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Assessment of Scotian Shelf Snow Crab in 2010

Évaluation des stocks de crabes des neiges du plateau néo-écossais en 2010

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ABSTRACT

Landings in 2010 were 576 and 13,150 t for northern and southern areas of Eastern Nova Scotia (ENS), respectively and 229 t for Crab Fishing Area (CFA) 4X in 2009/2010. The associated TACs were 576, 13,200 and of 230 t, respectively. Average, non-standardized catch rates were 55.0, 102.5 and 36.0 kg trap^{-1}, respectively. These catch rates represent a 27% decrease for N-ENS, a 14% increase in S-ENS, and a 27% increase in CFA 4X, relative to 2009.

The capture of soft-shelled crab in N-ENS declined from 6.6% in 2009 to 3.5% in 2010, This continues an improving trend in soft crab rate since 2007 in N-ENS when 111% of the landings were estimated to have been discarded as soft crab. This is largely due to a spring fishery; 91% of the total 2010 N-ENS landings were captured in the spring, when soft-shell catchability is lower. In S-ENS, soft-shell handling decreased from 16% in 2009 to 7.7% of landings in 2010. The shift towards earlier fishing seasons appears to have improved soft shell crab handling rates in S-ENS in the 2010 season. Soft-shell discard rates in CFA 4X remain very low, in large part to a fall & winter fishery. Soft-shell incidence and associated potential handling mortality will continue to be an issue that requires continued diligence and adaptability by the snow crab fleet. Bycatch of non-target species is extremely low, being estimated to be less than 0.01% and 0.93% of total snow crab landings in ENS and CFA 4X, respectively, over the past four years.

Recruitment into the fishery is expected to continue for the next 2-4 years in N-ENS as high densities of adolescents between 70 to 90 mm CW (carapace width) have been observed. The relatively stable distribution of male crab across all size classes in S-ENS may create more stable recruitment in future years, as opposed to a cyclical recruitment observed in the past in all areas. In CFA 4X, high densities of crab between 20 to 50 mm CW were observed though a distinct lack of adolescent crab between 50 and 90mm may force the reliance of the 4X fishery on movement of crab from S-ENS. 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 CFA 4X. The reproductive potential of the Scotian Shelf population peaked in 2007/2008 and is now on a declining trend. Larval production should continue for another 1-2 years in N-ENS and longer in S-ENS and 4X.

The post-fishery fishable biomass of snow crab in N-ENS was estimated to be 2,810 t (95% confidence interval (CI): 2,180 to 3,780 t; relative to 2,790 t (95% CI: 2,220 to 3,840 t) in 2009. In S-ENS, the post-fishery fishable biomass of snow crab was estimated to be 48.5×10^3 t (95% CI of: 32.2 to 77.9×10^3 t) relative to 49.3×10^3 t (95% CI of: 33.2 to 79.3×10^3 t) in 2009. In CFA 4X, the pre-fishery fishable biomass was 930 t (with a 95% CI of 590 to 1,440 t), relative to 1,070 t (95% CI of 640 to 1,730 t) in 2009/2010, representing a decrease of 13%.

These positive population characteristics are tempered by a number of additional uncertainties: The influence of predation, especially upon immature and soft shelled snow crab by groundfish. Large and rapid temperature swings as they can have both direct and indirect influences upon snow crab. For example, a strong warming event can have direct deleterious effects as snow crab are cold-water stenotherms. Even the very significant cooling trend observed throughout

the Scotian Shelf in 2009 with an associated habitat expansion was observed can have negative indirect consequences such as the introduction or proliferation of invasive species or disease (e.g, *Hematodinium sp.*) or the reduction of gross primary production. In addition to these factors, the signs of an initial return of ecological, social and economic indicators of system state in the direction of a low invertebrate dominated system adds, further uncertainty to the medium to long-term sustainability of the Scotian Shelf snow crab population.

Fishing mortality in N-ENS was estimated to be 0.19 (95% CI: 0.14, 0.24) or a harvest rate of 17.3%, unchanged relative to 2009. Good recruitment and significantly reduced soft-shell handling results in a positive outlook. Until a strong and persistent increase in fishable biomass is observed, long-term harvest rates between 10% and 20% is part of the strategy for sustainability in this fishery. A decreased or status quo harvest strategy is recommended.

Fishing mortality in S-ENS was estimated to be 0.23 (95% CI: 0.15, 0.33) or a harvest rate of 20.5%, a small increase relative to F=0.20 in 2009. Good recruitment suggests a positive outlook; however, the capture of soft shell crab remains an important issue for this fleet. Long-term harvest rates between 10% and 30% are part of the strategy for sustainability in this fishery. A decreased or status quo harvest strategy is recommended.

Fishing mortality in CFA 4X for 2009/2010 was estimated to be 0.22 (95% CI: 0.15, 0.33) or a harvest rate of 19.7%, relative to F=0.19 in 2008/2009. Long-term harvest rates between 10% and 30% are part of the strategy for sustainability in this fishery. As recruitment into the 2011/2012 season is uncertain, a decreased or status quo harvest strategy is recommended.

RÉSUMÉ

En 2010, les débarquements de crabes des neiges ont respectivement atteint 576 t et 13 150 t dans les zones nord-est et sud-est de la Nouvelle-Écosse, et 229 t dans la zone de pêche du crabe 4X en 2009-2010, alors que les totaux autorisés des captures étaient respectivement de 576 t, 13 200 t et 230 t. Les taux de prises moyens non normalisés ont atteint respectivement 55, 102,4 et 36 kg/casier levé$^{-1}$. Ces taux de prises représentent une diminution de 27 % dans le nord-est de la Nouvelle-Écosse, une augmentation de 14 % dans le sud-est et une augmentation de 27 % dans la zone de pêche du crabe 4X par rapport à 2009.

Le taux de capture de crabes à carapace molle dans le nord-est de la Nouvelle-Écosse est passé de 6,6 % en 2009 à 3,5 % en 2010, continuant ainsi l'amélioration du taux depuis 2007, où il était estimé que 111 % des débarquements étaient rejetés comme crabes à carapace molle. Ce résultat est en grande partie attribuable à une pêche printanière : 91 % des débarquements totaux dans le nord-est de la Nouvelle-Écosse en 2010 ont été pris au printemps, où la capturabilité des crabes à carapace molle est plus basse. Au sud-est de la Nouvelle-Écosse, la manutention des crabes à carapace molle est passée de 16 % en 2009 à 7,7 % des débarquements en 2010. La transition à des saisons de pêche plus précoces semble avoir amélioré les taux de manutention des crabes à carapace molle au sud-est de la Nouvelle-Écosse lors de la saison de pêche de 2010. Les taux de rejets de crabes à carapace molle dans la zone de pêche du crabe 4X demeurent très bas, principalement en raison de la pêche automnale et printanière. L'incidence des crabes à carapace molle et de la mortalité potentielle connexe due à la manutention continuera d'être un enjeu nécessitant une diligence continue et une adaptabilité de la flottille du crabe des neiges. Le taux de prises accidentelles d'espèces non ciblées est très bas, étant estimé à moins de 0,01 % et 0,93 % du total des débarquements de crabes des neiges dans l'est de la Nouvelle-Écosse et dans la zone de pêche du crabe 4X, respectivement, au cours des quatre dernières années.

Il est prévu que le recrutement dans la pêche continue au cours des deux à quatre prochaines années dans le nord-est de la Nouvelle-Écosse puisque des densités élevées d'adolescents dont la carapace mesure de 70 à 90 mm de largeur ont été observées. La distribution relativement stable de crabes mâles de toutes les catégories de taille dans les sud-est de la Nouvelle-Écosse pourrait entraîner un recrutement plus stable au cours des prochaines années, par opposition au recrutement cyclique observé par le passé dans tous les secteurs. Dans la zone de pêche du crabe 4X, des densités élevées de crabe dont la carapace mesure de 20 à 50 mm de largeur ont été observées, bien qu'un manque flagrant d'adolescents avec une carapace entre 50 et 90 mm puisse forcer la pêche dans la zone 4X à dépendre du mouvement des crabes provenant du sud-est de la Nouvelle-Écosse. 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 la zone de pêche du crabe 4X. Le potentiel de reproduction de la population du plateau néo-écossais a atteint son plus haut niveau en 2007-2008 et présente maintenant une tendance à la baisse. La production de larves devrait continuer pendant encore une ou deux années au nord-est de la Nouvelle-Écosse et plus longtemps dans le sud-est et dans la zone de pêche du crabe 4X.

La biomasse exploitable de crabes des neiges après la pêche dans le nord-est de la Nouvelle-Écosse a été estimée à 2 810 t (intervalle de confiance de 95 % : 2 180 à 3 780 t) par rapport à 2 790 t (intervalle de confiance de 95 % : 2 220 à 3 840 t) en 2009. Dans le sud-est de la Nouvelle-Écosse, la biomasse exploitable de crabes des neiges après la pêche a été estimée à 48,5 x 10^3 t (intervalle de confiance de 95 % : 32,2 à 77,9 x 10^3 t) par rapport à 49,3 x 10^3 t

(intervalle de confiance de 95 %:33,2 à 79.3 x 10^3 t) en 2009. Dans la zone de pêche du crabe 4X, la biomasse exploitable de crabes des neiges avant la pêche était de 930 t (intervalle de confiance 95 % : 590 à 1 440 t) par rapport à 1 070 t (95 % : 640 à 1 730 t) en 2009-2010, ce qui représente une réduction de 13 %.

Ces caractéristiques positives des populations sont modérées par un certain nombre d'incertitudes additionnelles, 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, puisque celles-ci peuvent avoir des incidences directes et indirectes sur les crabes des neiges. Par exemple, un réchauffement élevé peut avoir des répercussions négatives directes sur les crabes des neiges puisqu'ils sont sténothermes d'eau froide. Même les importants refroidissements observés dans l'ensemble du plateau néo-écossais en 2009, avec une expansion de l'habitat connexe, peuvent avoir des conséquences négatives indirectes telles que l'introduction ou la prolifération d'espèces envahissantes ou de maladies (p. ex. *Hematodinium sp.*), ou la réduction de la production primaire brute. Outre ces facteurs, les signes d’un retour initial des indicateurs écologiques, sociaux et économiques de l’état du système vers un système légèrement dominé par les invertébrés accroissent davantage l’incertitude quant à la viabilité à moyen et long termes de la population de crabes des neiges du plateau néo-écossais.

Le taux de mortalité par la pêche dans le nord-est de la Nouvelle-Écosse a été estimé à 0,19 (intervalle de confiance de 95 % : 0,14 à 0,24), soit un taux de capture de 17,3 %, le même qu'en 2009. Le bon recrutement et une réduction importante de la manutention des crabes à carapace molle entraînent une perspective favorable. Jusqu'à ce qu'une forte augmentation persistante de la biomasse exploitable soit observée, les taux de capture à long terme entre 10 % et 20 % font partie de la stratégie visant à assurer la durabilité de cette pêche. Une stratégie de pêche réduite ou inchangée est recommandée.

Le taux de mortalité par la pêche dans le sud-est de la Nouvelle-Écosse a été estimé à 0,23 (intervalle de confiance de 95 % : 0,15 à 0,33), soit un taux de capture de 20,5 %, une légère augmentation par rapport au taux de mortalité par la pêche de 0,20 en 2009. Le bon recrutement laisse présager une perspective favorable, toutefois, la pêche de crabes à carapace molle demeure un problème important pour cette flottille. Des taux de capture à long terme entre 10 % et 30 % font partie de la stratégie visant à assurer la durabilité de cette pêche. Une stratégie de pêche réduite ou inchangée est recommandée.

Le taux de mortalité par la pêche dans la zone de pêche du crabe 4X en 2009-2010 a été estimé à 0,22 (intervalle de confiance de 95 % : 0,15 à 0,33), soit un taux de capture de 19,7 %, par rapport au taux de mortalité par la pêche de 0,19 en 2008-2009. Des taux de capture à long terme entre 10 % et 30 % font partie de la stratégie visant à assurer la durabilité de cette pêche. Puisque le recrutement dans la période 2011-2012 est incertain, une stratégie de pêche réduite ou inchangée est recommandée.

MANAGEMENT

The SSE snow crab fishery is managed as three main areas: Northern-Eastern Nova Scotia (N-ENS), Southern-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. 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 CFA 4X, respectively). Vessel Monitoring Systems (VMS) have been implemented in S-ENS 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 licence” 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 DFO within 24 hours of landing, plotted on a 2-minute grid and re-broadcast to all members of industry on the web location: http://sites.google.com/site/nssnowcrab/ as well as via email and fax.

Fishers 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 adopted in CFA 4X due to the low incidence of soft crab in the catch and 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 moult to maturity and so maximise the total yield per crab captured and simultaneously the total lifetime reproductive success of these large-sized males.

In 1996, DFO (Gulf Fisheries Centre, 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 CFA 4X in 2004. This Joint Project Agreement continues to the present.

HISTORY

The snow crab fishery is the second most valuable commercial fishery in Atlantic Canada (http://www.dfo-mpo.gc.ca/stats/commercial/sea-maritimes-eng.htm). The SSE snow crab fishery has been in existence since the early 1970s (Figure 2). The earliest records of landings were at levels of < 1,000 t, mostly in the near-shore areas of Eastern Nova Scotia (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 CFA 4X, the southern-most range of distribution which continues at low levels.

Annual TACs 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, a more precautionary exploitation strategy was adopted throughout the SSE. TACs have increased annually since 2005 in S-ENS due to strong recruitment. TACs in N-ENS were maintained at low levels since 2005 in N-ENS, due to negligible recruitment, until 2009 when increased recruitment resulted in a moderate increased TAC. This TAC was maintained in 2010 even though recruitment to did not increase to expected levels. In CFA 4X, TACs remained low between 2007 and 2009 due to continued signs of low recruitment and high exploitation (Tables 2-4). The 2010/2011 TAC for 4X was increased to near 2005 and 2006 levels due to improved recruitment.

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 in this 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 2009, version 2.10.1; Venebles and Ripley 2002) to allow migration and documentation of methods into the future. The complete analytical suite, coded in R, is posted to: http://sites.google.com/site/autocatalysis/snowcrabanalysis/

A number of spatial and/or temporal interpolation methods are used in this assessment. Thin-plate-splines 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). This interpolation method was used only for rapid data visualisation. 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 km × 1 km and weekly time scales. (See below for methods related to abundance index estimation). 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

Catch rates are *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 behaviour, substrate/shelter availability, relative occurrence of soft and immature crab and associated discards, 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. Catch rates are herein regarded as a measure of fishery, 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 provide information about the size structure and the carapace condition 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 (i.e., *kriging*; 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 2010 survey, 407 stations were sampled, the same number as 2009.

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. For the purposes of monitoring such changes in spatial distribution, sampling is required in areas where crab have not been previously observed. In addition, the distributional patterns of immature, soft-shelled, very old and female crabs do not correspond closely 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 more marginal environments or substrates with greater cover (gravel, rocks; Comeau et al. 1998). Focusing 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 CFA 4X). The timing of the surveys have stabilised to this latter period only since 2002. Prior to 2002, 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-2001 period. In the southern-most area of snow crab distribution (CFA 4X) trawl survey coverage has been historically sporadic but have stabilised since 2004.

A *Bigouden Nephrops* trawl, a net originally designed to dig into soft sediments for the capture of lobsters 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 Netmind sensors; depth and temperature were recorded with Minilog sensors; and positional information was recorded with a global positioning system. Tows were conducted for approximately 5 minutes in duration. Actual duration of bottom contact was assessed from Netmind and Minilog data streams. The ship speed was maintained at approximately 2 knots. The warp length was approximately 3 × 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). Data entry and quality control was provided by Javitech 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 carapace width (*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):

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

The maturity status of males was determined from a combination of biological staging (carapace condition) 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 moulted males; Sainte-Marie 1993), the latter is more readily/rapidly determined. In the terminal moult 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:

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

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 carapace width (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 modelled from trawl surveys, snow crab fisher logbook records and RV groundfish surveys. A binomial Generalised Additive Model 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 (ordination via Correspondence analysis upon quantiles; CA1 was associated with a temperature gradient, 6% of the total variance; CA2 was associated with a depth gradient, 4% of the total variance) and richness and biological productivity indices (Figures 8, 9; Table 6; see Choi et al. 2005b for more details on methods). These modelled 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 mean predicted probability of finding snow crab was > 0.5, using posterior predictive simulations (Gelman and Hill 2007; Figure 10).

The biomass and numerical densities of crab was predicted upon this dynamically changing habitat surface using a lognormal Generalised Additive Model. As such, the approach is a hierarchical modelling of presence and absence (0, 1) followed by the modelling of abundance, the non-zero elements (Gelman and Hill 2007). The same covariates used for the habitat model entered into the abundance model (Table 6, Figure 9). Total abundance indices of each component of the snow crab population was estimated using conditional posterior predictive simulations. For the fishable biomass, the combined models accounted for 50% of the total variance (Figure 11). Ideally, a Generalised 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 available or (practical) at present.

Stock Assessment Model

Biomass dynamics models describe the variations in biomass over time and represent one of the simplest and therefore most robust types of stock assessment models. Discrete time variations in the biomass B_t at time t can be specified as a function g of biomass in the previous year B_{t-1} and various parameters θ:

$$B_t = g(B_{t-1}, \theta)$$

One of the simplest such functions is the discrete logistic function, which assumes biomass to increase at a rate r, to some upper limit or carrying capacity K:

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

where, $b_t = B_t / K$ is the biomass normalised by carrying capacity, at the start of a year t, before the prosecution of a fishery. That is, $\theta = \{r, K\}$.

In a fisheries context, to reflect the catch C taken from the population, this model is modified to:

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

where $c_t = C_t / K$ is the catch normalised by carrying capacity in the year t. Thus, the intrinsic rate of increase is some function f of growth, recruitment, and mortality (natural mortality, handling mortality and/or incidental bycatch, but excluding fishing mortality). That is,

$$r = f\,(growth, recruitment, mortality)$$

In this formulation of the biomass dynamics model, r and K are assumed to be constant. Clearly, these quantities are not constant, especially given the systemic changes in the SSE associated with the collapse of groundfish in the mid 1990s.

For the purposes of this assessment, a nonlinear Bayesian state space approach is used to estimate the parameters of this model. This is due to the greater numerical stability of this approach; the ability of Bayesian methods to propagate credible errors; its ability to estimate unobserved states (true fishable biomass); and its proficiency in estimating and discriminating between model "process" errors and data "observation" errors. Process errors refer to uncertainties that feeds back into future states via error propagation – in this case, via the recursive form of the logistic equation (simplistically, model transition errors only in b_{t+1} in the state space of b_t *vs* b_{t+1}). Observation errors refer to the uncertainties associated with measurement and observation (simplistically, data measurement errors in both variables in the state space of b_t *vs* b_{t+1}). This ability is important because parameter estimates and forecasts based on observation-only errors provide unrealistically optimistic (small and constant) error bounds. In contrast, parameter estimates and forecasts based on process-only errors expand rapidly into the future, resulting in potentially unrealistic and pessimistic (large and usually growing) error bounds. A more credible solution likely lies somewhere intermediate between these extremes which Bayesian methods have demonstrated to be able to elucidate.

As the fishable biomass of snow crab, like most other species, follows a lognormal distribution, a multiplicative observation error model was assumed, with a variance σ_o^2. The observed fishable biomass index O_t was assumed to be a linearly related to the "true" unobserved, fishable biomass by a proportionality constant q such that $O_t = q\, K\, b_t$:

$$O_t \sim lognormal\,(\,log\,(q\, K\, b_t\,),\, \sigma_o^2\,)$$

where "~" indicates "is distributed as". Thus, 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, it serves as a first-order estimate of such influences.

The process or "model" error was assumed to also follow a (multiplicative) lognormal distribution with variance σ_p^2

$$b_t \sim lognormal\ (\ log(\ b_{t-1} + r\ b_{t-1}\ (1 - b_{t-1}) - c_{t-1}),\ \sigma_p^2\ )$$

As there are three separate Crab Fishing Areas (CFAs), denoted by *a*, the fishable biomass was modeled as the following:

$$b_{t,a} \sim lognormal\ (\ log(b_{t-1,a} + r_a\ b_{t-1,a}\ (1 - b_{t-1,a}) - c_{t-1,a}),\ \sigma_{p,a}^2\ )$$

$$O_{t,a} \sim lognormal\ (\ log(q_a\ \ K_a\ \ b_{t,a}),\ \sigma_{o,a}^2\ )$$

with the parameter set now expanded to, $\theta = \{\ r_a,\ K_a,\ q_a,\ \sigma_{r,a}^2,\ \sigma_{K,a}^2,\ \sigma_{q,a}^2,\ \sigma_{o,a}^2,\ \sigma_{p,a}^2,\ b_{t=0,a}\ ,\ b_{t,a}\ \}$.

The posterior distribution of the parameters of interest, θ, conditional upon the data $\{O_t,\ c_t\ \}$ were estimated via MCMC (Gibbs) sampling using the JAGS platform (Plummer 2003, 2010; see Appendix 2). Three Markov chains were followed to ensure convergence; 10,000 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.

Priors for the model were assumed to follow a lognormal distribution as the abundance distribution of many organisms are lognormal, being derived from many multiplicative processes associated with survival/mortality:

$$K_a \sim lognormal\ (\ log\ (\mu_{K,a}),\ \sigma_{K,a}^2\ \ )$$

$$r_a \sim lognormal\ (\ log(\mu_{r,a}),\ \sigma_{r,a}^2\ )$$

$$q_a \sim lognormal\ (\ log(\mu_{q,a}),\ \sigma_{q,a}^2\ )$$

The hyperpriors of the magnitude of carrying capacity μ_K were marginally informative, being derived from a random uniform distribution with an interval that bounded previously estimated historical maxima in fishable biomass by +/-50%. Hyperpriors of the intrinsic rate of increase, were also marginally informative, in that they were derived from random uniform distributions bounded by the interval +/-50% of r = 1. This is loosely based upon estimates of $\mu_r \approx 1$ for crab of similar longevity and body size, *Cancer pagurus* in Europe (Laurans and Smith 2007). Catchability was historically assumed to be 1 due to the nature of the sampling design analytical methodology. As a result, the hyperprior of the magnitude of catchability was also derived from a random uniform distribution bounded by +/-50% of μ_q = 1. Hyperpriors for the $\mu_{b(t=0)}$ were assumed to have magnitudes of 0.8, 0.6, and 0.1, based upon the relative fishable biomass in year t=1. A random uniform distribution with bounds spanning +/- 50% of these magnitudes were used as priors. Marginally informative hyperpriors were used for modeling the errors of these lognormally distributed variables, again using a bounded random uniform distribution: with the standard deviation bounded by 0.01 and 0.25. This range bounded the empirically observed coefficients of variation of ~ 10 to 20% (for estimates of biomass) obtained in historically observed data. The other parameters were assumed to have similar coefficients of variation.

Gamma errors were also examined as hyperpriors of the variances, but their influence was found to be problematic as they were strongly informative relative to the uniform distribution. This resulted in convergence problems and erratic estimates with multiple modes in the posteriors. Simpler, hierarchical models were also examined based upon the penalised Deviance Information Criterion (Plummer 2008), however, their performance was generally similar to the full model and parameter estimated were sufficiently different between regions such that the full model was used in this assessment as this most flexibly estimated all the parameters of interest. Traditional maximum-likelihood based observation error methods (also known as "time-series" methods in fisheries science, with no process error) were also used in the prototyping stage. While they produced numerically similar parameter estimates to those derived from Bayesian state-space methods, the type of optimizer and optimizing algorithm used were observed to be erratic.

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. 2005b). 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.

Diet information from DFO's groundfish surveys was obtained from the groundfish RV surveys/diet analysis to identify snow crab predators on the SSE.

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 (Tremblay 1997). In the SSE, commercially fished snow crab are generally observed between depths of 60 to 280 m and between temperatures of -1 to 6 C (Figure 9). Near 7 C, metabolic costs are thought to match metabolic gains (Foyle et al. 1989). Snow crab are generally observed on soft mud bottoms although small-bodied and moulting 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 2 years, depending upon ambient temperatures, food availability and the maturity status of the mother (up to 27 months in primiparous females – first breeding event; and up to 24 months in multiparous females – second or possibly third breeding events; Sainte-Marie 1993). More rapid development of eggs (from 12 to 18 months) has been observed in other systems (Elner and Beninger 1995; Webb et al., 2007). 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 3 to 5 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, moulting approximately twice a year (Sainte-Marie et al. 1995; Comeau et al. 1998; Figure 12). The first inter-moult stage (instar 1) is approximately 3 mm CW. After the 5th instar (15 mm CW) the frequency of moults decline, moulting occurring once a year in the spring until they reach a terminal maturity moult. Growth is allometric with weight increasing approximately 250% with each moult (Figure 7). Terminal moult 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 moult, male crab may skip a moult in one year to moult 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 9 years since settlement to the bottom and 11 years since egg extrusion. Thereafter, the life expectancy of a male is approximately 5 to 6 years. Up to 10 months are required for the shell to harden (carapace conditions 1 and early 2; Table 5) and up to 1 year for meat yields to be commercially viable. After hardening of the carapace (carapace conditions 3 to 4) the male is able to mate. Near the end of the lifespan of a snow crab (carapace condition 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 carapace condition 5 crab.

Females reproducing for the first time (primiparous females) generally begin their moult 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 CFA 4X). A second mating period later in the year (May to June) has also been observed for multiparous females (Hooper 1986). Complex behavioural patterns have also been observed: the male helps the primiparous female moult, 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 3 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 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 are here provided to form a basis for discussion of the place of snow crab in its ecosystem. Utilizing the same multivariate approach to the statistical summary and synthesis of indicators as in Choi et al. (2005b), key environmental (climatic), social, economic and fishery-related indicators were identified and summarized as standardised residuals in Figure 13. Appendix 1 provides a list of these indicators and their sources.

The first axis of variation accounted for 18% of the total variation in the data (Figure 14), and was dominated by the influence of socio-economic indicators of ocean use by humans and associated changes in their relative abundance: landings and landed values of groundfish (declining), invertebrates (increasing), 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 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 (Figures 4, 13) suggests that the abundance of snow crab was quite 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 crabs require 9 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 6 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 stage.

1. Larval Dispersion

The potential for hydrodynamic transport of snow crab larvae from the southern Gulf of St. Lawrence to the SSE has been studied by J. Chassé (Ocean Sciences Division, BIO, DFO; pers. comm.). 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. 2005a, 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. 2005a, page 14). The timing of this pulse is concordant with the growth schedules of the currently expected 'local' recruitment. Approximately 9 years would be required to grow from the zoea stages to instar 11/12, the stages in which snow crab begin to moult 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 to the conservation of large mature males (i.e., reduced exploitation rates) to allow them to mate with the more rapidly maturing females in 2006/7.

2. Movement

Spaghetti tags have been applied opportunistically to monitor snow crab movement since the early 1990s (Table 7; Figure 15, 16). Movement information was primarily limited to single recaptures of mature, terminally moulted male crab as crab cannot survive a moult once a tag is applied and tag returns are from the male-only snow crab fishery. They suggest that while snow crab do not generally 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 is a source of uncertainty.

Since 2004, 7,682 tags have been applied and a total of 526 distinct tags (6.8%) have been recaptured and reported. If tags recaptures are not reported, they are not considered as having been recaptured as no information is received to aid in movement studies. Of these 526 tags, 23 have been captured, released and recaptured at least one time. Any tags that were captured within 10 days of initial release are not included in the following summary statistics to avoid the effect of "drift" while crab is falling to ocean floor once tagged. The average distance travelled was 14.5 km with a maximum distance traveled of 280 km. Thus, locomotory capacity can be very large. On a monthly basis, the mean distance traveled was 1.4 km/month. These distances are linear distances from mark-recapture and are therefore 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 tagged between 2004 and 2010 were recaptured in the season following the tagging event (mean time to recapture was 319 days) with the longest time interval between release and initial capture being 1379 days. This crab had moved 30 km in that 4 year period. During this 6-year period, movement between N-ENS and S-ENS was seldom observed. However, N-ENS fishers in the Glace Bay Hole have explicitly stated that they would not report tagged crab recaptures, rendering this result uncertain. Indeed, historically, movement between N- and S-ENS has been observed. Additional tagging is planned near area lines to help determine prevalent direction of movement of adult male crab. These areas include: CFA 24 / 4X line, S-ENS/ N-ENS line and ENS / Gulf line.

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 characterised 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 1997-98, 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 2 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 which 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-1990.

Indeed, the spatial extent of what may be considered potential snow crab habitat in the SSE has been mostly quite stable in the historical record (Figure 10). In N-ENS, the surface area of predicted snow crab habitat has varied between 1.4 to 3.5×10^3 km^2 (Figure 18) with higher levels than the climatological mean in 2010. For S-ENS, the surface area of potential habitat has varied with similar oscillations, ranging from between 25 to 44×10^3 km^2 with higher levels than the climatological mean in 2010. In CFA 4X, the southern-most limit of the distribution of snow crab, potential habitat has been highly variable, ranging from 0 to 2.2×10^3 km^2, with an historical maximum in 2009/2010 (Figure 18).

Within the area that may be considered potential snow crab habitat, average bottom temperatures were generally quite stable: 3.2, 3.3 and 6.2 ^oC in N-, S-ENS and CFA 4X, respectively (Figure 19). Average bottom temperatures in 2010 were generally close to the long-term means, especially in CFA 4X. Bottom temperature variations have been mostly in phase throughout the three sub-areas in the historical record.

Top-down Control (Predation)

Top-down influences refer to the *role of predators* in controlling a population (Paine 1966; Worm and Myers 2003; Frank et al. 2005). 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 (Tremblay 1997, Boudreau et al. 2011). 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 moult 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 emphasised 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 are 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 and 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 specialise upon snow crab (Table 8). 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 specialised 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).

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*). Recent 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. 2005b):

- 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. 2005b; 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. Whether this potentially elevated gross primary production reaches the detrital system is not yet known.

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, 23, 24). A strong negative relationship was not found between snow crab and other bycatch species (Table 9), suggestive of little competitive interactions.

Human

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 moulted 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 CFA 4X. Additionally, bycatch of snow crab in Danish seines has been reported from 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 10a, 10b). In ENS, a total of 13,717 t of snow crab were landed in 2010 with associated estimates of bycatch at 2.4 t (0.018% of snow crab landings). CFA 4X shows an order of magnitude higher bycatch rates, with a total estimated bycatch of 0.4 t associated with 229.4 t of snow crab landings (0.17 %).

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 one leatherback turtle as having been entangled in buoy lines. This turtle was reported to be released alive though bleeding. As the possibility of entanglement of this SARA (Species at Risk Act) species exists, a development of best handling practices requires attention.

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, or upstream 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. They are abundant and will continue to be so in future years in all areas.
- 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 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. The bioaccumulation of such products is beginning to be monitored in commercial sized crab on the Scotian Shelf.
- Substantial sacrifices were made from 2004 to 2006 by snow crab fishers to reduce any risks of damaging the reproductive potential of Scotian Shelf snow crab. In the face of such uncertainties and sacrifice, Hunt Oil 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). The numerous uncertainties associated with such oil and gas exploration/development activities increases the risk of destabilising the snow crab population in the SSE. Husky Oil, in July 2010 also conducted additional seismic studies over the Sidney Bight (Husky Oil 2010). Others seismic studies continued on Artimon Bank, Banquereau Bank and the Stone Fence in 2009 and 2010 (RPS Group 2010).

4. 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 population base with the ageing of the "baby-boomers". The total population size has also been increasing over the historical record to approximately 935,000 people in 2007 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. 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 have increased over time. However, the relative importance of fishing to the Nova Scotia GDP and the total number of fish harvesters have both been on the decline. The recent world-wide economic down-turn in the late 2000's may have lasting influences upon all economic sectors, by creating greater uncertainty for the economic viability of the snow crab fishery.

The fished species have changed greatly since the early 1990s in conjunction with the rapid changes in species dominance structure. Since this time, all groundfish landings have declined, falling from 232 kt to 60 kt. Exceptions include dogfish, haddock and halibut. Similarly, the pelagic fish landings have decreased from 125 kt to 55 kt. It should be noted that tuna landings have increased since the 1990s, and swordfish landings are now on the rise. In contrast, invertebrate landings have increased from 111 kt to 135 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 $661 ($550 from invertebrates) million due in part to falling prices of seafood in past seasons.

The links between the socio-economic changes observed and the changes in the Scotian Shelf ecosystem are complex and cannot be treated in depth in this forum. 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.

FISHERY

Effort

In S-ENS, fishing effort (Figure 26) was spatially distributed in a similar manner to 2008, with a shift away from inshore 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. There was again a complete absence of effort in the western portion (along the "Eastern Shore") of CFA 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").

In N-ENS, a spring season was introduced in 2008 and retained over the past two seasons in an effort to reduce soft and white crab capture and handling. This season was in addition to the traditional summer season and individual fishers were able to fish during either (or both) seasons. After a successful trial in 2008, the majority of landings (>85%) from N-ENS were caught during the spring season in 2009 with a further increase to 91% in 2010. The fishing effort was focused on the trench of deep water located along the north-eastern coast of Cape Breton (formerly CFAs 21 and 22 Inside) and along the line between N-ENS and CFA 19 with some minimal summer effort in the Glace Bay Hole.

In CFA 4X, the fishing effort was similar to the previous season. Fishing effort was somewhat concentrated around Sambro with additional effort applied to the north and west of Roseway Bank.

In 2010, a total of 10,500 and 128,300 trap hauls were applied in N- and S-ENS, respectively. In 4X, since 2007, fishers used industry standard large conical traps. In 2009/2010, a total of 6,400 trap haul were applied in 4X (Figures 2, 27).

Landings

Landings in 2010 for N-ENS and S-ENS were 576 and 13,150 t, respectively, and they were 229 t in CFA 4X for the 2009/10 season, representing increases of 0%, 24% and 0% relative to the previous year. TACs in 2010 were 576, 13,200 and of 230 t in N-ENS, S-ENS and CFA 4X.

Catch Rates[1]

Non-standardized catch rates in 2010 were 55.0 kg/trap haul in N-ENS, 102.5 kg/trap haul in S-ENS, and 36.0 kg/trap haul in 4X in 2009/2010 – representing an decrease of 27%, an increase of 14% and an increase of 27%, respectively, relative to the previous year.

In N-ENS, the 2010 catch rates were 55.0 kg trap^{-1}, a 27% decrease relative to 2008. N-ENS catch rates are at the 14 year mean (55.4 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 moderate with the exception of one localized area on the northern side of the Glace Bay Hole (Figure 28).

In S-ENS, the 2010 catch rates were 102.5 kg trap^{-1}, a 14% increase relative to 2009 and above the 14-year mean of 90.6 kg trap^{-1} (Figure 4; Table 3). In 2009, a return to catch rates being distributed throughout these areas, a more normal historic state, was found as opposed to 2006-2008 when the highest catch rates (and landings) were from offshore fishing grounds (Figure 28). This offshore focus of increased catch rates was again true for the 2010 season. Peak levels were found North of Misaine Bank and the Sable Island areas of S-ENS. The lack of very low localised catch rates suggests that fishers were efficiently identifying high abundance locations and therefore avoiding over-depletion of lower abundance areas.

In CFA 4X, the 2009/2010 catch rates were 36.0 kg trap^{-1} (Table 4) an increase of 27% from 2008/2009. This catch rate is the highest on record for the eight year time series. The catch rates were marginally higher in the eastern area of CFA 4X (Figure 28) but 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 CFA 4X is impossible due to shifts in the gear complement (both size and number of traps used) over the past eight seasons.

At-Sea-Observer Coverage

In N-ENS, the at-sea-observer coverage exceeded the target level of 5% of the TAC, at 6.3% (Figure 5, 29). This decreased from 2009 when 14.5% occurred to compare the capture of soft crab in the nascent spring and summer seasons. The success of the spring fishery in protecting soft crab allowed observer coverage levels to return to historic levels. A total of 122 traps were sampled (approximately 1.2% of commercial trap hauls). In S-ENS, 8.7% of the TAC was observed (with a target level of 10%). A total of 2,273 traps (approximately 1.8% of commercial

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

trap hauls) were sampled. In CFA 4X, 6.8 % of the TAC was observed, relative to a target level of 10% and a total of 539 traps were sampled.

The lack of undersize crab in the commercial catch of N-ENS possibly suggests a high mortality or movement of undersize crab. The spring fishery may under-represent the undersize crab as many of these individuals would be unavailable to enter traps shortly after moulting in the spring. This was in contrast to the high proportion of undersize crab in N-ENS in 2008 when high recruitment was expected and more of the fishery was summer based (Figure 29, relative to past years and other CFAs).

Newly Matured Crab (CC1 and CC2)

In N-ENS, CC1 crab represented 3% of the total catch while CC2 crab represented 2% (Figure 29). This is a substantial reduction from 2008 levels (~30% of landings in spring) and 2007 (no spring landings) The spring season was adopted to reduce fishing intensity in the summer season and also to encourage fishing during the earlier period when newly moulted crab are too weak and soft to move into traps. As expected, landings during the spring fishery had negligible catches of CC1 and CC2 crab. High incidence of soft-shelled crab has been suggested anecdotally as being a result of localised 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. If one assumes no recaptures, this amounts to an additional 21 t (3.5% of landings) being discarded as soft crab with potentially high handling-associated mortalities. This is a substantial improvement from 49% in 2008 and 111% in 2007. The continuation of spring fishing efforts and the implementation of area closures during the summer fishery based on observer reports and shorter summer fishing period will likely help to control the potential total mortality of soft shell crab in future seasons. Continuing to monitor the situation and adapt as required is essential into the future to avoid the negative consequences of high soft shell incidence in N-ENS in the past.

In S-ENS, the occurrence of CC1 and CC2 crab in 2008 (8% and 6%, respectively) was less than that observed in 2009, 16 and 6%, respectively (Figure 29). Catches of high soft shell percentage (>20% by count) were less widely distributed throughout the fishing grounds in both CFAs 23 and 24 during the 2010 fishery as compared to 2009 (Figure 30). When extrapolated to the S-ENS TAC, this amounts to a potential additional mortality of 1,011 t (8% of landings), an decrease from 2009 when soft crab catches represented 16% of the landings and 13% in 2008. The low incidence of soft crab in the spring months was very helpful at maintaining low levels of soft crab with continued recruitment to the fishery. Voluntary closures of areas showing high incidence of soft crab must be adhered to by all members of the fleet to be effective. Unfortunately, this was not always the case in the past three seasons. As many quotas are fished by individuals that do not own quota personally, and thus have no long term stake in this fishery, disregard for soft shell crab (and the long term health of the ENS snow crab stock) is potentially a problem. All individuals involved in every level of the fishery must realize the potential damage caused by handling soft crab. This must be stressed to the chosen fisher by any individual choosing to not fish their own quota. This communication is sadly not always possible with quotas been sold through processors and other brokers.

In CFA 4X for the 2009/10 season, CC1 and CC2 crab represented a total of 5% and 0% of the total catch and comparable to those of 2008/2009 (Figure 29). The data from CFA 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 1% or less in all areas (Tables 11-13). Similarly low to undetectable proportions of CC5 crab were observed in the trawl surveys (Tables 14-16).

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 CFA 4X (Figure 31). They continue to grow and propagate throughout the SSE. The presence of small immature snow crab spanning almost all size ranges observed by the survey also suggests that steady recruitment to the fishery will likely continue for at least the next 4-5 years S-ENS. There is even evidence of a new year-class developing in the 20-40 mm CW that is likely the product of the leading edge of the reproductive females from 2007 to 2008. This is observed in CFA 4X at strong levels, more moderate levels in S-ENS and at further reduced levels in N-ENS. In S-ENS, there are near consistent levels across all size classes where there is a “gap” in the size classes of N-ENS in the 30-60mm size classes.

The size frequency distributions of female snow crab indicate that the strong size-classes first detected in 2003 for N-ENS and in 2004 for S-ENS peaked in 2007/2008 (Figure 32) and their numbers are in decline in all areas. Reproductive activity should continue for another year in N-ENS. However, as there is little to no female recruitment evident in N-ENS, another gap in reproductive output is expected at the end of this time frame. S-ENS shows the potential for reduced but continuing recruitment of mature females and 4X shows potential large increases in mature female crab abundance and associated egg production. Isolated concentrations of mature females exist in all areas with more a more diffuse distribution around the CFA 23 / 24 management line (Figure 1).

Size frequency distributions in CFA 4X exist in a very erratic state, with the disappearance in 2008 of the incoming immature crab observed in 2006 and 2007 and their re-appearance in 2009. The large temperature fluctuations in the area and the different predator fields associated with the warmer waters in the area likely result in these highly unstable size structures.

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 33). This is because female snow crab of a given year-class will mature 2 to 4 years earlier than a male from the same year-class. Females also have a shorter 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 33, 34). Currently, sex ratios of mature crab are again declining with the ageing and mortality of reproductive females.

The sex ratios of immature snow crab (Figure 35) are currently, between 20 to 40% female. The spatial patterns of the sex ratios are generally distinct between offshore and inshore areas: immature males are found in greater proportion (blue) in offshore whereas immature females (red) are found in greater proportion towards the inshore areas (Figure 36). However, in 2010, there was greater heterogeneity in sex ratios. When spatial segregation is observed, the sexes are likely exposed to differential predation effects. Inshore females are likely fed upon by inshore fish, other macro-invertebrates (including other female snow crab, other crabs and lobster – immature snow crab have been reportedly caught in large numbers in lobster traps; Sainte-Marie and Lafrance 2002; Squires and Dawe 2003). 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 moulting 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 behaviour (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 since historical lows in 2002 (N-ENS) and 2003 (S-ENS), reaching historical highs in 2006 (Figure 37). Their numbers declined rapidly mostly due to their entry into the mature segment of the population and the lack of small juvenile crab. However, their numbers have increased rapidly since lows in 2007. Most immature females are primarily found in very shallow areas along the shore of mainland Nova Scotia and in offshore areas of CFA 24 near-shore in southern SSE (Figure 38) at the current time.

In all areas, the numerical abundance of mature females declined after reaching peak levels in 2006 though they still remain at high levels (Figures 39, 40) compared to the historical record. Most of the mature females are currently located in small concentrations throughout the SSE; these were therefore the core areas where larval production occurred from 2006 to 2010.

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.

The numerical abundance estimates of carapace condition 5 crab are close to being undetectable in the SSE by the trawl survey (Tables 14-16).

Fishable Biomass

The post-fishery fishable biomass of snow crab in N-ENS was estimated to be 2,810 t (95% CI: 2,180 to 3,780 t; relative to 2,790 t (95% CI: 2,220 to 3,840 t) in 2009 (Figures 41 – 45, Table 17).

In S-ENS, the post-fishery fishable biomass of snow crab was estimated to be 48.5 × 10^3 t (95% CI of: 32.2 to 77.9 × 10^3 t) relative to 49.3 × 10^3 t (95% CI of: 33.2 to 79.3 × 10^3 t) in 2009.

In CFA 4X, the pre-fishery fishable biomass was 930 t (with a 95% CI of 590 to 1,440 t), relative to 1,070 t (95% CI of 640 to 1,730 t) in 2009/2010, representing a decrease of 13%.

Recruitment

The index of recruitment, into the fishable biomass (CC1 and CC2 > 95mm CW) was low from 2004 to 2007 in N-ENS and S-ENS but has returned to higher levels in the past three years. CFA 4X recruitment has been increasing in the historical record (Figures 46, 47) and remains high with a slight down-turning trend in 2010.

It must be emphasised 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 (and biased) index that is sensitive to annual variations in temperature, food availability and crowding, factors that control the onset of moulting and the speed of shell hardening.

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. Some preliminary analysis suggests that for early benthic females stages (i.e., unfished snow crab), instantaneous mortality may be near 1 (Kuhn and Choi, 2011). Further, based upon diet studies (Bundy 2004; see also section: Top-down Control (Predation)), 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). Other potential mortality factors include: bitter crab disease derived from a parasitic dinoflagellate infection (*Hematodinium sp.)* which was found to be prevalent in the SSE since 2008, seals (near Sable Island; although see arguments to the contrary in Ecosystem considerations, above), soft-shell mortality, unreported landings, bycatch in other fisheries (lobster and other crab traps, long-lining, gill-nets, trawling) and activities associated with exploration and development of oil and gas reserves.

Fishing Mortality

Fishing mortality in N-ENS has historically been in the range of 0.1 to 0.5, peaking in 2004 (Figures 48, 49; Table 17 In 2010, fishing mortality is estimated to have been 0.19 (95% CI: 0.14, 0.24; harvest rate of 1-exp(-0.19) = 17.3%), unchanged relative to 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 48, 49). In 2010, fishing mortality is estimated to have been 0.23 (95% CI: 0.15, 0.33; harvest rate of 1-exp(-0.23) = 20.5%); a small increase from 0.20 in 2009. Realised exploitation rates are likely higher as not all areas where biomass estimates are provided are utilised (e.g., continental slope areas and western, inshore areas of CFA 24).

In CFA 4X, fishing mortality has historically ranged from 0.2 to 0.45, only declining towards target levels since 2008 (Figure 48, 49). In 2009/2010, fishing mortality was 0.22 (95% CI: 0.15, 0.33; harvest rate of 1-exp(-0.22) = 19.7%). In 2008/2009, fishing mortality was marginally lower 0.19. However, due to the very specific spatial extent of the fishery in area 4X, focussed primarily upon the area near Sambro and Roseway, realized exploitation rates are likely to be higher, since the computed exploitation rates incorporate biomass from throughout the CFA 4X area

THE PRECAUTIONARY APPROACH

Historical Context

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 recognising 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 EEZ; the FAO (1995) Code of Conduct for Responsible Fisheries emphasising conservation and the precautionary approach, 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 Precautionary Approach (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 way of synthesising this information to somehow measure 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 overpopulates 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 it's 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 minimised 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).

As the snow crab fishery is a male-only fishery that primarily targets post-reproductive males, it has a built-in protection mechanism for the SSB. With these measures alone, the snow crab fishery goes well beyond DFO's (2006) one-dimensional criterion for PA-compliance. The following additional management measures that are currently implemented in the snow crab fishery attempt to further reduce the footprint of this fishery:

- Reproductive potential maintained:
    - The spawning stock biomass is not harvested (i.e., mature females)
    - "Immature" males are still able to mate (not harvested)
    - Small mature males are able to mate as they will never enter the fishery
    - Mature males are exploited at low levels and mostly after the mating season (spring)
- Immature crab are not harvested
    - Alleviate potential genetic selection upon early size at maturity
    - Voluntary return to water, area closures
- Soft-shelled are not harvested
    - Reduce unnecessary fishing mortality of the fishable component
    - Voluntary return to water, area closures
    - Soft-shell protocol to assist fleet movement away from problem areas
- Mature male harvest:
    - Harvest rates of the fishable biomass are amongst the lowest in the NW Atlantic, generally ranging between 10 to 30%

- Fishing refugia
  - o Gully MPA
  - o Unfished areas on Continental Slope Edge, western inshore portion of CFA 24
- Indicators of population status are monitored annually and spatially:
  - o fishable biomass
  - o short-term potential recruitment
  - o long-term potential recruitment
  - o potential egg production
  - o size (age) structure
  - o carapace conditions
  - o spatial distributions
  - o sex ratios
  - o prevalence of bitter crab disease
- Indicators of ecosystem status are monitored annually (and spatially where available):
  - o bottom habitat space
  - o bottom and surface temperature conditions/variability
  - o abundance metrics of potential predators
  - o abundance metrics of potential prey
  - o species composition
  - o taxonomic richness
  - o size-abundance relationships of the whole community (macrofauna)
  - o various human pressures (landings of fish, pollution, population size, price)
- Open and transparent consultation and communication of scientific information and stakeholders' observations (fishers, aboriginal groups, NGOs)
  - o Incorporation of traditional and fishers' knowledge into assessment approaches
  - o Foster self-knowledge and long-term sustainability perspectives / stewardship
- At-sea-observers and 100% dockside monitoring
  - o Reduce illegal fishing

To reiterate, the primary objective of the above management measures attempt to maintain the long-term (adaptability) and short-term (resilience) sustainability of the snow crab population and the fishery that is dependent upon it. It is therefore explicitly PA-compliant.

Reference Points

Even though the fishery may be already PA-compliant, for the purposes of annual TAC advice and management decisions, reference points (RPs) are used to provide consistency across different fisheries. Two such types of RPs are used in this context: harvest rate based RPs and biomass based RPs (see Figures 50, 51).

Harvest Rate Based Reference Points

The primary harvest rate based reference point used in the SSE snow crab fishery has been the target harvest reference point. It is scaled to the natural turnover rates of the fished component, terminally moulted crab. As terminally moulted snow crab have a longevity of approximately 5 years, this equates to turnover rates of approximately 1/5 or 20% per year. That is, approximately 20% of the fishable biomass is expected to turnover in a year, all else being equal. Exploitation strategies that are larger than this scale will have a larger influence than natural processes. Thus, to ensure medium-term stability of the fishable biomass, harvest rates less than this magnitude are appropriate (i.e., total turnover rates of 40% per year should represent an upper bound under most circumstances). When the population and ecosystem context is uncertain, as is the case in the SSE, harvest rates even lower harvest rates are advisable. When recruitment expectations are strong and ecosystem considerations positive/stable, harvest strategies greater than 20% are conceivable (F=0.22; solid line in Figure 51). To date, a harvest rate in the range of 10-30% (F=0.11 to F=0.36; stippled lines in Figure 51) has been used, depending upon recruitment expectations and ecosystem uncertainty/context.

Alternatively, some (arbitrary) fraction of fishing mortality at maximum sustainable yield (FMSY) can instead be used as benchmark RPs. The FMSY {and 95% CI} for NENS, SENS and CFA4X were, respectively: 0.31 {0.24, 0.42}, 0.32 {0.23, 0.53}, and 0.66 {0.48, 0.86}. Note that for NENS and SENS, FMSY is approximately equal to the upper bound of 30% harvest rate (above). The historical average F for NENS has been just under FMSY, and consistently above FMSY from 2002 to 2006 (Figures 50, 51, top). In contrast, in SENS, the average F has been near ½ of FMSY, well below FMSY (Figures 50, 51, middle). For CFA 4X, the high estimate of FMSY=0.66 is suspect and may be a relic of the short data and variable series in the area (Figures 50, 51, bottom). There is, however, no biological justification or guarantee that some arbitrary fraction of FMSY is appropriate, especially given the single species nature of the population dynamic model used (simple biomass dynamics models). Ultimately, the lower the better as far as fishing mortality and the PA is concerned.

Note that model diagnostic suggest that process and observation errors are high in CFA 4X (Figures 52) and that model fits are marginal in general (Figure 53). Further, intrinsic rate of increase estimates (Figure 54) and catchability estimates (Figure 55) for CFA 4X are potentially problematic as they deviate from those estimated for NENS and SENS. This is likely the confounding effect of immigration from CFA 24, high and variable bottom temperatures and substrates, and associated highly dynamic species composition in the area.

Biomass Based Reference Points

The primary biomass based reference points are those that simplistically delimit areas of "healthy", "cautious" and "critical" levels of fishable abundance (but see caveats, above, as they pertain to the use of simplistic models of population dynamics). If, however, the abundance of snow crab declines sufficiently, some triggers in fishery management actions are prudent (DFO 2005), even if only for socio-economic reasons (see section: The precautionary approach and sustainability, above).

Based on historical decisions, the thresholds of fishable biomass that resulted in concern and socio-economic action were when fishable biomass dropped to at or below BMSY (Figures 50). BMSY {and 95% CI} are estimated to be 2.7 {2.1, 3.4}, 29.1 {20.5, 40.1}, and 0.6 {0.43, 0.84} kt, respectively for NENS, SENS and CFA 4X (Figure 56). When fishable biomass is less than this threshold and in the context of poor recruitment trends and/or environmental variability, more precautionary approaches towards harvest rates were deliberated and implemented (NENS: 2005-2008; SENS: 2005-2006; CFA 4X: 2004). When the fishable biomass declined to values approaching consistently, ½ of BMSY and poor recruitment, discussions of fishery closures occurred (in NENS: 2005-2008; Figure 50).

Alternatively, some arbitrary fraction of biomass at maximum sustainable yield (BMSY or K; Figures 50, 57) can be used as these thresholds. There is no correct choice, especially given the fact that the underlying carrying capacity and intrinsic rate of increase is episodic and the fact that the SSB is full protected. Any of these thresholds can serve as triggers to formally agreed upon management actions such as harvest rate reduction or closure. Explicit formalisation of these decision rules are expected in the updated Integrated Fisheries Management Plan (IFMP) for snow crab.

RECOMMENDATIONS

General Remarks

1. High catches of soft-shelled crab will likely continue to be a major issue for the next 3 to 4 years in the SSE. N-ENS and CFA 4X are now able to manage this due to the timing of fishing season. 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 mortality of recruits is to be averted. In 2010, to encourage rapid avoidance measures, soft-shell maps were implemented as interactive Googleearth™ maps which can be found at the following web address: http://sites.google.com/site/nssnowcrab .

2. The longevity of the fishable biomass (i.e., the stabilisation of the fishery) can be improved by fishing solely upon morphometrically mature crab. The arguments for this approach are as follows:

- Fishing mature crab would allow them to mate as the fishing season is generally post-mating season (in ENS, but not CFA 4X). This has the important result of reducing Darwinian selection for early maturation which is a long-term hazard for any fishery that harvests immature individuals.
- 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 2 to 3 years as immature crab go through a soft- and white shelled phases that exclude them from the fishery. 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”.
- There is a significantly large weight increase if immature crab are allowed to grow and mature (an increase of 250 to even 400%; Figure 7).
- In the 2011 season, much of the catchable biomass will still be composed of immature individuals. Indeed, many of these immature crab will potentially represent the largest-sized individuals in future catches, if allowed to grow and reach terminal moult. They will contribute to reproduction and represent high quality crab for the industry. Harvesting of this component of the catchable biomass is unwise.

S-ENS

The long-term, precautionary approach adopted by the S-ENS fishers since 2004 has allowed the S-ENS fishers to position themselves well to benefit from the new entry of recruits into fishable sizes. This is an important consideration, given the current economic woes of the world and the status of other Atlantic Canadian snow crab populations. With the consistent recruitment pulses entering into the fishable biomass and with large numbers of females having had the opportunity to mate with larger and older males (from 2006 to 2009), the health of the S-ENS stock can definitely be said to be good. The fishable biomass continues to be at historically high levels with strong and steady recruitment expected for at least the next 4-5 years. There is a strong potential for production for at least the next four years but this strength will be dependent upon how aggressively they are exploited. Long-term harvest rates between 10% and 30% is part of the strategy for sustainability in this fishery. Ensuring the longevity of the fishable biomass is important as in the SSE, recruitment has so far occurred in pulses and not at a constant rate as is the case in the Gulf of St. Lawrence. A decreased or status quo harvest strategy is recommended.

N-ENS

The more aggressive exploitation strategies in N-ENS had pushed the fishable component of the N-ENS snow crab population to historic lows for a number of years. The consequence was collateral damage upon the recruitment via soft-shell mortality. This delayed recovery in the region by several years. The reduced exploitation rate in 2008 had helped this recovery to make it through to the fishable biomass. However, recruitment into the fishable biomass in 2009 and 2010 was low although they are expected to continue for the next 2 to 4 years. Until a strong and persistent increase in fishable biomass is observed, maintaining long-term harvest rates between 10% and 20% is part of the strategy for sustainability in this fishery. A decreased or status quo harvest strategy is recommended.

CFA 4X

In CFA 4X, exploitation rates are now in the same range as that in other areas of the SSE. As CFA 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 precautionary approach towards this fishery is essential. Further, the lower recruitment into the fishable biomass and the large inter-annual temperature variations in the area increase the uncertainty associated with this area. These factors are tempered by excellent control of soft-shell capture and the buffering influence of S-ENS via immigration. The fishable biomass in the area has finally shown signs of recovery and even an expansion of the spatial range. Long-term harvest rates between 10% and 30% is part of the strategy for sustainability in this fishery. As recruitment into the 2010/2011 season is uncertain, a decreased or status quo harvest strategy is recommended.

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Table 1: Snow crab fishing seasons on the Scotian Shelf in the year 2010.

Area	Season
N-ENS	Apr 17 – May 16 & July 19- Aug 29
S-ENS (CFA 23)	Apr 7 – Sept 30
S-ENS (CFA 24)	Apr 7 – Sept 30 (Closed Sept 1- TAC reached)
CFA 4X	Nov 1 – March 31 (2011)

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)
1997	74	540	534	23.3	22.9
1998	74	660	657	41.6	15.8
1999	78	900	899	54.8	16.4
2000	79	1,015	1,017	68.3	14.9
2001	80	1,065	1,066	94.3	11.3
2002	80	1,493	1,495	101.0	14.8
2003	80	1,493	1,492	76.8	19.4
2004	79	1,416	1,418	60.6	23.4
2005	78	566	562	30.6	18.4
2006	78	487	486	35.6	13.7
2007	78	244	233	23.6	9.9
2008	78	244	238	33.7	7.0
2009	78	576	579	75.7	7.6
2010	78	576	576	55.0	10.5

Table 3: Summary of snow crab fisheries activity of S-ENS.

Year	Licenses	TAC (t)	Landings (t)	CPUE (kg/trap haul)	Effort (x1000 trap hauls)
1997	59	1,163	1,157	50.9	22.7
1998	67	1,671	1,558	68.9	22.6
1999	-	2,700	2,700	71.1	38.0
2000	158	8,799	8,701	85.0	102.4
2001	163	9,023	9,048	87.8	103.1
2002	149	9,022	8,891	111.7	79.6
2003	145	9,113	8,836	98.6	89.6
2004	130	8,241	8,022	105.6	76.0
2005	114	6,353	6,407	109.5	58.5
2006	114	4,510	4,486	90.9	49.4
2007	115	4,950	4,942	100.1	49.3
2008	115	8,316	8,253	96.1	85.9
2009	116	10,800	10,645	89.6	118.8
2010	116	13,200	13,150	102.5	128.3

Table 4: Summary of snow crab fisheries activity of CFA 4X.

Year	Licenses	TAC (t)	Landings (t)	CPUE (kg/trap haul)	Effort (x1000 trap hauls)
1997/08	4		42		
1998/09	4		70		
1999/2000	4		119		
2000/01	6		213		
2001/02	8	520	376		
2002/03	9	600	221	10.1	21.9
2003/04	9	600	289	12.7	22.8
2004/05	9	600	413	20.3	20.8
2005/06	9	337.6	306	28.6	10.8
2006/07	9	337.6	317	27.7	11.5
2007/08	9	230	220	18.1	12.1
2008/2009	9	230	229	28.4	8.0
2009/2010	9	230	229	36.0	6.4
2010/2011	9	346	*280		

* As of February 1, 2011. Season still in progress.

Table 5: Snow crab carapace conditions and their description. Hardness is measured by a durometer.

Carapace condition	Category	Hardness	Description	Age after terminal moult (approx)
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 Arrhenius-adjusted metabolic intensity (smrA), expected Arrhenius-adjusted total metabolic output (mrA), and easting and northing (plon, plat). The combined predictive coefficient of determination is 56% of the total variation.

Habitat (presence-absence)

```
Parametric coefficients:
            Estimate Std. Error z value Pr(>|z|)
(Intercept)   0.0124     0.0674    0.18     0.85

Approximate significance of smooth terms:
                     edf Ref.df   Chi.sq     p-value
s(yr)               5.79   6.88  72445.3     < 2e-16 ***
s(weekno)           1.87   2.25   6844.5     < 2e-16 ***
s(tmean)            4.89   6.06  50161.4     < 2e-16 ***
s(dt.annual)        2.04   2.47   5672.0     < 2e-16 ***
s(dt.seasonal)      2.30   2.71  10285.8     < 2e-16 ***
s(tamp.annual)      2.57   2.87   1612.0     < 2e-16 ***
s(wmin.annual)      2.04   2.45   3535.4     < 2e-16 ***
s(z)                5.09   6.33 117761.2     < 2e-16 ***
s(dZ)               1.73   2.14     37.2     < 0.001 ***
s(substrate.mean)   1.59   1.98   1771.4     < 2e-16 ***
s(ca1)              1.99   2.40   7534.2     < 2e-16 ***
s(ca2)              2.26   2.67   1946.7     < 2e-16 ***
s(Npred)            1.87   2.34   9536.3     < 2e-16 ***
s(Z)                1.83   2.29   5231.7     < 2e-16 ***
s(smrA)             1.92   2.34  10798.9     < 2e-16 ***
s(mrA)              1.97   2.36   2009.7     < 2e-16 ***
s(plon,plat)      246.96 247.00 611636.4     < 2e-16 ***

R-sq.(adj) =  0.773   Deviance explained = 56.1%
UBRE score =  48.42  Scale est. = 1         n = 46919

---
Signif. codes:
  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

Abundance (positive-values)

```
Parametric coefficients:
             Estimate  Std. Error t value Pr(>|t|)
(Intercept)  -0.6069   0.0496     -12.2   <2e-16 ***

Approximate significance of smooth terms:
                      edf  Ref.df     F p-value
s(yr)               5.213   6.226 52.20 < 2e-16 ***
s(weekno)           1.050   1.249 50.27 5.4e-15 ***
s(tmean)            1.896   2.542 11.37 1.3e-06 ***
s(dt.annual)        1.046   1.185 35.91 1.2e-10 ***
s(dt.seasonal)      0.949   1.101  9.30  0.0017 **
s(tamp.annual)      1.097   1.239  3.85  0.0408 *
s(wmin.annual)      1.021   1.171 38.98 2.4e-11 ***
s(z)                3.791   4.683 60.94 < 2e-16 ***
s(dZ)               0.517   0.754  0.42  0.4610
s(substrate.mean)   0.578   0.783  1.14  0.2696
s(ca1)              1.266   1.539  7.33  0.0019 **
s(ca2)              0.974   1.152  9.61  0.0012 **
s(Npred)            0.463   0.725  3.32  0.0801 .
s(Z)                0.612   0.865  3.20  0.0791 .
s(smrA)             0.632   0.901  0.37  0.5191
s(mrA)              0.925   1.077  4.74  0.0270 *
s(plon,plat)      137.560 168.595  4.79 < 2e-16 ***

R-sq.(adj) =  0.573   Deviance explained =   55%
GCV score = 632.24  Scale est. = 610.6     n = 4691

---
Signif. codes:
0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

Table 7: Tagging effort since 2004.

	Tags Applied	Number of Tags Returned	Number of Distinct Tags Returned	Avg. Displacement (km)	Max Displacement (km)	Avg. Days to Capture	Max Days to Capture	Avg. km/month
2004	787	0	0					
2005	246	6	6	16.67	67.6	338	347	1.47
2006	3219	113	113	5.82	103.8	28	661	6.04
2007	0	252	241	13.55	263.7	335	704	1.21
2008	953	79	76	20.94	280.9	409	1363	1.53
2009	195	9	9	33.36	176	563	1073	1.77
2010	2282	82	77	12.41	57.8	320	1379	1.16
All Years (1st Capture)	7682	549	526	14.49	280.9	319	1379	1.35
All Years (all captures)	7682	549	526	14.01	280.9	308	1379	1.36

Table 8: The relative proportion of stomachs sampled that contained snow crab.

	2000	*2001*	*2002*	*2003*	*2004*	*2005*	*2006*	*2007*	*2008*	***Average***
AMERICAN_PLAICE	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.03	0.00	0.23
ATLANTIC_WOLFFISH	1.41	0.00	0.00	0.00	0.00	0.00	0.00	15.38	15.00	3.53
COD(ATLANTIC)	0.38	0.00	0.00	0.00	0.00	0.00	0.99	0.42	0.54	0.26
EELPOUT_NEWFOUNDLAND	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	16.67	1.85
HADDOCK	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.27	0.03
HALIBUT(ATLANTIC)	0.94	0.00	0.00	14.29	0.00	0.00	0.00	0.00	0.00	1.69
LONGHORN_SCULPIN	0.00	0.00	0.00	0.00	0.00	0.37	0.00	12.38	1.61	1.60
SEA_RAVEN	0.00	0.00	0.00	0.00	0.00	0.84	0.00	0.00	0.00	0.09
SHORTHORN_SCULPIN	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SMOOTHSKATE	0.00	0.00	0.00	0.00	0.00	0.00	0.00	13.04	0.00	1.45
THORNY_SKATE	0.64	0.00	0.00	0.00	0.00	0.00	0.00	3.51	0.00	0.46
WHITE_HAKE	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.84	0.00	0.09

Table 9: Model coefficients from a log-linear model of snow crab densities as a function of by catch species from snow crab surveys. Significant, high magnitude negative relationships are highlighted.

```
Coefficients:                  Estimate   Std. Error   t value   Pr(>|t|)
(Intercept)                     4.91693      0.45267     10.86   < 2e-16    ***
t                              -0.26453      0.01645    -16.08   < 2e-16    ***
tamp.annual                      0.1067       0.0204      5.23   1.80E-07   ***
z                               0.59177      0.07787       7.6   3.60E-14   ***
ddZ                             0.03142      0.01847       1.7    0.08904   .
AtlanticCod_10                 -0.03659      0.00632     -5.79   7.60E-09   ***
Haddock_11                     -0.09195       0.0125     -7.36   2.30E-13   ***
WhiteHake_12                    0.04921      0.01325      3.71    0.00021   ***
RedHake_13                     -0.09345      0.01874     -4.99   6.40E-07   ***
SilverHake_14                   0.05379      0.00937      5.74   1.00E-08   ***
AtlanticTomcod_17              -0.20444      0.14378     -1.42    0.15512
Redfishsp_23                    -0.0299      0.00679     -4.41   1.10E-05   ***
AtlanticHalibut_30             -0.05543      0.03345     -1.66     0.0976   .
TurbotGreenlandHalibut_31      -0.02444      0.01147     -2.13     0.0332   *
AmericanPlaice_40               0.16284       0.0095     17.15   < 2e-16    ***
YellowtailFlounder_42          -0.03954      0.00926     -4.27   2.00E-05   ***
GulfStreamFlounder_44          -0.04407      0.02561     -1.72    0.08538   .
StripedAtlanticWolffish_50     -0.12097      0.01715     -7.05   2.00E-12   ***
SpottedWolffish_51             -0.19052      0.07242     -2.63    0.00855   **
Wolffish_59                    -0.20697      0.03009     -6.88   6.80E-12   ***
HerringAtlantic_60              0.05849      0.01025      5.71   1.20E-08   ***
Capelin_64                      0.03881      0.01793      2.16    0.03049   *
AtlanticMackerel_70            -0.09187      0.05293     -1.74    0.08265   .
LongfinHake_112                  0.0534      0.02375      2.25    0.02458   *
FourbeardRockling_114           0.06558      0.01372      4.78   1.80E-06   ***
GreenlandCod_118               -0.15482      0.09861     -1.57     0.1165
BrillWindowpane_143             0.14984      0.08054      1.86    0.06288   .
LittleSkate_203                 0.11216      0.06543      1.71    0.08659   .
WinterSkate_204                 0.05698      0.03178      1.79    0.07303   .
Dogfish_274                    -0.08508      0.03472     -2.45    0.01431   *
Sculpinfamily_311               0.04213      0.00747      5.64   1.80E-08   ***
MonkfishGoosefishAngler_400    -0.04152      0.01458     -2.85    0.00441   **
MarlinSpikeGrenadier_410       -0.09975      0.02416     -4.13   3.70E-05   ***
RoughheadGrenadier_411         -0.20638      0.12918      -1.6     0.1102
RockGrenadierRoundnose_414      -0.1346      0.02519     -5.34   9.60E-08   ***
Seasnails_500                   -0.0183      0.01237     -1.48    0.13901
SandLances_590                  0.07383      0.01781      4.15   3.50E-05   ***
AmericanSandLance_599            -0.069      0.03514     -1.96    0.04963   *
AmericanEel_600                 0.40143      0.25033       1.6    0.10888
CuskEels_660                    0.37352      0.16344      2.29    0.02234   *
AtlanticSauryNeedlefish_720     0.16855      0.09365       1.8    0.07198   .
SeaPotato_1823                 -0.13158      0.01194    -11.03   < 2e-16    ***
PandalusBorealis_2211           0.04451      0.00671      6.63   3.80E-11   ***
PandalusMontagui_2212          -0.03362      0.00955     -3.52    0.00043   ***
Argissp_2410                    0.26398      0.16661      1.58    0.11318
Crangonsp_2416                  0.07093      0.00968      7.33   2.80E-13   ***
JonahCrab_2511                 -0.09932      0.01405     -7.07   1.80E-12   ***
---
Signif. codes:  0 ‘***’ 0.00   1 ‘**’ 0   .01 ‘*’ 0.0   5 ‘.’ 0.   1 ‘ ’ 1

Residual standard error: 1.41 on 4411 degrees of freedom
Multiple R-squared: 0.421, Adjusted R-squared: 0.415
F-statistic: 69.8 on 46 and 4411 DF, p-value: <2e-16
```

Table 10a. By-catch (kg) estimates from the ENS snow crab fishery. The estimates are extrapolated from at-sea-observed by-catch 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 by-catch levels are <0.01% of snow crab landings for the past four years in ENS. At-sea-observers have noted that one leather back turtle was entangled in buoy lines in 2010. This animal was released alive with some bleeding.

Species	2007	2008	2009	2010
American Lobster	0	65	0	65
Witch Flounder	0	0	0	12
Northern Stone Crab	48	32	220	1366
Redfish	12	0	50	73
Sea Cucumber	36	0	100	148
Sea Urchin	0	0	10	0
Spotted Wolffish	0	0	30	313
Striped Wolffish	0	32	80	116
Sand Dollars	0	0	0	35
Toad Crab	12	11	50	35
Atlantic Cod	0	0	579	278
Plaice	0	0	10	0
Winter Flounder	0	0	20	0
Flatfish Sp.	0	0	10	0
Wolffish Sp.	0	0	120	0
Greenland Cod	0	0	40	0
Toad Crab	0	0	50	0
Hermit Crab	0	0	40	0
Whelk	0	0	50	0
Starfish Sp.	0	0	50	0
Basket Stars	0	0	10	0
Snow Crab Landings	**5,174,000**	**8,491,000**	**11,224,000**	**13,717,290**

Table 10b. By-catch (kg) estimates from the CFA 4X snow crab fishery. The estimates are extrapolated from at-sea-observed by-catch 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)]. By-catch levels have been at 0.83% of total landings in the past four years, with most by-catch species being other crabs and lobster.

Species	**2007**	**2008**	**2009**	**2010**
Jonah Crab	0	0	23	59
Northern Stone Crab	26	3393	3823	220
Deepsea Red Crab	0	56	503	0
Sea Raven	0	45	0	0
Sea Cucumber	0	11	0	0
Sculpin	0	45	0	0
American Lobster	0	11	11	59
Rock Crab	0	0	0	0
Toad Crab	0	45	0	44
Snow Crab Landings	**319,000**	**220,000**	**229,443**	**229,443**

Table 11: Carapace condition of crab ≥ 95 mm CW (percent by number) over time for N-ENS from at-sea-observed data.

Year	Carapace condition				
	1	2	3	4	5
2004	2.5	4.9	72.5	19.8	0.4
2005	18.1	2.1	61.0	18.0	0.8
2006	4.4	9.5	71.6	13.4	1.1
2007	44.0	11.3	36.6	7.4	0.6
2008	28.6	3.2	60.8	6.7	0.7
2009	3.2	2.4	90.2	4.1	0.0
2010	2.1	1.5	92.2	4.0	0.2

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

Year	Carapace condition				
	1	2	3	4	5
2004	3.2	3.6	74.5	18.0	0.7
2005	5.9	11.0	68.2	14.3	0.7
2006	6.7	17.4	68.4	7.2	0.3
2007	8.8	15.0	58.4	16.3	1.5
2008	11.9	8.4	66.6	12.8	1.0
2009	14.9	5.0	61.0	16.7	2.5
2010	7.9	6.2	77.7	7.2	1.0

Table 13: Carapace condition of crab ≥ 95 mm CW (percent by number) over time for CFA 4X from at-sea-observed data.

Year	Carapace condition				
	1	2	3	4	5
2004/5	0.2	1.8	93.4	4.4	0.1
2005/6	0.1	11.8	85.0	3.2	0.0
2006/7	0.1	0.5	98.0	1.4	0.0
2007/8	1.2	0.1	78.1	20.4	0.2
2008/9	1.1	0.2	56.3	42.4	0.1
2009/10	2.3	0.0	97.1	0.6	0.0

Table 14: Carapace condition 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	Carapace condition				
	1	2	3	4	5
2003	6.6	18.7	56.3	18.4	0.0
2004	2.0	3.5	51.3	38.7	4.5
2005	5.4	0.0	51.7	32.9	10.1
2006	17.1	9.5	16.2	40.0	17.1
2007	16.2	12.0	63.4	7.0	1.4
2008	38.3	4.1	51.0	6.6	0.0
2009	25.2	17.4	55.8	1.7	0.0
2010	19.5	23.6	53.1	3.8	0.0

Table 15: Carapace condition 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	Carapace condition				
	1	2	3	4	5
2003	30.6	7.4	48.5	12.2	1.4
2004	10.1	12.5	56.1	20.8	0.7
2005	7.8	16.2	60.6	15.1	0.4
2006	14.1	10.6	56.8	17.1	1.4
2007	15.2	46.4	29.7	8.5	0.3
2008	13.2	3.8	69.8	12.8	0.4
2009	18.0	15.2	59.3	7.3	0.2
2010	21.5	15.0	61.2	2.2	0.1

Table 16: Carapace condition of crab ≥ 95 mm CW (percent by number) over time for CFA 4X from trawl surveys. The transition from a spring to a fall survey occurred in 2002/2003. Crude, unadjusted proportions.

Year	Carapace condition				
	1	2	3	4	5
2003	14.3	0.0	57.1	28.6	0.0
2004	0.0	0.0	84.2	15.8	0.0
2005	9.3	2.3	86.0	2.3	0.0
2006	1.4	5.7	82.8	8.6	1.4
2007	3.8	13.5	76.9	5.8	0.0
2008	11.3	0.0	80.7	8.1	0.0
2009	8.1	6.5	80.6	4.9	0.0
2010	14.7	11.8	68.6	4.9	0.0

Table 17: Survey index fishable biomass and landings entering into the assessment model and the resultant modelled fishable biomass estimates and harvest rates. Harvest rate is the modeled estimate. Projected harvest rate$_t$ is the calculated harvest rate applied (targeted) upon the fishable biomass of the previous year (Landings$_{t+1}$ / Fishable biomass$_t$).

	Year	Fishable biomass (kt)	TAC (kt)	Landings (kt)	Harvest rate (%)	Projected harvest rate (%)
NENS	**1998**	3.87	0.66	0.657	14.5	
	1999	3.90	0.9	0.899	18.7	23.3
	2000	3.71	1.015	1.017	21.5	26.0
	2001	3.29	1.065	1.066	24.5	28.7
	2002	3.36	1.493	1.495	30.8	45.3
	2003	2.74	1.493	1.492	35.2	44.5
	2004	2.15	1.416	1.418	39.5	51.7
	2005	1.46	0.566	0.562	27.5	26.3
	2006	1.50	0.487	0.486	24.4	33.5
	2007	1.63	0.244	0.233	12.5	16.3
	2008	2.15	0.244	0.238	9.5	15.0
	2009	2.79	0.576	0.579	17.1	26.7
	2010	2.81	0.576	0.576	17.0	20.6
SENS	**1998**	33.17	1.671	1.558	4.5	
	1999	46.63	2.7	2.7	5.5	8.1
	2000	44.22	8.799	8.701	16.4	18.9
	2001	37.28	9.023	9.048	19.5	20.4
	2002	35.41	9.022	8.891	20.1	24.2
	2003	31.29	9.113	8.836	22.0	25.7
	2004	28.86	8.241	8.022	21.9	26.3
	2005	26.06	6.353	6.407	19.6	22.0
	2006	27.00	4.51	4.486	14.2	17.3
	2007	32.48	4.95	4.942	13.2	18.3
	2008	42.04	8.316	8.253	16.3	25.6
	2009	49.28	10.8	10.645	17.9	25.7
	2010	48.48	13.2	13.15	20.8	26.8
CFA 4X	**1998/09**	0.15		0.07	31.8	
	1999/2000	0.26		0.119	31.5	
	2000/01	0.44		0.213	32.5	
	2001/02	0.67	0.52	0.376	35.8	117.6
	2002/03	0.61	0.6	0.221	26.5	88.9
	2003/04	0.52	0.6	0.289	35.6	97.6
	2004/05	0.62	0.6	0.413	31.7	114.8
	2005/06	0.72	0.336	0.306	37.0	53.9
	2006/07	0.64	0.336	0.317	32.3	46.5
	2007/08	0.77	0.23	0.22	29.4	35.7
	2008/2009	0.90	0.23	0.229	19.6	29.9
	2009/2010	1.07	0.23	0.229	17.6	25.4
	2010/2011	0.93	0.346	0.346	19.8	32.2

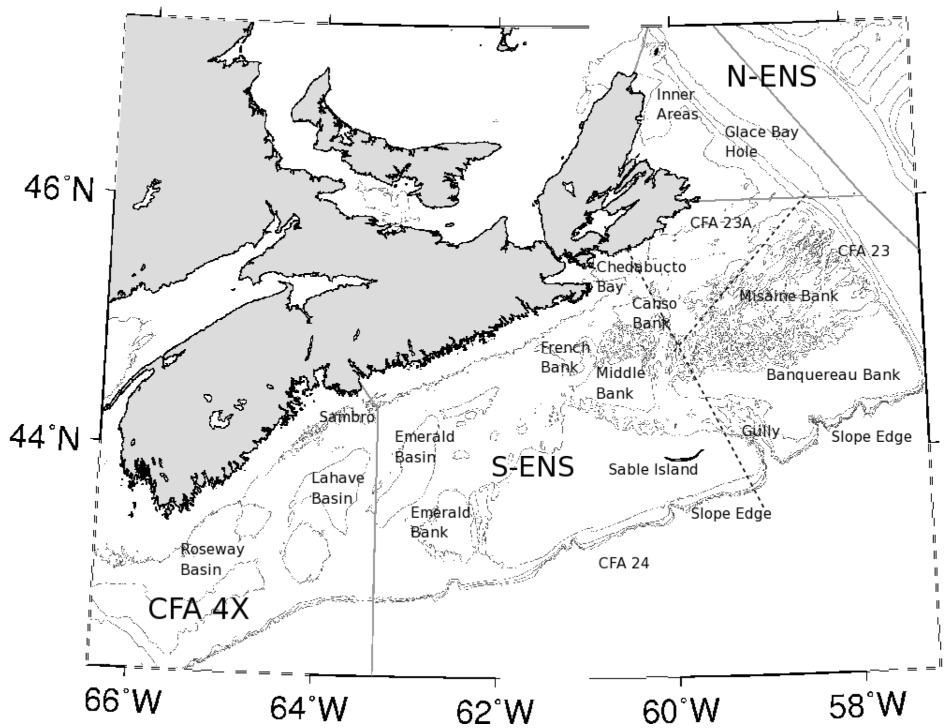


Figure 1: Location of geographic areas and management areas on the Scotian Shelf.

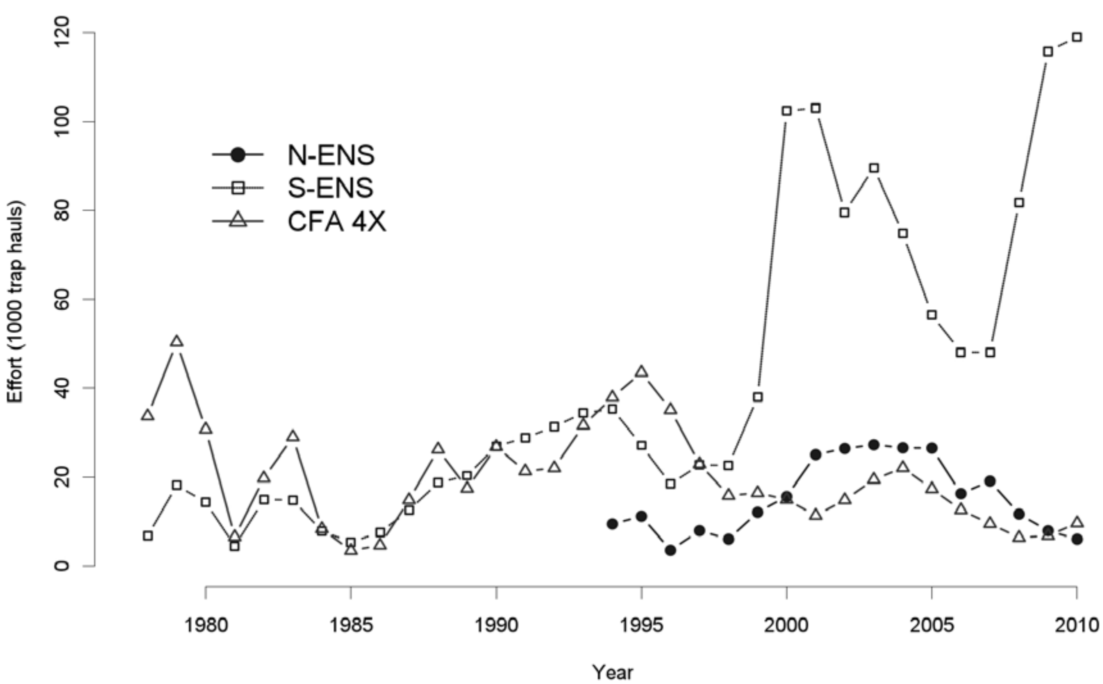


Figure 2: Temporal variations in the fishing effort, expressed as the number of trap hauls. For CFA 4X, year refers to the starting year.

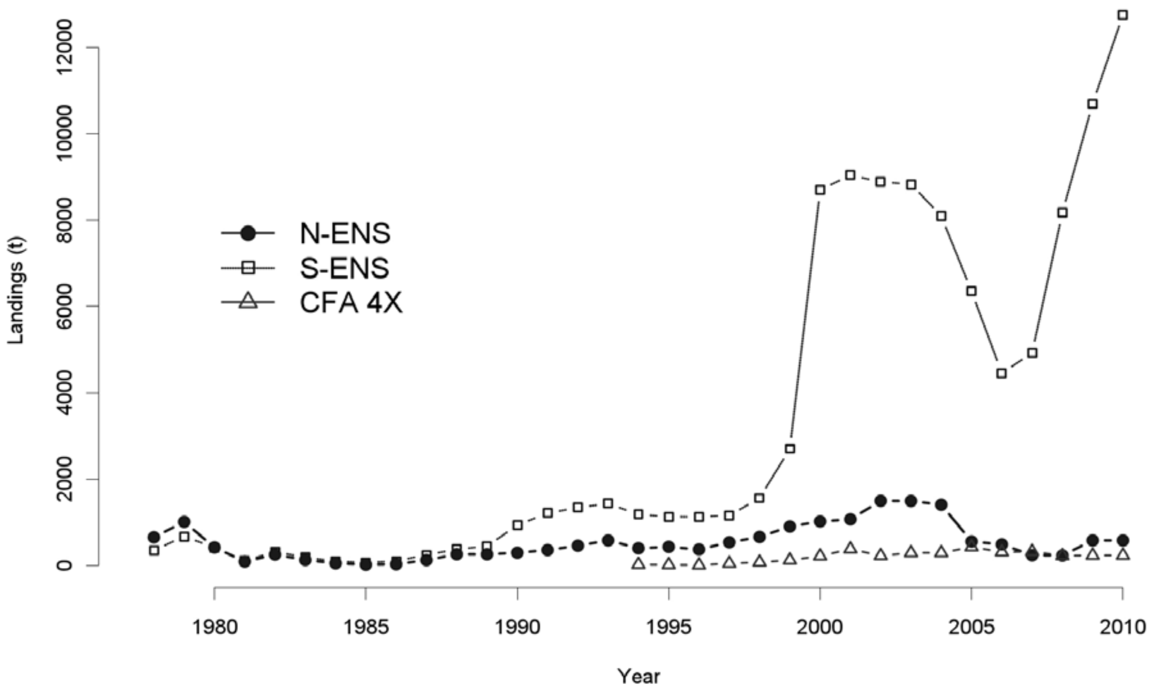


Figure 3: Temporal variations in the landings of snow crab on the Scotian Shelf (t). Note the sharp increase in landings associated with dramatic increases to TACs and a doubling of fishing effort in the year 2000. The landings follow the TACs with little deviation (and so are not shown). For CFA 4X,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

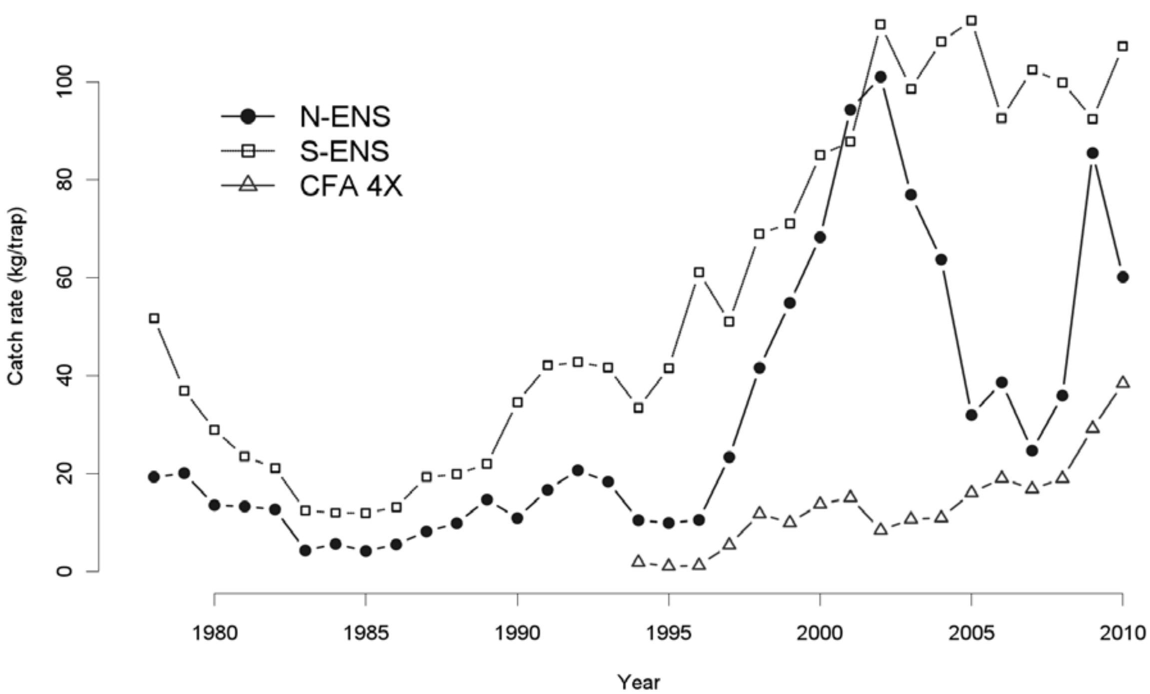


Figure 4: Temporal variations in catch rates of snow crab on the Scotian Shelf, expressed as kg per trap haul. Trap design and size have changed over time. No correction for these varying trap-types nor soak time and bait-type has been attempted (see Methods). For CFA 4X, year refers to the starting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

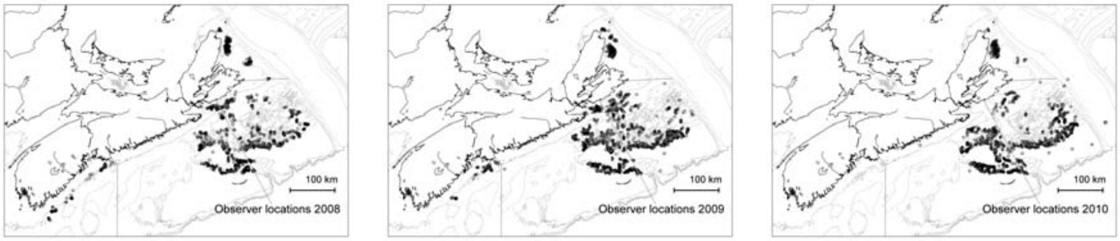


Figure 5: At-sea-observer monitored locations on the Scotian Shelf.

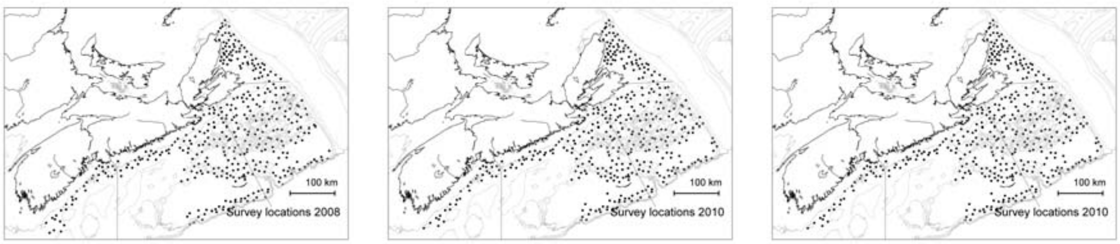


Figure 6: Trawl survey locations on the Scotian Shelf.

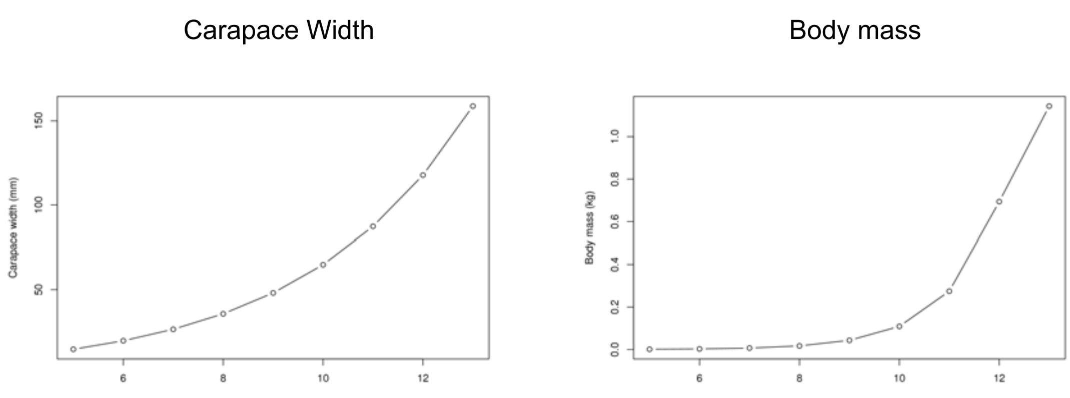


Figure 7: Growth curves determined from Scotian Shelf male snow crab.

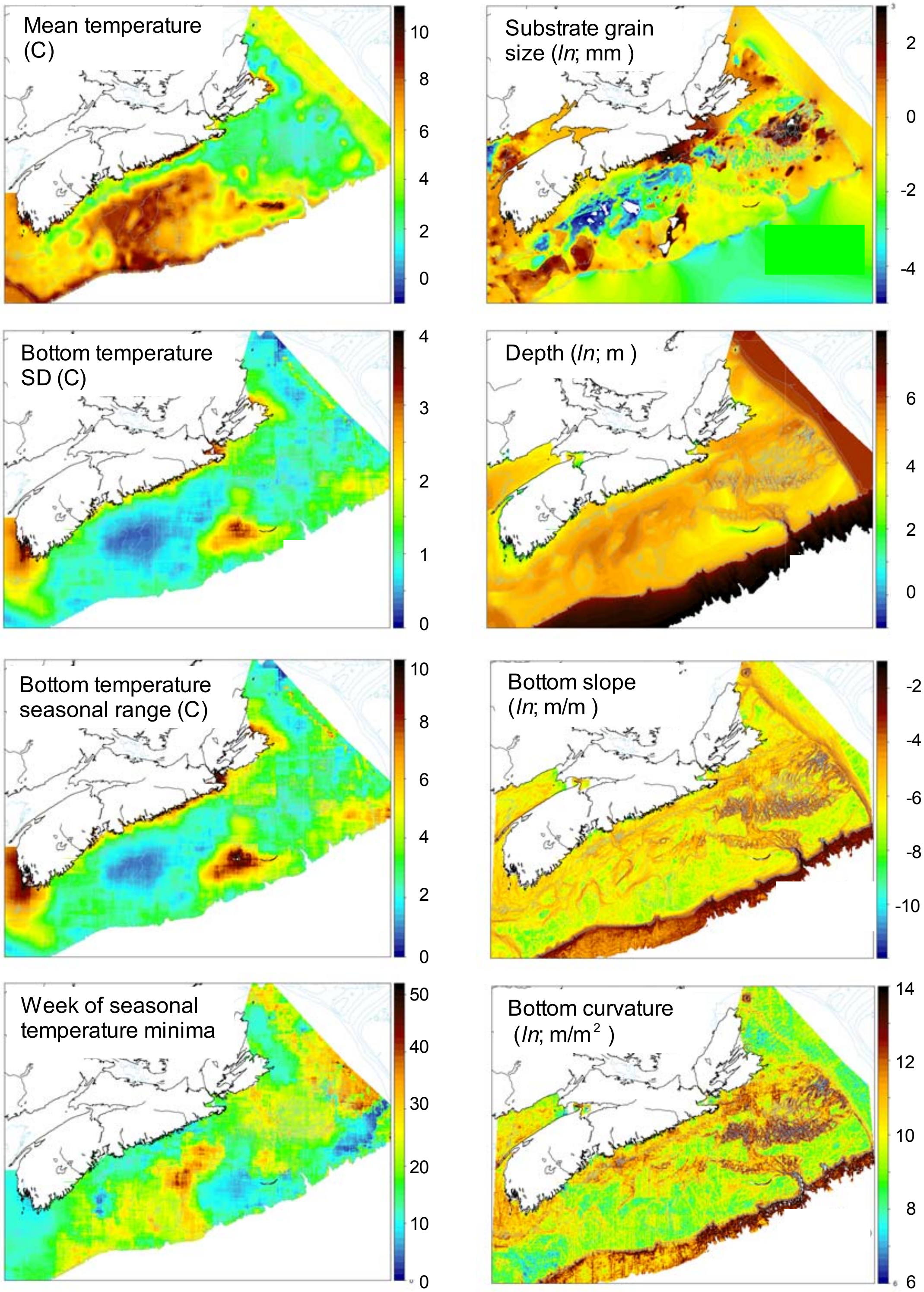


Figure 8: Bottom characteristics used for modelling snow crab habitat delineation. The visualisations of temperature variations are for climatological means. Annual temperature variation estimates were used for modelling. (Continued below.)

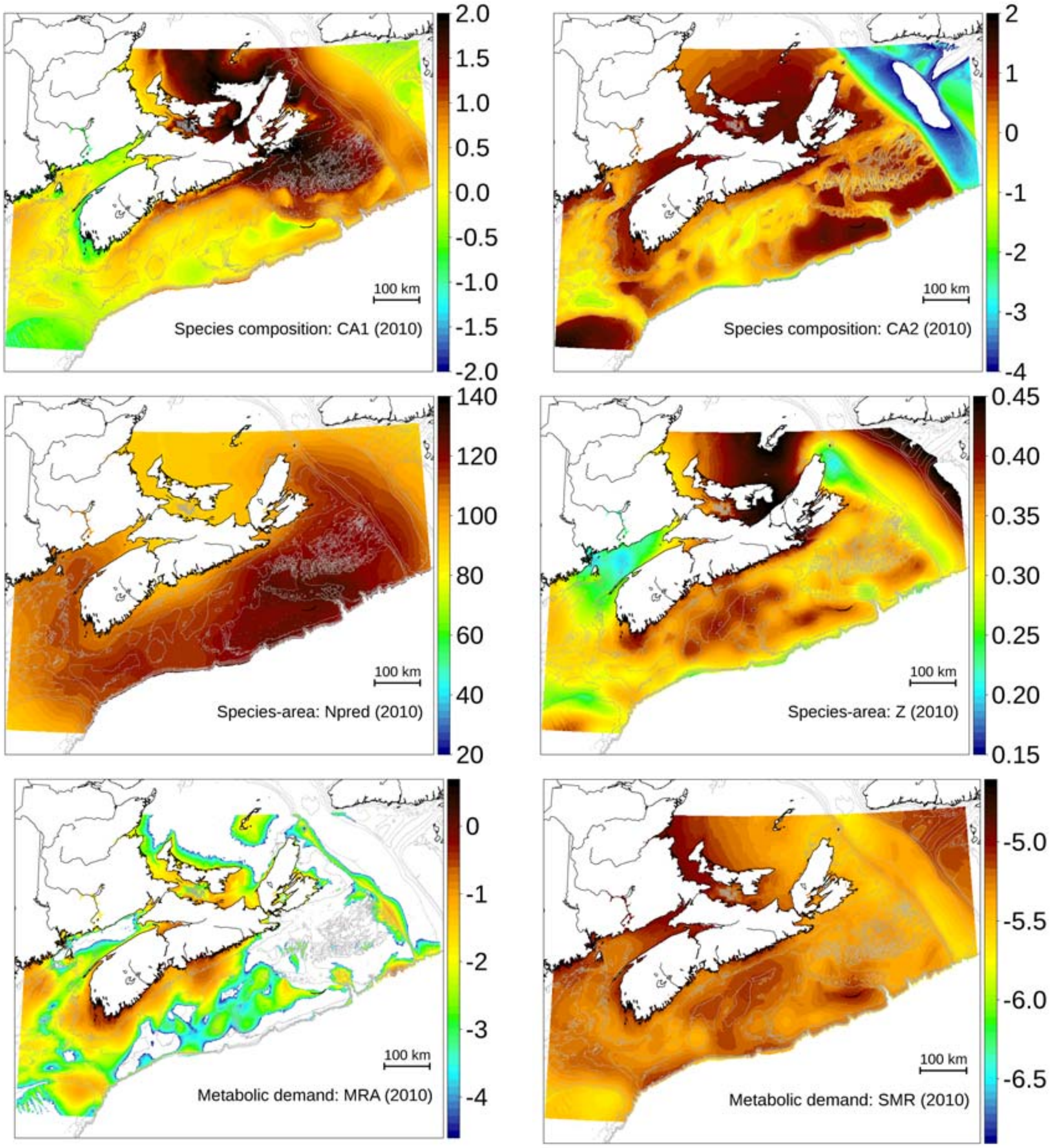


Figure 8: Bottom characteristics used for modelling snow crab habitat delineation. The visualisations of temperature variations are for climatological means. Annual temperature variation estimates were used for modelling. (Continued from above).

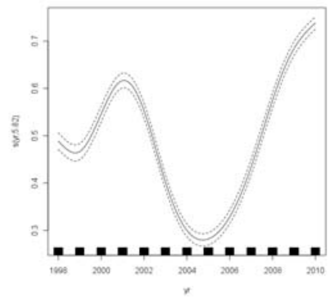
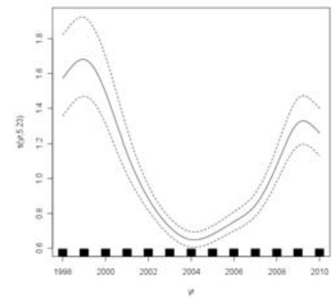
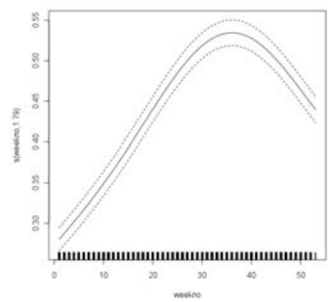
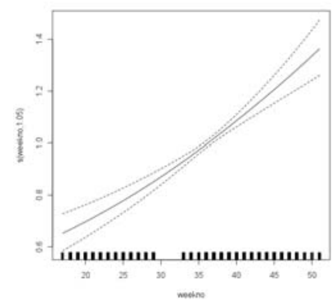
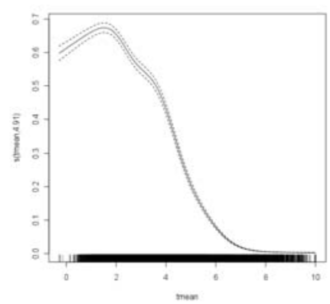
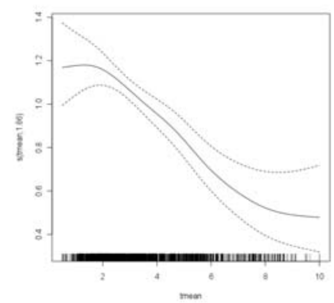
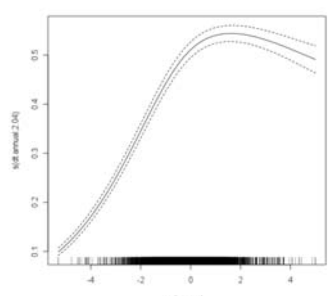
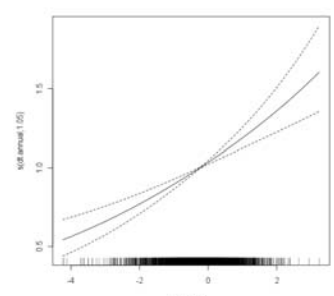
	Habitat	Abundance
Year of capture		
Week number of capture		
Climatological mean bottom temperature		
Deviation of annual mean bottom temperature from Climatological mean in the year of capture (positive = colder than climatology)		

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% CI are presented.

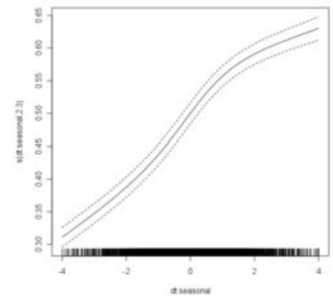
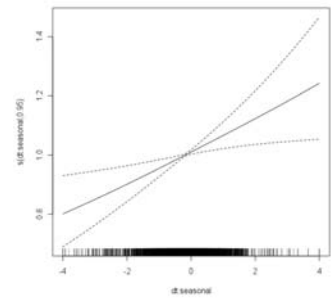
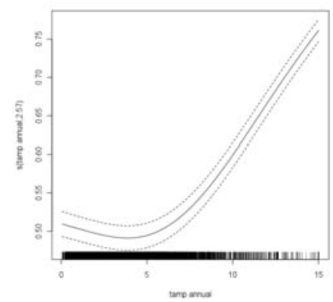
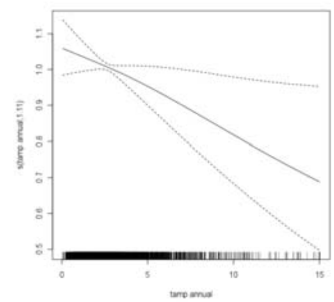
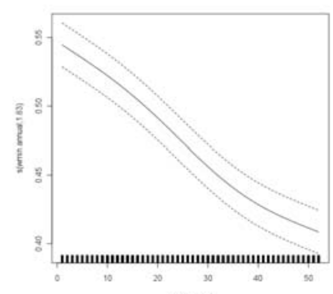
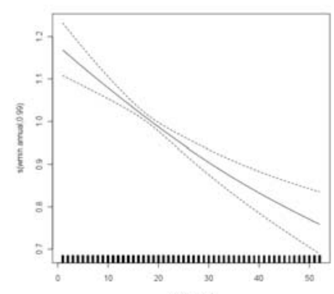
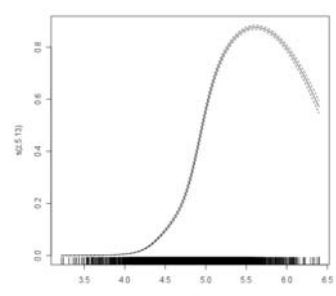
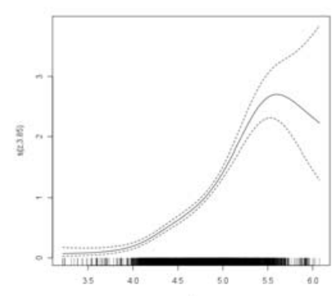
	Habitat	Abundance
Deviation of bottom temperature from the annual mean bottom temperature at time of capture (positive = colder than annual average)		
Annual amplitude of bottom temperatures in the year of capture		
Week number at which bottom temperatures reach seasonal minima in the year of capture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

Figure 9: (Continued.)

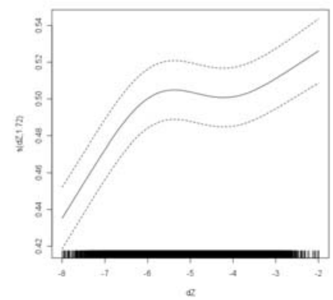
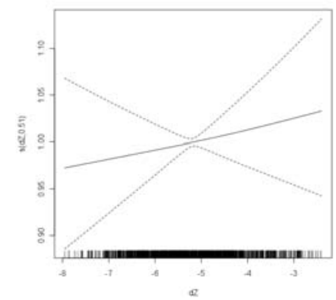
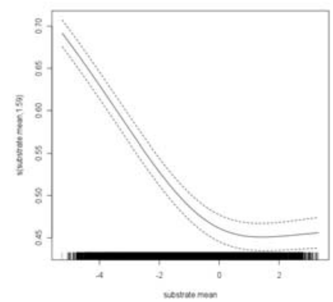
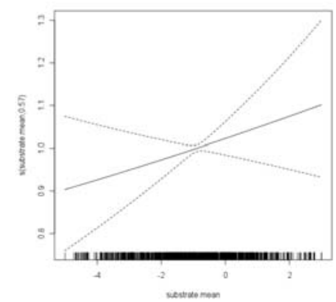
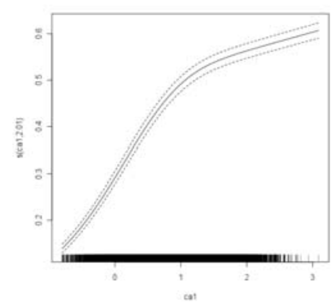
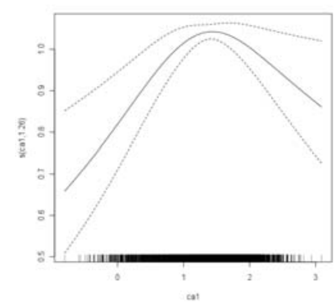
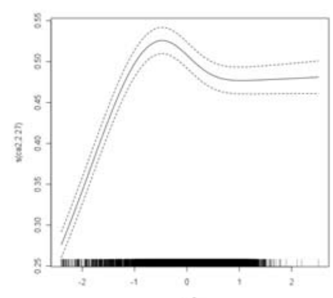
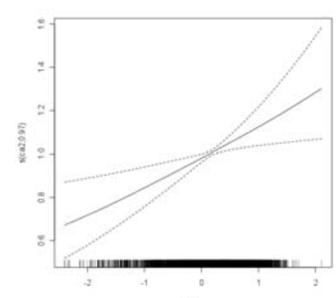
	Habitat	Abundance
Bottom slope at location of capture (log)		
Mean grain size at location of capture (log)		
Species composition axis 1 (temperature related gradient) at location and year of capture		
Species composition axis 2 (depth related gradient) at location and year of capture		

Figure 9: (Continued.)

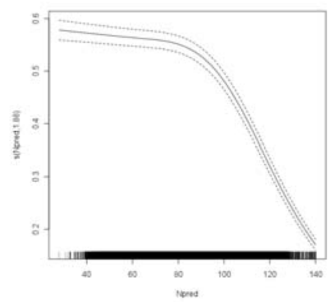
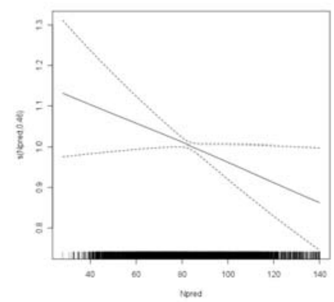
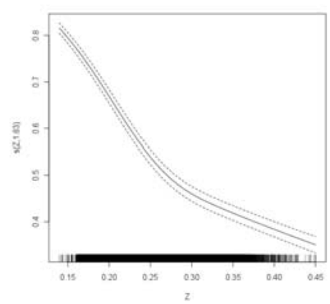
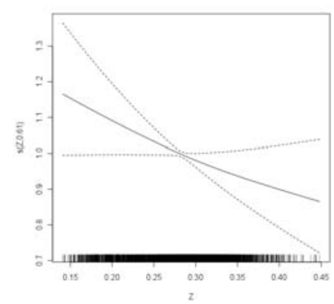
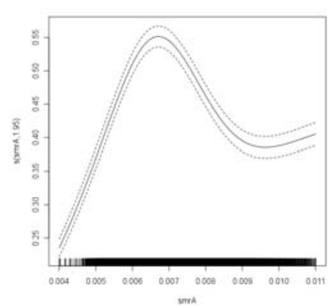
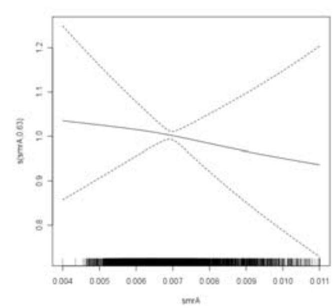
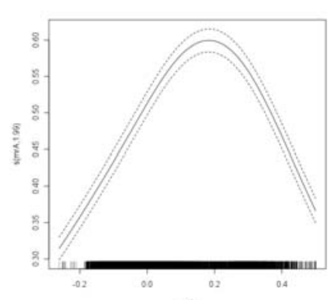
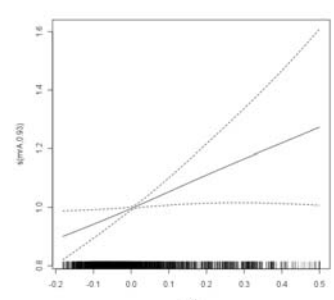
	Habitat	Abundance
Number of species predicted, based upon a species-area saturation curve		
Curvature of the species-area relationship		
Specific metabolic rate (intensity) predicted from size structure		
Total metabolic rate predicted from size structure (an estimate of gross productivity)		

Figure 9: (Continued.)

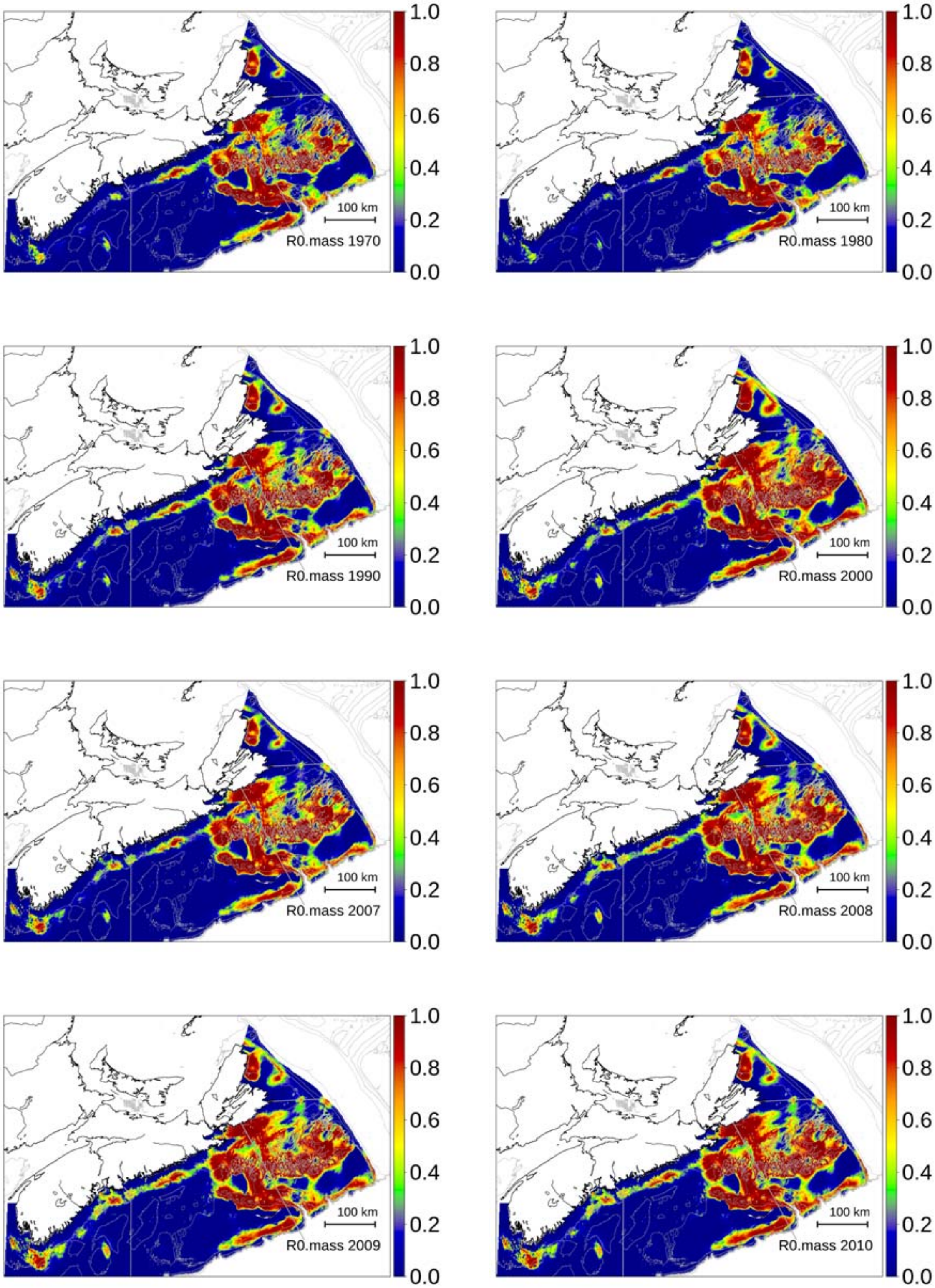


Figure 10: Predicted probabilities of viable habitat for fishable snow crab.

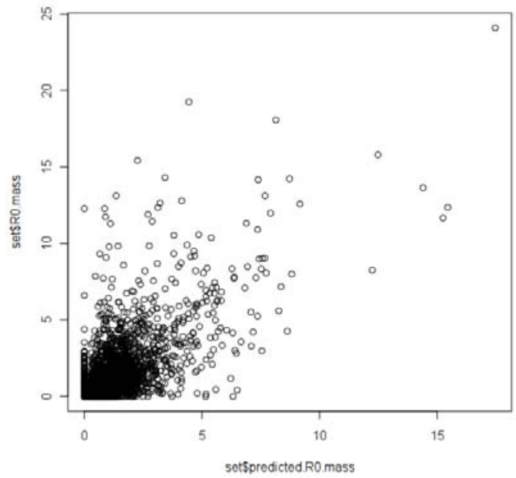


Figure 11: Correlation between observed and predicted densities of fishable biomass. The coefficient of determination was 50%.

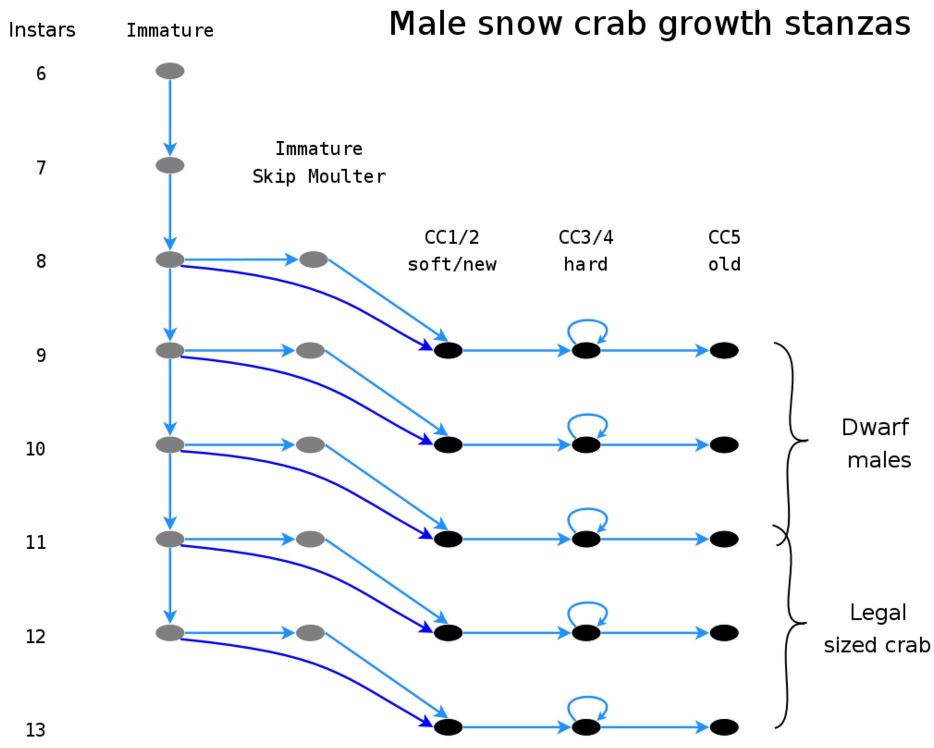


Figure 12: The growth stanzas of male snow crab. Each instar is determined from carapace width bounds obtained from modal analysis and categorized to carapace condition (CC) and maturity from visual inspection and/or maturity equations. Snow crab are resident in each growth stanza for 1 year, with the exception of CC2 to CC4 which are known from mark-recapture studies to last from 2 to 5 years.

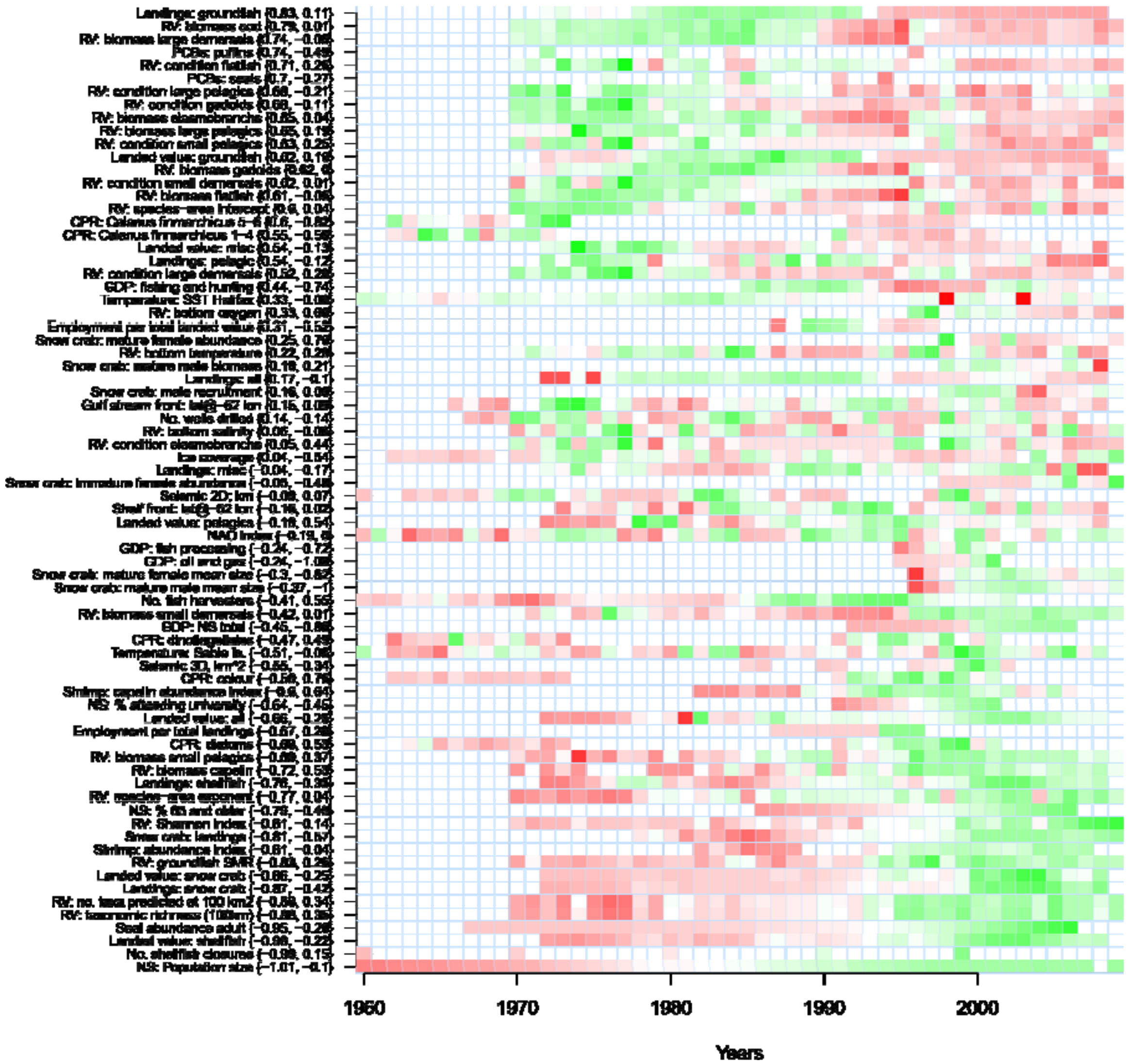


Figure 13: Sorted ordination of anomalies of key social, economic and ecological patterns on the Scotian Shelf relevant to snow crab. Red indicates below the mean and green indicates above the mean.

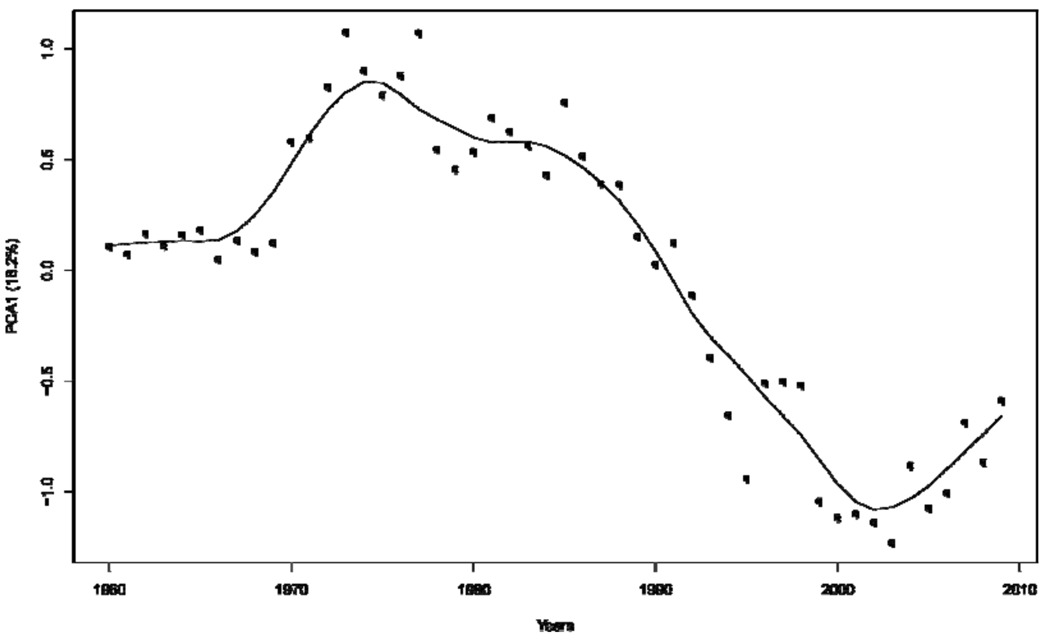


Figure 14: First axis of variations in ordination of anomalies of social, economic and ecological patterns on the Scotian Shelf. Note strong variability observed near the time of the fishery collapse in the early 1990s. Note strong variability observed near the time of the fishery collapse in the early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

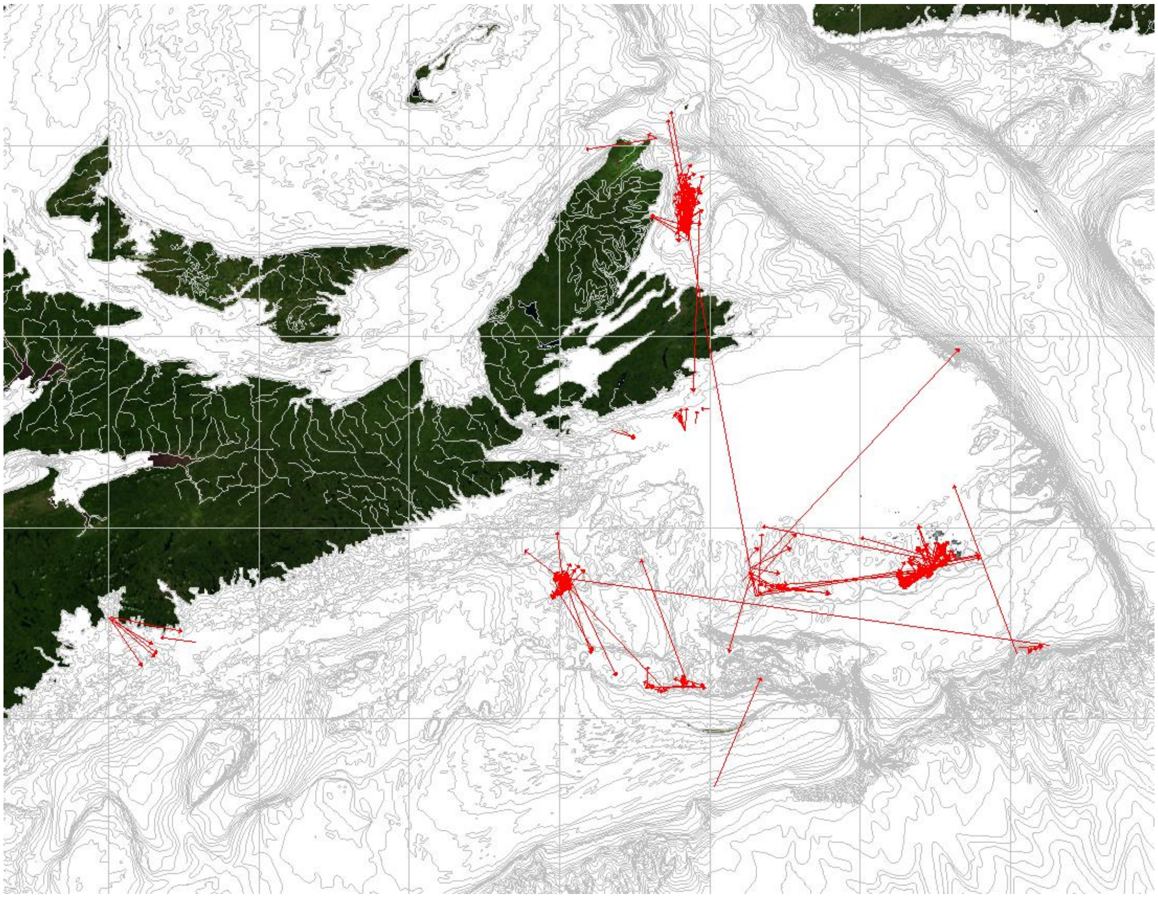


Figure 15: Movement of terminally moulted fishable snow crab.

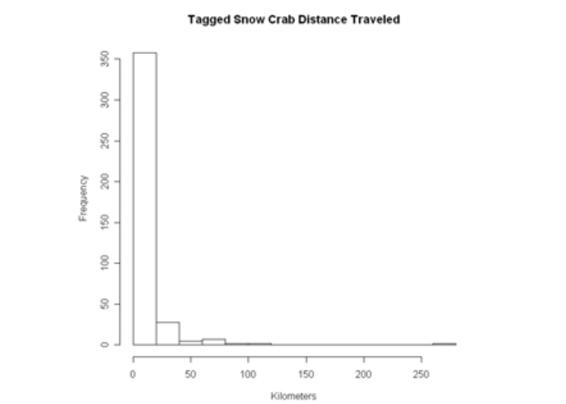
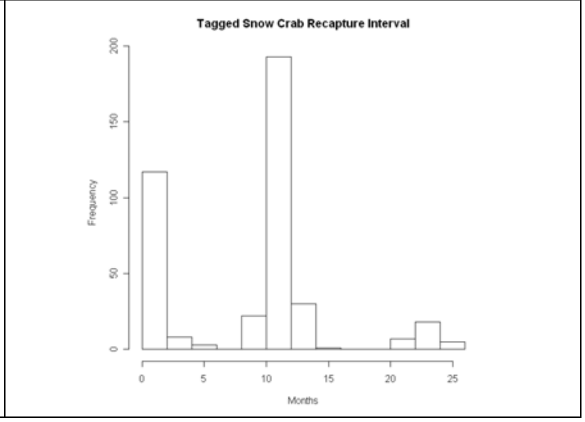
Distances Traveled	Recapture Interval
	

Figure 16: (Left) Distance traveled by Tagged Snow Crab in ENS 2004-2008. (Right) Tagged snow crab in ENS: return interval in months between initial release and first recapture.

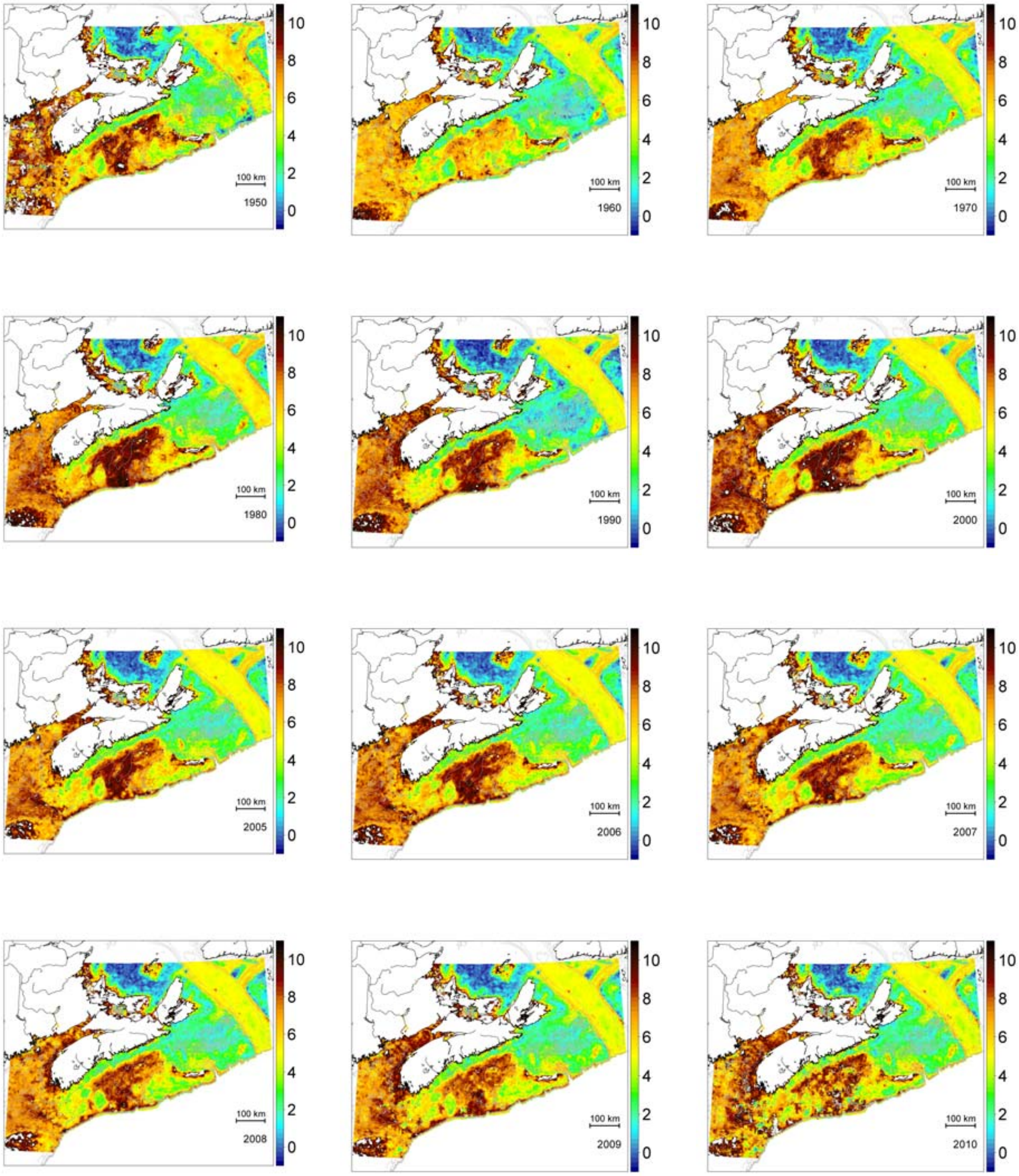


Figure 17: Mean annual bottom temperatures on the Scotian Shelf for selected years.

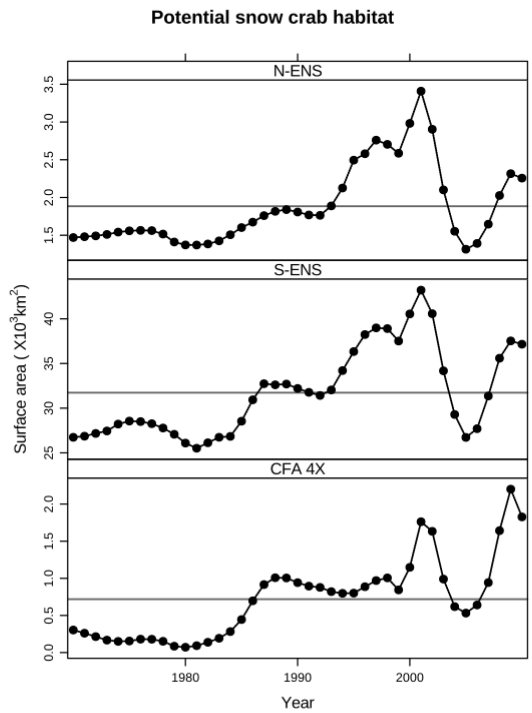


Figure 18: Annual variations in the surface area of potential snow crab habitat. The horizontal line indicates the long-term arithmetic mean surface area within each subarea.

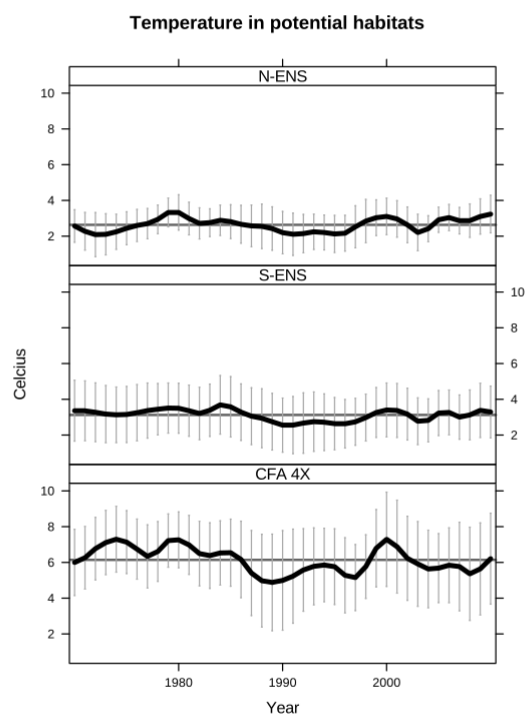


Figure 19: Annual variations in bottom temperature within potential snow crab habitat. The horizontal line indicates the long-term arithmetic mean surface area within each subarea. Error bars are 1 standard deviation .

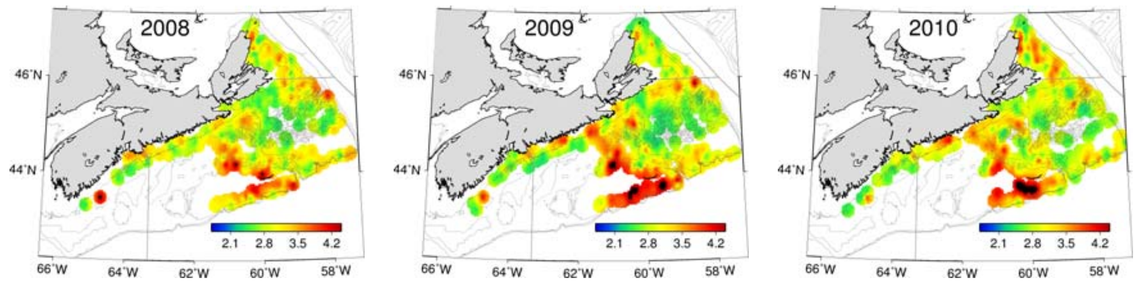


Figure 20: Locations of potential predators of snow crab: cod. Scale is log_{10} (numerical density [number/km^2]).

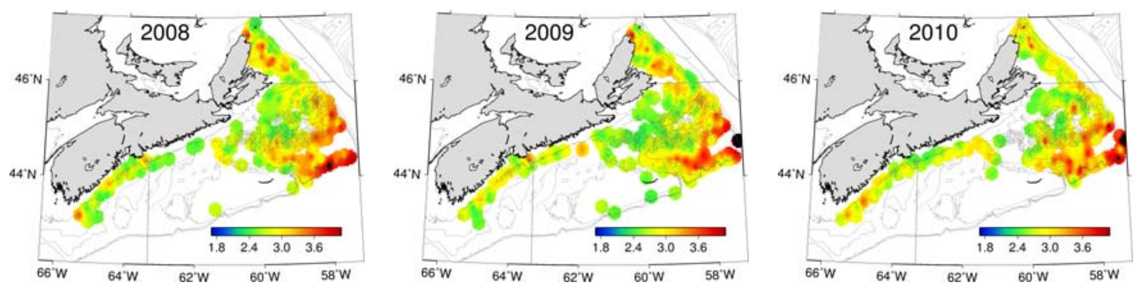


Figure 21: Locations of potential predators of snow crab: thorny skate. Scale is log_{10} (numerical density [number/km^2]).

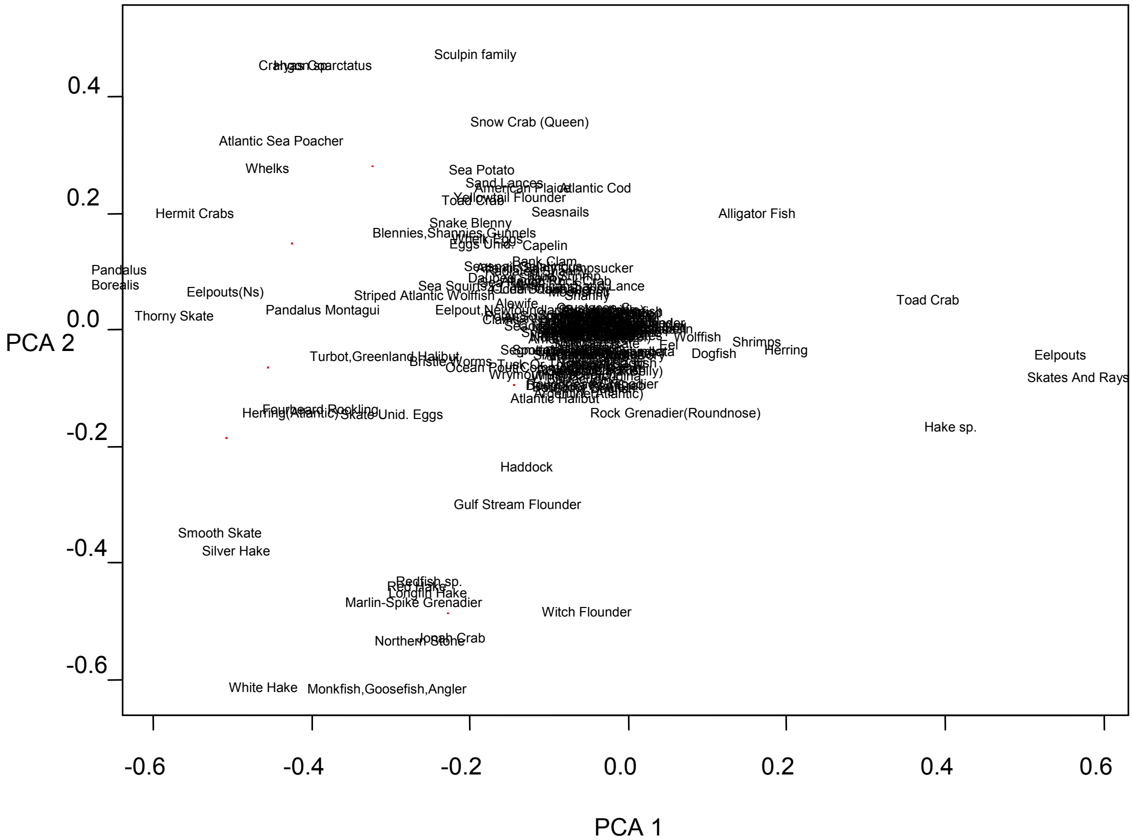


Figure 22: Ordination from a Principle Components Analysis of log-transformed numerical densities based on Pearson correlation matrices.

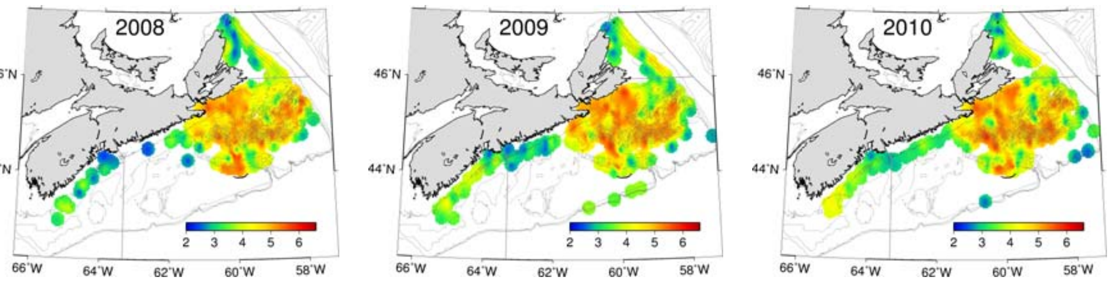


Figure 23: Locations of potential food items of snow crab: northern shrimp. Abundance of these potential food sources roughly match the spatial distributions of snow crab. Scale is $\log_{10}$ (numerical density [number/km^2]).

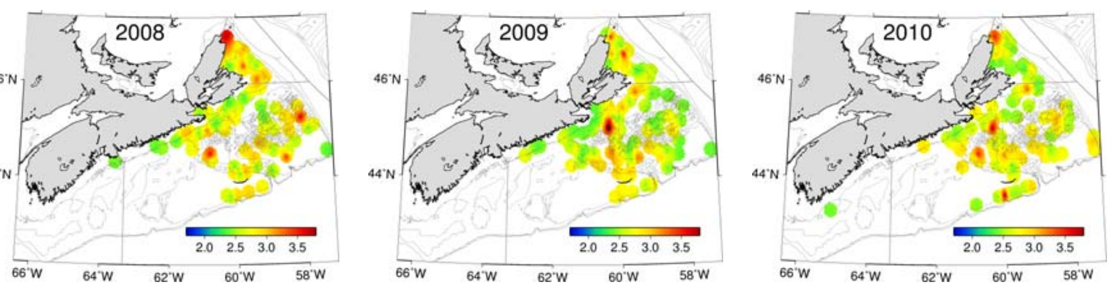


Figure 24: Locations of potential competitors of snow crab: lesser toad crab. High competitive interactions are probable in inshore areas. Scale is $\log_{10}$ (numerical density [number/km^2]).

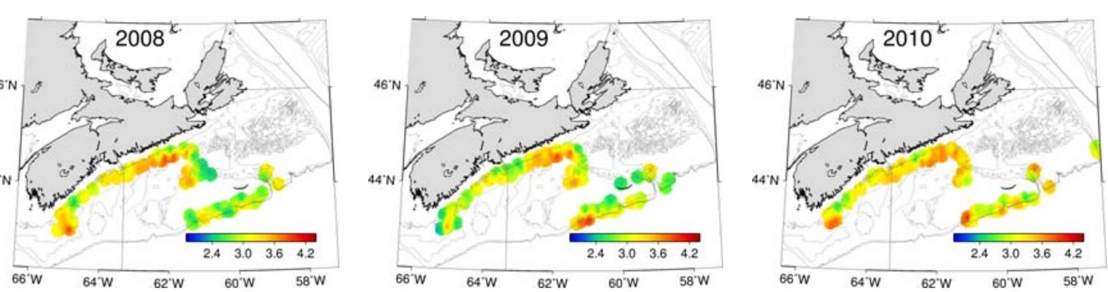


Figure 25: Locations of potential competitors of snow crab: Jonah crab. High competitive interactions are probable in inshore areas. Scale is $\log_{10}$ (numerical density [number/km^2]).

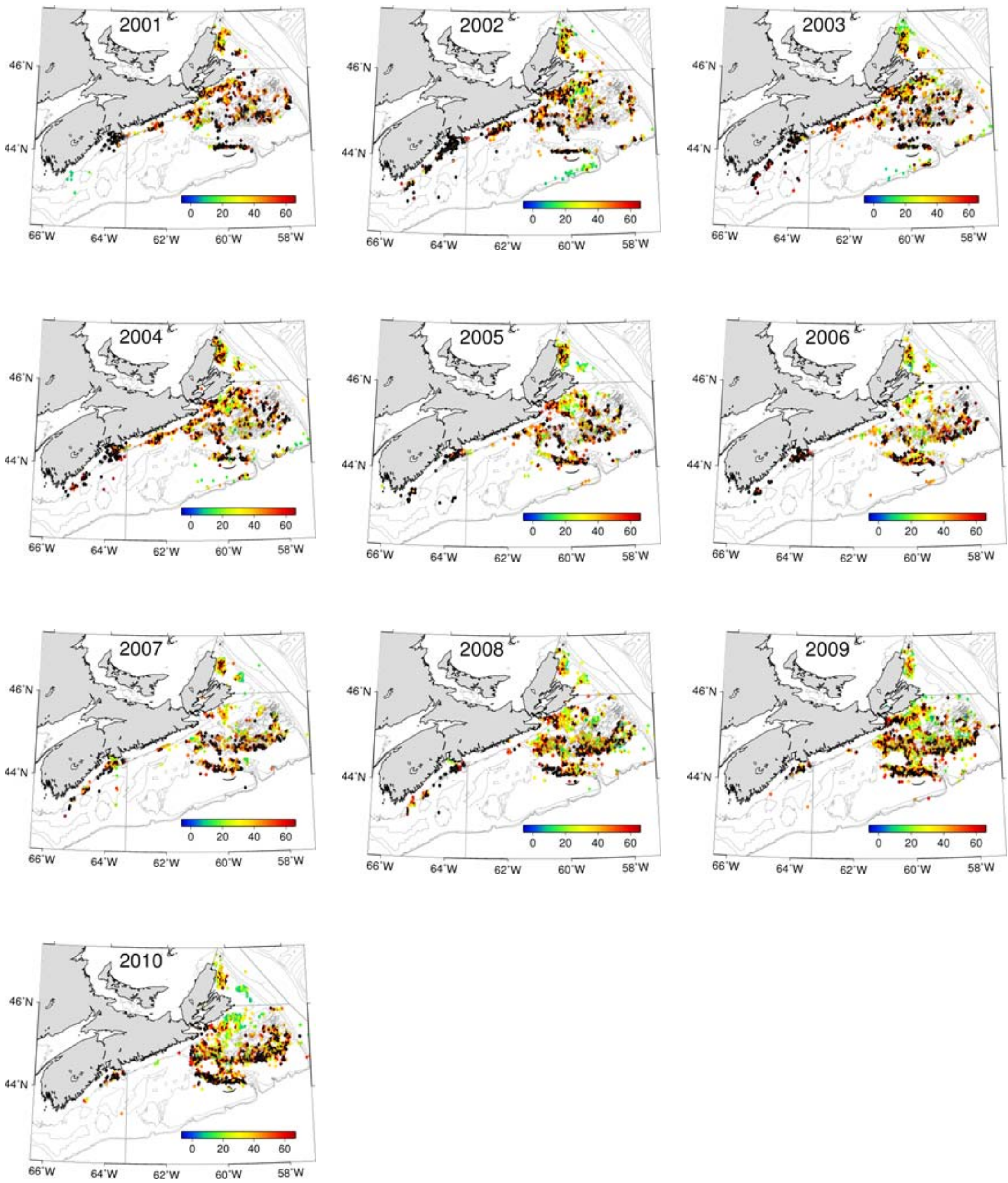


Figure 26: Fishing effort (number of trap hauls / 1 minute grid) from fisheries logbook data. Note the increase in effort offshore and reduction inshore in S-ENS and the return of some fishing activity in the Glace Bay Hole area (offshore) of N-ENS. For CFA 4X, year refers to the starting year.

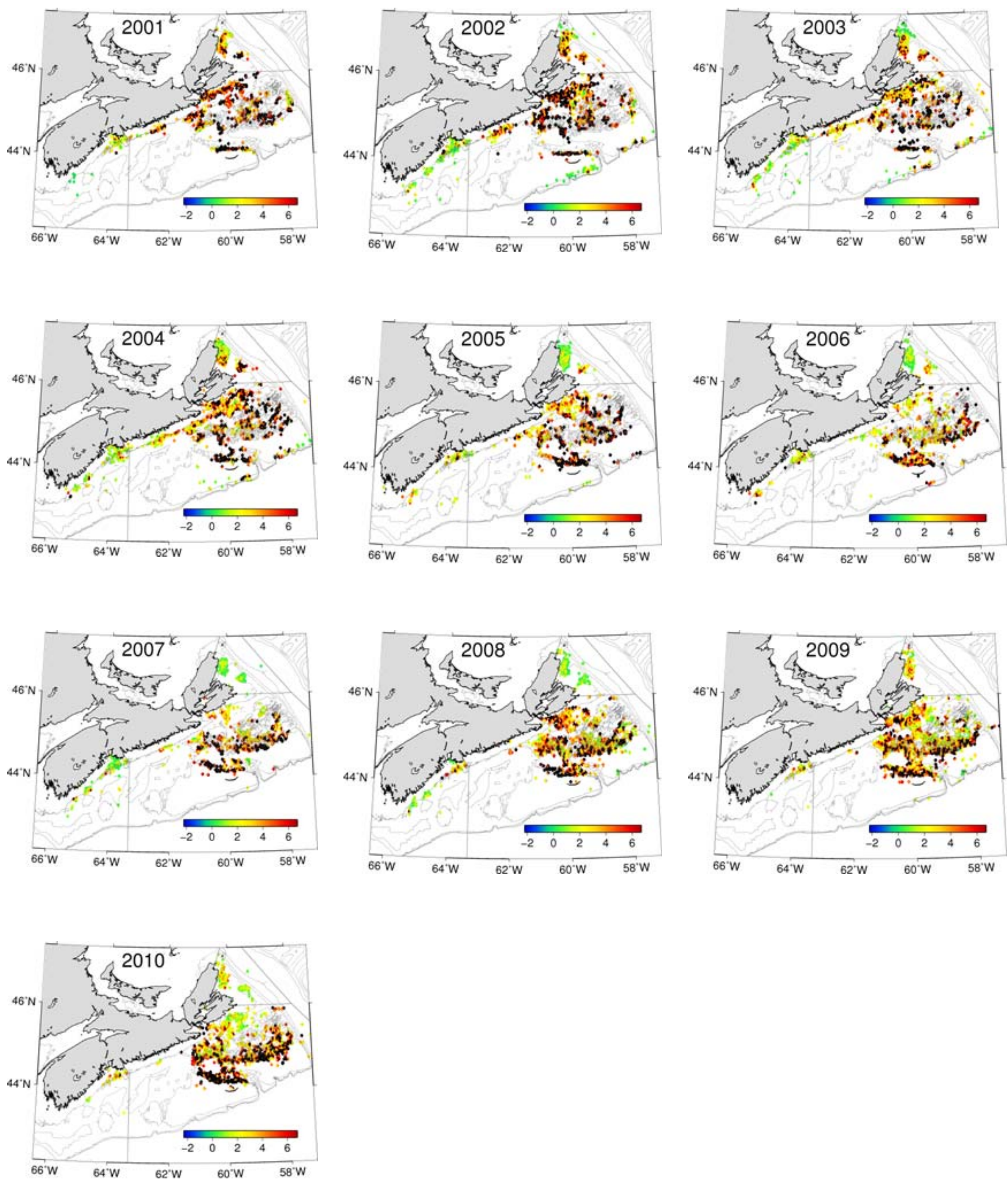


Figure 27: Crab landings (kg / 1 minute grid) from fisheries logbook data. Note the increase in landings offshore and reduction inshore for S-ENS. For CFA 4X, year refers to the starting year.

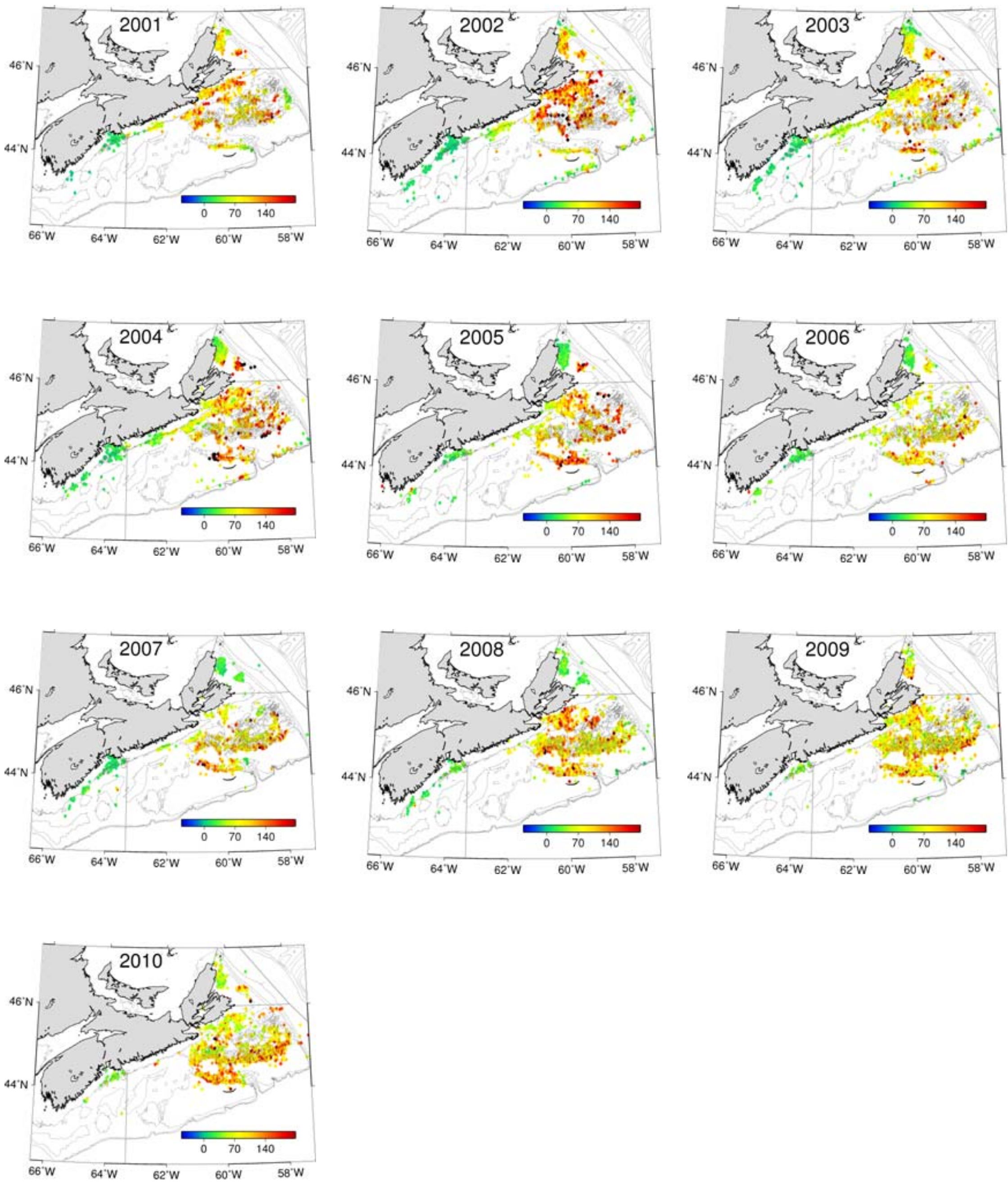


Figure 28: Catch rates (kg trap^{-1}) in each 1 minute grid from logbook data. For CFA 4X, year refers to the starting year.

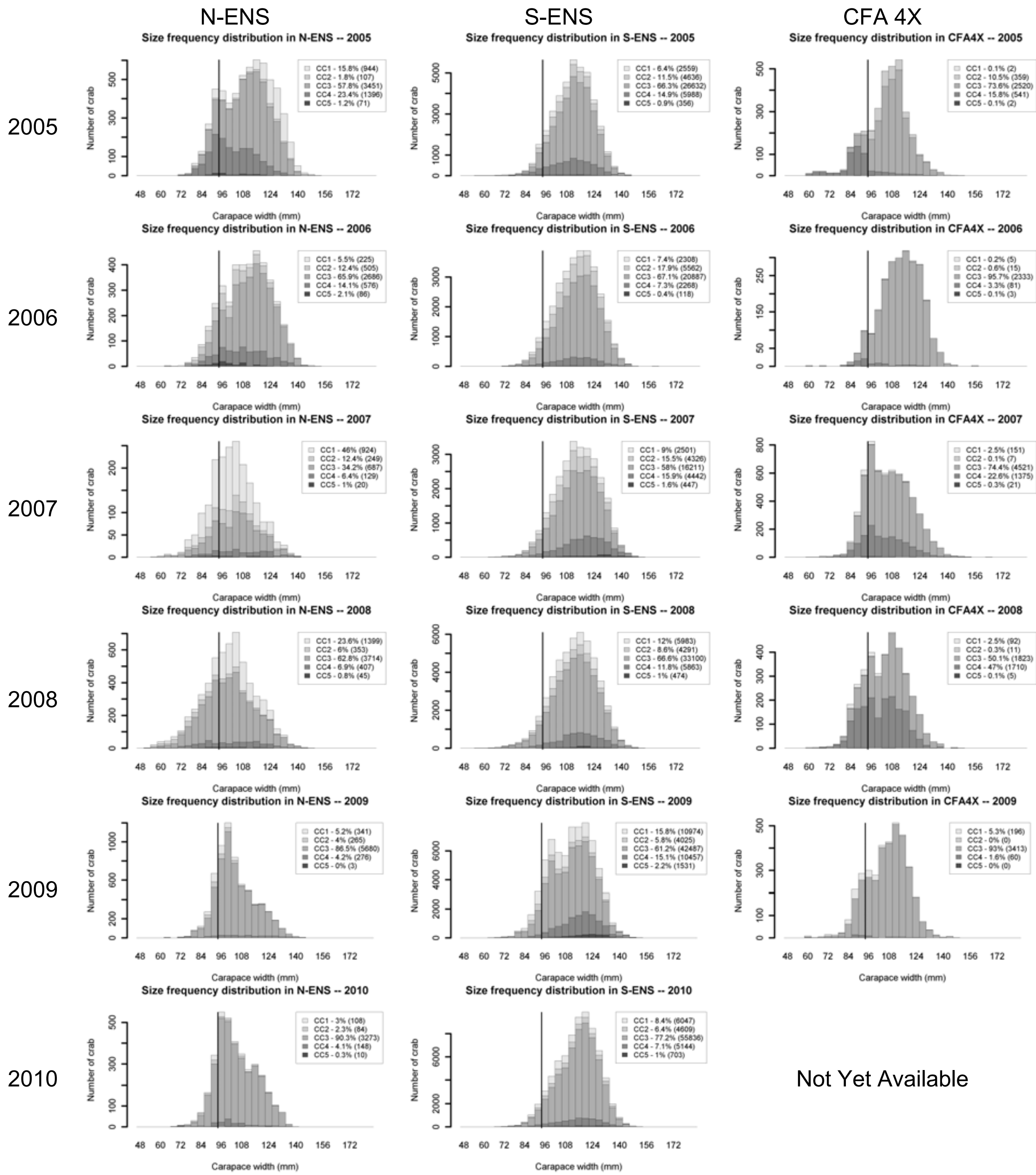


Figure 29: Size frequency distribution of all at-sea-observer monitored snow crab broken down by carapace condition. For CFA 4X, the year refers to the starting year of the season. Vertical lines indicate 95 mm CW.

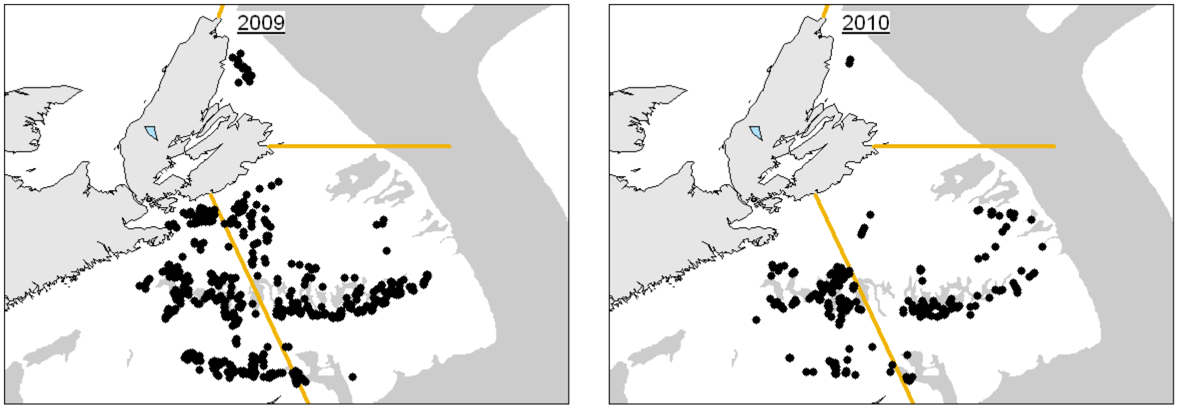


Figure 30: Location of traps sampled by at-sea observers which had 20% or greater soft crab. Lower soft shell catches over the 2010 season are reflected in the reduced number of locations as compared to 2009.

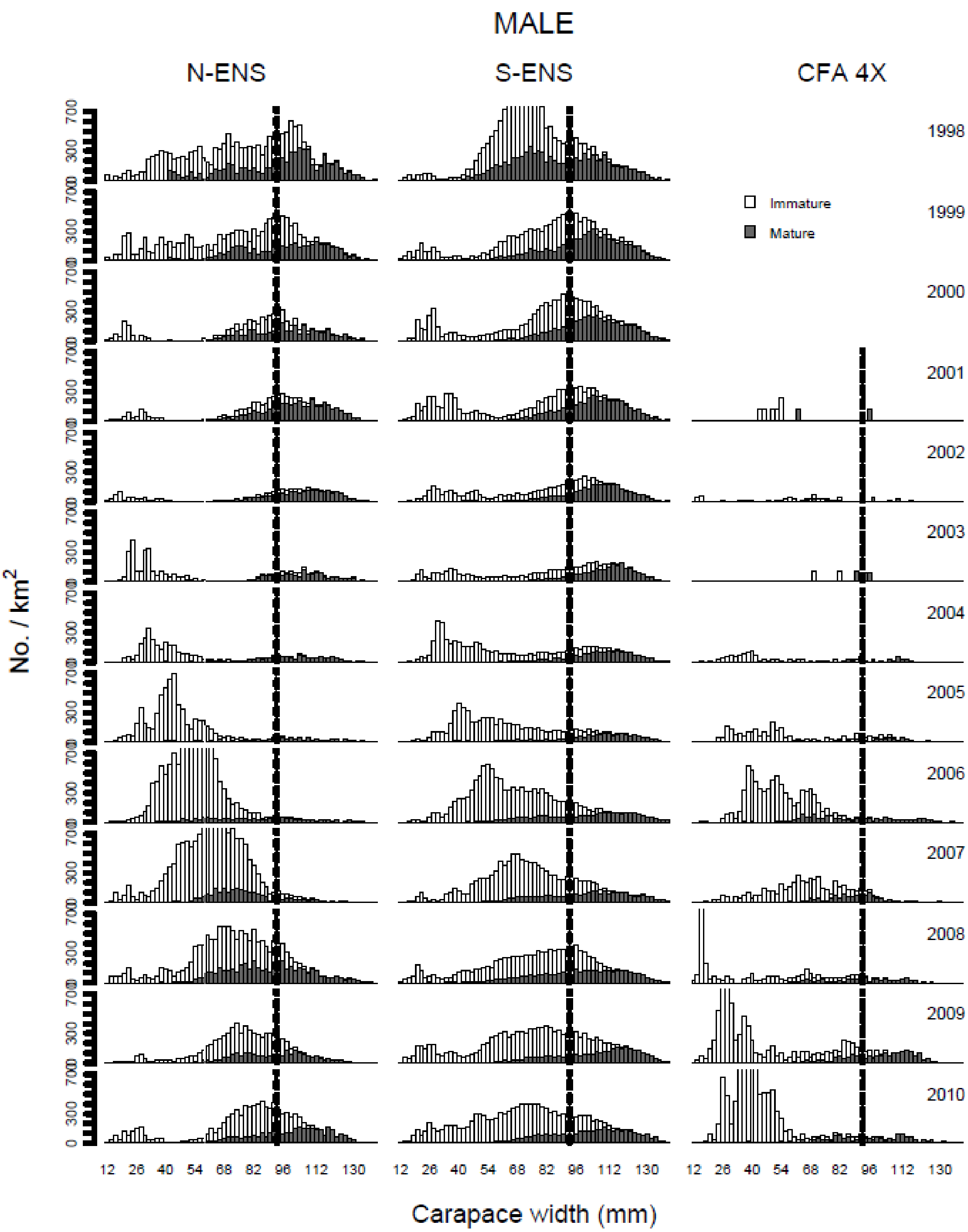


Figure 31: Size-frequency histograms of carapace width of male snow crabs. Note the relatively uniform distribution of adolescent crab across all size classes in S-ENS as compared to other areas and previous patterns in S-ENS. Due to the expansion of the survey from core areas to the full extent of the snow crab grounds, the areal densities of crab in S-ENS and CFA 4X are not directly comparable between all years. For N-ENS, however, the relative heights are comparable. For S-ENS and CFA 4X, 2004 to the present are comparable.

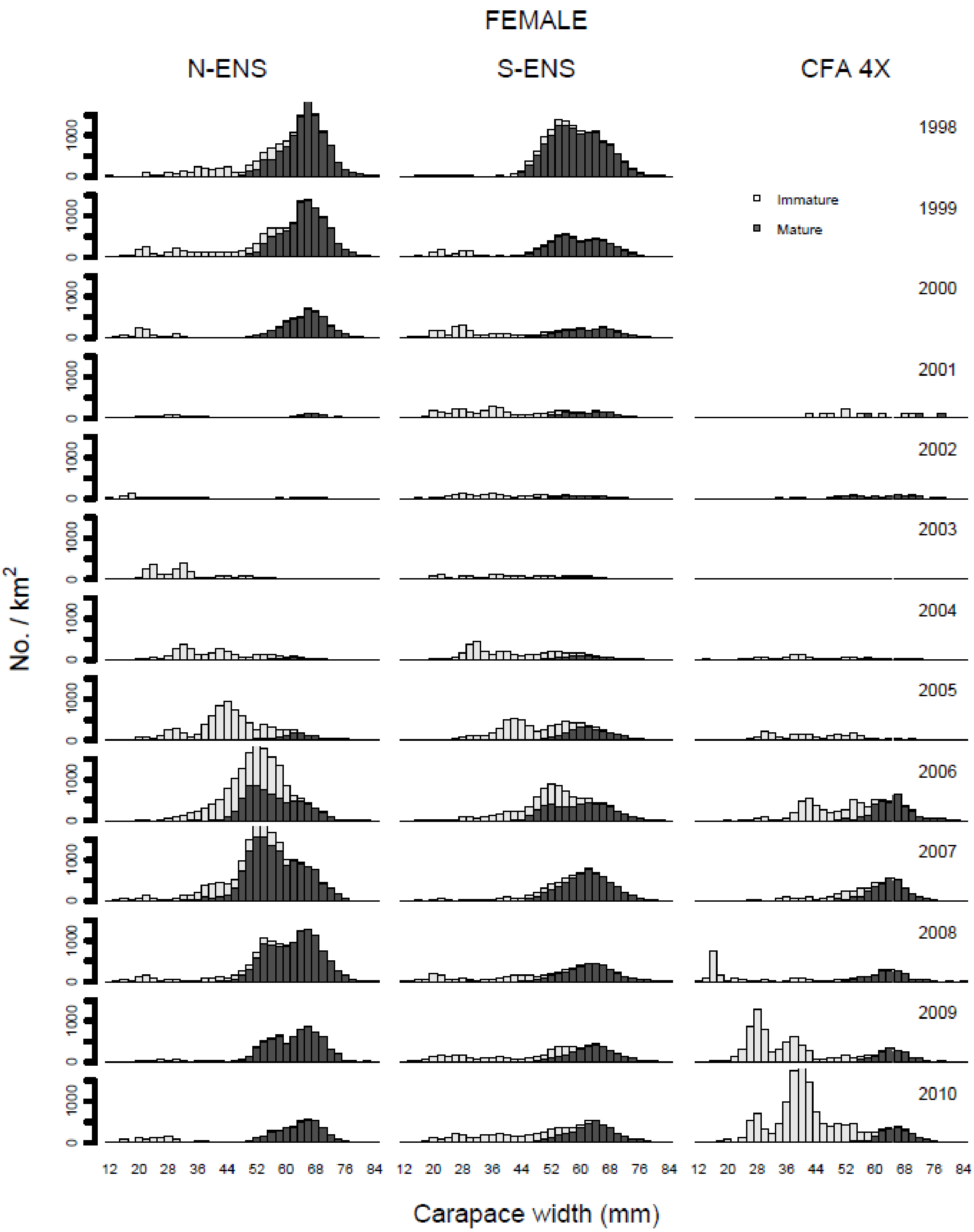


Figure 32: Size-frequency histograms of carapace width of female snow crabs. Note the decrease in mature females in all areas. Due to the expansion of the survey from core areas to the full extent of the snow crab grounds, the areal densities of crab in S-ENS and CFA 4X are not directly comparable between all years. For N-ENS, the relative heights are comparable between all years. For S-ENS and CFA 4X, data from 2004 to the present are comparable.

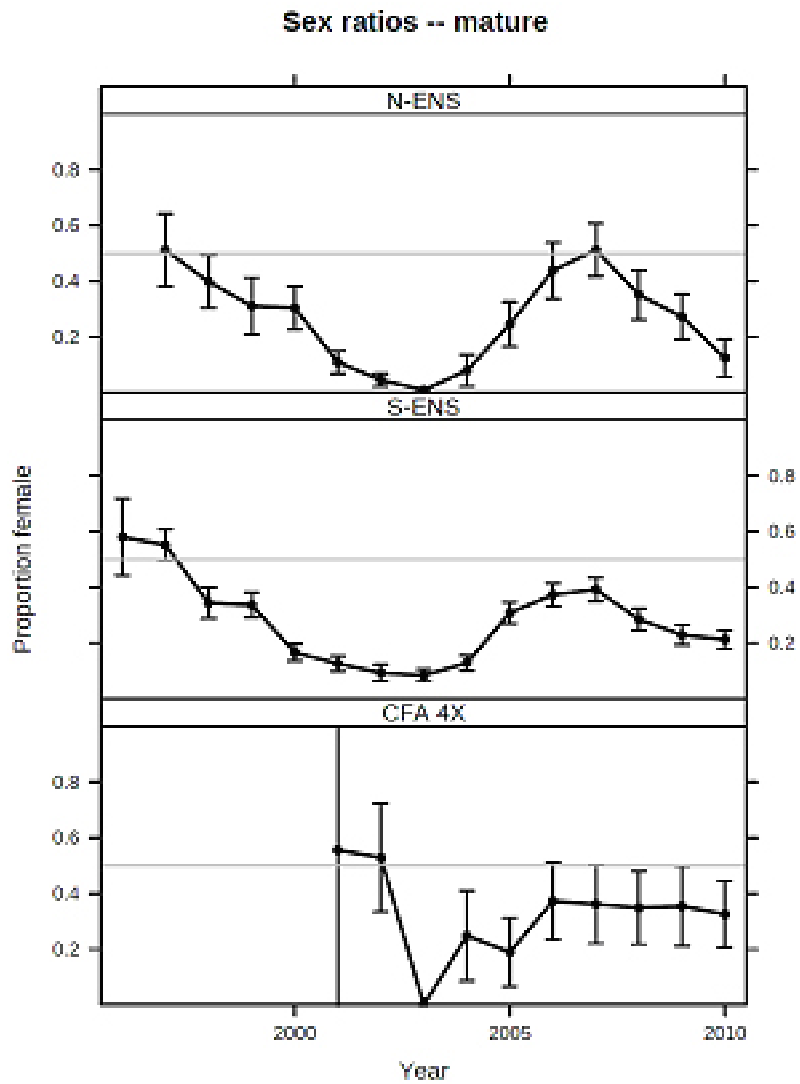


Figure 33: Annual sex ratios (proportion female) of mature snow crab. Since 2000, most of the Scotian Shelf was uniformly male dominated. There has been a decline in the relative proportion of mature female to male crab in both N and S-ENS since peaking in 2007. One standard error bars are presented.

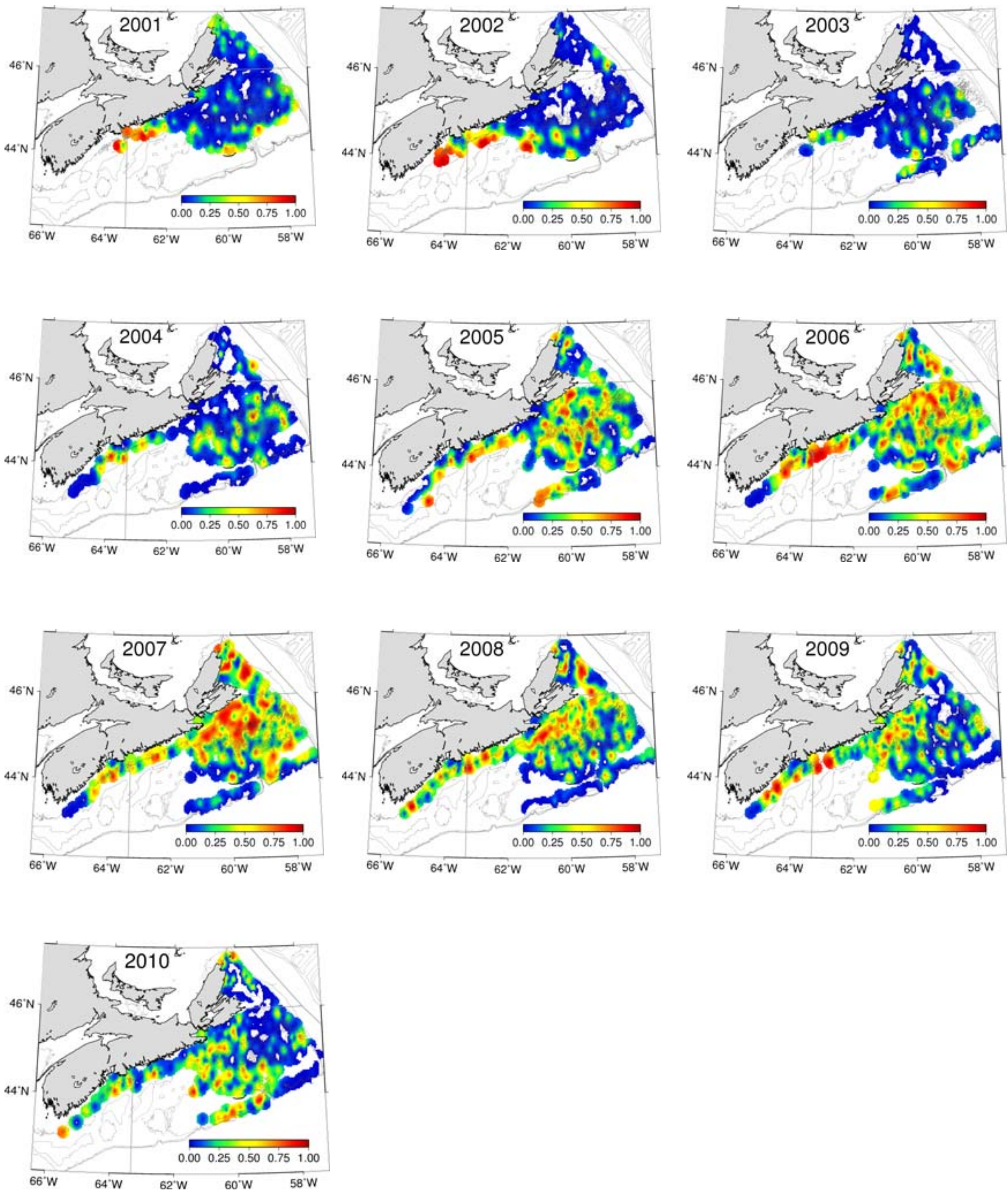


Figure 34: Morphometrically mature sex ratios (proportion female).

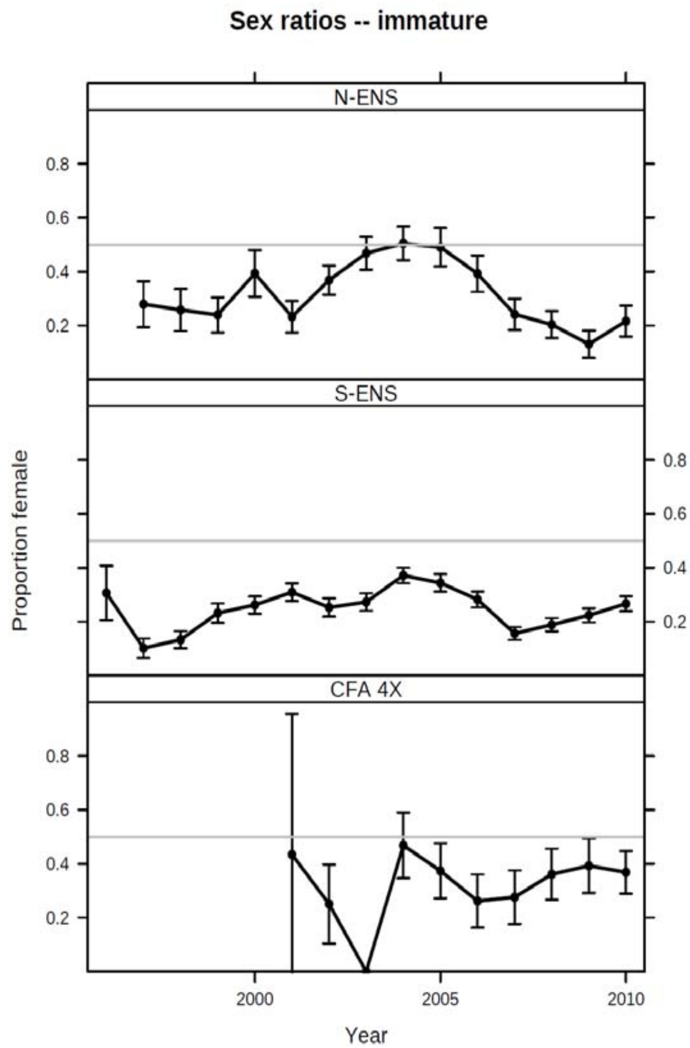


Figure 35: Annual variations in the mean sex ratio (proportion female) for morphometrically immature crabs. One standard error bars are presented.

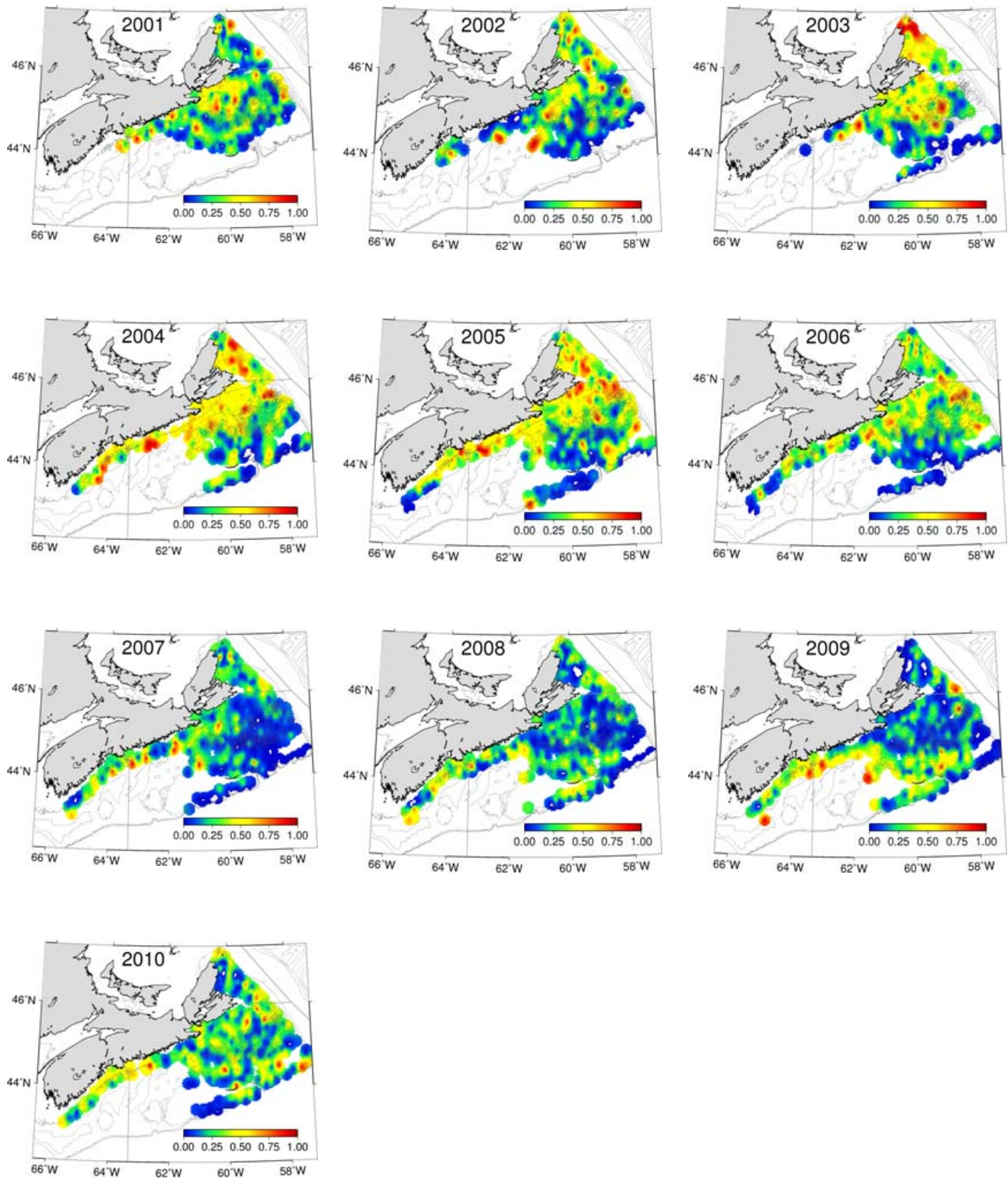


Figure 36: Morphometrically immature sex ratios (proportion female).

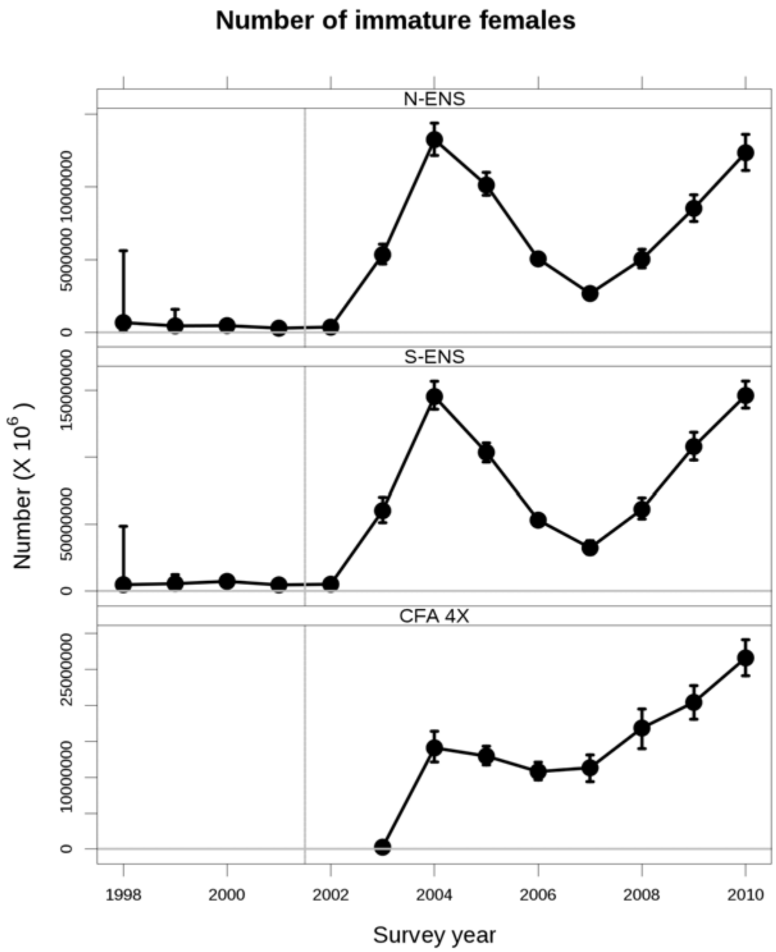


Figure 37: Number of immature females in the SSE.

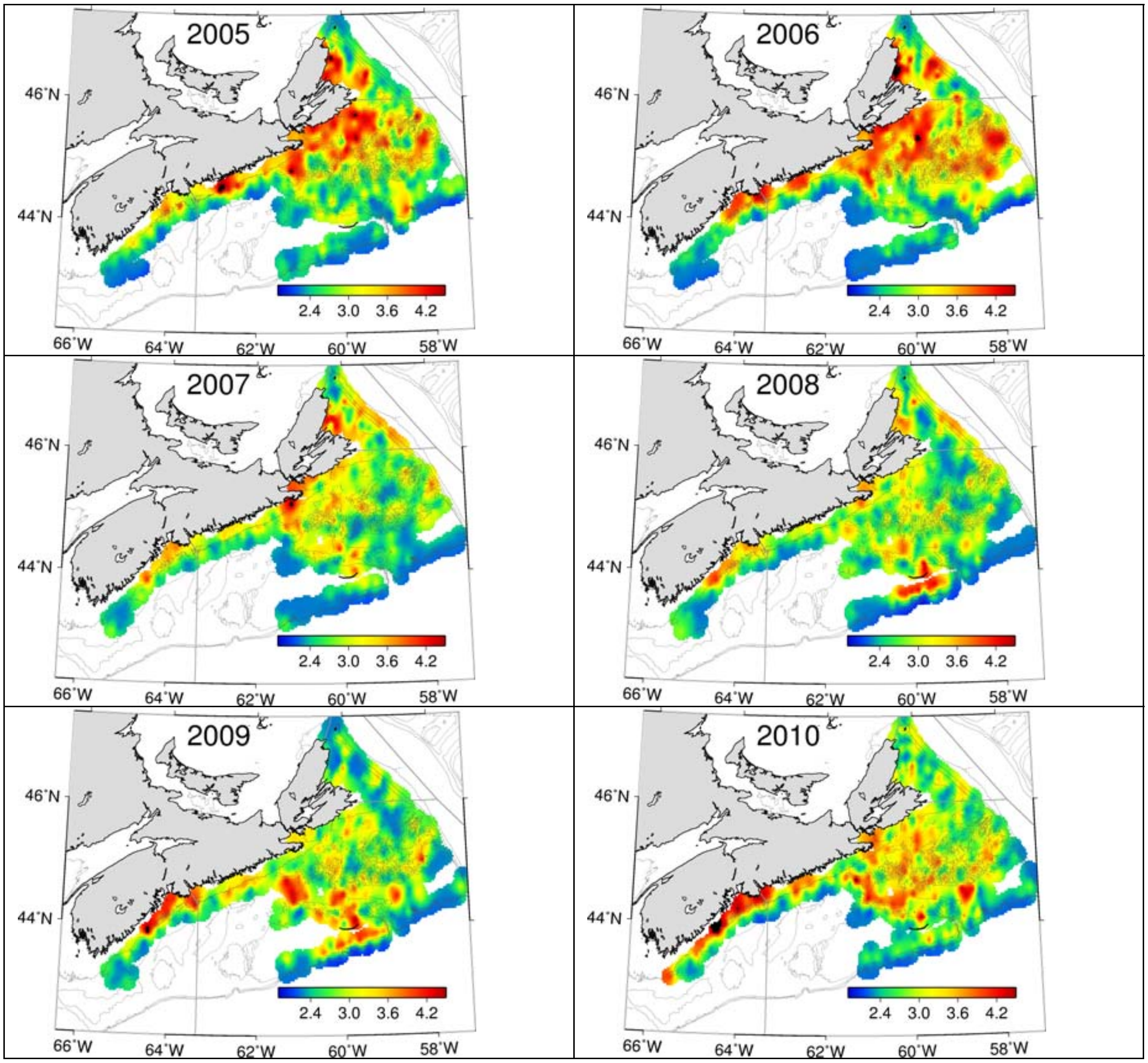


Figure 38: Numerical densities of the immature female snow crabs on the Scotian Shelf; log_{10}(number/km^2).

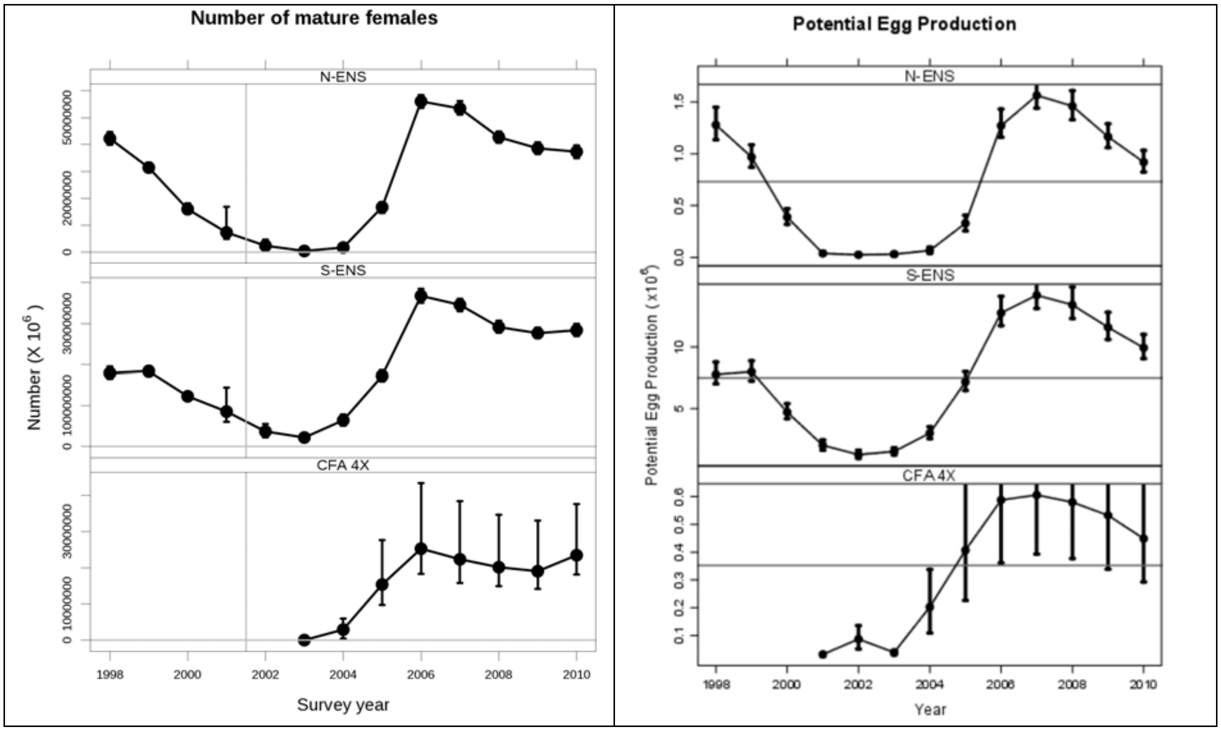


Figure 39: Number of mature females in the SSE (left) and associated estimates of potential egg production (right).

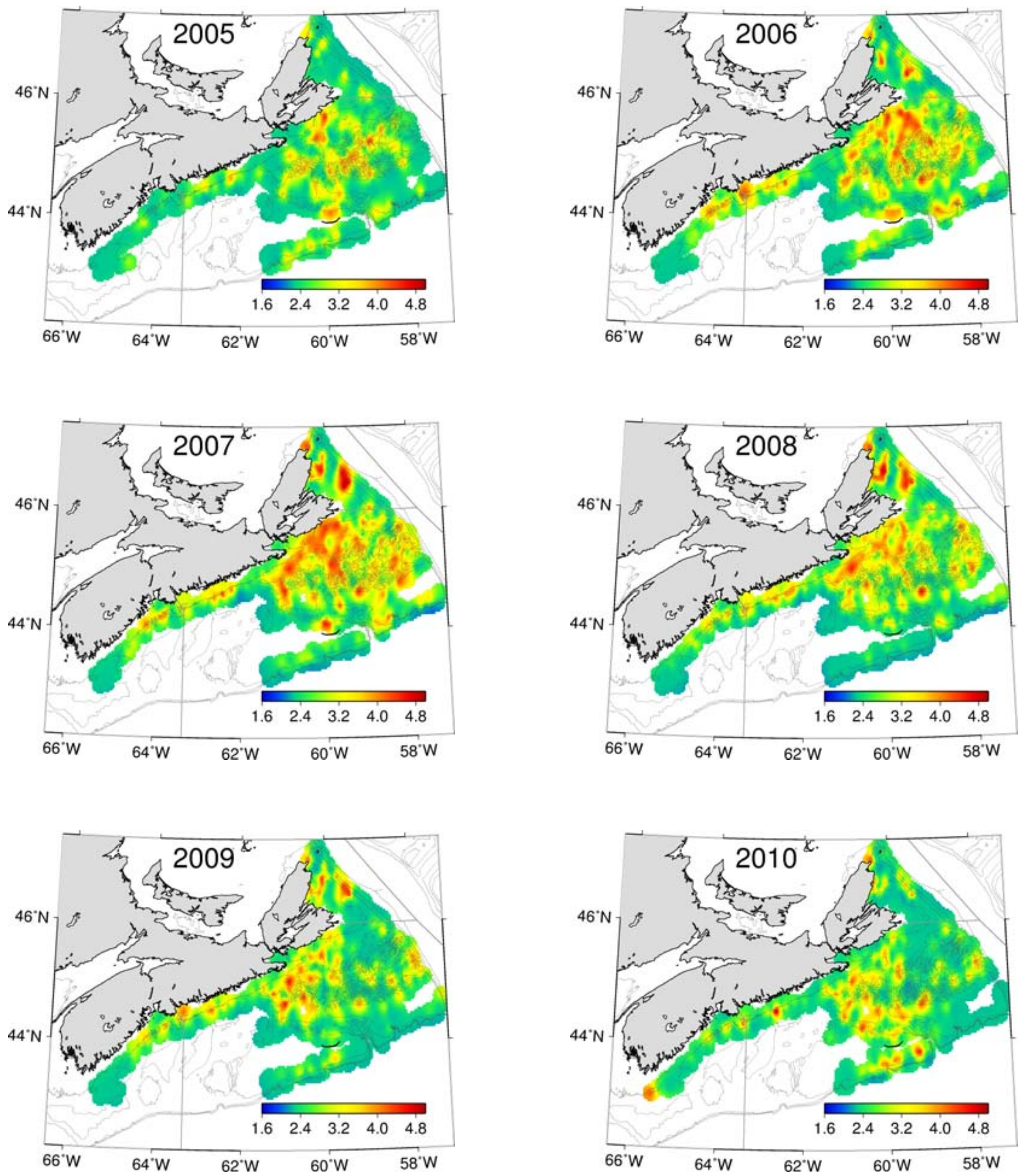


Figure 40: Numerical densities of the berried female snow crabs on the Scotian Shelf; $\log_{10}$ (number/km^2).

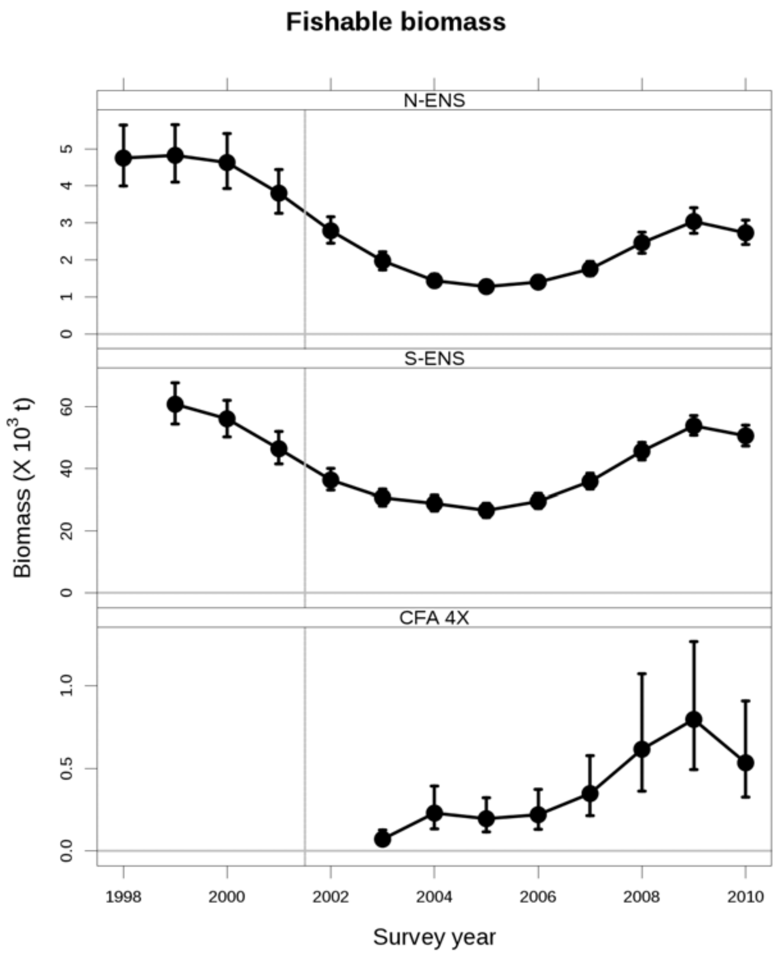


Figure 41: Temporal variations in the fishable biomass index. Error bars are 95% confidence intervals about the estimated total biomass. The vertical line near 2002 indicates the period in which trawl surveys changed from a spring to an autumn sampling period.

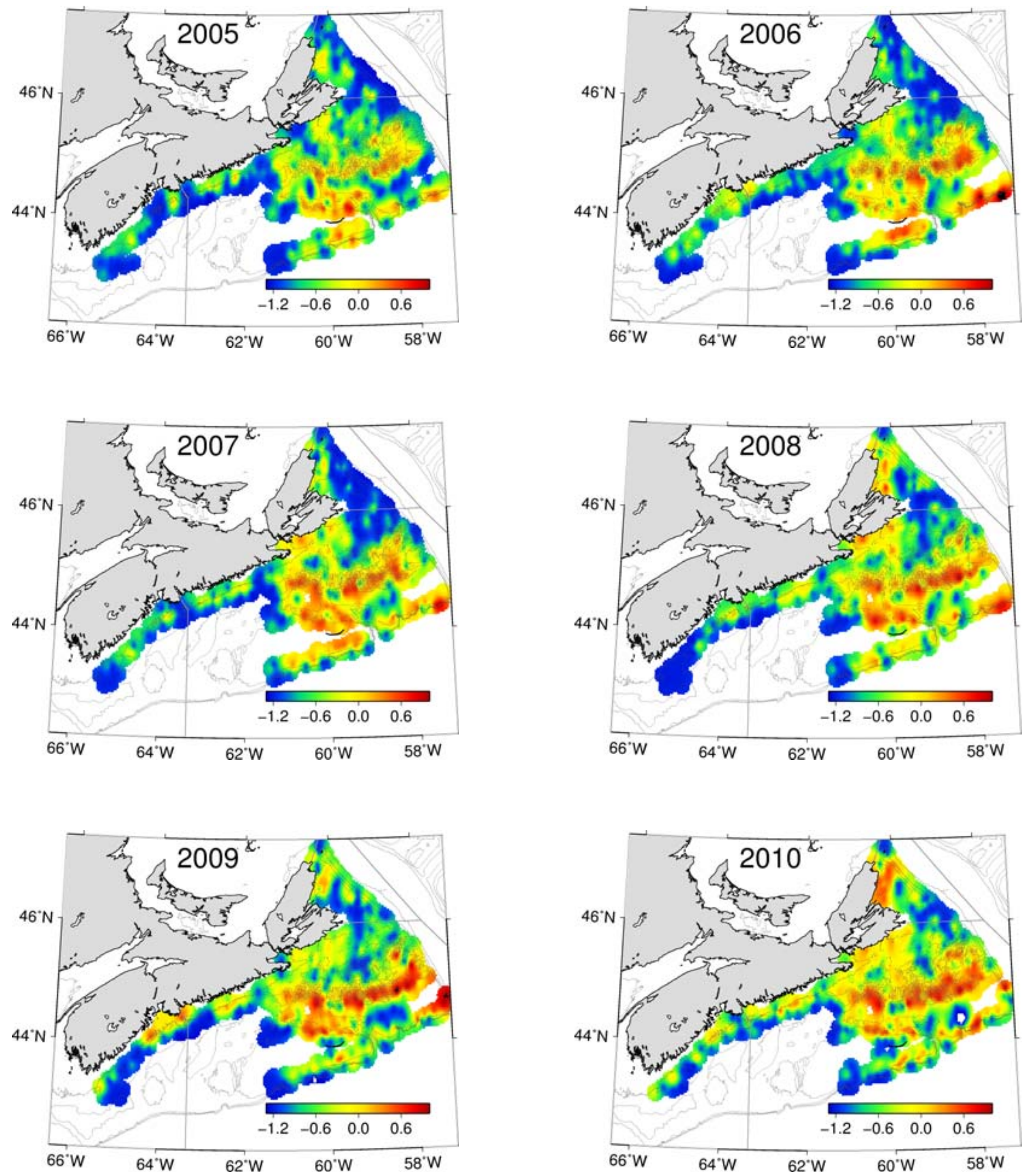


Figure 42: Fishable biomass densities on the Scotian Shelf; log_{10} (t/km^2).

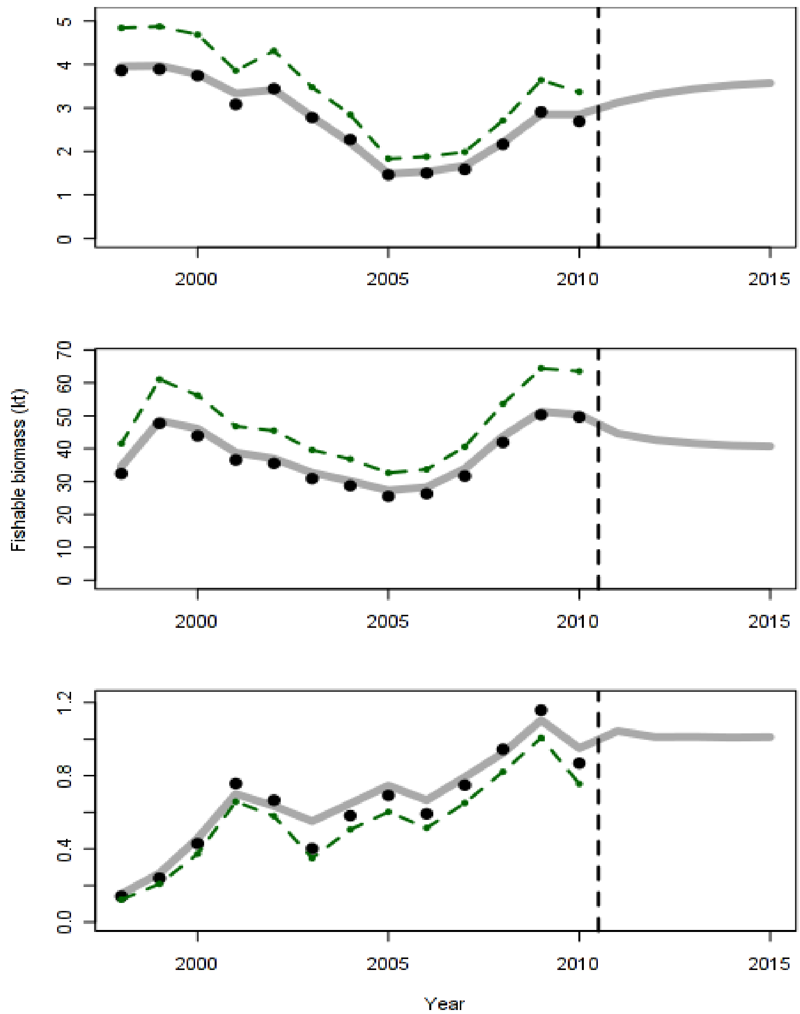


Figure 43: Time-series of the fishable biomass index (green dashed lines) and fishable biomass estimated from the biomass dynamics model (solid gray lines). Catchability-corrected fishable biomass estimates are presented (black dots). A five year projection assuming a constant exploitation strategy of 20% is also provided.

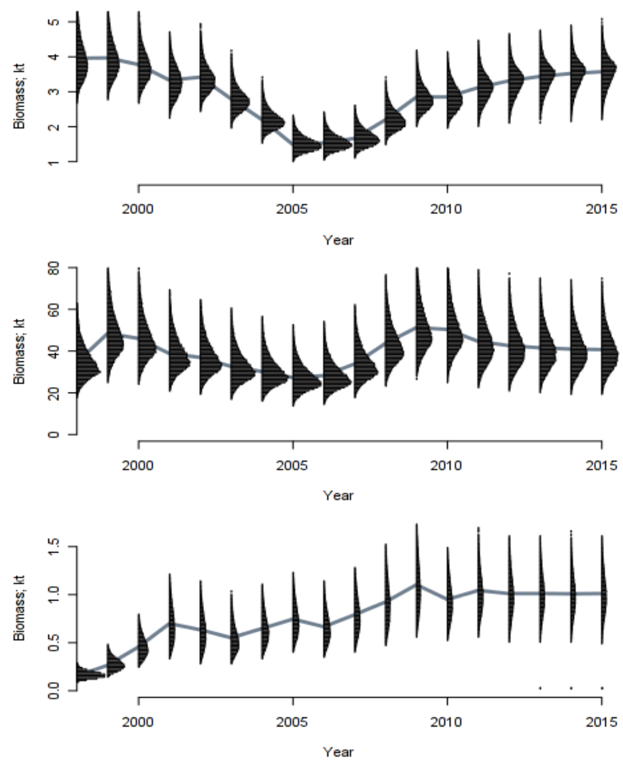


Figure 44: Fishable biomass estimates as a function of year for NENS, SENS and CFA4X, respectively. The posterior density distributions are presented.

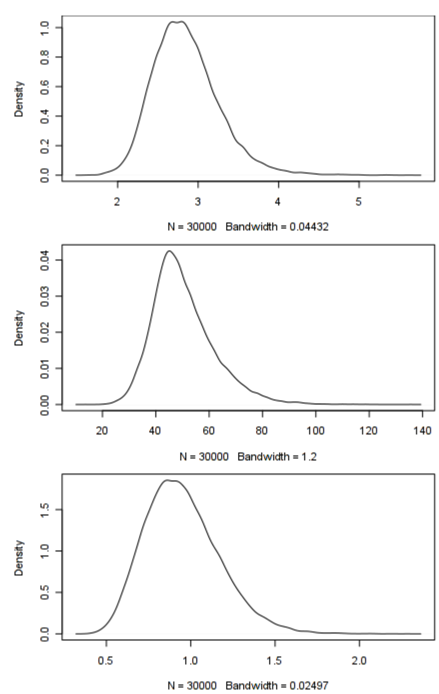


Figure 45: Estimates of fishable biomass in 2010 for NENS, SENS and CFA4X, respectively, from top to bottom. Posterior median estimates were 2.8, 48.5, and 0.93 kt respectively. The 95% CI were, respectively: {2.2, 3.8}, {32.2, 77.9} and {0.59, 1.44} kt.

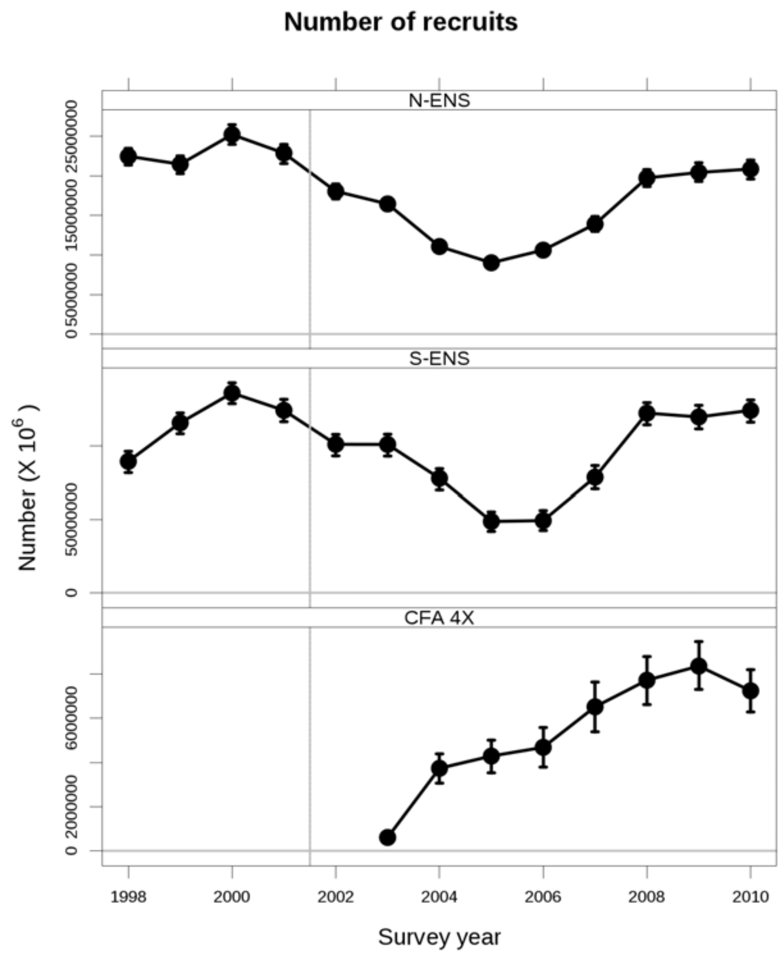


Figure 46: Recruitment into the fishable biomass. As surveys are conducted in the autumn (since 2002/2003), the majority of "recruitment" into the fishable biomass has already occurred. This figure shows the additional recruitment expected that has not yet become part of the fishable biomass. Error bars are 95% confidence intervals 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.

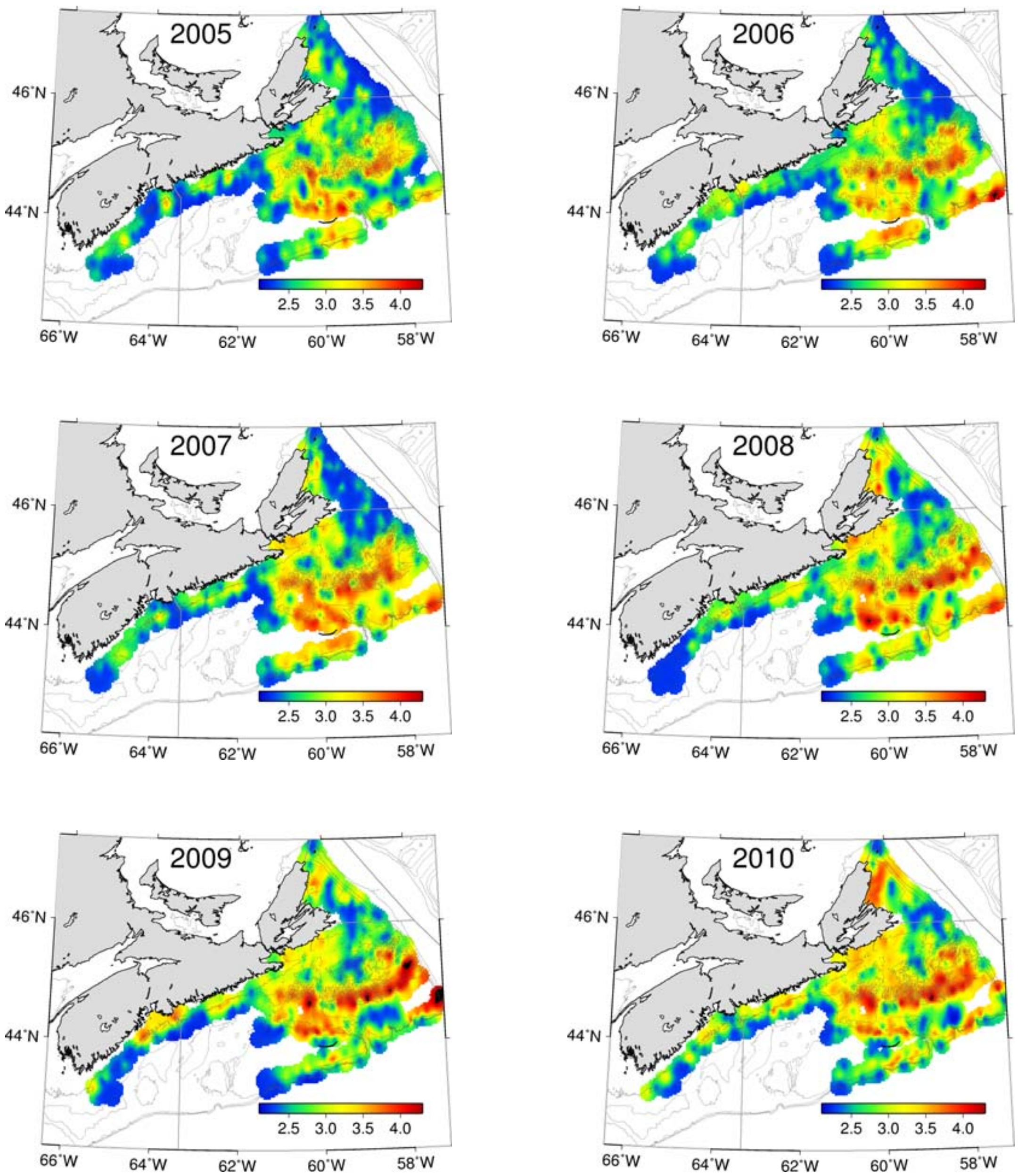


Figure 47: Numerical densities of snow crab recruiting into the next year; log_{10} *(number/km²).*

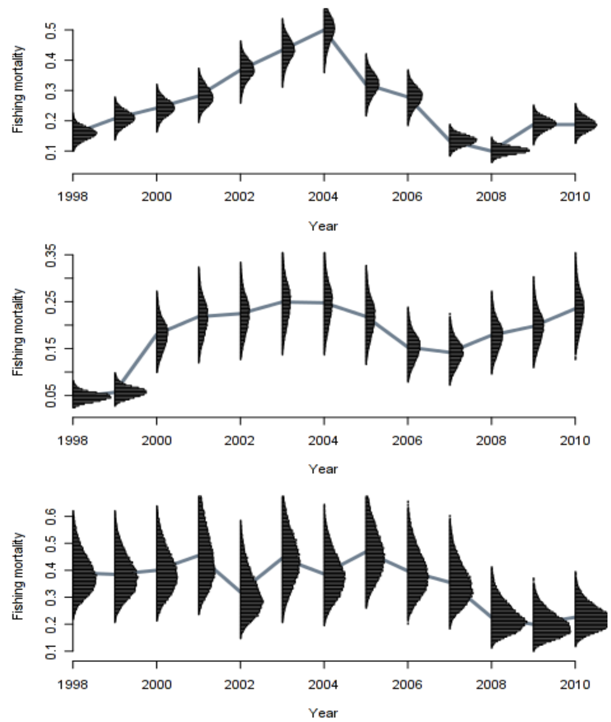


Figure 48: Time-series of fishing mortality for NENS, SENS and CFA4X, respectively. Posterior density distributions are presented.

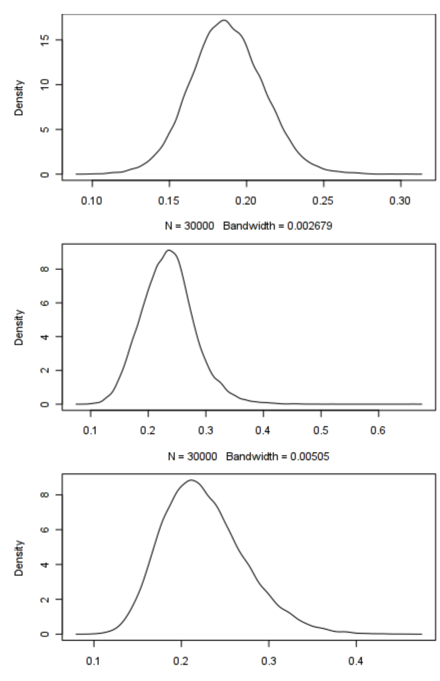


Figure 49: Estimates of fishing mortality in 2010 for NENS, SENS and CFA4X, respectively, from top to bottom. Posterior median estimates were 0.19, 0.23, and 0.22, respectively. The 95% CI were, respectively: {0.14, 0.24}, {0.15, 0.33} and {0.15, 0.33}.

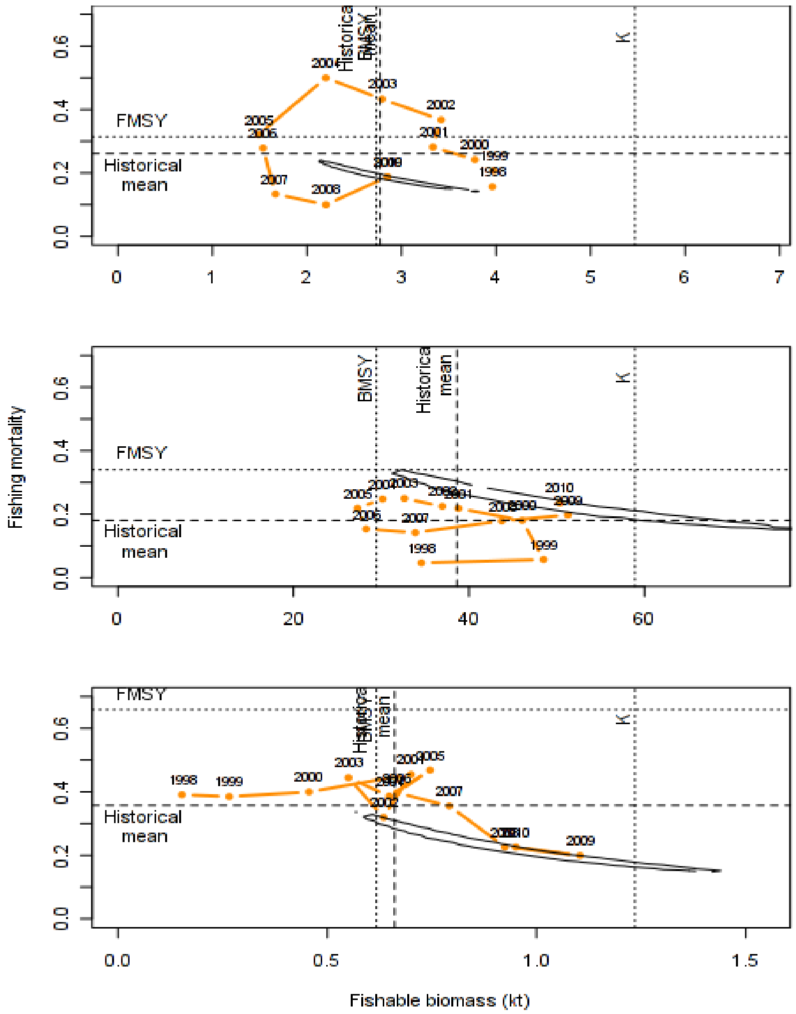


Figure 50: Fishing mortality as a function of fishable biomass for NENS (top), SENS (middle) and CFA4X (bottom). The 95% confidence bounds are presented for the current assessment year.

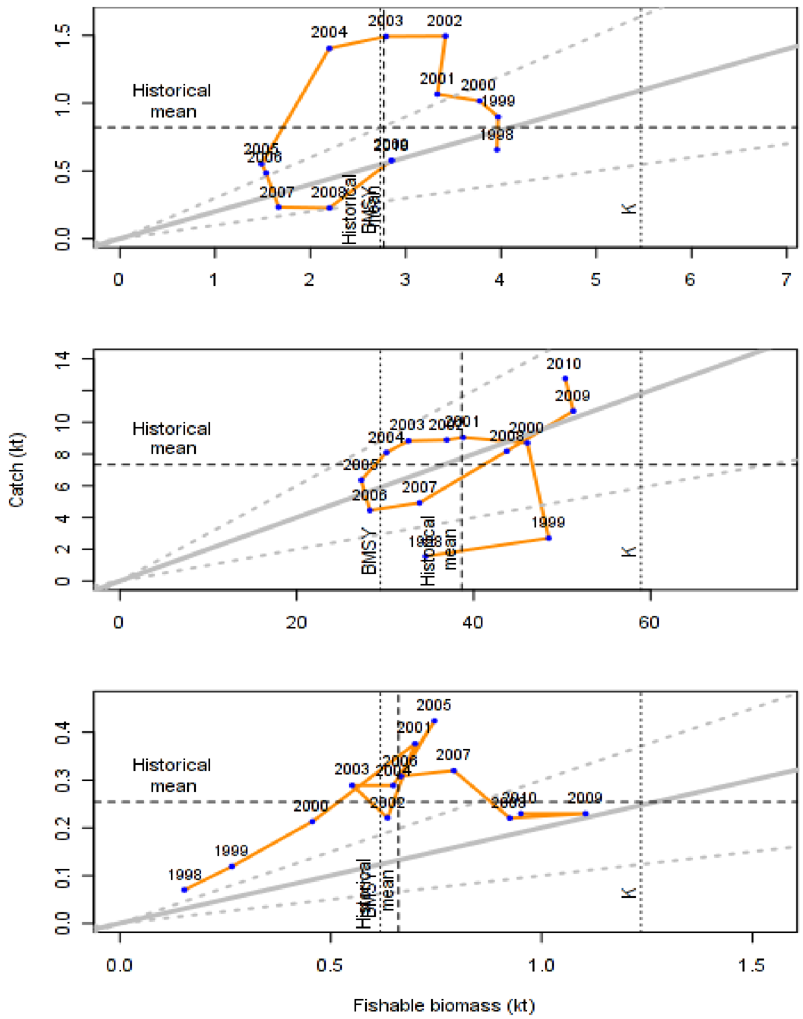


Figure 51: Fishery catch as a function of fishable biomass for NENS (top), SENS (middle) and CFA4X (bottom). Exploitation rates of 20% are indicated by the solid gray line. Bounding this are the lines associated with 10% and 30% exploitation rates, in dashed lines.

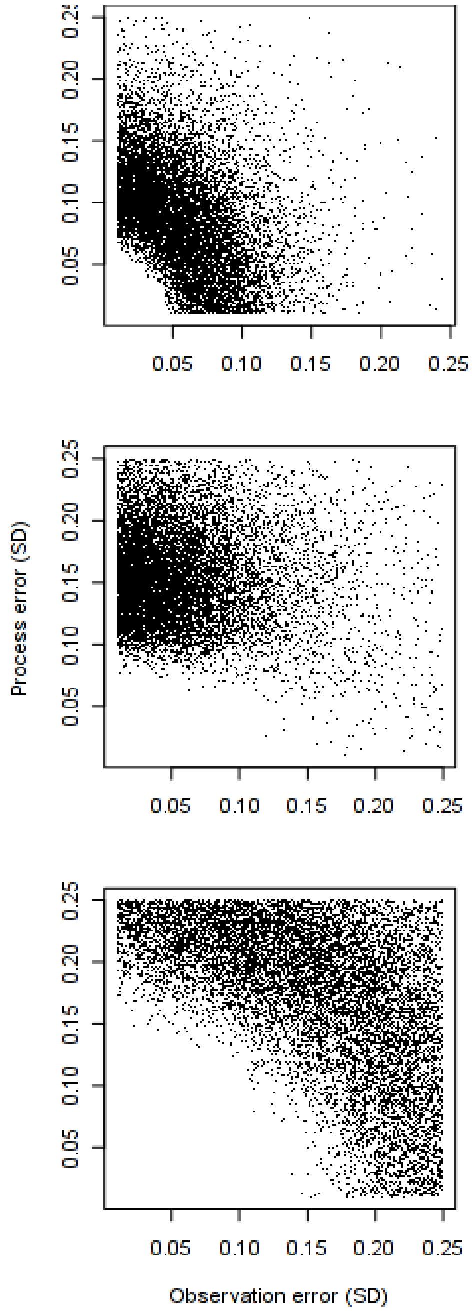


Figure 52: Comparison of model and observation error estimates for NENS, SENS and CFA4X, respectively, from top to bottom. Note that for CFA 4X, these errors are large and greater than the range permitted in the priors. Further studies are required with less severe constraints.

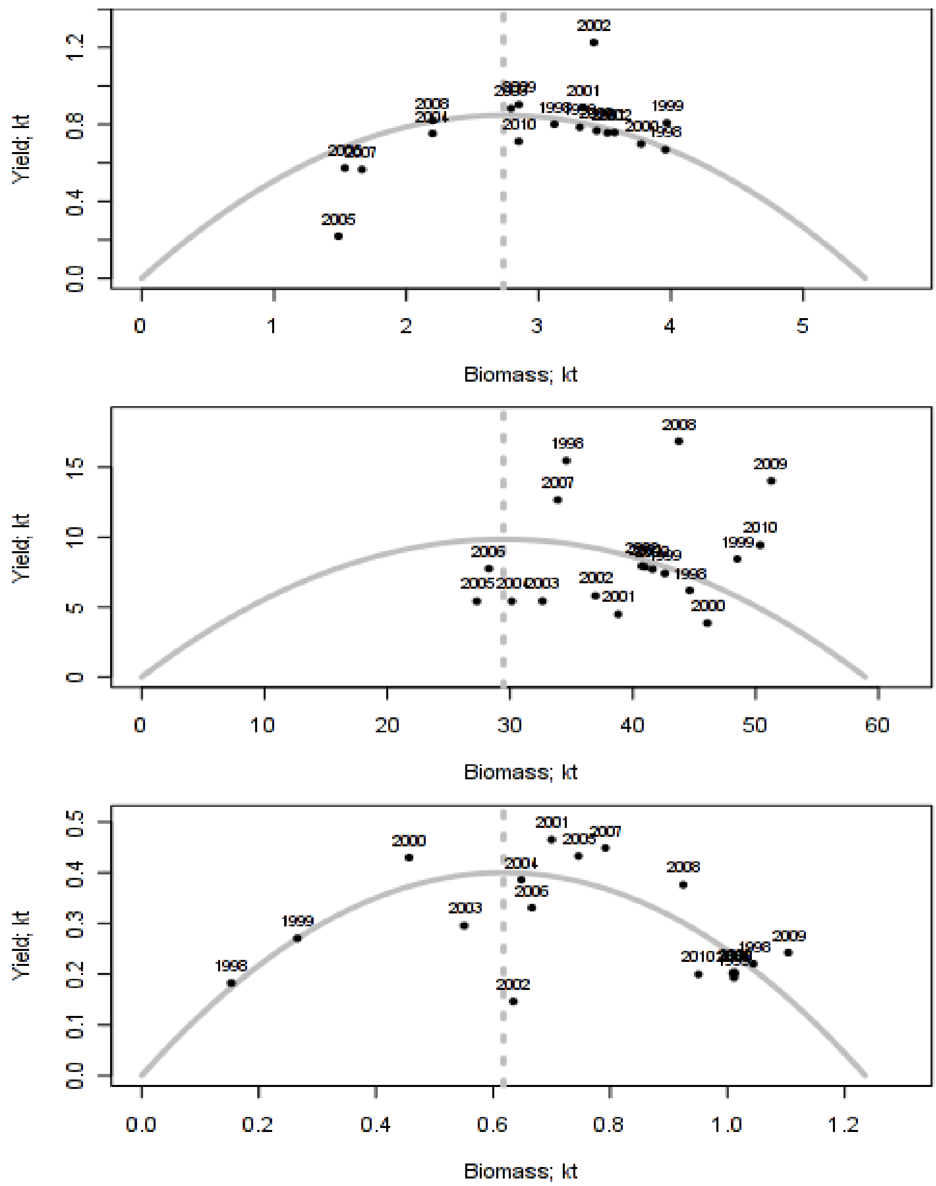


Figure 53: Yield as a function of fishable biomass for NENS, SENS and CFA4X, respectively. The theoretical yield curve for the Schaeffer model is presented.

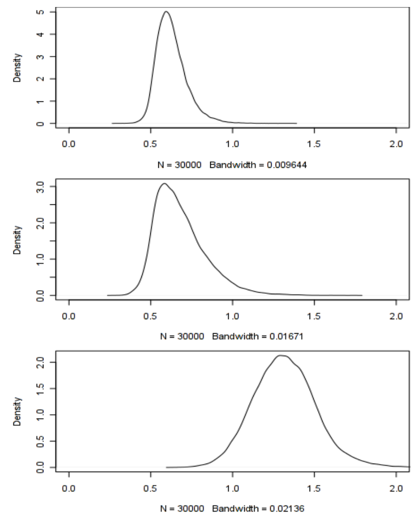


Figure 54: Posterior density distributions of the intrinsic rate of increase of fishable biomass for NENS, SENS and CFA4X, respectively. Posterior median estimates were 0.61, 0.65, and 1.31, respectively. The 95% CI were, respectively: {0.49, 0.85}, {0.46, 1.06} and {0.96, 1.73}.

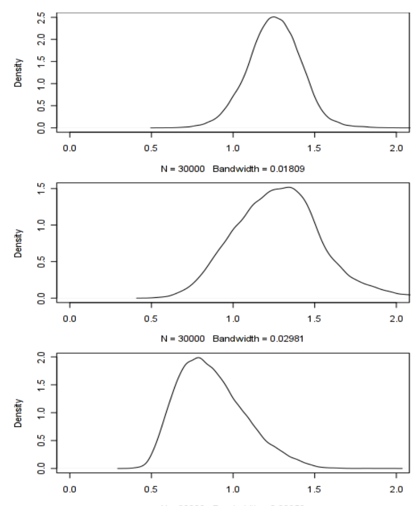


Figure 55: Posterior density distributions of the catchability coefficient for NENS, SENS, and CFA4X, respectively. Posterior median estimates were 1.25, 1.27 and 0.84, respectively. The 95% CI were, respectively: {0.93, 1.56}, {0.79, 1.87} and {0.55, 1.33}.

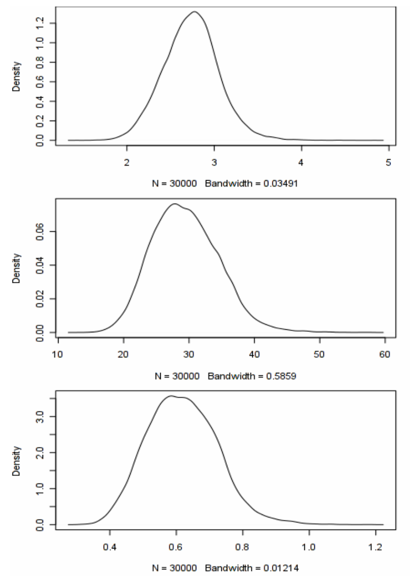


Figure 56: Posterior density distributions of BMSY for NENS, SENS, and CFA4X, respectively. Posterior median estimates were 2.7, 29.1, and 0.6, respectively. The 95% CI were, respectively: {2.1, 3.4}, {20.5, 40.1} and {0.43, 0.84}.

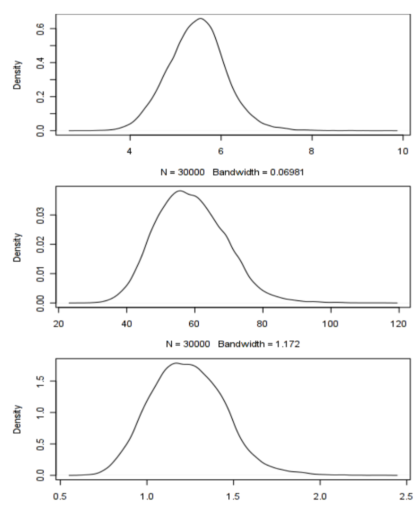


Figure 57: Posterior density distributions of the carrying capacity of the fishable biomass (K) for NENS, SENS and CFA 4X, respectively. Posterior median estimates were 5.5, 58.3, and 1.2 kt, respectively. The 95% CI were, respectively: {4.1, 6.8}, {41.1, 80.3} and {0.85, 1.68} kt.

GLOSSARY

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

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

Benthic – Occurring on the ocean floor.

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

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.

CC, Carapace Condition – The condition of the shell of a snow crab. Generally related to the age of the organism and the time since last moult. See Table 5 for more details.
CC1 - Newly moulted 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.

CW, Carapace width – the distance across the carapace of a snow crab (millimetres)

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

CFA, Crab fishing area – 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.

CPUE, Catch per unit effort – 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 NAFO statistical divisions 4VW).

ER, Exploitation rate – The ratio of biomass fished relative to their abundance. Historically, the GFC calculated ER(t) = Landings(t) / Fishable biomass (t-1), where t is time or year. The Fishable biomass was of the mature segment of the male population ≥ 95 mm CW, estimated from kriging. In this document, the exploitation rate is calculated as ER(t) = Landings(t) / (Landings(t) + Fishable biomass(t)). This change was made as the the time interval between the end of trawl surveys [Biomass(t-1)] and the beginning of fishing [Landings(t)] was up to 10 months. With the alternate method, this lag is approximately 2 months and so likely more accurate.

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 (Carapace conditions 2 to 5). Note that Carapace condition 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, relative – see Exploitation rate.

IBQ – Individual Boat Quota, 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 moults.

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 moult), 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.

Moult – 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 moulted. The final growth increment is estimated to increase the body weight by approximately 250%.

Physiological maturity – Biologically (functionally) able to reproduce.

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

Recruitment – Snow crab that will 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).

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

TAC – Total Allowable Catch, 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 moult – Snow crab moulted for a final time once mature. The size of these crab will not increase further.

Variogram – The manner in which the variability of data changes with distance from a given location. Empirical variograms depict the data-derived variation as a function of distance. Theoretical/modelled variograms are fitted curves which are ultimately used by the kriging methodology.

APPENDIX 1: Ecosystem Indicators

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

NS: Population size	Total population size for Nova Scotia, a proxy of the influence of human of 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 colour, 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 teleconnections, even broader-scale forcings.
No. fish harvesters	Number of fish harvesters in Nova Scotia
No. shellfish closures	Number of shellfish closures
No. wells drilled	Number of oil and gas wells drilled on the Scotian Shelf
NS: % 65 and older	Nova Scotia demographics
NS: % attending university	Nova Scotia demographics
PCBs: puffins	PCB concentrations in Atlantic puffins
PCBs: seals	PCB concentrations in Grey seals
RV: biomass capelin	Research survey estimates of capelin biomass
RV: biomass cod	Research survey estimates of cod
RV: biomass elasmobranchs	Research survey estimates of elasmobranch fish
RV: biomass flatfish	Research survey estimates flatfish
RV: biomass gadoids	Research survey estimates gadoids
RV: biomass large demersals	Research survey estimates large demersal fish
RV: biomass large pelagics	Research survey estimates large pelagic fish
RV: biomass small demersals	Research survey estimates of small demersal fish

RV: biomass small pelagics	Research survey estimates small pelagic fish
RV: bottom oxygen	Research survey estimates of bottom oxygen concentration
RV: bottom salinity	Research survey estimates bottom salinity
RV: bottom temperature	Research survey estimates bottom temperature
RV: condition elasmobranchs	Research survey estimates of elasmobranch physiological condition
RV: condition flatfish	Research survey estimates of flatfish physiological condition
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 km2	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 (100km)	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: BUGS Assessment Model

There seems to be an unwritten rule where the code used for Bayesian analysis are provided in stock assessment documents. The following is the BUGS code written in the JAGS dialect to estimate the parameters of the biomass dynamics model. For more code, see also:

http://sites.google.com/site/autocatalysis/snowcrabanalysis/

```
parameters:
    b0x = c(0.8, 0.6, 0.1)  # biomass initial, scaled to K
    q0x = c(1, 1, 1)  # catchability
    r0x = c(1, 1, 1)  # intrinsic rate of increase
    K0x = c(5, 50, 1) # carrying capacity estimate
    O = surplus.production.db( "B" )  # observed index of abundance
    C = landings      # catches
    sigma = 1/4       # upper bound of lognormal sd (~ CV 0f 25%)
    cv = 1/2          # range of variation to consider for hyperpriors of scale
    er = 0.2          # target exploitation rate
    nProj = 5         # no years for prediction scenarios

data {
  Odim <- dim(O)
  N <- Odim[1] # no years with data
  R <- Odim[2] # number of regions
  M <- nProj   # no years for projections
  eps <- 1e-4  # small non-zero number
}

model {
  # -------------------
  # hyperpriors of scale and precision terms
  for (j in 1:R) {
    sd.q[j] ~ dunif( 0.01, sigma )
    sd.p[j] ~ dunif( 0.01, sigma )
    sd.r[j] ~ dunif( 0.01, sigma )
    sd.K[j] ~ dunif( 0.01, sigma )
    sd.o[j] ~ dunif( 0.01, sigma ) # uninformative observation error -- same scale as with K
    b0[j]   ~ dunif( b0x[j]*(1-cv), b0x[j]*(1+cv) )
    K0[j]   ~ dunif( K0x[j]*(1-cv), K0x[j]*(1+cv) )
    r0[j]   ~ dunif( r0x[j]*(1-cv), r0x[j]*(1+cv) )
    q0[j]   ~ dunif( q0x[j]*(1-cv), q0x[j]*(1+cv) )
  }

  # -------------------
  # priors of key stochastic nodes for estimation
  for (j in 1:R) {
    q[j] ~ dlnorm( log(q0[j]), pow( sd.q[j] , -2 ) )
    r[j] ~ dlnorm( log(r0[j]), pow( sd.r[j] , -2 ) )
    K[j] ~ dlnorm( log(K0[j]), pow( sd.K[j] , -2 ) )
  }

  # -------------------
  # standardize catches to K
    for (j in 1:R) {
      c[1:N,j] <- C[1:N,j] / K[j]
    }

  # -------------------
  # observation model for biomass index and observation error
    for (j in 1:R) {
    for (i in 1:N) {
      O[i,j] ~ dlnorm( log( max( q[j] * K[j] * b[i,j] , eps) ), pow( sd.o[j] , -2 ) );
    }}
```

```
  # -------------------
  # biomass model and process error
    for(j in 1:R) {
      b[1,j] ~ dlnorm( log( b0[j]), pow( sd.p[j], -2 ) ) ; # biomass at first year
      for(i in 2:N) {
        b[i,j] ~ dlnorm( log(max(b[i-1,j]*(1+r[j]*(1-b[i-1,j]))-c[i-1,j], eps)), pow(sd.p[j], -2));
    }}

  # -------------------
  # forecasts
    for(j in 1:R) {
    for(i in (N+1):(N+M)) {
      b[i,j] ~ dlnorm( log(max(b[i-1,j]*(1+r[j]*(1-b[i-1,j]))-er*b[i-1,j], eps)), pow(sd.p[j], -2));
    }}

  # -------------------
  # monitoring nodes and parameter estimates for output
    for(j in 1:R) {
      collapse[j] <- 1 - step( b[N+M,j]-0.1 ) ; # test if b >= 0.1
      XMSY[j] <- 1 - step( b[N+M,j]-0.5 ) ; # test if b >= 0.5
      MSY[j] <- r[j] * K[j] / 4  # maximum height of of the latent productivity (yield)
      BMSY[j] <- K[j]/2  # biomass at MSY
      FMSY[j] <- 2 * MSY[j] / K[j] # fishing mortality at MSY
      Fcrash[j] <- 4 * MSY[j] / K[j] # fishing mortality at which the stock will crash
    }

    # -------------------
    # fishing mortality
    # force first year estimate assuming catches in year 0 to be similar to year 1
    for(j in 1:R) {
      for(i in 1:N) {
        F[i,j] <- -log(1 - c[i,j] / (b[i,j] + c[i,j]) )
      }
      for(i in (N+1):(N+M)) {
        F[i,j] <- -log(1 - er * b[i-1,j] / (b[i,j] + er * b[i-1,j] ) )
      }
    }

    # -------------------
    # annual production
    for(j in 1:R) {
      p[1,j] <- b[2,j]- b[1,j] + c[1,j] # approximation
      for (i in 2:(N) ){
        p[i,j] <- (b[i+1,j]- b[i-1,j])/2 + c[i,j]  # linear interpolation cancels out b[i,j] terms
      }
      for(i in (N+1):(N+M-1)) {
        p[i,j] <- (b[i+1,j]- b[i-1,j])/2 + er * b[i-1,j] # linear interp. cancels out b[i,j] term
      }
      p[(N+M),j] <- (b[(N+M),j]- b[(N+M-1),j]) + er * b[(N+M-1),j]   # approximation
    }

    # -------------------
    # rescale estimates
    for(j in 1:R) {
    for(i in 1:(N+M)) {
      B[i,j] <- b[i,j]*K[j]
      P[i,j] <- p[i,j]*K[j]
    }}

    for(j in 1:R) {
    for(i in 1:M) {
      TAC[i,j] <- er*b[N+i-1,j]*K[j]
    }}
}
```