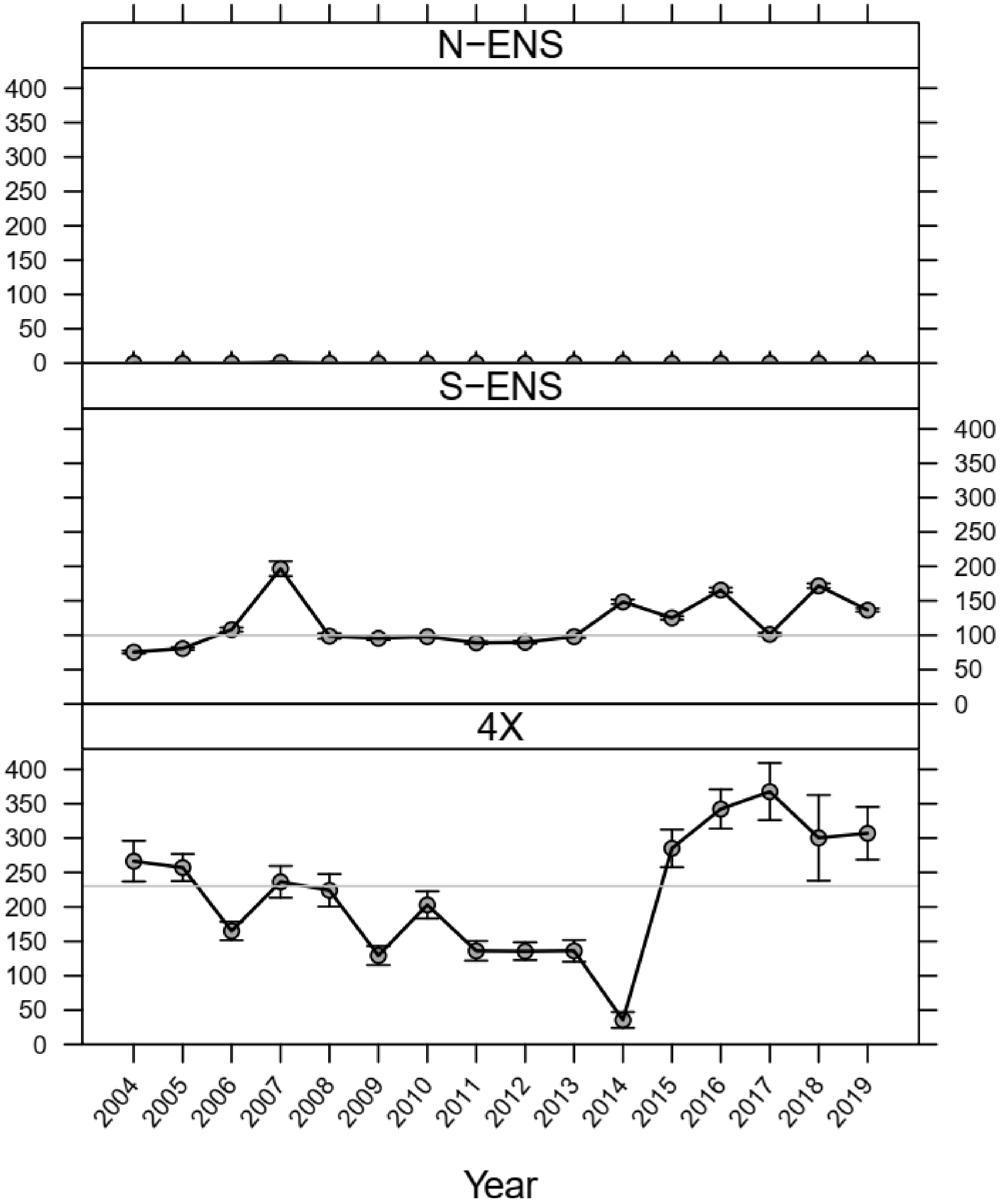


*Figure 38. Trends in biomass (kg/km^2) of potential predators of Snow Crab from the annual Snow Crab survey on the Scotian Shelf: **Jonah Crab**. Grey line indicates long-term mean.*

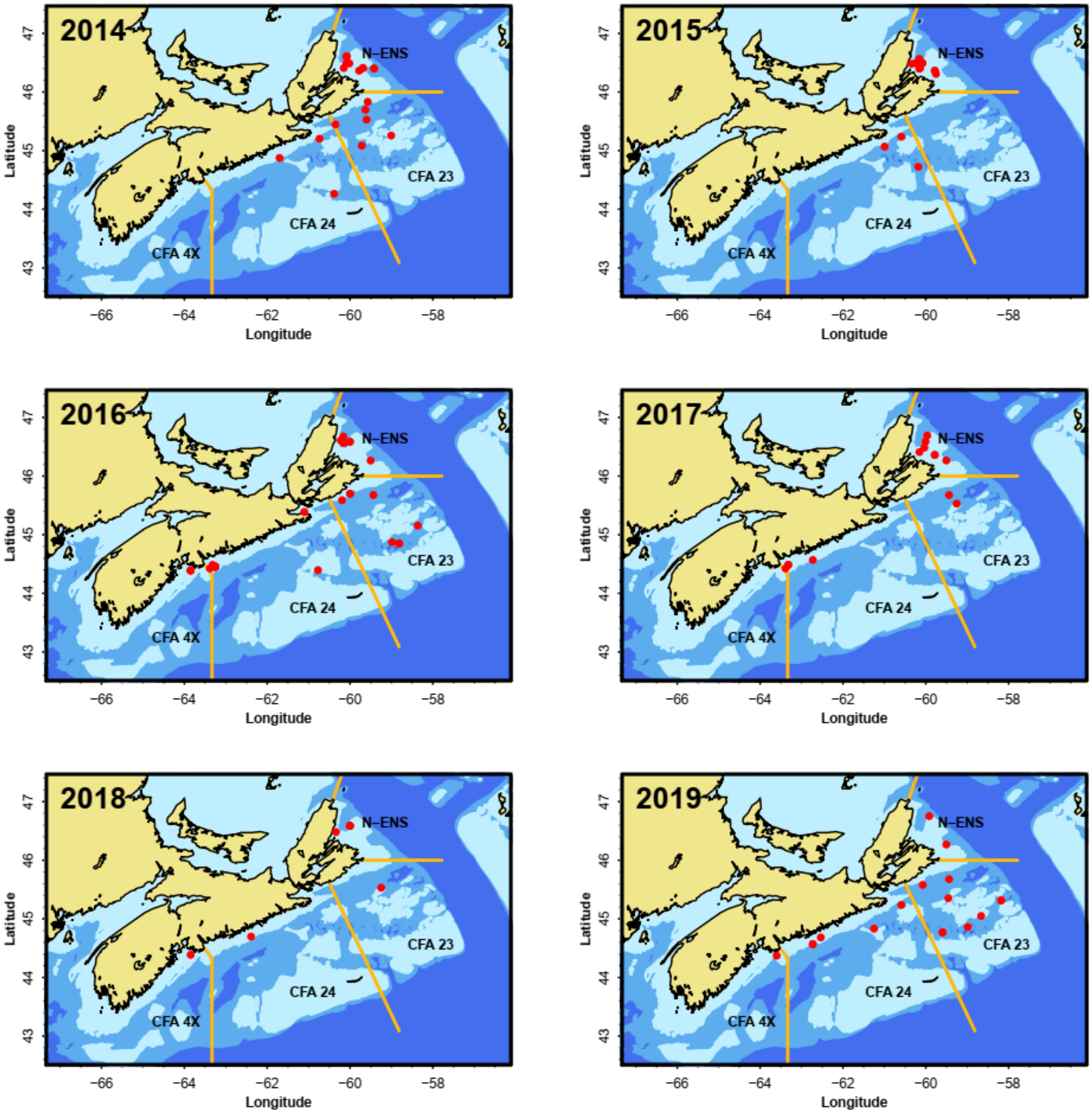


Figure 39. Annual locations of Bitter Crab Disease observations in Snow Crab trawl survey.

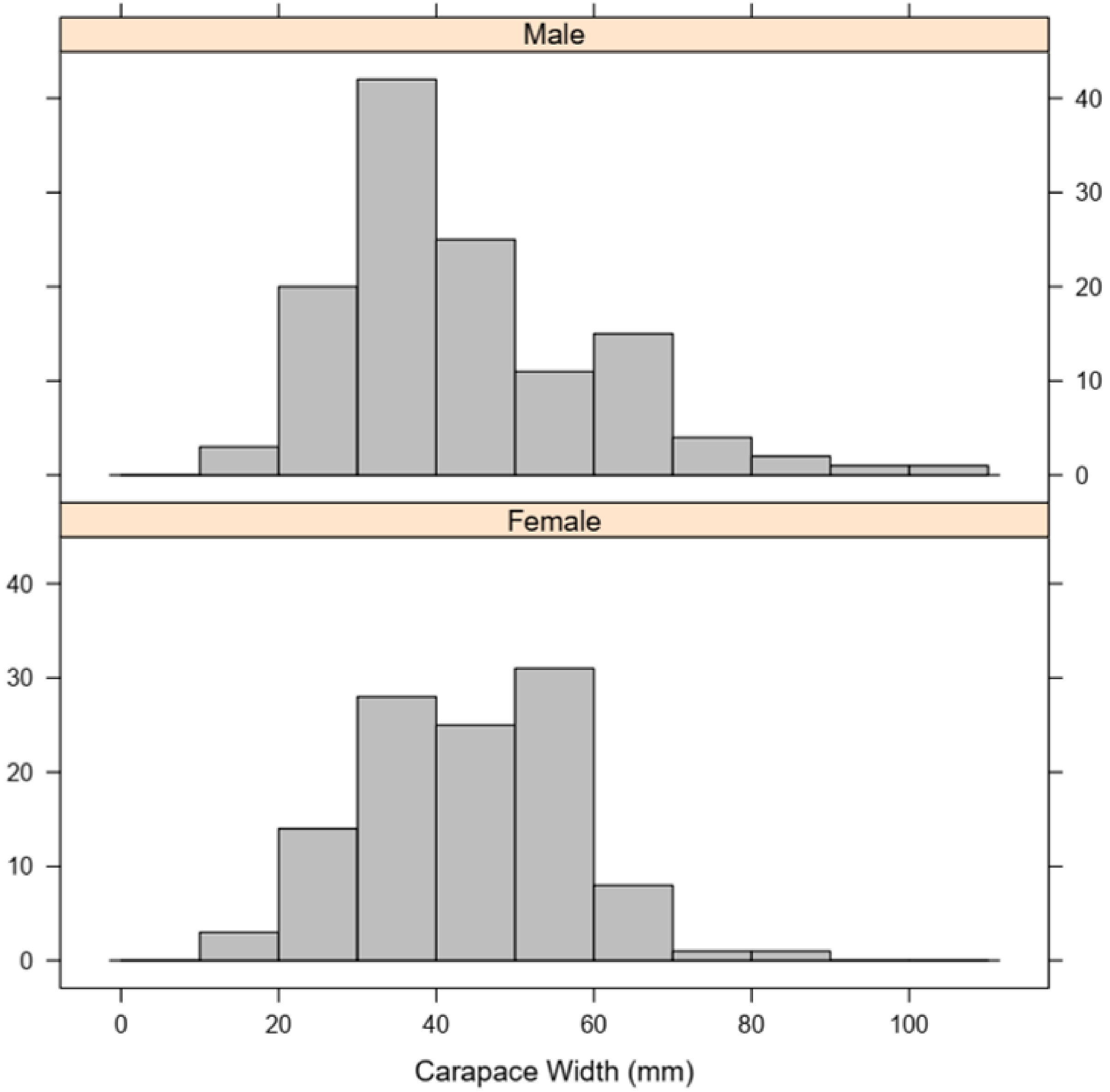
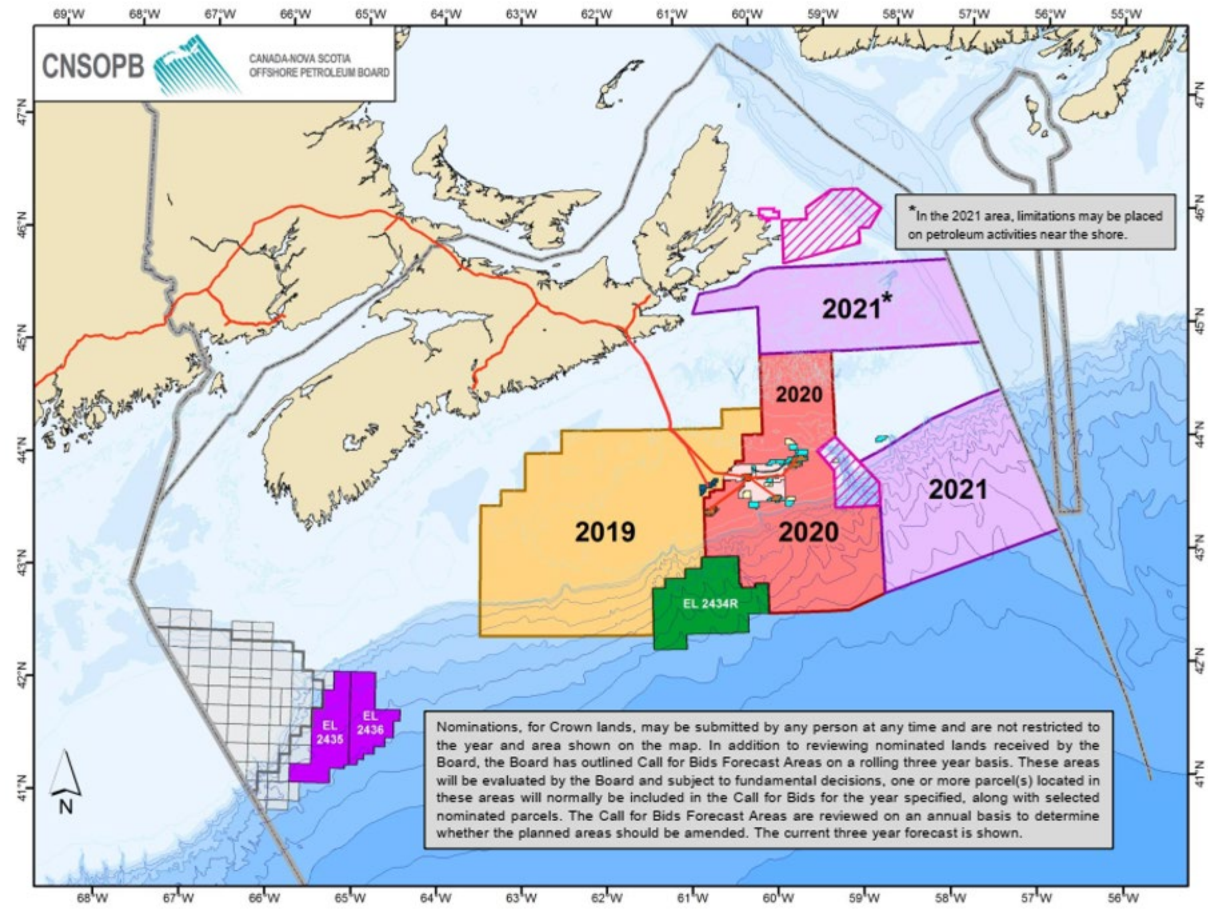


Figure 40. Numerical size-frequency distribution of Snow Crab visibly infected with BCD from 2009–present.



*In the 2021 area, limitations may be placed on petroleum activities near the shore.

Nominations, for Crown lands, may be submitted by any person at any time and are not restricted to the year and area shown on the map. In addition to reviewing nominated lands received by the Board, the Board has outlined Call for Bids Forecast Areas on a rolling three year basis. These areas will be evaluated by the Board and subject to fundamental decisions, one or more parcel(s) located in these areas will normally be included in the Call for Bids for the year specified, along with selected nominated parcels. The Call for Bids Forecast Areas are reviewed on an annual basis to determine whether the planned areas should be amended. The current three year forecast is shown.

Figure 41. Map of current Canadian Nova Scotia Offshore Petroleum Board call for exploration bids.

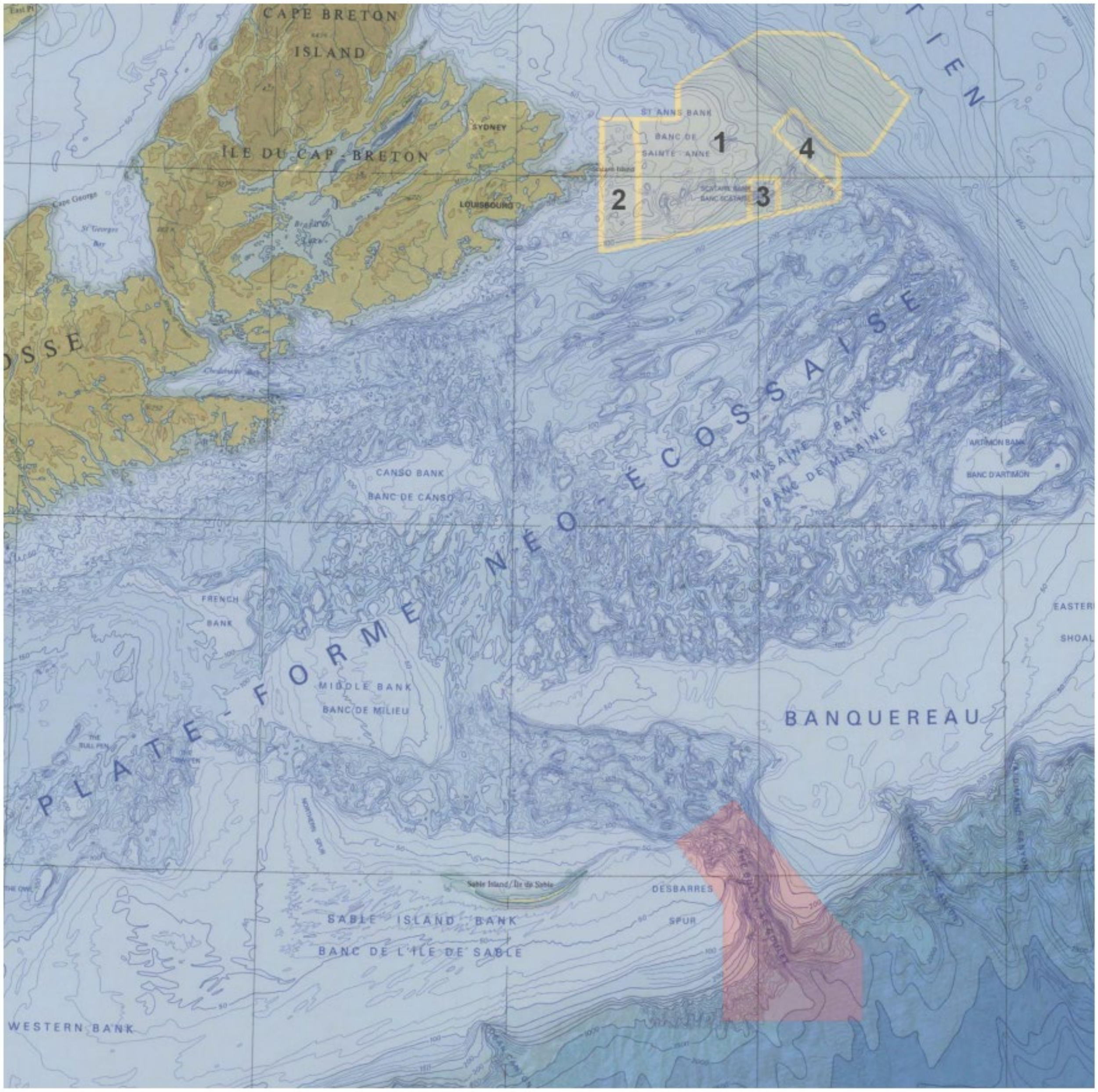


Figure 42. Large Marine Protected Areas (MPAs) on the Eastern Scotian Shelf. St. Anns Bank MPA with sub-zone designations shown in yellow. The Gully MPA shown in red.

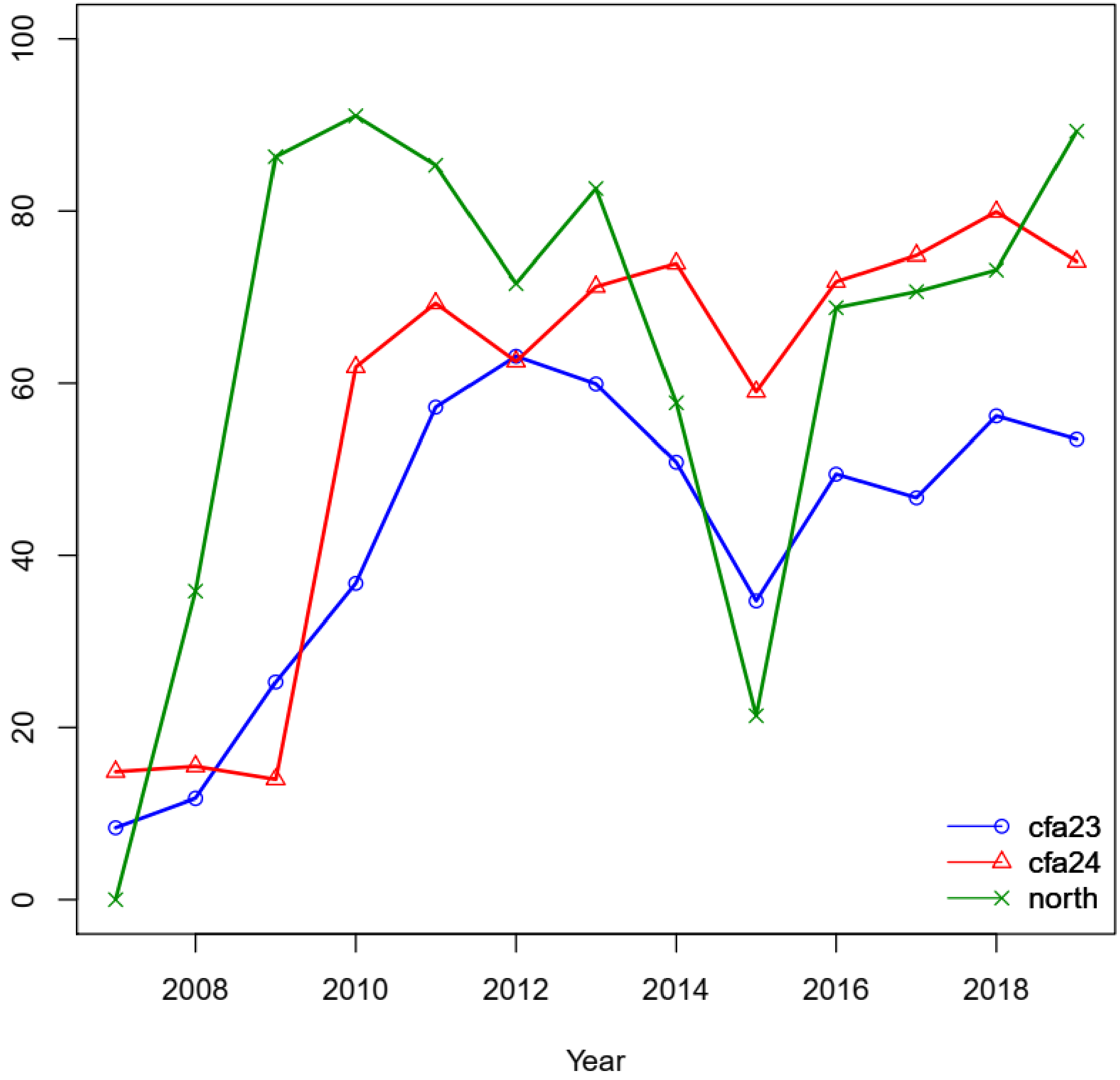


Figure 43. The percent of total annual Snow Crab landings caught during the months of April–June separated by Crab Fishing Area (CFA).

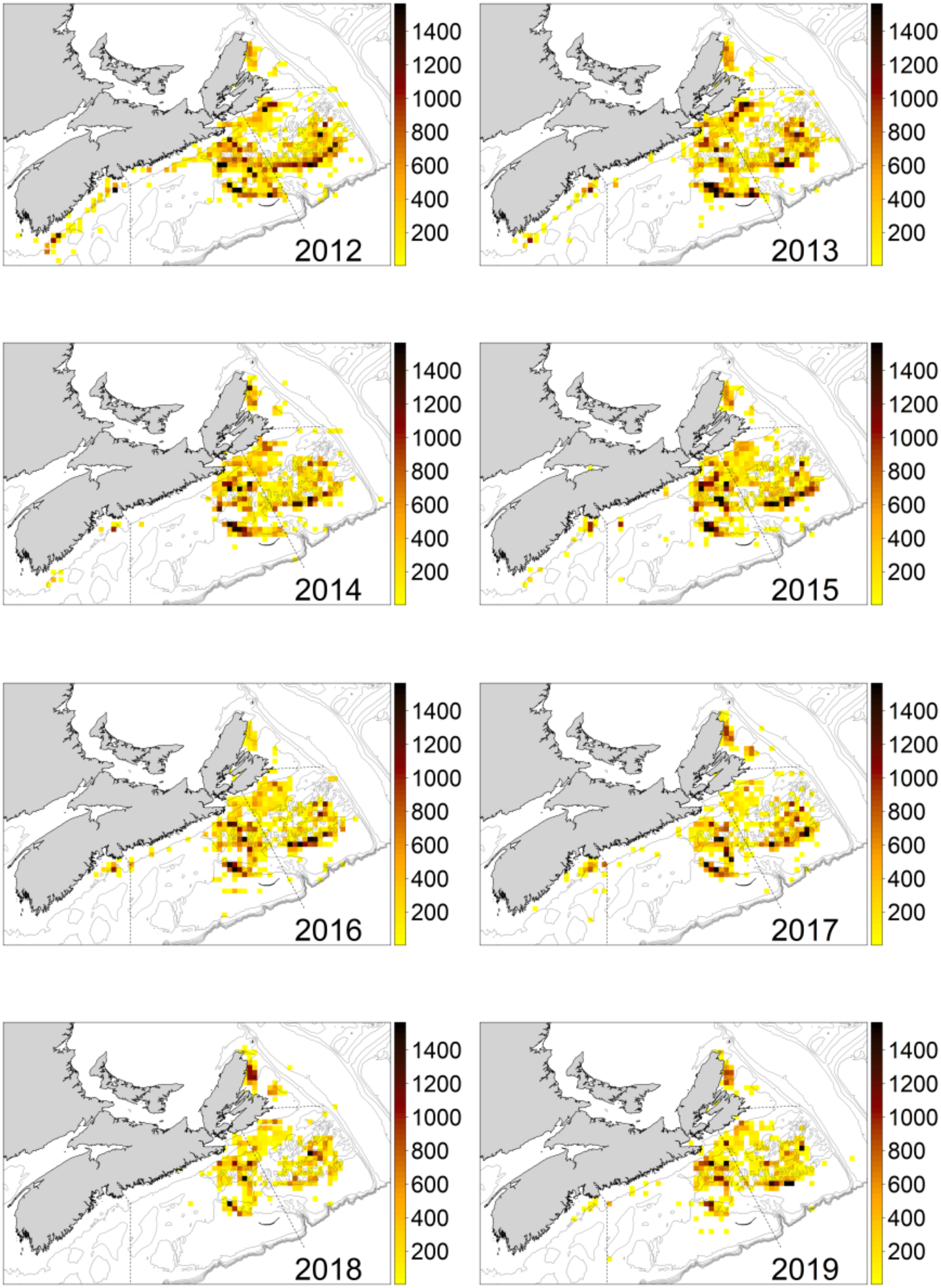


Figure 44. Fishing effort (number of trap hauls/10 x 10 km grid) from fisheries logbook data. For 4X (see Figure 1) year refers to the starting year.

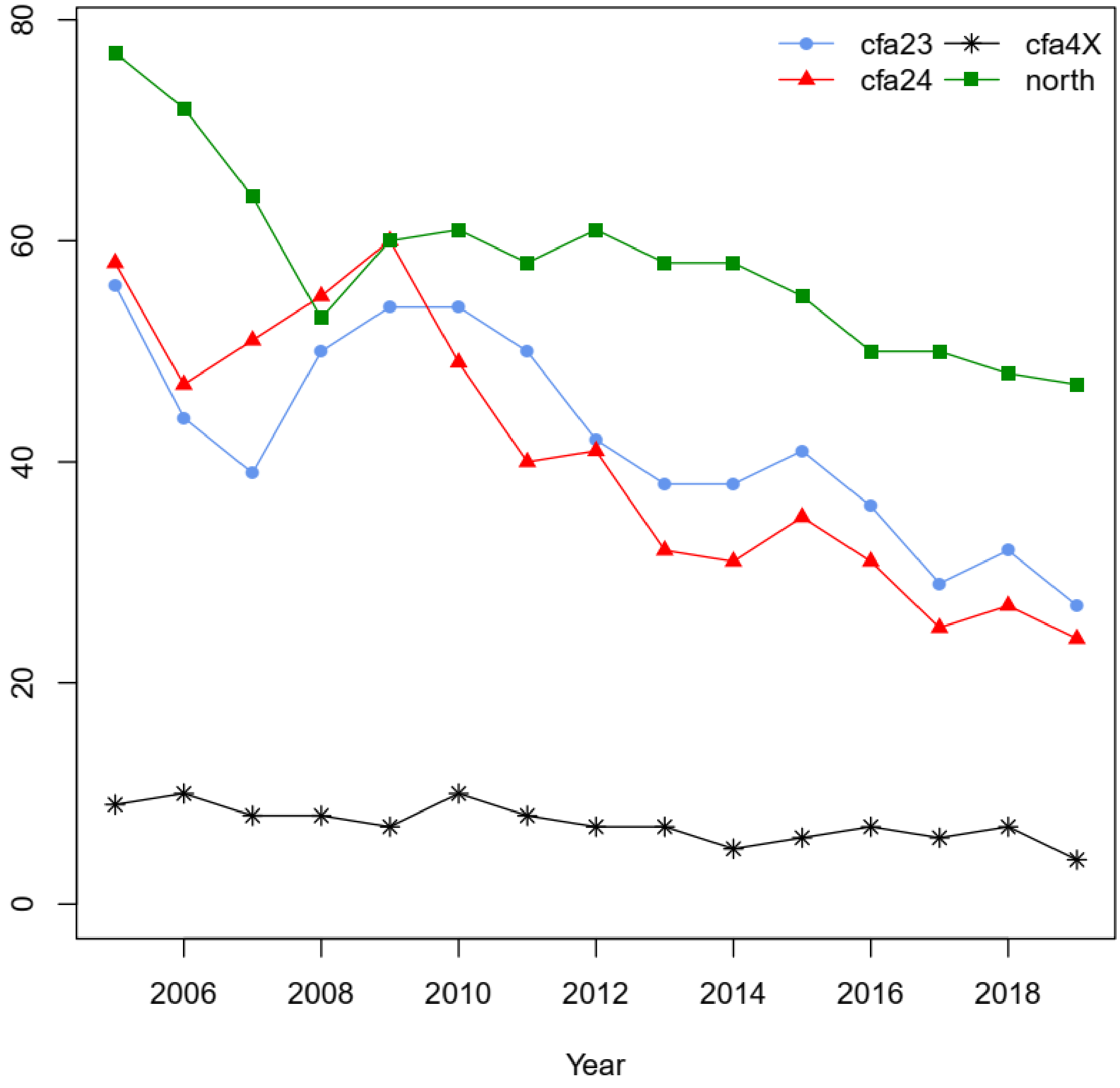


Figure 45. Number of active vessels fishing in each of the Scotian Shelf Snow Crab fishing areas. South-Eastern Nova Scotia is separated into CFA23 and CFA24 to maintain consistency with historic information. The number of licenses within each area has been stable since 2004.

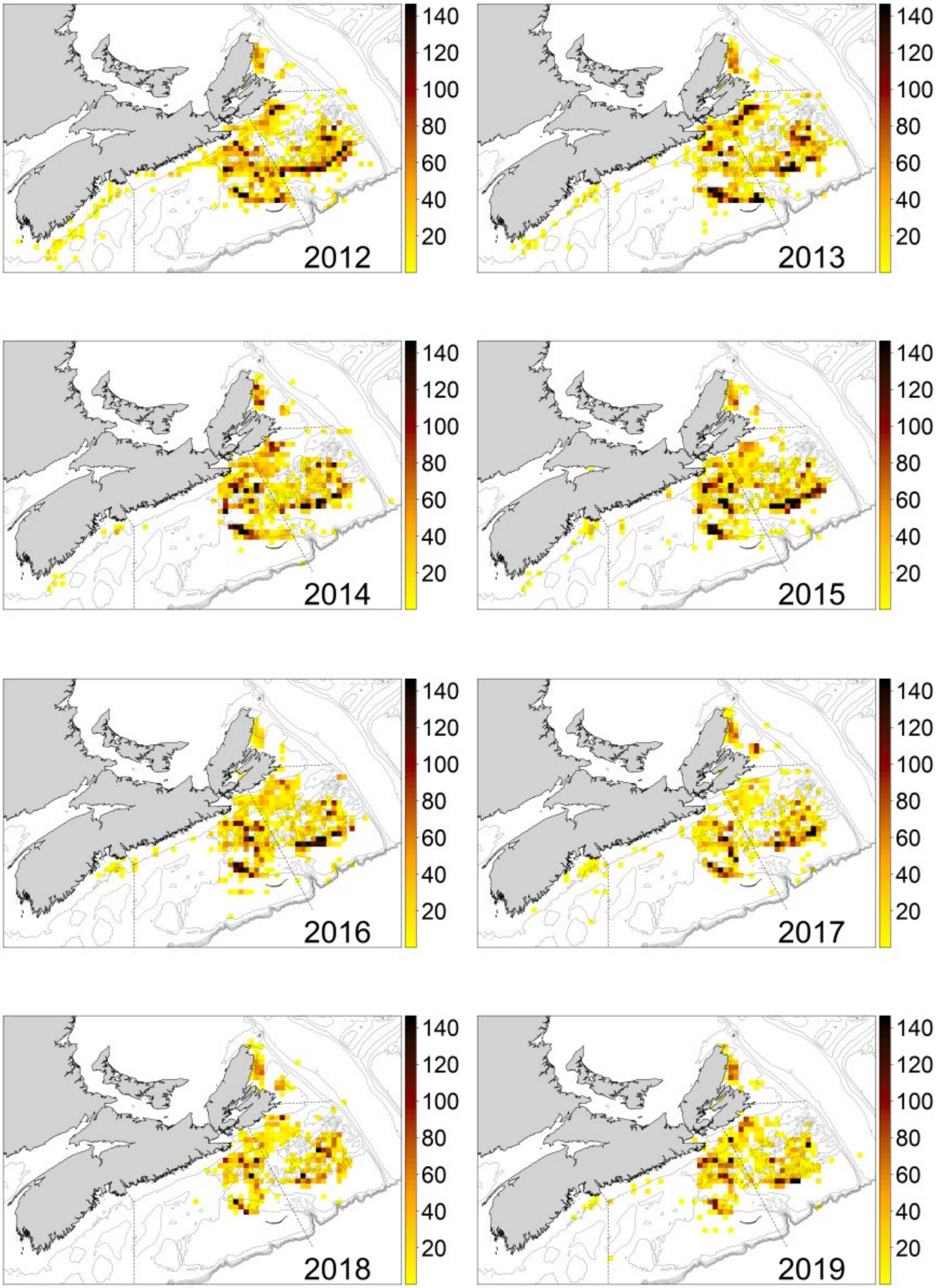


Figure 46. Snow Crab landings (tons/10 x 10 km grid) from fisheries logbook data. For 4X year refers to the starting year.

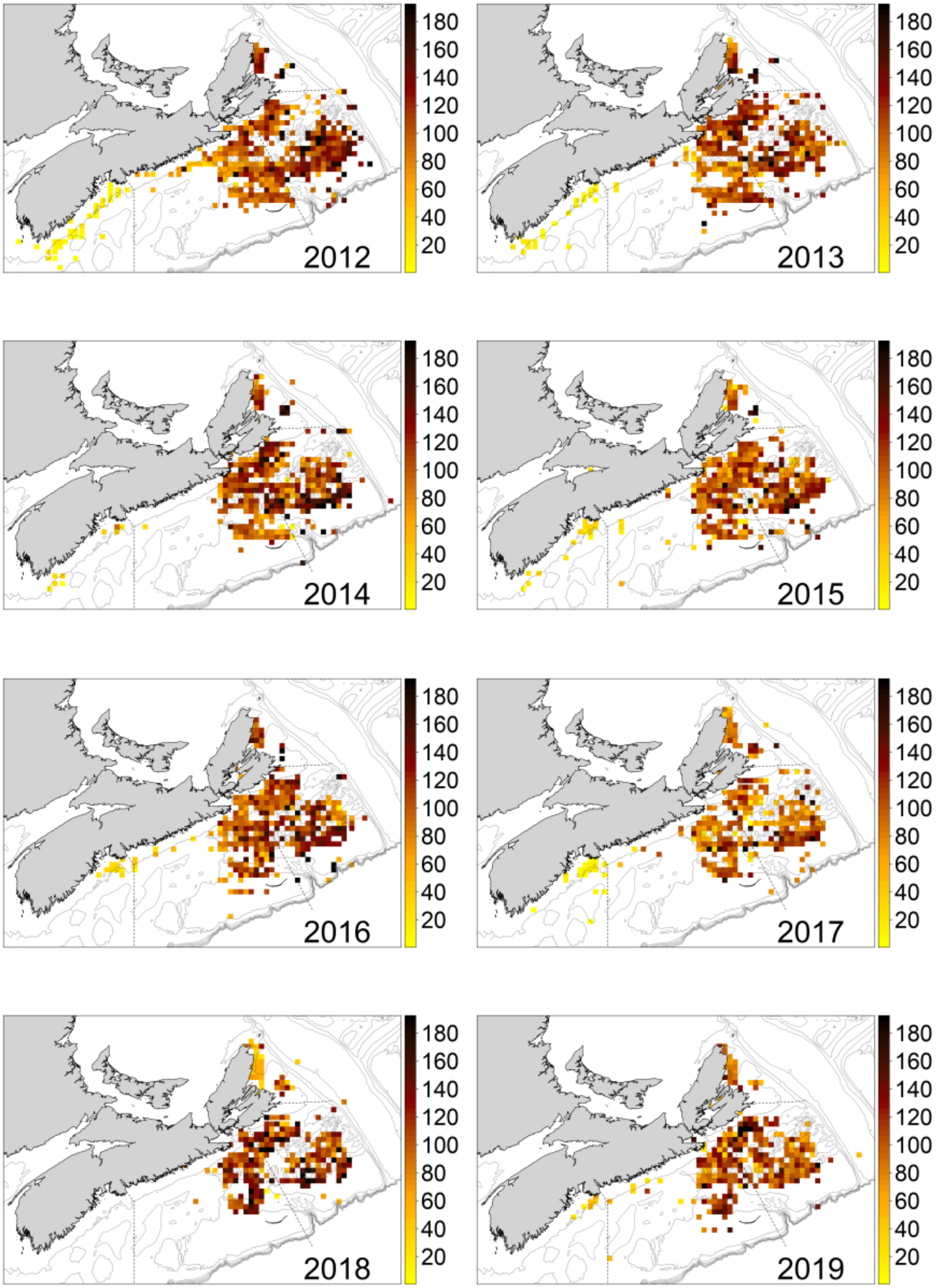


Figure 47. Catch rates (kg/trap haul) of Snow Crab in each 10 x 10km grid from fisheries logbook data. For 4X, year refers to the starting year.

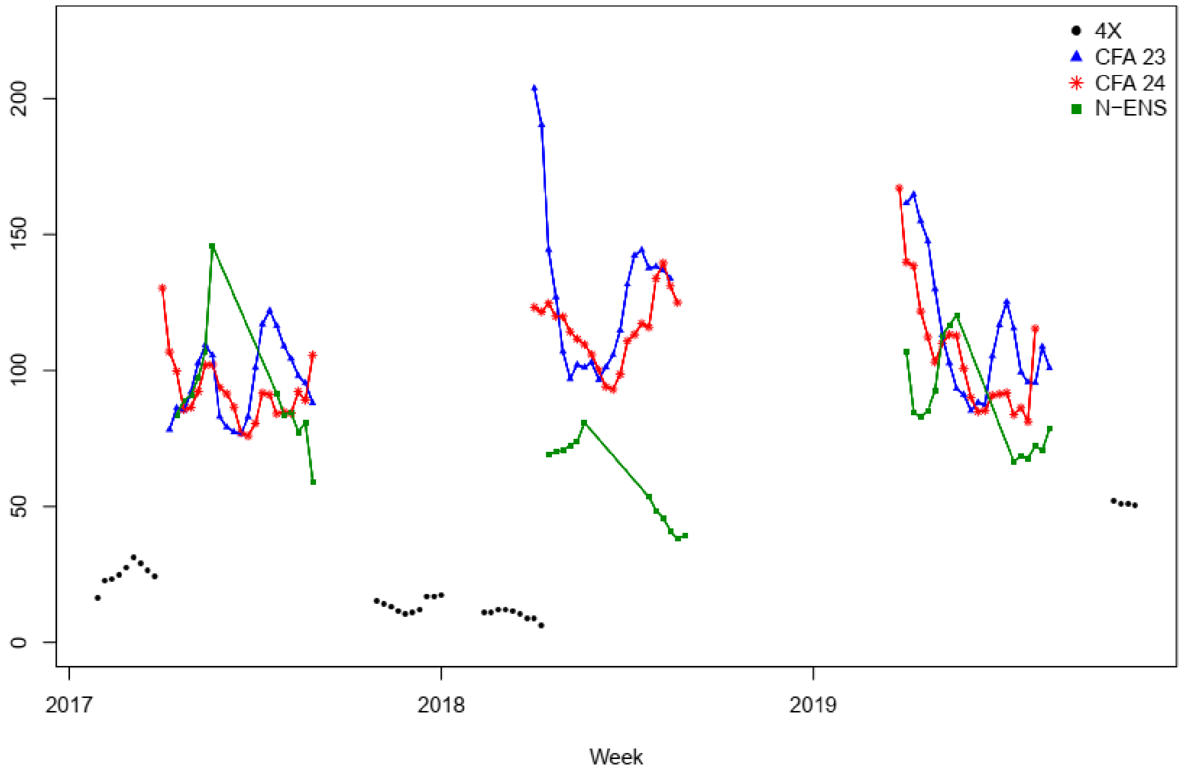


Figure 48. Smoothed catch rates (kg/trap haul) by week for the past three seasons. Split season in North-Eastern Nova Scotia (N-ENS; spring and summer portions) create the apparent gap in N-ENS data within each year.

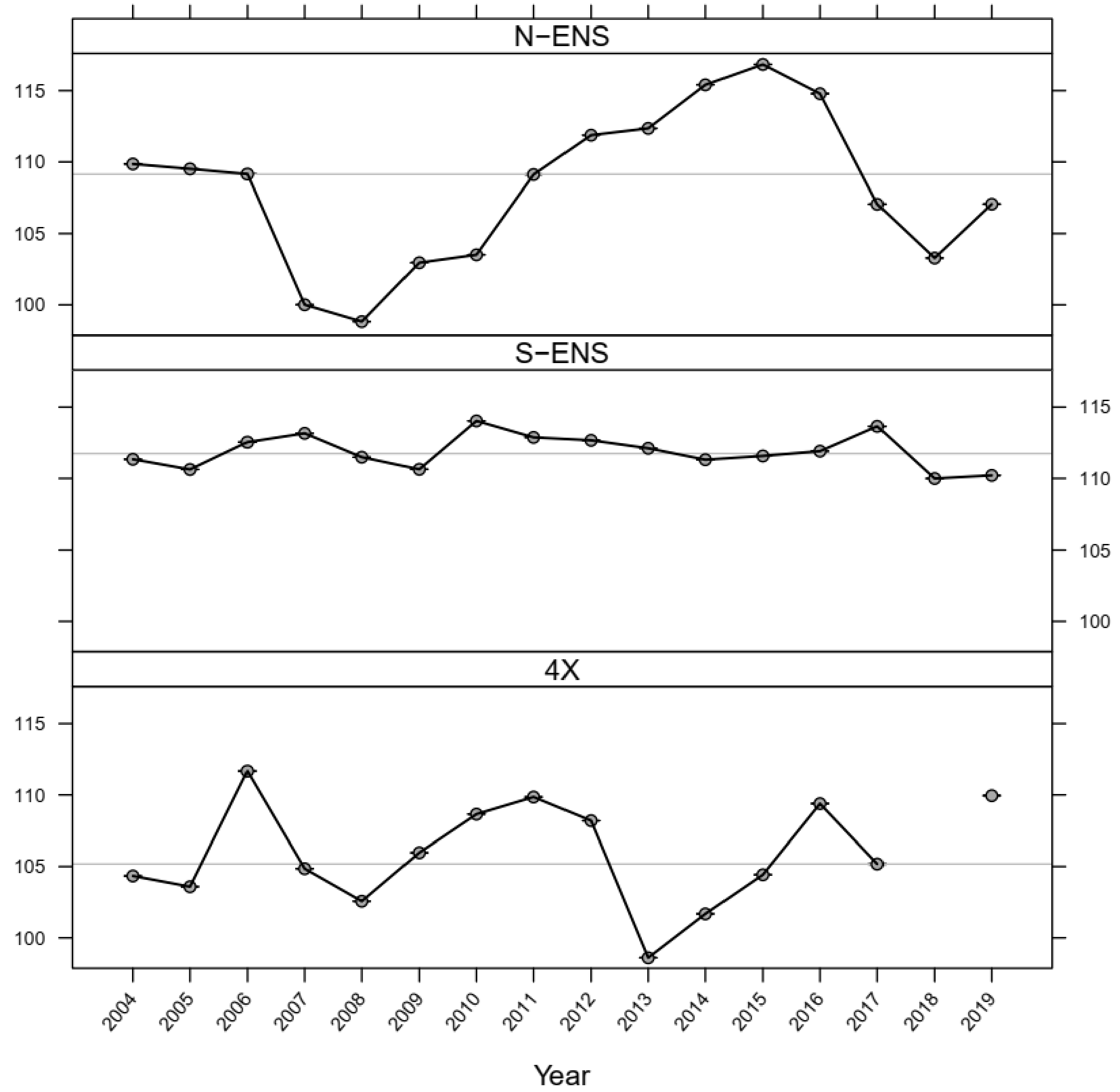


Figure 49. Time series of mean carapace width (mm) of commercial Snow Crab measured by at-sea observers. For 4X, the year refers to the starting year of the season. Grey line indicates long-term mean within each area.

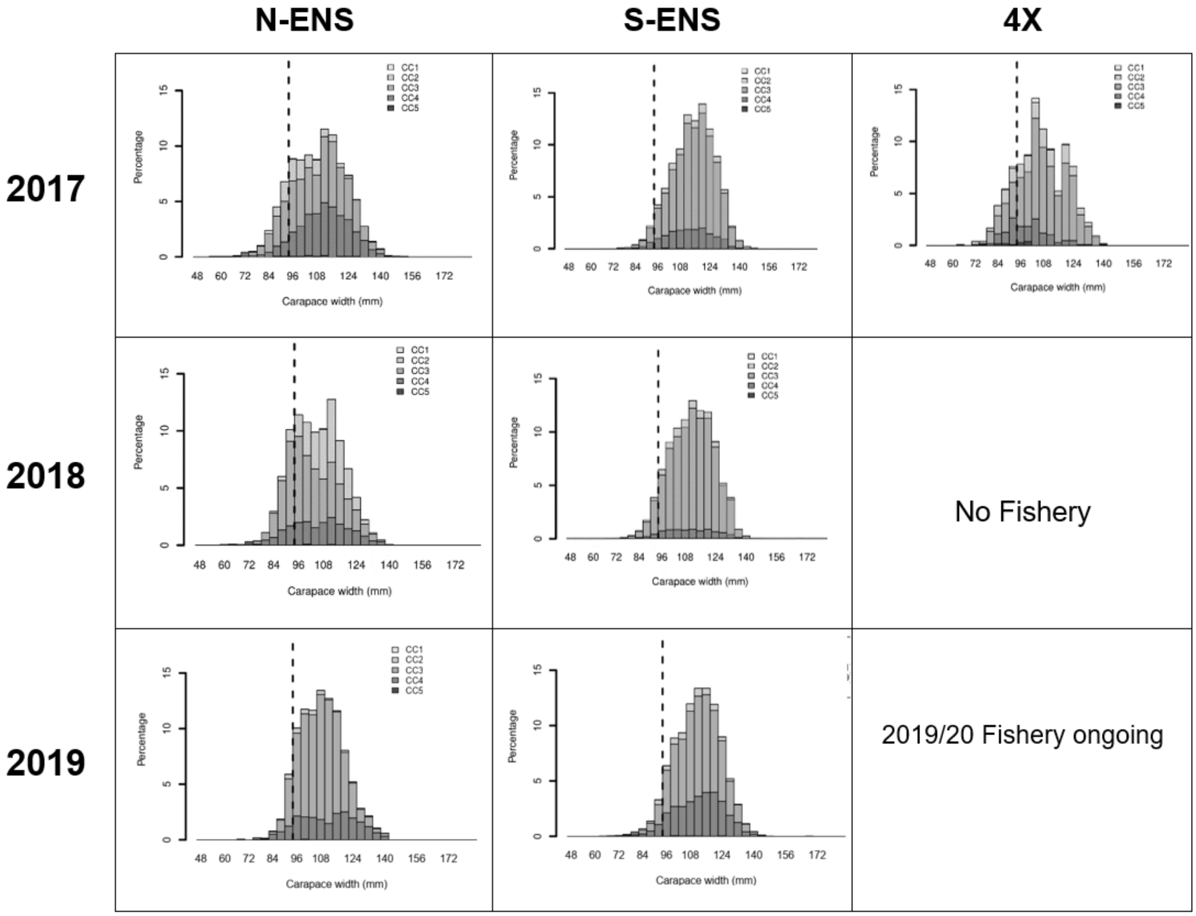


Figure 50. Size-frequency distribution of all at-sea-observer-monitored Snow Crab broken down by carapace condition. For 4X, the year refers to the starting year of the season. Dashed vertical lines indicate 95 mm Carapace Width (CW), the minimum legal size.

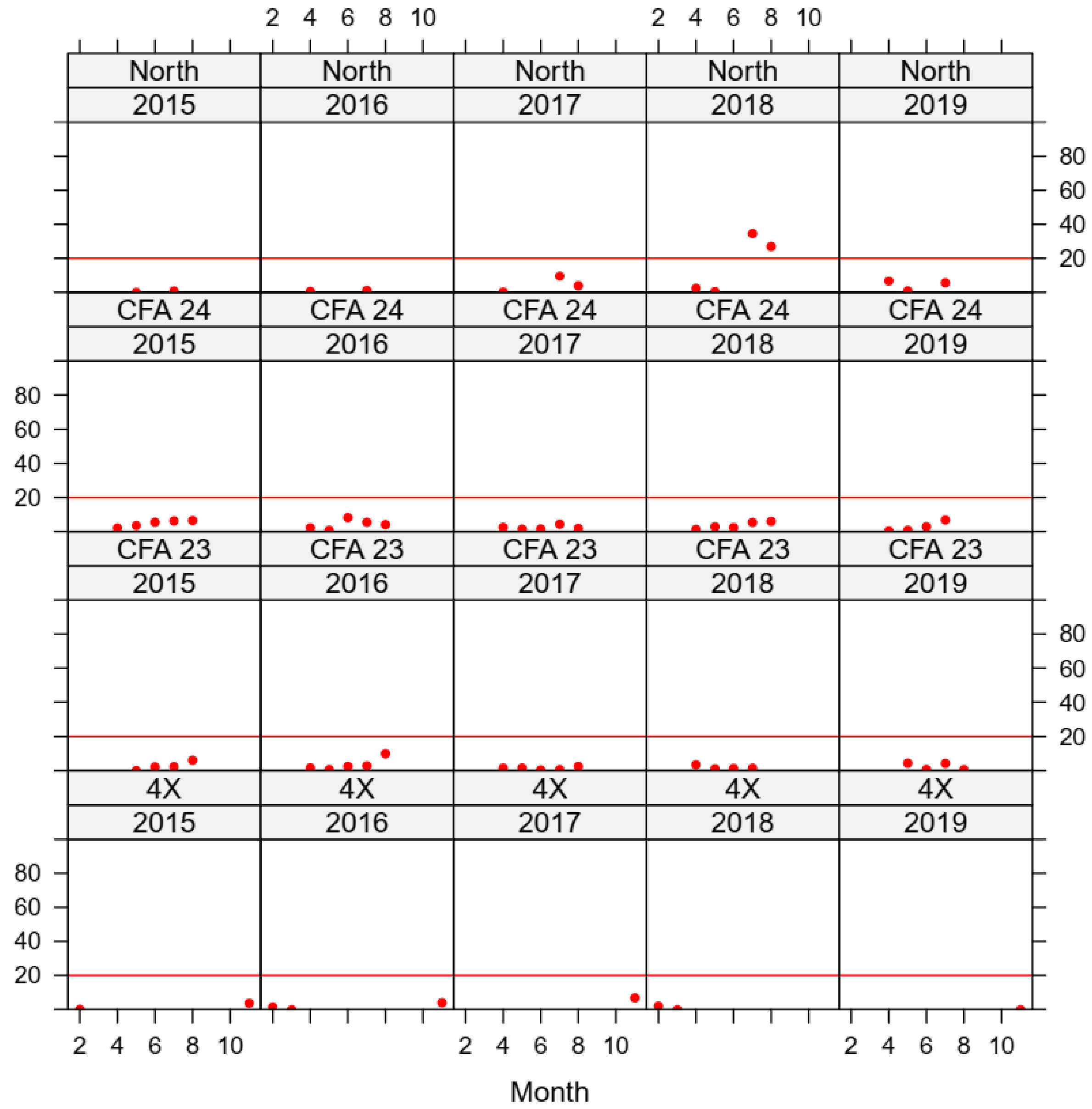


Figure 51. The percent of sampled Snow Crab in the soft-shelled state (less than 68 durometer) as determined by at-sea observers from commercial Snow Crab traps. Red horizontal line shows 20% soft, a level traditionally considered to be of concern.

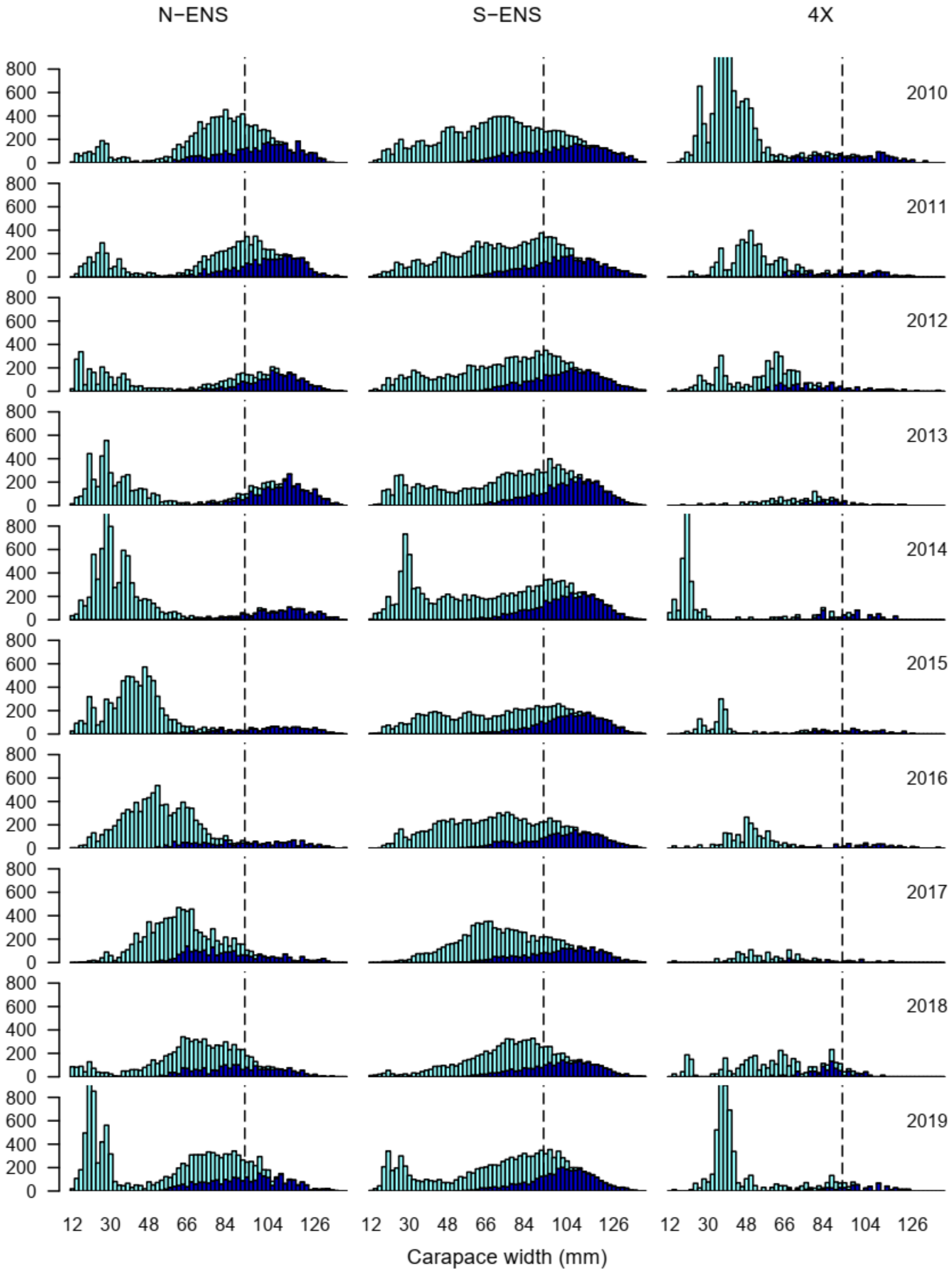


Figure 52. Size-frequency histograms of Carapace Width (CW) of male Snow Crab (number/km^2) obtained from the Snow Crab survey. Dark bars represent mature Snow Crab; light bars represent immature Snow Crab. Dashed line is the minimum legal size, 95mm CW.

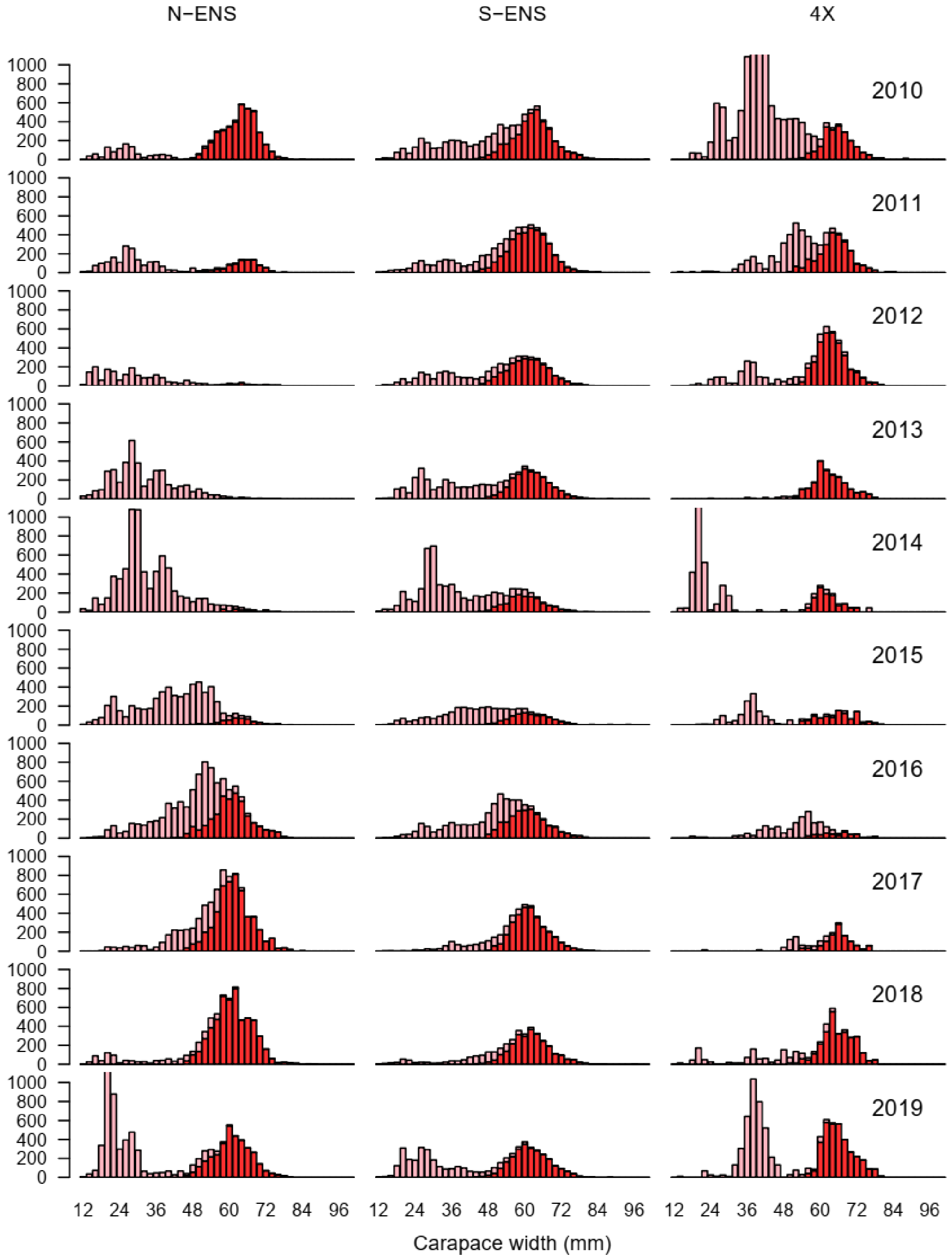


Figure 53. Size-frequency histograms of carapace width of female Snow Crab (number/km^2) obtained from the Snow Crab survey. Dark bars represent mature Snow Crab; light bars represent immature Snow Crab.

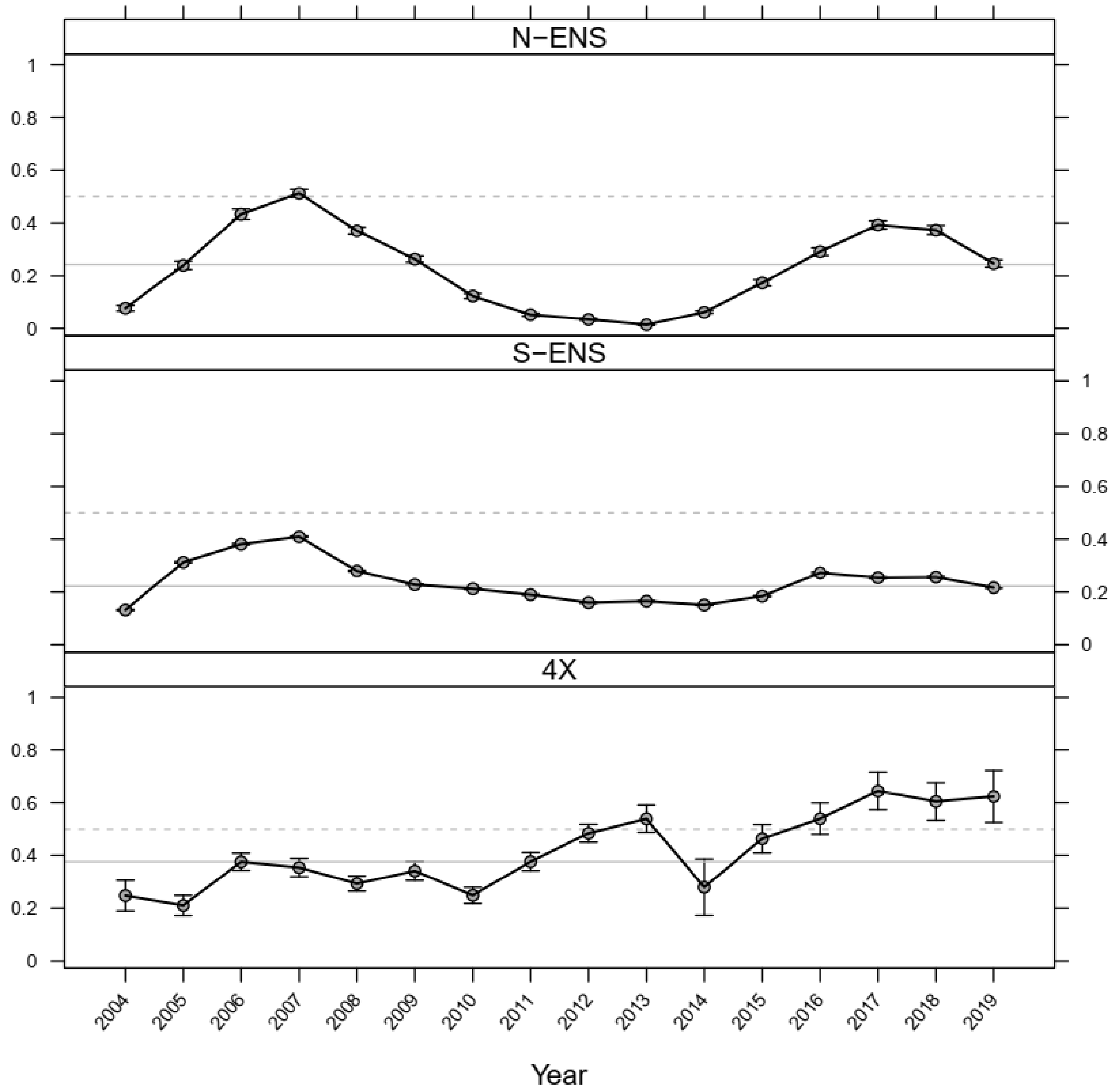


Figure 54. Annual proportion female of mature Snow Crab observed in the survey. Since 2001, most of the Scotian Shelf was uniformly male dominated. One standard error bar is presented. The dashed line represents a 1:1 (0.5 proportion) female: male ratio. Solid grey line indicates long-term mean within each area.

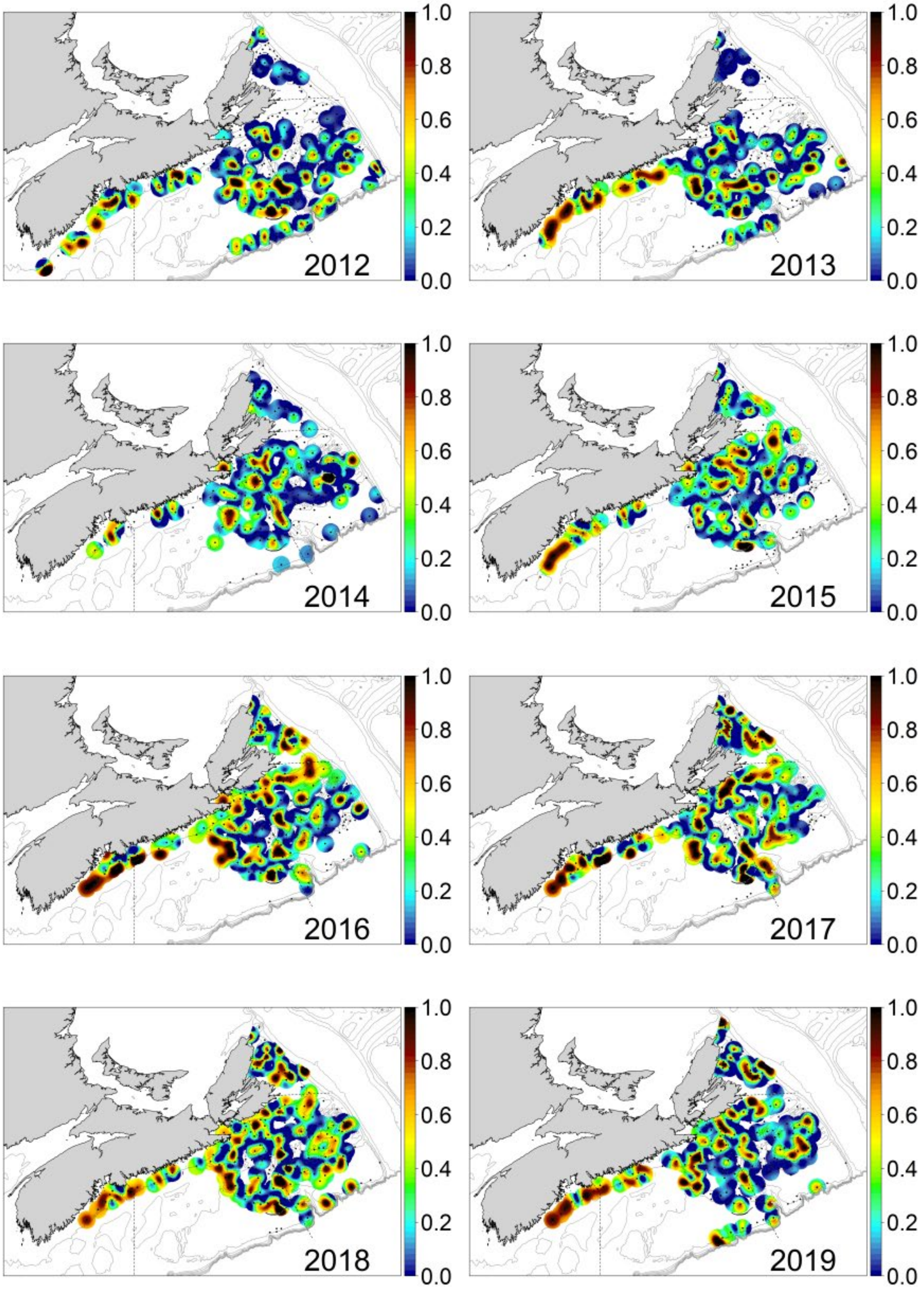


Figure 55. Proportion of females in the mature fraction of the total morphometrically mature segment of Snow Crab on the Scotian Shelf. Spatial representations generated using thin plate spline interpolations of data from the annual Snow Crab survey.

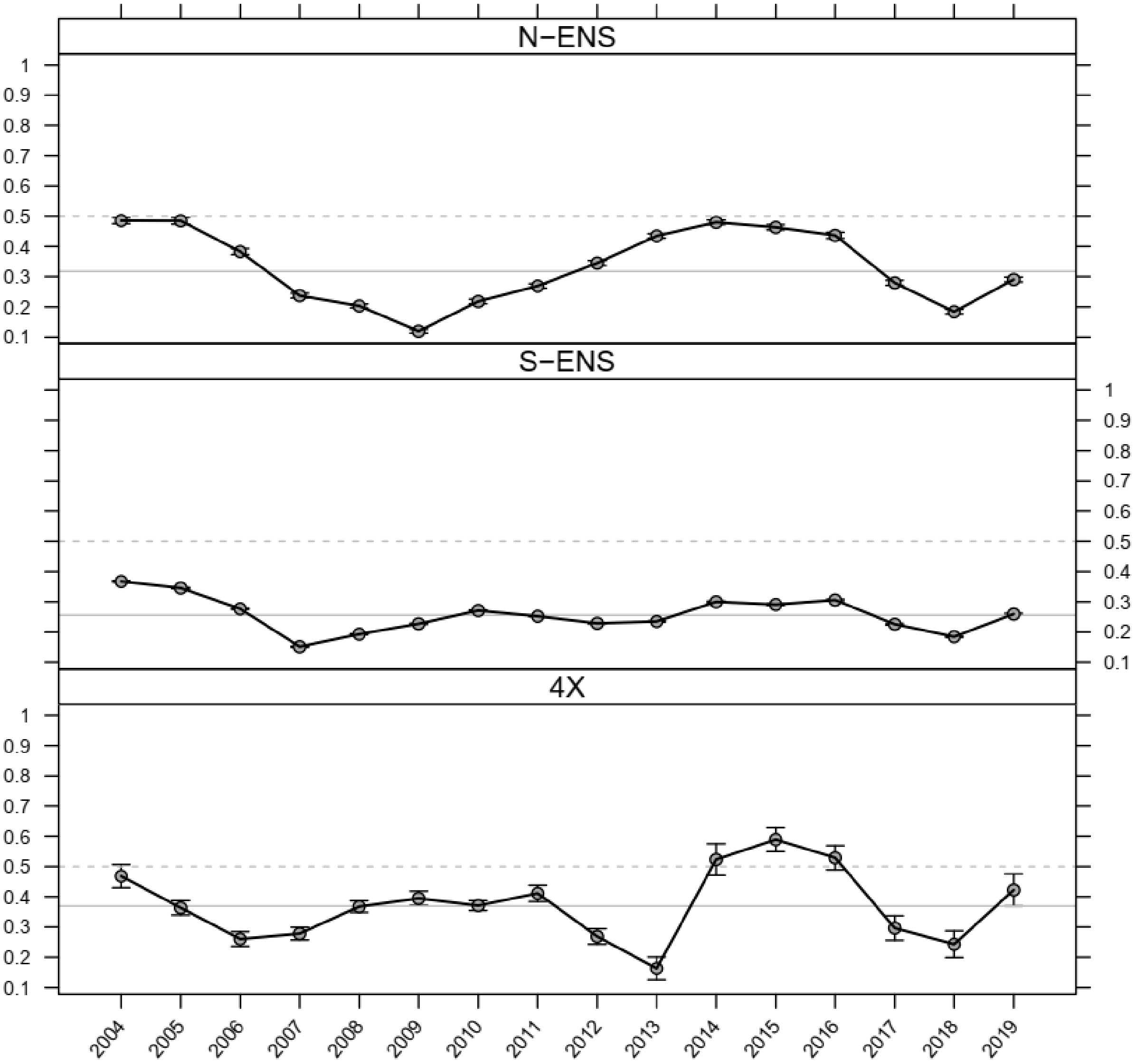


Figure 56. Annual sex ratios (proportion female) of immature Snow Crab on the Scotian Shelf. Dashed line represents a 1:1 (0.5 proportion) female: male ratio. Solid line indicates long-term mean within each area.

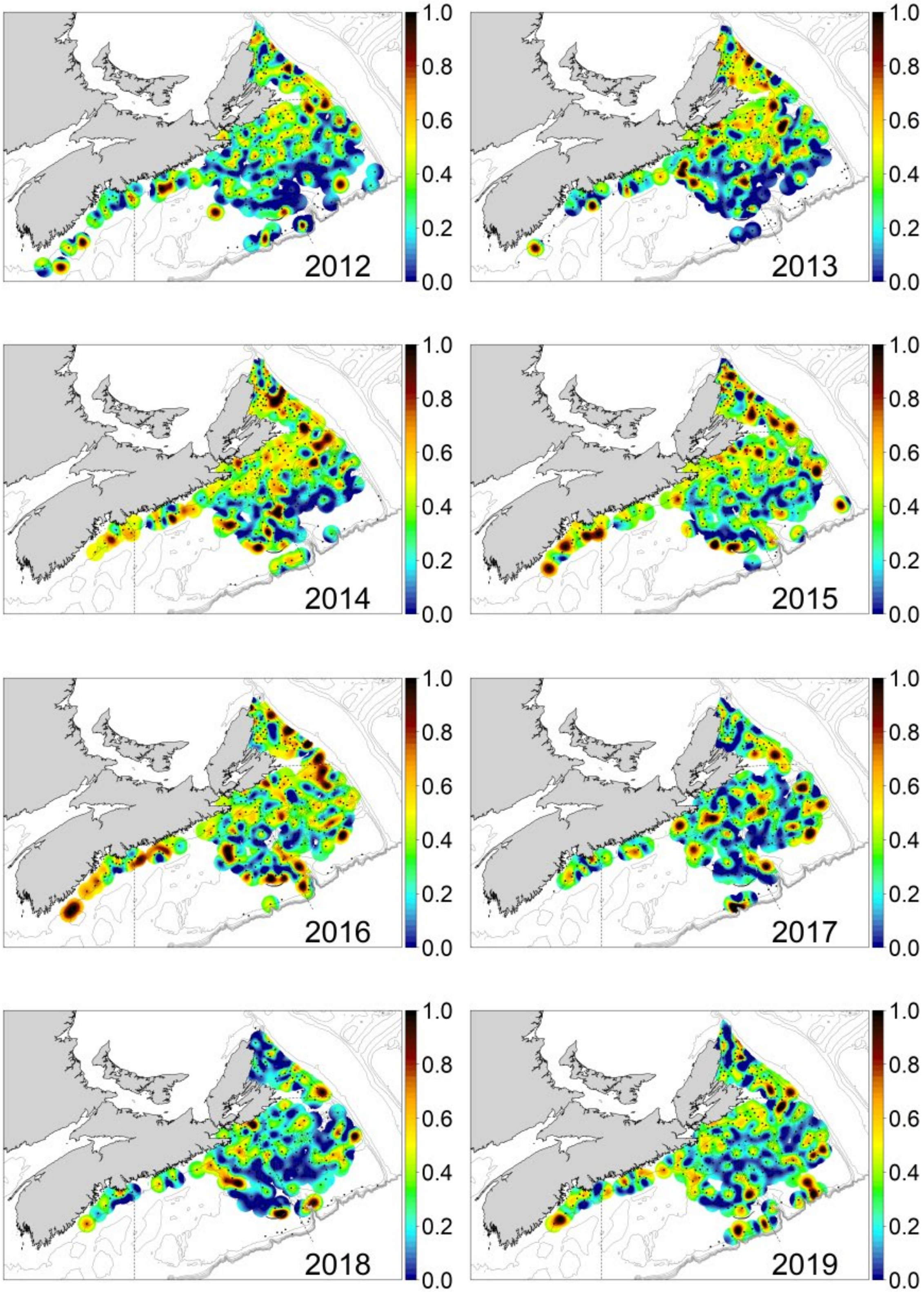


Figure 57. Morphometrically immature sex ratios (proportion of females in the immature fraction of the total numbers) of Snow Crab on the Scotian Shelf with spatial representations generated using thin plate spline interpolations of data from the annual Snow Crab survey.

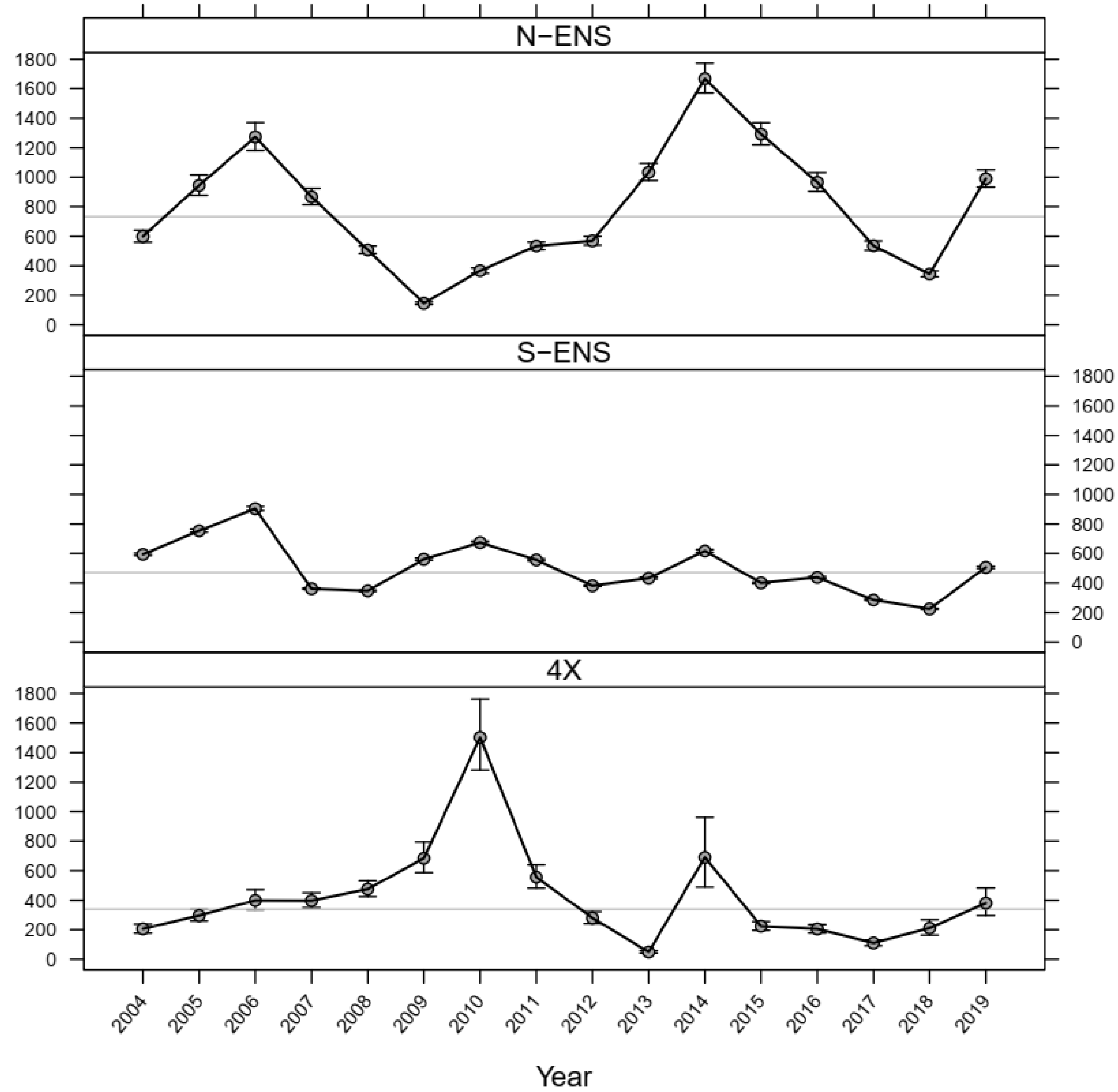


Figure 58. Geometric mean numeric density of immature female Snow Crab (number/km^2) on the Scotian Shelf. Solid grey line indicates long-term mean.

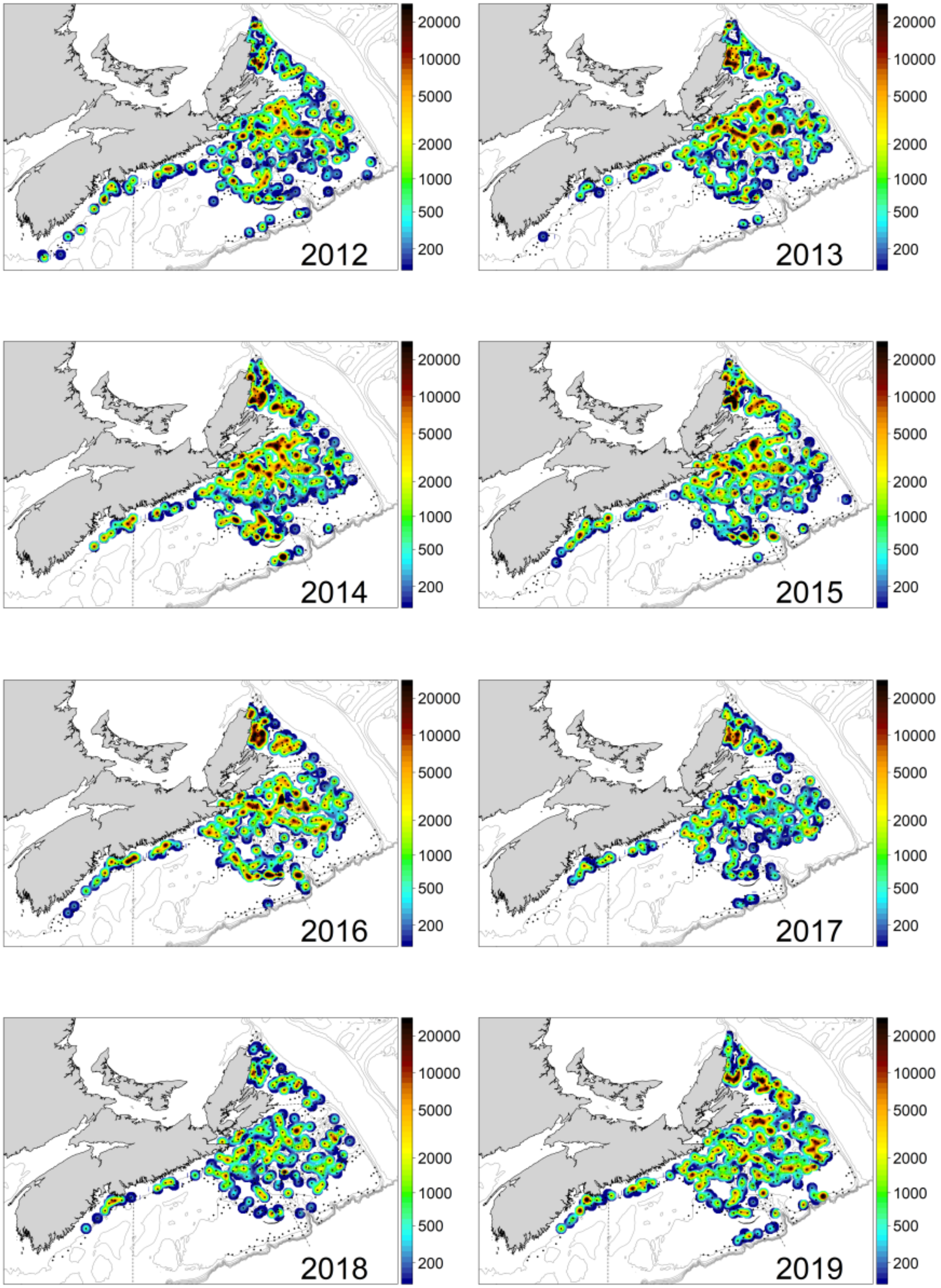


Figure 59. Numerical densities (number/km^2) of the immature female Snow Crab on the Scotian Shelf with spatial representation generated using thin plate spline interpolations of data from the annual Snow Crab survey.

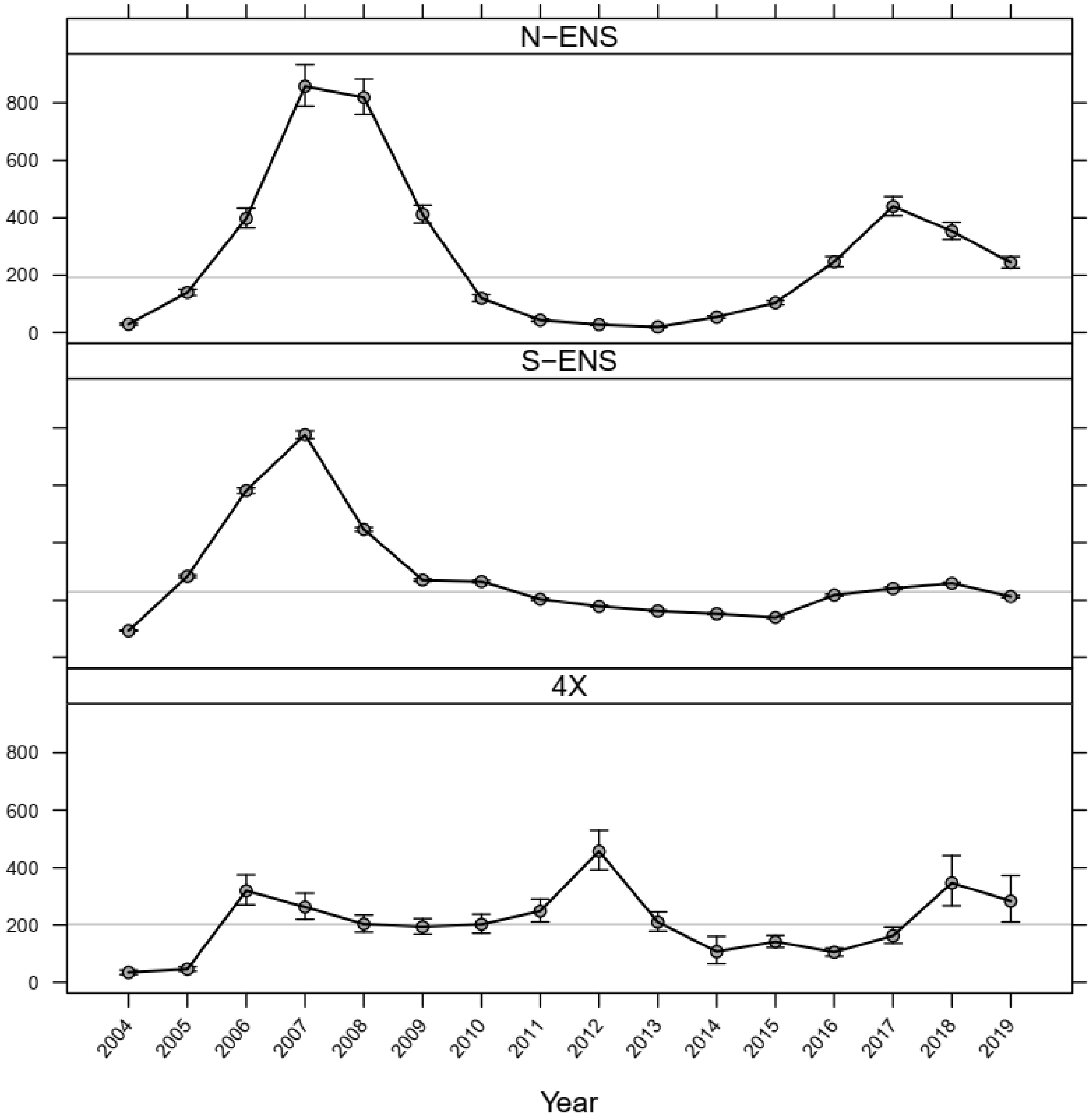


Figure 60. Geometric Mean numeric density of mature female Snow Crab (number/km^2) on the Scotian Shelf. Solid grey line indicates long-term mean.

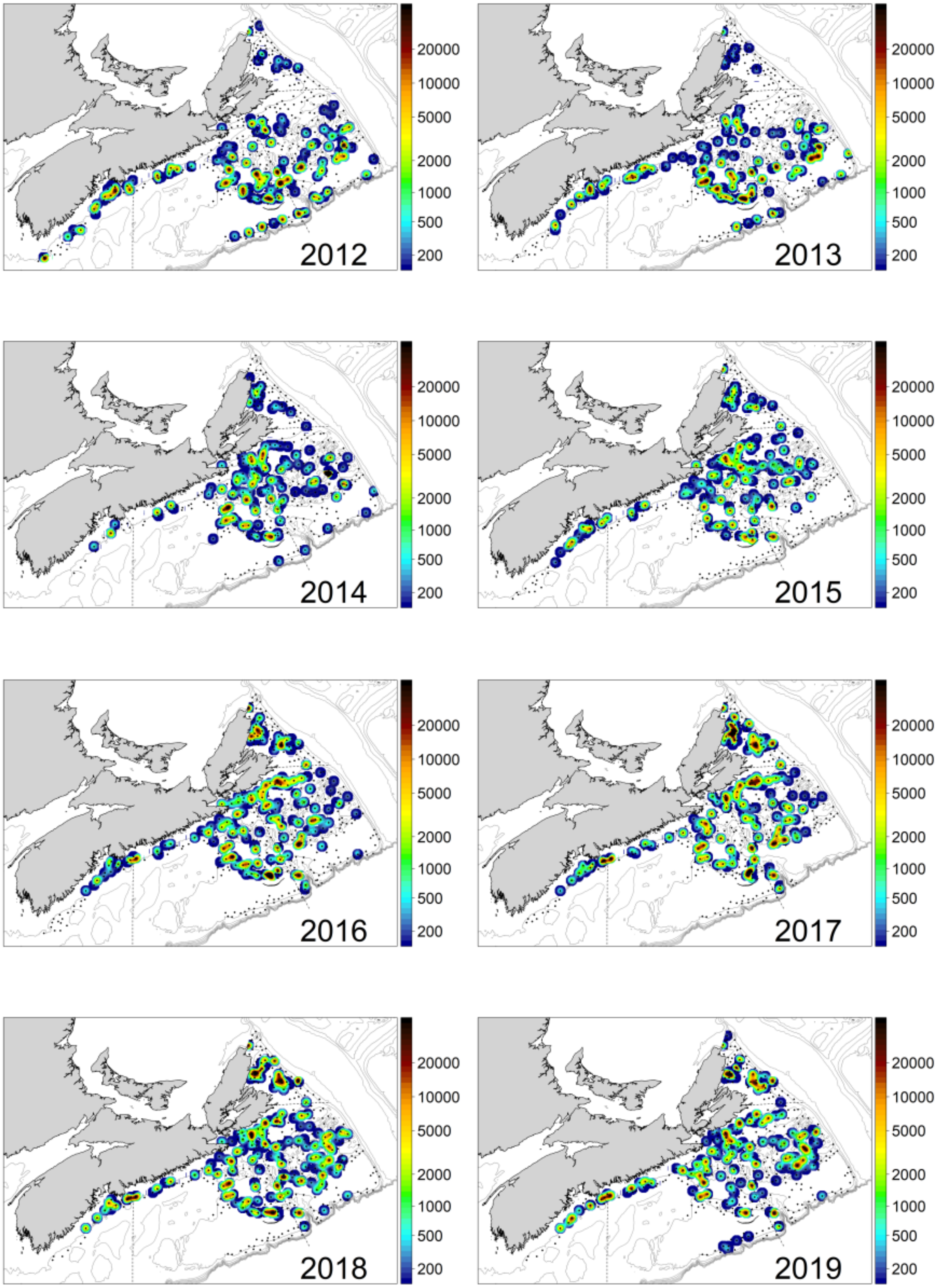


Figure 61. Numerical densities (number/km^2) of the mature female Snow Crab on the Scotian Shelf. Spatial representation generated using thin plate spline interpolations of data from the annual Snow Crab survey.

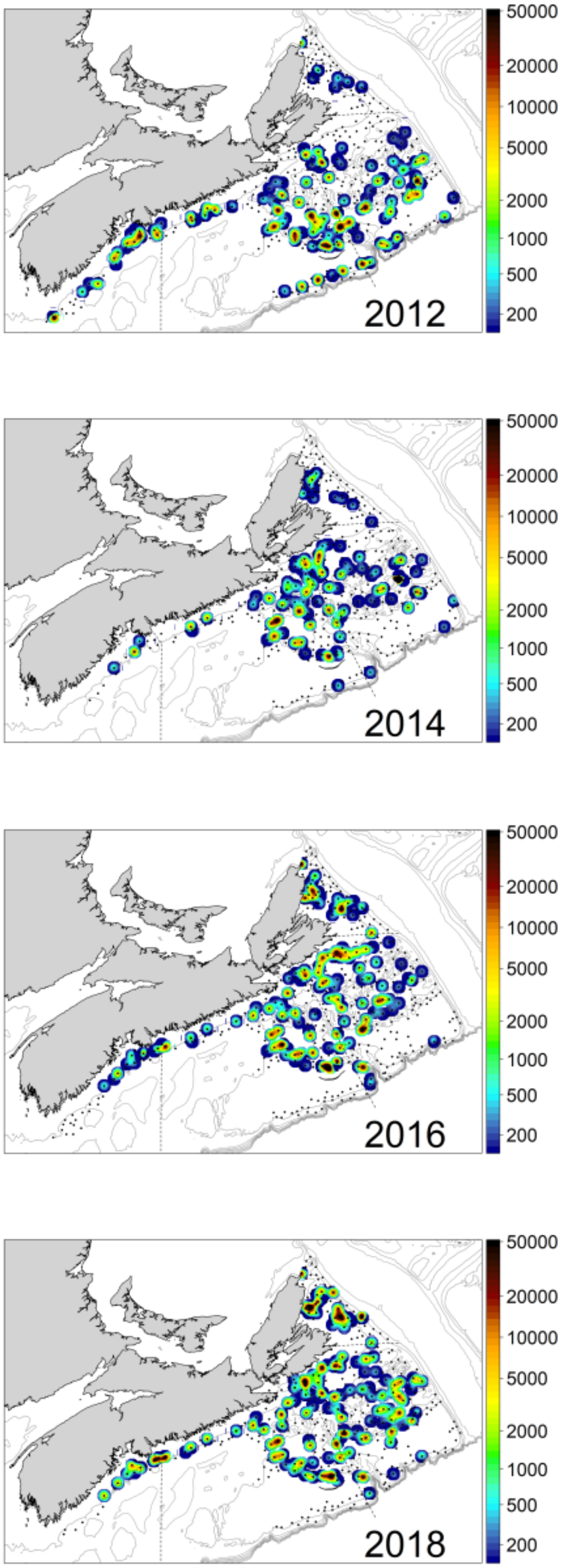


Figure 62. Numerical densities (number/km^2) of the ovigerous female Snow Crab on the Scotian Shelf with spatial representation generated using thin plate spline interpolations of data from the annual Snow Crab survey.

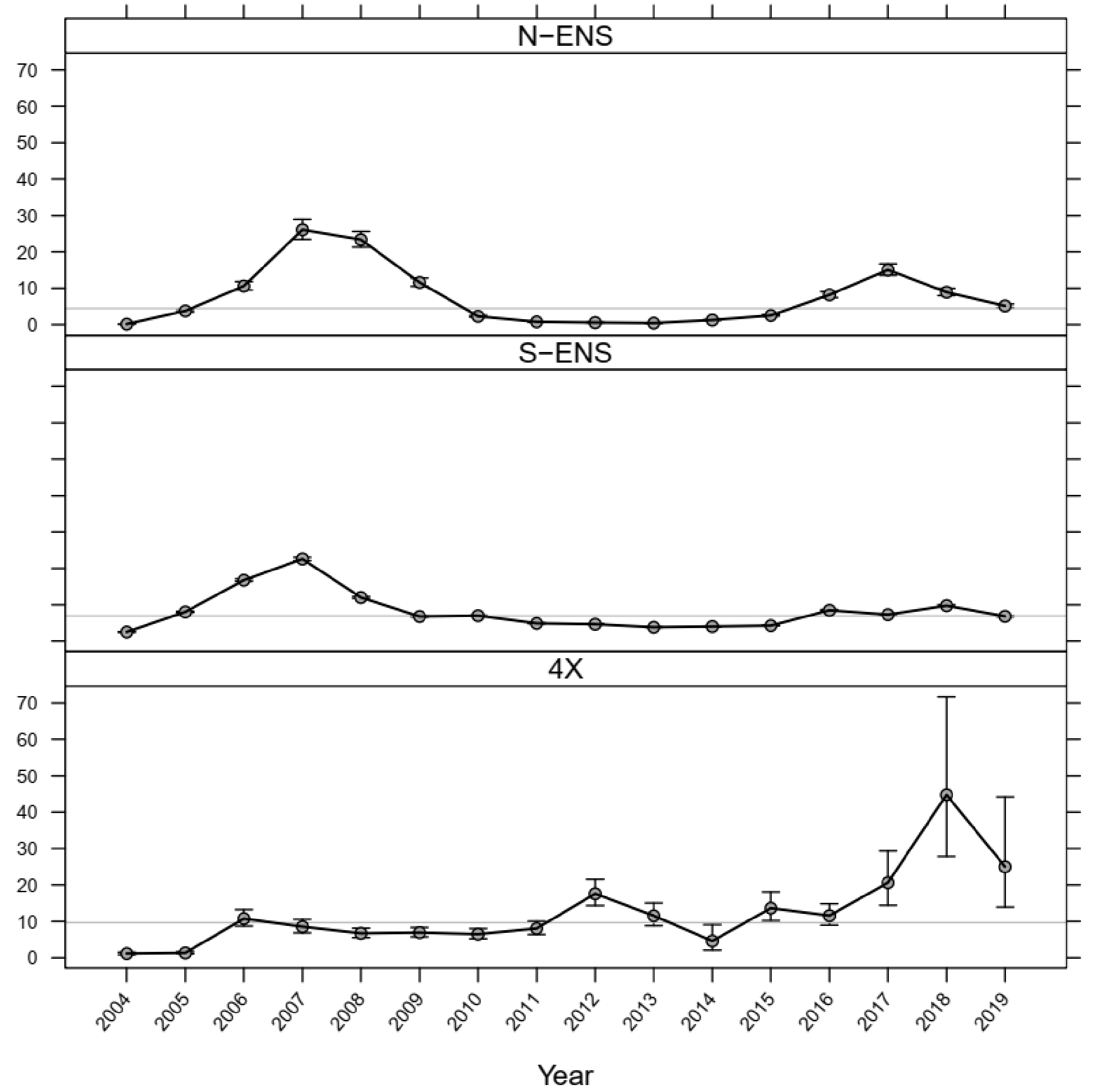


Figure 63. Geometric mean index of egg production on the Scotian Shelf determined from the number of berried female Snow Crab and fecundity-at-weight estimates. Error bars are 95% CI. Solid grey line indicates long-term mean.

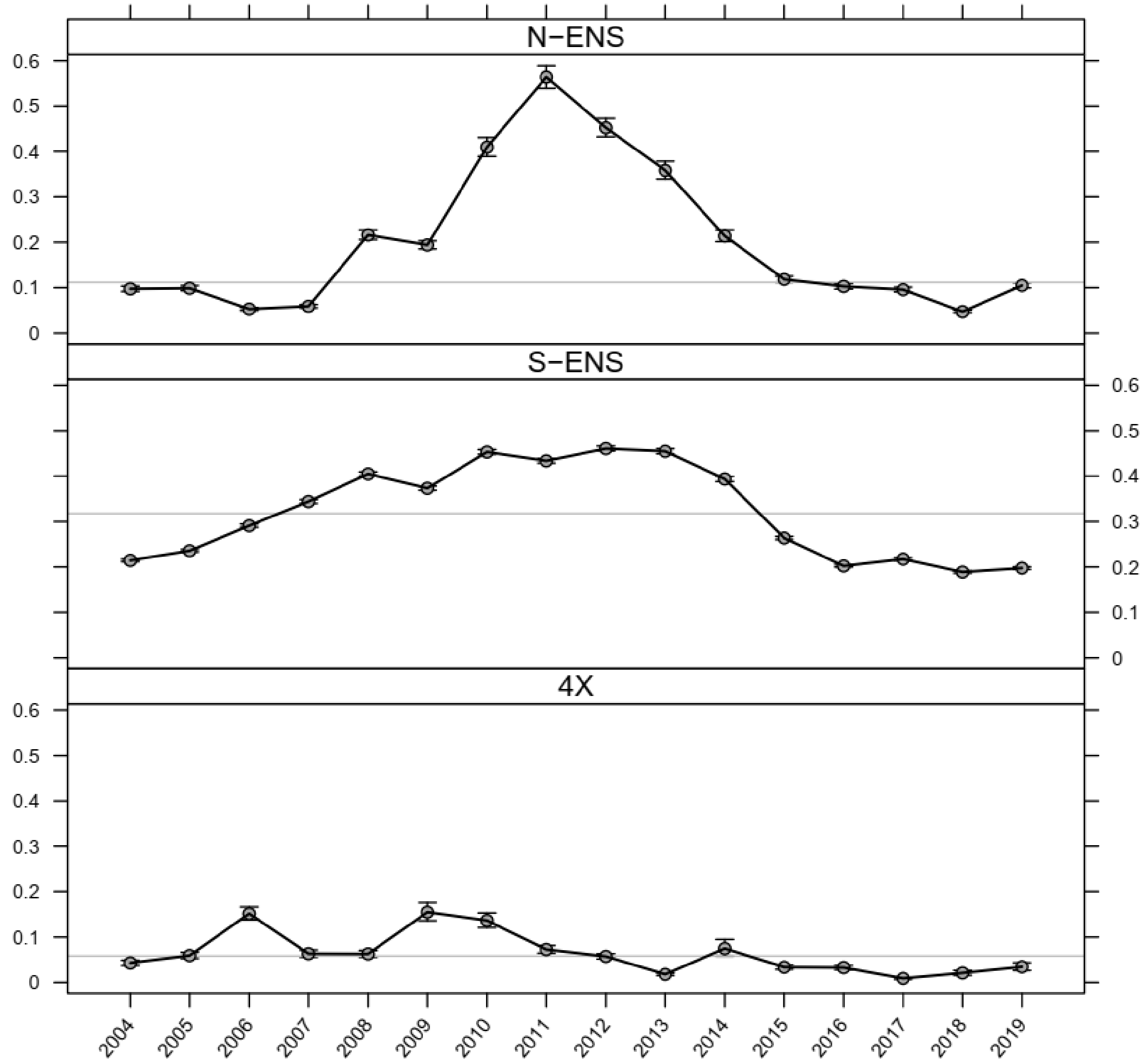


Figure 64. Trends in the geometric mean of fishable biomass (t/km^2) obtained from the annual Snow Crab survey. Error bars are 95% CI about geometric mean. Solid grey line indicates long-term mean.

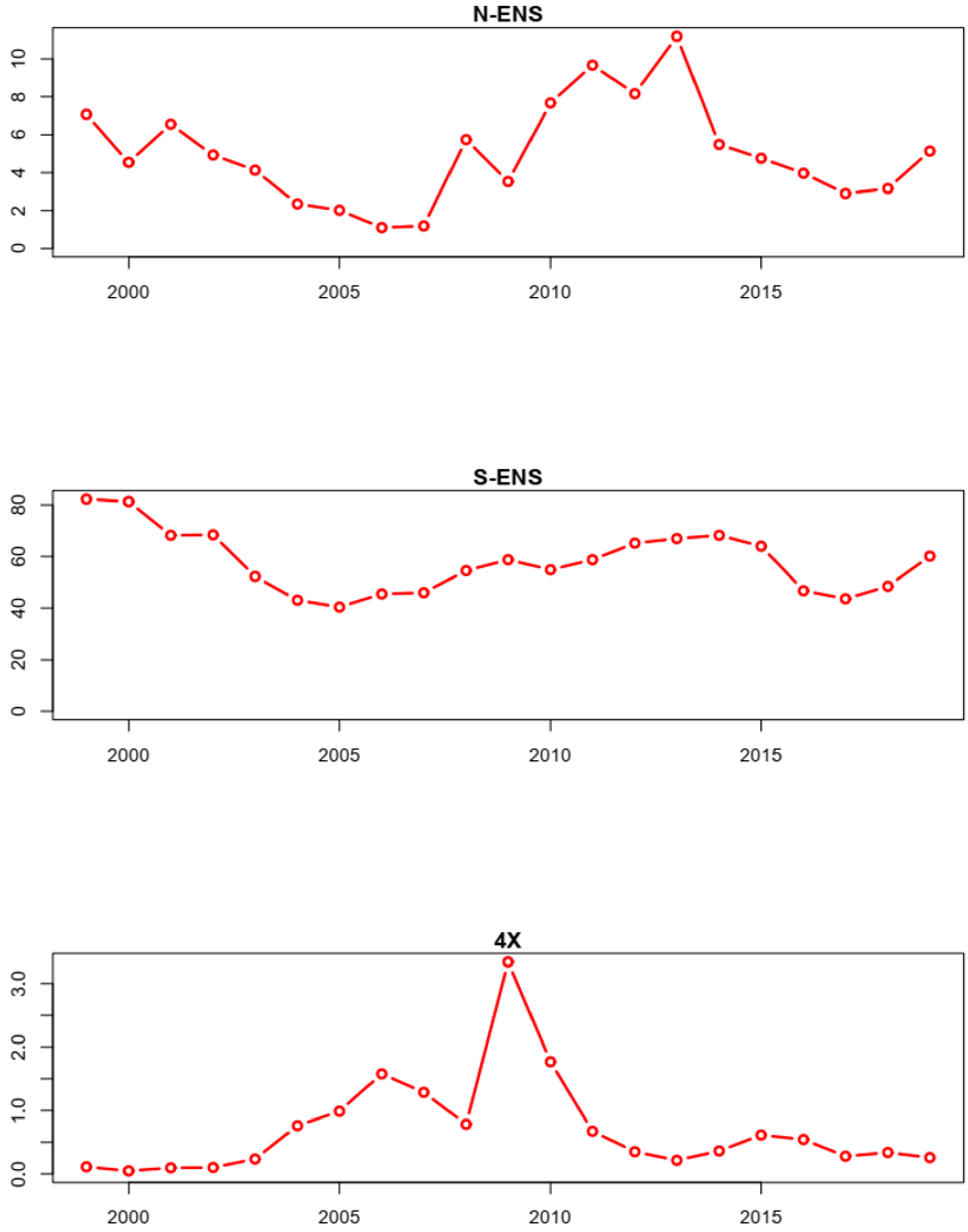


Figure 65. Area expanded total abundance estimate (t x 103) by area as predicted by carstm.

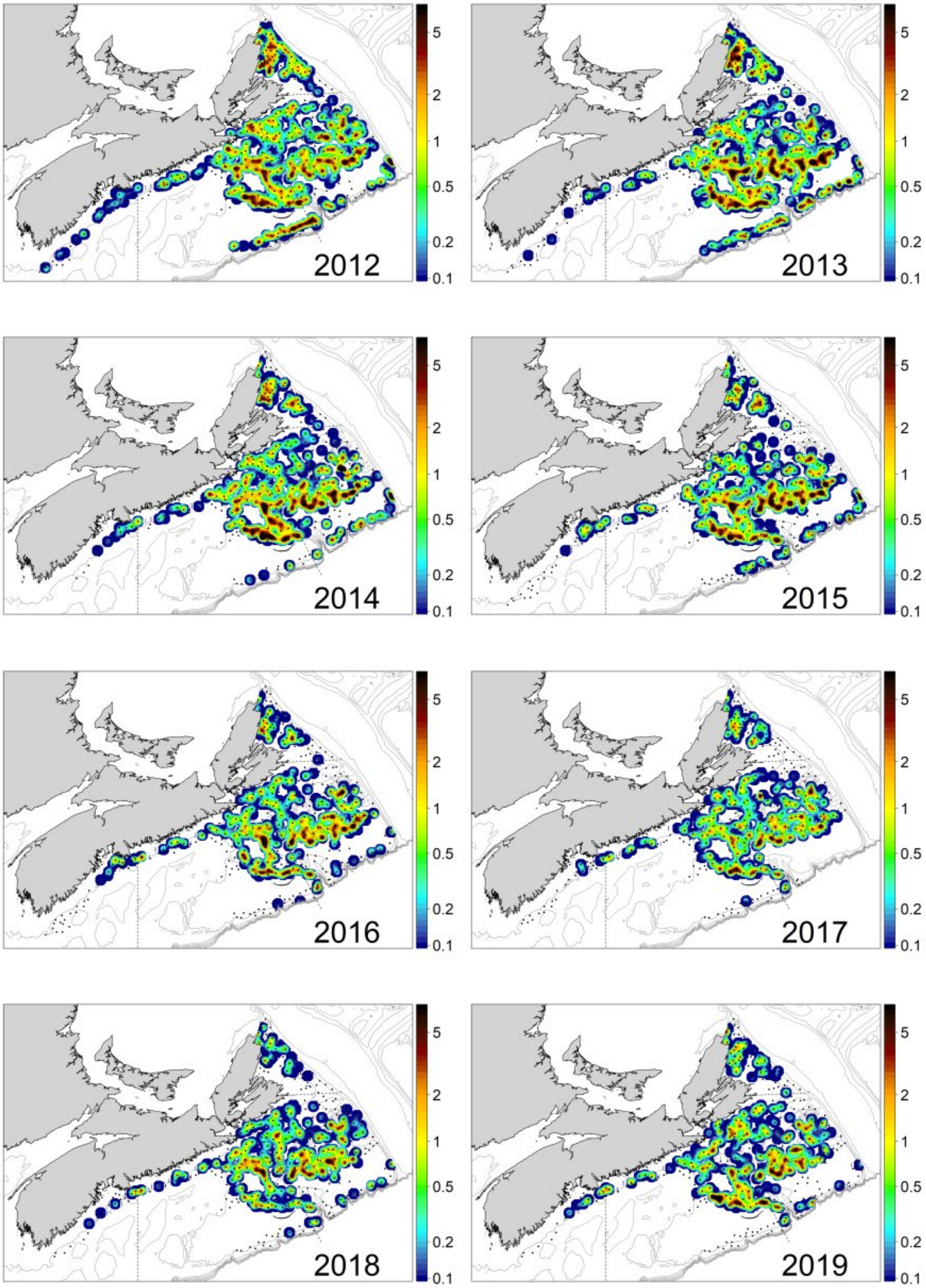


Figure 66. Fishable biomass densities (t/km^2) of Snow Crab on the Scotian Shelf with spatial representation generated using thin plate spline interpolations of data from the annual Snow Crab survey.

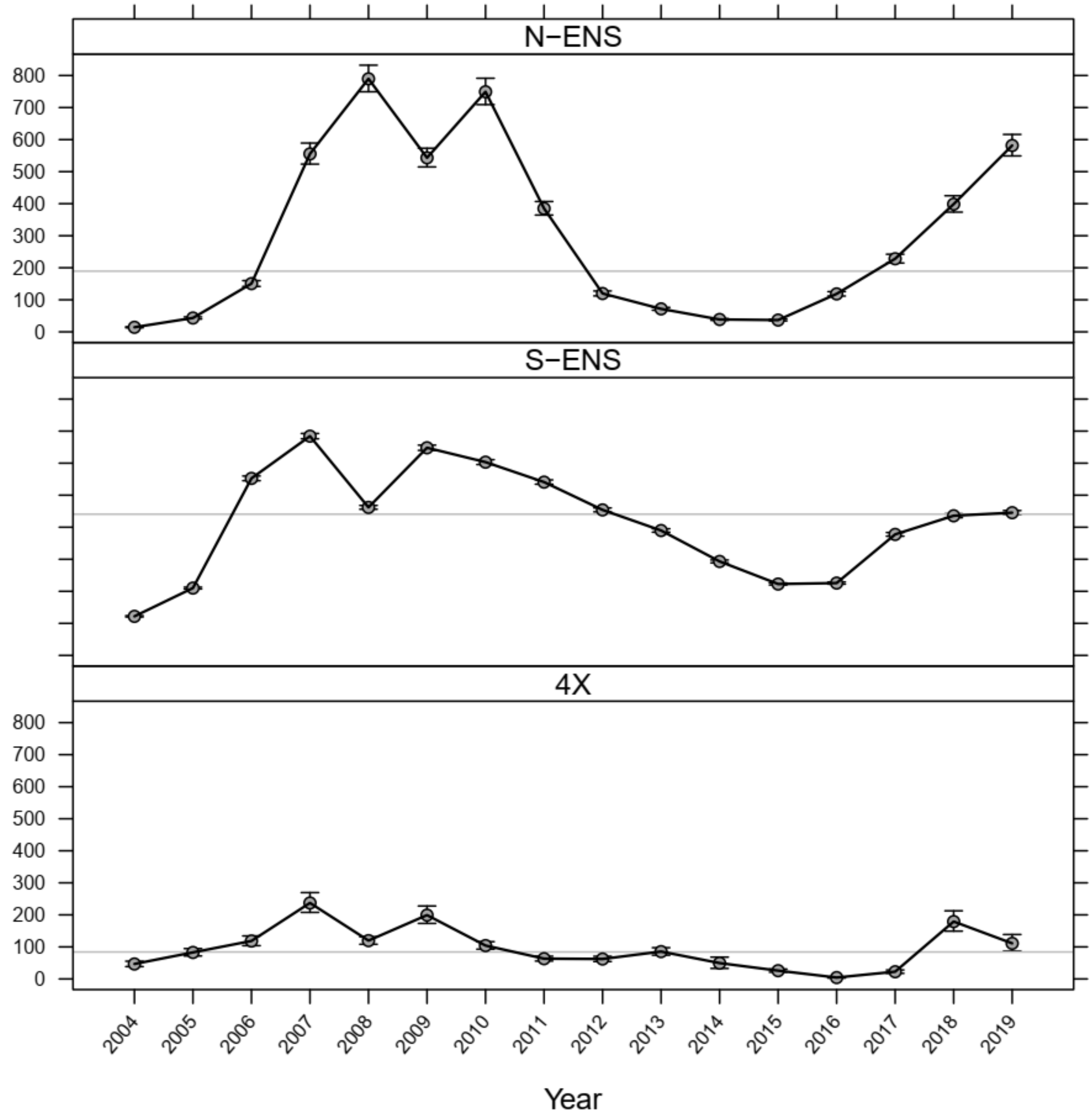


Figure 67. Trends in the geometric mean abundance (t/km^2) of male Snow Crab (75–95 mm CW) obtained from the annual Snow Crab survey. Error bars are 95% CI about geometric mean. Solid grey line indicates long-term mean.

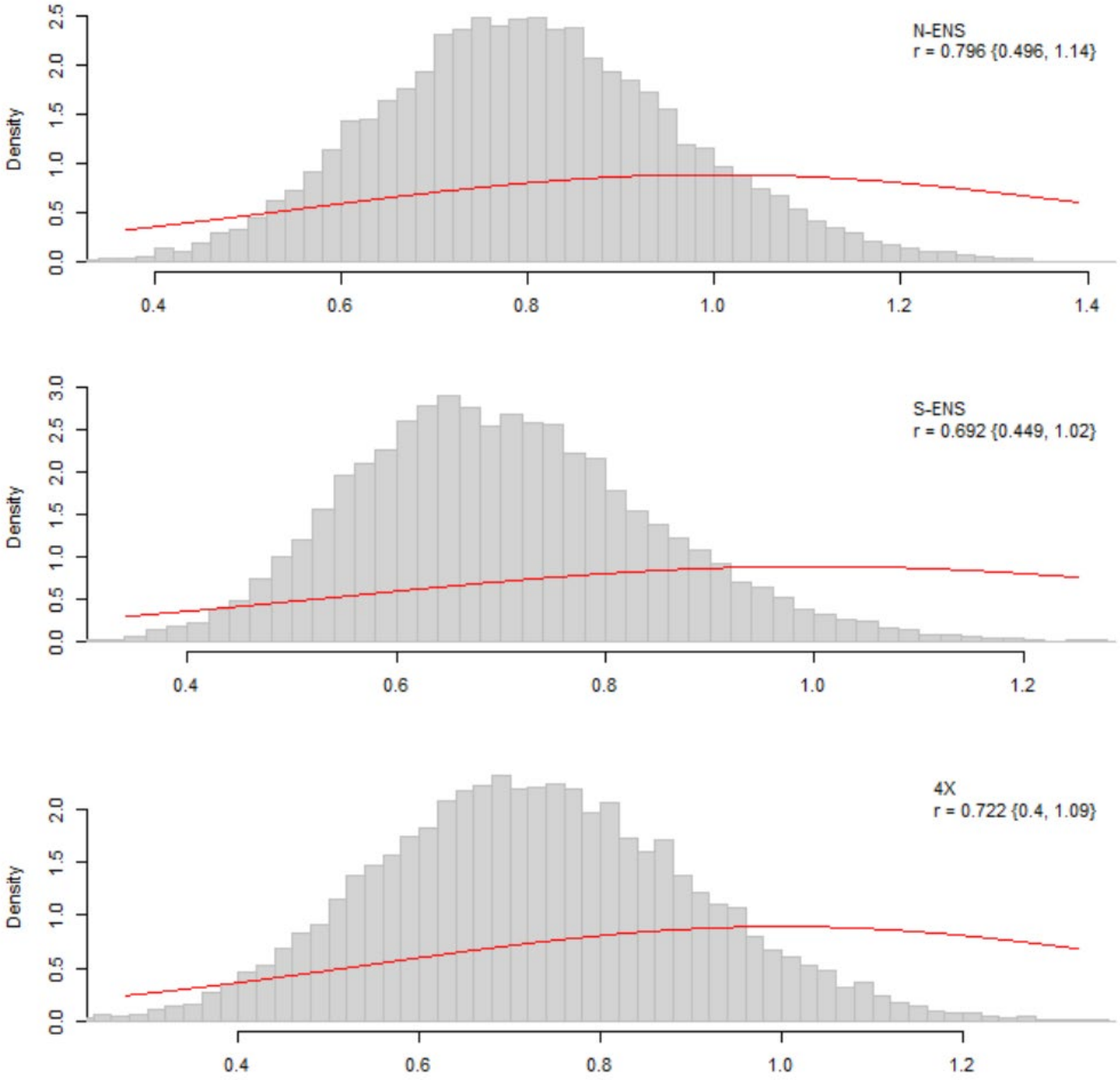


Figure 68. Prior (red) and posterior (bars) distribution for population growth parameter, r, from the biomass dynamic model of Snow Crab production in crab fishing areas on the Scotian Shelf. Within each panel, estimates of posterior median and 95% credible intervals are given in the legend.

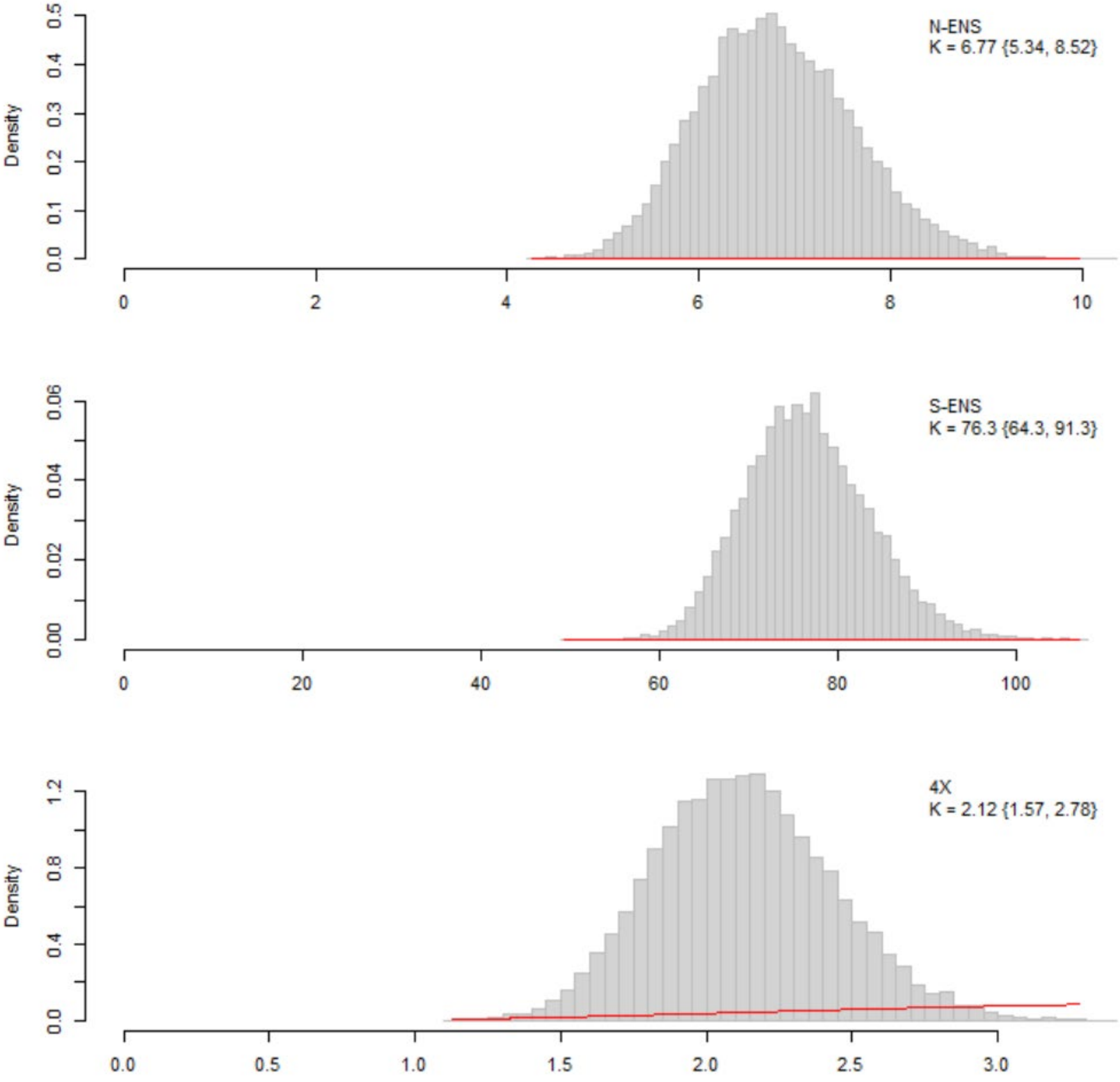


Figure 69. Prior (red) and posterior (bars) distribution for carrying capacity parameter, K, from the biomass dynamic model of Snow Crab production in crab fishing areas on the Scotian Shelf. Within each panel, estimates of posterior median and 95% credible intervals are given in the legend.

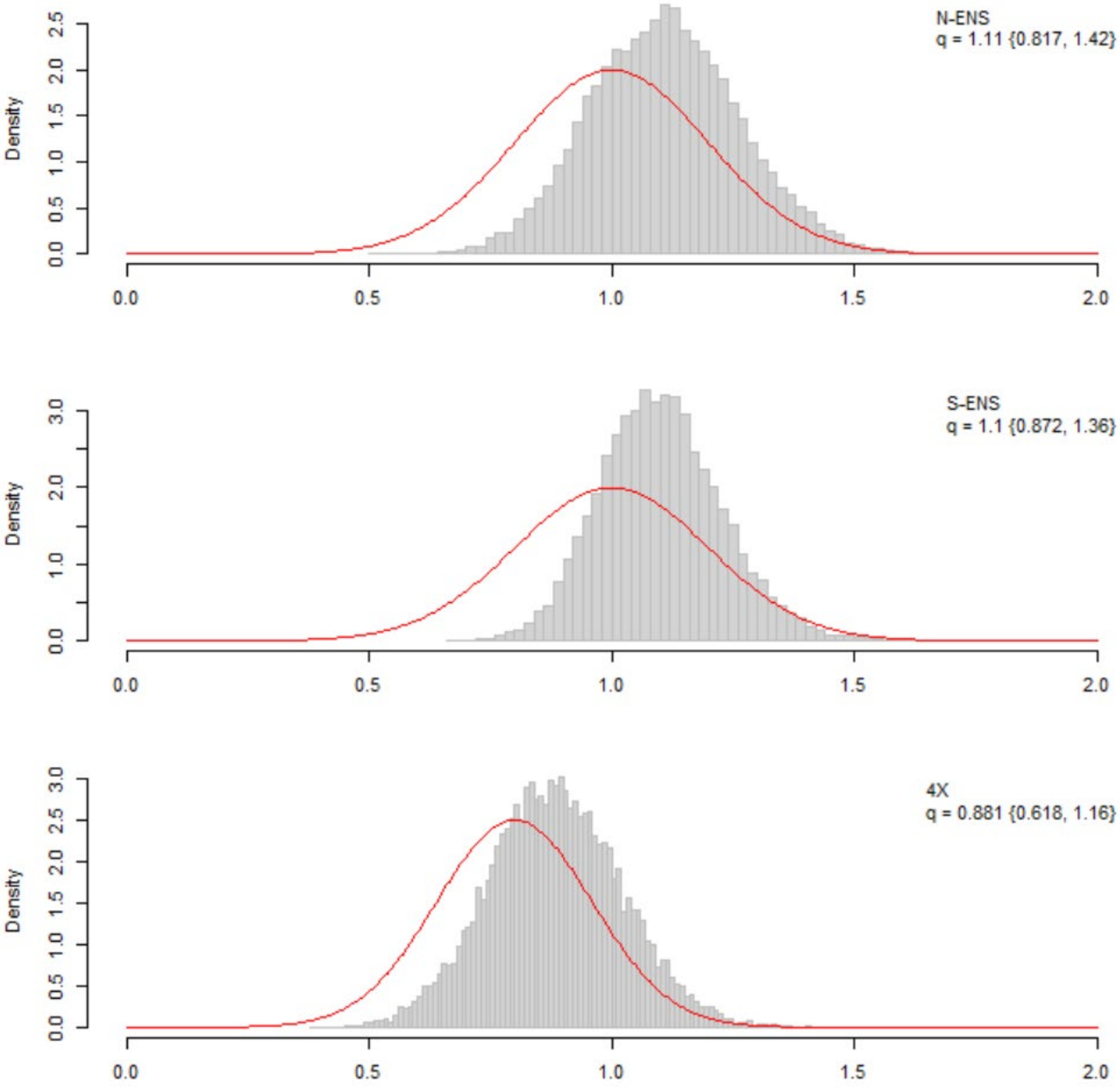


Figure 70. Prior (red) and posterior (bars) distribution for catchability parameter, q, from the biomass dynamic model of Snow Crab production in crab fishing areas on the Scotian Shelf. Within each panel, estimates of posterior median and 95% credible intervals are given in the legend.

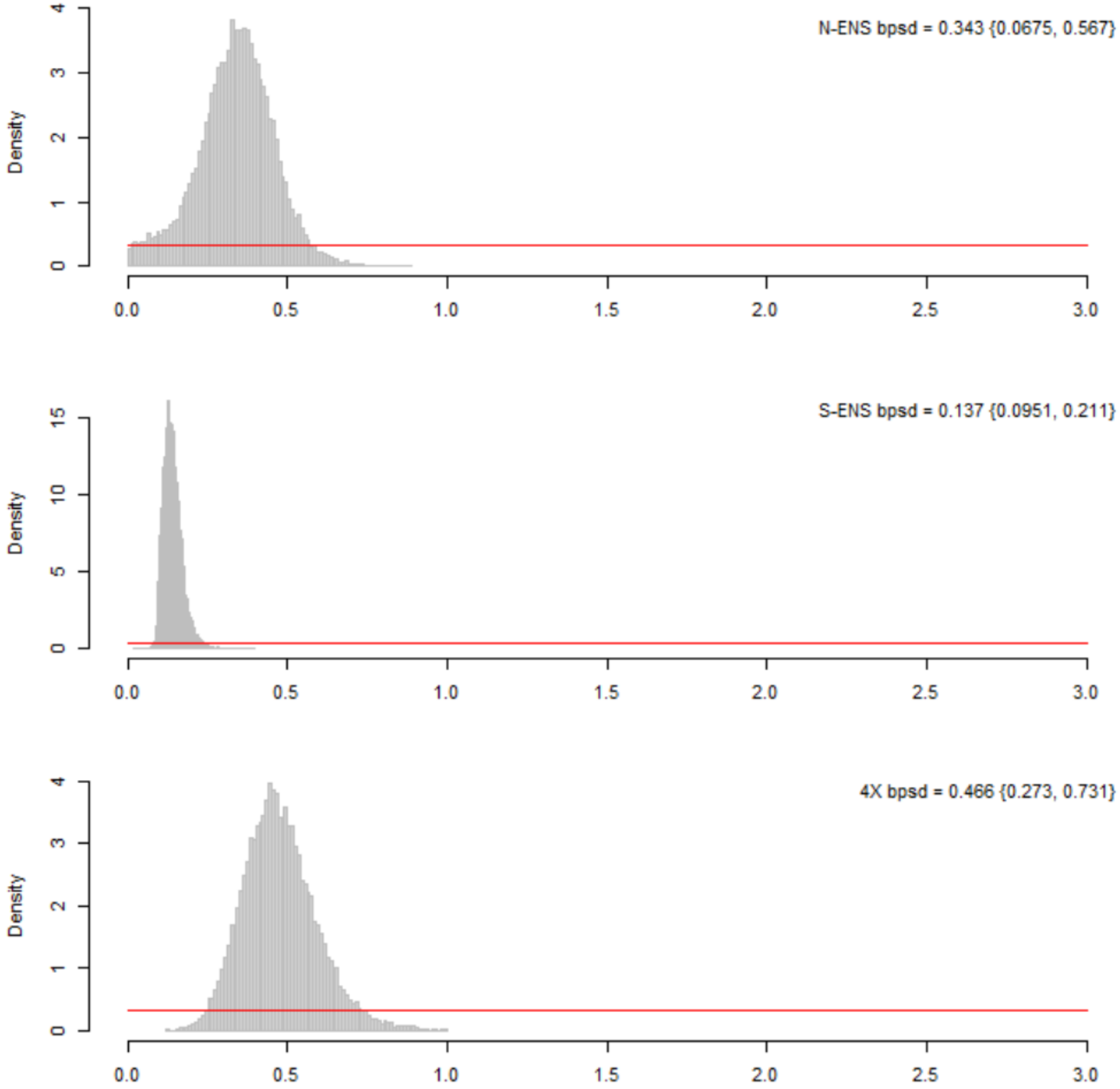


Figure 71. Prior (red) and posterior (bars) distribution for process error from the biomass dynamic model of Snow Crab production in crab fishing areas on the Scotian Shelf. Within each panel, estimates of posterior median and 95% credible intervals are given in the legend.

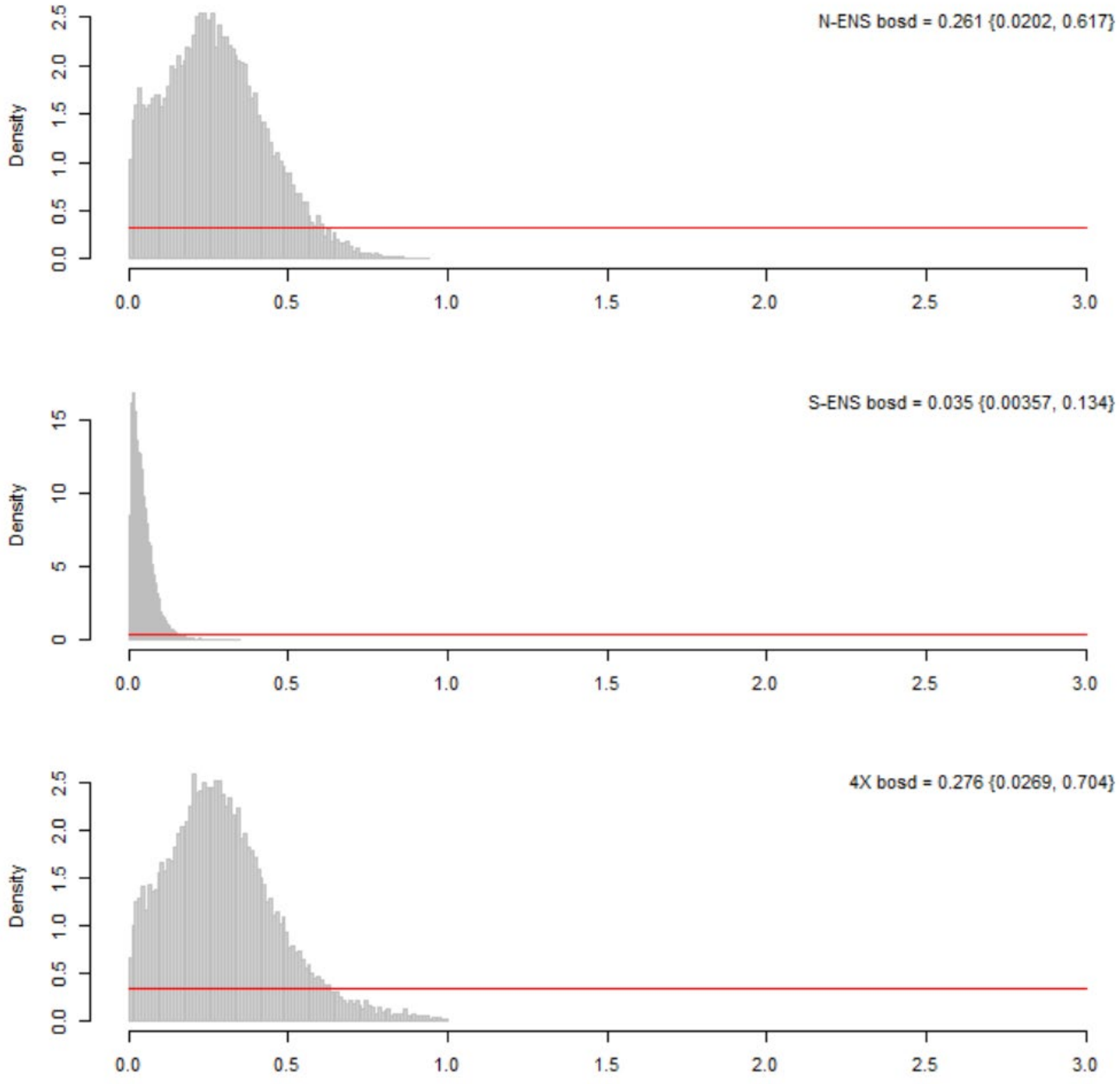


Figure 72. Prior (red) and posterior (bars) distribution for observation error from the biomass dynamic model of Snow Crab production in crab fishing areas on the Scotian Shelf. Within each panel, estimates of posterior median and 95% credible intervals are given in the legend.

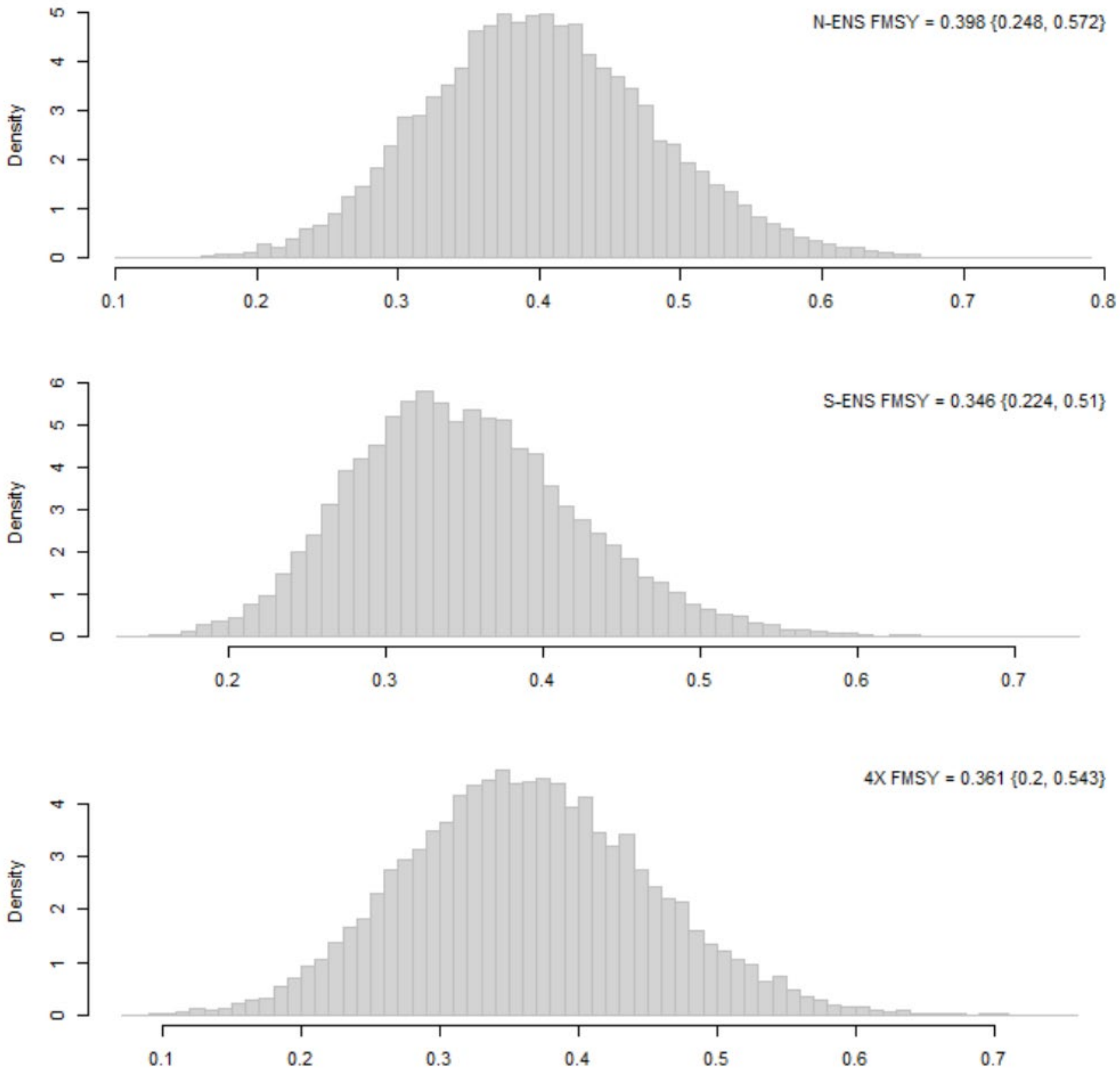


Figure 73. Posterior distribution for fishing mortality at maximum sustainable yield from the biomass dynamic model of Snow Crab production in crab fishing areas on the Scotian Shelf. Within each panel, estimates of posterior median and 95% credible intervals are given in the legend.

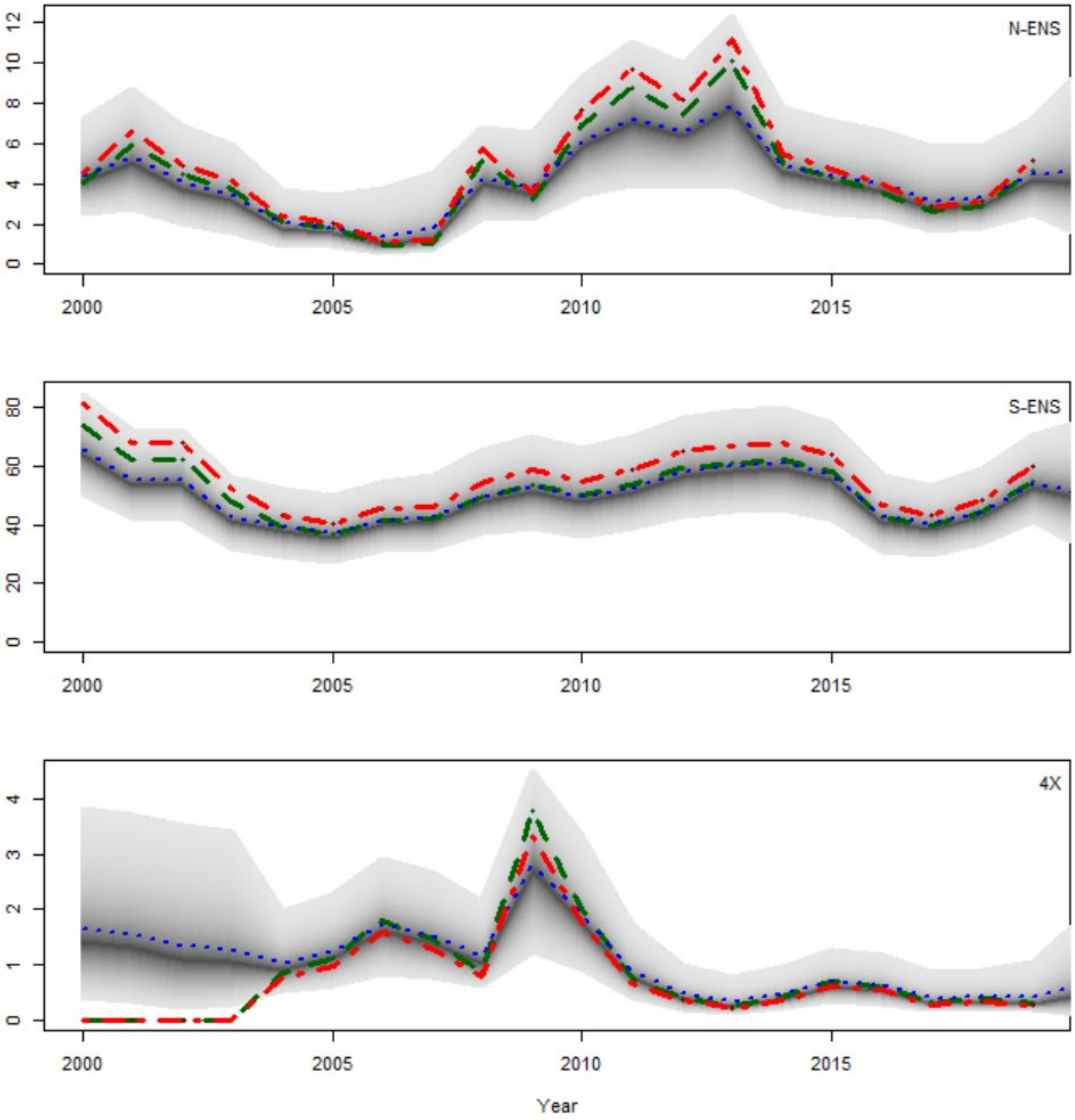


Figure 74. Time series of fishable biomass from the logistic population models. The fishable biomass index is shown in red dashed lines. The q-corrected fishable biomass index is shown in green dashed lines. The posterior mean fishable biomass estimated from the logistic model are shown in blue stippled lines. The density distribution of posterior fishable biomass estimates are presented with 95% CI (gray) with the darkest area being medians.

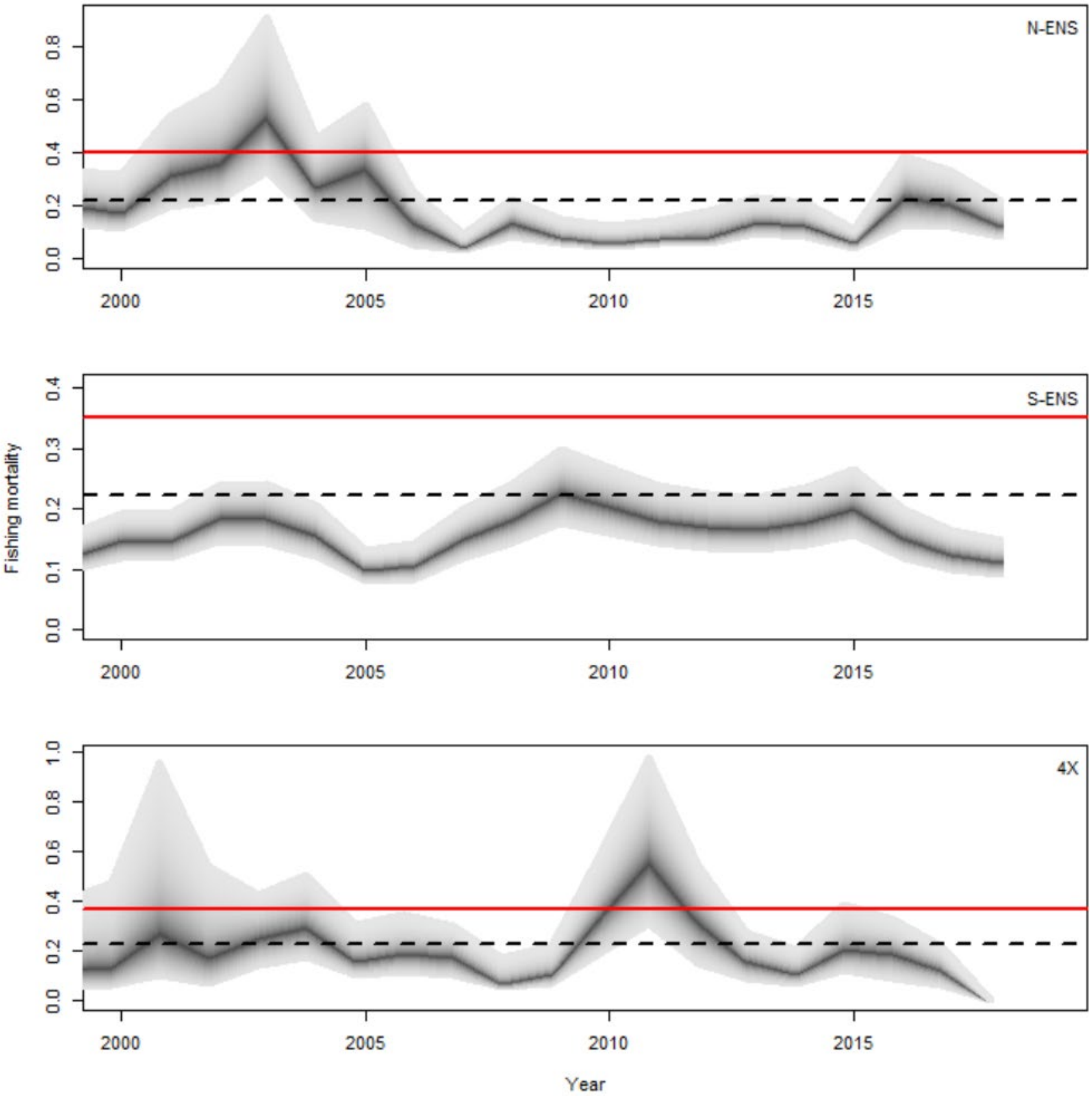


Figure 75. Time series of fishing mortality from the logistic population models for North-Eastern Nova Scotia (N-ENS), South-Eastern Nova Scotia (S-ENS), and 4X, respectively. Posterior density distributions are presented in gray, with the darkest line being the median with 95% CI. The red line is the estimated F_{MSY} and dark stippled line is the 20% harvest rate (F = 0.22).

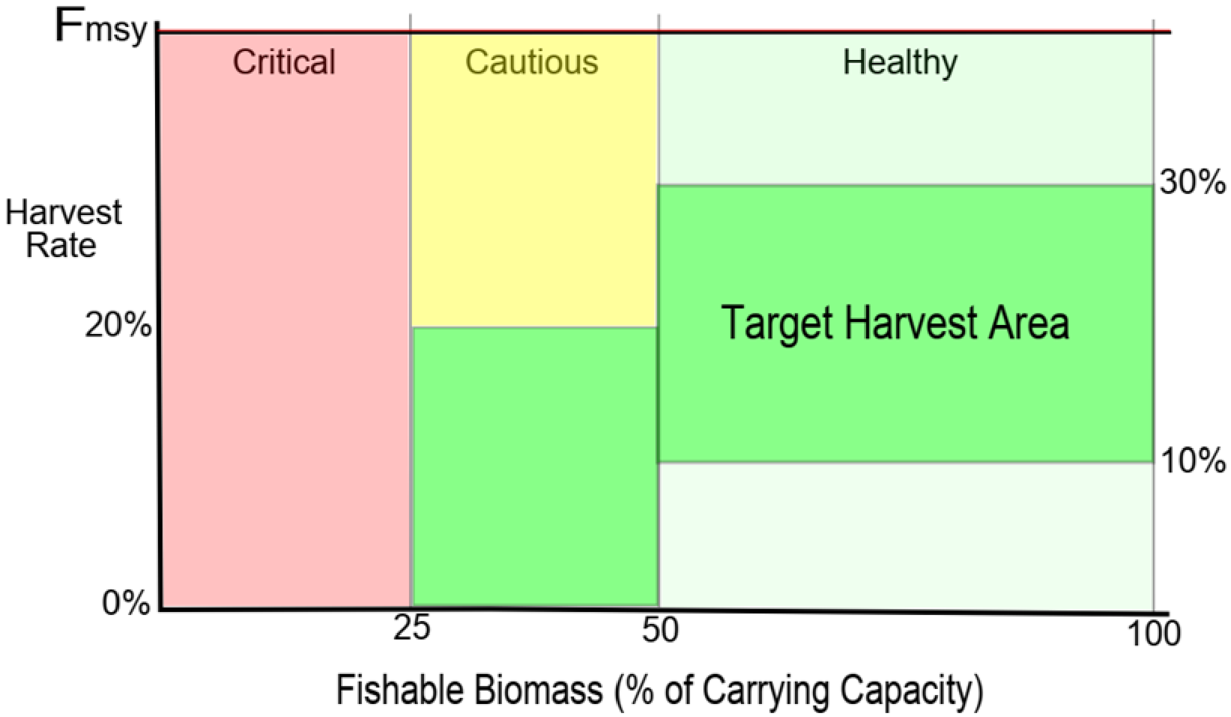


Figure 76. Harvest Control Rules for the SSE Snow Crab fishery.

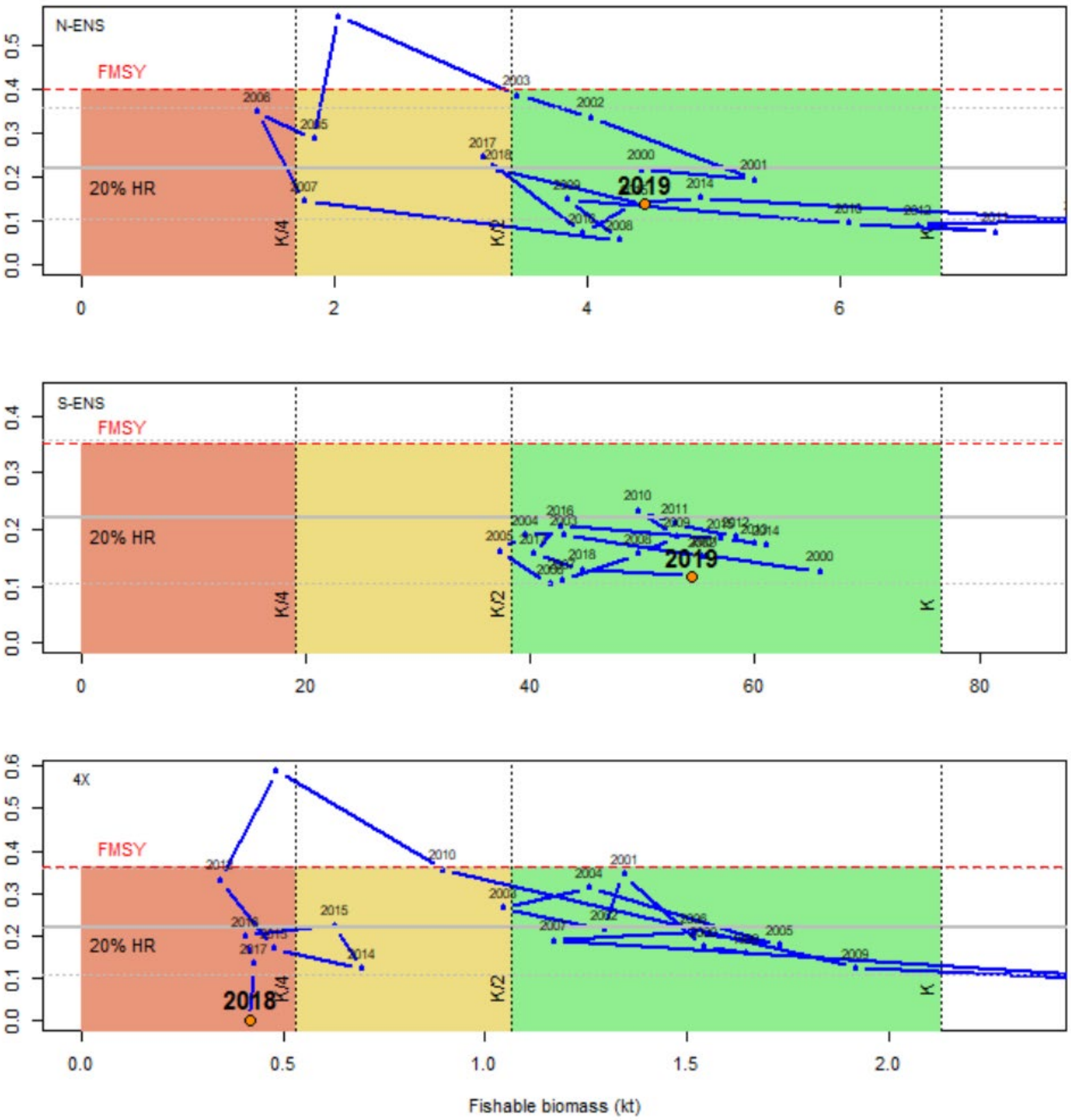


Figure 77. Time series of fishing mortality and pre-fishery biomass for N-ENS (top), S-ENS (middle), and 4X (bottom) as obtained from the logistic population models. Relative position of biomass within the stock status ranges is highly constrained due to current survey-abundance estimation techniques. Actual variability is likely higher based on raw indices of abundance such as density of survey catches.

APPENDICES

APPENDIX 1: CONTEXT OF THE PRECAUTIONARY APPROACH

In the context of natural resource management, the Precautionary Approach (PA) identifies the importance of care in decision making by taking into account uncertainties and avoiding risky decisions. This is because natural ecosystems are intrinsically complex and unexpected things can and often do happen (e.g., Choi and Patten 2001). The origin of the PA is diffuse but has its first precursor in Rachel Carson's 1962 book, Silent Spring, which caused widespread concern about the use of synthetic pesticides and eventually resulted in the abolition of DDT in many parts of the affluent world. The Stockholm Declaration of the United Nations Conference on the Human Environment (UNCHE 1972) was the first international environmental law recognizing the right to a healthy environment. This was taken a little further by the World Commission on Environment and Development (WCED 1987, or the Brundtland Commission's Report "Our Common Future"), which highlighted the need for sustainable development. Subsequently, another conference was undertaken in Rio de Janeiro, Brazil (1992), which attempted to establish international agreements to protect the integrity of the environment while recognizing state sovereignty and, therefore, state responsibility for providing equitable resources for both present and future generations. Sustainable development, public participation in the decision making process (especially youth, indigenous people and women), environmental impact assessments and management in particular of environmental pollution and degradation, especially when harmful to human health, were key points of agreement.

Many other international agreements were undertaken that re-affirmed these positions: the UN Convention on the Law of the Sea (UNCLOS 1982) that recognized territorial jurisdiction with a pollution focus in the Exclusive Economic Zone; the FAO (1995) Code of Conduct for Responsible Fisheries emphasizing conservation and the PA, promoting selective fishing gear and responsible fishing methods; the UN Fishing Agreement (UNFA 2001) dealing with straddling and highly migratory fish stocks; the UN Convention on Biological Diversity which identified Ecosystem-Based Management as a global responsibility; the World Summit on Sustainable Development (WSSD 2002) in Johannesburg reaffirmed the common agreement to "maintain or restore stocks to levels that can produce the maximum sustainable yield with the aim of achieving these goals for depleted stocks on an urgent basis and where possible not later than 2015".

Canada, as a signatory to these international agreements, has a legally binding obligation to manage natural resources using a PA. Ultimately, a PA means to not risk the long-term sustainability of the resource in focus and the ecosystem in which it is embedded. Fortunately, fostering the long-term sustainability of a natural resource in a fishery context also has the direct consequence of fostering the highest possible catch rates (CPUE) and associated socio-economic benefits of an efficient and vigorous fishery. Fostering the long-term biological and ecological sustainability can, therefore, foster the long-term socio-economic sustainability of the dependent industry.

Sustainability

Implementing a PA to resource management requires the careful consideration of all sources of information relating to the sustainability of both the resource in focus and the ecosystem in which it is embedded: scientific and traditional information and associated uncertainties. A further requirement is a transparent mechanism for synthesizing this information and measuring the sustainability of the resource. The latter is required in order to provide feedback upon the success or lack thereof of specific management actions. To address this requirement, DFO (2006) suggested the use of spawning stock biomass (SSB) as a measure of "sustainability".

High levels of SSB were to be considered "healthy" and low levels "unhealthy". Similarly, in the Snow Crab fishery, the focus is naturally upon the exploitable component: the "fishable biomass". If the relative abundance of fishable biomass is high, most fishers, fisheries managers and fisheries scientists would consider it to be in a more "sustainable" state, and vice versa.

Unfortunately, this perspective is problematic. High abundance can cause a destabilization and collapse of a population through over-crowding, habitat degradation, disease and other density-dependent mechanisms. Well known examples include deer on islands that eventually overpopulate and eat themselves to extinction; humans on Easter Island that have over-harvested trees leading to population, societal and ecological collapses; or, the over-dominance of species (monocultures in farms and forests) that results in disease or fire outbreaks and eventually large-scale collapse (Diamond 2005). A high abundance does not necessarily equate to high sustainability. The problem lies with not the metric, but rather the focus upon a single indicator. Sustainability is a multidimensional concept that requires reliance upon a broader set of criteria that describes both the resource status and relationships between the focal resource and the surrounding ecosystem (Choi and Patten 2001).

For example, a sustainable Snow Crab population requires, *at a minimum*: stable and positive levels of egg production, recruitment and stable and comparable levels of natural mortality and ecosystem structure and function. "Natural mortality" and its converse, "recruitment" are of course catch-all terms that are actually quite complex, involving age and size structure, sex ratios, genetic diversity and numerous ecosystem-level interactions (e.g., habitat variability, resource availability, predation, contaminant loads, disease prevalence, nutrient regeneration and mixing, carbon flux, control of invasive species). Any rapid change in one or more of these potential determinants of sustainability can undermine the long-term sustainability of Snow Crab. As all of these factors are variable in time and space, the stock assessment of Snow Crab in the ESS is highly attentive of these potential determinants of population and ecosystem sustainability.

The primary tools of fishery management are the control of fishing catch and effort. Generally, by reducing catch and effort, stock status and/or ecosystem context is expected to improve. However, the lack of recovery of cod since the cod-moratorium in the early 1990s in Atlantic Canada, suggests that even this "universal" expectation of fisheries control is more a belief than reality. A more risk-averse management approach would, therefore, seem to be prudent. For the Snow Crab fishery, the need for additional precaution is further demanded by the fact that the Scotian Shelf is the southern-most limit of the spatial distribution of Snow Crab. If environmental fluctuations occur in oceanographic currents and bottom temperatures, this is the area that can be expected to be most significantly influenced by such changes.

Ultimately, a population that is "sustainable" is one that is able to maintain the tenuous balance between the various conflicting demands placed upon it by the ecosystem in which it resides, in addition to the humans that influence or exploit it. The maintenance of this balance operates on many space-time scales and, therefore, requires adaptability (long-term: evolutionary processes) and resilience (short-term: ecological and population dynamic processes). To increase the chances that fishing practices and management actions will result in a sustainable resource, the fisheries influence must simply be small enough that the ability of a population to maintain this balance (adaptability and resilience) is not overtly disturbed or damaged. This requires that the footprint of the fishery (i.e., magnitude of its influence upon this ability) be small, relative to the biological footprint of the population (i.e., magnitudes of egg production, recruitment, "natural" mortality, and numerous other ecosystem-level processes).

Significantly, as the footprint of a fishery is itself context dependent (i.e., population and ecosystem), the use of fixed biological limit reference points of a single indicator is not PA-compliant as they are not sensitive to natural and human-induced alterations in the ecosystem context. To determine appropriate thresholds and reactive/mitigative measures for each ecosystem trait is also untenable due to the sheer size and complexity of the SSE and the longevity of the Snow Crab. However, relevant indicators are evaluated to at least detect rapid alterations. This information is used qualitatively and quantitatively to provide the context by which the Snow Crab fishery footprint is assessed. The magnitude of the fishery footprint is minimized aggressively when greater uncertainty is associated with this context (environmental variability, age and size structure irregularities, etc.). For example, if recruitment is poor or environmental conditions erratic, then a more conservative approach (lower exploitation rate) is adopted. Further, all scientific information is brought forward and deliberated in an open and transparent manner with scientists, managers, fishers, aboriginal groups and various stakeholders, as per the Rio Accord (UNCED 1992).

Reference Points

Many pre-existing existing management measures and fishing practices in the Snow Crab fishery on the SSE are precautionary:

- Reproductive potential of the spawning stock biomass is not disrupted as only mature males are exploited. The fishery does not remove females.
- Mature males are exploited mostly after the mating season (spring), reducing the possibility of sperm-limitation and potential genetic selection towards earlier (i.e., smaller) size at maturity.
- Conservative exploitation strategies have generally been the norm, especially in recent years. Harvest rates are amongst the lowest in the Northwest Atlantic, usually ranging from 10% to 30% of the fishable biomass. This precaution is warranted as this stock is at the southern-most limit of the spatial distribution of Snow Crab in the western Atlantic. If fluctuations occur in environmental factors, such as oceanographic currents and/or bottom temperatures, this area could be significantly influenced. Further, the persistent collapse of groundfish in the area suggests that species in this area may be susceptible to collapse and subsequent existence in a collapsed state.
- Refugia from directed fishing pressures exist in The Gully MPA, in the St Anns Bank MPA, along the continental slope, and much of the western inshore portion of CFA 24. Movement within all subareas has been observed, with mean distance traveled being 10–20 km/annum, with high variability (> 200 km/annum maximum).
- Sub-legal (< 95 mm CW) mature males and immature males are able to mate. As a result, even if the abundance of commercially exploitable mature males were severely depleted, this would not be a conservation issue. This is especially the case as female Snow Crab are not exploited.
- Immature and soft-shelled (newly-molted, easily damaged) Snow Crab are not harvested and handling mortality is minimized via voluntary area closures and at-sea-observer monitoring of soft-shell incidence helping to maximize the potential yield per animal to the biomass.
- Traditional and fishers' knowledge is incorporated by DFO Science into assessment approaches; fostering self-knowledge and long-term sustainability perspectives/stewardship by industry. This is achieved through open and transparent consultations and communications between all stakeholders' (fishers, aboriginal groups, NGO’s, managers and scientists).

- This fishery is well monitored through 100% dockside monitoring, at-sea-observer coverage (5–10% of landings) and mandatory VMS (Vessel Monitoring System) usage in most areas.

To reiterate, the primary objective of the above management measures and practices attempt to balance the stability processes operating on long-term (adaptability) and short-term (resilience) (see Choi and Patten 2001) in order to maintain the sustainability of the Snow Crab population as a whole and the fishery that is dependent upon it. It is, therefore, explicitly PA-compliant.

Even with these measures, knowledge of biological reference points for the targeted fraction of the population (mature males ≥ 95 mm CW) are required to guide annual TAC advice and related management measures. There is no 'correct' or 'best' choice of reference points, especially given the fact that the underlying carrying capacity is quite variable over time; recruitment has been episodic and the SSB remains protected. In other words, the 4VWX Snow Crab population is not at, nor near any equilibrium state. As a result, the parameter estimates from the logistic model provide only first order estimates of the true biological reference points (see Methods).

APPENDIX 2: STOCK ASSESSMENT MODEL

A modified discrete logistic model of the fishable biomass component is used to determine the relevant biological reference points (i.e., carrying capacity and F_{MSY}) associated with the Harvest Control Rules of the Snow Crab fishery. In the fishery literature, this model is commonly referred to as a surplus production or biomass dynamics model. The rationale for using a discrete logistic model is due to its minimal data requirements:

- ageing is currently not possible with Crustacea;
- complex life cycle results in high variability of maturity ogives, individual growth trajectories and spatially and temporally variable size and sex structure; and
- a reliable stock-recruitment relationship has not been demonstrated/established.

Arguing against the usage of any standard fishery model (including the discrete logistic model) is the fact that the fishable component (large males) is not the same as the spawning stock biomass (reproductive females). Due to sex-related differences in longevity, body size/growth, maturity ogives, habitat usage, predation risk and fishery exploitation, any such model would require a large number of assumptions to convert SSB to the fishable component.

Rather than attempting to make any such potentially untenable assumptions, we instead follow the more general formulation of the logistic model as a truncated Taylor series approximation of some constrained time series. For any general variable of state, *B* (e.g., fishable biomass), its time rate of change is, in general, some function **F** of itself and a variety of other parameters *θ:*

$$dB / dt = \mathbf{F}(B; \theta)$$

If we proceed with a Taylor series expansion of **F**(B=B*; *θ*) at some value B*:

$$\mathbf{F}(B; \theta) = c_1B + c_2 B^2 + c_3 B^3 + \dots ;$$

where *c* are constants. And only polynomials of order 2 and lower are retained:

$$\mathbf{F} (B; \theta) \approx c_1B + c_2 B^2$$

And if we set $c_1 = r$ and $c_2 = - r/K$ and simplify, we obtain the basic form of the classical logistic model:

$$\mathbf{F} (B; \theta) \approx rB (1 - B/K)$$

With normalization by *K,* this simplifies further to:

$$\mathbf{F} (B; \theta) \approx rb (1 - b)$$

Which, in discrete form, becomes:

$$b_t - b_{t-1} \approx r\, b_{t-1} (1 - b_{t-1})$$

Removals of the fishable component by a fishery is commonly expressed as an additive term, *c*, the K-normalized catch*:*

$$b_t - b_{t-1} \approx r\, b_{t-1} (1 - b_{t-1}) - c_{t-1}$$
$$b_t \approx b_{t-1} + r\, b_{t-1} (1 - b_{t-1}) - c_{t-1}$$

The intrinsic rate of increase, *r,* is therefore, some function **G** of growth, recruitment, natural mortality, handling mortality and/or incidental bycatch, etc., but excluding fishery catch, *c*:

$$r = \mathbf{G} \text{ (growth, recruitment, mortality)}$$

Generally, *r* and *K* are assumed constants. These quantities, however, are not constant, especially given the systemic changes in the SSE associated with the collapse of groundfish in the mid-1990s and the punctuated nature of its time dynamics. We will return to this issue below.

Nonlinear, Bayesian state space methods were used to estimate the parameters of this model, θ. This is due to its greater numerical stability; ability to realistically propagate credible errors; ability to estimate unobserved states ("true" fishable biomass); and its ability to simultaneously estimate model "process" errors and data "observation" errors. Process errors (${}_{p}\sigma^2$) are the uncertainties that feed back into future states via error propagation: for example, via the recursive form of the logistic equation (i.e., errors in b_{t+1} in the state space of b_t *vs* b_{t+1}). Observation errors (${}_{o}\sigma^2$) refer to the uncertainties associated with measurement and observation (i.e., measurement/data-related errors of both variables in the state space of b_t *vs* b_{t+1}). This latter ability is particularly important as parameter estimates and forecasts based on observation-only errors provide unrealistically optimistic (small and constant) error bounds; and parameter estimates and forecasts based on process-only errors expand rapidly into the future, resulting in potentially unrealistically pessimistic (large and usually growing) error bounds.

The main distributional assumptions of the model of fishable biomass are as follows. The reader is referred to the code below for the distributional assumptions and derivations of each of the specific priors.

As the fishable biomass of Snow Crab follows a lognormal distribution, a multiplicative observation error model was assumed, with a variance $\sigma^2_{t,o}$. The observed fishable biomass index O_t was assumed to be linearly related to the "true" unobserved fishable biomass by a proportionality constant q such that $O_t = q\ K\ b_t$ for each of the three separate CFAs, denoted by a:

$$O_{t,a} \sim \text{Lognormal}\ (\ \log(q_a\ K_a\ b_{t,a}),\ {}_{o}\sigma^2{}_{a}\ )$$

The "~" indicates "is distributed as", which in this case is a lognormal distribution with mean $log(q_a\ K_a\ b_{t,a})$ and variance ${}_{o}\sigma^2{}_{a}$. The prior on the observation error, ${}_{o}\sigma^2{}_{a}$, was assumed to be minimally informative and diffuse, following a half-Cauchy distribution with center of mass in the interval (0,1), parameterized with location 0 and scale 0.5.

Catchability, *q,* is a factor that simplistically quantifies the influence of a number of differing biases, including survey gear, survey protocols, areal expansion protocols, survey stratification and statistical modeling, etc. It is overly simplistic as such biases are non-constant over time and space. However, here, it serves as a first-order estimate of such influences. Historically, it was assumed to be 1 due to the nature of the sampling design and analytical methodology. For modeling purposes, it is separated into two components for each of spring (pre-2004) and summer (post-2004) surveys with a Gaussian prior with a mean of 1 and a standard deviation of 0.25:

$$q_a \sim \text{Normal}\ (1,\ 0.25)$$

Process error was assumed to follow a (multiplicative) lognormal distribution with variance ${}_{p}\sigma^2$ whose prior was similar to the observation error, assumed to follow a half-Cauchy distribution with center of mass in the interval (0,1), parameterized with location 0 and scale 0.5.

Normalized catch, *c*, was assumed to be known without error:

$$b_{t,a} \sim \text{Lognormal}\ (\ \log(b_{t-1,a} + r_{t-1,a}\ b_{t-1,a}\ (1 - b_{t-1,a}) - c_{t-1,a}),\ {}_{p}\sigma^2{}_{a}\ )$$

and a starting biomass that followed a Beta distribution shifted to the right:

$$b_{0,a} \sim \text{Beta}\ (8,\ 2).$$

Carrying capacity was assumed to follow a log-normal distribution:

$$K_a \sim \text{Lognormal}\ ({}_K\mu_a,\ {}_K\sigma^2_a\ )$$

Where the area specific ${}_K\mu_a$ and ${}_K\sigma^2_a$ were chosen based on previous knowledge of the production in the area and were set to means of ln(1.83), ln(4.17) and ln(0.78) for N-ENS, S-ENS and 4X, respectively, and standard deviations that corresponded to a 25% coefficient of variation. The intrinsic rate of increase was assumed to be stationary with a prior of

$$r_a \sim \text{Normal}\ (0.96,0.25)$$

These priors were marginally informative. For carrying capacity, the distribution was assumed to be bounded to be within previously estimated historical maxima. For the intrinsic rate of increase, the distribution was chosen to center on ~1. This is loosely based upon estimates of ${}_r\mu \approx 1$ for crab of similar longevity and body size, *Cancer pagurus* in Europe (Laurans and Smith 2007). The posterior distribution of the parameters of interest, θ, conditional upon the data were estimated via MCMC (NUTS) sampling using the STAN platform (STAN Development Team 2015). Four Markov chains were followed to ensure convergence and mixing; 2,000 simulations in the burn-in phase were sufficient to ensure such convergence of the Markov chains. Another 8,000 simulations were used to describe the posterior distributions of the parameters.

The Stan model used for parameter estimation is as follows:

```
data {

  int<lower=0> N; // no. years
  int<lower=0> U; // no. regions
  int<lower=0> M; // no. years to project
  int ty;
  real er ;
  real eps ;
  vector[U] Ksd;
  vector[U] rsd;
  vector[U] qsd;
  vector[U] Kmu ;
  vector[U] rmu ;
  vector[U] qmu ;
  matrix[N,U] CAT;
  matrix[N,U] IOA;
  matrix[N,U] missing;
  int missing_n[U];
  int missing_ntot;
}

transformed data {
  int MN;
  int N1;
  MN = M+N ;
  N1 = N+1;
}

parameters {
  vector <lower=eps>[U] K;
  vector <lower=eps,upper=3>[U] r;
  vector <lower=eps,upper=2>[U] q;
  vector <lower=eps,upper=2>[U] qs;
  vector <lower=eps,upper=(1-eps)>[U] bosd;  // observation error
  vector <lower=eps,upper=(1-eps)>[U] bpsd;  // process error
  vector <lower=eps,upper=(1-eps)>[U] b0;
  vector <lower=eps>[missing_ntot] IOAmissing;
  matrix <lower=eps>[M+N,U] bm;
}
```

```
      transformed parameters {
        matrix[N,U] Y;  // index of abundance
        matrix[N,U] Ymu;  // collator used to force positive values for lognormal
        matrix[MN,U] bmmu; // collator used to force positive values for lognormal
        matrix[MN,U] rem;  // observed catch

        // copy parameters to a new variable (Y) with imputed missing values
        {
          int ii;
          ii = 0;
          for (j in 1:U) {
            for (i in 1:N) {
              Y[i,j] = IOA[i,j];
              if ( missing[i,j] == 1 ) {
                ii = ii+1;
                Y[i,j] = IOAmissing[ii];
              }
            }
          }
        }

        // -------------------
        // removals (catch) observation model, standardized to K (assuming no errors in observation of
catch!)
        for (j in 1:U) {
          rem[1:N,j] =  CAT[1:N,j]/K[j] ;
          rem[(N+1):MN,j] =  er*bm[ N:(MN-1),j] ;  // forecasts
        }

        // -------------------
        // observation model calcs and contraints:
        // Ymu = 'surveyed/observed' residual biomass at time of survey (Bsurveyed)
        // cfanorth(1) and cfasouth(2)
        //   This is slightly complicated because a fall / spring survey correction is required:
        //   B represents the total fishable biomass available in fishing year y
        //     in fall surveys:    Btot(t) = Bsurveyed(t) + removals(t)
        //     in spring surveys:  Btot(t) = Bsurveyed(t) + removals(t-1)
        // spring surveys from 1998 to 2003
        //   this is conceptualized in the following time line:
        //     '|' == start/end of each new fishing year
        //     Sf = Survey in fall
        //     Ss = Survey in spring
        //     |...(t-2)...|.Ss..(t-1)...|...(t=2004)..Sf.|...(t+1).Sf..|...(t+2)..Sf.|...
        // Cfa 4X -- fall/winter fishery
        // assume similar to a spring fishery but no need for separate q's
        //    Btot(t) = Bsurveyed(t)+ removals(t-1)
        //    NOTE: year designation in 4X is for the terminal year: ie. 2001-2002 => 2002

        for (j in 1:2) {
          Ymu[1,j]        = qs[j] * bm[1,j] - rem[1,j] ; // starting year approximation
          Ymu[2:(ty-1),j] = qs[j] * bm[2:(ty-1),j] - rem[1:(ty-2),j] ; //spring surveys
          Ymu[ty,j]       = q[j]  * bm[ty,j] - (rem[(ty-1),j] + rem[ty,j] )/2.0  ; // transition year ..
approximation
          Ymu[(ty+1):N,j] = q[j]  * bm[(ty+1):N,j] - rem[(ty+1):N,j] ;   // fall surveys
        }
        {
          int k;
          k=3;
          Ymu[1,k]        = q[k] * bm[1,k]   - rem[1,k] ; // starting year approximation
          Ymu[2:(ty-1),k] = q[k] * bm[2:(ty-1),k] - rem[1:(ty-2),k];
          Ymu[ty:N,k]     = q[k] * bm[ty:N,k] - rem[(ty-1):(N-1),k];
        }
```

```
        for (j in 1:U) {
          for (i in 1:N) {
            Ymu[i,j] = K[j] * fmax( Ymu[i,j], eps); // force positive value
          }
        }


        // -------------------
        // process model calcs and constraints
        for (j in 1:U) {
          bmmu[1,j] = b0[j] ; // biomass at first year
          for (i in 2:MN) {
            bmmu[i,j] = bm[i-1,j] * ( 1.0 + r[j]*(1-bm[i-1,j]) ) - rem[i-1,j] ;
          }
        }
        for (j in 1:U) {
          for (i in 1:MN) {
            bmmu[i,j] = fmax(bmmu[i,j], eps);  // force positive value
          }
        }


      }

      model {

        // -------------------
        // priors for parameters
        K ~ normal( Kmu, Ksd )  ;
        r ~ normal( rmu, rsd )  ;
        q ~ normal( qmu, qsd )  ;
        qs ~ normal( qmu, qsd )  ;
        b0 ~ beta( 8, 2 ) ; // starting b prior to first catch event
        bosd ~ cauchy( 0, 0.5 ) ;  // slightly informative .. center of mass between (0,1)
        bpsd ~ cauchy( 0, 0.5 ) ;


        // -------------------
        // biomass observation model
        for (j in 1:U) {
          log(Y[1:N,j]) ~ normal( log(Ymu[1:N,j]), bosd[j] ) ;  // stan thinks Y is being transformed due
to attempt to impute missing values .. ignore
        }


        // -------------------
        // biomass process model
        for (j in 1:U) {
          log(bm[1:MN,j]) ~ normal( log(bmmu[1:MN,j]), bpsd[j] ) ;
        }

        // could have used lognormal but this parameterization is 10X faster and more stable
        target += - log(fabs(Y));  // required due to log transf above
        target += - log(fabs(bm));

      }

      generated quantities {
        matrix[MN,U] pd;
        vector[U] MSY;
        vector[U] BMSY;
        vector[U] FMSY;
        matrix[MN,U] B;
        matrix[MN,U] P;
```

```
        matrix[MN,U] C;

        matrix[MN,U] F;
        matrix[M,U] TAC;


        // -------------------
        // annual production
         for(j in 1:U) {
           pd[1,j] = bm[2,j]- bm[1,j] + rem[1,j] ; // approximation
           for (i in 2:N ){
             pd[i,j] = (bm[i+1,j]- bm[i-1,j])/2 + rem[i,j] ; // linear interpolation cancels out the
bm[i,j] term
           }
           for(i in N1:(MN-1)) {
             pd[i,j] = (bm[i+1,j]- bm[i-1,j])/2 + er * bm[i-1,j] ;  // linear interpolation cancels out
the bm[i,j] term
           }
           pd[MN,j] = (bm[MN,j]- bm[(MN-1),j]) + er * bm[(MN-1),j]  ; // approximation
         }

        // -------------------
        // fishing mortality
         for (j in 1:2) {
           for (i in 1:N) {
             F[i,j] =  1.0 - rem[i,j] / bm[i,j]  ;
           }
         }
         {
           int j;
           j=3;
           F[1,j] =  1.0 - rem[1,j] / bm[1,j] ;
           for (i in 2:N) {
             F[i,j] =  1.0 - rem[i-1,j] / bm[i,j]  ;
           }
         }

         for (j in 1:U) {
           for (i in N1:MN) {
             F[i,j] =  1.0 - er * bm[i-1,j] / bm[i,j]  ;
           }
           for (i in 1:MN) {
             F[i,j] =  -log( fmax( F[i,j], eps) )  ;
           }
         }

        // -------------------
        // parameter estimates for output

        for(j in 1:U) {
           MSY[j]    = r[j]* exp(K[j]) / 4 ; // maximum height of of the latent productivity (yield)
           BMSY[j]   = exp(K[j])/2 ; // biomass at MSY
           FMSY[j]   = 2.0 * MSY[j] / exp(K[j]) ; // fishing mortality at MSY
      //    BX2MSY[j] = 1.0 - step( bm[N1,j]-0.25 ) ; // test if bm >= 1/2 bmY
      //    Bdrop[j]  = 1.0 - step( bm[N1,j]-bm[N,j] ) ; // test if bm(t) >= bm(t-1)
      //    Fcrash[j] = 4.0 * MSY[j] / exp(K[j]) ; // fishing mortality at which the stock will crash
        }

        // recaled estimates
         for(j in 1:U) {
           for(i in 1:MN) {
             B[i,j] = (bm[i,j] - rem[i,j]) * K[j] ;
             P[i,j] = pd[i,j]*K[j] ;
             C[i,j] = rem[i,j]*K[j] ;
```

```
          }
          for(i in 1:M) {
            TAC[i,j] = rem[N+i,j]*K[j] ;
          }
        }

     }
   "
   )
 }
```