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Assessment of Scotian Shelf Snow Crab in 2018

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Foreword

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

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GLOSSARY

Acoustic Tag – a device bonded to the carapace of Snow Crab to allow for tracking of animal movement through the use of acoustic receivers. These tags emit a unique acoustic signature. This tagging methodology does not require the recapture of the animal for movement studies.

Agonistic – Behavioral term relating to aggression, appeasement and avoidance behavior that occurs between members of the same species. Agonistic behavior is a much broader term than "aggression," which simply refers to behavior patterns that serve to intimidate or damage another.

Anthropogenic – Resulting from the influence of human beings on nature.

Benthic – Occurring on the ocean floor.

Biological Reference Points – In the context of the Precautionary Approach, agreed-upon levels of an indicator that are considered bounds to a “healthy” or “unhealthy” population or stock.

Biomass – The abundance of living organisms measured in terms of its weight, mass, volume or caloric energy.

Bitter Crab Disease (BCD) – A fatal disease found in numerous crustacean species worldwide caused by the *Hematodinium* dinoflagellate, a parasite which inhabits the host organism’s blood.

Brachyura (Infraorder) – Known as “true crabs” of which the Snow Crab is a member. Brachyurans are characterized by a body that is short, wide, and flat. The abdomen is reduced from a strong swimming muscle (e.g., shrimp) to a simple flap covering reproductive appendages and carry eggs. The uropods, which along with the telson form the tail fan in other decapods, are totally absent. All five pairs of walking legs are generally large with the first pair being chelipeds. The antennae and antennules are greatly reduced and originate before the eye stalks.

Carapace Condition (CC) – The condition of the shell of a Snow Crab. Generally related to the age of the organism and the time since last molt. See Table 5 for more details.

- **CC1** - Newly molted crab. The top of carapace is light brown and shiny without surface growth of moss or barnacles. Shell is soft and claw is easily broken.
- **CC2** - The top of carapace is light brown and less shiny with little to no surface growth of moss or barnacles. Shell is clean but hard.
- **CC3** - The top of carapace is light brown and not shiny. Some growth of moss or barnacles. Shell is hard.
- **CC4** - The top of carapace is brown and not shiny. Usually some surface growth of moss or barnacles. Shell is hard with small scars. Underneath is yellow brown.
- **CC5** - Old crab. Carapace is dark brown with substantially mossy (“dirty”) surface. Decalcification (black spots) noticeable often at joints. Shell may be soft.

Carapace Width (CW) – The distance across the carapace of a Snow Crab (millimetres).

Carrying Capacity (K) – The maximum population size of the species that the environment can sustain indefinitely.

Chela – Pincer-like claw of a crustacean or arachnid.

Crab Fishing Area (CFA) – Refers to an individual management area. On the Scotian Shelf they are from north to south: 20 to 24 and 4X.

Commercial Biomass – see Fishable biomass.

Catch Per Unit Effort (CPUE) – The amount caught by a single fishing event, such as the weight or number of crab captured by a single trap haul.

Density – The amount (biomass or number) of crab per unit area.

Distribution (Spatial) – The geographic area in which an organism exists.

Durometer – A calibrated instrument used to measure the hardness of an object (such as a crab shell), scaled from 0 (soft) to 100 (hard). A durometer reading of ≥68 has been historically used to determine a hard shelled crab.

Dynamic – Characterized by continuous change or time. Not fixed.

Ecosystem – The whole of a system with all the interactions between parts, living and non-living.

ENS – Eastern Nova Scotia (essentially Northwest Atlantic Fisheries Organization (NAFO statistical divisions 4VW).

Exploitation Rate (ER) – The ratio of biomass fished relative to their fishable biomass, where $ER = 1-e^{(-F)}$.

Extrapolate – To infer or estimate by extending or projecting known information.

Fishable Biomass (FB) – The biomass of Snow Crab exploited by the commercial fishery: male, mature, ≥ 95 mm CW and hard shell condition (CC2 to CC5). Note that CC2 Snow Crab do not have optimal meat yields at the time of the fishery. While immature crab ≥95 mm CW is part of the biomass that can be legally fished, this component is voluntarily returned to allow greater growth.

Fishing Mortality (instantaneous; F) – The exponential rate of death of organisms.

Fishing Mortality (relative) –See Exploitation rate.

Generalized Additive Model (GAM) - A statistical method used to model and predict values of a variable of interest (e.g., biomass) as a function of non-parametric functions of dependent variables (e.g., temperature, depth, substrate grain-size, etc.).

Harvest Control Rules (HCR) – A predetermined method for linking biological reference points and exploitation based reference points under the Precautionary Approach to management actions.

Individual Boat Quota (IBQ) –The amount of Snow Crab allowed to be legally removed by an individual fisher in a given area over a given period of time.

Individual Transferable Quota (ITQ) –The amount of Snow Crab allowed to be legally removed by an individual fisher in a given area over a given period of time. This quota allowance be transferred to another fisher to catch.

Instar – A stage of an organism between molts (i.e., the hard-shelled phase).

Interpolation – The method of determining unknown values through the use of surrounding known values.

Kriging – A method of interpolation for obtaining statistically unbiased estimates of intrinsic variables (i.e., Snow Crab biomass density) from a set of neighbouring points with known values, constrained by the relative change in variability of the data as a function of distance.

Larvae – The early, immature form of any animal before the assumption of the mature shape.

Metabolic Costs – The amount of energy dispensed by an organism in the process of living (e.g., heat, organic compounds, faeces, urea/uric acid, etc.).

Metabolic Gains – The amount of energy gained through the intake of food or other energy sources.

Morphometric Maturity – Maturity status determined from measurements of body shape and size. Male Snow Crab claw height increases very rapidly in the adult stage (terminal molt), whereas females' abdominal width increases with maturity. While morphometric maturity generally coincides with physiological maturity, morphometrically immature males are known to be able to fertilize females.

Molt – The act of growing, through the shedding of an organism's current shell.

Multiparous – Female crab bearing eggs resulting from their second or third breeding event (mating).

North Atlantic Fisheries Organization (NAFO) - an intergovernmental organization with a mandate to provide scientific advice and management of fisheries in the northwestern part of the Atlantic Ocean.

Numerical Density – The number of Snow Crab in a given surface area.

Pelagic – Occurring in the water column (not on bottom).

Pencil-clawed Crab – Immature crab that are legally exploitable (≥95 mm CW) but not yet terminally molted. The final growth increment is estimated to increase the body weight by approximately 250%.

Physiological Maturity – Biologically (functionally) able to reproduce (even though a crab may not be terminally molted).

Precautionary Approach (PA) – In the context of resource management, management approaches that seeks to not risk the long-term sustainability of a resource, as well as its ecosystem.

Primiparous – Female crab bearing eggs resulting from their first breeding event (mating).

Recruitment – Snow Crab that are expected to enter the fishable biomass in the next fishing season, designates as "R-1".

Scotian Shelf Ecosystem (SSE) - The marine environment extending (both South and East) from the land mass of Nova Scotia to the continental shelf edge. This includes NAFO divisions 4VW and the eastern portion of 4X.

Sexual Dimorphism – When shape and/or size differences exists between sexes of a species.

Soft-shell – Carapace condition in which the shell produces a durometer reading of less than 68 durometer units.

Spatial – Relating to space (such as a given geographic region such as the Scotian Shelf).

Spaghetti Tag – a traditional marked-recapture tag which is place around the carapace of a Snow Crab between its walking legs. Consists of a polymer band, a disk containing unique identification and a crimp to attach tag. Requires recapture of the tagged animal and subsequent reporting to be used in movement studies.

Spawning Stock Biomass (SSB) - The biomass of the members of a stock able to contribute to the future propagation of the stock, generally considered as the biomass of mature females.

Substrate – Bottom type on which an animal exists (rocks, boulders, mud, sand, etc.).

Total Allowable Catch (TAC) – the amount of Snow Crab allowed to be legally removed in a given area over a given period of time.

Temporal – Relating to time (such as a given period of time).

Terminal Molt – Snow Crab molted for a final time once mature. The size of these crab will not increase further.

White Crab – Refers to recently molted crab mostly of carapace conditions (CC) 1 and 2. These are not commercially desirable crab due to low meat yield.

ABSTRACT

In 2018, landings of Snow Crab (*Chionoecetes opilio*) for North-Eastern Nova Scotia (N-ENS) and South-Eastern Nova Scotia (S-ENS) were 742 t and 6,064 t, respectively, and were 55 t in 4X for the 2016–2017 season, representing decreases of 9% (N-ENS), 10% (S-ENS), and 31% (4X) relative to the previous year. Total Allowable Catches (TACs) in 2018 were 786 t, 6,057 t, and 110 t in N-ENS, S-ENS, and 4X, respectively. The TAC was not reached in N-ENS or 4X. Non-standardized catch rates in 2018 were 62 kg/trap haul in N-ENS, 116 kg/trap haul in S-ENS, and 12 kg/trap haul in 4X in 2017–2018—which, relative to the previous year, represents a decrease of 31% (N-ENS), an increase of 23% (S-ENS), and a decrease of 52% (4X). The capture of soft-shelled crab in N-ENS increased to 25% from approximately 5% in 2017, almost exclusively during the summer fishery. In S-ENS, the relative occurrence of soft-shell crab was 1.6% for the 2018 season. Soft-shell discard rates in 4X remain very low, due to the timing of the season. 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 3–4 years) based on size-frequency histograms. In CFA 4X, there appears to be limited potential for both internal (low sub-legal numbers of crab) and external (immigration from neighbouring areas) recruitment to the fishery. Since 2016, there has been a substantial recruitment of female crab into the mature segment of the population in all CFAs. The potential population benefits of the maturation/recruitment of both sexes are tempered by a number of uncertainties, including the influence of predation and temperature changes (especially in CFA 4X and parts of CFA 24). Predation from Atlantic Halibut is a potentially large and increasing source of natural mortality for Snow Crab on the Scotian Shelf. The results from the current spatiotemporal models of variability (stmv) modelling approach produce abundance estimates with very little inter-annual variability, particularly in N- and S-ENS. This hyper-stability is incongruous with the temporal abundance trends observed in geometric mean survey catch densities, length frequencies, catch rates, etc. This disparity from other data suggests caution is warranted when using the modelled biomass and fishery mortality estimates. The modelled post-fishery fishable biomass index of Snow Crab in N-ENS was estimated to be 3,203 t, relative to 3,358 in 2017. In S-ENS, the post-fishery fishable biomass index was 33,190 t, relative to 32,040 t in 2017. In 4X, the pre-fishery fishable biomass was 403 t, relative to 354 t in 2017. The N-ENS fishing mortality (*F*) estimate for 2018 is 0.24, an increase from 0.17 in 2017. The S-ENS *F* estimate for 2018 is 0.22, a decrease from 0.26 in 2017. The 4X *F* estimate for 2017–2018 is 0.23 (exploitation rate 0.21), a decrease from 0.26 in 2016–2017. In N-ENS, the fishery removals for the past two seasons appear to have been an overly aggressive harvest strategy, as catch rates have fallen and the 2018 TAC was not reached. A more conservative harvest approach in N-ENS could stabilize catch rates, protect incoming recruitment, and allow commercial biomass to rebuild. Substantial TAC reductions over the past three seasons have helped maintain stable fishery performance in S-ENS in spite of contracting habitat, reduced recruitment, and increased predation. Geometric mean catches from the survey are stable and, based on stock structure, increased recruitment to the fishery is likely to occur for the upcoming season. A moderately more aggressive harvest strategy can be considered. Habitat in CFA 4X is “marginal” relative to the other CFAs. Low internal recruitment and the large inter-annual temperature variations increases the uncertainty associated with this area. The Snow Crab population has not rebounded from an extreme warm-water even in 2012–2013. A zero TAC was set for the 2018–19 fishing season due to low commercial biomass. Survey catches indicate that 4X commercial biomass levels remain very low but have improved.

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). South-Eastern Nova Scotia (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 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 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 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 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, 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 crab (≥ 95 mm Carapace Width (CW); “pencil-clawed” crab) was implemented in 2006 for all areas on the SSE, to allow these crab to complete their molting cycle and molt to maturity, thereby simultaneously increasing the total yield per 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 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 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. In MSC Version 2, habitat and ecosystem considerations are much broader, taking into account cumulative impacts of all certified fisheries 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 interactions between Snow Crab fishing gear 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. The results of this audit will be published in 2019.

HISTORY

The Snow Crab fishery is currently the second most valuable commercial fishery in Atlantic Canada and third in 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 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.

From 2004–2008, TACS declined sharply in N-ENS due to negligible recruitment. Increasing recruitment and fishable biomass estimates resulted in increased TACs until 2014. In 2015 and 2016, TACs were reduced due to low commercial biomass and very low recruitment to the fishery. These declines were exacerbated by the adoption of Harvest Control Rules (HCRs), forcing the exploitation strategy in N-ENS to be more conservative. A new biomass estimation model (LBM) 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 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 into the current stmv approach (details in *Methods* section).

In S-ENS, TACs rose from 2005 to reach a record high in 2010, then gradually declined until 2013. The S-ENS TAC has again been declining since 2016 due to decreased biomass estimates.

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 TAC 4X has remained low (relative to pre-2013 levels) as have commercial biomass estimates. No commercial fishery occurred in 4X for the 2018–19 season due to commercial biomass estimates that placed the stock in the "Critical Zone".

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 has been used (see below) since 2017.

FISHERIES DATA

Fishery catch rates are potentially biased indicators of Snow Crab abundance. The spatial and temporal distribution of both crabs 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 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 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 provide 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 Observer Database System (ISDB). At-sea-observers are deployed randomly with the coverage being as evenly distributed as possible between vessels. The target coverage (as a percent of total landings) is 5% in S-ENS and N-ENS and 10% for 4X. This information was also 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. Proper bycatch monitoring did occur in 4X for the 2017–2018 fishery. As such, for the ENS fisheries, no species-specific data are available for 2018, but application of mean bycatch levels for the past 3 years, applied to current landings, will give an approximate measure of overall bycatch levels. This breech of reporting protocol has been discussed with the at-sea observer contractor to ensure future compliance.

RESEARCH SURVEY DATA

Spatial coverage in the survey is (1) extensive, going 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*. To maintain a consistent time series the same captain, net, and net monitoring systems have been used since 2004. Due to adverse weather conditions throughout the survey season of 2017, 32 stations did not get sampled. 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. Total station numbers in 4X were strategically reduced from 34 to 20 over the past two surveys 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 female crabs 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 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 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 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 fauna (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 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), claw hardness measured with a durometer, and weighed with motion-compensated scales. Captured crabs 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 (Fisheries and Oceans Canada, Bedford Institute of Oceanography, Dartmouth, Nova Scotia).

In cases where individual Snow Crab cannot be weighed (missing legs, excessive barnacle growth, etc.), individual weight estimates were approximated from Carapace Width (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 male Snow Crab 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, GFC, personal communication):

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

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

The maturity status of female crab is assessed from direct 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, GFC, personal communication):

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

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. After comparing 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 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}; i.e., the arithmetic mean numerical density per unit area). Modes and the bounds of each modal group were identified from size-frequency distributions. Throughout development, Snow Crab molt through several instar (I) stages. Each instar was determined after an analysis of size-frequency distributions to have a lower bound of CW (mm) approximated by (see also Figure 7):

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

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

SPACE-TIME MODELING

For the assessment of Snow Crab fishable biomass, an R-package (stmv) was developed to assimilate, model, and interpolate space-time process. A description of the stmv (spatiotemporal models of variability) approach can be found in Appendix 1. The stmv approaches a given smooth space-time process such as Snow Crab biomass as an hierarchical, two-stage process that is conceptually similar to kriging with "external drift" (Cressie 1993; Diggle et al 2003). The influence of environmental and biological factors are modelled globally as a first pass ("external drift") and the residual spatial (and in our case, spatio-temporal) patterns are modelled separately at a second stage. Most model-based geostatistical methods, including kriging with external drift, generally assume a simple spatial covariance (variogram) for the whole space-time domain. In stmv, the form of the spatial and spatio-temporal dependence of these residuals is determined from data for localized areas of interest centered on the nodes of a statistical spatial lattice and a range based upon a local variogram using a Matern formulation. It is, therefore, similar to a "Geographically Weighted Regression". However, a structured time-series model with seasonal and annual harmonic components is used to interpolate time trends at each datum inside this area of interest, using a Lognormal Generalized Additive Model (GAM; R-package "mgcv"; Wood 2006). These temporal interpolations were in turn used to inform the spatial interpolation via a localized kriging using a Fast Fourrier Transform (FFT)-based approximation for each time slice. All parameterizations specific to the assessment can be found online.

Using stmv, the "Viable habitat" for fishable Snow Crab was modelled globally from Snow Crab trawl surveys using a binomial GAM with a logit log link function. Smoothed (thin-plate-spline) covariates were: year, year fraction (seasonality), depth, bottom slope, bottom curvature, bottom temperature, bottom temperature standard deviation, number of degree days, ln(substrate grain size; mm), species composition (PCA axes 1 and 2) (Figures 8 and 9; see Choi et al. 2005a for more details on methods). These modelled relationships were used to predict SSE Snow Crab habitat after discretizing covariate information to a spatial resolution of 1 × 1 km grids, also using stmv (Figures 8 and 9). Potential Snow Crab habitat was identified as locations where the predicted probability of finding Snow Crab was > 0.05 (Figure 10).

For fishable biomass, a second stage of modeling was conducted upon the positive valued estimates of abundance using the same global-local procedure with a log-link. After estimation, the fishable biomass density in the viable habitat was determined (Figure 11). The same covariates used for habitat delineation were used for abundance modeling.

Biomass estimates resulting from the initial use of this approach in 2017 appeared to be over-smoothed inter-annually. The estimates did not capture the magnitude of the multi-year cyclical nature of Snow Crab populations observed elsewhere in the data (length frequencies, geometric mean densities, etc.). This was assumed to be a result of over-smoothing by local GAM models. To address this issue, local spatial modelling was conducted using an FFT approximation for local spatial interpolations in combination with GAMs for local temporal interpolation.

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 groundfish 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 HCRs 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 2 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

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 crabs are also found on more complex (e.g., 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% 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 crab 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 female crabs 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, 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 male crabs and the 9th to 10th instar in female crabs. Just prior to the terminal molt, male crab may skip a molt in one year to molt in the next (Conan et al. 1992; Figure 12). Male Snow Crab 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 male crab 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 4), the male 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 carapace condition.

Female crabs 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 female crabs (Hooper 1986). During mating, complex behavioral patterns have also been observed; the male crab helps the primiparous female crab molt, protects her from other males and predators, and even feeds her (indirectly; 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). Female crabs 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 crabs compete heavily for females and often injure themselves (losing appendages) while contesting over a female crab. Larger male crabs 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: 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 crab 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 (Figures 2 and 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 crabs 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 male crabs (i.e., moderate exploitation rates) will help ensure that the earlier maturing female crab 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 male and female crab 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 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 female crab 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 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 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 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 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 (Crab Fishing Areas 12 and 19) during these periods. Unfortunately, immigration into N-ENS was not observed as no crab were tagged in the Gulf for an extended period of time. The movement of immature and female 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, 23,766 tags have been applied and 1,726 distinct tagged crab recaptures (7.3%) have been reported (Table 6) in 4X, N- and S-ENS. Even with potential tagging-related mortality and exploitation rates of 15–30%, a higher (than 7.3%) proportion of tags are likely recaptured but not reported. Since 2004, 168 individuals have reported 1,867 total recaptures (Table 6) of 1,726 crab. On average, each individual 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 1,726 distinct tags recaptured, 1,247 have been returned to the water and 141 recaptured again. Tracking tagged crab over multiple recaptures provides further insight into the movement patterns over the life cycle of Snow Crab. When subsequent recaptures are reported, everyone who previously captured that particular crab are notified to encourage returning tagged 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 crab 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, crab tagged between 2004 and 2017 were first recaptured in the season following the tagging event (mean time to recapture was 463 days), with the longest time interval between release and initial capture being 2,278 days (approximately 6 years, 3 months; Figure 14). This crab had moved a minimum of 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 crab fishing operations. Tags are generally applied where commercial 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 is large. The average distance traveled was 27 km, with a maximum distance of 504 km (Table 6). The average rate of movement was 1.79 km/month. These distances and rates are likely underestimates, as the actual distance traveled by 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 2.05 km/month, slightly higher than N-ENS of 1.65 km/month. In 4X, the displacement rate is the lowest at 1.30 km/month (Table 7).

From 2004–2018, movement between N-ENS and S-ENS was rarely observed. In total, 10 crab tagged in S-ENS were recaptured in N-ENS and 4 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).

Reported recaptures of crab tagged between 2010 and 2014 suggest significant movement from N-ENS into the southern Gulf of Saint Lawrence (“the Gulf”, Figure 13). The apparent unidirectional movement (from N-ENS to the Gulf) is confounded by a period of without tagging in the Gulf Region during this period of time. As such, the degree of connectivity between the Gulf and N-ENS remains unknown, and it may be substantial given the high concentrations of commercial Snow Crab in the adjacent Area 19 (M. Moriyasu, GFC, personal communication). It is hoped that the renewed tagging program in Area 19 (a joint effort of the Maritimes and Gulf DFO regions) 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. 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; 5 were recaptured a third time. No movement of tagged 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 crab be released immediately with the tag still attached after relevant data are recorded (date, location, depth, condition of crab, as well as information about the vessel and 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.

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 and 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 female crab 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 crab have been detected within, or near, the Gulf Region. Of the 27 released crab, 23 were detected within 15 nautical mile 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. These crab have all been detected within N-ENS.

To determine if crab movement is unidirectional or bidirectional, acoustic tags have been released in the areas adjoining N-ENS t. Since 2015, 57 tags were released in the Gulf Region (CFA 19) and 79 tags were released un S-ENS (CFA 23). To date, there have been no detections in N-ENS.

In 2017, 10 crab with acoustic tags were released near the CFA 4X and CFA 24 boundary. Four of the five crab 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 crab released on the CFA 24 side was detected by a wave glider.

If reproduction is the main driver of movement patterns, limited levels of emigration from N- or S-ENS is presently expected, as mature female crab abundance is currently high and expected to remain high for the next 1–2 years.

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 increasing consistently since the early-1990s (Figures 17, 18 and 19). 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 female crabs 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 2012–13 (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.

The modelled potential Snow Crab habitat in the SSE for 2018 is shown in Figures 10 and 20.

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 crabs, 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).

The unintended removal of 32 stations (see *Methods: Research Survey Data* section for details) on the continental slope edge in CFA 23 for the 2017 survey, likely reduced the apparent mean densities of some Snow Crab predators. This unsampled area often has high localized densities of Atlantic Cod and skate species. The 2018 survey sampled these areas as intended.

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 (Figures 21 and 22). Only Snow Crab < 65 mm CW are typically observed in fish stomachs because maximum span exceeds the predator’s 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 female crab will impact the reproductive potential Scotian Shelf Snow Crab. Halibut are likely the largest source of predation of Snow Crab on the Scotian Shelf.

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 (Figures 23 and 24). If the Snow Crab survey is more reflective of predators in Snow Crab habitat (vs. groundfish surveys), the biomass of Thorny Skate (Figures 25 and 26) and Smooth Skate (Figures 27 and 28) 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 (Figures 29 and 30). Haddock may represent an additional increasing source of predation in localized areas of S-ENS and particularly 4X (Figures 31 and 32).

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 of the other predator species (Figure 33 and 34). 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 crabs 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 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. Overall predation mortality from groundfish does appear to be an increasing source of mortality for Snow Crab on SSE.

Seals are considered by fishers to be a potential predator of Snow Crab, and their continued increase in abundance (Figure 35; 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 crab species were found in < 1% of the seal scat samples examined with a diet focusing predominantly on Sand Lance, Atlantic Cod, and flatfishes. 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 potential predators of crab (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) 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 crabs appear to be more capable predators than female crabs 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 crabs (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.

For 2017, annual chlorophyll a levels were below normal on the Eastern Scotian Shelf and near long-term mean levels on the western Scotian Shelf. The timing of the spring phytoplankton bloom was variable and of a lower magnitude on the Scotian Shelf, with a long bloom in the central region and near-average length in the rest of the zone (DFO 2018b). The shift in species structure of the zooplankton on the Scotian Shelf has continued into 2017, with low abundance of the energy rich *Calanus finmarchicus,* although the intensity declined from 2016.

The distribution of Northern Shrimp (*Pandalus borealis*) on the Scotian Shelf appears to remain broad (Figure 36); however, Snow Crab survey shrimp densities (Figure 37) and stock-specific stock assessment results (DFO 2019) suggest that the SSE stock is in a depressed 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 (Figures 38 and 39) and Jonah Crab (Figures 40 and 41), remain in relatively patchy distributions and, therefore, do not currently appear to threaten the overall health of the Snow

Crab stock. Steady increases in near-shore American 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 (Steniford 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 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 they 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 42) across a wide range of sizes (20–100 mm CW; Choi and Zisserson 2012), though generally, in immature animals below legal commercial size (Figure 43). 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 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 assessment). 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 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 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 seldom used currently.

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 (Tables 10 and 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 approximate total bycatch levels, the 3-year mean bycatch (0.016% of landings) was applied to the 2018 landings. In ENS, a total of 6,806 t of Snow Crab were landed in 2018, with associated estimates of bycatch (based on 3-year mean levels) at 1.1 t. Bycatch rates in ENS are traditionally very low.

Total estimated bycatch in 4X was 0.2 t associated with 55 t of Snow Crab landings (0.4%). Crab Fishing Area (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 exclude 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 fishery in at least one of the three fishing seasons from 2015–2017. Striped Wolffish (SARA-listed species of “Special Concern”) have been observed in each of the three seasons from 2015–2017. 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, 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 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 female crab 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 44), 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 Marine Protected Area, whereas the inshore block runs completely with S-ENS. All potential exploration areas overlap with juvenile, female, and commercial Snow Crab habitat. If there is future seismic exploration in offshore areas occupied by Snow Crab, potential impacts on the species may need to be evaluated.

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, EMERA Newfoundland and Labrador , personal communication). 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 45). The majority of the MPA (Zone 1) is a core protection area. The remaining (smaller) 3 zones are referred to as “adaptive management zones”, allowing 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 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 it is comprised of 3 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.

An “Area of Interest” has been identified as potential location for an MPA along the southern coast of mainland Nova Scotia, referred to as Eastern Shore Islands. The discussion/consultation process is ongoing for this area. If designated as currently proposed, this area would have very little (if any) overlap with Snow Crab fishing efforts. The current boundaries would also overlap with few Snow Crab survey stations.

FISHERY

Effort

In N-ENS, a spring season was introduced in 2008 in an effort to reduce soft and white crab capture and handling, and it now represents the majority of the fishing efforts. This season was in addition to the traditional summer season, and individual fishers are able to fish during either (or both) seasons. After a successful trial in 2008, landings associated with spring fishing efforts peaked at 91% in 2010 and have remained above 65% since that time, with the exception of 2014 and 2015, when sea ice conditions limited spring fishing efforts (Figure 46). Total effort increased in N-ENS in 2018 (Figure 2). The 2018 fishing effort (Figure 47) focused on the trench of deep water located along the north-eastern coast of Cape Breton (“inside”) with some effort in the Glace Bay Hole. For the first time since 2012, limited fishing occurred on the northern-most portion of N-ENS along the CFA 19 boundary line in 2017. This was not the case in 2018. The number of active vessels in N-ENS continues to slowly decline each fishing season (Figure 48).

In S-ENS, fishing effort is gradually shifting from exclusively offshore to a mix of offshore (> 75km) and inshore fishing grounds (Figure 47), with higher landings from offshore areas. In 2018, the CFA 23 fishing effort was primarily focused on the holes between Misaine and Banquereau banks, though effort was observed in the inshore/mid-shore “bad neighbours” area particularly during the spring.

Crab Fishing Area 24 continued a pattern of fishing effort that shifts away from the area directly north of Sable Island with increased effort proximal to Canso and Canso Banks. Summer efforts in CFA 24 were focused around Middle Bank. In 2017, less fishing effort (relative to past years) occurred immediately adjacent to the CFA 23 boundary line, particularly inshore. There was increased effort on the boundary line in 2018. Throughout S-ENS, fishing effort was negligible in the western-most portion (along the “Eastern Shore”) of CFA 24 (west of 61.5^0 Longitude) and on the continental shelf edge. 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 (“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. Previous to 2010, less than 20% of S-ENS landings occurred prior to 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 46), 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 48). 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 crab, fish in strategic ways to avoid soft-shelled crab capture, and choose not to report tagged crab 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 4X, the fishing effort was focused almost exclusively south of Sambro, proximal to the 4X/CFA 24 line (Figure 47).

In 2018, a total of 12,000 and 52,300 trap hauls were applied in N-ENS and S-ENS, respectively. In 2017–2018, a total of 4,600 trap hauls were applied in 4X (Tables 2–4; Figure 2).

Landings

In 2018, landings for N-ENS and S-ENS were 742 t and 6,064 t, respectively, and were 55 t in 4X for the 2017–2018 season. This represents decreases of 9% (N-ENS), 10% (S-ENS), and 31% (4X) relative to the previous year (Figures 3 and 49). Total allowable catches in 2018 were 786 t, 6,057 t, and 110 t in N-ENS, S-ENS and 4X, respectively. The TAC was not reached in N-ENS or 4X .

The majority of N-ENS landings came from the inner trench, while S-ENS saw a general inshore migration of spatial landings patterns from the 2017 season. In 4X, the limited landings (2017–2018) were focused toward the 4X/CFA 24 line (Figure 49). There were no landings on the continental slope areas of S-ENS in 2018.

Catch Rates[1]

In 2018, non-standardized catch rates were 62 kg/trap haul in N-ENS, 116 kg/trap haul in S-ENS, and 12 kg/trap haul in 4X in 2017–2018 . This represents a decrease of 31% (N-ENS), an increase of 23% (S-ENS), and a decrease of 52% (4X) (Figure 4; Tables 2–4) relative to the previous year. The effect of TACs on catch rates can confound direct comparison over time and between management areas.

In N-ENS, the 2018 the average catch rate was 62 kg/trap, a decrease relative to 2017 (90 kg/trap). N-ENS catch rates are below the 15-year mean (75 kg/trap; Table 2; Figure 4) and at the lowest level since 2011. Catch rates in N-ENS were higher in the Glace Bay Hole area (predominantly in the spring), as opposed to the "inside" where catch rates were more variable (Figure 50). In 2017, fishers felt that a 2 km wide exclusion zone through productive crab grounds, due to Emera cable laying activities, negatively impacted catch rates though the decreasing trend continued in 2018. Catch rates from the summer fishery were lower catch rates in the 2017 and 2018 spring fishery (Figure 51). The 2018 spring fishery catch rates showed an increasing trend over time but declined over the summer fishery. In recent years, the catch rates in N-ENS, have been closely tied to the mean size of crab in the catches rather than just the numerical abundance (Figure 52). In 2018, the reliance of the fishery on a new recruitment pulse, with few large commercial crab existing, has lowered the catch rates (by weight) and resulted in the removal of additional crab to maintain landings.

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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.

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) are no longer being maintained.

In S-ENS, the 2018 average catch rate was 116 kg/trap, an increase from 2017 rates (94 kg/trap) and above the 15-year mean of 103 kg/trap (Table 3; Figure 4). Catch rates increased from 2017 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, with the localized higher catch rates in the deep-water holes between Misaine, Banquereau, and Middle banks (Figure 50). The lack of low localized catch rates suggests that fishers were efficiently identifying high abundance locations and 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 2018 season (Figure 51) indicates a high catch rate at the opening of the season in CFA 23. This is followed by a general decreasing trend with a marked resurgence in catch rates with the opening of the “shrimp boxes” (late June) and a declining trend after that time. These initial high catch rates at the opening of the season were driven by a limited number of active vessels experiencing universally high catches. A similar catch rate pattern is seen in CFA 24 over the course of the season. This suggest that catch rates are affected by 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 average catch rate was 12 kg/trap (Table 4; Figure 4), the lowest level since 2003. This represents a decrease of 52% from 2016–2017 and approximately half of the 14-year mean of 25 kg/trap. The 4X catch rates are consistently lower than catch rates in N-and S-ENS. Weekly catch rates in 4X (Figure 51) generally show an oscillating pattern over the course of the season. This oscillation is likely caused by varying amounts of effort, as most fishers shift their efforts away from Snow Crab for the Lobster fishery in late-November and return to Snow Crab fishing in mid-January. Localized warming and cooling of waters caused by weather patterns (such as extreme temperature events coupled with on- or off-shore wind direction) are believed by many fishers to further exacerbate these fluctuations in catch rates.

At-sea-observer Coverage

In N-ENS, the at-sea-observer coverage was 4.9% of landings (5% target). A total of 627 trap hauls were observed (approximately 5.3% of commercial trap hauls). In S-ENS, 4.7% of the landings were observed (5% target). A total of 2,426 traps (approximately 4.6% of commercial trap hauls) were observed. In 4X for the 2017–2018 fishing season, 7.3% of landings were observed, relative to a target level of 10%. A total of 211 traps were observed, 4.8% of commercial trap hauls.

Carapace Conditions of Catch and Soft-Shelled Crab

In N-ENS, CC1 and CC2 crab collectively represented approximately 28% of the total catch (Table 12; Figure 53), relative to 12% in 2017. A shift towards a predominantly spring fishery has lowered the catch of CC1 and CC2 crab (as they are less able to climb into traps earlier in the year due to recent molting). The leading edge of a recruitment pulse, coupled with limited summer fishing, resulted in an increase in the soft-shell (“white”) component of the catch. In

2018, CC1 and CC2 crab were observed by at-sea observers almost exclusively in the summer fishery. Higher incidence of soft-shelled crab in the summer fishery may result from a localized depletion of stronger, hard-shell males, and a consequent increased trapability of new-shelled males. This increased appearance of CC1 and CC2 supports the findings of previous trawl surveys which indicated the leading edge of a recruitment pulse entering the fishery. There was decrease in the proportion of the CC4 crab in the observed component of the fishery, which further supports the lack of a residual (from past seasons) population of commercial male crab in N-ENS. The level of CC5 crab remain negligible. There was a shift towards smaller bodied crab in the fishery (Figure 52), likely due to the smaller size of the earliest maturing crab of a recruitment pulse.

The incidence of soft-shell catches in the N-ENS summer fishery were at the highest levels observed in ten years (Figure 54). If no recaptures are assumed and the observed landings are prorated to total landings, this results in an additional 188 t (approximately 25% of landings) being discarded as soft crab, with potentially high handling-associated mortalities. This represents an increase in the incidence of soft crab (approximately 5%) from 2017. The soft-shell catches occurred during the summer fishery, where the soft crab discard rate was estimated (based on at-sea-observer coverage) to be 48%. 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 crab population.

In S-ENS, the occurrence of CC1 crab remains low at < 1% (Table 13; Figure 53). The proportion of CC2 crab in the catch remained constant from 2017 at approximately 6%. CC3 crab dominated the catch (~85%). A relative decrease in CC4 crab from 2017 may reflect the reliance of the fishery on crab that have matured in the past 2 seasons rather than an older residual biomass. In 2018, traps with a high soft-shell percentage (> 20% by count) were seldom observed by at-sea observers throughout S-ENS. When prorating observed landings to total landings in S-ENS, this represents a potential additional mortality of 99 t (1.6% of landings), consistent with 2017. Voluntary avoidance of areas showing high incidence of soft crab must be adhered to by all members of the fleet if this mitigation is to be effective.

In 4X for the 2017–18 season, CC1 and CC2 crab collectively represented approximately 17% of the total catch (Table 14, Figure 53). This level is higher than traditionally observed in 4X. The commercial catches are heavily dominated by CC3 and CC4 crab with a combined percent of approximately 80%. Recent warming conditions following an extreme warm-water event in 2013–2013 is hypothesized to have been detrimental to the Snow Crab population in 4X. Mortality (direct and incidental) caused by this warming likely continues to influence stock structure and species composition in 4X. The data from 4X are not directly comparable to N-ENS and S-ENS, as its winter fishing season is disjunct. This fall/winter 4X fishery continues to show negligible levels of soft crab.

Old Crab (CC5)

The CC5 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 crab were observed in the trawl surveys (Tables 15–17). Increasing levels of senescent 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 (30–95 mm CW) in the survey suggests that recruitment to the fishery is probable for the next 4 to 5 years and beyond (Figure 55). Low numerical abundance of crab < 30 mm CW in S-ENS could be due to low abundance or low catchability of the survey trawl at that small size.

In N-ENS, the size distribution of male Snow Crab appears comparable to 2017, with few large mature animals. The leading edge of a recruitment pulse has begun to enter the fishery. Internal recruitment to the fishery is expected to continue for the next 3+ years, though high suspected natural mortality of Snow Crab in N-ENS could limit this recruitment.

Based on the trawl survey results, the Snow Crab in 4X show erratic inter-annual size distribution patterns, currently with minimal potential for internal recruitment to the fishery. Few commercial size Snow Crab were observed in the Snow Crab survey in 4X. Movement is potentially an important source of crab in this area, and a lack of any commercial fishing effort in the western portion of CFA 24 hold potential benefits for 4X. Erratic temperature fields and associated constriction of viable Snow Crab habitat in 4X create strong uncertainties for the future of commercial Snow Crab stocks.

Female

In 4X, N- and S-ENS, there has been a substantial recruitment of female crab into the mature (egg-bearing) segment of the population from 2016–2018. Almost all female crab are now mature (Figure 56), and egg/larval production is expected to be high. In N- and S-ENS, densities of mature female crab appear to be declining, potentially indicating high natural mortality of this segment of the population. These crab may be more susceptible to predation as they are smaller than mature male crab and are potentially a more energy-rich food source for predators. Although mature (egg-bearing) female crab abundance is at its highest levels in recent years, it exists at lower levels than observed previous to 2009.

CFA 4X is unique with regards to the potential for internal recruitment from egg production. Being downstream of all other crab areas increases the chance of larval settlement in 4X regardless of a resident population of mature female crab. 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 crab away from traditional locations within 4X, in reaction to such temperature and predation changes, may also confound inter-annual survey results.

SEX RATIOS

When the relative number of mature female crab 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 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 crabs, based on varying habitat preferences for the sexes and the smaller size of mature female snow crab. 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. Crab (particularly large males) may move to find mature females. This appears to have been the case in the early 2010s with mature male crab emigrating from N-ENS to the neighboring Area 19.

There is a high likelihood that sex ratios will naturally fluctuate over time (Figure 57), 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 (Figures 57 and 58). A similar lull is anticipated in the early 2020s. In N- and S-ENS, sex ratios (% female of mature animals) in 2018 are at their highest levels in the past 10 years. This increase is reflective of a decreasing male population and increases in mature female crab. Sex rations of mature crab in 4X have increased steadily since 2014, likely due to decreasing abundance of mature male crab.

The sex ratios of immature Snow Crab (Figure 59 and 60) have been decreasing in all areas since 2016. This is due to female crab of the recent population pulse maturing before the males of the same age cohort, lowering immature sex ratios while increasing mature ratios.

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 (Figure 60). When this spatial segregation is observed, male and female crab 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 61–64). In N-ENS, the density of immature female crab increased steadily from 2009–2014 and has been declining since. Maturation of these immature crab began in 2015 and continued into 2018, lowering the immature component of the female population (Figure 61), but increasing the mature component (Figure 63). In S-ENS, immature female crab were at historical highs in 2006. Since 2010, there has been a generally decreasing trend in the numerical abundance of immature female crab (Figure 61). There was a decreasing trend in numbers of mature female Snow Crab in S-ENS from 2008–2015 (Figure 63). As in N-ENS, maturation of a pulse of female crab began 2016 and has been increasing the numerical abundance of mature female crab numbers (Figure 56).

Based on population size structure, mature female crab abundance is expected to decline for the next 4–5 years. As few immature crab exist currently, the numerical abundance of immature

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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.

females is expected to increase, contingent on successful large-scale breeding events and larval survival.

Immature females in 4X have declined from a high in 2010. Immature female crab numbers remain consistent (at low levels) for the past four years. The abundance of mature female crab has increased since 2016 (Figure 63). This increase may be due to temperature-driven shifts in crab distribution (into surveyed areas) or reduction in total survey stations in 4X artificially increasing density estimates for the area.

Most of the female crab are primarily found in shallower areas along the shore of mainland Nova Scotia and in offshore areas (Figures 62 and 64). For female Snow Crab, immature crab appear to have a more diffuse distribution than mature crab (Figures 62, 64, 65).

Maturation of immature female crab in N- and S-ENS in 2016 and 2017 increased potential egg production (Figure 66). Above-average egg production is expected to continue for 1–3 years in all areas as recently matured animals mate and produce broods of eggs. Larger egg clutches in multiparous (vs. primiparous) crab should further bolster 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 67. The stmv approach generates area biomass estimates through aerial expansion of survey catches (Figure 68) to produce the survey biomass index. In N-ENS, the highest fishable biomass densities appeared less concentrated in 2018 compared to 2017 (Figure 69). In S-ENS, densities appeared more concentrated. In 4X, the limited remaining pocket of fishable crab is in close proximity to the 4X/S-ENS line (Figure 69). 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 crab, and predict the age that male crab will terminally molt. Based on size-frequency histograms of the male Snow Crab population, increased (though moderate) internal recruitment to the fishery is expected for the next year in N-ENS and S-ENS (Figures 55 and 70). Internal recruitment in 4X is expected to be minimal. Immigration of crab from outside a given area can represent recruitment to its fishery, though 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 55), 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. 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 crab in this area, and a lack of any commercial fishing effort in the western portion of CFA 24 hold potential benefits for 4X. Erratic temperature fields in 4X create strong uncertainties for the future of commercial 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 3 for more details). There is considerable uncertainty around current stmv biomass estimates. The inter-annual variability and trends observed in other indices (survey catch densities, catch rates, etc.) are severely dampened or absent in the modelled survey index of biomass. Attempts to further refine this approach to stock assessment have not yet yielded wholly consistent results.

As this survey index is the base abundance input to the fisheries model, coupled with TAC-constrained landings, resultant parameters such as carrying capacity, modelled fishable biomass, and fishing mortality are highly uncertain and unreliable. Caution is warranted in the interpretation and use of these values in their application to potential harvest strategies.

Posterior distributions for K, r, q and process error (bp.sd) were updated from the prior distributions suggesting the data did inform the model output (Figures 71–76). Estimates of median population growth rate, r, were 0.999 for N-ENS, 0.821 for S-ENS, and 0.888 for 4X (Figure 72), whereas the carrying capacity (Figure 74) for S-ENS (55.7 kt) is approximately 10 times higher than for N-ENS (4.85 kt), largely reflecting the differences in area of suitable crab habitat (Figure 20). There were also differences in catchability coefficient (q) for N-ENS and S-ENS with estimates of 0.64 and 1.07, respectively (Figure 75). These differences in q may reflect the relative ability of the survey fishable biomass index to accurately describe the stock biomass. The posterior distributions for process error (bp.sd) are shown in Figure 74 and observation error (bo.sd) is shown in Figure 75.

The median estimates of F_{MSY} were 0.499 for N-ENS, 0.411 for S-ENS, and 0.444 for 4X (Figure 76).

FISHABLE BIOMASS

The modelled post-fishery fishable biomass index of Snow Crab (Figure 77) in N-ENS was estimated to be 3,203 t, relative to 3,358 t in 2017. In S-ENS, the post-fishery fishable biomass index was 33,190 t, relative to 32,040 t in 2017. In 4X, the pre-fishery fishable biomass was 403 t, relative to 354 t in 2017. The 4X biomass estimate is generally more uncertain, as it fluctuates more dramatically than other areas, probably a result of more extreme temperature fluctuations and potential migration in and out of the area.

FISHING MORTALITY

The N-ENS fishing mortality (F) estimate for 2018 is 0.24 (exploitation rate 0.21), an increase from 0.17 in 2017 (Figure 78).

The S-ENS F estimate for 2018 is 0.22 (exploitation rate 0.20), a decrease from 0.26 in 2017 (Figure 78). 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 there are reports of illegal landings in this area.

The 4X F estimate for 2017–2018 is 0.23 (exploitation rate 0.21), a decrease from 0.26 in 2016–2017 (Figure 78). Localized exploitation rates are likely to be higher, since the computed exploitation rates incorporate biomass throughout CFA 4X and are not limited to the fishing 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 female crab have been estimated between 0.66 and 0.78 in the northern Gulf of St. Lawrence (Drouineau et al. 2013). For early benthic females 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 male crab) seems to be generally smaller in magnitude than that of natural mortality and natural mortality seems to be higher for mature females than mature male crabs. Diet studies (Bundy 2004; see also 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 Ecosystem 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 “HCRs” can be found in Appendix 2.

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 2).

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 71–76).

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 Harvest Control Rules (Figure 79) 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)

Given uncertainty around current fishable biomass estimates (See Stock Assessment Model section above), these secondary, contextual indicators should be strongly considered.

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.

As a result, the following research priorities exist with regard to formulating more appropriate reference points:

- Describe environmental influence upon biological cycles (molting, mating, and egg production) and integrate into a more biologically reasonable model.
- Refine the fishery model and survey index:
    - Incorporate predators and prey to the fishery model.
    - Incorporate growth and variable r, K parameters.

- Identify core spawning and nursery grounds.
- Refine larval production estimates.
- Describe benthic and pelagic movement/connectivity.
- Describe the role of environment/climate and predator-prey interactions upon pelagic and benthic larval survivorship.

The development of stmv was an attempt to address some of the above issues. Further effort will be placed towards improving this new direction in stock assessment.

RECOMMENDATIONS

GENERAL REMARKS

1. The capture of soft-shelled 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 crab. As some summer fishing still occurs, timely responses from industry to avoid fishing in areas showing high incidence of soft 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 crab. The arguments for this approach are as follows:
    a. Fishing mature 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 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 crab go through a soft- and white-shelled phases that exclude them from the fishery, so extends the fishable period by this time.
    c. Specifically targeting mature (male) crabs is an optimal exploitation strategy (CC3 and CC4 crab) since the fishable biomass is harvested when “ready and maximized”. This is because there is a significant weight increase if immature crab are allowed to grow and mature (an increase of 250–400%; Figure 7).

    In the 2019 season, a portion of the ≥ 95 mm CW male crab will still be composed of immature individuals (Figure 55). Indeed, these immature 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 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 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), likely 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. Prior to the 2016 survey results, the survey estimates of fishable biomass were used as the key biomass index when considering potential target exploitation rates. The biomass dynamic model was used to define stock status relative to estimated MSY reference points. Beginning in 2016, the modelled biomass obtained from biomass dynamic model was used as the primary indicator of biomass. In the current iteration of this model, the survey index (now stmv-derived) is coupled with landings to provide estimates of carrying capacity, fishing mortality, and catchability along with a posterior mean fishable biomass estimate. The resulting mean fishable biomass estimates were higher than the stmv fishery index, particularly in N-ENS (lower q value). Applying the HCRs target exploitation of 10–30% (when in the "Healthy" zone) to this modelled biomass estimate, as opposed to the survey index, dramatically increased the TAC in N-ENS in 2017 (288% increase). This TAC was reduced by only 5% in 2018. Since the TAC increase in 2017, catch rates have fallen by more than 40%, after six years of relatively high and stable catch rates. In 2018, the TAC was not reached for the first time in the past 20 years. The application of the target exploitation rate ranges, as defined by the HCRs, must be tempered by this shift in biomass estimation methodology. The upper end of the target exploitation ranges are likely too high, particularly in N-ENS where the modelled biomass estimate is higher than the survey index that was used previously to determine target exploitation rates for the coming fishing season.
6. The biomass estimation procedure failed to complete in 2014 and 2015. This required a redesign in the biomass estimation approach. The introduction of a new (LBM) approach for the 2016 assessment (2016 survey; 2017 fishery) provided biomass estimates with large inter-annual fluctuations, etc. The further refinement into the current stmv (past two years) approach has simplified the model inputs by limiting the number of environmental inputs and added a level of local temporal smoothing. The 2017 results appeared to be over-smoothing inter-annual variability, inhibiting the ability of the survey index to track biomass trends. Attempts to improve the stmv biomass index for 2018 still yield hyper-stable results that appear to be driven by relatively stable (in a broad temporal context) environmental covariates informing the model. These stable abundance levels are incongruous with most other data sources. Results do not show the cyclical population patterns apparent in other data sources, such as survey catch densities, length frequencies, and fishery catch rates.

   This disparity stresses the importance of using all available (presented herein) data sources when choosing harvest strategies for the coming fishing season.

NORTH-EASTERN NOVA SCOTIA (N-ENS)

High exploitation rates and limited recruitment, caused by handling mortality of soft-shelled crab in the past, pushed the N-ENS fishable biomass to historic lows. The 2018 fishing season saw substantial increases (potentially detrimental) in soft-shell crab catches, almost exclusively in the summer season. All efforts should be made to further reduce or eliminate summer fishing to protect incoming recruitment.

The 288% TAC increase in 2017 and 5% reduction in 2018 appears to have been an overly aggressive harvest strategy. Catch rates have fallen steadily over the past two seasons to the lowest levels since 2011. The TAC was not reached in 2018 for the first time since the introduction of individual transferable quotas and removal of sub-area lines.

The presence of large male crab are required for breeding and to protect both the female crab and occupied Snow Crab habitat. Low catch rates (fishery and survey), increased incidence of soft crab, increased predation, and the uncertainty around biomass estimates suggest extreme caution is warranted in the consideration of harvest strategies.

A more conservative harvest approach that lowers exploitation in N-ENS could stabilize catch rates, protect incoming recruitment essential to the fishery, and allow commercial biomass to rebuild.

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.

Substantial TAC reductions over the past three seasons have helped maintain stable fishery performance (catch rates) in S-ENS in spite of contracting habitat, reduced recruitment, and increased predation. Geometric mean catches from the survey are stable and, based on stock structure, increased recruitment to the fishery is likely to occur for the upcoming season. A moderately more aggressive harvest strategy would be appropriate under these conditions.

4X

As CFA 4X is the southern-most extent of Snow Crab distribution in the North Atlantic, existing in more “marginal” environments relative to the “prime” areas of S- and N-ENS, an explicitly precautionary approach should be used in this fishery. Further, very low recruitment into the fishable biomass and large inter-annual temperature variations increases the uncertainty associated with this area. The extreme warm bottom temperature event of 2012–2013 was detrimental to the Snow Crab population in 4X, which has not recovered to previous abundance levels. A zero TAC was set for the 2018–2019 fishing season due to low commercial biomass. Catches from the Snow Crab survey indicate that commercial biomass levels in 4X remain very low but have improved.

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TABLES

Table 1. Snow Crab fishing seasons on the Scotian Shelf in 2018.

Area	Season
N-ENS	April 14th–May 13th and July 21st– August 18th
S-ENS (CFA 23)	April 1st – August 31st
S-ENS (CFA 24)	April 1st –August 31st
4X	Nil (no season dates set due to 0 TAC decision)

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)
2004	79	1,416	1,418	61	23.4
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

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)
2004	130	8,241	8,022	106	76.0
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

Table 4. Summary of Snow Crab fisheries activity of 4X. Dash (-) indicates no data.

Year	Licenses	TAC (t)	Landings (t)	CPUE (kg/trap haul)	Effort (x1000 trap hauls)
2004–05	9	600	413	20	20.8
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[1]	9	0	-	-	-

[1] No fishery (0 TAC) due to low commercial biomass.

Table 5. Snow Crab Carapace Conditions (CC) 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. NA = Not Applicable

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
2010	2,256	159	148	32.86	150.07	408.47	1,124	2.45
2011	1,789	107	106	59.89	259.67	541.43	2,278	3.37
2012	1,571	150	131	36.36	278.83	417.27	2,219	2.65
2013	3,910	373	337	40.89	503.97	607.52	1,572	2.05
2014	3,112	273	249	18.39	229.42	605.53	1,472	0.92
2015	1,929	172	160	20.25	231.85	386.52	1,125	1.59
2016	1,206	90	75	21.86	141.81	402.2	742	1.65
2017	1,318	41	38	10.30	65.46	96.95	364	3.23
2018	1,247	0	0	NA	NA	NA	NA	NA
All Years/ Areas	**23,766**	**1,867**	**1,726**	**27.22**	**504**	**463**	**2,278**	**1.79**

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	14,458	807	26.65	394	2.05	84
N-ENS	8,337	821	30.04	554	1.65	69
4X	971	100	10.0	233	1.30	18

Table 8. Predators of Snow Crab in ENS from 1995–2016. 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	2,101	0.38	0.36
Cod	6,510	0.37	0.16
Thorny Skate	2,789	0.32	0.60
Sea Raven	736	0.27	0.45
Winter Skate	560	0.18	0.10
White Hake	2,729	0.07	0.01
American Plaice	8,570	0.06	0.06
Haddock	4,777	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 (+) 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

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 species-specific as bycatch levels are extrapolated to be approximately 0.016% of Snow Crab landings for the 2015–2017 in ENS. ***No species specific data are available for 2018.***

Species	**2015**	**2016**	**2017**	**3-Year Total**
Rock Crab	19	0	0	19
Cod	187	84	353	624
Jonah Crab	19	854	0	873
Northern Stone Crab	0	670	18	688
Toad Crab	0	84	35	119
Soft Coral	0	0	18	18
Basket Star	0	0	18	18
Sea Urchin	0	33	18	51
Sand Dollars	0	17	0	17
Purple Starfish	0	0	35	35
Sea Cucumbers	19	50	495	564
Whelk	0	17	0	17
Winter Flounder	0	0	35	35
Eelpout	0	0	35	35
Redfish	75	50	247	372
Sea Raven	37	33	0	70
Skate	0	67	18	85
Northern Wolffish	112	17	0	129
Spotted Wolffish	0	0	194	194
Striped Wolffish	149	100	371	620
Total Bycatch	617	2,076	1,890	4,583
Snow Crab Landings	**11,911,000**	**9,896,000**	**7,532,000**	**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 three 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.

Species	2015	2016	2017	3 Year Total
American Lobster	98	48	55	201
Cod	0	16	0	16
Jonah Crab	0	16	14	30
Rock Crab	0	0	14	14
Lumpfish	11	0	0	11
Northern Stone Crab	130	81	82	293
Redfish	0	0	14	14
Sea Raven	239	0	41	280
Total Bycatch	478	161	219	858
Snow Crab Landings	**142,000**	**80,000**	**55,000**	**277,000**

Table 12. Carapace Condition (CC) of Snow Crab ≥ 95 mm carapace width (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	0.16	37.52	46.36	15.56	0.4

Table 13. Carapace Condition (CC) of Snow Crab ≥ 95 mm carapace width (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	0.04	8.34	83.23	8.11	0.27

Table 14. Carapace Condition (CC) of Snow Crab ≥ 95 mm carapace width (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).

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

Table 15. Carapace Condition (CC) of Snow Crab ≥ 95 mm carapace width (percent by number) over time for N-ENS from trawl surveys.

Year	CC1	CC2	CC3	CC4	CC5
2006	0	18.52	15.74	42.59	23.15
2007	0	23.81	67.35	7.48	1.36
2008	0.14	41.77	50.88	7.21	0
2009	3.53	30.59	64	1.88	0
2010	0	39.05	56.67	4.17	0.12
2011	0.11	38.2	56.75	4.94	0
2012	0	16.89	73.91	9.2	0
2013	0.24	51.22	43.4	5.01	0.12
2014	0	14.08	79.31	6.61	0
2015	0	16.53	29.03	53.63	0.81
2016	0	9.47	41.05	48.42	1.05
2017	0	27.17	43.4	27.2	2.31
2018	0.00	73.00	21.5	5.5	0.00

Table 16. Carapace Condition (CC) of Snow Crab ≥ 95 mm carapace width (percent by number) over time for S-ENS from trawl surveys. Crude unadjusted proportions.

Year	CC1	CC2	CC3	CC4	CC5
2006	1.15	17.98	61.55	17.56	1.76
2007	1.37	57.88	31.29	8.89	0.57
2008	0.58	15.12	69.83	13.93	0.54
2009	0.17	25.09	66.45	8.01	0.28
2010	0.22	26.29	71.08	2.22	0.2
2011	0.03	18.87	78.32	2.68	0.1
2012	0.03	18.76	77.57	3.41	0.23
2013	0.09	28.24	65.94	5.54	0.19
2014	0.07	12.11	83.87	3.85	0.1
2015	0.69	22.05	66.92	9.13	1.21
2016	0.31	17.84	69.82	11.36	0.66
2017	0.00	30.84	57.8	11.2	0.54
2018	0.05	32.05	54.5	13.0	0.41

Table 17. Carapace Condition (CC) of Snow Crab ≥ 95 mm carapace width (percent by number) over time for 4X from trawl surveys. Crude, unadjusted proportions.

Year	CC1	CC2	CC3	CC4	CC5
2006	0	6.94	83.33	8.33	1.39
2007	0	15.79	78.95	5.26	0
2008	0	1.61	90.32	8.06	0
2009	1.06	10.05	83.6	5.29	0
2010	2.88	21.15	71.15	4.81	0
2011	0	11.11	85.19	3.7	0
2012	0	3.7	51.85	40.74	3.7
2013	7.69	15.38	69.23	7.69	0
2014	0	0	94.12	5.88	0
2015	2.44	2.44	63.41	31.71	0
2016	0	19.44	77.78	2.78	0
2017	16.67	0	50	16.7	16.7
2018	0.00	26.32	63.2	10.5	0.00

FIGURES

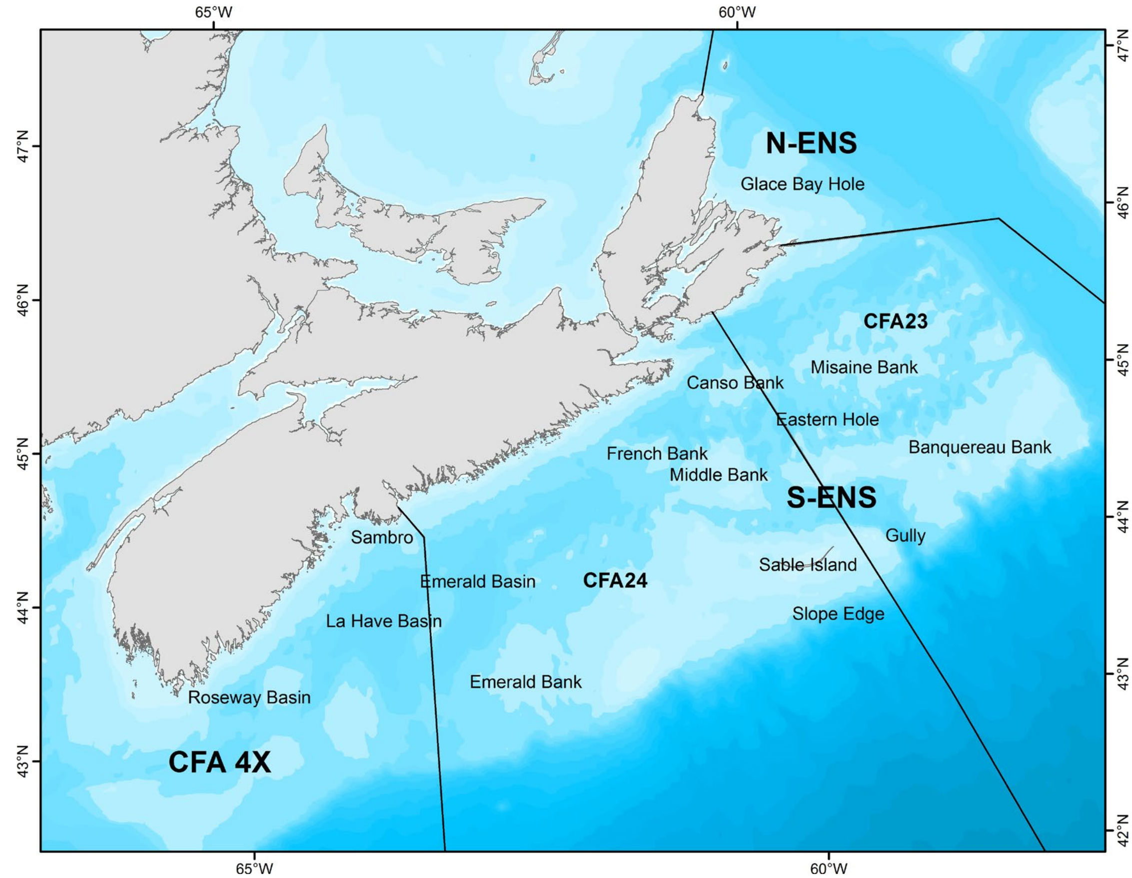


Figure 1. Location of geographic areas and the management areas for Snow Crab on the Scotian Shelf.

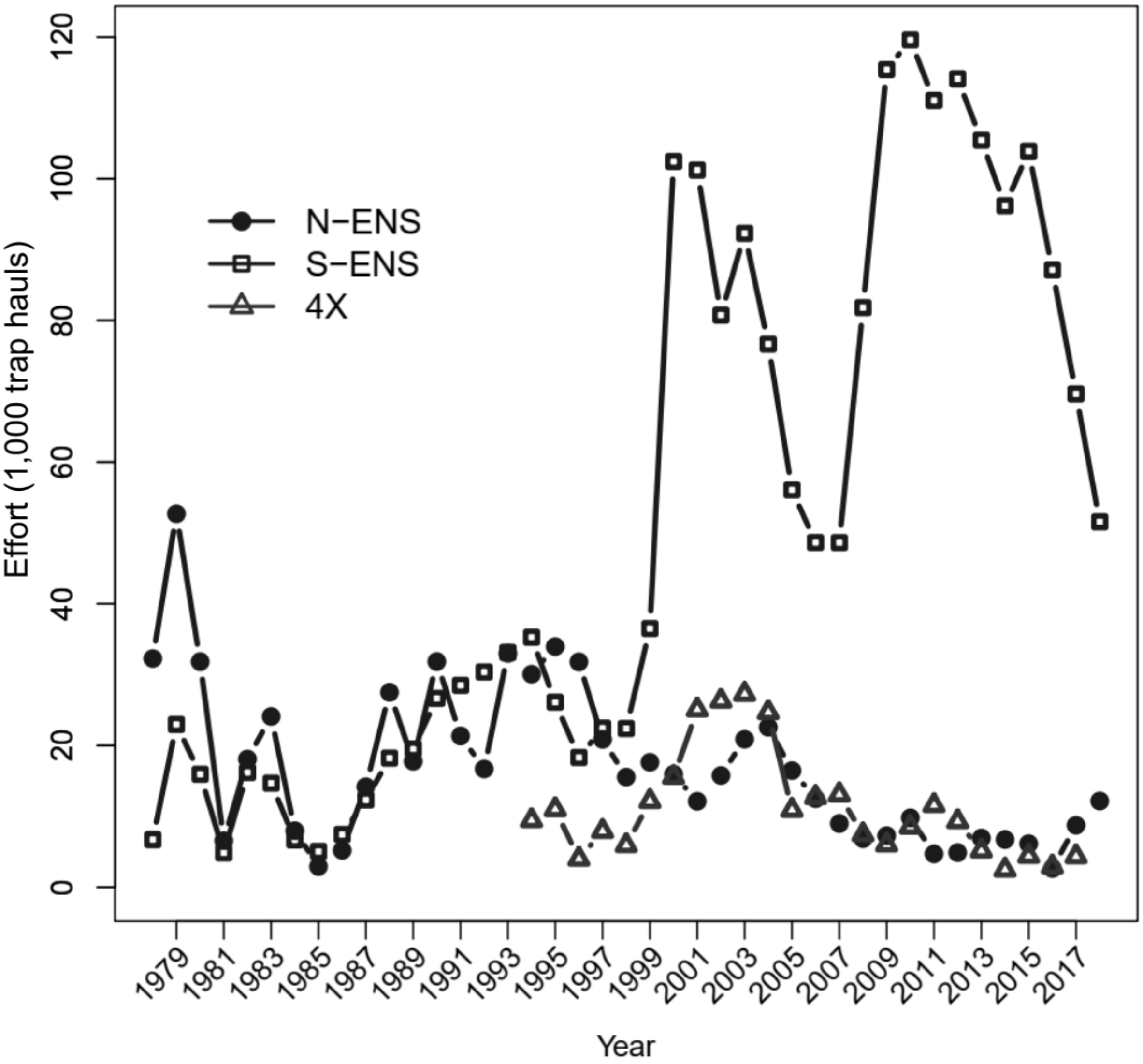


Figure 2. Temporal variations in the fishing effort for Snow Crab on the Scotian Shelf, expressed as the number of trap hauls. Year in 4X refers to the year at the start of the fishing season.

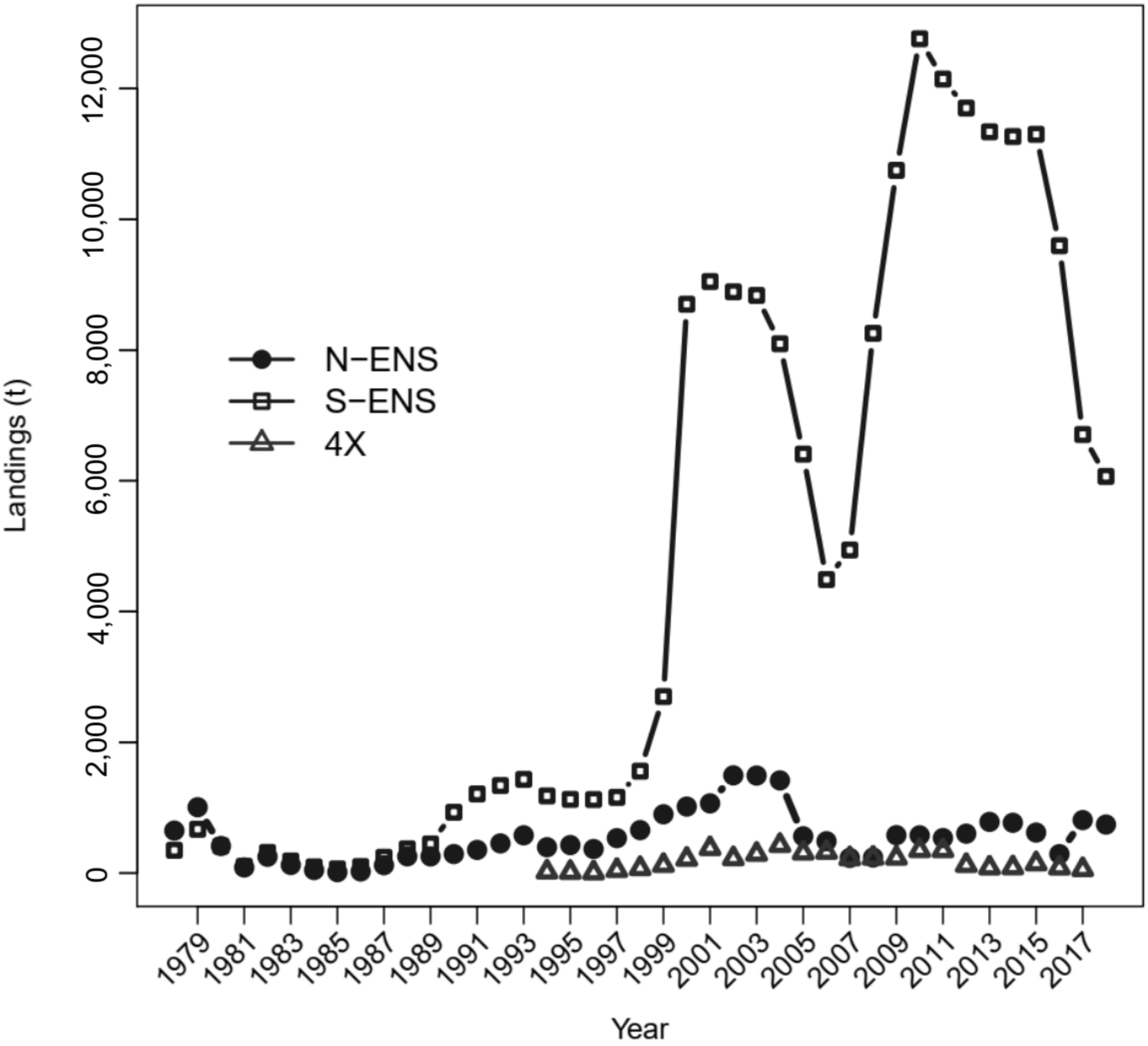


Figure 3. Temporal variations in the landings of Snow Crab on the Scotian Shelf (t). The landings follow the TACs with little deviation (Table 2–4).

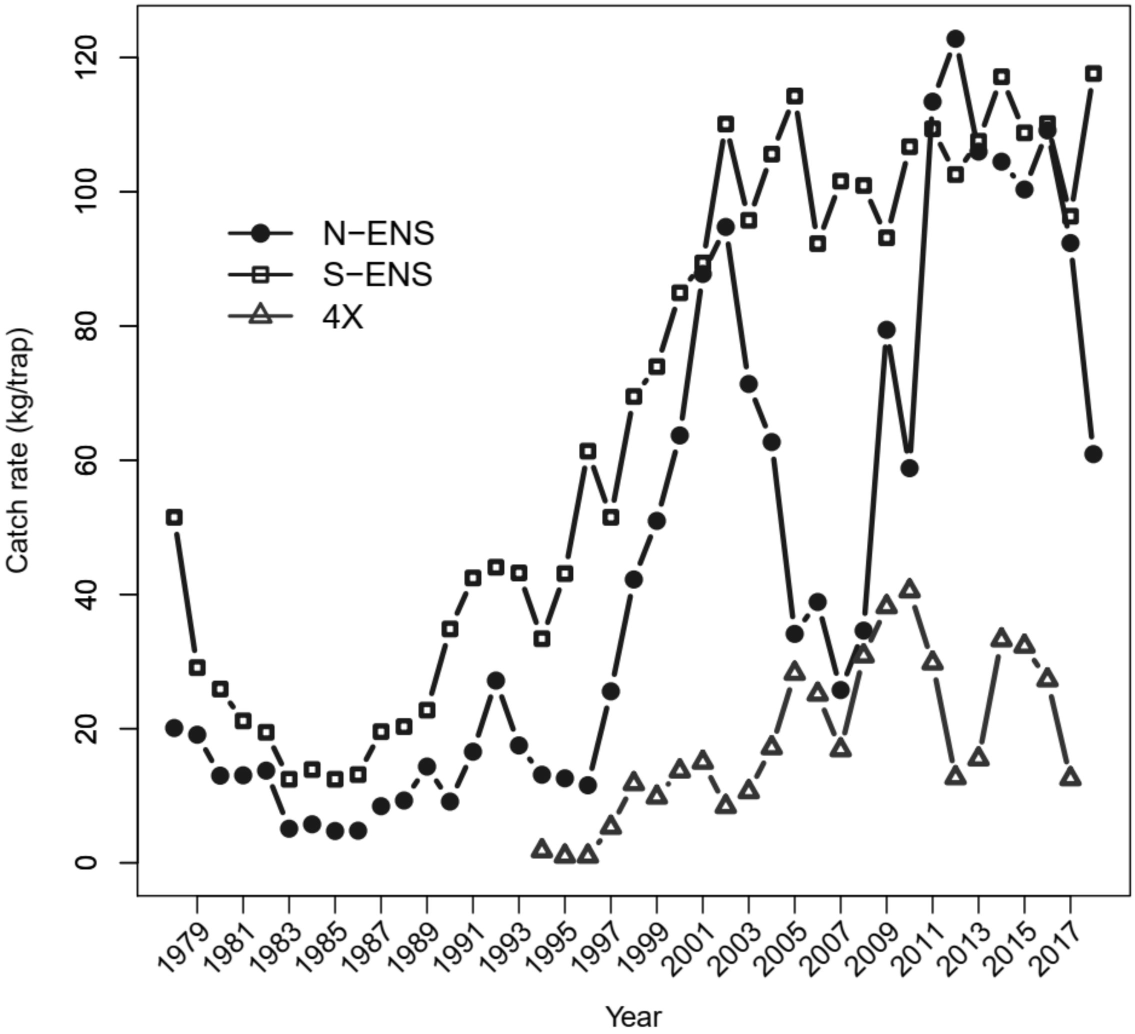
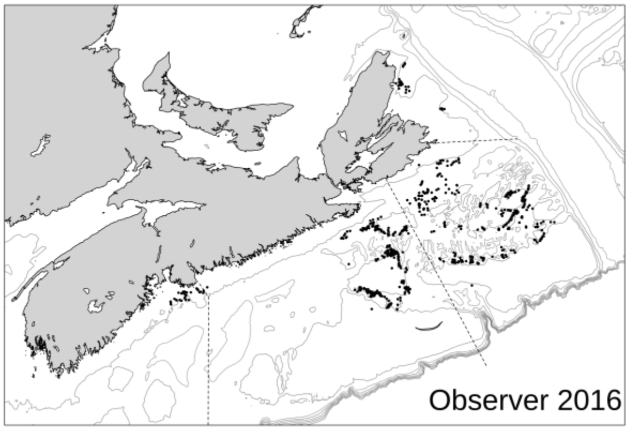
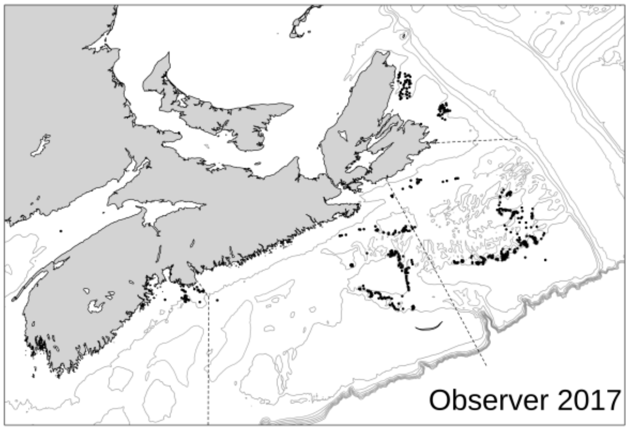


Figure 4. Temporal variations in catch rates of Snow Crab on the Scotian Shelf, expressed as kg per trap haul. Trap design and size have changed over time. No correction for these varying trap-types nor soak time and bait-type has been attempted (see Methods). Year in 4X refers to the year at the start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





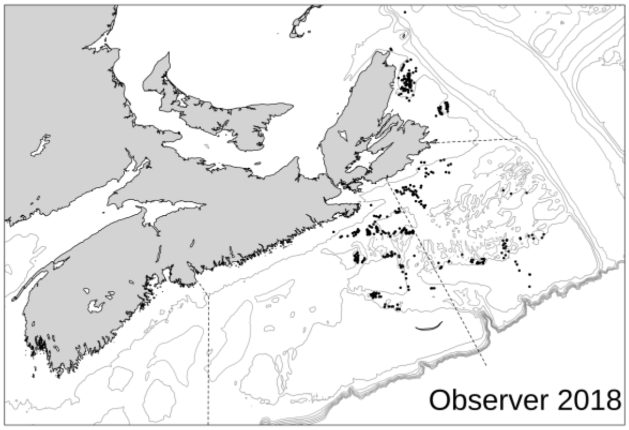


Figure 5. Snow Crab fishing locations monitored by at-sea-observers on the Scotian Shelf during each of the past three fishing seasons.

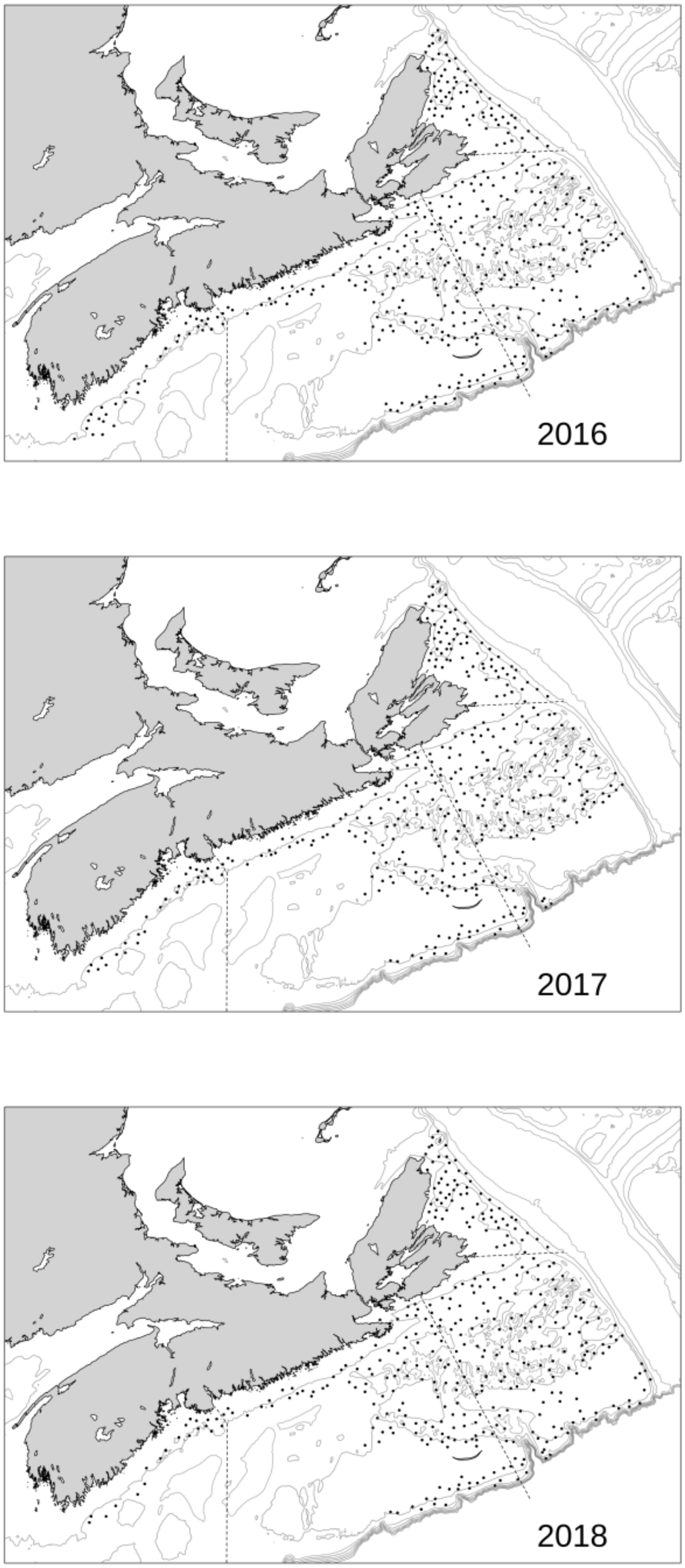
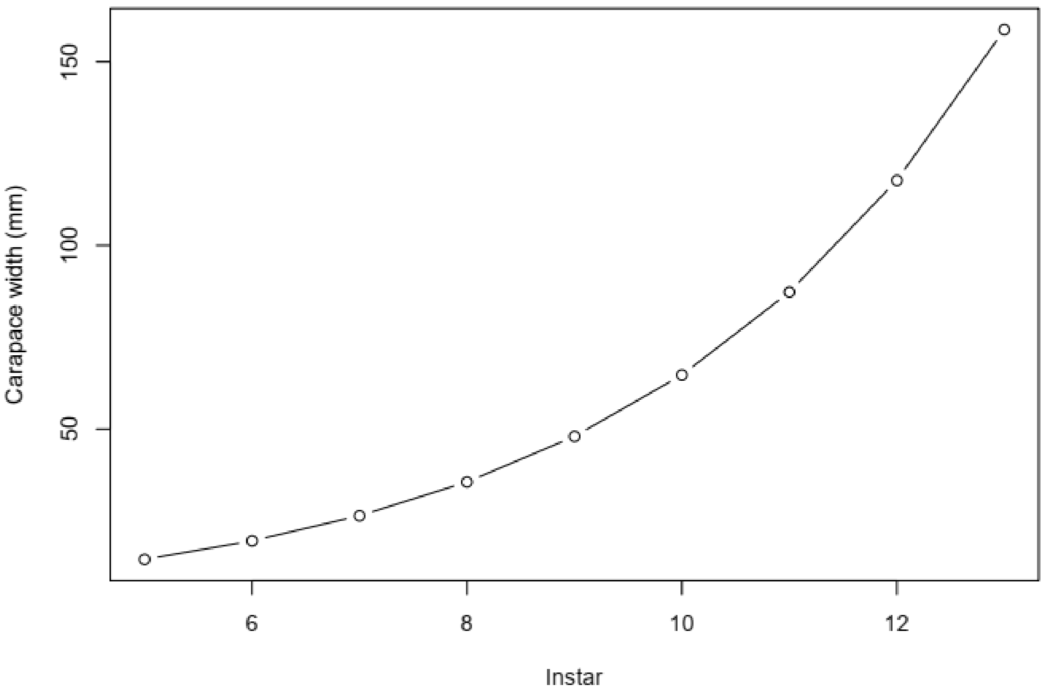


Figure 6. Locations of Snow Crab survey trawl sets on the Scotian Shelf during each of the past three years. Note stations not completed in Southeastern-most region for 2017 survey as compared to other years.



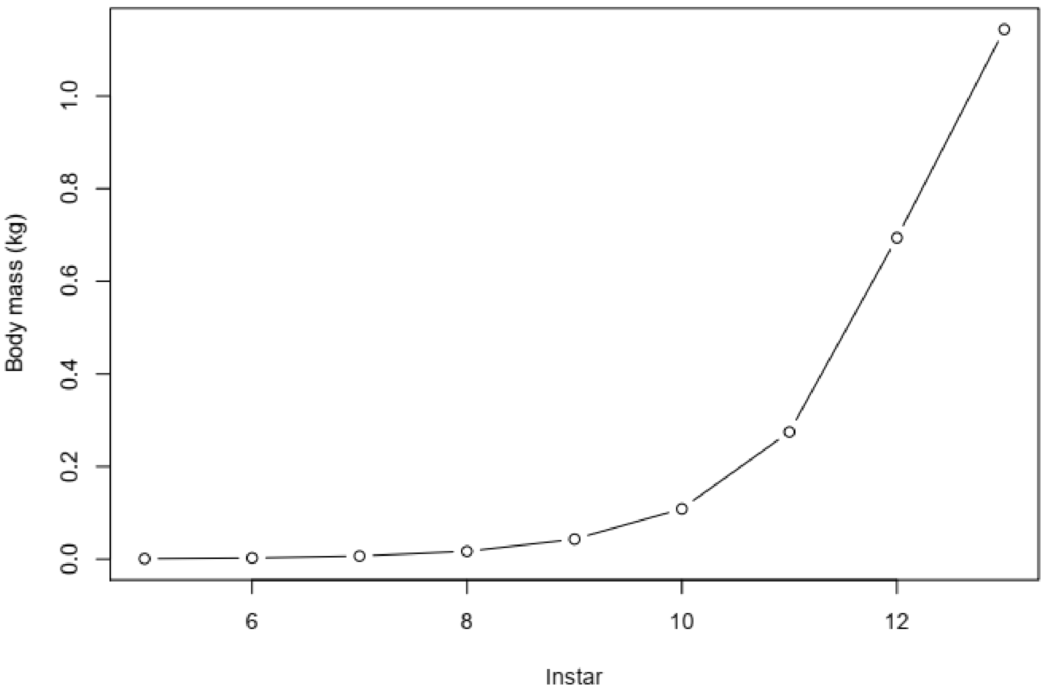


Figure 7. Growth curves determined from modal length frequency analysis of male Snow Crab on the Scotian Shelf.

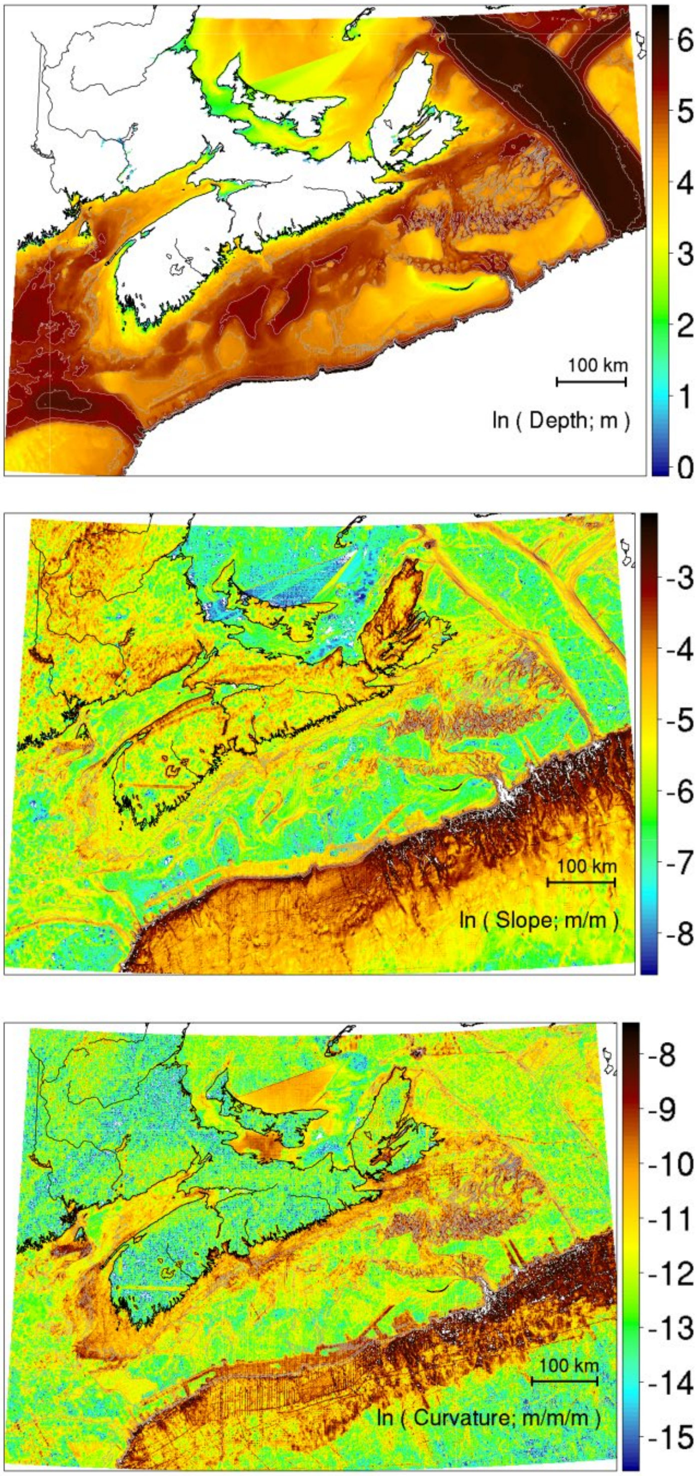


Figure 8. Habitat characteristics used for modeling Snow Crab habitat delineation. From top to bottom panels: depth, slope, curvature.

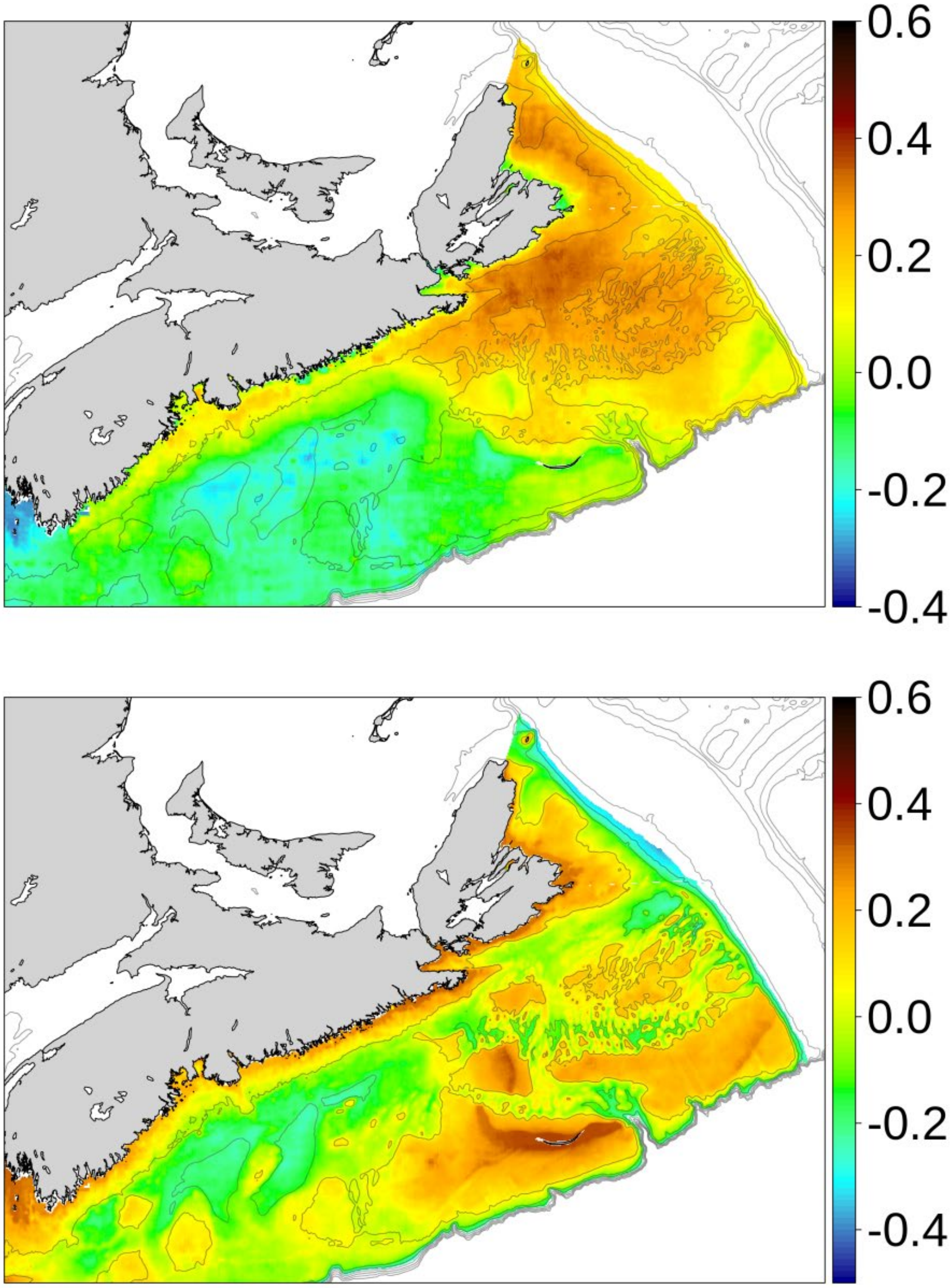


Figure 9. Principal component analysis of species composition (community) characteristics on the Scotian Shelf used in Snow Crab habitat determination modelling. Annual time series are used. Top figure is the first axis or ordination; bottom figure is second axis of ordination.

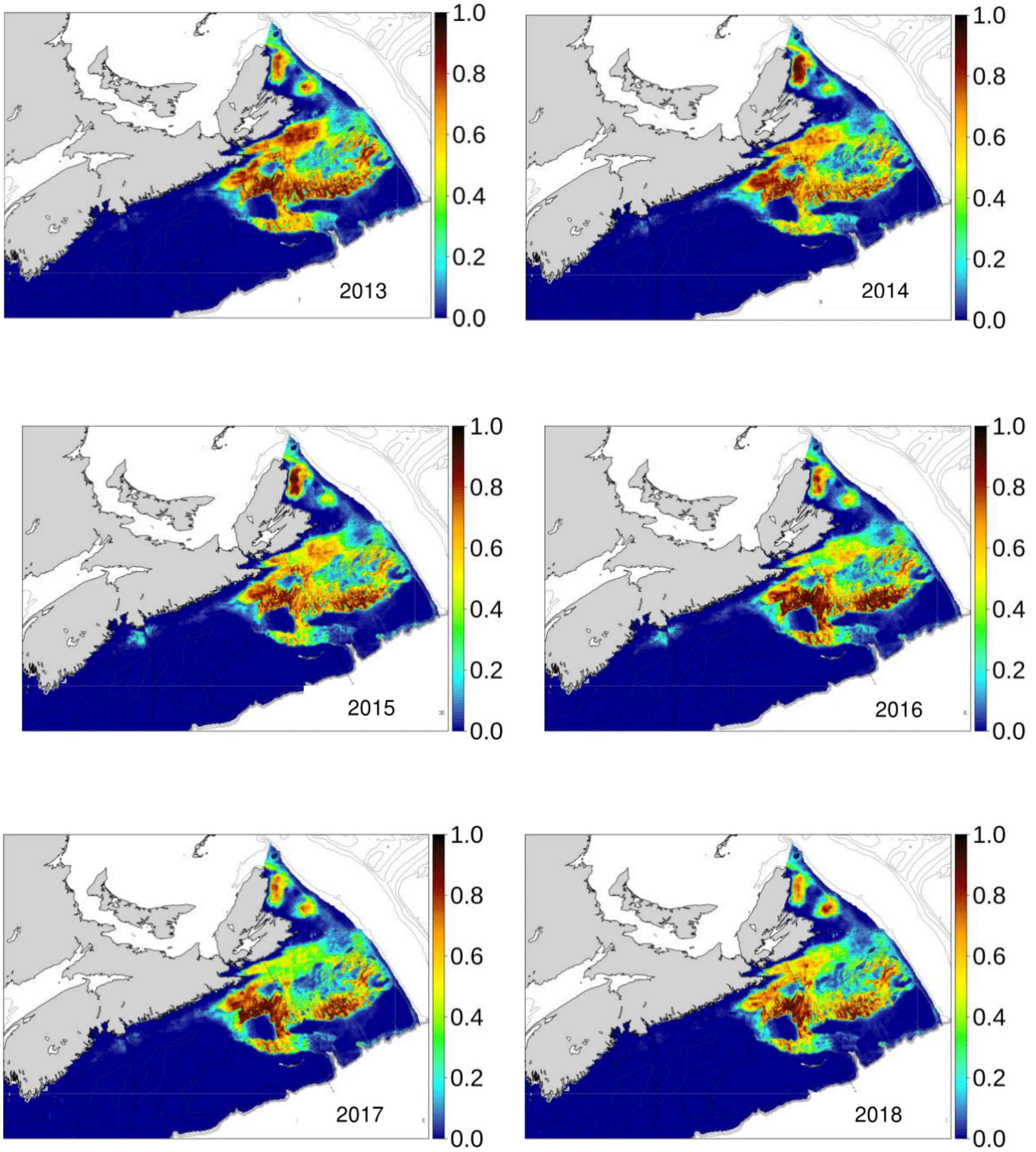


Figure 10. Annual interpolations of potential habitat for the fishable component of Scotian Shelf Snow Crab represented as the probability of finding Snow Crab. Spatial representations are generated with stmv modelling using generalized additive models of several habitat, environmental, and biological variables.

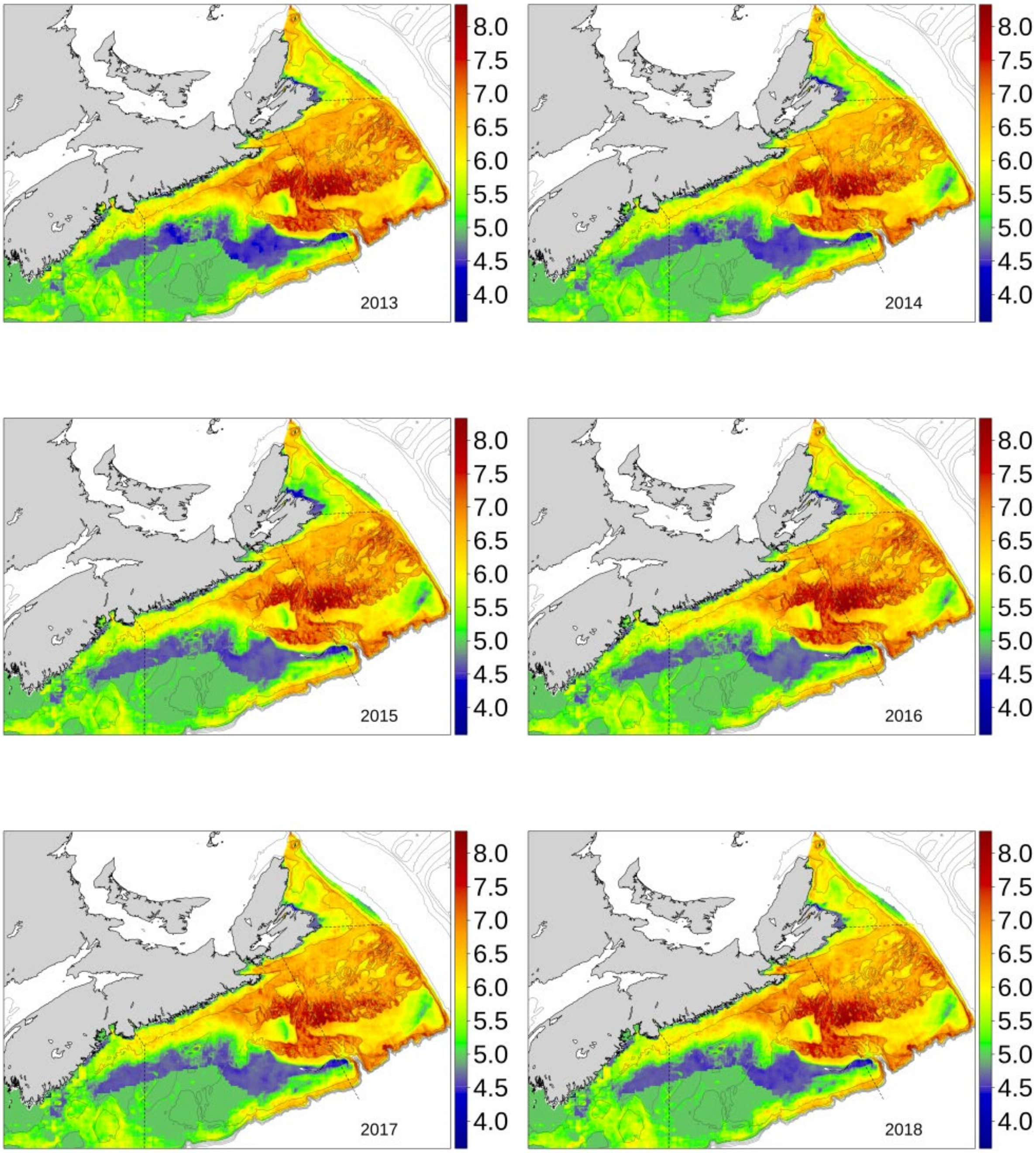


Figure 11. Annual interpolations of fishable Snow Crab biomass expressed as log(t/km^2). Spatial representations are generated with stmv modelling using generalized additive models of several habitat, environmental and biological variables. Likely an over-representation given the current limitations of this modelling approach.

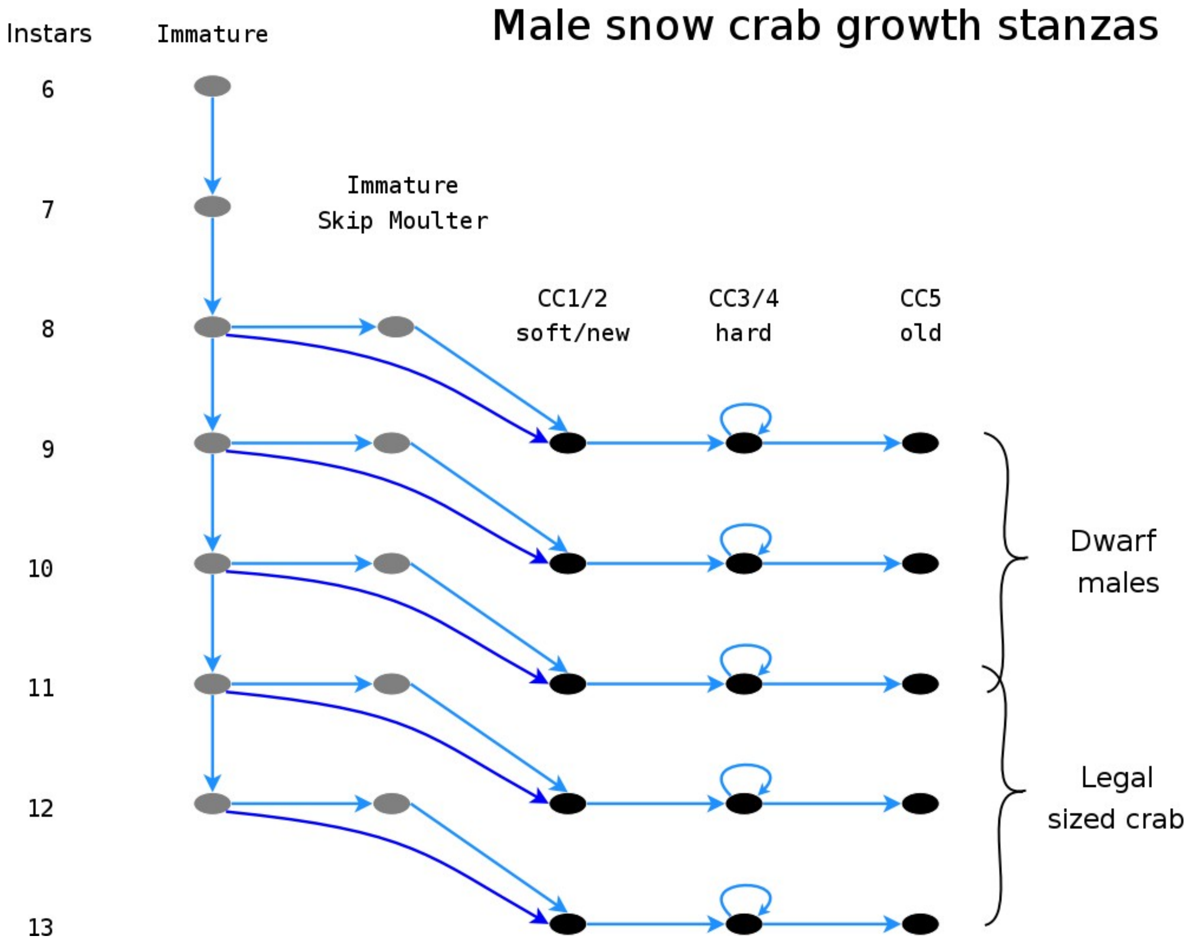


Figure 12. The growth stanzas of male Snow Crab. Each instar is determined from Carapace Width bounds obtained from modal analysis and categorized to Carapace Condition (CC) and maturity from visual inspection and/or maturity equations. Snow Crab are resident in each growth stanza for 1 year, with the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

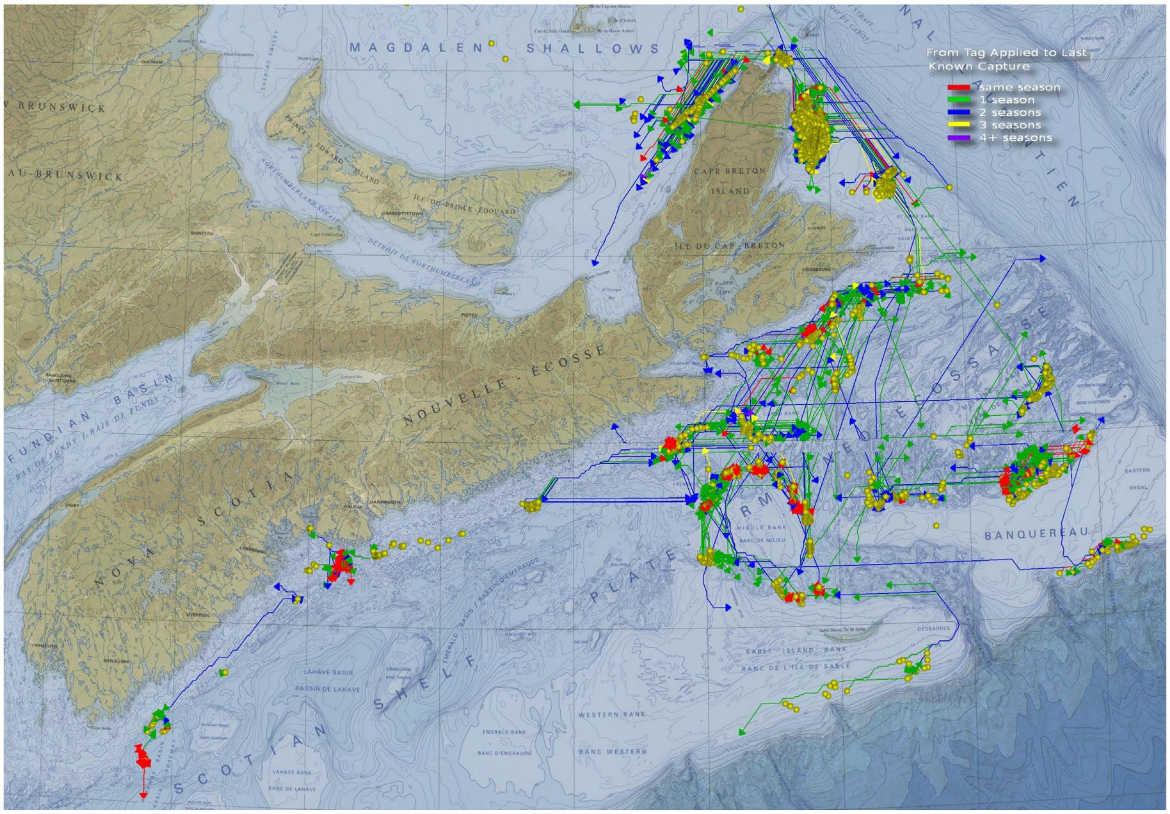


Figure 13. Movement of mature male Snow Crab on the Scotian Shelf. Movement path between release and recapture locations is constrained to the shortest path within depth contours of 60 and 280 m. Circles represent release locations and colours represent time interval (in years) between initial tagging and last recapture.

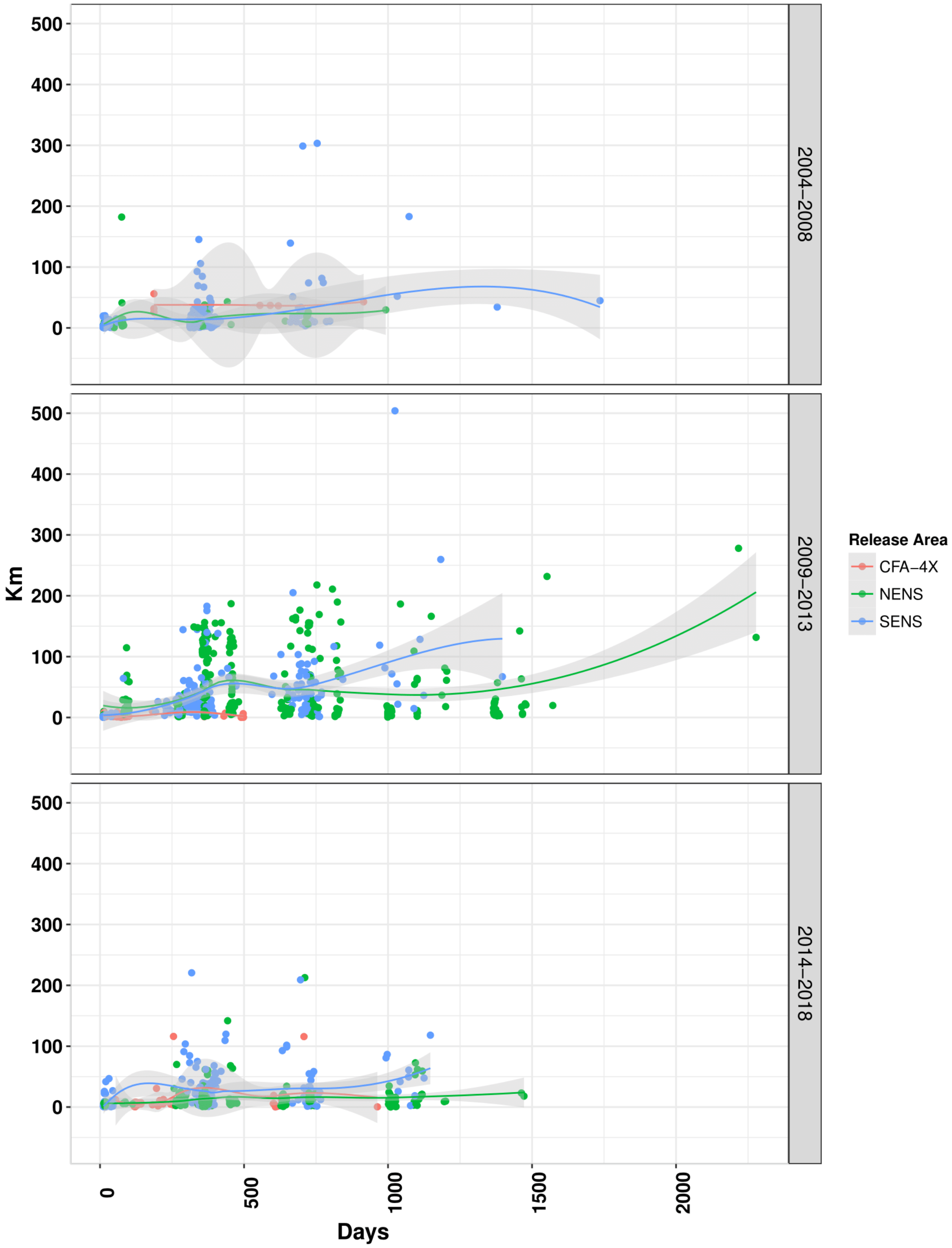
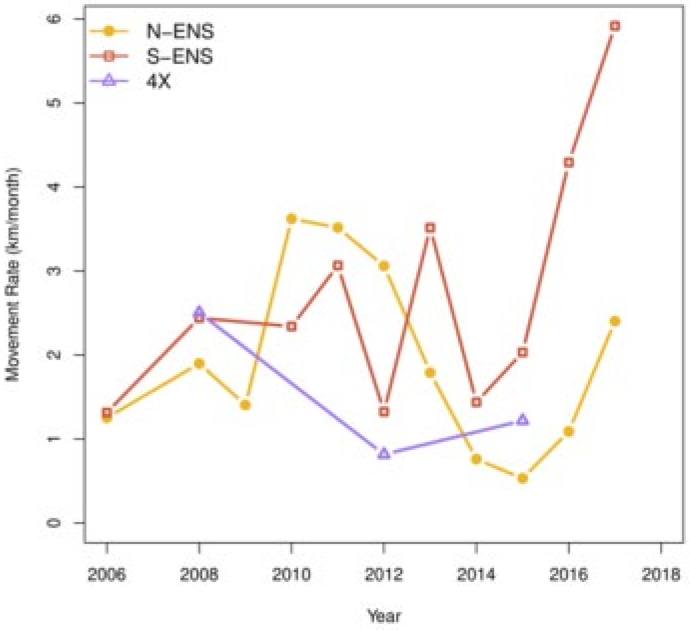


Figure 14. Distance travelled vs. time to capture for tagged Snow Crab on the Scotian Shelf since 2004. Data grouped by release year with release area distinguished by color. Periodicity in time intervals are explained by recaptures occurring during seasonal fishing operations.



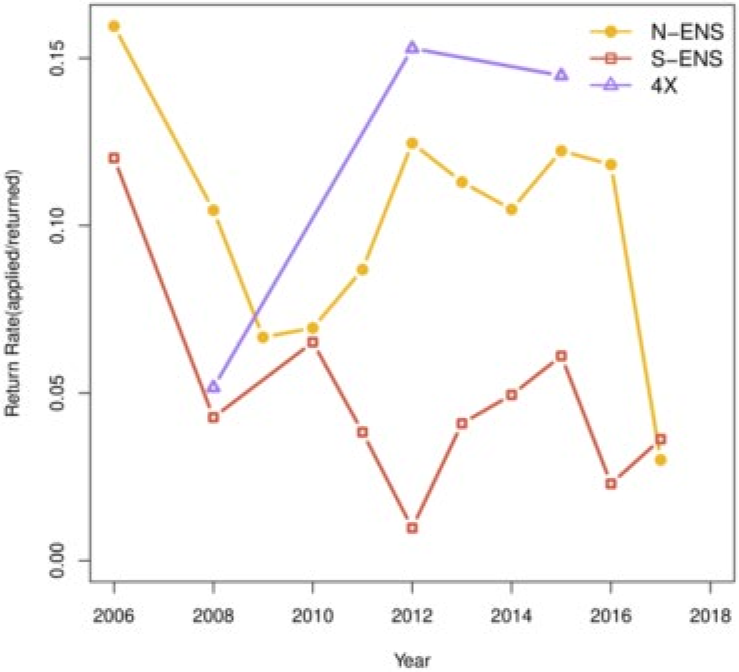


Figure 15. (Top) Mean rate of movement of Snow Crab tagged on the Scotian Shelf by area and year. Route lengths derived from calculated shortest paths as constrained by depth range of 60–280 m. Small sample size and short time between mark and potential recapture account for the higher than normal rates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

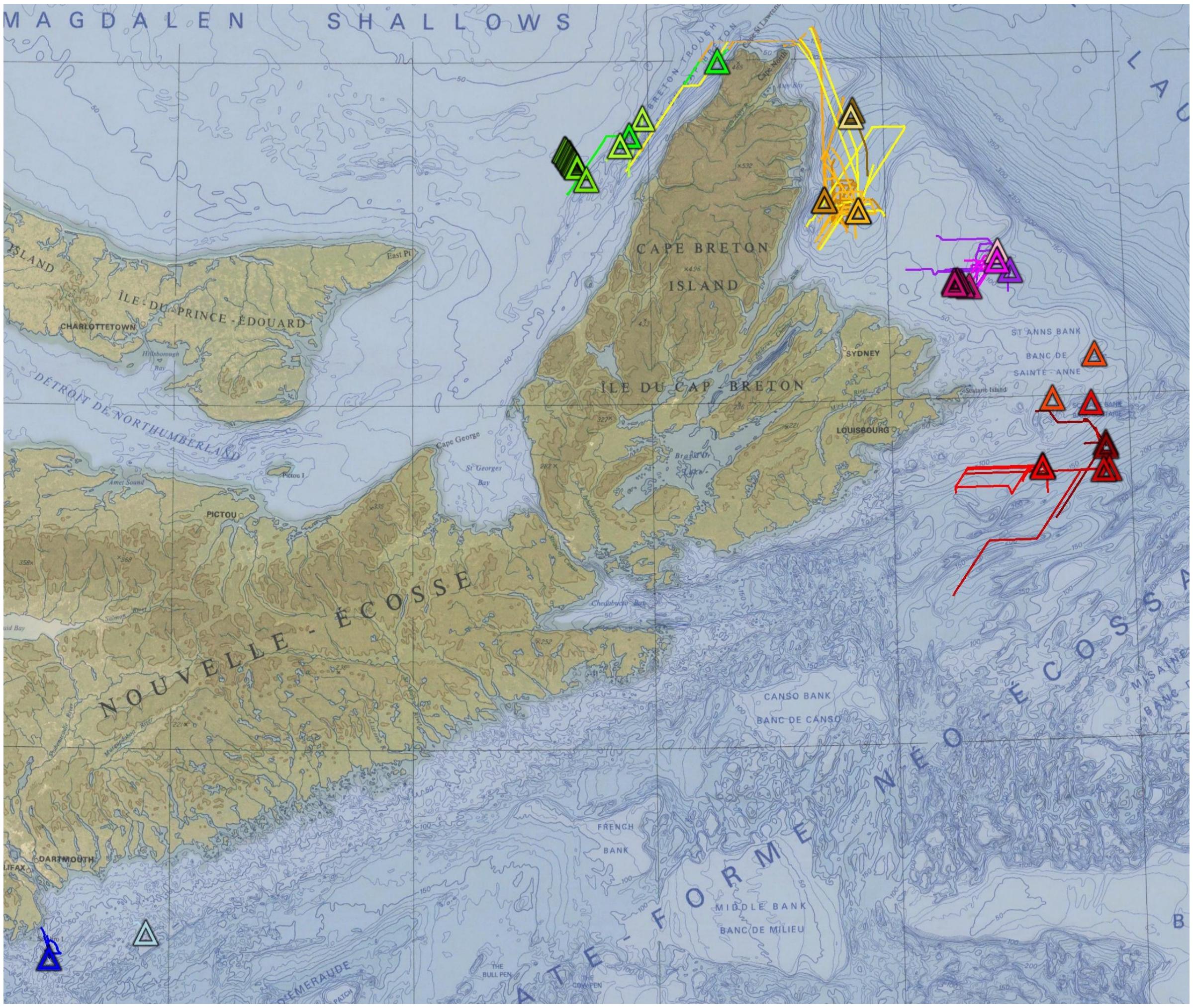


Figure 16. Movement of acoustic tagged Snow Crab on the Scotian Shelf. Movement path between mark and detection locations is constrained to the shortest path within depth contours of 60 and 280 m. Triangles represent release locations and individual colours represent individual tagged animals.

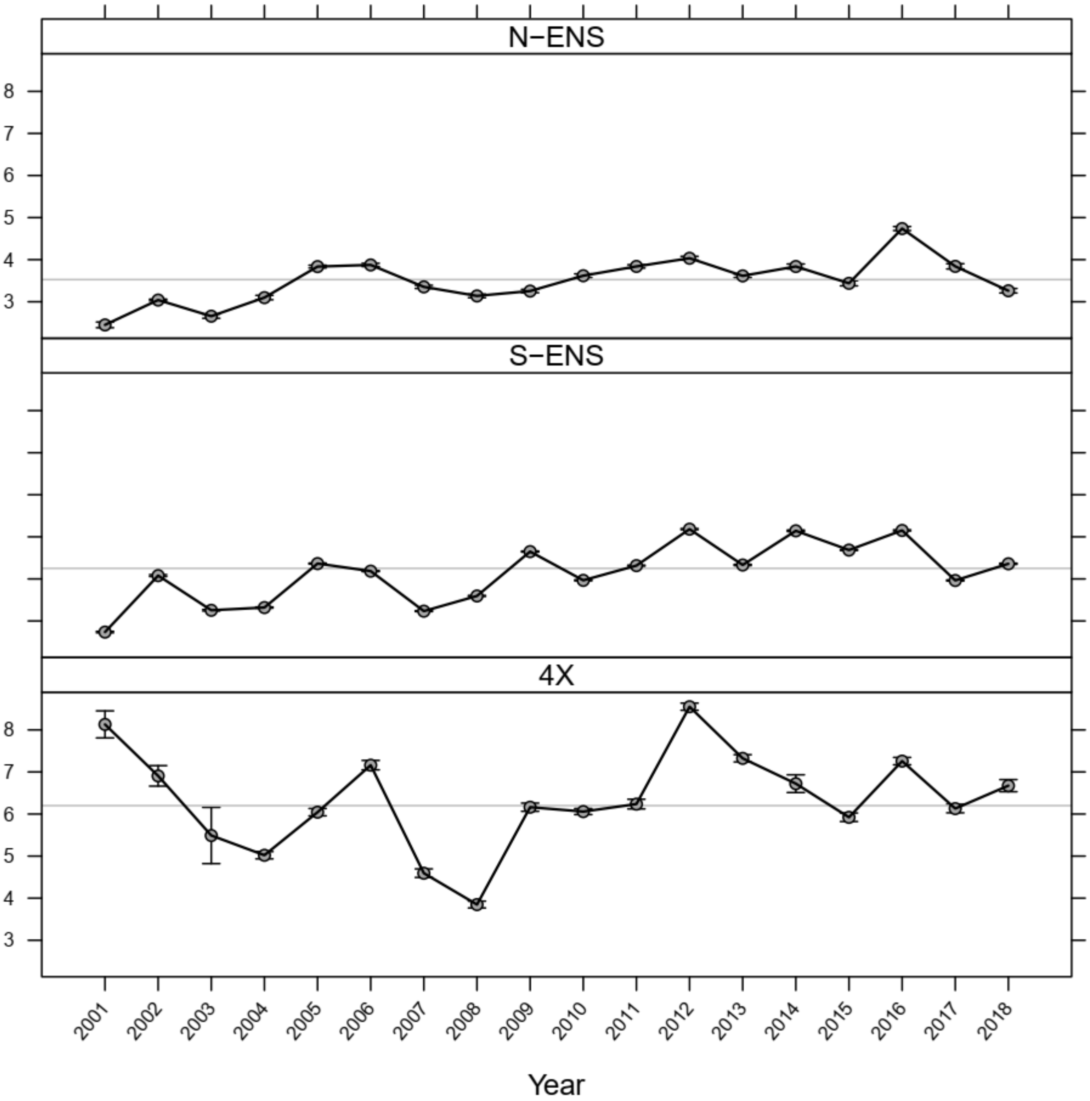


Figure 17. Annual variations in bottom temperature (°C) observed during the Eastern Nova Scotia (ENS) Snow Crab survey. The horizontal line indicates the long-term median temperature within each subarea. Error bars are 1 standard deviation.

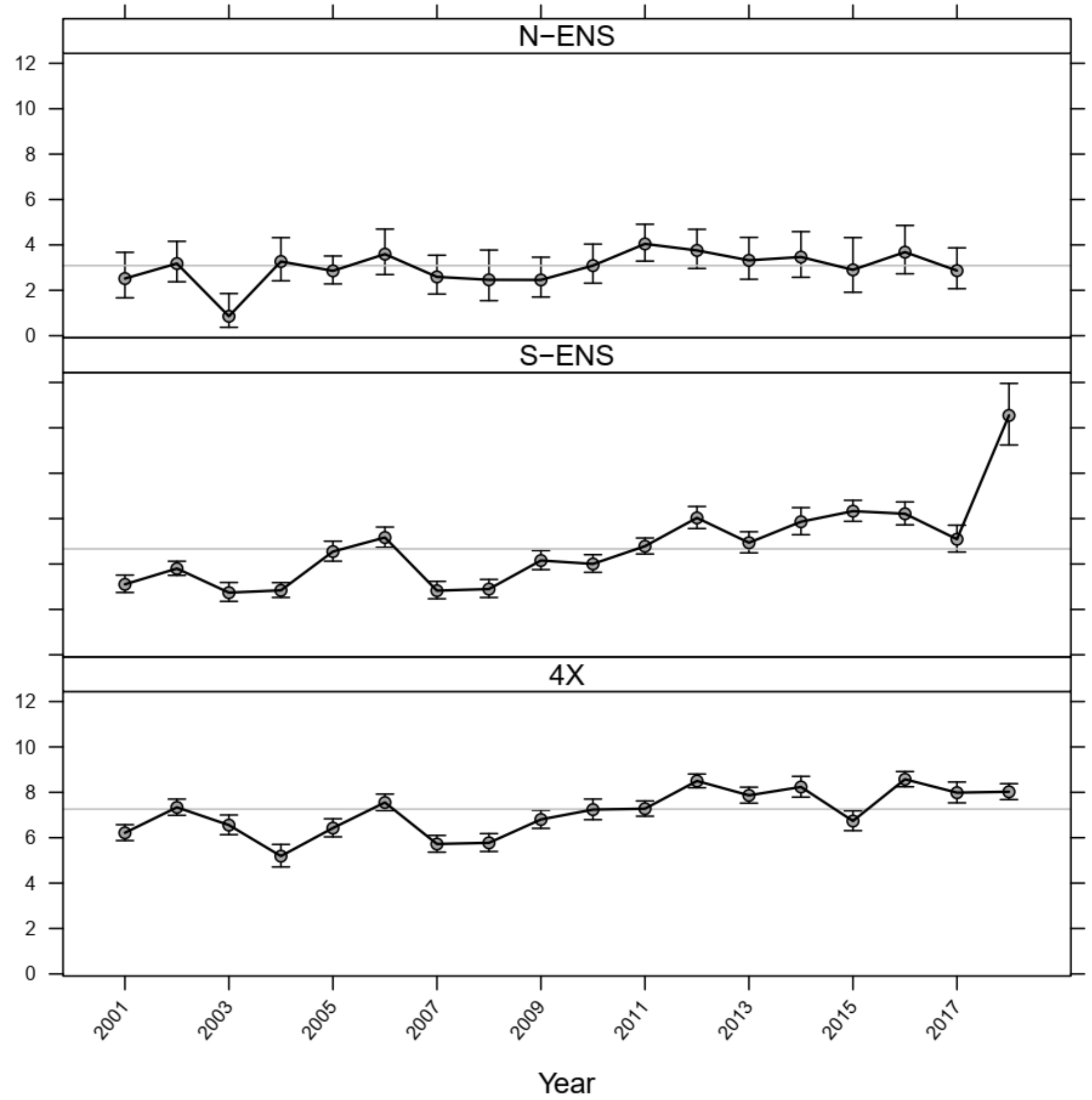


Figure 18. Annual variations in bottom temperature (°C) observed during the DFO Summer Research Vessel Survey. The horizontal line indicates the long-term median temperature within each subarea. Error bars are 1 standard deviation. Very few of the intended stations were completed on the Eastern Scotian Shelf in 2018—no data for North-Eastern Nova Scotia (N-ENS), incomplete for South-Eastern Nova Scotia (S-ENS).

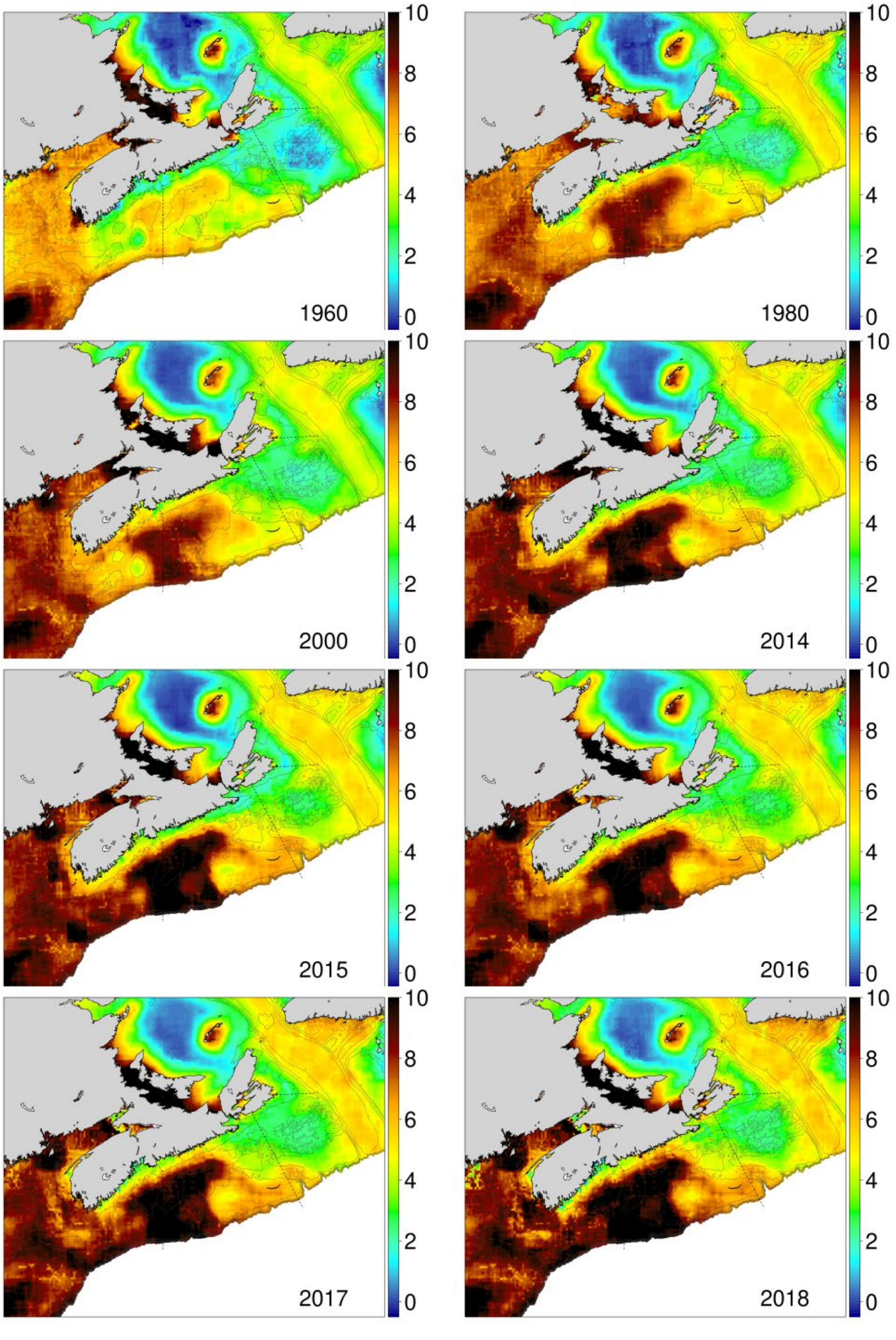


Figure 19. Interpolated mean annual bottom temperatures on the Scotian Shelf for selected years. These interpolations use all available water temperature data collected in the area including DFO Summer RV Surveys, Snow Crab survey, and AZMP monitoring stations.

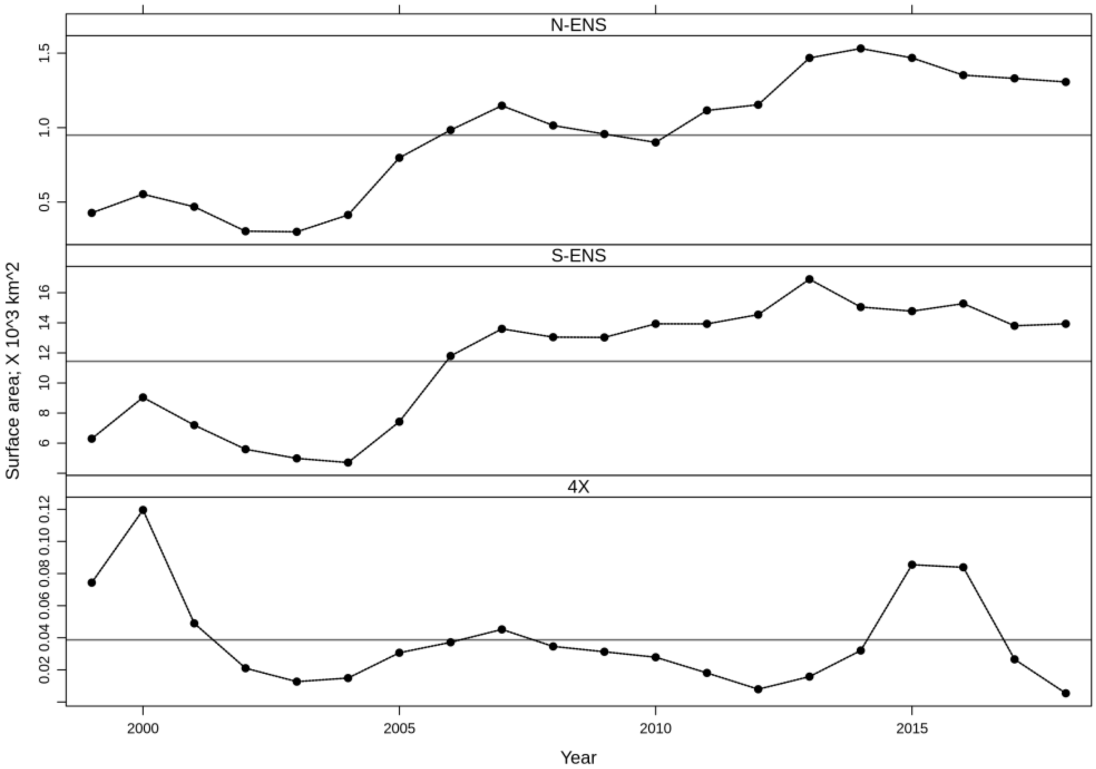


Figure 20. Annual variations in the surface area of potential Snow Crab habitat. The horizontal line indicates the long-term median surface area within each subarea.

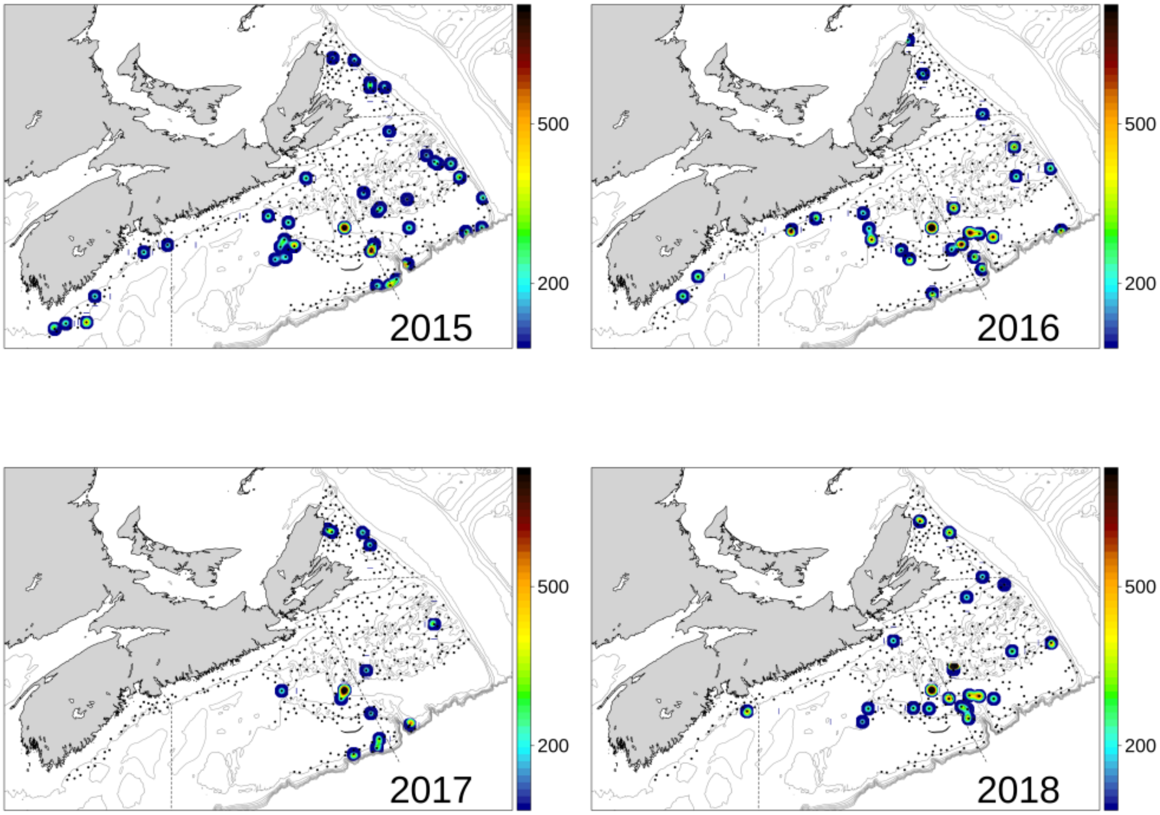


Figure 21. Locations of potential predators of Snow Crab on the Scotian Shelf from the annual Snow Crab survey. ***Atlantic Halibut.*** *Scale is number/km^2.*

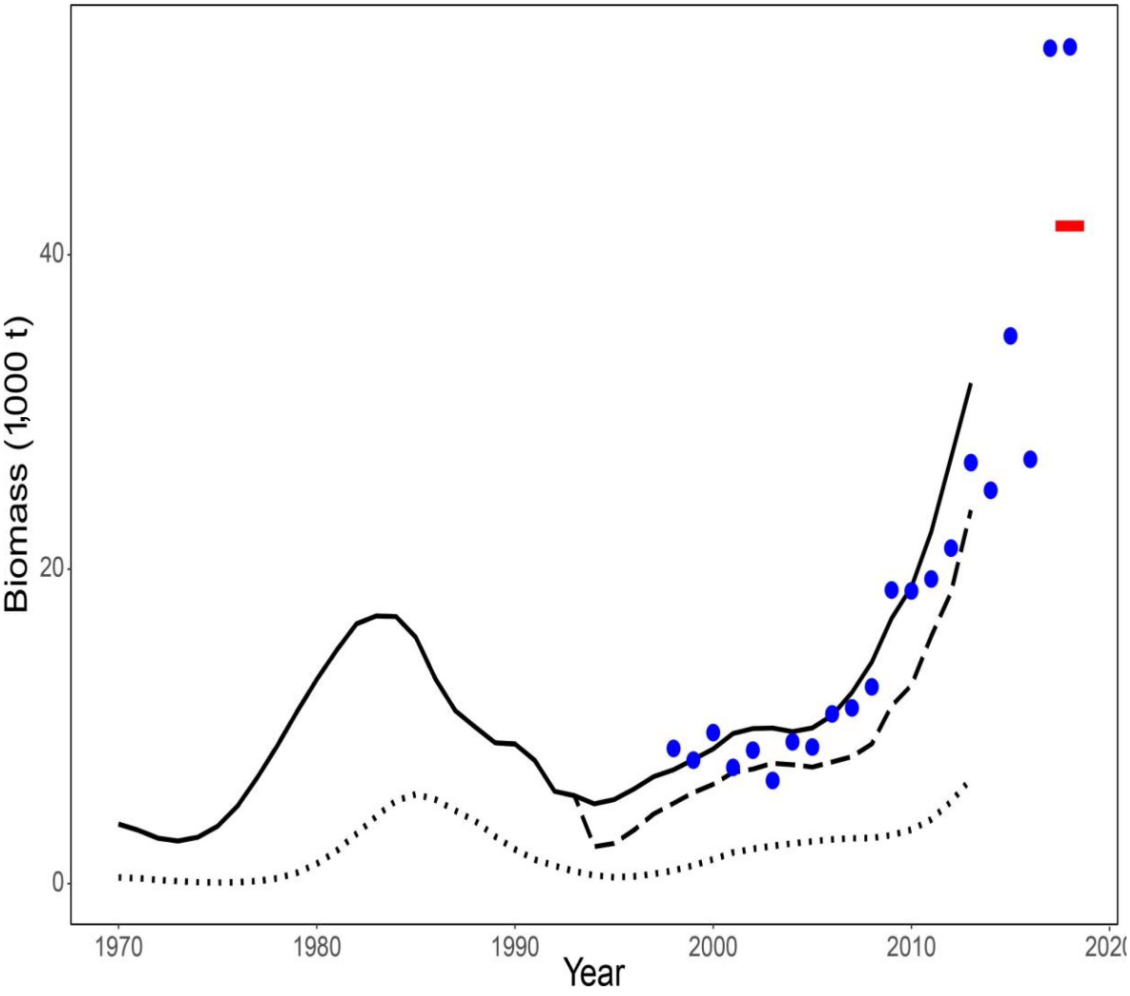


Figure 22. Atlantic Halibut biomass for Scotian Shelf and Southern Grand Banks from stock assessment model (black lines) and the Halibut Survey Index Stations (blue circles). The solid black line is total biomass, the dashed line is legal biomass, and the dotted line is spawning stock biomass. The solid red bar is the current 3-year mean of the Halibut Survey biomass index. Source: DFO 2018a.

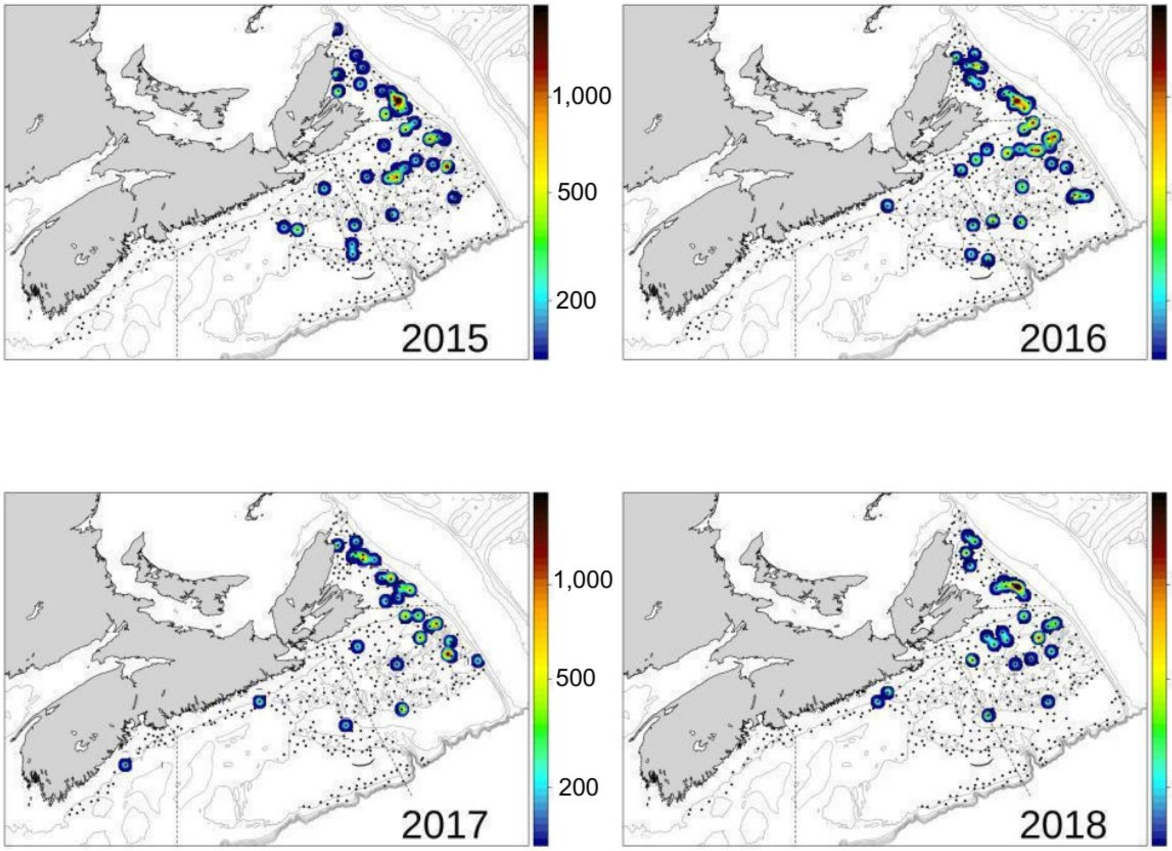


Figure 23. Locations of potential predators of Snow Crab on the Scotian Shelf from the annual Snow Crab survey: ***Atlantic Striped Wolffish****. Scale is number/km*^{2} *.*

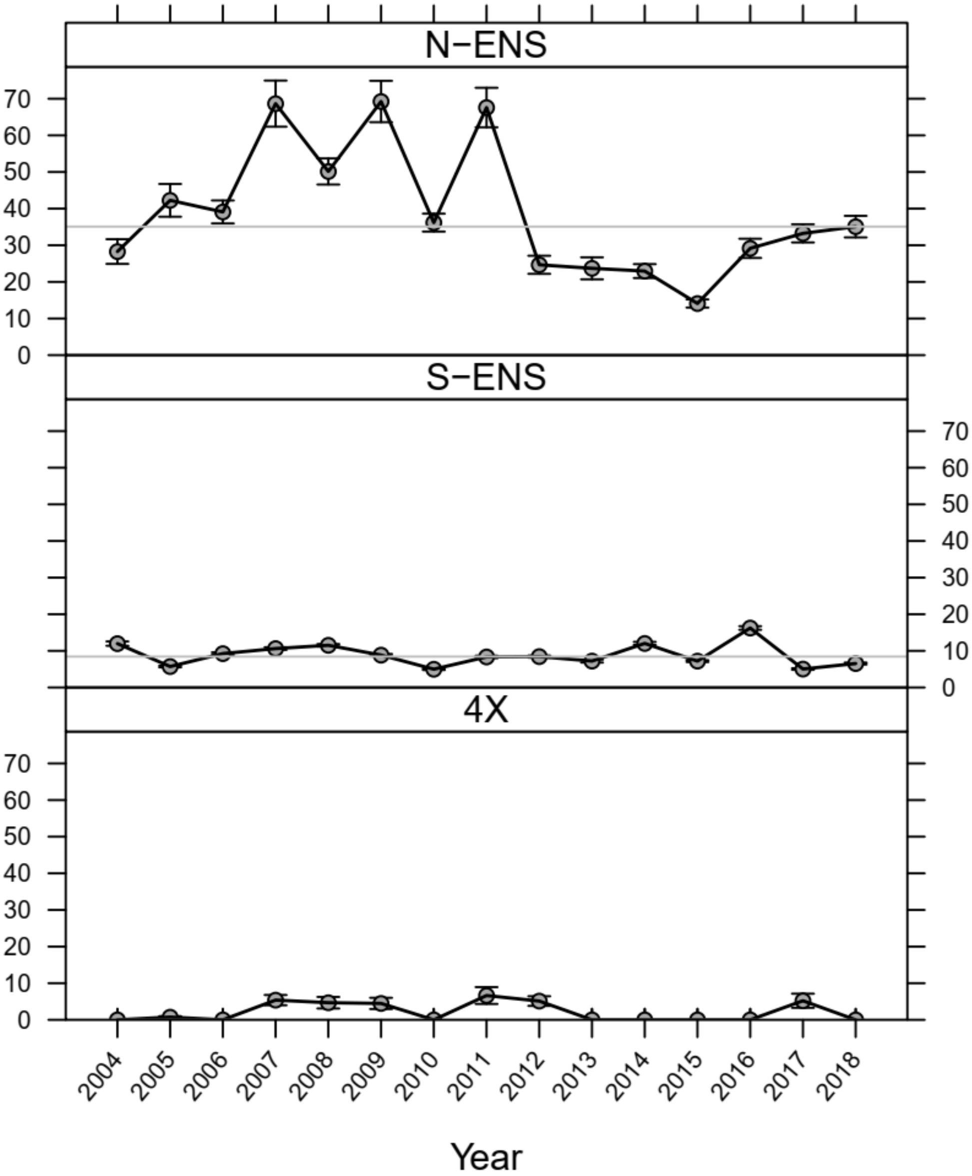


Figure 24. Trends in biomass (kg/km^2) of potential predators of Snow Crab from the annual Snow Crab survey on the Scotian Shelf: ***Atlantic Striped Wolffish***.

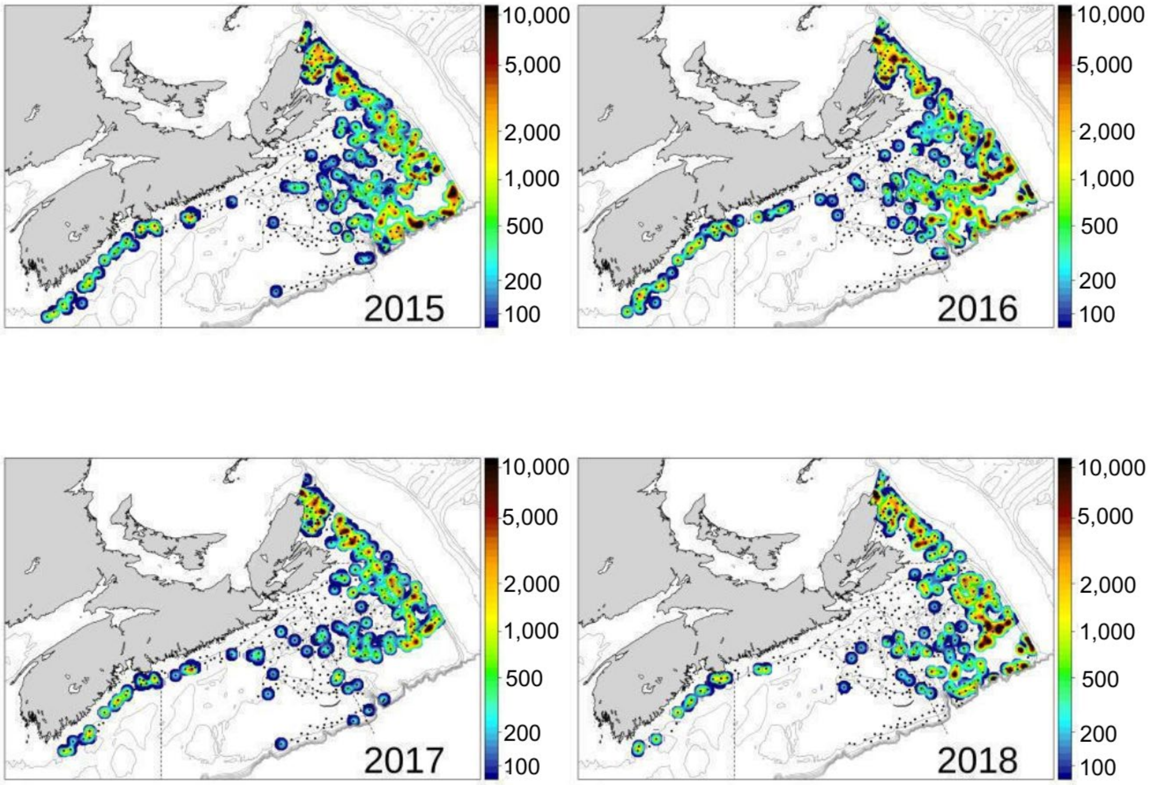


Figure 25. Locations of potential predators of Snow Crab on the Scotian Shelf from the annual Snow Crab survey: ***Thorny Skate****. Scale is number/km*^{2}*.*

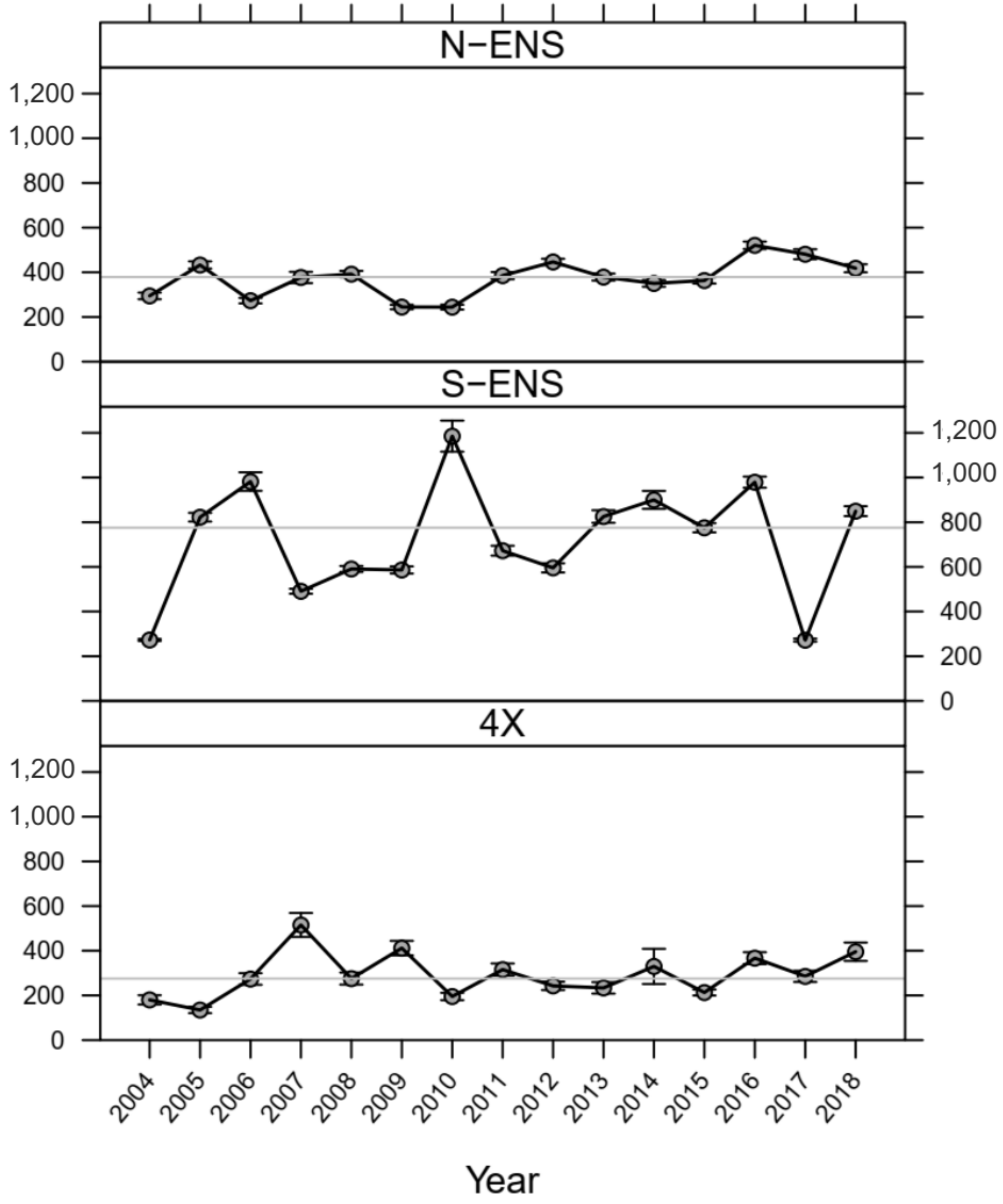


Figure 26. Trends in biomass (kg/km^2) of potential predators of Snow Crab from the annual Snow Crab survey on the Scotian Shelf: ***Thorny Skate****.*

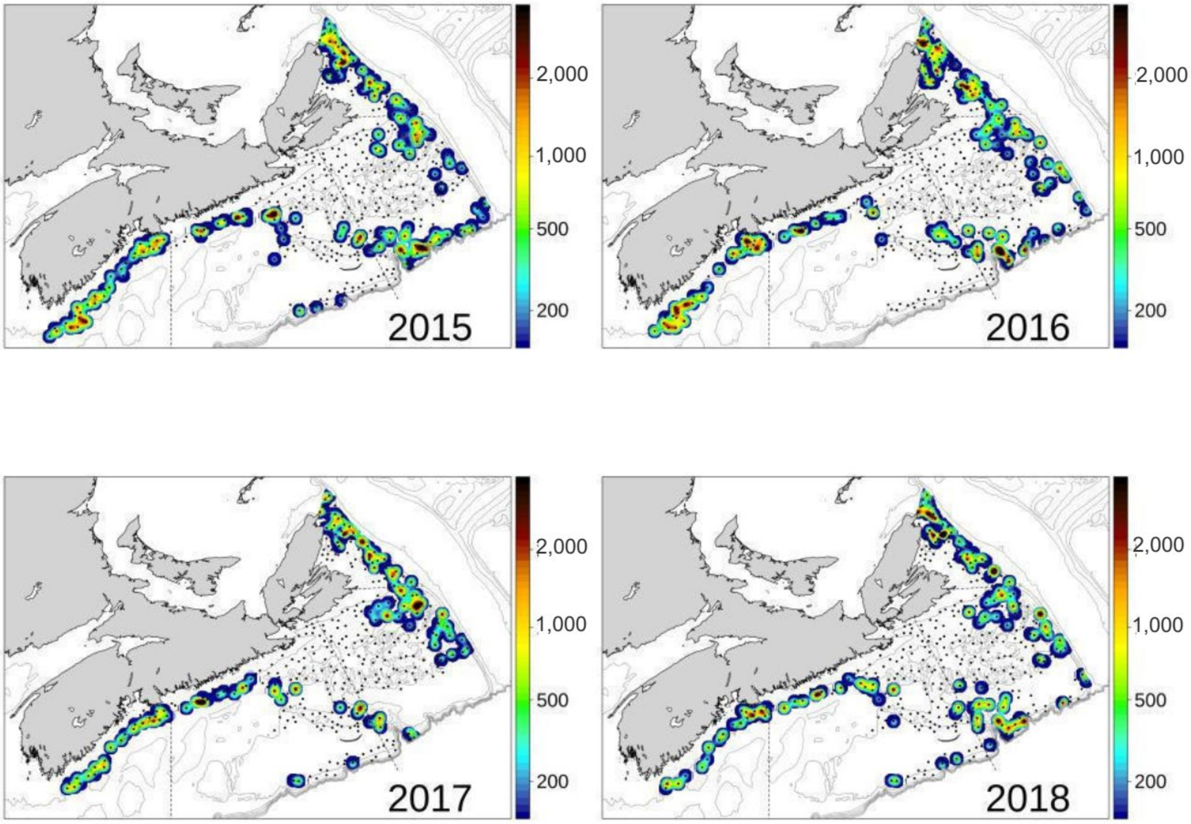


*Figure 27. Locations of potential predators of Snow Crab on the Scotian Shelf from the annual Snow Crab survey: **Smooth Skate**. Scale is number/km^2.*

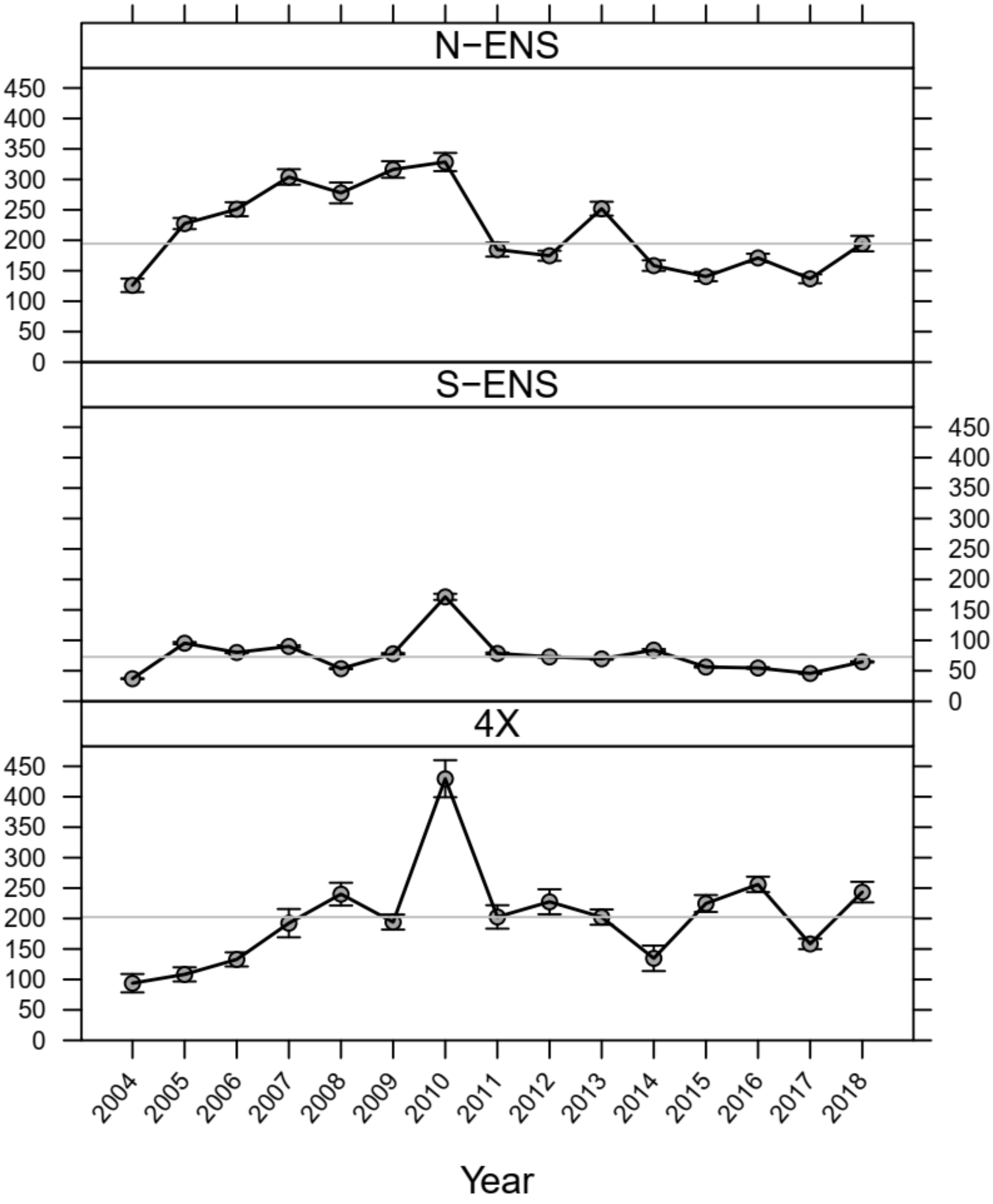


Figure 28. Trends in biomass (kg/km^2) of potential predators of Snow Crab from the annual Snow Crab survey on the Scotian Shelf: ***Smooth Skate****.*

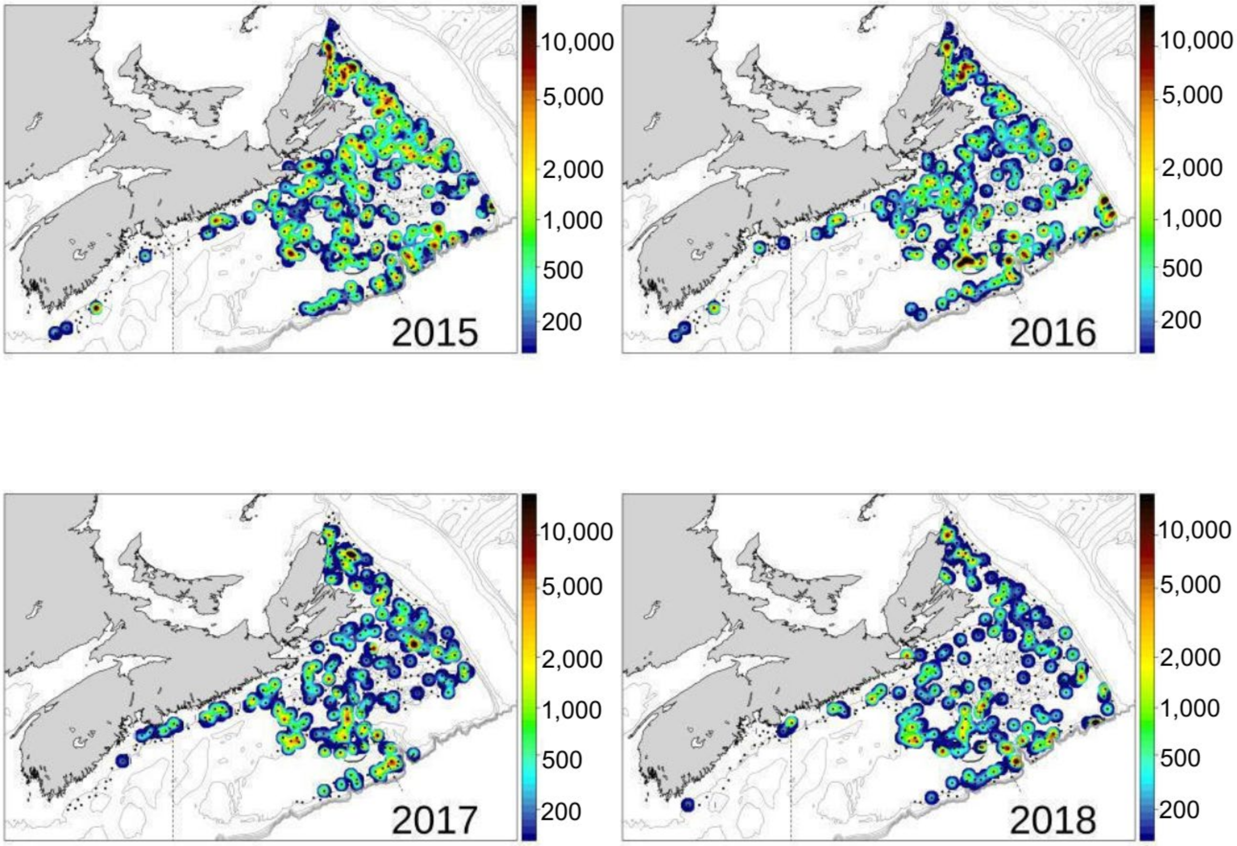


*Figure 29. Locations of potential predators of Snow Crab on the Scotian Shelf from the annual Snow Crab survey: **Atlantic Cod**. Scale is number/km^2.*

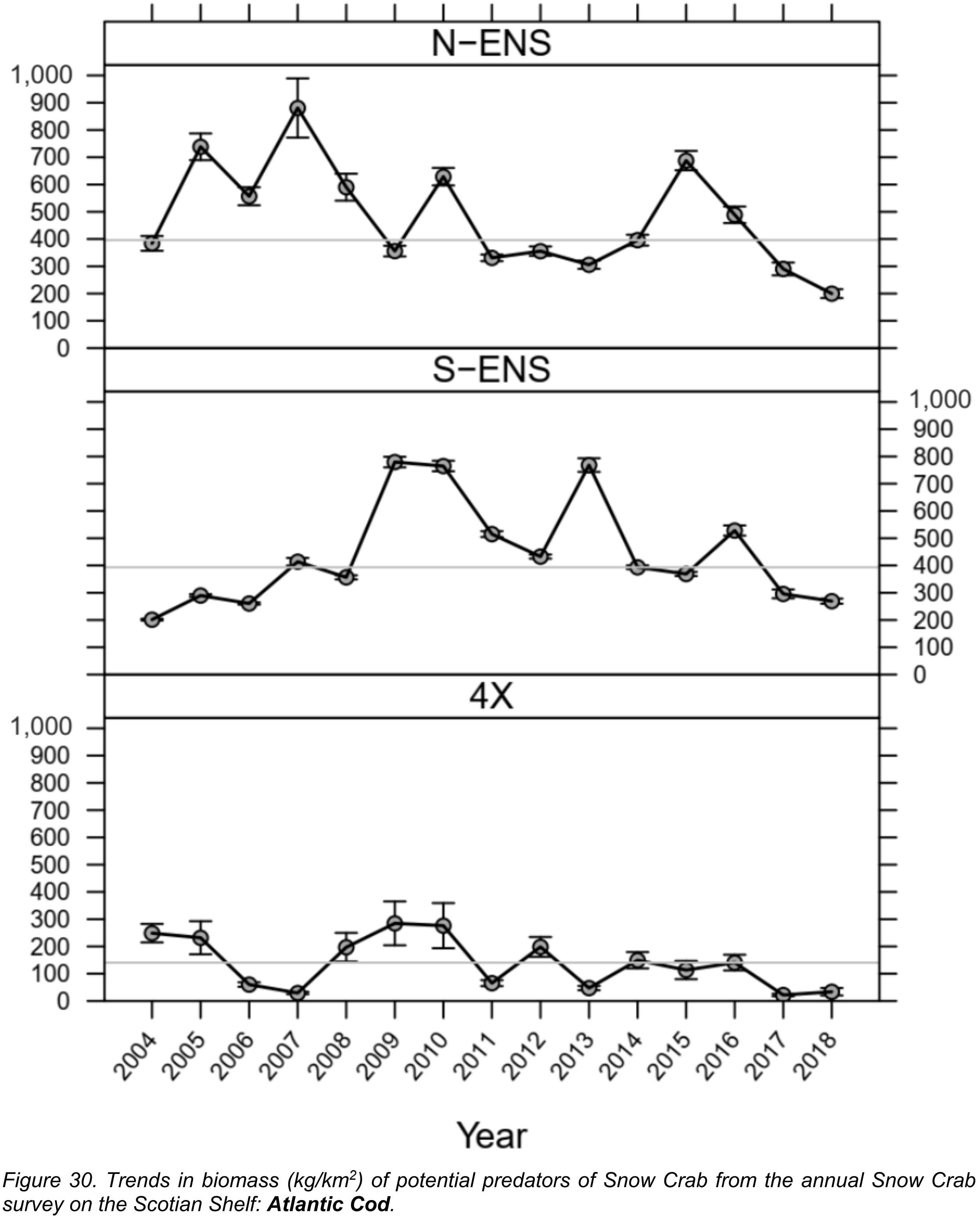


Figure 30. Trends in biomass (kg/km^2) of potential predators of Snow Crab from the annual Snow Crab survey on the Scotian Shelf: ***Atlantic Cod****.*

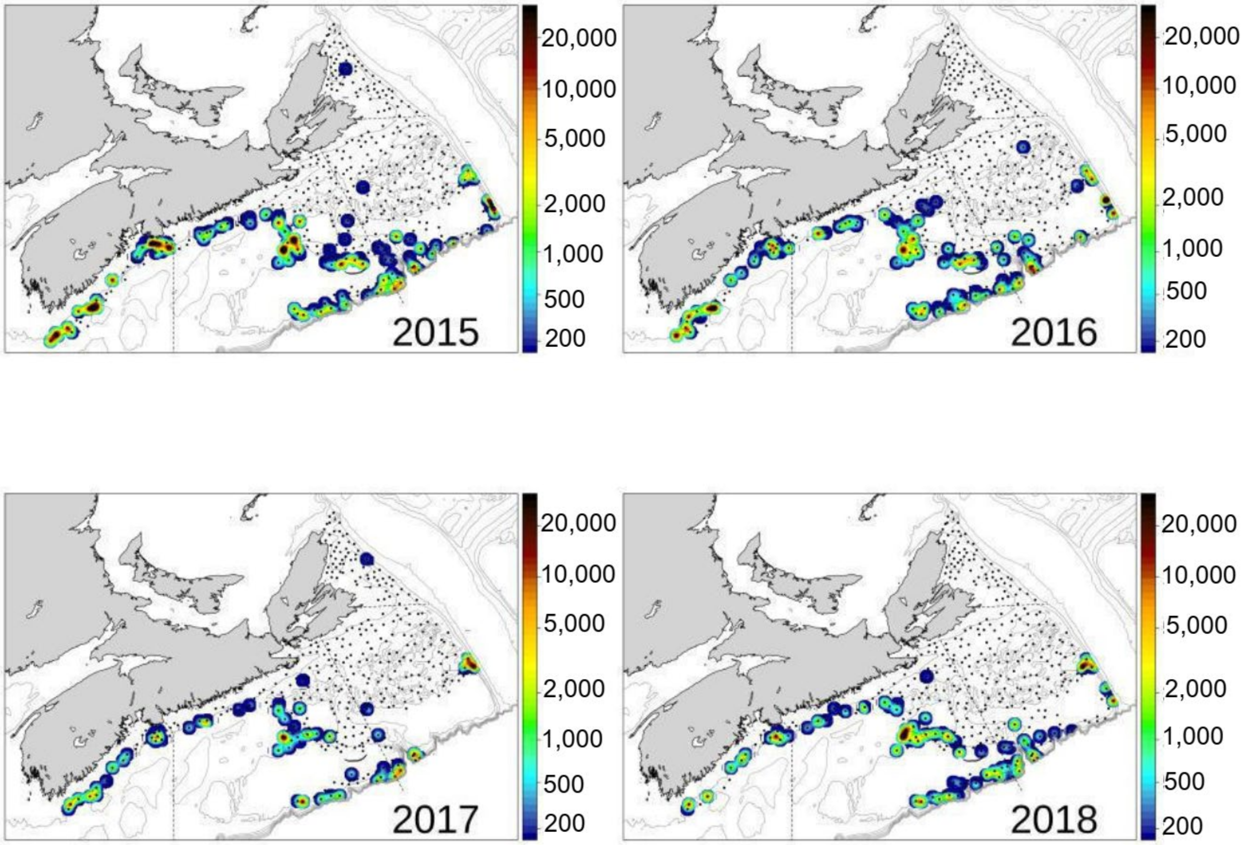


Figure 31. Locations of potential predators of Snow Crab on the Scotian Shelf from the annual Snow Crab survey: ***Haddock.*** *Scale is number/km^2.*

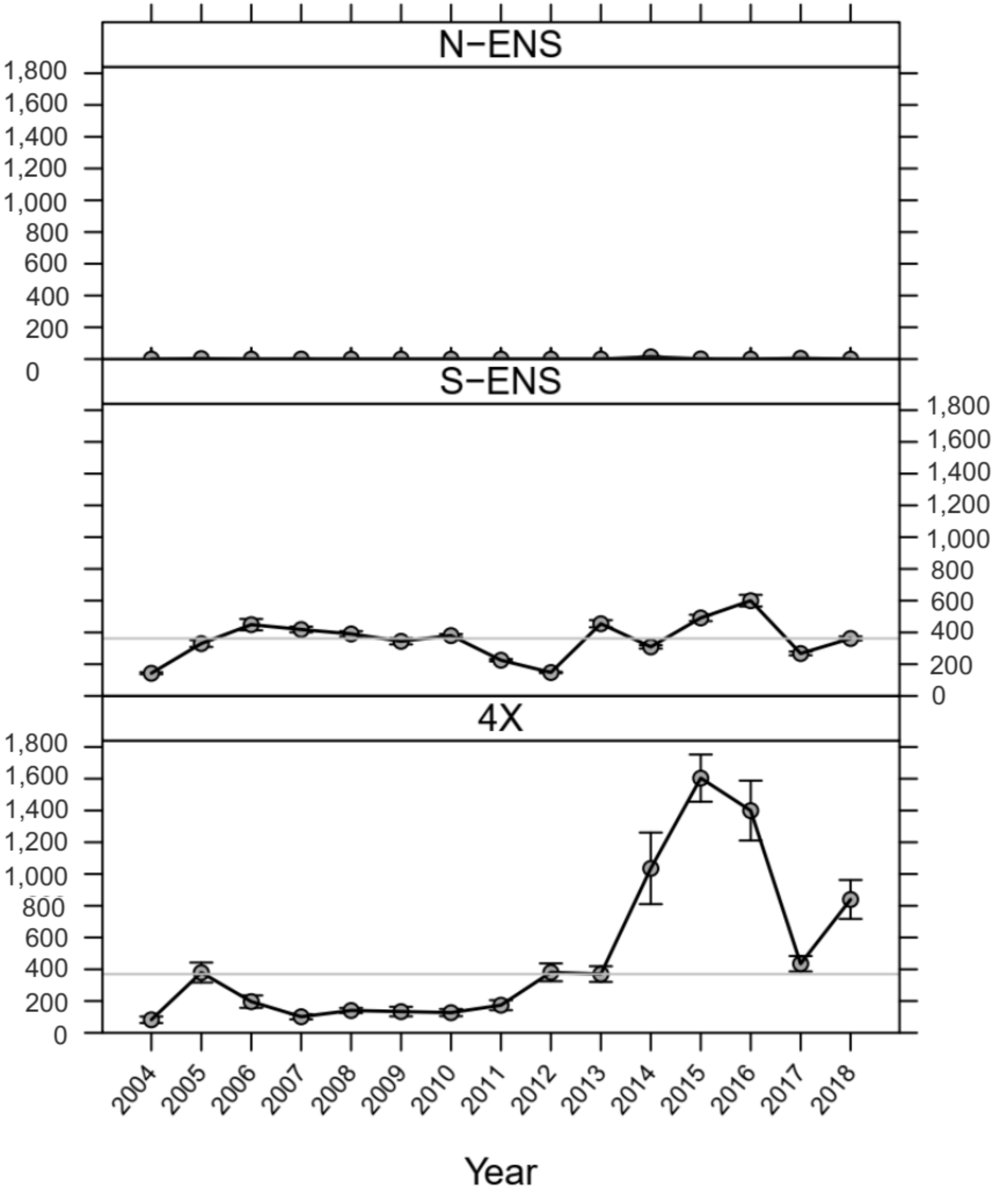


*Figure 32. Trends in biomass (kg/km^2) of potential predators of Snow Crab from the annual Snow Crab survey on the Scotian Shelf: **Haddock.***

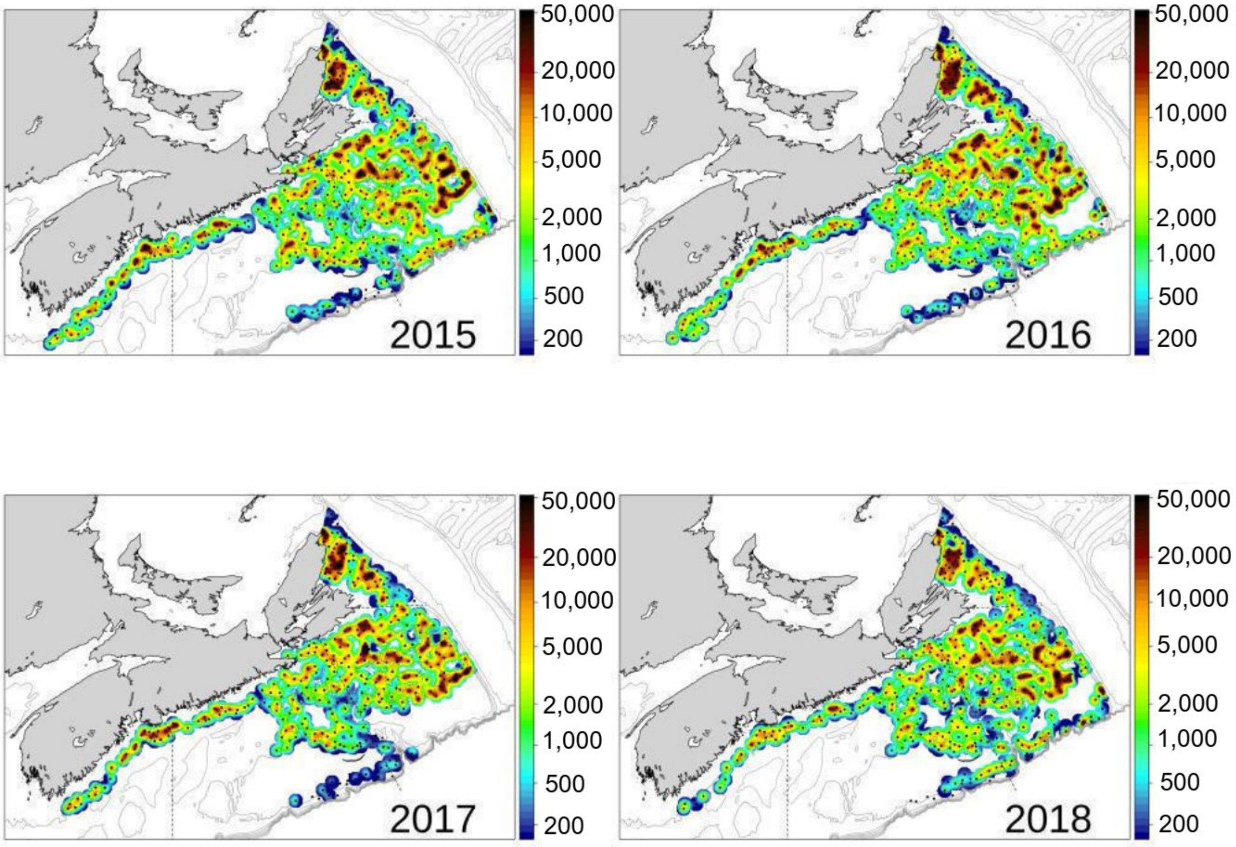


Figure 33. Locations of potential predators of Snow Crab on the Scotian Shelf from the annual Snow Crab survey: ***American Plaice****. Scale is number/km^2.*

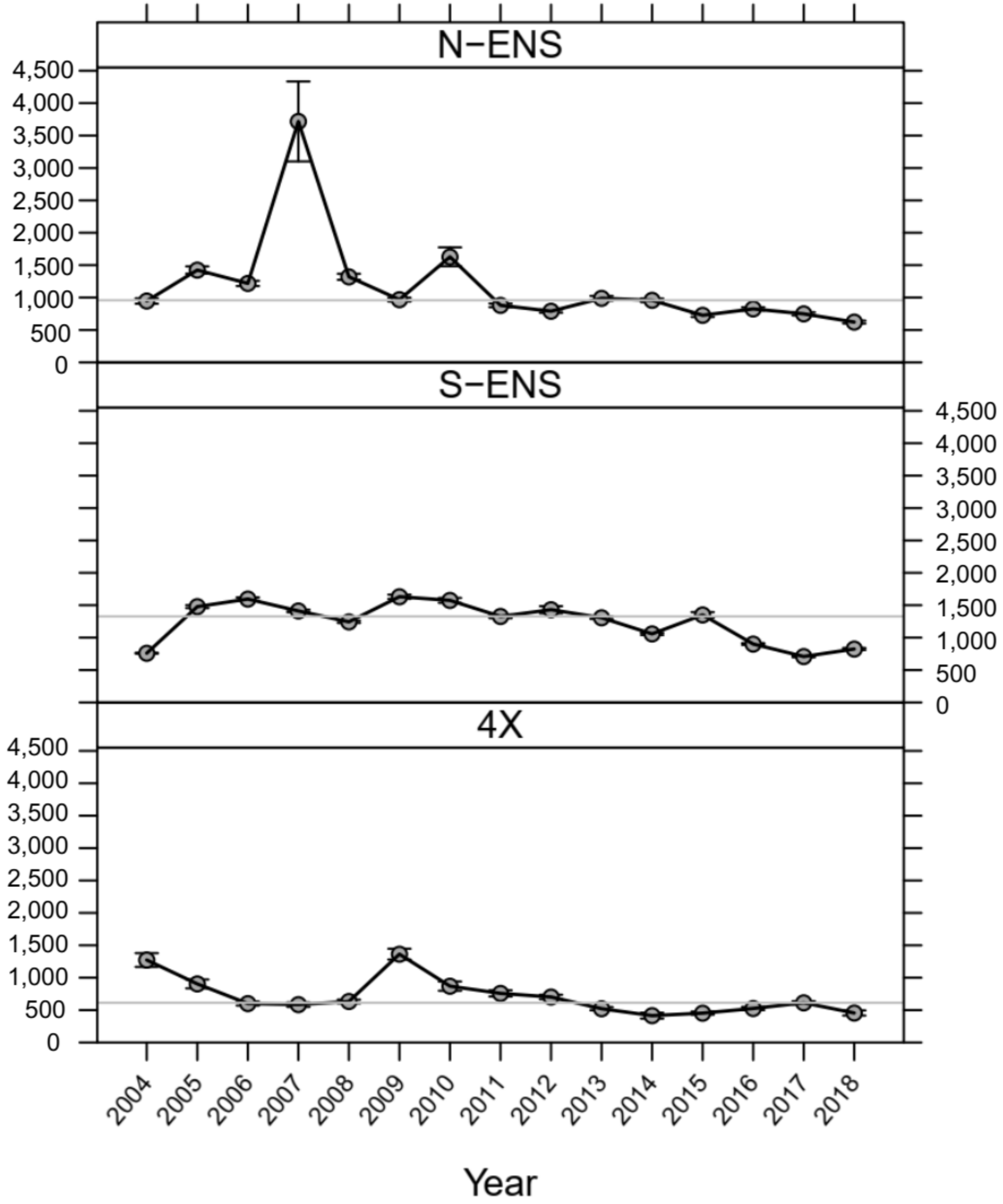


Figure 34. Trends in biomass (kg/km^2) of potential predators of Snow Crab from the annual Snow Crab survey on the Scotian Shelf: ***American Plaice****.*

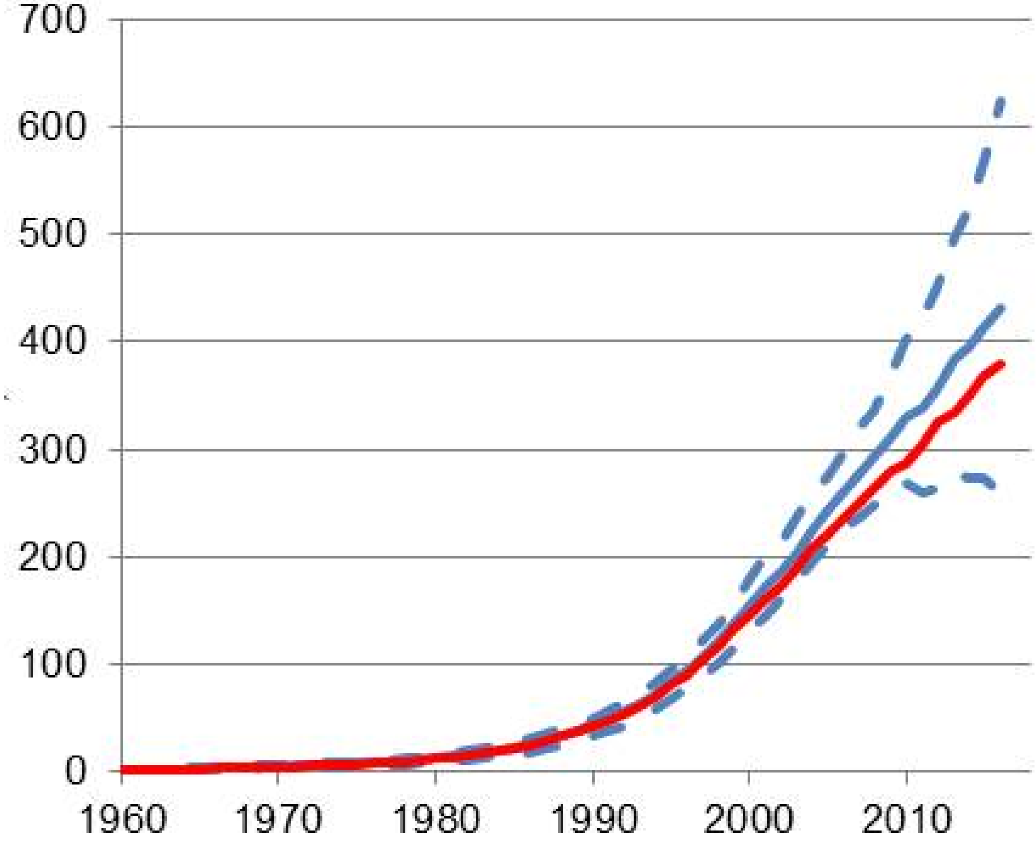


Figure 35. Trends in numerical abundance (in thousands) of Grey seals on the Scotian Shelf. The blue line is 1:1 (male:female) ratio, red line is 0.69:1. Source: DFO 2017a.

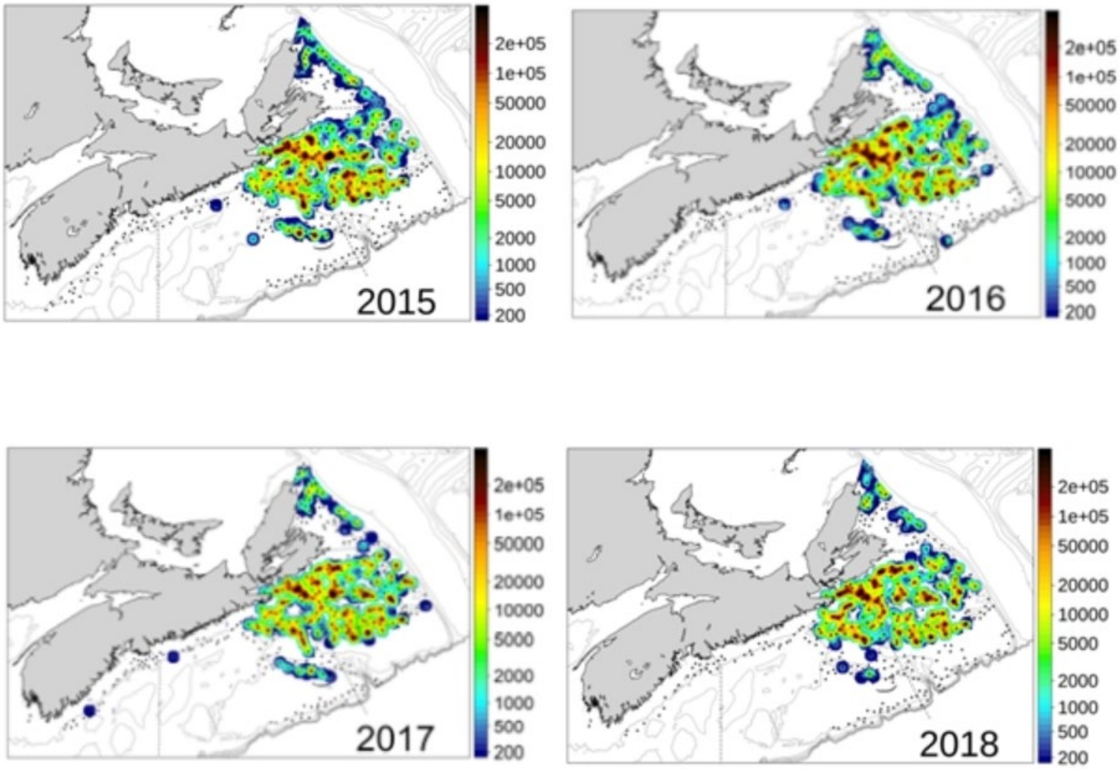


Figure 36. Locations of potential prey of Snow Crab on the Scotian Shelf from the annual Snow Crab survey: ***Northern Shrimp****. Scale is number/km^2.*

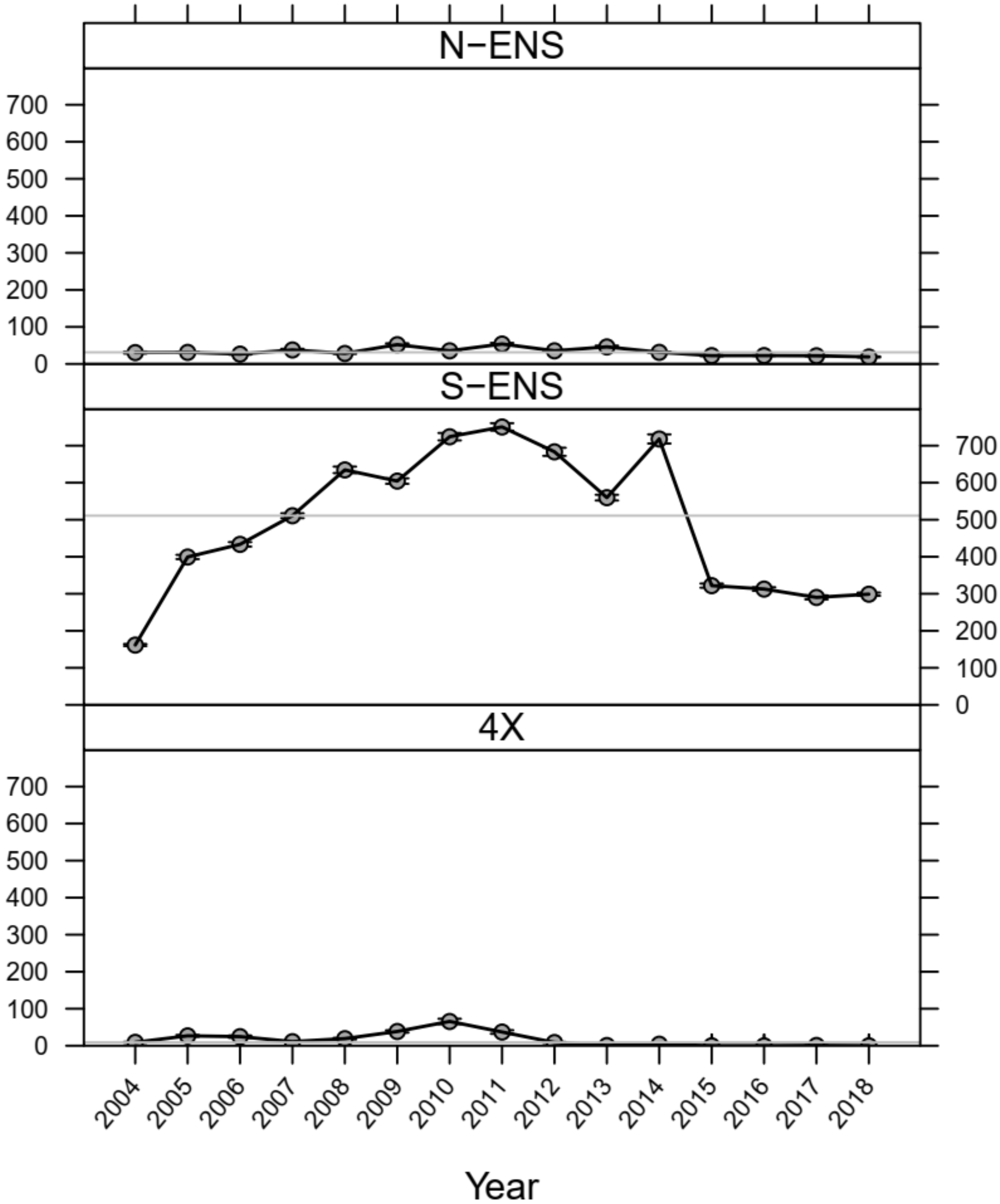


Figure 37. Trends in biomass (kg/km^2) of potential predators of Snow Crab from the annual Snow Crab survey on the Scotian Shelf: ***Northern Shrimp****.*

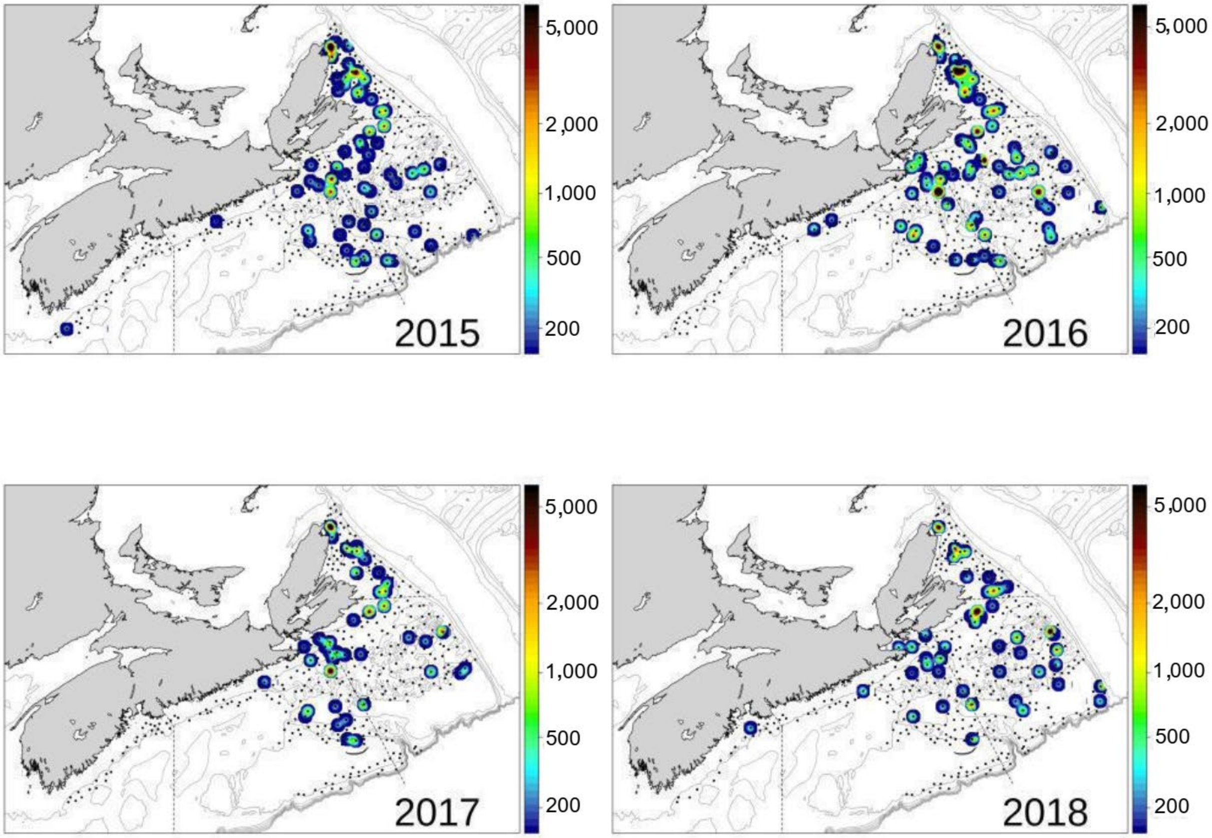


Figure 38. Locations of potential competition of Snow Crab on the Scotian Shelf from the annual Snow Crab survey: ***Lesser Toad Crab****. Scale is number/km^2.*

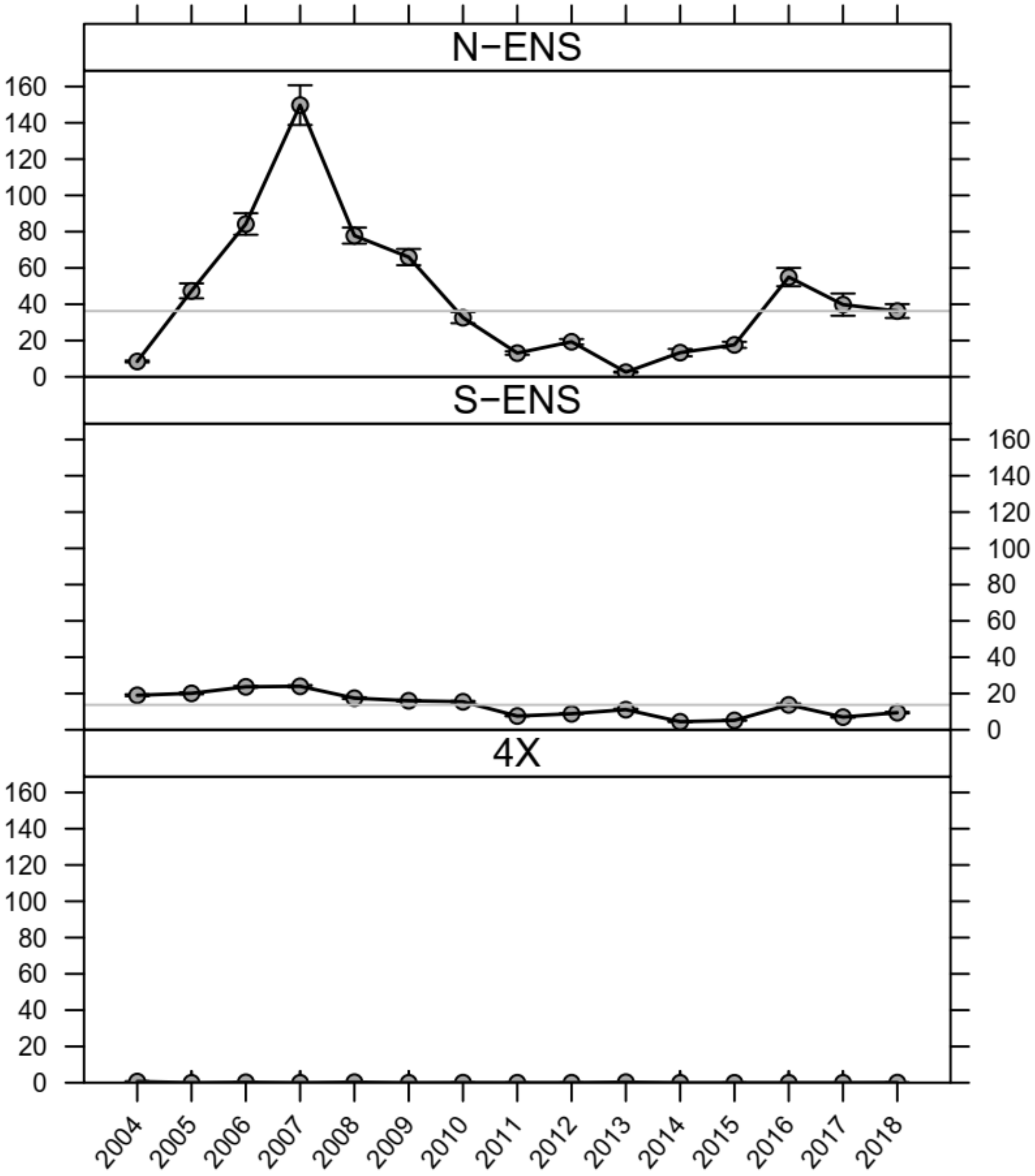


*Figure 39. Trends in biomass (kg/km^2) of potential predators of Snow Crab from the annual Snow Crab survey on the Scotian Shelf: **Lesser Toad Crab**.*

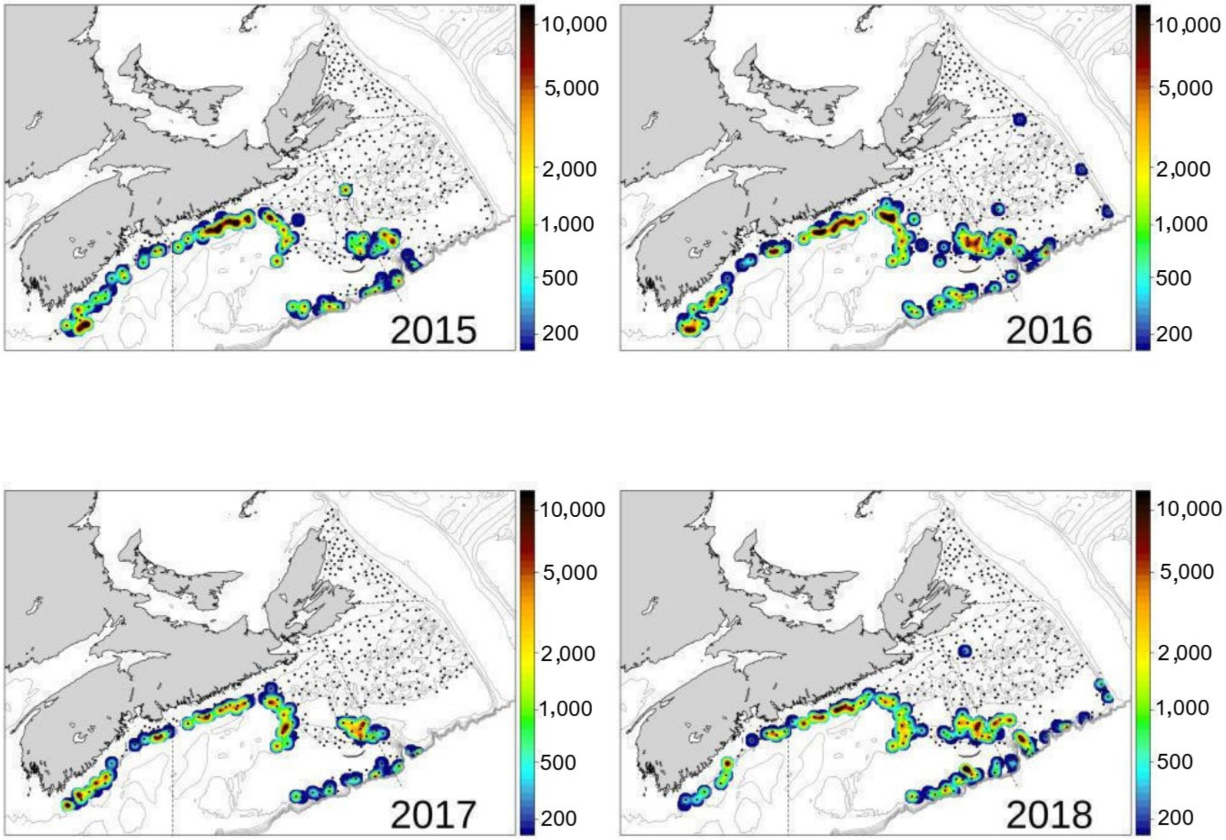


Figure 40. Locations of potential competition of Snow Crab on the Scotian Shelf from the annual Snow Crab survey: ***Jonah Crab****. Scale is number/km^2.*

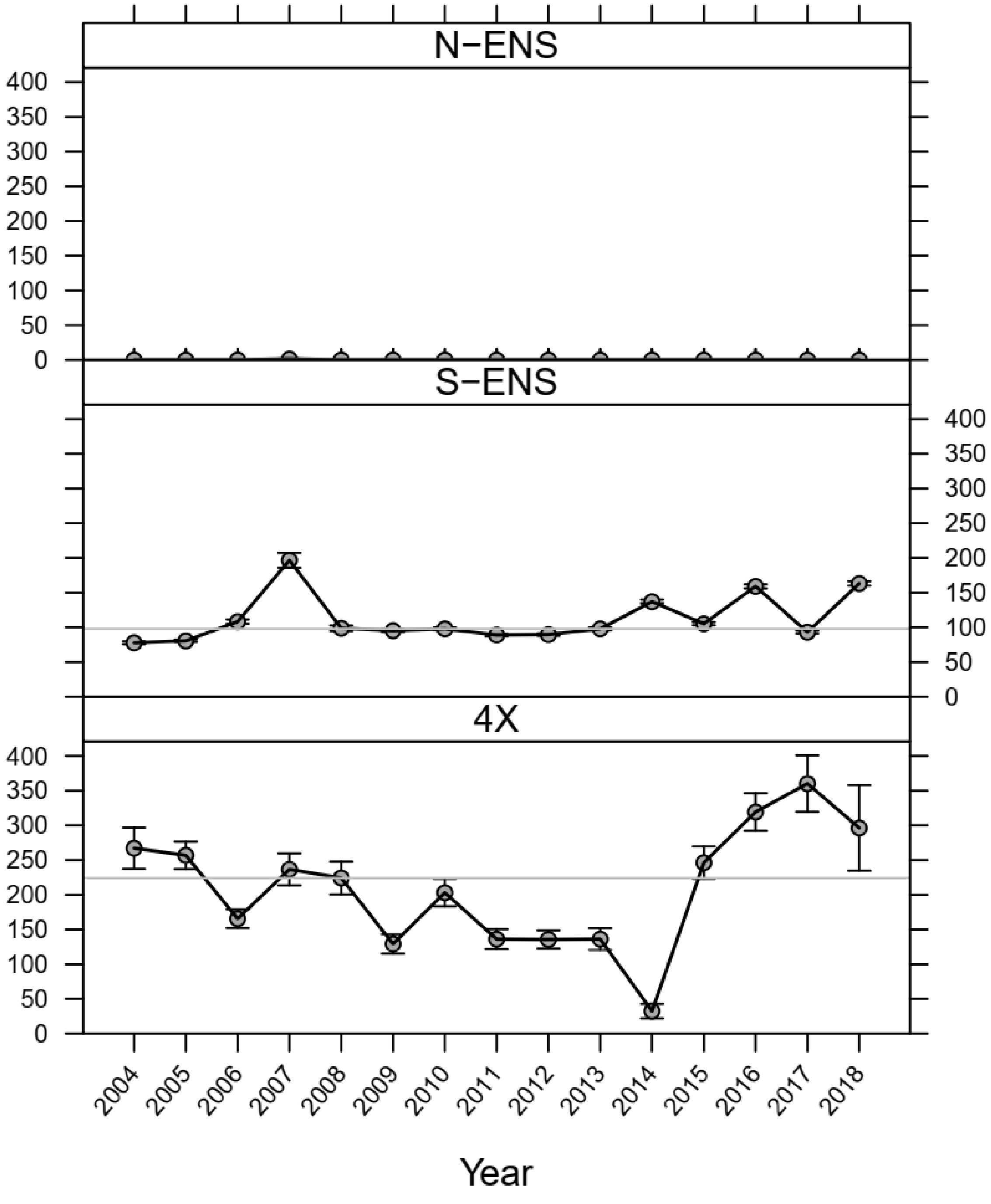


Figure 41. Trends in biomass (kg/km^2) of potential predators of Snow Crab from the annual Snow Crab survey on the Scotian Shelf: ***Jonah Crab****.*

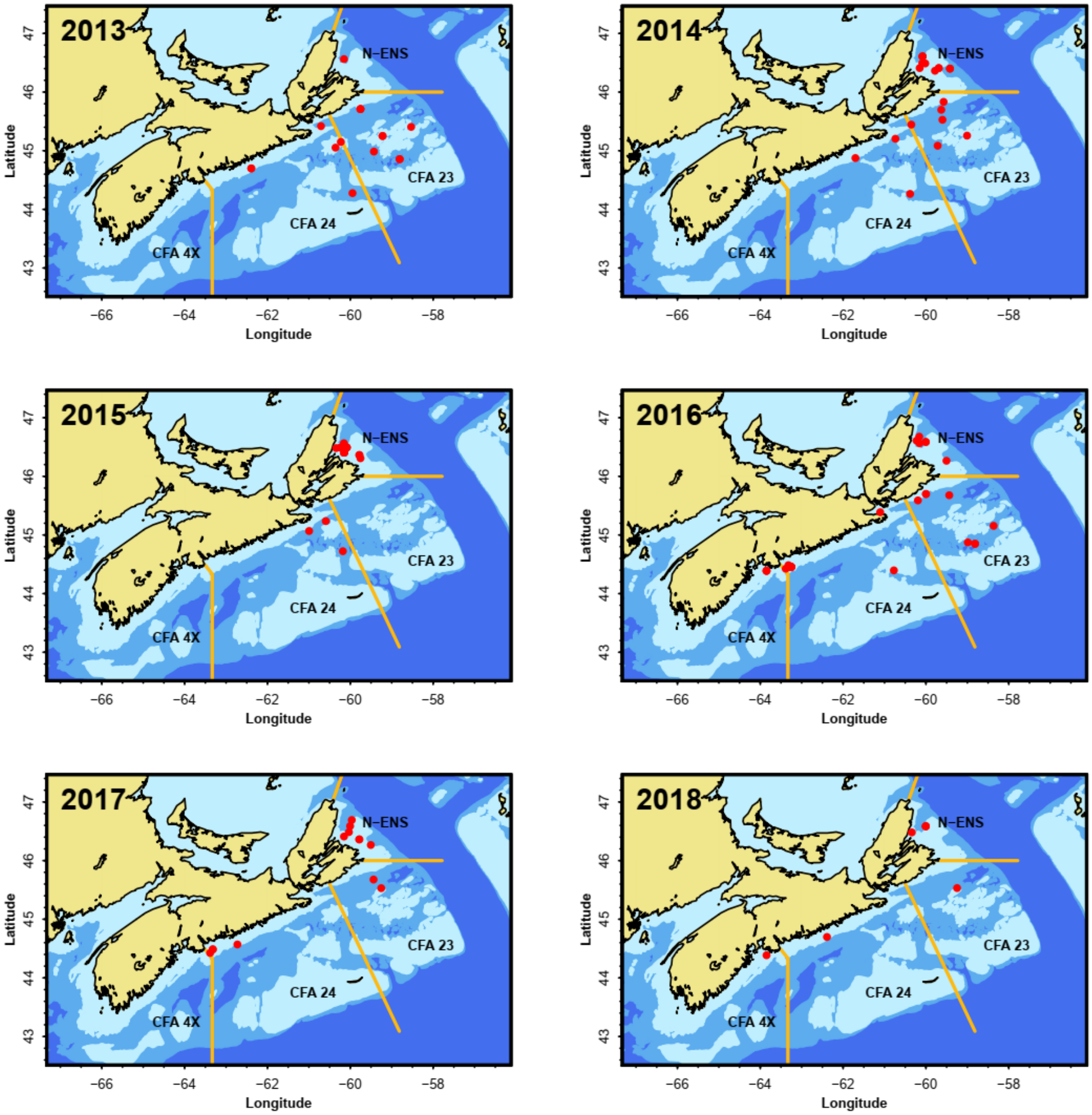


Figure 42. Annual locations of Bitter Crab Disease observations in Snow Crab trawl survey.

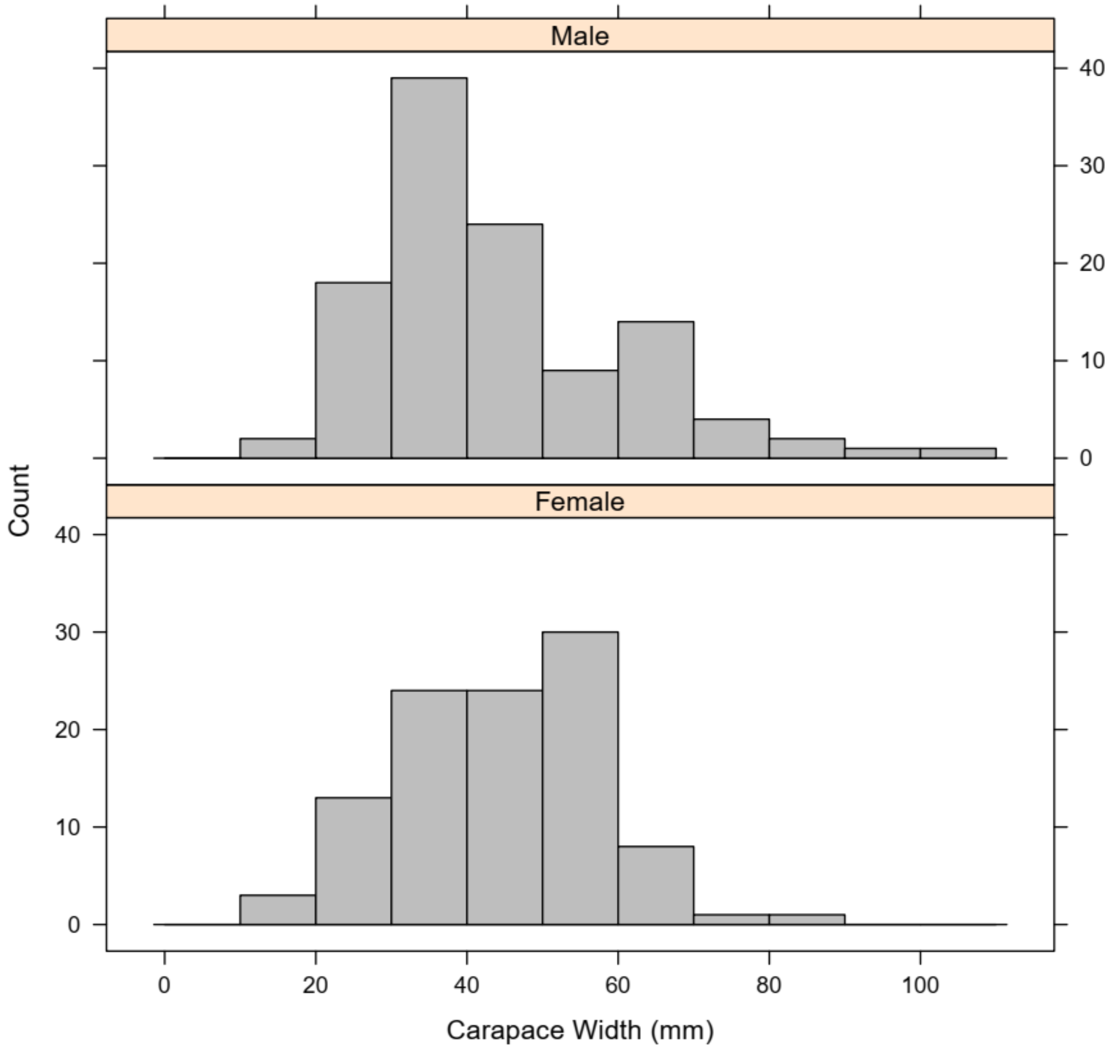
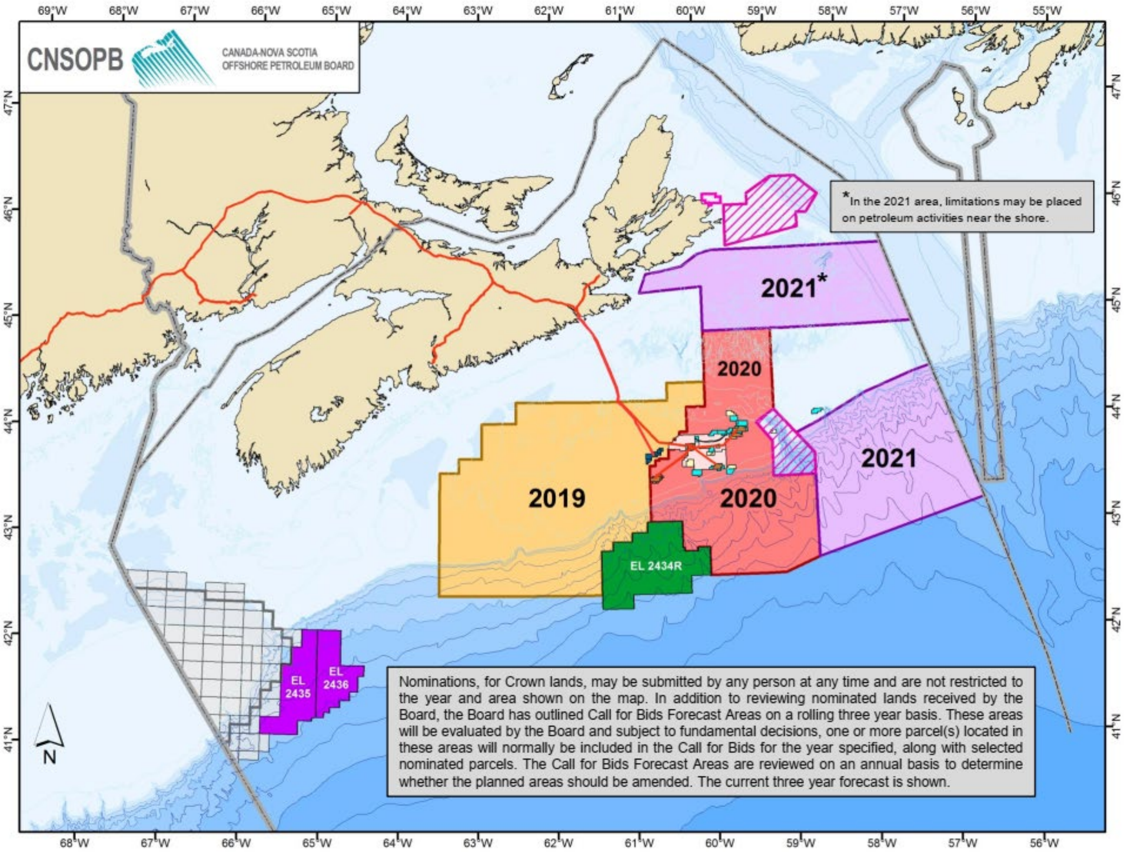


Figure 43. Size frequency distribution of Snow Crab visibly infected with Bitter Crab Disease since 2009.



*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 44. Map of current Canadian Nova Scotia Offshore Petroleum Board call for exploration bids.

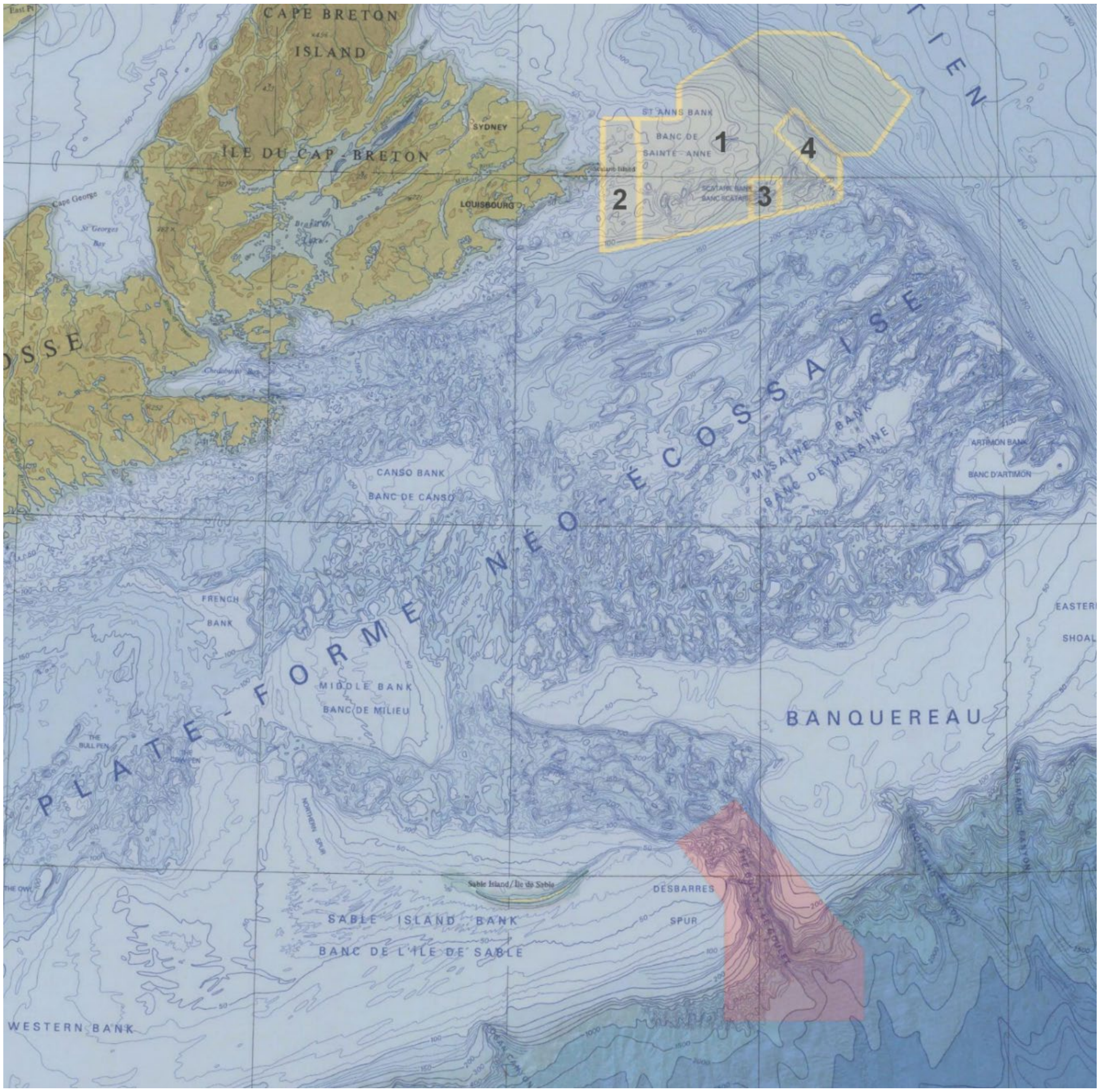


Figure 45. Marine Protected Areas on the Eastern Scotian Shelf. Yellow: St. Anns Bank Marine Protected Area with sub-zone designations. Red: The Gully.

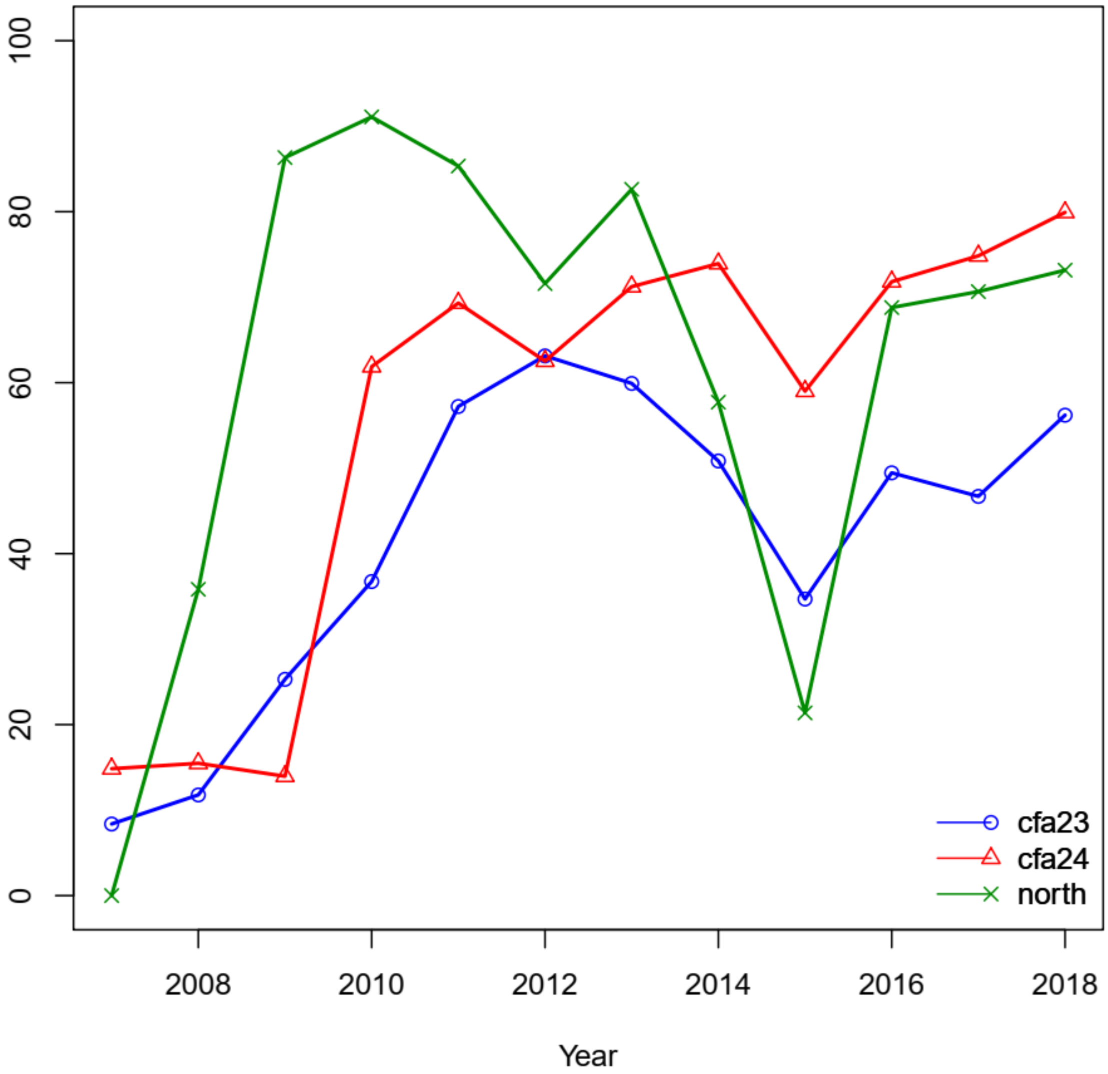


Figure 46. The percent of total annual Snow Crab landings caught during the months of April–June separated by Crab Fishing Area (CFA).

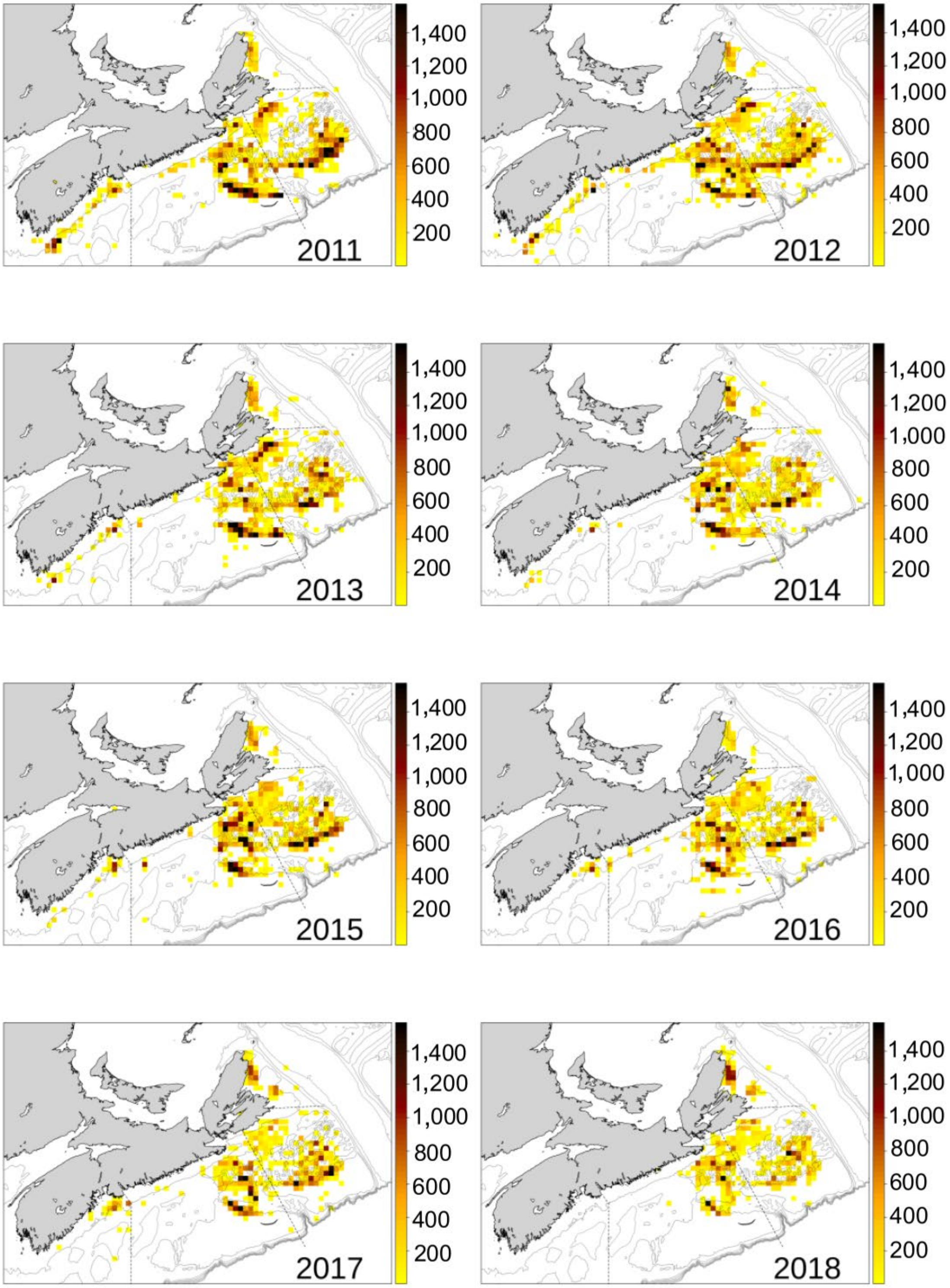


Figure 47. Fishing effort [number of trap hauls/(10 x 10 km grid)] from fisheries logbook data. For 4X, year refers to the starting year.

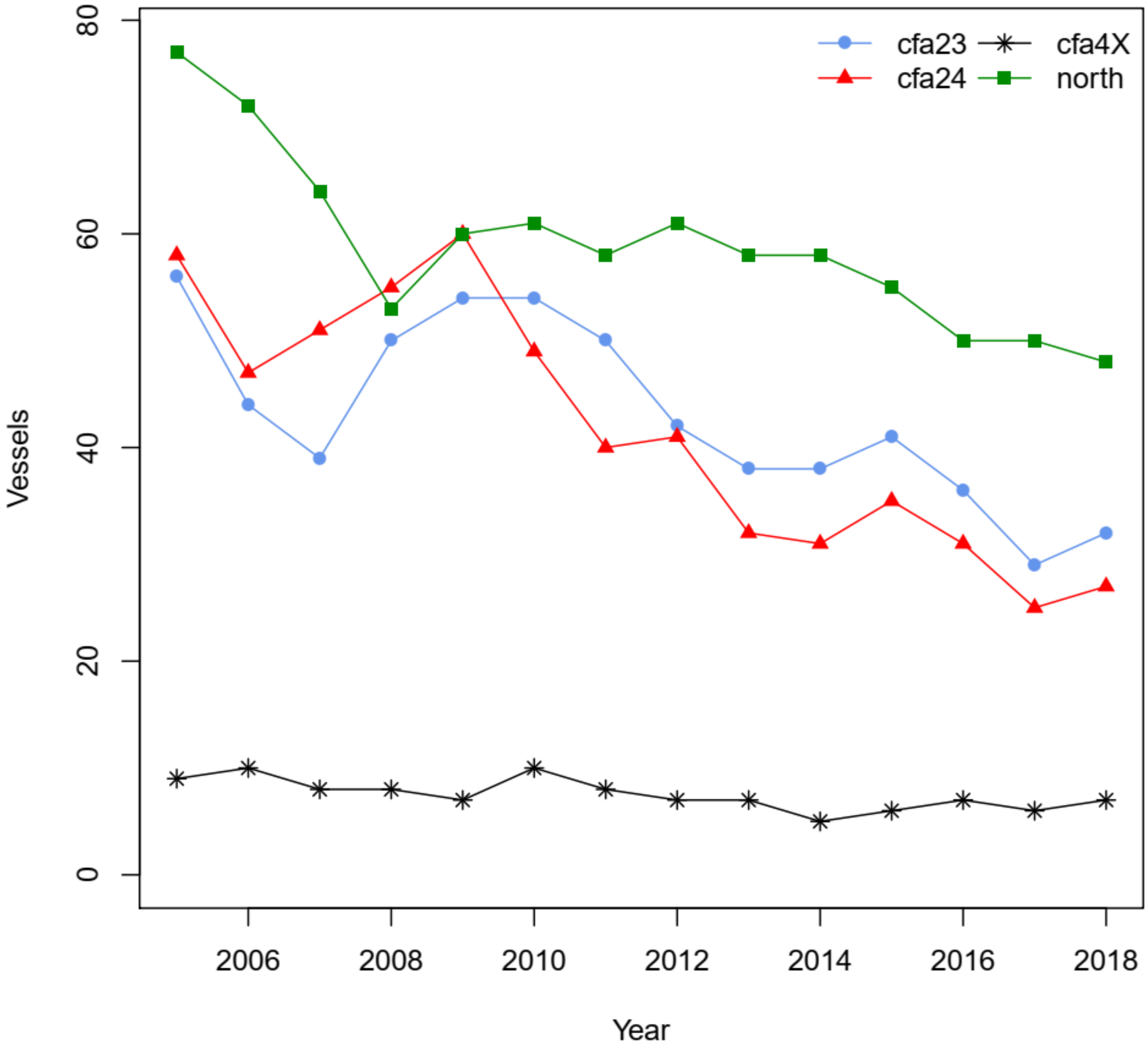


Figure 48. Number of active vessels fishing in each of the Scotian Shelf Snow Crab fishing areas. South-Eastern Nova Scotia is separated into CFA23 and CFA24 to maintain consistency with historic information. The number of licenses within each area has been stable since 2004.

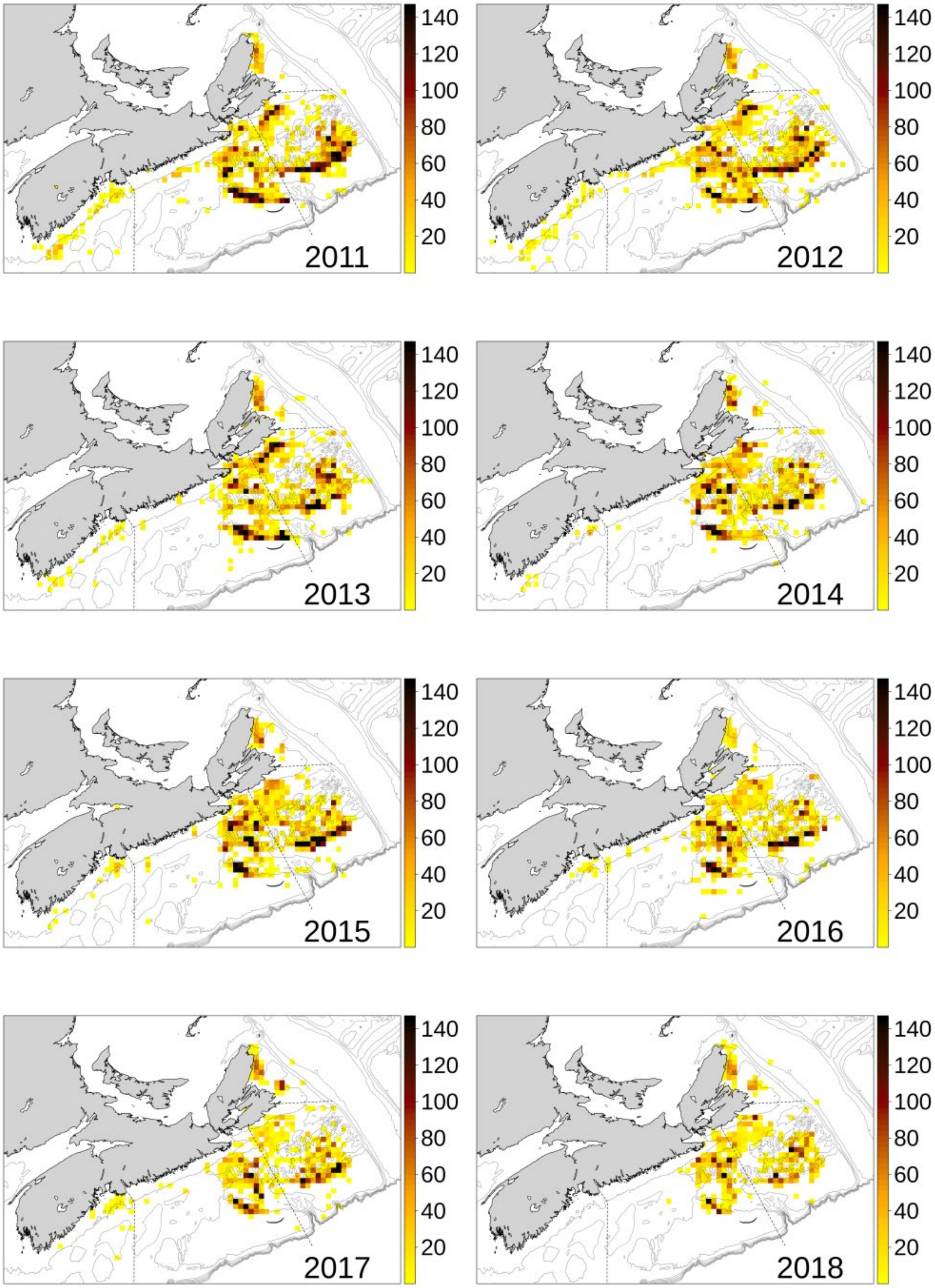


Figure 49. Snow Crab landings [tons/(10 x 10 km grid)] from fisheries logbook data. For 4X, year refers to the starting year.

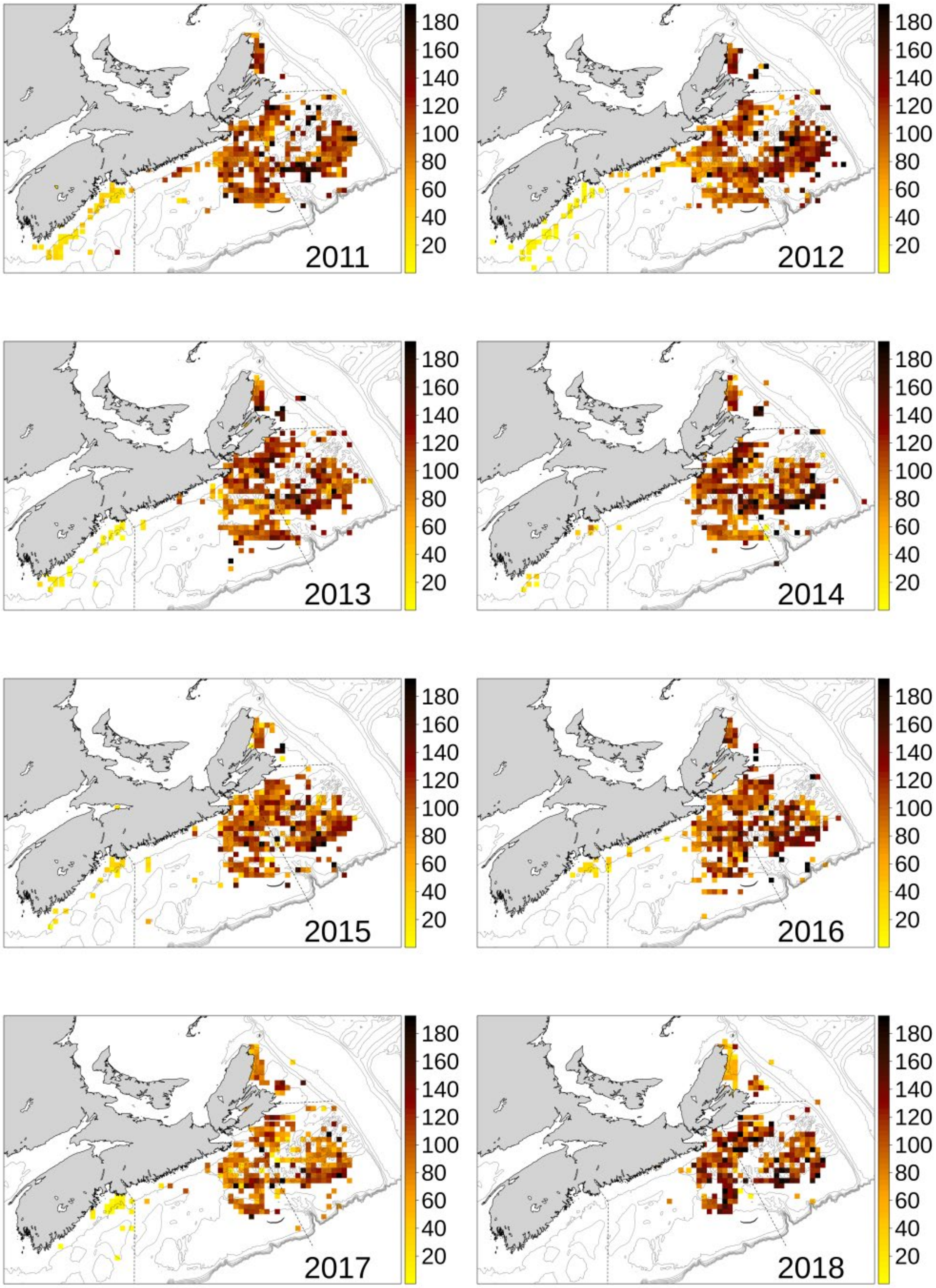


Figure 50. Catch rates (kg/trap haul) of Snow Crab in each 10 x 10km grid from fisheries logbook data. For 4X, year refers to the starting year.

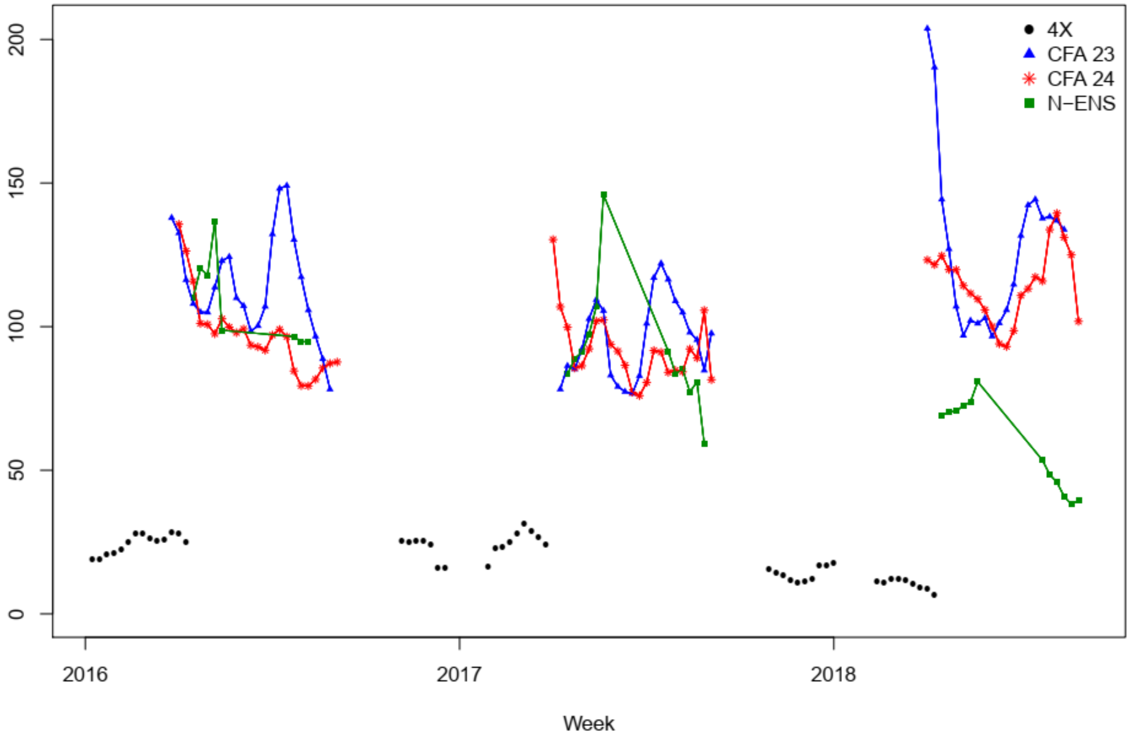


Figure 51. Smoothed catch rates (kg/trap haul) by week for the past three seasons. Split season in North-Eastern Nova Scotia (N-ENS; spring and summer portions) create the apparent gap in N-ENS data within each year.

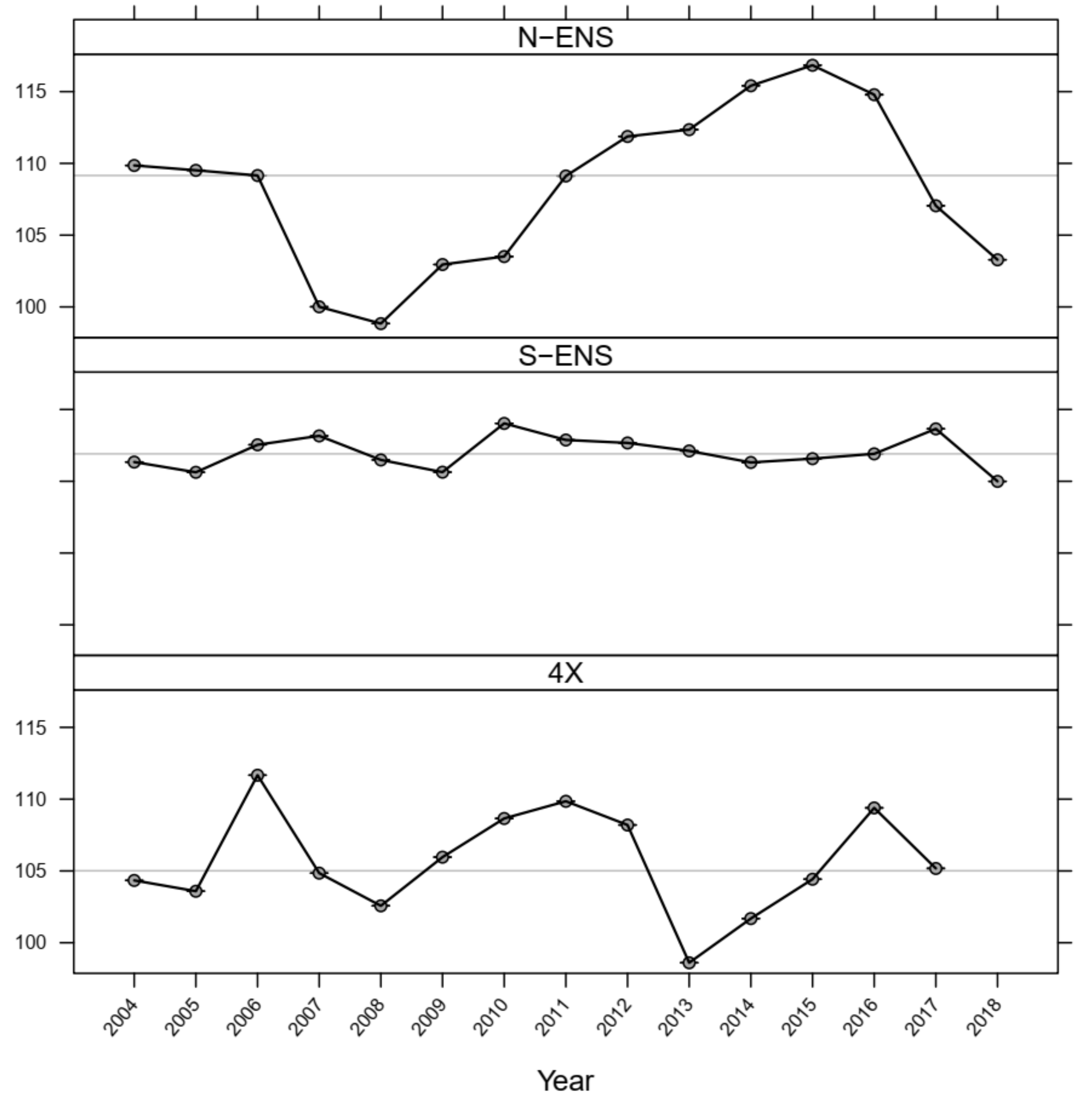


Figure 52. Time series of mean carapace width (mm) of commercial crab measured by at-sea- observers. For 4X, the year refers to the starting year of the season.

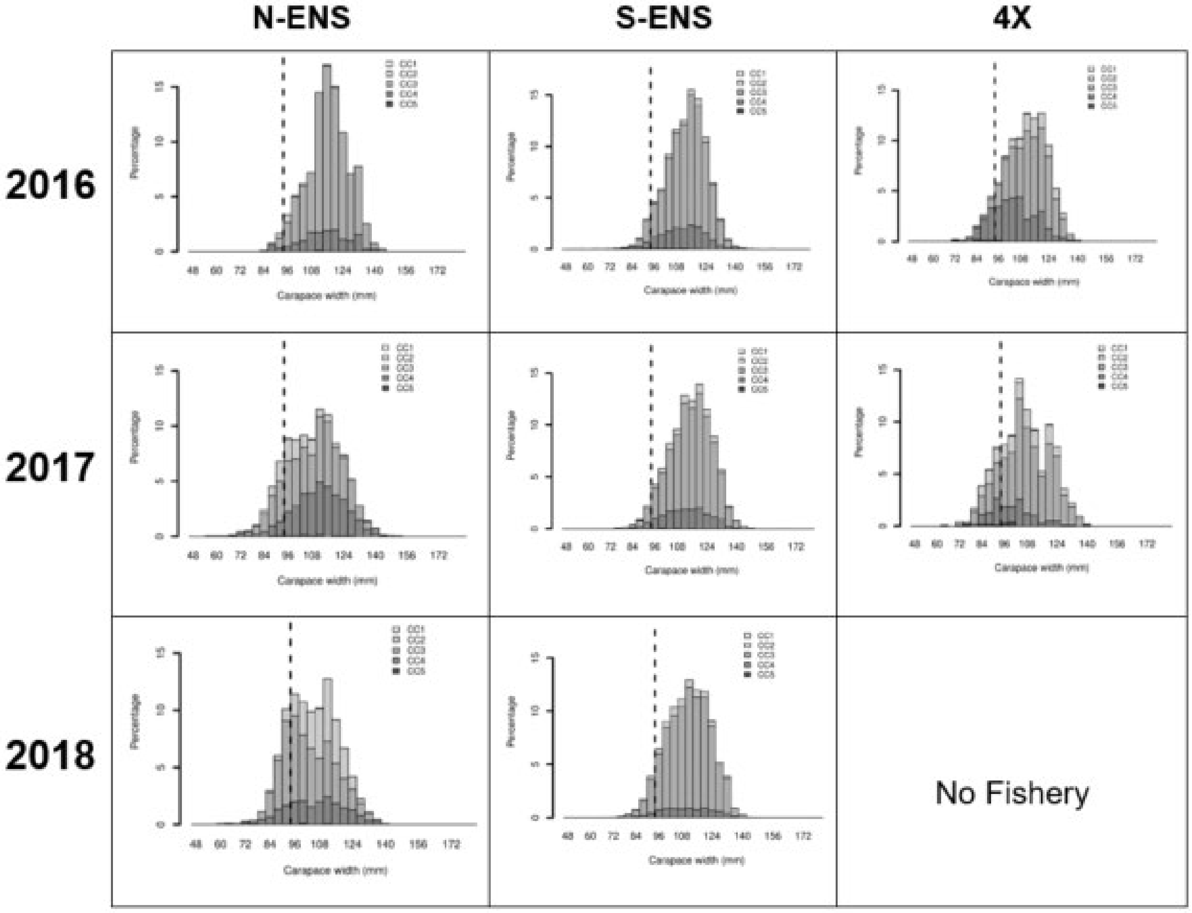


Figure 53. Size frequency distribution of all at-sea-observer monitored Snow Crab broken down by carapace condition. For 4X, the year refers to the starting year of the season. Vertical lines indicate 95 mm Carapace Width (CW), the minimum legal size.

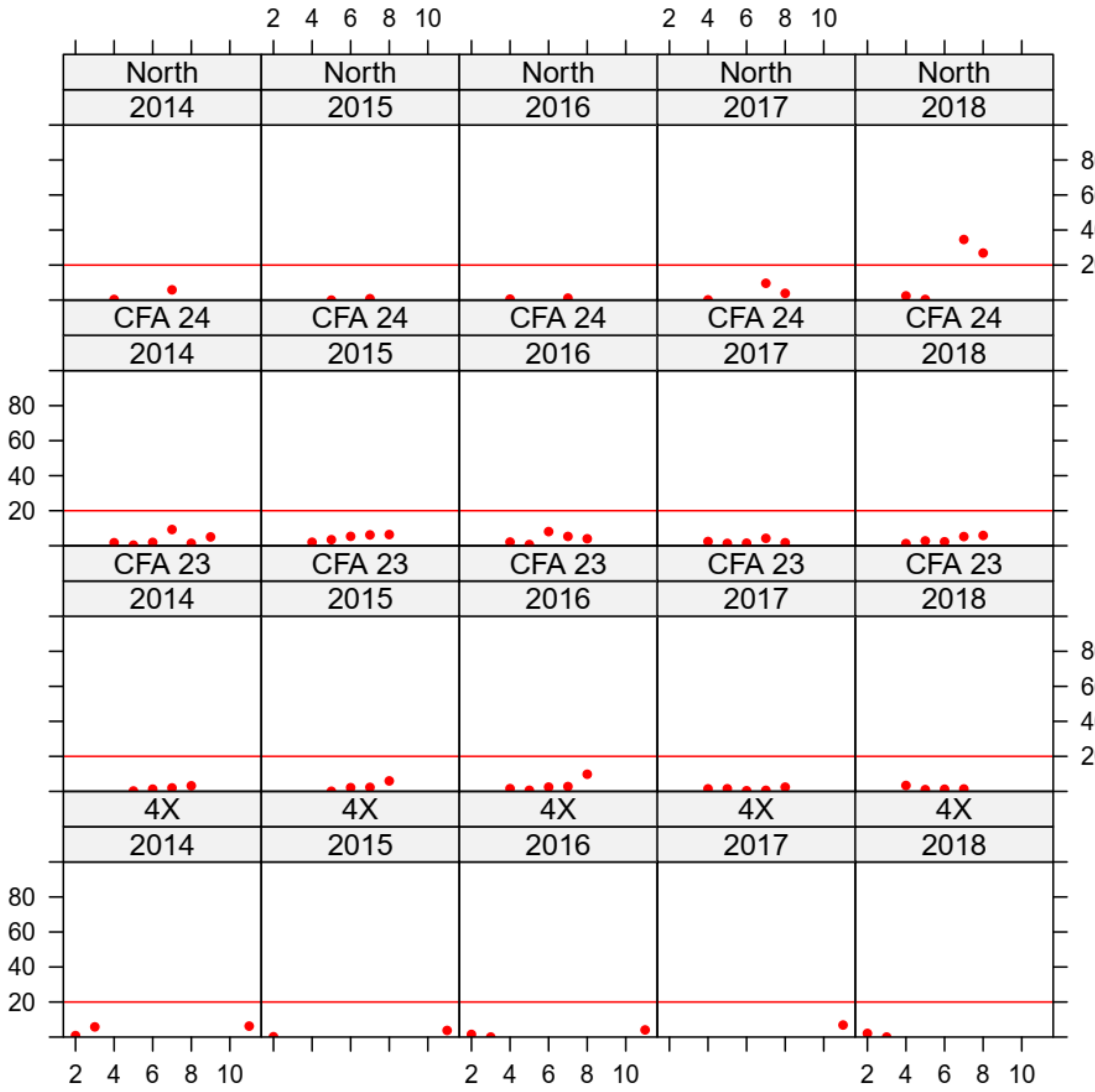


Figure 54. The percent of sampled Snow Crab in the soft shelled state (less than 68 durometer) as determined by at-sea-observers from commercial Snow Crab traps by month. Red line shows 20% soft, a level traditionally considered to be of concern.

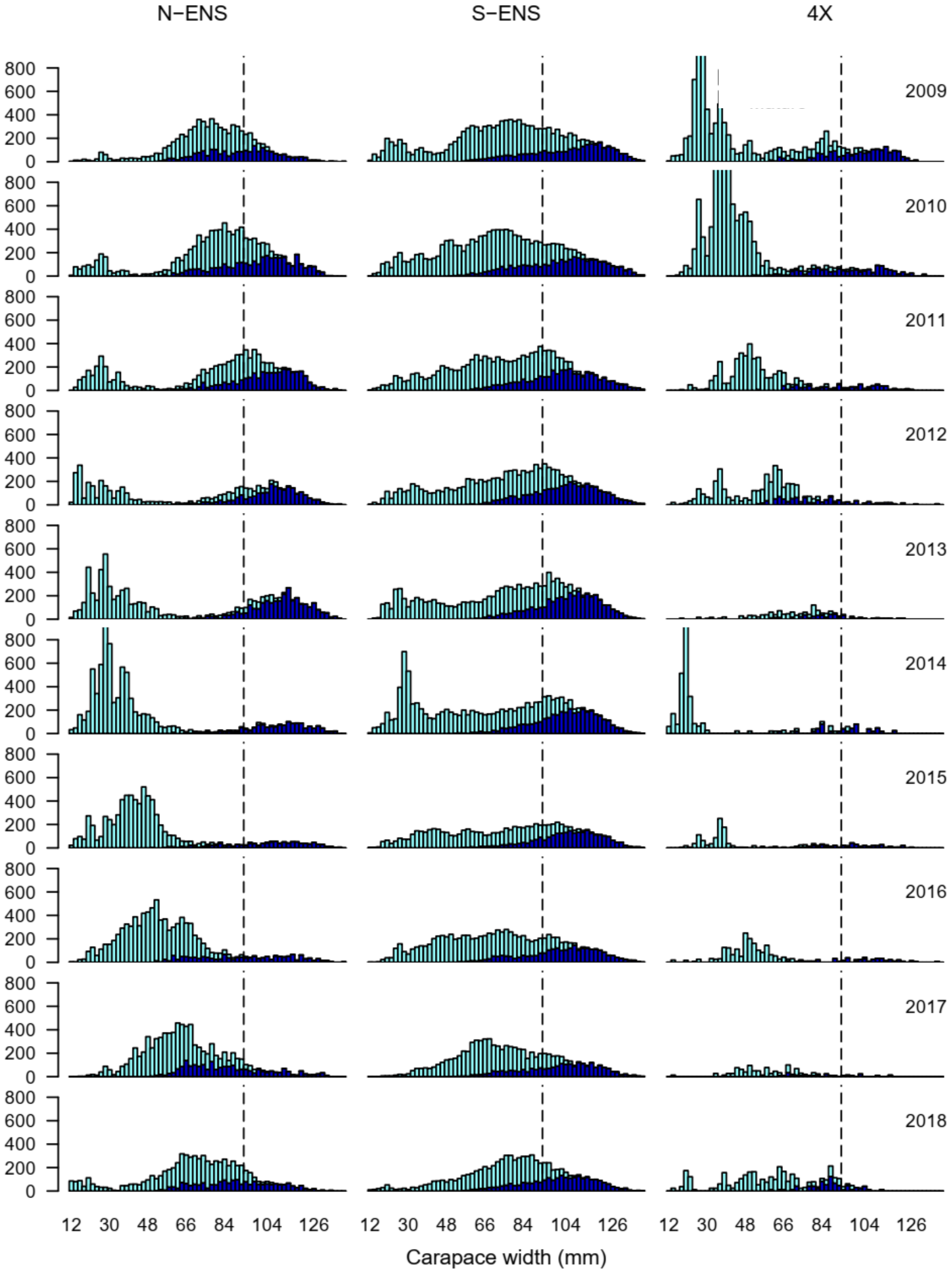


Figure 55. Size-frequency histograms of carapace width of male Snow Crab (number/km^2) obtained from the Snow Crab survey. Dark bars represent mature crab; light bars represent immature crab. Dashed line is the minimum legal size, 95mm Carapace Width.

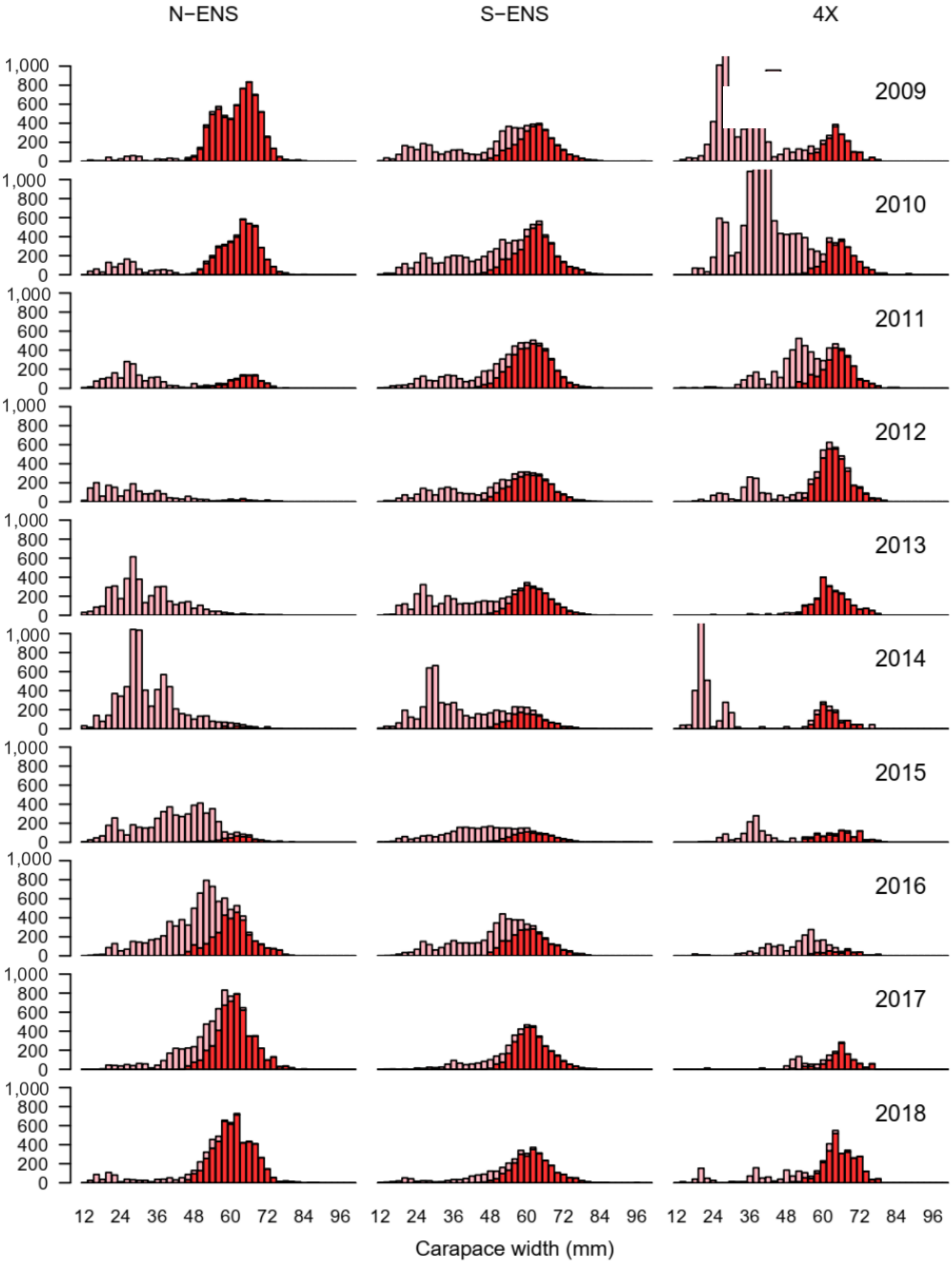


Figure 56. Size-frequency histograms of carapace width of female Snow Crab (number/km^2) obtained from the Snow Crab survey. Dark bars represent mature Snow Crab; light bars represent immature Snow Crab.

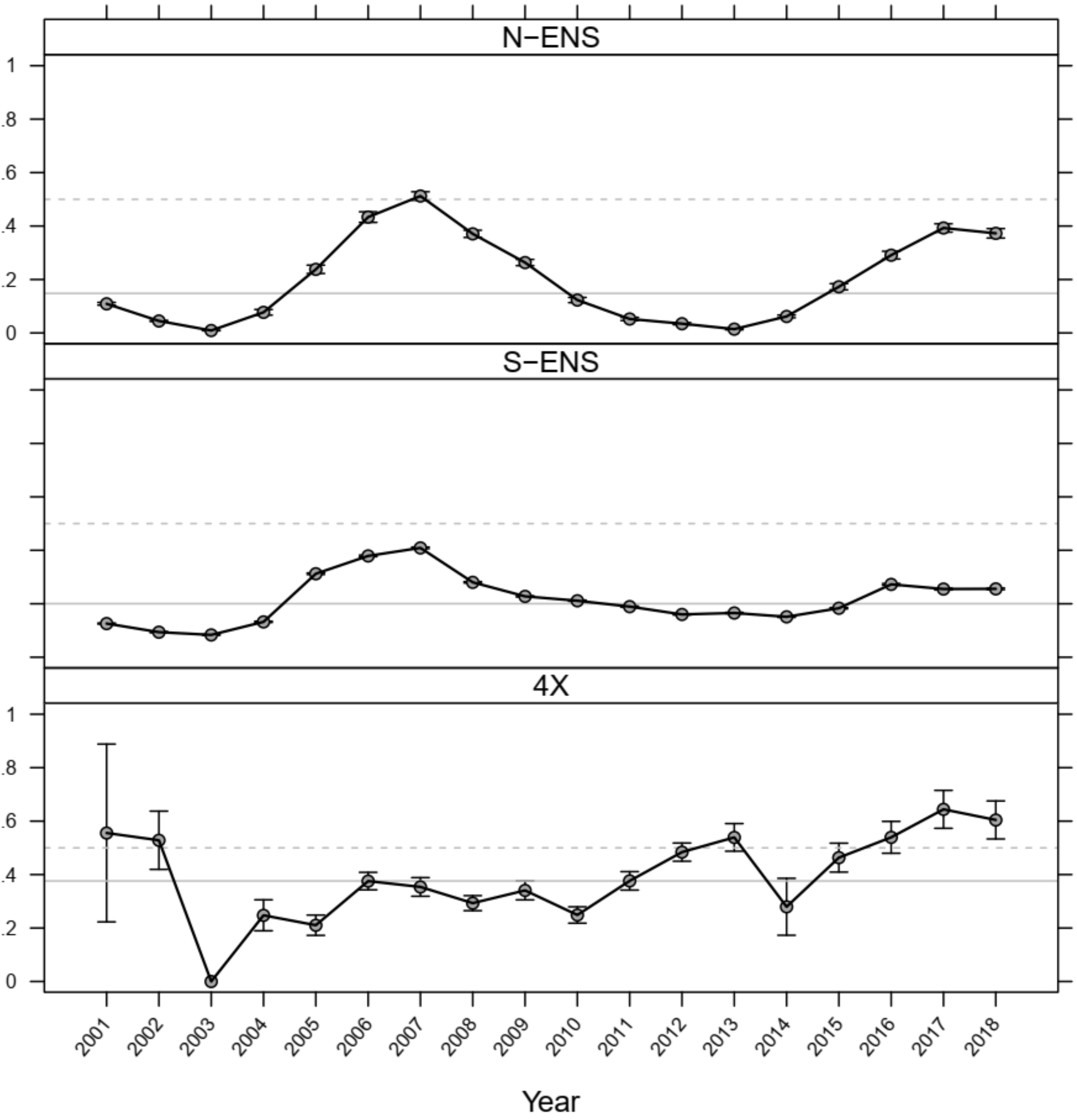


Figure 57. Annual proportion female of mature Snow Crab observed in the survey. Since 2001, most of the Scotian Shelf was uniformly male dominated. One standard error bar is presented. The dashed line represents a 1:1 (0.5 proportion) female: male ratio.

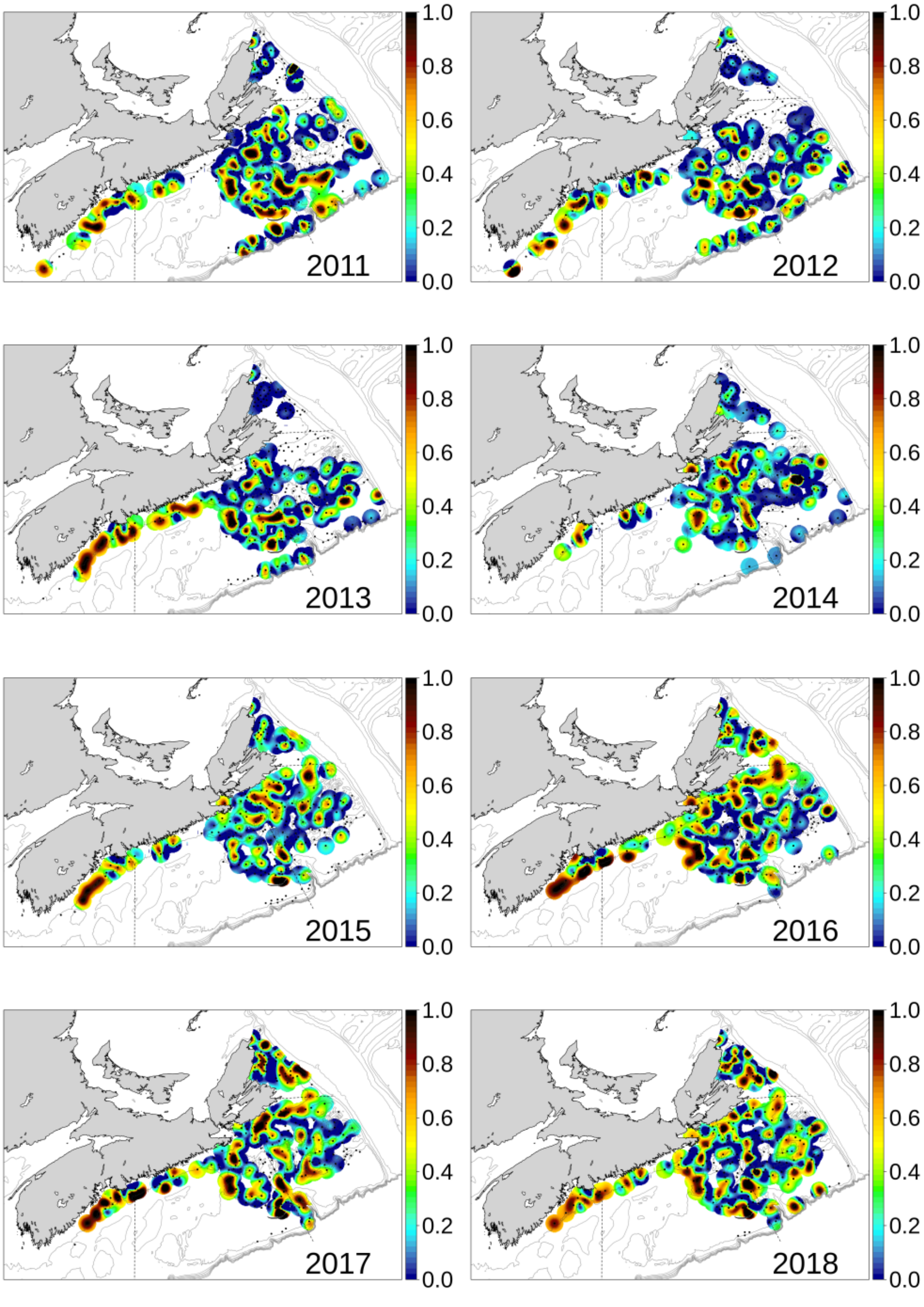


Figure 58. Proportion of females in the mature fraction of the total morphometrically mature segment of Snow Crab on the Scotian Shelf. Spatial representations generated using thin plate spline interpolations of data from the annual Snow Crab survey.

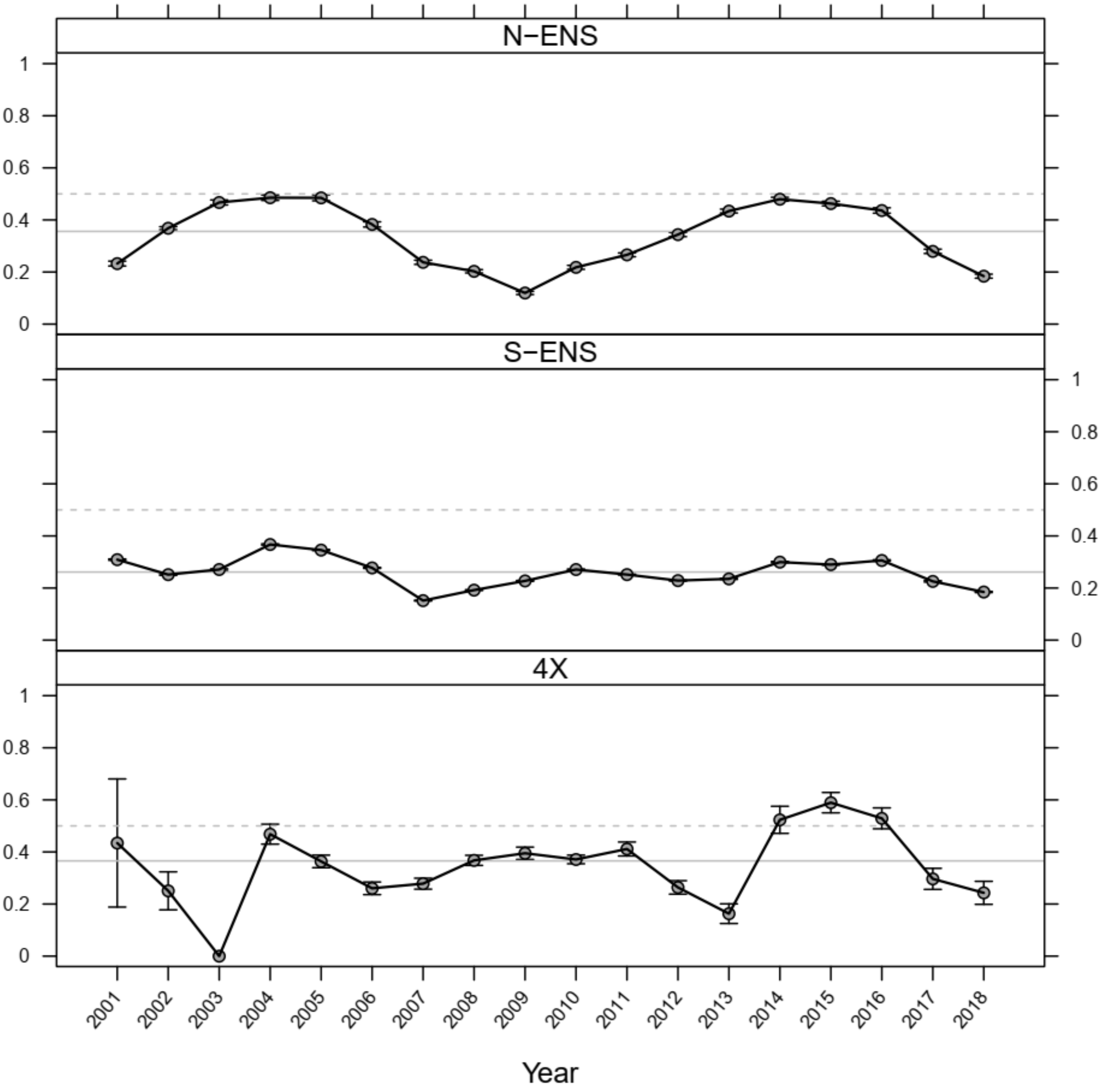


Figure 59. Annual sex ratios (proportion female) of immature Snow Crab on the Scotian Shelf. Dashed line represents a 1:1 (0.5 proportion) female: male ratio. Solid line indicates long-term mean within each area.

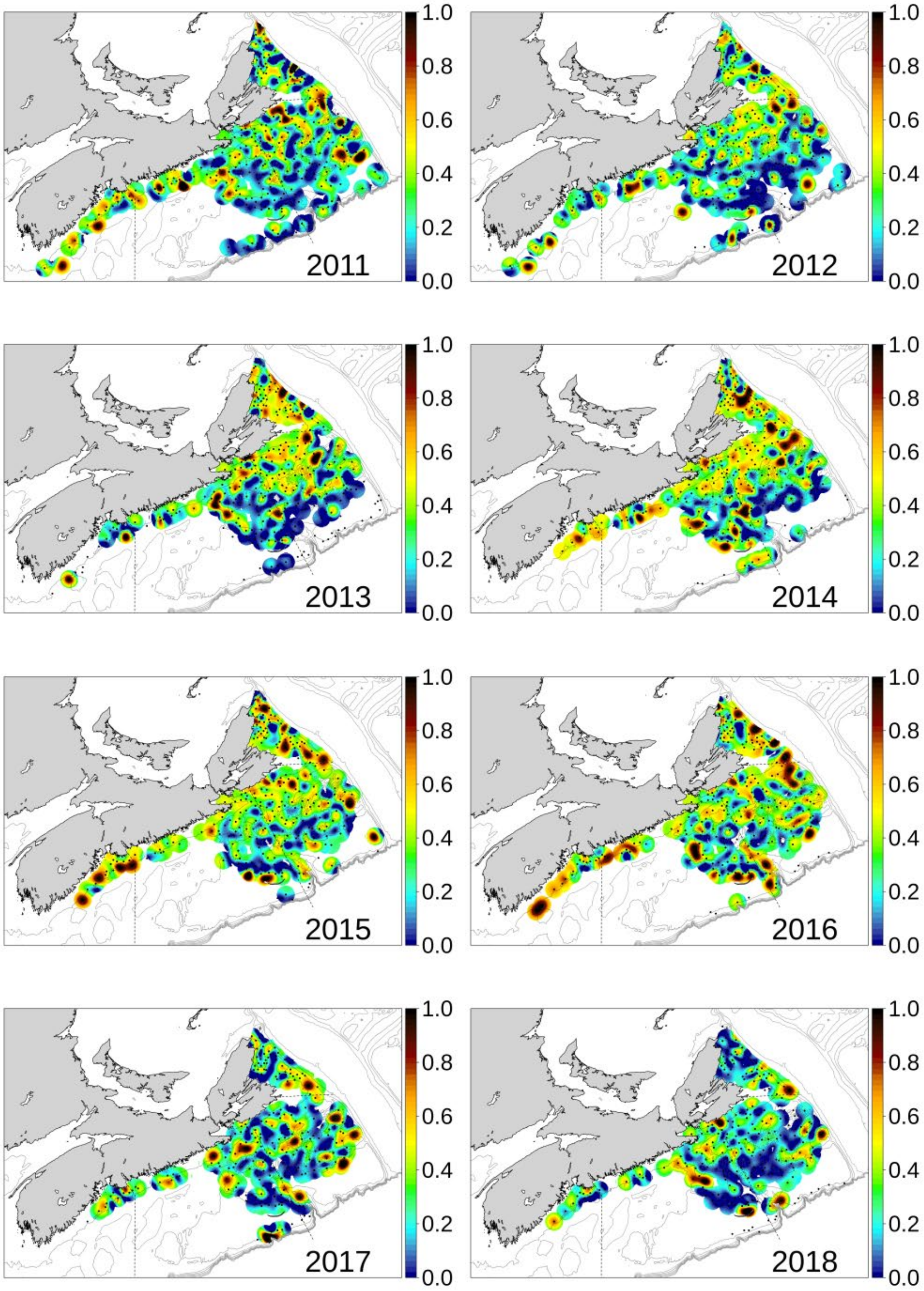


Figure 60. Morphometrically immature sex ratios (proportion of females in the mature fraction of the total numbers) of Snow Crab on the Scotian Shelf. Spatial representations generated using thin plate spline interpolations of data from the annual Snow Crab survey.

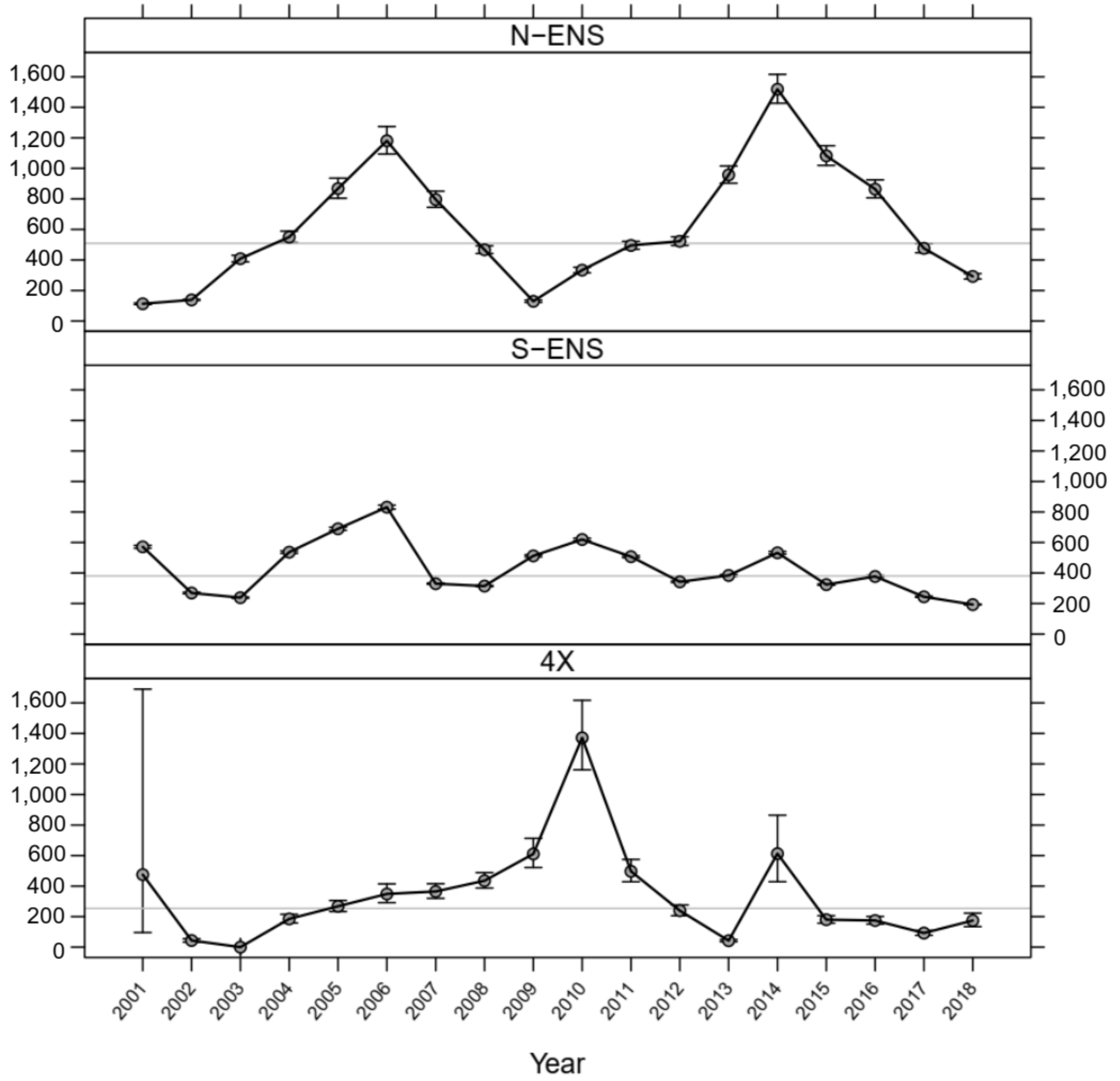


Figure 61. Geometric mean numeric density of immature female Snow Crab (number/km^2) on the Scotian Shelf.

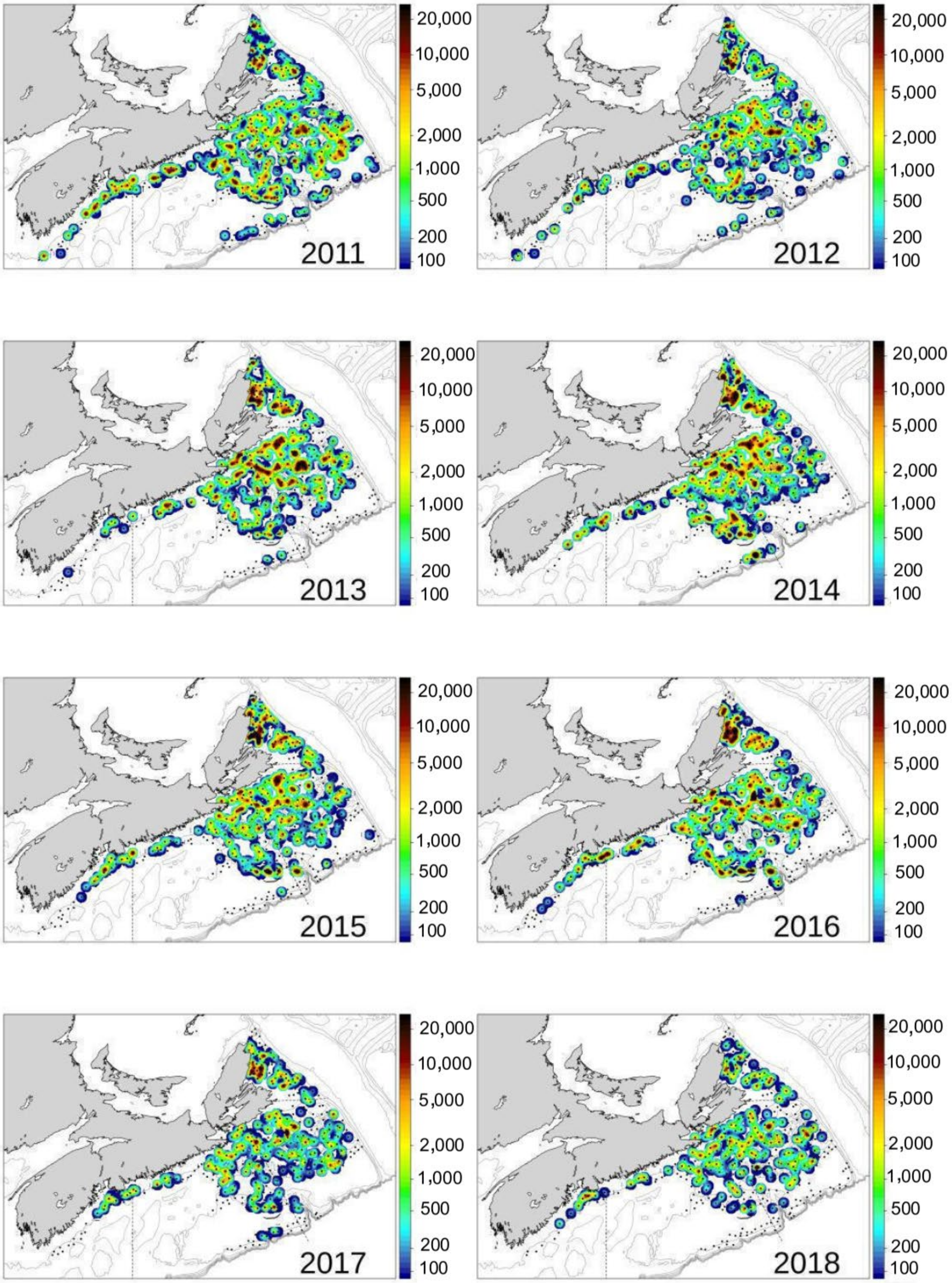


Figure 62. Numerical densities (number/km^2) of the immature female Snow Crab on the Scotian Shelf. Spatial representation generated using thin plate spline interpolations of data from the annual Snow Crab survey.

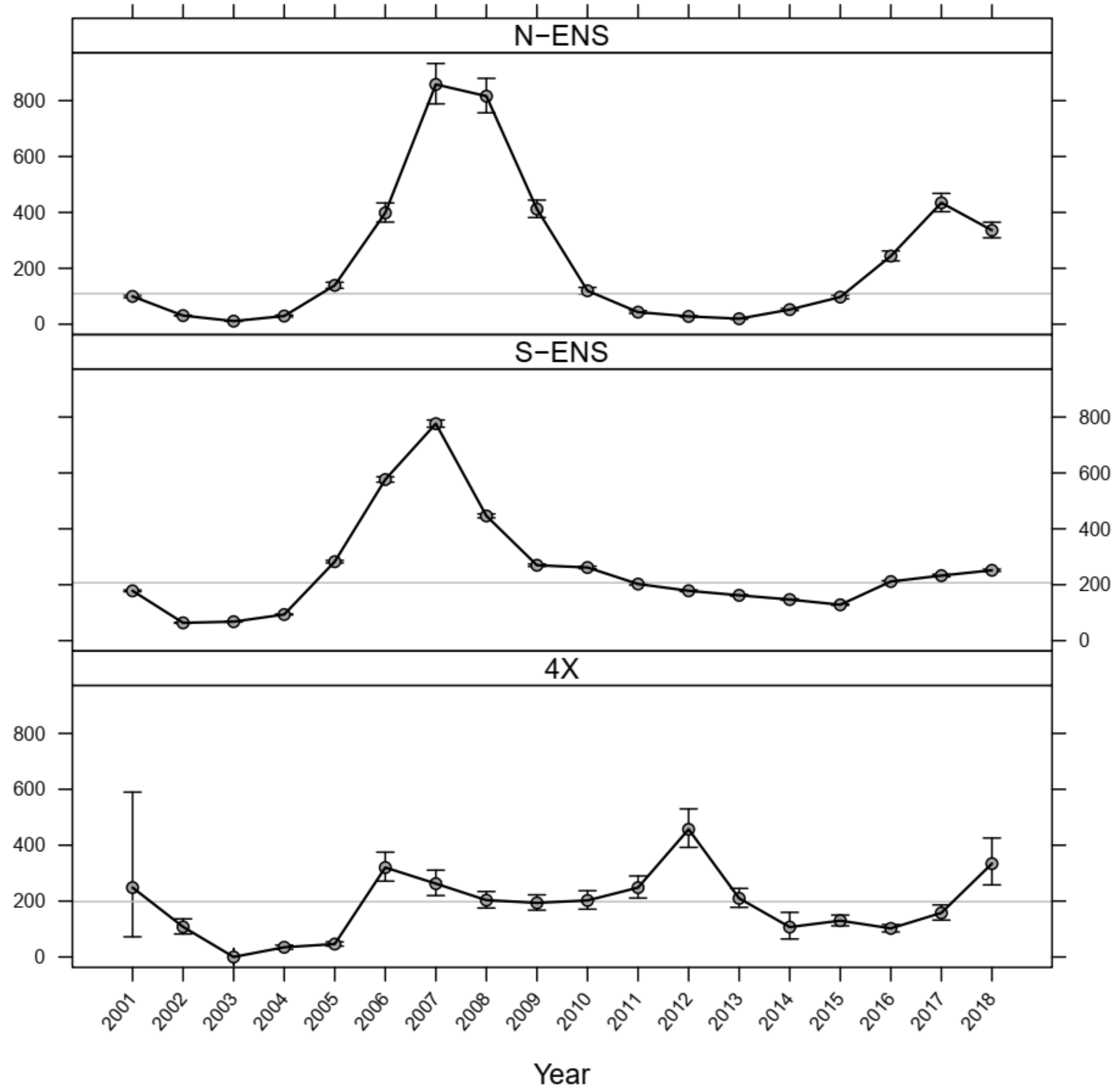


Figure 63. Geometric Mean numeric density of mature female Snow Crab (number/km^2) on the Scotian Shelf.

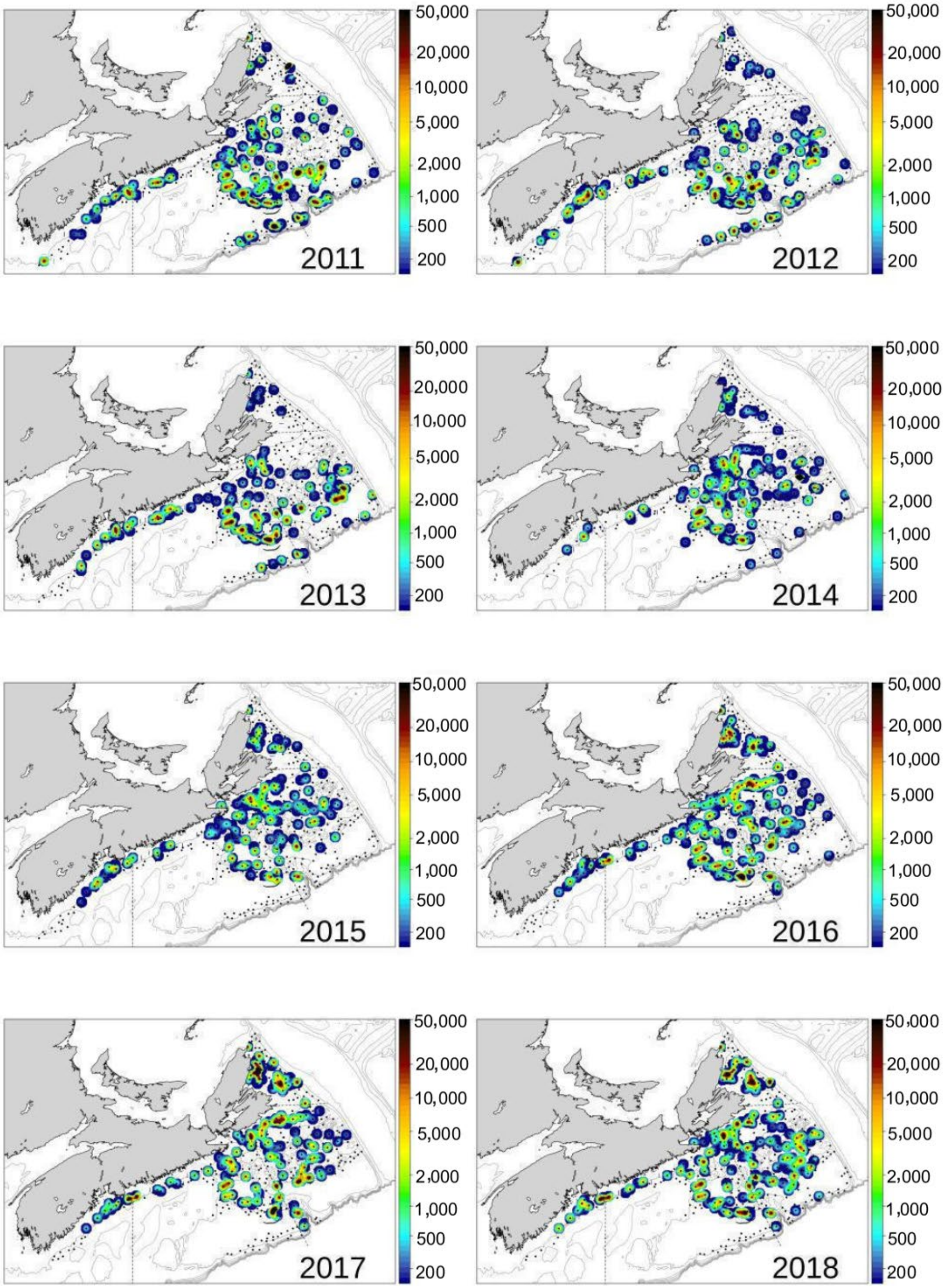


Figure 64. Numerical densities (number/km^2) of the mature female Snow Crab on the Scotian Shelf. Spatial representation generated using thin plate spline interpolations of data from the annual Snow Crab survey.

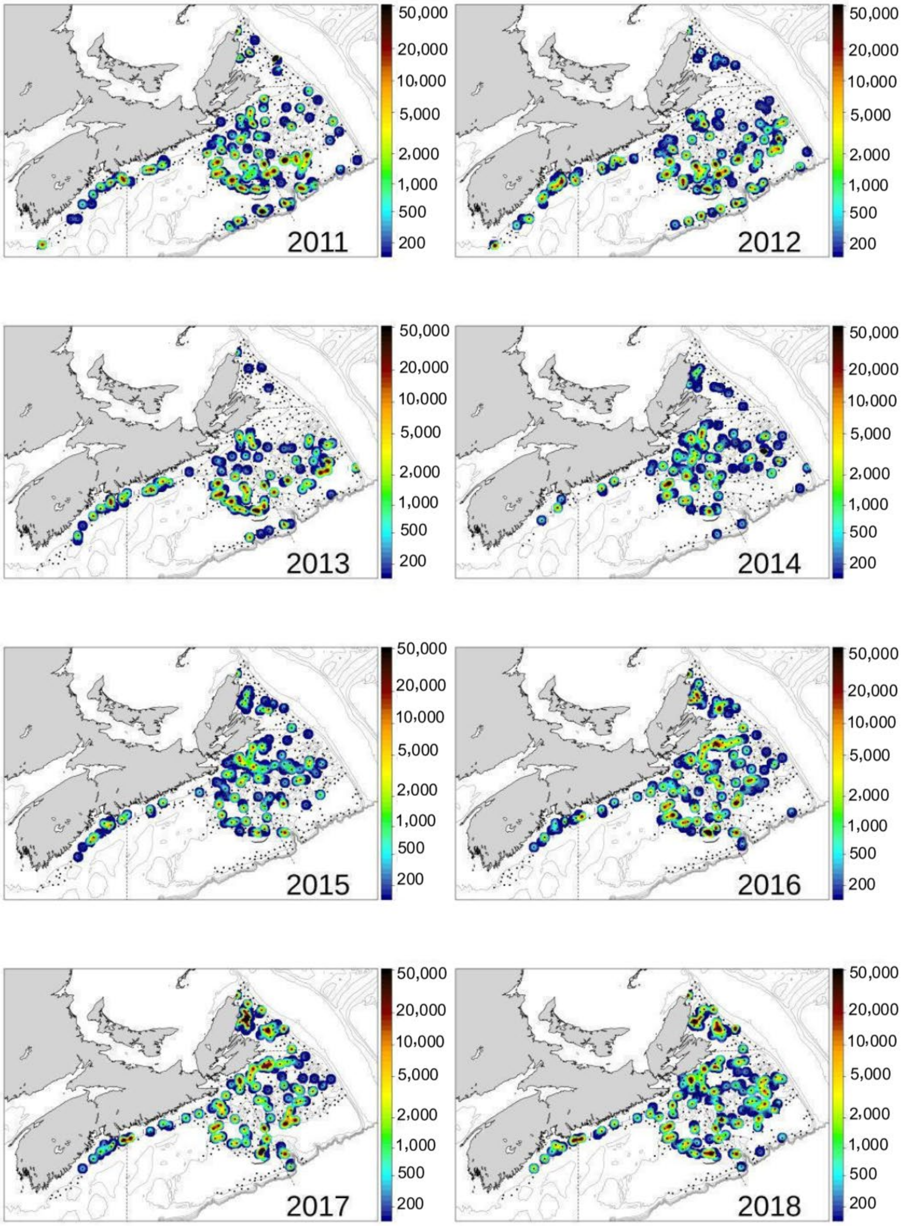


Figure 65. Numerical densities (number/km^2) of the ovigerous female Snow Crab on the Scotian Shelf with spatial representation generated using thin plate spline interpolations of data from the annual Snow Crab survey.

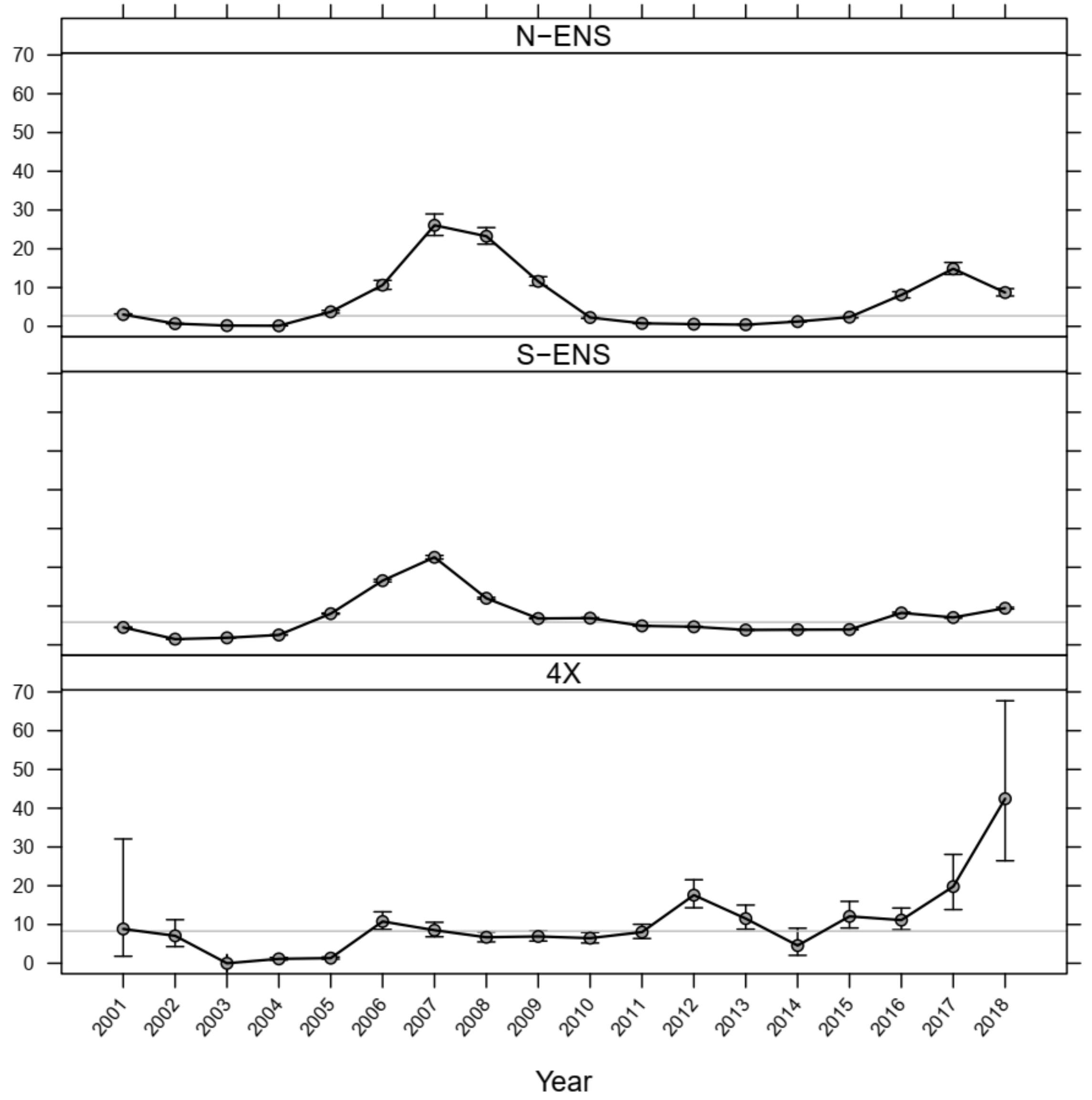


Figure 66. Geometric mean index of egg production on the Scotian Shelf determined from the number of berried female Snow Crabs and fecundity-at-weight estimates.

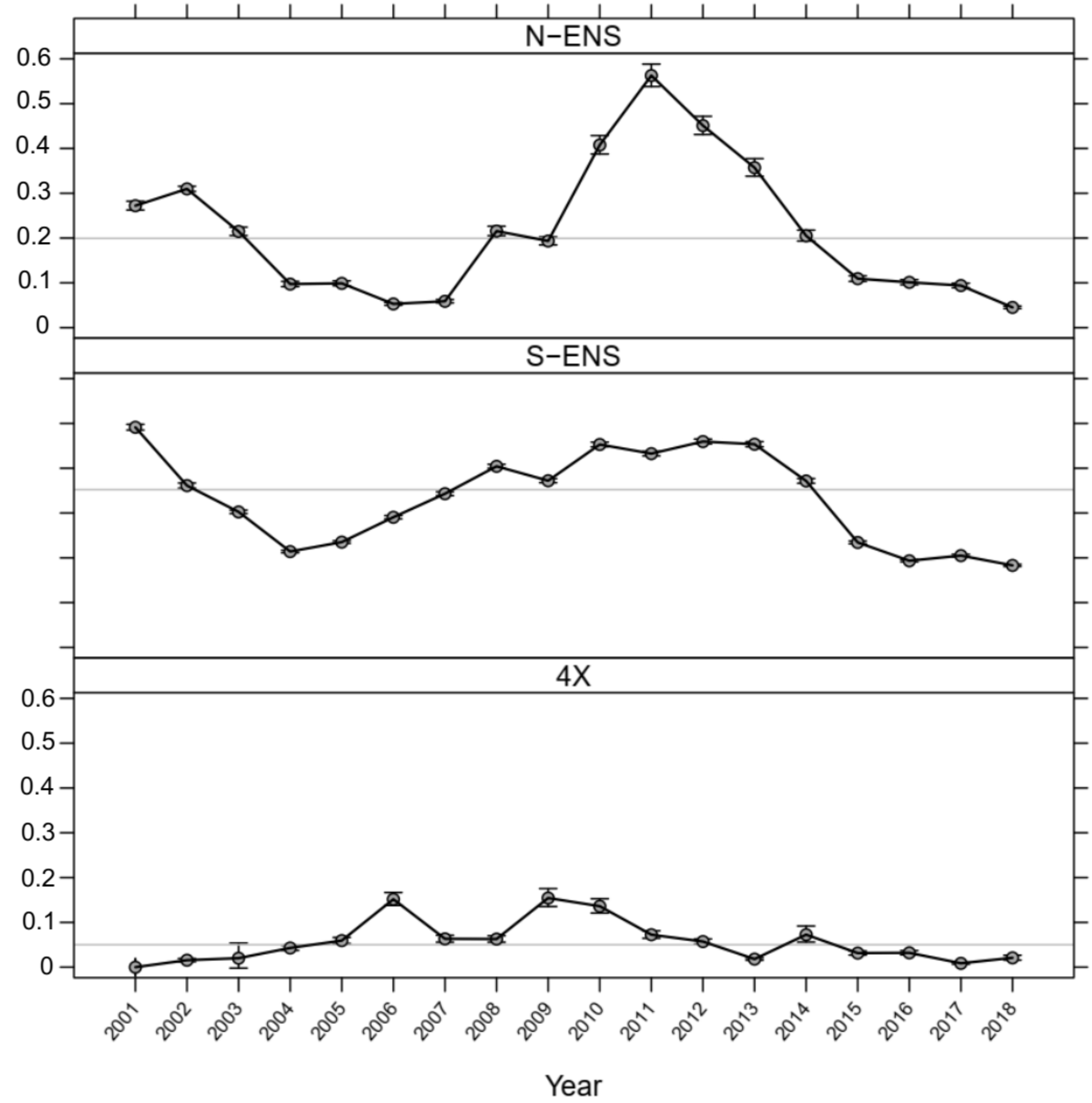


Figure 67. Trends in the geometric mean of fishable biomass (t/km^2) obtained from the annual Snow Crab survey. Error bars are 95% CI about geometric mean.

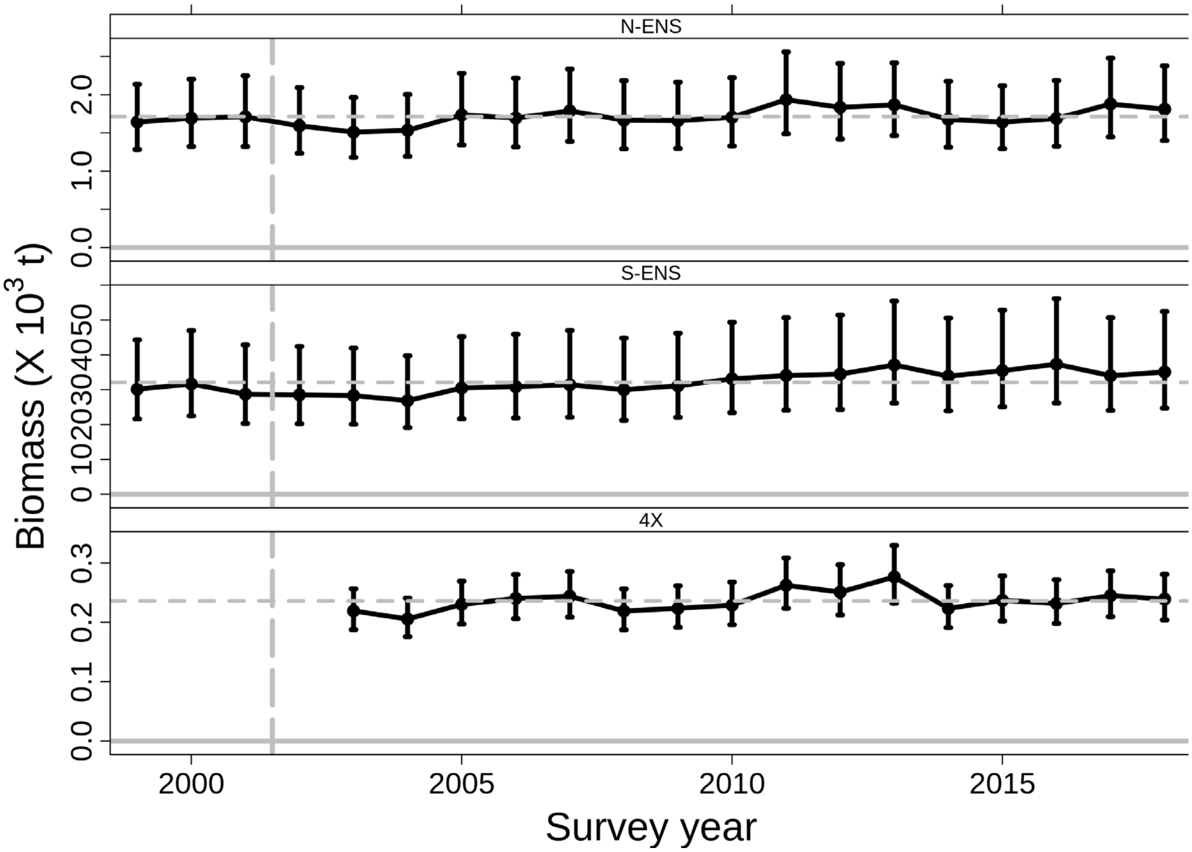


Figure 68. Trends in the area expanded geometric mean fishable biomass (t/km^2) obtained from the annual Snow Crab survey. Error bars are 95% CI about geometric mean. Area estimates are obtained from stmv. Vertical dashed line represents timing shift from a spring survey to a fall survey. Horizontal dashed line is mean.

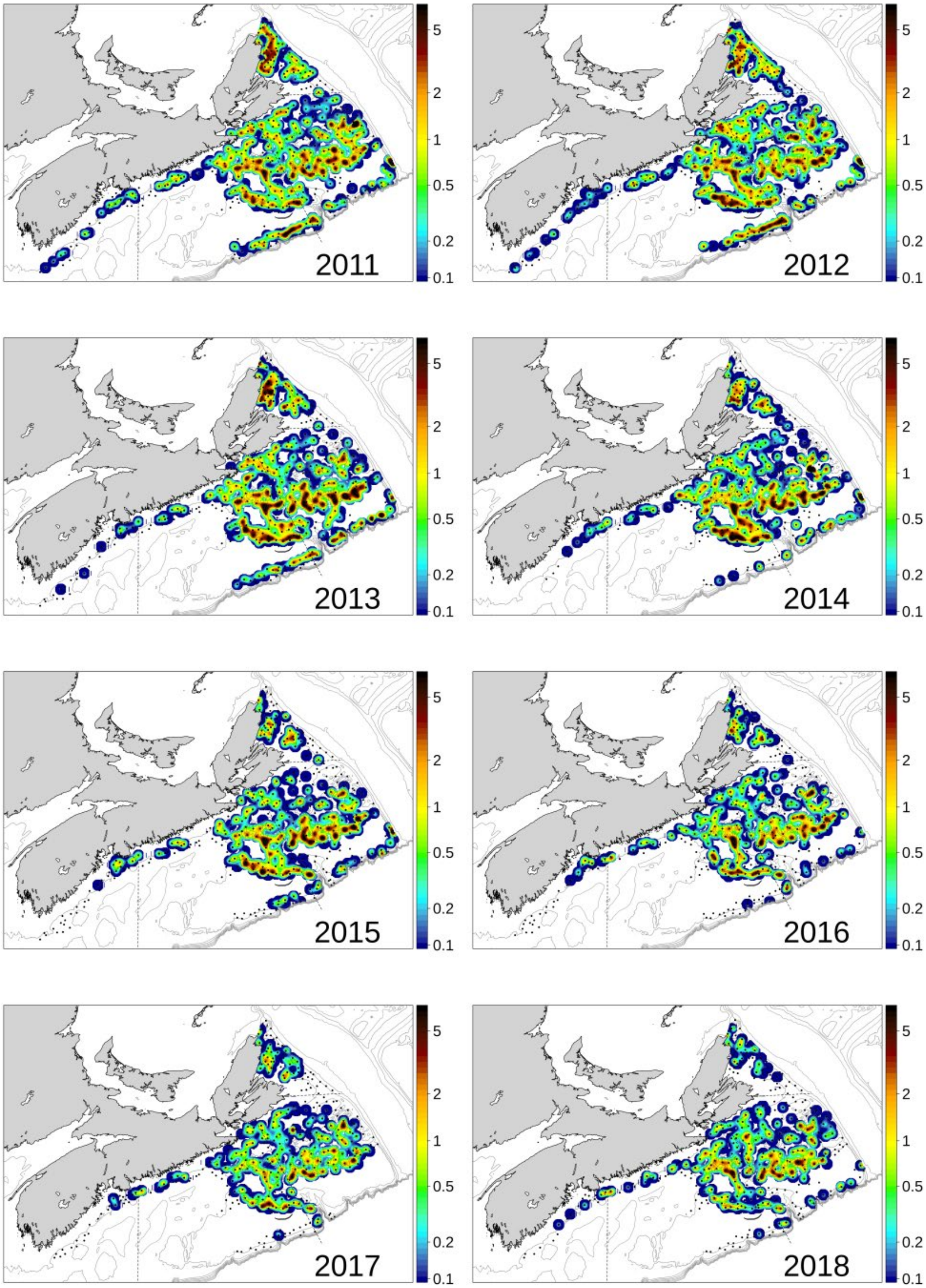


Figure 69. Fishable biomass densities (t/km^2) of Snow Crab on the Scotian Shelf with spatial representation generated using thin plate spline interpolations of data from the annual Snow Crab survey.

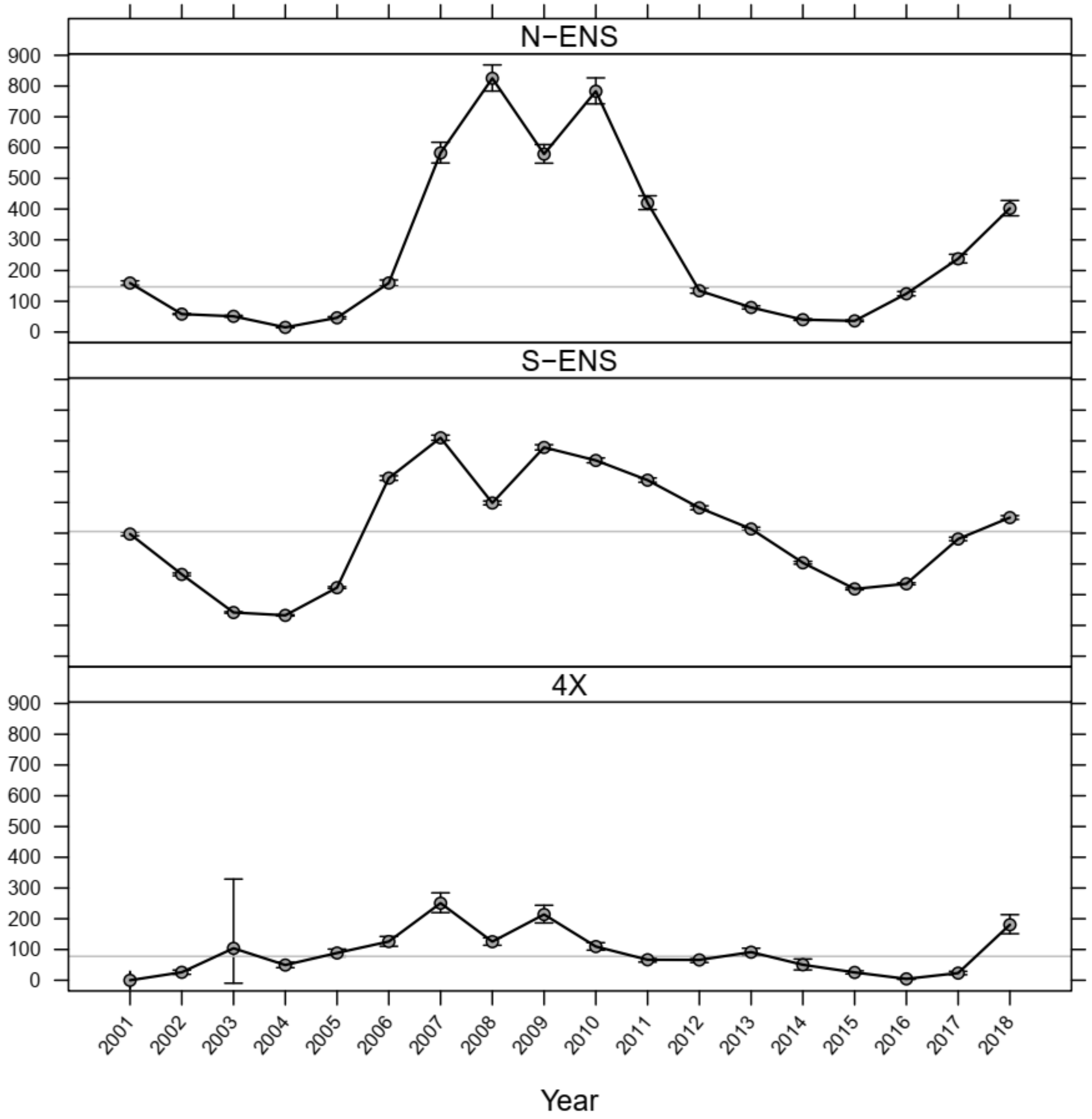


Figure 70. Trends in the geometric mean abundance (t/km^2) of male Snow Crab (75–95 mm CW) obtained from the annual Snow Crab survey. Error bars are 95% CI about geometric mean.

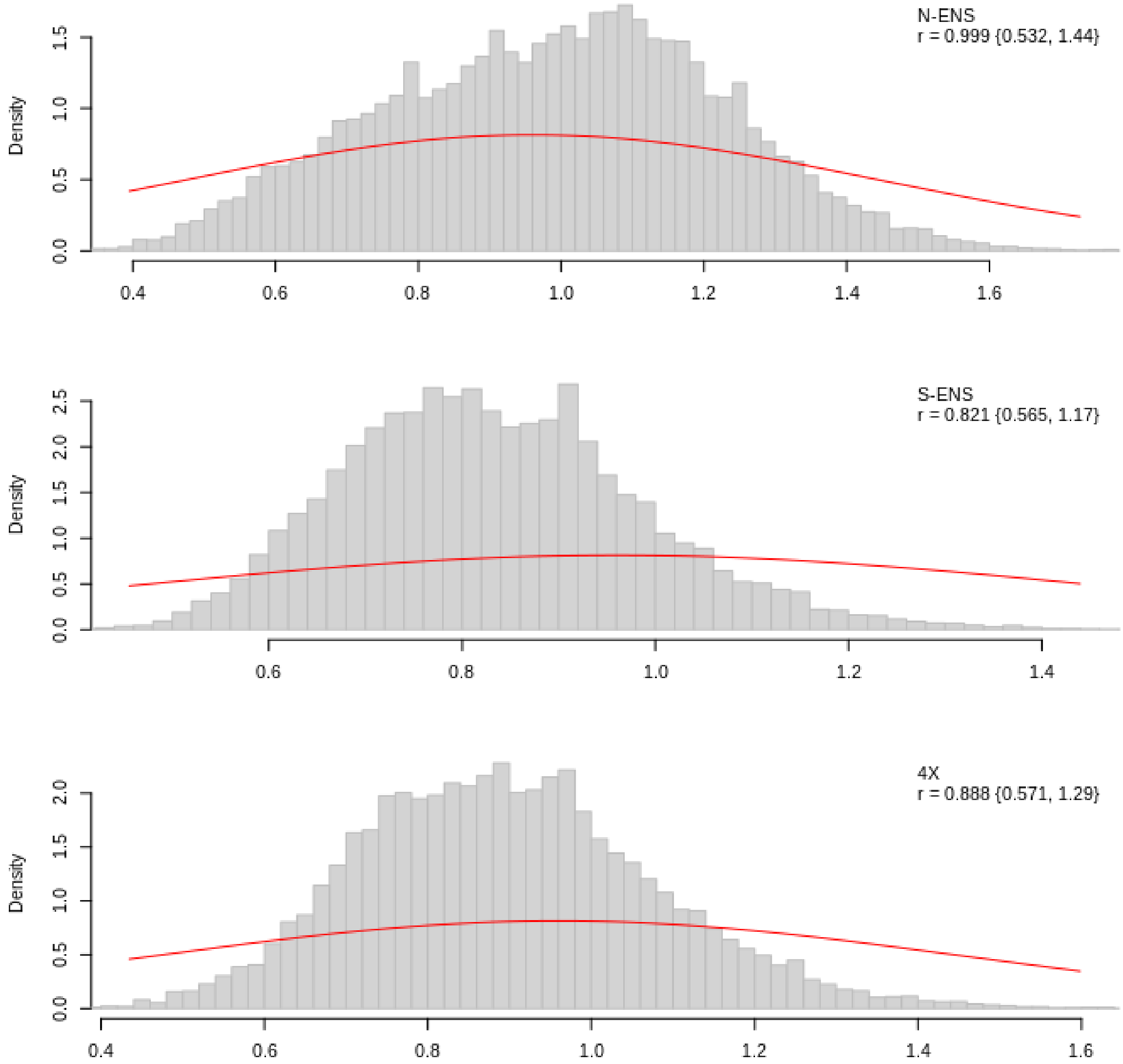


Figure 71. Prior (red) and posterior (bars) distribution for population growth parameter, r, from the biomass dynamic model of Snow Crab production in crab fishing areas on the Scotian Shelf. Within each panel, estimates of posterior median and 95% credible intervals are given in the legend.

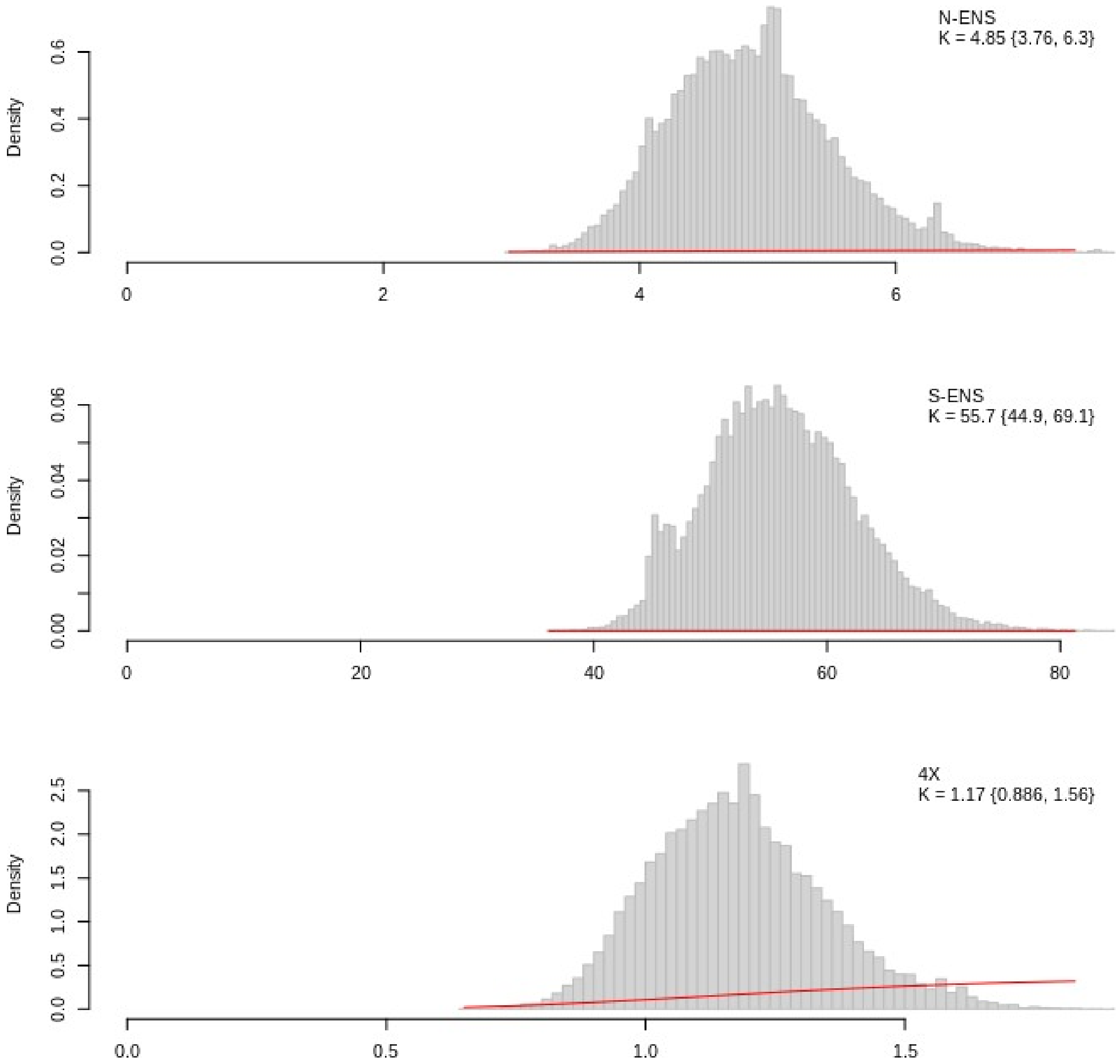


Figure 72. Prior (red) and posterior (bars) distribution for carrying capacity parameter, K, from the biomass dynamic model of Snow Crab production in crab fishing areas on the Scotian Shelf. Within each panel, estimates of posterior median and 95% credible intervals are given in the legend.

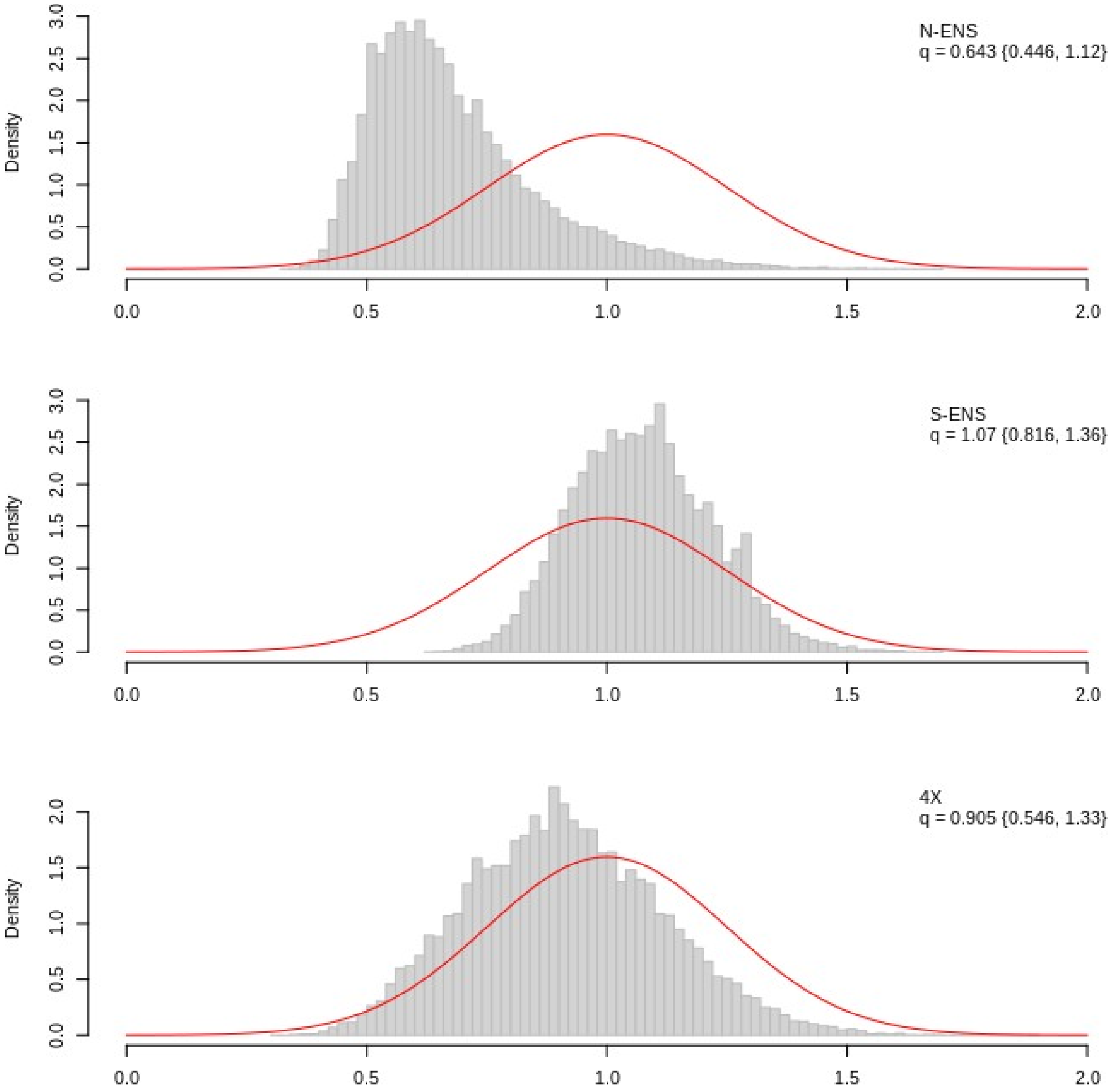


Figure 73. Prior (red) and posterior (bars) distribution for catchability parameter, q, from the biomass dynamic model of Snow Crab production in crab fishing areas on the Scotian Shelf. Within each panel, estimates of posterior median and 95% credible intervals are given in the legend.

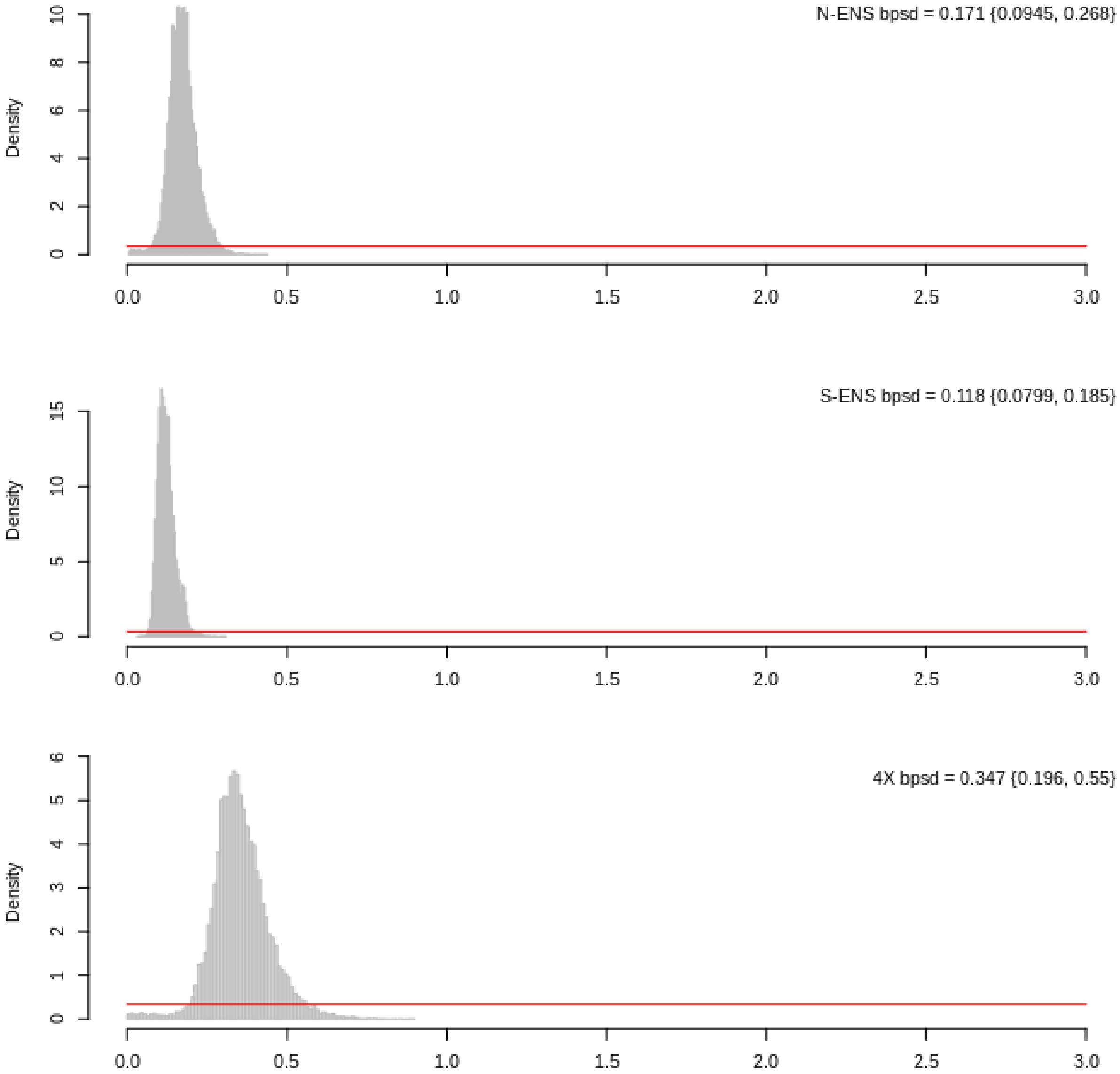


Figure 74. Prior (red) and posterior (bars) distribution for process error from the biomass dynamic model of Snow Crab production in crab fishing areas on the Scotian Shelf. Within each panel, estimates of posterior median and 95% credible intervals are given in the legend.

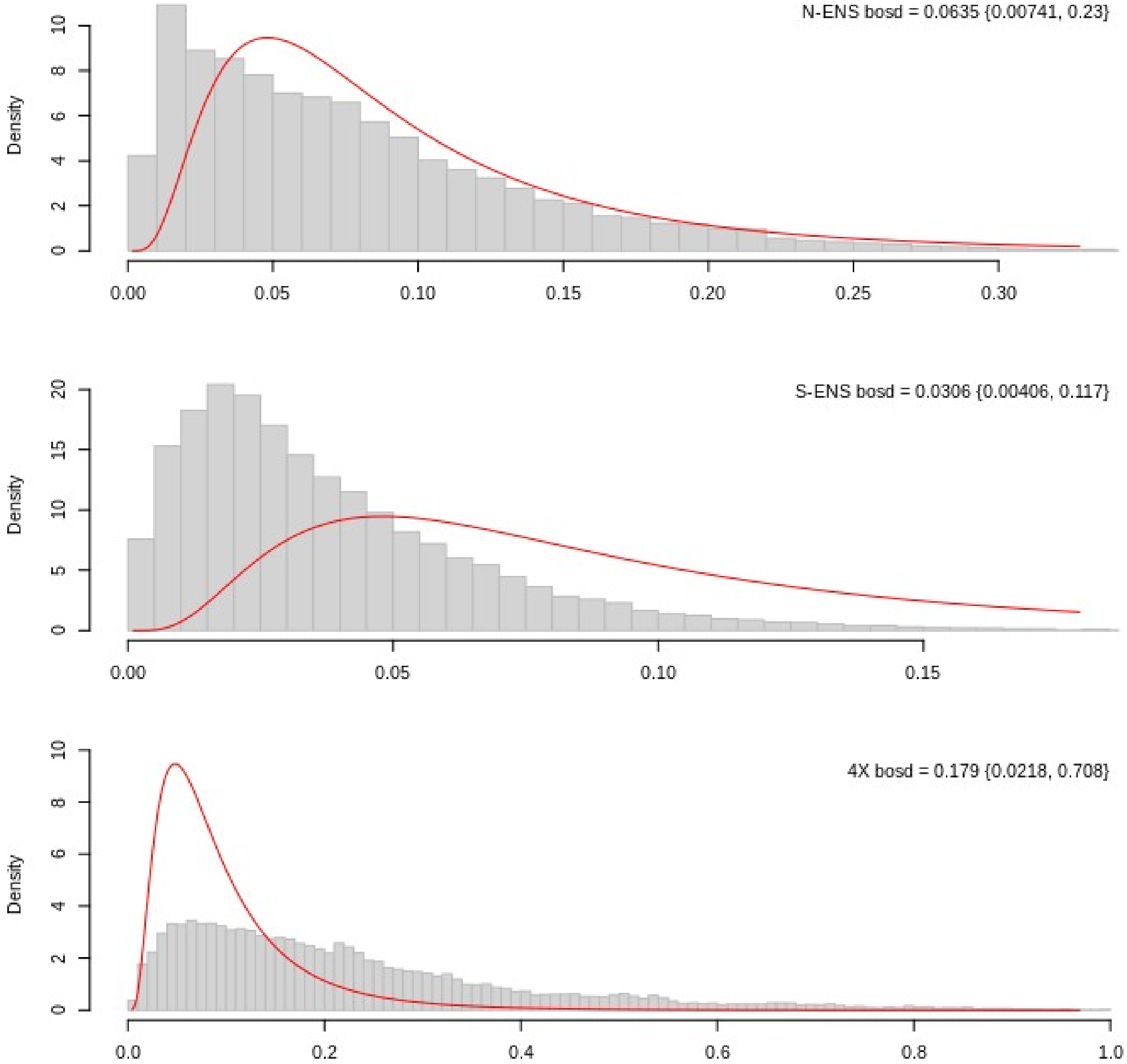


Figure 75. Prior (red) and posterior (bars) distribution for observation error from the biomass dynamic model of Snow Crab production in crab fishing areas on the Scotian Shelf. Within each panel, estimates of posterior median and 95% credible intervals are given in the legend.

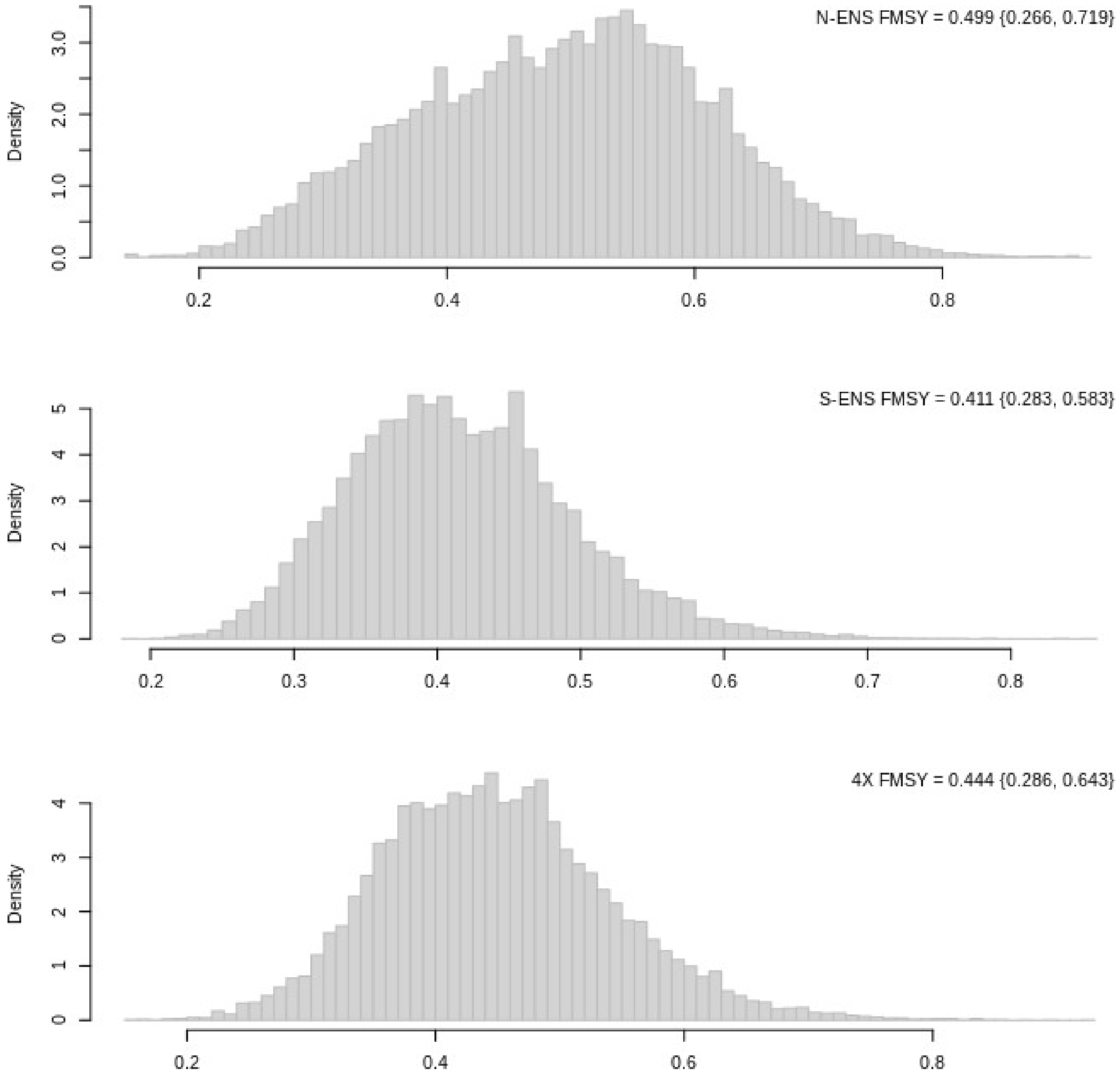


Figure 76. Posterior distribution for fishing mortality at maximum sustainable yield from the biomass dynamic model of Snow Crab production in crab fishing areas on the Scotian Shelf. Within each panel, estimates of posterior median and 95% credible intervals are given in the legend.

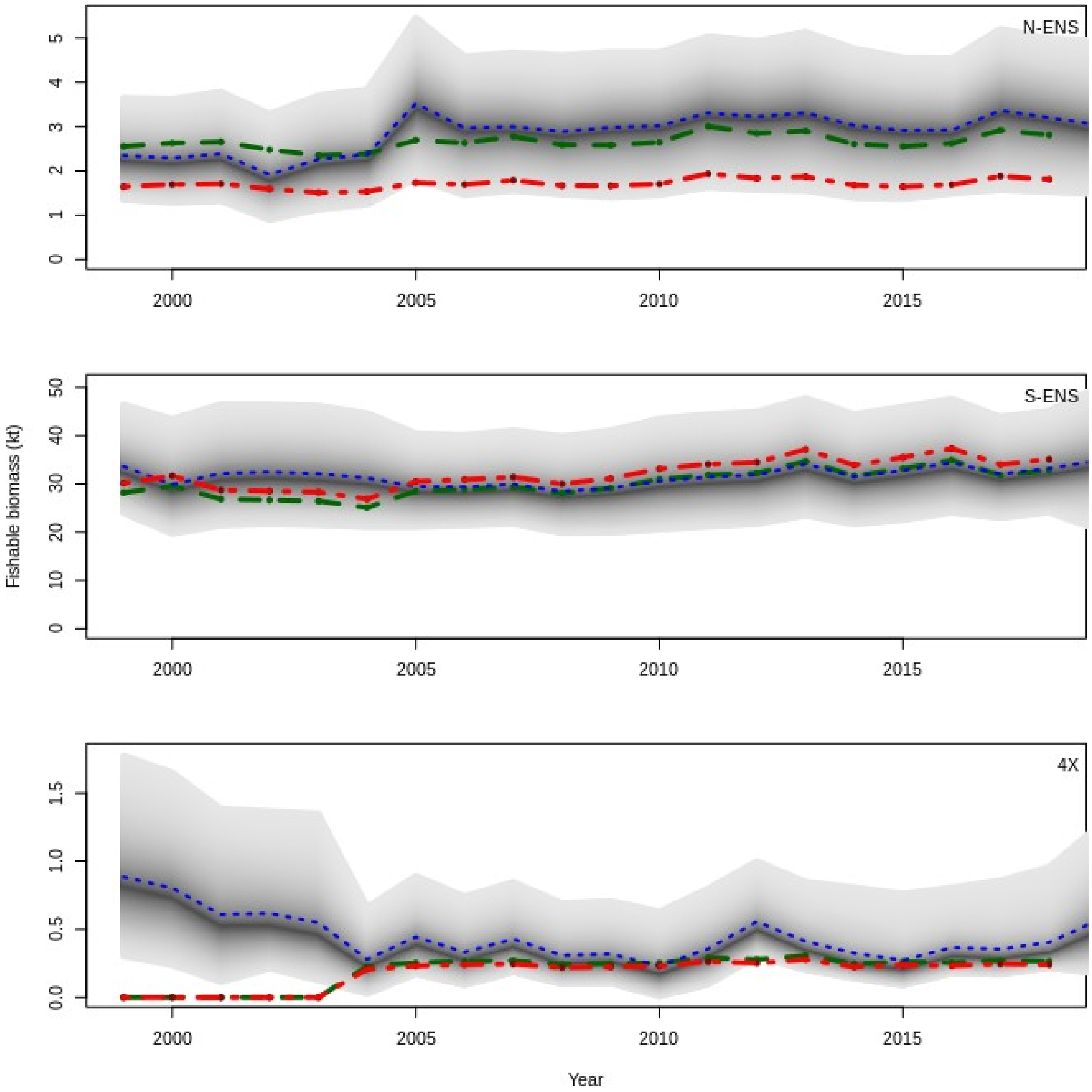


Figure 77. Time series of fishable biomass from the logistic population models. The fishable biomass index is shown in red dashed lines. The q-corrected fishable biomass index is shown in green dashed lines. The posterior mean fishable biomass estimated from the logistic model are shown in blue stippled lines. The density distribution of posterior fishable biomass estimates are presented with 95% CI (gray) with the darkest area being medians.

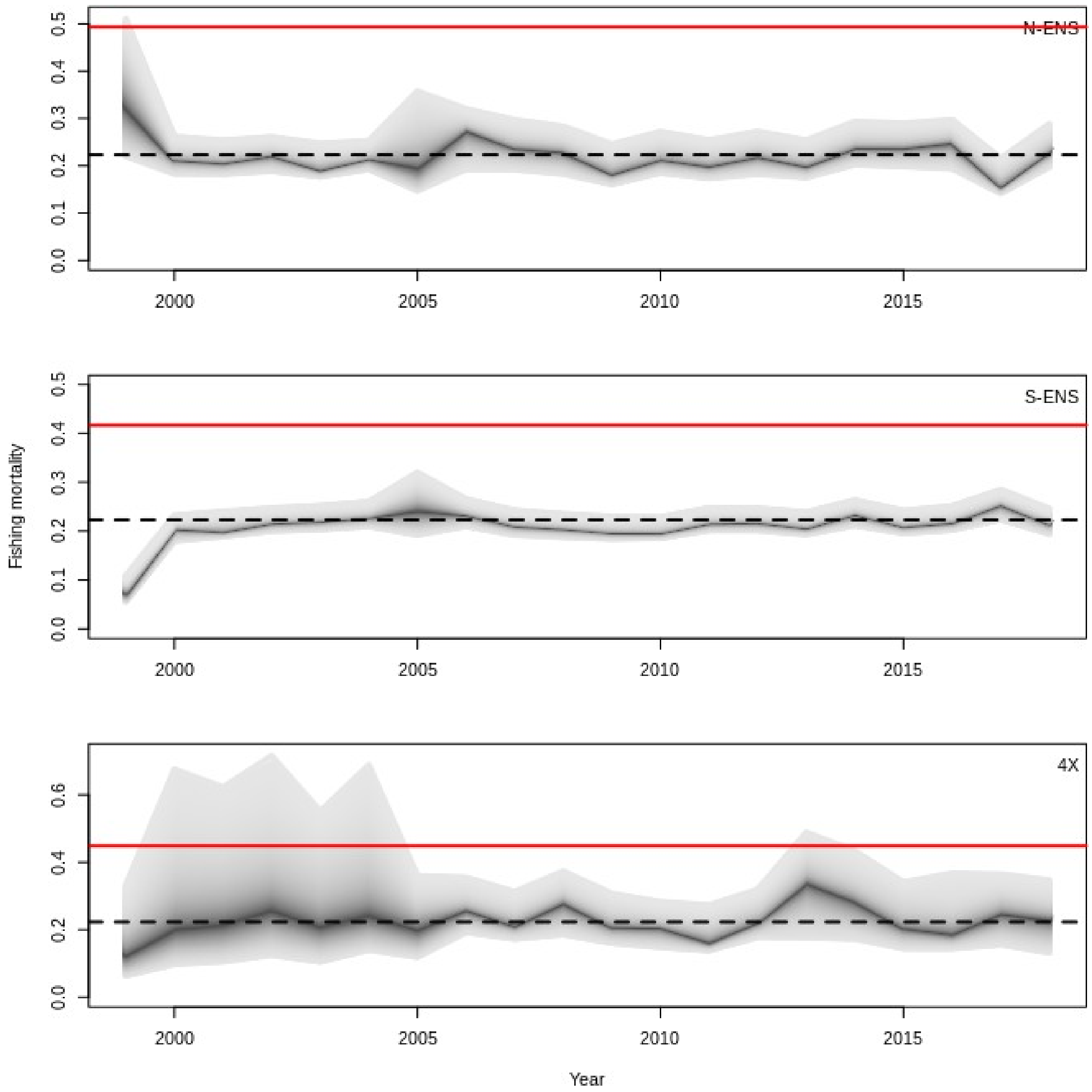


Figure 78. Time-series of fishing mortality from the logistic population models for North-Eastern Nova Scotia (N-ENS), South-Eastern Nova Scotia (S-ENS), and 4X, respectively. Posterior density distributions are presented in gray, with the darkest line being the median with 95% CI. The red line is the estimated F_{MSY} and dark stippled line is the 20% harvest rate.

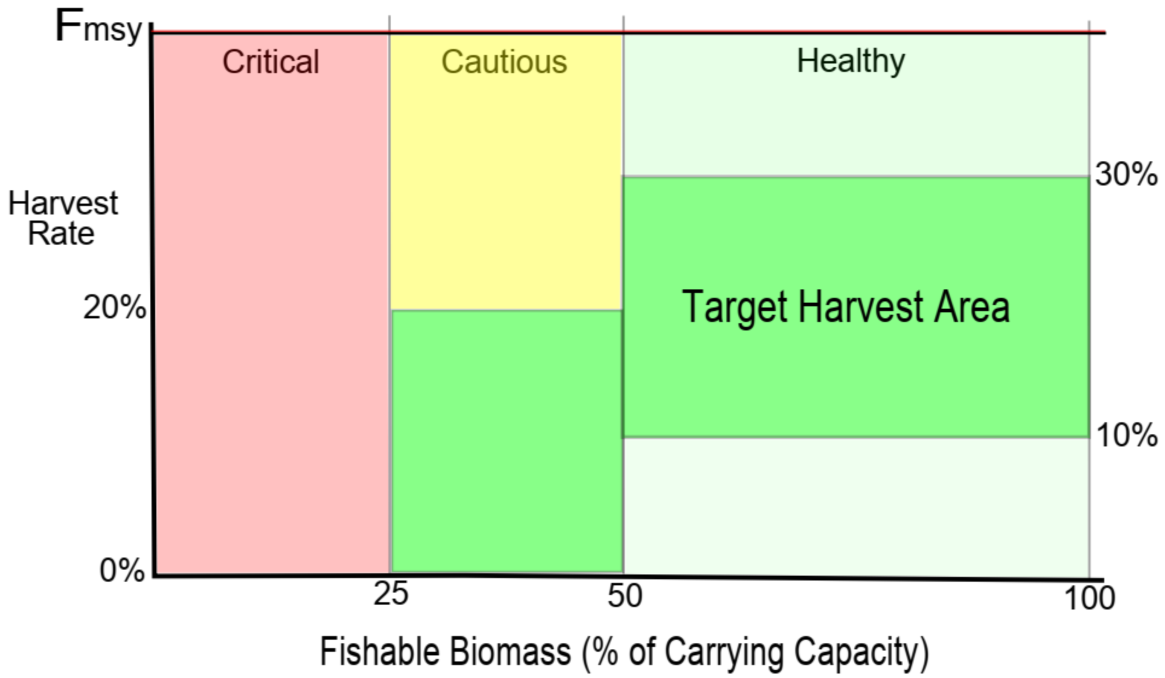


Figure 79. Harvest control rules for the Scotian Shelf Snow Crab fishery.

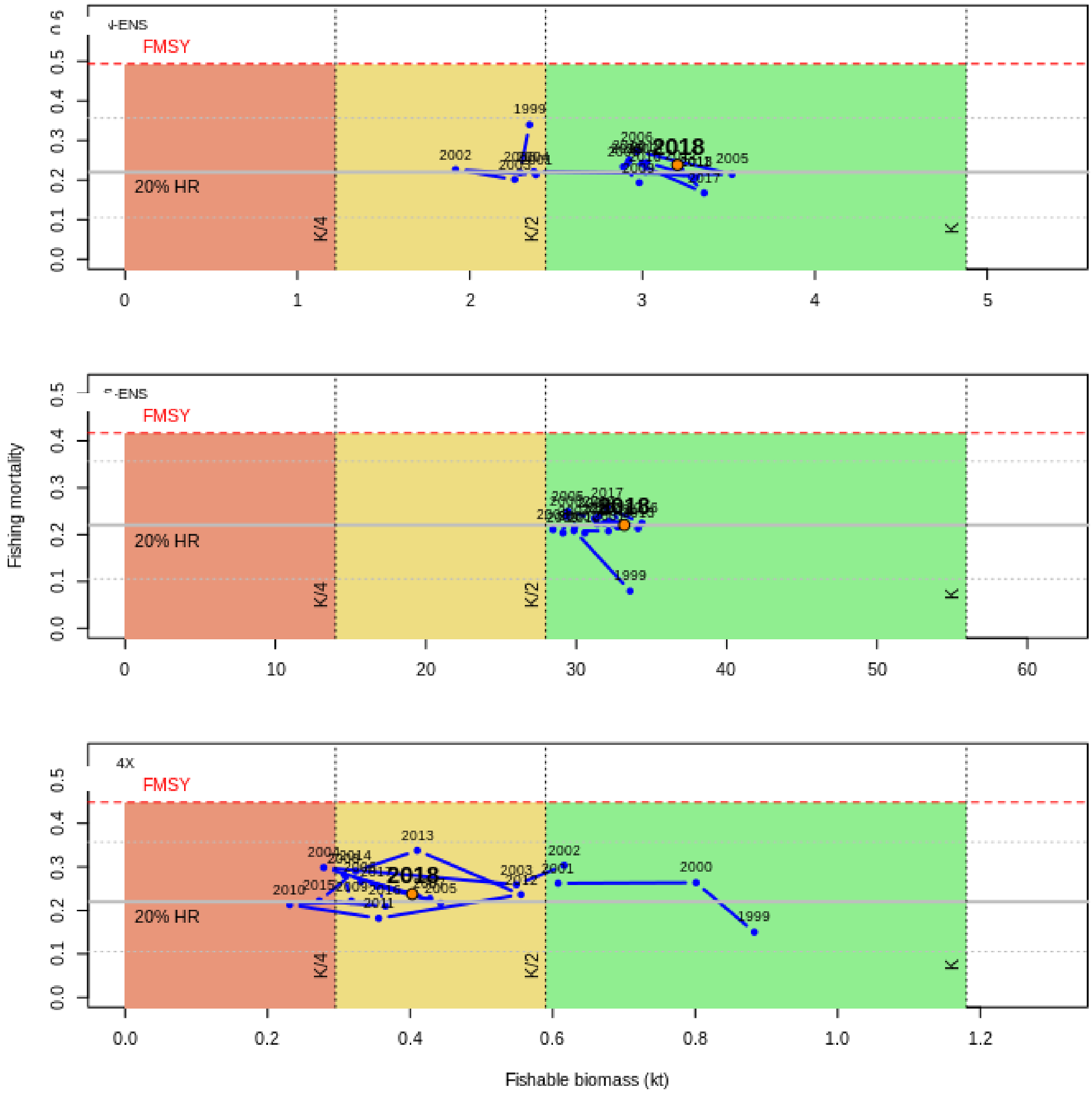


Figure 80. Time series of fishing mortality and pre-fishery biomass for N-ENS (top), S-ENS (middle) and 4X (bottom) as obtained from the logistic population models. Relative position of biomass within the stock status ranges is highly constrained due to current survey abundance estimation techniques. Actual variability is likely higher based on raw indices of abundance such as density of survey catches.

APPENDICES

APPENDIX 1: SPATIO-TEMPORAL MODELS OF VARIABILITY

Introduction

Ecological and biological processes demonstrate variability in space and in time. Characterizing this variability and understanding them is relevant for understanding the processes and characterizing/predicting them. Sampling design tries to approach such issues by trying to balance information obtained versus costs of sampling. Strategies can range from completely random sampling in the absence of additional information, to some form of stratified random design that randomly chooses samples from strata constrained by factors believed to be pertinent or informative. A common one is of course areal stratification based upon some prior knowledge that is known or believed to be informative (e.g., depth, temperature, or some oceanic feature), such that the variability within strata will be smaller than that between strata. The lower the variability within strata (relative to between-strata variability), the better the stratification of spatial areas ("design") has captured local homogeneities in the process of interest (e.g., abundance of some organism); that is, each sample is thought to be more representative of the stratum that it represents.

The problem, of course, is that the size of these strata can shrink to unmanageable numbers as the number of informative factors increase and the kinds of processes also increase. Further, the locations of such strata can shift if they are based upon features that are not geographically fixed, such as with temperature, oxygen levels, abundance of prey or predators, light levels, etc. This approach, therefore, crudely "adjusts" for the influence of these "extraneous" factors by a crude re-weighting of the total variance such that they can thereafter be ignored. These factors, are however, highly informative and ignoring them for the sake of simplicity by "factoring them out" can lead to erroneous conclusions about the focal process(es) of interest, especially when they are dynamic.

There exist two main approaches towards incorporating such additional information: (1) a spatially continuous process and (2) spatially aggregated areal units. Both approaches decompose the spatial patterns into those that are associated with: informative factors; structured spatial autocorrelation patterns; and completely spatially unstructured errors. In the following, we will summarize the general background to the field, following closely Banerjee et al. (2004)'s exceptionally clear and thorough exposition of these ideas. To assist in the context of stock assessment and general spatial and spatiotemporal modeling of potentially large areas, some of these methods have been formulated in an R Package, "stmv". This appendix will also serve to document these methods.

Continuous Representation

Spatial Autocorrelation

To be precise, we focus upon any spatially referenced observation $\mathrm{Y_s}$ at locations s, measured in a coordinate space whose domain D has dimensionality d such that $\{\mathrm{s} \in \mathrm{D} \in \Re^{\mathrm{d}}\}$. We focus upon the simple case of $\mathrm{d} = 2$ spatial dimensions, such that for example, $\mathrm{s} = (\mathrm{northing}, \mathrm{easting})$. The observations $\mathrm{Y_s}$ are assumed to be realizations of a **spatial stochastic process**, y, that is some latent unobservable but real, stochastic, generative function (i.e., a spatial random field) such that $\mathrm{y_s} \rightarrow \mathrm{Y_s}$ at $\{\mathrm{k} = 1, \ldots, \mathrm{K}\}$ spatial locations. The manner in which the variability of $\mathrm{y_s}$ changes as a function of distance, $\mathrm{h} = \| \mathrm{s} - \mathrm{s}' \|$, is known as the spatial autocorrelation function. The $\|\cdot\|$ indicate a norm which in $\mathrm{d} = 2$ dimensions is the Euclidean distance, $\mathrm{h} = (\Delta\mathrm{northing}^2 + \Delta\mathrm{easting}^2)^{1/2}$.

The spatial model is expressed as a regression model of a stochastic process (Banerjee et al. 2004):

$$\mathrm{Y_s} = \mathrm{g}(\mathrm{x_s^T}\beta + \omega_\mathrm{s} + \varepsilon_\mathrm{s}),$$

where, the observations $\mathrm{Y_s}$ are a function of some mean process $\mathrm{x_s^T}\beta$ (sometimes referred to as “external drift” in the kriging literature), and a residual error process $(\omega_\mathrm{s} + \varepsilon_\mathrm{s})$, operating potentially under the context of Generalized Linear Models via the link function $\mathrm{g}(\cdot)$. The $\mathrm{x_s}$ are spatially referenced predictors with associated parameters β. The residual error process is decomposed into spatially structured ω_s and spatially unstructured ε_s components, both with mean of zero. The latter is also commonly called the “nugget” error in geostatistics and used to represent measurement and/or microscale variability/processes; it is usually assumed to have a Normal distribution and standard deviation σ_ε. The spatial error is assumed to follow a **Gaussian process** with mean 0 and a spatial covariance function $\mathrm{C}(\mathrm{s},\mathrm{s}';\theta)$ that describes form of the variance of the process as a function of distance between data, controlled by the parameters θ and spatially structured standard deviation σ_ω (see below). The full model specification is, therefore:

$$\begin{array}{rcl} \mathrm{Y_s} & = & \mu_\mathrm{s}, \\ \mathrm{g}(\mu_\mathrm{s}) & = & \mathrm{x_s^T}\beta + \omega_\mathrm{s} + \varepsilon_\mathrm{s}, \\ \varepsilon_\mathrm{s} & \sim & \mathrm{N}(0,\sigma_\varepsilon^2), \\ \omega_\mathrm{s} & \sim & \mathrm{GP}(0,\mathrm{C}(\mathrm{s},\mathrm{s}';\theta)). \end{array}$$

The above is equivalent to assuming a Multivariate Normal likelihood for the observations $\mathrm{Y} = (\mathrm{Y}_{\mathrm{s}_1},\dots,\mathrm{Y}_{\mathrm{s}_\mathrm{K}})^\mathrm{T}$, with mean $\mu = \left[\mathrm{x}_{\mathrm{s_i}}^\mathrm{T}\right]_{\mathrm{i}=1}^{\mathrm{K}}\beta$ and a covariance matrix $\Sigma = \left[\mathrm{C}(\mathrm{s_i},\mathrm{s_j};\theta)\right]_{\mathrm{i,j}=1}^{\mathrm{K}} + \tau^2\mathrm{I_K}$, such that $\mathrm{Y} \sim \mathrm{MVN}(\mu,\Sigma)$; with $\mathrm{I_K}$ an identity matrix of size K. It is also computationally more efficient as fewer likelihood evaluations are conducted and fast and sparse implementations of the Multivariate Normal exist.

The spatial covariance function $\mathrm{C}(\mathrm{h}) = \mathrm{C}(\mathrm{s},\mathrm{s}';\theta)$ expresses the tendency of observations closer together to be more similar to each other than those further away. Commonly used forms include:

$$\begin{array}{rcl} \mathrm{C(h)_{Spherical}} & = & \begin{cases} \sigma_\mathrm{s}^2(1 - \frac{3}{2}\mathrm{h}/\phi + \frac{1}{2}(\mathrm{h}/\phi)^3); & 0 < \mathrm{h} <= \phi \\ 0; & \mathrm{h} > \phi, \end{cases} \\ \mathrm{C(h)_{Exponential}} & = & \sigma_\mathrm{s}^2 e^{-\mathrm{h}/\phi}, \\ \mathrm{C(h)_{Gaussian}} & = & \sigma_\mathrm{s}^2 e^{-(\mathrm{h}/\phi)^2}, \\ \mathrm{C(h)_{Powered\ exponential}} & = & \sigma_\mathrm{s}^2 e^{-|\mathrm{h}/\phi|^\mathrm{p}}, \\ \mathrm{C(h)_{Matérn}} & = & \sigma_\mathrm{s}^2 \frac{1}{2^{\nu-1}\Gamma(\nu)}(\sqrt{2\nu}\mathrm{h}/\phi)^\nu\ \mathrm{K}_\nu(\sqrt{2\nu}\mathrm{h}/\phi). \end{array}$$

At zero distance, $\mathrm{C}(0) = \mathrm{Cov}(\mathrm{Y_s},\mathrm{Y_s}) = \mathrm{Var}(\mathrm{Y_s}) = \sigma_\varepsilon^2 + \sigma_\mathrm{s}^2$ (i.e., global variance), where σ_ε is the nonspatial, unstructured error, σ_s is the spatially structured error, and $\theta = \{\phi,\nu,\mathrm{p},\dots\}$ are function-specific parameters including ϕ the range parameter. $\Gamma(\cdot)$ is the Gamma function and $\mathrm{K}_\nu(\cdot)$ is the Bessel function of the second kind with smoothness ν. The Matérn covariance function is frequently used in the more recent literature as the shape of this function is more flexible (Figure A1.1).

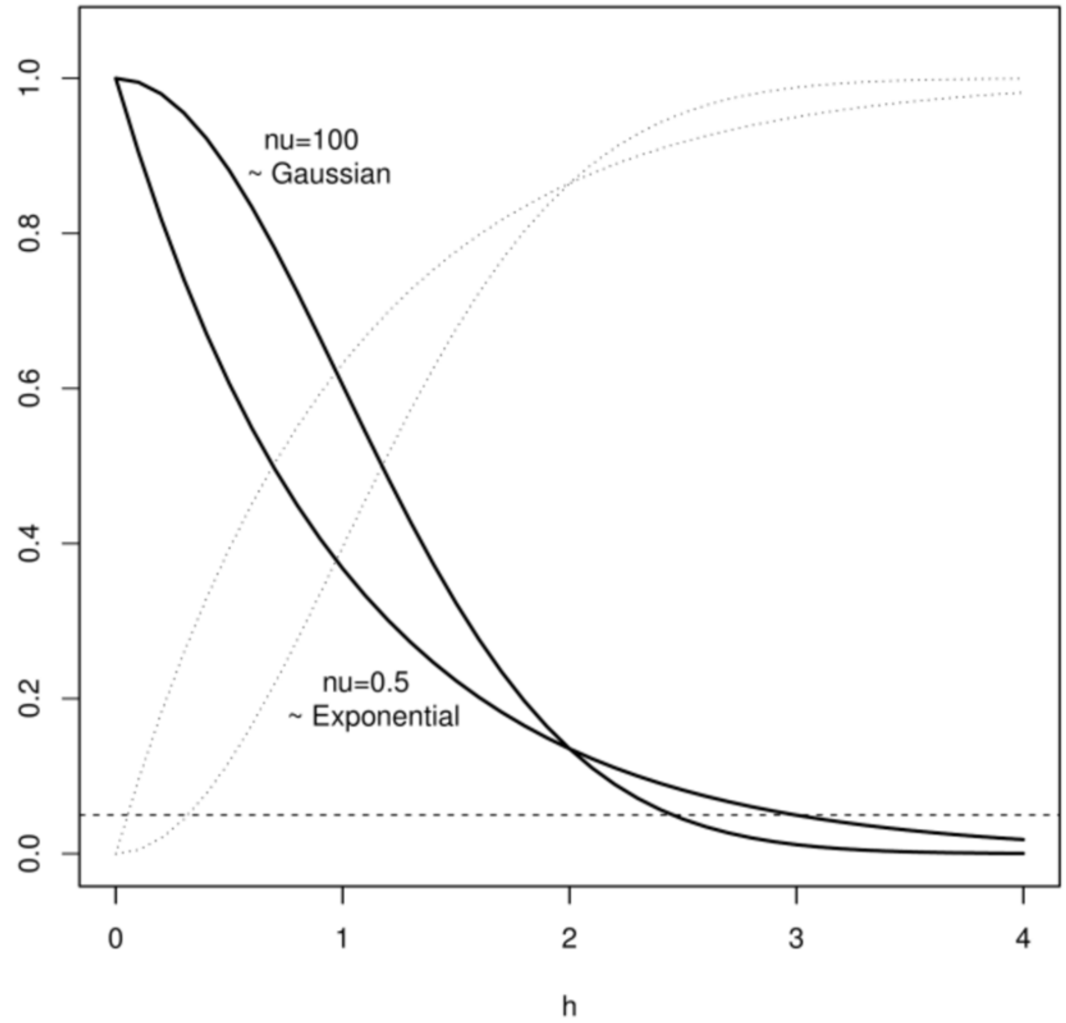


Figure A1.1. Matérn autocorrelation function, $\rho(h) = C(h)/C(0)$, the covariance function $C(h)$ scaled by the total variance $C(0)$, for two values of ν (dark lines). As ν increases $(\nu = 100)$, it approaches the Gaussian curve (upper dark curve on the left side) while at smaller values $(\nu = 0.5)$ the curve is exponential (lower dark curve on the left side). This flexibility has made it a popular choice in geostatistics. The associated semivariograms (scaled to unit variance) $\gamma(h)$ are shown in light stippled lines. Spatial scale is defined heuristically as the distance h at which the autocorrelation falls to 0.05 (dashed horizontal line) – in this example between 2.5 and 3 distance units, depending upon value of ν. The semivariance (also called "semivariogram") $\gamma(h)$, is more commonly used in the kriging literature, and is simply the covariance function $C(h)$ reflected on the horizontal axis of the global variance $C(0)$ such that $\gamma(h) = C(0) - C(h) = \frac{1}{2}\, Var[Y_s - Y_s{}'] = \sigma_\omega^2[1 - \rho(h)]$.

Defining the spatial scale of a given observation or process is imperative for the development of any ecological assessment or monitoring. The **spatial autocorrelation function** is defined as the covariance function scaled by the global variance: $\rho(\mathrm{h}) = \mathrm{C}(\mathrm{h})/\mathrm{C}(0)$. Heuristically, we define the **spatial autocorrelation scale** to be the distance at which the spatial autocorrelation decreases asymptotically to $\rho(\mathrm{x}) \rightarrow 0.05$ (occasionally called the "practical" range in the literature). This spatial scale of an ecological process is informative in that when short-range processes dominate relative to the scale of the whole domain, such as when focusing upon less mobile species, weakly dispersing, low currents, habitat heterogeneity; then monitoring these processes can be meaningful and fruitful in discriminating what is structuring an area of interest.

If, however, long-ranging processes dominate relative to the scale of the whole domain, such as when focusing upon higher mobility species or dispersal processes/current, and stronger spatial connectivity, habitat heterogeneity, then there is a lower likelihood that monitoring such processes will provide insights to the internal structure of the area of interest.

This is perhaps clearest when spatial scale is studied in the context of specific organisms. For example, when a spatial feature (e.g., abundance distribution in space) demonstrates short characteristic spatial scales (i.e., a lot of spatial variability at smaller scales), sampling approaches must respect this and similarly operate at such shorter scales or even smaller if one is to be able to resolve the patterns and describe properly the subject of interest. Similarly, if a spatial feature is long-ranged and one wishes to resolve the patterns properly, then a sampling protocol must be similarly long-ranged to resolve the pattern. A sampling program much smaller than the characteristic spatial scale would be beneficial, but the accrued benefits relative to cost of sampling would diminish rapidly, in that time, effort and resources requirements generally increase more rapidly than any benefit (e.g., in the simplest case, if one is looking only naively at standard error as a measure of benefit, then it would increase asymptotically with increased effort with a power of $-1/2$).

Temporal Autocorrelation

Ecological systems being dynamic, also exist in a temporal frame. As such, similar to the above spatial considerations, there also exists some characteristic temporal scale upon which the processes internal to an area of interest and time period of interest operate. The canonical example is how some quantity changes from one time period to another. This discrete-time notion of temporal autocorrelation is the slope parameter from a plot of a variable as a function of itself with an offset of one time unit:

$$\upsilon_{t+1} = \rho \upsilon_t + \eta_t,$$

with $\eta_t \sim N(0, \sigma_t^2)$ and a temporal (linear) autocorrelation parameter ρ. This is known as an AR(1) process, where the 1 indicates 1 unit time lag. More complex models with moving averages and additional time-lags can also be specified. Collectively these are known as AR, ARMA, and ARIMA models. The difficulty with these autocorrelation timeseries formulations is the requirement of a complete data series without missing data.

The **cumulative periodogram** expresses the variance $f(\omega)$ as a function of temporal distance (wavelengths ω) and so is an analogue of the spatial semivariogram. It is a discrete sample estimate of the continuous concept of spectral density, $\gamma(t)$:

$$\gamma(t) = \int_{-1/2}^{1/2} e^{2\pi i \omega t} f(\omega) d\omega \quad \leftrightarrow \quad f(\omega) = \sum_{h=-\infty}^{h=\infty} \gamma\,(t) e^{-2\pi i \omega t}.$$

Usefully, as the autocovariance and spectral density are Fourier transform pairs, a Fast Fourier Transform can be used to rapidly assess the power spectrum and determine the empirical form of the periodogram.

Indeed, any spatial autocorrelation function (above) can be used to describe the empirical form of the temporal autocorrelation pattern and modelled in a manner completely analogous to the spatial case as a **temporal stochastic process**, y_t, that is, some latent, unobservable but real, stochastic, generative function such that $y_t \rightarrow Y_t$, where Y_t are any temporally referenced observation at some time t, measured in a coordinate space whose domain D has dimensionality 1 such that $\{t \in D \in \Re\}$with $\{l = 1, \dots, L\}$ temporal locations. The manner in which the variability of y_t changes as a function of the norm (distance), $h = \| t - t' \|$, is known as the temporal autocorrelation function. The latter can take any form including the same as the spatial autocorrelation functions. The model formulation is identical to the spatial case:

$$\begin{aligned} Y_t &= \mu_t, \\ g(\mu_t) &= x_t^T \beta + \omega_t + \varepsilon_t, \\ \varepsilon_t &\sim N(0, \sigma_\varepsilon^2), \\ \omega_t &\sim GP(0, C(t, t'; \theta)). \end{aligned}$$

The covariance function, for example, when expressed as an exponential decay model controlled by time range parameter ϕ_t is:

$$C(t, t'; \theta_t) = \sigma_t^2 e^{-|h|/\phi_t}.$$

Similar to the case of spatial scales, temporal scales also have a simple implication in terms of monitoring and assessment. Short time-range variations require higher sampling effort to resolve/understand the issues and vice-versa. As temporal scale is an informative metric for monitoring and assessment of an ecological process, we must be precise in its definition. The cumulative distribution permits a rapid identification of the time scale at which correlation drops to some arbitrary level. To be approximately comparable to the spatial scale, we define the **temporal autocorrelation scale** as the time difference (wavelength) at which the temporal autocorrelation function (1 - Cumulative Power Spectral Density) decreases to 5% of the total variance. If resolving short-term processes is a study's goal, then sampling must also necessarily be more frequent. However, similar to spatial scale issues, there is a point where there will be diminishing returns for any increase in the resolution of a temporal signal.

Spatiotemporal Autocorrelation

Spatial and temporal patterns coexist and co-evolve. They are correlated processes and a challenge to model. This renders the independent treatment and estimation of autocorrelation in time and space problematic. Nonetheless, new developments in computational methods are bringing such models within range of use. This is primarily due to efficient methods associated with numerical modeling of Stochastic Partial Differential Equations (SPDEs), and the use of spectral (Fourier) methods.

Again, following Banerjee et al.'s (2004) development, spatiotemporal models can be seen as a simple extension of the spatial regression model. The observations, $Y_{s,t}$ are measured in a coordinate space $\{(s,t) \in D \in \Re^d \times \Re\}$ in the domain D of dimensionality $d + 1$ with $\{k = 1, \ldots, K\}$ spatial and $\{l = 1, \ldots, L\}$ temporal locations. The space-time regression model can then be specified as:

$$Y_{s,t} = g(\mu_{s,t} + \omega_{s,t} + \varepsilon_{s,t}),$$

where, $\mu_{s,t} = x_{s,t}^T \beta_{s,t}$ is the mean process (or "external drift" in the kriging literature) and the error process is decomposed into a spatiotemporally structured component ω and an unstructured component ε, operating again under a generalized linear model framework, through the action of the link function $g(\cdot)$. The parameters $\beta_{s,t}$ of the spatially and temporally referenced predictors $x_{s,t}$ can have variable forms:

- β – completely fixed with no variation in time and space;
- $\beta_{-,t}$ – temporally varying and no spatial structure;
- $\beta_{s,-}$– spatially varying and no temporal structure;
- $\beta_{s,-}\text{\ensuremath{\divideontimes}}\beta_{-,t}$ – space and time varying independently (separably, the "$\divideontimes$" indicates additive or multiplicative);

- $\beta_{s,t}$– varying in both time and space complex (nonseparable) and potentially hierarchically (nonsimply).

The unstructured error is assumed to be a Normal iid error process: $\varepsilon_{s,t} \sim \mathrm{N}(0, \sigma_\varepsilon^2)$. However, the manner in which the spatiotemporally structured error should be parameterized is not straight-forward. Some common approaches include:

- $\omega_{-,t}$ – temporal effects nested in sites (temporal autocorrelation at each site, no spatial autocorrelation);
- $\omega_{s,-}$ – spatial effects nested in time (spatial autocorrelation at each time slice, no temporal autocorrelation);
- $\omega_{s,-} \ast \omega_{-,t}$ – separable (spatial and temporal autocorrelations are independent, the "$\ast$" indicates additive or multiplicative) with $\omega_{-,t} \sim \mathrm{GP}(0, \mathrm{C}(t, t'; \theta_t))$ and $\omega_{s,-} \sim \mathrm{GP}(0, \mathrm{C}(s, s'; \theta_s))$;
- $\omega_{s,t}$ – non-separable (both time and space structure evolve in a nonsimple manner).

The spatial and temporal errors are usually assumed to be derived from a **Gaussian Process** with mean 0 and some covariance $\mathrm{C}(\cdot,\cdot;\theta)$. The spatial covariance can be modelled with any spatial form such as: $\mathrm{C}(\Delta s)_{\text{Matérn}} = \sigma_s^2 \frac{1}{2^{\nu-1}\Gamma(\nu)} (\sqrt{2\nu}|\Delta s|/\phi)^\nu \ \mathrm{K}_\nu(\sqrt{2\nu}|\Delta s|/\phi)$. Similarly, the temporal covariance can be formulated as any similar autocorrelation model such as:

$$\mathrm{C}(\Delta t)_{\text{Exponential}} = \sigma_t^2 e^{-|\Delta t|/\phi_t}.$$

While conceptually coherent and elegant, the evaluation of the likelihoods in these models requires the repeated computation of the inverse of the covariance matrix $\Sigma_{n\times n}$ of size n, an operation that scales with $\mathcal{O}(n^3)$ operations. This has been a bottleneck to further development of these covariance-based methods in large scaled problems of space and space-time. Approximations have been suggested to overcome this computational limit: modeling the spatial process ω with a lower dimensional process via kernel convolutions, moving averages, low rank splines/basis functions and predictive processes (projection of spatial process onto a smaller subset; Sølna and Switzer 1996; Wikle and Cressie 1999; Huang et al. 2004; Xu et al. 2005; Banerjee et al. 2004); approximating the spatial process as a Markov random field with Laplace and SPDE Approximations (Lindgren and Rue 2015); and approximating the likelihood of the spatial-temporal SPDE process with a spectral domain process (Sigrist et al. 2012).

In the spatiotemporal setting, separable models are almost always used for the sake of computational speed as this treats space and time independently, reducing the problems crudely from $\mathcal{O}((\mathrm{KL})^3)$ to $\mathcal{O}(\mathrm{K}^3) + \mathcal{O}(\mathrm{L}^3)$ operations; where K is the number of spatial locations and L the number of time slices. In reality, however, such separable models are usually inappropriate unless the study area is homogeneous and truly first and second order constant (i.e., constant mean, variance, across time and space), a fact that is seldom true in most ecological systems (see below).

Spatiotemporal Models of Variability (stmv)

A central assumption of all spatial and spatiotemporal models is that the form and magnitude of the autocorrelation in space (and time) are stationary (constant mean and variance). This can be forced to be the case by modeling the mean effects and operating upon a residual error that is stationary. However, in practice, there is spatial heterogeneity of variance as well which cannot be easily modelled though a simple regression context. This is notoriously the case with biology where aggregation and behaviour is highly context (location and time) dependent (nonlinear).

In stmv, we address this nonstationarity and nonseparability of spatial and temporal structure and associated issues of computational speed and complexity by formulating a simplistic but operational approach to the overall spatiotemporal problem. This is done by reducing the problem into small manageable subdomains where assumptions of stationary are valid and modeling of spatiotemporal processes become computationally feasible. There is, therefore, some conceptual similarity of this approach to "geographically weighted regression" (e.g., Fotheringham et al. 2002) in that each subdomain can have their own model parameters $\beta_{s,t}$. However, we emphasize in stmv, it is not only the model parameters $\beta_{s,t}$ that are permitted to be variable, but so too the spatiotemporal errors $\varphi_{s,t}$.

To be more precise, in the spatiotemporal domain D, where $\{(s,t) \in D \in \Re^d \times \Re | d = 2\}$ defines the coordinate space, we also define statistical nodes $\{N_{m=(1,\ldots,M)} | m \in \Re^d\}$ in a spatial lattice (or conceivably as centroids of a mesh, though this is not yet implemented). The norm (distance) of data from each node is $h_m = ||s_m, s_Y||$. A local subdomain of a given node m is $\{S_{m=(1,\ldots,M)} \in D | h_m < h_u\}$ or more briefly as S_m which represents all locations within some distance to the statistical node $\{h_u | C(h_u)_{\text{Matérn}} = 0.05\}$; that is, the distance at which the local spatial autocorrelation drops to a negligible value (< 0.05). The data found within the subdomain m is $\{Y_{s,t} | (s,t) \in D | h_m < h_u\}$ which will be notationally abbreviated as $Y_{s,t|m}$.

Operating upon all components of the regression model is computationally prohibitive. Even with very simplistic Generalized Additive Model (GAM) or Generalized Additive Mixed effects Model (GAMM) parameterizations of spatial and temporal structure, the solutions take many days on fast machines (5 GHz CPU, 64GB RAM), depending of course upon the amount of data and resolution and model complexity. As a compromise between model complexity and computational speed, stmv uses a global covariate model $F(\cdot) \equiv x_{s,t}^T \beta_{s,t}$ is parameterized using a linear, generalized linear or generalized additive model. Here, $F(\cdot)$ represents some potential penalized basis splines of the covariate predictors and potentially some function $g(\cdot)$ that represents a link function such that the residual error in the link-space can be assumed to be Normal with mean zero and standard deviation σ_φ, the latter accounting for the residual error process $\varphi_{s,t}$:

$$\begin{aligned} Y_{s,t} &= \mu_{s,t}, \\ g(\mu_{s,t}) &= F(\cdot) + \varphi_{s,t}, \\ \varphi_{s,t} &\sim \text{Normal}(0, \sigma_\varphi^2). \end{aligned}$$

The spatiotemporal structure is decomposed from this residual error process and so the approach is in fact quite similar to "regression kriging" and (universal) "kriging with external drift" (Hengl et al. 2004).

The local spatial autocorrelation scale is derived from a rapid (coarse grained) fit of the local residuals $\varphi_{s,t|m}$ to a Matérn autocorrelation function. To be symmetrical in time, one would also need to determine temporal nodes and define appropriate temporal autocorrelation scales. In practice, temporal data are often sparse and limiting in survey data and so data from all time periods are used. Once the approximate bounds of the subdomain are estimated, the $\varphi_{s,t|m}$ are modelled as some functional $f_m(\cdot) \equiv \varphi_{s,t|m}^T \beta_{s,t|m}$ a Fourier series with two harmonics, one interannual and one subannual (seasonal): $f_m(\text{interannual}, \text{seasonal})$. In other words, a full temporal autocorrelation (covariance) model is not used but rather one that uses only a subset of the components at fixed wavelengths. The spatial coordinate space (depth, northing and easting) are (optionally) used as covariate or covariate-smooths in a GAM as they can be informative when large variations in topography exist or sampling is sparse inside the subdomain $f_m(\text{ interannual}, \text{seasonal}, \text{northing}, \text{easting}, \text{depth })$:

$$\begin{aligned} \varphi_{s,t|m} &= f_m(\cdot) + \zeta_{s,t|m}, \\ \zeta_{s,t|m} &\sim \mathrm{Normal}(0, \sigma^2_{\zeta|m}). \end{aligned}$$

Data are (optionally) weighted by the inverse squared distance h_m^{-2} from the coordinates of each statistical node m to make data closer to the area of interest and prediction more influential. The temporal autocorrelation is, therefore, carried by the individual temporal processes at each spatial datum and the temporally structured error $\sigma_{t|m}$ is the variance component of the model $f_m(\cdot)$, that is, $\sigma_{t|m} = \mathrm{Var}[\varphi_{s,t|m}] - \sigma^2_{\zeta|m}$.

The spatial autocorrelation function is parameterized as being derived from the subdomain mean Gaussian process with a Matérn covariance function with parameters $\theta_m = \{\phi_m, \nu_m\}$ and a time-varying spatially structured standard error $\sigma_{s|m}$. As the data used to estimate the spatial autocorrelation structure are often sparse, the data are augmented by temporal predictions of the residual error process at each spatial datum (and notationally designated by an asterisk). These augmented residual processes are modelled independently for each time slice $\varphi^*_{s,t|m}$ as the sum of a time-varying spatial **Gaussian process** $\omega_{s,t|m}$ parameterized as a Matérn spatial covariance function $\sigma^2_{s,t|m} \frac{1}{2^{\nu_{t|m}-1}\Gamma(\nu_{t|m})} (\sqrt{2\nu_{t|m}}h/\phi_{t|m})^{\nu_{t|m}} K_{\nu_{t|m}}(\sqrt{2\nu_{t|m}}h/\phi_{t|m})$ with a local spatial error $\sigma_{s,t|m}$; and a spatially and temporally unstructured error process assumed to be derived from a Normal error process with mean zero and error $\sigma_{\varepsilon|m}$:

$$\begin{aligned} \varphi^*_{s,t|m} &= \omega_{s,t|m} + \varepsilon_{s,t|m}, \\ \omega_{s,t|m} &\sim \mathrm{GP}(0, C(s, s'; \theta_{t|m} = \{\nu_{t|m}, \phi_{t|m}, \sigma_{t|m}\})), \\ \varepsilon_{s,t|m} &\sim \mathrm{Normal}(0, \sigma^2_{\varepsilon|m}). \end{aligned}$$

Other more flexible and complex models can be defined in this framework and they will be expanded upon in a future document. The above represents the basic approach that provides a practical balance between computational time and model complexity/realism. A fully Bayesian approach is being developed that removes the need to work with external drift.

The Snow Crab Assessment

The Snow Crab estimation process interpolates a number of covariates to the same continuous spatial support as they are surveyed using alternate survey designs. This is required to refine predictions of Snow Crab abundance and habitat while avoiding issues of bias due to aliasing (also known as upscaling and downscaling issues). Some of these covariates change on geological time scales relative to the timescale of the biological and ecological processes of interest and so can be considered functionally a “pure” spatial model (though of course they are not truly static). And others that are more biological in nature vary at similar or even shorter time scales and so require a temporal component. Here we detail some of these core data sources and their model assumptions in the context of the temporal autocorrelation scale of Snow Crab abundance in the Maritimes Region of Canada. The methods are encoded in the **aegis** R Package**.**

Bathymetry (depth; m) is a spatial covariate which is informative in that it determines ambient light levels, surface complexity/rugosity, hydrodynamic stability and overall environmental stability. Here, it is modelled as a Lognormal process:

$$
\begin{aligned}
Y_s &= \mu_s, \\
\log(\mu_s) &= F(\text{constant offset}) + \varphi_s, \\
\varphi_s &\sim \text{Normal}(0, \sigma_\varphi^2), \\
\varphi_{s|m} &= \omega_{s|m} + \varepsilon_{s|m}, \\
\omega_{s|m} &\sim GP(0, C(s, s'; \theta_m = \{\nu_m, \phi_m, \sigma_m\})), \\
\varepsilon_{s|m} &\sim \text{Normal}(0, \sigma_{\varepsilon|m}^2).
\end{aligned}
$$

As it is a pure space model, there is no need to “augment” the data leaving a direct decomposition of the global residual error process $\varphi_{s|m}$ into a local spatial process $\omega_{s|m}$ and a local unstructured error $\varepsilon_{s|m}$.

Similarly, substrate grain size (mm) is a pure space model which is a proxy measure of the type of substrate (mud, sand, gravel, rock, etc.) and so informative for benthic, demersal and infaunal habitat. It is also modelled as a Lognormal process:

$$
\begin{aligned}
Y_s &= \mu_s, \\
\log(\mu_s) &= F(\text{depth}, \text{slope}, \text{curvature}) + \varphi_s, \\
\varphi_s &\sim \text{Normal}(0, \sigma_\varphi^2), \\
\varphi_{s|m} &= \omega_{s|m} + \varepsilon_{s|m}, \\
\omega_{s|m} &\sim GP(0, C(s, s'; \theta_m = \{\nu_m, \phi_m, \sigma_m\})), \\
\varepsilon_{s|m} &\sim \text{Normal}(0, \sigma_{\varepsilon|m}^2).
\end{aligned}
$$

Temperature is a fundamentally important to metabolism, growth, reproduction, predator and prey distribution and abundance, and disease incidence. Bottom temperatures, in particular, are the focus due to their relevance to benthic and demersal organisms and modelled as an hierarchical, spatiotemporal, “inseparable” spatiotemporal process. As their variations have high frequency variations, some additional complexity is required in modeling their spatiotemporal variations. Here, the temporal effects are nested in spatial subdomains S_m. The global covariate model is simply a intercept model with an identity link such that $\varphi_{s,t}$ are centered upon zero. Salinity or water density data can conceivably enter to delineate water masses and origins, however, this data does not exist at sufficient density and coverage to be informative enough to merit the additional computational load (at present). Instead, the residuals errors are modelled locally in each subdomain as a weighted time series with two Fourier harmonics in time (an interannual and a subannual/seasonal component). The weights are determined from the inverse squared distance from each statistical node h_m. Additional penalized thin-plate spline smooth terms for local depth and position are used to resolve local spatial trends and aliasing to third order or less (via shrinkage). Temporal predictions at each spatial datum are then used to “augment” the modeling of the spatial processes $\varphi^*_{s,t|m}$ which are treated independently for each time slice as a **Gaussian process**. The temporal autocorrelation is, therefore, carried only indirectly by the individual temporal processes centered at each spatial datum. For faster computations, an FFT-based convolution method is used to approximate the spatial Gaussian process. The model specification is, therefore:

$$
\begin{array}{rcl}
Y_{s,t} & = & \mu_{s,t}, \\
\mu_{s,t} & = & F(\text{identity}) + \varphi_{s,t}, \\
\varphi_{s,t} & \sim & \text{Normal}(0, \sigma_{\varphi}^2), \\
\varphi_{s,t|m} & = & f_m(\text{interannual, seasonal, northing, easting, depth}) + \zeta_{s,t|m} \\
\zeta_{s,t|m} & \sim & \text{Normal}(0, \sigma_{\zeta|m}^2), \\
\varphi_{s,t|m}^{*} & = & \omega_{s,t|m} + \varepsilon_{s,t|m}, \\
\omega_{s,t|m} & \sim & \text{GP}(0, C(s, s'; \theta_{t|m} = \{\nu_{t|m}, \phi_{t|m}, \sigma_{t|m}\})), \\
\varepsilon_{s,t|m} & \sim & \text{Normal}(0, \sigma_{\varepsilon|m}^2).
\end{array}
$$

Additional covariates that express the ecosystem state at a given time and location ("indicators") are informative in delineating spatiotemporal processes that are structured from those that are random. Their model formulation is similar in that they follow a similar model structure with temporal effects nested in spatial subdomains and the use of link functions in a Generalized Linear Model/Generalized Additive Model setting where the covariates used to model these indicators rely upon spatial predictions of depth and substrate grain size and the spatial derivatives of the former (slope and curvature). The spatiotemporal error process is modelled locally in each subdomain as a space-time "inseparable" model, using time-varying covariates related to bottom temperature variations and associated statistics:

$$
\begin{array}{rcl}
Y_{s,t} & = & \mu_{s,t}, \\
g(\mu_{s,t}) & = & F(\text{depth, slope, curvature, substrate grainsize}) + \varphi_{s,t} \\
\varphi_{s,t} & \sim & \text{Normal}(0, \sigma_{\varphi}^2), \\
\varphi_{s,t|m} & = & f_m(\text{interannual, seasonal, northing, easting, depth}) + \zeta_{s,t|m} \\
\zeta_{s,t|m} & \sim & \text{Normal}(0, \sigma_{\zeta|m}^2), \\
\varphi_{s,t|m}^{*} & = & \omega_{s,t|m} + \varepsilon_{s,t|m}, \\
\omega_{s,t|m} & \sim & \text{GP}(0, C(s, s'; \theta_{t|m} = \{\nu_{t|m}, \phi_{t|m}, \sigma_{t|m}\})), \\
\varepsilon_{s,t|m} & \sim & \text{Normal}(0, \sigma_{\varepsilon|m}^2).
\end{array}
$$

For the estimation of habitat preferences and the creation of species distribution maps that rely upon presence-absence data. The data Y are assumed to come from a Bernoulli binomial process with a logit link function $g(\cdot)$:

$$
\begin{array}{rcl}
Y_{s,t} & = & \mu_{s,t}, \\
\text{logit}(\mu_{s,t}) & = & F(\text{depth, slope, curvature, substrate grainsize}) + \varphi_{s,t} \\
\varphi_{s,t} & \sim & \text{Normal}(0, \sigma_{\varphi}^2), \\
\varphi_{s,t|m} & = & f_m(\text{ecosystem indicators}) + \zeta_{s,t|m} \\
\zeta_{s,t|m} & \sim & \text{Normal}(0, \sigma_{\zeta|m}^2), \\
\varphi_{s,t|m}^{*} & = & \omega_{s,t|m} + \varepsilon_{s,t|m}, \\
\omega_{s,t|m} & \sim & \text{GP}(0, C(s, s'; \theta_{t|m} = \{\nu_{t|m}, \phi_{t|m}, \sigma_{t|m}\})), \\
\varepsilon_{s,t|m} & \sim & \text{Normal}(0, \sigma_{\varepsilon|m}^2).
\end{array}
$$

For the estimation of abundance, the positive valued data Y are assumed to come from a lognormal process:

$$
\begin{array}{rcl}
\mathrm{Y_{s,t}} & = & \mu_{\mathrm{s,t}}, \\
\log(\mu_{\mathrm{s,t}}) & = & \mathrm{F}(\text{depth, slope, curvature, substrate grainsize}) + \varphi_{\mathrm{s,t}} \\
\varphi_{\mathrm{s,t}} & \sim & \mathrm{Normal}(0, \sigma^2_{\varphi}), \\
\varphi_{\mathrm{s,t|m}} & = & \mathrm{f_m}(\text{ecosystem indicators}) + \zeta_{\mathrm{s,t|m}} \\
\zeta_{\mathrm{s,t|m}} & \sim & \mathrm{Normal}(0, \sigma^2_{\zeta|\mathrm{m}}), \\
\varphi^*_{\mathrm{s,t|m}} & = & \omega_{\mathrm{s,t|m}} + \varepsilon_{\mathrm{s,t|m}}, \\
\omega_{\mathrm{s,t|m}} & \sim & \mathrm{GP}(0, \mathrm{C}(\mathrm{s,s'}; \theta_{\mathrm{t|m}} = \{\nu_{\mathrm{t|m}}, \phi_{\mathrm{t|m}}, \sigma_{\mathrm{t|m}}\})), \\
\varepsilon_{\mathrm{s,t|m}} & \sim & \mathrm{Normal}(0, \sigma^2_{\varepsilon|\mathrm{m}}).
\end{array}
$$

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APPENDIX 2: 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, e.g., evolutionary processes) and resilience (short-term, e.g., 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 at all 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 crab are not exploited.
- Immature and soft-shelled (newly-molted, easily damaged) 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 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 3: 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 HCR 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 female crab). 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 $\mathbf{F}(B=B^*; \theta)$ at some value B^*:

$$\mathbf{F}(B; \theta) = c_1 B + c_2 B^2 + c_3 B^3 + \dots ;$$

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

$$\mathbf{F}(B; \theta) \approx c_1 B + c_2 B^2$$

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]        = qs[k] * bm[1,k]   - rem[1,k] ; // starting year approximation
          Ymu[2:(ty-1),k] = qs[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));

      }
```