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An assessment of the snow crab resident on the Scotian Shelf in 2005

Évaluation de stock du crabe des neiges du plateau continental de la Nouvelle-Écosse en 2005

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Abstract

For the 2005 fishing season, landings of snow crab were 562 and 6407 t for N-ENS and S-ENS, respectively. Relative to 2004 landings, this represents a decline of 61% and 24%, respectively. These declines were due to reductions in TACs, which were attained by both areas. Most landings were obtained from offshore areas. Catch rates were 30.6 kg/trap and 109.4 kg/trap for N-ENS and S-ENS, respectively. N-ENS catch rates have declined 50% relative to 2004 levels while those of S-ENS have increased marginally. However, due to the removal of sub-area lines, higher catch rates were expected, apriori. The offshore slope areas were minimally exploited. Discard rates of soft-shelled crab were high as was the exploitation of immature crab.

Mature female numbers have increased from the maturation of the leading edge of juvenile female pulses observed for the past three years. Mature male numbers have declined, resulting in increasingly more balanced sex ratios. The abundance of snow crab on the Scotian Shelf declined in 2005, continuing the downward trend observed since the peak abundances of the late 1990s and early 2000s. Fishable biomass estimates as of the winter of 2005 stands at approximately 1200 t and 20800 t, in N-ENS and S-ENS, respectively. They represent declines of 11% and 29%, respectively, even with the large TAC reductions of the 2005 season. Recruitment to the mature fishable biomass expected for 2006 was very low, whereas recruitment to the immature fraction of the fishable biomass is expected to be large. Forecasts of potential future trends indicate that soft-shell incidence will be a major issue in the 2006 season. The 2007 season should see the beginning of a recovery of the fishery.

Due to the (1) continued declines in fishable biomass, even though exploitation rates were reduced in the 2005 season; (2) the Scotian shelf snow crab entering a reproductive mode with dwindling numbers of large adult males; (3) high likelihood of soft-shell incidence in the 2006 season; and (4) the untested nature of the (optimistic) projections of future fishable biomass, a conservative approach to the fishery is recommended for the 2006 season.

Résumé

En 2005, les débarquements total du crabe des neiges du plateau continental de la Nouvelle-Écosse étaient de 562 t dans la région nord (zone de pêche commerciale ou ZPCs 20 à 22; N-ENS) et de 6,407 t dans la région sud (ZPCs 23 et 24; S-ENS). Ceci représente un déclin associé aux réductions des allocations totale de captures (ATC) de 61% et 24% par rapport à 2004, pour N-ENS et S-ENS, respectivement. La plupart des débarquements provenaient loins de la côte. Les taux de capture de la pêche commerciale étaient de 30.6 et 109.4 kg/casier levé pour N-ENS et S-ENS, respectivement. Les taux de capture de N-ENS ont diminué de 50% par rapport à 2004, alors que ceux de S-ENS ont augmenté légèrement. Cependant, en raison de la restructuration des zones de pêche commerciale, des taux de capture plus élevés avaient été prévus, a priori. L'exploitation sur la pente continentale était minimale en 2005. Les taux d'écart de crabe à carapace molle étaient élevé de même que l'exploitation de crabe adolescent.

Le nombre de femelles adultes a augmenté avec la maturation des femelles juvéniles observées depuis les trois dernières années, alors que celui des mâles adultes a diminué. L'indice d'abondance commerciale relevé au chalut du plateau continental a diminué en 2005, continuant la tendance à la baisse observée depuis la fin des années 1990. En 2005, la biomasse du crabe commerciale a été estimée à environ 1,200 t pour N-ENS et 20,800 t pour S-ENS, représentant une diminution respective de 11% et 29% par rapport à 2004. Il est à noter que pour ces régions, la biomasse du crabe a continuée de diminuer malgré les réductions importantes de TAC pour la saison 2005. Le recrutement de la biomasse commerciale prévue pour 2006 est très bas, alors que celui associé avec la fraction de la biomasse de crabe adolescents est élevé. Une incidence plus élevée de crabe à carapace molle est prévue pour 2006. La saison 2007 devrait donc voir le début d'un rétablissement de la pêche.

En raison (1) de la diminution continue de la biomasse commerciale observée malgré la réduction des taux d'exploitation de la saison 2005; (2) de l'entrée du crabe de neige dans un mode reproducteur avec un nombre réduit de grands mâles d'adulte; (3) de la probabilité élevée d'incidence de crabe à carapace molle pour la saison 2006; et (4) de la nouveauté des méthodes de projection (optimistes) de la biomasse commerciale, une approche conservatrice à la pêche est recommandée pour la saison 2006.

1 Introduction

This report documents the currently understood **status** of the snow crab resident on the Scotian Shelf (Figure 1) from fisheries data and a dedicated trawl survey. The mandate to provide scientific advice as it pertains to the Scotian Shelf snow crab population was transferred in 2004 from the Gulf Fisheries Centre (GFC; Moncton, New Brunswick) to the Bedford Institute of Oceanography (BIO; Dartmouth, Nova Scotia). Since that time, analytical approaches to the assessment has been adapted to accomodate for the high interannual variability in the spatial distribution of this population of snow crab that exists on the southern-most extreme of their distributional range. These changes in analytical methods are also detailed in this document.

2 Ecology and 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. On the Scotian Shelf, commercially fished snow crab are generally observed between depths of 60 to 280 m (Figures 2, 3) and between temperatures of -1 to 6 °C (Figure 4). 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 & Hazel 1992; Comeau *et al.* 1998).

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 crabs (Rock crab, *Cancer irroratus*; Toad and Lesser toad crabs, *Hyas coarctatus*, *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 crabs primarily feed upon, in order of importance: echinoderms, polychaete worms, large zooplankton, detritus and bivalves (e.g., *Mytilus edulis, Modiolus modiolus, Hiatella arctica*). More recent studies have also demonstrated that cannibalism is highly prevalent in intermediately sized (morphometrically) mature crabs, especially mature females (Sainte-Marie & Lafrance 2002; Squires & Dawe 2003).

The known predators of snow crab are, 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 and thorny skate have been noted 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). Robichaud *et al.* (1991). Snow crab in the size range of 5 to 30 mm CW (where CW is carapace width; 7 mm CW mode; that is instars 2 to 7, with instar 7 being strongly selected) were targeted by thorny skate and cod as well as soft-shelled males in the size range of 77 to 110 mm CW during the sring moult.

Snow crab eggs are brooded by their mothers for 2 years or more, depending upon ambient temperatures, food sources and the maturity status of the mother (27 months in primiparous females – first breeding event; and 24 months in multiparous females – second or possibly third breeding events; Sainte-Marie 1993). More rapid development of eggs (from 12 to 18 months) have been observed in other systems (Elner & Beninger 1995). 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 begin to settle to the bottom in autumn to winter (September to October in the Gulf area; on the Scotian Shelf pelagic stages seem highest 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). The first inter-moult stage (instar 1) is approximately 3 mm CW. After the 5th instar (15 mm CW) the frequency of moults decine, 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 (Figures 5 and 6). On the Scotian Shelf, the terminal moult has been determined 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 ($>$ 95mm 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; see Table 1) 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.

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; i.e., 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 with larger males with larger chela generally being more successful in mating.

3 The fishery

3.1 Management

The snow crab fishing grounds on the Scotian Shelf were agglomerated into four main areas for the 2005 fishing season: N-ENS (formerly CFAs 20 to 22), S-ENS (composed of CFAs 23 and 24) and 4X (where CFA is a Crab Fishing Area; Figure 1). The management of this fishery was based on effort controls (size, sex, shell-hardness, season, license, trap limits) from 1982 to 1993. 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. Voluntary management measures requested by fishermen were also introduced in some areas, such as a shortened fishing season and reduced numbers of traps. The fishing seasons for 2005 are summarised in Table 2.

3.2 History

The snow crab fishery in eastern Canada began in 1960 with incidental by-catches by groundfish draggers near Gaspé, Quebec (Elner & Bailey 1986). Its development was slow until the 1980s when it began expanding rapidly to become one of the largest fisheries in Canada (93000 t in 2001; Dufour & Dallaire 2003). In Nova Scotia, the fishery has been in existence since the late 1970's (Figure 7). The earliest records of landings were at levels of < 1000 t. By 1979, this rose to 1500 t subsequent to which the fishery declined substantially in the mid-1980s and considered a collapsed fishery.

Strong recruitment to the fishery occurred in 1986 and since that time, landings have increased considerably (Figure 7). A trawl survey was used for biological assessment in 1999, after 3 years of development by the GFC (Gulf Fisheries Centre, Moncton, New Brunswick). The survey detected the presence of unexploited stocks in the south-east areas of the shelf. As a consequence, TACs were increased from 900 t to 1015 t in the north and from 2700 t to 8800 t in the south between 1999 and 2000 and landings doubled (Tables 3, 4). New temporary allocations were granted to areas outside of the traditional fishing grounds. Trends in catch rates continued to increase during this period (Figure 8) as did fishing effort (Figure 9). Following voluntary trap surveys in 2000, additional allocations (200 t) were made in 2001 and 2002 with further additions in 2003 to 300 t. Annual TACs increased to historical maxima in 2002/2003 at 8,800 t in S-ENS and 1,500 t in N-ENS and landings were stable at > 10000 t each year between 2000 to 2004. The *post-1998 period was one of rapid expansion* of both the economic importance of the crab fishery and also the spatial extent of exploitation.

Declines in the abundance of immature males were detected since 1997 while the abundance of legal size males remained stable. In 2004, due to continuing signs of poor recruitment and consistently lower catch rates in most areas, a 10% reduction in TACs was implemented. The former CFA 22 Outer (Glace Bay Hole) was an exception to this rule, with an increase of 15% in TAC due to locally very high catch rates. With the persistently low levels of recruitment into the fishery, and a steady decline in fishable biomass since the early-2000s, a more precautionary tactic was adopted for the 2005 fishing season: TACs and total landing were reduced further to 6919 and 6968 t, respectively (Tables 3, 4). These 2005 TACs represented reductions of 60% in N-ENS and 23% in S-ENS relative to the 2004 TACs.

4 Methods

4.1 Analytical tools

Maps for visualisations were constructed with GMT (Generic Mapping Tools, Wessel & Smith 1998, version 4.1). For results that were not kriged, the *splines-in-tension* data smoothing and interpolation technique was used with the tension parameter T set at 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 (see below). Conversions between cartographic and cartesian co-ordinate systems for analytical purposes were computed with PROJ (Evenden 1995, version 4.4.9), using a Lambert conformal conic projection and the WGS84 spheroid with the central meridian at 63°W and standard parallels at 43°N and 47°N. All other data analyses were implemented in the statistical computing language and environment R (Team 2004, version 2.2.1) to allow migration and documentation of methods into the future. Kriging was conducted with the R package, GSTAT (Pebesma 2004, version 0.9-18). All analytical tools were open-sourced software.

4.2 Fisheries data

Catch rates are biased indicators of abundance as both the spatial and temporal distribution of crabs and the fishing effort are not uniform varying strongly with season, bottom temperatures, food availability, timing of spring plankton blooms, reproductive behaviour and substrate/shelter requirements. They are presented here only to maintain continuity with historical records. Mandatory logbooks provide information on location, effort (number of trap hauls) and landings (verified by dockside monitoring). The data are stored in the Maritime Fisheries Information System (MARFIS) of the Maritimes Branch Statistics Division of DFO. Exhaustive data quality checks were completed. Catch rates (kg trap^{-1}) were computed as the ratio of total landings to total trap hauls, using data from properly completed logbook records. Catch rates are reported without standardisation. Total trap hauls for a given group is computed by dividing the total landings by their respective catch rate.

At-sea-observer data provided information about the size structure and the carapace condition of the commercially exploited stock. The data are stored in a centrally organised relational database (Observer Database System). At-sea-observers are deployed randomly (Figure 10) with the coverage being as evenly distributed between CFAs as possible. The target coverage (by quota) was 5% and 10% for the northern and southern areas, respectively.

4.3 Research survey data

A trawl survey dedicated to snow crab assessment on the Scotian Shelf was first introduced by the GFC in 1996 (Biron *et al.* 1997) and is funded by the fisheries through a Joint Project Agreement. 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 $\times$ 10 minute area (Figure 11). This sampling design was developed to facilitate geostatistical estimation techniques (i.e., *kriging*; Legendre & Legendre 1998; Kern & Coyle 2000; Venebles & Ripley 2002). In the 2005 survey, 389 stations were sampled on the same fishing vessel as that used in the 2004 survey: The Gentle Lady (a 65 foot dragger).

Concern has been expressed by fishermen about the location of sampling stations in areas known to have low abundance of fishable biomass and the possibility of biasing abundance estimates towards smaller values. However, abundance estimates will not necessarily be biased towards smaller values even if many zero-catches are observed for while the *mean* value may decline this would be compensated by an increase in total surface area. This factor is not an issue on the Scotian Shelf as the spatial bounds of snow crab spatial distributions are determined objectively and the geostatistical abundance estimation techniques used limits the spatial extent of the influence of low-values to be bounded to a specified distance determined from the spatial autocorrelation function (generally less than 50 km in extent).

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 even 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 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.

With the evolution of the areal extent, intensity and timing of surveys since the mid-1990s, direct inter-annual comparisons of the data are made difficult. The survey is conducted in the autumn (September to November; i.e. post-fishing season in CFAs 20 to 24 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 (April to July; i.e., pre-fishing season in CFAs 20 to 24). As a consequence, temporal trends are most reliable for the post-2002 period. In the southern-most area of snow crab distribution (CFA 4X) trawl survey coverage has been historically sporadic. A renewed effort has been made to stabilise the spatial coverage in this area.

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). Tows were conducted for ~ 5 minutes in duration with actual duration of bottom contact being monitored by Netmind sensors. The width of the mouth of the net was also monitored with Netmind sensors. The ship speed was maintained at ~ 2 knots. The warp length was ~ 3 times the depth. Positional information as well as water temperature measurements were collected using a global positioning system and Minilog data recorders, respectively. The surface area swept by the net was calculated from swept distance and net width information.

All crab were enumerated, measured with calipers, shell condition described (see Table 1), claw hardness determined 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).

Pre-2004 snow crab biomass estimates were approximated from carapace width (CW) measurements by applying the allometric relationships developed for the Scotian Shelf adult hard shelled snow crab (Biron *et al.* 1999; $R^2 = 0.98, n = 750$):

$$mass[g] = 1.543 \times 10^{-4} \times (CW[mm])^{3.206} \tag{1}$$

The maturity status of males was determined from morphometric maturity. 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 quantified. In the terminal moult of male snow crab, a disproportionate increase of chela height (CH) relative to carapace width (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):

$$M_{male} = -25.324 \times \ln(CW[mm]) + 19.776 \times \ln(CH[mm]) + 56.650 \quad (2)$$

where the 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 carapace width (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):

$$M_{female} = -16.423 \times \ln(CW[mm]) + 14.756 \times \ln(AW[mm]) + 14.900 \quad (3)$$

where the individual is considered mature if $M_{female} > 0$.

Sex ratios were calculated as:

$$Sex\ ratio_{(immature)} = \frac{N_{(female,\ immature)}}{N_{(female,\ immature)} + N_{(male,\ immature)}} \quad (4)$$

$$Sex\ ratio_{(mature)} = \frac{N_{(female,\ mature)}}{N_{(female,\ mature)} + N_{(male,\ mature)}} \quad (5)$$

Size-frequency histograms were constructed (expressed as number per unit area swept by the trawl (km^{-2}); i.e., the arithmetic mean numerical density per unit area in each size interval). Modes and the bounds of the each modal group were identified from size frequency distributions. Each instar was determined to have a lower bound of carapace width (mm) approximated by (see also Figure 6):

$$CW_{(lower,\ male)}\ [mm] = \exp(1.918 + 0.299 \times (Instar - 3)) \quad (6)$$

$$CW_{(lower,\ female)}\ [mm] = \exp(2.199 + 0.315 \times (Instar - 4)) \quad (7)$$

The locations of "*most likely snow crab habitats*" were determined on high resolution depth maps (15 arc-second resolution) obtained from the Canadian Hydrographic Service. The range of observed depths of Scotian Shelf snow crab (between 60 m to 280 m; Figures 2, 3) were used to delineate these potential snow crab grounds. For each year, maps of preferred snow crab temperature locations were made using Optimally Estimated bottom temperature maps (obtained from the Ocean Science Division of BIO, DFO). Preferred snow crab temperatures on the Scotian Shelf ranged between $-1°C$ to $+6\ °C$ (Figure 4). These two sources of information were combined to delineate the most probable locations of snow crab habitat (Figure 12). This dynamically changing habitat range was used to predict the biomass and numerical densities of crab.

The estimation of biomass and numerical densities involved the use of geostatistical methods: modelling of variograms (the behaviour of variance as a function of distance) for each of the individual variables, in each year. Variograms were constructed using an automated process that chose a functional form (bessel, spherical, exponential, circular, gaussian or generalised Matern) that best described the spatial variance using a nonlinear least-squares criterion. When solutions did not converge, a moving time averaged empirical variograms (scaled to unit variance) of varying window sizes were constructed until a reliable solution was obtained. A three-year window was generally sufficient for stabilisation. The final solution was re-scaled to the local variance of the region and year of interest.

Spatially explicit means and variances were then obtained using Universal Kriging with External Drift which were used for visualisations. External Drift is a technique that linearly accounts for variations in external parameters. The most significant such variables were determined from bi-variate analyses to be: depth, bottom temperature, total fishery landings since 1998 and fishery catch rates, all discretised to $2 \times 2\ km^2$. Where the relationship to abundance measures were nonlinear, the variables were transformed to a linear relationship. Due to the extreme irregularity of the potential snow crab habitat space, Ordinary Block Kriging, using blocks of $1\,km^2$ resolution was used to estimate 95% confidence bounds of the predicted intensive variables (biomass and numerical densities). When problems of solution convergence were observed (due to sparse spatial coverage in some classes such as immature, female, carapace condition 1 and 5 crabs), categories were agglomerated when appropriate. The numerical abundance of each of the nominal growth stanzas (Figure 5) were also determined via kriging.

Relative exploitation rates (ER) were historically calculated by the GFC as:

$$ER_{(t)} = Landings_{(t)}/Mature\ fishable\ biomass_{(t-1)} \quad (8)$$

where t is time; Landings are the total landed snow crab in year t; and Mature fishable biomass is the total biomass of the mature segment of the male population > 95 mm CW, estimated from kriging for year t.

In this document, the exploitation rate is calculated as:

$$ER_{(t)} = Landings_{(t)}/(Landings_{(t)} + Fishable\ biomass_{(t)}) \quad (9)$$

where t is time; Landings are the total landed snow crab in year t; and Fishable biomass is the total legally fishable biomass (male snow crab > 95 mm CW; i.e., including immature crab) estimated from kriging for year t. This redefinition was made for two reasons. Firstly, the time interval between the end of trawl surveys [t-1] and the beginning of fishing [t] was 8 to 9 months for the former method. With the alternate method, this lag is approximately 2 months and so the influence of other population demographic trends (variable immigration, emigration, mortality and recruitment rates) likely to be reduced. Secondly, instead of restricting abundance measurements to the mature fishable biomass, all of the legally fishable biomass was used to characterise the true exploition of the exploitable biomass.

Relative numerical exploitation rates of each growth stanza was also estimated from at-sea-observed catches for each major area with the assumption of 100% catchability of legal sized crab (> 95 mm CW) from trawl surveys:

$$ER_{(t,i)} = Number\ landed_{(t,i)}/(Number\ landed_{(t,i)} + Number\ surveyed_{(t,i)}) \quad (10)$$

where t is time; i is growth stanza; Number landed are the total number of snow crab estimated to have been landed from at-sea-observed proportions of each growth stanza i, in the catches in year t; and Number surveyed is the total number of snow crab estimated from kriged numerical abundance of each growth stanza i, in the trawl surveys for year t.

Markov-type transition matrices were determined for each nominal growth stanza of male snow crab based upon historical data from 2003 to the present. Data prior to 2003 could not be used to compute the transition matrix due to the very different timing of the surveys (spring). Due to gear and sampling bias and the bi-annual moulting of snow crab instars 1 to 5, numerical abundance and transition matrix estimates were limited to instars 6 and greater. No information on reproduction and early pelagic and benthic survival were assumed and so these transition matrices are referred to as pseudo-transition matrices. Further, the relative differences in catchability of the various size and maturity classes were not separated from survivorship resulting in transfer functions that can be greater than 1. The catchability of the commercially exploitable population was assumed to be 100%. These pseudo-transition matrices were developed for each major region separately (N-ENS, S-ENS, 4X) where-ever possible and used for forward projection under varying scenarios of exploitation rates.

Forward projection scenarios were derived from fishing patterns in the most recent year of at-sea-observer estimates of relative exploitation for each of the above growth stanzas and the most recent year of abundance estimates from trawl surveys. Errors (Δx) from all potential sources were propagated assuming all n variables (x_n) were independent of each other:

$$z = f(x_1, x_2, \ldots, x_n) \quad (11)$$

$$(\Delta z)^2 = (\frac{\partial f}{\partial x_1}\Delta x_1)^2 + (\frac{\partial f}{\partial x_2}\Delta x_2)^2 + \ldots + (\frac{\partial f}{\partial x_n}\Delta x_n)^2 \quad (12)$$

5 Environmental conditions

The spatial extent of what may be considered potential snow crab habitat based upon bottom temperature and depth, has been very stable in N-ENS, at about $6 \times 10^3 km^2$ (Figures 13, 14). However, for S-ENS, the surface area of potential habitat decreased substantially in 2005 relative to 2004 (Figure 14), dropping from 61 to $42 \times 10^3 km^2$ (a 31% reduction in habitable space). This sharp decrease would increase the crowding of the snow crab and therefore also their catchability as they are concentrated into stronger aggregations in core areas. In CFA 4X, the southern-most limit of the distribution of snow crab, potential habitat has been highly variable; since 2004, it has declined from 22 to 12 $\times 10^3 km^2$ (45%).

An overall warming of the habitat space to an average of over 3.5 °C was observed over the past three years in ENS (Figures 13, 15). This was particularly evident in the cold water centers of Misaine Bank in S-ENS and most of N-ENS. Warm-water incursions into the offshore-slope area of the former CFA

24 were also marked, forcing most crab in the area to move or die. The slope area towards the Gully in the former CFA 23 was also quite warm. The strong temperature forcings were likely responsible for alterations in the life cycle of the crab in these areas, accelerating their moult cycles and potentially increasing the capture of soft-shelled crab in these warmer areas (as was observed in the fishery in the 2005 season). In N-ENS, while total potential habitat area was stable, bottom temperatures also increased in the area (Figures 13, 15) and may have contributed to a disruption of their moult cycles and increased observation of soft-shell crabs, even when catch rates were high.

6 Fishery performance

6.1 Effort

The spatial distribution of fishing effort continued the trend of increasing effort in offshore areas and declines in inshore areas (Figure 16). Peak effort in the 2005 fishing season was applied near the Misaine Bank, Sable Island and French Bank areas in S-ENS; the north basin area of N-ENS; and the area just south of Sambro in CFA 4X. The effort on the offshore slope areas declined in 2005 relative to 2004. A decline in effort was also quite notable in the inshore areas of the western part of CFA 24, an area where temperature conditions were also quite warm in the 2005 season (see below: Environmental conditions). In 2005, a total of 18354 and 58546 trap hauls were applied in N-ENS and S-ENS, respectively. Relative to 2004 effort levels, this represents a decline of 21 and 24%, respectively, due in part to the reduced TACs.

6.2 Landings

The spatial distribution of total landings have also shifted from being mostly derived from inshore areas in the past (2000-2002) to presently being derived mostly from the offshore areas (especially near Sable Island and Misaine Bank). Local peak landings were also detected near Sambro and the north basin in N-ENS, but their spatial extents were greatly diminished relative to historical records (Figure 17). The total landings were 562 and 6407 t in N-ENS and S-ENS, respectively. Relative to 2004 levels, this represents a decline of 60 and 20%, respectively (Figure 7). Both management areas reached (surpassed) their respective TACs (Tables 3 and 4).

6.3 Catch rates

The spatial distribution of catch rates were highest in the offshore areas and very low in most inshore areas (Figure 18). Peak levels were found in the Glace Bay area in N-ENS and towards the Misaine Bank and Sable Island area in S-ENS. The catch rate for all of ENS (CFAs 20 to 24) was 90.6 kg/trap in 2005, an 5% decline relative to 95.0 kg/trap in 2004 (Figure 8). Most of this decline was due to the large declines in catch rates in N-ENS which was 30.6 kg/trap in 2005, relative to 60.6 kg/trap in 2004 (a decline of 50%), a steady decline since the peak levels of 101 kg/trap in 2002 (Table 3). In S-ENS, catch rates have been stable and high at record levels for the past 4 years. In 2005, catch rates were 109.4 kg/trap, a slight increase from the 2004 catch rate of 105.6 kg/trap (Table 4). It should however be noted that catch rates were expected to increase in the 2005 season due to:

- The removal of management sub-area lines that restricted many fishermen to depauperate inshore areas in the past, allowing greater access to high catch areas.
- A contraction in the spatial extent of potential snow crab habitat in the 2005 season due to warmer temperatures. This contraction would force increased densities (crowding) of snow crab and thus potentially catch rates.

Thus the marginal increase in catch rates in the S-ENS for the 2005 fishing season should be taken with a note of caution.

6.4 Carapace condition

In N-ENS, 5.8% of the quota was observed at sea where the target coverage was 5% (i.e., see Figure 10). A total of 143 traps were sampled (0.78% of commercial trap hauls). Of a total of 5593 male snow crabs sampled at sea from the commerical fishery, 3667 were of legal commercial size. In S-ENS, 10.6% of the quota was observed at sea (with a target coverage of 10%) and a total of 923 traps were sampled (1.582% of commercial trap hauls). Of a total of 39934 male snow crabs sampled, 31610 were of legal size. Thus discard rates (based upon the simple size criterion of legal snow crab being >95 mm CW), increased in 2005 with 34% and 21% in N-ENS and S-ENS, respectively, relative to 21% and 18% in 2004, respectively.

The relative composition of moult stages of at-sea-monitored snow crab remained similar between 2004 and 2005 in both N- and S-ENS (Figure 19). In the size fraction that are below legal size (<= 95 mm CW), the relative abundance was generally dominated by CC3 and CC4 snow crab. The relative proportion of CC5 snow crab increased from approximately 1% in 2004 to 2% in 2005 in both N- and S-ENS (Tables 5, 6). Increased representation of CC1 crab was also observed in 2005 relative to 2004. In the size fraction that are legal sized (> 95 mm CW), CC3 (61%) and CC4 (18%) snow crab dominated (Table 7). In S-ENS, the majority of legal sized male snow crab were also dominated by CC3 (68%) and CC4 (14%) crab (Table 8). The relative proportion of old crab (CC5) in the legal sized males was comparably low in both years in both areas, at <1% in both areas (approximately 1/2 the proportion in the sub-legal males). Very low levels of CC5 males has been suggested by some to be indicative of high exploitation rates.

Trawl survey abundance estimates of the legal sized fraction of male snow crab (Tables 9, 10) were also dominated by the CC3 and CC4 categories, with very few indivuals being found in the CC1 (due to the lateness of the survey season) and the CC5 categories (similar to the data observer in the commerical catch).

6.5 Soft-shelled snow crab

A high occurrence of soft-shell crab was observed in N-ENS in 2005 (Table 7; Figure 20). This high incidence of soft-shelled crab was *not* an observation found only in areas of low catches (Figure 21); rather both high and low catches were found to demonstrate high soft shell incidence and was distributed throughout the N-ENS (though predominantly centred around the former CFA 21). If one assumes no recaptures, this amounts to an additional 118 t being discarded as soft crab with associated high handling-asscoiated mortality.

In S-ENS, the incidence of soft-shelled crab catches was lower (Table 7). However, when extrapolated to the whole of the S-ENS quota, this would amount to a potential additional mortality of 316 t or a total of 434 t for all of ENS. The actual mortality will be less depending upon actual mortality rates of handing soft-shelled crab, however, this can have important direct, deleterious effects upon the fishable biomass.

Exploitation rates estimated from the at-sea-observed snow crab of the CC1 and CC2 classes was high in N-ENS (up to 100% of instar 12 crab may have been caught in 2005). In S-ENS, estimated exploitation rates of CC1 and CC2 crab 2005 ranged from 30% to 75% for instars 11 and 12, respectively. These high rates are problematic for the fishery as these crab have poor meat yields, and for the snow crab population as these crab have not had a chance to mate.

6.6 Immature snow crab

Snow crab grow approximately 250% in body weight with every moult. The exploitation of immature snow crab is problematic in that the full potential of the crab to grow is being under-valued. For example, if an immature instar 11 snow crab is not harvested (average weight of 0.28 kg) and grows to another moult, it will be approximately 0.69 kg (instar 12; Figure 6). If it does not terminally moult at instar 12 and matures instead at instar 13, then it will grow to approximately 1.2 kg (i.e., a 430% increase relative to an instar 11 male; this last growth increment does not seem to follow an allometric formulation and so was directly computed from trawl survey data). There is therefore a potential to increase total biomass yield by 250 or even 430% of the immature crab if they are returned to the water. The cost of this additional yield would be any natural and handling mortality of crab returned to the water.

In N-ENS, exploitation rates (by number) have been at <1 to 70% of instar 11 immature males and 4 to 95% of instar 12 immature males in the past 3 years (Table 11). Using 2005 exploitation estimates (Table 11), numerical abundance estimates (Table 12) and the average weights caught in N-ENS, approximately $0.05 \times 95 = 0.5$ t of instar 11 immature and $0.359 \times 44 = 16$ t immature skip moulter crab were landed. Of the instar 12 crab, $0.042 \times 83 = 3.5$ t were immature and $0.79 \times 80 = 63$ t were immature skip moulters. Instar 11 crab after one moult would increase on average 250% by mass from 16.5 to 41 t, whereas instar 12 crab after one moult would increase some 175% by mass from 66.5 t to 116 t. That is, if all 83 t of immature crab had been returned, they would have grown to 157 t, an increase of 190% in fishable biomass and also perhaps more imporantly for the crab fishermen, the quality of the crab. A annual natural mortality rate of over 47% would be required to nullify any gains in fishable biomass. Of course some proportion of the instar 11 crab would also grow again to instar 13, and thus the gains in fishable biomass would likely be higher.

In S-ENS, exploitation rates (by number) have been at 1 to 50% of instar 11 immature males and 24 to 94% of instar 12 immature males in the past 3 years (Table 13). Using the numerical abundance estimates in Table 14: of instar 11 crab that were landed in 2005, $0.037 \times 4800 = 178$ t were immature and $0.2 \times 2427 = 485$ t were immature skip moulters. Of the instar 12 crab, $0.24 \times 4061 = 974$ t were immature and $0.75 \times 3084 = 2313$ t were skip moulters. The instar 11 crab would have increased from 663 to 1658 t, while the instar 12 crab would have been expected to increase from 3287 to 5720 t. That is, growth from an single moult increment would have increased the fishable biomass from 3950 to 7378 t, an increase of 187%. To counter-balance this growth-related increase in fishable biomass, annual natural mortality rate of over 46% would be required. Again, gains in fishable biomass would likely be larger as an unkown proportion of instar 11 crab would grow to instar 13 in a subsequent year.

In many respects, a redefinition of what may be considered fishable biomass is urgently required. The current use of length and shell softness as a cutoff of legally fishable crab is sub-optimal in terms of the exploitation of the productive potential of the snow crab and biologically unwise as the likelihood of a mature crab having even a single mating event is reduced dramatically. Specifically targeting mature (male) crabs would be a more optimal exploitation strategy (CC3 and CC4 crab). This would also have the advantage of allowing the possibility of at least a single mating event for males before capture (preferably more as crab are by nature a multiply mating species).

6.7 Summary

Fisheries performance as measured by CPUE continued to decline in N-ENS while in S-ENS, a moderate increase was observed. Due to the removal of sub-area lines and reduced TACs, CPUE was expected to increase in all areas.

Capture of recently-matured (CC1 to CC2) crab, estimated from at-seas-observations, was significant. These are segments of the population with poor meat yields.

Soft shell incidence has increased. The reaction of the fishery to the presence of soft-shelled crab was ineffective, except for a few fishermen moving their traps voluntarily from high incidence locations. High discard mortality of soft-shells is expected. A new soft-shell crab prototcol is required.

Exploitation of (fishable) immature snow crab was significant. The exploitation of this segment of the population is biologically and economically unsound.

7 Resource Status

7.1 State variables

Size structure

The size frequency distributions of males in N-ENS (Figure 22) indicated that the pulse of immature male crab detected in 2003 and 2004 continue to grow and propagate through the system. In N-ENS, the main pulse of potential recruits are currently centered over the 40 mm modal group (instar 9). A smaller, but still significant pulse near the 60 mm CW modal (instar 10) group was evident. Very little recruiting crab greater than this size/stage was observed, a remnant of the recruitment bottleneck observed since 2000. A fraction of the instar 10 crab will moult and enter fishable size in the 2006 season however, they will mostly be still soft-shelled or white crab. There is therefore a high likelihood that soft-shell incidence will become quite significant in the 2006 and 2007 season, with the moulting of the main pulse from instar 9 crab. The full entry of these latter crab will not begin until the 2007 season (when their carapace will be hard and meat content elevated). The main pulse centered over the 40 mm CW group will also begin entering the fishery in a significant fashion in the 2008 fishing season. All these projections are contingent upon no significant increases in natural mortality of crab (e.g., predation, etc).

In S-ENS, similar to N-ENS, the main pulse was also centered over the 40 mm CW modal group (instar 9). However, unlike the N-ENS, immature crab were also observed spanning all size ranges from 40 to 100 mm CW. This is a positive sign for the S-ENS, in that a steadily increasing recruitment to the fishery is possible into the next five years. The recruitment bottleneck that had been observed for the past five years seems to be starting to dissipate in S-ENS. Based upon established growth patterns, the main pulse centered over the 40 mm CW modal group should enter the fishable biomass by the 2008 fishing season.

The size frequency distributions of female snow crab in 2005 indicate that the pulses of immature females detected in 2003 in N-ENS and 2004 in S-ENS are continuing to grow and intensify (Figure 23). The beginning of a large scale maturation of female snow crab was detected in N-ENS. This trend should continue for another 3 years as the systems begins to enter a reproductive mode. A similarly important increase in the number of mature females have been observed in S-ENS for the first time since the late 1990s. This increase will likely continue into the next few years as large increases in the number of immature female snow crab are currently found centered over the 40 mm CW and 50 mm CW modal groups.

Sex ratios

Whether there will be enough large mature males to mate with and protect the more rapidly maturing females remains a key conservation issue. An important consequence of the extended period of very low sex ratios observed in the early-2000s throughout the Scotian Shelf is that very poor egg and larval production in the system likely occurred for at least a four to five year period (Figure 24). If indeed, the shelf represents an internally regenerating system (as one must assume until proven otherwise and which circumstantial evidence of the timing of the new recruitment pulses seems to indicate to be the case), this may likely entail very poor recruitment into the fishable biomass for an extended period of time in the early 2010s. Stabilisation of such strong oscillations in abundance into the future would be prudent. High exploitation rates are known (empirically and theoretically) to increase such oscillations (Choi *et al.* 1999; Choi & Patten 2001). Parenthetically, it has been suggested that snow crab dynamics are naturally pre-disposed to an accentuation of oscillations in population abundance due to the numerical abundance of mature males being out-of-phase with mature (primiparous) females, a discordance due to the earlier maturation of females of the same cohort (by approximately 2 or more years) and the overall greater longevity of males.

The sex ratios of immature snow crab are currently balanced in N-ENS, while in S-ENS, males continue to dominate (Figure 25). Inshore areas are either showing balanced sex ratios or are dominated by immature females whereas offshore areas tend to be dominated by immature males (Figure 26). It was surprising that a consistent bias in the sex ratio was also present amongst immature crabs prior to 2002, as their ecology and growth patterns are quite similar at the early immature stages. However, the sizes that the trawl can capture are in the range of 30 mm CW or more, a size range where differential growth rates begin (8th instar; Sainte-Marie *et al.* 1995; Comeau *et al.* 1998). Thus immature females may be more susceptible to predation than males of the same year-class as they stay at smaller sizes for longer periods. The spatial segregation of immature females (inshore) and immature males (offshore) likely exposes the crabs to differential predation effects. Inshore females are likely more intensely predated upon by benthic fish (unlikely due to their low numbers) 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 & Lafrance 2002; Squires & Dawe 2003)).

The sex ratios of mature snow crab have been consistently very low since 1998 in all areas, being dominated by males. This is a very different situation relative to the very high ratios observed in the Gulf of St. Lawrence where male limitation is an issue. What caused this historically poor reproductive potential is not known, especially as the fishery is a male-only fishery. There has however been an increase in sex ratios (% female) of mature snow crab in 2005. This more balanced sex ratio may be indicative of the ENS crab entering an important reproductive mode (Figure 24) after a 5 year period of low reproductive output. If the indications from the size frequency distributions are correct, sex ratios should shortly reach the more balanced ratios seen only in the mid- to late-1990s. A strong coherence in the manner in which sex ratios have been changing over time throughout the Scotian Shelf was evident (Figure 27). For the first time since the late 1990s, a more heterogeneous (mixed) distribution of sexes was observed: pockets of male dominated areas were mixed with pockets of female dominated areas (Figure 27). During mating periods, mature crab would therefore be able find the other sex with minimal movement.

Primiparous females mate during their moulting stage when they are highly vulnerable without protection from a large male (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 having large males would certainly increase the likelihood of successful reproduction for the new wave of maturing females. Further in a 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. However, it is important to note that phenotypic plasticity can accelerate the rate of morphometric change in this very numerically dominant and adaptive species.

Numerical abundance

The number of immature females has increased after reaching a historical low between 2001 to 2003 (Figures 28, 29). Mature females are beginning to increase in number (Figures 30, 31); however, this increase is mostly due to an accumulation of older multiparous females in N- and S-ENS. In S-ENS, the number of new primiparous females has increased in the past two years, representing the leading edge of the adolescent pulses entering the mature phase.

The numerical abundance of older immature males of instars 10 to 12 consistently declined throughout the Scotian Shelf (Figure 32). However, a resurgence of instars 8 and 9 was seen in 2004 that has continued into 2005. This is the leading edge of the pulse of recruits that the fishery will be dependent upon for the next decade. Skip moulters have been similarly decreasing in number throughout the Scotian Shelf. Their numbers should begin to increase once the pre-recruit pulse enters mature size ranges (Figure 33).

Newly matured crab (CC1 and CC2; Figure 34) are also currently in low numbers. However, instar 9 crab (destined to be dwarfed crab, inaccessible to the fishery due to their small size) have begun to increase in number due to their early maturation. These are the males that will mate with the maturing females if there are no large male competitors. The early reduction in number of CC1 and CC2 crab (since 2001) in N-ENS may be due to their more complete exploitation in the area (as immature crab are also landed in substantial numbers; Table 11). In S-ENS, a reduction in their numbers has also been evident, but only since 2002 to 2004 (see instar 12 in Figure 34) due to the more recent nature of the expansion of the fishing ground in the area (Table 11). The gradual and consistent reduction in hard-shelled snow crab (CC3 and CC4) is evident for all instars on the Scotian Shelf (Figure 35). The numerical abundance estimates of carapace condition 5 crab are close to being undetectable on the

Scotian Shelf (Figure 36). Their representation in survey data and the fishery-observed data ($< 1\%$) may be indicative of high exploitation rates upon the hard-shelled phase.

Fishable biomass

In N-ENS, (post-fishery) fishable biomass of snow crab are currently estimated to be 1200 t (with a 95% confidence range of: 1000 to 1500 t; see Figure 37). This represents an 11% decline in fishable biomass relative to the 2004 estimate of 1400 t.

In S-ENS, fishable biomass of snow crab are currently estimated to be 20.80 $\times 10^3$ t (with a 95% confidence range of: 19.20 to 22.60 $\times 10^3$ t; Figure 37). This represents a 29% decline in fishable biomass relative to the 2004 estimate of 29.20 $\times 10^3$ t. The declines were evident in most areas (Figure 38).

7.2 Inputs and outputs

Recruitment

Based upon survey estimates, recruitment into the mature fishable biomass for the 2006 fishing season is expected to be very weak (Figures 39, 40). However, the leading edge of the pre-recruit pulses will begin to enter the fishery in this year (see projections below). The timing of these pre-recruits (a decade after the main pulse of mature females in the late 1990s) indicates that they may have been originated internally. While it is possible that the northern areas may also be influenced by larval drift and benthic migration from the Gulf of St. Lawrence snow crab, the Scotian Shelf seems to be (or at least is capable of acting as) a self-generating system. Unfortunately, the Scotian Shelf snow crab's reproductive system has been in poor condition for five years: i.e., low densities of mature females and therefore low levels of larval production. It is likely that the extended period of few reproducing females is due to there having been only one major pulse of crabs in a system that had previously been mostly devoid of snow crabs. This main pulse had their origins in the late 1980s and early 1990s (it takes approximately 9 years or more to reach reproductive size). That is, the Scotian Shelf population has not yet stabilised. However, the newly maturing females that have begun to enter the system should generate increased egg and larval production for at least the next 3 to 7 years. This extended period of potential reproduction may help to stabilise recruitment levels into the future, moderating the snow crab population dynamics away from a boom-bust cycle. This is a welcome direction of change as the snow crab population would become less susceptible to mortality factors such as environmental variations, predation, competition and fishing (Choi & Patten 2001).

Natural mortality

Natural mortality rates of snow crab on the Scotian Shelf have not been estimated. However, Wade *et al.* (2003) suggested that mortality rates for legal sized crab resident in the southern Gulf of St. Lawrence to be within the range of 0.26 to 0.48. Based upon diet studies (Bundy 2004), very few natural predators seem to exist for large snow crabs (i.e., legal sized) on the Scotian Shelf. This has been particularly the case since the demise of most large-bodied predatory groundfish from the eastern part of the Scotian Shelf (Choi *et al.* 2004). As such these natural mortality estimates seem high. The mature stage of snow crab has been suggested to be between 4 to 6 years, based upon tagging studies (B. Sainte-Marie, pers. comm.). The numerical turnover rate of crab in this stage would therefore be expected to be between 1/4 to 1/6. Near local-steady states, natural mortality rates should converge towards numerical turnover rates.

Concentrations of thorny skate have been found in the offshore slope areas, suggesting that mortality may be high especially for small crabs (instars 7 and less) as well as soft-shelled crab in these areas. Other potential mortality factors include: seals (near Sable Island), overfishing as a consequence of season extensions and soft-shell mortality, unreported landings, by-catch in other fisheries (long-lining, trawling) and potentially activities associated with exploration and development of oil and gas reserves.

Fishing mortality

Exploitation rates were increasing exponentially from 2001 to 2004 in N-ENS (Figure 41). Large reductions in TAC were implemented for the 2005 season, resulting in sharp reductions of exploitation rates from 50% to 31% by biomass. In S-ENS, the relative exploitation rate continued to increase from 21.5% to 24% even with the reduced 2005 TACs.

7.3 Scenarios and decision rules

Based upon the historical approach to the management of this species on the Scotian Shelf and the overall poor nature of all main fisheries-independent indicators of the abundance and recruitment of the snow crab (with the exception of female numbers and sex ratios), a conservative approach would again be recommended for the 2006 fishing season with associated strong reductions in TACs or exploitation rates.

However, adolescent crab approaching maturity remains a strong signal, the leading edge of the pulse is fast approaching entry into the fishery. In two years time, they should enter mature stages and even by next year strong incidences of soft-shell catches may begin to be expected. A portion of the immature crab will also be available to the fishery. While it may be tempting to exploit this leading entry, they are also the individuals that would grow to large males. As was suggested above, exploitation of this segment of the population is a sub-optimal strategy, both biologically and economically.

Based upon the pseudo-transition matrices determined for the Scotian Shelf snow crab growth stanzas, some qualified projections of future (pre-fishery) fishable biomass can be made based upon the size distribution of male snow crab found by the 2005 surveys (Figures 42, 43; Tables 15, 16). (We must emphasize the novelty and the crudity of this approach as a snow crab assessment tool – it requires many more refinements.) Regardless, these scenarios indicate the that a wide range of exploitation rates will soon be available to the fishery again due to the continued strength of pre-recruits that will enter the fishery in the near future. While based upon these tentative scenarios it may be tempting to ignore the warning signs noted throughout this document, we would again recommend caution until the forecasts can be corroborated. In particular the higher levels of fishable biomass projected for the 2006 season are almost all composed of immature and immature skip moulting individuals (Tables 12, 14).

High catches of soft shell are also predicted to become a major issue beginning in 2006 as a major spike in the number of recruits will begin to increase (Tables 12, 14). The rapidity of reaction by industry must be improved if the soft-shell protocol is to be effective. Another reason that caution should be exercised for the 2006 season.

7.4 Summary

The size structure continues to show the growth of several strong instars close to entering the fishable segment of the population. Sex ratios are improving for the first time in five years with mature females becoming more abundant (while mature males are declining in number).

Fishable biomass continued to decline, with the immature segment of the landed crab becoming a rather significant portion of the total landings.

Exploitation rates continued to increase in S-ENS, even with the reductions in TAC of the previous year. In N-ENS, exploitation rates have returned to more moderate historical rates after the heavy reduction in the 2005 season.

Substantial improvement in the fishable biomass is expected in the near future. In the 2006 season, much of the fishable biomass will be composed of immature individuals. Excessive fishing of this component of the fishable biomass is unwise.

8 Other considerations

The interests of the oil and gas industry to explore and develop areas on the Scotian Shelf near to or upstream of major crab fishing grounds and population centers (both N- and S-ENS) has been identified by numerous fishermen as a source of concern. The potential effects of seismic methods of exploration upon vulnerable components of the snow crab population and the uncertainties associated with the long-term biological effects of development need to be made explicit and include the following issues:

- Females are beginning to mature and become reproductive. This will continue for another 3 years minimum. They hold eggs for two years. That is, the snow crab are entering an important reproductive phase that will last at least 5 years into the future. The snow crab is behaviourally very complex, especially as they pertain to reproductive behaviour. 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 on the Scotian Shelf. Damage to eggs and reproductive behaviour will be critical to the future of the fishery.
- Males are recruiting shortly into the fishery (2 years) after many years of a decline. Their soft-shell phase will become proportionately more important. Soft-shelled crab are particularly sensitive to physical trauma.
- Many immature male and female are found in shallower waters. They are currently increasing rapidly in number. Damage to this component will have short- and long-term repercussions to the fishery.
- The earliest stages (instars 1 to 6) moult twice a year. Moulting crab are extremely vulnerable to all forms of mortality factors.

- No information is available for the effects of seismic pressure waves upon the planktonic forms of snow crab.

- Being a very long-lived species, the snow crab is exposed to environmental hazards for up to 13 to 16 years (since egg extrusion). As such, simple short-term studies (e.g., of exposure to strong pressure impulses and associated direct and indirect phenomena) cannot express the long-term, compounded (cumulative) effects of oil and gas exploration and development upon snow crab. This is a very large uncertainty.

- Snow crab are known to jettison legs or die when physically shocked (dropped onto the deck of a boat). This is an important unknown, especially as pressure waves can be amplified when moving through media of differing densities.

- Snow crab are top-level benthic predators. Bioaccumulation of heavy metals and toxic organic chemicals released from oil and gas development are quite likely, especially as they are so very long-lived. Any damage to the quality of snow crab can be highly detrimental to the reproductive capacity of the population and also taint the reputation of the quality of the Scotian Shelf snow crab.

- Recruitment has been observed centered over the area of potential exploration in historical data (1999 to 2002). The complex topography and cool temperature conditions in the area may have served as good ”nursery” areas. Destruction and pollution in the area would act to increase the uncertainty of the future viability of the fishery.

- The Misaine Bank area in particular, due to its complex topography and consistently cool bottom temperature conditions has been acting with high probability as a refuge from the fishery (and the predators of snow crab). Any direct or indirect harm to the snow crab in the region would dismantle this important refugial function in stabilising the fishery. This is particularly important if exploration and exploitation causes movement away from these core areas.

The snow crab population is currently in a critical state. Substantial sacrifices were made in the 2004 season by snow crab fishermen to reduce any risks of damaging the reproductive potential of Scotian Shelf snow crab. The numerous uncertainties associated with oil and gas exploration/development would undermine these sacrifices and increase the risk of destabilising the snow crab population on the Scotian Shelf.

9 Recommendations

A fisheries dependent only upon recruits makes for a volatile fishery, especially as strong snow crab year classes have so far been separated by 9 to 10 years on the Scotian Shelf. The consequence of a more conservative strategy may result in an accumulation of older males on the fishing grounds. This may be “wasted” from a purely short-term economic perspective; however in the long run, their presence can serve to stabilise the population by maintaining and occupying prime crab habitats, which keep at bay potential competitors in the guise of other crabs or even groundfish and to serve as large and strong mates for the more rapidly maturing females that require/prefer large males.

High catches of soft shell will likely become a major issue in 2006. The rapidity of reaction by industry must be ameliorated if unnecessary mortality of future recruits is to be averted.

A reduction in exploitation rates is suggested. Little additional recruitment into the mature segment of the fishable biomass is evident for 2006. However, many immature individuals will be within legally exploitable size. Exploitation of this component of the population is sub-optimal for several reasons. Further if exploitation rates are not modulated, the largest and most catchable males may be quickly eliminated from the whole population, leaving only small dwarf sized mature crab to mate with the maturing females. Larval production and recruitment into the fishery a decade into the future may be jeopardized if this reproduction by the current pulse of females is somehow destabilised. While thinking ahead a decade in advance may seem to be a bit much to demand, the snow crab fishery has shown itself to be a very proactive and mature industry that needs to consider its future carefully. This is especially the case as the Scotian Shelf crab population represents the southern-most limit of the distribution of this species. Continued caution for at least another year is advisable if the modulation of the snow crab population cycles is desired.

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Table 1. 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 2. Snow crab fishing seasons on the Scotian Shelf in the year 2005. Note the lateness of the fishing season which increases the likelihood of capturing soft-shelled and newly moulted white crab.

Area	Season
20-22	July 22, extended to October 1
23	June 17, extended to November 1
24	June 1, extended to November 11

Table 3. Summary of snow crab fisheries activity of N-ENS.

Year	Landings (t)	TAC (t)	Licenses	CPUE (kg/trap)	Effort (10^3 traps)
1997	534	540	74	23.3	22.9
1998	657	660	74	41.6	15.8
1999	899	900	78	54.8	16.4
2000	1,017	1,015	79	68.3	14.9
2001	1,066	1,065	80	94.3	11.3
2002	1,495	1,493	80	101.0	14.8
2003	1,492	1,493	80	76.8	19.4
2004	1,418	1,416	79	60.6	23.4
2005	562	566	78	30.6	18.4

Table 4. Summary of snow crab fisheries activity of S-ENS. Catch rates and trap hauls for 2001 to 2004 are calculated excluding slope area landings and effort as they were design-constrained trap surveys, however these landings are included in total landings and TACs. These slope allocations were for 200 t in 2001-2002 and 300 t in 2003-2004.

Year	Landings (t)	TAC (t)	Licenses	CPUE (kg/trap)	Effort (10^3 traps)
1997	1,157	1,163	59	50.9	22.7
1998	1,558	1,671	67	68.9	22.6
1999	2,700	2,700	-	71.1	38.0
2000	8,701	8,799	158	85.0	102.4
2001	9,048	9,023	163	87.8	103.1
2002	8,891	9,022	149	111.7	79.6
2003	8,836	9,113	145	98.6	89.6
2004	8,022	8,241	130	105.6	76.0
2005	6,407	6,353	118.5	109.4	58.6

Table 5. Carapace condition of crab smaller than 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	3.97	0.29	56.18	38.53	1.03
2005	12.41	1.20	41.10	43.24	2.05

Table 6. Carapace condition of crab smaller than 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	7.14	2.75	64.30	24.34	1.47
2005	11.31	17.09	49.64	19.72	2.24

Table 7. Carapace condition of crab larger than 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	2.46	4.9	72.49	19.78	0.37
2005	18.09	2.1	61.01	18.03	0.77

Table 8. Carapace condition of crab larger than 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	3.17	3.58	74.54	17.99	0.72
2005	5.87	10.98	68.15	14.29	0.71

Table 9. Carapace condition of crab larger than 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.

Year	Carapace condition				
	1	2	3	4	5
1999	44.62	5.42	30.65	19.31	0.00
2000	5.20	0.76	73.55	20.48	0.00
2001	5.19	2.96	67.89	23.97	0.00
2002	0.00	2.08	68.08	29.47	0.37
2003	0.91	16.32	63.10	19.66	0.00
2004	0.00	0.00	63.31	36.69	0.00
2005	0.00	0.00	59.71	38.61	1.68

Table 10. Carapace condition of crab larger than 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.

Year	Carapace condition				
	1	2	3	4	5
1999	25.04	3.93	62.53	8.50	0.00
2000	16.03	9.77	72.91	1.29	0.00
2001	17.40	0.00	75.83	6.78	0.00
2002	4.86	15.13	75.75	4.25	0.00
2003	3.79	8.08	67.62	19.28	1.23
2004	0.00	7.28	61.46	31.27	0.00
2005	0.00	9.60	73.81	16.59	0.00

Table 11. N-ENS numerical fishing mortality broken down by instar, carapace condition and maturity status. Immature SM refers to immature skip moulters. Note the rather complete exploitation of almost all mature instars.

Instar	Class	1999	2000	2001	2002	2003	2004	2005
11	Immature	0.007	0.0271	0.044	0.366	0.234	0.096	0.005
11	Immature SM	0.164	0.203	0.286	0.798	0.720	0.699	0.359
11	CC1to2	0.046	0.085	0.164	0.647	0.845	1.0	0.028
11	CC3to4	0.165	0.208	0.266	0.615	0.463	0.615	0.441
11	CC5	1	1	1	0.312	1	1	0.077
12	Immature	0.117	0.340	0.377	0.729	0.551	1	0.041
12	Immature SM	0.904	0.894	0.943	0.975	0.954	1	0.787
12	CC1to2	0.182	0.745	0.729	0.917	0.721	1.0	1.0
12	CC3to4	0.724	0.811	0.788	0.904	0.869	0.910	0.791
12	CC5	1	1	1	1	1	1	1
13	CC1to2	1	1	1	1	1	1	1
13	CC3to4	1	1	1	1	1	1	1
13	CC5	1	1	.	.	.	.	.

Table 12. N-ENS projection of future numerical abundance ($\times 10^3$) based on 2005 survey and fishery performance broken down by instar, carapace condition and maturity status. Exploitation rate is fixed at 30% by biomass for these projections. Note in particular the large numbers of immature and immature skip moulters projected for the 2006 fishing season, in especially the instar 11 and 12 classes.

Instar	Class	2005	2006	2007	2008	2009	2010
5	Immature	0	0	0	0	0	0
6	Immature	426	0	0	0	0	0
7	Immature	909	341	0	0	0	0
8	Immature	1866	1508	565	0	0	0
9	Immature	3915	2873	2321	870	0	0
9	Immature SM	0	0	0	0	0	0
9	CC1to2	277	204	164	62	0	0
9	CC3to4	0	0	0	0	0	0
9	CC5	0	0	0	0	0	0
10	Immature	1464	3945	2895	2339	877	0
10	Immature SM	0	633	464	375	141	0
10	CC1to2	128	344	252	204	76	0
10	CC3to4	0	31	92	84	70	36
10	CC5	0	0	0	0	0	0
11	Immature	372	1662	4469	3292	2661	999
11	Immature SM	158	2097	5606	4192	3395	1279
11	CC1to2	244	1014	2938	2181	1764	663
11	CC3to4	741	316	424	1089	1061	920
11	CC5	106	23	10	13	34	33
12	Immature	123	294	1304	3557	2625	2129
12	Immature SM	119	324	1419	4012	2974	2432
12	CC1to2	0	119	836	2309	1722	1403
12	CC3to4	1321	275	81	196	537	490
12	CC5	0	2	0	0	0	1
13	CC1to2	0	1	2	8	23	17
13	CC3to4	0	0	0	0	1	3
13	CC5	0	0	0	0	0	0

Table 13. S-ENS numerical fishing mortality broken down by instar, carapace condition and maturity status. Immature SM refers to immature skip moulters. Note the rather complete exploitation of almost all mature instars.

Instar	Class	1999	2000	2001	2002	2003	2004	2005
11	Immature	0.002	0.003	0.017	0.064	0.043	0.014	0.037
11	Immature SM	0.031	0.104	0.140	0.491	0.411	0.487	0.203
11	CC1to2	0.013	0.022	0.113	0.391	0.238	0.209	0.309
11	CC3to4	0.051	0.109	0.226	0.558	0.408	0.374	0.436
11	CC5	1	1	1	1	0.579	1	1
12	Immature	0.0411	0.071	0.242	0.503	0.319	0.343	0.241
12	Immature SM	0.527	0.689	0.833	0.960	0.908	0.936	0.748
12	CC1to2	0.102	0.195	0.394	0.714	0.531	0.808	0.834
12	CC3to4	0.301	0.440	0.680	0.869	0.752	0.724	0.778
12	CC5	1	1	1	1	0.900	1	1
13	CC1to2	1	1	1	1	1	1	1
13	CC3to4	1	1	1	1	1	1	1
13	CC5	1	1	.	.	.	1	1

Table 14. S-ENS projection of future numerical abundance ($\times 10^3$) based on 2005 survey and fishery performance broken down by instar, carapace condition and maturity status. Exploitation rate is fixed at 30% by biomass for these projections. Note in particular the large numbers of immature and immature skip moulters projected for the 2006 fishing season, in especially the instar 11 and 12 classes.

Instar	Class	2005	2006	2007	2008	2009	2010
5	Immature	0	0	0	0	0	0
6	Immature	672	0	0	0	0	0
7	Immature	3528	649	0	0	0	0
8	Immature	11932	3157	581	0	0	0
9	Immature	26802	17049	4510	830	0	0
9	Immature SM	0	0	0	0	0	0
9	CC1to2	1365	868	230	42	0	0
9	CC3to4	0	0	0	0	0	0
9	CC5	0	0	0	0	0	0
10	Immature	32345	39846	25345	6705	1234	0
10	Immature SM	4887	6353	4041	1069	197	0
10	CC1to2	2860	3523	2241	593	109	0
10	CC3to4	1500	1999	2537	2235	1358	714
10	CC5	0	0	0	0	0	0
11	Immature	17921	28792	35467	22570	5974	1100
11	Immature SM	8734	19607	24138	15439	4107	759
11	CC1to2	2331	6695	8374	5346	1420	262
11	CC3to4	8786	5842	6582	7905	7049	4527
11	CC5	0	35	23	26	32	29
12	Immature	7085	9334	14988	18558	11871	3154
12	Immature SM	5262	10699	17140	21636	14100	3798
12	CC1to2	1820	9918	17982	22422	14474	3874
12	CC3to4	20962	10613	9544	13021	17057	15368
12	CC5	0	59	30	27	39	52
13	CC1to2	0	10	21	34	43	28
13	CC3to4	0	0	5	13	23	32
13	CC5	0	0	0	0	0	0

Table 15. N-ENS projection of future biomass (t) based on 2005 survey and fishery performance broken down by instar, carapace condition and maturity status. Exploitation rate is fixed at 30% by biomass. FB is fishable biomass.

Year	FB prefishery	SE	Projected landings	FB postfishery	Expected recruitment
2005	1657	61	562	1095	
2006	1165	40	350	816	71
2007	3499	169	1050	2450	2684
2008	8130	449	2439	5691	5681
2009	6442	331	1933	4510	751
2010	5103	267	1531	3572	594

Table 16. S-ENS projection of future biomass (t) based on 2005 survey and fishery performance broken down by instar, carapace condition and maturity status. Exploitation rate is fixed at 30% by biomass. FB is fishable biomass.

Year	FB prefishery	SE	Projected landings	FB postfishery	Expected recruitment
2005	29542	485	6407	23135	
2006	31058	213	9318	21741	7923
2007	40983	278	12295	28688	19242
2008	49435	340	14830	34605	20747
2009	39275	243	11783	27493	4671
2010	21063	131	6319	14744	−6430

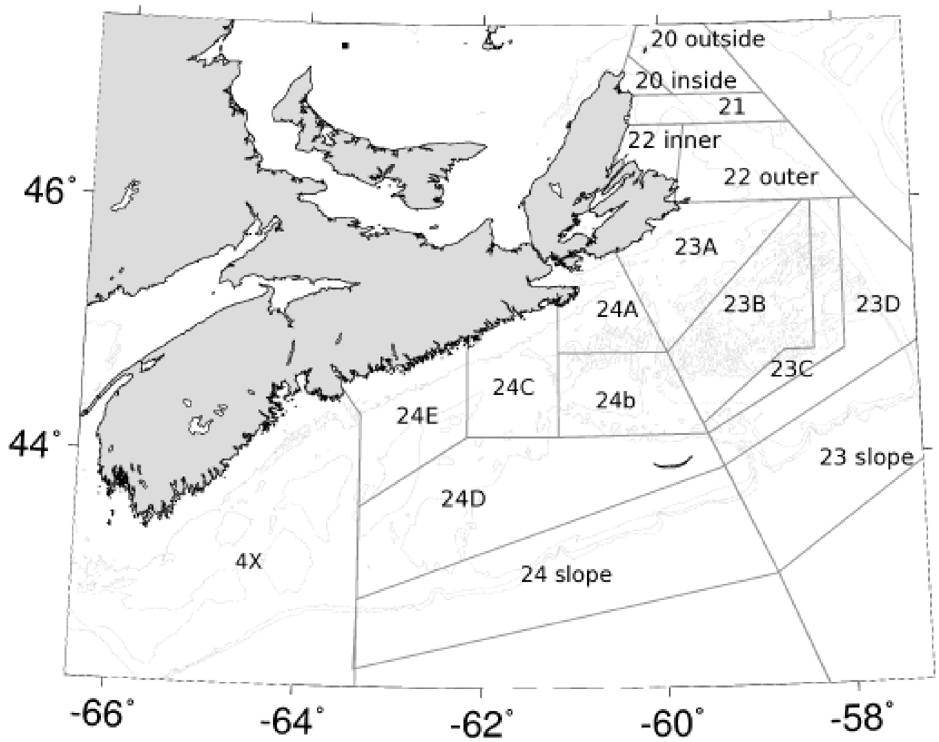

Figure 1. Location of historical management crab fishing areas (CFAs) on the Scotian Shelf.

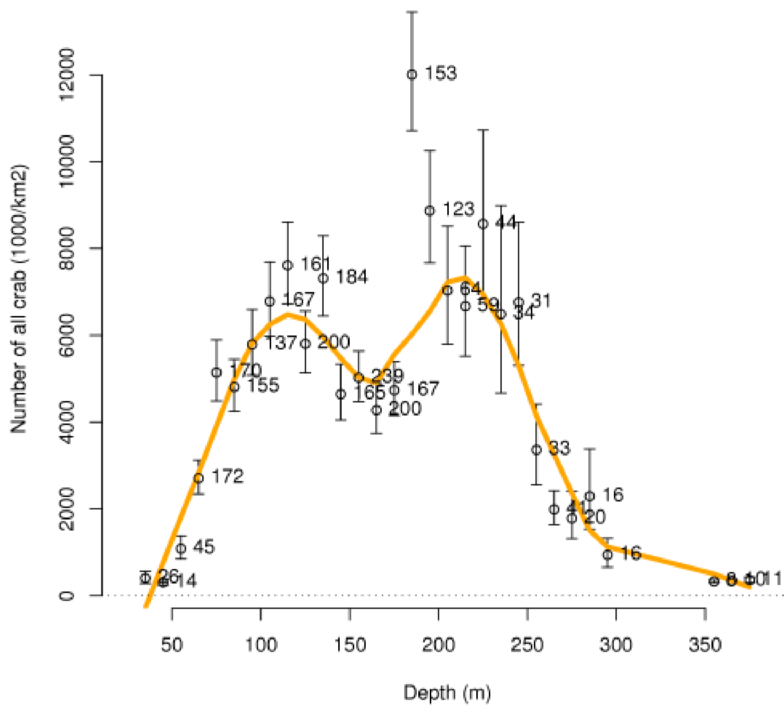

Figure 2. Habitat preferences of snow crab on the Scotian Shelf. Numerical densities ($\times 10^3/km^2$) of all snowcrab as a function of sampling depth (m). 1 standard error bars are presented with numbers indicating the number of stations. A loess filter was used for the heuristic trend line.

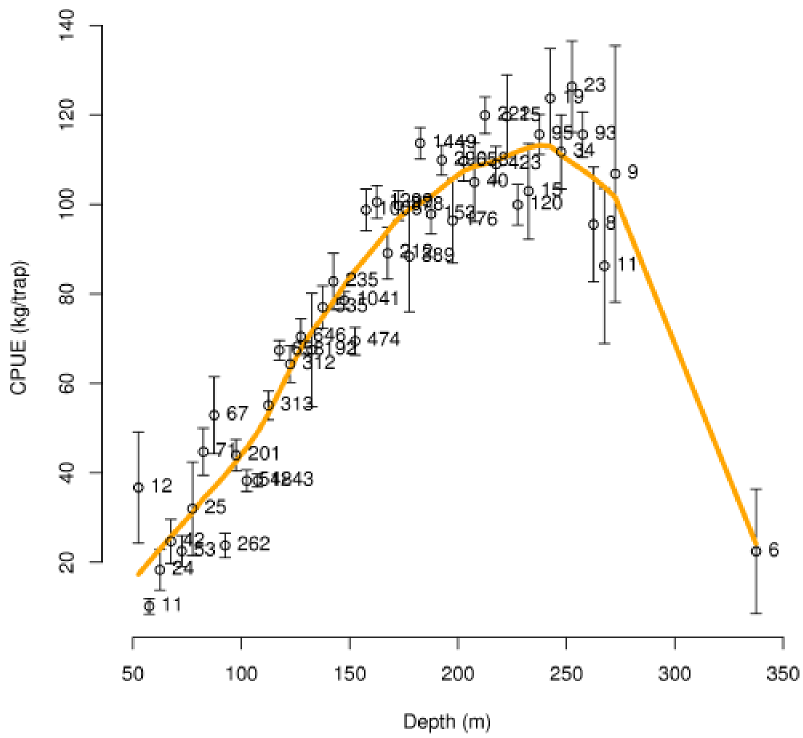

Figure 3. Habitat preferences of snow crab on the Scotian Shelf. Fishery catch rates (kg/trap) as a function of trap depth (m). 1 standard error bars are presented with numbers indicating the number of trap hauls. A loess filter was used for the heuristic trend line.

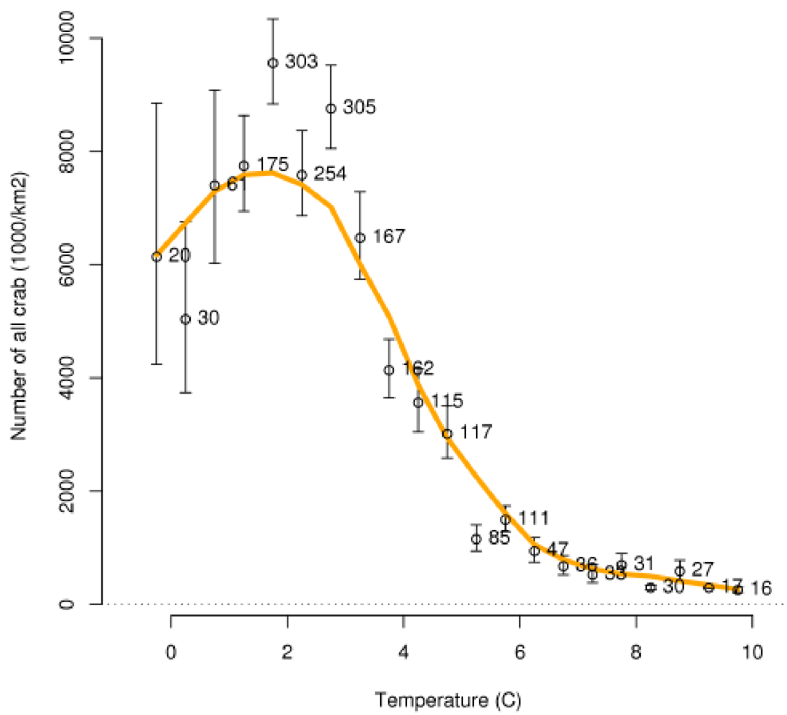

Figure 4. Habitat preferences of snow crab on the Scotian Shelf. Numerical densities of snow crab ($\times 10^3/km^2$) as a function of bottom temperature (°C). 1 standard error bars are presented with numbers indicating the number of stations. A loess filter was used for the heuristic trend line.

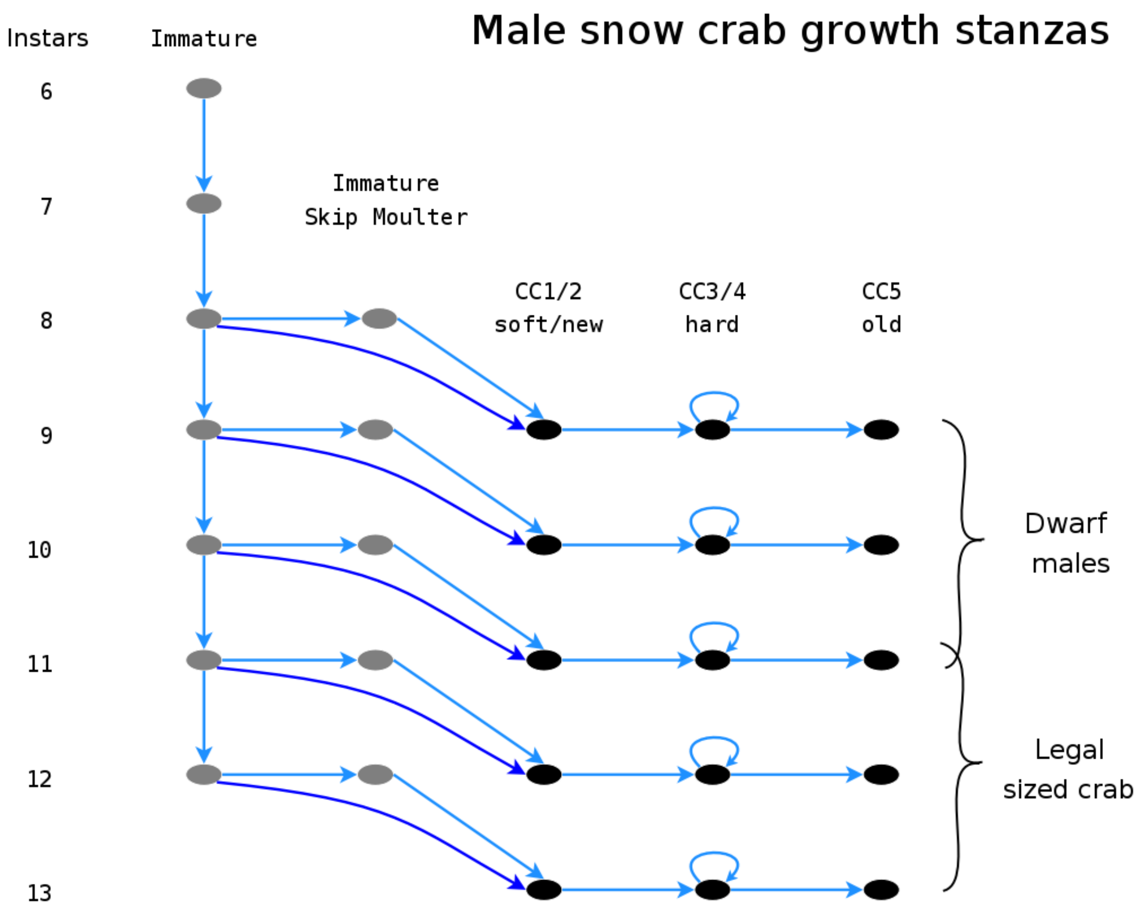

Figure 5. The growth stanzas of male snow crab. Each instar is determined from carapace width bounds obtained from modal analysis and categorised to carapace condition (CC) and maturity from visual inspection and/or maturity equations. Snow crab are resident in each growth stanza for 1 year, with the exception of CC2/4 which are known from mark-recapture studies to last from 2 to 5 years.

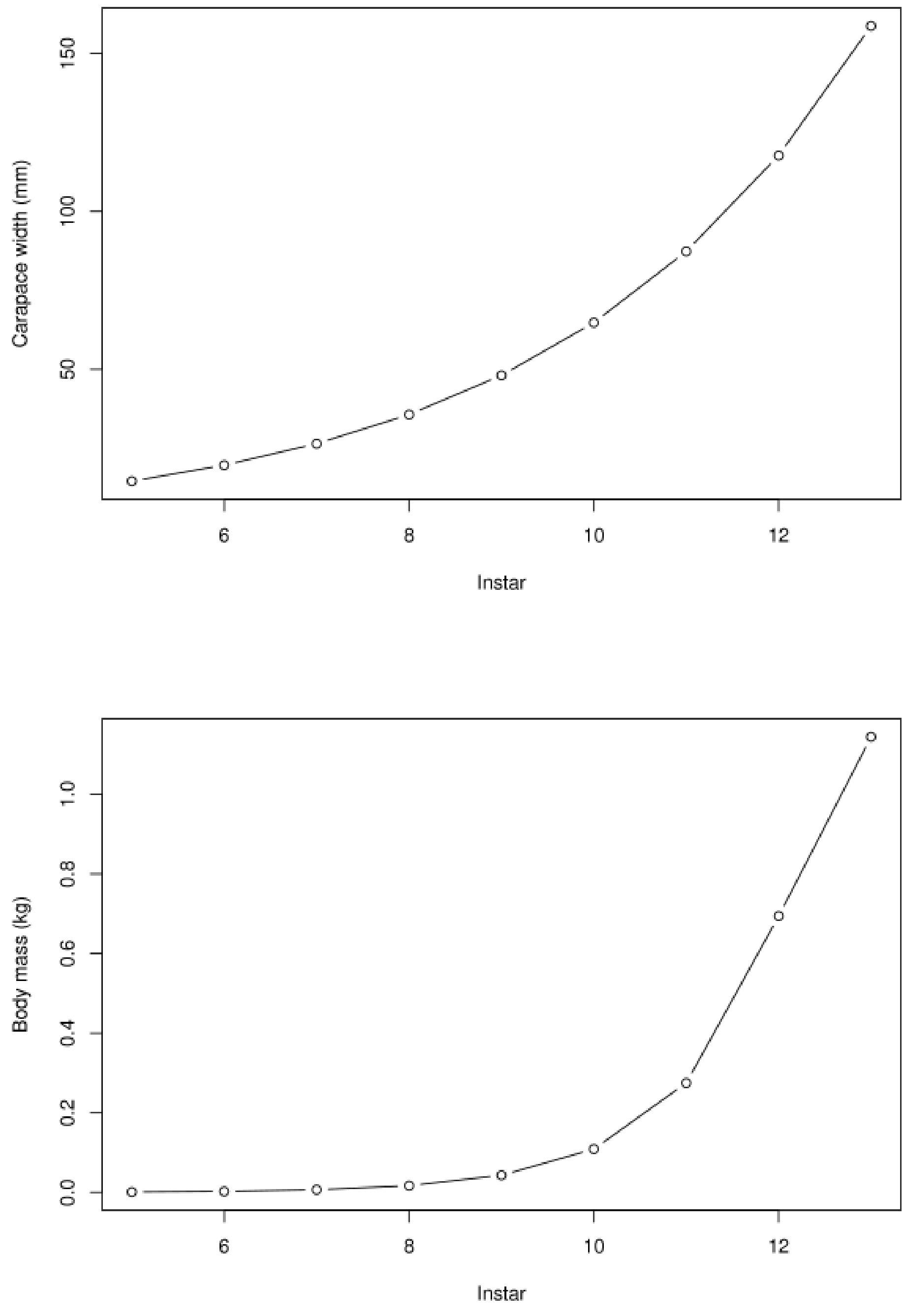

Figure 6. Growth curves determined from Scotian Shelf male snow crab.

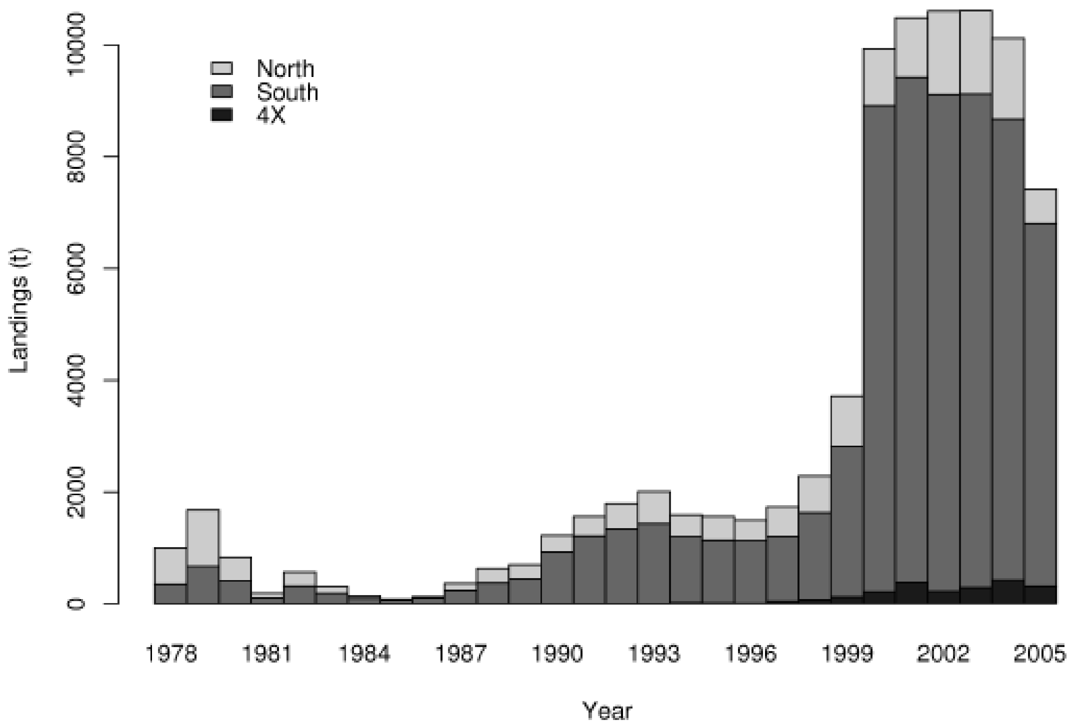

Figure 7. Temporal variations in the landings of snow crab on the Scotian Shelf (t). Note the sharp increase in landings associated with dramatic increases to TACs and a doubling of fishing effort in the year 2000. The landings follow the TACs with little deviation (and so are not shown) indicating that the use of baited traps is very efficient at exploiting snow crabs. Nonetheless increased fishing effort was observed in the northern areas in recent years (see Figure 9).

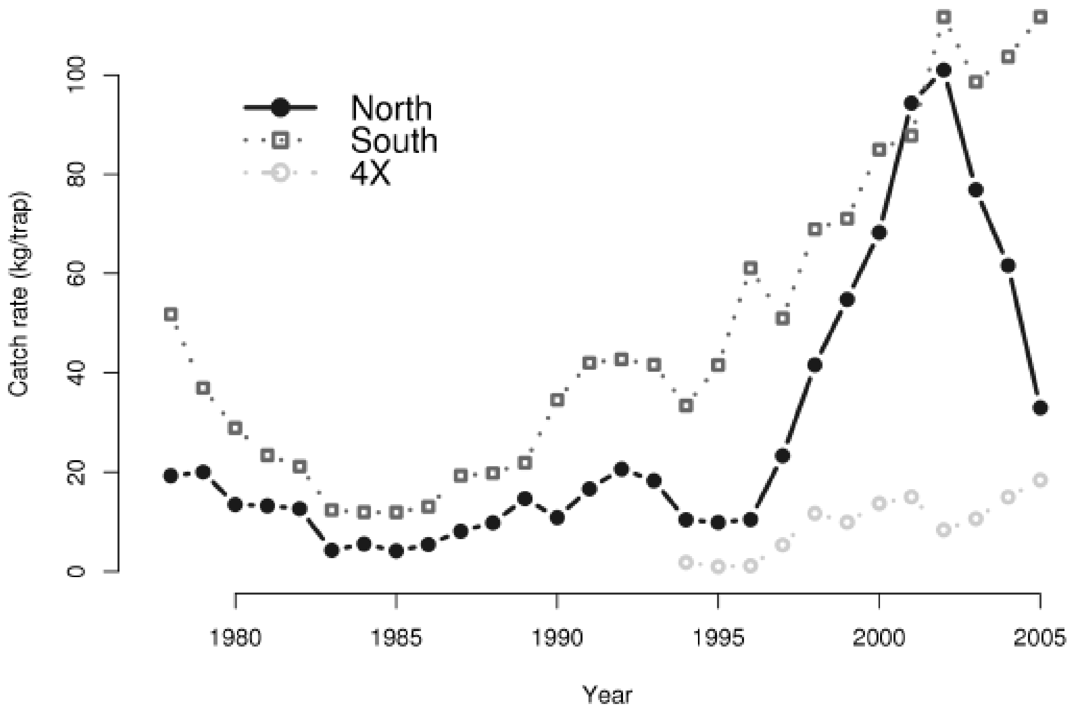

Figure 8. Temporal variations in catch rates of snow crab on the Scotian Shelf, expressed as kg per trap haul. Trap design and size have changed over time. No correction for these varying trap-types nor soak time and bait-type have been attempted.

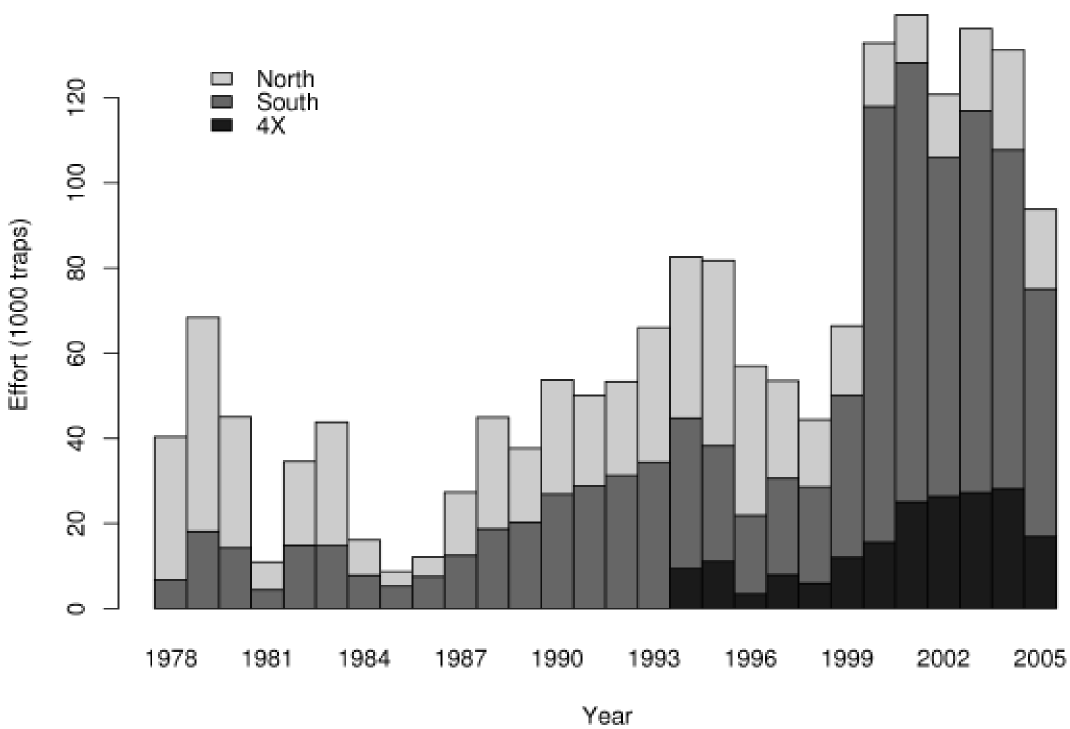

Figure 9. Temporal variations in the fishing effort, expressed as the number of trap hauls. Note the doubling of effort in the year 2000.

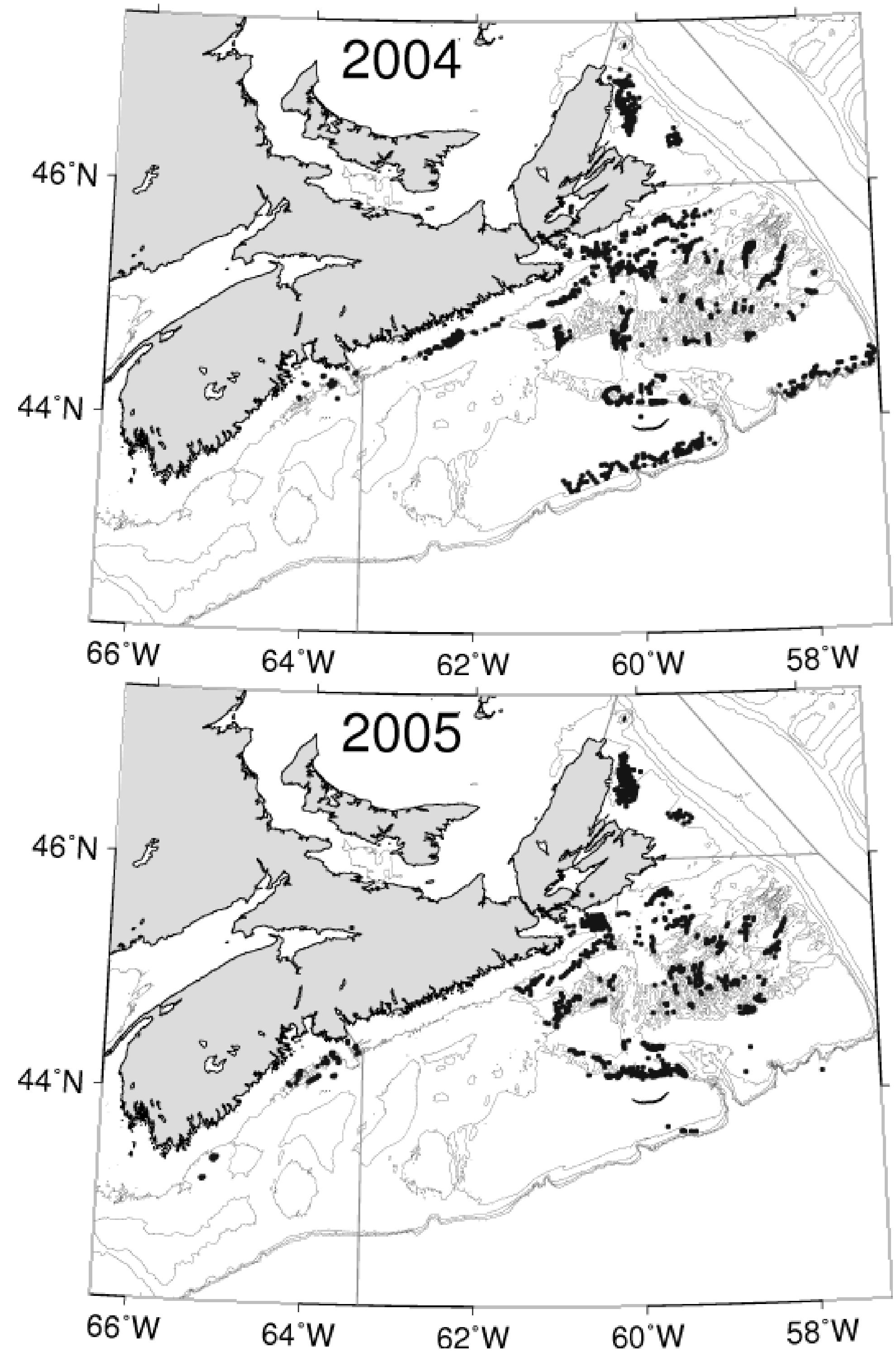

Figure 10. At-sea-observer monitored locations on the Scotian Shelf for 2004 and 2005.

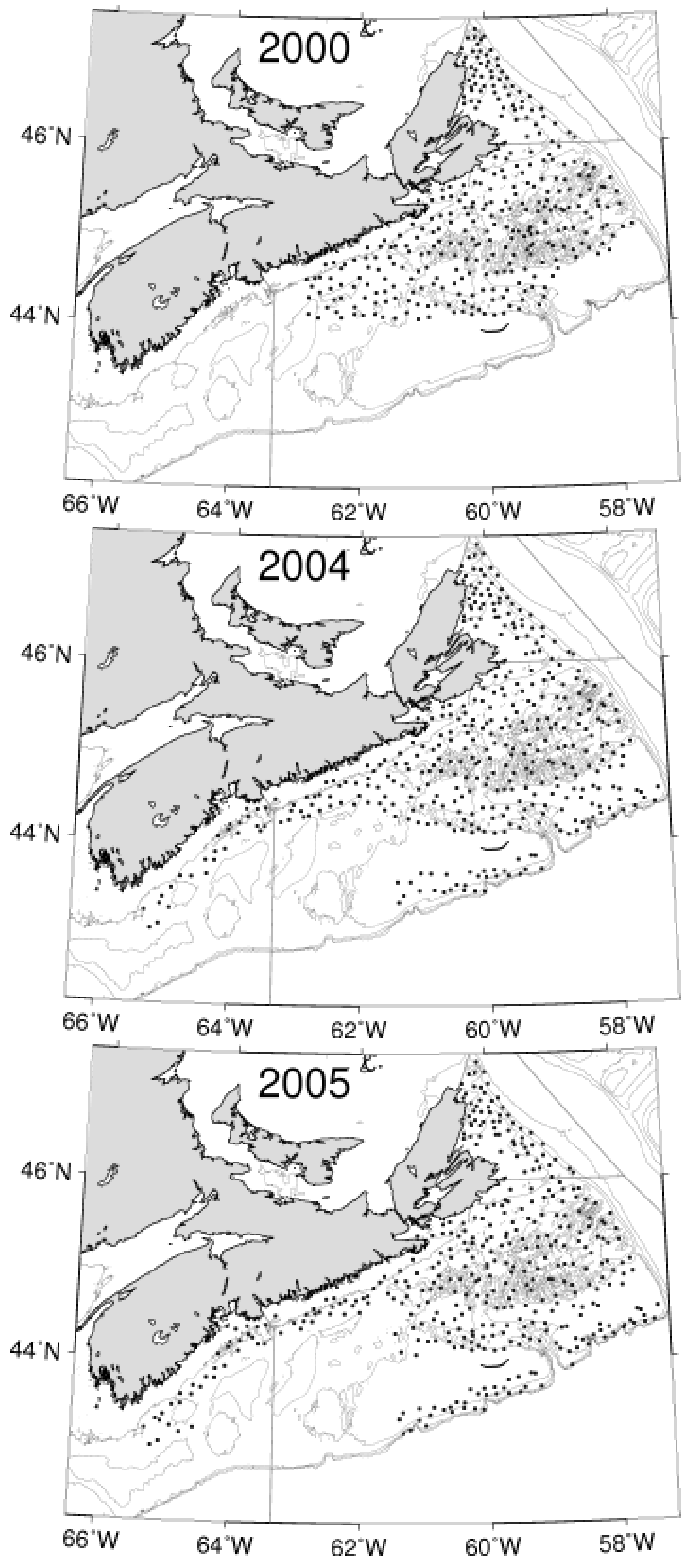

Figure 11. Trawl survey locations on the Scotian Shelf for 2000, 2004 and 2005. A total of 389 stations were sampled in 2005 between 8 September to 30 November. The 2000 locations are shown to illustrate how the stations have changed over time.

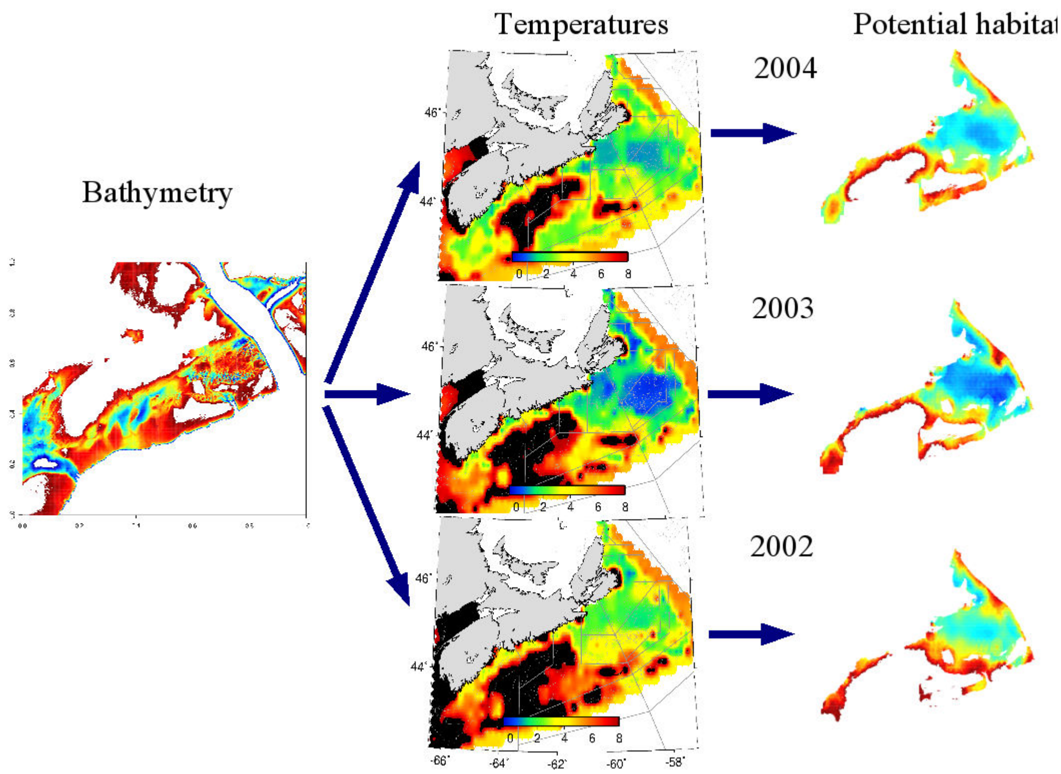

Figure 12. Schematic of geostatistical methods used to estimate potential snow crab habitat area.

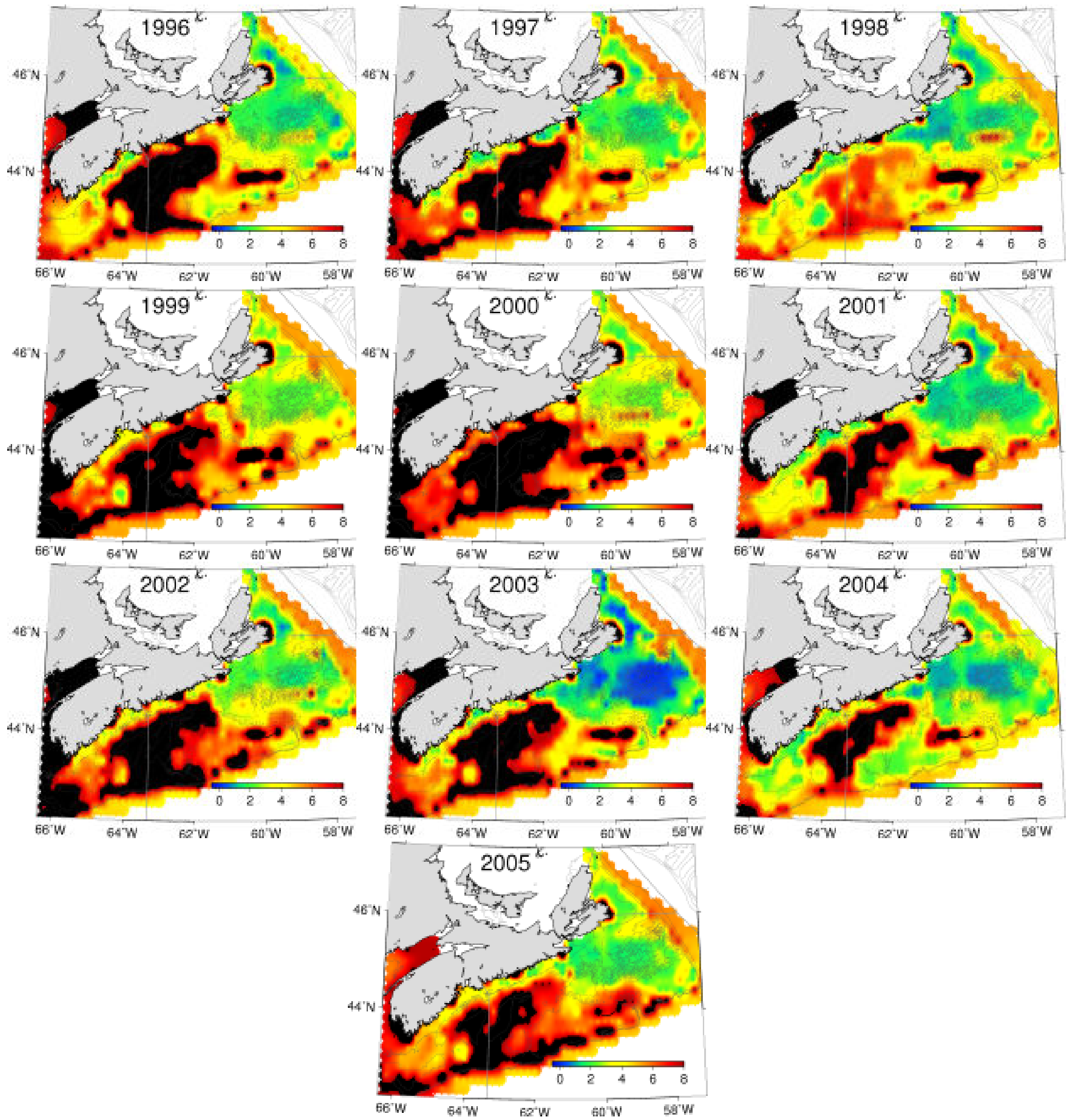

Figure 13. Map of bottom temperatures on the Scotian Shelf during late summer/autumn.

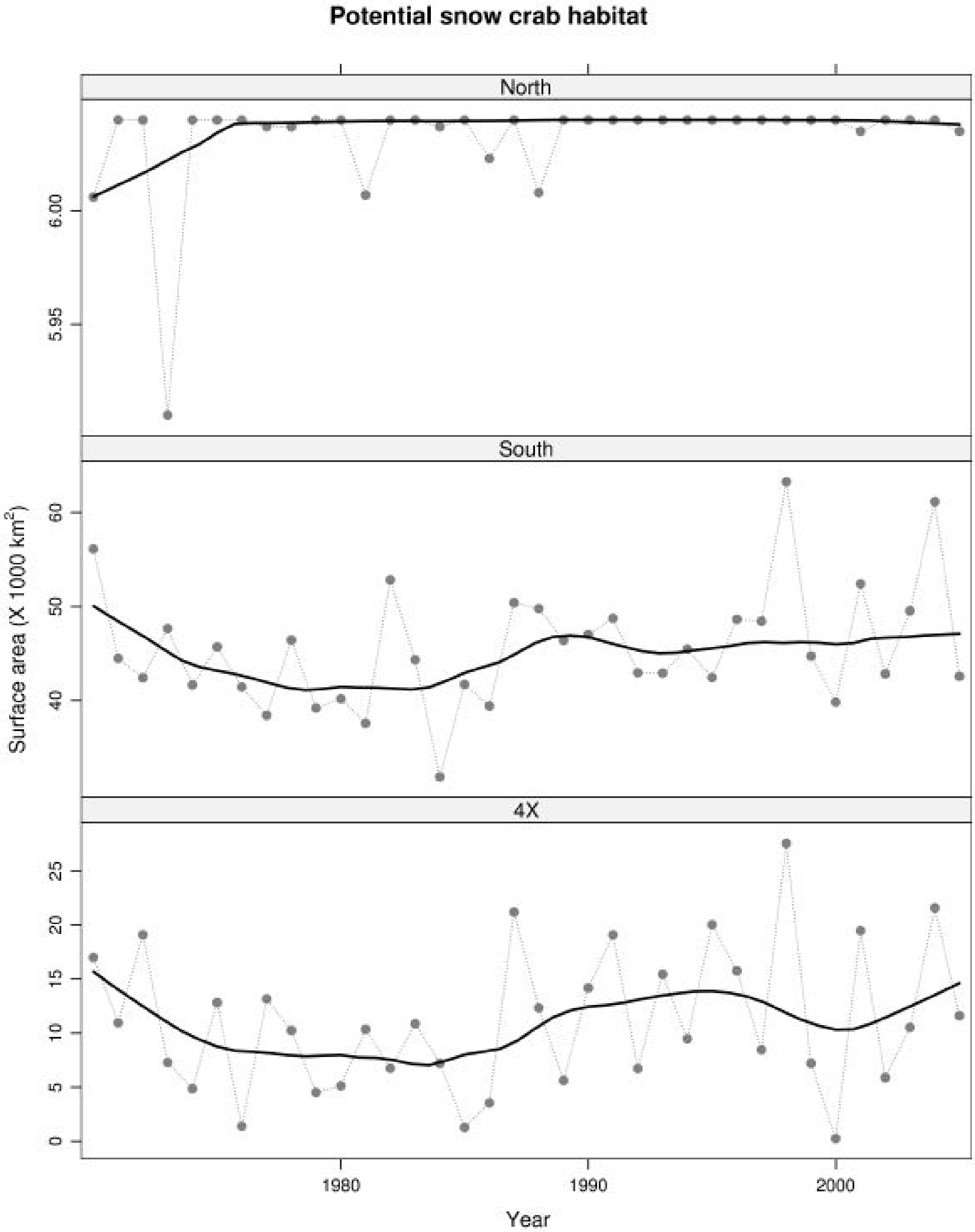

Figure 14. Annual variations in the surface area of potential snow crab habitat. Note that in N-ENS, very little variations occur between years (i.e., total habitat space does not change, although the quality of the habitat does vary (see Figure 15). In S-ENS, the potential surface has been more variable with the 2005 season being at near the long-term mean for the area. Stronger variations have been occurring in the area since the late 1990s, relative to the historical record. In 4X, the southern-most limit of the distribution of snow crab, the fluctuations are also quite pronounced.

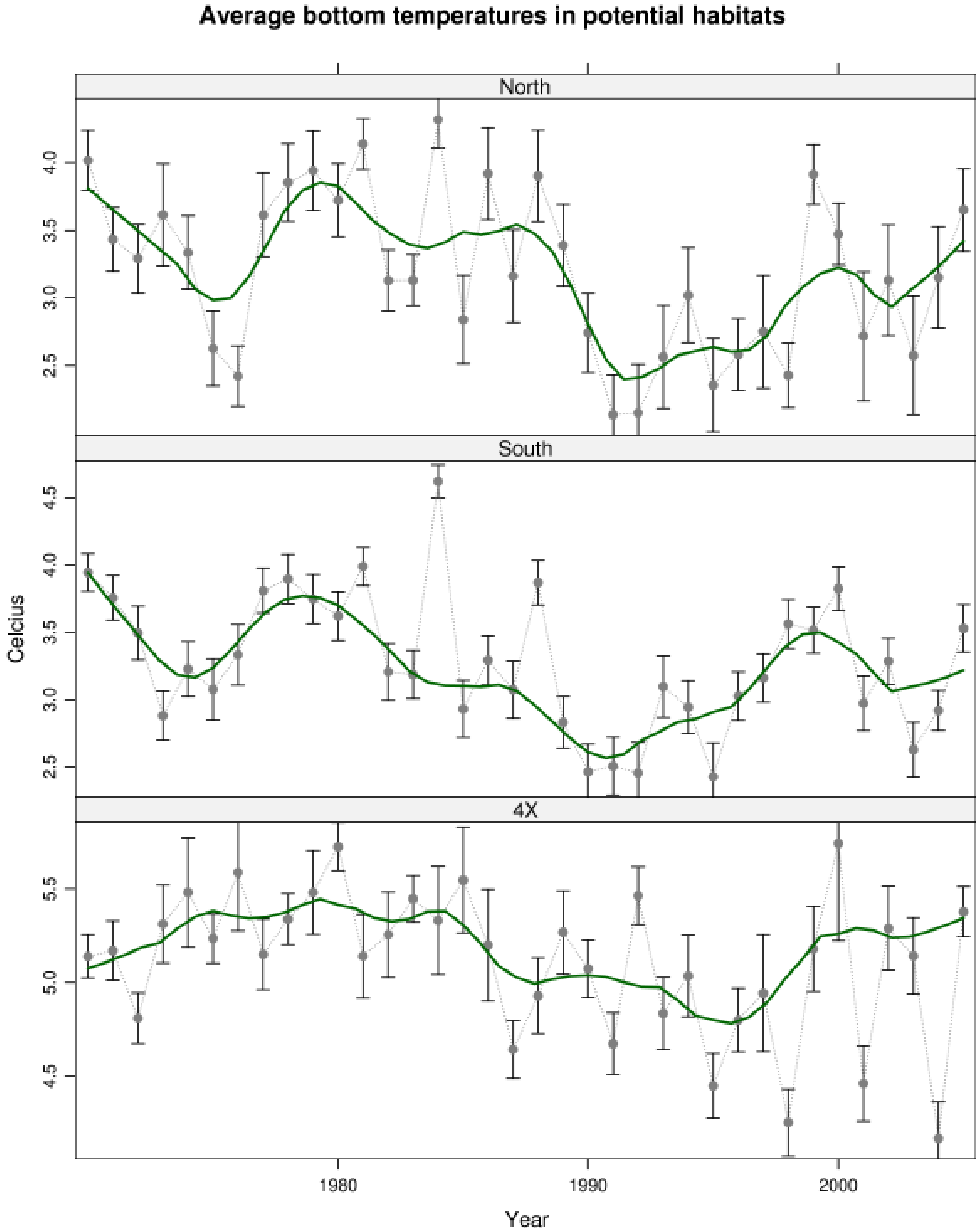

Figure 15. Annual variations in the summer/autumn mean bottom temperature in the areas of potential snow crab habitat.

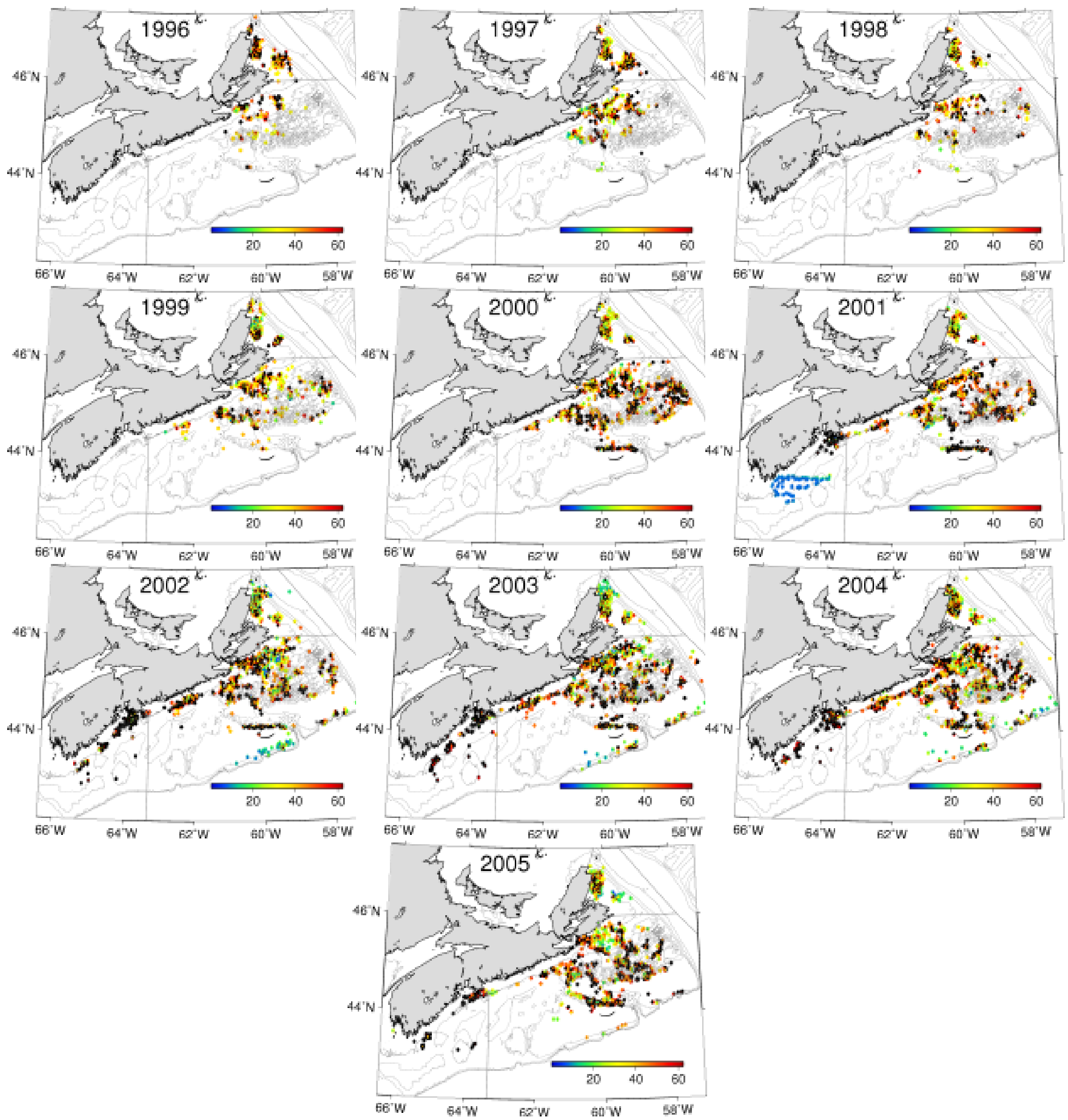

Figure 16. Fishing effort (number of trap hauls) from fisheries logbook data for the years 1996 to present. Note the increase in effort offshore and reduction inshore in the southern CFAs. No visible changes are evident in the northern CFAs.

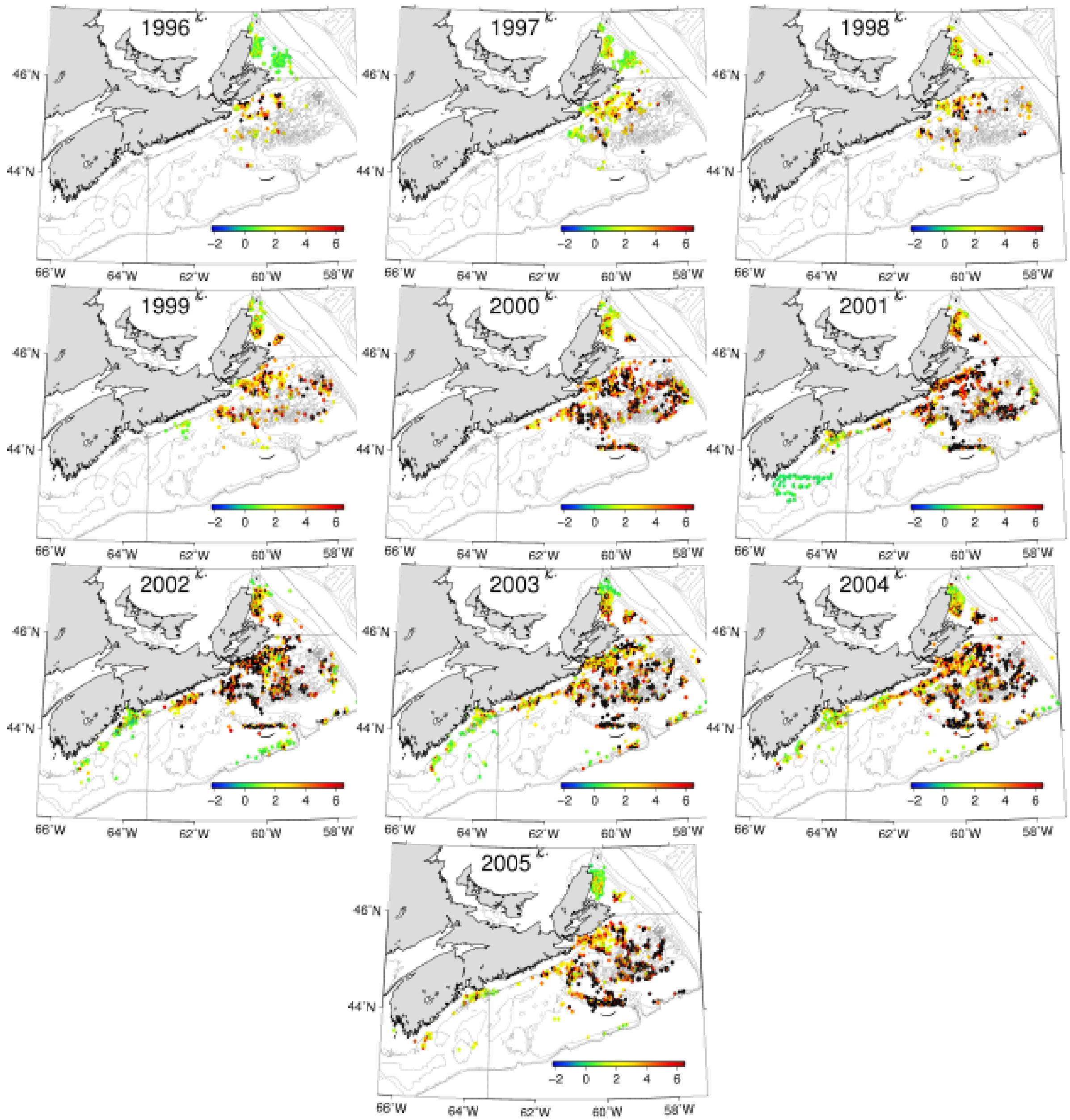

Figure 17. Crab landings (kg) from fisheries logbook data for the years 1996 to the present. Note the increase in landings offshore and reduction inshore for the southern CFAs. No visible changes are evident in the northern CFAs.

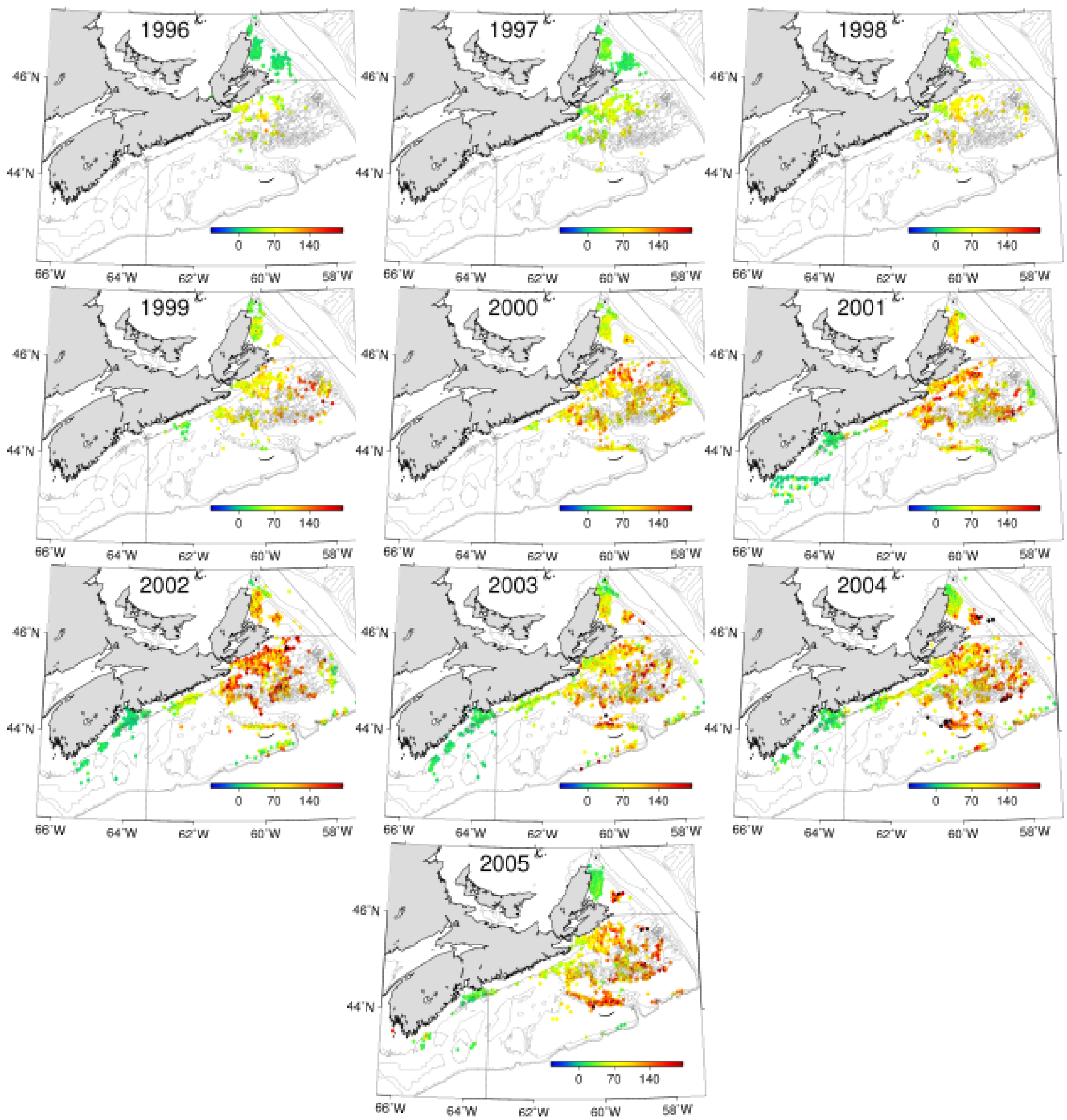

Figure 18. Catch rates (kg/trap) from logbook data for the years 1996 to the present. Note the expansion of fisheries activity to more offshore locations with time. TACs were raised dramatically in 2000. Since that time, large decreases of catch rates in the inshore areas have become evident, indicating strong depletion. The movement to more offshore areas (in the southern CFAs 23 and 24) has offset this lowering of catch rates, where previously unexploited areas became more fully exploited. The temporal increases in crude catch rates of the southern CFAs are therefore due to the spatial expansion of the targeted areas and the fishers learning to find newer fishing grounds.

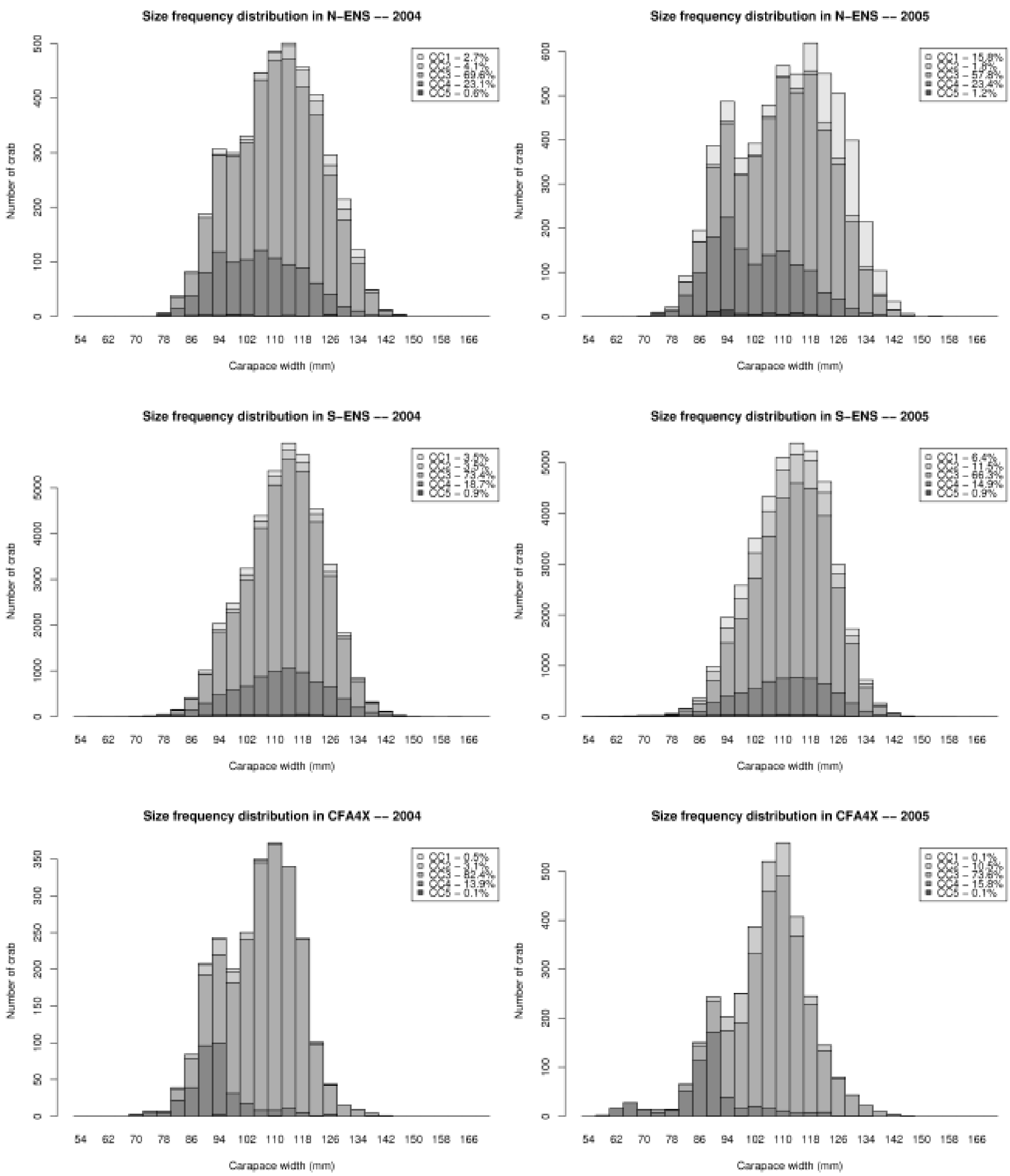

Figure 19. Size frequency distribution of at-sea-observer monitored snow crab broken down by carapace condition.

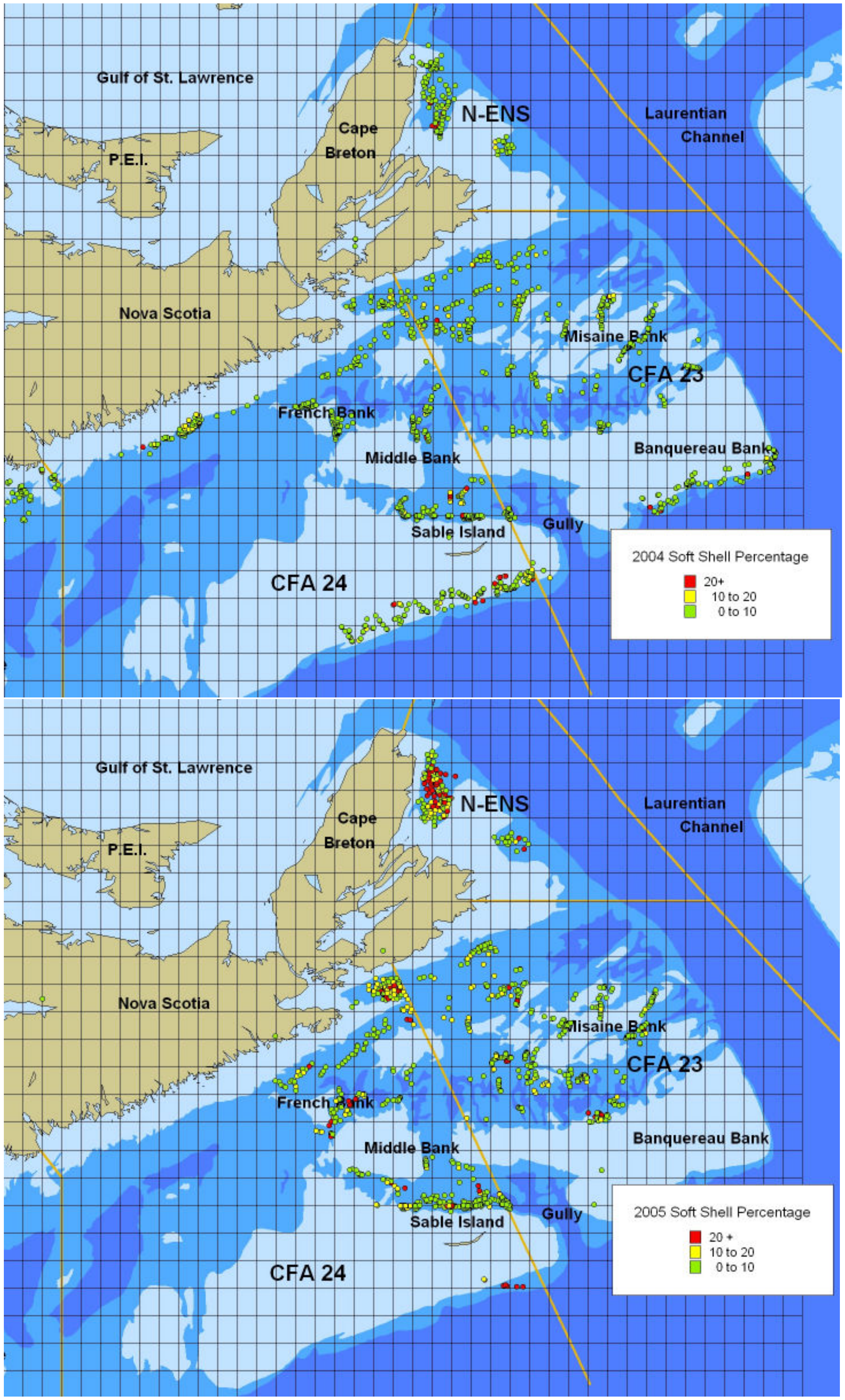

Figure 20. Location of soft-shell snow crab occurence in the commerical fishery in 2004 and 2005.

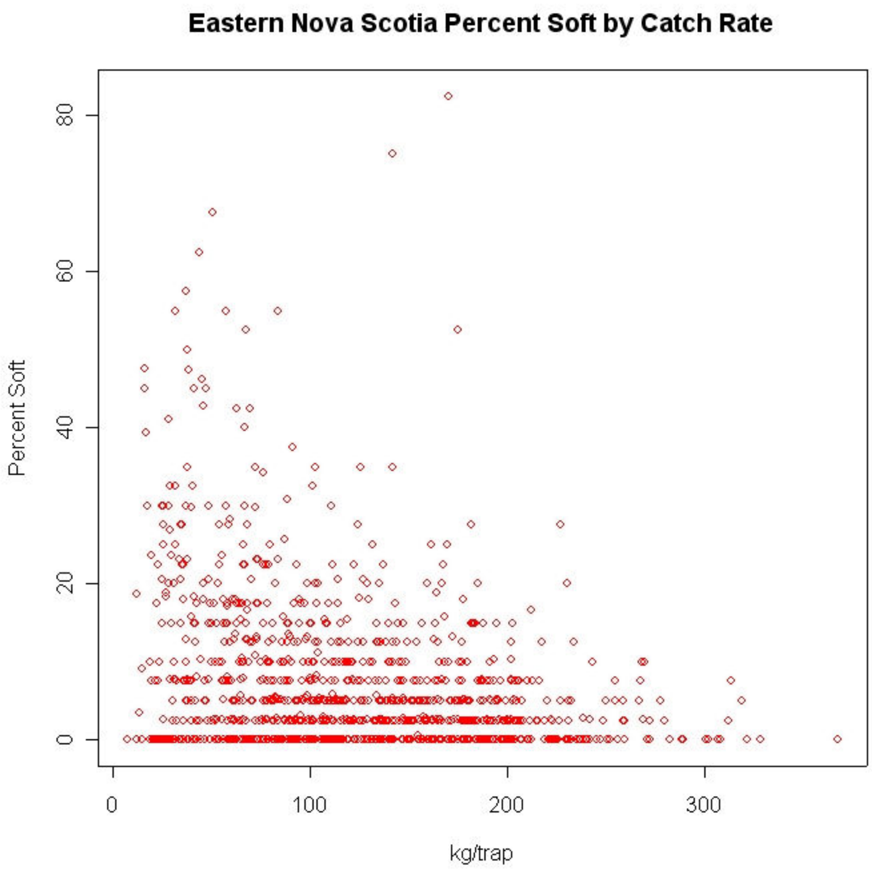

Figure 21. The relationship between the percentage soft-shell as a function of the catch rates in at-sea-observed catches. Higher relative numbers of soft-shelled crab are expected in depleted areas as soft-shelled crab generally avoid hard-shelled males. However, high proportions of soft-shelled crab are found even in areas with high catch rates indicating that there is a large potential for damaging the fishable biomass if soft-shell catches are not carefully managed.

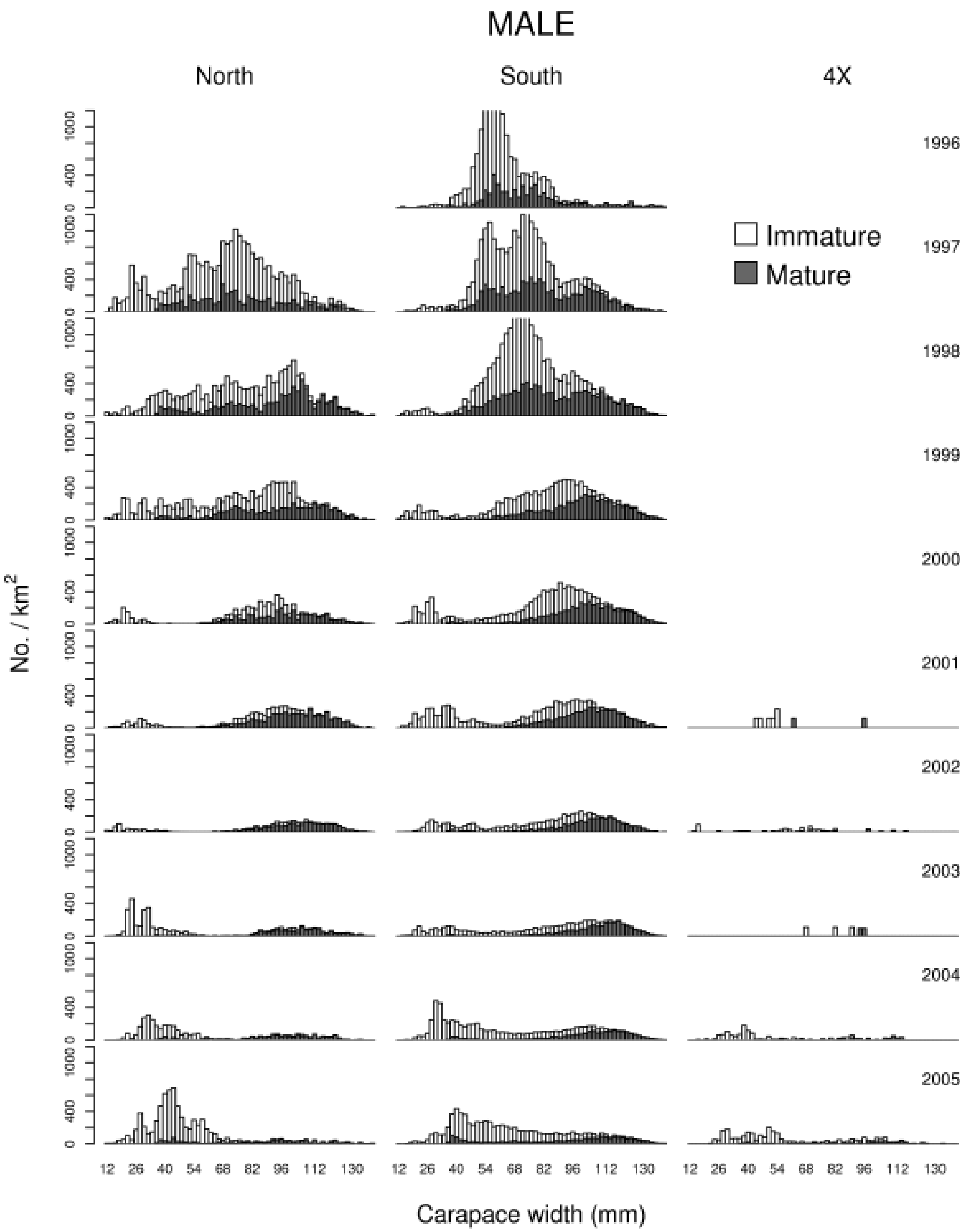

Figure 22. Size-frequency histograms of carapace width of male snow crabs. Note the increasing numbers of juvenile crab, 2 to 4 years from entering morphometrically mature size classes.

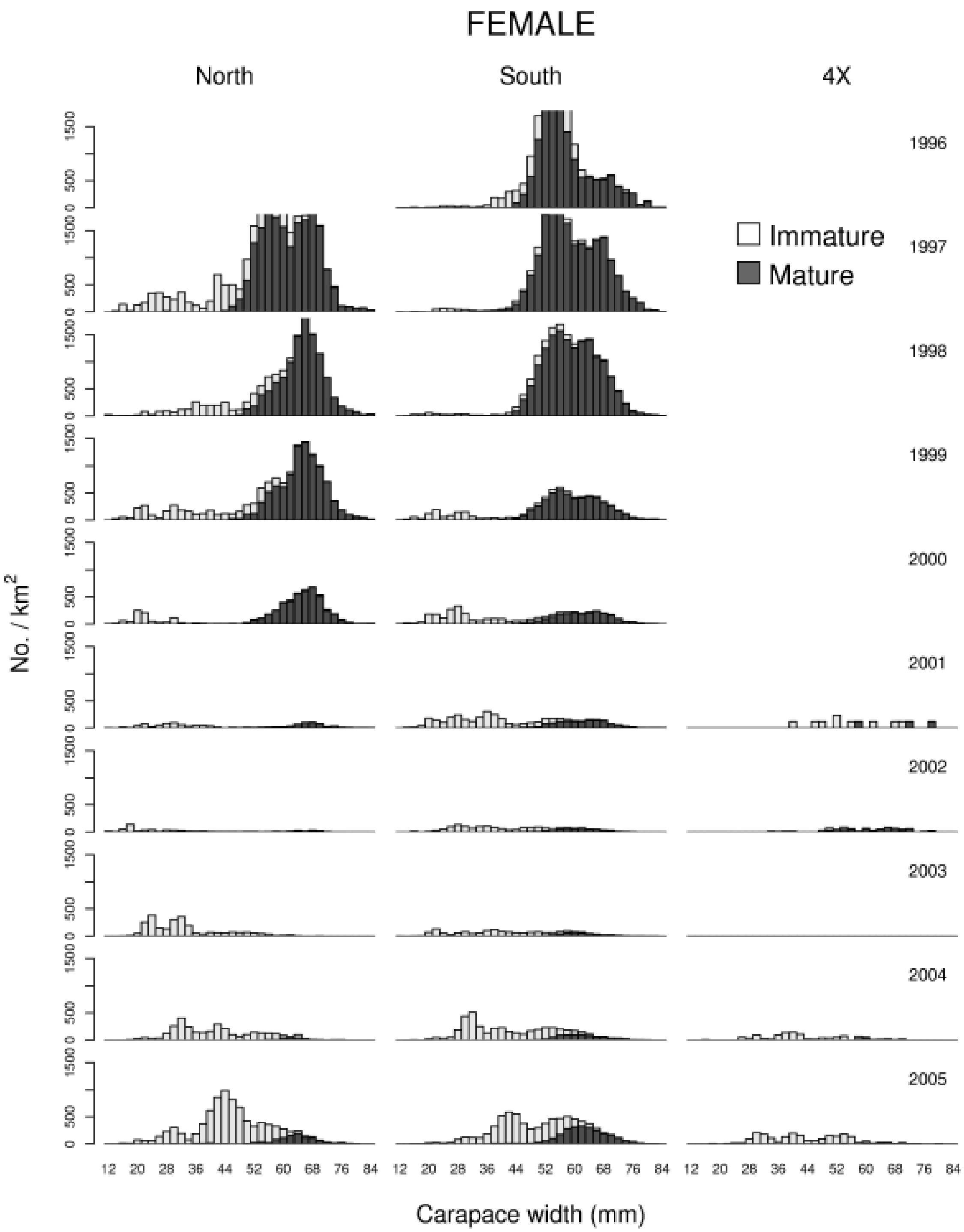

Figure 23. Size-frequency histograms of carapace width of female snow crabs. Note the increasing numbers of juvenile crab, 1 to 3 years from entering morphometrically mature size classes.

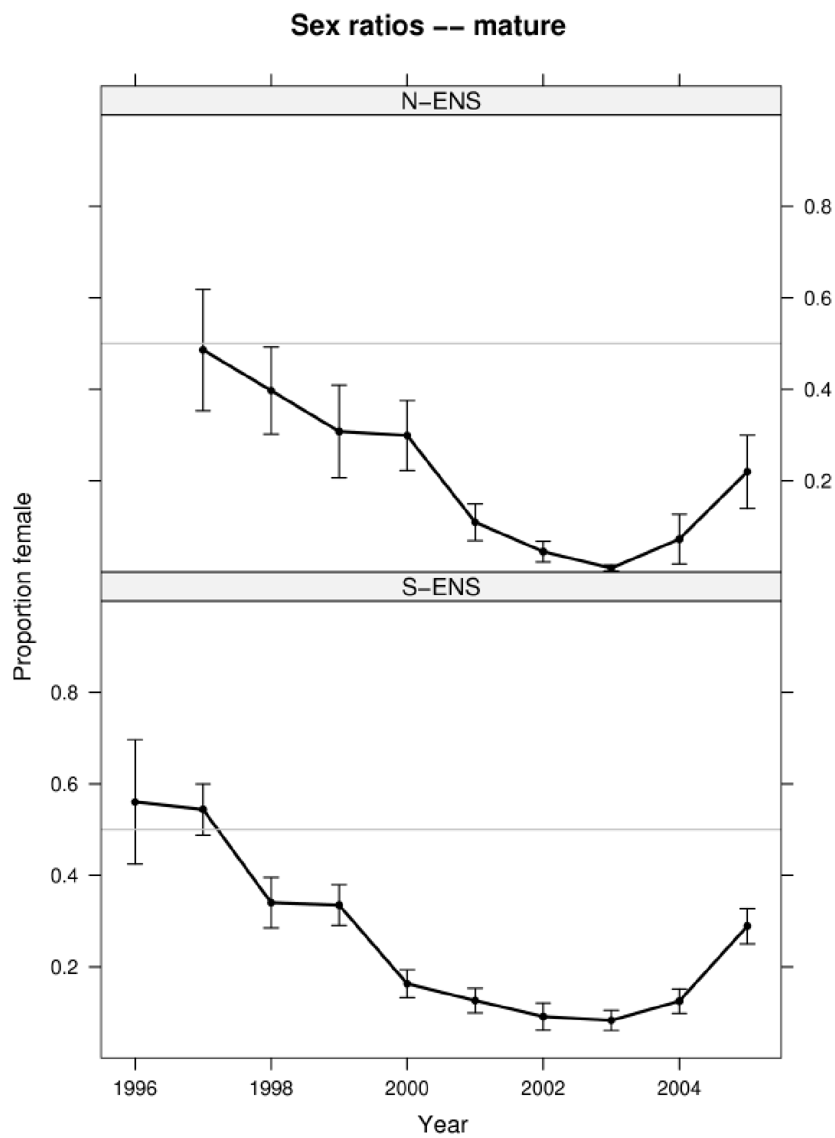

Figure 24. Annual variations in the mean sex ratio (proportion female) for morphometrically mature crabs. One standard error bars are presented. The sex-ratio of mature crabs has been declining steadily since 1996 and increasing since historic lows in 2003.

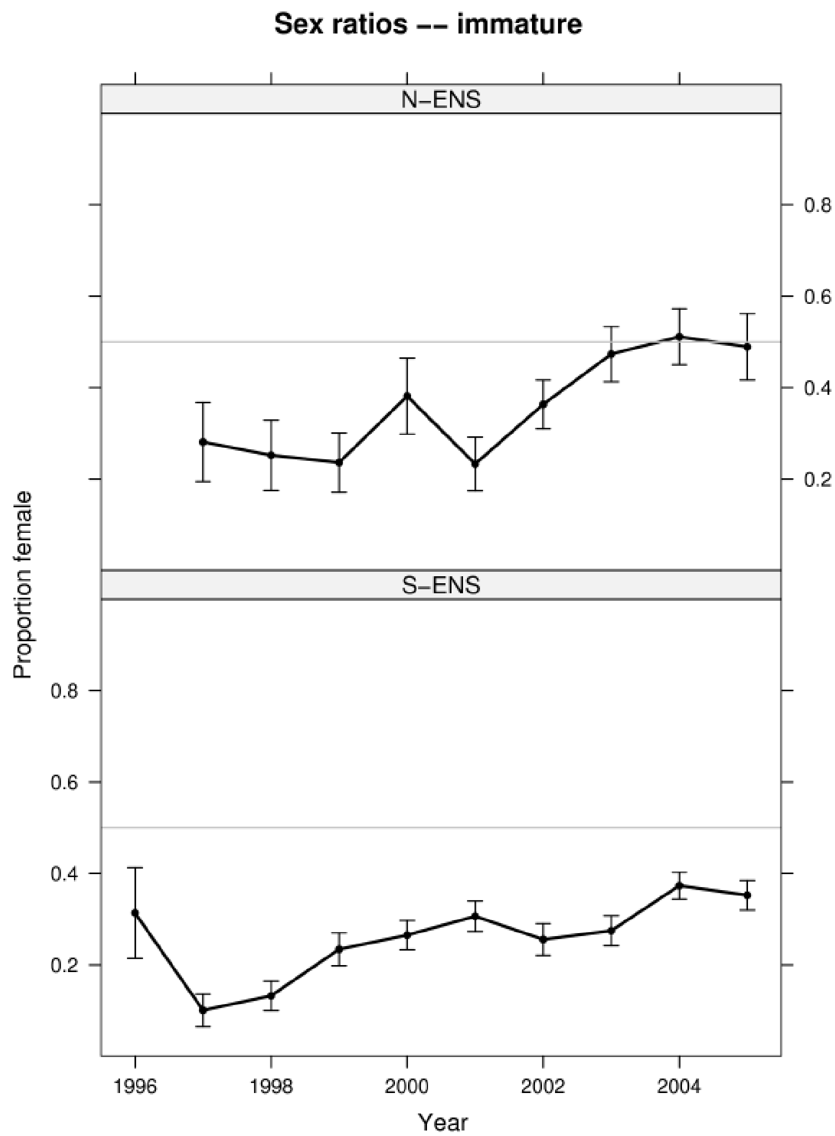

Figure 25. Annual variations in the mean sex ratio (proportion female) for morphometrically immature crabs. One standard error bars are presented. The sex-ratio of immature crabs have been steadily returning to more balanced numbers. The initial decline of immature sex ratios may have been due to size-selective snow crab cannibalism and/or predation from groundfish and macro-invertebrates (other crabs, lobsters).

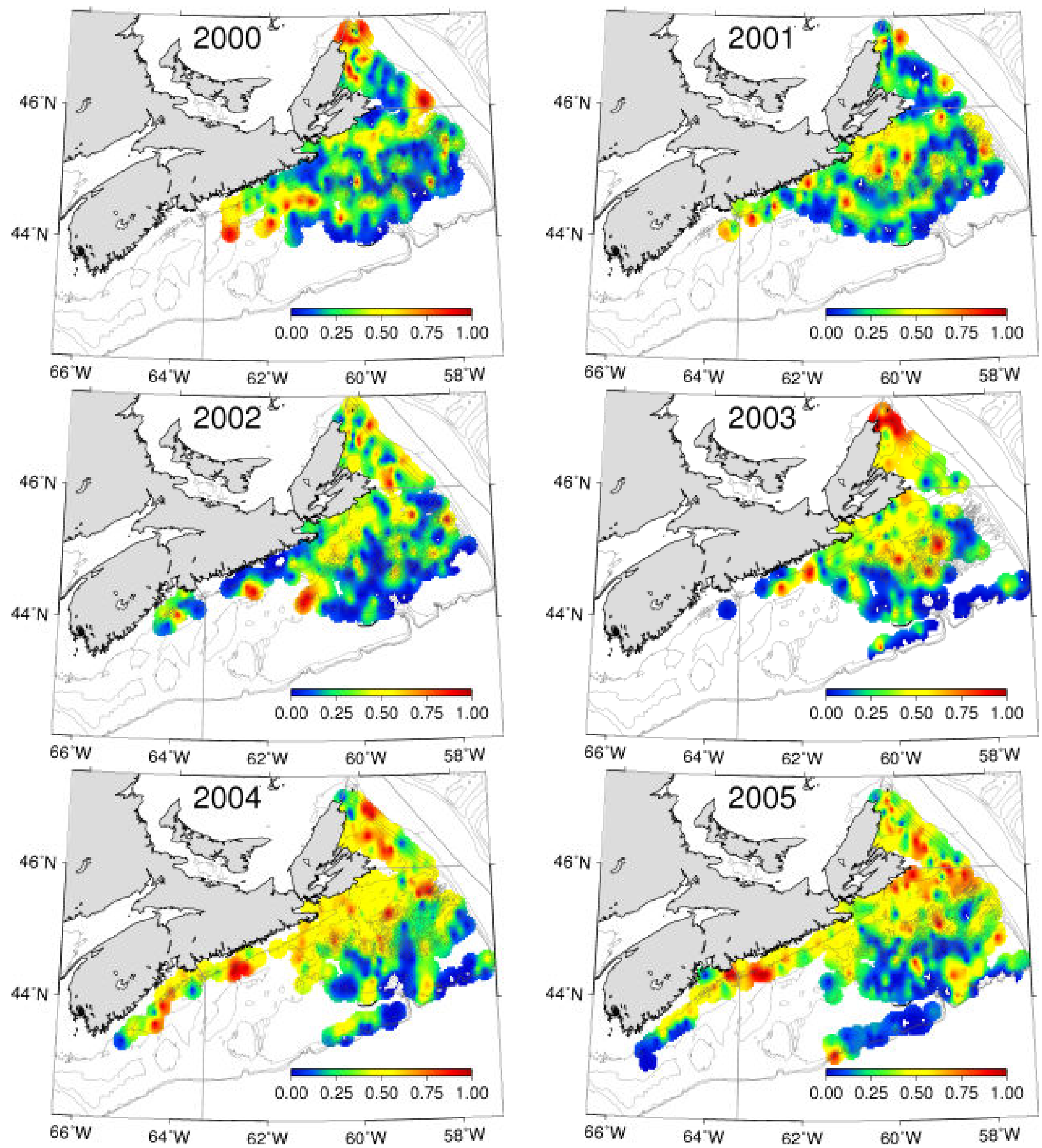

Figure 26. Morphometrically immature sex ratios. Inshore areas are generally more balanced in sex ratios or more female dominated. Offshore areas were more male dominated. In the past, this was not always the case and sex ratios of immature crabs were more heterogeneous. Currently, a return to this more heterogeneous state has been observed.

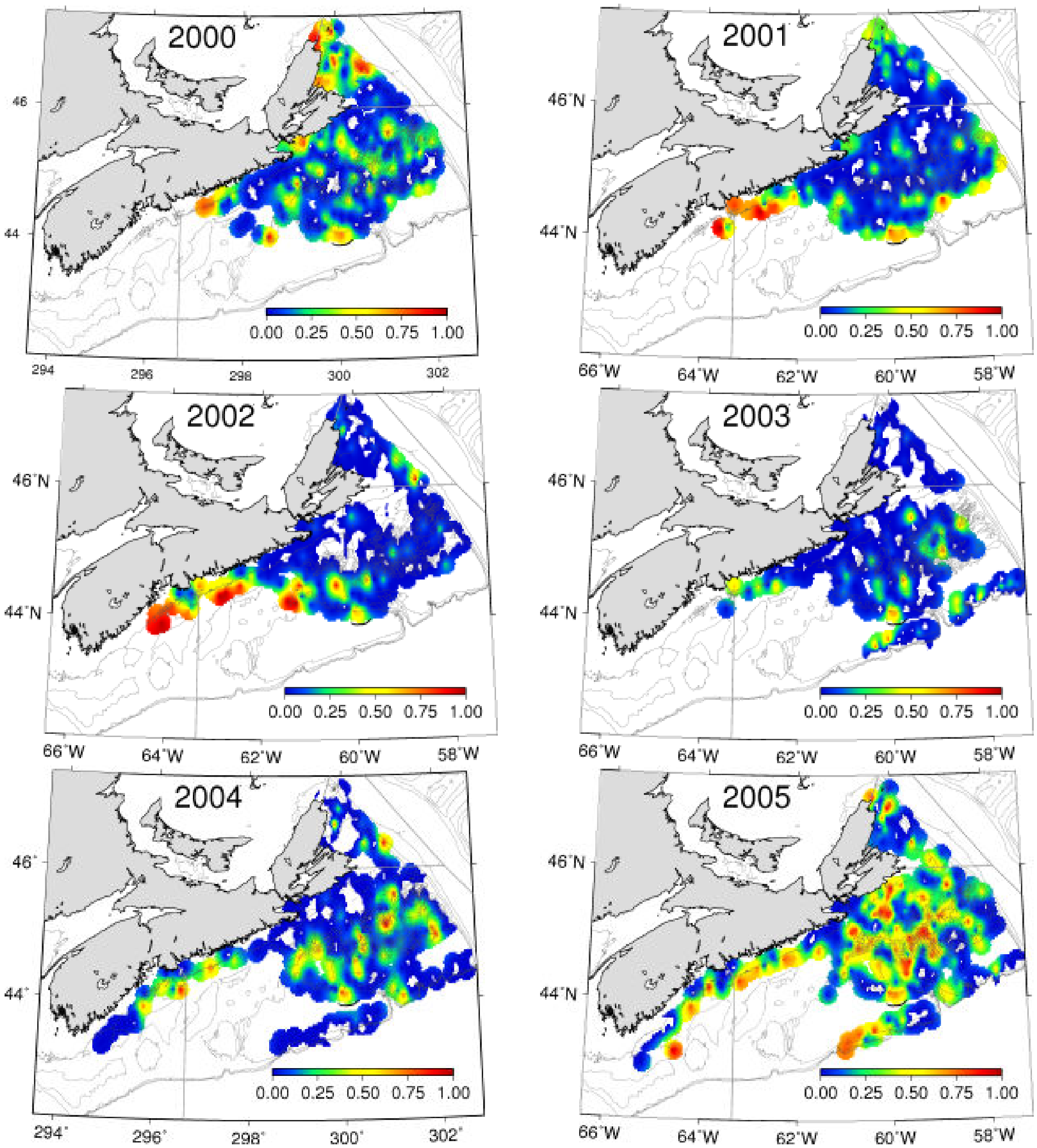

Figure 27. Morphometrically mature sex ratios. Since 2000, most of the Scotian Shelf was uniformly male dominated. A slight amelioration of the mature sex ratio was observed in 2004 (Figure 24 which was centered in the Misaine and Middle Banks and the near-shore areas of CFA 4X. This trend has continued and currently, the whole of the shelf can be seen to be entering a reproductive mode.

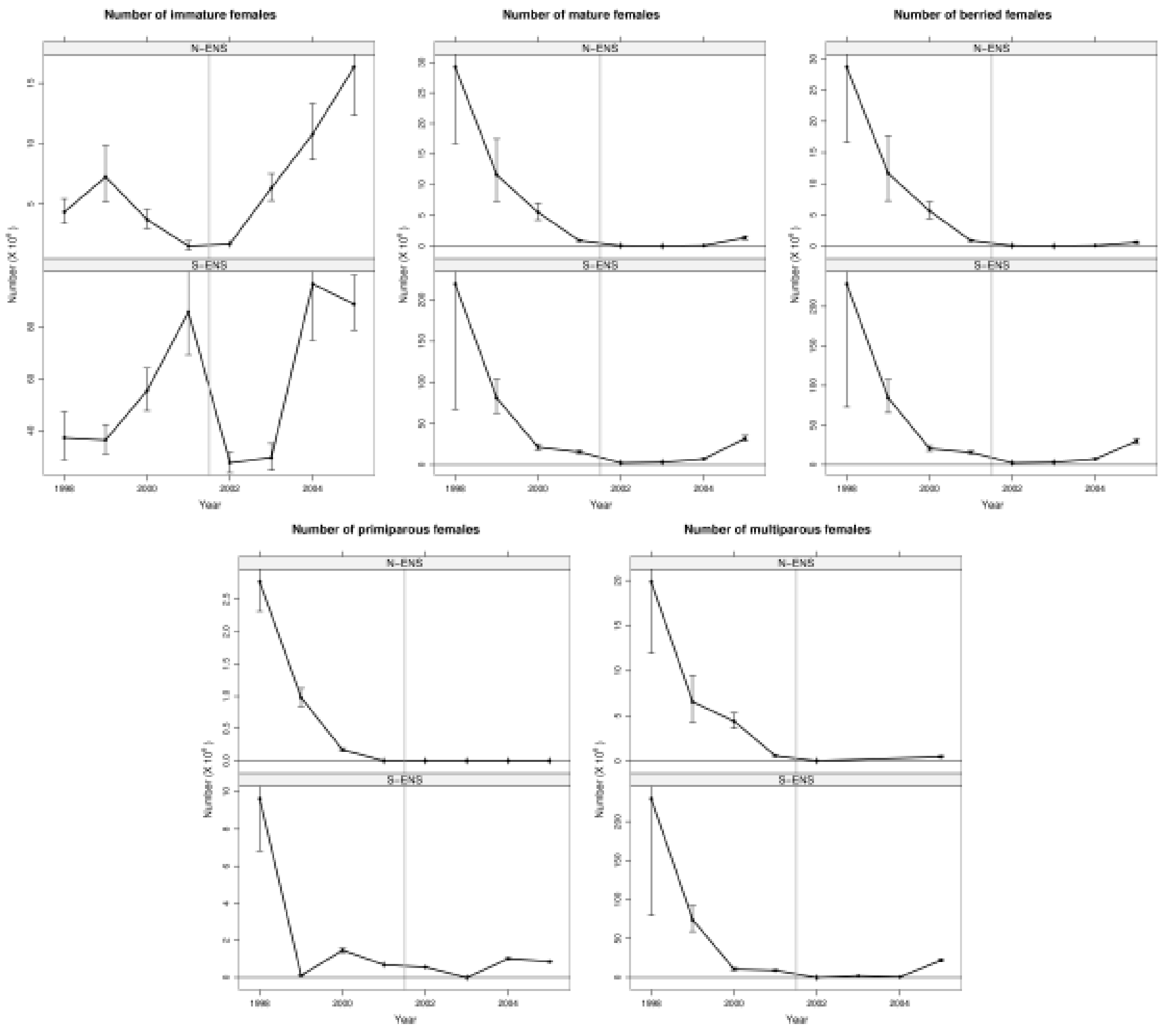

Figure 28. Temporal variations in female snow crab obtained from Kriged estimates. Error bars are 95% confidence intervals about the estimated total number. The verticle line near 2002 indicates the period in which trawl surveys changed from a spring to an autumn sampling period.

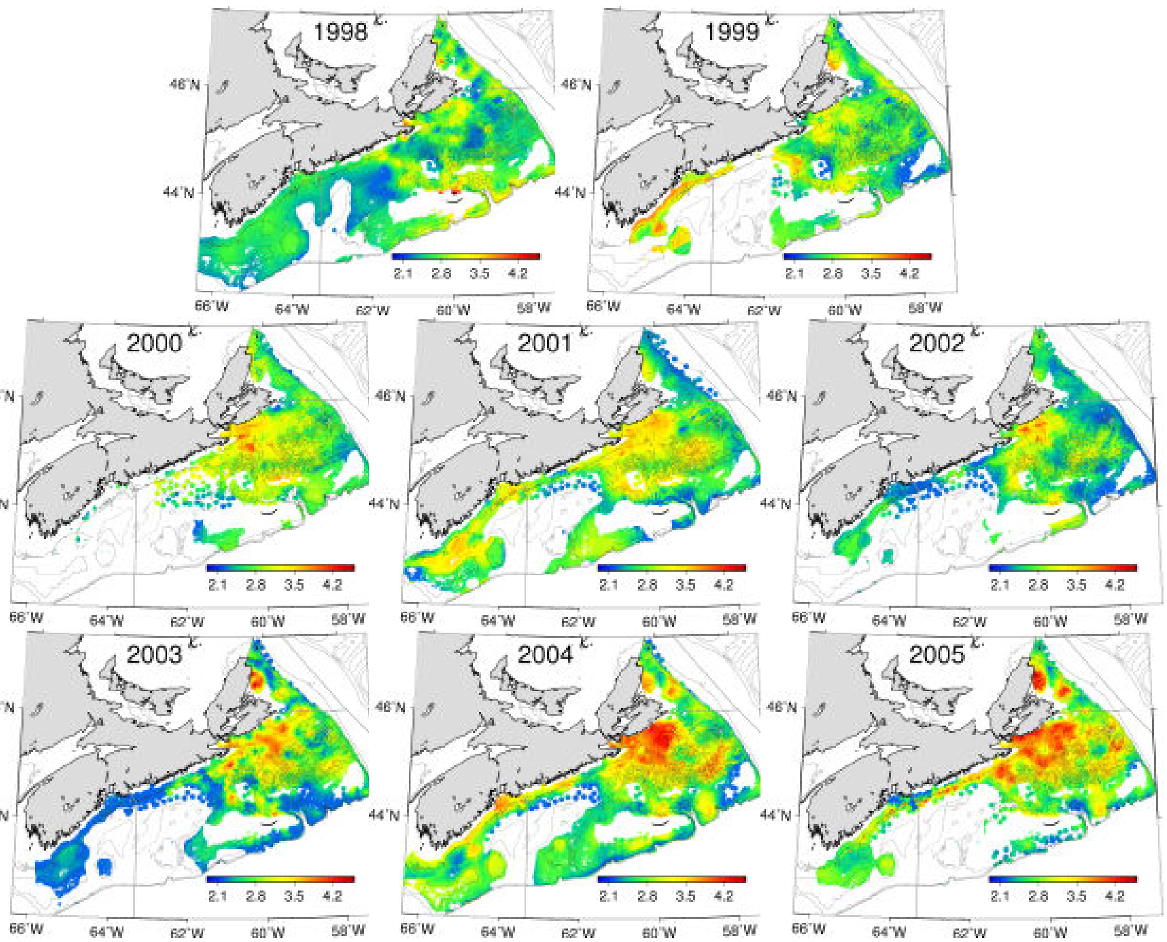

Figure 29. Numerical densities of the immature female snow crabs on the Scotian Shelf; $\log_{10}$ (number/km^2).

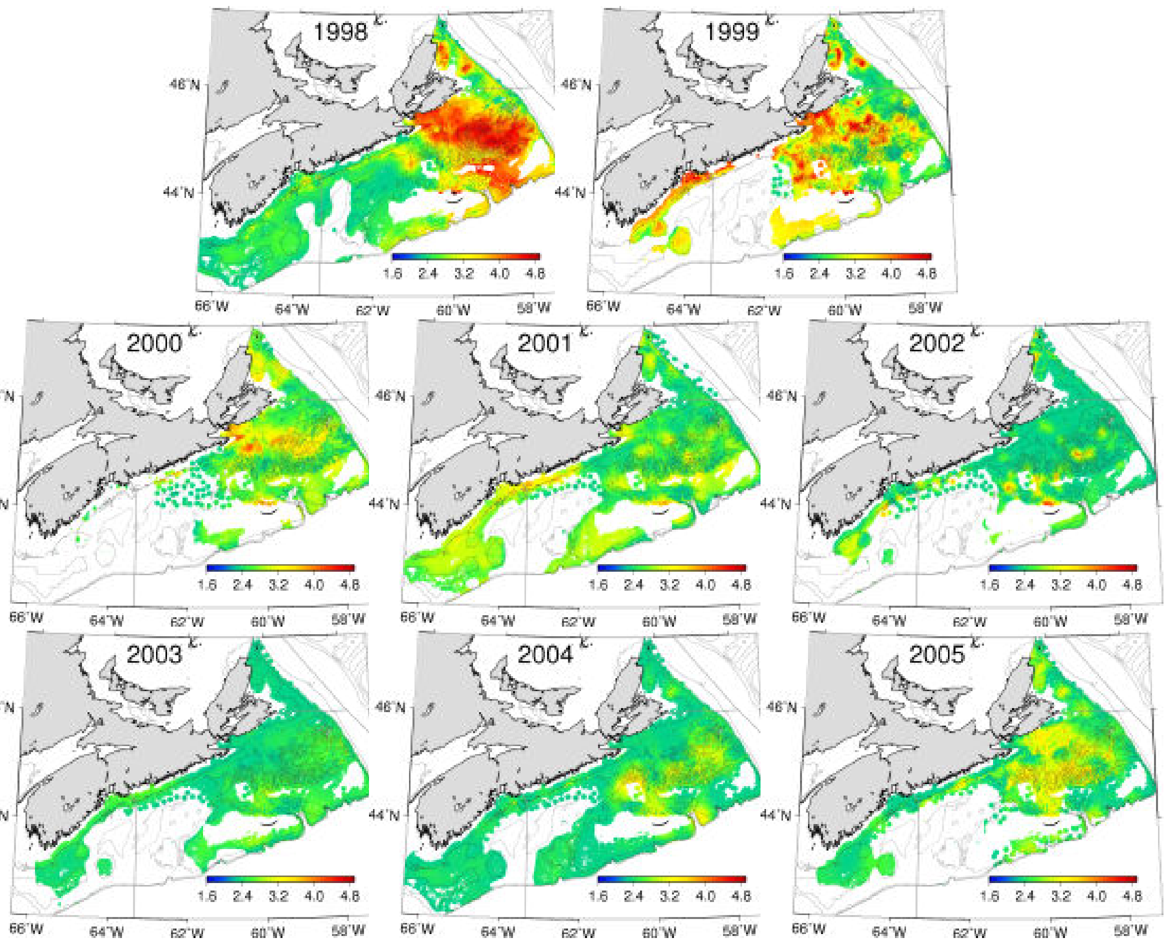

Figure 30. Numerical densities of the mature female snow crabs on the Scotian Shelf; $\log_{10}$ (number/km^2).

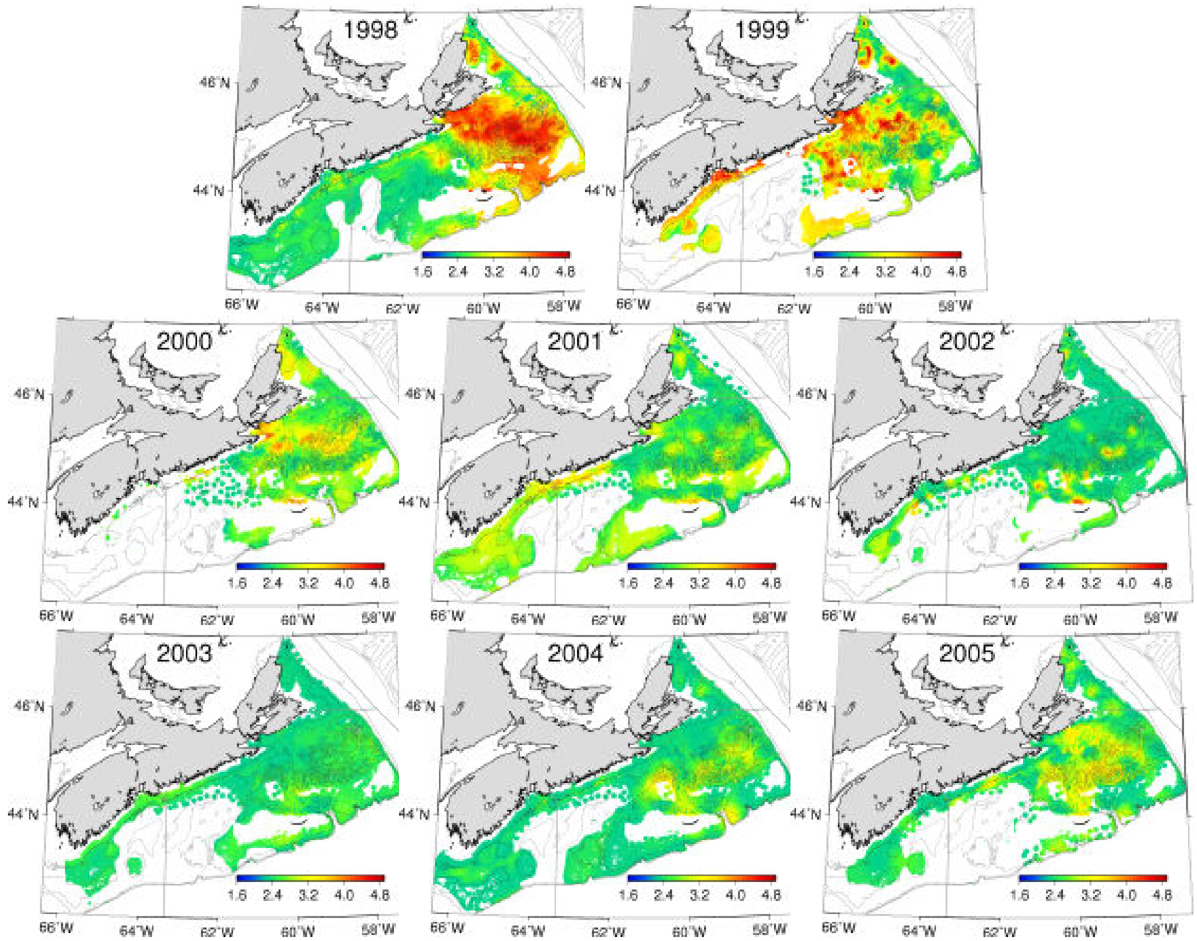

Figure 31. Numerical densities of the berried female snow crabs on the Scotian Shelf; $\log_{10}$ (number/km^2).

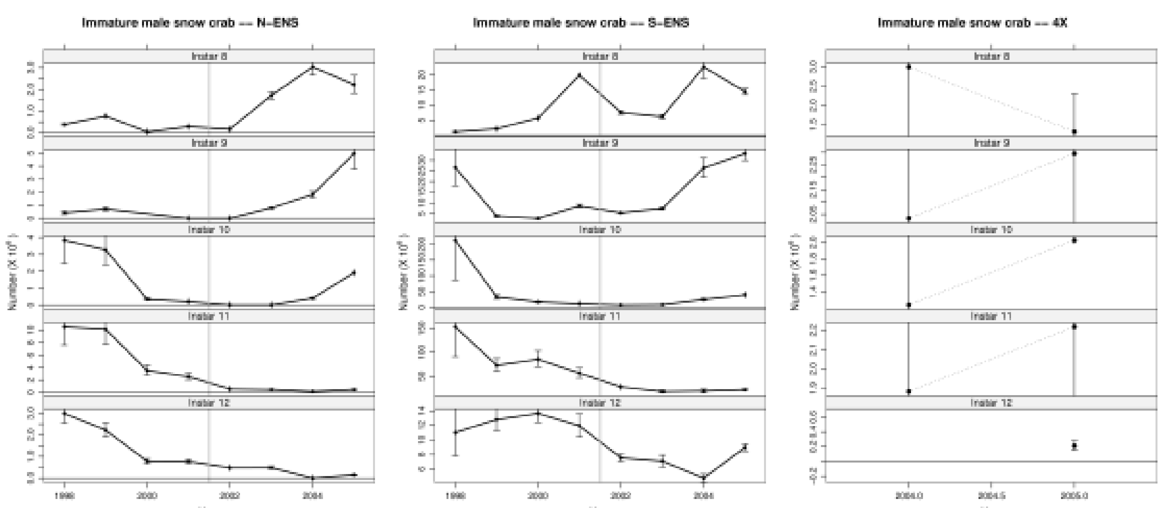

Figure 32. Temporal variations in immature instars (9 to 12) of male snow crab obtained from Kriged estimates. Error bars are 95% confidence intervals about the estimated total number. The verticle line near 2002 indicates the period in which trawl surveys changed from a spring to an autumn sampling period.

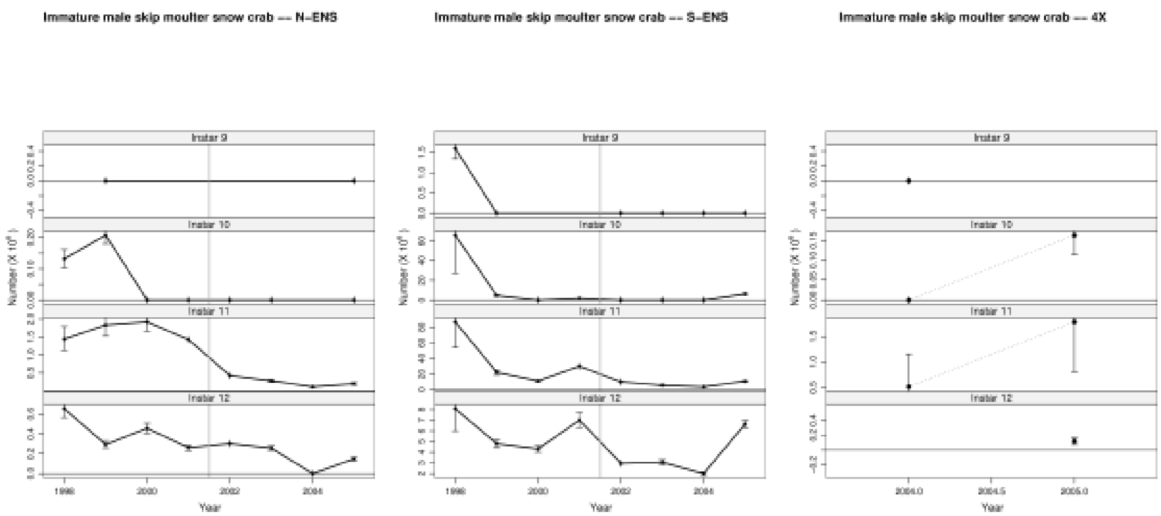

Figure 33. Temporal variations in immature skip moulting instars (9 to 12) of male snow crab in N-ENS obtained from Kriged estimates. Error bars are 95% confidence intervals about the estimated total number. The verticle line near 2002 indicates the period in which trawl surveys changed from a spring to an autumn sampling period.

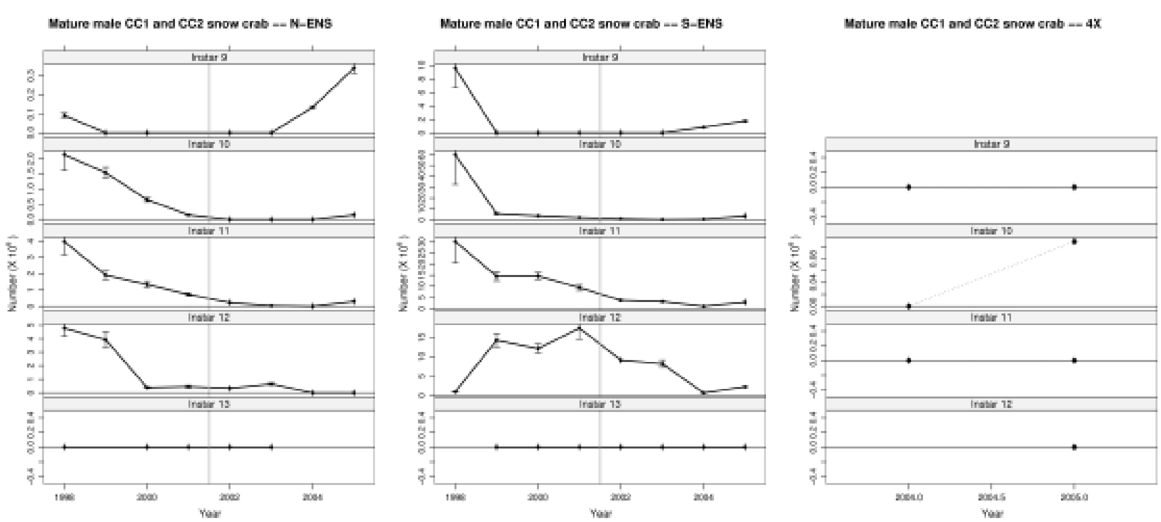

Figure 34. Temporal variations in mature CC1 and CC2 instars (9 to 13) of male snow crab obtained from Kriged estimates. Error bars are 95% confidence intervals about the estimated total number. The verticle line near 2002 indicates the period in which trawl surveys changed from a spring to an autumn sampling period.

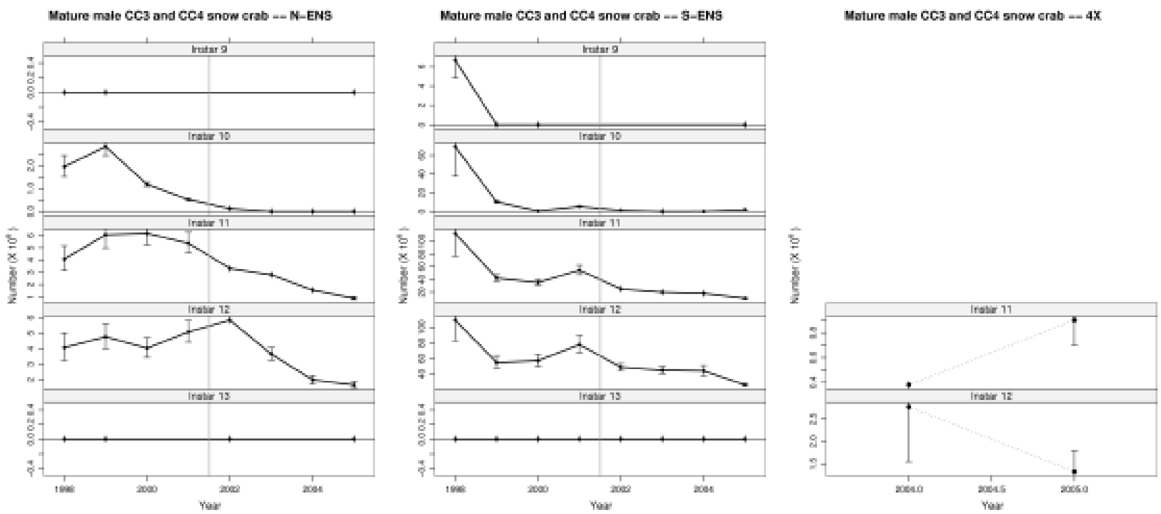

Figure 35. Temporal variations in mature CC3 and CC4 instars (9 to 13) of male snow crab obtained from Kriged estimates. Error bars are 95% confidence intervals about the estimated total number. The verticle line near 2002 indicates the period in which trawl surveys changed from a spring to an autumn sampling period.

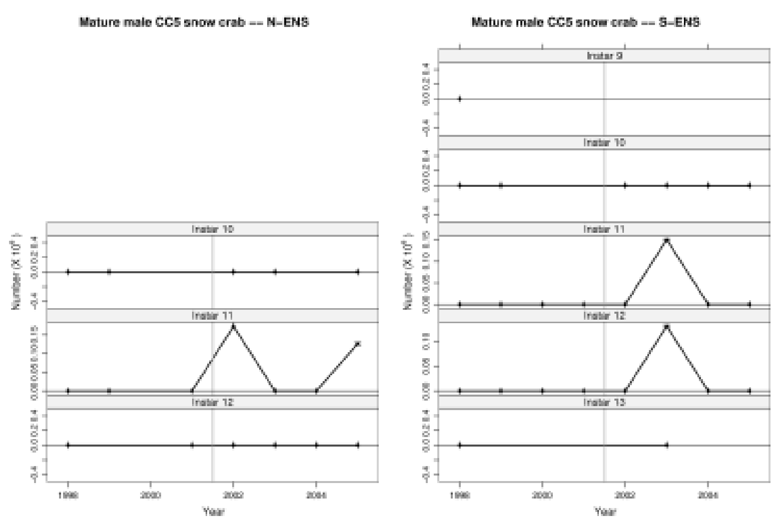

Figure 36. Temporal variations in mature CC5 instars (9 to 13) of male snow crab obtained from Kriged estimates. Error bars are 95% confidence intervals about the estimated total number. The verticle line near 2002 indicates the period in which trawl surveys changed from a spring to an autumn sampling period.

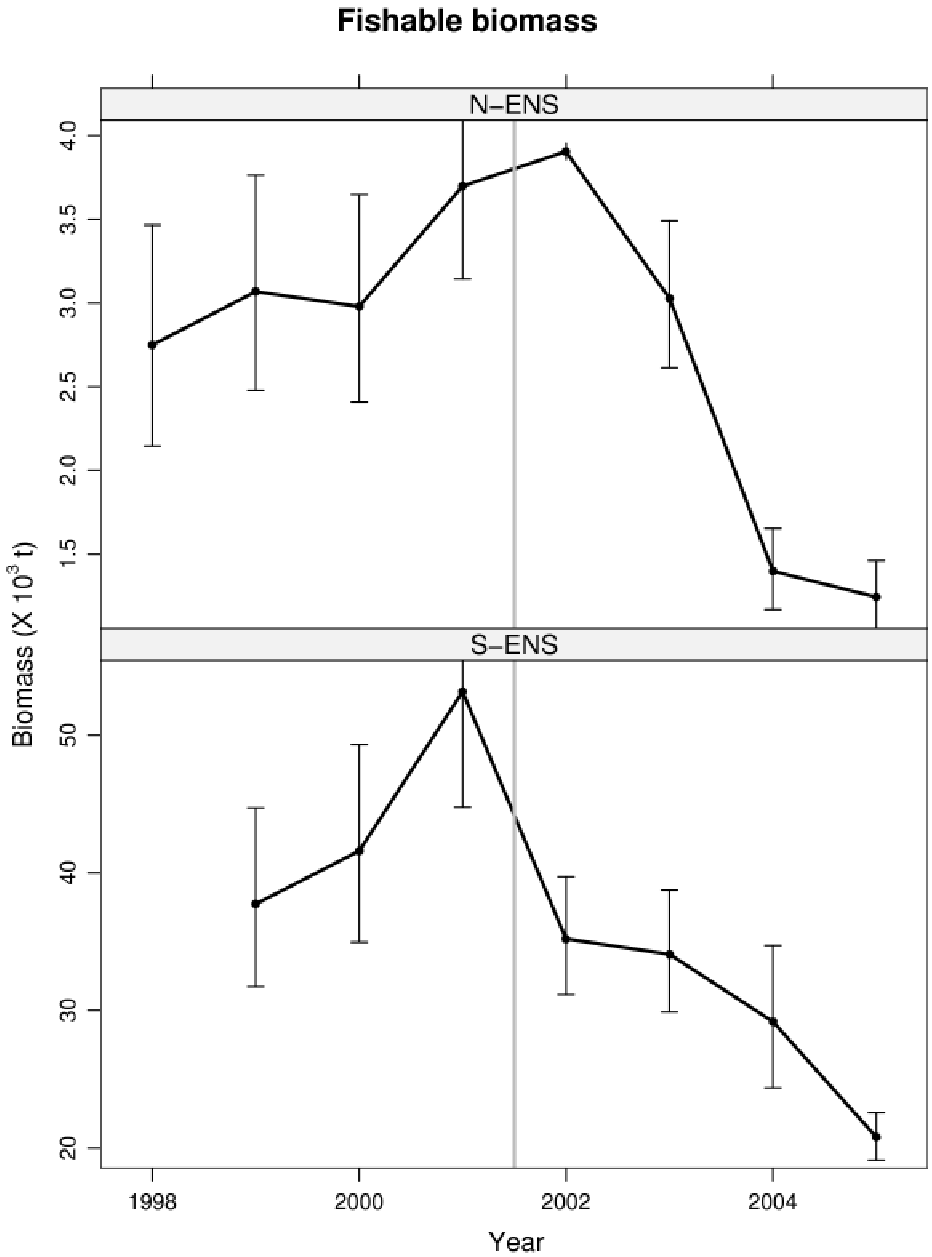

Figure 37. Temporal variations in fishable biomass estimates. Error bars are 95% confidence intervals about the estimated total biomass. The verticle line near 2002 indicates the period in which trawl surveys changed from a spring to an autumn sampling period.

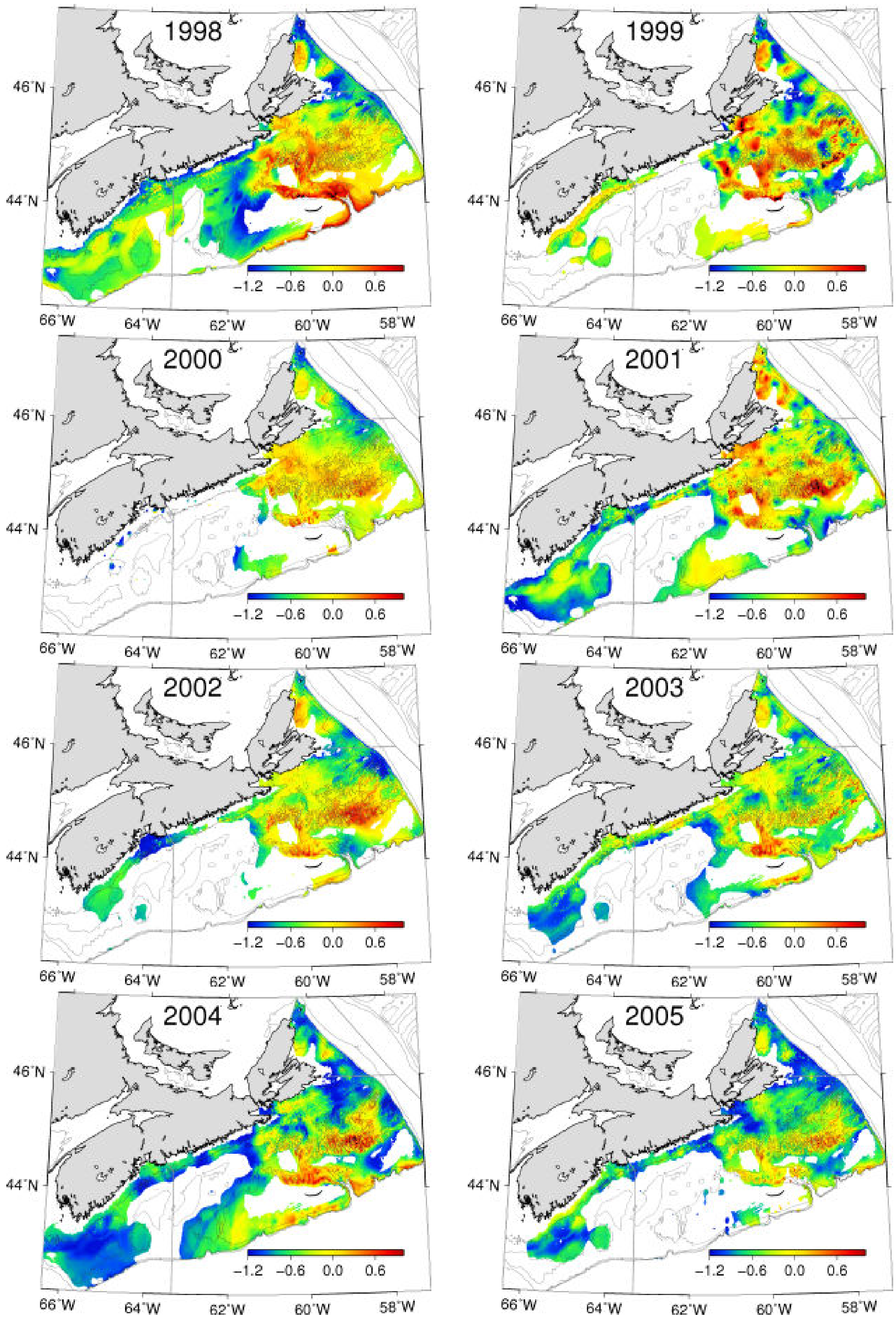

Figure 38. Fishable biomass densities on the Scotian Shelf; $\log_{10}$ (t/km^2).

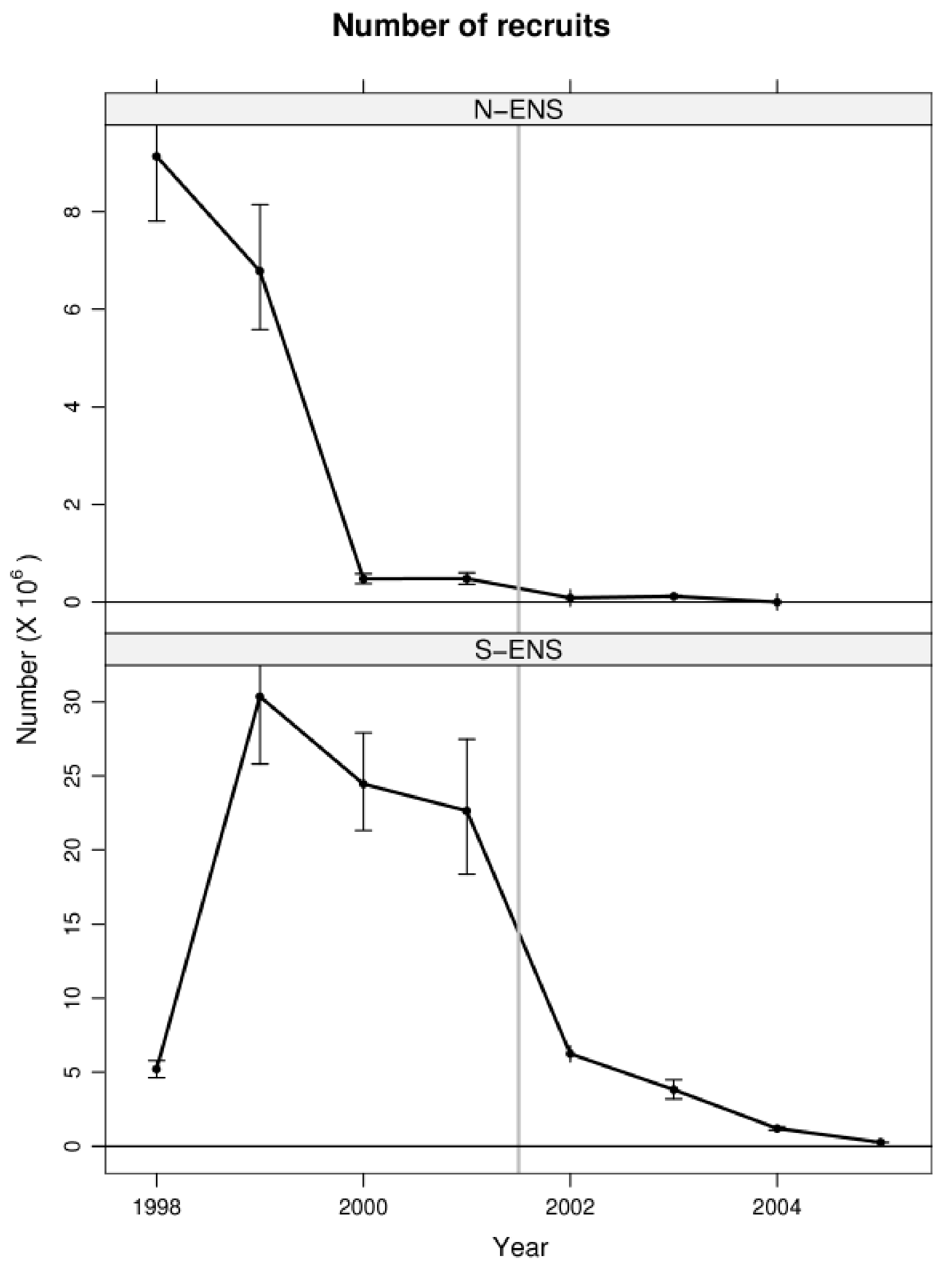

Figure 39. Temporal variations in the expected recruitment into the fishable biomass. Error bars are 95% confidence intervals about the estimated total biomass. The verticle line near 2002 indicates the period in which trawl surveys changed from a spring to an autumn sampling period.

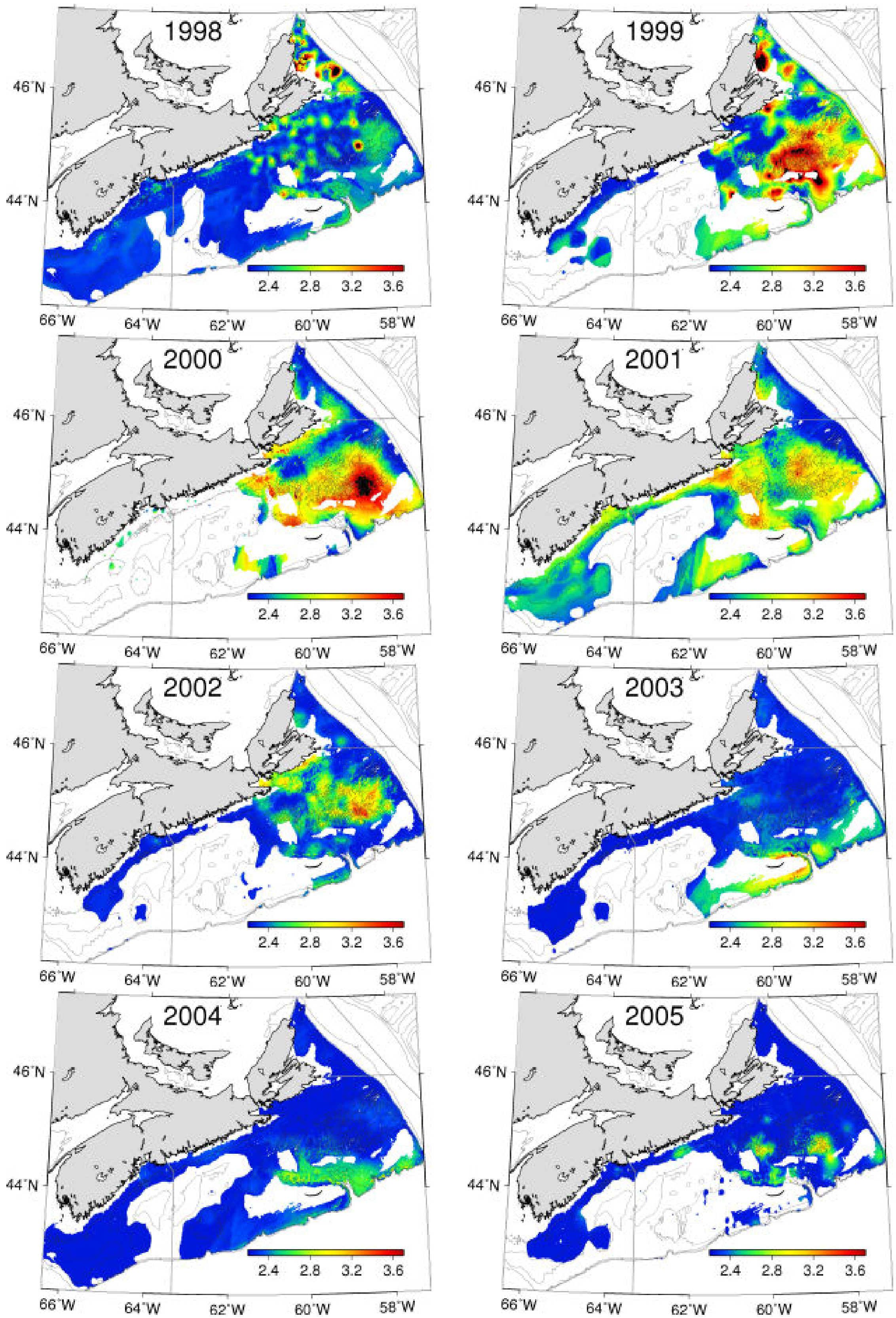

Figure 40. Numerical densities of snow crab recruiting into the next year; $\log_{10}$ (number/km^2).

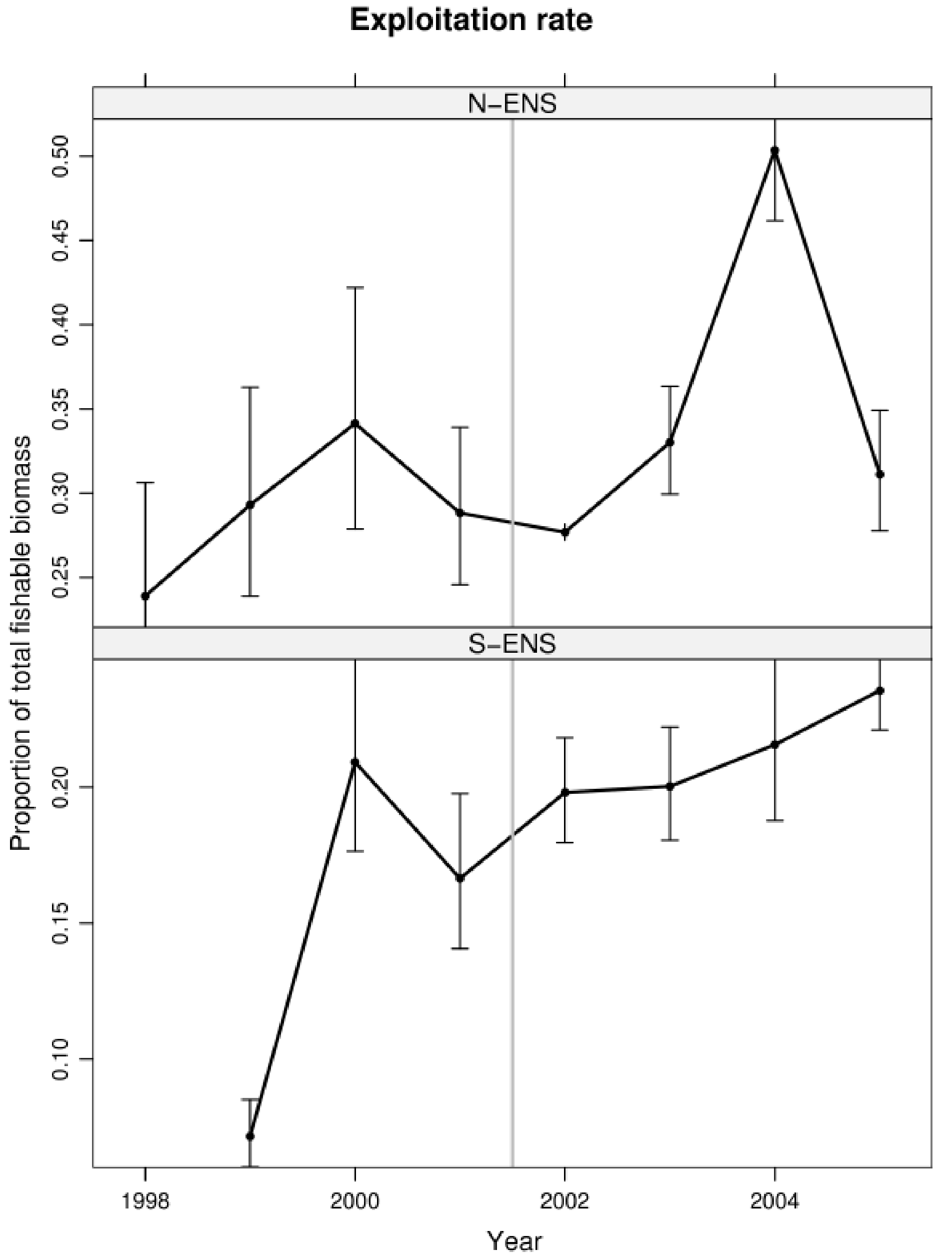

Figure 41. Temporal variations in the amount of biomass landed relative to biomass estimates. Note the rapid increase in exploitation rates even though the standing biomass has been shrinking.

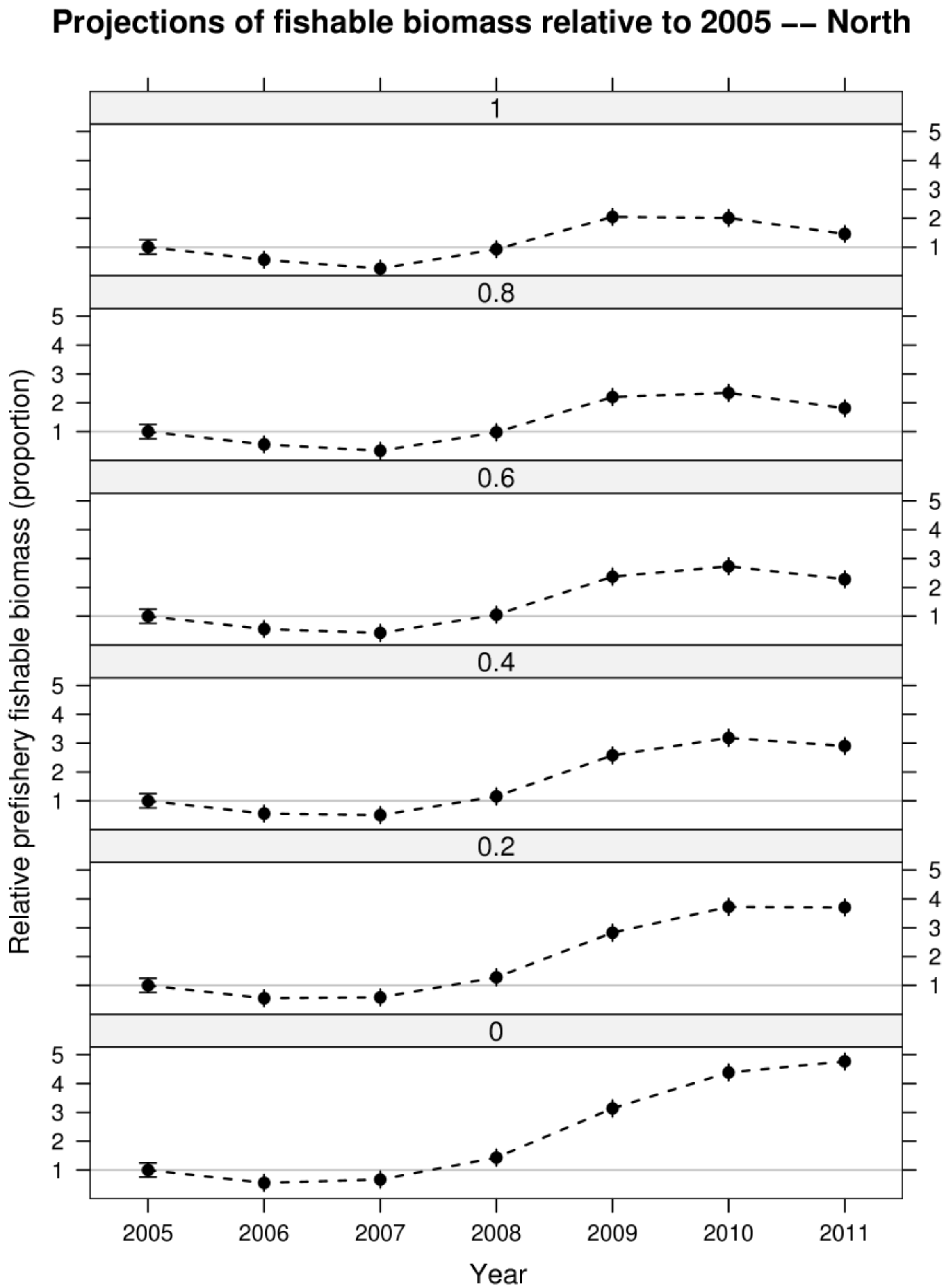

Figure 42. Temporal variations in fishable biomass relative to that of 2005 (pre-fishery) projected into the future based upon differing exploitation rates for N-ENS.

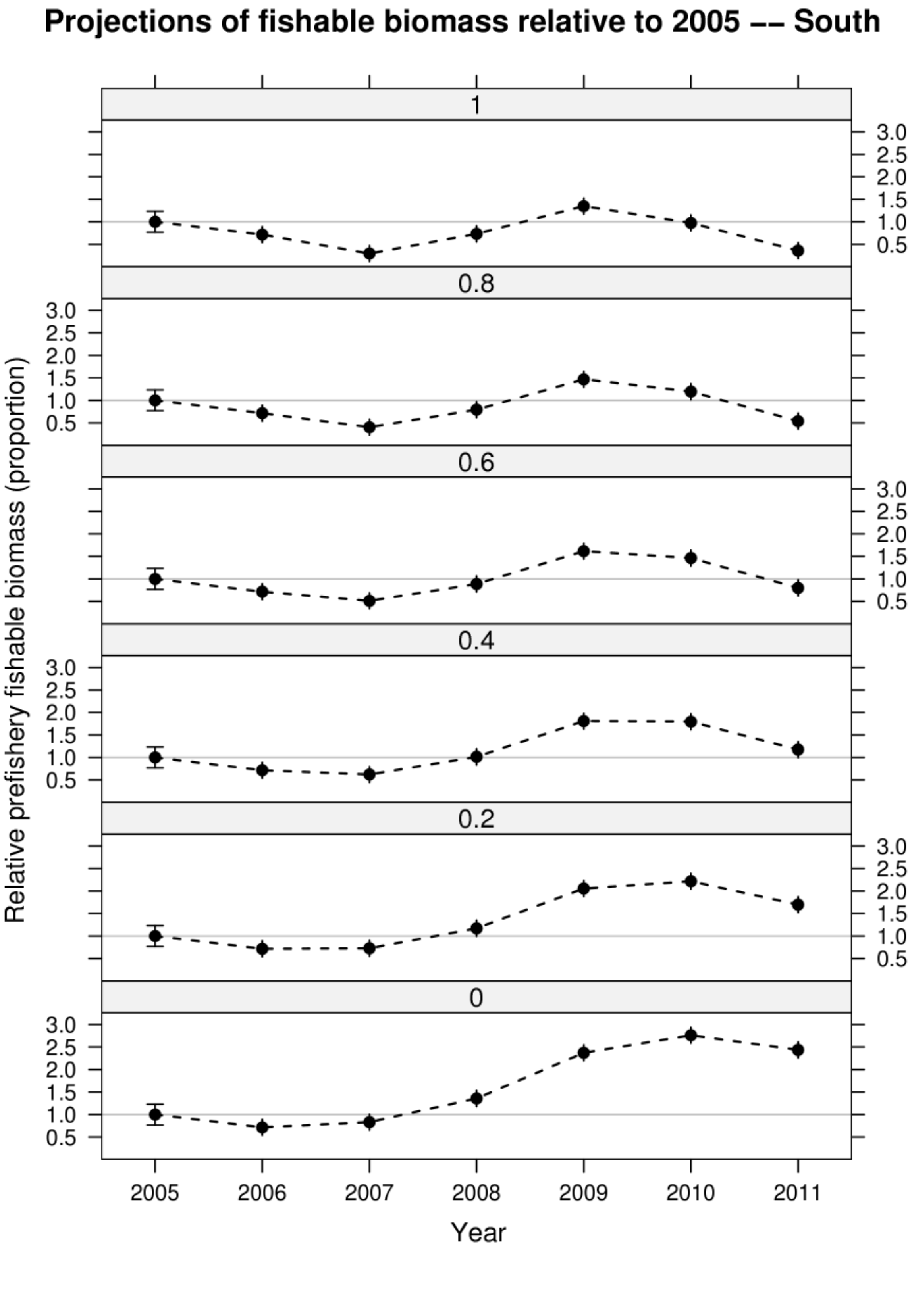

Figure 43. Temporal variations in fishable biomass relative to that of 2005 (pre-fishery) projected into the future based upon differing exploitation rates for S-ENS.

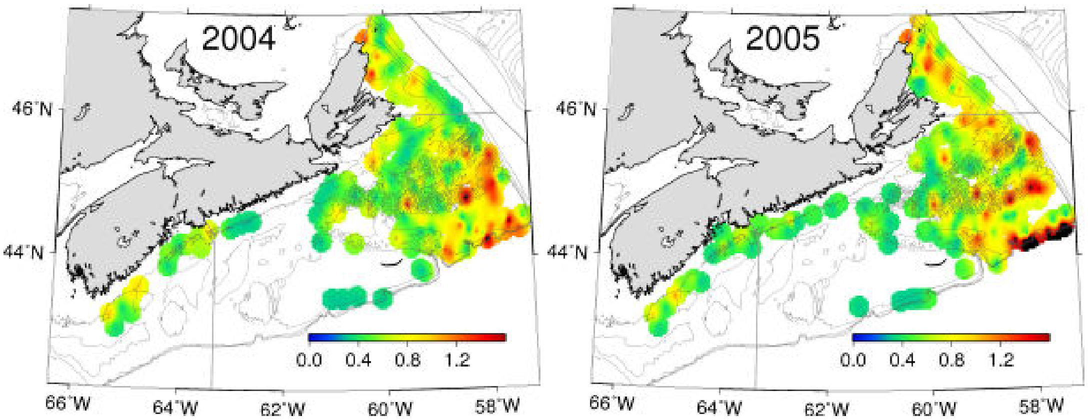

Figure 44. Locations of potential predators of snow crab: thorny skate. Scale is $\log_{10}$ (numerical density [number/km^2]).

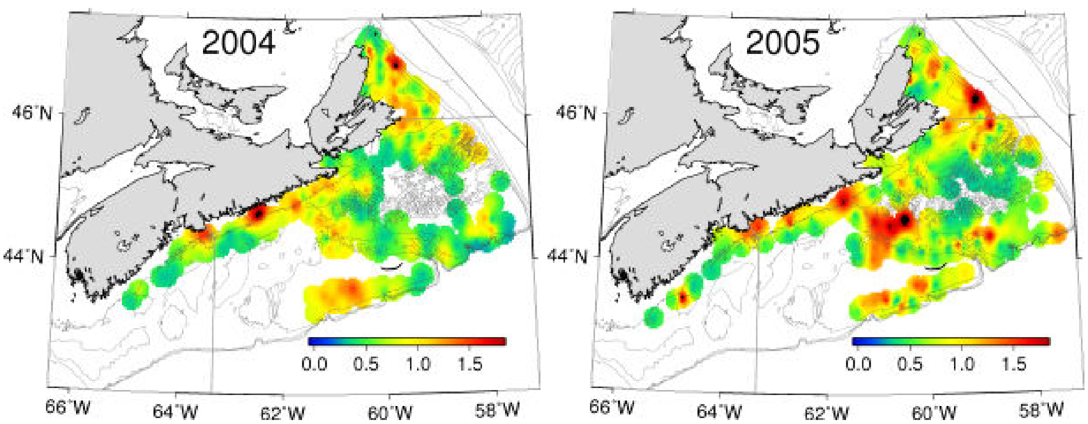

Figure 45. Locations of potential predators of snow crab: cod. Scale is $\log_{10}$ (numerical density [number/km^2]).

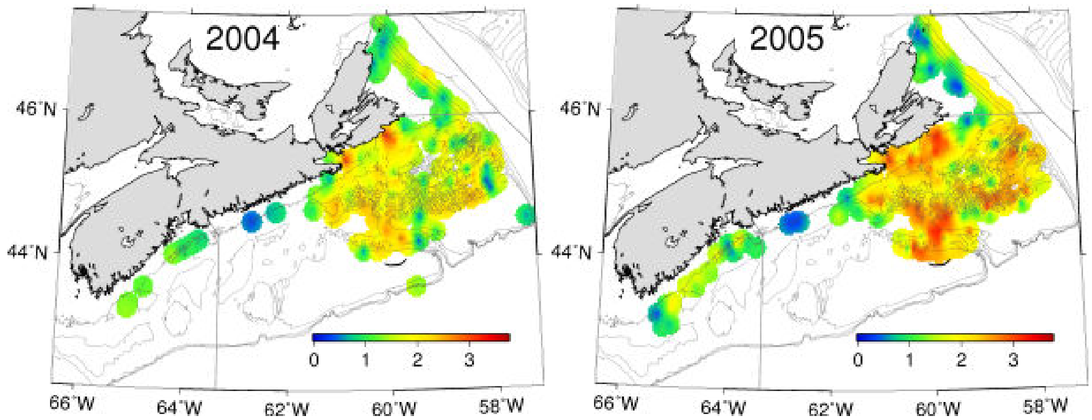

Figure 46. Locations of potential food items of snow crab: northern shrimp. Abundance of these potential food sources roughly match the spatial distributions of snow crab. Scale is $\log_{10}$ (numerical density [number/km^2]).

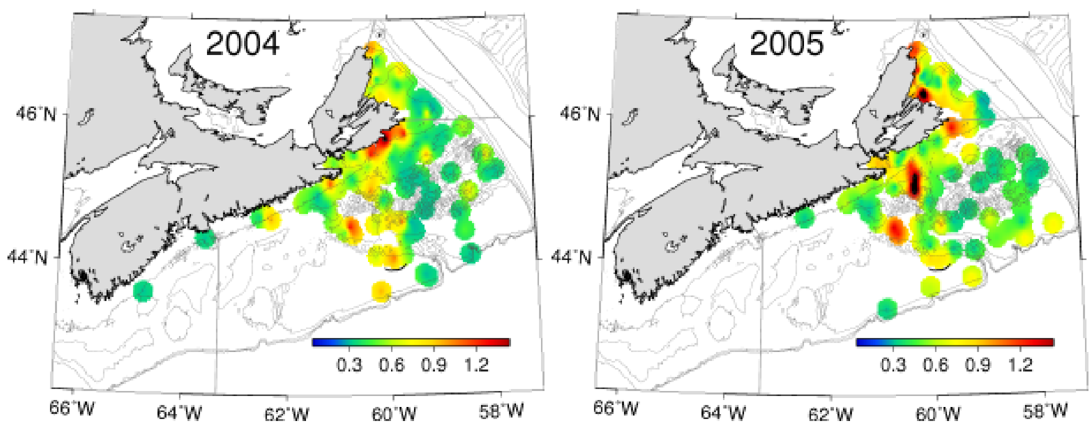

Figure 47. Locations of potential competitors of snow crab: lesser toad crab. High competitive interactions are probable in inshore areas. Scale is $\log_{10}$ (numerical density [number/km^2]).

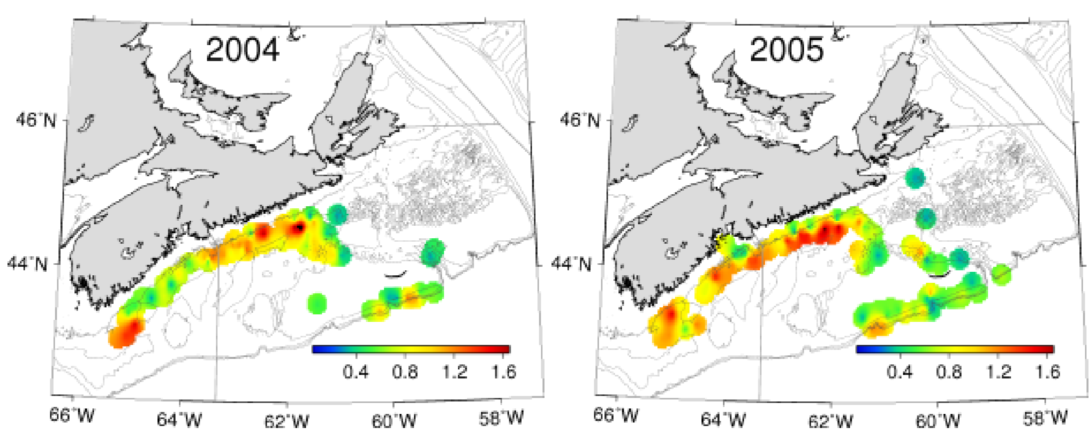

Figure 48. Locations of potential competitors of snow crab: Jonah crab. High competitive interactions are probable in inshore areas. Scale is $\log_{10}$ (numerical density [number/km^2]).

A Factors controlling snow crab abundance

Anecdotal information from fishers and fishery-based catch rates (Figure 8) suggests that the abundance of snow crab was historically quite low on the Scotian Shelf (at least in the inshore areas). Increases in catch rates were observed throughout the shelf since the mid-1980s and 1990s in the southern and northern Crab Fishing Areas (CFAs), 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 (Comeau *et al.* 1998), their increasing dominance on the shelf must have had their origins as early as the late-1970s and 1980s (in the southern and northern CFAs, respectively). These time-lines are confounded by the expansion of the fishing grounds towards increasingly offshore areas, exploiting previously unexploited crab populations. However most of this expansion was observed in the post-2000 period when total allowable catches (TACs) and landing increased up to 6 fold relative to the TACs and landings of the 1990s (Figure 7) and a doubling of fishing effort (Figure 9). The catch rate increases observed in the 1980s and 1990s therefore were likely reflecting real increases in their abundance.

The possible causes of this increase in abundance can be broken down into four main categories of influence:

1. **Top-down** influences refer to the role of predators in controlling a population (Paine 1966; Tremblay 1997; Worm & Myers 2003). The capacity of predatory groundfish to opportunistically feed upon snow crab (Robichaud *et al.* 1991), in combination with their numerical dominance prior to the 1990s (Choi *et al.* 2004, 2005; Frank *et al.* 2005), suggests that they indeed could have been an important regulating factor controlling the recruitment of snow crabs. Conversely, the recent demise of the 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 dominance of snow crab on the Scotian Shelf. Certainly, due to the size-selectivity of snow crab predators (Robichaud *et al.* 1991), crab > 30 mm CW are likely experiencing much less (non-human) predation-related mortality, than in the past. However, the trends of increasing groundfish biomass in the early 2000s (however slight) indicates that predation levels upon small immature crabs are likely to be on the rise (Figures 45, 44).

2. **Bottom-up** influences refer to changes in a population due to resource (food) availability. Large increases in food availability can result in increased crab abundance due to reduced competition for resources. The question is: Have large-scale changes in the productivity of the Scotian Shelf occurred co-incident with the increases in abundance of snow crab? Phytoplankton abundance in the most recent decade (1991-2001) was considerably higher and more variable than in the 1960s and early 1970s (Choi *et al.* 2005). Very little information has been encountered describing the abundance of potentially important benthic food sources on the Scotian Shelf. However, the recent proliferation of northern shrimp (*Pandalus borealis*), a potential food item of snow crab which has overlapping spatial distributions (Figure 46), co-incident with the rise in abundance of snow crab may be an indication that resource levels for snow crab are high. Certainly their rapid rate of increase would seem to indicate that resource competition may not have been a limiting factor up to the late 1990s. However, the recent declines in their abundance since 2002 may be an indication that some form of a carrying capacity had indeed been reached. This interpretation is of course confounded by the heavy exploitation of crabs at levels of almost the same order of magnitude as their biomass and the recent nature of the proliferation of snow crab on the Scotian Shelf.

3. **Lateral and internal influences**: refers to the release from competitive interactions with ground-

fish, other crab species, cannibalism, 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 other crab species (Figures 47, 48). The centers of high abundance may be areas where interactions may be strong causing resource competition, not only for food but habitat space as well. Of course these interactions are complex in that crabs may also serve as predators upon small snow crab as well as being food items for large snow crab. Nonetheless, where concentrations are elevated, the probability of strong negative (competitive) interactions are greater.

4. **Environmental influences**: altered conditions over extended periods of time have been observed on the Scotian Shelf (Figure 15). Prior to 1986, the shelf was characterised by relatively warm bottom waters, low volume of the cold intermediate layer of water, and a Gulf Stream frontal position close to the shelf (Choi *et al.* 2005). 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. In addition to these subsurface temperature changes, there have also been important physical changes in the near surface waters. Foremost among these has been the increase in vertical density gradient. For example, the density difference between 0 and 50 m increased to its highest level in the past 50 years during most of the 1990s. This was principally the result of record low salinities in the near-surface waters that were advected onto the shelf from the Grand Banks. Freshwater discharge into the Gulf of St. Lawrence decreased during the 1990s but its contribution to inter-annual variation in salinities on the Scotian Shelf was likely minimal. 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 and not caused by environmental change. That is, some other cause had allowed their numbers to build up to very large numbers prior to these environmental changes. What this may be is not yet understood. But certainly, changes in predation pressure seems to be a definite possibility that cannot be excluded.

A.1 Sources of snow crab larvae

The potential for hydrodynamic transport of snow crab larvae from the southern Gulf of St. Lawrence to the Scotian Shelf has been studied by J. Chassé (Ocean Sciences Division, BIO, DFO; pers. comm.). By treating larvae as passive particles, he was able to demonstrate that a large number of larvae can be transported onto the Scotian Shelf and deposited in areas of strong eddies (near the Sable Bank area and in the shallow areas further west). While pelagic organisms can maintain their position in a single location in even very strong advective conditions via control of vertical migrations, the possibility of snow crab larvae entering the Scotian Shelf from the Gulf of St. Lawrence region cannot be ignored. However, the biological importance of this upstream flow has yet to be quantified empirically. The possibility of some external sources of larvae does not mean that we can ignore the reproductive potential of the snow crab resident on the Scotian Shelf proper. In fact, the mortality bottleneck seems to be extensive: from eggs up to crabs of the 7th instar (4 years since settling to the bottom; Robichaud *et al.* 1991) meaning that larval drift would have to be very high if they are to recruit into the fishable biomass.

Planktonic samples from the Scotian Shelf indicate that the number of Brachyuran larvae have been consistently low, even with the assumed constant input from upstream sources, from 1976 to 1996 (with a small pulse being detected in 1980). However, a significant pulse of larval abundance was detected from 1997 to 1999 with peak levels in 1998. The time of the current recruitment pulses are concordant with being produced from these larval pulses (approximately 6 years to reach instar 9). This was precisely the same period in which biomass levels of mature males and females on the Scotian Shelf seems to have been at their peak and fishery catch rates began to increase sharply. From this concurrent increase in larval densities and spawning biomass in the system, we suggest that the snow crab resident on the Scotian Shelf is more than capable of being a self-reproducing system, regardless of inputs from other systems. Parenthetically, the spatial distribution of the larvae have been observed to be quite pervasive throughout the Scotian Shelf with no declines in abundance with distance form the Gulf of St. Lawrence area.

B Glossary

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 it's weight, mass, volume or caloric energy.

Brachyura (Infraorder) – Known as "true crabs" of which the snow crab is a member. Brachyurans are characterised 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 hold eggs. The uropods, which along with the telson form the tailfan 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 eyestalks.

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 1 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)

CFA, Crab fishing area – Refers to individual management area. On the Scotian Shelf they are from north to south: 20 to 24 and 4X.

Commercial biomass – The biomass of snow crab which are legally exploitable by the commercial fishery: size $>$ 95 mm 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. Note also that immature crab larger than 95 mm are also part of the 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 or greater 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. N-ENS refers to the northern part of the Scotian Shelf, specifically the former CFAs 20 to 22. S-ENS refers to the southern part of the Scotian Shelf.

ER, Exploitation rate – The ratio of biomass fished relative to their abundance. Historically, the GFC calculated ER(t) = Landings(t) / Biomass(t-1), where t is time or year. The Biomass was of the mature segment of the male population $>$ 95 mm in CW, estimated from kriging. In this document, the exploitation rate is calculated as ER(t) = Landings(t) / (Landings(t) + FB(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. Further, instead of the mature fishable biomass (Biomass), all of the legally fishable biomass (FB) was used as the estimate of abundance of the fishable segment of the population to estimate a more realistic exploitation rate.

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

Fishable biomass, FB – see Commerical biomass.

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 in an organism between moults.

Interpolation – The method of determining intermediate 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.

Larva – 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, 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 grows very rapidly in the adult stage (terminal moult), whereas females' abdominal width increases with maturity. While morphometric maturity generally co-incides with physiological maturity, morphometrically immature males are known to be able to fertilise 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).

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.

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

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

Substrate – Habitat; 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.