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Assessment of Scotian Shelf Snow Crab in 2016

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Foreword

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

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ABSTRACT

Landings in 2016 for North-Eastern Nova Scotia (N-ENS) and South-Eastern Nova Scotia (S-ENS) were 290 t and 9,606 t, respectively, and they were 142 t in 4X for the 2015/2016 season, representing a decrease of 53% (N-ENS) and 15% (S-ENS) and an increase of 73% (4X) relative to the previous year. Total Allowable Catches in 2016 were 286 t, 9,614 t and 140 t in N-ENS, S-ENS and 4X, respectively. Non-standardized catch rates in 2016 were 110 kg/trap haul in N-ENS, 106 kg/trap haul in S-ENS, and 31 kg/trap haul in 4X in 2015/2016 – which relative to the previous year represents an increase of 7%, no change and an decrease of 9%, respectively. The capture of soft-shelled crab in N-ENS remained below 1% over the past two seasons. In S-ENS, the relative occurrence of soft-shell crab was 4.5% for the 2016 season. Soft-shell discard rates in 4X remain very low, due to it being a fall and winter fishery. Soft-shell incidence and associated potential handling mortality is forever an issue requiring diligent and adaptive management action. Bycatch of non-target species is extremely low (<0.1%) in N-ENS and S-ENS. Crab Fishing Area (CFA) 4X bycatch levels decreased to <1%, likely due to a constriction of fishery footprint. Although very limited local recruitment into the fishery is expected for the short term in N-ENS, the persistent gap between immature and mature male crab continues to shrink. The leading edge of this recruitment pulse could result in significant recruitment in 2-3 years. Male crab were observed in all size classes in S-ENS, suggesting stable recruitment into the future. Crab Fishing Area 4X shows little potential for substantial internal recruitment to the fishery for the next 4 to 5 years. Movement will likely be an important source of 4X crab for the next several years. The low abundance of both the mature and immature crab in the adjacent portion of CFA 24 and strong constriction of ideal Snow Crab habitat fields in 4X create future uncertainties. The mature component of female Snow Crab in all areas appear to be increasing, likely to be further bolstered by strong signals of immature female Snow Crab in both N-ENS and S-ENS. The post-fishery fishable biomass index of Snow Crab in N-ENS was estimated to be 3,750 t (2,799 t in 2015). In S-ENS, the post-fishery fishable biomass index was estimated to be 19.8×10^3 t (25.7×10^3 t in 2015). In 4X, the pre-fishery fishable biomass was 907 t (476 t in 2015/2016). These population characteristics are tempered by a number of uncertainties, including the influence of predation, especially upon immature and soft-shelled Snow Crab by groundfish, as well as large and rapid temperature swings (especially in CFA 4X and parts of CFA 24), as they can have both direct and indirect influences upon Snow Crab, which are cold-water stenotherms. Signs of a potential return of ecological, social, and economic indicators in the direction of a system less dominated by invertebrates, adds further uncertainty to the medium- to long-term sustainability of the population. Fishing mortality in N-ENS was estimated to be 0.07, a sharp decrease from 0.20 in 2015 and 0.28 in 2014. Fishable biomass had been decreasing, mainly through a lack of recruitment, but has recovered somewhat since 2014. In N-ENS, long-term prospects have improved due to the presence of pre-recruits between 30 and 80 mm. The fishable biomass has returned to the “healthy” zone likely supported by a reduction of fishing mortality in last year’s fishery. In N-ENS, a modest increase in TAC is recommended. Fishing mortality in S-ENS was estimated to be 0.39, an increase from 0.26 in 2013. Good recruitment still suggests a positive outlook. The fishable biomass remains in the “healthy” zone, but is declining and very close to the “cautious” zone. In S-ENS a decrease in harvest strategy is recommended. Fishing mortality in 4X for 2015/2016 was estimated to be 0.26. In 4X, the modeled fishable biomass is highly erratic and is currently estimated to be in the “cautious” zone, albeit with considerable uncertainty, and recruitment into next season is uncertain. A continued conservative harvest strategy is recommended pending further analysis prior to the 2015-2016 season.

Évaluation des stocks de crabes des neiges du plateau néo‑écossais en 2016

RÉSUMÉ

En 2016, les débarquements dans le nord-est et le sud-est de la Nouvelle-Écosse ont atteint respectivement 290 t et 9 606 t, et les débarquements dans la zone de pêche du crabe (ZPC) 4X ont atteint 142 t pour la saison 2015-2016, ce qui représente une diminution de 53 % (nord-est de la Nouvelle-Écosse), une diminution de 15 % (sud-est de la Nouvelle-Écosse) et une augmentation de 73 % (ZPC 4X) par rapport à l'année précédente. En 2016, les totaux autorisés des captures étaient de 286 t, de 9 614 t et de 140 t dans le nord-est de la Nouvelle-Écosse, le sud-est de la Nouvelle-Écosse et la ZPC 4X, respectivement. En 2015-2016, les taux de prise non normalisés étaient de 110 kg/casier levé dans le nord-est de la Nouvelle-Écosse, de 106 kg/casier levé dans le sud-est de la Nouvelle-Écosse, et de 31 kg/casier levé dans la ZPC 4X, ce qui représente une augmentation de 7 %, aucun changement et une diminution de 9 %, respectivement, par rapport à l'année précédente. Le nombre de prises de crabes à carapace molle dans le nord-est de la Nouvelle-Écosse est demeuré inférieur à 1 % au cours des deux dernières saisons. Dans le sud-est de la Nouvelle-Écosse, la présence relative de crabes à carapace molle était de 4,5 % pour la saison 2016. Les taux de rejet de crabes à carapace molle dans la ZPC 4X demeurent très bas, étant donné que la pêche a lieu pendant l'automne et l'hiver. La présence des crabes à carapace molle et la mortalité potentielle connexe due à la manutention est toujours un enjeu nécessitant des mesures de diligence et de gestion adaptative. Les prises accessoires d'espèces non ciblées sont très faibles (moins de 0,1 %) dans le nord-est et le sud-est de la Nouvelle-Écosse. Les niveaux de prises accessoires dans la ZPC 4X ont diminué à moins de 1 %, probablement en raison d'une réduction de l'empreinte de la pêche. Même si l'on s'attend à ce que le recrutement local dans la pêche soit très limité à court terme dans le nord-est de la Nouvelle-Écosse, l’écart persistant entre les crabes mâles immatures et matures continue de diminuer. Le front de la vague de recrutement peut mener à un important recrutement dans deux ou trois ans. Des crabes mâles de toutes les catégories de taille ont été observés dans le sud-est de la Nouvelle-Écosse, ce qui laisse entrevoir un recrutement futur stable. Dans la ZPC 4X, le potentiel de recrutement interne important à la pêche au cours des quatre à cinq prochaines années est faible. Les déplacements seront probablement une source importante de la présence de crabes dans la ZPC 4X au cours des prochaines années. La quantité limitée de crabes matures et immatures dans la partie voisine de la ZPC 24 et une diminution importante de l’habitat du crabe des neiges dans la ZPC 4X créent des incertitudes pour l'avenir. Le nombre de crabes des neiges femelles matures dans toutes les zones semble augmenter; ce nombre devrait croître davantage en raison de la forte présence de crabes des neiges femelles immatures dans le nord-est de la Nouvelle-Écosse et le sud-est de la Nouvelle-Écosse. Dans le nord-est de la Nouvelle-Écosse, l'indice de la biomasse exploitable de crabes des neiges après la saison de pêche a été estimé à 3 750 t (2 799 t en 2015). Dans le sud-est de la Nouvelle-Écosse, l'indice de la biomasse exploitable de crabes des neiges après la saison de pêche a été estimé à $19{,}8 \times 10^3$ t ($25{,}7 \times 10^3$ t en 2015). Dans la ZPC 4X, la biomasse exploitable avant la pêche était de 907 t (476 t en 2015-2016). Ces caractéristiques des populations sont modérées par un certain nombre d'incertitudes, y compris l'influence de la prédation par les poissons de fond, plus particulièrement sur les crabes des neiges immatures et à carapace molle, et les fluctuations rapides et importantes de température (surtout dans la ZPC 4X et certaines parties de la ZPC 24), car celles-ci peuvent avoir des répercussions directes et indirectes sur les crabes des neiges, qui sont des sténothermes d'eau froide. Les signes d'un retour potentiel des indicateurs écologiques, sociaux et économiques pointant vers l'émergence d'un système moins dominé par les invertébrés accroissent l’incertitude quant à la viabilité à moyen et à long terme

de la population. La mortalité par pêche dans le nord-est de la Nouvelle-Écosse a été estimée à 0,07, ce qui représente un fort déclin par rapport à 0,20 en 2015 et à 0,28 en 2014. La biomasse exploitable a diminué au cours des dernières années, principalement en raison d'un manque de recrutement. Cependant, elle s'est rétablie un peu depuis 2014. Dans le nord-est de la Nouvelle-Écosse, les perspectives à long terme se sont améliorées en raison de la présence de prérecrues entre 30 et 80 mm. La biomasse exploitable est revenue dans la zone « saine », probablement appuyée par la réduction de la mortalité par pêche au cours de la dernière année. Dans le nord-est de la Nouvelle-Écosse, on recommande une légère augmentation dans les captures. La mortalité par pêche dans le sud-est de la Nouvelle-Écosse a été estimée à 0,39, ce qui représente une augmentation par rapport à 0,26 en 2013. Le bon recrutement continue d'être de bon augure. La biomasse exploitable continue d'être dans la zone « saine », mais elle décline et s'approche de la zone de « prudence ». Dans le sud-est de la Nouvelle-Écosse, on recommande une diminution dans les captures. La mortalité par pêche dans la ZPC 4X en 2015-2016 a été estimée à 0,26. Dans la ZPC 4X, la biomasse exploitable modélisée est très imprévisible et se trouve présentement dans la zone de « prudence », bien qu'une incertitude considérable règne et que le recrutement pour la prochaine saison est incertain. Il est recommandé d'adopter une stratégie de pêche prudente en attendant une analyse plus poussée avant la saison 2015-2016.

MANAGEMENT

The Scotian Shelf Ecosystem (SSE) Snow Crab (*Chionoecetes opilio*) fishery is managed as three main areas: North-Eastern Nova Scotia (N-ENS), South-Eastern Nova Scotia (S-ENS) and Crab Fishing Area (CFA) 4X (Table 1; Figure 1). 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: severe weather conditions; catch of soft-shell and white crab; disruption of mating periods; and overlap with other fisheries, especially lobster and Northern Shrimp. From 1982 to 1993, the management of the 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.

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 very short 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 Certification was granted to the ENS fishery in September 2011. Four surveillance audits have been completed since that time. Recertification under MSC Version 2 is currently underway and expected to be finalized in 2017. The fundamental difference between the prior standard and Version 2 is that the habitat and ecosystem considerations are much broader, taking into account cumulative impact of all certified fishery in the fishing area being assessed (Peter Norsworthy, Affiliation of Seafood Producers Association of Nova Scotia; personal communication).

HISTORY

The Snow Crab fishery is currently the third most valuable commercial fishery in Atlantic Canada and fourth 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. In S-ENS, TACs rose from 2005 to reach a previously unseen level in 2010. They gradually declined until 2015 and a more substantial decrease was observed in 2016. In N-ENS, due to negligible recruitment, TACs declined sharply from 2004- 2008. Increasing recruitment and fishable biomass saw increased TACs until 2013. They have declined substantially over the past two seasons due to low commercial biomass and an almost complete lack of new recruitment to the fishery. These recent declines have been exacerbated by the adoption of harvest control rules forcing the exploitation strategy in N-ENS to be more conservative. The TACs in 4X varied between 230 mt and 346 mt 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 for 4X has remained low (relative to pre-2013 levels) as biomass levels have also remained low.

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 was used (see below).

FISHERIES DATA

Fishery catch rates are potentially biased indicators of 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 and 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.

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

At-sea-observed data provides information about the size structure and the carapace condition (CC) of the commercially exploited stock (Table 5; Figure 5). The data are stored in the Observer Database System. 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 observed) was 5% in S-ENS and N-ENS and 10% for 4X. This information was also used to compute the potential bycatch of other 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:

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

RESEARCH SURVEY DATA

Spatial coverage in the survey is (1) extensive, going well beyond all known commercial fishing grounds and (2) intensive, with a minimum of one survey station located pseudo-randomly in every 10 × 10 minute area (Figure 6). This sampling design was initially developed to facilitate geostatistical estimation techniques (Cressie 1993). Additional stations have been added adaptively, based upon attempts to reduce local estimates of prediction variance, as well as identifying the spatial bounds of Snow Crab habitat. Between 2004 and 2016, approximately 400 stations have been sampled annually. The survey vessel *F/V Gentle Lady* was used from 2004-2013. Due to the sinking of 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, crew, net and net monitoring systems have been used since 2004.

The extensiveness of the sampling design allows the objective determination of the spatial bounds of the Snow Crab population; information that must be known if reliable estimates of biomass and population structure (e.g., size, sex, maturity) are to be made. The spatial distribution of Snow Crab is quite dynamic and so can rapidly shift to areas where they are not "traditionally" found. In addition, the distributional patterns of immature, soft-shelled, very old and female crabs do not correspond completely 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 only those areas where large hard-shelled males occur in high frequency would preclude the reliable estimation of the relative abundance of these other important 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 made difficult over the entire time series. Currently, surveys are conducted in the autumn (September to December; i.e., post-fishing season in ENS and just prior to the fishing season in 4X). The timing of the survey has stabilized to this latter period only since 2004. Prior to 2004, surveys were conducted during the spring/summer (April to July; i.e., prior to the fishing season in ENS). As a consequence, temporal trends are most reliable for the post-2004 period. In the southern-most area of Snow Crab distribution (4X), trawl survey coverage has been historically sporadic but has stabilized since 2004. In all areas, fishing grounds are left fallow for as long as possible from timing of commercial fishing to the surveying of that particular area. This allows for crab populations to redistribute as naturally as possible following localized removals (i.e., commercial catches). Late fishing efforts, resulting from possible fishing season extensions, can impact this natural redistribution of crab.

A *Bigouden Nephrops* trawl, a net originally designed to dig into soft sediments for the capture of a lobster species in Europe, was used to sample the 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 crab were enumerated; measured with callipers; shell condition determined (Table 5); claw hardness measured with a durometer; and weighed with motion-compensated scales. The latter allowed direct biomass measurement rather than relying upon allometric relationships between body parts to approximate biomass (the latter was the approach prior to 2004; see below). 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 (Bedford Institute of Oceanography, Dartmouth, Nova Scotia).

Snow Crab biomass estimates prior to 2004 were approximated from CW measurements by applying an allometric relationship developed for SSE adult hard shelled Snow Crab (Biron et al. 1999; R^2=0.98, n=750):

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

Weights of individual animals have been directly assessed by digital scale since 2004. This replaces weights approximated from CW whenever possible.

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

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

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

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

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

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

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

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

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

Bitter Crab Disease infections of Snow Crab were first detected on the trawl survey in 2008. From 2009-2011, laboratory analysis of haemolymph occurred to monitor actual infection rates within the Scotian Shelf Snow Crab population. This method was suggested to improve the detection rates as visual assessments are only effective in identifying late-stage infections. Upon critical comparison of the visual and laboratory results of BCD detection, visual assessment was determined to be a more robust method of detection. As such, the laboratory testing of crab haemolymph was discontinued due to high costs (approximately $5 per sample) 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. Through development Snow Crab moult through several instar stages. Each instar (I) was determined after an analysis of size-frequency distributions to have a lower bound of CW (mm) approximated by (see also Figure 7):

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

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

SPACE-TIME MODELING

For assessment of Snow Crab fishable biomass, a novel R-package, lattice-based models (LBM) was developed specifically for the Maritime Region Snow Crab assessment to assimilate, model and interpolate space-time processes. Lattice-based models approaches a given smooth space-time process such as Snow Crab biomass as a two-stage process that is conceptually similar to kriging with "external drift" (Cressie 1993) in that the influence of environmental and biological factors are modeled globally as a first pass ("external drift") and then the residual spatial (and in our case, spatio-temporal) patterns are modeled separately at a second stage. Generally, a simple spatial covariance (variogram) is assumed or estimated for the whole space-time domain and forms the basis of kriging with external drift. In LBM, the form of the spatial and spatio-temporal dependence is determined from data for localised areas of interest centered on the nodes of a statistical spatial lattice and a range based upon a local variogram using a Matern formulation. A structured time-series model with seasonal and annual harmonic components was used to interpolate time trends at each datum inside this area of interest. These temporal interpolations were in turn used to inform the spatial interpolation via a localised kriging for each time slice. All parameterizations specific to the assessment can be found at this link.

Using LBM, the “Viable habitat” for fishable Snow Crab was modeled globally from Snow Crab trawl surveys using a binomial generalized additive model (GAM; R-package “mgcv”; Wood 2006) with a logit link function. Smoothed (thin-plate-spline) covariates were: year, year fraction (seasonality), northing and easting, depth, bottom slope, bottom curvature, bottom temperature, bottom temperature standard deviation, ln(substrate grain size; mm), species composition (correspondence analysis, axes 1 and 2), predicted species richness and biological productivity indices (total metabolic rate and specific metabolic rate; Figures 8-9, see Choi et al. 2005a for more details on methods). These modeled relationships were used to predict SSE Snow Crab habitat after discretizing covariate information to a spatial resolution of 1 × 1 km grids, also using LBM (Figures 8 and 9). Potential Snow Crab habitat was identified as those locations where the predicted probability of finding Snow Crab was > 0.05 or when the 95% confidence interval of the probability of observing crab did not intersect 0 (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, however, with a log-link. After estimation, the probability of a location being viable habitat was used as a weighting factor to these positive-valued abundance estimates to determine the fishable biomass density adjusted for viable habitat in a given location (Figure 11). The same covariates used for habitat delineation was used for abundance modeling. The methods for estimating standard errors associated with LBM are incomplete and so not presented in this assessment. The numerical densities of non-commercial life stages of Snow Crab were estimated using the geometric mean of the annual Snow Crab survey stations.

PREDATION

The predators of Snow Crab 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 160,000 individuals representing 68 ground and pelagic fish species collected from various sources since 1958. There was consistent sampling of diet data in ENS between 1999 and 2016. From this data set, the predators of Snow Crab were determined, as well as the frequency with which Snow Crab have been observed as part of the predator species diet and the percent of total weight of stomach contents represented by Snow Crab . As the impact of predation relates not only to the frequency of the species consumed, but also the biomass of the predator species, the trends in biomass for the identified Snow Crab 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 at maximum sustainable yield, or F_{MSY}) associated with the harvest control rules of the Snow Crab fishery. Bayesian state space methods are used to estimate the parameters of this model and associated Harvest Control Reference Points. See Appendix 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). 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. Note that there was insufficient time to update these data series and so they are left here for context only.

LIFE HISTORY

The Snow Crab (*Chionoecetes opilio*, Brachyura, Majidae, O. Fabricius) 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 (boulder, cobble) substrates (Sainte-Marie and Hazel 1992; Comeau et al. 1998).

Snow Crab eggs are brooded by their mothers for up to two 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 development of eggs (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 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 Saint Lawrence; Sainte-Marie 1993). The observable range of fecundity is quite large, especially as multiparous females are thought to be more fecund with more than 100,000 eggs being produced by each female. Eggs are hatched from April to June when the pelagic larvae are released. The pelagic larval stage lasts for three to five months (zoea stages 1 and 2 and then the megalopea stage) during which Snow Crab are feeding upon plankton. The larvae settle to the bottom in autumn to winter (September to October in the Gulf area). In the SSE, pelagic stages seem to have highest abundance in October and so may begin settling as late as January. Very little is known of survival rates at these early life stages.

Once settled to the bottom (benthic phase), Snow Crab grow rapidly, molting approximately twice a year (Sainte-Marie et al. 1995; Comeau et al. 1998; Figure 12). The first inter-molt stage (instar 1) is approximately 3 mm CW. After the 5th instar (15 mm CW), the molting frequency declines to annual spring molts until they reach a terminal maturity molt. Growth is allometric with weight increasing approximately 250% with each molt (Figure 7). Terminal molt has been observed to occur between the 9th to the 13th instar in males and the 9th to 10th instar in females. 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 12^{th} 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 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 is able to mate. Near the end of the lifespan of a Snow Crab (CC5), the shell decalcifies and softens and may be heavy 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 CC5 crab.

Females reproducing for the first time (primiparous females) generally begin their molt to maturity at an average size of 60 mm CW and mate while their carapace is still soft (early spring: prior to the fishing season in ENS and during the fishing season in 4X). A second mating period later in the year (May to June) has also been observed for multiparous females (Hooper 1986). During mating, complex behavioral patterns have also been observed; the male helps the primiparous female 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). Females are selective in their mate choice, as is often the case in sexually dimorphic species, and they have been seen to die in the process of resisting mating attempts from unsolicited males (Watson 1972; Hooper 1986). Males compete heavily for females and often injure themselves (losing appendages) while contesting over a female. Larger males with larger chela are generally more successful in mating and protecting females from harm.

ECOSYSTEM CONTEXT

OVERVIEW

Note that the data were not available for a full re-analysis at the time of this assessment and so will be revisited at another time. The following are the results from the previous year and provided only for context.

An overview of some relevant social, economic and ecological factors is provided here to form a basis for discussion of the place of Snow Crab in its ecosystem (for more details, see Choi et al. 2005a and Appendix 3). The key environmental, social, economic and fishery-related indicators were identified and summarized in Figure 13.

The first axis of variation accounted for 21.9% of the total variation in the data (Figure 14), and 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 (Figure 14).

Importantly, temperature-related changes were generally orthogonal (independent) to the above axis of variation (not shown). 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 nine years from time of settlement to reach the legal size of 95 mm CW, their increasing dominance on the shelf must have had their 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. However, 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- 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 simplistically broken down into the following categories of explanation: connectivity (metapopulation dynamics); environment (habitat); top-down (predation); bottom-up (resource limitation); lateral (competition) and human (complex perturbations). These will be briefly discussed below.

CONNECTIVITY

In the context of 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. In the case of Snow Crab, connectivity between populations exists due to two main processes: 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 can be transported onto the SSE (especially near Sable Bank and in the shallows further west). The possibility of Snow Crab larvae entering the SSE from the Gulf of St. Lawrence region and the Labrador current cannot be ignored, 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 even 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 quite pervasive throughout the SSE with no spatial clines (i.e., no declines in abundance with distance from the Gulf of St. Lawrence area) as one might expect 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 time difference between 1998 and 2007.
- The period in the late-1990s, when high larval production was observed, was precisely the same period in which the abundance of mature males and females on the SSE were at their peak.

The above circumstantial evidence 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. To this end, the Snow Crab industry adopted a PA to the conservation of large mature males (i.e., reduced exploitation rates) to allow them to mate with the more rapidly maturing females.

Movement

Traditional Tagging Program

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

Movement information was 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 15).

Short term seasonal movement patterns remain unidentified and are a source of uncertainty. Long term movement patterns are more easily observed. There are two distinct time periods (2-4 years each) within the time series where appreciable increases in movement rates were observed (Figure 16). In both cases, the mature crab population was male dominated with mature females being almost non-existent (Figure 57). 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, no mechanisms existed to observe immigration into N-ENS as no crab were tagged in the Gulf for an extended period of time. The movement of immature and female crab is not known and remains a source of uncertainty. Additional analysis of potential factors influencing patterns of short and long term movement patterns is required.

Since 2004, 21,948 tags have been applied and 1,455 distinct crab (6.6%) have been reported (Table 6) in N- and S-ENS. An unknown (and potentially large) proportion of tag recaptures remain unreported. These unreported captures negatively impact the understanding of movement patterns. Even with potential tagging-related mortality and exploitation rates of 15-30%, a much higher (than 6.6%) proportion of tags are likely recaptured. Anecdotal information suggests that fishers do not always report recaptures. Since 2004, there have been 161 individuals who have reported recaptures and there have been 1,553 total recaptures (Table 7) of 1,455 crab. On average, each person participating has reported nine or more different captures. Other fishers, operating in close proximity to these individuals, have not reported any tag recaptures.

Of the 1455 tags recaptured, 973 have been returned to the water and 88 of these have been captured 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, all people who previously captured that particular crab are notified to encourage returning tagged crab to the water.

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 (eg. 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 more conservative estimate of Snow Crab habitat use as compared to previous methods ignoring habitat preferences. On average, crab tagged between 2004 and 2016 were first recaptured in the season following the tagging event (mean time to recapture was 389 days), with the longest time interval between release and initial capture being 1,736 days (approximately 4 years, 9 months; Figure 16). This crab had moved at least 17 km in that period. Very few [reported] recaptures occur beyond two years of the tagging event. Most tagging is done on a commercial fishing vessels engaged in crab fishing operations, so tags are generally applied where commercial crab concentrations and resulting harvesting is high. This high localized exploitation may explain the majority of the recaptures being from crab captured in the same or following season after tagging. As such, much higher recaptures and reporting are expected.

The locomotory ability of Snow Crab can be very large, as the average distance traveled was 27 km, with a maximum distance traveled of 504 km (Figure 16). The average rate of movement was 2.1 km/month. These distances and rates are most likely underestimates as the actual distance traveled by the crab will be greater due to the topographical complexity and the meandering nature of most animal movement. On average, crab captured in N-ENS have a “shortest path” (habitat constrained) movement rate of 2.22 km/month, slightly higher than S-ENS (2.01 km/month, Figure 17). In 4X, the displacement rate is slightly lower again at 1.50 km/month (Table 7).

From 2004-2016, movement between N-ENS and S-ENS was seldom observed. In total, 7 crab tagged in S-ENS were recaptured in N-ENS and 3 crab tagged in N-ENS were recaptured in S-ENS. These numbers may be underestimates of total movement due to non-reporting of recaptures (Figure15).

Within S-ENS, from 2004 to 2014 movement between CFA 23 and CFA 24 has been observed, however, there does not seem to be any net gain or loss between these areas.

Returns from crab tagged between 2010 and 2014 suggest significant movement from N-ENS into the southern Gulf of Saint Lawrence (“the Gulf”, Figure 15). The apparent unidirectional nature of this movement (from N-ENS to the Gulf) is confounded by the fact that there had been no tagging program in recent years in the Gulf region until 2015. As such, the true degree of connectivity between the Gulf and N-ENS remains unknown, and may be substantial given the high concentrations of commercial crab in the adjacent Area 19 (M. Moriyasu, 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.

Reporting of tag recaptured in 4X is believed to be much higher than other areas, due to the small size (5-6 boats) and high engagement of the 4X Snow Crab fleet. Of the 881 tags deployed in 4X since 2008, 129 (14%) have been captured at least once. Of these, 20 (15%) were captured a second time, 6 (30%) of the 20 were captured a third time and 1(16%) of these was captured for a fourth time. There has yet to be any substantial movement observed between 4X and S-ENS.

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. A comprehensive 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 6 have been applied to mature female Snow Crab. 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, personal motivations to report (or not report) 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 of these were later detected within the Gulf region (Figure 18). This tagging was repeated in 2015 at the same locations. Interestingly, as of yet, none of these crab have been detected within, or near, the Gulf region. This supports the episodic nature of connectivity between the Gulf and N-ENS, further supporting this result derived from spaghetti tag movement data. Forty (40) acoustic tags were released in the Glace Bay Hole area of N-ENS in 2015. Detections of these animals have all been from within N-ENS.

Acoustic tags have been released in the areas adjoining N-ENS to help determine if the movement is unidirectional or bidirectional. 35 tags were released in the Gulf Region (CFA 19) since 2015, with no detections in N-ENS to date. Sixty-seven (67) tags were release in S-ENS (CFA 23) since 2015, also with no detections in N-ENS.

If reproduction is in fact the main driver of movement patterns, we would expect to see limited levels of emigration from N- or S-ENS in the near future as mature female abundance is currently high and expected to rise further in the next 1-3 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 (Figures 13, 19 and 20). 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 south western 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.

Juvenile crab (approximately instar 5, or two years since settlement) were already present in high numbers in the transitional year of 1986. These crab were, therefore, the benefactors of environmental amelioration; that is, some other factors(s) had allowed their larval and adolescent numbers to increase prior to these large environmental changes. What these factors(s) are is not yet fully understood, but the reduction in predation mortality associated with the demise of groundfish may be an important hypothesis. Further, it is important to note that bottom temperatures in the distributional centers of S-ENS Snow Crab have been increasing consistently since the early-1990s (Figures 20-22), while Snow Crab continues to dominate the bottom environment in S-ENS, somewhat weakening the validity of the temperature-hypothesis. The orthogonal nature of the second major axis of the ordination of ecosystem indicators that was dominated by climatic indicators suggests that climatic variation may not be the direct cause of the changes observed in the SSE in the early-1990s (Figure 13).

Overall, the potential Snow Crab habitat in the SSE for 2016 was below the long-term mean. North-Eastern Nova Scotia showed marginal increases in 2016 as compared to 2015 but 4X and S-ENS both saw decreasing habitat available to Snow Crab (Figures 21 and 22).

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 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.

The known predators of Snow Crab in the SSE were, in order of importance: Atlantic Halibut (*Hippoglossus hippoglossus*), Atlantic Wolffish (*Anarhichas lupus*), skates (Smooth Skate ,*Malacoraja senta;* Thorny Skate, Raja radiate; 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*). The level of predation on Snow Crab appears to be negligible on the SSE as only Atlantic Halibut, Atlantic Wolffish and Smooth Skate have Snow Crab observed in more than 1% of the stomachs sampled (Table 8), which constitutes less than 2.2% of diet by weight within each species, particularly to compared to other regions where the frequency of observing Snow Crab as prey is often greater than 10% (Robichaud et al. 1989, 1991).

Atlantic Halibut biomass have increased, particularly in S-ENS, suggesting that the total number of Snow Crab consumed may be increasing in relation to this predator. This additional source of mortality should be examined more thoroughly (Figures 23 and 24). Atlantic Wolfish are second in order of importance as a potential Snow Crab predator; however, their biomass indices suggest that they are currently at low levels across all areas (Figures 25 and 26). If the Snow Crab survey is more reflective of predators in Snow Crab habitat (vs. Groundfish surveys), the biomass of Thorny Skate (Figures 27 and 28) and Smooth Skate (Figures 29 and 30) may be greater across all areas than previously thought. In contrast to many other areas, Atlantic Cod do not appear to be a strong predator of Snow Crab (Bailey 1982; Lilly 1984; Robichaud et al. 1989, 1991, Table 8). Moreover, the cod populations on the SSE are currently at reduced biomass index levels in all regions relative to historic levels (Figures 31 and 32); however, there have been increases in recent years in S-ENS (Figure 32). Haddock may represent an increasing source of predation in localized areas of S-ENS and 4X (Figures 33 and 34).

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 (Figures 35 and 36). Due to the American Plaice's small gape size and mode of feeding, they will only be capable of consuming early instar Snow Crab. Reports of Snow Crab predation by squids, seals 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) 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 13) is a source of concern for many fishers. While they 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 currently found in the immediate vicinity of Sable Island, an area where the abundance of grey seals is extremely high. The actual evidence indicating that seals have a negative influence upon the Snow Crab population, therefore, seems to be minimal. In fact, it is quite possible that seals and other marine mammals may be having a positive influence by physically importing food and food waste (Katona and Whitehead 1988) from other more outlying areas to the immediate vicinity of Sable Island, so 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*, i). Studies have also demonstrated that cannibalism is also highly prevalent in intermediately sized (morphometrically) mature female crabs (Sainte-Marie and Lafrance 2002; Squires and Dawe 2003).

Most of these food items are part of the detrital food web, and so the proliferation of Snow Crab under the hypothesis of bottom-up control would be indicative of the proliferation of the detrital subsystem (potentially at the expense of the other parts of the shelf ecosystem, including that of the demersals). This hypothesis is consistent with what is known of the current structure of the SSE (Choi et al. 2005a):

- Phytoplankton abundance in the most recent decade (1991-2001) was considerably higher and more variable than in the 1960s and early-1970s. This likely resulted in increased sedimentation of organic matter to the ocean bottom (Choi et al. 2005a; Figure 12).
- The recent proliferation of Northern Shrimp (*Pandalus borealis*), another detritivore and also a potential food item of Snow Crab (Figures 12-34) was co-incident with the rise in abundance of Snow Crab.
- The demise of the groundfish that would competitively feed upon benthic invertebrates (Figure 12).

Certainly the rapid rate of increase in abundance of Snow Crab would seem to indicate that resource competition was not a limiting factor (up to the late-1990s).

Near the ocean surface, there has been a trend towards increased ocean colour, an index of chlorophyll concentrations. Therefore, total primary production may be increasing (in the form of diatoms and dinoflagellates). This is likely enhanced by the reduction in abundance of *Calanus finmarchicus*, an important zooplankton link in the pelagic food web.

The distribution of Northern Shrimp on the Scotian Shelf appears to remain broad (Figure 37); however, stock assessment results suggest that the SSE stock is in a declining state (Figure 38).

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 in many ways with that of 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 also resource competition. The spatial distribution of Snow Crab overlaps with that of 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), suggestive of little competitive interactions. The potential competitors, Lesser Toad Crab (Figures 39 and 40) and Jonah Crab (Figures 41 and 42), remain in relatively patchy distributions and, therefore, do not currently appear to pose much threat to the overall health of the Snow Crab stock.

DISEASE

Bitter Crab Disease is observed in crustaceans throughout the world, though most-commonly in the northern hemisphere (Stentiford and Shields 2005). The name arises from the bitter (aspirin-like) taste, which infected animals exhibit once cooked, rendering them unmarketable. Bitter Crab Disease infections in Snow Crab have been observed in Alaska, Newfoundland, Greenland, and most recently 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 ESS. 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 take place during molting, and virtually all infections appear to be of animals that have molted within the past year (new shell). As such, there is a high likelihood of infection in juvenile animals as they molt frequently. It is not known if animals infected with *Hematodinium* will always develop the disease. It 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 and can be confirmed through the use of a Polymerase Chain Reaction (PCR) laboratory assay performed on an alcohol-fixed haemolymph sample from the infected animal or microscopically of stained haemolymph smears.

The number of visibly infected animals has remained constant and at low levels with prevalence rates near 0.1% (Table 9). Crab of both sexes have been observed with BCD in all areas (Figure 43) across a wide range of sizes (20-100 mm CW; Choi and Zisserson 2012), though, generally, in immature animals well below legal commercial size. Indeed, mature, older-shelled crab infected with BCD have yet to be observed in the region. This suggests that infection may be linked to molting and that it increases mortality rates substantially. The pulsed nature of ESS Snow Crab populations can cause infection rates to climb when larger segments of the population are found in smaller size classes.

HUMAN INFLUENCE

The human influence is a quite 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 that of Snow Crab, and 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 particularly relevant as areas with high shrimp fishing activity are the same areas with the highest catch rates and landings of Snow Crab. The inshore lobster fishery may also represent a source of juvenile and adult female Snow Crab mortality in some areas, as anecdotal reports suggest capture in lobster traps and (illegal) use 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. This bycatch of Snow Crab in the lobster traps generally occurs only 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.

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 ENS, a total of 9,897 t of Snow Crab were landed in 2016 with associated estimates of bycatch at 2 t. Bycatch rates in ENS are traditionally very low and 2016 levels of 0.02% continue this trend. The 2016 bycatch estimates show more species diversity than in the past. This could be an early indicator of a shift away from the macro-invertebrate domination of the Scotian Shelf observed since the 1990s.

Crab Fishing Area 4X had a total estimated bycatch of 0.5t associated with 142 t of Snow Crab landings (0.35%). Crab Fishing Area 4X traditionally shows higher (relative to ENS) bycatch rates due to lower densities of commercial Snow Crab and a higher species diversity in some of the fishing grounds. In 2013 and 2014, 4X bycatch rates were unusually high (relative to past seasons) due to very low catch rates and increase in searching 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 in 2015 likely decreased bycatch levels as compared to the previous two seasons.

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

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

The majority of bycatch for all areas is generally composed of other invertebrate species (e.g., Northern Stone Crab and American Lobster) for which higher survival rates can be expected after being released, as compared to fin fish discards. In ENS, both Northern and Striped Wolffish have been observed in the past two seasons in the bycatch of the Snow Crab fishery at extremely low levels. These species are both *Species at Risk Act* (SARA)-listed species with “threatened status” and “special concern status”, respectively. 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 to, or upstream of, 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, are still not known (DFO 2004; Boudreau et al. 2009; Courtenay et al. 2009). However, anecdotal evidence 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), where immature and female crab are generally abundant, suggested that seismic may have 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 2017-2019 (Figure 44), as part of its current three year plan (CNSOPB 2017). The exploration block for 2017 includes most of N-ENS and CFA 23, for 2018 a block west of Sable Island and for 2019 an adjacent block west of The Gully. Future seismic exploration in offshore areas occupied by Snow Crab may need to evaluate the impacts on the species.

Undersea Cables

Undersea cables have been identified by fishers as another source of concern, in particular, the Maritime Link subsea cables in N-ENS. Two subsea High Voltage DC Cables will 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 are planned to be laid directly through the most productive Snow Crab fishing grounds of N-ENS (Figure 45) and will be spaced by up to 1400 m. Spatially-specific jet benthic fluidizing and trenching (EMERA 2016) of the cables (20cm path for each cable) should lower the likelihood of a physical barrier to movement being created, as opposed to other more destructive and expansive methods of cable trenching. The cables may, however, 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). At present, there is no information that has been presented to definitively describe their effects upon Snow Crab. Additional tagging effort has been undertaken in this area since 2013 (see above section on Movement). It will be useful to understand the natural movements of Snow Crab into and out of this area prior to 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 Scotian Shelf ecosystem (Figure 13). 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 943,000 people in 2014, as well as a trend toward a population with higher levels of education. Nova Scotia’s GDP 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 shell-fish 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 59 kt in 2006 for the province of Nova Scotia. Similarly, the pelagic fish landings have decreased from 125 kt in 1990 to 54 kt in 2008. In contrast, invertebrate landings have increased from 111 kt to 179 kt since the 1990s as has the total landed value for all fisheries combined, increasing from $445 million in 1990 to $845 million in 2013.

The links between the socio-economic changes observed and the changes in the Scotian Shelf ecosystem 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 unity of voice of fishers with a long-term vision for their resource can definitely 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 has been identified as an Area of Interest (AOI) for designation as a Marine Protected Area (MPA) pursuant to the Oceans Act. The outcomes of this designation are still to be determined and likely to be complex. The presence of a refuge from fishing activities is always positive as it serves as a fallowing area. However, if the protection is disproportionately beneficial to other organisms, be they predators of Snow Crab or prey items, the effects upon Snow Crab can be mixed. The long-term effects of an AOI/MPA cannot be determined at this point.

The Snow Crab survey continues to operate within the St. Anns Bank AOI and the Gully MPA, 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) occurs at paired reference stations within and immediately outside the AOI/MPA boundaries.

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 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 had remained above 70% of landings since that time with the exception of 2014 and 2015 when sea ice conditions limited spring fishing efforts (Figure 46). The 2016 fishing effort (Figure 47) was focused on the trench of deep water located along the north-eastern coast of Cape Breton ("inside") with limited effort in the Glace Bay Hole. Since 2012, no fishing has occurred on the northern-most portion of N-ENS along the CFA 19 line as had occurred in previous seasons. This is potentially associated with strong tides confounding fishing efforts during the spring season. The number of vessels active each season in N-ENS has decreased marginally in each of the last two seasons (Figure 48). Relatively low quotas are likely concentrating fishing effort to fewer vessels.

In S-ENS, fishing effort continues to be focused on offshore fishing grounds (Figure 47). Much of the fishing effort in CFA 23 still continued to be focused on the holes found 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 showed a similar fishing pattern to the previous year with spring fishing occurring primarily north of Sable Island and between Middle and Canso Banks. The fishing effort in CFA 24 between 2010 and 2013 was more focused north of Sable Island (“44^0 10 Line”). There was an almost complete absence of effort in the western-most portion (along the “Eastern Shore”) of CFA 24 (west of 61.5^0 Longitude). Decreased summer fishing activity occurred in the near shore area of CFA 24 as compared to the previous year.

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. CFA 24 consistently shows a higher percentage of spring landings as compared to CFA 23 (Figure 46), possibly indicating that CFA 23 is more affected/ limited by spring shrimp box closures.

In S-ENS, the number of active vessels has remained relatively stable over the past four years (Figure 48). The number of active is approximately 20% lower than the 2006-2011 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 price, with perhaps less 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, near the 4X/CFA 24 line (Figure 47).

In 2016, a total of 2,600 and 90,600 trap hauls were applied in N-ENS and S-ENS, respectively. In 2013/2014, a total of 2,300 trap hauls were applied in 4X (Tables 2-4; Figure 2).

Landings

Landings in 2016 for N-ENS and S-ENS were 290 t and 9,606 t, respectively, and they were 142 t in 4X for the 2015/2016 season, representing a decrease of 53% (N-ENS) and 15 (S-ENS) and an increase of 73% (4X) relative to the previous year (Figures 3 and 49). Total Allowable Catches in 2016 were 286 t, 9,614 t and 140 t in N-ENS, S-ENS and 4X, respectively. The majority of N-ENS landings came from the inner trench. S-ENS saw a landings pattern distributed between the near shoe and off shore with the strongest concentration of landings offshore. Crab Fishing Area 4X landings continue a constricting trend toward the 4X/24 line (Figure 49).

Catch Rates[1]

Non-standardized catch rates in 2016 were 110 kg/trap haul in N-ENS, 106 kg/trap haul in S-ENS, and 31 kg/trap haul in 4X in 2015/2016 – which relative to the previous year represents an increase of 7%, no change and an decrease of 9%, respectively (Figure 4; Tables 2-4). The effect of TACs on catch rates can confound direct comparison over time and between management areas.

In N-ENS, the 2016 catch rates were 110 kg/trap, a slight increase relative to 2015 (103 kg/trap). N-ENS catch rates remain well above the 15 year mean (76 kg/trap; Table 2; Figure 4). Catch rates in N-ENS have been very similar to those observed in S-ENS since 2011. Catch rates in N-ENS were universally high within the areas fished in 2016. Previous to 2011, catch rates in N-ENS were often quite variable within the entire area with pockets of high or low catch rates. Catch rates from the summer fishery were stable over time and somewhat lower than those experienced in the spring fishery in 2016. In the spring fishery catch rates showed an increasing trend over time. It is important to note that the maintenance of high catch rates in N-ENS since 2011 is in part a consequence of increasing mean size of crab in the catches rather than just numerical abundance (Figure 52). The N-ENS fishermen feel that their maintenance of high catch rates since 2011 indicates a much larger biomass of commercial crab than is indicated by survey-driven biomass estimation. They feel the discordant timing of the survey (fall) versus the fishery (spring-focused) causes this discrepancy.

In S-ENS, the 2016 catch rates were 106 kg/trap, stable from 2015 rates and slightly above the 15-year mean of 103 kg/trap (Table 3; Figure 4). Catch rates were relatively stable from 2015 in each of the two CFAs in S-ENS, CFA 23 and CFA 24. CFA 23 has had higher annual catch rates since 2009. 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 along the 23/24 line and in the holes between Misaine, Banquereau and Middle banks (Figure 50). The lack of very low localized catch rates suggests that fishers were efficiently identifying high abundance locations and, therefore, generally avoiding over-depletion of lower abundance areas. Limitations on access to all fishing grounds caused by temporal exclusions (“Shrimp Boxes”) may lead to short-term localized depletion in available fishing grounds during spring fishing activities. Examination of weekly catch rates over the course of the 2016 season (Figure 51) shows a general decreasing trend in catch rates in CFA 23 over the initial half of the season, with a marked resurgence with the opening of the “shrimp boxes” and a declining trend after that time. However, CFA 24 shows a generally declining catch rate trend over the course of the season. This would suggest that CFA 23 catch rates are more affected by limited access to fishing grounds caused by seasonal closure of the “shrimp boxes”. It is important to note that in all areas it is common to see a strong divergence in catch rate from the trend during the final weeks of the season. This is assumed to be caused by the almost complete lack of effort and landings during this time. Some catch in traps is not retained on the final trip as individual quotas have been reached.

In 4X, the 2015/2016 catch rates were 31 kg/trap (Table 4; Figure 4), a decrease of 9% from the 2014/2015 catch rate, though above the 14-year mean of 24 kg/trap. The 4X catch rates are consistently well below those of N-and S-ENS, even for the 2005-2008 low abundance period in

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

N-ENS. Weekly catch rates in 4X (Figure 51) generally show an oscillating pattern over the course of the season. This oscillation is most 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. In the 2015/16 season fleet catch rates after January were generally lower than those before the New Year. This is in contrast to the previous season which showed more similar catch rates before and after January 1st. Localized warming and cooling of waters caused by weather patterns 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 above the target level of 5% of the TAC, at 7.2% (Figure 5). This overage was likely caused by high catch rates and the relatively small number of trips required by the fleet to catch their TAC. A total of 122 trap hauls were observed (approximately 4.7% of commercial trap hauls). In S-ENS, 5.9% of the TAC was observed (with a target level of 5%). A total of 5,497 traps (approximately 6.1% of commercial trap hauls) were observed. In 4X, 9.2% of the TAC was observed, relative to a target level of 10%. A total of 372 traps were observed, 8.1% of commercial trap hauls.

Newly Matured (CC1 and CC2) and Soft-Shelled Crab

In N-ENS, CC1 and CC2 crab collectively represented approximately 1.8% of the total catch (Table 12; Figure 53), relative to 3% in 2015. 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. All observed CC1 and CC2 crab were caught in the summer fishery in 2016. Higher incidence of soft-shelled crab in the summer fishery has been suggested anecdotally as being a result of localized depletion of stronger, hard-shelled males, and a consequent increased trapability of new-shelled males due to the lack of competition/inhibition. This almost complete lack of CC1 and CC2 supports the extremely low levels of internal recruitment to the fishery predicted from the previous year's trawl survey. There was an increase in the proportion of the CC4 crab in the observed component of the fishery, which further supports the lack of recruitment predicted. CC5 levels remain negligible.

Extremely low incidence of soft-shell catches (relative to very high levels in 2005-2008) were observed in both the spring and summer fisheries in N-ENS (Figure 54). If one assumes no recaptures and prorates the observed landings to total landings, this amounts to an additional 2 t (<1% of landings) being discarded as soft crab with potentially high handling-associated mortalities. This is consistent with the 2015 soft crab incidence. A continuation of spring fishing efforts, and shorter summer fishing period, will likely help to control the potential total mortality of soft-shell crab in future seasons. This is particularly important 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 at low (<1%) levels (Table 13; Figure 53). There was a decrease in the proportion of CC2 crab from 9% in 2015 to 3.6% in 2015. This increase may be partially attributable to increased spring (as opposed to summer) fishing in 2015. Observed catches of high soft-shell percentage (>20% by count) were rare throughout S-ENS in 2016. When prorating observed landings to total landings in S-ENS, this amounts to a potential additional mortality of 200 t (4.5% of landings). 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. Unfortunately, this is not always the case. There is potential miscommunication as quotas are sold through processors and other brokers and fished by individuals that do not own quota personally, and thus, have no long-term stake in this fishery. All individuals involved in every level of the fishery must realize the potential damage caused by handling soft crab.

In 4X for the 2015/16 season, CC1 and CC2 crab collectively represented approximately 9% 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 90%. An extreme warm-water even in 2013/2013 is hypopthesized to have been very detrimental to the Snow Crab population in 4X. Mortality caused by this warming likely continues to influence species composition in 4X. The data from 4X are not directly comparable to ENS as their fishing season is disjunct from that of N- and S-ENS. This fall/winter 4X fishery continues to show negligible levels of soft crab.

Old Crab (CC5)

Carapace Condisition 5 (CC5) crab represented a low proportion of the 2016 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

In S-ENS, the presence of small immature male Snow Crab spanning almost all size ranges (20-95 mm CW) observed by the survey also suggests that recruitment to the fishery is probable for the next four to five years and beyond (Figure 55).

In N-ENS, the distribution of male size crab appears very similar to that of 2015 with few large mature animals. No appreciable recruitment to the fishery has occurred since 2012 based on the size distributions observed through the trawl survey. The lack of soft shell crab catches potentially supports depressed recruitment levels. The persistent gap between immature and mature male crab continues to shrink. The leading edge of this potential recruitment pulse is now approximately 80 mm which could result in significant recruitment in 2-3 years. A lack of immature animals near- or at- commercial size will likely result in depressed recruitment for the next year without an immigration of crab from adjacent crab fishing areas (likely CFA 19 and less likely CFA 23, based on movement studies).

Area 4X shows minimal potential for internal recruitment to the fishery for the next 3-4 years, based on size frequency distributions from the trawl survey. Movement is likely 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. As always, erratic temperature fields and associated constriction of viable Snow Crab habitat in 4X create strong uncertainties for the future.

The leading edge of a recruitment pulse created substantial increases in the amount of mature female crab in N-ENS in 2016 (Figure 56). This large-scale maturation of female crab is expected to continue for the next 3-4 years. South-Eastern Nova Scotia also showed the first increase in mature female levels since the early to mid-2000s, though at densities lower than those of N-ENS. Though limited numbers of mature female crab exist in 4X, low to moderate future recruitment to the mature segment of the female population is expected in the next 1-3 years based on the current size distributions. Being downstream of all other crab areas increases the chance of larval settlement in 4X regardless of a resident population of mature females.

Male size frequency distributions in 4X appear to exist in a very erratic state, with less annual consistency as compared to N-ENS and S-ENS. The large temperature fluctuations and the different predator fields associated with the warmer waters in the area, and potential movements with CFA 24, likely result in these unstable size structures. Movement of crab away from traditional locations within 4X, in reaction to such temperature and predation changes, may confound inter-annual survey results.

SEX RATIOS

When the relative number of mature females is high, the possibility of reproductive limitation becomes a conservation issue. This is particularly the case 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 females (e.g., the extended period observed in the early 2000s throughout the SSE) there is low egg and larval production. What may have caused this extended period of poor reproductive potential in the SSE is not known, especially as this fishery is a male-only fishery. A possible explanation for this may arise from differential predation pressures for males and females, as they are spatially segregated in their immature stages and as they are also sexually dimorphic. Irrespective of the specific cause, extreme sex ratios represent an unhealthy reproductive state and, therefore, 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.

There is a high likelihood that sex ratios will naturally fluctuate over time (Figure 57). This is because 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 will be 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 and again in 2007, with a major trough in the early 2000s and again in early 2010s (Figures 57 and 58). Since 2007, sex ratios of S-ENS and N-ENS Snow Crab have declined, although, in 2015/2016 slight increases in sex ratio were observed, reflective of decreasing male population and a slight increase in females. In Area 4X current sex ratios of mature crab continue to fluctuate at levels just below 50% female.

The sex ratios of immature Snow Crab (Figure 59 and 60) are currently, between 30-50% female on the Scotian Shelf. The spatial patterns of the sex ratios are generally distinct between offshore and inshore areas: immature males are found in greater proportion (blue) in most areas in ENS, whereas immature females (red) are found in greater proportion in areas bordered by warm water, such as the western portion of CFA 24 and along the eastern and southwest shore of Nova Scotia (Figure 60). When such spatial segregation is observed, the sexes are likely exposed to differential predation effects. Immature females are likely preyed upon by fish and other macro-invertebrates (including other female Snow Crab, other crabs and lobster) favouring 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 have been variable across areas (Figures 61-65). In N-ENS, the density of immature female crab increased steadily from 2009-2014. Maturation of these immature crab began in 2015 and continued in 2016, lowering the immature component of the female population. (Figure 61) but increasing the mature component (Figure 63). Based on population size structure, increases in mature female abundance are expected for the next 2-3 years as was seen during the 2004-2007 period.

In S-ENS, immature female crab were at historical highs in 2006. Since 2007, there has been no apparent increasing or decreasing trend in immature female crab. (Figure 61). There has however been 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 substantial pulse of female crab has begun to occur in 2016 and is expected to increase mature female crab numbers for 2-3 more years (Figure 56).

Immature females in 4X have declined dramatically between the extreme high in 2010 and 2013; however, there was an increase in 2014. Immature female crab numbers remain low. The mature fraction of the female abundance has been decreasing since 2012 (Figure 63).

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 and 64).

Maturation of immature female crab in N- and S-ENS in 2016 has increased potential egg production (Figure 66).Egg production is expected to continue increasing for 2-4 years as more immature animals reach sexual maturity. Larger egg clutches in multiparous (vs primiparous) crab should further bolster egg production.

FISHABLE BIOMASS

Fishable biomass is presented as the geometric mean from the survey (Figure 67) and the results from the LBM analysis (Figure 68). The LBM analysis was used to inform the assessment model to produce the biomass index. The post-fishery fishable biomass index of Snow Crab in N-ENS was estimated to be 3,750 t, relative to 2,799 t in 2015 (Figures 77). In S-ENS, the post-fishery fishable biomass index was 19,835 t, relative to 25,672 t in 2015. In 4X, the pre-fishery fishable biomass was 907 t, relative to 476 t in 2015/2016. The 4X biomass estimate is generally more uncertain, as it fluctuates more dramatically than other areas probably a result of migration in and out of the area. In N-ENS and S-ENS the highest fishable biomass densities appeared more concentrated in 2016 compared to 2015 (Figure 69). In 4X, the remaining pocket of fishable crab is in close proximity to the 4X/S-ENS line (Figure 69).

RECRUITMENT

Quantitative determination of recruitment levels into the fishable biomass is confounded by a number of factors. These include terminal molt (and the timing offset of molting in spring and the survey in the fall) as well as the inability to age crab and predict absolutely at what age male crab will terminally molt. Based on size-frequency histograms of the male Snow Crab

[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.

population, very limited internal recruitment to the fishery is expected for the next year in N-ENS and 4X (Figure 55). South-Eastern Nova Scotia internal recruitment is expected to remain at moderate levels. Immigration of crab from outside a given area can represent recruitment to its fishery though is unreliable based on its episodic nature.

In terms of size structure (Figure 55) in S-ENS, the presence of small immature male Snow Crab spanning almost all size ranges (20-95 mm CW) observed by the survey also suggests that recruitment to the fishery is probable for the next four to five years and beyond. In N-ENS, the size distribution of male crab remains to have few mature animals though the continued propagation of a pulse of recruitment through the system provides reasonable expectation of increased recruitment in 2 years and beyond.

Area 4X shows minimal potential for internal recruitment to the fishery for the foreseeable future, based on size frequency distributions from the trawl survey. Movement is likely 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. As always, erratic temperature fields in 4X create strong uncertainties for the future.

STOCK ASSESSMENT MODEL

The logistic production model shown here is largely 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 1 for more details). Both the N-ENS and S-ENS models were relatively well behaved and the three MCMC chains did converge; however, initial fits were overly smooth and did not fit to the biomass estimates well. To remediate this, the informative prior previously placed on process error was changed to an uninformative prior that allowed for more variability in the population dynamics. 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). The posterior distributions for observation error (bo.sd) were not updated from the prior, suggesting that this prior was influential in forcing the model to fit closely to the biomass estimates produced from the space time modelling (Figure 77). This was not interpreted as a problem as those biomass estimates were the result of extensive analysis. In future assessments, standard error estimates from the space time modelling could be used to inform more appropriate priors on observation error. Estimates of population growth rate, r, were similar for N- and S-ENS with median values of 0.975 and 0.926 (Figure 72), whereas the carrying capacity for S-ENS (57.3 kt) is nearly 10 times higher than for N-ENS (6.87 kt), largely reflecting the differences in area of suitable crab habitat (Figure 22). Higher estimates of r and lower estimates of K in this latest application of the model are likely a result of a more variable biomass time series produced from the space time modelling. There were also differences in catchability coefficient (q) for N-ENS and S-ENS with estimates of 1.011 and 0.932 respectively (Figure 73). These differences in q may reflect the ability to survey and accurately describe the stock biomass, which is higher in N-ENS as the density of stations is substantially higher than those in S-ENS. The median estimates of F_{MSY} were 0.487 for N-ENS, 0.463 for S-ENS and 0.494 for 4X (Figure 78).

FISHING MORTALITY

In N-ENS, fishing mortality (F) has been estimated to have been in the range of 0.06 to 0.64 (exploitation rate 0.06 to 0.48), peaking in 2002 (Figures 78). In 2016, fishing mortality is estimated to have been above 0.07 (exploitation rate 0.07), a sharp decrease from 0.20 in 2015 and 0.28 in 2014 as a result of decreased TAC implemented because of concerns that the stock had entered the cautious zone (Figure 80).

Fishing mortality for S-ENS has historically ranged from 0.05 to 0.42 (exploitation rate 0.05 to 0.34), peaking in 2010 (Figure 78). In 2016, fishing mortality was estimated to have been 0.39 (exploitation rate 0.33). 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.

In 4X, fishing mortality has historically ranged from 0.06 to 0.76 (exploitation rate 0.06 to 0.53), peaking in 2008 (Figure 78). In 2015/2016, fishing mortality was 0.26. Realized exploitation rates are likely to be higher, since the computed exploitation rates incorporate biomass from throughout the 4X area and not just the fishery grounds.

NATURAL MORTALITY

Wade et al. (2003) suggested that instantaneous mortality rates for southern Gulf of St. Lawrence Snow Crab >95 mm CW are within the range of 0.26 to 0.48. For early benthic females stages (i.e., unfished Snow Crab), instantaneous mortality may be near 1 (Kuhn and Choi 2011). Thus, the magnitude of fishing mortality seems to be generally smaller in magnitude than that of natural mortality. Diet studies (Bundy 2004; see also section: Top-down Control (Predation)), suggest that very few natural predators seem to exist for large Snow Crabs (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 (Figure 13). Although, recent reports suggest an increase in the relative abundance of predators of Snow Crab these levels remain a small proportion of historic reports (DFO 2014; Figures 23-36). This can especially impact recruiting, juvenile and larval crab and may have been contributing factors for the absence of 40-90 mm CW crab in N-ENS.

Other potential mortality factors include: BCD derived from a parasitic dinoflagellate infection (*Hematodinium* sp.), 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 installation.

THE PRECAUTIONARY APPROACH

In the context of natural resource management, the Precautionay 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). Details on the PA and caveats related to its implementation in the form of simplistic “Harvest Control Rules” can be found in Appendices 1 and 2.

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. While it is well known that this is not always the case (Appendix 2), its usage in DFO has been formalized into the determination of Reference Points and Harvest Control Rules.

REFERENCE POINTS AND HARVEST CONTROL RULES

The 4VWX 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).

From the logistic model output the current estimates of “carrying capacity” for the fishable biomass of Snow Crab is estimated to be {and 95% CI}:

- N-ENS: 6.87 {5.14, 9.58} kt
- S-ENS: 57.3 {45.6, 77.9} kt
- 4X: 2.21 {1.68, 2.96} kt

The estimates of F_{MSY} {and 95% CI} were:

- N-ENS: 0.487 {0.389, 0.586}
- S-ENS: 0.463 {0.366, 0.562}
- 4X: 0.494 {0.397, 0.592}

Estimates for 4X should be considered highly uncertain, due to the brevity of their data series and uncertain nature of their error distributions.

Future Research Priorities Associated with 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 completely ignored. 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 LBM 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 has been low for the past several seasons. However, it remains an issue requiring continued diligence in the SSE. The timing of fishing efforts can help avoid periods traditionally associated with high captures of soft crab (winter and spring fisheries). In S-ENS, this is not always the case, and 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 has the important result of reducing 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, and so extends the fishable period by this time.
   c. Specifically targeting mature (male) crabs is a more optimal exploitation strategy (CC3 and CC4 crab) in that the fishable biomass is harvested when "ready and maximized". This is because there is a significant weight increase if immature crab were allowed to grow and mature (an increase of 250-400%; Figure 7).

In the 2017 season, some of the >95 mm CW will still be composed of immature individuals (Figure 48). Indeed, these immature crab will become the largest-sized 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 unwise.

3. Anecdotal reports suggest that illegal fishing activities and mis-reporting of catch is occurring, 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 sacrifices 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.

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 continued uncertainty in world markets and the more volatile state of other Atlantic Canadian Snow Crab populations.

Fishable biomass estimation has been less reliable in 2014 and 2015 based on difficulties in assessment methodology. Newly implemented, more robust assessment methodologies indicate that the fishable biomass has been declining since 2013. Without TAC decreases relative to fishable biomass reductions, the exploitation rate (fishing mortality) has been steadily increasing since 2013. The S-ENS population is considered to be in the "healthy" zone but close to the transitional area (FB > USR, Figure 80). As recruitment is expected for at least the next three to four years, there remains scope for flexibility. A decrease in TAC is strongly recommended.

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 (approximately 2007). The capture of soft-shelled crab has been nearly eliminated, helping to protect recruitment. Fishable biomass declined rapidly from 2013 to 2014 without significant reductions in TAC, placing the stock in the “cautious” zone (FB > USR, Figure 80) although the stock remains in the “healthy” zone (FB > USR, Figure 80). Over the past few years, the harvest strategy adopted by fishers in N-ENS has been more conservative, with exploitation rates being closer to those historically adopted in S-ENS.

Fishable biomass estimation has been less reliable in 2014 and 2015 based on difficulties in assessment methodology. Newly implemented, more robust assessment methodologies indicate that the TAC reductions taken in the past two seasons have helped stabilize the fishable component of the population and the stock is in the “healthy” zone (FB > USR, Figure 80). Recruitment to the fishable biomass is expected to continue being very low for the coming season supporting a cautious harvest strategy. Based on current fishable biomass estimates an increased TAC is recommended.

AREA 4X

As Area 4X is the southern-most area of Snow Crab distribution, existing in more “marginal” environments relative to the “prime” areas of S- and N-ENS, an explicitly PA towards this fishery is essential. Further, the lower recruitment into the fishable biomass and the large inter-annual temperature variations (especially in 2012) increases the uncertainty associated with this area. Indeed the speculated increases in mortality associated with the warm temperature event in 2012, most likely occurred as all measures of Snow Crab productivity decreased in the area. In the past, S-ENS has been assumed to provide a buffer for 4X via immigration as evidenced by a large portion of 4X’s commercial biomass being proximal to the S-ENS line.

Fishable biomass estimation has been less reliable in 2014 and 2015 based on difficulties in assessment methodology. Newly implemented, more robust assessment methodologies indicate that the stock is in the “cautious” zone (FB > USR, Figure 80) though at absolute levels well below those N-ENS or S-ENS. The erratic temperature fields and constriction of Snow Crab habitat in 4X support the continuation of a very cautious approach in harvesting strategy. In addition, recruitment into next season is uncertain leading to the recommendation of a status quo to a marginal increase in the harvest strategy.

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TABLES

Table 1. Snow Crab fishing seasons on the Scotian Shelf in the year 2016.

Area	Season
N-ENS	April 16th – May 15th and July 23rd - August 23rd
S-ENS (CFA 23)	March 23rd – August 31st
S-ENS (CFA 24)	March 23rd – August 31st
4X	November 7th (2016) – March 31st (2017)

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)
2002	80	1,493	1,495	101	14.8
2003	80	1,493	1,492	77	19.4
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

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)
2002	149	9,022	8,891	112	79.6
2003	145	9,113	8,836	99	89.6
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	120.0
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

Table 4. Summary of Snow Crab fisheries activity of 4X.

Year	Licenses	TAC (t)	Landings (t)	CPUE (kg/trap haul)	Effort (x1000 trap hauls)
2002/03	9	600	221	10	21.9
2003/04	9	600	289	13	22.8
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[1]	9	80	55	24	2.3

[1] As of February 2, 2016. Season still in progress.

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 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. A dash (--) represents no data.

Year	Tags Applied	Tags Returned	Distinct Tags Returned	Avg. Displacement (km)	Max Displacement (km)	Avg. Days to Capture	Max Days to Capture	Avg. km/ Month
2010	2,256	159	148	32.9	150	408	1124	2.45
2011	1,789	106	105	58.9	260	519	1203	3.46
2012	1,676	194	167	25.6	232	312	1552	2.50
2013	3,966	317	291	42.5	504	492	1102	2.63
2014	3,112	177	167	16.6	120	430	745	1.18
2015	1,929	80	78	11.7	116	240	420	1.49
2016	1,097	5	5	24.6	47	34	90	--
All Years/ Areas	**21,948**	**1,553**	**1,455**	**27.0**	**504**	**389**	**1736**	**2.11**

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

Area	Tags Applied	Distinct Tags Returned	Avg. Displacement (km)	Avg. Days to Capture	Avg. km/month	Number of Fishermen Returning Tags
S-ENS	13,024	684	25.2	380	2.01	79
N-ENS	7,346	629	33.4	453	2.24	65
4X	881	129	7.8	160	1.5	17

Table 8. Predators of Snow Crab in ENS during the 1995-2009 time period. In each period, N stomachs represents the number of stomachs examined, Freq (%) is the percent of stomachs containing Snow Crab as prey, and Weight (%) is the percent of total weight represented by Snow Crab as prey.

Predator Species	N Stomachs	Freq (%)	Weight (%)
Atlantic Cod	6059	0.31	0.18
Haddock	4059	0.05	0.01
White Hake	2523	0.08	0.01
Atlantic Halibut	556	1.44	1.35
American Plaice	7694	0.05	0.05
Atlantic Wolffish	519	1.35	1.62
Thorny Skate	2528	0.24	0.73
Smooth Skate	502	1.00	2.14
Winter Skate	547	0.18	0.11
Longhorn Sculpin	1888	0.32	0.34
Sea Raven	611	0.33	0.57

Table 9. Prevalence of Bitter Crab Disease (BCD) on the Scotian Shelf. Total crab refers to the number of 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

Table 10. Bycatch (kg) estimates of finfish and invertebrates from the ENS Snow Crab fishery. The estimates are extrapolated from at-sea-observed bycatch and at-sea-observed biomass of catch [i.e., estimated biomass of bycatch = observed biomass of bycatch species / (observed landings of Snow Crab / total landings of Snow Crab)]. The Snow Crab fishery is very species-specific as bycatch levels are extrapolated to be approximately 0.018% of Snow Crab landings for the past three years in ENS.

Species	**2014**	**2015**	**2016**	**3-Year Total**
Rock Crab	0	19	0	19
Cod	23	187	84	294
Jonah Crab	0	19	854	873
Northern Stone Crab	0	0	670	670
Northern Wolffish	0	112	17	129
Redfish	0	75	50	125
Sand Dollars	0	0	17	17
Sea Cucumbers	0	19	50	69
Sea Raven	0	37	33	71
Sea Urchin	0	0	33	33
Skate	0	0	67	67
Striped Wolffish	0	149	100	250
Toad Crab	0	0	84	84
Whelk	0	0	17	17
Total Bycatch	23	616	2077	2716
Snow Crab Landings	**5,187,866**	**5,200,717**	**9,897,000**	**15,097,717**

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 1.96% of total landings in the past three years. The 2013 and 2014 fishery showed a substantial increase in bycatch levels as Snow Crab catch rates were very low and the spatial extent of the fishery expanded to attempt to locate crab. The 2016 season ongoing so not presented.

Species	**2013**	**2014**	**2015**	**3 Year Total**
American Lobster	500	0	98	598
Cod	0	0	0	0
Jonah Crab	97	7	0	104
Longhorn Sculpin	8	0	0	8
Lumpfish	8	0	11	19
Northern Stone Crab	1,250	438	130	1,819
Deepsea Red Crab	339	75	0	414
Redfish	8	0	0	8
Sea Raven	2,210	521	239	2,969
Total Bycatch	4,419	1,041	478	5,939
Snow Crab Landings	**79,000**	**82,000**	**142,000**	**303,000**

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

Year	CC1	CC2	CC3	CC4	CC5
2006	3.87	9.68	71.14	13.67	1.64
2007	44.53	11.17	36.26	7.22	0.82
2008	26.84	4.21	61.33	6.86	0.75
2009	0.23	3.3	92.11	4.35	0.02
2010	1.6	1.56	92.61	3.97	0.25
2011	0	1.9	95.55	2.49	0.07
2012	0	2.99	95.68	1.33	0
2013	0	1.82	73.93	22.52	1.73
2014	0.09	25.65	72.58	1.67	0
2015	0.06	2.89	89.21	7.59	0.25
2016	0	1.26	84.96	13.66	0.11

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

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

Table 14. Carapace Condition (CC) of crab ≥ 95 mm CW (percent by number) over time for 4X from at-sea-observed data. Year refers to the starting year of the season (ie. 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

Table 15. Carapace Condition (CC) of crab ≥ 95 mm CW (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

Table 16. Carapace Condition (CC) of crab ≥ 95 mm CW (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

Table 17. Carapace Condition (CC) of crab ≥ 95 mm CW (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

FIGURES

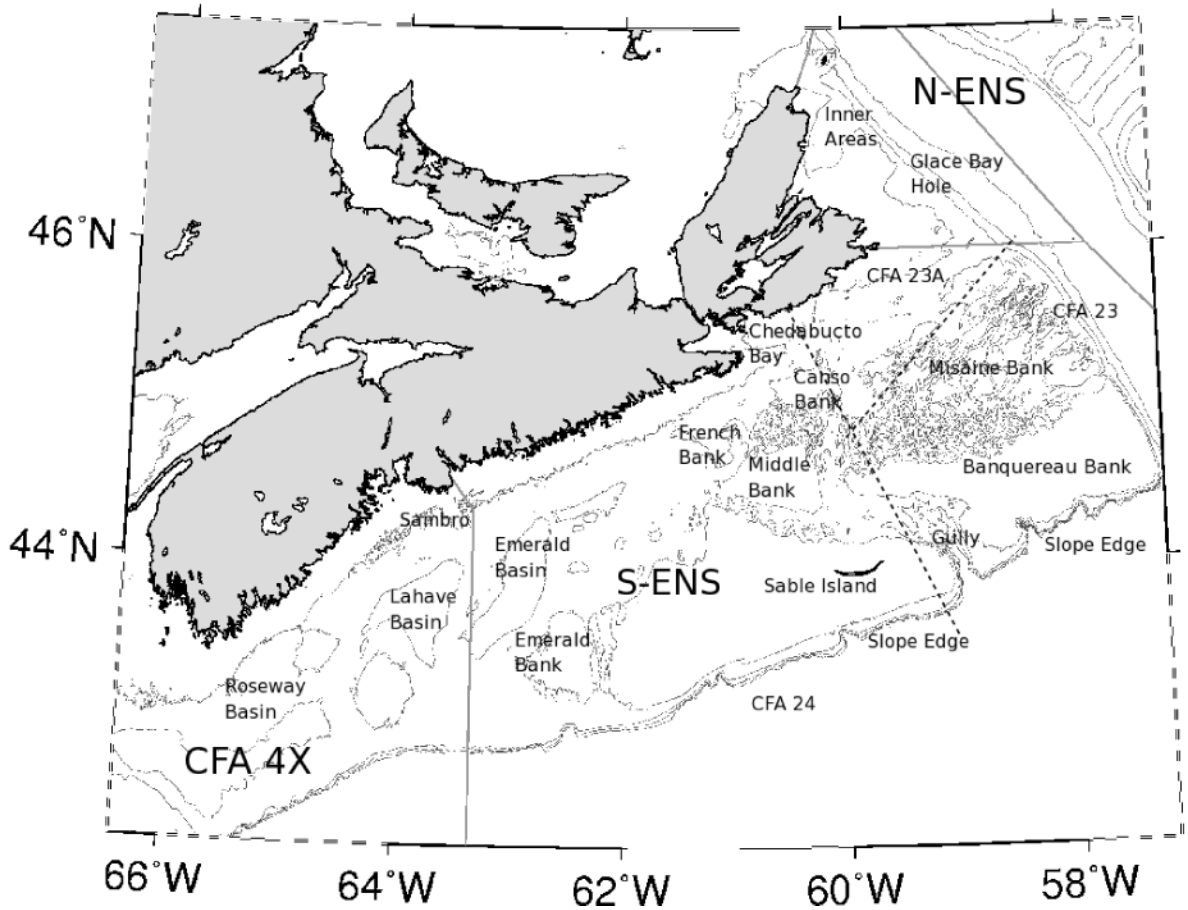

Figure 1. Location of geographic areas and the management areas for Snow Crab on the Scotian Shelf.

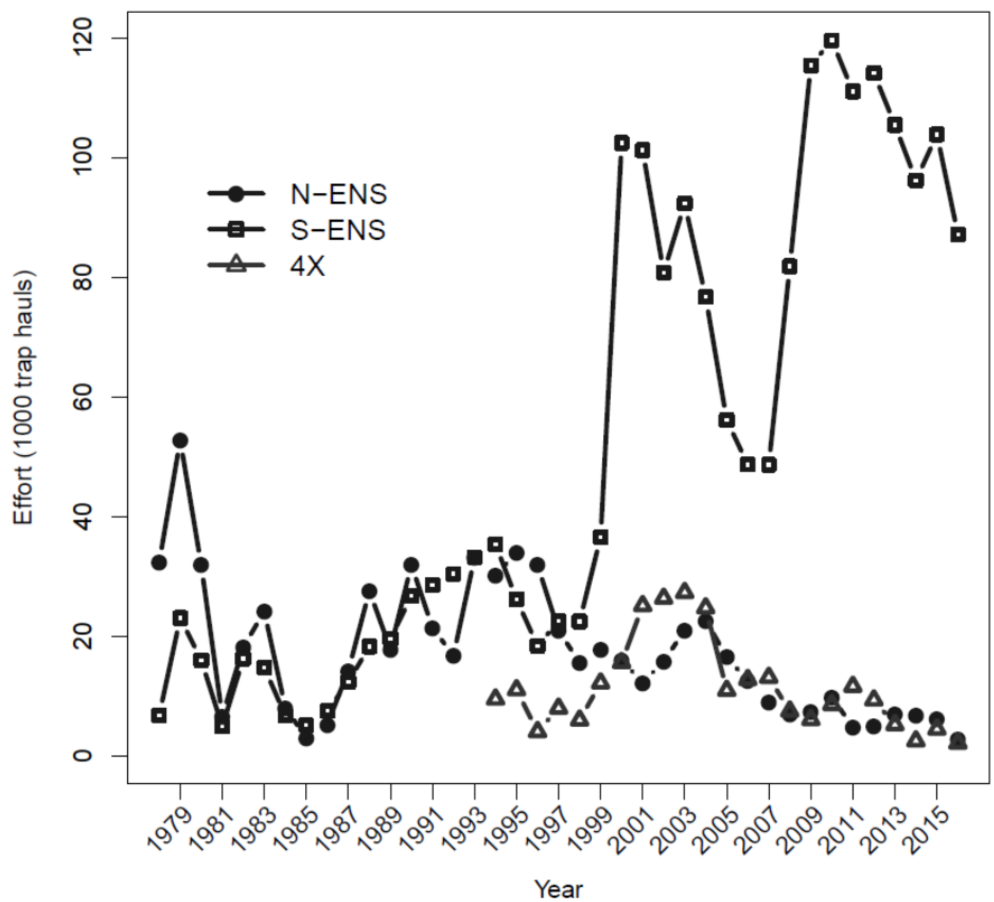

Figure 2. Temporal variations in the fishing effort for Snow Crab on the Scotian Shelf, expressed as the number of trap hauls per 1 minute grid. Year in 4X refers to the year at the start of the fishing season.

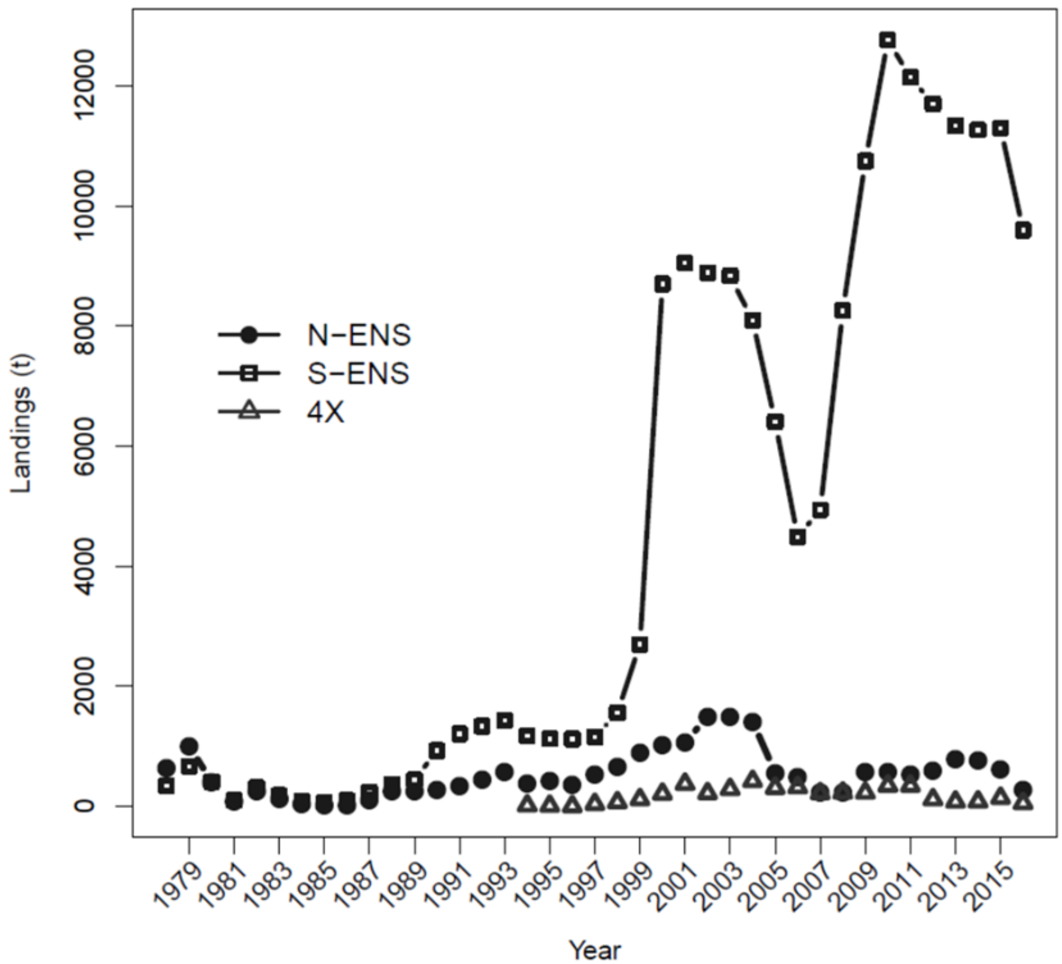

Figure 3. Temporal variations in the landings of Snow Crab on the Scotian Shelf (t). Note the sharp increase in landings associated with dramatic increases to total allowable catches (TACs) and a doubling of fishing effort in the year 2001. The landings follow the TACs with little deviation (Tables 2-4). Year in 4X refers to the year at the start of the fishing season.

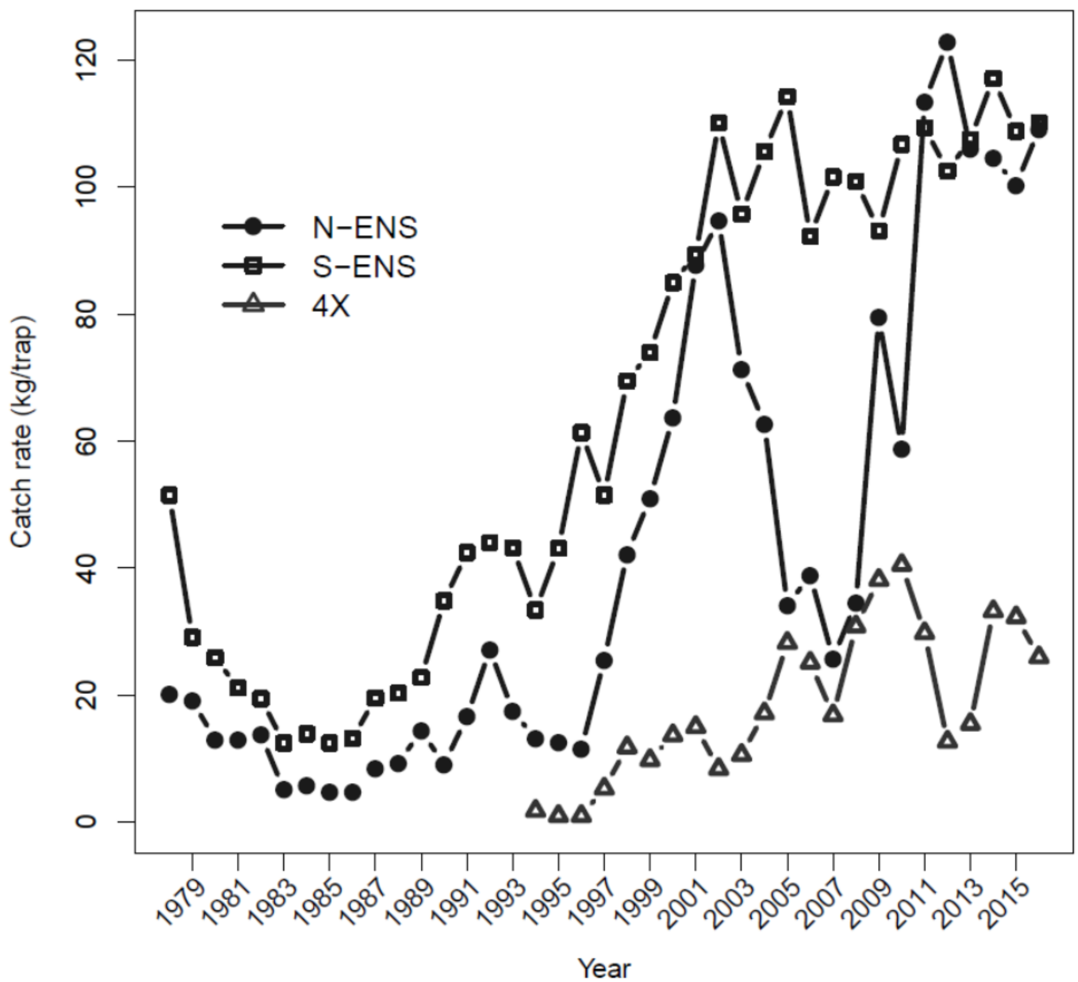

Figure 4. Temporal variations in catch rates of Snow Crab on the Scotian Shelf, expressed as kg per trap haul. Trap design and size have changed over time. No correction for these varying trap-types nor soak time and bait-type has been attempted (see Methods). Year in 4X refers to the year at the start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

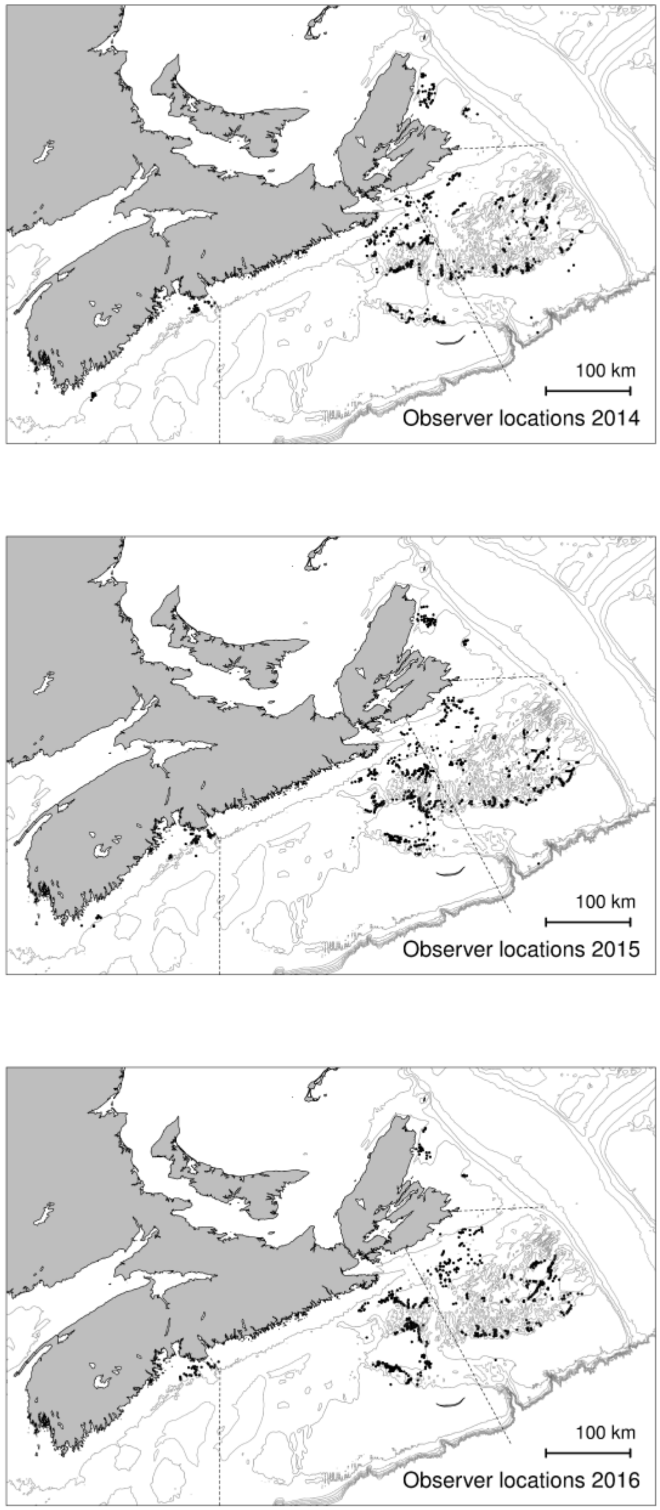

Figure 5. Locations of monitored Snow Crab fishing trips by at-sea observers on the Scotian Shelf during each of the past three fishing seasons.

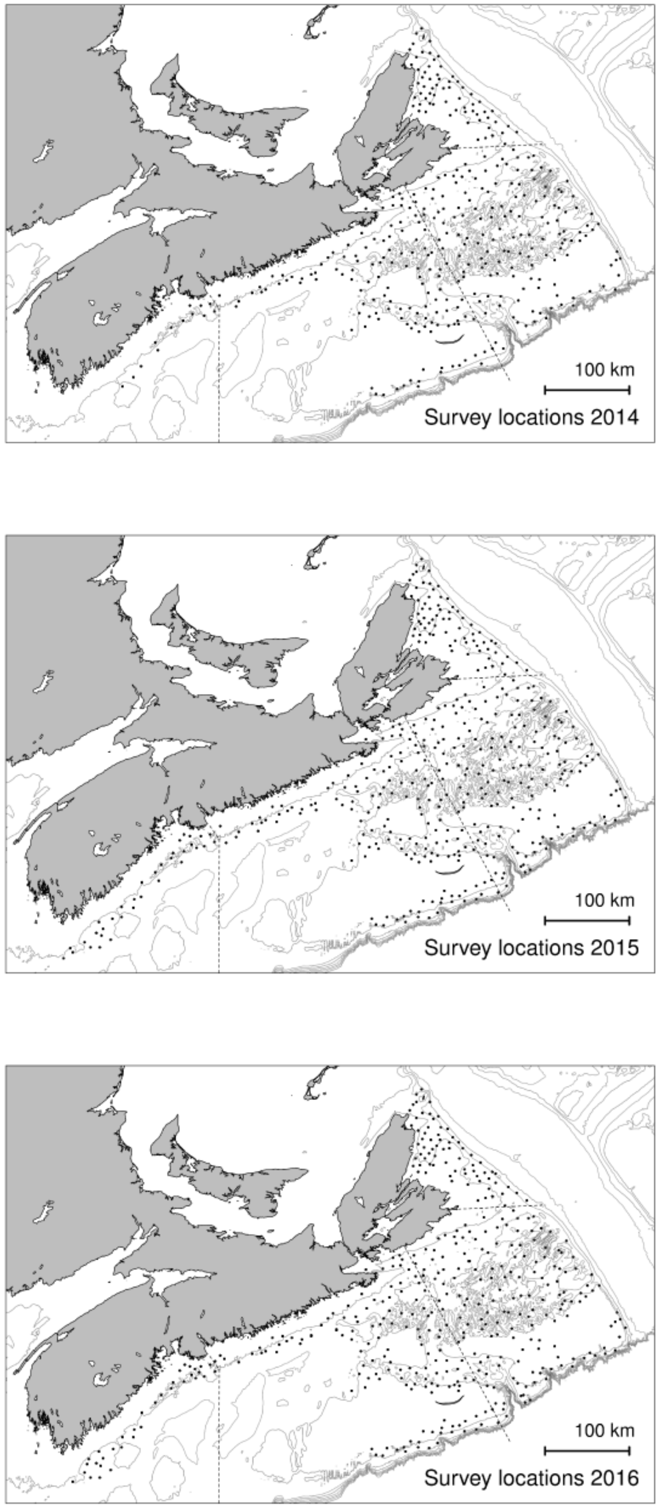

Figure 6. Locations of Snow Crab survey trawl sets on the Scotian Shelf during each of the past three years.

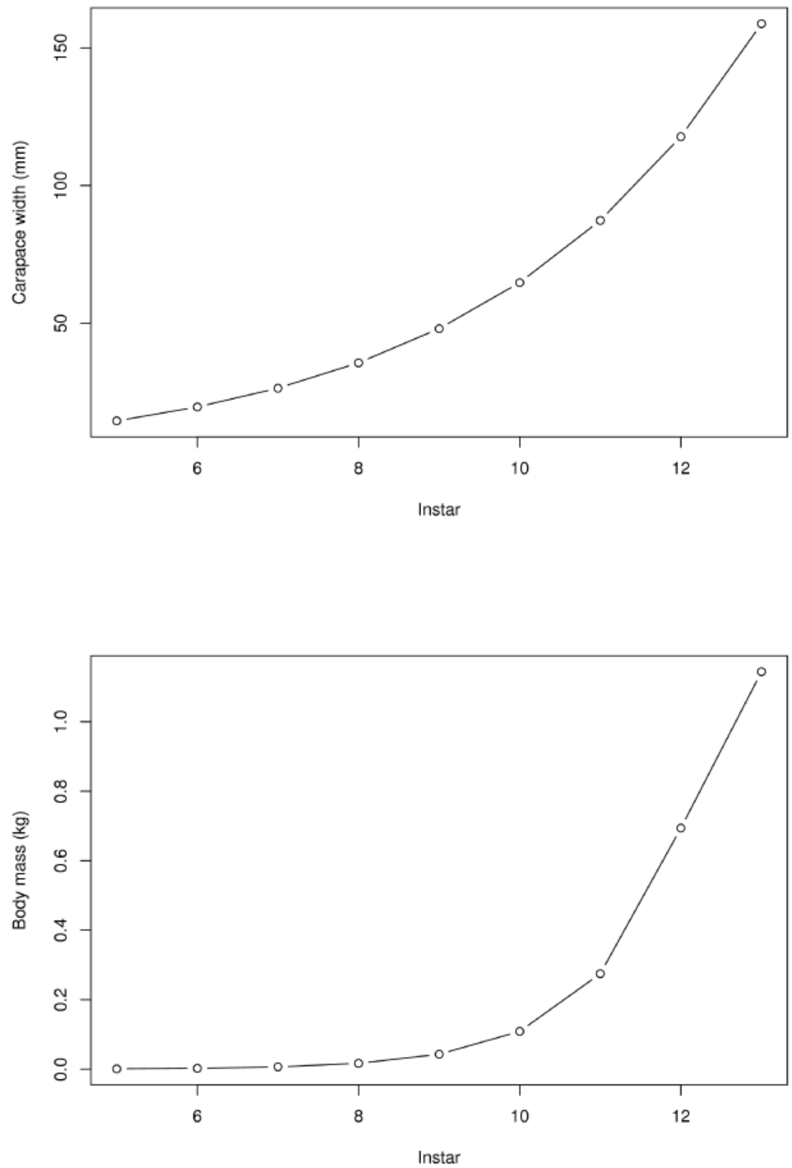

Figure 7. Growth curves determined from modal length frequency analysis of male Snow Crab on the Scotian Shelf.

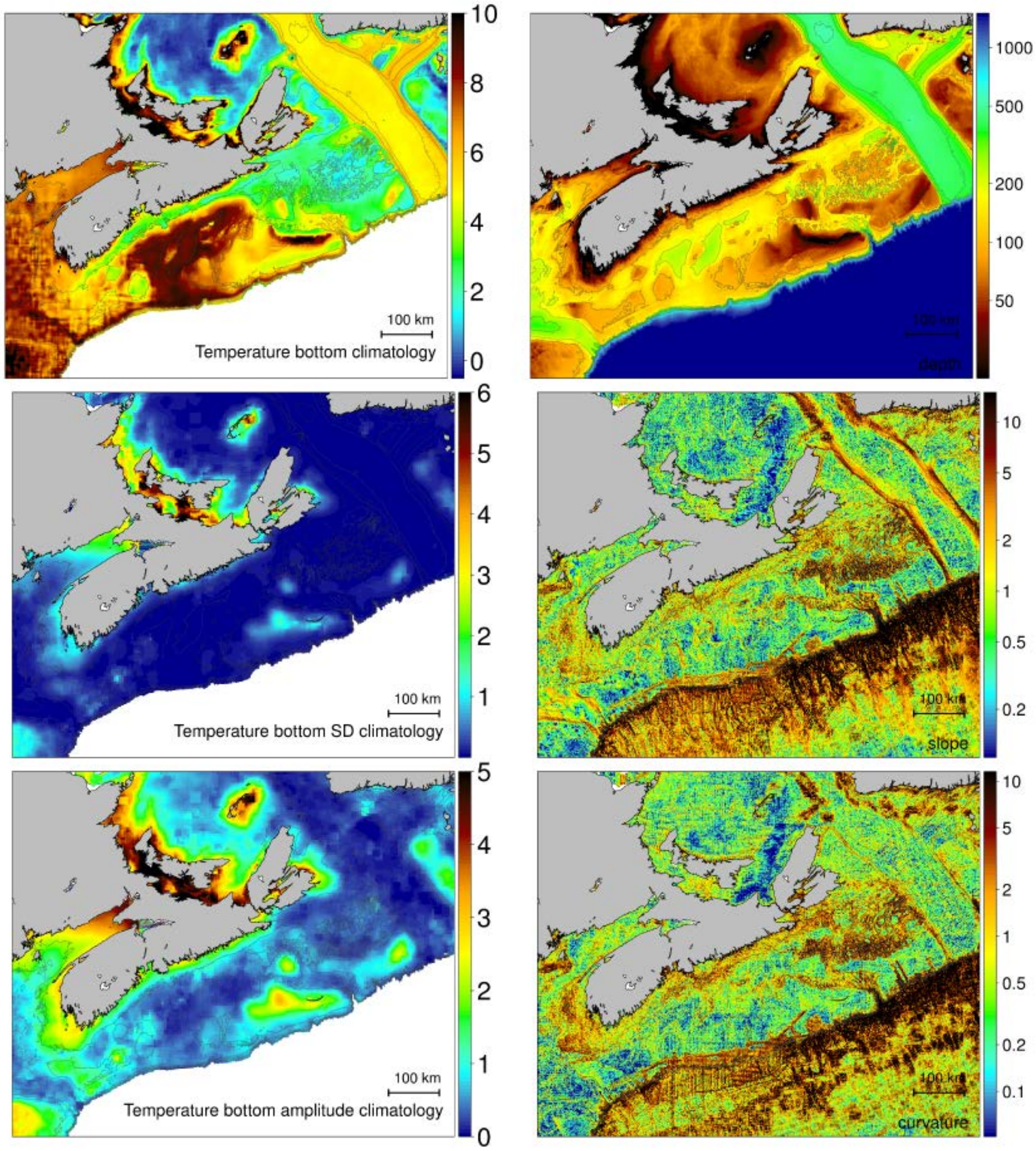

Figure 8. Bottom characteristics used for modeling Snow Crab habitat delineation. The visualizations of temperature variations are for climatological means. Annual temperature variation estimates were used for modeling.

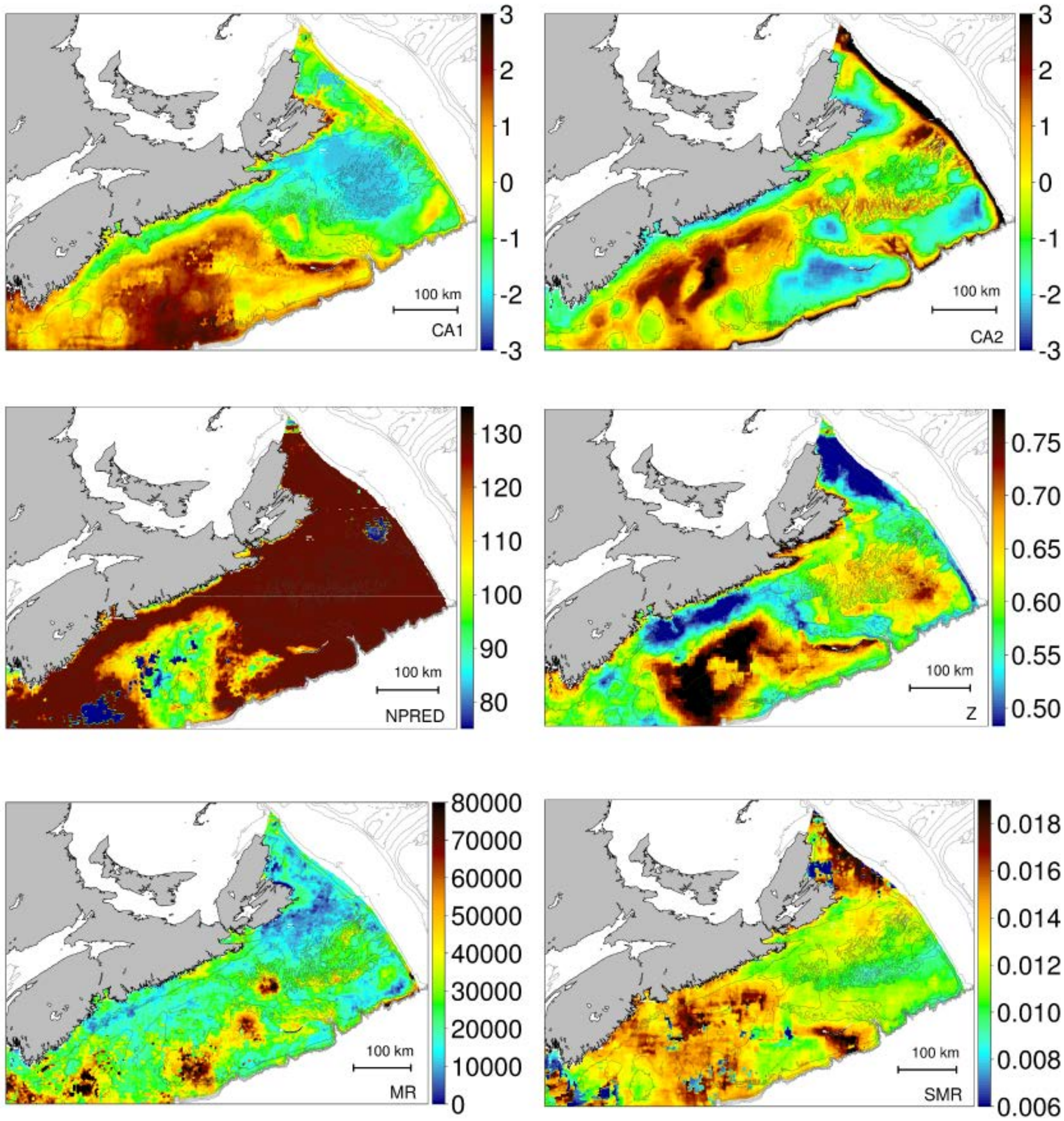

Figure 9. Community composition and ecological characteristics on the Scotian Shelf used in Snow Crab habitat determination modelling. Annual time series are used. Shown are results from 2016.

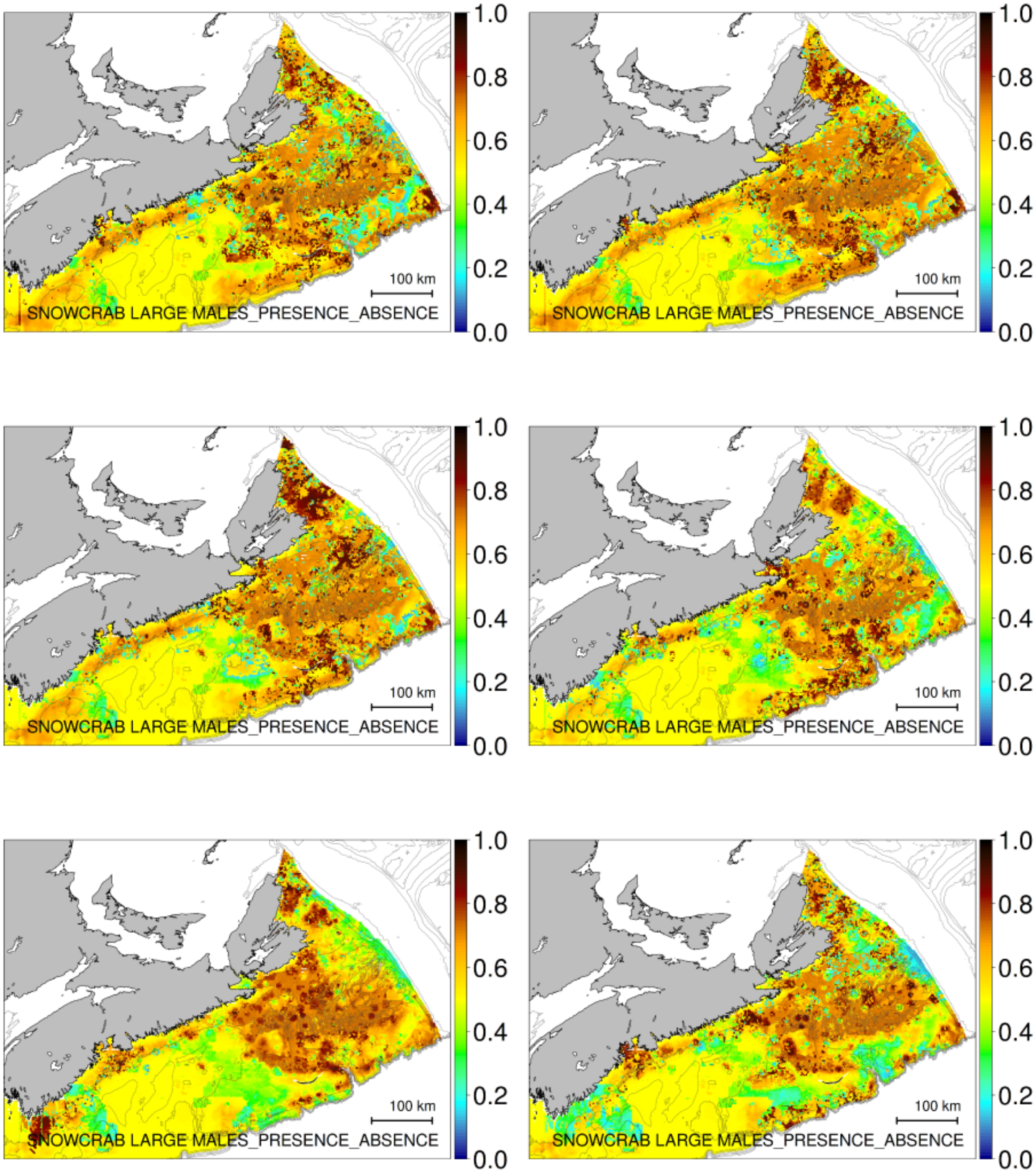

Figure 10. Annual interpolations of potential habitat for the fishable component of SSE Snow Crab represented as the probability of finding Snow Crab. Spatial representations are generated with lattice based methods using generalized additive models of several habitat, environmental and biological variables.

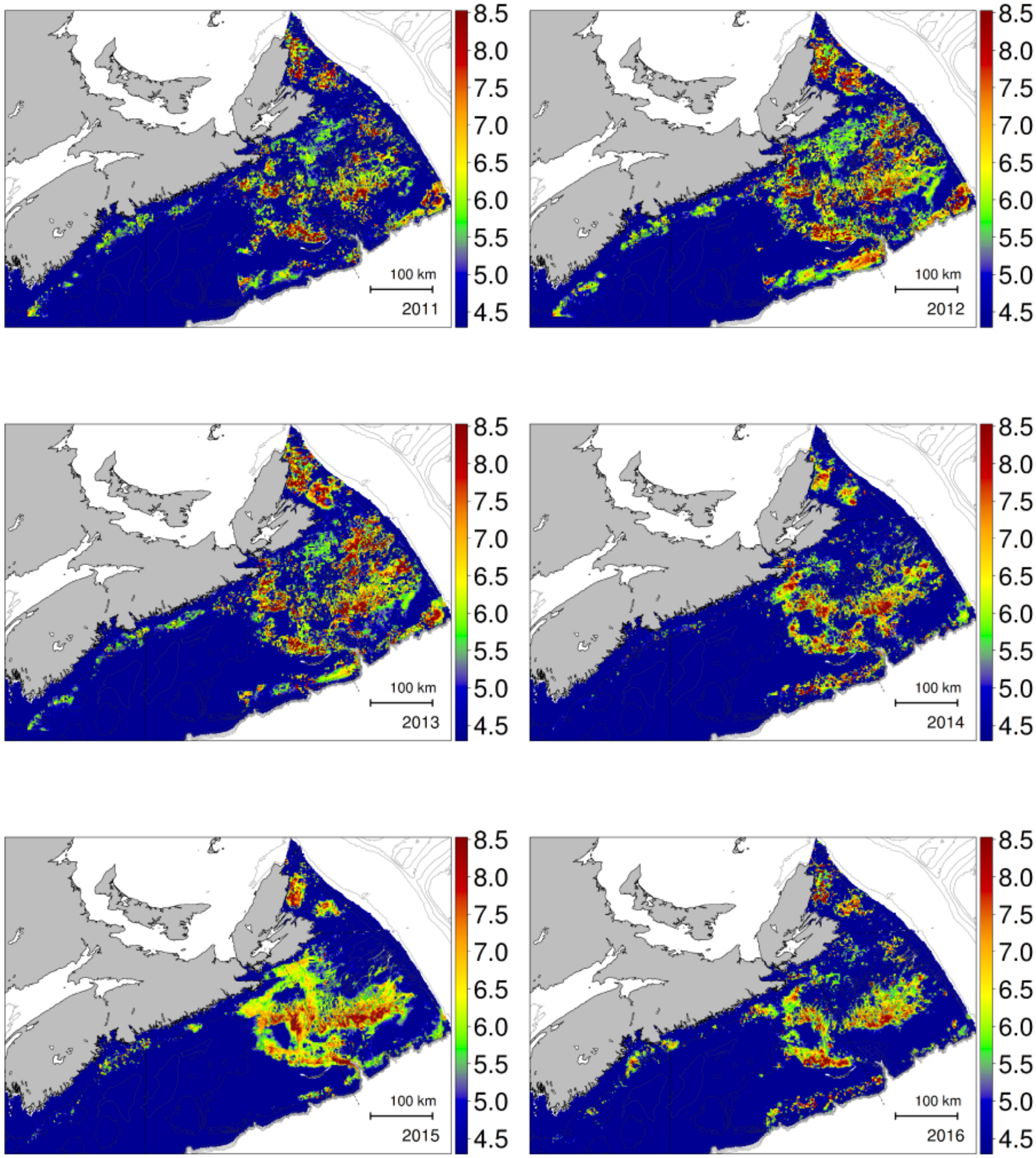

Figure 11. Annual interpolations of fishable Snow Crab log $\left(\frac{t}{km^2}\right)$. Spatial representations are generated with lattice based methods using generalized additive models of several habitat, environmental and biological variables.

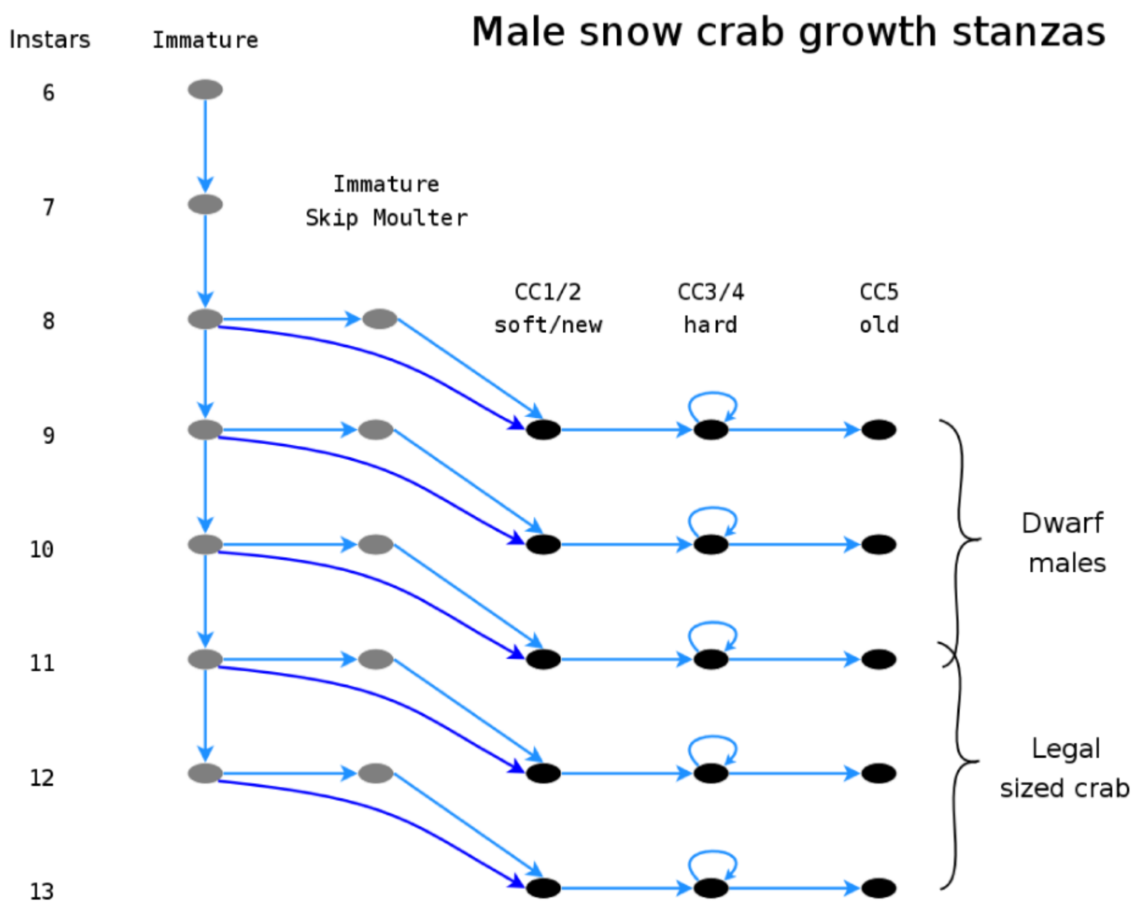

Figure 12. The growth stanzas of male Snow Crab. Each instar is determined from CW bounds obtained from modal analysis and categorized to carapace condition (CC) and maturity from visual inspection and/or maturity equations. Snow Crab are resident in each growth stanza for 1 year, with the exception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

Figure 13. Sorted ordination of anomalies of key social, economic and ecological patterns on the Scotian Shelf relevant to Snow Crab. Red indicates below the mean and green indicates above the mean.

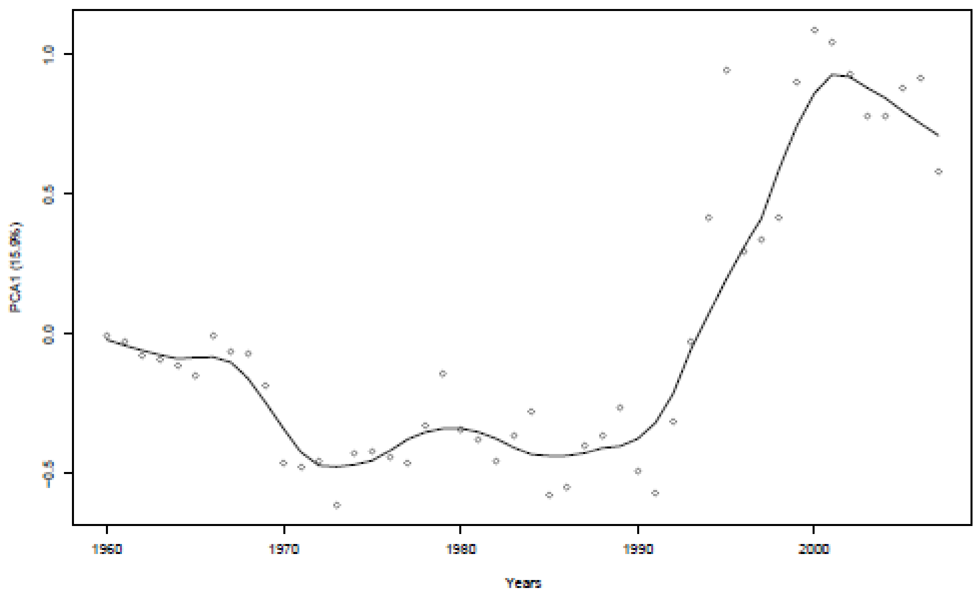

Figure 14. First axis of variations in ordination of anomalies of social, economic and ecological patterns on the Scotian Shelf. Note strong variability observed near the time of the fishery collapse in the early 1990s. Note strong variability observed near the time of the fishery collapse in the early 1990s.

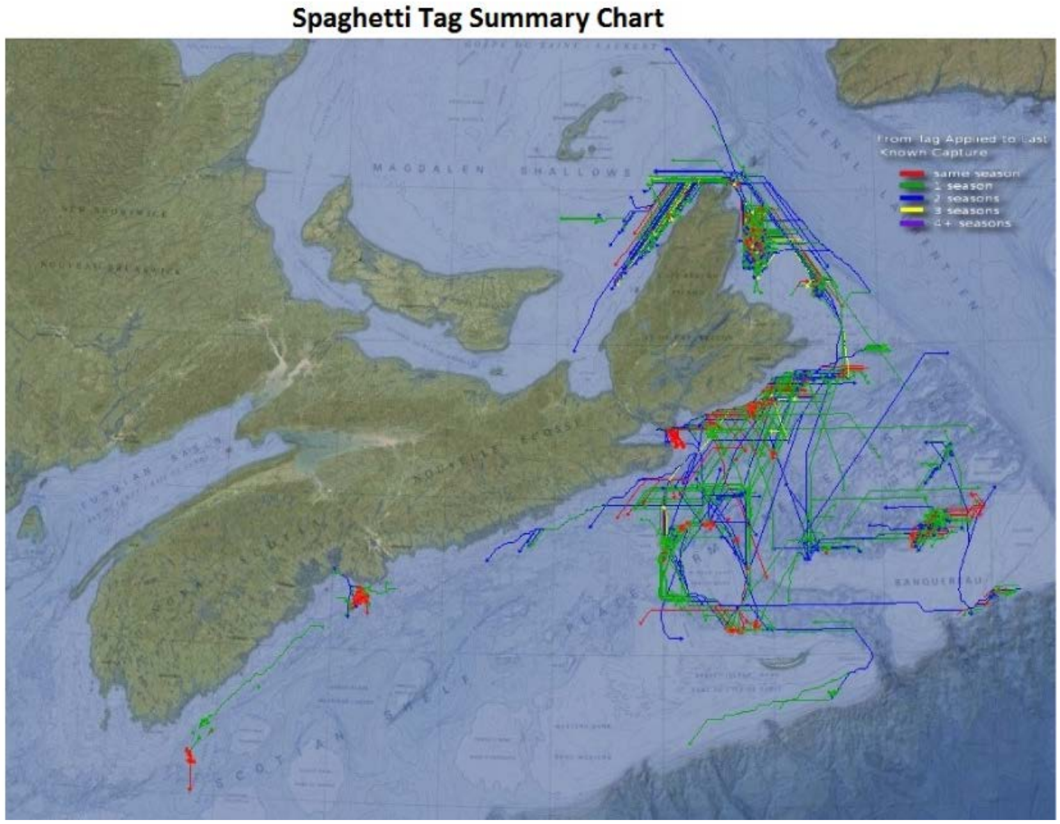

Figure 15. Map of movements for tagged terminally moulted commercial Snow Crab on the Scotian Shelf with movements between mark and recapture locations constrained to the shortest path within depth contours of 60 and 280 m.

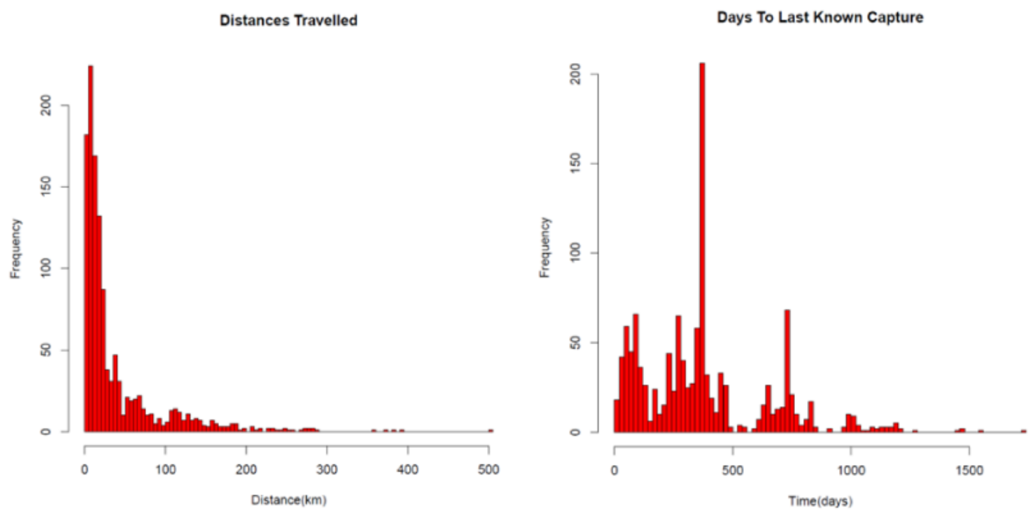

Figure 16. (Left) Distance travelled by tagged Snow Crab on the Scotian Shelf between 2005 and 2016. (Right) Return intervals in days between initial release and last capture of Snow Crab tagged on the Scotian Shelf. Periodicity in time intervals are explained by recaptures occurring during seasonal fishing operations.

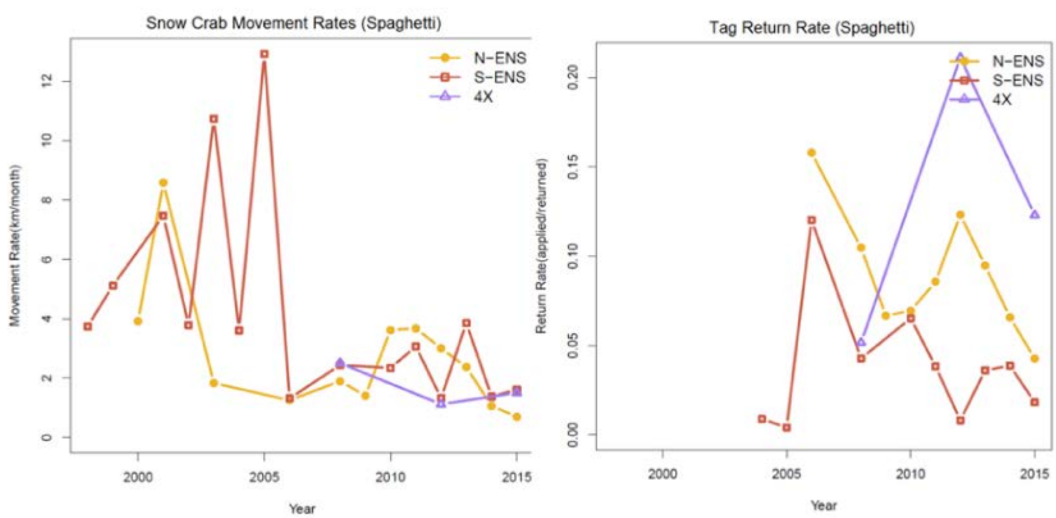

Figure 17. (Left) Mean rate of movement of Snow Crab tagged on the Scotian Shelf by area and year. Route lengths derived from calculated shortest paths constrained by depth range of 60-280 m. Sample size small (approximately 8 returns per area) for years 2003 to 2005 which accounts for the high variability especially in S-ENS for those years. (Right) Tags return rate, number of returns from tags applied in given area and year. Shows downward trend in recent years.

Acoustic Tag Summary Chart

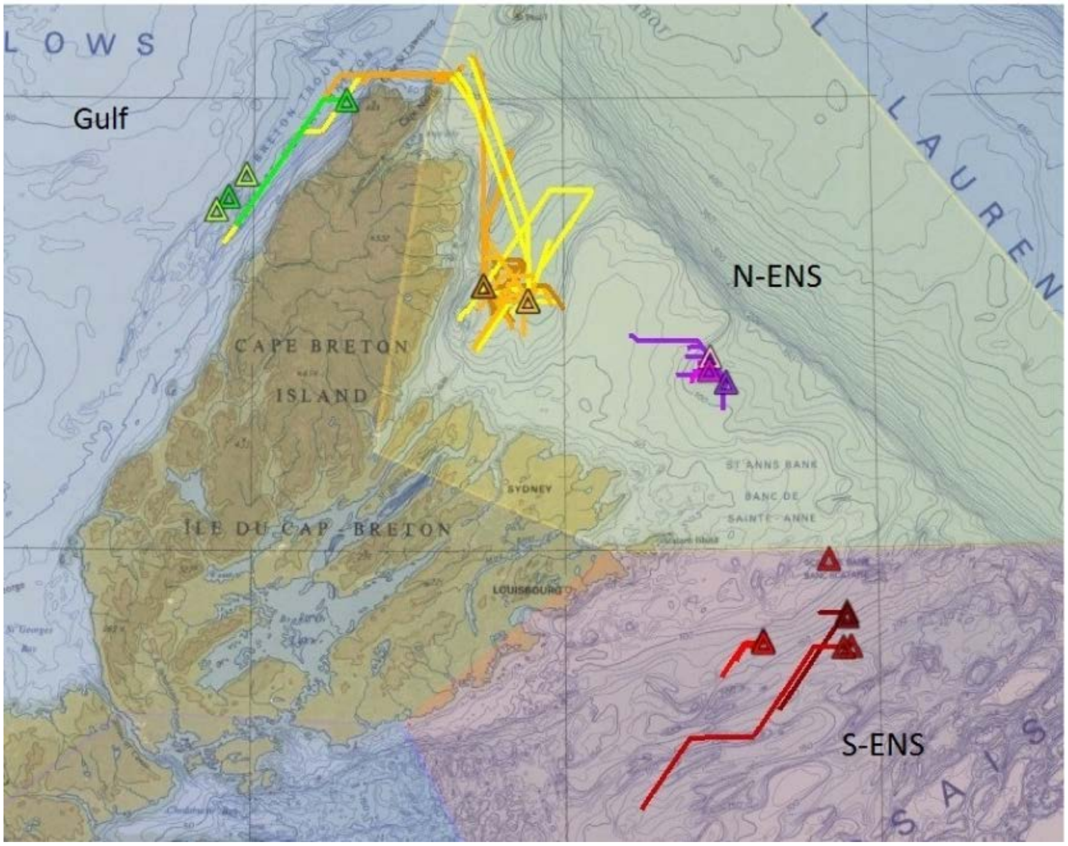

Figure 18. Map of movements for acoustic tagged Snow Crab on the Scotian Shelf with movements between mark and detection locations constrained by depth range of 60-280 m. Triangles represent release locations.

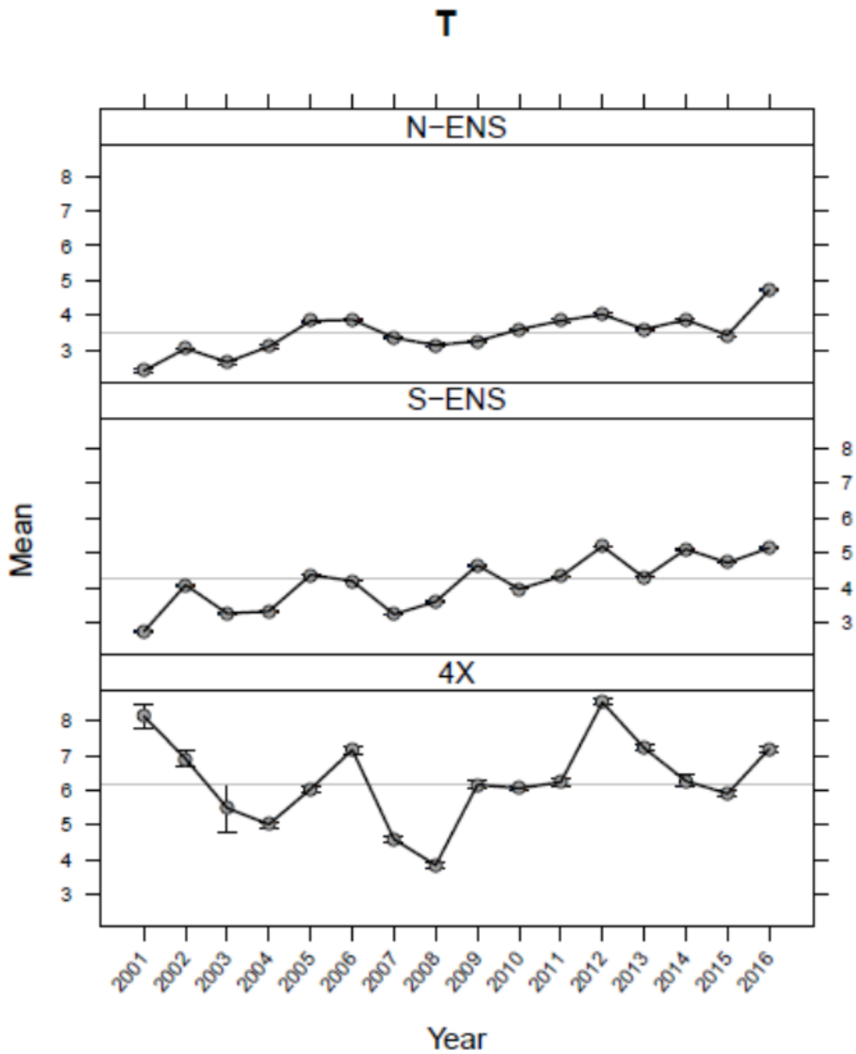

Figure 19. Annual variations in bottom temperature observed during the ENS Snow Crab survey. The horizontal line indicates the long-term median temperature within each subarea. Error bars are 1 standard deviation.

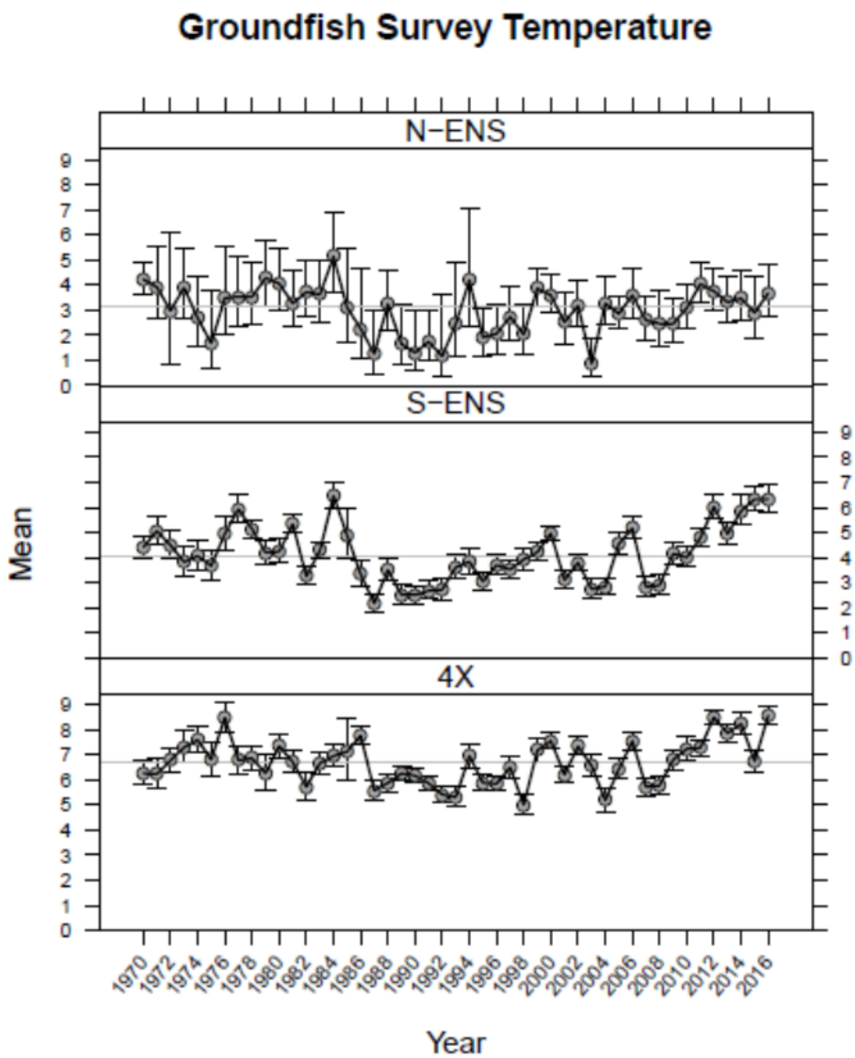

Figure 20. Annual variations in bottom temperature observed during the DFO July RV Groundfish Survey. The horizontal line indicates the long-term median temperature within each subarea. Error bars are 1 standard deviation.

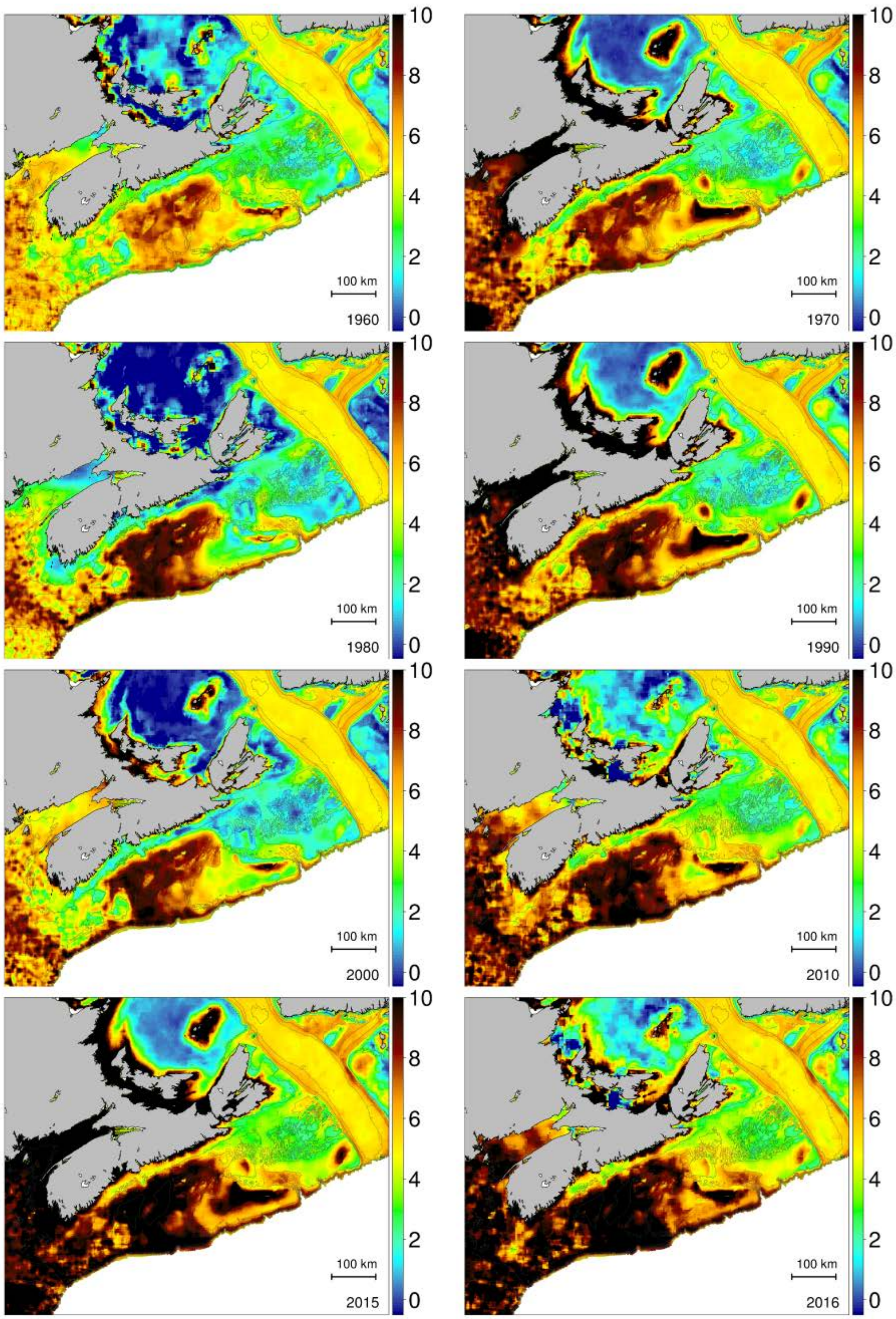

Figure 21. Interpolated mean annual bottom temperatures on the Scotian Shelf for selected years. These interpolations use all available water temperature data collected in the area including Groundfish Surveys, Snow Crab survey, and AZMP monitoring stations.

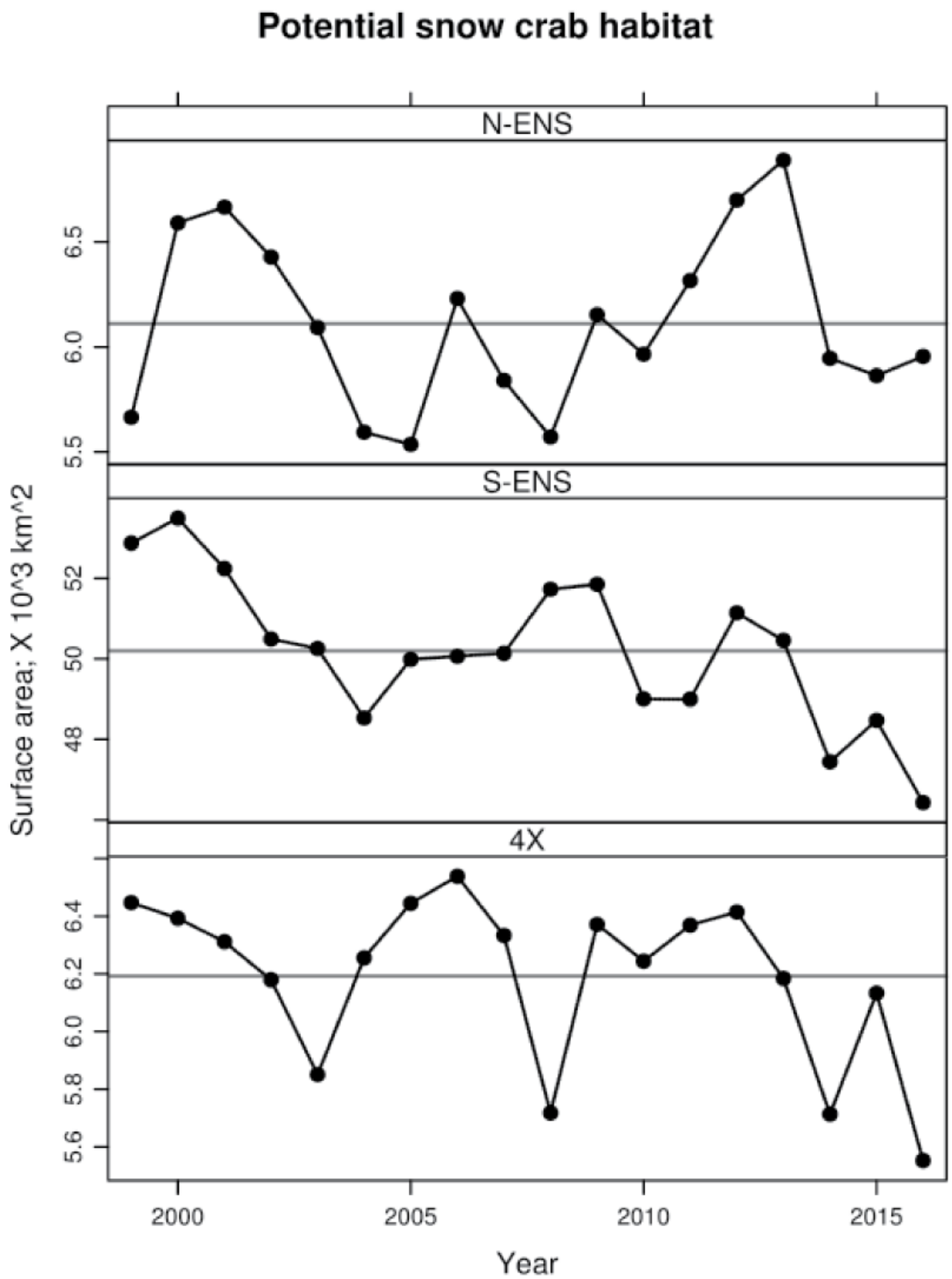

Figure 22. Annual variations in the surface area of potential Snow Crab habitat. The horizontal line indicates the long-term median surface area within each subarea.

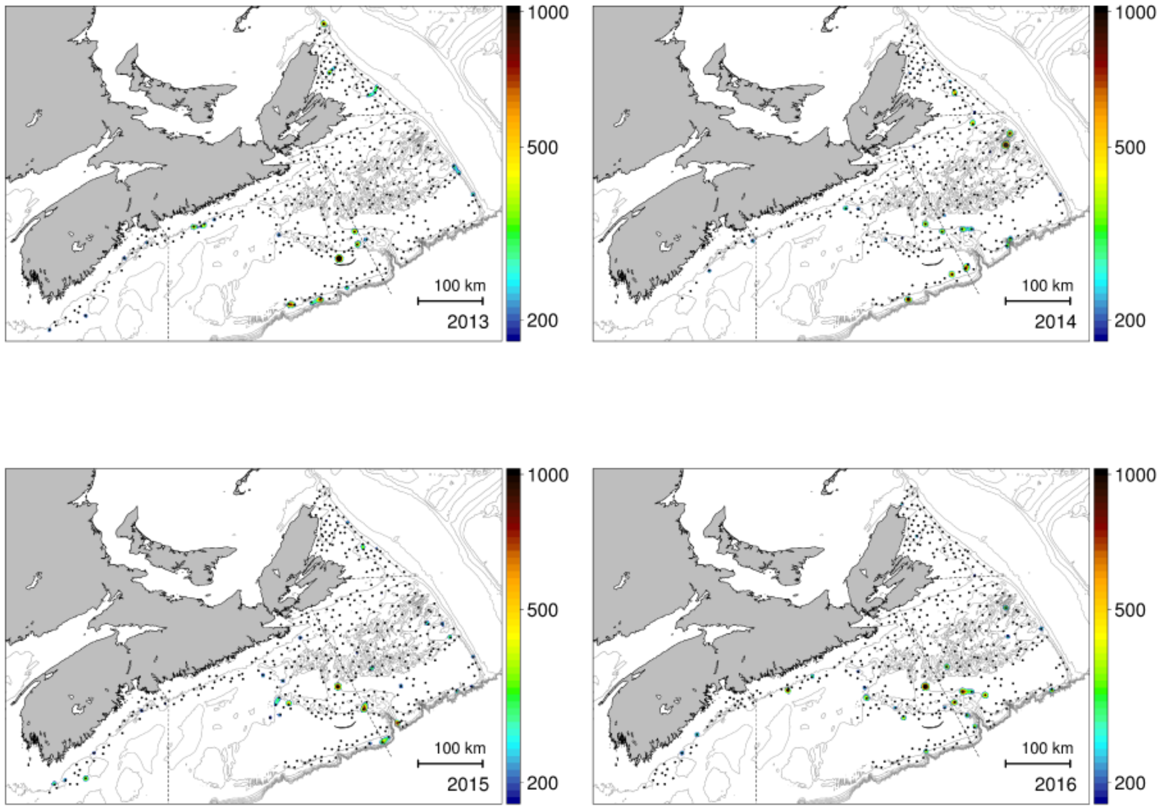

*Figure 23. Locations of potential **predators** of Snow Crab on the Scotian Shelf: **Atlantic Halibut**. Scale is* $\left(\frac{number}{km^2}\right)$.

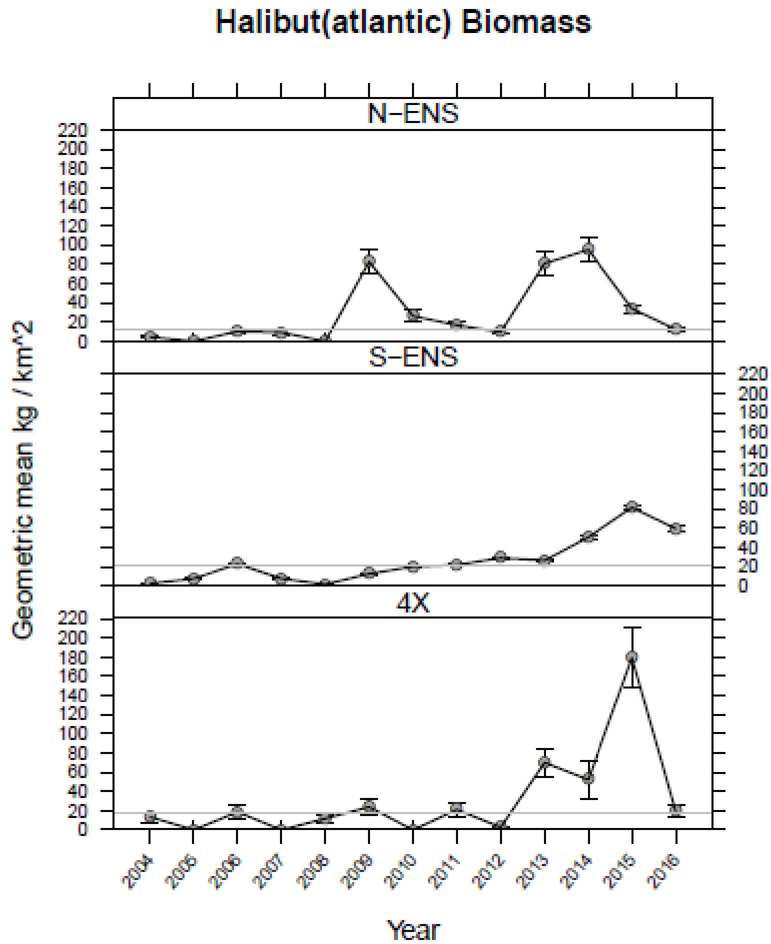

*Figure 24. Trends in Biomass $\left(\frac{t}{km^2}\right)$ from the annual Snow Crab survey for potential **predators** of Snow Crab on the Scotian Shelf: **Atlantic Halibut**.*

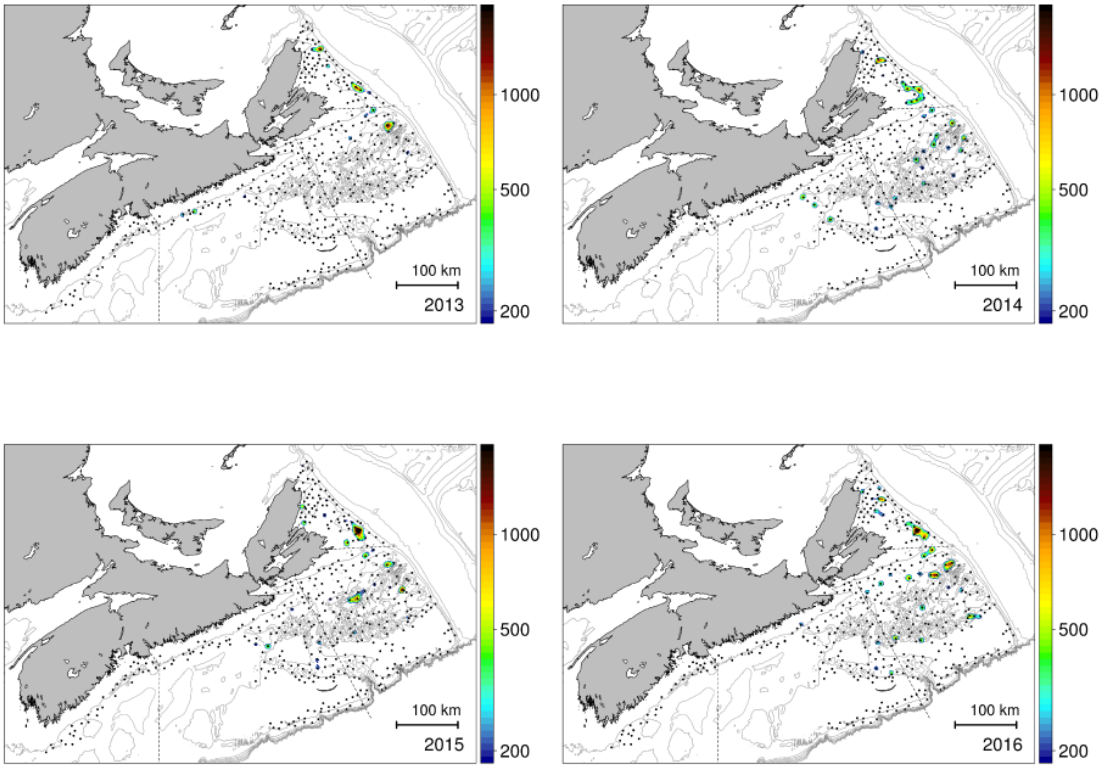

*Figure 25. Locations of potential **predators** of Snow Crab on the Scotian Shelf: **Atlantic Wolffish**. Scale is* $\left(\frac{number}{km^2}\right)$.

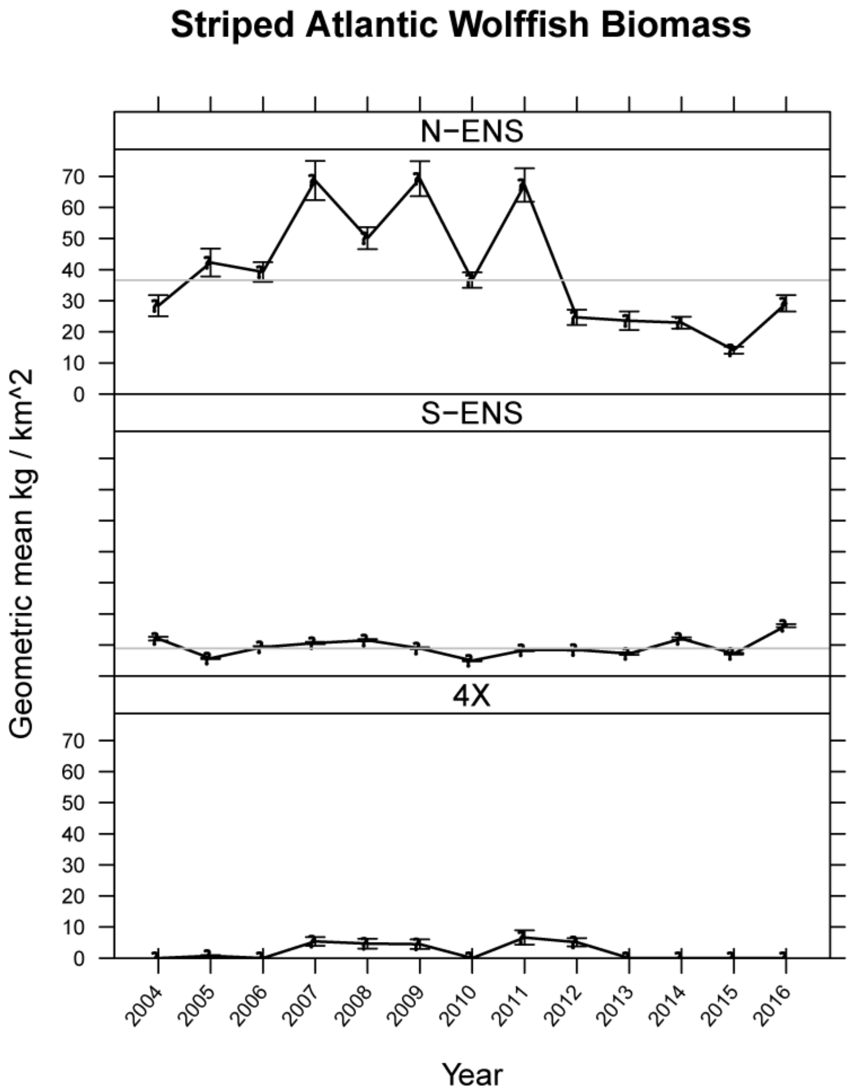

Figure 26. Trends in biomass $\left(\frac{t}{km^2}\right)$ from the annual Snow Crab survey for potential ***predators*** *of Snow Crab on the Scotian Shelf:* ***Atlantic Wolffish****.*

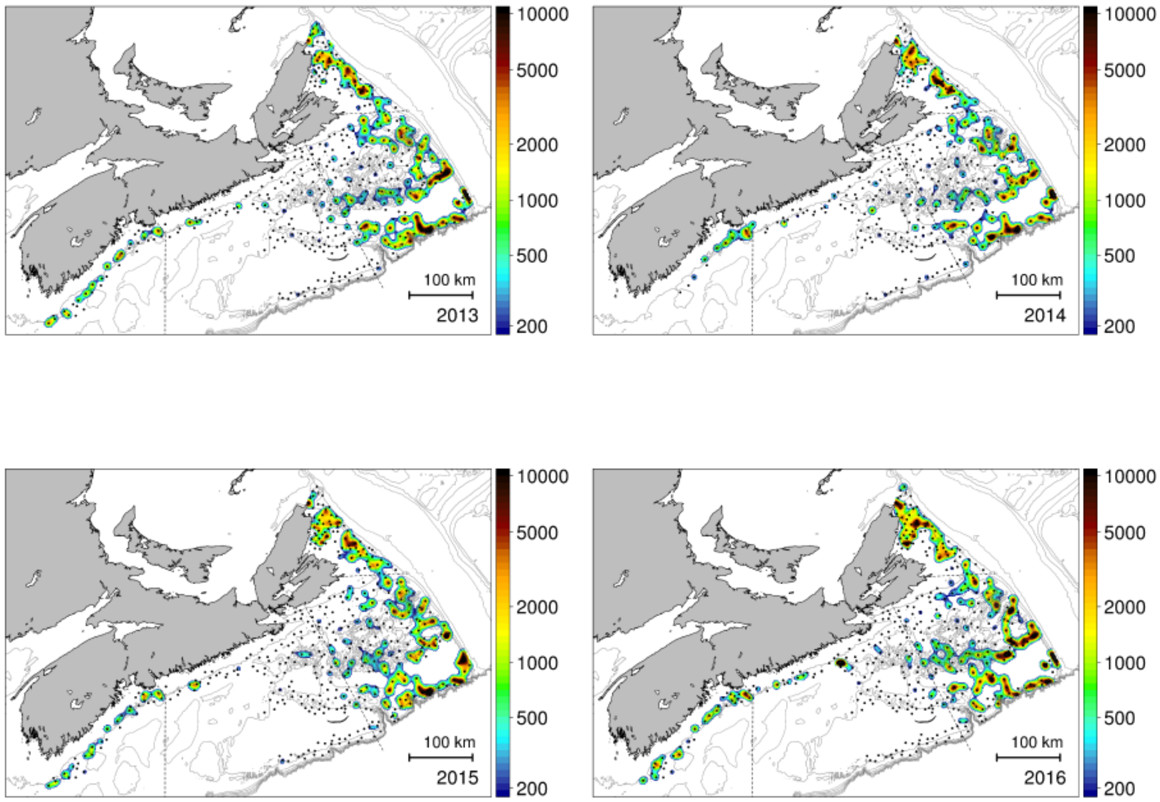

Figure 27. Locations of potential ***predators*** *of Snow Crab on the Scotian Shelf:* ***Thorny Skate****.*
Scale is $\left(\frac{number}{km^2}\right)$*.*

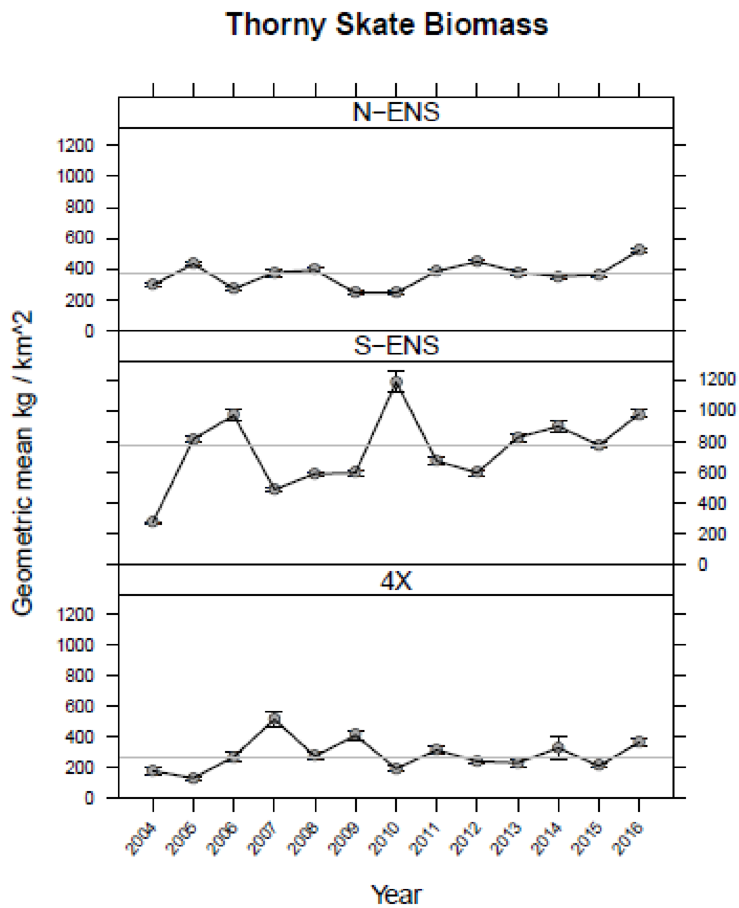

*Figure 28. Trends in biomass $\left(\frac{t}{km^2}\right)$ from the annual Snow Crab survey for potential **predators** of Snow Crab on the Scotian Shelf: **Thorny Skate**.*

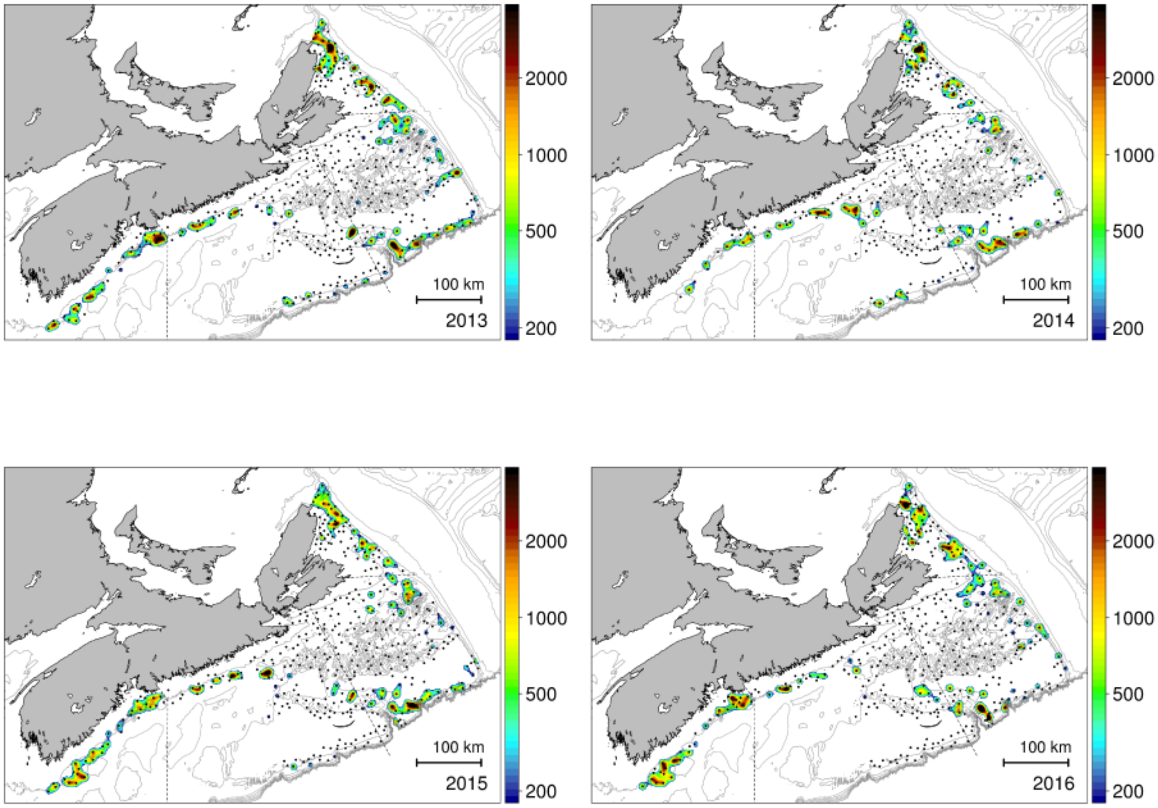

Figure 29. Locations of potential predators of Snow Crab on the Scotian Shelf: Smooth Skate. Scale is $\left(\frac{number}{km^2}\right)$.

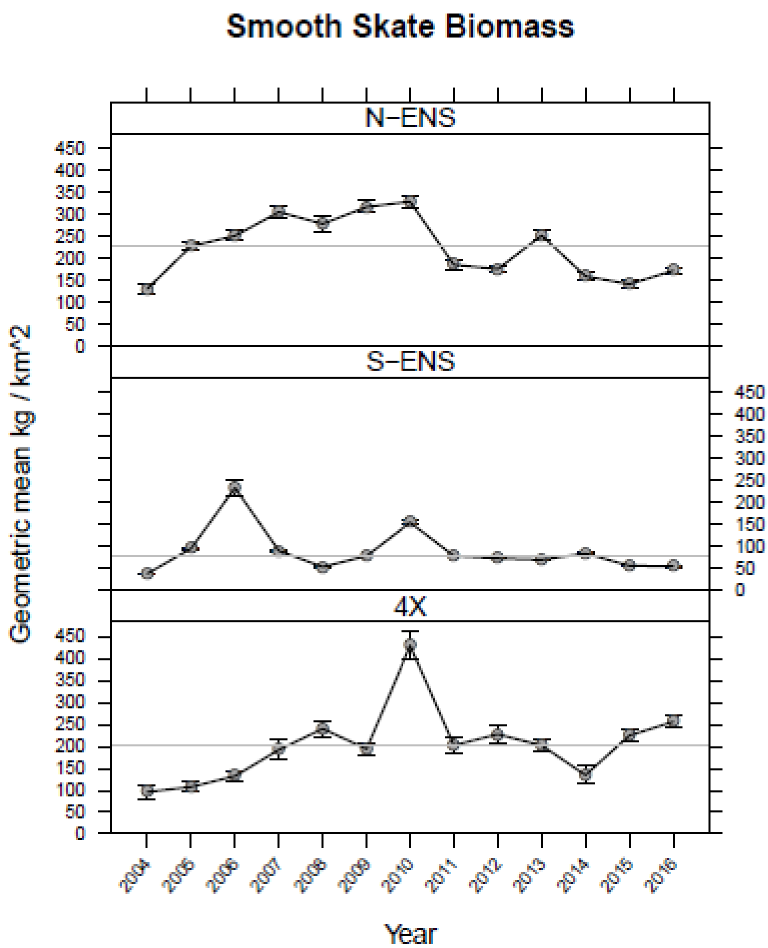

*Figure 30. Trends in biomass $\left(\frac{t}{km^2}\right)$ from the annual Snow Crab survey for potential **predators** of Snow Crab on the Scotian Shelf: **Smooth Skate**.*

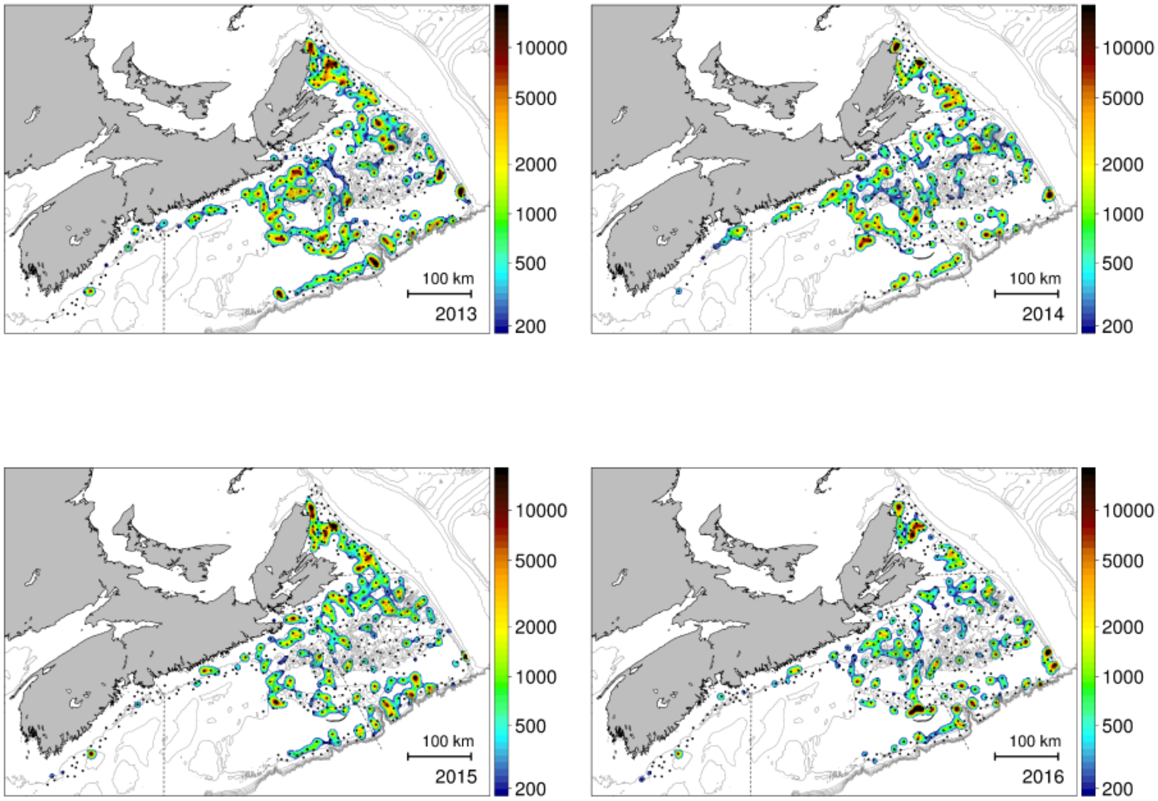

Figure 31. Locations of potential predators of Snow Crab on the Scotian Shelf: Atlantic Cod. Scale is $\left(\frac{number}{km^2}\right)$.

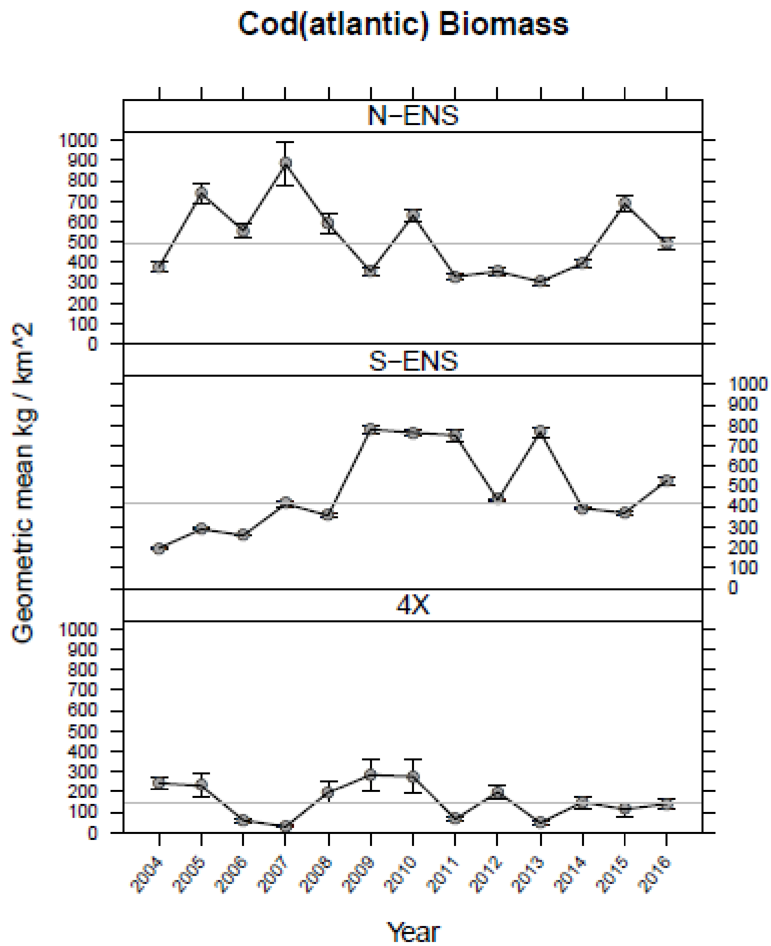

Figure 32. Trends in biomass $\left(\frac{kg}{km^2}\right)$ *from the annual Snow Crab survey for potential* ***predators*** *of Snow Crab on the Scotian Shelf:* ***Atlantic Cod****.*

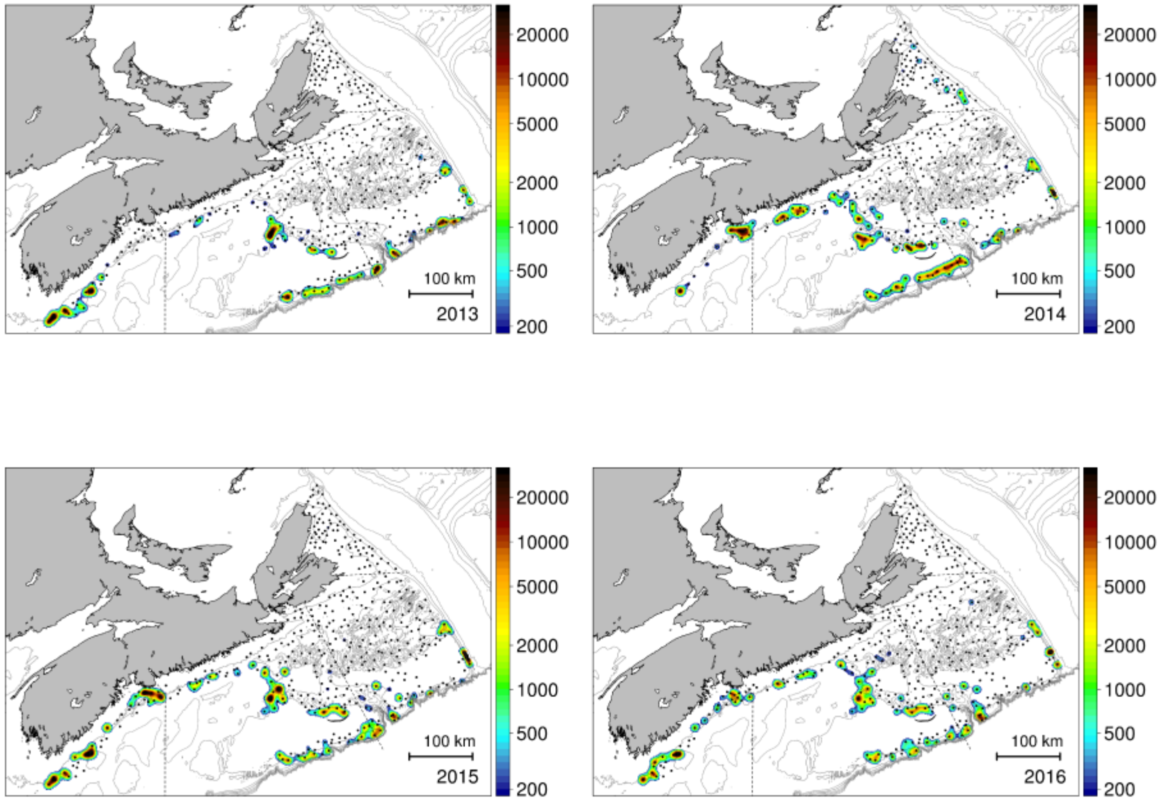

*Figure 33. Locations of potential **predators** of Snow Crab on the Scotian Shelf: **Haddock**.*
Scale is $\left(\frac{number}{km^2}\right)$.

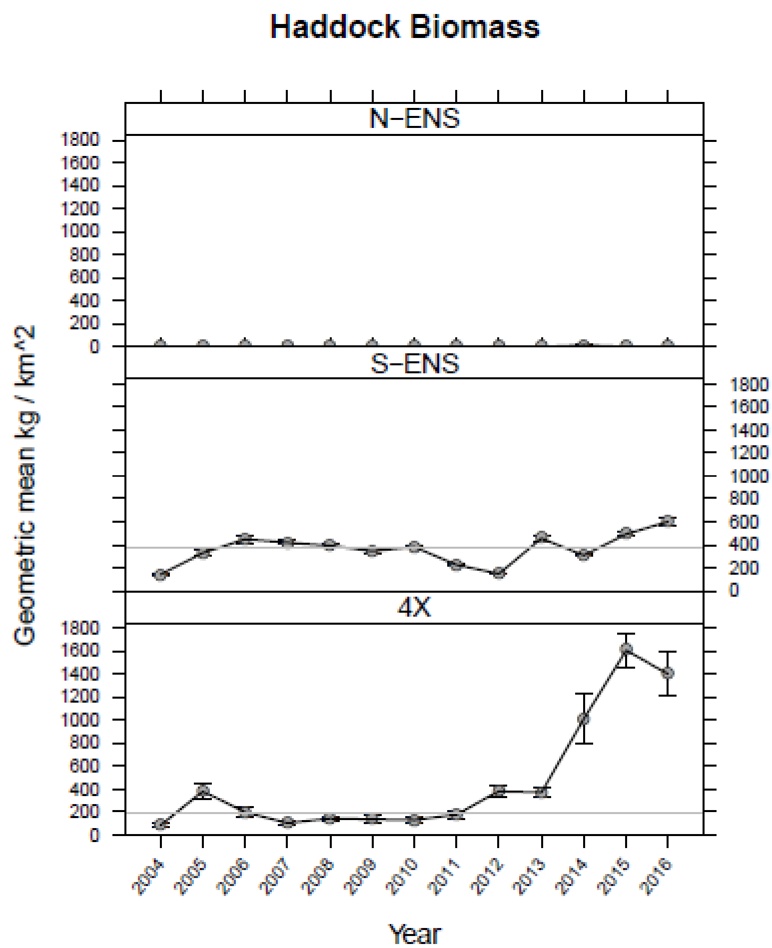

*Figure 34. Trends in biomass $\left(\frac{kg}{km^2}\right)$ from the annual Snow Crab survey for potential **predators** of Snow Crab on the Scotian Shelf. **Haddock**.*

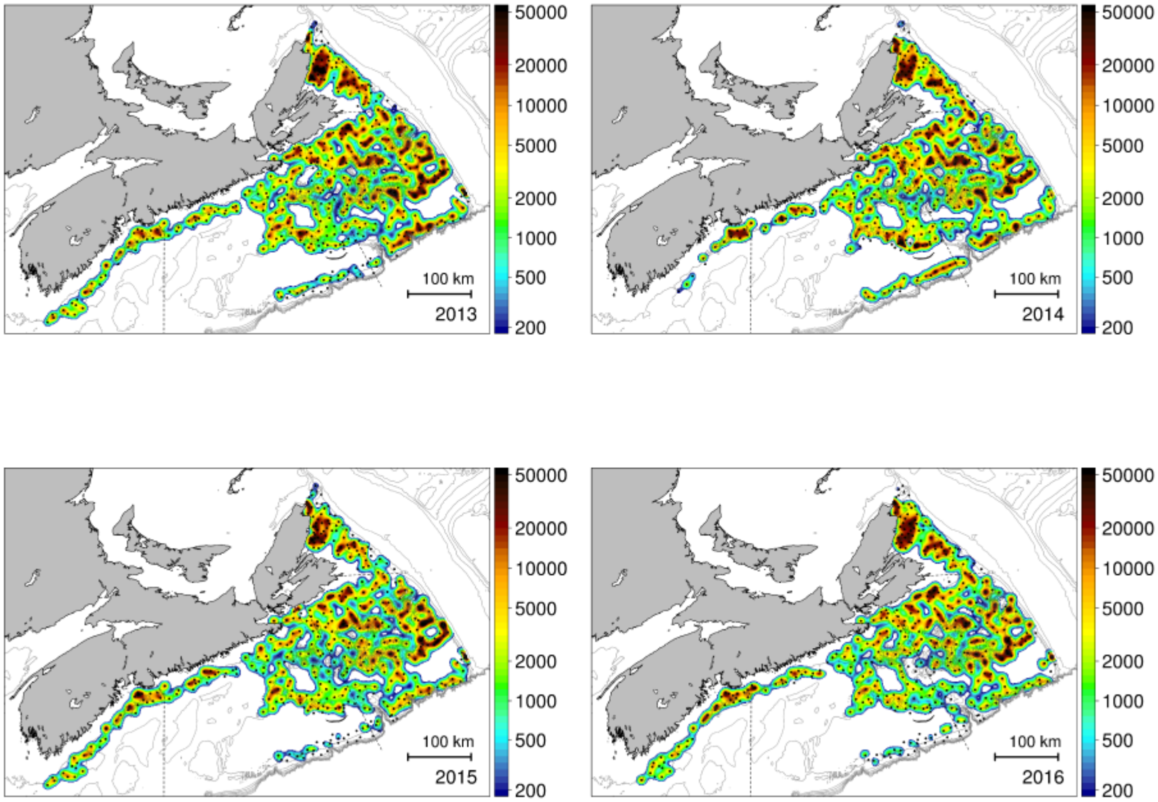

Figure 35. Locations of potential ***predators*** *of Snow Crab on the Scotian Shelf:* ***American Plaice****.*
Scale is $\left(\frac{number}{km^2}\right)$.

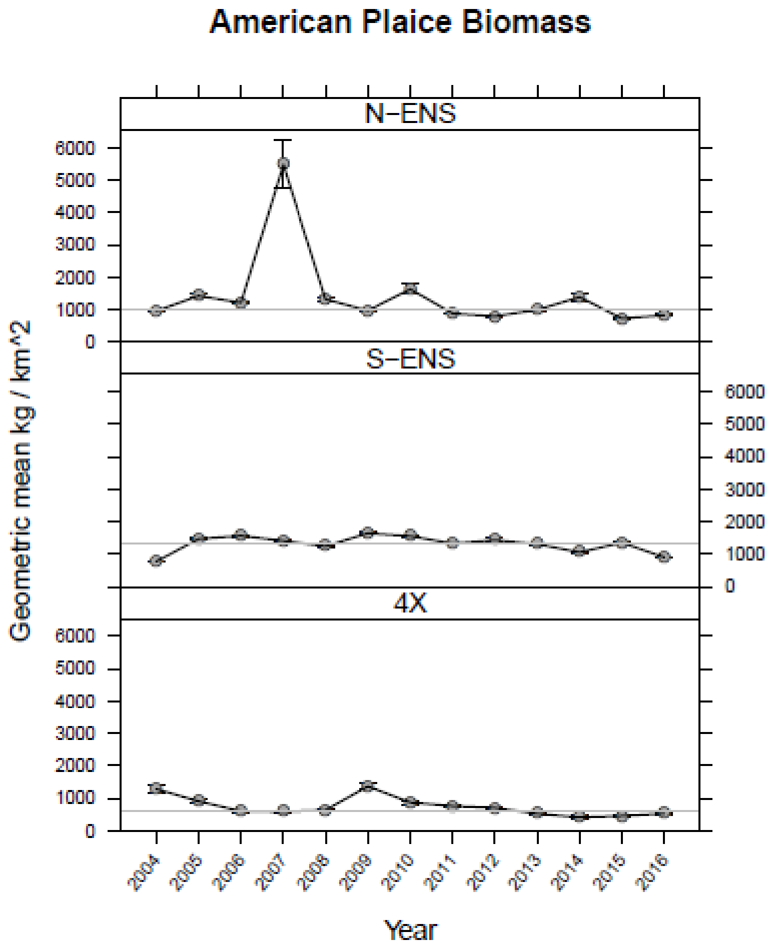

Figure 36. Trends in biomass $\left(\frac{kg}{km^2}\right)$ *from the annual Snow Crab survey for potential* ***predators*** *of Snow Crab on the Scotian Shelf:* ***American Plaice.***

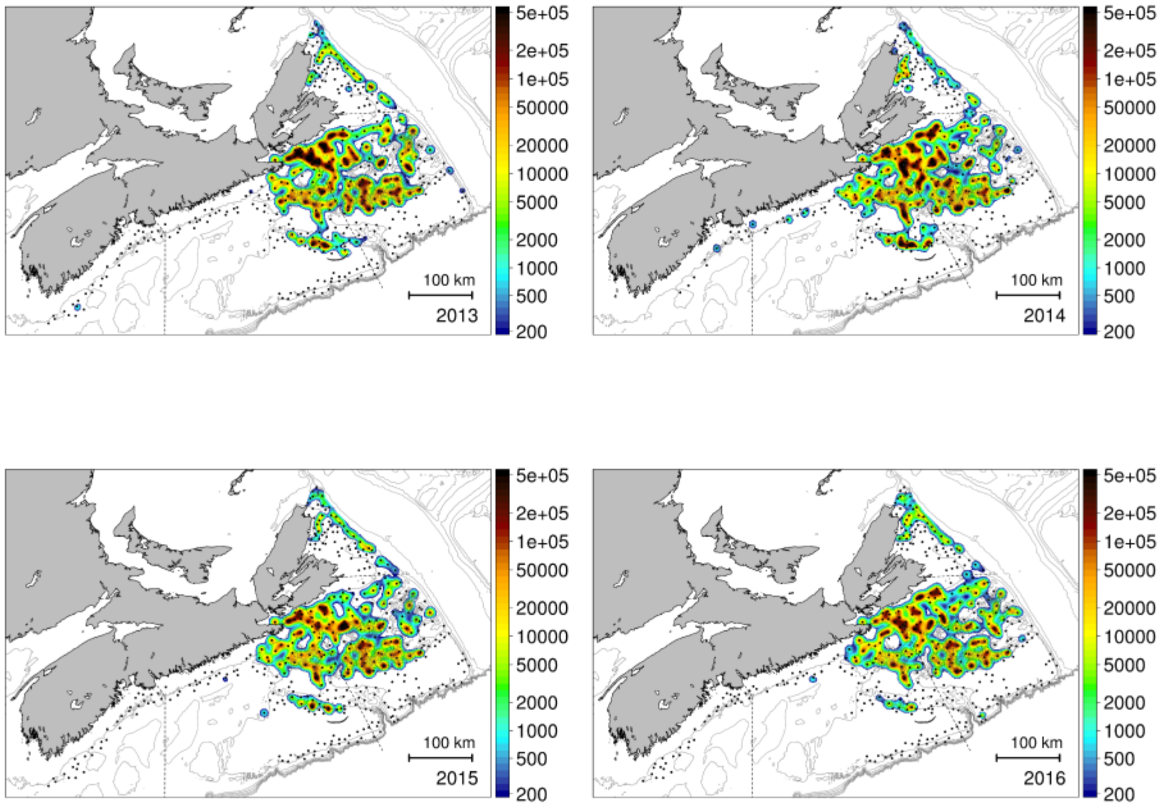

Figure 37. Locations of potential ***prey*** *of Snow Crab on the Scotian Shelf:* ***Northern Shrimp****.*
Scale is $\left(\frac{number}{km^2}\right)$.

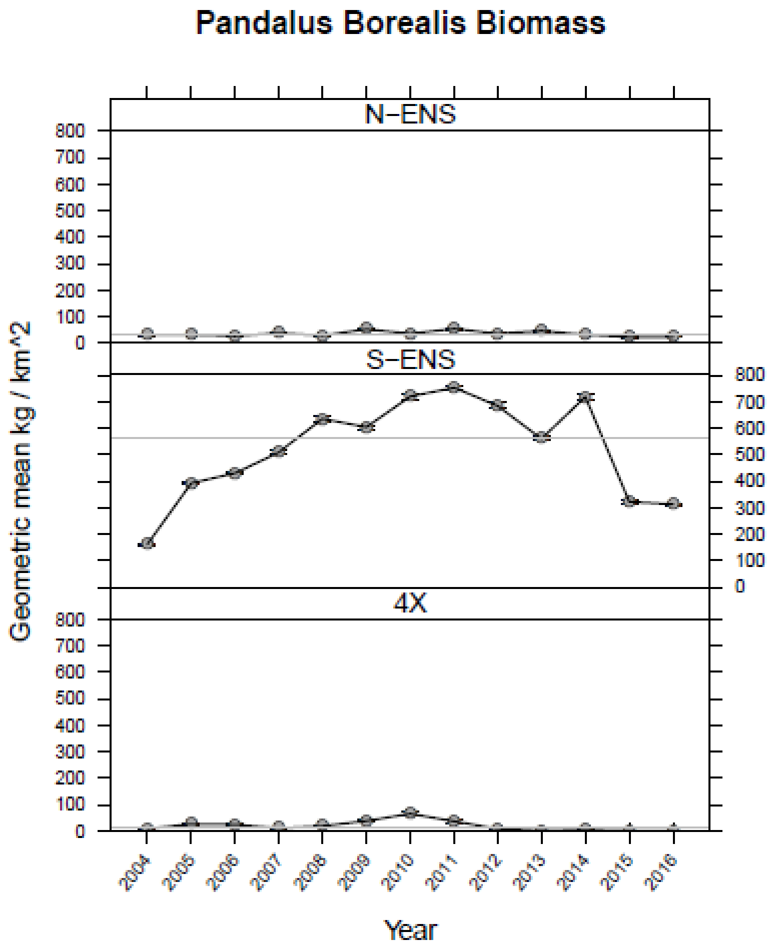

*Figure 38. Trends in biomass $\left(\frac{kg}{km^2}\right)$ from the annual Snow Crab survey for potential **prey** of Snow Crab on the Scotian Shelf: **Northern Shrimp**.*

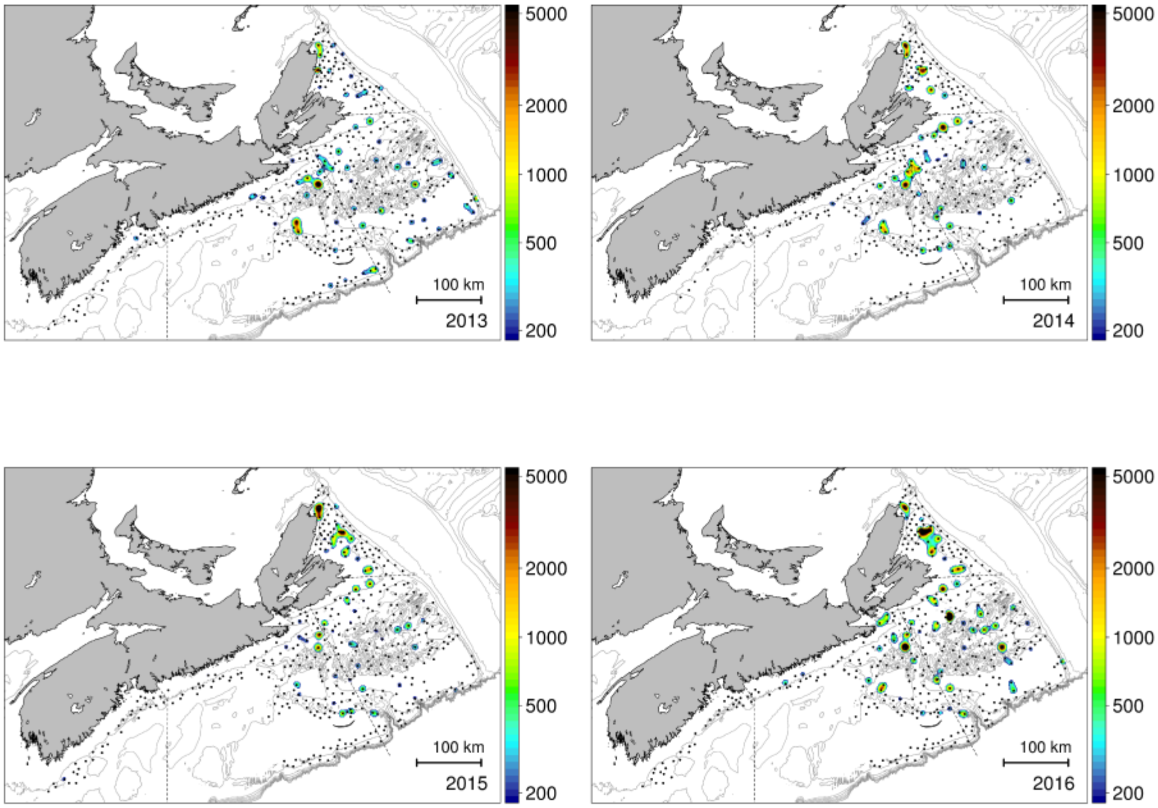

*Figure 39. Locations of potential **competition** of Snow Crab on the Scotian Shelf: **Lesser Toad Crab**. Scale is* $\left(\frac{number}{km^2}\right)$.

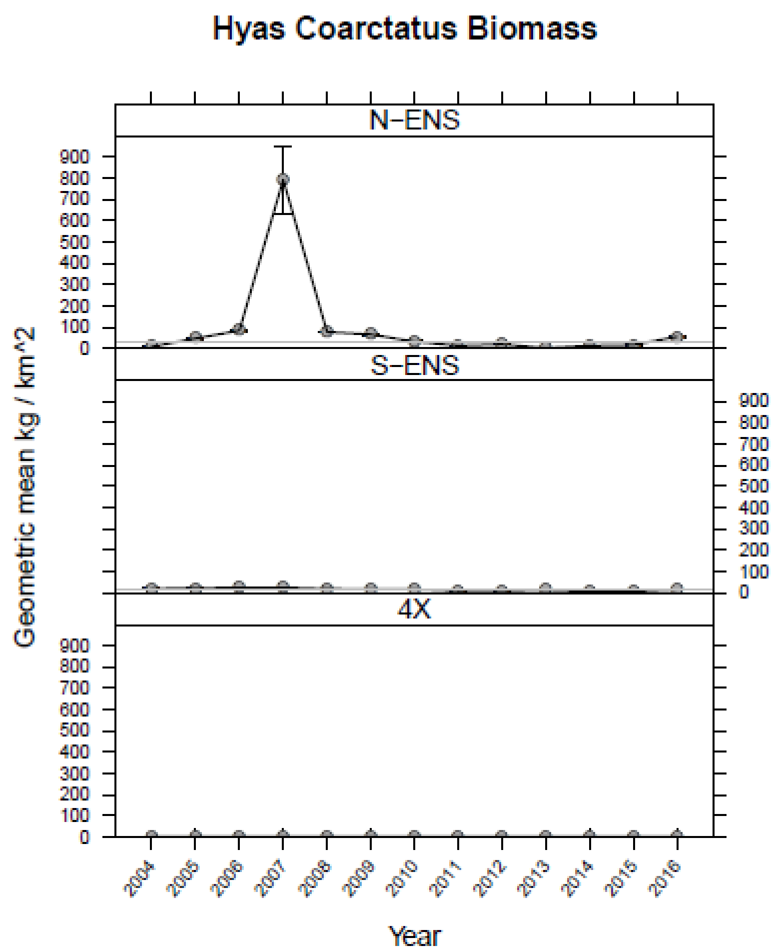

Figure 40. Trends in biomass $\left(\frac{kg}{km^2}\right)$ *from the annual Snow Crab survey for potential **competition** of Snow Crab on the Scotian Shelf: **Lesser Toad Crab**.*

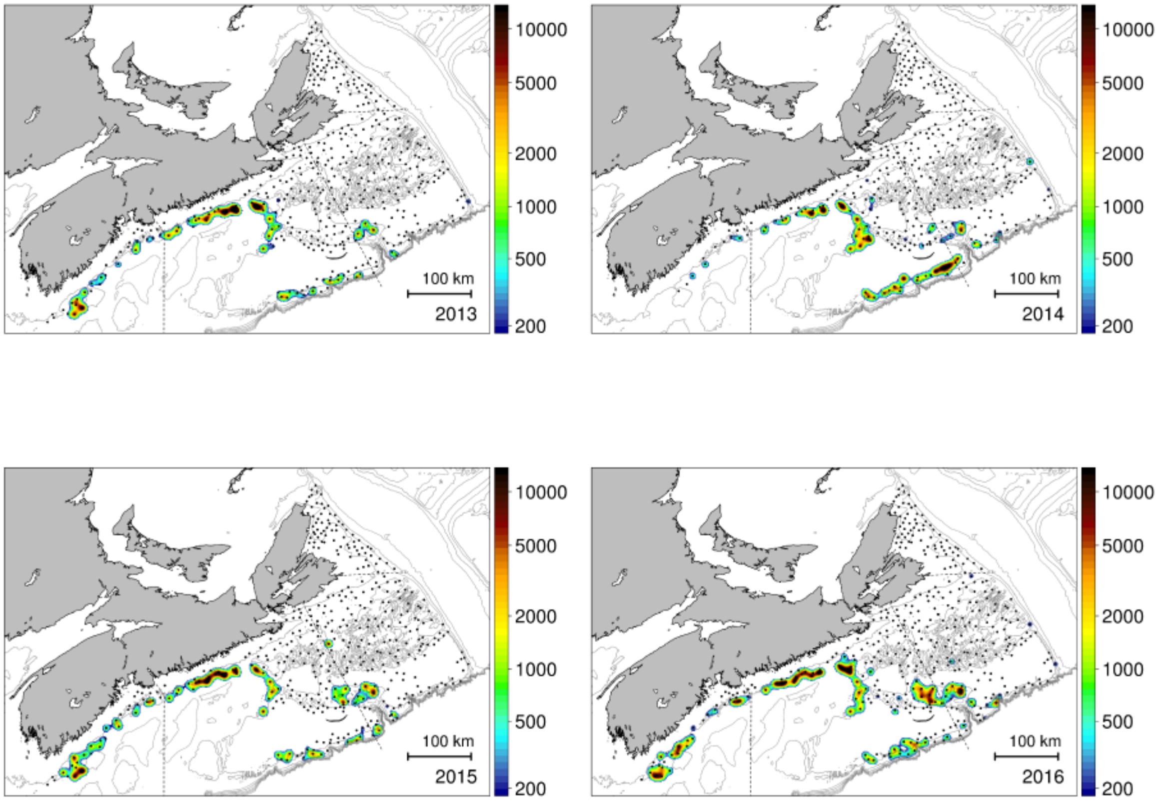

Figure 41. Locations of potential ***competition*** *of Snow Crab on the Scotian Shelf:* ***Jonah Crab****.*
Scale is $\left(\frac{number}{km^2}\right)$.

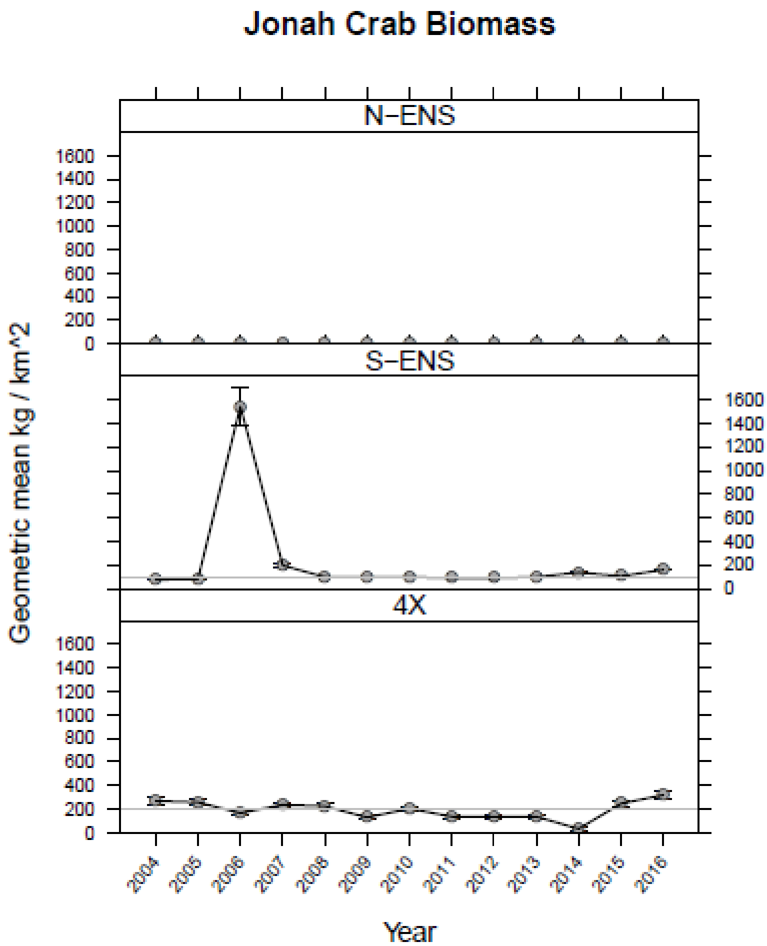

*Figure 42. Trends in biomass $\left(\frac{kg}{km^2}\right)$ from the annual Snow Crab survey for potential **competition** of Snow Crab on the Scotian Shelf: **Jonah Crab**.*

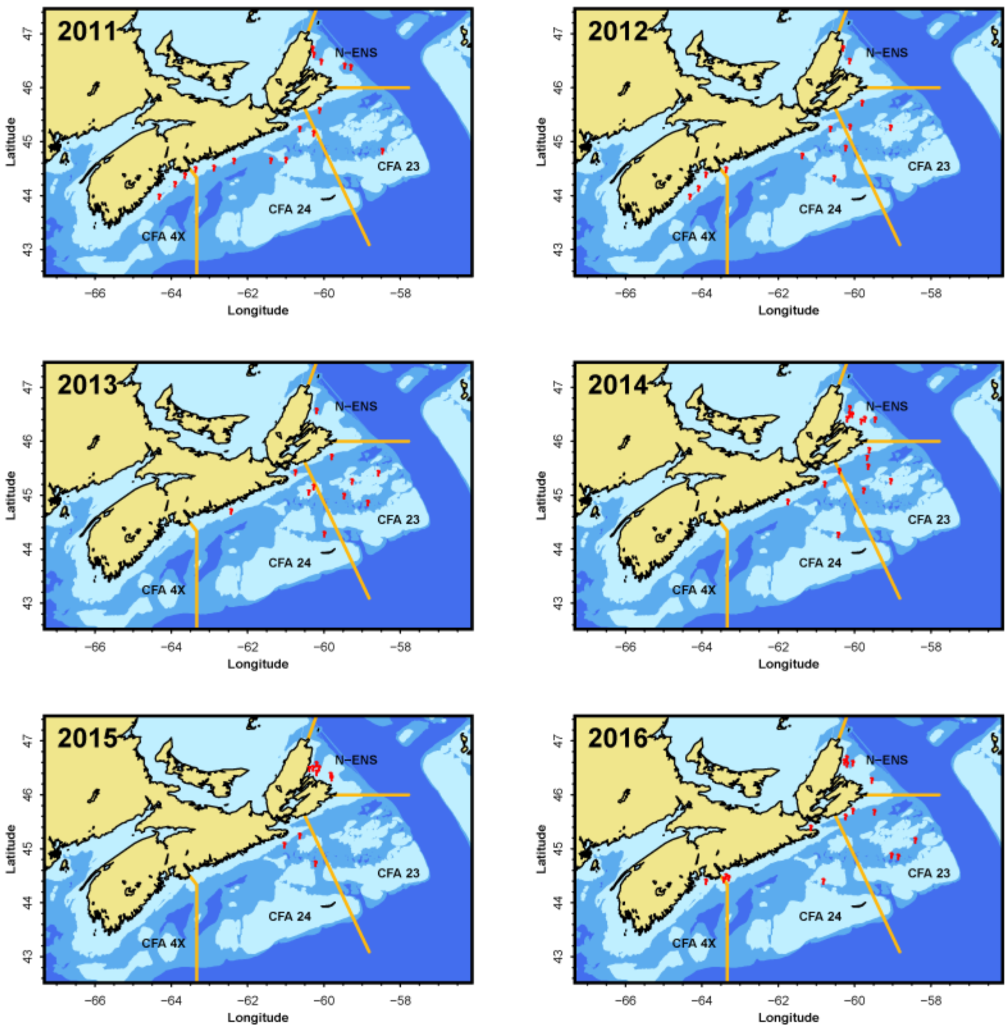

Figure 43. Annual locations of Bitter Crab Disease observations in the Snow Crab travel surveys.

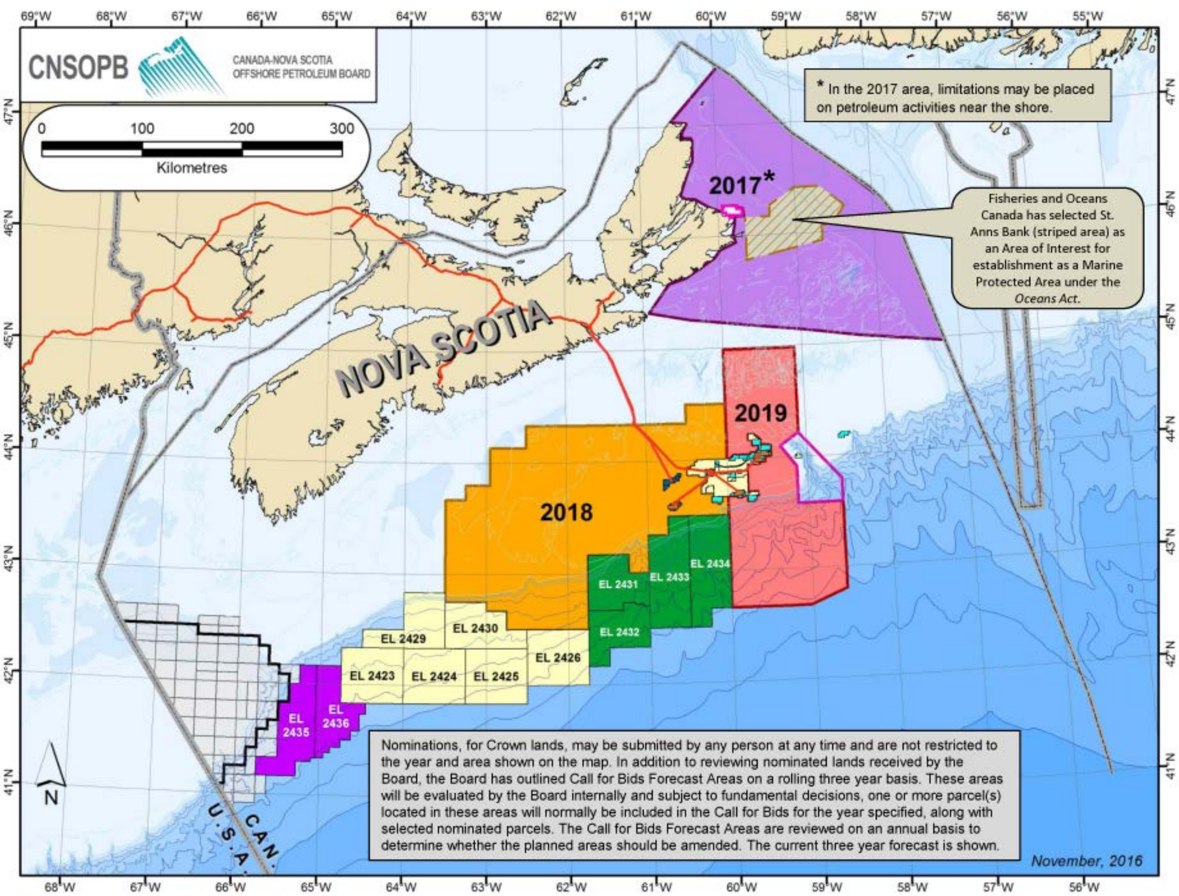

Figure 44. Map of Canadian Nova Scotia Offshore Petroleum Board call for exploration bids for 2017-2019.

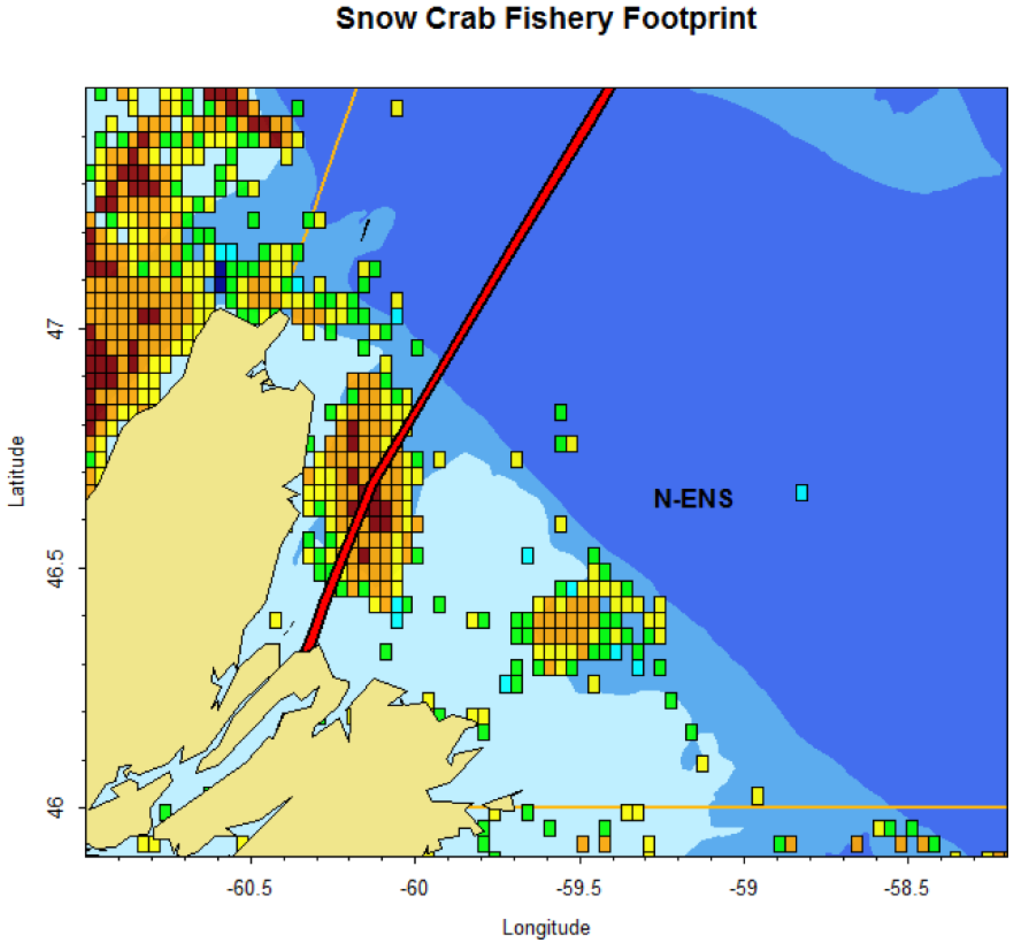

Figure 45. : Fishery footprint map of the N-ENS Snow Crab fishery using landings data from logbook records between 2006 - 2010. Blue is low, yellow is medium and red is high total landings within each 2 minute grid. The red line represents the proposed corridor for placement of two transmission cables.

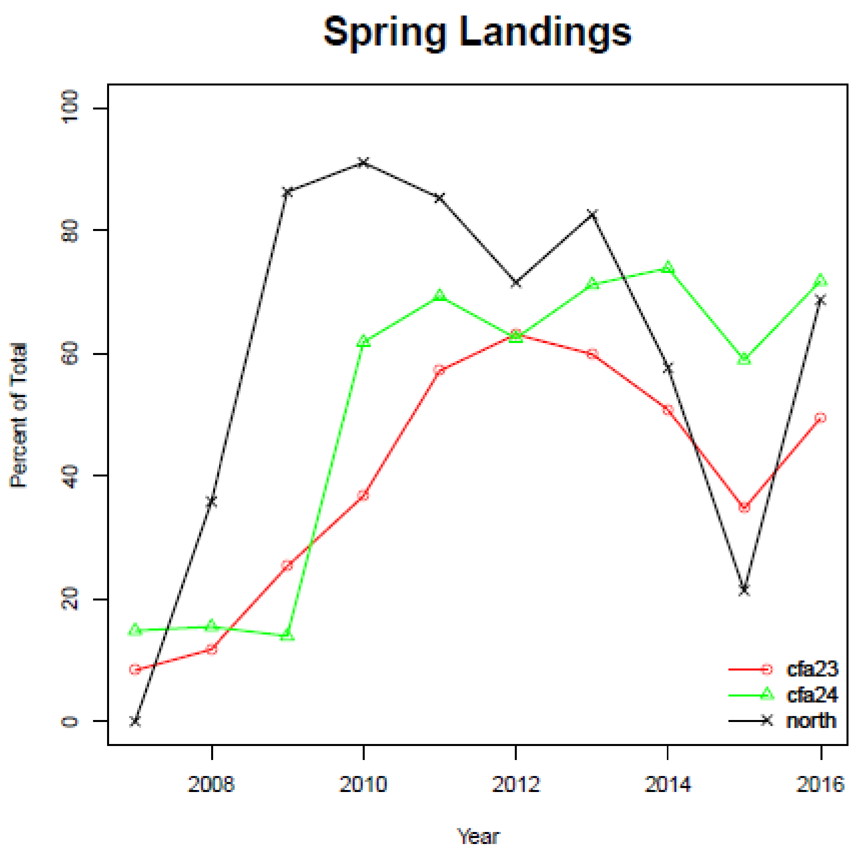

Figure 46. The percent of total annual Snow Crab landings caught during the months of April – June separated by crab fishing area.

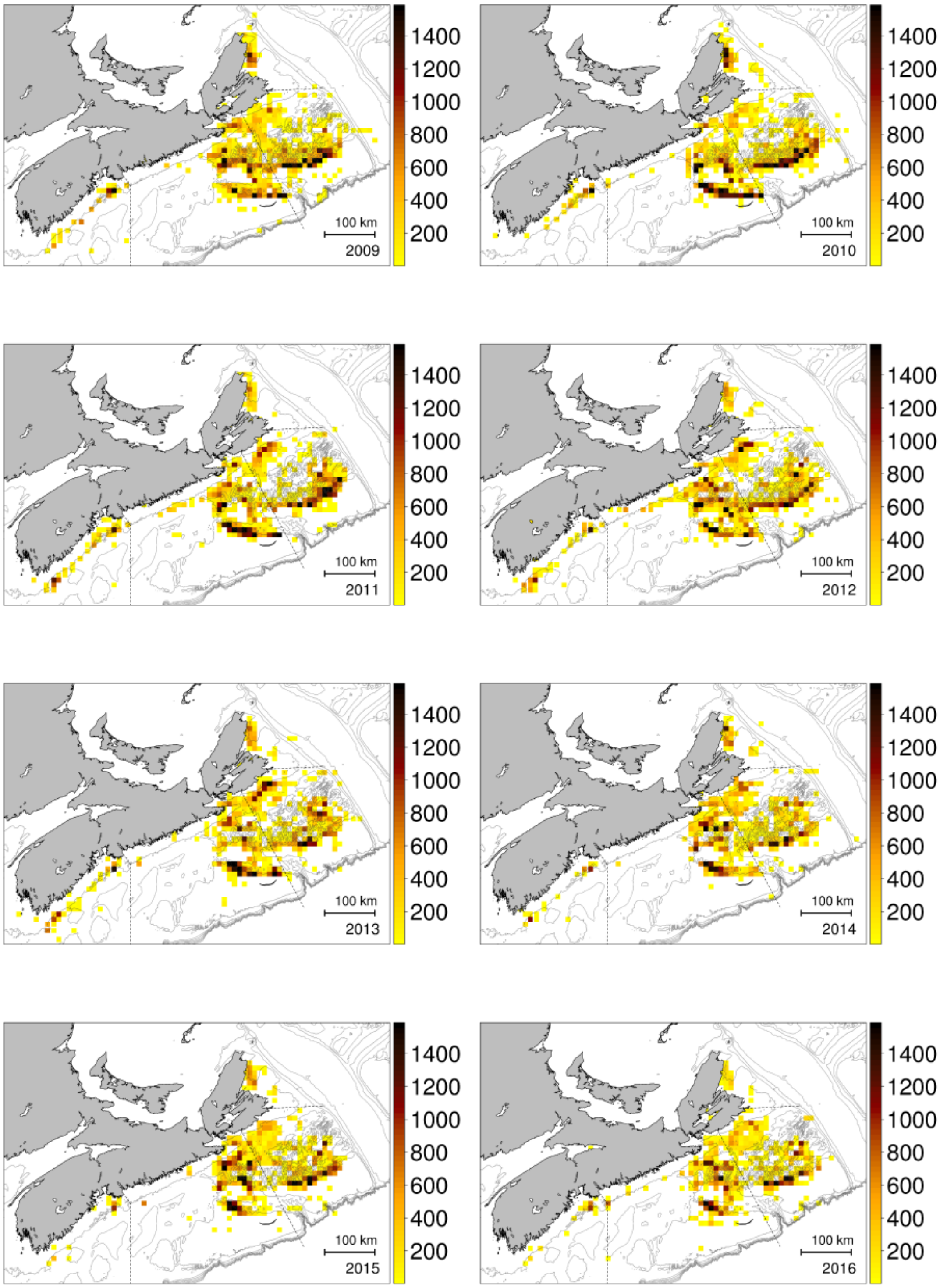

Figure 47. Fishing effort (number of trap hauls/10 km^2 grid) from fisheries logbook data. Note the increase in effort inshore in S-ENS and the almost complete lack of fishing activity in the Glace Bay Hole area (offshore) of N-ENS. For 4X, year refers to the starting year.

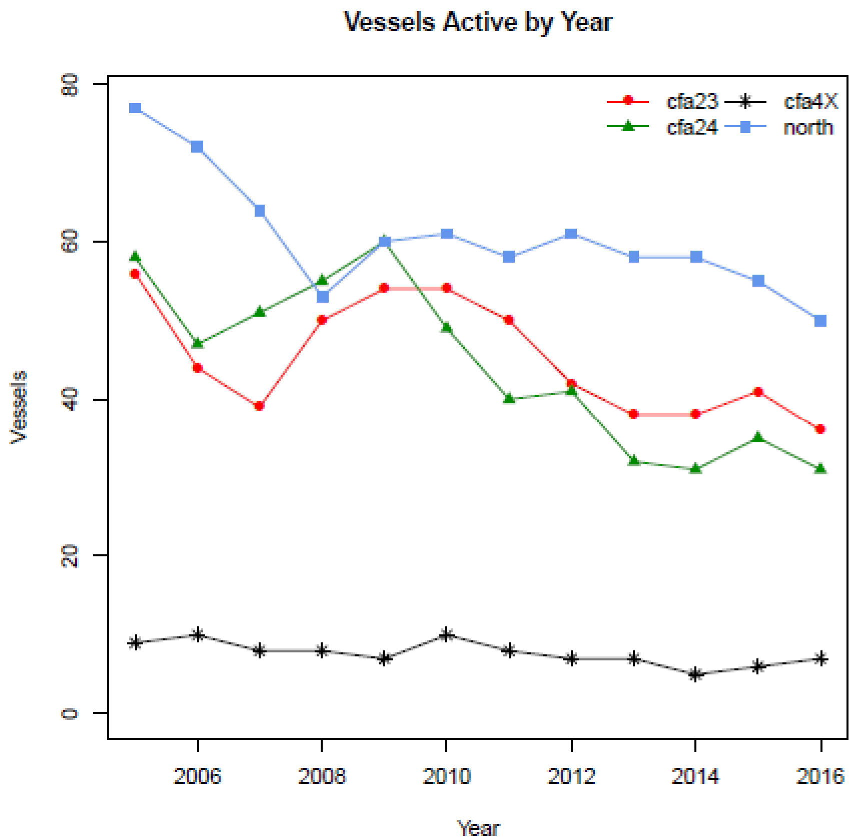

Figure 48. Number of active vessels fishing in each of the SSE Snow Crab fishing areas. South-Eastern Nova Scotia (S-ENS) is separated into CFA23 and CFA24 to maintain consistency with historic information. The number of licences within each area has been stable since 2004.

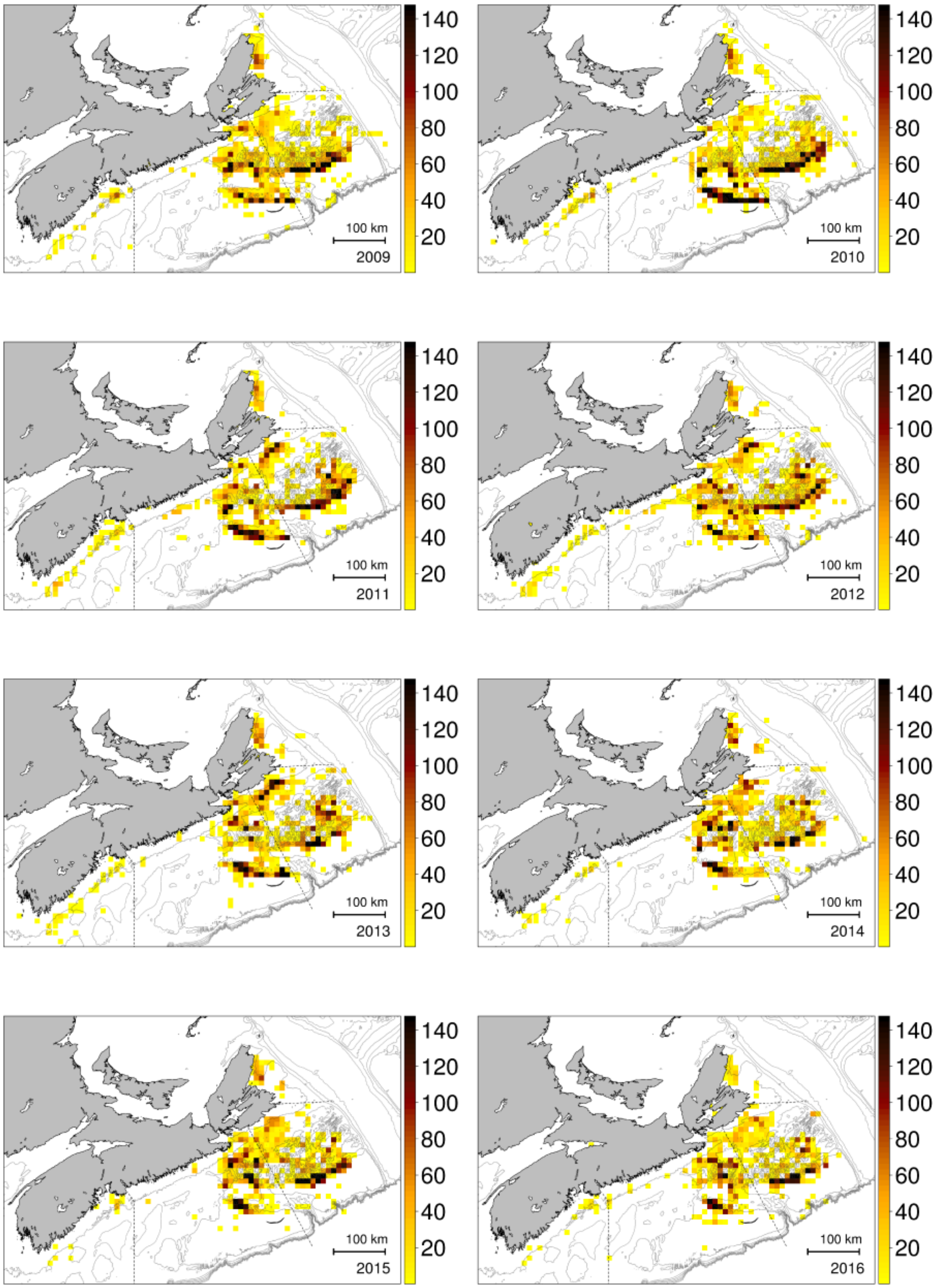

Figure 49. Snow Crab landings (tons/10 km^2 grid) from fisheries logbook data. For 4X, year refers to the starting year.

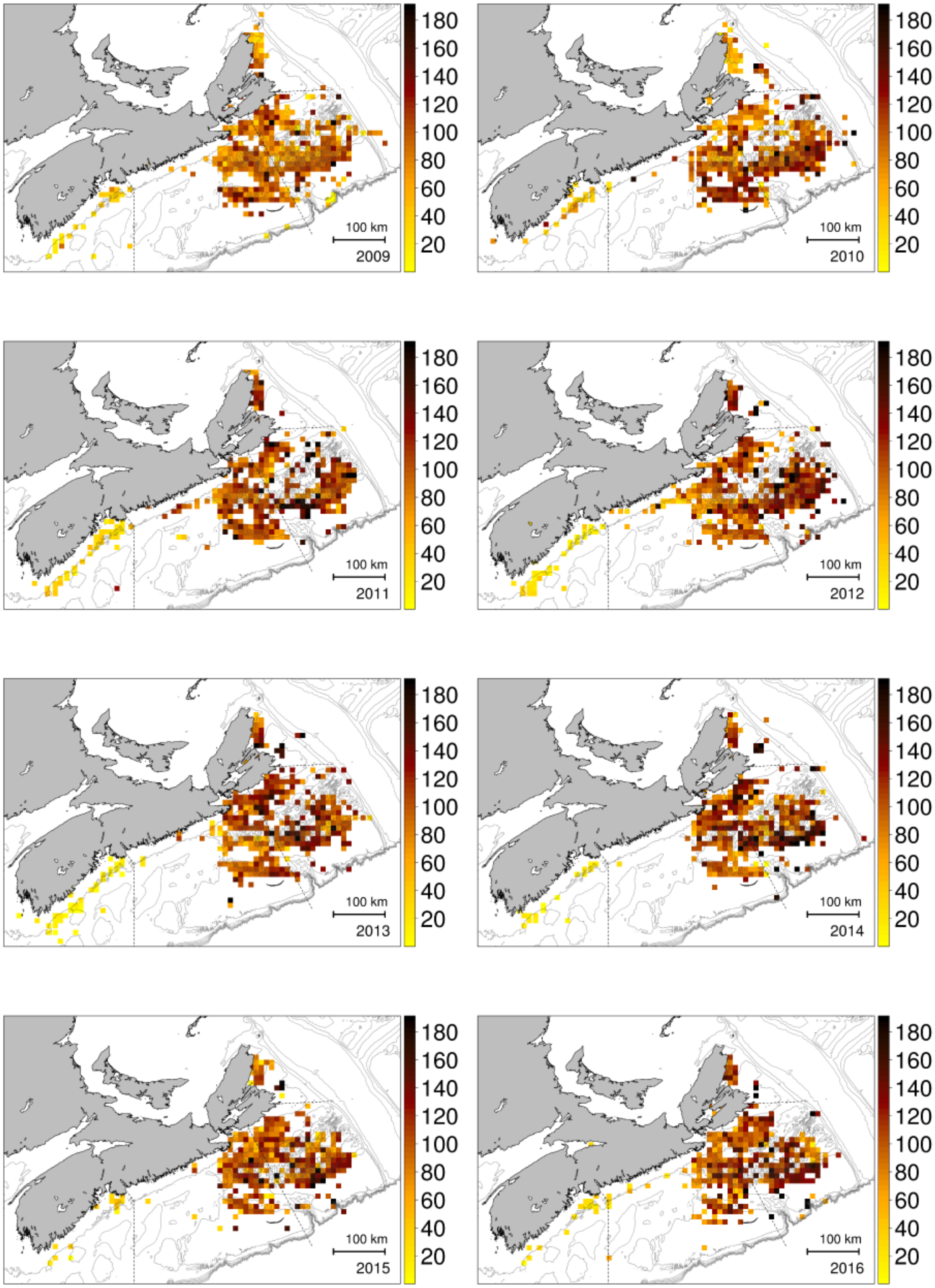

Figure 50. Catch rates (kg/trap) of Snow Crab in each 10 km^2 minute grid from fisheries logbook data. For 4X, year refers to the starting year.

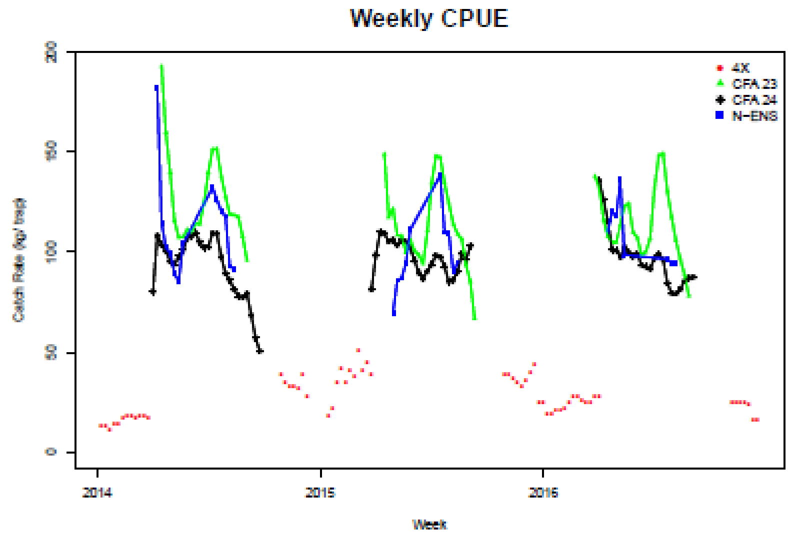

Figure 51. Smoothed catch rates (kg/trap haul) by week for the past three seasons. Split season in N-ENS (spring and summer portions) create the apparent gap in N-ENS data within each year.

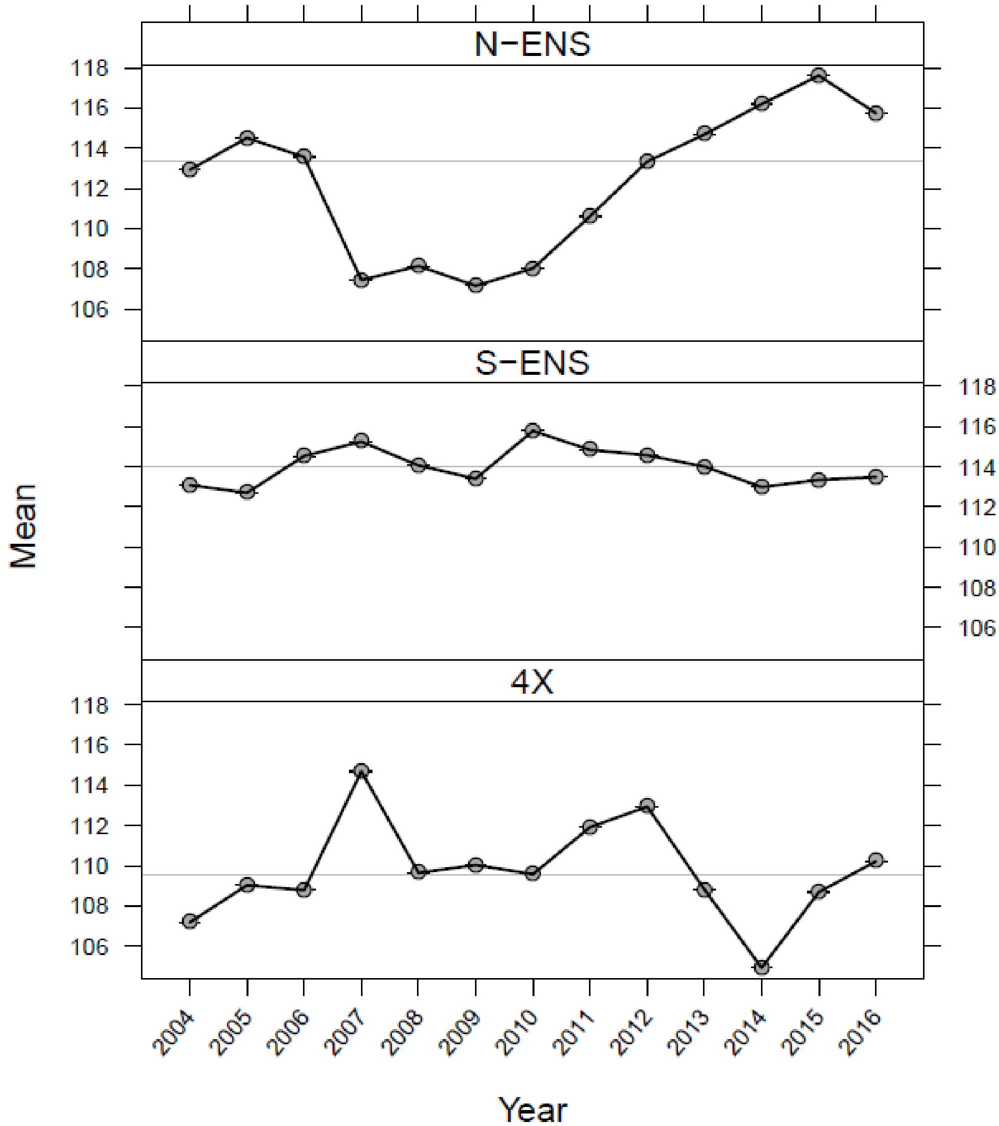

Figure 52. Time series of mean carapace width of commercial crab measured by at-sea observers. For 4X, the year refers to the starting year of the season.

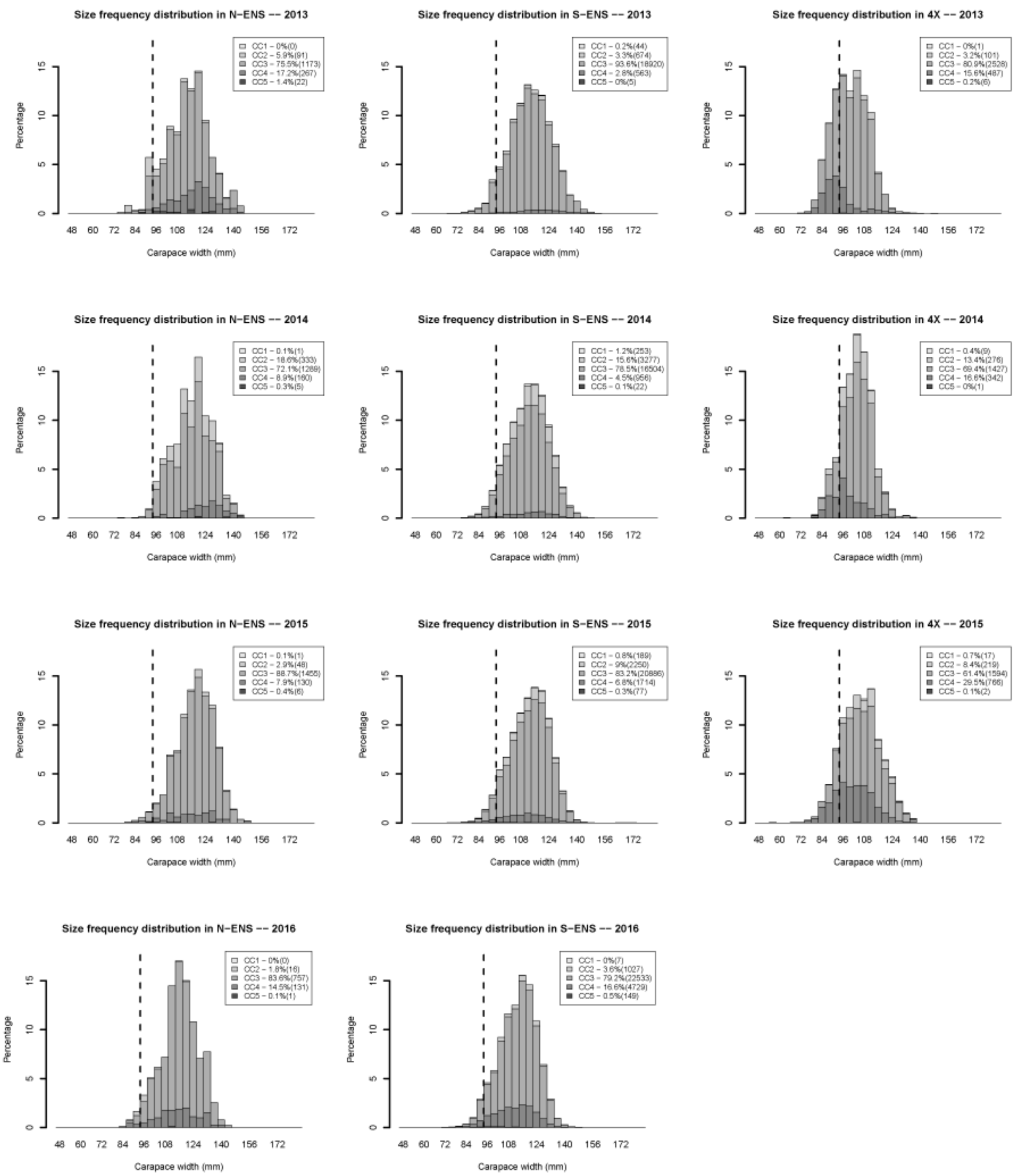

Figure 53. Size frequency distribution of all at-sea observer monitored Snow Crab broken down by carapace condition. For 4X, the year refers to the starting year of the season. Vertical lines indicate 95 mm carapace width.

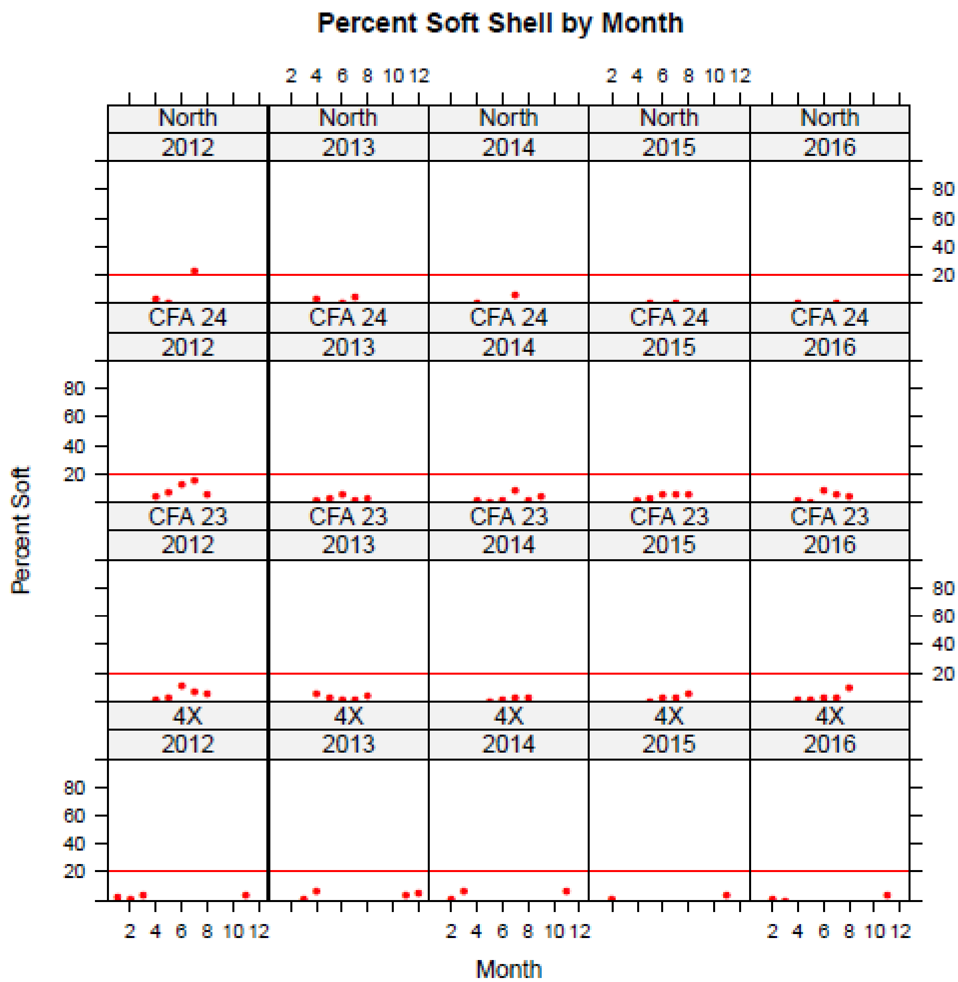

Figure 54. The percent of sampled Snow Crab in the soft shelled state (¡68 durometer) as determined by at-sea observers from commercial Snow Crab traps.

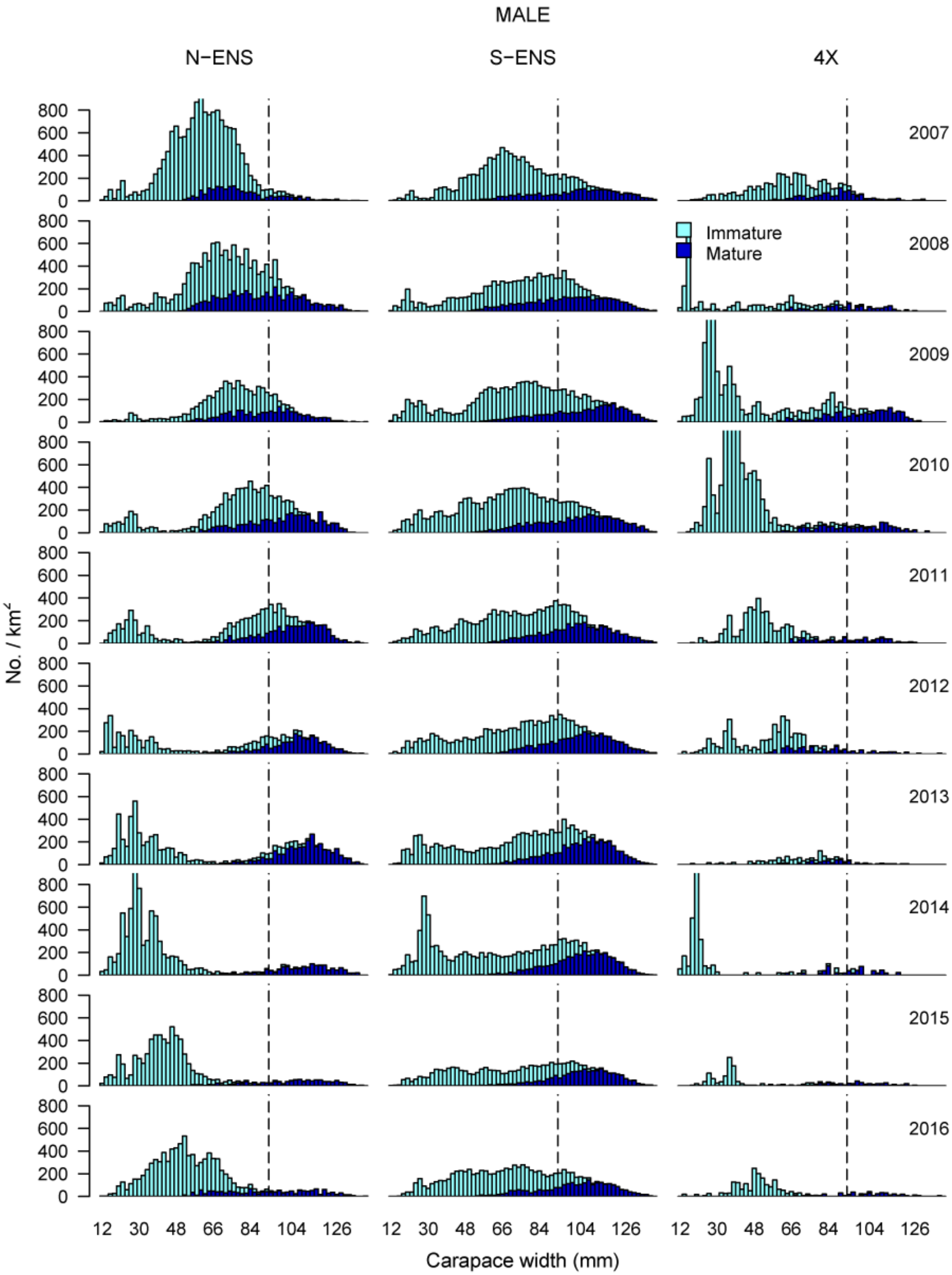

Figure 55. Size-frequency histograms of carapace width of male Snow Crabs obtained from the Snow Crab survey.

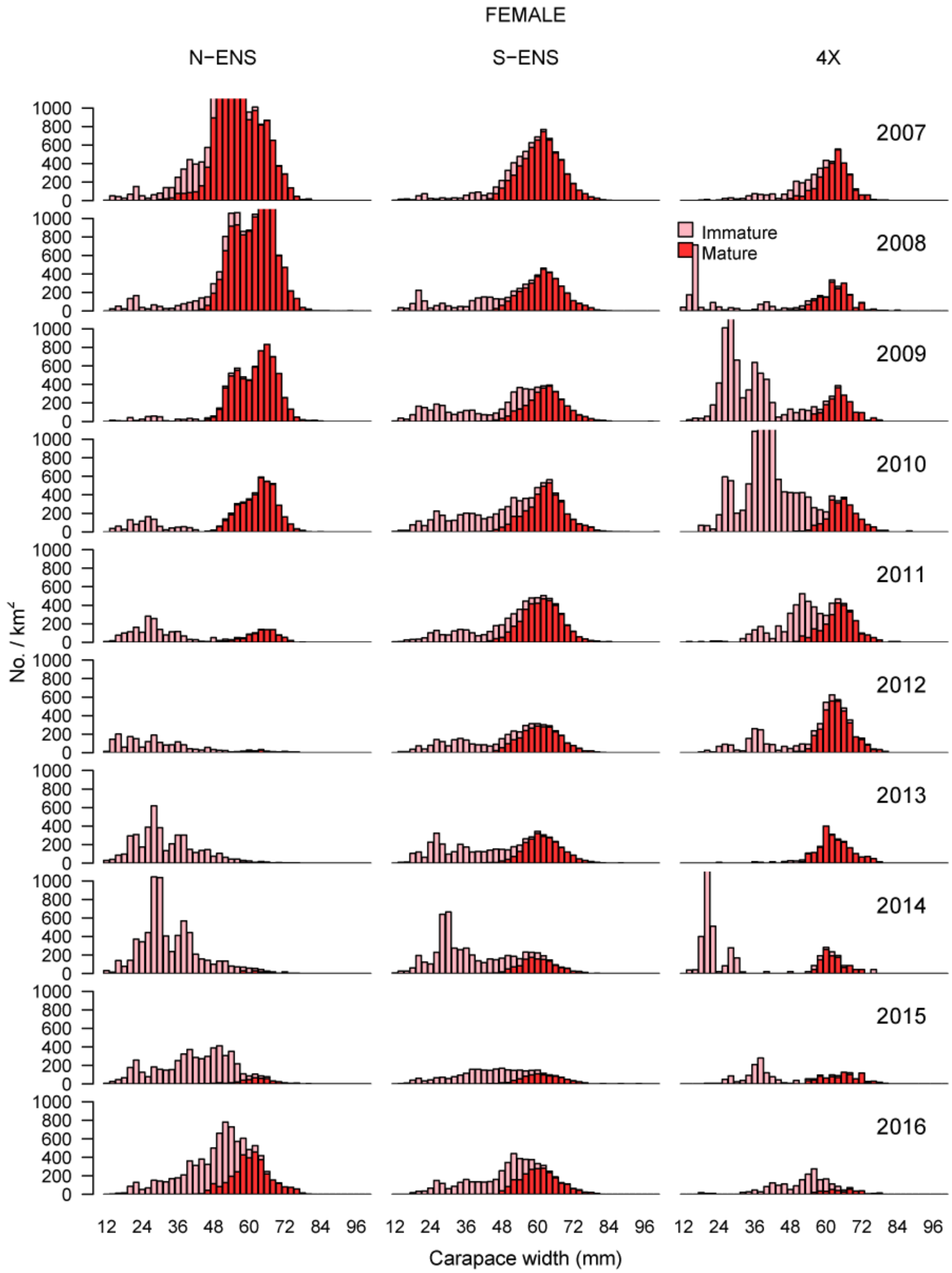

Figure 56. Size-frequency histograms of carapace width of female Snow Crab obtained from the Snow Crab fishery.

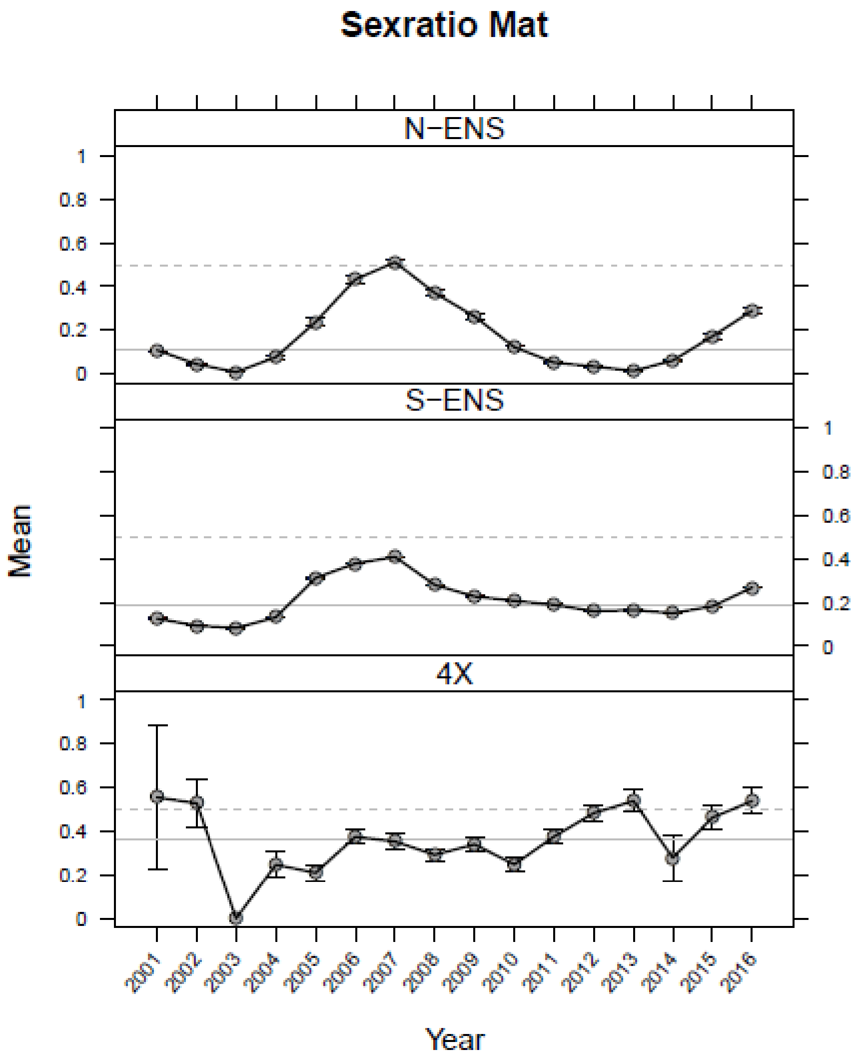

Figure 57. Annual sex ratios (proportion female) of mature Snow Crab observed in the survey. Since 2001, most of the Scotian Shelf was uniformly male dominated. One standard error bar is presented.

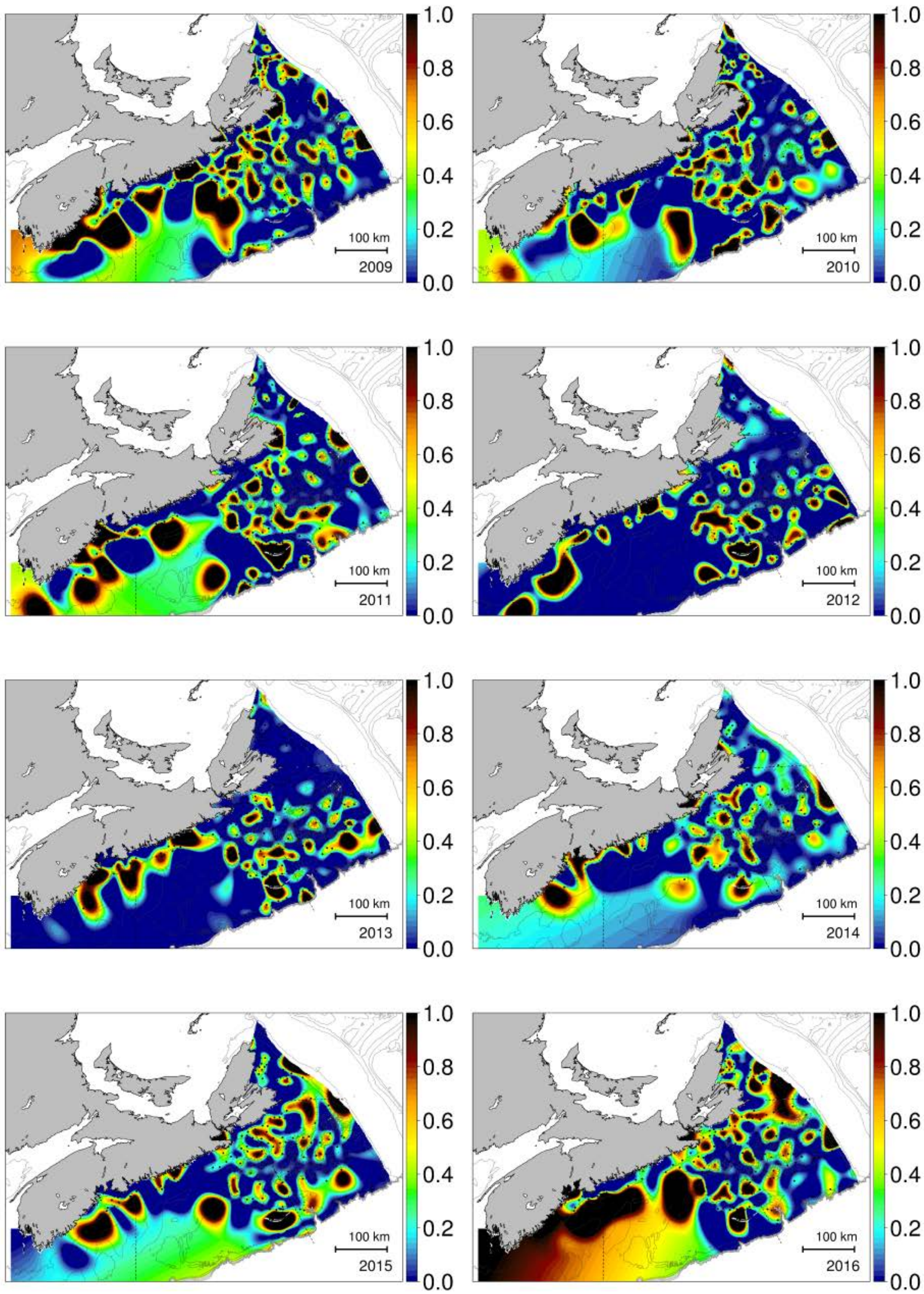

Figure 58. Morphometrically mature sex ratios (proportion of females in the mature fraction of the total numbers) of Snow Crabs on the Scotian Shelf with spatial representations generated using thin plate spline interpolations of data from the annual Snow Crab survey.

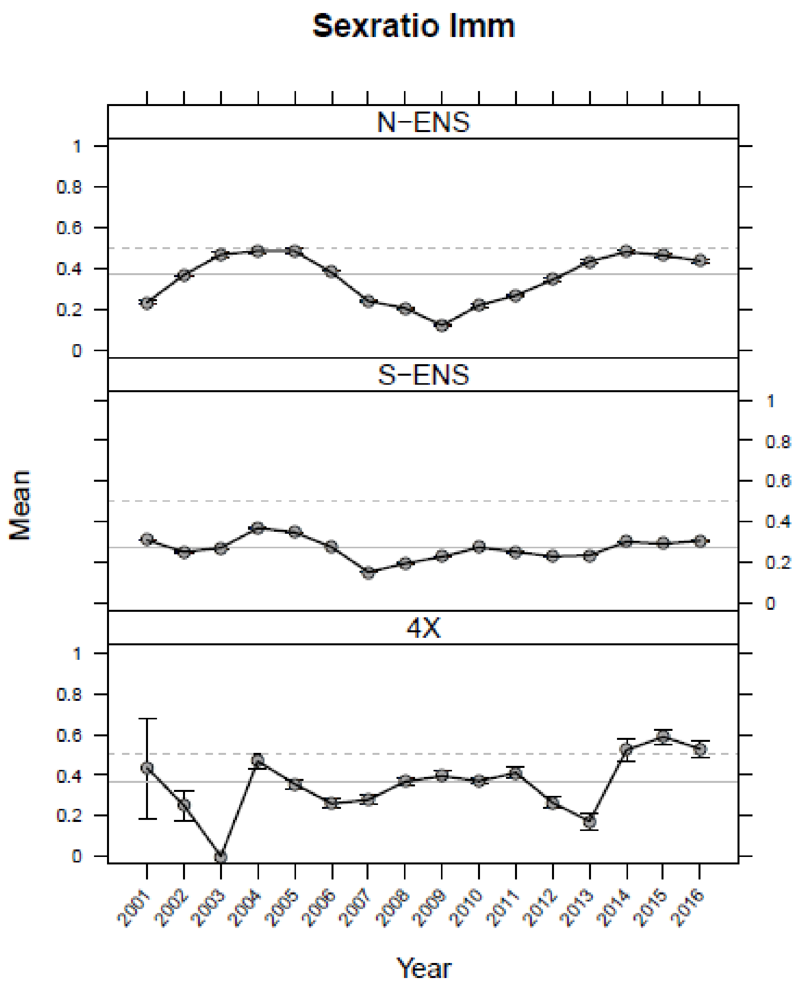

Figure 59. Annual sex ratios (proportion female) of immature Snow Crab on the Scotian Shelf.

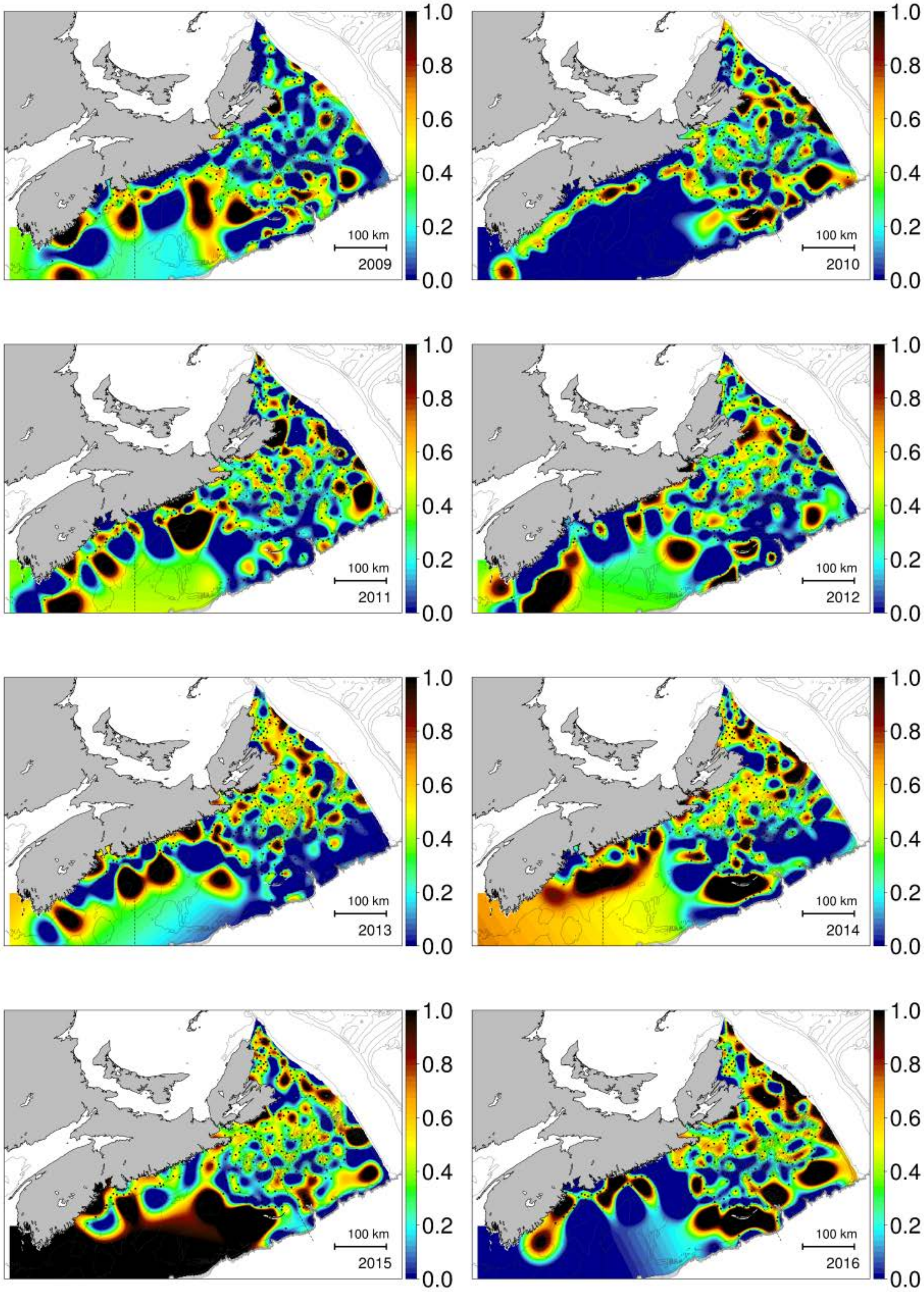

Figure 60. Morphometrically immature sex ratios (proportion of females in the mature fraction of the total numbers) of Snow Crabs on the Scotian Shelf with spatial representations generated using thin plate spline interpolations of data from the annual Snow Crab survey.

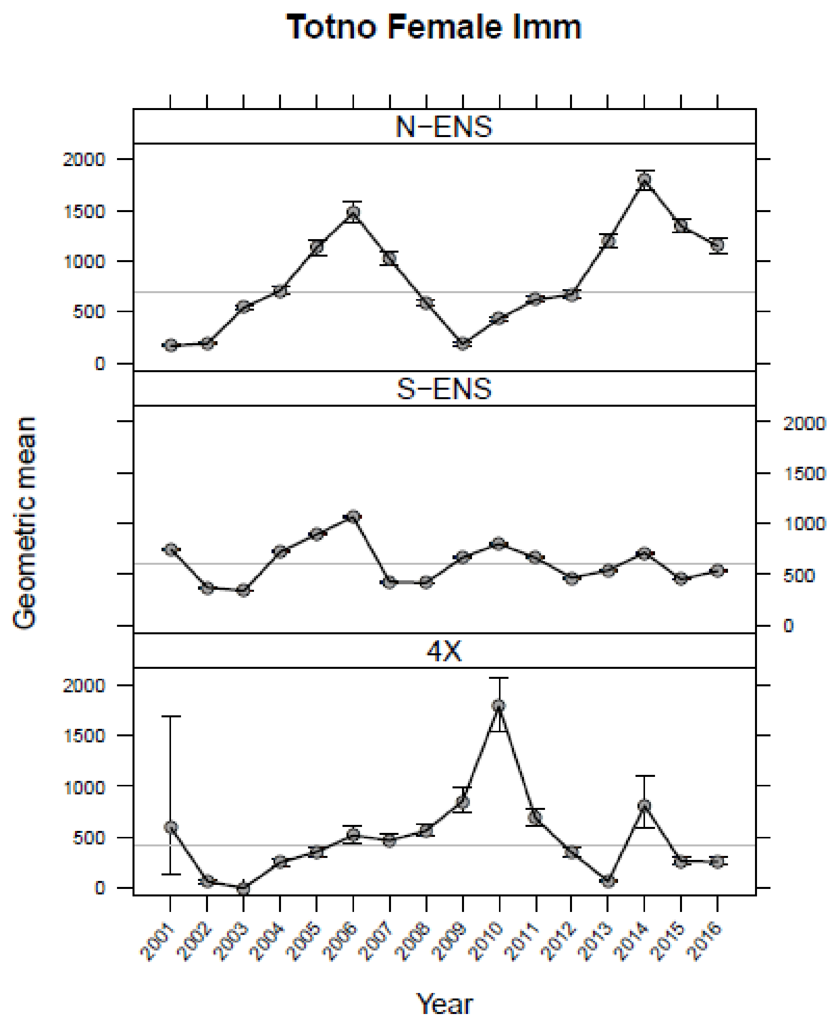

Figure 61. Numeric density of immature females in the SSE.

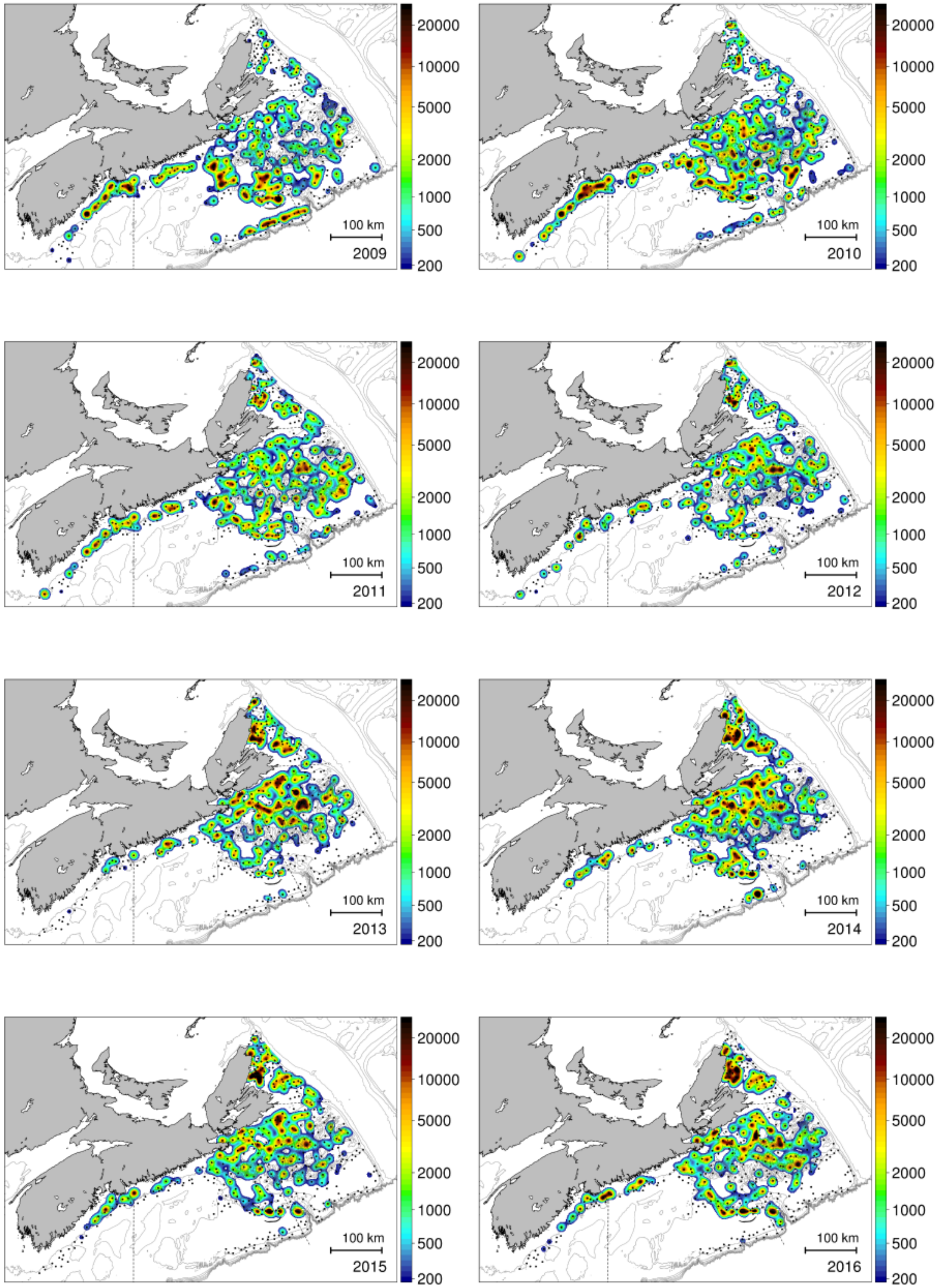

Figure 62. Numerical densities $\left(\frac{number}{km^2}\right)$ of the immature female Snow Crabs on the Scotian Shelf with spatial representation generated using thin plate spline interpolations of data from the annual Snow Crab survey.

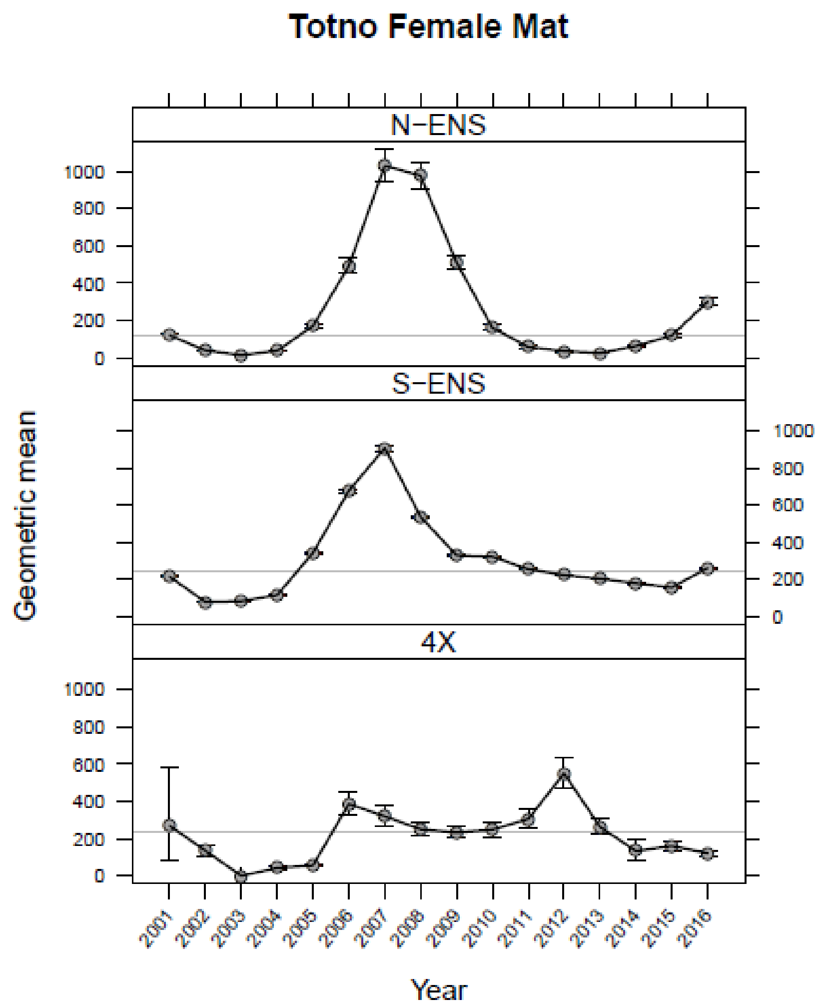

Figure 63. Numeric density of mature females from the annual Snow Crab survey.

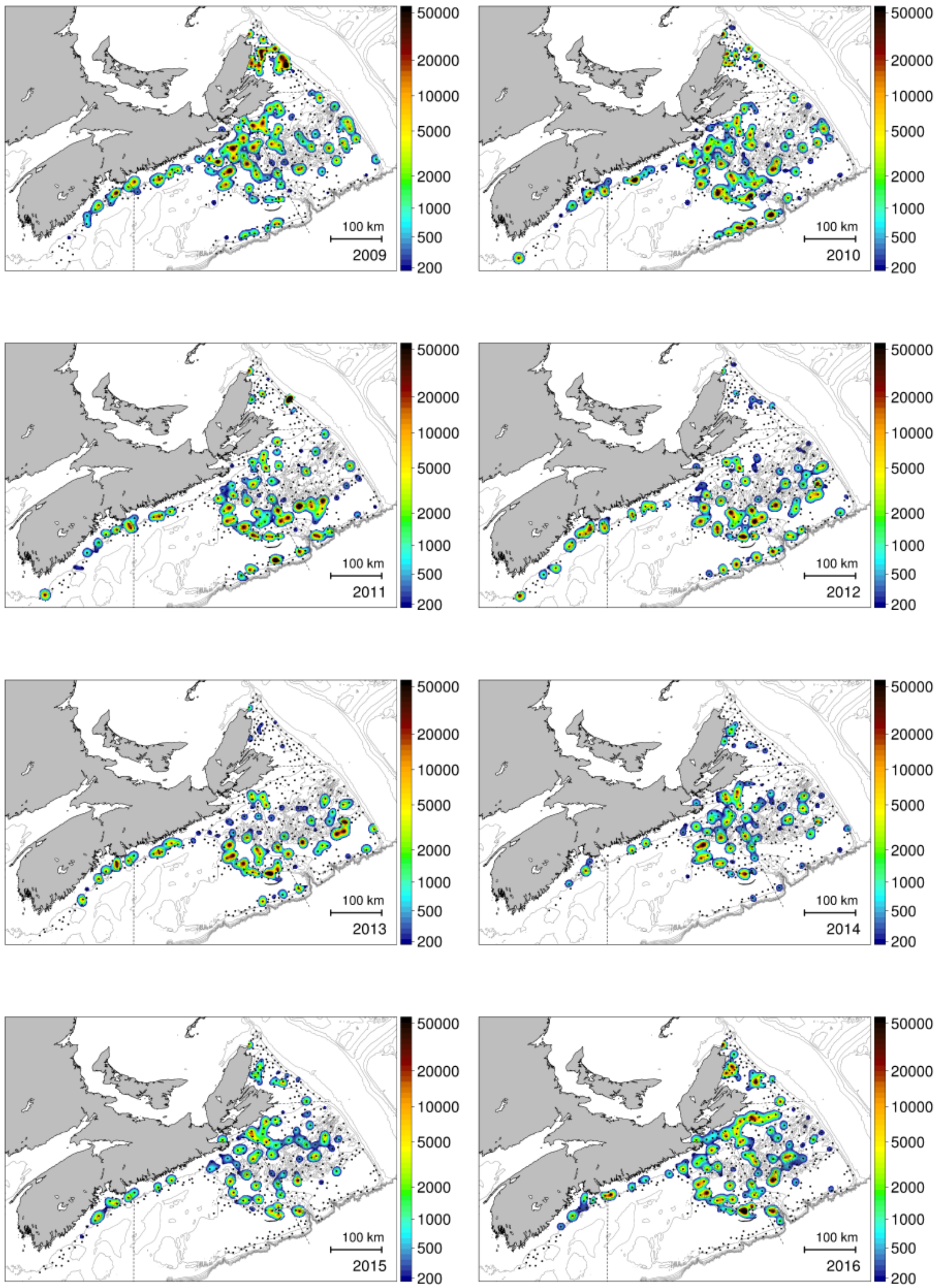

Figure 64. Numerical densities $\left(\frac{number}{km^2}\right)$ of the mature female Snow Crabs on the Scotian Shelf with spatial representation generated using thin plat spline interpolations of data from the annual Snow Crab survey.

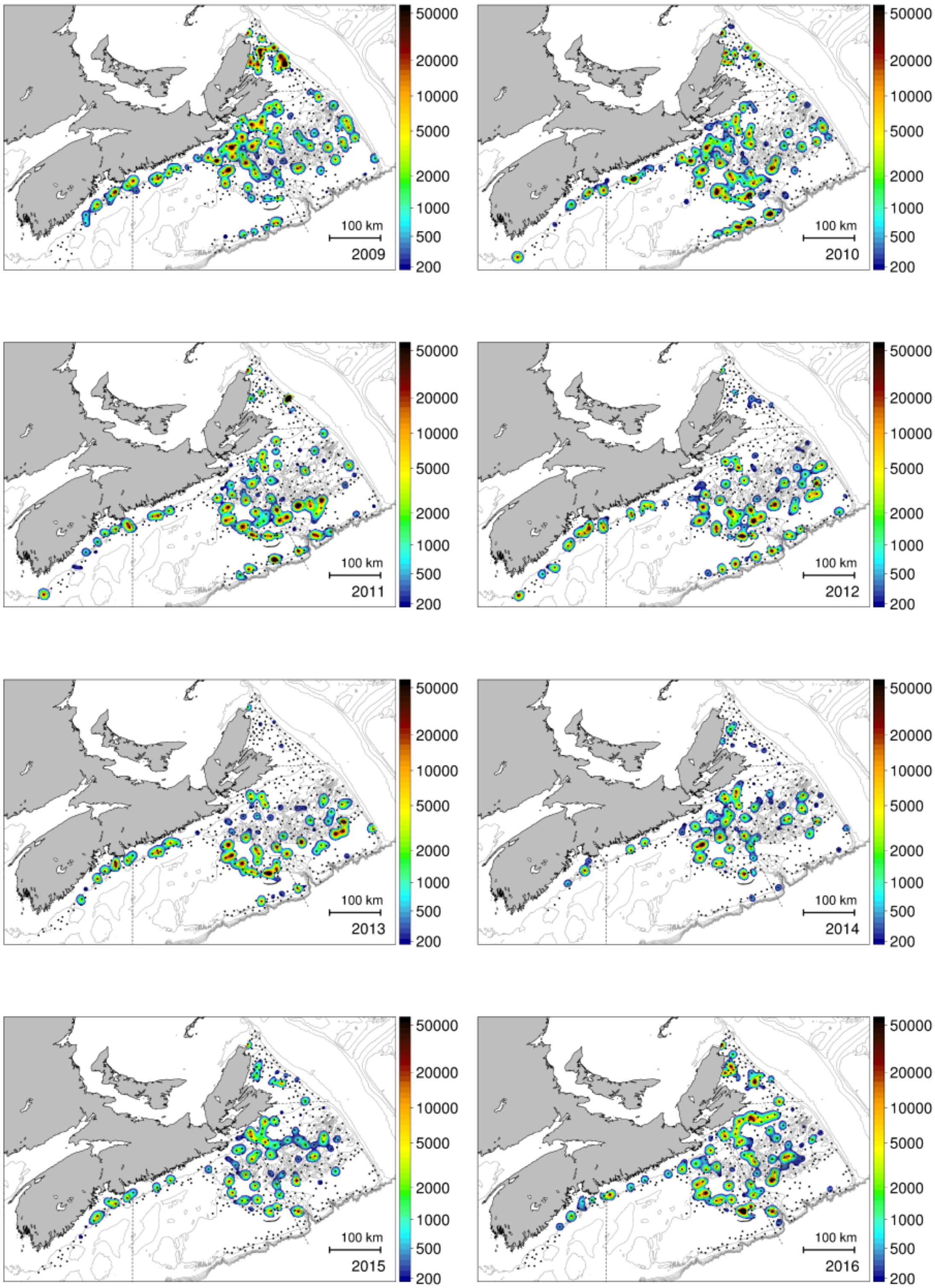

Figure 65. Numerical densities $\left(\frac{number}{km^2}\right)$ *of the berried female Snow Crabs on the Scotian Shelf with spatial representation generated using thin plate spline interpolations of data from the annual Snow Crab survey.*

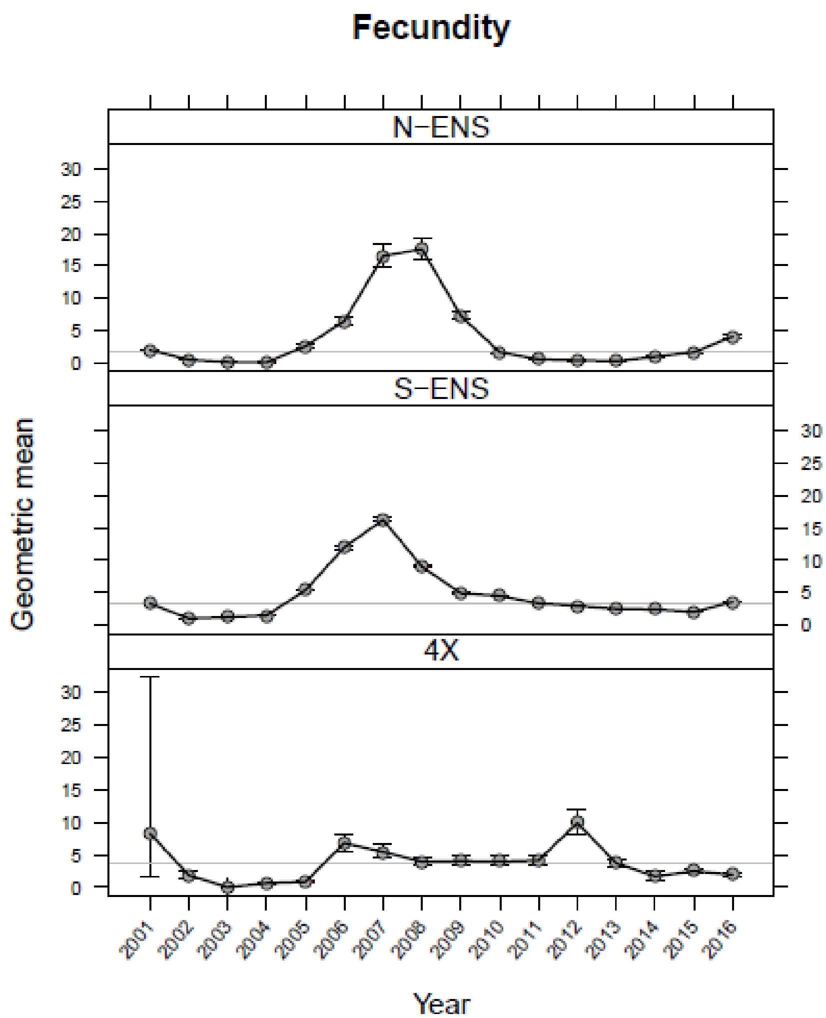

Figure 66. Index of egg production in the SSE, determined from the number of berried females and fecundity at weight estimates.

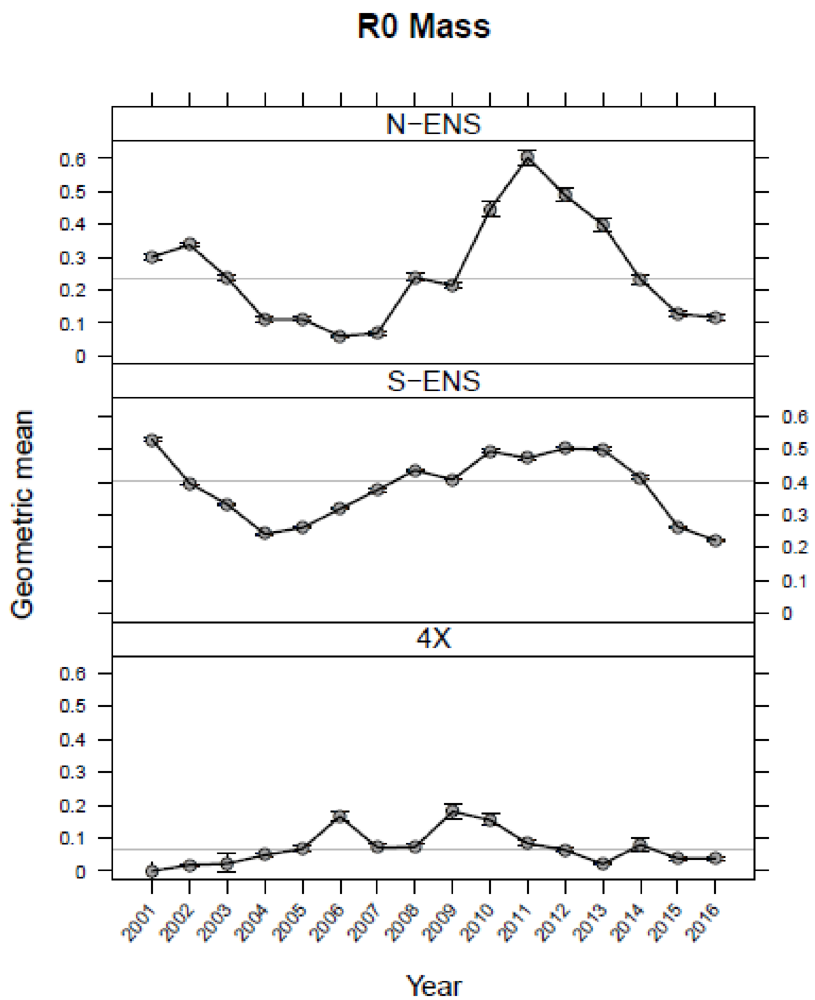

Figure 67. Trends in the geometric mean of fishable biomass obtained from the annual Snow Crab survey. Error bars are 95% CI about geometric mean.

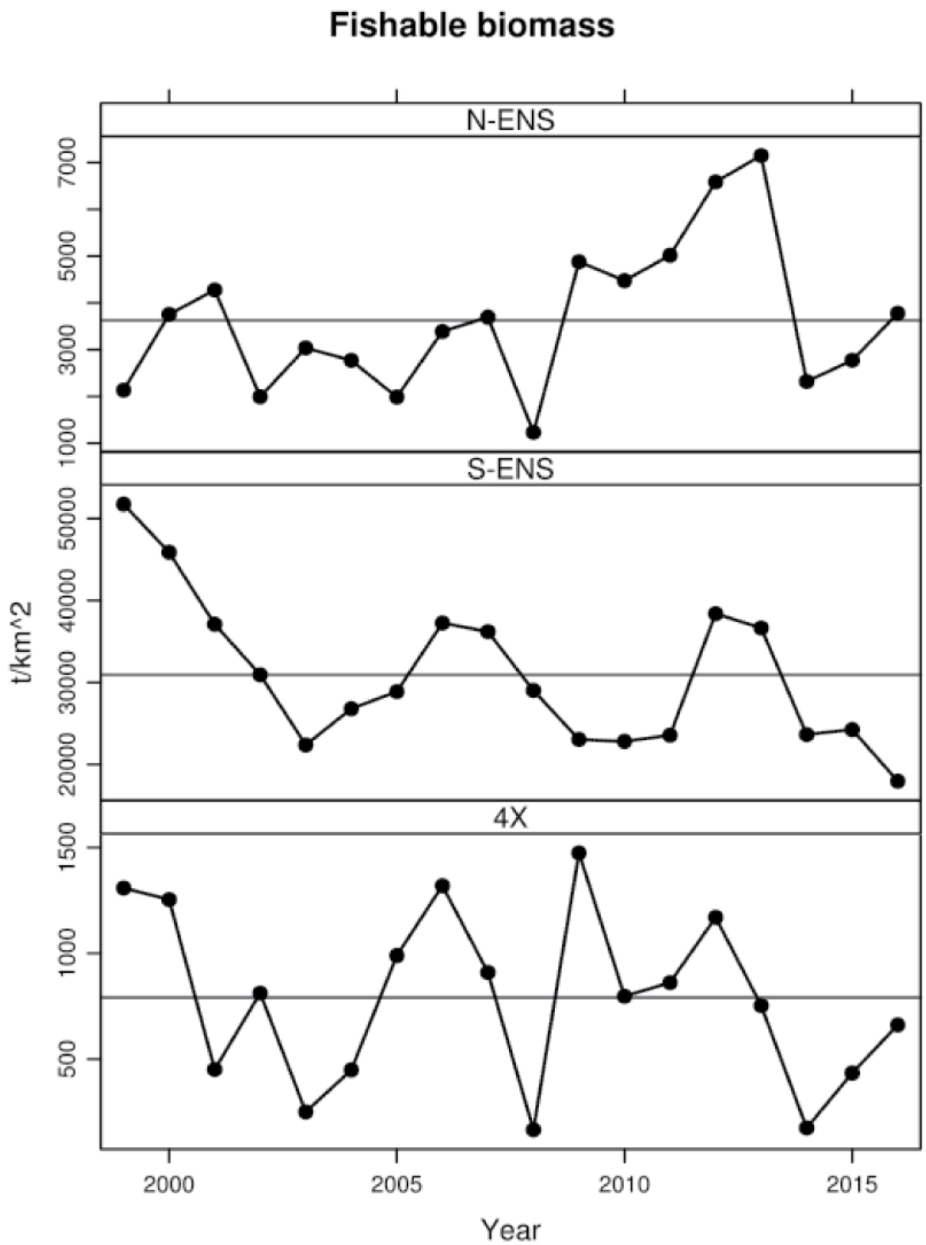

Figure 68. Trends in the area expanded geometric mean fishable biomass $\left(\frac{t}{km^2}\right)$ *obtained from the annual Snow Crab survey. Error bars are 95% CI about geometric mean. Area estimates are obtained from the GAM habitat model.*

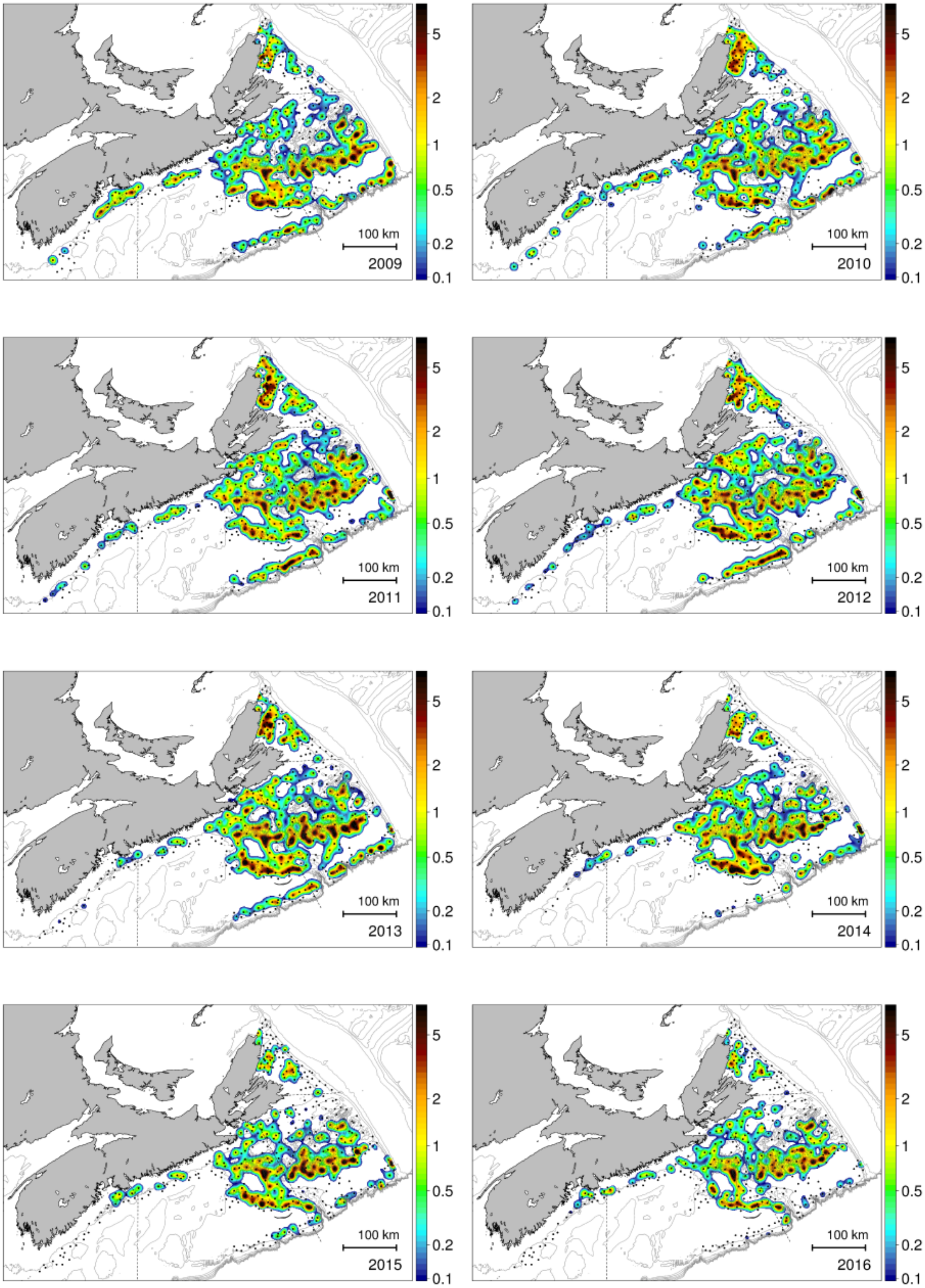

Figure 69. Fishable biomass densities $\left(\frac{t}{km^2}\right)$ on the SSE with spatial representation generated using thin plate spline interpolations of data from the annual Snow Crab survey.

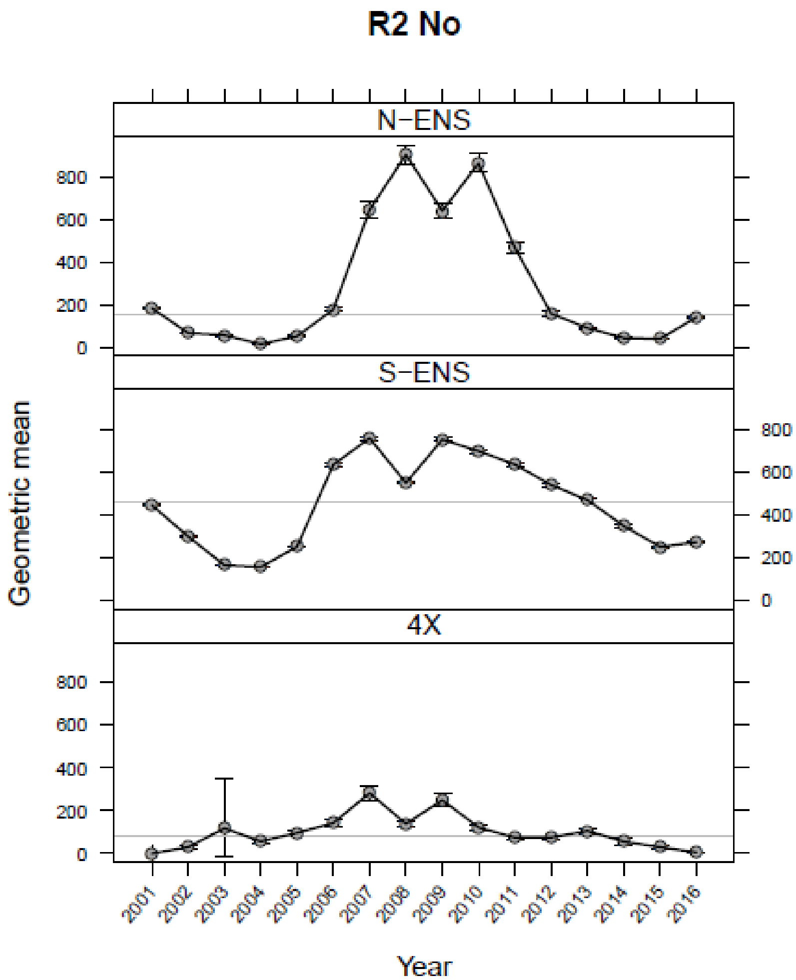

Figure 70. Trends in the geometric mean abundance of male Snow Crab (75-95 mm CWS) obtained from the annual Snow Crab survey. Error bars are 95% CI about geometric mean.

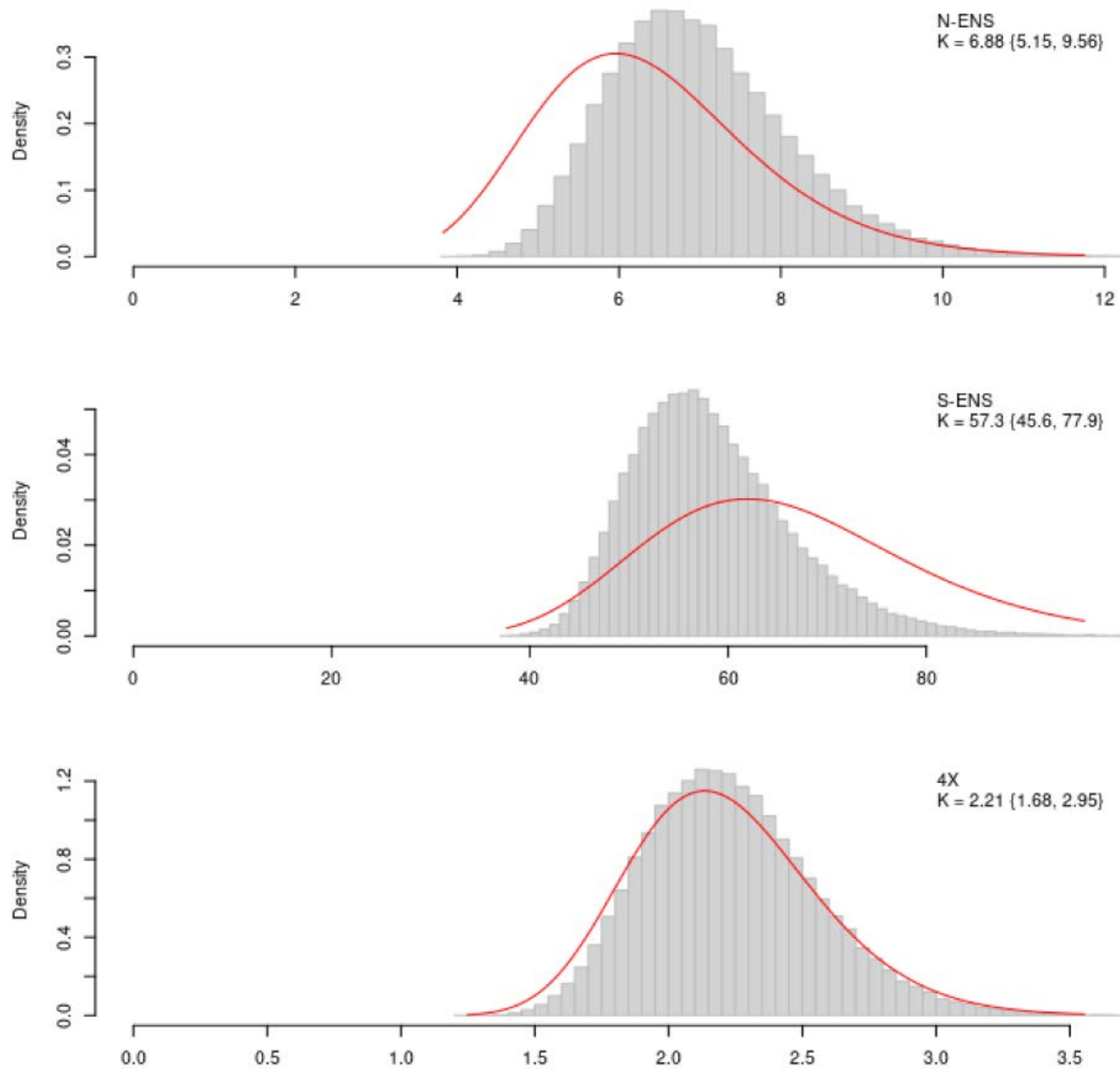

Figure 71. Prior (red line) and posterior (grey bars) distribution for carrying capacity parameter, K, from the biomass dynamic model of Snow Crab production in crab fishing areas on the Scotian Shelf. Within each panel, estimates of posterior median and 95% credible intervals are given in the legend.

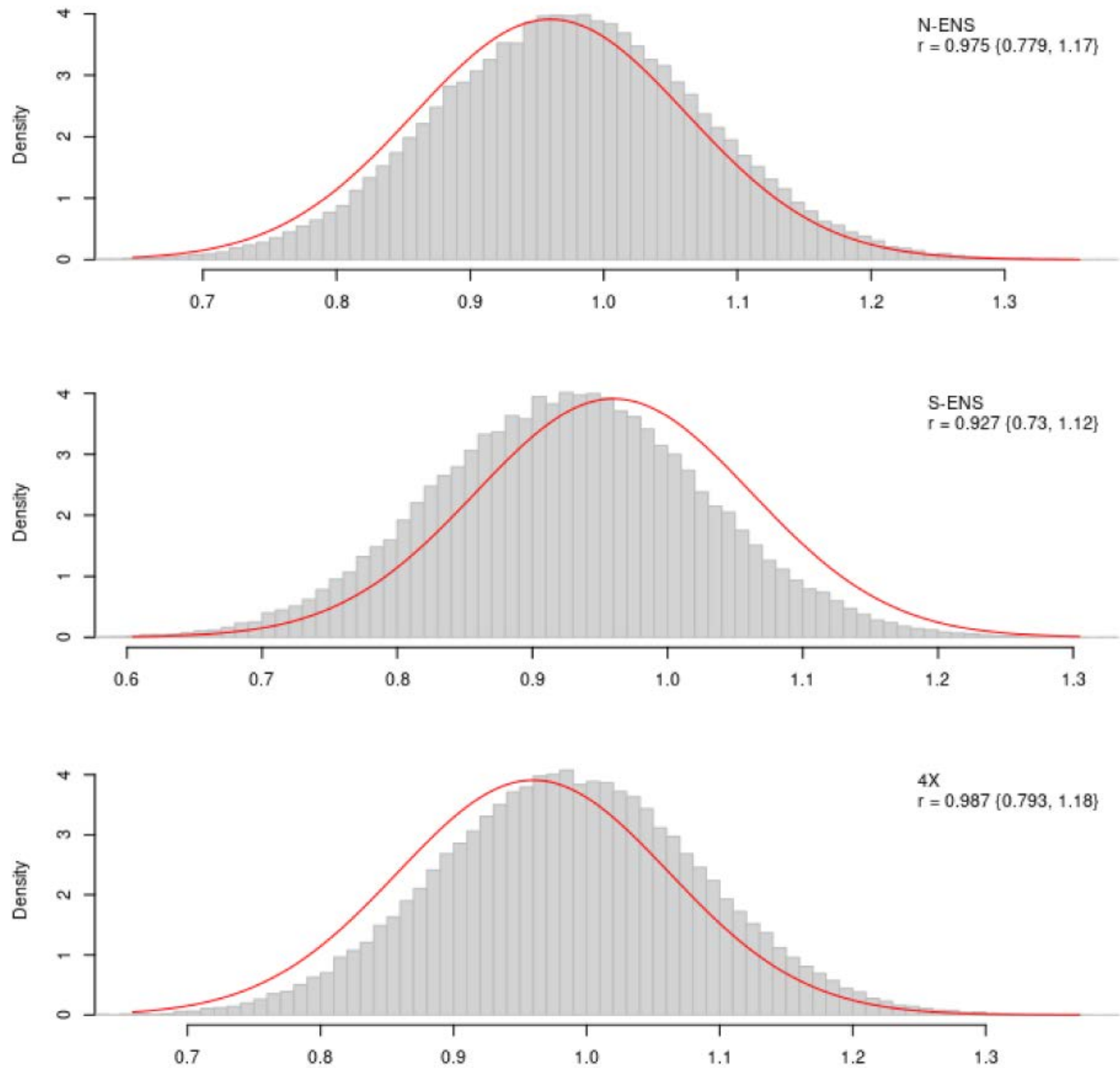

Figure 72. Prior (red line) and posterior (grey bars) distribution for population growth parameter, r, from the biomass dynamic model of Snow Crab production in crab fishing areas on the Scotian Shelf. Within each panel, estimates of posterior median and 95% credible intervals are given in the legend.

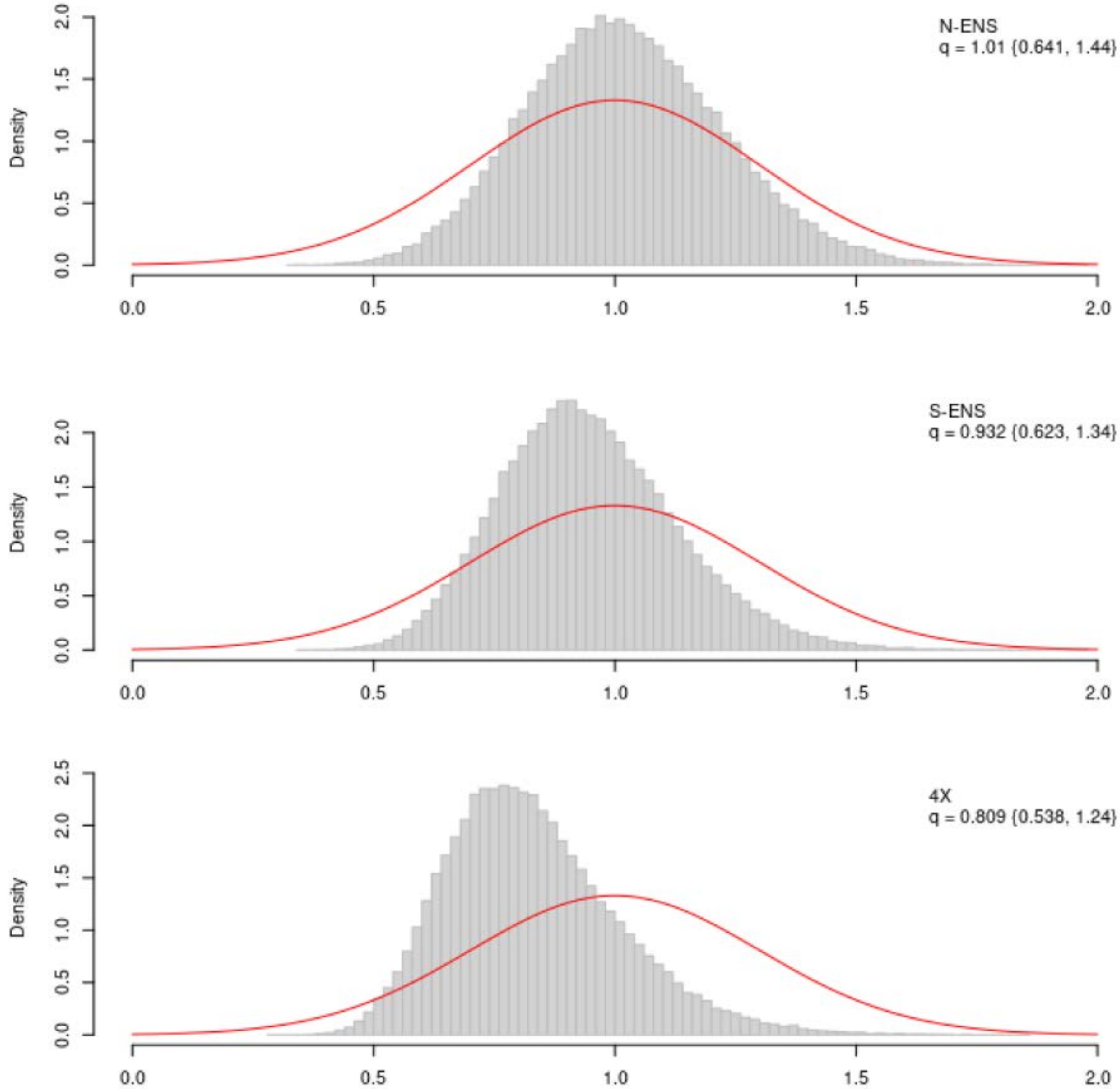

Figure 73. Prior (red line) and posterior (grey bars) distribution for catchability parameter, q, from the biomass dynamic model of Snow Crab production in crab fishing areas on the Scotian Shelf. Within each panel, estimates of posterior median and 95% credible intervals are given in the legend.

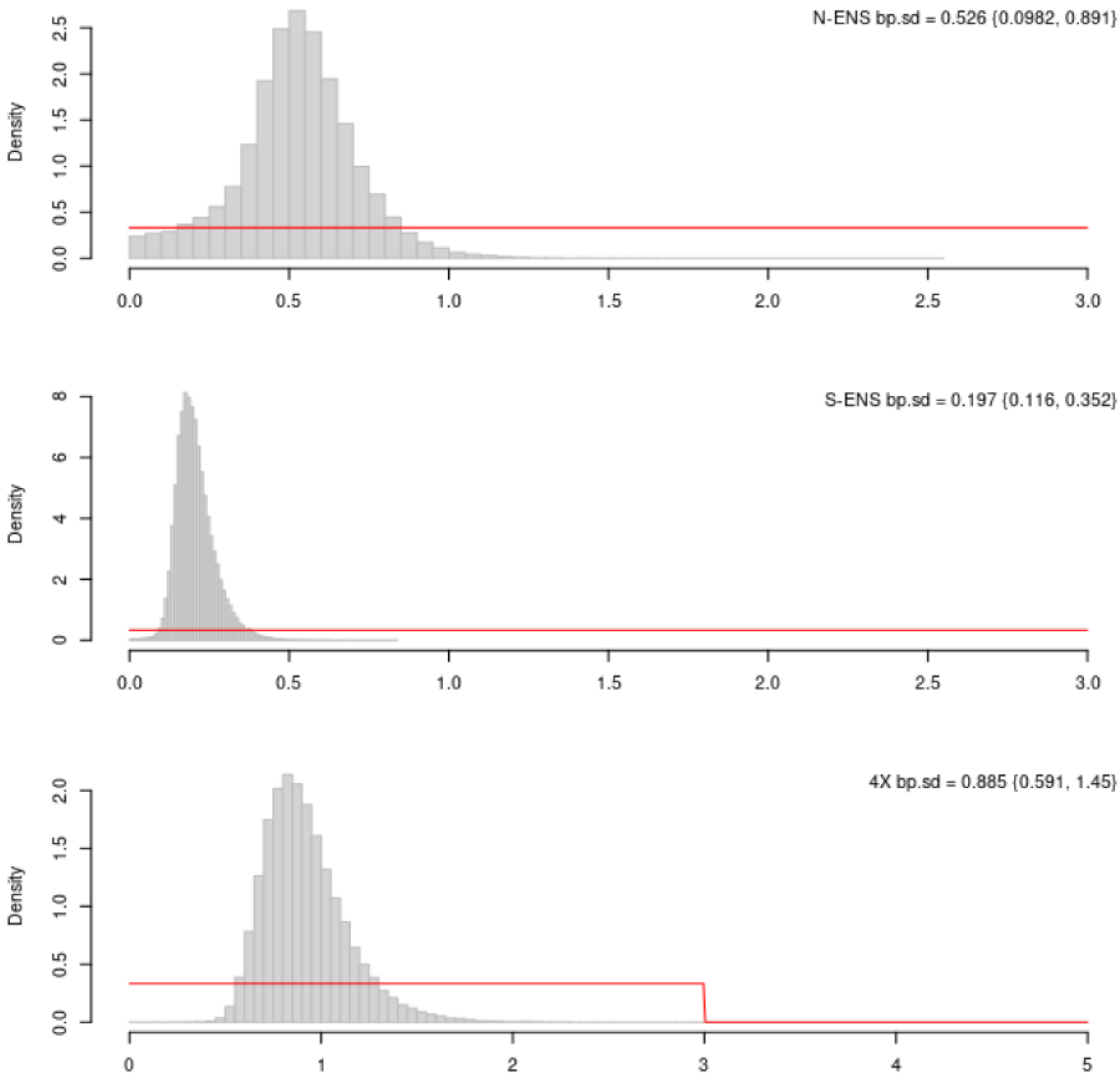

Figure 74. Prior (red line) and posterior (grey bars) distribution for process error from the biomass dynamic model of Snow Crab production in crab fishing areas on the Scotian Shelf. Within each panel, estimates of posterior median and 95% credible intervals are given in the legend.

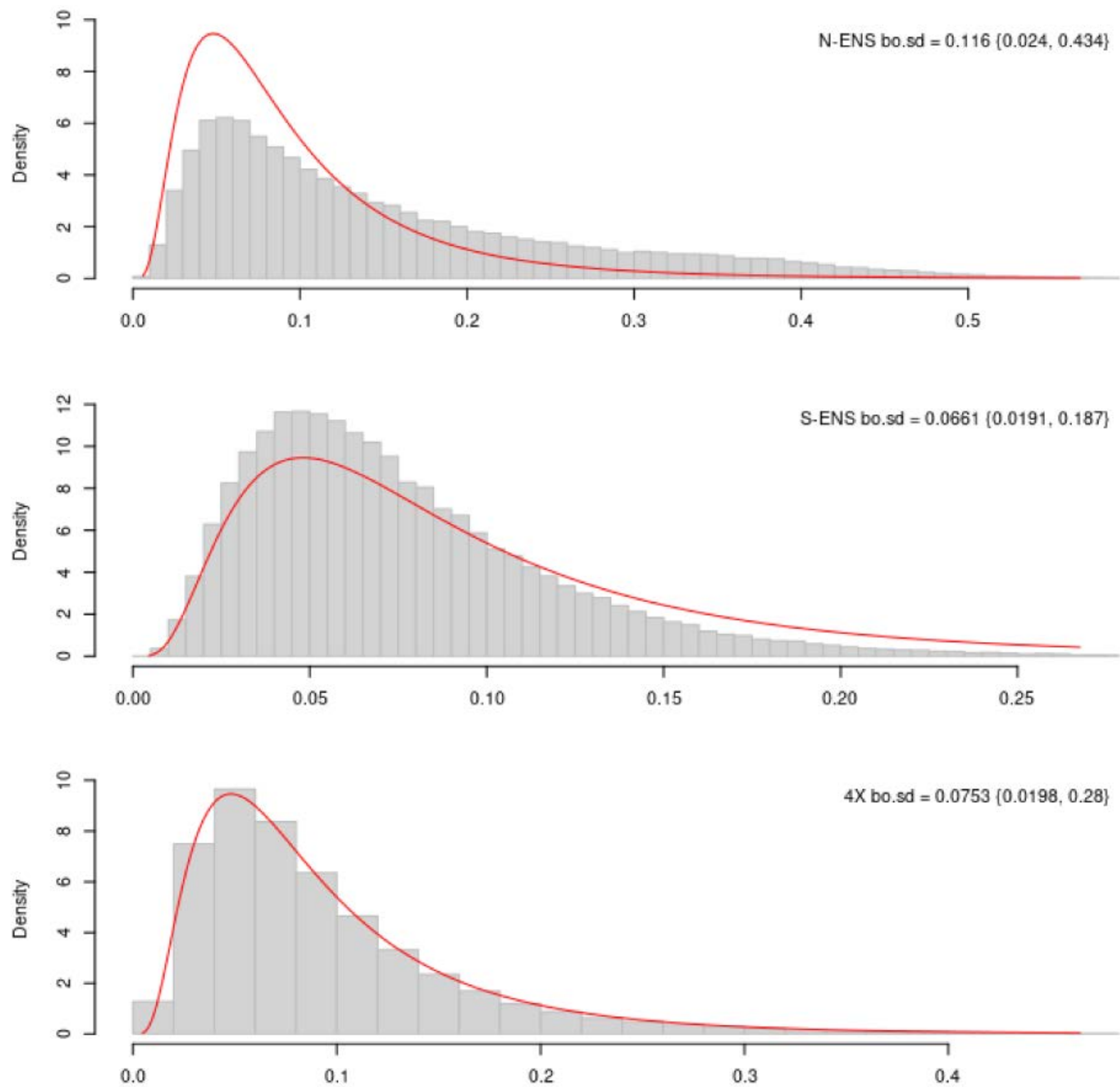

Figure 75. Prior (red line) and posterior (grey bars) distribution for observation error from the biomass dynamic model of Snow Crab production in crab fishing areas on the Scotian Shelf. Within each panel, estimates of posterior median and 95% credible intervals are given in the legend.

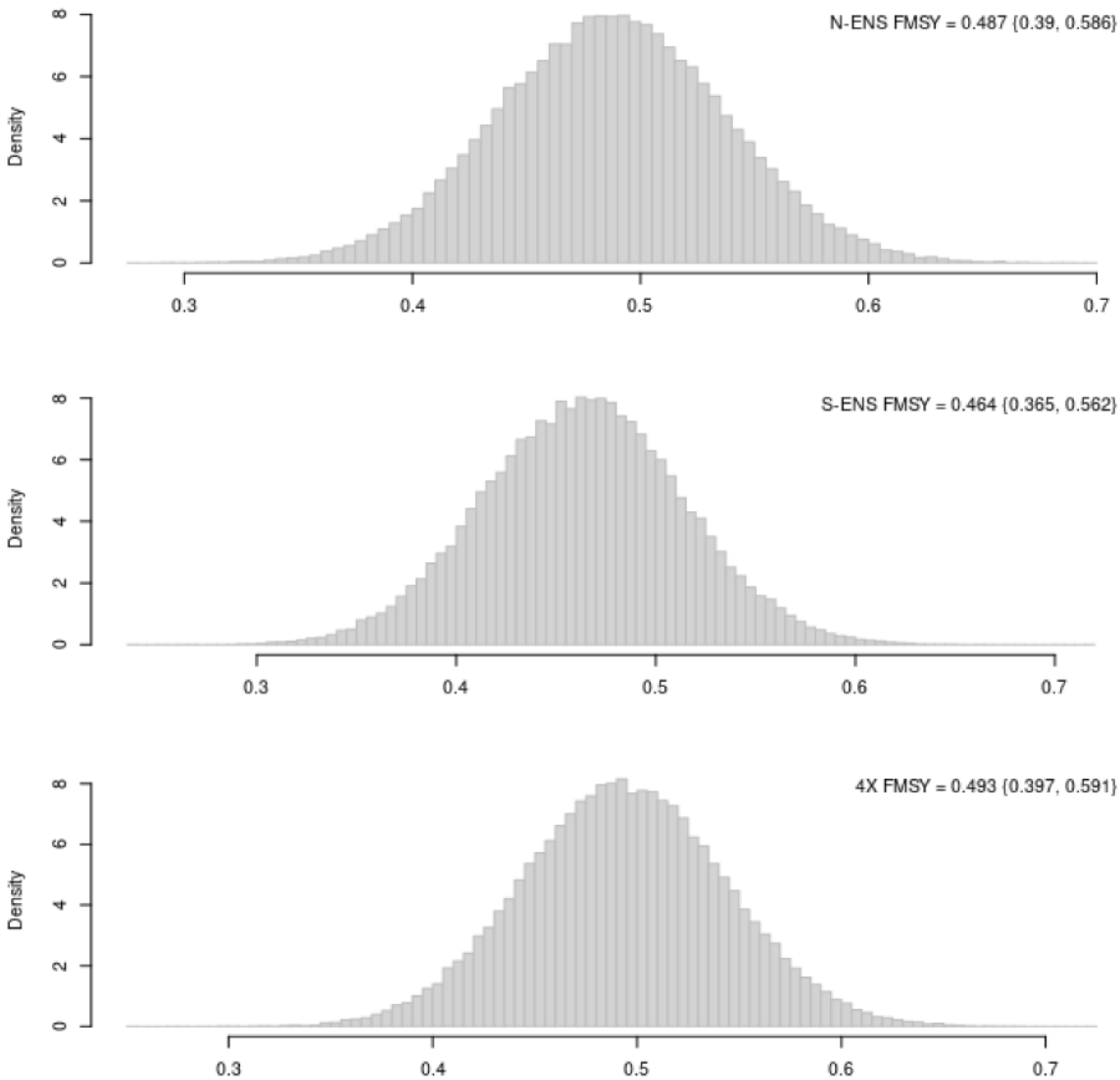

Figure 76. Posterior distribution for fishing mortality at maximum sustainable yield from the biomass dynamic model of Snow Crab production in crab fishing areas on the Scotian Shelf. Within each panel, estimates of posterior median and 95% credible intervals are given in the legend.

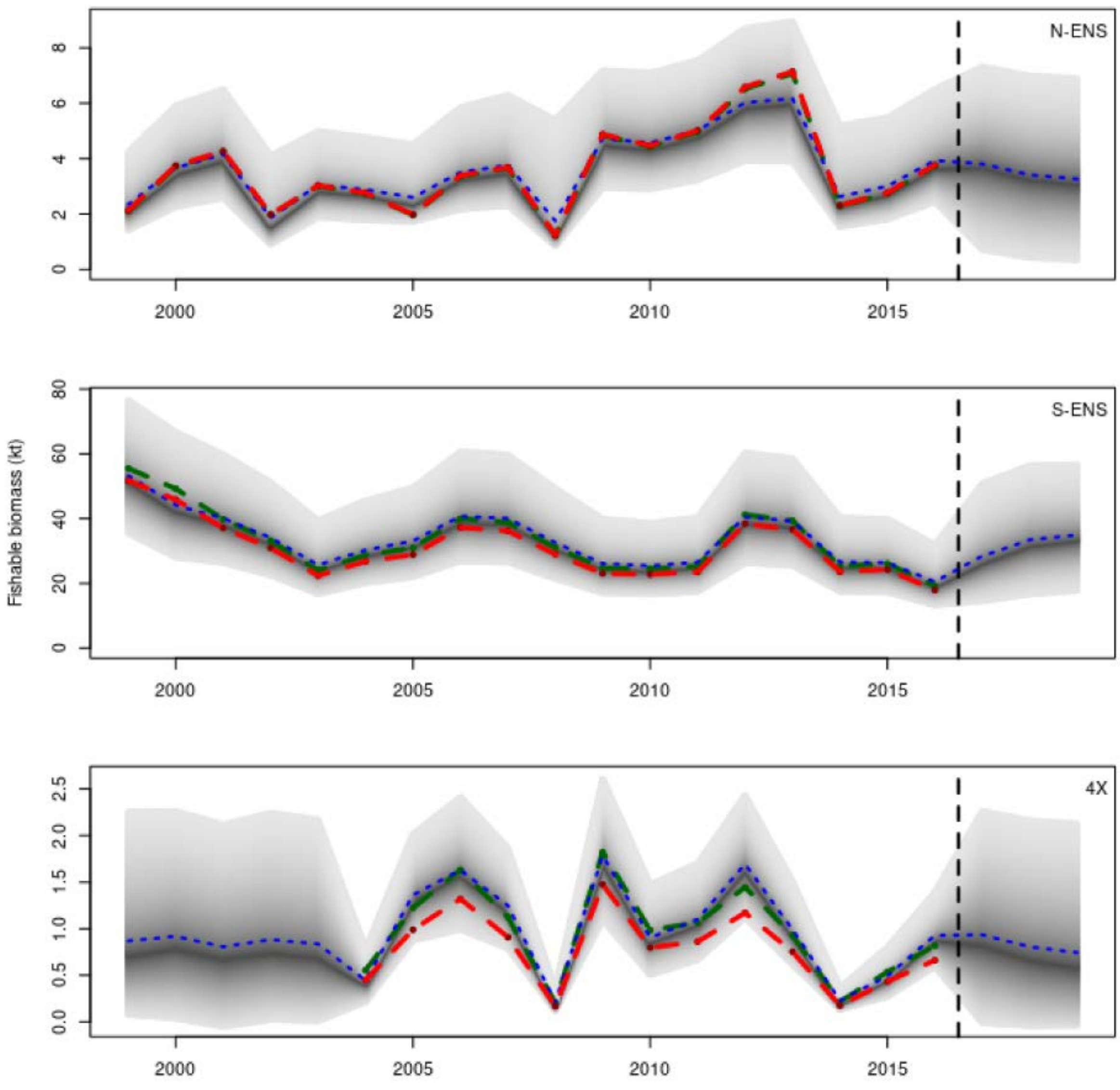

Figure 77. Time series of fishable biomass from the logistic population models. The fishable biomass index is shown in red dashed lines. The posterior mean fishable biomass estimated from the logistic model are shown in blue stippled lines. The density distribution of posterior fishable biomass estimates are presented (grey) with the darkest area being medians and the 95% CI. A three year projection assuming a constant exploitation strategy of 20% is also provided.

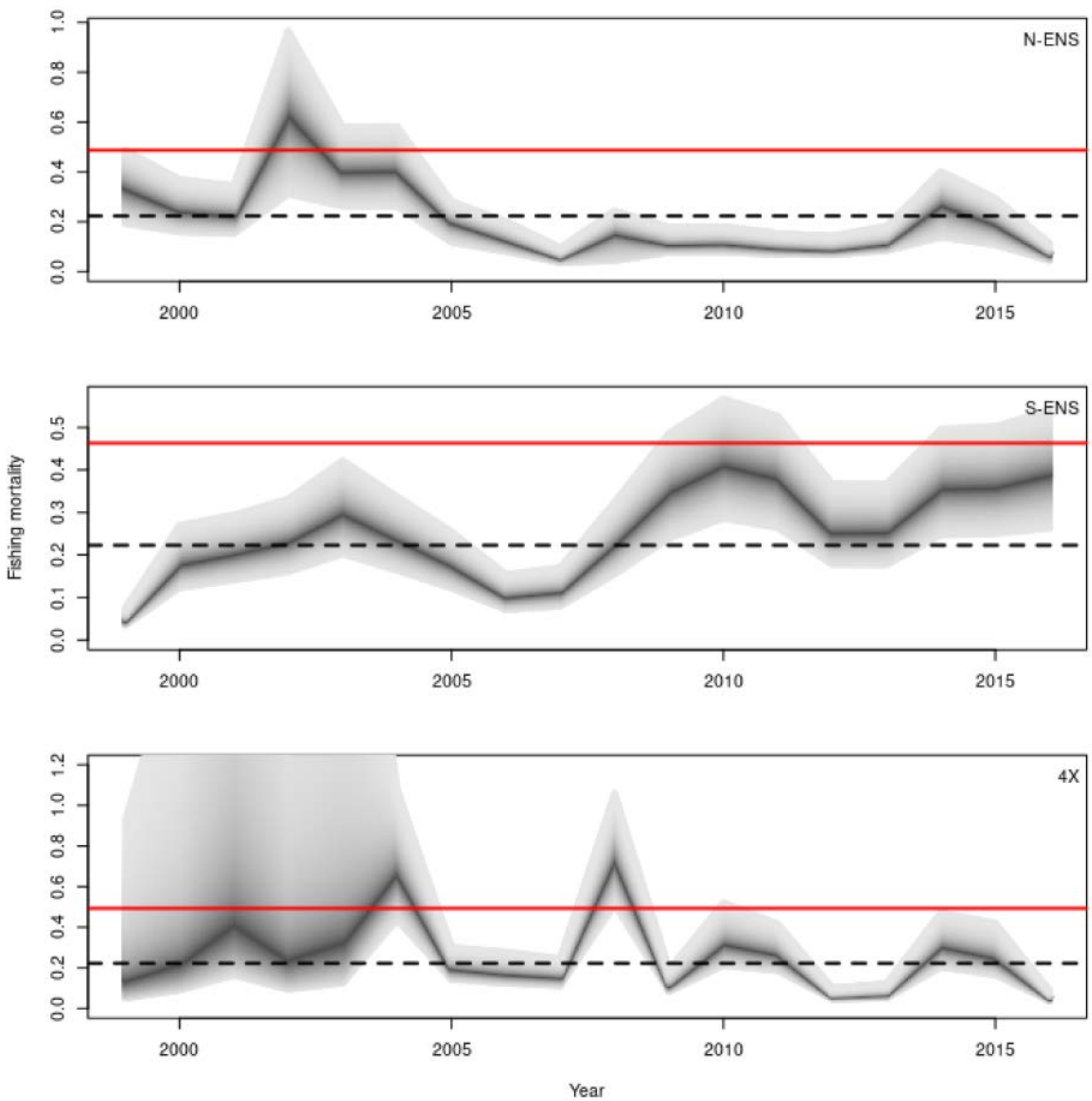

Figure 78. Time-series of fishing mortality from the logistic population models for N-ENS, S-ENS and 4X, respectively. Posterior density distributions are presented in grey, with the darkest line being the median with 95% CI. The red line is the estimated F_{MSY} and dark stippled line is the 20% harvest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

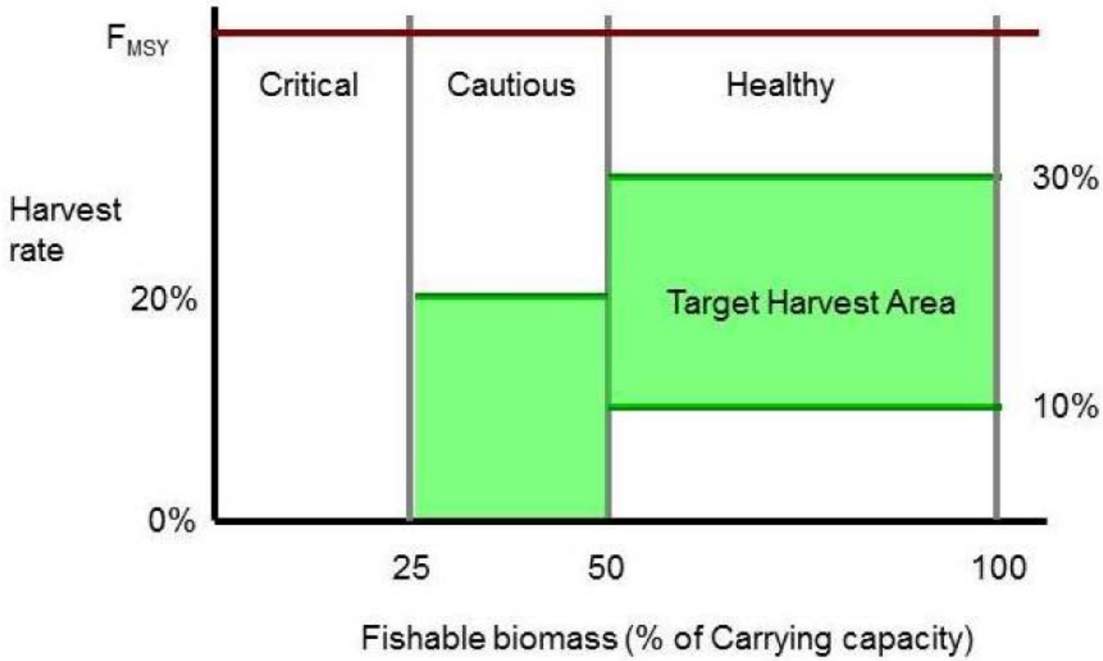

Figure 79. Harvest control rules for the SSE Snow Crab fishery.

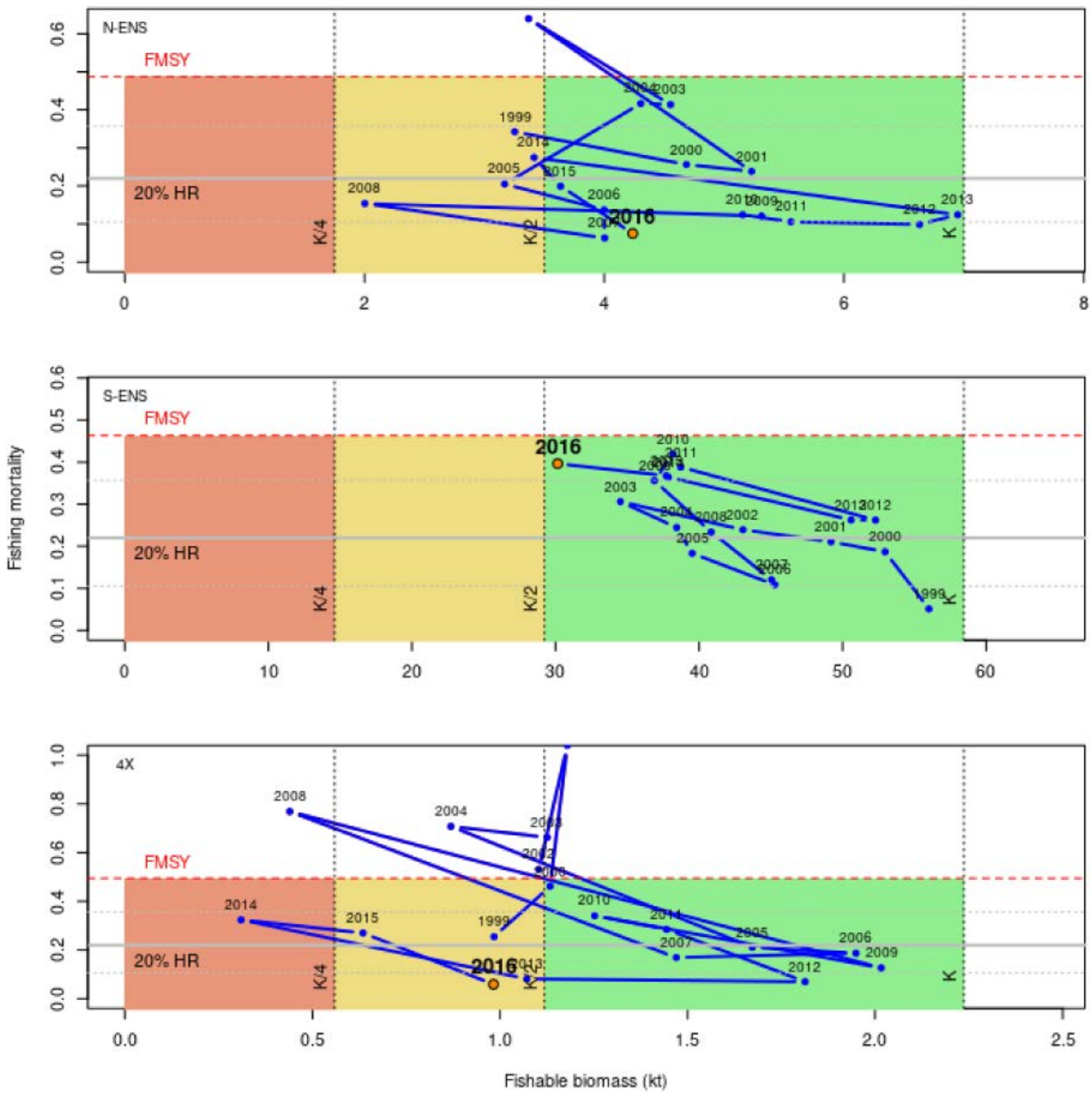

Figure 80. Time series of fishing mortality and pre-fishery biomass for N-ENS (top), S-ENS (middle) and 4X (bottom) as obtained from the logistic population models.

APPENDICES

APPENDIX 1: STOCK ASSESSMENT MODEL

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

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

Arguing against the usage of neither the discrete logistic model nor any other standard fishery model is the fact that the fishable component (large males) is not the same as the spawning stock biomass (reproductive females). Due to sex-related differences in longevity, body size/growth, maturity ogives, habitat usage, predation risk and fishery exploitation, any standard model formulation (including the logistic model) would require a large number of assumptions to convert SSB to the fishable component.

Here, 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.

For any general variable of state, B (e.g., fishable biomass), its time rate of change is, in general, some function **F** of itself and a variety of other parameters θ:

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

If we proceed with a Taylor series expansion of $F(B=B^*; \theta)$ 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*:

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

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. 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*:

$$O_{t,a} \sim Lognormal\ (\ log(q_a\ K_a\ b_{t,a}),\ _o\sigma^2{}_a\ )$$

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 set to be lognormal with mean and standard deviation of -2.559 and 0.69.

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:

$$q_a \sim dunif\ (0.1, 4)$$

Process error was assumed to follow a (multiplicative) lognormal distribution with variance $_p\sigma^2$ whose prior was log-normally distributed with mean and standard deviation of -2.559 and 0.69. Normalized catch, *c*, assumed to be known without error:

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

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

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

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 ln(1.83,0.22), ln(4.17,0.2) and ln(0.78,0.16) for N-ENS, S-ENS and 4X, respectively. The intrinsic rate of increase was assumed to be stationary with a prior of

$$r_a \sim Normal\ (0.96,0.4)$$

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 (Gibbs) sampling using the JAGS platform (Plummer 2003, 2010). Three Markov chains were followed to ensure convergence; 4,000 simulations in the burn-in phase were sufficient to ensure such convergence of the Markov chains. Another 2,500,000 simulations were used to describe the posterior distributions of the parameters. A thinning of 500 simulations was required to minimize autocorrelation in the sampling chains.

Other models were also examined based upon the penalized Deviance Information Criterion (Plummer 2008); however, their performance was generally similar.

The JAGS model used for parameter estimation is as follows:

```
model{
 #priors for r,K,q
for (j in 1:U) {   r[j] ~ dnorm( r.mu[j], pow( r.sd[j], -1 ) )  }
for (j in 1:U) {   q[j] ~ dunif( q.min[j] , q.max[j] ) }
for (j in 1:U) {   K[j] ~ dlnorm( K.mu[j], pow( K.sd[j], -1 )) # T(K.min[j], K.max[j] ) }
  # -----------------
 # removals (catch) observation model, standardized to K (assuming no errors in observation of catch!)
  for (j in 1:U) {  for (i in 1:N){   rem[i,j] <- CAT[i,j]/K[j]     }  }
 # biomass observation model
 #  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)
  for (j in 1:(U)) {
   bo.sd[j] ~ dlnorm(bo.mup[j],pow(bo.sdp[j],-1))
   bo.tau[j] <- pow( bo.sd[j], -2 )  }
  for (j in 1:(U-1)) {
   # spring surveys from 1998 to 2003
   IOA[1,j] ~ dlnorm( log( max( q[j] * K[j] * (bm[1,j] - rem[1,j]) , eps)), bo.tau[j] )  # approximation
   for (i in 2:(ty-1)) {
    IOA[i,j] ~ dlnorm( log( max( q[j] * K[j] * (bm[i,j]- rem[(i-1),j]), eps)), bo.tau[j] )    }
   # transition year
   IOA[ty,j] ~ dlnorm( log( max( q[j] * K[j] * (bm[ty,j] - (rem[(ty-1),j] + rem[ty,j] )/2 ), eps)), bo.tau[j] ) ;  # approximation
   # fall surveys
   for (i in (ty+1):N) {
    IOA[i,j] ~ dlnorm( log( max( q[j] * K[j] * (bm[i,j] - rem[i,j]), eps)), bo.tau[j] ) ;  } }
  # 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
  IOA[1,cfa4x] ~ dlnorm( log( max( q[cfa4x] * K[cfa4x] * (bm[1,cfa4x] - rem[1,cfa4x]), eps)), bo.tau[cfa4x] ) ;  #
approximation
  for (i in 2:N) {
   IOA[i,cfa4x] ~ dlnorm( log( max( q[cfa4x] * K[cfa4x] * (bm[i,cfa4x]- rem[(i-1),cfa4x]), eps)), bo.tau[cfa4x] ) ;   }
 # -----------------
 # biomass process model
        for (j in 1:U) {
    bp.sd[j] ~ dlnorm(bp.mup[j],pow(bp.sdp[j],-1))
   bp.tau[j] <- pow( bp.sd[j], -2 )   }
  for(j in 1:U) {
   b0[j] ~ dunif( b0.min[j], b0.max[j] ) # starting b prior to first catch event
   bm[1,j] ~ dlnorm( log( max( b0[j], eps)), bp.tau[j] ) T(b.min, b.max) ; # biomass at first year
   for(i in 2:(N+M)) {
    bm[i,j] ~ dlnorm( log( max(bm[i-1,j]*( 1 + r[j]*(1-bm[i-1,j])) - rem[i-1,j] , eps)), bp.tau[j] ) T(b.min, b.max) ;    }
 # forecasts
   for(i in 1:M) {
    rem[N+i,j] <- er*bm[N+i-1,j]    } }
 # -----------------
 # monitoring nodes and parameter estimates for output
  for(j in 1:U) {
   MSY[j]    <- r[j]* exp(K[j]) / 4  # maximum height of of the latent productivity (yield)
   BMSY[j]   <- exp(K[j])/2  # biomass at MSY
   FMSY[j]   <- 2 * MSY[j] / exp(K[j]) }# fishing mortality at MSY
# -----------------
  # fishing mortality
  # force first year estimate assuming catches in year 0 to be similar to year 1
  for(j in 1:U) {
   for(i in 1:N) {
    F[i,j] <- -log( max(1 - rem[i,j] / bm[i,j], eps))  }
   for(i in (N+1):(N+M)) {
    F[i,j] <- -log( max(1 - er * bm[i-1,j] / bm[i,j], eps))  } }
  # -----------------
```

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 (DFO 2005, 2006; Shelton and Sinclair 2008). 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 (Catch Per Unit EFFORT (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 Atlantic Cod since the cod-moratorium in the early 1990s in Atlantic Canada, suggests that even this "universal" expectation of fisheries control is more a belief than reality. A more risk-averse management approach would, therefore, seem to be prudent. For the Snow Crab fishery, the need for additional precaution is further demanded by the fact that the Scotian Shelf is the southern-most limit of the spatial distribution of Snow Crab. If environmental fluctuations occur in oceanographic currents and bottom temperatures, this is the area that can be expected to be most significantly influenced by such changes.

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

Significantly, as the footprint of a fishery is itself context dependent (i.e., population and ecosystem), the use of fixed biological limit reference points of a single indicator is not 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 of area 4VWX 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, 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 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, NGOs, managers and scientists).
- This fishery is well monitored through 100% dockside monitoring, at-sea-observer coverage (5-10% of landings) and mandatory VMS (Vessel Monitoring System) usage in most areas.

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

Even with these measures, knowledge of biological reference points for the targeted fraction of the population (mature males >95 mm CW) are required to guide annual TAC advice and related management measures. There is no 'correct' or 'best' choice of reference points, especially given the fact that the underlying carrying capacity is 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: ECOSYSTEM INDICATORS

The variables used as indicators in this study are listed and described in the following:

Index Variable Label	Description
NS: population size	Total population size for Nova Scotia, a proxy of the influence of human on the Scotian Shelf
CIL volume	Cold intermediate layer (water temperature < 3°C) in the Gulf of St. Lawrence from the September groundfish hydrographic survey.
CPR: *Calanus finmarchicus* 1-4	Continuous Plankton Recorder (CPR) relative abundance estimates: *Calanus finmarchicus* instars 1 to 4
CPR: *Calanus finmarchicus* 5-6	Continuous Plankton Recorder (CPR) relative abundance estimates: *Calanus finmarchicus* instars 5 to 6
CPR: colour	Continuous Plankton Recorder (CPR) relative estimate surface ocean color, a proxy for Chl-a concentrations
CPR: diatoms	Continuous Plankton Recorder (CPR) relative abundance estimates: Diatoms
CPR: dinoflagellates	Continuous Plankton Recorder (CPR) relative abundance estimates: Dinoflagellates
Employment per total landed value	Number of fishers employed per total landed value of the fishery
Employment per total landings	Number of fishers employed per total landings of fish
GDP: fish processing	Gross Domestic Product: fish processing sector in Nova Scotia
GDP: fishing and hunting	Gross Domestic Product: fishing and hunting sector in Nova Scotia
GDP: NS total	Gross Domestic Product:Total for Nova Scotia
GDP: oil and gas	Gross Domestic Product: Oil and gas sector in Nova Scotia
Gulf stream front: lat@-62 lon	Gulf stream front location at -62 longitude (latitude)
Ice coverage	Sea ice coverage, cumulative seasonal sum
Landed value: all	Landed value of all fish and invertebrates
Landed value: groundfish	Landed value of all groundfish in Nova Scotia
Landed value: pelagics	Landed value of all pelagic fish in Nova Scotia
Landed value: shellfish	Landed value of all shellfish
Landings: all	Total landings of all fish and invertebrates
Landings: groundfish	Total landings of all groundfish
Landings: pelagic	Total landings of all pelagic fish
Landings: shellfish	Total landings of all shellfish
NAO index	North Atlantic Oscillation index anomaly of December-February sea level atmospheric pressure difference (kPa) between the Azores and Iceland. This index has been shown to be related to air temperatures, SST, convection and circulation changes in the North Atlantic and through atmospheric tele-connections, even broader-scale forcings.
No. fish harvesters	Number of fish harvesters in Nova Scotia
No. shellfish closures	Number of shellfish closures
No. wells drilled	Number of oil and gas wells drilled on the Scotian Shelf
NS: % 65 and older	Nova Scotia demographics
NS: % attending university	Nova Scotia demographics
PCBs: puffins	PCB concentrations in Atlantic puffins
PCBs: seals	PCB concentrations in grey seals
RV: biomass capelin	Research survey estimates of capelin biomass
RV: biomass cod	Research survey estimates of cod
RV: biomass elasmobranchs	Research survey estimates of elasmobranch fish
RV: biomass flatfish	Research survey estimates flatfish
RV: biomass gadoids	Research survey estimates gadoids
RV: biomass large demersals	Research survey estimates large demersal fish
RV: biomass large pelagics	Research survey estimates large pelagic fish
RV: biomass small demersals	Research survey estimates of small demersal fish
RV: biomass small pelagics	Research survey estimates small pelagic fish
RV: bottom oxygen	Research survey estimates of bottom oxygen concentration
RV: bottom salinity	Research survey estimates bottom salinity
RV: bottom temperature	Research survey estimates bottom temperature
RV: condition elasmobranchs	Research survey estimates of elasmobranch physiological condition
RV: condition flatfish	Research survey estimates of flatfish physiological condition

Index Variable Label	Description
RV: condition gadoids	Research survey estimates of gadoid physiological condition
RV: condition large demersals	Research survey estimates of large demersal physiological condition
RV: condition large pelagics	Research survey estimates of large pelagic physiological condition
RV: condition small demersals	Research survey estimates of small demersal physiological condition
RV: condition small pelagics	Research survey estimates of small pelagics physiological condition
RV: groundfish SMR	Research survey estimates of mass specific metabolic rates of all fish
RV: no. taxa predicted at 100 km^2	Research survey estimates of the number of taxa predicted at 100 km^2
RV: Shannon index	Research survey estimates of the Shannon diversity index of fish species
RV: species-area exponent	Research survey estimates the mean species-area exponent on the Scotian Shelf. The average scaling exponent derived from a species richness vs surface area relationship for the fish community, using a spatially constrained (locally calculated saturation curves within a radius of 10 to 300 km) fractal-like approximation method.
RV: species-area intercept	Research survey estimates the mean species-area intercept on the Scotian Shelf. The average scaling exponent derived from a species richness vs surface area relationship for the fish community, using a spatially constrained (locally calculated saturation curves within a radius of 10 to 300 km) fractal-like approximation method.
RV: taxonomic richness (100 km)	Research survey estimates the mean number of taxa observed at 100 km^2 scale
Seal abundance adult	Abundance of seal adults
Seismic 2D; km	The length of seismic exploration tracks; km
Seismic 3D; km^2	The amount of seismic exploration conducted (3D); km^2
Shelf front: lat@-62 lon	Shelf front location at -62 longitude (latitude)
Shrimp: abundance index	Shrimp abundance index from shrimp surveys
Shrimp: capelin abundance index	Capelin abundance index for areas overlapping the shrimp fishery
Snow Crab: habitat area	Snow Crab survey estimates of Snow Crab potential habitat area (km^2) determined from temperature and depth masks
Snow Crab: immature female abundance	Snow Crab survey estimates of immature female abundance (no.)
Snow Crab: landings	Snow Crab total landings
Snow Crab: male recruitment	Snow Crab survey estimates of male recruitment
Snow Crab: mature female abundance	Snow Crab survey estimates of mature female abundance (no.)
Snow Crab: mature female mean size	Snow Crab survey estimates of female mean size
Snow Crab: mature male biomass	Snow Crab survey estimates of male mean biomass (kt)
Snow Crab: mature male mean size	Snow Crab survey estimates of mature male mean size
Snow Crab: temperature mean	Snow Crab survey estimates of mean temperature in the Snow Crab potential habitat
Snow Crab: temperature SD	Snow Crab survey estimates of the standard deviation of the mean temperature in the Snow Crab potential habitat
Temperature: Sable Is.	Temperature at Sable Island
Temperature: SST Halifax	Temperature: sea surface temperature at Halifax station

APPENDIX 4: GLOSSARY

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(t) = Landings(t) / (Landings(t) + Fishable biomass(t)).

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) – 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 – 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.

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 – Females bearing eggs resulting from their second or third breeding event (mating).

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 – Females 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".

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).

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.