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# Assessment of Scotian Shelf Snow Crab in 2012

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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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## TABLE OF CONTENTS

## ABSTRACT

Landings in 2012 for North-Eastern Nova Scotia (N-ENS) and South-Eastern Nova Scotia (S-ENS) were 603 and 11,707 t, respectively, and 345 t in 4X for the 2011/2012 season, representing an increase of 13% (N-ENS), a decrease of 4% (S-ENS) and no change relative to the previous year. Total Allowable Catches (TACs) in 2012 were 603 t, 11,733 t and 346 t in N-ENS, S-ENS and 4X. Average, non-standardized catch rates were 117, 98, and 29 kg $trap^{-1}$, respectively. These catch rates represent an increase of 6%, and decreases of 8% and 24%, respectively, relative to the previous year. The capture of soft-shelled crab in N-ENS increased to 9% of landings from 1.7% in 2011, though they are still lower than the soft crab catches in 2005-2008. This increase is likely associated with a return to more summer fishing activities (less spring fishing) in 2012. In S-ENS, the relative occurrence of soft-shell crab was 6.3%, unchanged since 2011 and lower than the soft crab catches in 2010 and 2009 (8% and 16%, respectively). This decline is also attributable to earlier fishing activities. 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 continues to be an issue requiring diligent and adaptive management action. Bycatch of non-target species is extremely low, 0.0% and 0.2% of total snow crab landings in Eastern Nova Scotia (ENS) and 4X, respectively, over the past three years. Very limited recruitment into the fishery is expected for the short to medium term in N-ENS due to a lack of male crab between 20 and 85 mm carapace width. Male crab were observed in all size classes in S-ENS, suggesting more stable recruitment into the future. 4X shows little potential for substantial internal recruitment to the fishery in the next three to four years. Movement has likely been an important source of 4X crab in the past. The low abundance of both the mature and immature crab in the adjoining portion of Area 24 and erratic temperature fields in 4X create future uncertainties. The leading edge of the current recruitment pulse began entering the fishable biomass in 2007 in S-ENS; 2008 in N-ENS; and 2009 in 4X. Female snow crab in all areas appear to be completely recruited as of the 2012 survey with a distinct lack of immature snow crab in all areas. Current egg and larval production is expected to be low in both S-ENS and 4X and nearly non-existent in N-ENS. The post-fishery fishable biomass index of snow crab in N-ENS was estimated to be 3,130 t (3,430 t in 2011). In S-ENS, the post-fishery fishable biomass index was estimated to be $34.1 \times 10^3$ t ($35.4 \times 10^3$ t in 2011). In 4X, the pre-fishery fishable biomass was 1.7 t (2.4 t in 2011/2012). These generally positive 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 4X and parts of Area 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 0.11, relatively unchanged since 2009. High biomass and significantly reduced soft-shell handling results in a positive short-term outlook. Medium to long-term prospects are poor due to an absence of pre-recruits. The fishable biomass is in the “healthy” zone. A status quo TAC is recommended. Fishing mortality in S-ENS was estimated to be 0.21, relatively unchanged since 2011. Good recruitment suggests a positive outlook; however, the capture of soft-shell crab and illegal landings remain important issues for this fleet. The fishable biomass is in the “healthy” zone. A status quo to a marginal decrease in harvest strategy is recommended. Fishing mortality in 4X for 2010/2011 was estimated to be 0.23. The fishable biomass is in the “healthy” zone. However, as recruitment into the 2011/2012 season is uncertain and biomass trends are declining, a decreased harvest strategy (rate) is recommended.

### Évaluation des stocks de crabes des neiges du plateau néo-écossais en 2012

## RÉSUMÉ

En 2012, les débarquements dans le nord-est et le sud-est de la Nouvelle-Écosse ont atteint respectivement 603 t et 11 707 t, et les débarquements dans 4X ont atteint 345 t pour la saison 2011-2012, ce qui représente une augmentation de 13 % (nord-est de la Nouvelle-Écosse), une diminution de 4 % (sud-est de la Nouvelle-Écosse) et le statu quo par rapport à l'année précédente (4X). Les totaux autorisés des captures en 2012 étaient de 603 t dans le nord-est de la Nouvelle-Écosse, de 11 733 t dans le sud-est de la Nouvelle-Écosse et de 346 t dans 4X. Les taux de prise moyens non normalisés ont atteint respectivement 117, 98 et 29 kg/casier$^{-1}$. Ces taux de prise représentent respectivement une augmentation de 6 % et des diminutions de 8 % et de 24 % par rapport à l'année précédente. Les prises de crabes à carapace molle dans le nord-est de la Nouvelle-Écosse ont augmenté et représentent maintenant 9 % des débarquements, comparativement à 1,7 % en 2011. Ce pourcentage est toutefois beaucoup plus faible que le pourcentage très élevé lié aux prises relatives de crabes mous obtenu de 2005 à 2008. Cette augmentation est probablement attribuable à la hausse des activités de pêche estivale (diminution des activités de pêche printanière) en 2012. Dans le sud-est de la Nouvelle-Écosse, la présence relative de crabes à carapace molle était de 6,3 % (elle est demeurée pratiquement la même depuis 2011). Il s'agit d'une amélioration par rapport aux prises de crabes mous de 8 % et de 16 % en 2010 et en 2009, respectivement. Cette diminution est probablement attribuable à l'avancement des activités de pêche. Les taux de rejet de crabes à carapace molle dans 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 continuent d'être un enjeu nécessitant des mesures de diligence et d'adaptation. Les prises accidentelles d'espèces non ciblées sont très faibles, se chiffrant à 0 % et à 0,2 % du total des débarquements de crabes des neiges dans l'est de la Nouvelle-Écosse et dans 4X, respectivement, au cours des trois dernières années. On s'attend à ce que le recrutement dans la pêche soit très limité à court et à moyen terme dans le nord-est de la Nouvelle-Écosse en raison de l'absence presque absolue de crabes mâles dont la largeur de la carapace est de 20 mm à 85 mm. Des crabes mâles de toutes les catégories de taille ont été observés dans le sud-est de la Nouvelle-Écosse, laissant entrevoir un recrutement futur plus stable. Dans 4X, le potentiel de recrutement interne important dans la pêche au cours des trois ou quatre prochaines années est faible. Les déplacements ont probablement été une raison importante de la présence de crabes dans 4X par le passé. Cependant, la quantité limitée de crabes matures et immatures dans la partie voisine de la zone 24 et les champs de température irréguliers dans 4X créent des incertitudes pour l'avenir. Les premiers crabes de la vague actuelle de recrutement ont commencé à s'intégrer à la biomasse exploitable en 2007 dans le sud-est de la Nouvelle-Écosse, en 2008 dans le nord-est de la Nouvelle-Écosse et en 2009 dans 4X. Les crabes des neiges femelles dans toutes les zones semblaient être complètement recrutés en date du relevé de 2012, mais il existe un manque flagrant de crabes des neiges immatures dans toutes les zones. La production actuelle d'œufs et de larves devrait être faible dans le sud-est de la Nouvelle-Écosse et dans 4X, et presque inexistante dans le nord-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 3 130 t (3 430 t en 2011). 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 34,1 × $10^3$ t (35,4 × $10^3$ t en 2011). Dans 4X, la biomasse exploitable avant la pêche était de 1,7 t (2,4 t en 2011-2012), mais elle est considérée comme préliminaire. Ces caractéristiques généralement positives 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 4X

et certaines parties de la zone 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 0,11 (elle est demeurée relativement la même depuis 2009). La biomasse élevée et la réduction considérable de la manutention des crabes à carapace molle entraînent des perspectives favorables à court terme. Les perspectives à moyen et à long terme sont médiocres en raison de l'absence de prérecrues. La biomasse exploitable se situe dans la zone saine. On recommande le maintien d'un même total autorisé des captures. La mortalité par pêche dans le sud-est de la Nouvelle-Écosse a été estimée à 0,21 (elle est demeurée relativement la même depuis 2011). Un bon recrutement laisse présager des perspectives favorables, mais la pêche de crabes à carapace molle et les débarquements illégaux demeurent des enjeux importants pour cette flottille. La biomasse exploitable se situe dans la zone saine. On recommande le statu quo ou une diminution très légère dans les captures. La mortalité par pêche dans 4X pour la saison 2010-2011 a été estimée à 0,23. La biomasse exploitable se situe dans la zone saine. Toutefois, compte tenu de l'incertitude du recrutement pour la saison 2011-2012 et de la tendance à la baisse de la biomasse, on recommande de prime abord une baisse dans les captures jusqu'à ce que toutes les analyses soient effectuées pour cette zone.

## MANAGEMENT

The Scotian Shelf Ecosystem (SSE) snow crab 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 (Figure 1, Table 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, 5%, 10%, 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 Department of Fisheries and Oceans (DFO) Canada 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 due to the very short season in N-ENS. 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, and the potential closure of sub-areas based on observer reports of high soft crab incidence. Finally, the voluntary return to the sea of immature, legal sized crab (“pencil-clawed” crab) was implemented in 2006 for all areas on the SSE to allow these crab to molt to maturity and so maximize the total yield per crab captured and simultaneously 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 to 4) and the addition of new participants. Trawl surveys were formally extended to 4X in 2004. This Joint Project Agreement has continued to the present.

## HISTORY

The snow crab fishery is currently the second most valuable commercial fishery in both Nova Scotia and Atlantic Canada. It has been active since the early 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 (Figure 3). 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 have increased considerably (Figure 3). 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 1,500 t in N-ENS. Approximately 10,000 t of snow crab were landed each year from 2000 to 2004. Thus, the post-1998 period was one of rapid expansion of both the economic importance of the crab fishery and also the spatial extent of their 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 have declined slightly in each of the last two seasons due to declines in fishable biomass estimates. In N-ENS, due to negligible recruitment, TACs were maintained at low levels until 2009 and have been relatively stable between 530 and 603 mt since 2009. The 2011/2012 TAC for 4X was maintained from the previous season.

A Marine Stewardship Council Certification was granted to the ENS fishery in September 2011.

## METHODS

The primary driver of the analytical approaches developed for the assessment of snow 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 their 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.

A number of spatial and/or temporal interpolation methods are used in this assessment. Thin-plate-splines visualizations were computed with Generic Mapping Tools (Wessel and Smith 1998, version 4.1) with a tension parameter T=0.4 and a spatial extent of interpolation of 20 km radius from every datum, a range comparable with that observed in the empirical variograms of many variables (see below). For historical temperature data (1950 to present), spatially and temporally constrained Generalized Additive Models (GAMs) were computed with the “mgcv” R-library (Wood 2006, version 1.6-1) at a resolution of 1 × 1 km and weekly time scales. Conversions between cartographic and Cartesian co-ordinate systems for analytical purposes were computed with PROJ (Evenden 1995, version 4.4.9) onto the Universal Transverse Mercator grid system (UTM region 20).

### 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 (by quota) was 5% for N-ENS and 10% for S-ENS and 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:

$$Bycatch_i\ [kg] = Observed\ catch_i\ [kg] \times Total\ snow\ crab\ landings\ [kg]\ /\ Observed\ catch_{snow\ crab}\ [kg]$$

## 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 at reducing local estimates of prediction variance, as well as identifying the spatial bounds of snow crab habitat. Since 2004, approximately 400 stations have been sampled annually on the fishing vessel, *The Gentle Lady*, with the same captain. In the 2012 survey, 407 stations were sampled, a decrease from 414 stations in 2011.

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 surveys have 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 have stabilized since 2004.

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 substrate (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. Tows were conducted with approximately five minutes of actual fishing (net on bottom) time. 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 net width.

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 estimates relying upon allometric relationships between body parts (the approach in 2003 and earlier; see below). Captured crabs were also monitored visually 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):

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

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 (CC) and morphometric analysis. While physiological maturity is not directly co-incident with the onset of morphometric maturity (morphometrically immature male crabs are more than capable of mating in the absence of competition from terminally molted males; Sainte-Marie 1993), the latter is more readily/rapidly determined. In the terminal molt of male snow crab, a disproportionate increase of chela height (*CH*) relative to CW is generally observed, a factor which may be associated with increased mating and/or reproductive success. Such morphometrically mature males can be discriminated from those that have not undergone the rapid chela growth via the following equation (E. Wade, personal communication, GFC):

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

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 can be delineated via the following equation (E. Wade, personal communication, GFC):

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

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

Sex ratios (proportion female) were calculated as:

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

BCD infections of snow crab were first detected 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 hoped to improve the detection rates as visual assessments are only effective in identifying late-stage infections. In 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 ceased due to high costs (approximately 5$ / 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 the each modal group were identified from size frequency distributions. 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):

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

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

"*Viable habitat*" for fishable snow crab was modeled from trawl surveys, snow crab fisher logbook records and research vessel groundfish surveys. A binomial GAM with a logit link function was used with smoothed (thin-plate-spline) covariate functions (R-library "mgcv"; Wood 2006). Statistically significant covariates were determined to be year, week number, northing and easting, depth, bottom slope, bottom curvature, bottom temperature, annual amplitude of temperature fluctuations, the week number at which temperature minima were observed, substrate grain size, species composition (correspondence analysis) and richness and biological productivity indices (figures 8, 9; Table 6; see Choi et al. 2005a for more details on methods). These modeled relationships were used to predict SSE snow crab habitat after discretising covariate information to a spatial resolution of 1 × 1 km grids (Figure 8). Potential snow crab habitat was identified as those locations where the predicted probability of finding snow crab derived from posterior predictive simulations (Gelman and Hill 2007; e.g., Figure 10) was > 0.05 or when the 95% confidence interval of the probability of observing crab did not intersect 0.

The biomass and numerical densities of crab was predicted upon this dynamically changing habitat surface using a lognormal GAM. As such, the approach is a hierarchical modeling (*sensu* Gelman and Hill 2007) of presence and absence (0, 1) followed by the modeling of abundance, the non-zero elements. The same covariates used for the habitat model entered into the abundance model (Table 6; Figure 9). Total abundance indices and associated confidence bounds of each component of the snow crab population was estimated using conditional posterior predictive simulations. For the fishable biomass, the combined models accounted for approximately 50% of the total variance (Table 6; Figure 11). Ideally, a Generalized Additive Mixed Effects Model (GAMM) is most appropriate given the hierarchical nature of the spatial covariates; however, such methods required computational resources (RAM > 64 GB) and computational time (CPU) beyond that which is currently available or practical.

## 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. However, empirically determined fishable biomass estimates are used in preference over modeled estimates until such a time that more data years stabilize the modeled results. See Appendix 2 for more details of methods. Bayesian state space methods are used to estimate the parameters of this model and associated Harvest Control Reference Points. See Appendix 3 for a general background to the 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 (Brodziak and Link 2002; Koeller et al. 2000, 2006;

Choi et al. 2005a). Indicators were made directly comparable to one another 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), 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.

## 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 to 280 m and between temperatures of -1 to 6 $^{o}$C (Figure 9). Near 7 $^{o}$C, metabolic costs are thought to match metabolic gains (Foyle et al. 1989) though snow crab have been observed above the “break-point” temperature in S-ENS. 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, 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; Sainte-Marie 1993). The actual range of fecundity is, however, 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 larvae become pelagic, feeding upon the plankton for three to five months (zoea stages 1 and 2 and then the megalopea stage). 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 frequency of molts decline, molting occurring once a year in the spring 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 (see Results). Just prior to the terminal molt, male crab may skip a molt in one year to molt in the next (Conan et al. 1992). Male snow crab generally reach legal size (≥ 95 mm CW) by the 12th instar; however, a variable fraction of instar 11 snow crab are also within legal size. Male instar 12 snow crab represent an age of approximately nine years since settlement to the bottom and 11 years since egg extrusion. Thereafter, the life expectancy of a male 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 (CC 5), the shell decalcifies and softens, often with 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). 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

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 1). The key environmental, social, economic and fishery-related indicators were identified and summarized as standardized residuals in Figure 13.

The first axis of variation accounted for 18% 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). Gross Domestic Product (GDP) associated with the Oil and Gas sector, as well as total Nova Scotia GDP, were also influential factors that have also been increasing. Further, PCB (polychlorinated byphenyl) levels in Atlantic puffins and grey seals have been declining, as has the physiological condition of many groups of fish. However, the total number of shellfish closures have increased with time, as has the amount of seismic activity. Increasing ocean colour and abundance of diatoms and dinoflagellates, and declining abundance of *Calanus finmarchicus,* were also influential to the first axis of variation. 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 9% 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- and S-ENS, respectively. As commercially exploitable snow crab require nine years or more from the 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- and S-ENS, respectively). For S-ENS, these time-lines 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 discussed below, in brief.

## 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.

### 1. 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. 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 (Ichthyoplankton Sampling program 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 Precautionary Approach (PA) to the conservation of large mature males (i.e., reduced exploitation rates) to allow them to mate with the more rapidly maturing females.

### 2. Movement

Spaghetti tags have been applied opportunistically to monitor snow crab movement since the early 1990s (Table 7; figures 15, 16). To encourage participation, a reward program exists and an online alternative for submitting the tag recapture information has been developed.

Movement information was primarily limited to single recaptures of mature, terminally molted male crab as crab cannot survive a molt once a tag is applied and tag returns are from the male-only snow crab fishery. They suggest that while snow crab do not move very large distances, the potential connectivity between regions even at the large benthic stages are still high. The movement of immature and female crab is not known and remains a source of uncertainty. Anecdotal information from other regions and fishers suggests seasonal patterns but none have yet been discerned for the SSE.

Since 2004, 11,147 tags have been applied and 802 recaptures (7.2%) have been reported. An unknown proportion of tag recaptures are not reported. These unreported captures are detrimental to understanding movement patterns and increases the cost per unit of information on movement. For example, if an annual exploitation rate of approximately 20% is assumed and a (pessimistically) high tagging-related mortality of 50% is assumed, at least 10% of the marked crab would be expected to be recaptured in the next year. Only 7.2% of the marked crab are reported to have been captured over all years. Anecdotal information suggests that fishers do not always report recaptures. Since 2004, there have been 123 individuals who have reported captures and there have been 802 total captures (Table 8). On average, each person participating has reported six or more different captures. This supports the belief that other fishers capture tags without reporting them.

Of the 802 tags recaptured, 348 are known to have been returned to the water and 44 of these have been captured again at least once. Tracking crab over multiple captures will give further insight into their movement and possibly help to provide a better idea of movement patterns over the life of the crab. When subsequent recaptures are reported, all people who previously captured that particular crab are notified of the additional movements in a report.

Crab recaptured within 10 days of initial release are not included in the following summary as this short-term movement could easily be caused by water currents moving crab as they settle to the bottom, etc. On average, crab tagged between 2004 and 2012 were recaptured in the season following the tagging event (mean time to recapture was 315 days), with the longest time interval between release and initial capture being 1,379 days. This crab had moved 30 km in that four year period. Very few returns of over two years from tagging are reported. Tagging is done on a vessel while it is directing for crab, so tags are generally applied where fishing effort is high. This, and high natural mortality, may be the reason for the majority of the returns being from crab captured in the same season or the season following tagging (Figure 16).

The average distance travelled was 17.9 km, with a maximum distance traveled of 281 km. Thus, locomotory capacity can be very large. The average rate of movement was 2.7 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 point to point displacement rate of 2.01 km/month, slightly higher than S-ENS (1.71 km/month). In 4X, the displacement rate is similar to S-ENS at 1.74 km/month (Table 8). However, please note the small sample size and high variability. In 2012, the point to point displacement rate from all areas was 2.12 km/month (3.75 km/month in 2011). There does not appear to be a pattern of preferred direction of overall movement for tagged snow crab. Patterns of directional movement are most apparent in N-ENS between different years, though these may reflect relative changes in fishing location patterns rather than the actual movement of crab (Figure 16).

From 2004-2011, movement between N-ENS and S-ENS was seldom observed. However, in 2012, there have been three returns that demonstrate movement between these areas, two of these with movement into the Glace Bay Hole from CFA 23. In the past, fishers in the Glace Bay Hole have explicitly stated that they would not report tagged crab recaptures. There have been five returns coming from Glace Bay Hole in 2012, and it is hoped that an effort to return tag data continues in this area. Prior to 2004, movement between N- and S-ENS was observed, and it is being observed again in 2012. Fishing pattern, water movement, relative abundance levels and predator and prey fields may all effect the movement between and even within a given management area.

Tags have been deployed on the ENS/Gulf line in 2011 and 2012. Returns from crab tagged in 2011 suggest significant movement from N-ENS into the Gulf during the 2011 and 2012 seasons (Figure 15). Tag returns from crab tagged near the ENS/Gulf line in 2012 have not yet been received. The apparent unidirectional nature of this movement (from N-ENS to Gulf) is confounded by the fact that there has been no tagging program in the Gulf region in recent years (M. Moriyasu, personal communication). As such the true degree of connectivity between the Gulf and N-ENS is still indeterminate. If the observed movement along the ENS/Gulf line continues to appear to be unidirectional, additional tracking methods may need to be explored.

Within S-ENS from 2004-2012, it appears there is net movement out of Area 23 into Area 24 (Figure 15), though this may result from higher opportunistic tagging on the Area 23 side of the Area 23-24 line.

It is believed that reporting of tags recaptured in 4X is much higher than other areas. Of the 100 tags deployed in 2011, 22(22%) have been captured once. Of these, 6(27%) were captured a second time and 2(33%) of the six were captured again. All of these captures occurred within the same season. There has yet to be any substantial movement observed between 4X and SENS. Directed tagging focusing on boundary lines between areas (Gulf/N-ENS, S-/N-ENS, S-ENS/4X) will continue to help determine the movement patterns between management areas.

We ask that captured 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.

## 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, 17). For example, prior to 1986, the Shelf was characterized by relatively warm bottom waters, 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 waters, a high volume of cold-intermediate layer waters, 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 build up to very large level 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 is an important hypothesis. Further, it is important to note that bottom temperatures in the distributional centers of snow crab have been increasing consistently since the early 1990s 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.

The surface area of potential snow crab habitat in the SSE was above the long-term mean in all areas and is actually closer to the maximum for the reference 1998-present period. Potential snow crab habitat was present (Figure 18). In N-ENS, the surface area of predicted snow crab habitat has varied between 5.4 to 9.0 × $10^3$ $km^2$ and is currently at higher levels than the 1998-2011 mean. For S-ENS, the surface area of potential habitat has varied with similar oscillations, ranging from between 45 to 95 × $10^3$ $km^2$ and is currently at higher levels than the 1998-2011 mean. In 4X, the southern-most limit of the distribution of snow crab, potential habitat has been variable, ranging from near zero to 25 × $10^3$ $km^2$ and has recently dropped rapidly with a strong warming event in 2012.

Temperature variations within the areas of potential habitat appeared to be robust throughout the historical record (Figure 19). Average bottom temperatures in 2012 were, however, generally warmer in all areas and indeed have been on a warming trend since the early 1990s. Within the area that may be considered potential snow crab habitat, average bottom temperatures were generally stable with long-term means of 3.4, 3.8 and 5.3°C in N-, S-ENS and 4X, respectively (Figure 19). Average bottom temperatures in 2012 were, respectively, 4.5, 5.8 and 8.1°C.

## 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.

Historically, the known predators of snow crab have been, in order of importance: Atlantic halibut (*Hippoglossus hippoglossus*), skates (especially thorny skate, *Raja radiata*), Atlantic cod (*Gadus morhua*), seals, American plaice (*Hippoglossoides platessoides*), squids, and other crabs (Bundy 2004). In particular, Atlantic cod (Figure 20) and thorny skate (Figure 21) have been noted for their high selectivity for snow crab and, therefore, their potential to weaken recruitment to commercial sizes (Bailey 1982; Lilly 1984; Robichaud et al. 1989, 1991). Certainly, in the inshore areas of the Scotian Shelf, the anecdotal information that extremely high densities of these early stage snow crabs are found in lobster traps indicates some degree of habitat overlap with adult lobsters. This suggests that one hypothesis for the current increase in lobster abundance in ENS may in part be related to the food base that the juvenile snow crab represent to lobsters. Predation levels upon small immature crabs are also likely to be on the rise in certain offshore areas. High local densities of these more traditional groundfish are found in areas where small immature crab are found in high densities. However, the trends in abundance and condition of groundfish and gadoids in particular continue to be in an impoverished state (Figure 13).

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 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 may be having a positive influence by physically importing food and food waste (organic matter) 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).

Gut analysis of fish species sampled on the SSE suggests that there are no predators that specialize upon snow crab (Table 8 in Choi and Zisserson 2012). The fish species found to most frequently prey upon snow crab was the Atlantic wolfish (3.5% of the guts sampled since the year 2000 contained snow crab, n = 253 guts). However, as total predation mortality is dependent upon the numerical abundance of the predator, and as the abundance of Atlantic wolfish and sculpins are thought to be low, their overall influence upon snow crab mortality is likely to be minimal. The formerly numerically more dominant groundfish likely exerted greater total predation mortality upon snow crab than these more specialized predators. Amongst these potential predators of snow crab, only cod, American plaice and yellowtail flounder are found in co-association with snow crab (Figure 22). A strong negative relationship with snow crab was, however, only found with wolfish species, possibly associated with differing habitat preferences (Table 9 in Choi and Zisserson 2012).

## 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; Bundy 2004) indicate that the primary food items of larger (mature) crab are, in order of importance: echinoderms, polychaete worms (*Maldane* sp., *Nereis* sp.) and other worm-like invertebrates, detritus, large zooplankton, shrimps, smaller juvenile crabs (rock crab, *Cancer irroratus*; toad crab, *Hyas coarctatus;* lesser toad crab, *Hyas araneus*), ocean quahog (*Artica islandica*), bivalve molluscs (e.g., *Mytilus edulis, Modiolus modiolus*), brittle stars (*Ophiura sarsi*, *Ophiopholis aculeata*) and sea anemones (*Edwardsia* sp., *Metridium senile*). Smaller snow crab have been observed to feed upon, in order of importance: echinoderms, polychaete worms, large zooplankton, detritus and bivalves (e.g., *Mytilus edulis, Modiolus modiolus, Hiatella arctica*). 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 13).
- The recent proliferation of northern shrimp (*Pandalus borealis*), another detritivore and also a potential food item of snow crab (figures 13, 23) was co-incident with the rise in abundance of snow crab.
- The demise of the groundfish that would competitively feed upon benthic invertebrates (Figure 13).

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.

## LATERAL CONTROL (COMPETITION)

Lateral (and internal) influences refers 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 groundfish; thus, the demise of groundfish in the late 1980s and early 1990s would have been doubly beneficial to snow crab: 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 (figures 22-24). A strong negative relationship was not found between snow crab and other bycatch species (Figure 22; see also Table 9 in Choi and Zisserson 2012), suggestive of little competitive interactions.

## DISEASE

BCD is observed in crustaceans throughout the world, though most-commonly in the northern hemisphere (Stentiford and Shields 2005). The name rises from the bitter (aspirin-like) taste, which infected animals exhibit once cooked, rendering them unmarketable. BCD infections in snow crab have been observed in Alaska, Newfoundland, Greenland and 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 Eastern Scotian Shelf (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 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) animals. 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 26) across a wide range of sizes (20-100 mm CW; Figure 27), though, generally, in immature animals. 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.

## 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.

### 1. Bycatch of Snow Crab in Other Fisheries

The bycatch of snow crab in other fisheries remains an area requiring attention. The spatial distribution of northern shrimp (*Pandalus borealis*) overlaps with that of snow crab and so represents an industry that requires particular attention. 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 due to their capture in lobster traps and (illegal) use as bait. This has been stated by fishers to be more prevalent in 4X. Additionally, bycatch of snow crab in Danish seines has been reported from the limited flatfish fisheries on the Scotian Shelf.

### 2. 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, 11). In ENS, a total of 12,229 t of snow crab were landed in 2012 with associated estimates of bycatch at 2.6 t (0.02% of snow crab landings). 4X shows higher (relative to ENS) bycatch rates, with a total estimated bycatch of 0.6 t associated with 345 t of snow crab landings (0.2%).

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 nets (at a minimum 5.25” knot to knot).

The majority of bycatch for all areas is 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 the three year record, observers reported two leatherback turtles as having been entangled in buoy lines (2010 and 2012). These turtles were both reported to be released alive though bleeding slightly. A dead basking shark was observed entangled in buoy lines in 2011. Additionally, a humpback whale was observed entangled in buoys lines in 2012 but this animal was released with very minimal damage (slight lacerations around tale area from rubbing of ropes) with a small amount of rope still attached loosely to the whale. The crew of the vessel “did everything in their power to remove the whale from the gear without harming it”. (Javitech Ltd., personal communication)

### 3. Oil and Gas Exploration and Development

The interests of the Oil and Gas industry to explore and develop areas in the SSE near to, upstream of, or even directly over major crab fishing grounds and population centers (both N- and S-ENS) has been identified by numerous fishers as a source of concern. Seismic exploration activities continue in the SSE (Figure 13). The potential effects of these seismic methods of exploration upon vulnerable components of the snow crab population and the uncertainties associated with the long-term effects of drilling and extraction include the following:

- Reproductive females can hold eggs for up to two years. Also, snow crab mating behavior is complex, and the disruption of their mating rituals is particularly likely as the courting/mating period can last up to several weeks. This can modify the reproductive/regenerative capacity of the snow crab resident in the SSE. Damage to eggs and modification of reproductive behavior can have lasting influences upon the population and fishery.
- Soft-shelled crab are particularly sensitive to physical trauma. Immature snow crab are found in shallower waters. In terms of seismic methods of exploration, the shallower areas are an important area of concern as the magnitude of seismic energy reaching the bottom will be much greater than in deep-water offshore applications.
- No information is available for the effects of seismic pressure waves upon the planktonic forms of snow crab. This is particularly important for the megalops which are generally found near areas of rapid water density changes (thermoclines and haloclines). Such areas of rapid density change represent areas where the influence of seismic energy upon biota is extremely uncertain as the nature of the seismic energy can be altered.
- Snow crab are known to jettison legs or die when physically shocked (i.e., dropped onto the deck of a boat). This is an important unknown especially as pressure waves can be amplified and wavelengths of pressure waves altered when moving through media of differing densities (e.g., when they are burrowed in mud).
- Being a very long-lived species, the snow crab is exposed to environmental hazards for up to 16 years (since egg extrusion). As such, simple short-term studies (of a few days duration) do not describe the more difficult questions of long-term, compounded (cumulative) effects of seismic energy and Oil and Gas exploration and development upon snow crab. This is a very large uncertainty.
- Snow crab are important benthic predators. Bioaccumulation of heavy metals and toxic organic chemicals released from Oil and Gas exploitation is possible, especially as they

are so very long-lived. The potential creation of anoxic conditions from drilling is also of concern. Any damage to the health of snow crab can be detrimental to the reproductive capacity of the population which in turn can also have subsequent economic repercussions. A baseline level for bioaccumulation of such products has been established for commercial sized crab on the Scotian Shelf.

The snow crab fishery was an early adopter of the spirit of the PA, well before the formal implementation of the PA in 2012. Yet seismic and Oil and Gas exploration continues even though numerous uncertainties associated with such Oil and Gas exploration/development activities increases the risk of destabilizing the snow crab population in the SSE. The Hunt Oil Company completed seismic exploration directly over the Glace Bay Hole (an area of high abundance of commercial crab) and the Sidney Bight (a refuge area for immature and female crab) in November 2005 (Hunt Oil 2005). Husky Energy, in July 2010, also conducted additional seismic studies over the Sidney Bight (Husky Energy 2010). Others seismic studies continued on Artimon Bank, Banquereau Bank and the Stone Fence in 2009 and 2010 (RPS Group 2010).

### 4. 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, NL to Point Aconi, NS (Emera 2013) to transport electricity from the Lower Churchill Hydro-electric project. These cables, laid directly through the most productive snow crab fishing grounds of N-ENS, will be spaced by up to 200 m. They may create a barrier to normal snow crab movement through static magnetic fields (and/or associated) induced electrical fields or as direct physical barriers created as a result of trenching activities and substrate disturbance. At present, there is no information that can be presented to definitively describe their effects upon snow crab.

### 5. 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 946,000 people in 2011, 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 232 kt to 52 kt in the province of Nova Scotia. Similarly, the pelagic fish landings have decreased from 125 kt to 61 kt. In contrast, invertebrate landings have increased from 111 kt to 140 kt since the 1990s as has the total landed value for all fisheries combined, increasing from $445 million in 1990 to $847 million in 2003. It has declined since then to $750 ($627 from invertebrates) million due in part to falling prices of seafood in past seasons. The shift has, therefore, been to increasingly exploit less so in bulk quantity but rather focus upon higher priced species that provide better cost-benefit returns.

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 a 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.

### 6. Marine Protected Areas

St. Anns Bank area has been identified as an Area of Interest (AOI) for designation as a Marine Protected Area (MPA). The consequences 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 fallow area. However, if the reserve is disproportionately beneficial to other organisms, be they predators of snow crab or prey items of snow, the effects upon snow crab can be mixed. The long-term effects of the AOI/MPA cannot be determined at this point.

## 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 has since declined to just under 70% of landings. The 2012 fishing effort (Figure 28) was focused on the trench of deep water located along the north-eastern coast of Cape Breton (formerly CFAs 21 and 22 Inside) with some minimal efforts in the Glace Bay Hole. No fishing occurred on the northern-most portion of N-ENS along the CFA 19 line as had occurred in past seasons. This was likely associated with strong tides confounding fishing efforts during the spring season.

In S-ENS, fishing effort continues to be focused on offshore fishing grounds in both CFAs 23 and 24. Much of the fishing effort in CFA 23 still continued to be focused on the holes found between Misaine and Banquereau banks, though additional effort was observed in the inshore/ mid-shore “bad neighbours” area particularly during the spring. There was a complete absence of effort in the western-most portion (along the “Eastern Shore”) of CFA 24 towards the 4X line though some minimal effort did occur along the “Eastern Shore” in 2012 as in 2011. This area had been unfished for a number of seasons before 2011. Summer fishing efforts in CFA 24 were not as heavily focused on the Sable Island (“44’10 line”) as they had been in past seasons but focused more on the mid-shore area north and east of Middle Bank. In both CFA 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”). Previous to 2010, less than 20% of S-ENS landings occurred prior to July 1st, whereas now over 60% of total landings occur in this spring period.

In 4X, the fishing effort was focused on three main areas: south of Sambro, south of Lunenburg and west of Roseway Bank. In the past two seasons, a shift in the most heavily fished area has occurred from the Sambro area to the western-most portion of the fishing grounds, west of Roseway Bank.

In 2012, a total of 5,126 and 120,015 trap hauls were applied in N- and S-ENS, respectively. In 2011/2012, a total of 11,813 trap hauls were applied in 4X (figures 2, 28).

### Landings

Landings in 2012 for N-ENS and S-ENS were 603 and 11,707 t, respectively, and they were 345 t in 4X for the 2011/2012 season, representing an increase of 13% (N-ENS), a decrease of 4% (S-ENS) and no change relative to the previous year (figures 3, 29). TACs in 2012 were 603 t, 11,733 t and 346 t in N-ENS, S-ENS and 4X.

### Catch Rates[1]

Non-standardized catch rates in 2012 were 117 kg/trap haul in N-ENS, 98 kg/trap haul in S-ENS, and 29 kg/trap haul in 4X in 2011/2012 – representing an increase of 6%, and decreases of 8% and 24%, respectively, relative to the previous year.

In N-ENS, the 2011 catch rates were 117 kg trap$^{-1}$, a slight increase relative to 2011 (110 kg trap$^{-1)}$ . N-ENS catch rates are the highest on record since 1997 and well above the 10 year mean (62 kg trap$^{-1}$; Figure 4; Table 2). The spring fishery had a higher proportion of legal sized, hard crab in the at-sea-observed records. The spatial distribution of catch rates in N-ENS was uniformly high (Figure 30a) with localized maxima in the Glace Bay Hole area. In the past, catch rates in N-ENS were often quite variable within the entire area with pockets of high (or low) catch rates. This was not the case in 2012. Catch rates across the area were uniformly high at levels above those experienced by fishers in S-ENS for a much longer time frame. Catch rates from the summer fishery (Figure 30b) were somewhat higher than those experienced in the spring fishery in 2012. This may be caused in part by reduced effort during the summer fishery relative to the spring fishery.

In S-ENS, the 2011 catch rates were 98 kg trap$^{-1}$, an 8% decrease relative to 2011 and just below the 10-year mean of 100 kg trap$^{-1}$ (Figure 4; Table 3). It is noteworthy that the catch rate for CFA 23 remained constant from 2011 but the catch rate for CFA 24 decreased by 14%, accounting for the overall decrease of catch rates in S-ENS. Catch rates were uniformly moderate throughout the majority of the exploited fishing grounds in S-ENS with the highest localized catch rates located in CFA 23, between Misaine and Banquereau banks (Figure 30). 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") can lead to short-term localized depletion in available fishing grounds during spring fishing activities. Examination of weekly catch rates over the course of the 2012 season (Figure 30b) shows a relatively consistent catch rate over the course of the season in CFA 23 with declining catch rates over the final six weeks of the fishing season. However, CFA 24 shows a general declining trend in catch rates over the course of the entire past season. 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.

In 4X, the 2011/2012 catch rates were 29 kg trap$^{-1}$ (Table 4) a decrease of 24% from the 2010/2011 catch rate which was the highest on record for the nine year time series. The 4X catch rates remain consistently below those of N-and S-ENS other than the 2005-2008 impoverished period in N-ENS. Calculation of longer-term averages in 4X is impossible due to shifts in the gear complement (both size and number of traps used) over the past ten seasons. Weekly catch rates in 4X (Figure 30b) generally show an oscillating pattern over the course of

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

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. 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 just exceeded the target level of 5% of the TAC, at 6.5% (figures 5, 31). A total of 56 traps were sampled (approximately 1.1% of commercial trap hauls). In S-ENS, 9.1% of the TAC was observed (with a target level of 10%). A total of 2,170 traps (approximately 1.8% of commercial trap hauls) were sampled. In 4X, 6.1% of the TAC was observed, relative to a target level of 10% and a total of 670 traps were sampled.

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

In N-ENS, CC1 and CC2 crab collectively represented approximately 3% of the total catch (Figure 31), similar proportions relative to 2011. This is a substantial reduction from 2008 and before, when most (or all) of the landings came from the summer fishing season. The spring season (2008-present) was adopted to reduce fishing intensity in this summer season and also to encourage fishing during the earlier period when newly molted crab are too weak and soft to easily enter into traps. As expected, landings during the spring fishery have had negligible collective catches of CC1 and CC2 crab (<1%), whereas this climbs to over 6% for the summer fishery. Incidentally, much lower levels of soft crab (Figure 32b) were observed by at-sea-observers in the spring fishery as compared to the summer fishery. High incidence of soft-shelled crab in the summer fishery has been suggested anecdotally as being a result of localized depletion of hard-shelled males and a consequent increased trapability of soft-shelled males due to the lack of competition/inhibition.

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 though the summer fishery show a much higher incidence of soft crab. If one assumes no recaptures, this amounts to an additional 54 t (8.9% of landings) being discarded as soft crab with potentially high handling-associated mortalities. This increases from only 1.7% in 2011. This increase is likely associated with a return to more summer fishing activities in 2012. A continuation of spring fishing efforts and the potential implementation of area closures during the summer fishery based on observer reports and shorter summer fishing period will likely help to continue to control the potential total mortality of soft-shell crab in future seasons.

In S-ENS, the occurrence of CC1 and CC2 crab in 2012 (0% and 10%, respectively) was similar to that observed in 2011 (1 and 10%, respectively; Figure 31). Catches of high soft-shell percentage (> 20% by count) were widely distributed throughout the fishing grounds in both CFAs 23 and 24 during the 2012 fishery, as was the case in 2011 (Figure 32a). When extrapolated to the S-ENS TAC, this amounts to a potential additional mortality of 747 t (6.3% of landings). This relative occurrence of soft-shell crab in the catch is consistent with the 2011 value of 5.5% and continues to improve upon the soft crab catches of 8% and 16% in 2010 and 2009, respectively. These reductions are primarily associated low capture rates of soft crab in the spring (Figure 32b). Voluntary closures 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 was not always the case in the past three seasons. There is miscommunication as quotas are sold through processors and other brokers 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 2011/2012 season, CC1 and CC2 crab collectively represented less than 2% of the total catch and are comparable to 2010/2011 (Figure 29). The data from 4X are not directly comparable to ENS as their fishing season is disjunct from that of N- and S-ENS. This winter, 4X fishery continues to show negligible levels of soft crab.

**Old Crab (CC5)**

CC5 crab represented a low proportion of the 2010 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).

# RESOURCE STATUS

## SIZE STRUCTURE

A strong size-class of male crab, first detected in 2003 (30 to 40 mm CW) began entry into fishable sizes by 2007 in S-ENS, 2008 in N-ENS and 2009 in 4X (Figure 33). In S-ENS, the presence of small immature 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, a pulse of crab was detected in the 20-40 mm CW range as it was in 2011, likely resulting from females reproducing in 2008-2010. However, the “gap” in the smaller size classes of crab has widened from 20-50 mm in 2010, 20-60 mm in 2011 to 20-85mm in 2012. This ever-widening gap in recruitment may indicate that the smallest size classes (20-40 mm) of snow crab in N-ENS are experiencing higher mortality than other regions. This lack of sub-legal snow crab in N-ENS will likely result in depressed recruitment in the next four to five years without an immigration of crab from adjacent crab fishing areas (CFAs 19 and 23).

Area 4X shows little potential for substantial internal recruitment to the fishery in the next three to four years. Movement has likely been an important source of crab in the past. However, the low abundance of both the mature and immature crab in the adjoining portion of Area 24 and erratic temperature fields in 4X create strong uncertainties for the future.

The size frequency distributions of female snow crab show strong size-classes, first detected in 2003 for N-ENS and in 2004 for S-ENS, which peaked in 2007/2008 (Figure 34) and have subsequently declined. Female snow crab in all areas appear to be completely recruited as of the 2012 survey with a distinct lack of immature snow crab in all areas. Current egg and larval production is expected to be low in both S-ENS and 4X and nearly non-existent in N-ENS (figures 41, 42). This is potentially worrisome, though a similar situation was observed in approximately 2000/2001 with a strong return of female snow crab after that time. Additionally, larval drift may occur from outside the SSE to help bolster recruitment.

Size frequency distributions in 4X exist in a very erratic state, with less annual consistency as compared to N- and S-ENS. The large temperature fluctuations in the area and the different predator fields associated with the warmer waters in the area and potentially high movement with Area 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, can 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.

There is a high likelihood that sex ratios will naturally fluctuate over time (Figure 35). 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 of the SSE. In the SSE, the sex ratios of mature snow crab have been oscillating with peaks observed in 1996 and again in 2007 with a major trough in the early 2000s (figures 35, 36). Currently, sex ratios of mature crab have further with the ageing and mortality of reproductive females. Area 4X sex ratios of mature crab are very near 50%.

The sex ratios of immature snow crab (Figure 37a) are currently, between 20 to 40% 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 37b). When such spatial segregation is observed, the sexes are likely exposed to differential predation effects. Immature females are likely fed 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.

Primiparous females mate during their molting period, a period when they are highly vulnerable (Watson 1972; Hooper 1986). If their mate is small and unable to definitively defend against other potential mates, females have been observed to be torn apart during the agonistic behavior (fighting). When potential mates are small, females have been observed to refuse mating and in the process of refusal are also killed. Thus, an abundance of large males would certainly increase the likelihood of successful reproduction for pre-primiparous females. Further, in an evolutionary context, if heavy fishing of large males causes increased mating with early maturing dwarf sized males, a greater selection for such traits would be passed onto future generations, potentially leading to stunted populations (a trend observed in many highly exploited species). This, however, is a genetic effect occurring over generational time scales. It is important to note that phenotypic plasticity can accelerate these rates of morphometric change in this adaptive species.

## NUMERICAL ABUNDANCE[2]

The number of immature females caught in the trawl surveys has been increasing, reaching historical highs in 2005 and 2010 (Figure 39). Their numbers declined in 2007 to 2009 due to their entry into the mature segment of the population and the lack of smaller juvenile crab. Most immature females are primarily found in shallower areas along the shore of mainland Nova Scotia and in offshore areas of CFA 24 (Figure 40).

[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.

In all areas, the numerical abundance of mature females declined to intermediate levels after reaching peak levels in 2006 to 2008 (Figure 41). Most of the mature females are currently located in small areas throughout the SSE (figures 42, 43).

The numerical abundance estimates of CC5 crab are close to being undetectable in the SSE by the trawl survey (tables 15-17).

## FISHABLE BIOMASS

The post-fishery fishable biomass index of snow crab in N-ENS was estimated to be 3,130 t, relative to 3,430 t in 2011 (figures 44-46). In S-ENS, the post-fishery fishable biomass index was $34.1 \times 10^3$ t, relative to $35.4 \times 10^3$ t in 2011. In 4X, the pre-fishery fishable biomass was 1.7 t, relative to 2.4 t in 2010/2011. However, the latter values for Area 4X should be considered preliminary until further analysis is conducted as the area experienced extreme temperature conditions in 2012.

## RECRUITMENT

The index of recruitment, into the fishable biomass (mature CC1 and CC2, > 95 mm CW; figures 47, 48) has decreased from highs in 2007 in S-ENS and 2008 in N-ENS. It is at low levels in N-ENS and at intermediate levels in S-ENS based on the post-2004 (stable survey design) time series. Recruitment in 4X has been decreasing since 2010 and is low and variable. Most of this recruitment was observed on the core fishing grounds.

It must be emphasized that as the snow crab survey is conducted in late autumn (since 2002), an unknown and variable proportion of the annual recruitment would have also progressed into the mature fishable biomass or soft-shelled crab component; and the catchability of soft-shelled crab is likely reduced due to their behaviour of sheltering in rocky burrows. Thus, the recruitment index is only a partial index that is sensitive to annual variations in temperature, food availability and crowding, factors that control the onset of molting and the speed of shell hardening.

## FISHING MORTALITY

Fishing mortality in N-ENS has been estimated to have been in the range of 0.1 to 0.5, peaking in 2004 (figures 49-51). In 2012, fishing mortality is estimated to have been 0.11 and relatively constant since 2009. The low fishing mortality in 2008 was implemented to reduce soft-shell handling.

Fishing mortality for S-ENS has historically ranged from 0.05 to 0.25, peaking in 2003-2004 and in 2010 (figures 49-51). In 2012, fishing mortality is estimated to have been 0.21. Realized 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 considerable illegal landings in this area.

In 4X, fishing mortality has historically ranged from 0.2 to > 0.7, peaking in 2005 and only declining towards target levels since 2008 (figures 49-51). In 2011/2012, fishing mortality was 0.24. 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., un-fished 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). However, recent trends suggest an increase in the relative abundance of predators of snow crab. 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 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 2 and 3.

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 3), 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).

The operational reference points associated with the 4VWX snow crab fishery are as follows:

- **Lower Stock Reference (LSR)**: 25% of carrying capacity.
- **Upper Stock Reference (USR)**: 50% of 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 52) are as follows:

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

The current "carrying capacity" of fishable biomass of snow crab is estimated to be {and 95% CI}:

- N-ENS: 6.3 {4.1, 9.5} kt
- S-ENS: 67.9 {42.6, 97.4} kt
- 4X: 2.1 {1.6, 3.0} kt

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

- N-ENS: 0.48 {0.38, 0.58}
- S-ENS: 0.48 {0.38, 0.58}
- 4X: 0.44 {0.36, 0.52}

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

**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 precludes a simple r-parameter estimation.
- Large spatial and temporal variations in environmental conditions increase uncertainty in abundance indices and precludes 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, precludes 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 (10-20% of TACs) and variable over time. This is not accounted for.
- Alteration of survey timing from spring (pre-2004) to fall (post-2004). 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 regards to formulating more appropriate reference points:

- Describe environmental influence upon biological cycles (molting, mating, 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.

## RECOMMENDATIONS

### GENERAL REMARKS

1. Capture of soft-shelled is an ongoing 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 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 are allowed to grow and mature (an increase of 250 to even 400%; Figure 7).

   In the 2013 season, some of the > 95 mm CW will still be composed of immature individuals. 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 high (10 to 20% of reported landings) and continue to rise, predominantly in S-ENS. Such activities must 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. Such greed-driven illegal 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.

### S-ENS

The long-term, PA adopted by the S-ENS fishers since 2004 appears to be creating 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. S-ENS population is considered to be in the "healthy" zone (FB > USR). As the fishable biomass continues to be near historically high levels with recruitment expected for at least the next three to four years, there is considerable scope for flexibility. A status-quo to a marginal decrease in TACs is recommended.

### 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. Over the past three seasons, the harvest strategy adopted by fishers in N-ENS has been conservative with exploitation rates being closer to those adopted in S-ENS. The capture of soft-shelled crab has been nearly eliminated, helping to protect recruitment. Fishable biomass has also been relatively stable over the past three years and in the “healthy” zone (FB > USR). Three years of consistent and relatively high biomass estimates suggest that the estimates are reliable. This optimism is, however, for the short-term. In the medium to long-term, there is also a need to be mindful of the gap in recruitment which may limit the scope for flexibility in this area without immigration from other areas. A status quo 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 in 2012, high natural mortality is possible due to the extended period of warm bottom temperatures in the area. Soft-shell captures are not a concern in 4X. 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 in almost all years. This was not the case for 2011 and 2012, and adds further uncertainty in the stability of the fishable biomass. At present, fishable biomass is in the “healthy” zone (FB > USR). However, as recruitment and potential immigration into the 2011/2012 season is uncertain, a more conservative harvest strategy is recommended for the present.

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## TABLES

*Table 1: Snow crab fishing seasons on the Scotian Shelf in the year 2012.*

| Area | Season |
|---|---|
| N-ENS | Apr 14 – May 12 & July 18- Aug 30 |
| S-ENS (CFA 23) | Apr 2 – Sept 30 |
| S-ENS (CFA 24) | Apr 2 – Sept 30 |
| 4X | Nov 1 – March 31 (2013) |

*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) |
|---|---|---|---|---|---|
| 1998 | 74 | 660 | 657 | 42 | 15.8 |
| 1999 | 78 | 900 | 899 | 55 | 16.4 |
| 2000 | 79 | 1,015 | 1,017 | 68 | 14.9 |
| 2001 | 80 | 1,065 | 1,066 | 94 | 11.3 |
| 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 |

*Table 3: Summary of snow crab fisheries activity of S-ENS. Dash (-) in number of licenses represents the year where rapid alterations in number of licences occurred with the Marshall Decision.*

| Year | Licenses | TAC (t) | Landings (t) | CPUE (kg/trap haul) | Effort (x1000 trap hauls) |
|---|---|---|---|---|---|
| 1998 | 67 | 1,671 | 1,558 | 69 | 22.6 |
| 1999 | - | 2,700 | 2,700 | 71 | 38.0 |
| 2000 | 158 | 8,799 | 8,701 | 85 | 102.4 |
| 2001 | 163 | 9,023 | 9,048 | 88 | 103.1 |
| 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 |

*Table 4: Summary of snow crab fisheries activity of 4X.Data prior to 2002/03 (dashes).*

| Year | Licenses | TAC (t) | Landings (t) | CPUE (kg/trap haul) | Effort (x1000 trap hauls) |
|---|---|---|---|---|---|
| 1997/08 | 4 | - | 42 | - | - |
| 1998/09 | 4 | - | 70 | - | - |
| 1999/00 | 4 | - | 119 | - | - |
| 2000/01 | 6 | - | 213 | - | - |
| 2001/02 | 8 | 520 | 376 | - | - |
| 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[1] | 9 | 263 | 51 | - | - |

Note: [1]As of February 15, 2013. Season still in progress.

*Table 5: Snow crab carapace conditions 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: Analysis of deviance of fishable snow crab habitat (presence/absence) and positive-valued abundance modeled as binomial and lognormal Generalized Additive Models. The "s(.)" indicates a smoothed term. The factors were year (year), week number (weekno), climatological mean temperature (tmean), mean annual variations from the climatological mean (dt.annual), seasonal variations in temperature from the annual mean bottom temperatures (dt.seasonal), annual amplitude of temperature oscillations (tamp.annual), week number of annual temperature minima (wmin.annual), depth (z), bottom slope (dZ), substrate grain size (substrate.mean), species composition axis 1 (ca1), species composition axis 2 (ca2), expected species richness (Npred), curvature of the species-area relationship (Z), expected metabolic intensity (smr), expected total metabolic output (mr), and easting and northing (plon, plat). The combined predictive coefficient of determination is 79% of the total variation.*

**Habitat (presence-absence)**

| | edf | Ref.df | Chi.sq | p-value | |
|---|---|---|---|---|---|
| s(weekno) | 3.0 | 3 | 58.732 | 7.66e-13 | *** |
| s(tmean) | 8.6 | 9 | 66.678 | 1.04e-11 | *** |
| s(dt.annual) | 0.7 | 3 | 0.699 | 0.29002 | |
| s(dt.seasonal) | 2.4 | 3 | 9.453 | 0.00935 | ** |
| s(tamp) | 3.0 | 3 | 25.392 | 8.78e-06 | *** |
| s(wmin) | 1.5 | 3 | 15.784 | 5.83e-05 | *** |
| s(z) | 8.0 | 9 | 223.771 | < 2e-16 | *** |
| s(dZ) | 0.9 | 3 | 5.978 | 0.00533 | ** |
| s(substrate.mean) | 0.5 | 3 | 0.129 | 0.61166 | |
| s(ca1) | 3.0 | 3 | 879.936 | < 2e-16 | *** |
| s(ca2) | 0.9 | 3 | 5.130 | 0.01340 | * |
| s(Npred) | 3.0 | 3 | 118.060 | < 2e-16 | *** |
| s(Z) | 3.0 | 3 | 28.055 | 1.44e-06 | *** |
| s(smr) | 3.0 | 3 | 395.911 | < 2e-16 | *** |
| s(mr) | 3.0 | 3 | 518.980 | < 2e-16 | *** |
| s(plon,plat) | 174.4 | 249 | 1223.812 | < 2e-16 | *** |

R-sq.(adj) = 0.628 Deviance explained = 58.7%

**Abundance (positive-values)**

| | edf | Ref.df | F | p-value | |
|---|---|---|---|---|---|
| s(weekno) | 0.8 | 3 | 7.554 | 1.08e-08 | *** |
| s(tmean) | 2.2 | 9 | 2.356 | 1.54e-07 | *** |
| s(dt.annual) | 0.9 | 3 | 8.107 | 2.79e-09 | *** |
| s(dt.seasonal) | 1.0 | 3 | 2.901 | 0.000814 | *** |
| s(tamp) | 1.1 | 3 | 4.364 | 8.95e-05 | *** |
| s(wmin) | 1.0 | 3 | 6.809 | 1.18e-06 | *** |
| s(z) | 2.2 | 9 | 21.884 | < 2e-16 | *** |
| s(dZ) | 0.8 | 3 | 0.592 | 0.099724 | . |
| s(substrate.mean) | 0.8 | 3 | 1.524 | 0.003928 | ** |
| s(ca1) | 1.0 | 3 | 2.456 | 0.002349 | ** |
| s(ca2) | 0.9 | 3 | 44.433 | < 2e-16 | *** |
| s(Npred) | 0.7 | 3 | 0.587 | 0.079509 | . |
| s(Z) | 0.6 | 3 | 0.712 | 0.038548 | * |
| s(smr) | 1.6 | 3 | 802.204 | < 2e-16 | *** |
| s(mr) | 3.0 | 3 | 1480.462 | < 2e-16 | *** |
| s(plon,plat) | 72.8 | 249 | 4.766 | < 2e-16 | *** |

R-sq.(adj) = 0.795 Deviance explained = 79.9%

*Table 7: Tagging effort by year since 2008.*

| 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 |
|---|---|---|---|---|---|---|---|---|
| 2008 | 979 | 58 | 56 | 16.74 | 106.36 | 251 | 915 | 2.03 |
| 2009 | 195 | 12 | 11 | 16.12 | 49.38 | 352 | 734 | 1.39 |
| 2010 | 2256 | 153 | 142 | 27.86 | 118.44 | 369 | 822 | 2.30 |
| 2011 | 1789 | 66 | 66 | 38.08 | 137.83 | 309 | 458 | 3.75 |
| 2012 | 1676 | 86 | 73 | 5.55 | 27.20 | 79 | 105 | 2.12 |
| All Years/ Areas | 11147 | 802 | 758 | 17.87 | 281.07 | 315 | 1379 | 1.73 |

*Table 8: Tagging data by area.*

| Area | Tags Applied | Distinct Tags Returned | Avg. Displacement (km) | Avg. Days to Capture | Avg. km/month | Number of individuals Returning |
|---|---|---|---|---|---|---|
| S-ENS | 8114 | 526 | 18.99 | 336 | 1.72 | 70 |
| N-ENS | 2581 | 190 | 21.72 | 281 | 2.07 | 47 |
| 4X | 515 | 48 | 7.79 | 136 | 1.74 | 5 |

*Table 9: Prevalence of BCD on the Scotian Shelf.*

| 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% | 70% |

*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 approximately 0.02% of snow crab landings for the past three years in ENS.*

| Species | 2010 | 2011 | 2012 | 3-Year Total |
|---|---|---|---|---|
| American Lobster | 65 | 34 | 0 | 99 |
| Witch Flounder | 12 | 0 | 0 | 12 |
| Northern Stone Crab | 1366 | 34 | 45 | 1445 |
| Redfish | 73 | 0 | 89 | 162 |
| Sea Cucumber | 148 | 68 | 668 | 884 |
| Spotted Wolffish | 313 | 56 | 189 | 558 |
| Striped Wolffish | 116 | 0 | 33 | 149 |
| Northern Wolffish | 0 | 0 | 22 | 22 |
| Sand Dollars | 35 | 0 | 0 | 35 |
| Toad Crab | 35 | 385 | 367 | 787 |
| Atlantic Cod | 278 | 307 | 724 | 1309 |
| Starfish Sp. | 0 | 11 | 0 | 11 |
| Northern Shrimp | 0 | 22 | 0 | 22 |
| Jonah Crab | 0 | 340 | 11 | 351 |
| Eelpout | 0 | 0 | 22 | 22 |
| Sculpin | 0 | 0 | 11 | 11 |
| Ocean Pout | 0 | 0 | 22 | 22 |
| Seals (NS) | 0 | 0 | 334 | 334 |
| Skate (NS) | 0 | 0 | 22 | 22 |
| Atlantic Rock Crab | 0 | 11 | 0 | 11 |
| **Snow Crab Landings** | **13,717,290** | **12,135,000** | **12,310,000** | **38,162,290** |

*Table 11: Bycatch (kg) estimates from the 4X snow crab fishery. The estimates are extrapolated from at-sea-observed bycatch and at-sea-observer coverage, by biomass [i.e., estimated biomass of bycatch = observed biomass of bycatch species / (observed landings of snow crab / total landings of snow crab)]. Bycatch levels have been at 0.17% of total landings in the past three years, with most bycatch species being other crabs and lobster.*

| Species | 2010 | 2011 | 2012 |
|---|---|---|---|
| Jonah Crab | 59 | 34 | 16 |
| Northern Stone Crab | 220 | 314 | 540 |
| Deepsea Red Crab | 0 | 2570 | 33 |
| American Lobster | 59 | 213 | 0 |
| Toad Crab | 44 | 0 | 0 |
| Lumpfish | 0 | 11 | 0 |
| Redfish | 0 | 22 | 0 |
| Thorny Skate | 0 | 56 | 0 |
| **Snow Crab Landings** | **229,443** | **345,220** | **344,687** |

*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 |
|---|---|---|---|---|---|
| 2004 | 1.63 | 5.23 | 72.36 | 20.33 | 0.44 |
| 2005 | 5.48 | 8.65 | 65.88 | 19.11 | 0.89 |
| 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 |

*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 |
|---|---|---|---|---|---|
| 2004 | 2.29 | 4.18 | 74.56 | 18.19 | 0.78 |
| 2005 | 4.94 | 11.42 | 68.48 | 14.42 | 0.74 |
| 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 | 8.34 | 7.43 | 64.73 | 16.97 | 2.53 |
| 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 |

*Table 14: Carapace condition of crab ≥ 95 mm CW (percent by number) over time for 4X from at-sea-observed data.*

| Year | CC1 | CC2 | CC3 | CC4 | CC5 |
|---|---|---|---|---|---|
| 2004/05 | 0.05 | 1.97 | 93.56 | 4.36 | 0.05 |
| 2005/06 | 0 | 11.79 | 84.96 | 3.22 | 0.04 |
| 2006/07 | 0.05 | 0.5 | 98.01 | 1.44 | 0 |
| 2007/08 | 0.18 | 0.09 | 78.75 | 20.75 | 0.23 |
| 2008/09 | 0.32 | 0.16 | 56.98 | 42.47 | 0.08 |
| 2009/10 | 0.04 | 0.5 | 98.89 | 0.57 | 0 |
| 2010/11 | 0.25 | 1.23 | 54.28 | 44.17 | 0.07 |
| 2011/12 | 0.05 | 0.17 | 94.37 | 5.32 | 0.1 |

*Table 15: Carapace condition (CC) of crab ≥ 95 mm CW (percent by number) over time for N-ENS from trawl surveys. The transition from a spring to a fall survey occurred in 2002/2003. Crude unadjusted proportions.*

| Year | CC1 | CC2 | CC3 | CC4 | CC5 |
|---|---|---|---|---|---|
| 2003 | 4.42 | 18.92 | 57.25 | 18.67 | 0.74 |
| 2004 | 0 | 4.48 | 51.74 | 39.3 | 4.48 |
| 2005 | 0 | 0 | 51.63 | 35.29 | 13.07 |
| 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 |

*Table 16: Carapace condition (CC) of crab ≥ 95 mm CW (percent by number) over time for S-ENS from trawl surveys. The transition from a spring to a fall survey occurred in 2002/2003. Crude unadjusted proportions.*

| Year | CC1 | CC2 | CC3 | CC4 | CC5 |
|---|---|---|---|---|---|
| 2003 | 26.92 | 8.59 | 50.36 | 12.46 | 1.67 |
| 2004 | 5.12 | 16.98 | 56.18 | 20.72 | 1 |
| 2005 | 0.68 | 19.96 | 62.92 | 15.72 | 0.72 |
| 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 |

*Table 17: Carapace condition (CC) of crab ≥ 95 mm CW (percent by number) over time for 4X from trawl surveys. The transition from a spring to a fall survey occurred in 2002/2003. Crude, unadjusted proportions.*

| Year | CC1 | CC2 | CC3 | CC4 | CC5 |
|---|---|---|---|---|---|
| 2005 | 0 | 4.4 | 93.41 | 2.2 | 0 |
| 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 |

## FIGURES

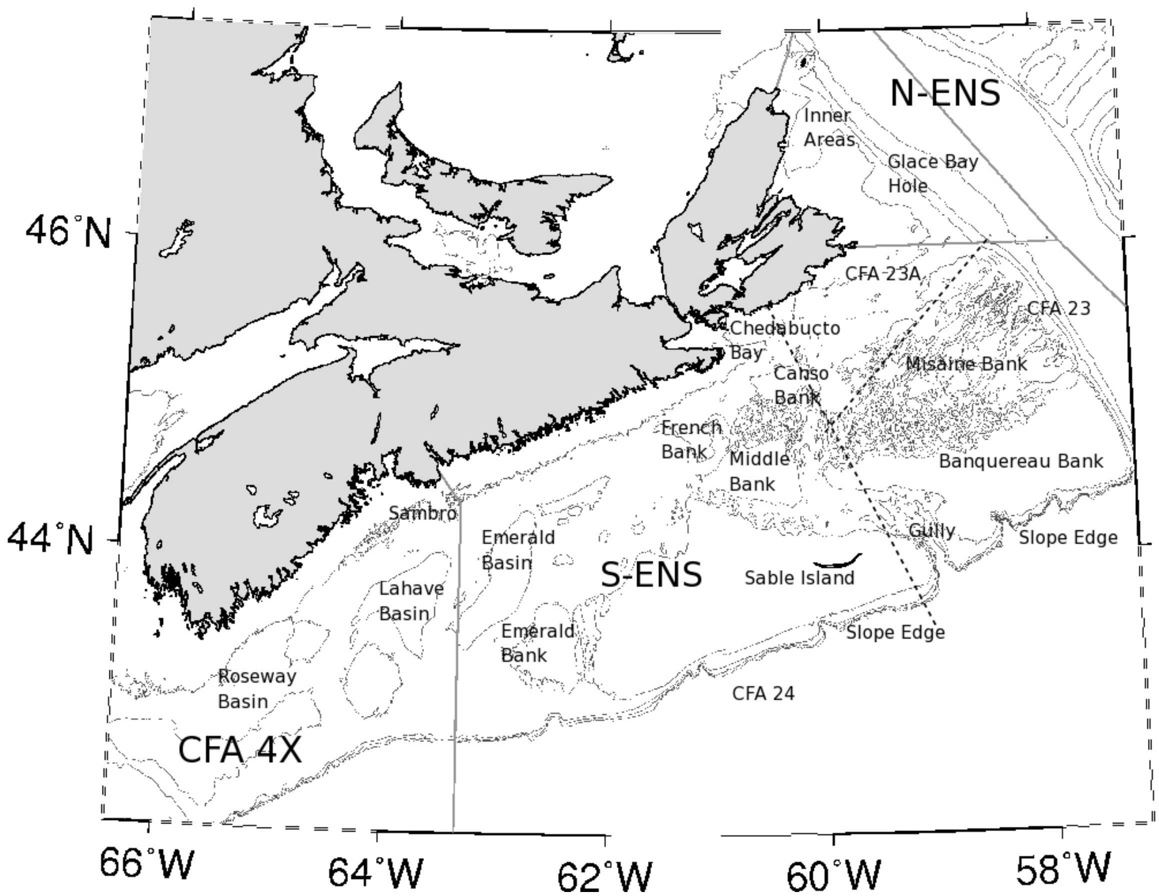



*Figure 1: Location of geographic areas and management areas on the Scotian Shelf.*

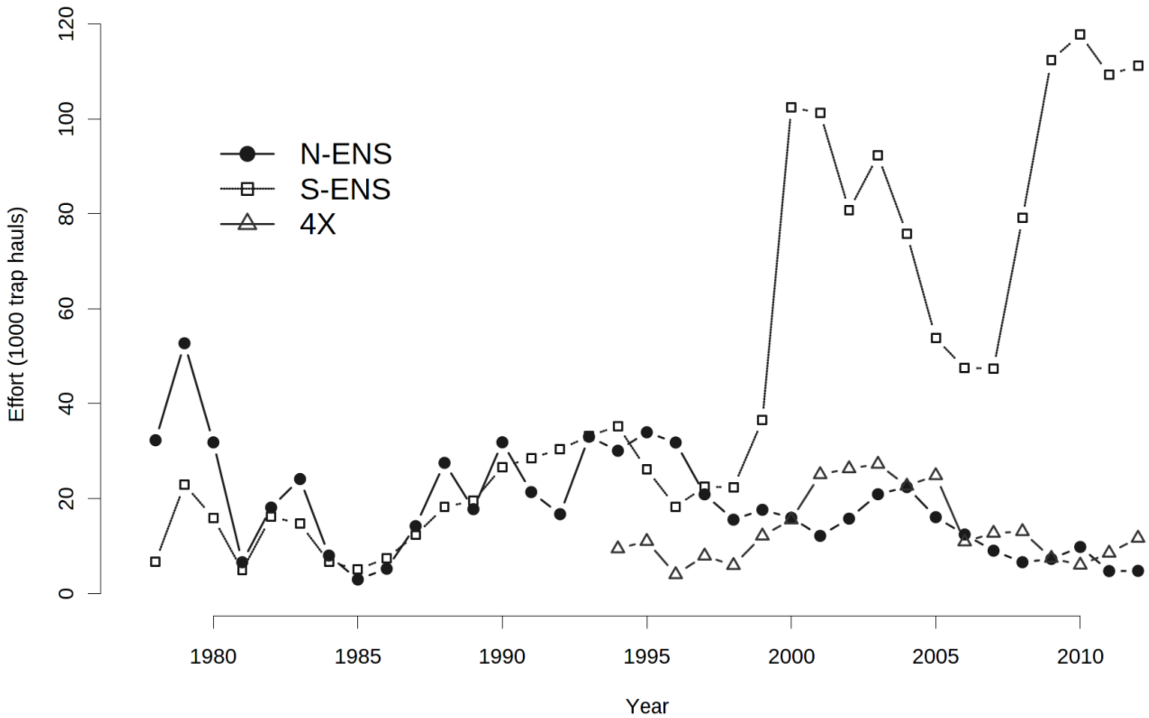



*Figure 2: Temporal variations in the fishing effort, expressed as the number of trap hauls on the Scotian Shelf, from 1978-2012. For 4X, year refers to the starting year.*

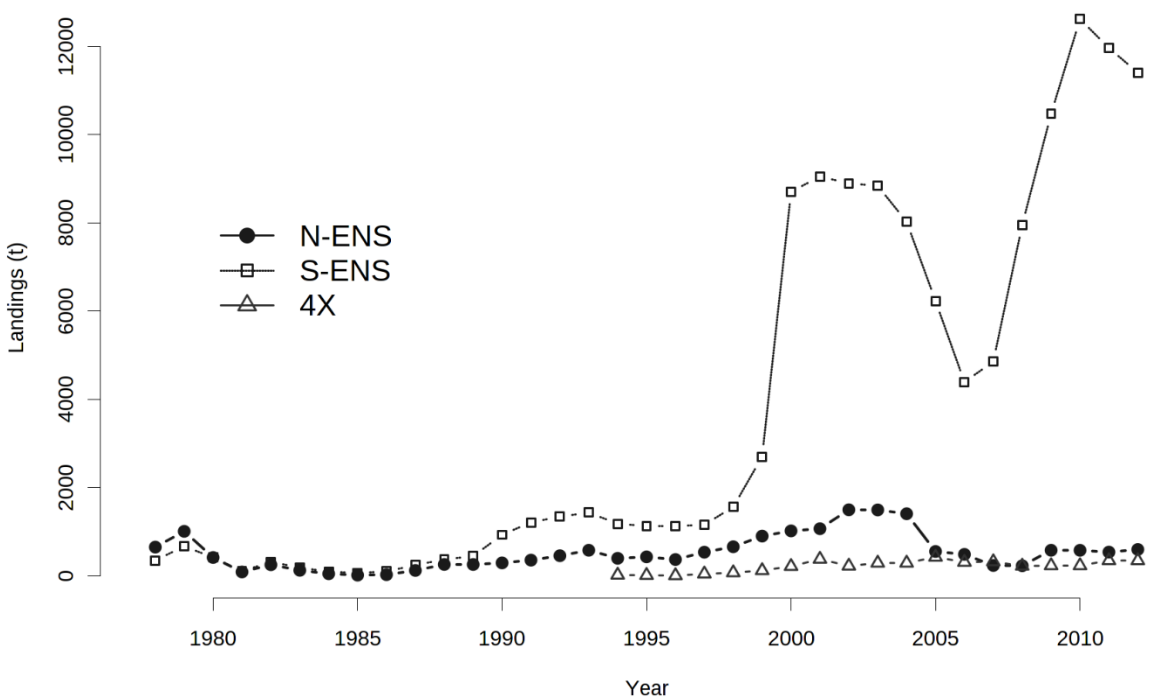



*Figure 3: Temporal variations in the landings of snow crab on the Scotian Shelf (t), 1978-2012. Note the sharp increase in landings associated with dramatic increases to TACs and a doubling of fishing effort in the year 2000. The landings follow the TACs with little deviation (and so are not shown). For 4X, year refers to the starting year.*

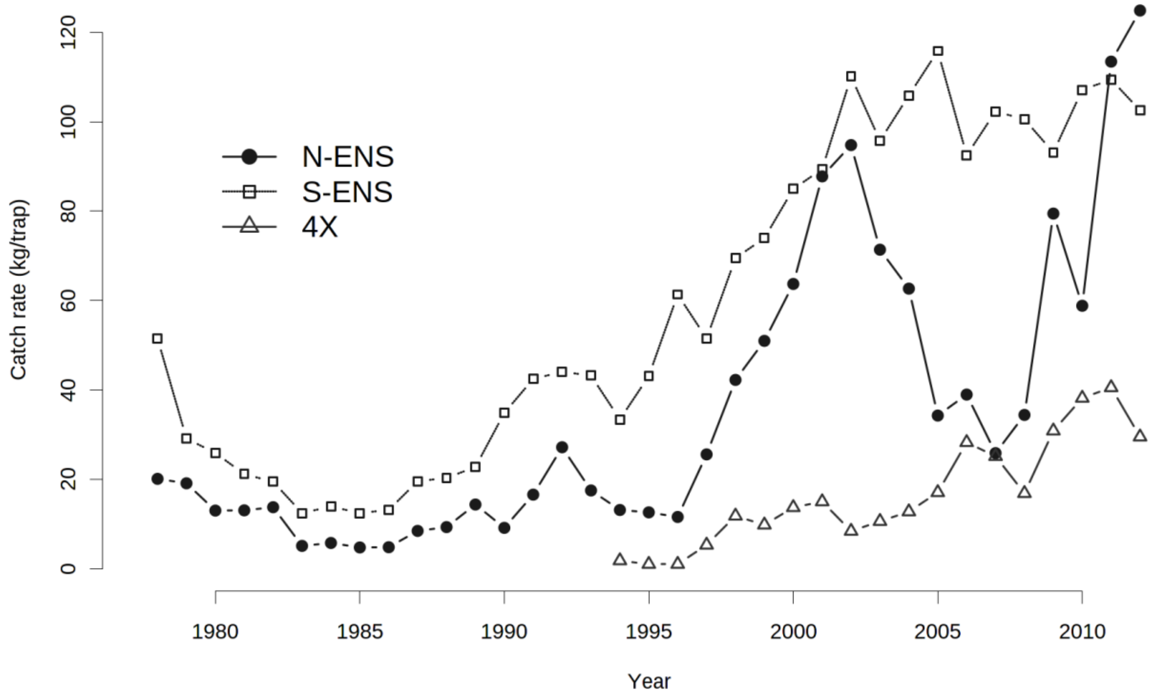



*Figure 4: Temporal variations in catch rates of snow crab on the Scotian Shelf, expressed as kg per trap haul. Trap design and size have changed over time, 1978-2012. No correction for these varying trap-types nor soak time and bait-type has been attempted (see Methods). For 4X, year refers to the starting year.*

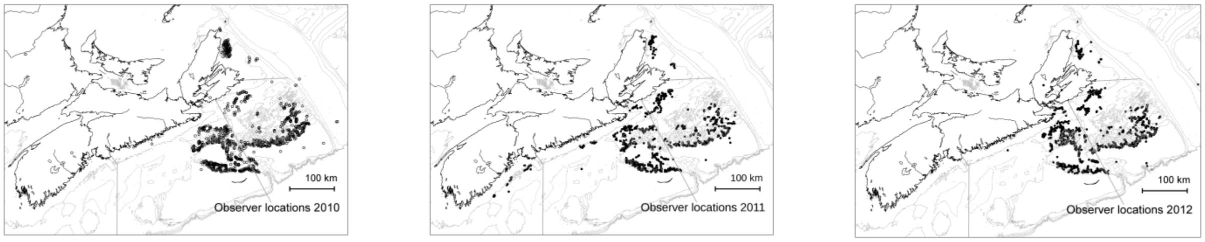



*Figure 5: At-sea-observer monitored locations on the Scotian Shelf.*

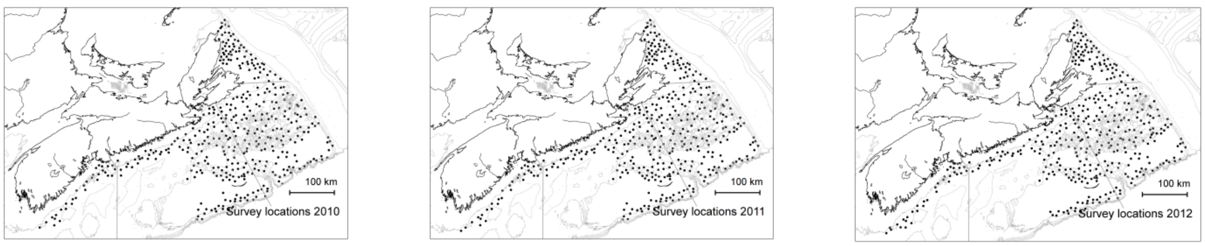



*Figure 6: Trawl survey locations on the Scotian Shelf.*

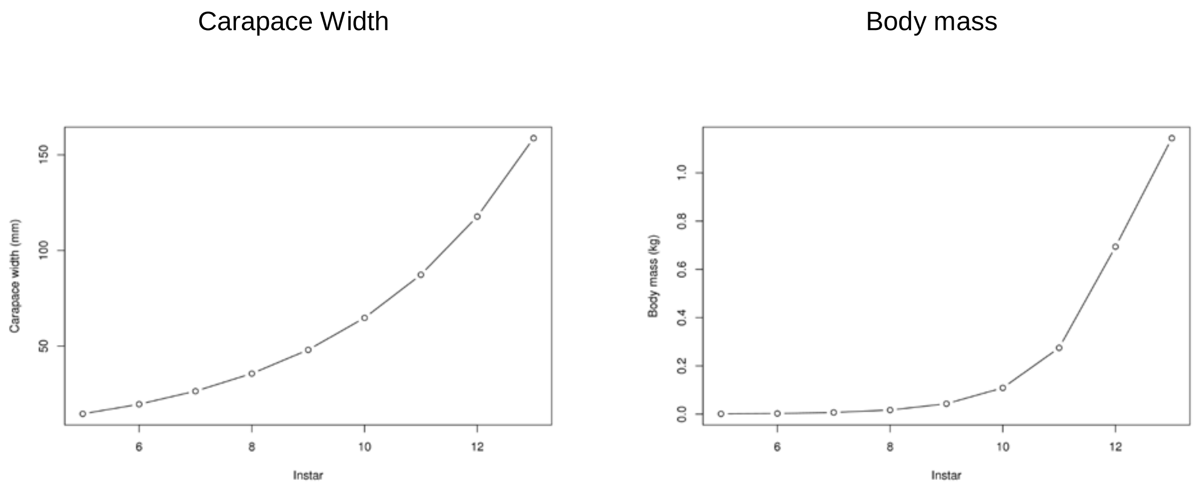



*Figure 7: Growth curves determined from Scotian Shelf male snow crab as a function of instar number.*

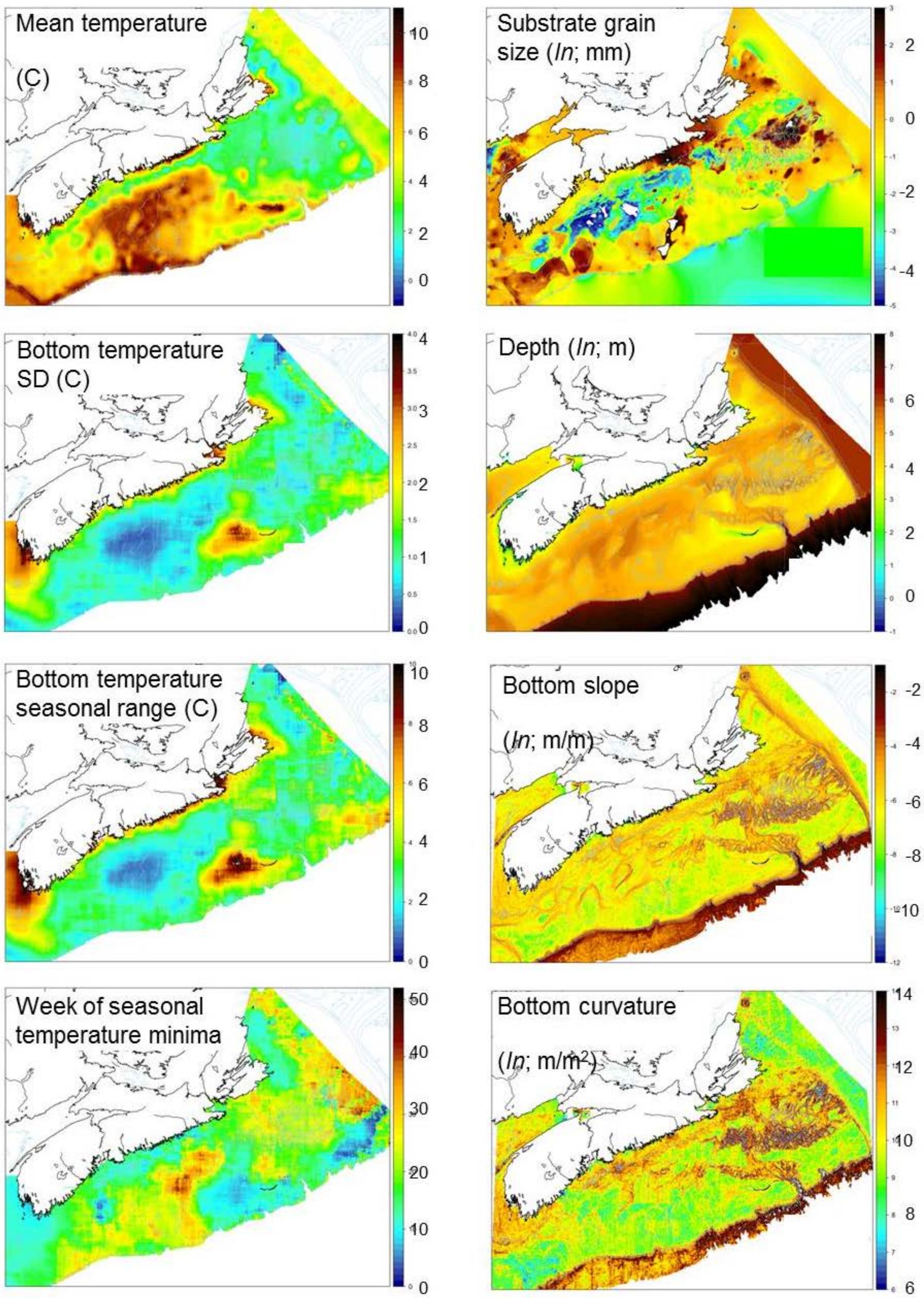



*Figure 8: Bottom characteristics used for modeling snow crab habitat delineation. The visualizations of temperature variations are for climatological means. Annual temperature variation estimates were used for modeling. (Continued below.)*

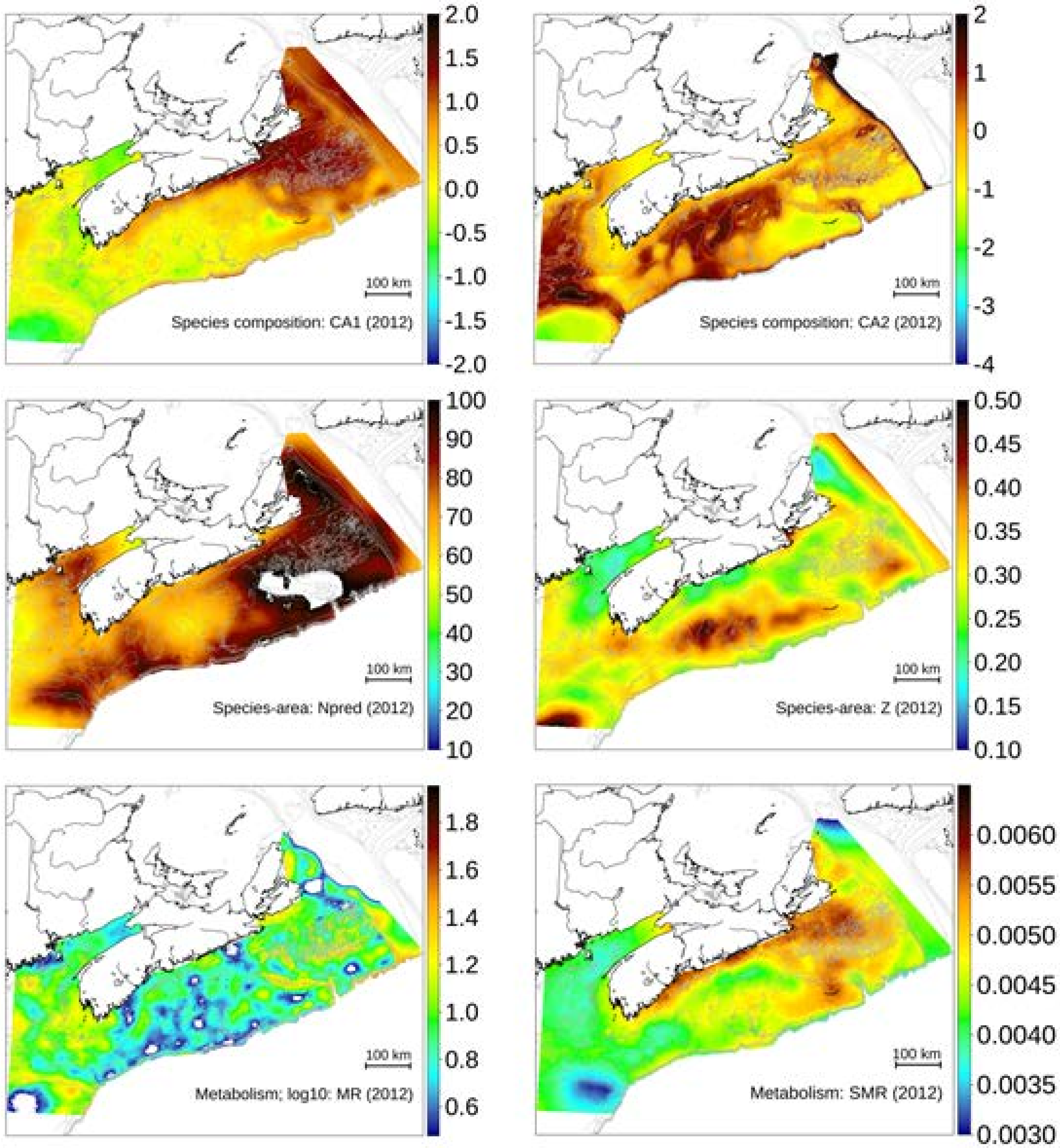
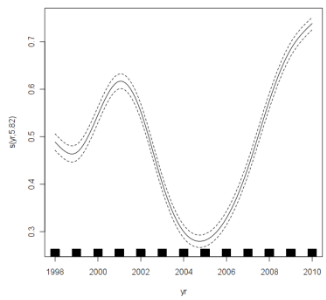
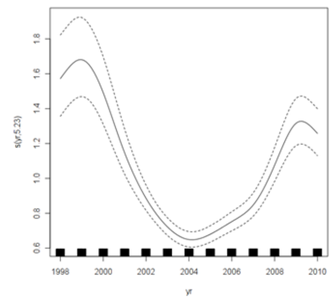
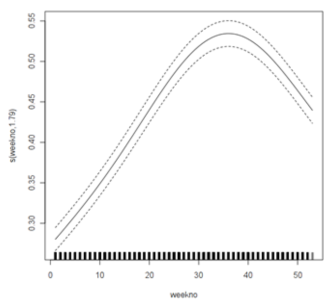
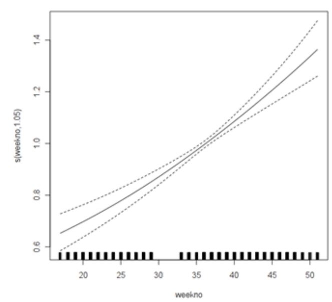
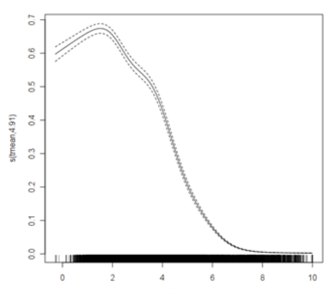
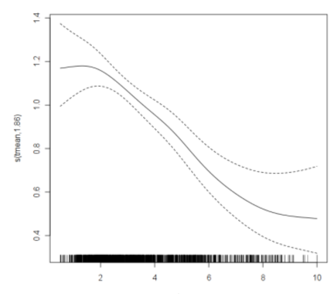
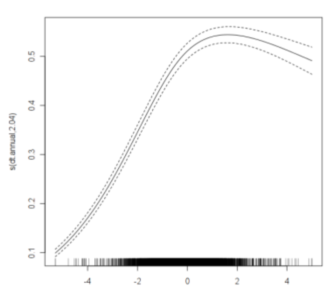
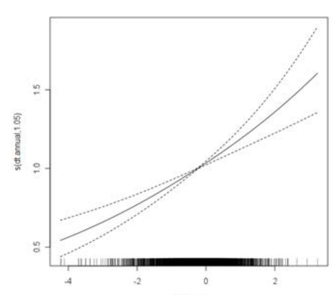
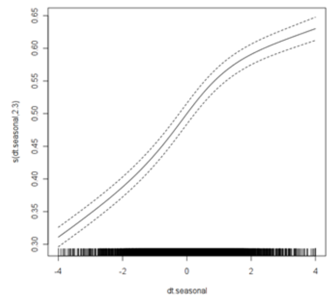
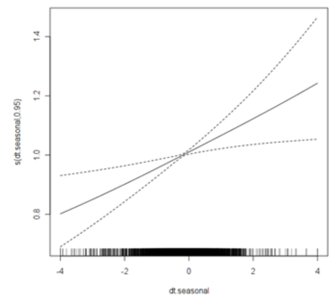
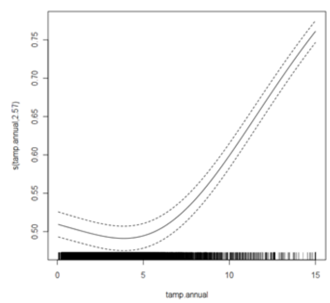
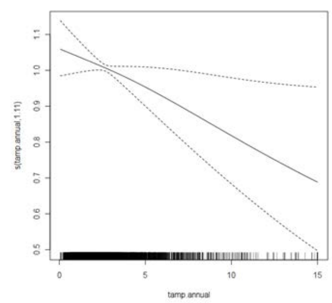
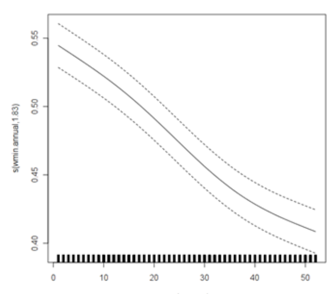
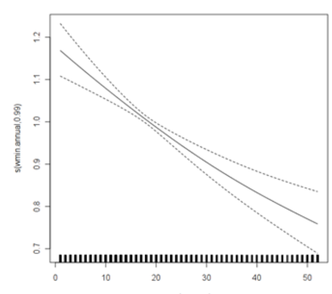
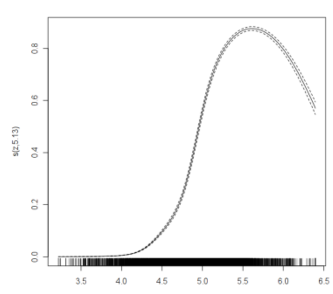
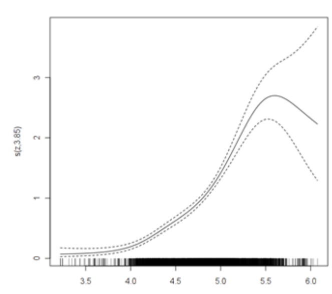
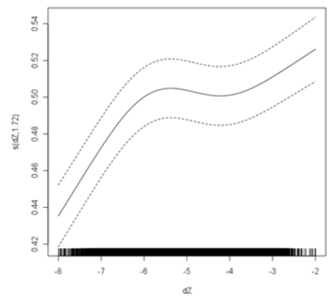
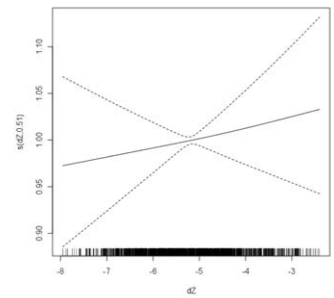
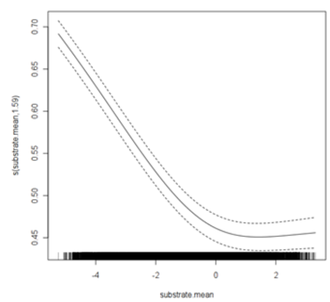
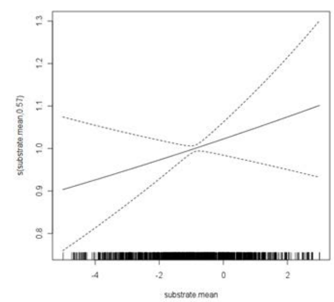
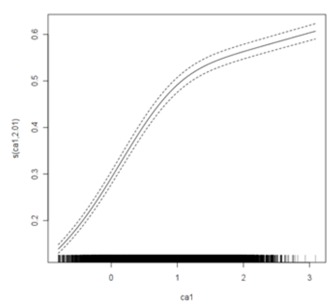
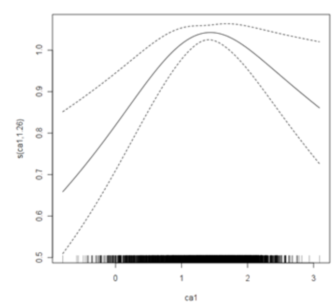
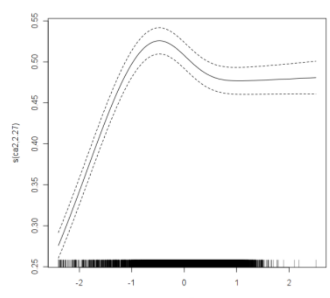
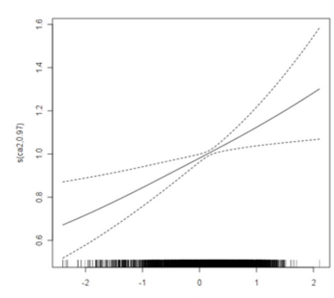



*Figure 8: continued.*

| X-variable | Habitat | Abundance |
|---|---|---|
| Year of capture |  |  |
| Week number of capture |  |  |
| Climatological mean bottom temperature |  |  |
| Deviation of annual mean bottom temperature from climatological mean in the year of capture (positive = colder than climatology) |  |  |

| **X-variable** | **Habitat** | **Abundance** |
|---|---|---|
| Deviation of bottom temperature from the annual mean bottom temperature at time of capture (positive = colder than annual average) |  |  |
| Annual amplitude of bottom temperatures in the year of capture |  |  |
| Week number at which bottom temperatures reach seasonal minima in the year of capture |  |  |
| Depth at capture (log) |  |  |

| **X-variable** | **Habitat** | **Abundance** |
|---|---|---|
| Bottom slope at location of capture (log) |  |  |
| Mean grain size at location of capture (log) |  |  |
| Species composition axis 1 (temperature related gradient) at location and year of capture |  |  |
| Species composition axis 2 (depth related gradient) at location and year of capture |  |  |

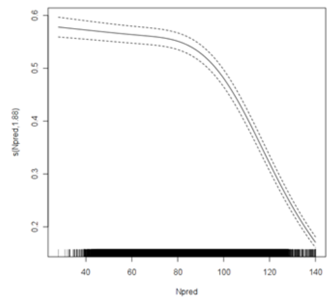
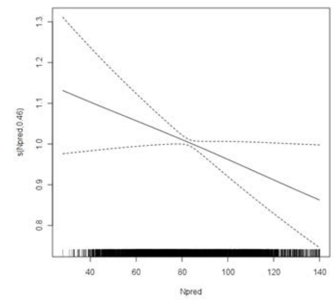
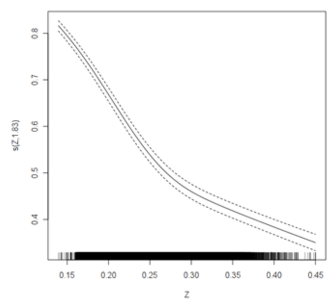
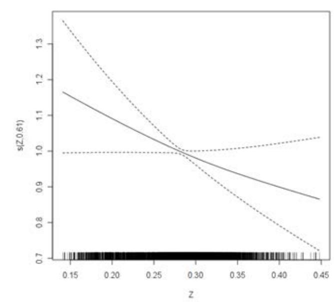
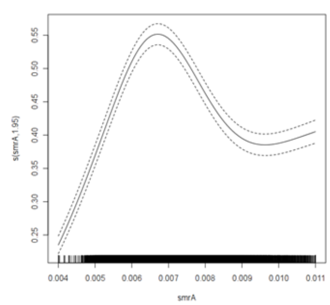
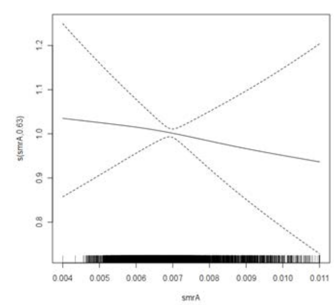
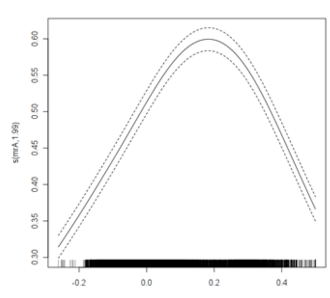
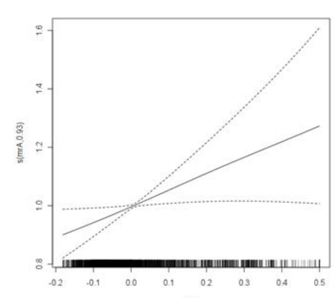
| X-variable | Habitat | Abundance |
|---|---|---|
| Number of species predicted, based upon a species-area saturation curve |  |  |
| Curvature of the species-area relationship |  |  |
| Specific metabolic rate (intensity) predicted from size structure |  |  |
| Total metabolic rate predicted from size structure (an estimate of gross productivity) |  |  |

*Figure 9: The empirically modeled relationship of snow crab habitat suitability (probability of observing snow crab habitat on the Scotian Shelf) and abundance (positive valued) as a function of key environmental variables. 95% confidence intervals (CI) are presented.*

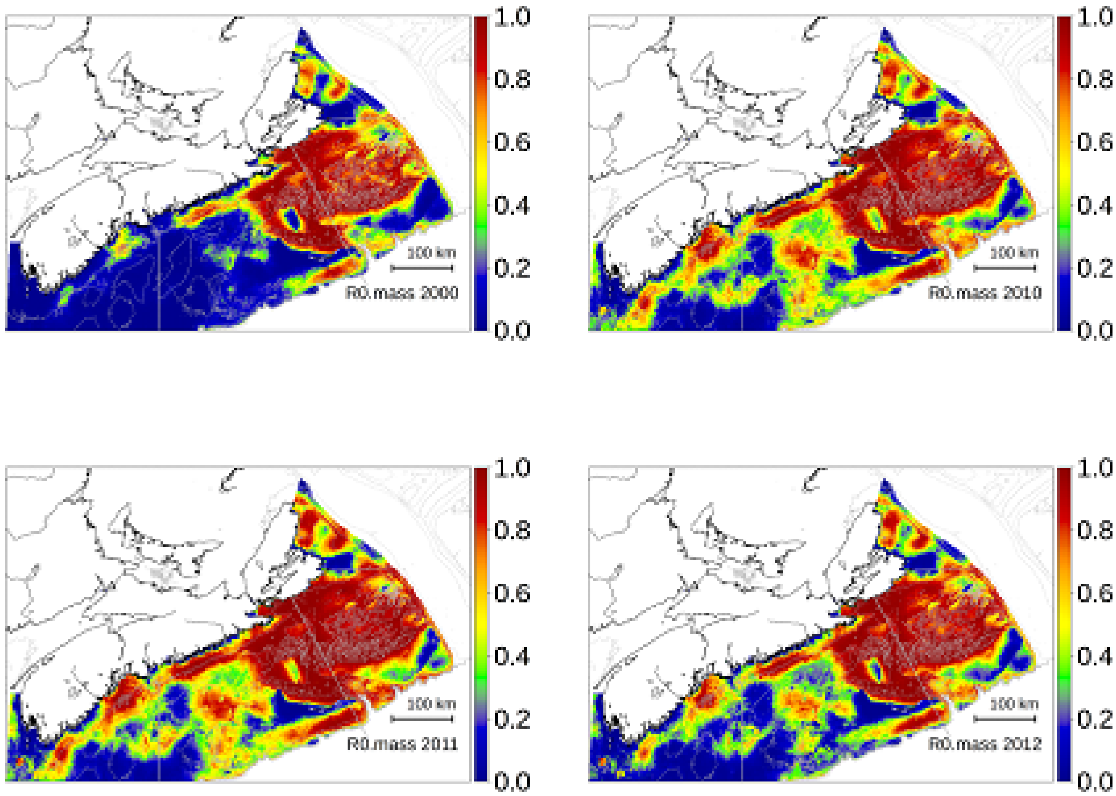



*Figure 10: Posterior predicted probabilities of viable habitat for fishable snow crab.*

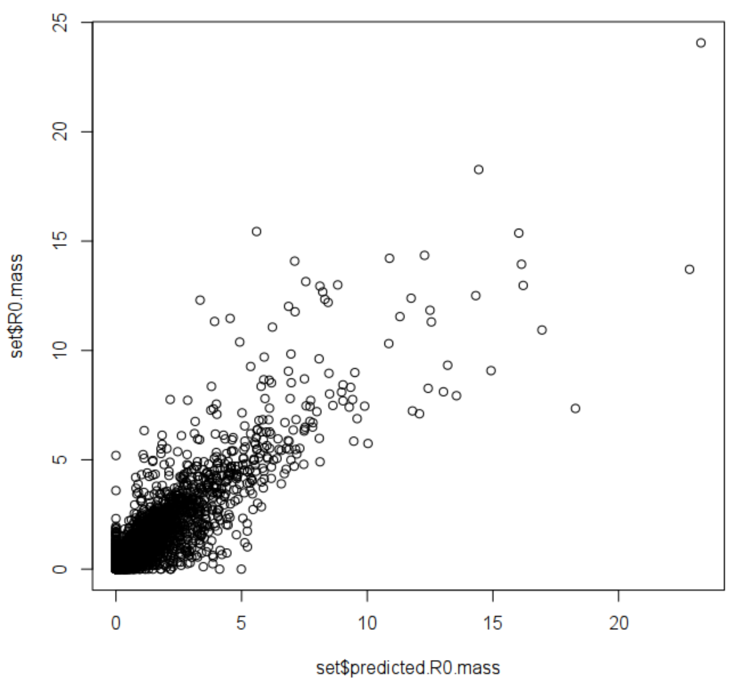



*Figure 11: Correlation between observed and predicted densities of fishable biomass (kg $m^{-2}$). The coefficient of determination was 79%.*

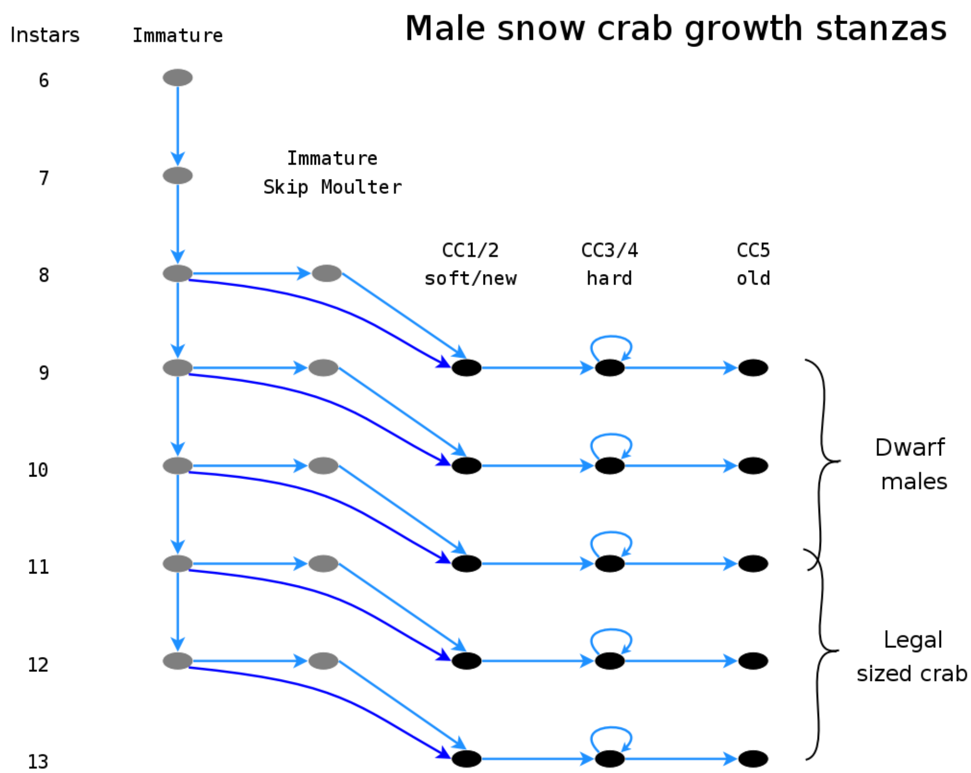



*Figure 12: The growth stanzas of male snow crab. Each instar is determined from CW bounds obtained from modal analysis and categorized to carapace condition (CC) and maturity from visual inspection and/or maturity equations. Snow crab are resident in each growth stanza for 1 year, with the exception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

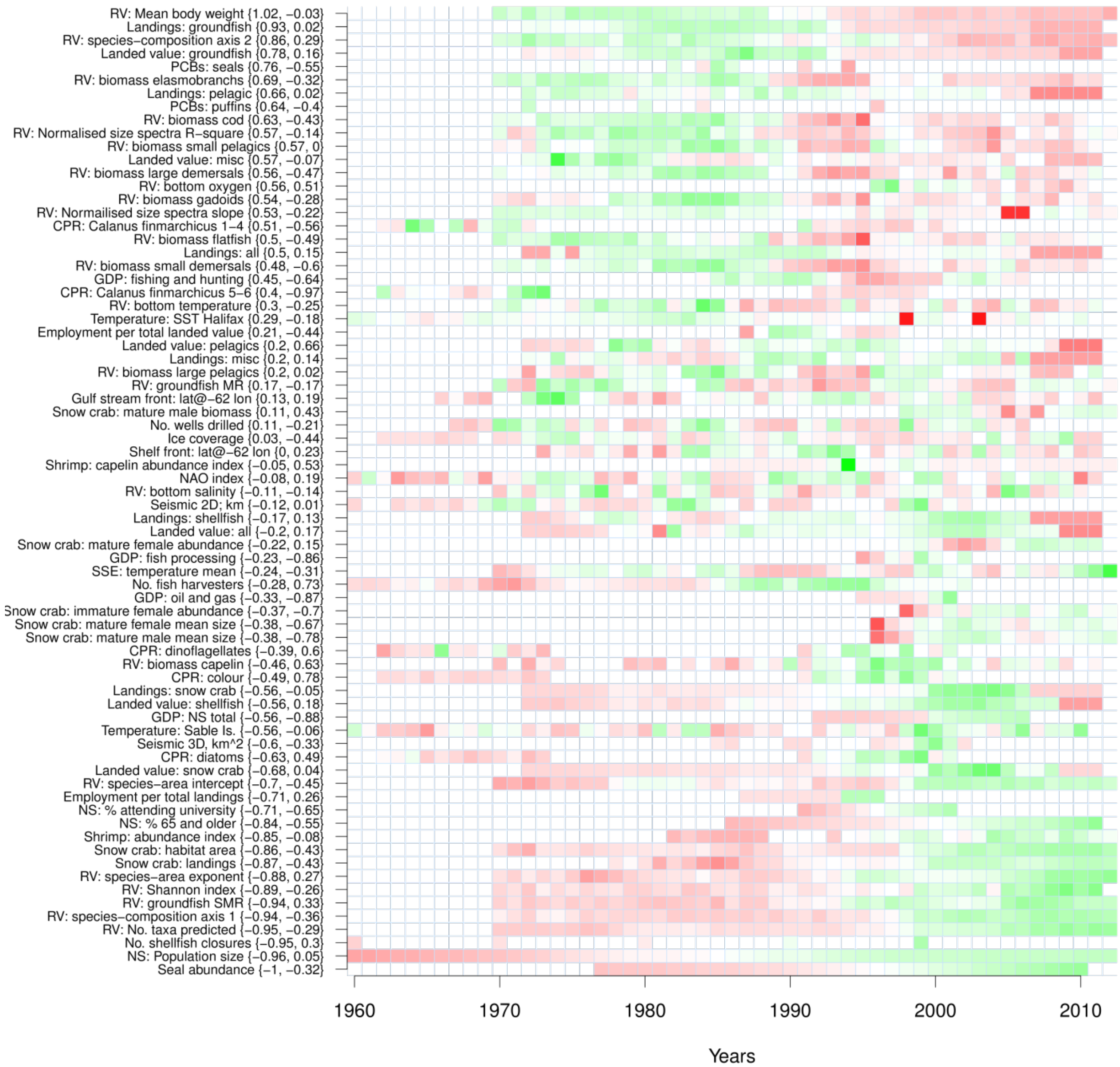



*Figure 13: Sorted ordination of anomalies of key social, economic and ecological patterns on the Scotian Shelf relevant to snow crab. Red indicates below the mean and green indicates above the mean.*

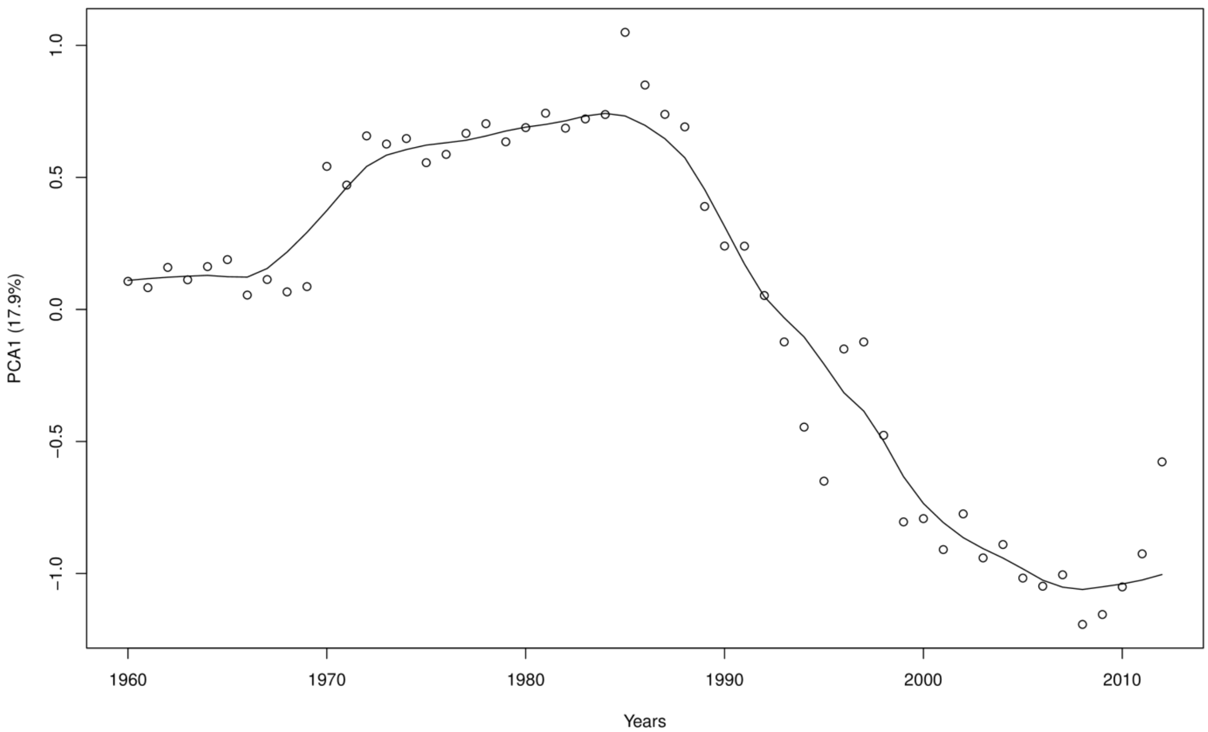



*Figure 14: First axis of variations in ordination of anomalies of social, economic and ecological patterns on the Scotian Shelf. Note strong variability observed near the time of the fishery collapse in the early 1990s. Note strong variability observed near the time of the fishery collapse in the early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

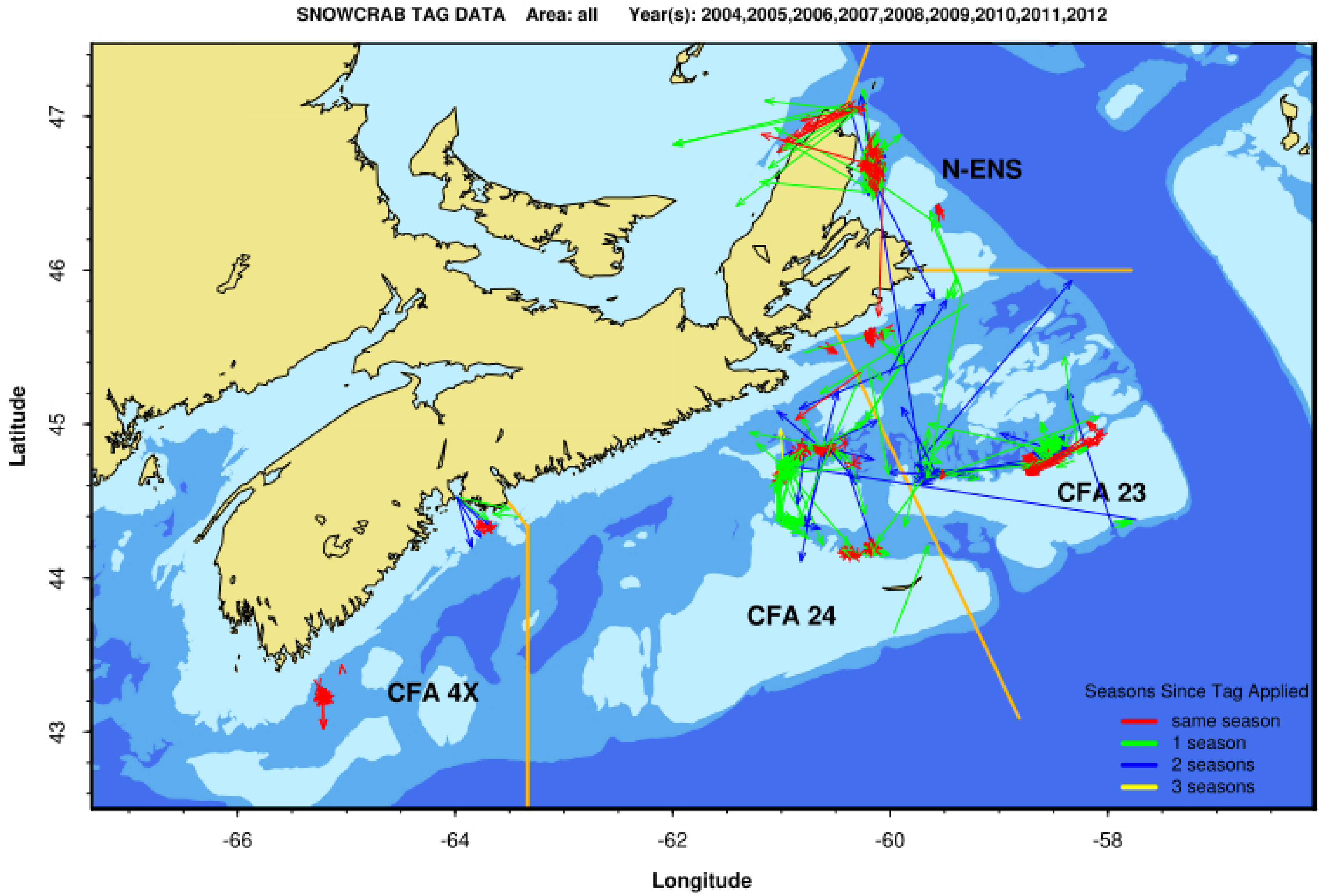



*Figure 15: Movement of terminally molted fishable snow crab. More detailed maps can be viewed at the ENS Snow Crab website.*

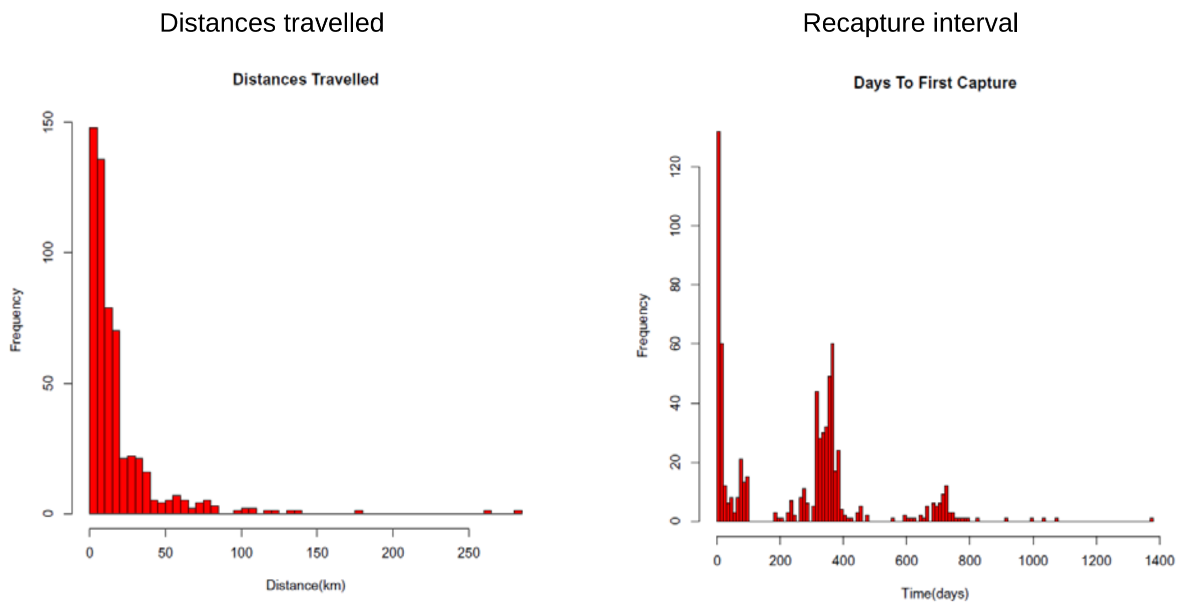



*Figure 16: (Left) Distance traveled by tagged snow crab in ENS 2004-2011. (Right) Tagged snow crab in ENS: return interval in days between initial release and first recapture.*

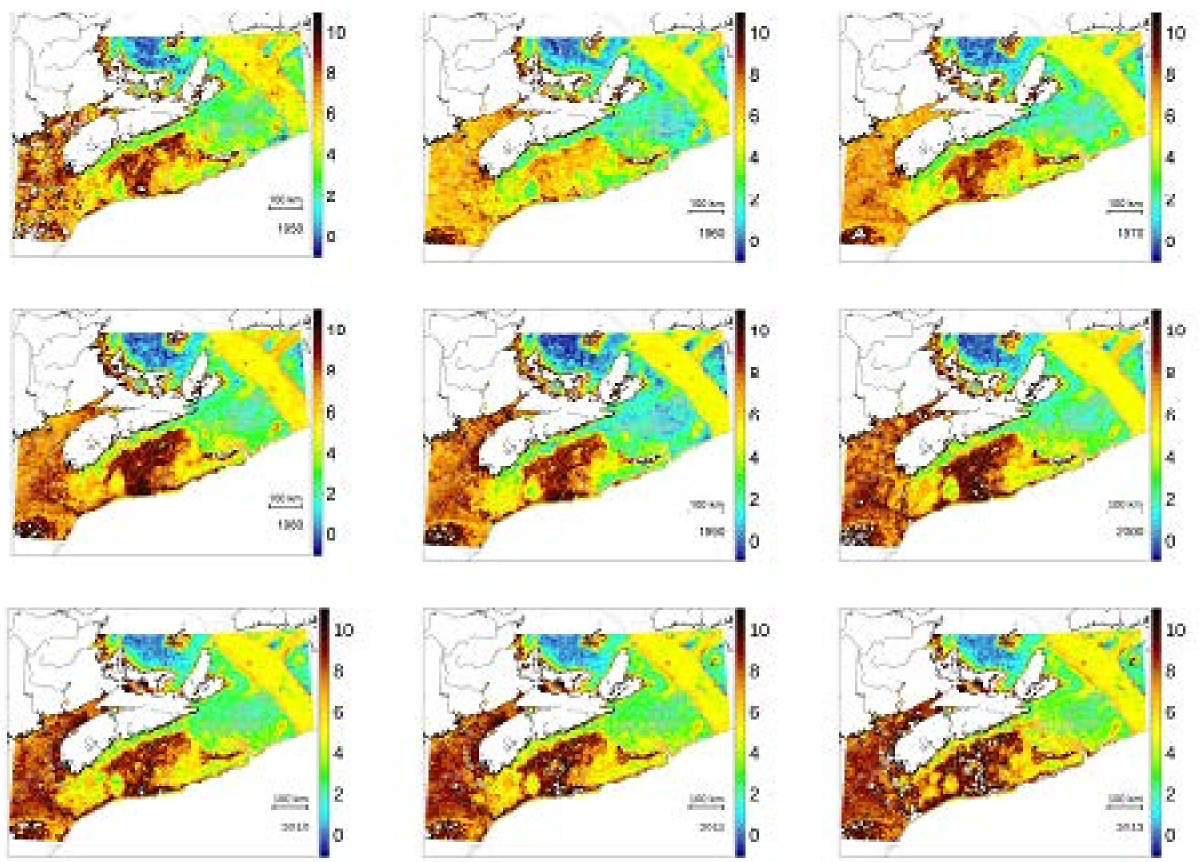


*Figure 17: Mean annual bottom temperatures on the Scotian Shelf for selected years.*

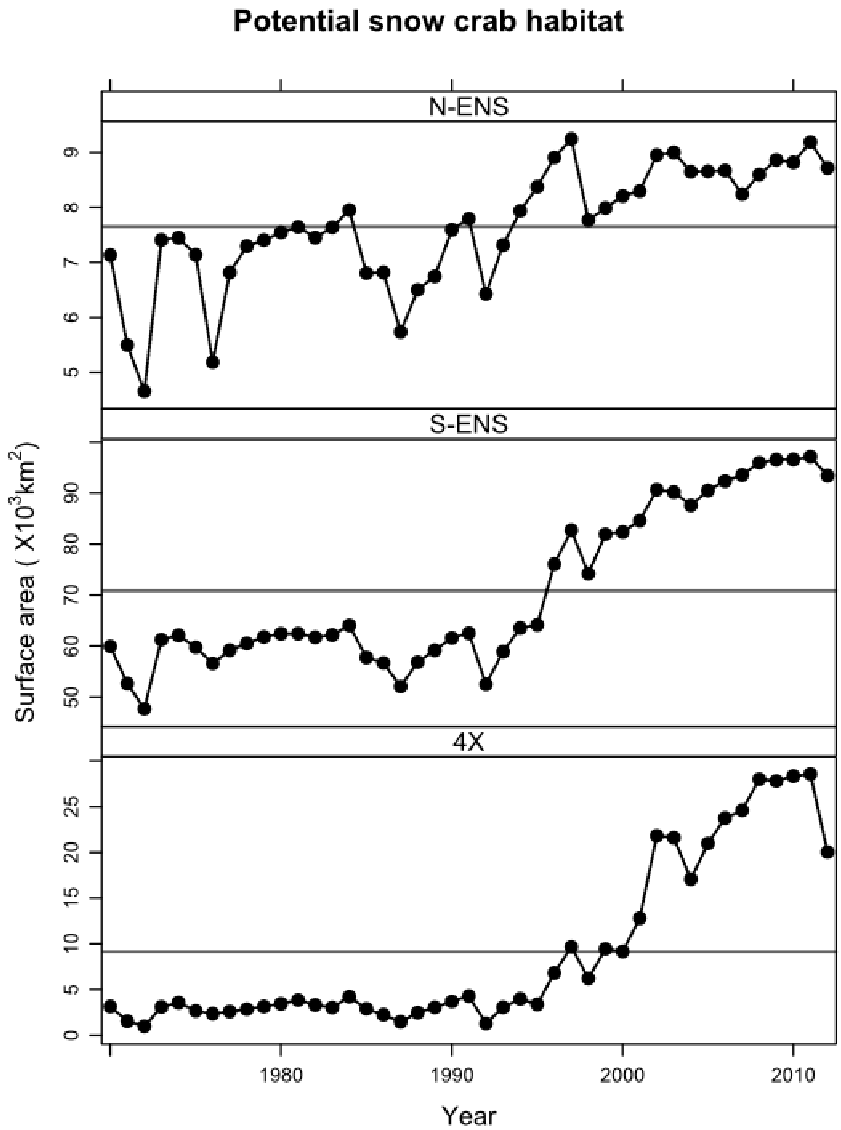



*Figure 18: Annual variations in the surface area of potential snow crab habitat. The horizontal line indicates the long-term arithmetic mean surface area within each subarea. The estimates for the period from 1998 to the present are based upon snow crab surveys while those prior to 1998 are projected using incomplete data (and so less reliable). The surface area of potential habitat is presently above the mean (actually close to the maximum) for the 1998-2011 period. A sharp decline was seen in 2012 in area 4X.*

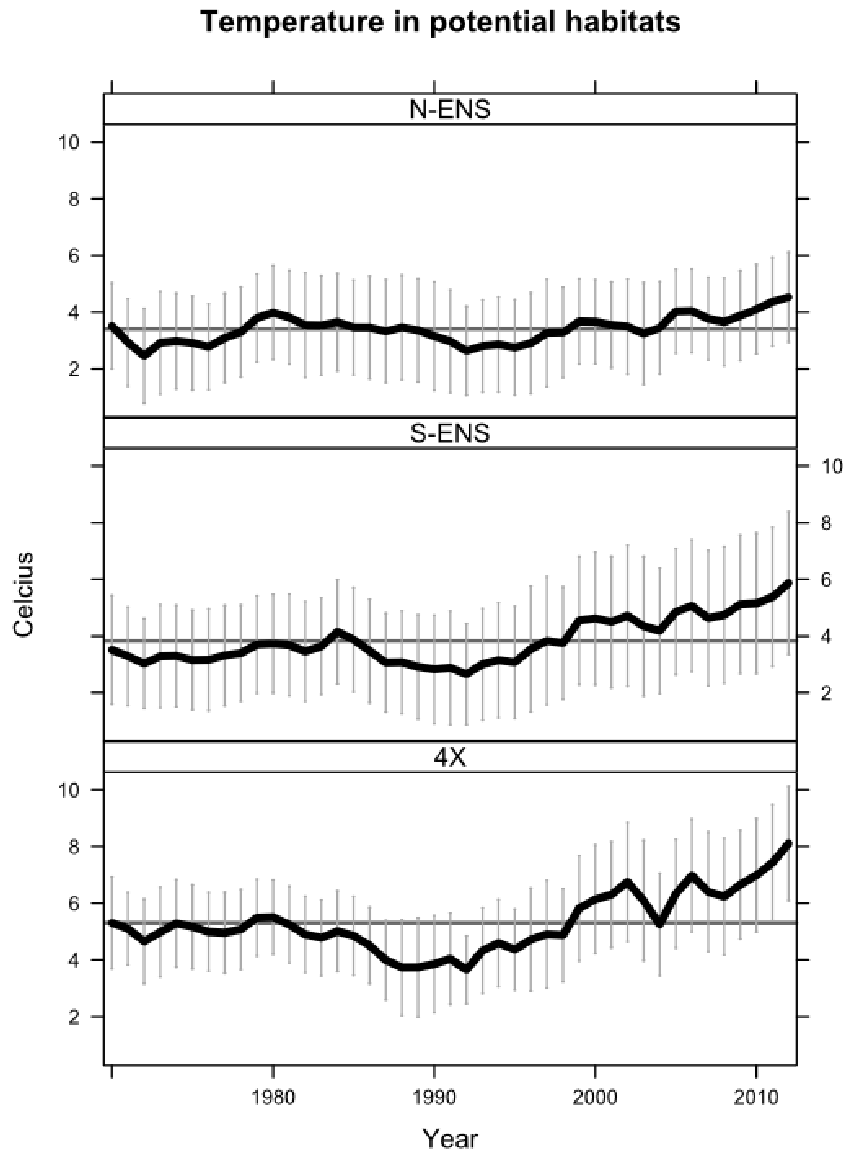



*Figure 19: Annual variations in bottom temperature within potential snow crab habitat. The horizontal line indicates the long-term arithmetic mean temperature within each subarea. Error bars are 1 standard deviation. See caveats in Figure 14. Note increasing temperatures in all areas since the mid-2000s, especially in area 4X. The current mean temperature in 4X is above the temperature requirements for snow crab.*

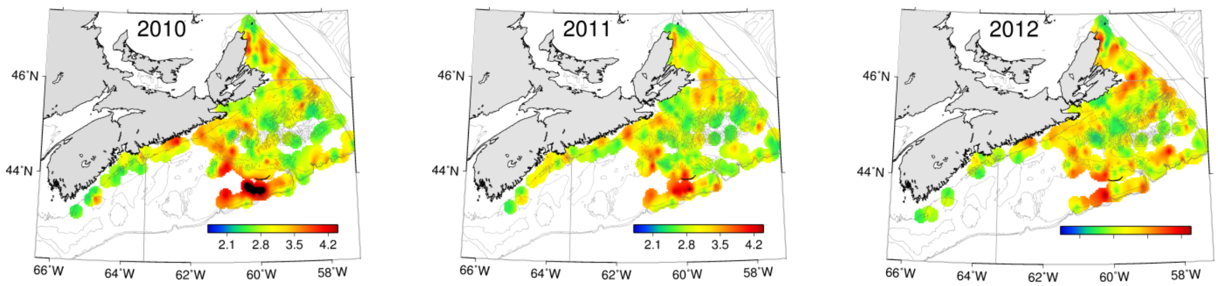



*Figure 20: Locations of potential predators of snow crab: cod. Scale is $log_{10}$ (numerical density [number/km$^2$]).*

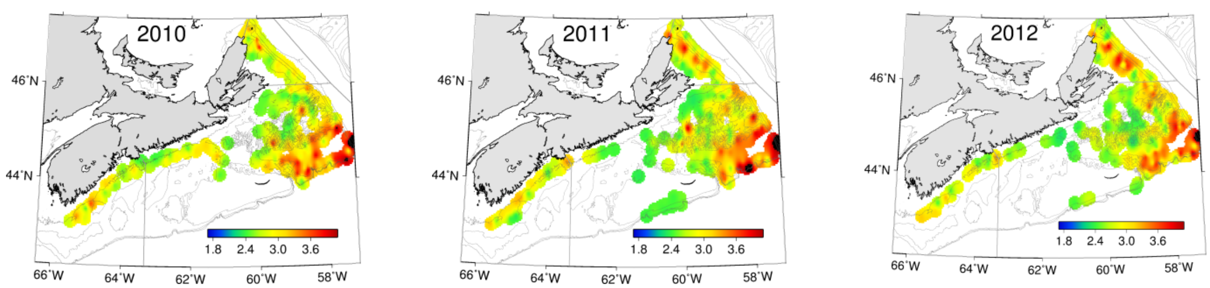



*Figure 21: Locations of potential predators of snow crab: thorny skate. Scale is $log_{10}$ (numerical density [number/km$^2$]).*

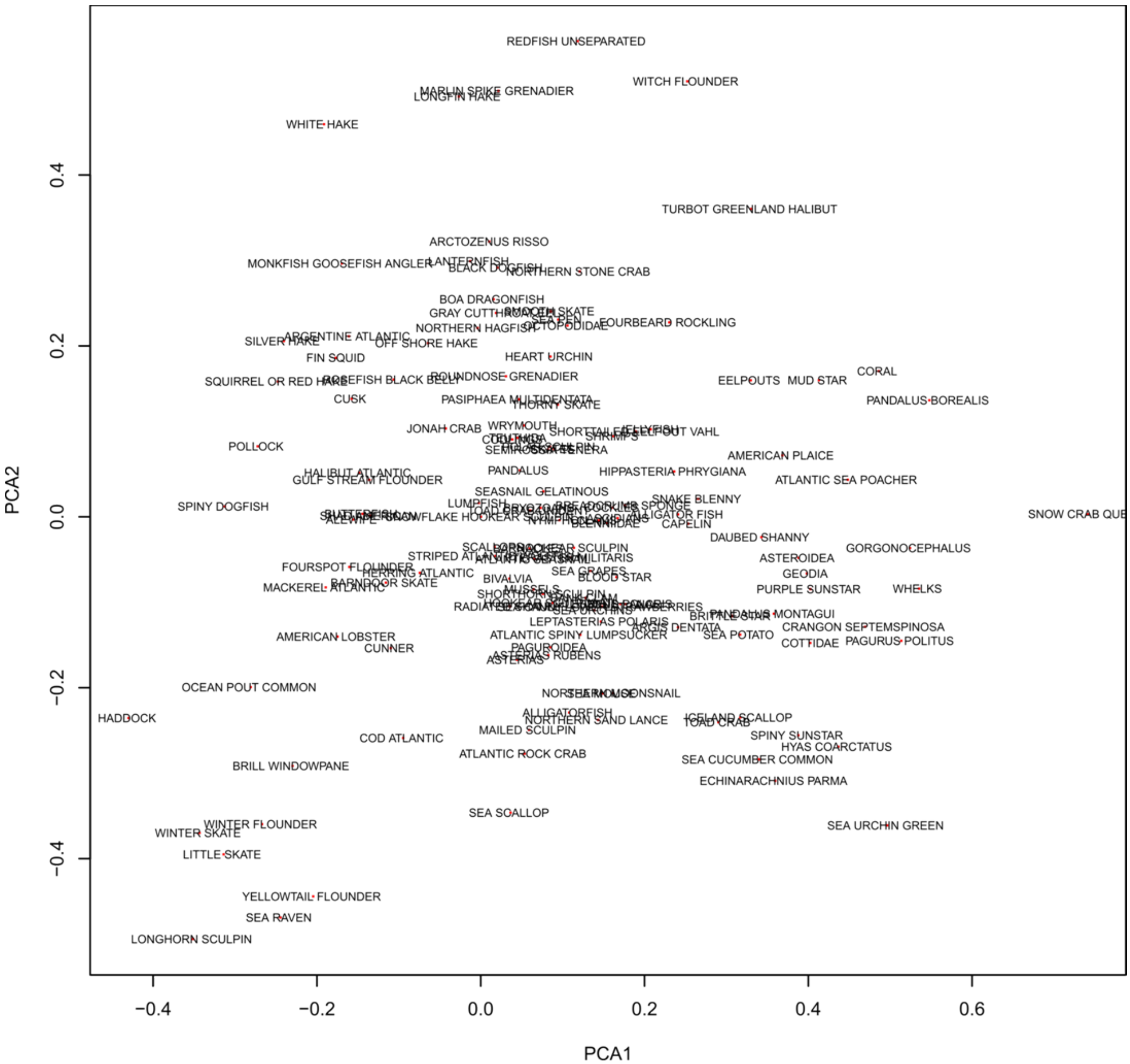



*Figure 22: Ordination from a Principle Components Analysis of log-transformed numerical densities based on Pearson correlation matrices.*

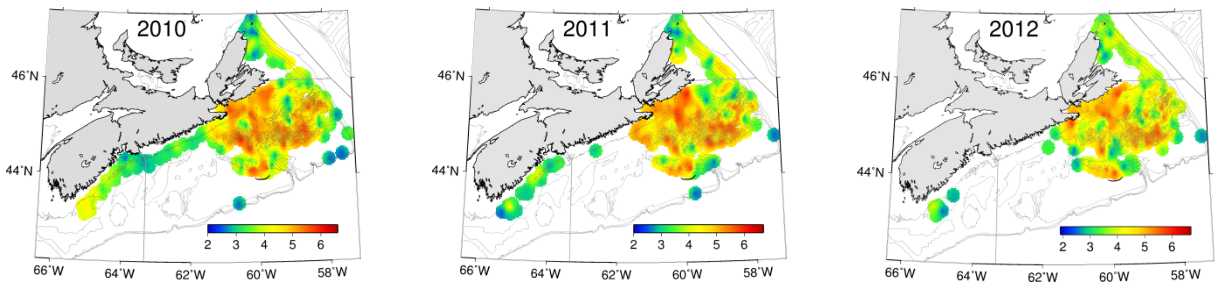



*Figure 23: Locations of potential food items of snow crab: northern shrimp. Abundance of these potential food sources roughly match the spatial distributions of snow crab. Scale is $log_{10}$ (numerical density [number/km$^2$]).*

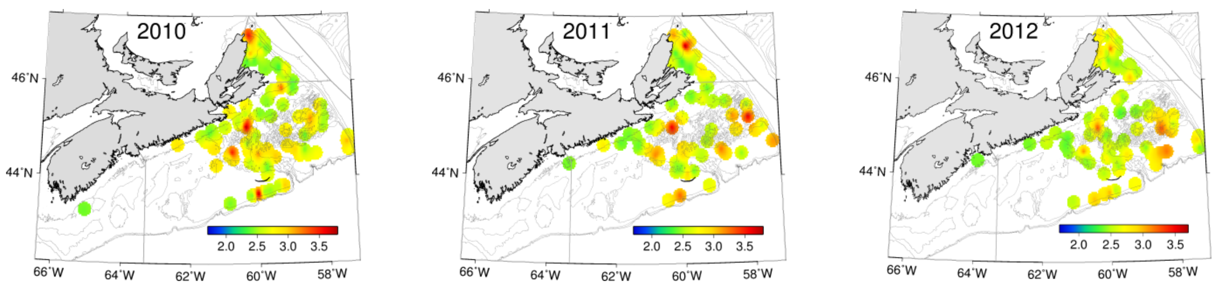



*Figure 24: Locations of potential competitors of snow crab: lesser toad crab. High competitive interactions are probable in inshore areas. Scale is $log_{10}$ (numerical density [number/km$^2$]).*

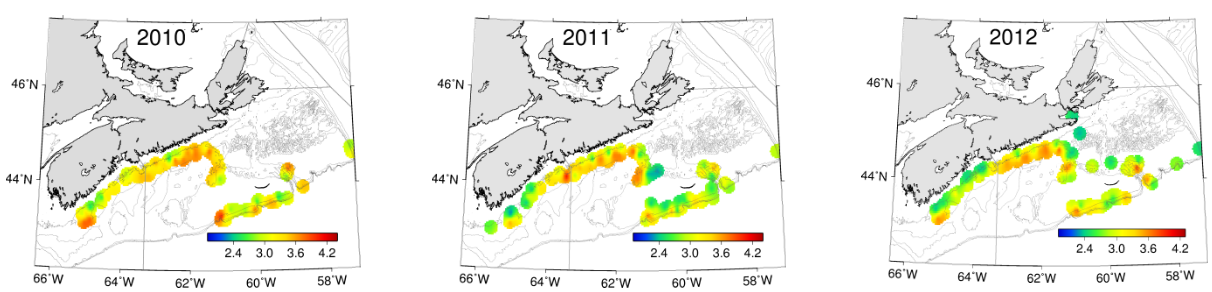



*Figure 25: Locations of potential competitors of snow crab: Jonah crab. High competitive interactions are probable in inshore areas. Scale is $log_{10}$ (numerical density [number/km$^2$]).*

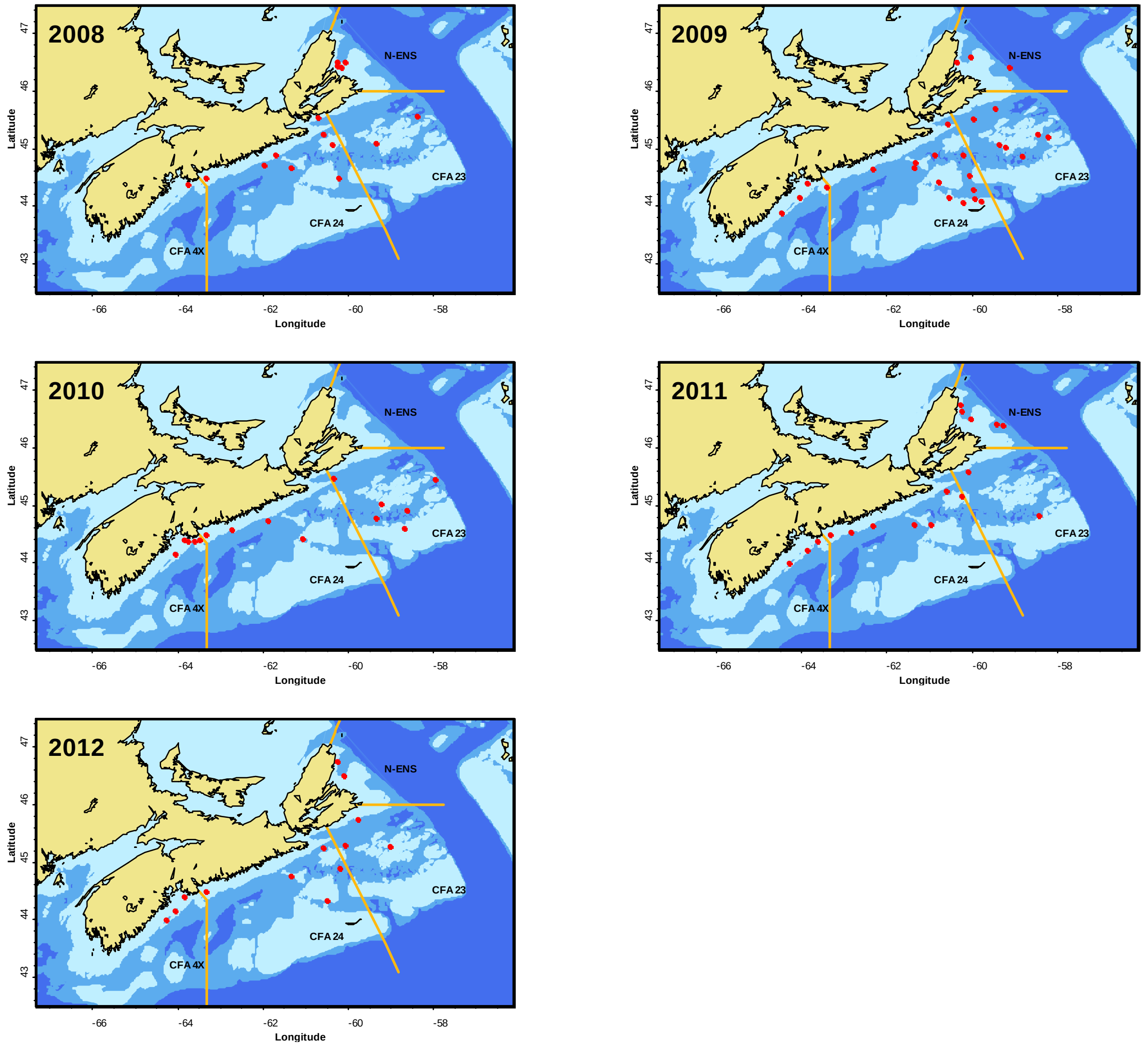



*Figure 26: BCD observations in snow crab trawl survey.*

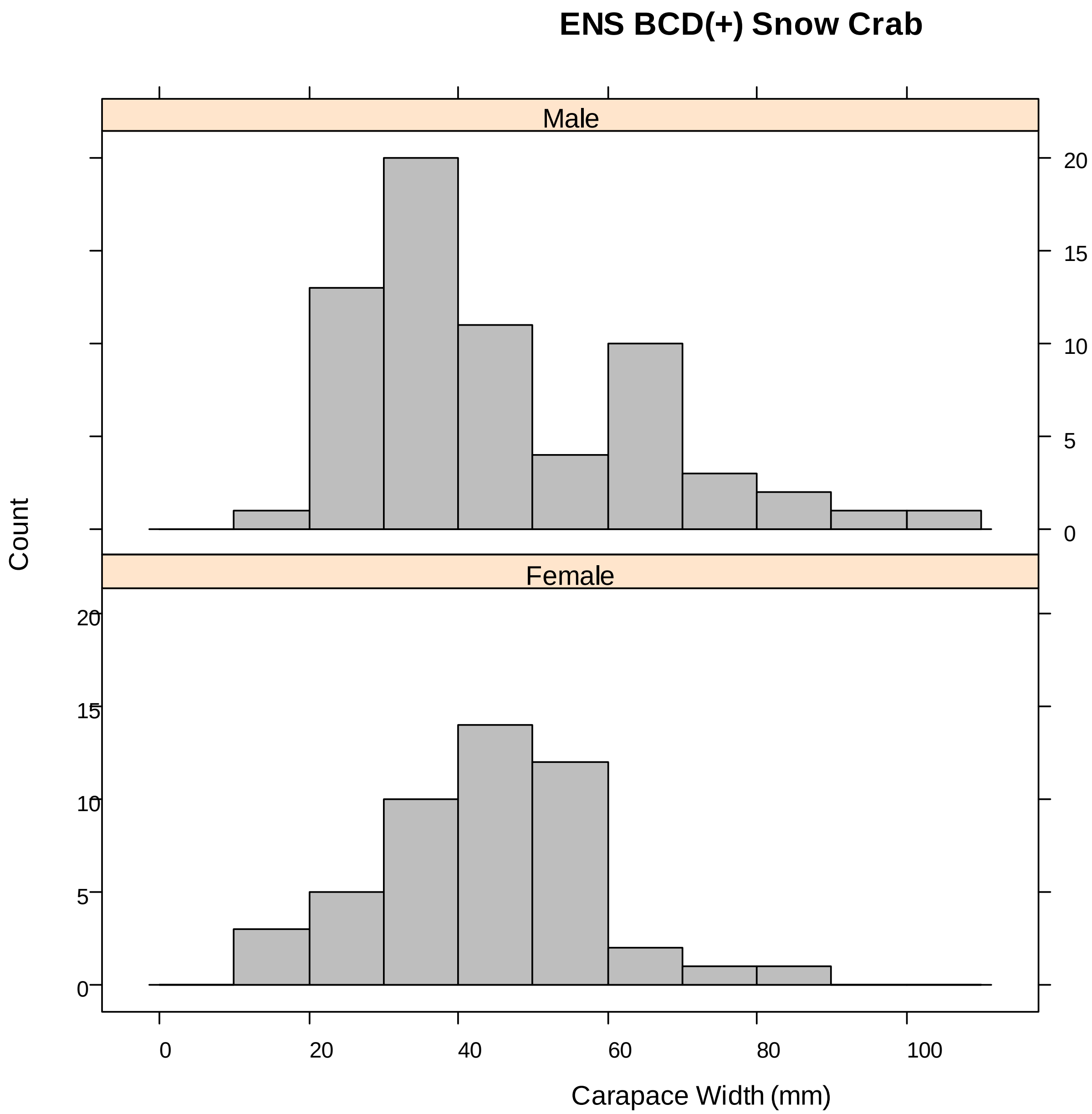



*Figure 27: Size frequency distribution of snow crab visibly infected with BCD from 2008-present.*

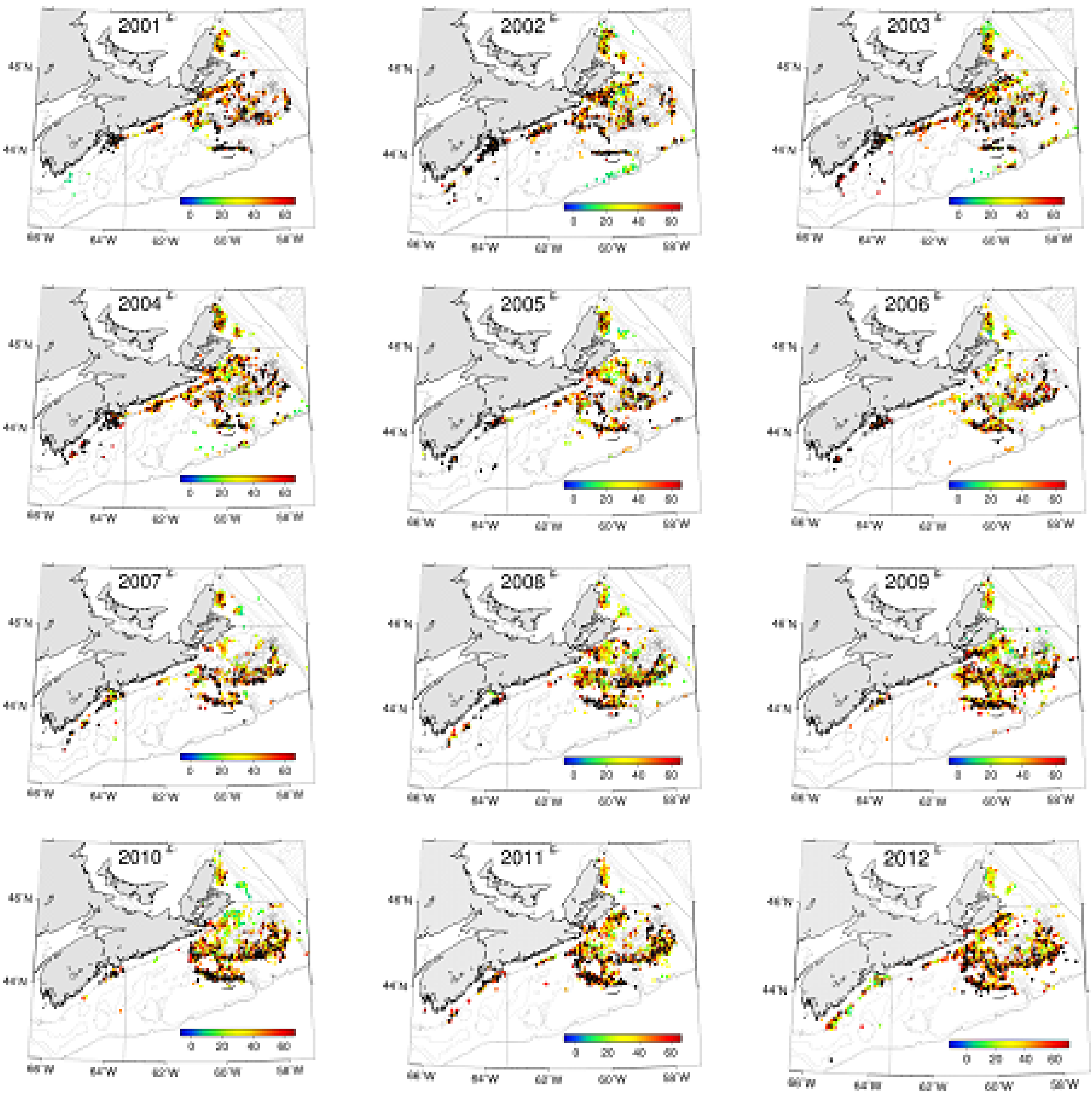



*Figure 28: Fishing effort (number of trap hauls/1 minute grid) from fisheries logbook data. Note the increase in effort inshore in S-ENS and the almost complete lack of fishing activity in the Glace Bay Hole area (offshore) of N-ENS. For 4X, year refers to the starting year.*

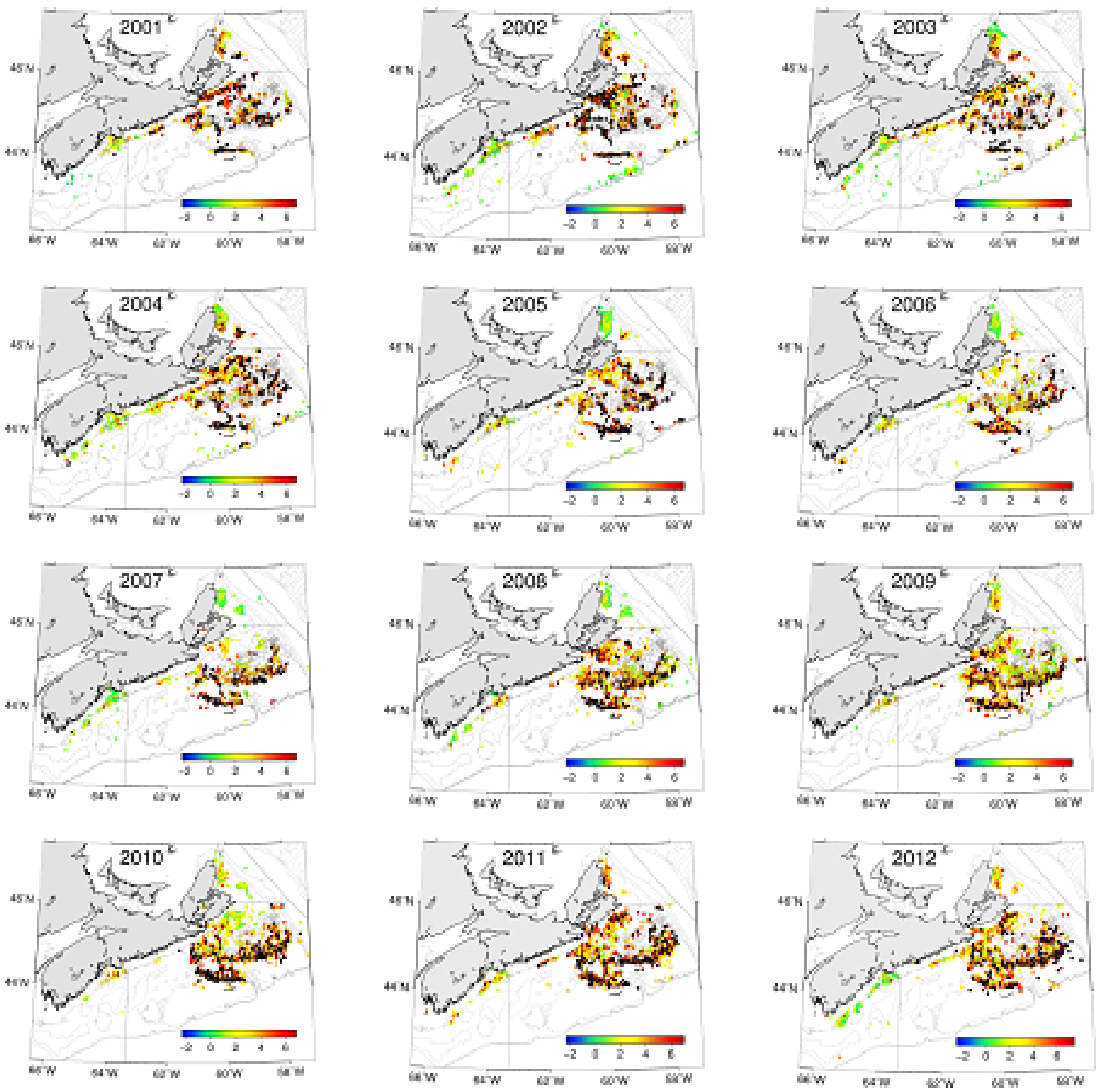



*Figure 29: Crab landings (scale is $log_{10}$ kg/1 minute grid) from fisheries logbook data. Note the increase in landings inshore for S-ENS. For 4X, year refers to the starting year.*

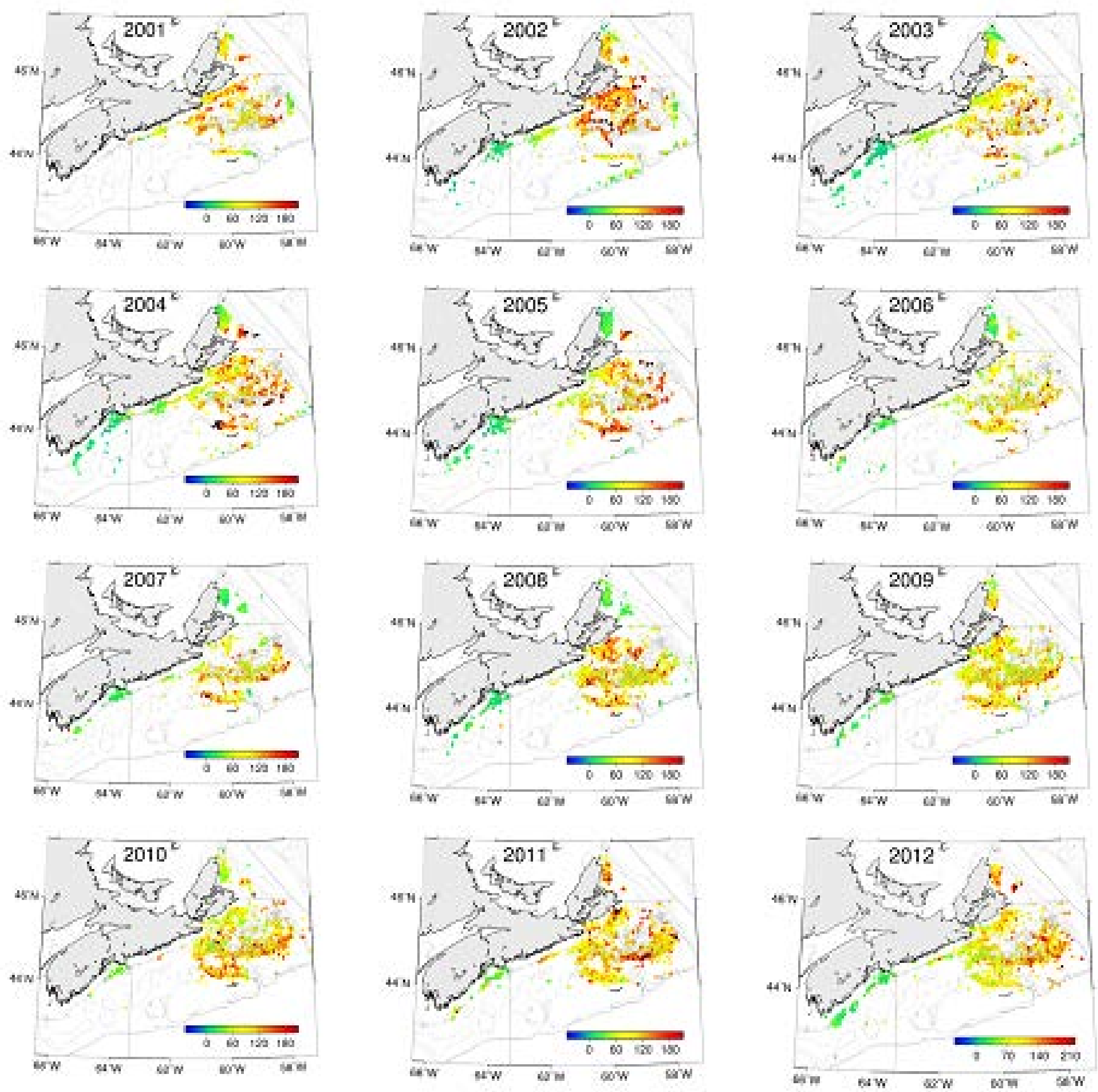


*Figure 30a: Catch rates (kg trap$^{-1}$) in each 1 minute grid from logbook data. For 4X, year refers to the starting year.*

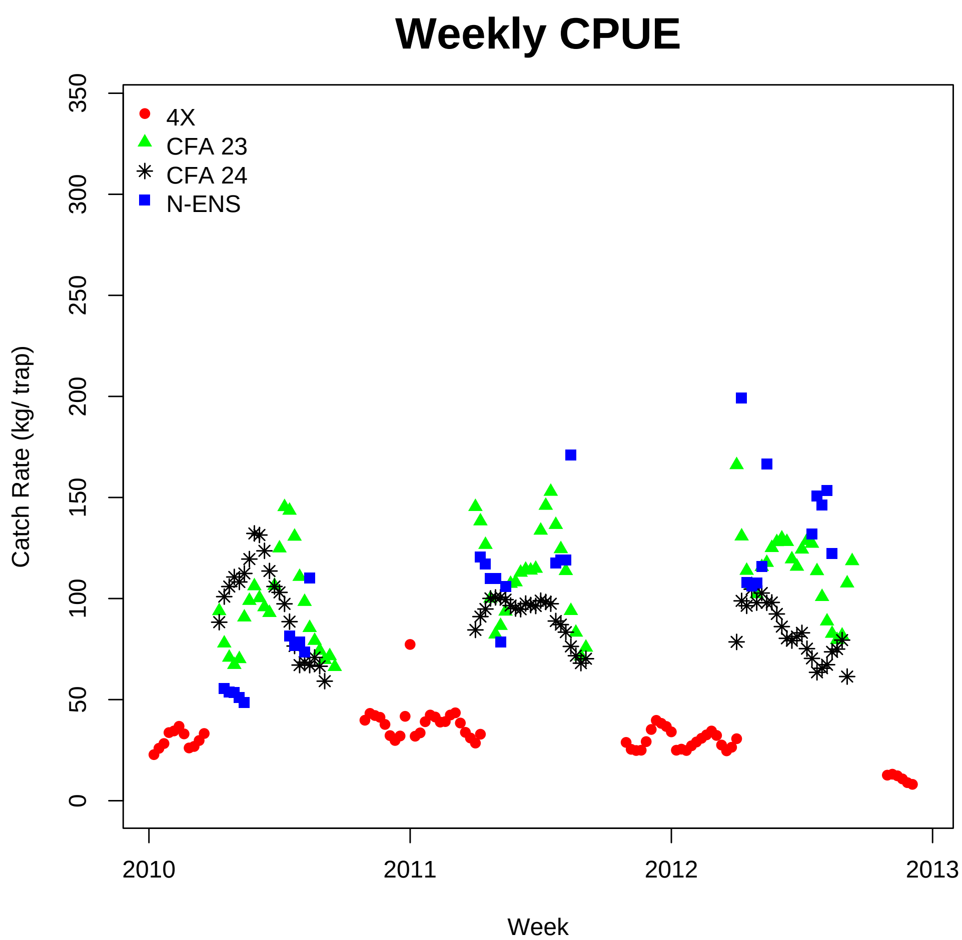



*Figure 30b: Catch rates (kg trap$^{-1}$) by week for the past three seasons. Split season in N-ENS (spring and summer portions) create the apparent gap in N-ENS data within each year.*

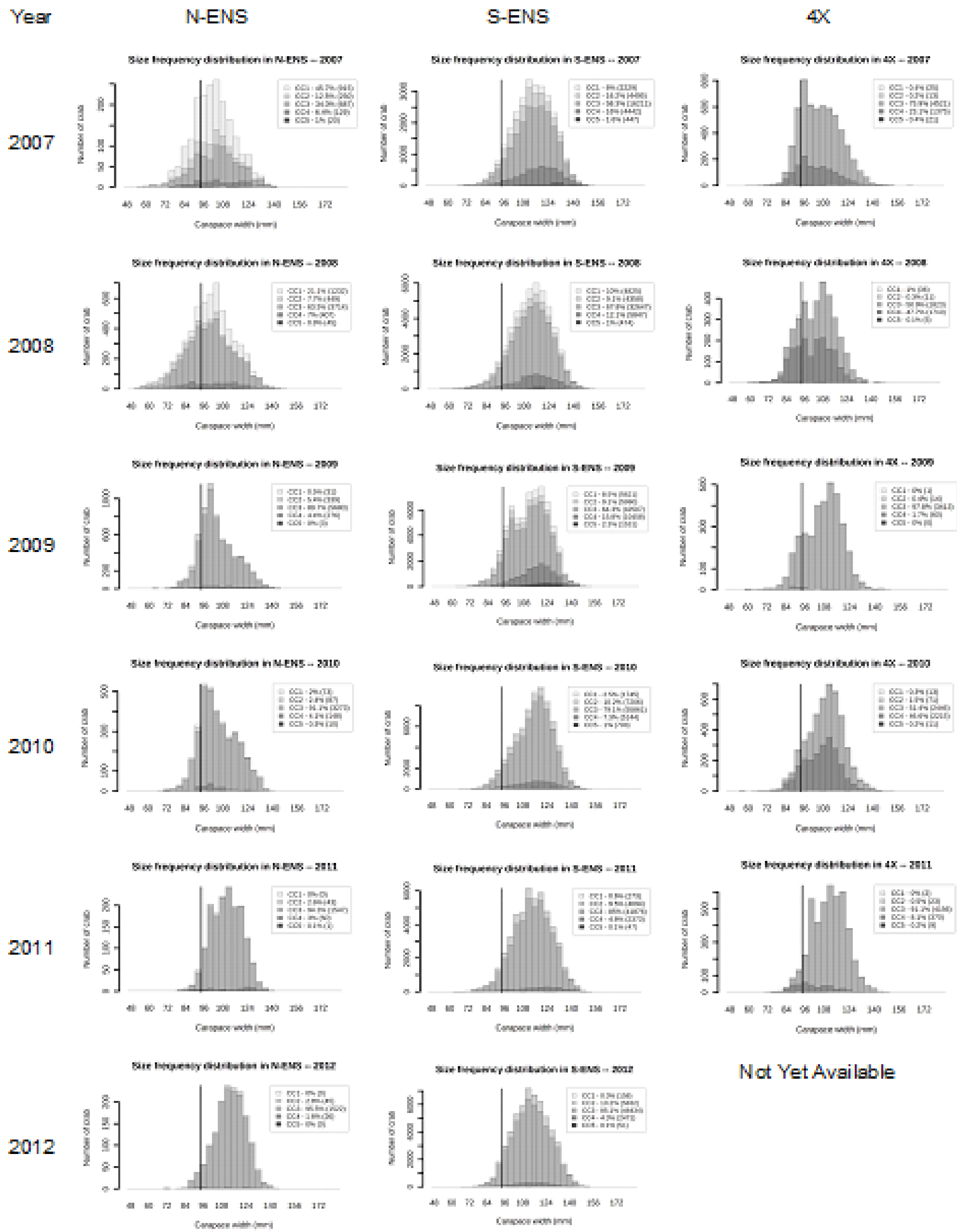



*Figure 31: Size frequency distribution of all at-sea-observer monitored snow crab broken down by carapace condition. For 4X, the year refers to the starting year of the season. Vertical lines indicate 95 mm CW.*

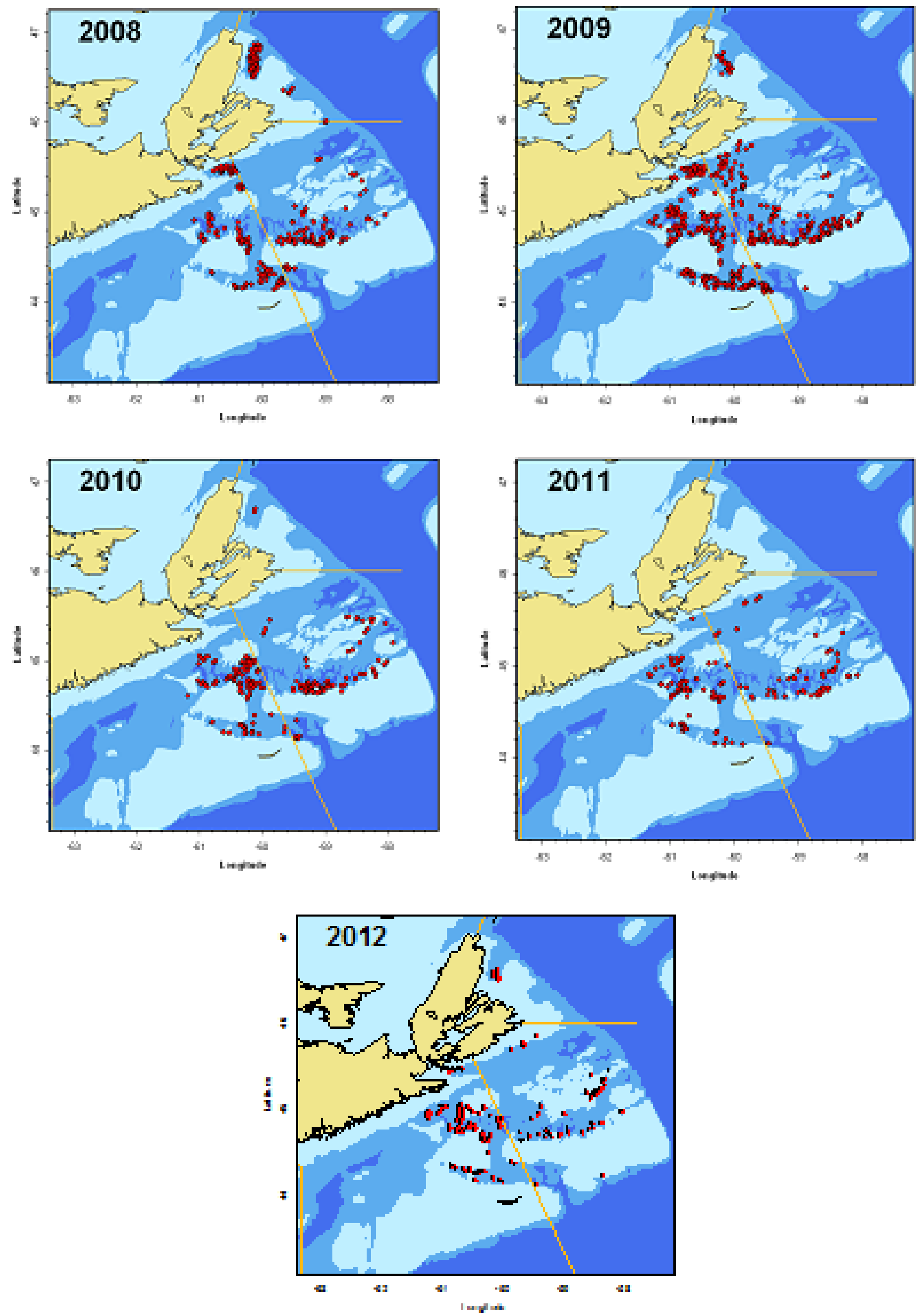



*Figure 32a: Location of traps sampled by at-sea-observers which had 20% or greater soft crab.*

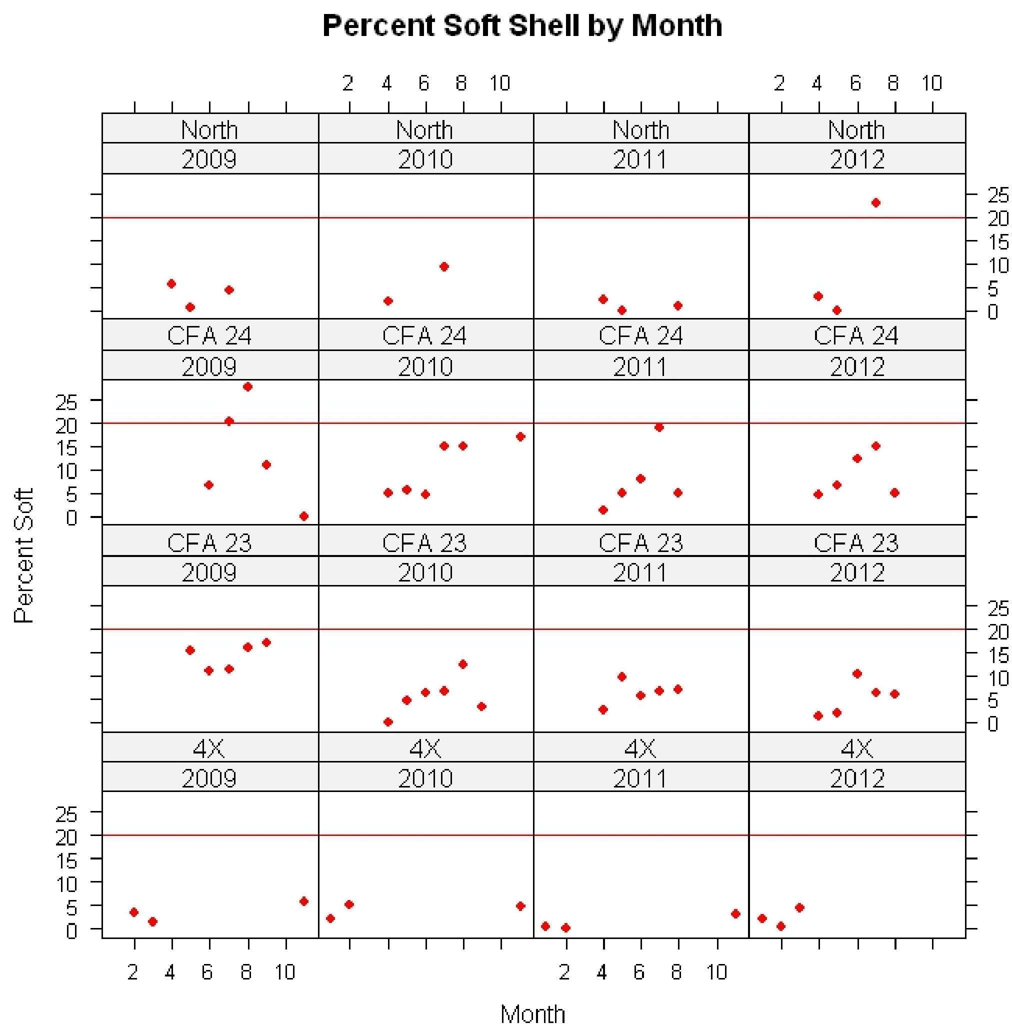



*Figure 32b: Occurrence of soft-shell crab sampled by at-sea-observers from commercial crab traps.*

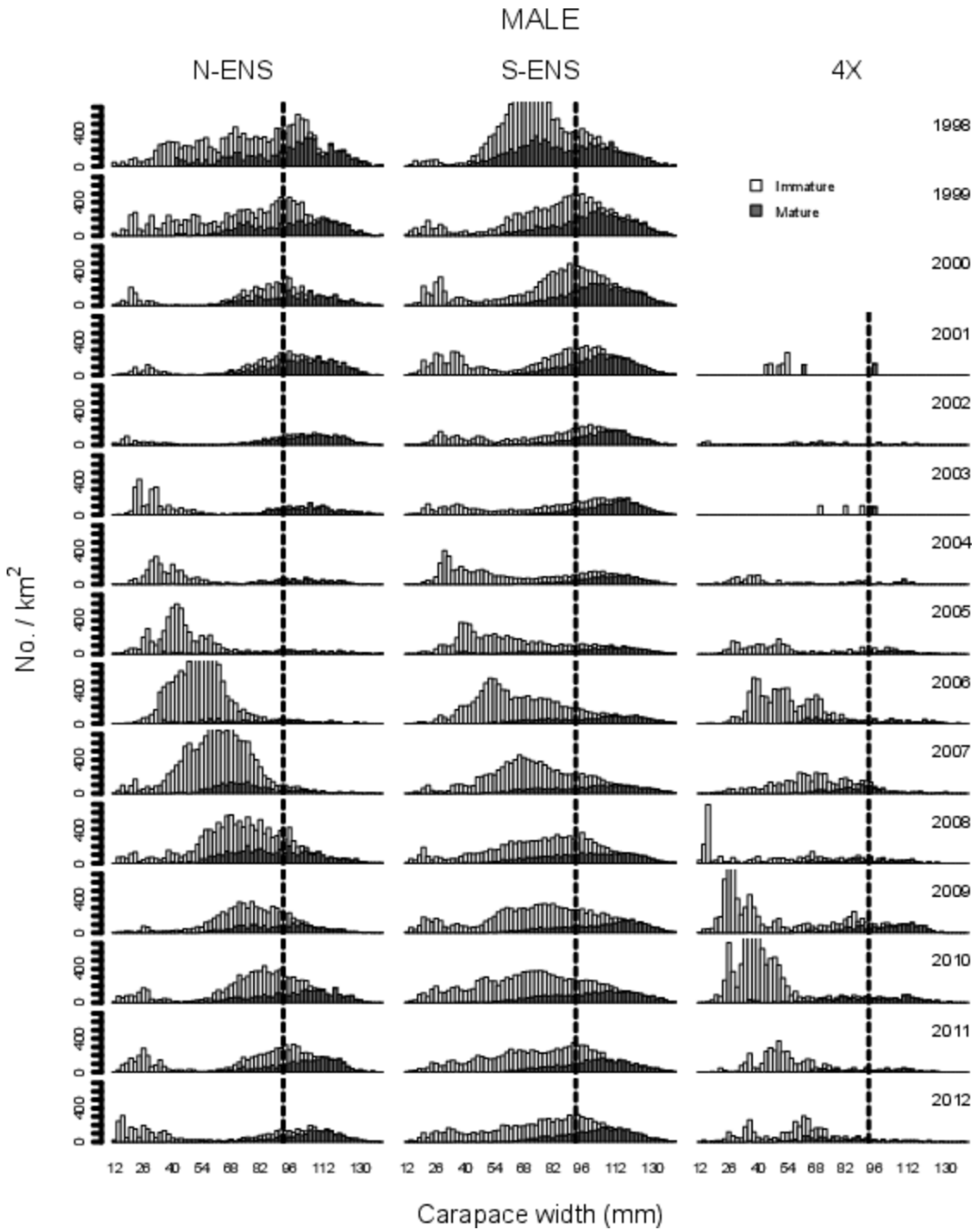



*Figure 33: Size-frequency histograms of carapace width of male snow crabs. Note the a more uniform distribution of adolescent crab across all size classes in S-ENS as compared to other areas and previous patterns in S-ENS. Due to the expansion of the survey from core areas to the full extent of the snow crab grounds, the areal densities of crab in S-ENS and 4X are not directly comparable between all years. For N-ENS, however, the relative heights are comparable. For S-ENS and 4X, 2004 to the present are comparable.*

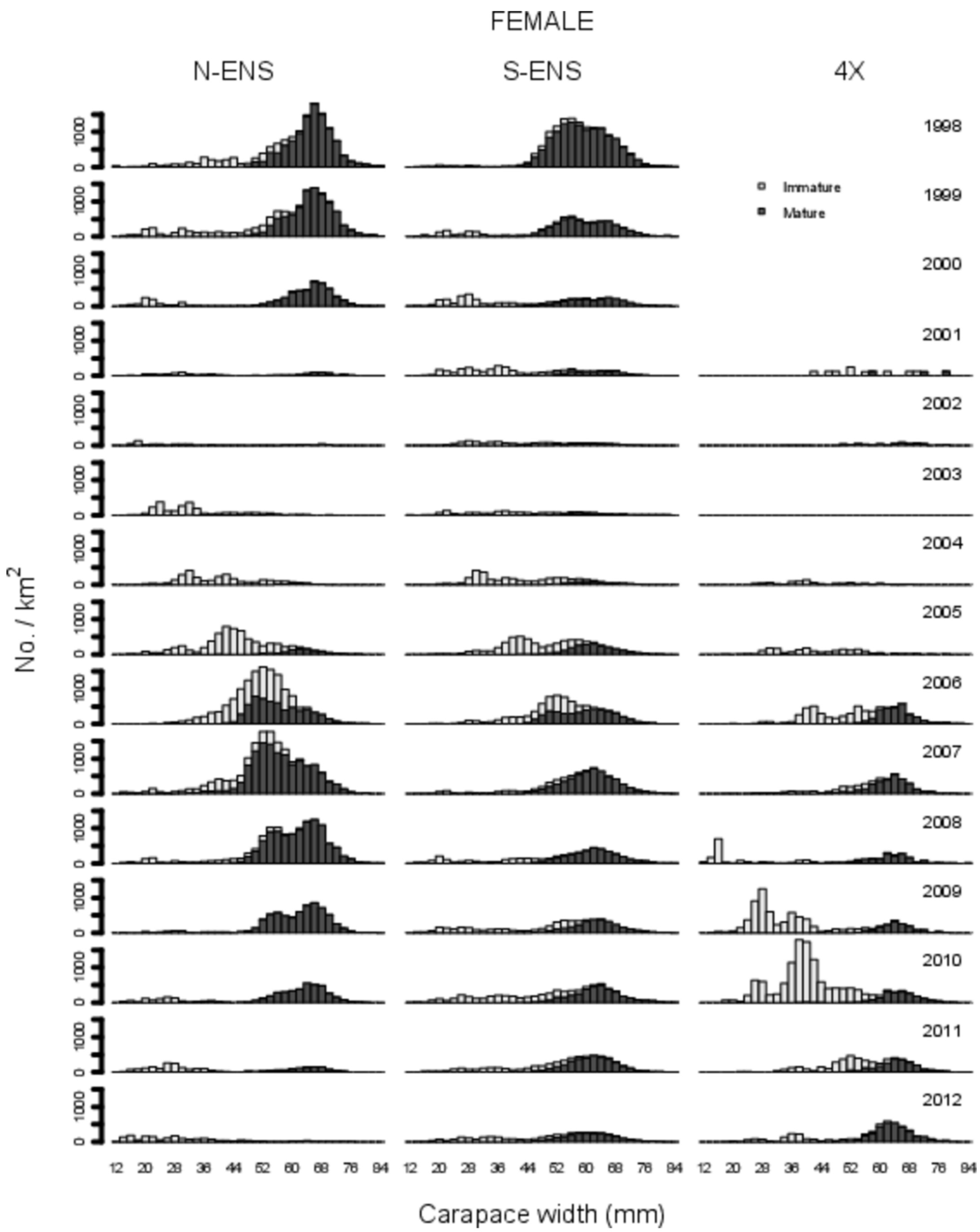



*Figure 34: Size-frequency histograms of carapace width of female snow crabs. Due to the expansion of the survey from core areas to the full extent of the snow crab grounds, the areal densities of crab in S-ENS and 4X are not directly comparable between all years. For N-ENS, the relative heights are comparable between all years. For S-ENS and 4X, data from 2004 to the present are comparable.*

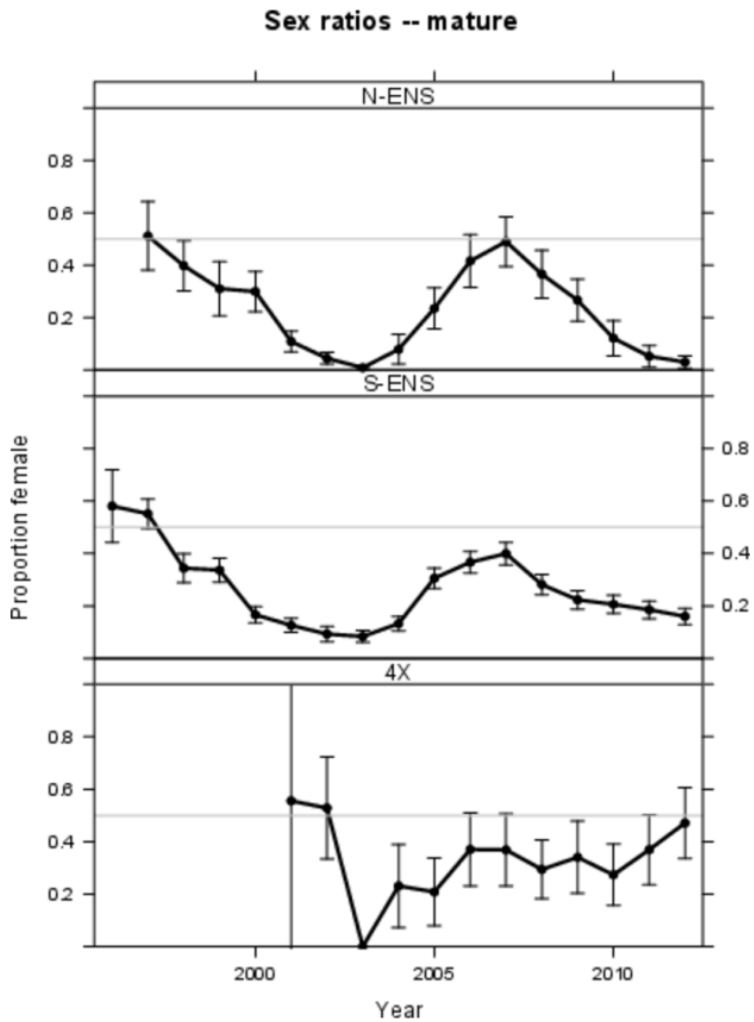



*Figure 35: Annual sex ratios (proportion female) of mature snow crab. Since 2000, most of the Scotian Shelf was uniformly male dominated. There has been a decline in the relative proportion of mature female to male crab in both N- and S-ENS since peaking in 2007. One standard error bar is presented.*

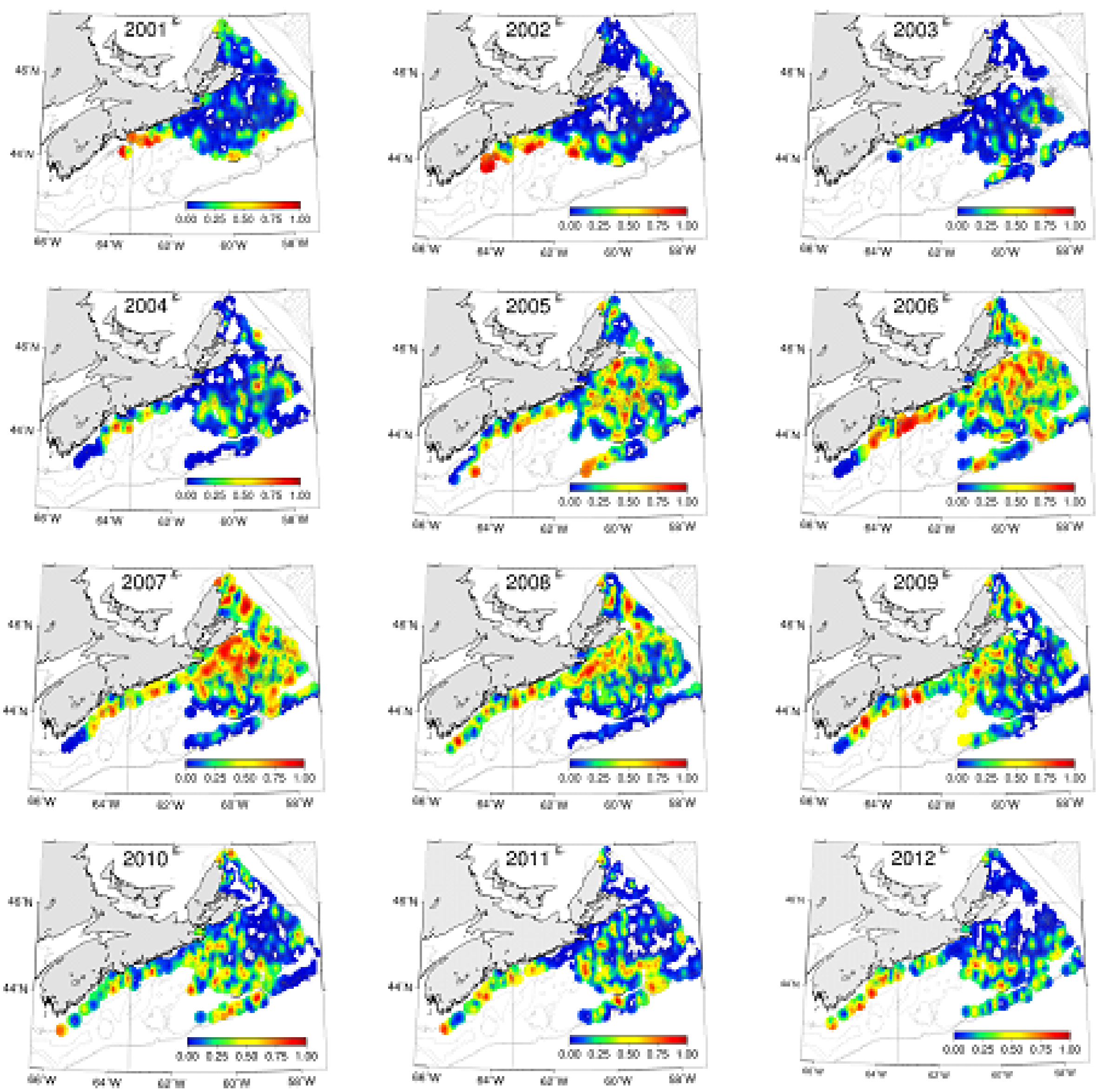



*Figure 36: Morphometrically mature sex ratios (proportion female).*

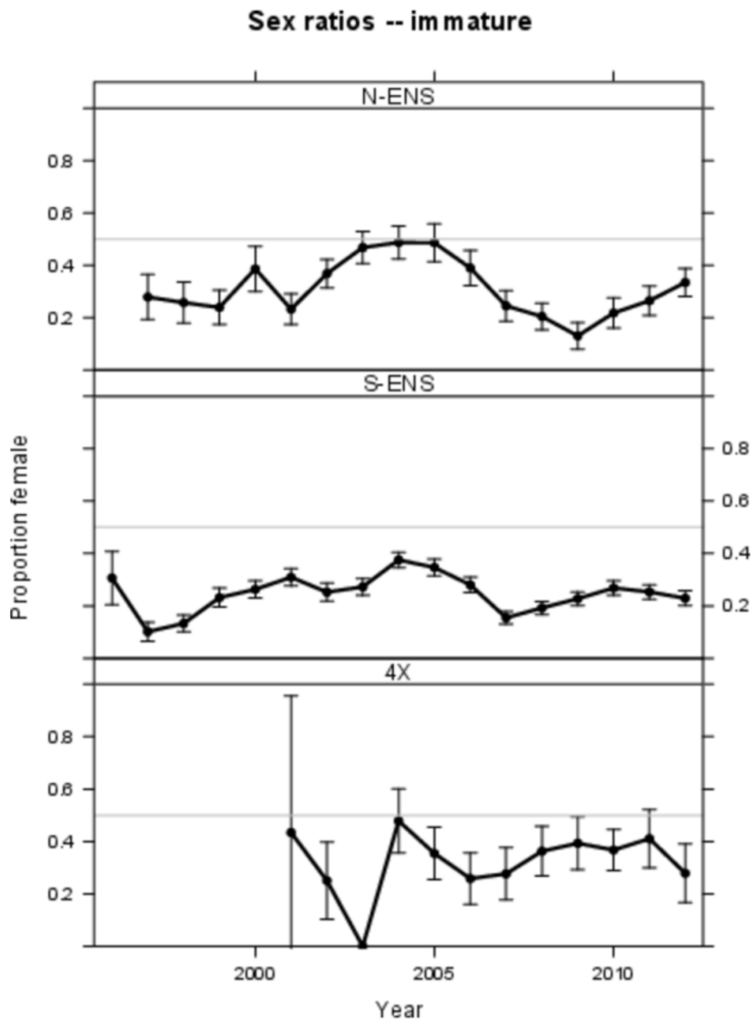



*Figure 37: Annual variations in the mean sex ratio (proportion female) for morphometrically immature crabs. One standard error bars are presented.*

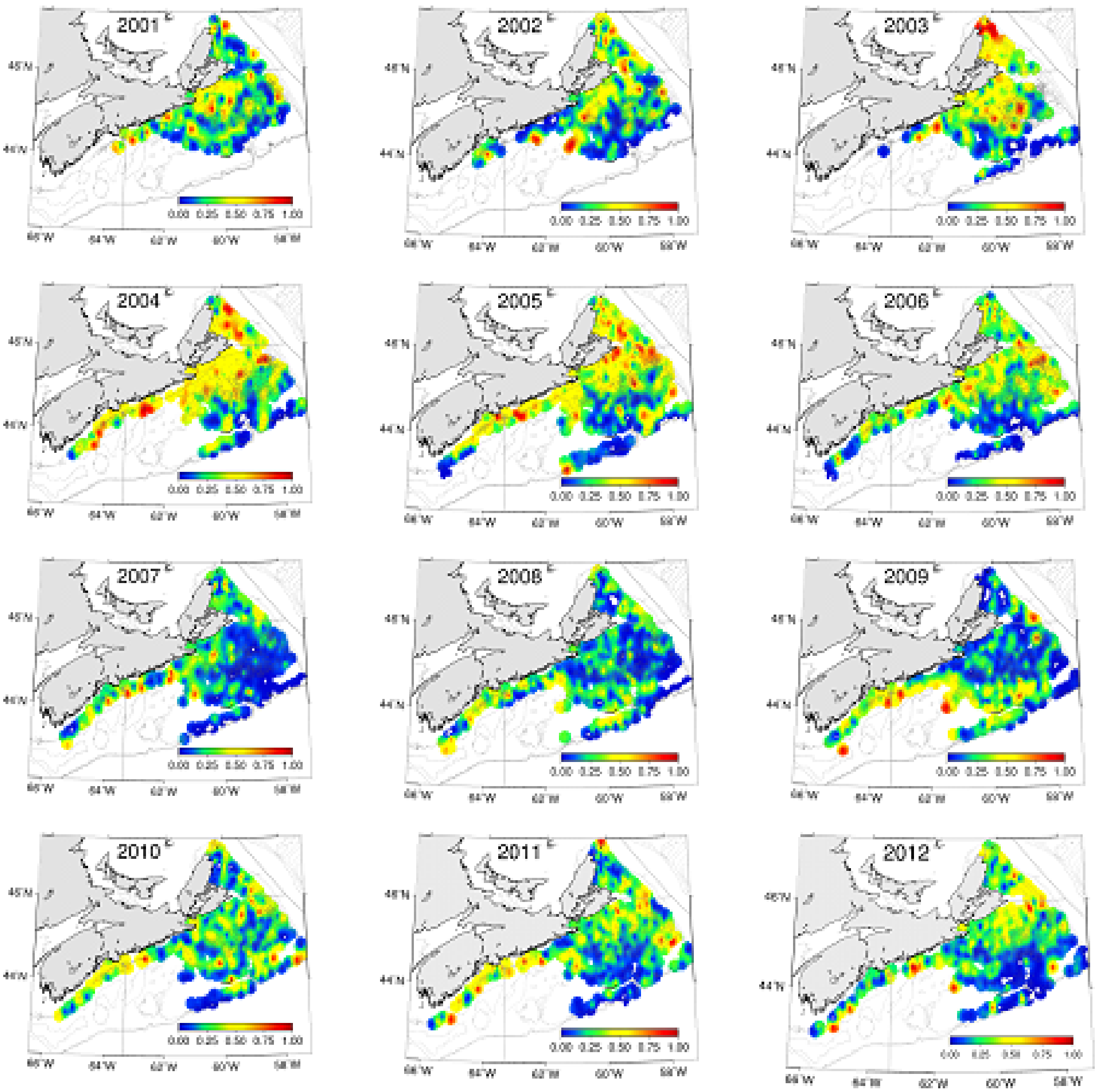



*Figure 38: Morphometrically immature sex ratios (proportion female).*

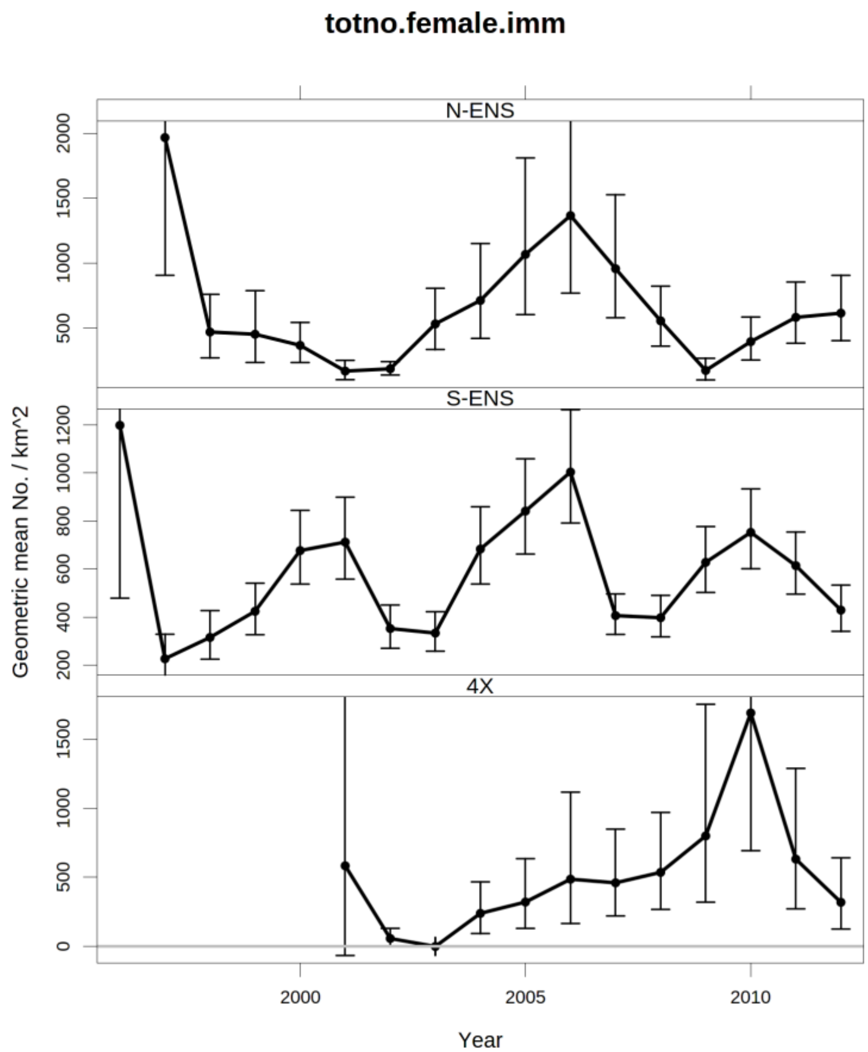



*Figure 39: Number of immature females in the SSE.*

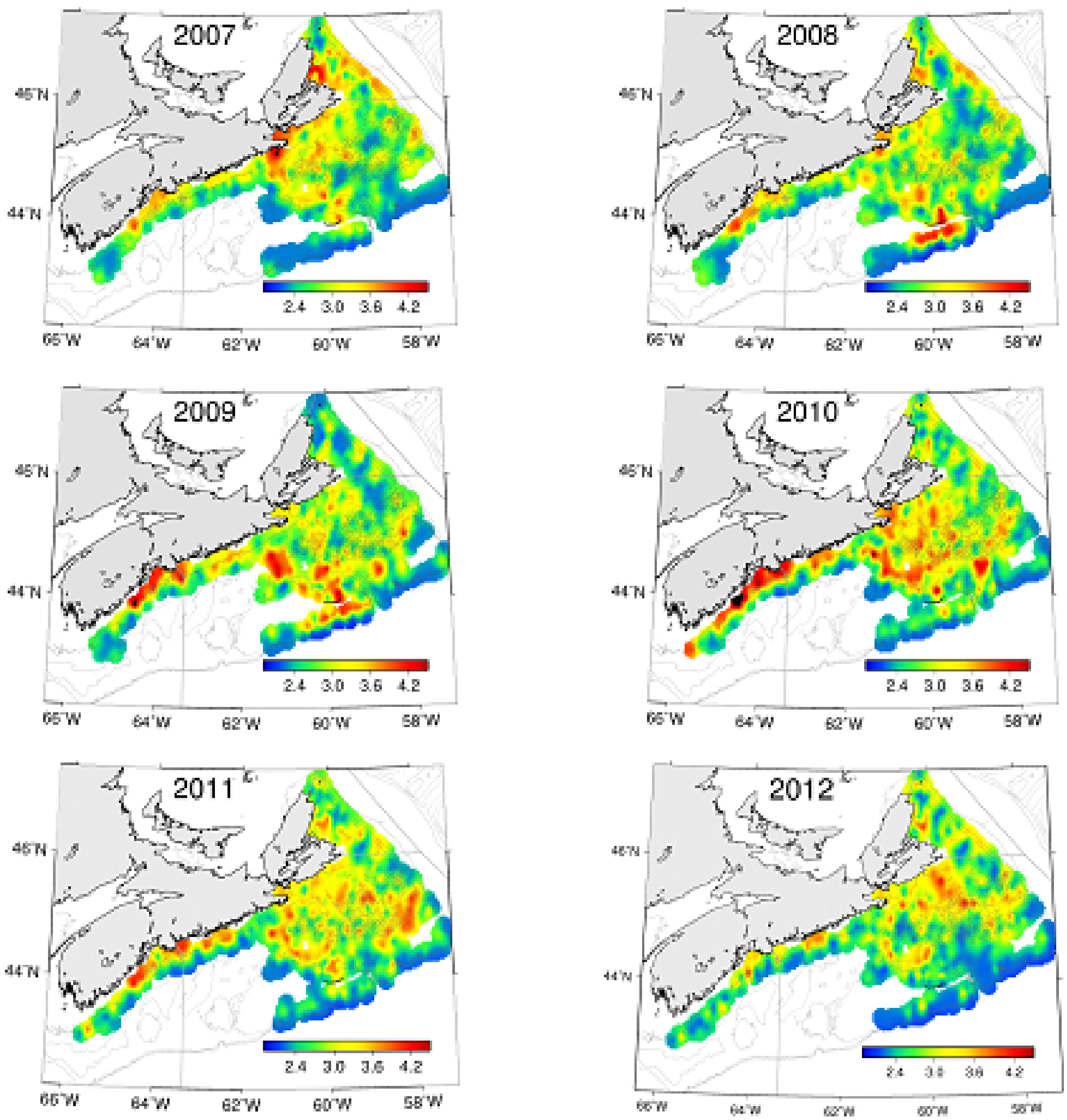



*Figure 40: Numerical densities of the immature female snow crabs on the Scotian Shelf; log10(number/km$^2$).*

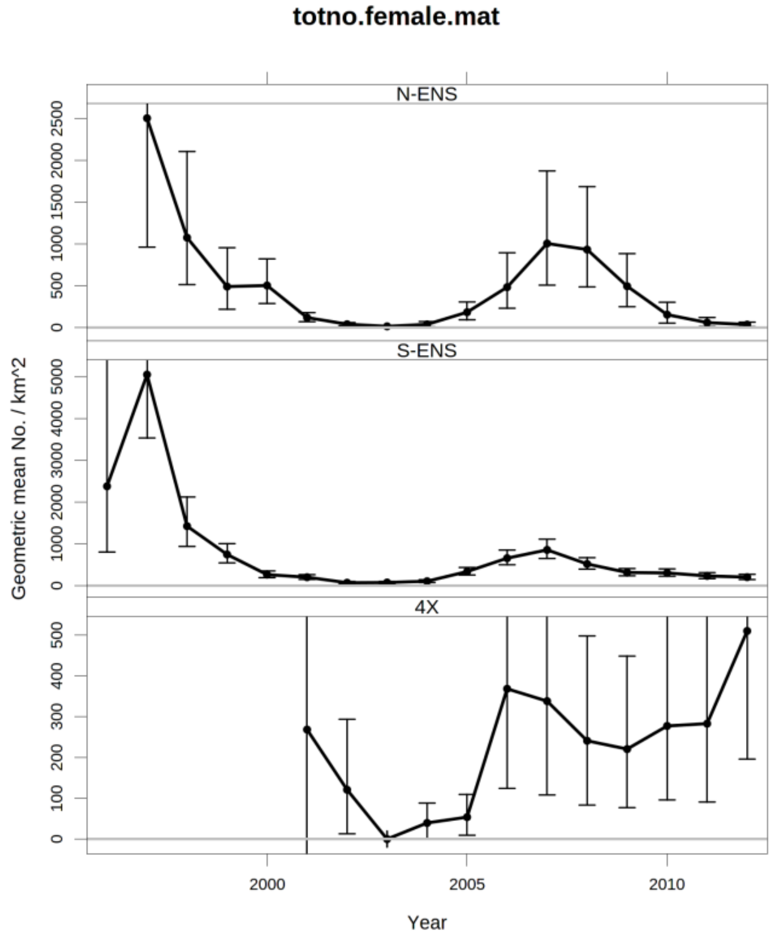



*Figure 41: Number of mature females in the SSE.*

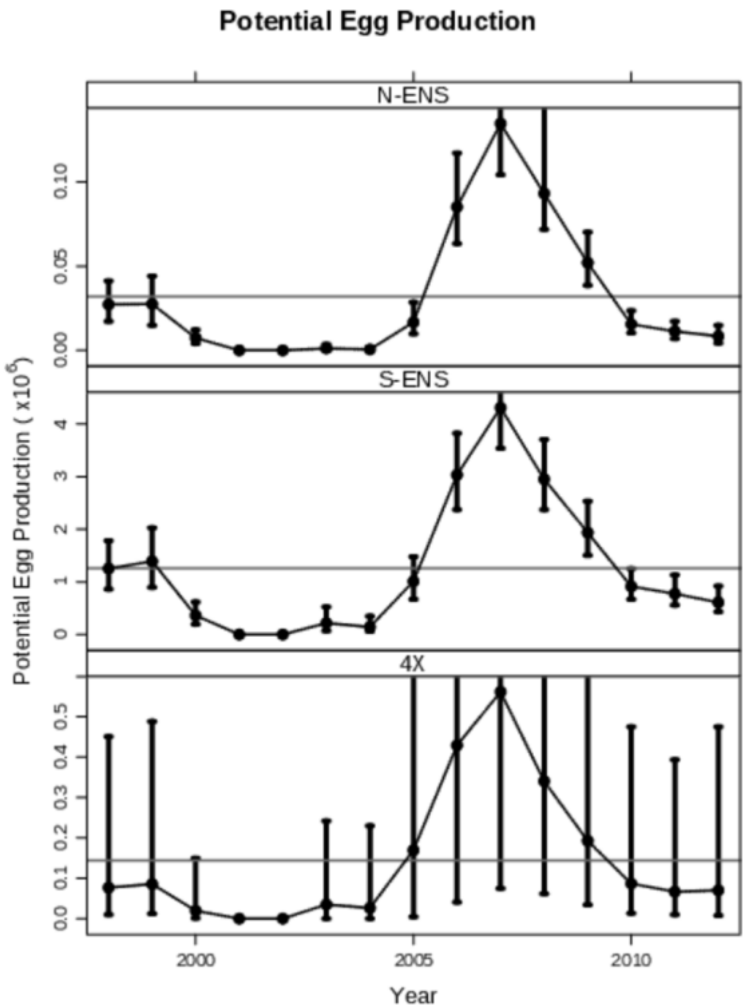



*Figure 42: Potential egg production in the SSE.*

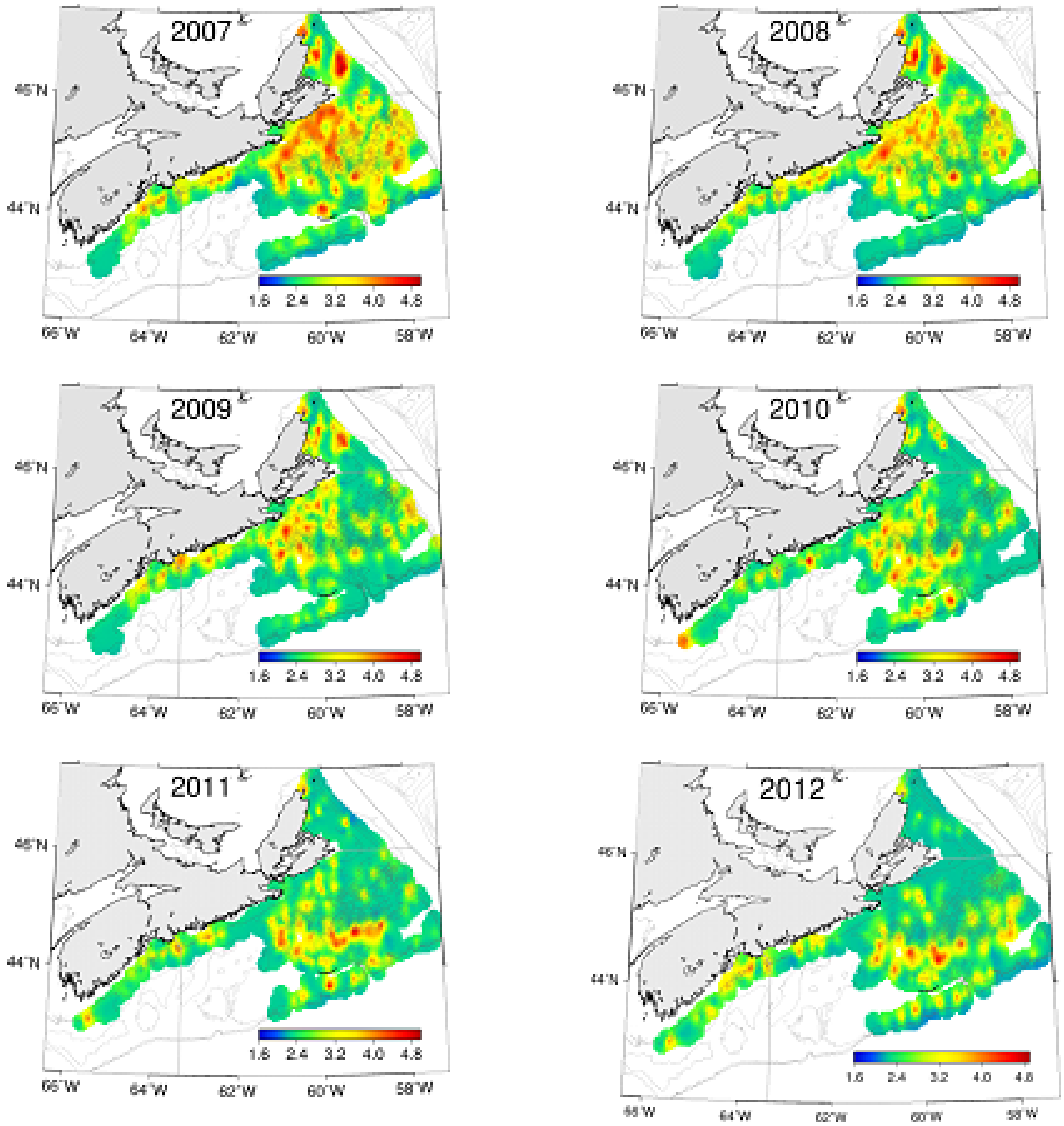



*Figure 43: Numerical densities of the berried female snow crabs on the Scotian Shelf; log10 (number/km$^2$).*

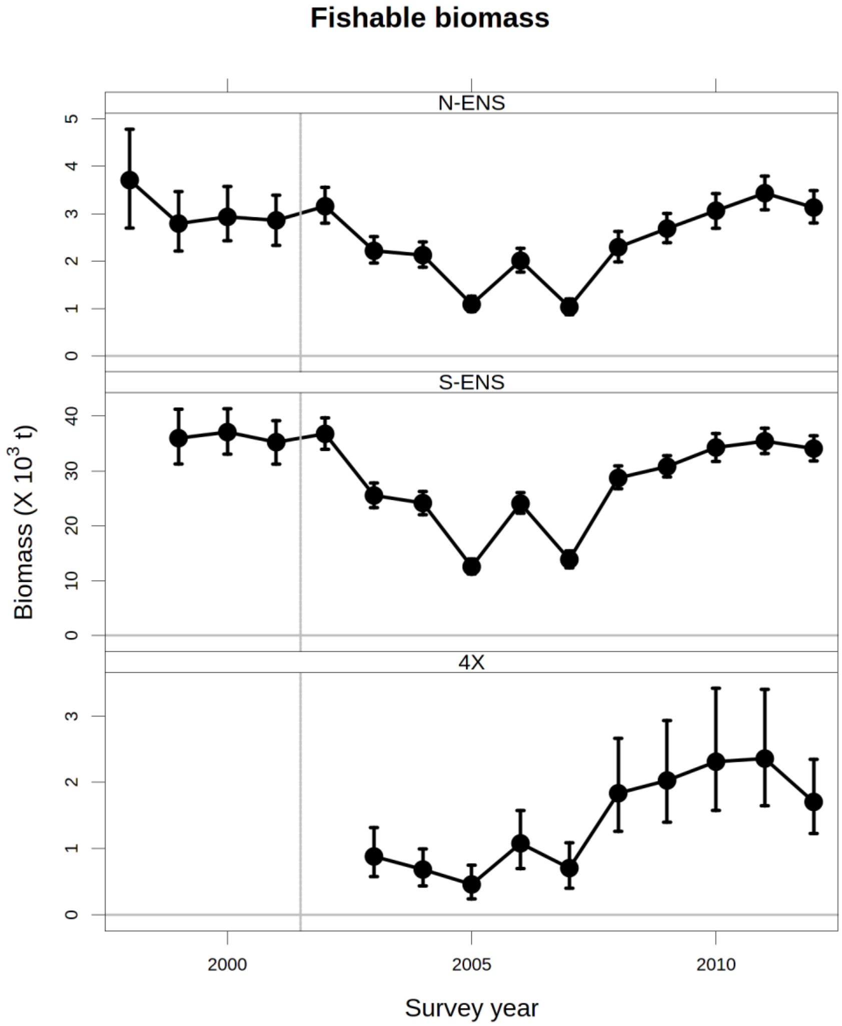



*Figure 44: Temporal variations in the fishable biomass index. Error bars are 95% CI about the estimated total biomass. The vertical line near 2002 indicates the period in which trawl surveys changed from a spring to an autumn sampling period.*

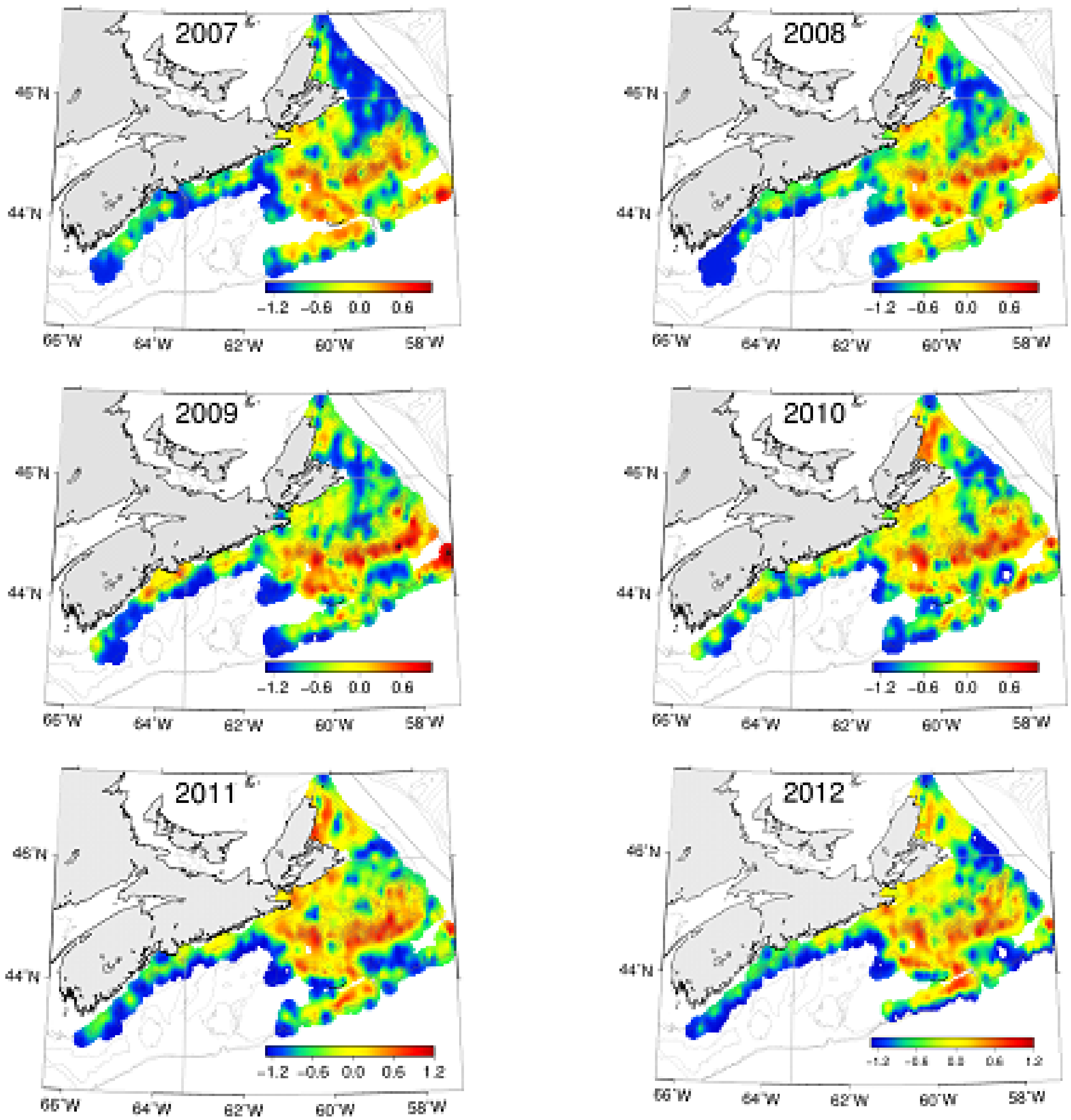



*Figure 45: Fishable biomass densities on the Scotian Shelf; log10 (t/km²).*

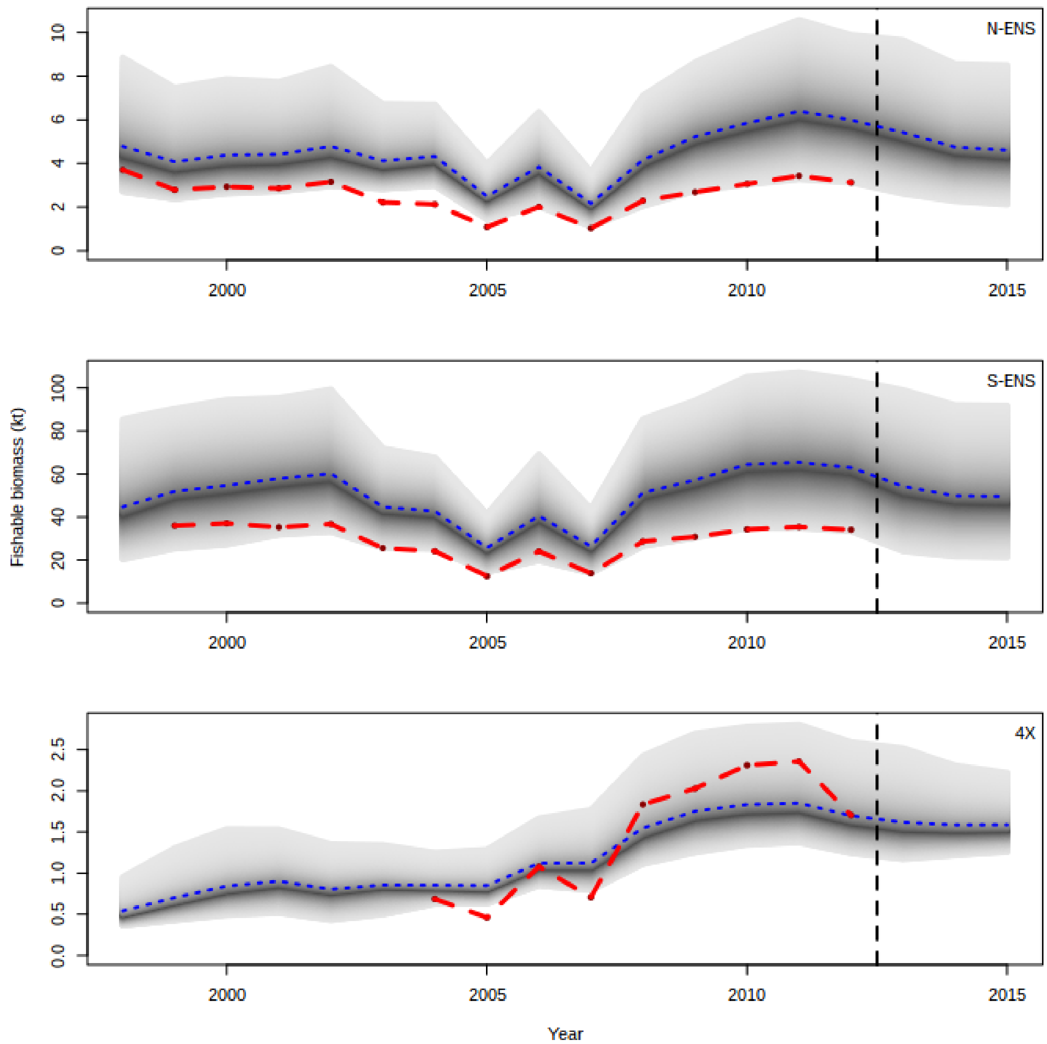



*Figure 46: Time series of fishable biomass. The fishable biomass index is shown in red dashed lines. The posterior mean fishable biomass estimated from the logistic model are shown in blue stippled lines. The density distribution of posterior fishable biomass estimates are presented (gray) with the darkest area being medians and the 95% CI. A three year projection assuming a constant exploitation strategy of 20% is also provided.*

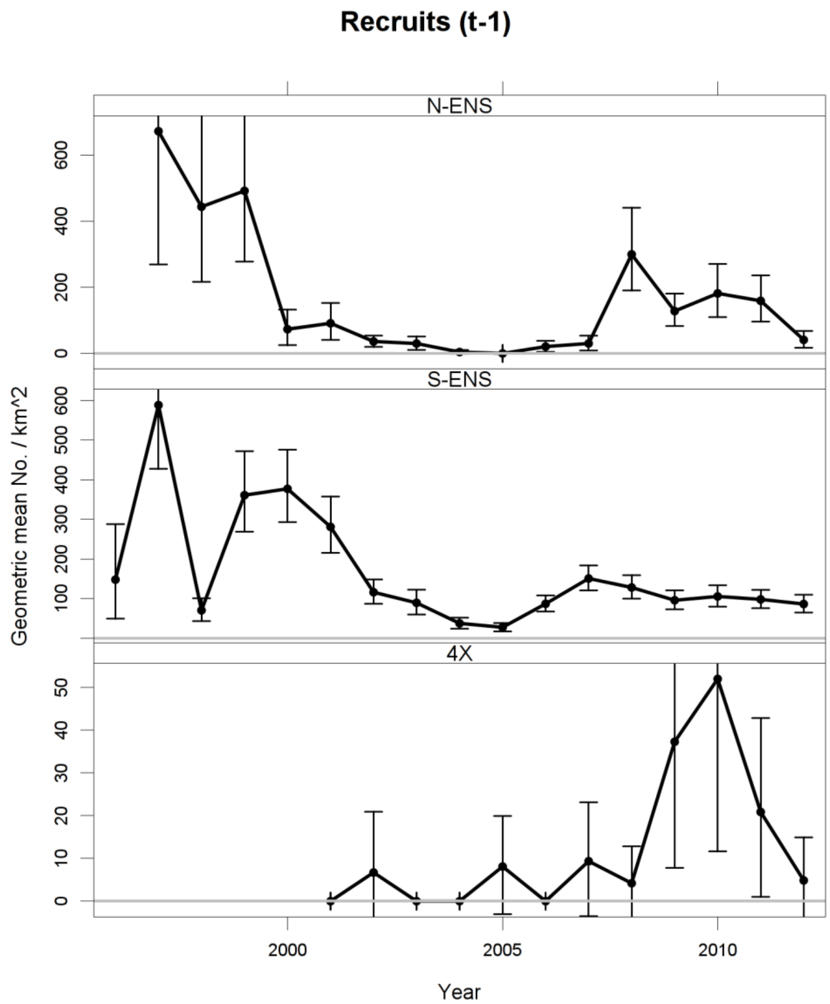



*Figure 47: Recruitment into the fishable biomass. Error bars are 95% CI about the estimated total biomass. The vertical line near 2002 indicates the period in which trawl surveys changed from a spring to an autumn sampling period.*

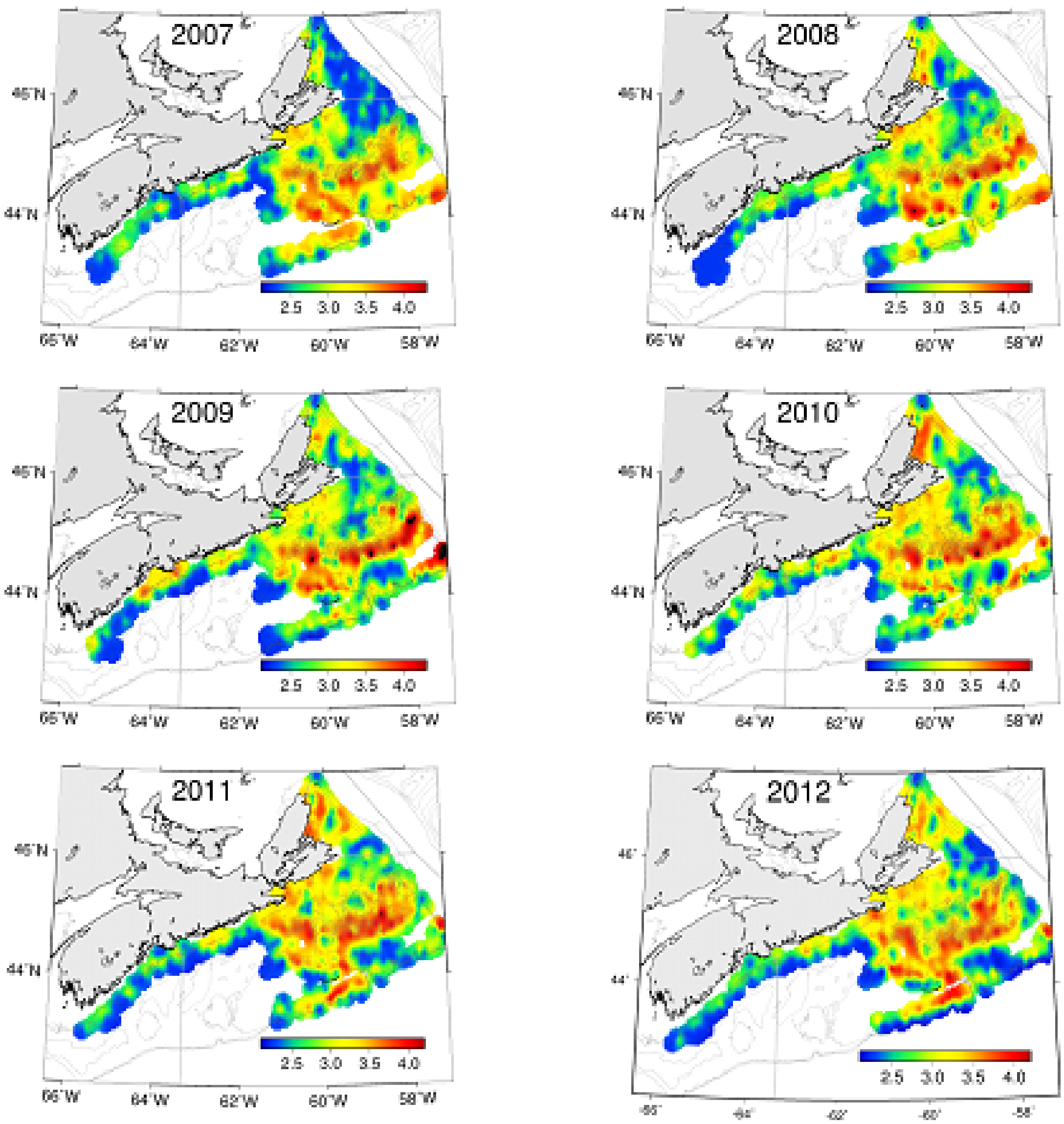



*Figure 48: Numerical densities of snow crab recruiting into the next year; log10 (number/km$^2$).*

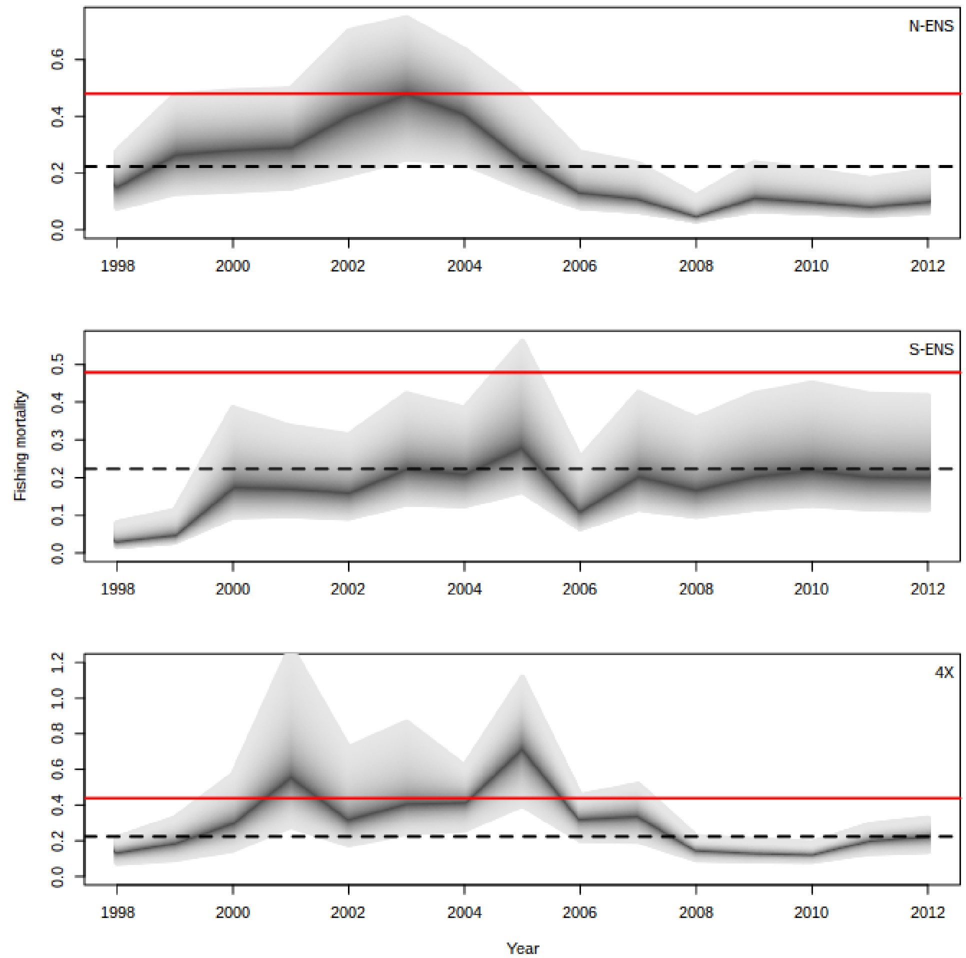



*Figure 49: Time-series of fishing mortality for N-ENS, S-ENS and 4X, respectively. Posterior density distributions are presented in gray, with the darkest line being the median with 95% CI. The red line is the estimated $F_{MSY}$ and dark stippled line is the 20% harvest rate.*

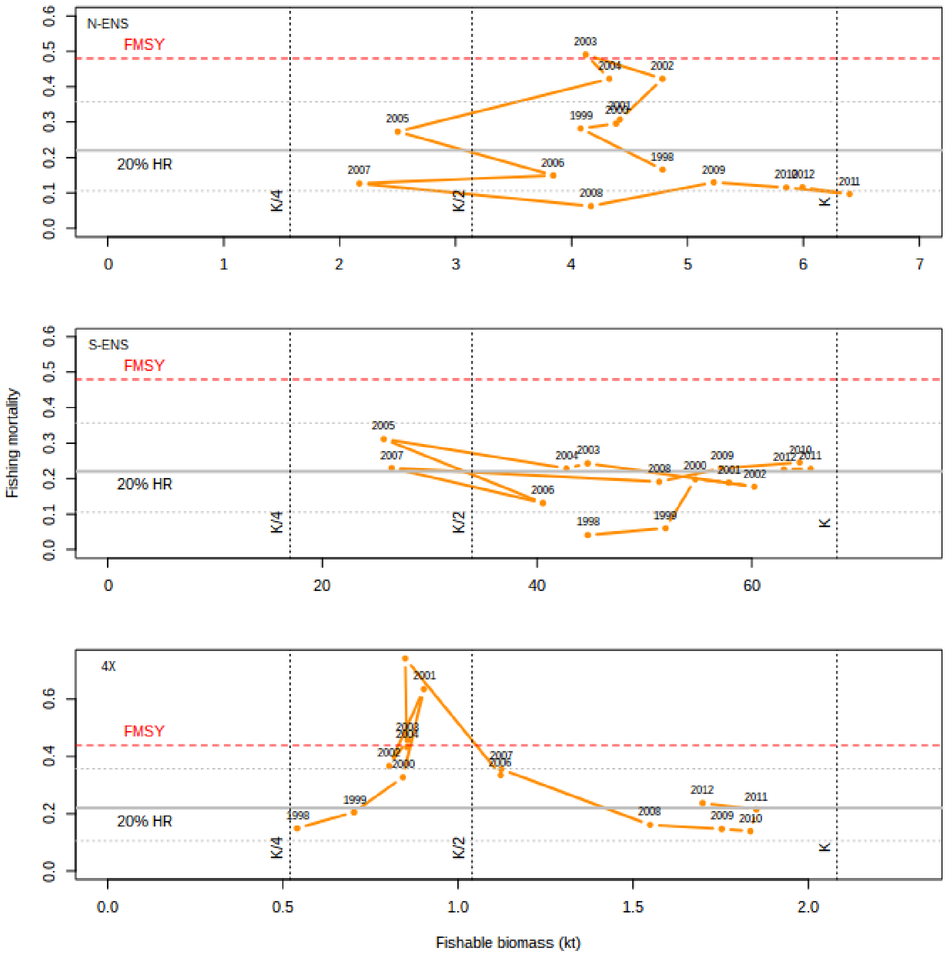



*Figure 50: Fishing mortality as a function of fishable biomass for N-ENS (top), S-ENS (middle) and 4X (bottom).*

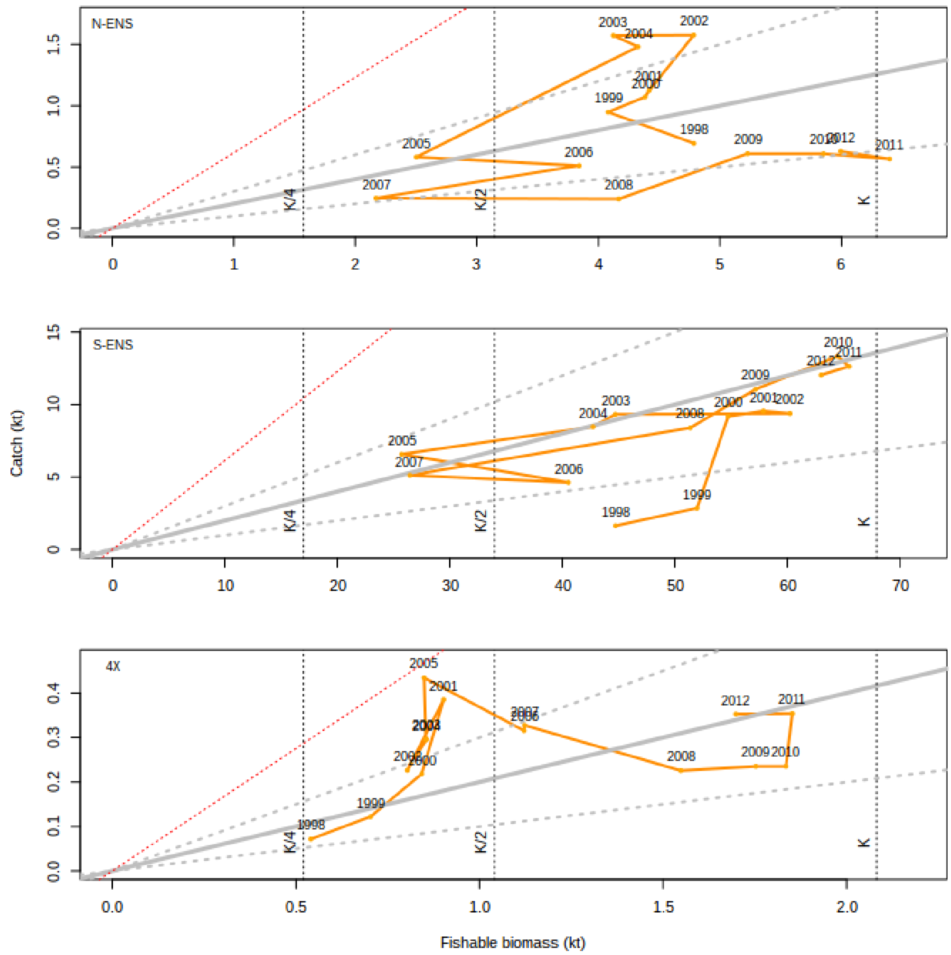



*Figure 51: Fishery catch as a function of fishable biomass for N-ENS (top), S-ENS (middle) and 4X (bottom). Exploitation rates of 20% are indicated by the solid gray line. Bounding this are the lines associated with 10% and 30% exploitation rates, in dashed lines.*

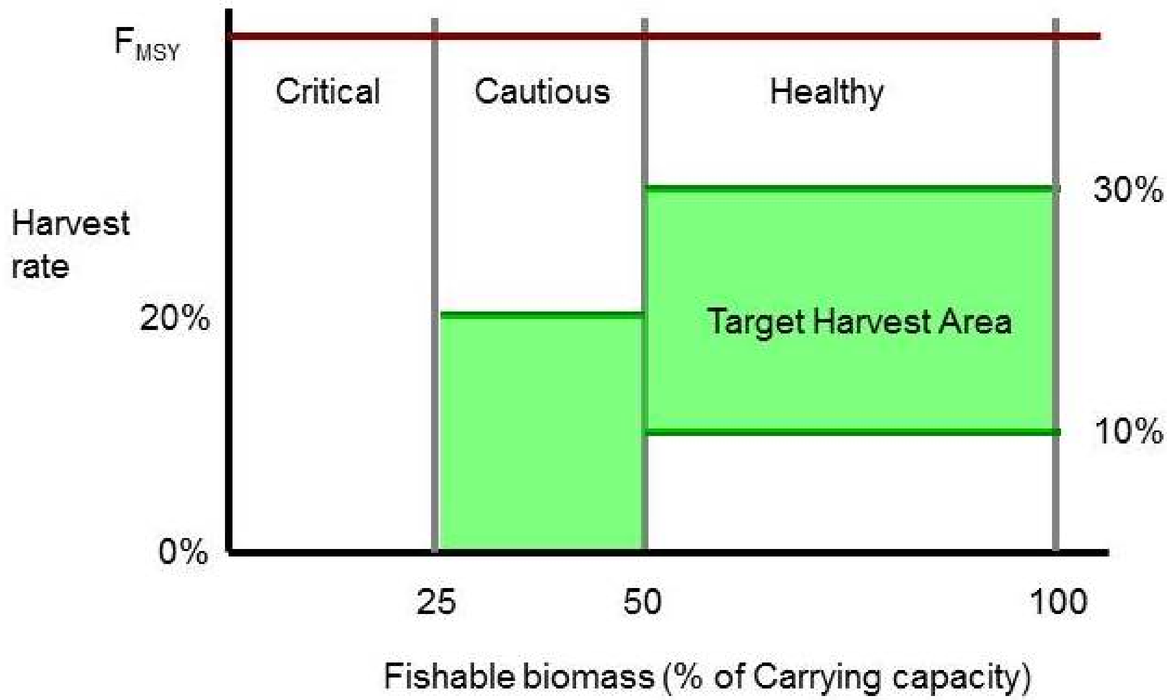



*Figure 52: Harvest control rules for the SSE snow crab fishery.*

## 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 which 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 abundance, 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 5). Note that CC 2 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)** –Ssee 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 (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 containing 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) - T**he 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.

# APPENDICES

## APPENDIX 1: 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 |

| Index variable label | Description |
|---|---|
| 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 |
| 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 2: STOCK ASSESSMENT MODEL

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

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

Arguing against the usage of 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 oogives, habitat usage, predation risk and fishery exploitation, any standard model formulation (including the logisitic 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=0; *θ*):

$$\mathbf{F}(B; \theta) = c_1 B + c_2 B^2 + c_3 B^3 + \ldots \text{ ; where } c \text{ are constants}$$

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:

$$c_1 = r \text{ and } c_2 = -r/K$$

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*:

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

Generally, *r* and *K* are assumed constants. Clearly, however, these quantities 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 feeds back into future states via error propagation – e.g., 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 hyperpriors.

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 observation error, $_o\sigma^2{}_a$, was assumed to be known without error and derived from survey indices of coefficients of variation (CV).

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. Clearly 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:

$$q_a \sim Normal\ ({}_q\mu_a,\ {}_q\sigma^2{}_a)$$

Process error was assumed to follow a (multiplicative) lognormal distribution with variance $_p\sigma^2$ and the 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 normal distribution:

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

The intrinsic rate of increase was assumed to be time-varying and linearly related to the logarithm of the recruitment index (R-1):

$$log(\ {}_{obs}RECRUIT_{t,a}\ ) \sim Normal\ (r_{t,a}\ {}_rq_a\ ,\ {}_r\sigma^2{}_a)$$

These priors and hyperpriors 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 bounded by the interval +/-75% of 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). Priors for the $\mu_{b(t=0)}$ were assumed to be uniformly distributed bounded by (0.5, 0.8), except in CFA 4X where it was assumed to be bounded by the interval (0.2,0.6), based upon the relative magnitudes of the fishable biomass indices in year t=1. Coefficients of variation were generally assumed to be random uniform in the interval (~0.05, 0.4) for both normal and lognormal distributions.

The posterior distribution of the parameters of interest, $\theta$, 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.

Simpler, hierarchical models were also examined based upon the penalized Deviance Information Criterion (Plummer 2008); however, their performance was generally similar to the full model and with parameters estimates that were sufficiently variable between regions such that the full model was used in this assessment as this most flexibly estimated all the parameters of interest.

The JAGS model used for parameter estimation is as follows:

```
model {
  # define marginally informative variance priors using CV's (coefficients of variation): uniform distribution seems most stable
  # eps = a small number non-zero number (essentially equivalent to zero but used to prevent infinity values)
  # uninformative CV's associated with process (bp.) and observation (bo.) errors
  # NOTE for lognormals: CV = sqrt(exp( SD ^2) - 1)  and CV ~ SD where SD~ < 0.5
  # SD= sqrt(log(1+CV^2)) and therefore, in terms of precision: TAU = 1/SD^2 = 1/log(1+CV^2) ; and SD = 1/sqrt(TAU)
  for (j in 1:U) {
    IREC.sd[j] ~ dunif( eps, cv.normal.max*rec.max[j] )
    IREC.tau[j] <- pow( IREC.sd[j], -2)
    IREC.q[j] ~ dunif( eps, rec.max[j] )
    for (i in 1:N) {
      r.mu[i,j] ~ dunif( r.min, r.max)
      IREC[i,j] ~ dnorm( r.mu[i,j] * IREC.q[j] , IREC.tau[j] ) T(eps, )
      r.sd[i,j] ~ dunif( r.min *cv.normal.min, r.max *cv.normal.max )  # intrinsic rate of increase (normal scale)
      r[i,j] ~ dnorm( r.mu[i,j], pow( r.sd[i,j], -2 ) ) T(r.min, r.max)
    }
  }
  for (j in 1:U) {
    #separate spring survey q's
    qs.mu[j]  ~ dunif( q.min, q.max )
    qs.sd[j]  ~ dunif( qs.mu[j] * cv.normal.min, qs.mu[j] *cv.normal.max )  # catchability coefficient (normal scale)
    qs[j] ~ dnorm( qs.mu[j], pow( qs.sd[j], -2 ) ) T(q.min, q.max)
    q.mu[j]  ~ dunif( q.min, q.max )
    q.sd[j]  ~ dunif( q.mu[j] * cv.normal.min, q.mu[j] *cv.normal.max )  #catchability coefficient (normal scale)
    q[j] ~ dnorm( q.mu[j], pow( q.sd[j], -2 ) ) T(q.min, q.max)
  }
  for (j in 1:U) {
    K.mu[j]  ~ dunif( K.min[j], K.max[j] )
    K.sd[j]  ~ dunif( K.mu[j] *cv.normal.min, K.mu[j] *cv.normal.max )  # Carrying capacity (normal scale)
    K[j] ~ dnorm( K.mu[j], pow( K.sd[j], -2 )) 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)
  #   this is conceptualized in the following time line:
  #     "|" == start/end of each new fishing year
  #     Sf = Survey in fall
  #     Ss= Survey in spring
  #     |...(t-2)...|.Ss..(t-1)...|...(t=2004)..Sf.|...(t+1).Sf..|...(t+2)..Sf.|...
  # Observed biomass CV's assumed to be known **without** error
    bo.tau <- pow( log( 1 + pow(IOA.cv, 2)), -1)
    bo.sd  <- pow( sqrt(bo.tau), -1 )
    for (j in 1:(U-1)) {
      # spring surveys from 1998 to 2003
      IOA[1,j] ~ dlnorm( log( max( qs[j] * K[j] * (bm[ 1,j] - rem[1,j]) , eps)), bo.tau[1,j] )  #approximation
      for (i in 2:(ty-1)) {
        IOA[i,j] ~ dlnorm( log( max( qs[j] * K[j] * (bm[i,j]- rem[(i-1),j]), eps)), bo.tau[i,j] )  ;
      }
      # transition year
      IOA[ty,j] ~ dlnorm( log( max( (qs[j]+q[j])/2 * K[j] * (bm[ty,j] - (rem[(ty-1),j] + rem[ty,j] )/2 ), eps)), bo.tau[ty,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[i,j] ) ;
      }
```

## APPENDIX 3: 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, or the Brundtland Commission's Report, Our Common Future, 1987), 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 (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) than results in disease or fire outbreaks and eventually large-scale collapse (Diamond 2005). A high abundance does not necessarily equate to high sustainability. The problem lies with not the metric, but rather the focus upon a single indicator. Sustainability is a multidimensional concept that requires reliance upon a broader set of criteria that describes both the resource status and relationships between the focal resource and the surrounding ecosystem (Choi and Patten 2001).

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

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

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

Significantly, as the footprint of a fishery is itself context dependent (i.e., population and ecosystem), the use of fixed biological limit reference points of a single indicator is not 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).