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The 2018 assessment of the snow crab (*Chionoecetes opilio*) stock in the southern Gulf of St. Lawrence (Areas 12, 19, 12E and 12F)

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Foreword

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

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ABSTRACT

The 2018 assessment of the southern Gulf of St. Lawrence (sGSL) snow crab, *Chionoecetes opilio*, stock (Areas 12, 19, 12E and 12F) is presented. Snow crab in the sGSL is considered as a single biological unit for assessment purposes. The 2018 assessment was conducted as per the recommendations of the Snow Crab Assessment Methods Framework Science Review held in November 2011. The exploitation rate of the 2018 fishery in the sGSL was 36.9%. The 2018 post-fishery survey biomass of commercial-sized adult male crabs was estimated at 80,746 t (95% confidence intervals 70,984 to 91,467 t), an increase of 22.8% from 2017. The available biomass for the 2019 fishery, derived from the 2018 survey, is within the healthy zone of the PA Framework. The residual biomass from the 2018 survey was estimated at 21,432 t, an increase of 46.3% compared to the 2017 estimate. Seventy-four percent (74%) of the 2018 survey biomass, available for the 2019 fishery, is composed of new recruitment (59,609 t). The recruitment to the commercial biomass from the 2018 survey increased by 16.6% compared to 2017. The predicted recruitment of commercial-sized adult male crab for the 2020 fishery was estimated at 49,820 t (33,790 to 70,970 t). Risk analysis of catch options for the 2019 fishery is provided.

1.0. INTRODUCTION

Snow crab, *Chionoecetes opilio*, has been commercially exploited in the southern Gulf of St. Lawrence (sGSL) since the mid-1960s. Until 1994, the snow crab fishery in Area 12 (Fig. 1) was exploited by 130 mid-shore crab harvesters from New Brunswick, Québec and Nova Scotia. In 1997, the Prince Edward Island (PEI) coastal fishery (formerly called Areas 25/26) was integrated into Area 12. In 2003, a portion of the coastal fishery off Cape Breton (formerly called Area 18) was also integrated into Area 12, and a northern part of Area 18 was set as a buffer zone (non-snow crab fishing zone, label C in Fig. 1). For the purpose of this assessment, Area 12 refers to the new management unit (Fig. 1). In 1978, Area 19 (Fig. 1) was established for the exclusive use of Cape Breton inshore crab harvesters with vessels less than 13.7 m (45 ft) in length. Areas 12E and 12F were introduced in 1995 as exploratory fishery areas. A two nautical mile buffer zone was created between Area 12F and the adjacent Area 19 in 1996 (label B in Fig. 1). In 2002, the status of Areas 12E and 12F was changed from exploratory to commercial.

Currently, there are four individually managed fishing areas (Areas 12, 19, 12E and 12F) (Fig. 1), with Area 12 being the largest in area, number of participants, and landings. There is no biological basis for the delimitations of snow crab management areas in the sGSL (Chiasson and Hébert 1990; Hébert et al. 2008; DFO 2009). Snow crab in the above four management areas is considered part of a single biological population and the sGSL is considered as a single unit for assessment purposes (Hébert et al. 2008).

Management of these fisheries is based on quotas (by management area and distributed among license holders) and effort controls (number of licenses, trap allocations, trap dimensions, and seasons).

In Areas 12, 12E and 12F, the fishing season generally starts as soon as the sGSL is clear of ice in late April to early May and lasts either until the closure of the fishing season in mid-July or when the quota is caught. In Area 19, the fishing season starts in July and ends in mid-September or when the quota is caught. The landing of females is prohibited and only hard-shelled males ≥ 95 mm carapace width (CW) are commercially exploited. Different limits on the number of traps apply to each license depending on the harvesters group and fishing area.

New management measures were introduced in 1990 following the premature closure of the Area 12 fishery in 1989 due to a rapid decline in catch rates and high incidence of soft-shelled crabs in catches. One of the measures was to set the total allowable catch (TAC) or quota as some proportion of the biomass of adult male crab ≥ 95 mm CW, as estimated from a trawl survey. Another management strategy was to close portions of the fishery based on the percentage of soft- or white crabs to maximize yield and reproductive potential by limiting the capture of soft-shelled males.

This assessment follows recommendations from the Framework Science Peer Review of stock assessment methods for the sGSL snow crab stock held on November 21-25, 2011 (DFO 2012a).

The present report presents the assessment and commercial biomass estimates for the 2019 snow crab fishery in the sGSL (Areas 12, 19, 12E and 12F). Biomass estimates and population characteristics by life stage are derived from a trawl survey conducted after the fishery covering the sGSL snow crab habitat. Risk analysis of catch options for the 2019 fishery relative to the commercial biomass and removal reference points is also presented.

2.0. SYNOPSIS OF SNOW CRAB BIOLOGY

In the sGSL, molting of snow crab occurs from December to April, prior to the fishery (Watson 1972; Conan et al. 1988; Sainte-Marie et al. 1995; Benhalima et al. 1998; Hébert et al. 2002). Crab normally molt annually until they reach the adult phase via a final or "terminal" molt (Conan and Comeau 1986). Males reach adulthood at sizes ranging from 40 to 150 mm CW and females at 30 to 95 mm CW (Conan and Comeau 1986). Estimates of longevity of adult males are (after reaching the terminal molt) between 5 (Sainte-Marie et al. 1995) and 8 years (Fonseca et al. 2008).

In contrast to immature females, pubescent (adolescent) females have a wider abdomen and fully developed orange gonads in the fall. These females then undergo a terminal molt between December and April and become nulliparous females having a fully enlarged abdomen and ripe ovaries. Generally, they mate immediately after molting, while their carapace is still soft, and then extrude fertilized eggs for the first time, becoming primiparous females (Watson 1969; Moriyasu and Conan 1988). Multiparous refers to females which are repeat spawners (second brood or more). Their mating season occurs from late-May to early-June, after their eggs have hatched (Conan and Comeau 1986; Moriyasu and Conan 1988; Sainte-Marie and Hazel 1992; Moriyasu and Comeau 1996; Sainte-Marie et al. 1999). In the sGSL, mature females normally carry their eggs under the abdomen for two years (Mallet et al. 1993; Moriyasu and Lanteigne 1998), while a negligible portion of mature females follow a one-year cycle in Baie Sainte-Marguerite (Sainte-Marie et al. 1995). However, Khun and Choi (2011) reported that over 80% of mature females were estimated to follow a one-year reproductive cycle on the Scotian Shelf.

Mature females, both primiparous and multiparous, may produce more than one viable brood from sperm stored in their spermathecae from the first mating, without any subsequent mating (Sainte-Marie and Carrière 1995). However, the probability that a single mating was sufficient to fertilize a female's lifetime production of eggs has been shown to be low (Rondeau and Sainte-Marie 2001). Mating after egg hatching seems to be a general rule for snow crab in the sGSL (Conan et al. 1988).

After molting, crabs have a soft shell engorged with water. It takes about 8-10 months for the carapace of an adult soft-shelled male to harden (Hébert et al. 2002) and one year to attain maximal meat yield (Dufour et al. 1997). Adult soft-shelled males are not able to mate during their postmolt period, but become active in reproductive activities with nulliparous females in February of the following year and in May-June with multiparous females (Conan et al. 1988; Moriyasu et al. 1988). Adult soft-shelled males of legal size represent the annual recruitment to the fishery, as they become commercially marketable in the following fishing season (Conan and Comeau 1986; Sainte-Marie et al. 1995; Comeau et al. 1998; Hébert et al. 2002).

Following Sainte-Marie et al. (1995), we use the term "adolescent" and "adult" to refer to what was formerly called morphometrically immature and mature, respectively (Conan and Comeau 1986).

3.0. METHODS

3.1. TRAWL SURVEY SAMPLING FOR BIOMASS ESTIMATION

There have been progressive changes in the sampling design and protocols of the sGSL trawl survey since its inception in 1988. Originally, the survey area was sub-divided using a lattice of 10 by 10 minute latitude-longitude grids. One or two sampling locations were then randomly selected and used as fixed stations in subsequent survey years. Initially, the survey area only covered Area 12 but was expanded to Area 19 in 1990. Area 12 was sampled before its fishery

(July to October) for all years (except 1996 where there was no survey) and Area 19 was sampled before its fishery from 1990 to 1992 and then after its fishery from 1993 onward (Moriyasu et al. 2008).

In 1997, the survey area was again extended to include the new management Areas 12E and 12F. New stations were added randomly within grids as the survey polygon expanded or if areas were targeted for more intensive sampling to reduce the variance. Further details of these survey design changes are provided by Moriyasu et al. (2008).

The sampling design from 2006 to 2011 was modified in accordance with recommendations from the 2005 Assessment Framework Workshop on the sGSL snow crab (DFO 2006; Moriyasu et al. 2008). A new design was introduced to achieve spatial sampling homogeneity. While this survey design was spatially unbiased in the sense that the expected number of stations per 10 by 10 minute grid was proportional to its surface area, in practice the realized number of stations per grid was either one or two stations, and grids along the survey area margins often had zero stations. Past survey stations were retained as much as possible, but others were removed or added to the grid as prescribed by the sampling method (Hébert et al. 2007; Moriyasu et al. 2008).

In 2012, the sampling design was again modified following recommendations from the 2011 Snow Crab Assessment Methods Framework Science Review (DFO 2012a). The boundaries of the survey area were extended to the 20 and 200 fathom isobaths, encompassing the vast majority of favorable snow crab habitat (i.e. bottom temperatures less than 5°C) and thus the sGSL biological unit. To further improve spatial homogeneity, grids were set to be square rather than rectangular with dimensions defined as a function of the number of total samples, so that each grid included only a single sampling station (DFO 2012a). This protocol resulted in an entirely new set of sampling stations. The revised survey sampling design in 2012 is presented in Wade et al. (2014). For 2013, the number of stations increased from 325 to 355 following recommendations from the snow crab advisory committee to increase the precision of the biomass estimates in smaller fishing zones. The survey area was partitioned into square grids of 12.7 km x 12.7 km and a new set of sampling stations was generated.

Since 2014, the number of target sampling stations has remained at 355 and the successfully sampled stations from the previous year survey were used as fixed stations. From 2014 to 2017, the number of successful sampling stations, that were used as fixed stations, varied from 346 to 348. A new set of sampling stations was generated randomly when sampling stations were abandoned or if the sampling stations were outside of their assigned square grids.

3.1.1. Trawl survey in 2018

In 2018, the number of target sampling stations remained at 355. The 350 successful sampling stations from the 2017 trawl survey were used as fixed stations in 2017 and a new set of five sampling stations (the two sampling stations that were abandoned and three sampling stations that were conducted outside their assigned square grid areas in 2017) was generated randomly (Fig. 2).

The trawl survey was conducted between July 18 and September 16 and covered Areas 12, 19, 12E and 12F (Fig. 2). The "*Jean-Mathieu*", a 65 foot stern-trawling (720 HP) steel boat, was used to conduct the trawl survey in 2018. A total of 354 stations were successfully trawled in 2018; one sampling square had to be abandoned due to failures to successfully trawl the area. A detailed description of the 2018 trawl survey is provided in Allain et al. (2020).

A Bigouden Nephrops bottom trawl net, originally developed for Norway lobster (*Nephrops norvegicus*) fisheries in France, was used (20 m opening with a 28.2 m foot rope). The net is

made of 2.5 mm diameter braided nylon twine and the mesh sizes are 80 mm in the wings, 60 mm in the belly and 40 mm in the cod-end (see Moriyasu et al. 2008 for more details on the description of the trawl).

All stations were trawled during the interval between morning and evening civil twilight hours. A predetermined amount of warp was let out (three times the distance of the depth) before the winch drums were locked. The start time of a standard tow was based on the information reported by the eSonar® depth and height sensors, later revised using data from a Minilog® temperature-depth or StarOddi probes attached to the trawl. The target duration of each tow was five minutes at a target speed of two knots. The horizontal opening of the trawl was recorded every four seconds with the eSonar® distance sensors. The swept distance of the trawl was estimated from the position (latitude/longitude) measured every second with a Differential Global Positioning System. The swept area for each tow was calculated by multiplying the swept distance and the horizontal opening of the trawl over the duration of the tow.

Tows were rejected if the net was damaged, the eSonar® system generated no usable data to determine the beginning of the tow, or the duration of the tow was less than five minutes. A replacement tow was conducted near the original start point or at the alternate sampling stations within the assigned grid (Fig. 2).

If the tow satisfied trawl survey protocols but the data signal quality from the eSonar® sensors was deemed to be inadequate to calculate the swept area, the swept area of the tow was set to the average of the values of the 10 nearest stations.

3.1.2. Biological sampling

The trawl catches were sorted on the vessel deck. Snow crabs were put aside for detailed sampling. All other organisms were sorted by species or species group and counted. Since 2010, individual length measurements for all fish species were made at 100 randomly selected stations. Fish length sampling was based on sub-samples of up to 100 individuals of each fish species in a selected tow. Starting in 2013, all species or species group were weighed.

The following information was recorded for all snow crabs: carapace width (CW), chela height (CH) for males only to the nearest 0.1 mm and carapace condition (Hébert et al. 1997). For females, the color (orange, dark orange, brown or black) and quantity (in percentages) of external eggs on ovigerous females, as well as the color (white, beige or orange) of the gonads of immature females were also noted.

The size frequency distributions for the population were derived from the samples weighted by the swept area (km^2) of each corresponding tow.

There was some discrepancy in the identification of carapace conditions during the 2018 trawl survey. The carapace condition is important to separate the recruitment to the fishery (adult male larger than 95 mm CW with carapace conditions 1 and 2) and the residual biomass (adult males larger than 95 mm CW with carapace conditions 3, 4 and 5). The misclassification of carapace condition also affects the mortality rates and therefore, the prediction of the recruitment to the fishery and commercial biomass. Since 2017, a new tool has been developed to objectively identify the carapace condition via precise colour measurements of large males (>90mm CW) chelae using a colorimeter. The premise is that new-shelled crab, i.e., molted during the survey year) are whiter than old-shelled crab, which get progressively yellower and darker with time. While not providing an absolute classification, i.e., there is some overlap in the coloration between these two categories, the differences are sufficiently large that the

proportions of new-shelled versus old shelled crab can be reasonably estimated using only chelae colouration observations.

The underside of chelae for a maximum of two large mature males (> 90mm CW) per carapace condition per tow were measured using a colorimeter during the 2017 (n = 817 crabs) and 2018 (n = 956 crabs) surveys. Figure 3 shows the frequency histogram for the b* value in the L*a*b* colour triplets, which approximately corresponds to the degree of yellowness in the carapace. The L* value refers to the luminance or "whiteness" of the colour, the a* value indicates the level of greenness or redness, and b* value indicates the level of blueness or yellowness. These three parameters are necessary to identify the colour of an object. Two modes are readily apparent and we interpret these modes as corresponding to differences in coloration between new-shelled and old-shelled crab. This interpretation is supported by common knowledge that newly moulted crab are white (hence the term "white" crab) and progressively acquire a yellow sheen as time passes. This is also supported by our colorimeter data as the position of the new-shelled component does tend progressively towards the yellower part of the spectrum as the survey season progresses. Figure 3 also illustrates the issue with the carapace condition observations for 2018, in that many carapace condition 2 assignments have b* values which strongly suggest that they are old-shelled, whereas the 2017 data show a much smaller proportion of such values.

Based on these observations, we analysed the colorimeter data using the following Bayesian model. Let $Zi \sim Bern(\pi)$ be an unobserved binary random variable indicating whether an observed colour value yi is new-shelled (Zi = 0) or old-shelled (Zi = 1) with probability π. We assume that the distribution of the colour observations, conditional on Zi as $Yi \mid Zi = j \sim N(\mu j, \sigma^2 j)$, where j = 0 or 1. While the mean of old shelled observations μ1 were assumed to be constant throughout the season, new-shelled means can vary. Priors were thus $\mu 1 \sim N(0,10^6)$ and $\mu 0k \sim N(m,s^2)$, with $m \sim N(0,10^6)$ and $s^{-2} \sim Gam(0.001,0.001)$, with k indexing survey week. Further, the mixture proportions were assumed to also vary by week and observed carapace condition, with hierarchical prior $logit(\pi jk) \sim N(mk',sk'^2)$ and $mk' \sim N(0,10^3)$ and $sk'^{-2} \sim Gam(0.1,0.1)$. This prior allowed for inference on the proportion of each of the carapace condition observations which were being assigned to new and old-shelled crab on the b* colour observations. Posterior inference was based on MCMC in WinBugs.

The hierarchical mixture returns, by survey week, the probability of each carapace condition being classified as new-shelled by the colorimeter (Table 1). The issue in the 2018 data, which was generally not the case for the 2017, is that significant proportions (~80% of samples) of carapace condition 2 crab seem to comprised of old-shelled crab, as identified by the colorimeter. This issue seems to be a minor one in 2017. As a corrective, a portion of large males identified as carapace condition 2 were reassigned as carapace condition 3 using the values in Table 1 as misclassification probabilities. These adjusted values were used in the estimates of the fishery recruitment and residual biomass of the population.

The colorimeter approach is promising but still under development to objectively identify and correctly separate the carapace conditions 2 and 3 and should be viewed with caution especially with samples collected during the fall season as new-shelled crabs tend to be yellower and can be identified as carapace condition 3 by the colorimeter reading. The criteria used in identifying carapace condition require experience and proper training of on-board staff is critical to maintain comparable standards from year to year.

3.1.3. Estimation of snow crab abundance

The assessment follows the recommendations from the November 2011 Framework Science Peer Review of stock assessment methods for the sGSL snow crab stock (DFO 2012a).

Small adjustments were made to the survey area polygon and its component sub-polygons, those used for kriging (which include fishing areas, buffer zones and unassigned zone), were done in 2018 to address some minor issues. The survey area had a small gap located north of the Magdalen Islands which added 2.8 km^2 to the survey polygon. Some parts of the buffer zones lay outside of the boundaries of the survey polygon while some small areas were not assigned to any management zones or to buffer zones. There were also polygon overlaps in some areas leading to a slight double counting of the abundance or biomass estimates. The differences between the surface areas of the original and revised polygons are shown in Table 2.

The revised survey area polygon has a total area of 57,842.8 km^2 (Table 2; Fig. 4) and the four corresponding management areas have areas of 48,074 km^2 for Area 12, 3,813 km^2 for Area 19, 2,436.9 km^2 for Area 12E, and 2,426.8 km^2 for Area 12F (Table 2; Fig. 4). An additional unassigned zone A (above Areas 12E and 12F, Fig. 3) is included in the expanded polygon and located where no fishing activities were observed. This zone has an area of 667.9 km^2, while the buffer zones B and C (Fig. 4) cover areas of 134.2 and 289.5 km^2, respectively.

The sGSL biomass estimates include the unassigned zone A and the buffer zones B and C (no fishing zones) (Fig. 4). Commercial biomass estimates in each management zone 12, 19, 12E and 12F were calculated excluding the buffer zones.

Commercial biomass estimates were also calculated for each of the buffer zones (B and C) and for the unassigned zone (A).

The current model, kriging with external drift (KED) using depth as a secondary variable, used for the snow crab assessment is considered suitable for biomass estimates (DFO 2012a).

A three-year average for the global variogram was calculated as this has been considered a more stable method for modeling the autocorrelation between the samples (Wade et al. 2014).

The 1997 to 2018 time series of estimated biomasses for the sGSL, using the expanded polygon of 57,842.8 km^2, was considered as a standardized time series for the purpose of stock assessment, development of reference points and provision of catch advice.

Kriging programs originally developed in MATLAB 7.10 by the Ecole Polytechnique de Montréal (MPOGEOS library) were translated to R 3.4 for easier accessibility for the 2018 stock assessment. During this translation process, where the output between the two programming languages were painstakingly compared step by step, a bug was uncovered in the main kriging function used in Matlab which has been in use since the last Framework Assessment in 2005 (DFO 2006). When analyzing a single variable, e.g. commercial crab and no other categories, the bug had no effect. However, when multiple variables were being analyzed simultaneously, the bug had the effect of mixing together variogram parameters from different variables, resulting in the wrong nugget and sill variogram parameters being used. Only the range parameter, which partly controls the degree of spatial autocorrelation, was properly assigned.

Unfortunately, this issue affects all kriging-based estimates performed since the Framework Assessment in 2005, although the effects are generally minor. For larger, well sampled areas in the sGSL, the variogram only has minor effects on overall abundance or biomass estimates, but using invalid nugget and sill parameters may have stronger effects on the confidence intervals estimates. We have thus re-analyzed the entire series of snow crab abundance and biomass estimates since 1997.

The differences between the original and revised commercial biomass estimates for the sGSL when applying both the kriging polygon and variogram parameter corrections from 1997 to 2017 are shown in Table 3.

Biomass was estimated using KED on commercial-sized adult catch weights (Wade et al. 2014), with the weight estimated using the size-weight relationship:

$$W = (2.665 \times 10^{-4})\ CW^{3.098}$$

where W is the weight in grams and CW is the carapace width in mm (Hébert et al. 1992).

Total biomasses were estimated for the following categories of male crab:

- commercial-sized adult male ≥ 95 mm CW all carapace conditions,
- commercial-sized adult male crab ≥ 95 mm CW with carapace conditions 1 and 2 at the time of the survey, which represents the annual recruitment to the fishery (called R-1), and
- adult male crab ≥ 95 mm CW with carapace conditions 3, 4 and 5 (hard-shelled) at the time of the survey, which represent the residual or remaining biomass post- fishery.

The abundance indices of prerecruits at the time of the survey (R-4, R-3 and R-2) were used to forecast the recruitment to the fishery over the next four years. Stages R-4, R-3 and R-2 represent adolescent males with a CW range of 56-68 mm, 69-83 mm and larger than 83 mm, respectively, and they are expected to recruit (CW ≥ 95 mm) to the fishery in four, three and two years, respectively. The size increments from molting of pre-recruits R-4, R-3 and R-2 were set using a growth model for adolescent male snow crab (Hébert et al. 2002). The abundance of adolescent males of instar VIII, defined as those with a CW between 34 and 44 mm, was also estimated as an index of longer term recruitment. It takes at least six years for an adolescent male of instar VIII to reach the commercial size of 95 mm CW. In addition, the abundance indices of pubescent, primiparous and multiparous females were estimated.

3.2. ESTIMATION OF THE ANNUAL TOTAL MORTALITY AND EXPLOITATION RATES

Total annual mortality of commercial-sized adult males, expressed as a proportion, is estimated as:

$$N_t^{3,4,5} / N_{t-1}$$

Where N_t^{345} is the biomass of commercial-sized adult males with carapace conditions 3, 4 and 5 after the fishery in year *t* (the residual biomass) and $N(_{t-1})$ is the abundance of commercial-sized males with carapace conditions 1 to 5 after the fishery in year *t-1* (the commercial biomass in the previous year).

The exploitation rate *(ER)* is calculated as the ratio of the catch *(t)* in the fishery of year *t* ($C_t^{3,4,5}$) and the commercial biomass (B_{t-1}) from the previous year.

$$ER = C_t^{3,4,5} / B_{t-1}$$

This exploitation rate does not take into account the natural mortality before and during the fishery.

3.3. RISK ANALYSIS AND CATCH OPTIONS

The Bayesian model described by Surette and Wade (2006) and Wade et al. (2014) was used to forecast the biomass of recruitment to the fishery (R-1) based on survey abundances of pre-recruits R-4, R-3 and R-2 from the sGSL, to project three, two and one year(s) into the future, respectively. The model incorporated uncertainties associated with observation errors.

3.4. SEPTEMBER MULTI-SPECIES BOTTOM TRAWL SURVEY INDEX

A second fishery independent index was calculated the 2001 to 2018 data from the September multi-species bottom trawl survey, a stratified random design, following the method presented in Benoît and Cadigan (2013). In areal extent, this survey covers that of the snow crab survey. While the catchability of the Western IIA trawl used in the September survey is much lower for snow crab than that used in the snow crab survey, it was shown that the index derived from the September survey broadly followed the same trends for commercial crab, though the uncertainty associated with the estimates was larger owing to the lower sampling intensity.

4.0. RESULTS AND DISCUSSION

4.1. ESTIMATES OF BIOMASS AND EXPLOITATION IN 2018

4.1.1. Southern Gulf

4.1.1.1. Variogram

The variogram is a model which describes the evolution of the variance as a function of the distance between the samples and allows the modelling of the spatial autocorrelations between the data. The variogram has three properties: the nugget effect, the sill, and the range. The nugget effect represents the variation between two very spatially proximate samples, which could be due to natural variability of the measured parameter, a variability in the measure instrument or a brutal variation of the measured parameter. The sill indicates the point where a plateau of the variance is reached whereas the range represents the distance where there are no longer spatial auto-correlations between the samples. The three-year averaged variogram model for commercial-sized adult males in 2018 had a nugget value of 2.7×10^6, a sill at 4.1×10^6 and a range of 98.3 km (Fig. 5). The annual variogram model for 2018 had a nugget value of 2.4×10^6, a sill at 4.4×10^6 and a range of 83.1 km (Fig. 6).

4.1.1.2. Biomass estimates

The 2018 southern Gulf commercial biomass estimate was 80,746 t (95% confidence interval (C.I.) range of 70,984 to 91,467 t), an increase of 22.8% from the 2017 estimate of 65,738 (57,221 to 75,157 t) (Table 4). The recruitment to the fishery at the time of the 2018 survey was estimated at 59,609 t (51,755 to 68,310 t), an increase of 16.6% from the 2017 estimate of 51,127 t (43,976 to 59,103 t) and represents 74% of the commercial biomass (Table 4). The 2018 residual biomass (adult commercial-sized males with carapace conditions 3, 4 and 5) was estimated at 21,432 t (17,270 to 26,291 t), an increase of 46.3% compared to the 2017 estimate of 14,650 t (12,134 to 17,534 t) (Table 4).

In 2018, local concentrations of commercial crab were mainly observed in Bradelle Bank, Chaleur Bay, Shediac valley, in the central and southern parts of the Magdalen channel and in the southeastern part of the sGSL (Fig. 7).

By carapace condition in the 2018 trawl survey, commercial crabs were comprised of 72.6% fishery recruitment (carapace conditions 1 and 2) and 27.4% residual biomass (carapace conditions 3, 4 and 5) (Table 5). A further split by carapace condition of the residual biomass, the total biomass is composed of 23.8% commercial crab with carapace condition 3, 3.1% crabs with carapace condition 4, and 0.5% of crabs with carapace condition 5 (Table 5). This suggests that the composition of the commercial male population observed in the 2018 trawl survey is young and there is no sign of an ageing population at this time. Close monitoring of catch composition from the at-sea observer sampling and survey data is necessary to monitor the ageing of the commercial male population in the coming years.

A comparison between fishery recruitment predicted by the Bayesian model for the fishery of 2019 (47,700 t; 95% C.I. 33,800 to 64,880 t) and the recruitment biomass from the 2018 survey (59,609 t; 51,755 to 68,310 t) indicated that the estimated recruitment for the 2019 fishery is within the limits of the 95% credibility interval of the predicted value (Table 6; Fig. 8). The relationship between the abundance of R-2 prerecruits in year t and the recruitment to the fishery in year t + 1 is shown in Figure 9. A number of factors can account for the variability in this relationship, including variations in bycatch mortality, natural mortality, the molting schedule of precreruits (skip molting, molting to adolescent phase or molting to adult phase), and sampling error. Since 1997, the proportion of skip molters larger than 83 mm CW, which are part of the R-2 component, varied from 3.7% in 1997 to 59.8% in 2003, corresponding to its abundance (Fig. 10). In 2018, the proportion of the skip molters larger than 83 mm CW was at 33.8% while it was at 52.6% in 2015 (Fig. 10). More study is needed to better predict the arrival and growth of skip molter crab into the population.

4.1.2. Estimation of the portion of total biomass in each management fishing zone and buffer zone

4.1.2.1. Area 12

The 2018 trawl survey estimate of commercial biomass for Area 12 was 68,953 t (60,344 to 78,439 t) (Table 7). This estimate corresponds to 84.9% of the sum of the independently estimated commercial biomasses in the four management zones.

4.1.2.2. Area 19

The 2018 post-fishery trawl survey estimate of the commercial biomass was 6,825 t (4,955 to 9,173 t) (Table 7). This estimate corresponds to 8.5% of the sum of the independently estimated commercial biomasses in the four management zones.

4.1.2.3. Areas 12E and 12F

Areas 12E and 12F lie at the margins of snow crab habitat in the sGSL and contain few sampling stations and have correspondingly more uncertain biomass estimates with very large confidence intervals.

The Area 12E commercial biomass from the 2018 trawl survey was estimated at 425 t (21 to 2,155 t) (Table 7). This estimate corresponds to 0.5% of the sum of the independently estimated commercial biomasses in the four management zones.

In Area 12F, the commercial biomass from the 2018 trawl survey was estimated at 3,883 t (2,452 to 5,855 t) (Table 7). This estimate corresponds to 4.8% of the sum of the independently estimated commercial biomasses in the four management zones.

4.1.2.4. Buffer zones and unassigned zone

Commercial biomass estimates in the buffer zones and in the unassigned zone have very large confidence intervals given the low number of stations within these small zones.

The commercial biomass in the unassigned zone A above Areas 12E and 12F (Fig. 4) was 214 t (11 to 1,074 t) (Table 7). The commercial biomass in buffer zone B (2 nautical mile wide buffer zone) adjacent to Area 19 and 12F (Fig. 4) was estimated at 234 t (84 to 523 t) (Table 7). The commercial biomass in buffer zone C (5-miles buffer zone) located south of Area 19 (Fig. 4) was 255 t (35 to 923 t) (Table 7).

The sum of the commercial biomass estimates in the management, buffer, and unassigned zones in 2018 was 80,789 t, very close to the sGSL biomass estimate, 80,746 t (Table 7).

4.1.3. Exploitation rate

The exploitation rate in 2018 was 36.9% (Table 8; Fig. 11). The exploitation rates have varied between 21.0% and 44.7% from 1998 to 2018.

4.1.4. Total annual mortality and difference in commercial-sized adult males

The total annual mortality of commercial-sized adult male snow crab in the sGSL was estimated at 67.4% in 2018 and has varied between 46.1% and 85.1% from 1997 to 2018 except for 2011 where it was estimated at 11.3% (Fig. 11).

Over the time series (1997-2018), the sum of commercial biomasses exceeded by an average 29.5% the sum of the residual biomasses and landings of the following year (Fig. 12). These differences could be attributed to a number of factors including misattribution of recruitment and residual groups, variability in survey estimates, natural mortality, by-catch mortality, unreported landings, as well as crab movement in and out of the sampling area. The difference was 30.5% in 2018 (Fig. 12).

4.1.5. Reproductive potential

The abundance of all adult males increased from 1997 to 1999, remained stable until 2004 and gradually decreased until 2009 (Fig. 13). From 2009 to 2018, the abundance of adult males increased to levels comparable to those observed during the 1999-2005 period (Fig. 13). The abundance of mature females (primiparous and multiparous) in 2018 remained high relative to the low values observed during 2006 to 2009 (Fig. 14). Over the time series, the annual mean size of mature females varied from 56.8 mm in 2018 to 61.7 mm CW in 2005 (Fig. 15).

5.0. RISK ANALYSIS OF CATCH OPTIONS AND PROGNOSIS

Within the Precautionary Approach framework (DFO 2009), the limit reference point for biomass (Blim) defines the boundary between the critical and cautious zones and the upper stock reference point (BUSR) delimits the cautious from the healthy zones on the stock status axis. A removal rate limit reference point (Flim) defines the maximum removal rate in the healthy zone. Reference points which conform to the Precautionary Approach were developed in 2010 for the snow crab biological unit of the sGSL (DFO 2010). The change in methodology derived from the 2011 Snow Crab Assessment Methods Framework Science Review required the recalculation of the time series of biomass estimates and the Precautionary Approach reference points (DFO 2012b).

The rescaled BUSR is set at 41,300 t of commercial-sized adult males of all carapace conditions, which is 80% of the biomass of maximum sustainable yield (BMSY) with the proxy for BMSY chosen as 50% of the maximum estimated commercial biomass for the 1997 to 2008 time period (Table 8; Fig. 16). The rescaled Blim value is 10,000 t (Table 8; Fig. 16). The Blim was chosen as the lowest biomass of hard shelled commercial-sized adult males, which was observed in 2000 (residual biomass estimated from the trawl survey) (DFO 2010). The rescaled Flim has been set at 34.3% (Table 8; Fig. 16), which is the average annual exploitation rate calculated as catch (weight) in year t+1 divided by the estimated biomass of commercial-sized adult male crab from the post-fishery trawl survey in year t for the 1997 to 2009 time period (DFO 2010).

5.1. RISK ANALYSIS OF CATCH OPTIONS FOR 2019

The estimated commercial biomass available for the 2019 fishery in the sGSL is 80,746 t (70,984 to 91,467 t; Table 4), which is in the healthy zone of the precautionary approach framework (Fig. 16).

The predicted recruitment of commercial crab for the 2019 fishery based on the Bayesian prerecruit model (Surette and Wade, 2006; Wade et al., 2014), using the 2018 survey data, is 49,820 t (33,790 to 70,970 t) (Table 6; Fig. 17).

Harvest decision rules that conform to the precautionary approach have been developed (DFO 2014). These precautionary approach compliant harvest decision rules include rules for which the exploitation rate exceeds F_{lim} when the stock is in the healthy zone (DFO 2014). The Snow Crab Advisory Committee agreed on the proportional harvest decision rule (variant 4 in DFO 2014; Fig. 18) to derive the exploitation rate and the TAC based on the estimated biomass from the southern Gulf of St. Lawrence snow crab survey. This decision rule and the corresponding estimated commercial biomass from the 2018 survey of 80,746 t, corresponds to an exploitation rate of 40.9%, and a TAC of 33,025 t for the 2019 fishery (Fig. 18).

A risk analysis was developed for the decision rule TAC and relative to other catch levels in 2019 (Table 9, Fig. 19). The risk analysis indicates that the TAC derived from the harvest decision rule will result in a near 100% chance of the biomass for the next year's fishery being above BUSR and in the healthy zone of the PA (Table 9, Fig. 19). The risk analysis also provides predictions of the commercial biomass in the 2019 survey, assuming the corresponding catch level is taken in 2019. At the decision rule TAC value of 33,025 t for the 2019 fishery, the commercial biomass predicted for the 2019 post-fishery survey and for the 2020 fishery, is 83,850 t, with a 95% confidence interval range of 72,820 to 94,870 t (Table 9), at the same level compared to the 2018 survey commercial biomass. The commercial biomass projections for 2020 according to different catch options for the 2019 fishery are presented in Table 9.

A number of factors can account for the variation in the recruitment rate of the prerecruits to the commercial-sized adult stage including unaccounted bycatch mortality, sampling uncertainties, natural mortality and variations in the molting schedule of precreruits (skip molting, molting to adolescent phase or molting to adult phase), especially if density-dependent phenomena occur. In addition, in these two-year commercial biomass projections, we used a forecast survivorship rate of 0.71, which is a five-year moving average. In the past, the survivorship rate has varied considerably year on year which affects directly the commercial biomass projections.

5.2. PROGNOSIS

The fishery recruitment and the commercial biomass (by taking into account the application of the decision rule of 40.9% exploitation rate for the 2019 fishery) are expected to be 49,820 t (33,790 to 70,970 t; Table 6) and 83,850 t (72,820 to 94,870 t; Table 9), respectively for the 2020 fishery. Small pulses of adolescent males, between 12 to 17 mm and 17 to 25 mm carapace width were observed in the 2018 survey (Fig. 20). The abundance of males with a CW between 34 and 44 mm in 2018, which will reach the commercial size in 6 years, remained at the same level as in 2017 (Fig. 21). The abundance of prerecruits ≥ 56 mm CW (R-4, R-3, R-2) remained high in 2018 (Table 6). The area occupied by these crabs in the 2018 survey was mostly in Chaleur Bay, in Shediac valley, on Bradelle Bank and in the southeastern part of sGSL (Fig. 22).

The estimated abundances of immature and pubescent females in the population increased from 2001 to 2012, decreased in 2013 and 2014 and increased since 2014 (Figs. 14 and 23).

The abundance of mature females remained high in 2018 relative to the low values observed during 2006 to 2009 (Figs. 14 and 23).

5.3. SEPTEMBER MULTI-SPECIES BOTTOM TRAWL SURVEY

The September multi-species research bottom trawl survey index shows generally similar trends (within the estimation precisions of the surveys) for commercial-sized adult male snow crab biomass between 2001 and 2018 (Fig. 24) as do the estimates from the dedicated snow crab trawl survey (Fig. 12). The September multi-species bottom trawl survey index indicated a decrease of 8.1% in the biomass of commercial-sized male crabs in 2018 (Fig. 24) while the dedicated snow crab survey data showed an increase of 22.8% (Fig. 12). Some adjustments in the September multi-species survey index are needed to account the swept area covered by the Western IIA trawl. Changes in the September multi-species survey index may not accurately reflect changes in stock size if there are significant differences in the annual mean swept area, which could result in different survey vessel catchabilities.

6.0. UNCERTAINTIES

6.1. CHANGE IN THE SURVEY PROTOCOL AND VARIABILITY IN THE COMPOSITION OF COMMERCIAL BIOMASS

A number of survey protocol changes have weakened the assumption of homogeneity of the biomass time series.

Four different boats have been used to conduct the trawl survey:

- the “Emy-Serge” (1988-1998), a 65-foot side-trawling (375 HP) wooden boat,
- the “Den C. Martin” (1999-2002), a 65-foot stern-trawling (402 HP) steel boat,
- the “Marco-Michel’’ (2003-2012), a 65 feet stern-trawling (660 HP) fiberglass boat, and
- the “Jean-Mathieu” since 2013, a 65-foot stern trawler (720 HP) steel boat.

Individual tows were standardized by trawl swept area using data from trawl acoustic monitoring sensors (Moriyasu et al. 2008). However, other factors may contribute to varying catchability among boats, but no comparative fishing studies were performed. A preliminary statistical comparison between snow crab survey and September multispecies survey data suggests that the boats did have different catchabilities, which can alter our perception of stock dynamics (Benoît and Cadigan 2013). Work is ongoing to refine the estimates of relative catchabilty of the vessels.

The kriging polygon or the area over which the abundance or biomass is estimated has increased over the years. The difference between the survey area, i.e. over which trawl samples are extracted, and the latest kriging polygon is more pronounced farther back in time. Thus there is more extrapolation and potential for bias during earlier years.

A Snow Crab Assessment Methods Framework Science Review conducted in November 2011 addressed these concerns as well as changes in survey design. Following this review, it was agreed that the time series from 1997 to the present was sufficiently coherent to be used in assessing stock status and providing catch advice (DFO 2012a). Further work is required to determine if the time series between 1989 and 1996, for which survey coverage was much less than the coverage from 1997 to the present, could also be used for assessment purposes.

6.2. GROWTH

Recruitment to the fishery for snow crab is highly variable from year to year (Comeau and Conan 1992; Sainte-Marie et al. 1995; Comeau et al. 1998; Moriyasu et al. 1998) depending on environmental conditions, predation and population levels. In sGSL snow crab stocks, the biomass of commercial-sized adult male crab appears to fluctuate from periods of three to four years of high recruitment followed by three to four years of low recruitment (Sainte-Marie et al. 1995; Comeau et al. 1998; Moriyasu et al. 1998). Since molting activity peaks in January for adolescent skip-molters and in March for normal molters, most postmolt males are potentially catchable as soon as the fishery starts (generally at the end of April). Soft-shelled males in the commercial catches are found from late April to August in the sGSL (Hébert et al. 2002).

The mechanism of molting to terminal phase is complex. Conan et al. (1988), and Comeau et al. (1998) hypothesized that the molt to terminal phase for a given size group may be density-dependent rather than genetically determined. Waiwood and Elner (1982) hypothesized that the removal of large old crab would release the snow crab population from a “stagnant” to a “dynamic” high-growth phase. Comeau et al. (1998) suggested that a high abundance of large mature (adult) males in the population may trigger molting to another larger juvenile (adolescent) instar stage instead of molting to the terminal phase. Alternatively growth could be inhibited resulting in an increased abundance of skip-molters. The annual trawl survey showed a very high (up to 50–60% in peak years) skip-molting rate in adolescent males larger than 50 mm CW. Such a high percentage of skip-molters may reflect a density-dependent effect on the molting schedule of larger adolescent males. Dawe et al. (2012) showed that the frequency of skip-molting is strongly and directly related to body size (i.e. larger than 50mm CW), and it is also inversely related to water temperature. Prediction of a given size of male crab belonging to the near-future recruitment population (R-1, R-2 and R-3) is difficult, which increases uncertainty of predicted and measured abundance of recruitment to the fishery. This may be a driving factor affecting the strength and timing of recruitment to the fishery.

6.3. ENVIRONMENTAL CONSIDERATIONS

Environmental factors, such as water temperature, can affect molting, reproductive dynamics and the movement of snow crab. Chassé and Pettipas (2009) reported that bottom temperatures over most of the sGSL are typically between -1 and 3ºC, a temperature range suitable for snow crab habitat. Data collected during research surveys indicate that the bottom temperatures in deeper waters of Areas 12E and 12F are higher (1 to 5ºC) than on the crab grounds (-1 to 2ºC) in Area 12. Bottom temperatures in Area 19 are usually 1 to 2 ºC warmer than on the traditional crab grounds in Area 12 (Chassé and Pettipas 2009).

In September 2018, near-bottom temperatures were near the mean value of the period 1981 to 2010 in most of the northern portion of Area 12 as well as in Area 19 (Fig. 25). However, the bottom waters in the southern portion of Area 12, in Area 12E, Area 12F and the northwestern portion of the southern Gulf of St. Lawrence (channels connecting the slope of the Laurentian Channel to the Magdalen Shallows) were significantly warmer than normal. Bottom waters outside of Miramichi Bay were also warmer than average (Fig. 25). There was a band of cooler-than-normal bottom waters in the southwestern part of Area 12 that was stretching down from Miscou Island to the east entrance of Northumberland Strait including St. George’s Bay (Fig. 25).

Most of the snow crab fishing grounds in the northern portion of Area 12 had similar temperatures, or slightly cooler, in 2018 compared to 2017 except at the head of Chaleur Bay where temperatures were cooler in 2018 (Fig. 25). The southern portion of Area 12 had significantly warmer water covering the fishing grounds in 2018 compared to 2017 (Fig. 25).

Area 19 bottom water temperatures in 2018 were similar to those observed in 2017. Areas 12E and 12F had a tendency to be cooler in 2018 than in 2017 (Fig. 25).

The snow crab habitat index (bottom area with temperatures from -1 to 3°C) was just below the 1981-2010 average (1% below) in 2018 and decreased by 5% from 2017 and was similar to the 2016 value (Fig. 26). The mean bottom water temperature (1.2°C) within the defined snow crab habitat area index (-1 to 3°C) in 2018 increased by about 0.3°C compared to 2017 (0.9ºC, Fig. 26). The mean bottom water temperature was at the highest of the 48 year time series in 2012, decreased in 2013 and 2014, and remained above the normal since then (Fig. 26).

Snow crab is a stenothermic species with a preference for colder water temperatures. A temperature regime shift from cold to warm may have impacts on population dynamics of snow crab such as shortened reproductive cycles, increased per capita fecundity, increased size at maturity, greater natural mortality, spatial contraction of habitat, and skewed sex ratio for reproduction. The outcome of climate change on snow crab population dynamics can be relatively abrupt and even detrimental, and the direction of the effect may be difficult to predict (Sainte-Marie et al. 2008).

7.0. ACKNOWLEDGMENTS

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9.0 TABLES

Table 1. Probability, by week, of correctly identifying the carapace conditions (CC) 1 or 2 (recruitment to the fishery) based on the colorimeter instrument taken on crab with assigned carapace conditions using standard approach based on shell condition and colour during the 2017 and 2018 trawl surveys.

		Probability correctly identifying carapace conditions (CC) 1 or 2			
Year	Week	CC1	CC2	CC3	CC4 and 5
2017	1	1.00	0.98	0.00	0.00
2017	2	1.00	0.98	0.00	0.00
2017	3	1.00	0.98	0.00	0.00
2017	4	0.99	0.99	0.00	0.00
2017	5	0.99	0.85	0.00	0.00
2017	6	0.99	0.59	0.00	0.00
2017	7	0.99	0.92	0.00	0.00
2017	8	0.99	0.98	0.00	0.00
2017	9	0.99	0.99	0.00	0.00
2017	10	0.99	0.99	0.00	0.00
2017	11	0.99	0.99	0.00	0.00
2018	1	0.97	0.33	0.01	0.00
2018	2	0.98	0.20	0.00	0.00
2018	3	0.98	0.02	0.00	0.00
2018	4	0.99	0.04	0.00	0.00
2018	5	0.99	0.02	0.00	0.00
2018	6	0.99	0.11	0.00	0.00
2018	7	0.98	0.40	0.00	0.00
2018	8	0.99	0.04	0.00	0.00
2018	9	0.99	0.60	0.01	0.00

Table 2. Difference in the kriging polygon (original versus revised) with the adjustments done in 2018.

Kriging polygon	Original (km^2)	Revised (km^2)	Difference
Gulf (survey area)	57,840	57,842.8	+0.005%
Zone 12	48,028	48,074.6	+0.097%
Zone 19	3,833	3,813.2	-0.517%
Zone E	2,443	2,436.9	-0.250%
Zone F	2,438	2,426.8	-0.459%
Zone E& F unassigned	674	667.9	-0.905%
Buffer zone 19 & F	112	134.2	+19.821%
Buffer zone 19 & 12	310	289.1	-6.742%
Total	57,838	57,842.7	+0.008%

Table 3. Difference (original – revised) between the original and revised biomass estimates (t, mean and 95% confidence interval in parentheses) of commercial-sized adult male snow crab, Chionoecetes opilio, in the southern Gulf of St. Lawrence, 1997 to 2017. The revised values are estimated using the corrected code for the selection of the variogram parameters.

Survey year	Revised commercial biomass (t)	Original commercial biomass (t)	Difference (t)
1997	64,518 (54,105-76,345)	65,310 (54,801-77,239)	791
1998	57,813 (45,856-71,931)	57,595 (45,630-71,735)	-218
1999	56,757 (47,641-67,102)	57,051 (47,946-67,376)	294
2000	50,621 (41,843-60,692)	49,823 (40,473-60,682)	-798
2001	60,328 (49,851-72,351)	59,150 (47,740-72,460)	-1,178
2002	79,228 (67,983-91,791)	79,559 (66,688-94,181)	331
2003	84,448 (73,486-96,574)	84,423 (71,964-98,410)	-25
2004	103,146 (92,426-114,758)	103,429 (91,029-117,036)	283
2005	82,565 (73,514-92,415)	82,537 (73,487-92,387)	-28
2006	73,645 (65,681-82,302)	74,285 (66,192-83,087)	640
2007	66,371 (59,971-73,264)	66,660 (60,183-73,638)	289
2008	52,921 (47,167-59,178)	52,564 (46,658-59,006)	-357
2009	31,015 (27,519-34,829)	30,920 (27,237-34,959)	-95
2010	35,929 (32,049-40,147)	35,795 (31,681-40,291)	-134
2011	62,841 (55,985-70,299)	63,162 (55,965-71,022)	321
2012	74,778 (64,881-85,748)	74,997 (65,822-85,086)	219
2013	66,709 (54,294-81,108)	65,868 (56,283-76,610)	-841
2014	67,990 (59,802-76,978)	67,534 (60,994-74,579)	-456
2015	58,927 (51,368-67,278)	58,808 (52,754-65,466)	-119
2016	98,394 (87,150-110,677)	99,145 (87,749-111,600)	751
2017	65,738 (57,221-75,157)	66,021 (57,456-75,495)	283
Mean difference (%)	na	na	-2.238%

Table 4. Estimated biomass (t, mean and 95% confidence interval in parentheses) with the revised polygon of commercial-sized adult male snow crab, Chionoecetes opilio, in the southern Gulf of St. Lawrence (all zones) by kriging, based on trawl survey data from 1997 to 2018. Recruitment refers to snow crab with carapace conditions 1 and 2 whereas residual biomass refers to snow crab with carapace conditions 3 to 5.

Survey year	Commercial biomass	Recruitment biomass	Residual biomass
1997	64,518 (54,105-76,345)	37,910 (30,911-46,018)	27,688 (21,982-34,422)
1998	57,813 (45,856-71,931)	30,603 (22,695-40,384)	28,295 (21,497-36,566)
1999	56,757 (47,641-67,102)	26,015 (20,709-32,265)	31,177 (25,044-38,356)
2000	50,621 (41,843-60,692)	40,734 (33,592-48,942)	9,979 (6,987-13,827)
2001	60,328 (49,851-72,351)	42,358 (33,800-52,422)	17,612 (13,853-22,077)
2002	79,228 (67,983-91,791)	66,076 (55,416-78,180)	13,060 (10,793-15,662)
2003	84,448 (73,486-96,574)	58,270 (50,270-67,175)	26,993 (22,124-32,613)
2004	103,146 (92,426-114,758)	83,764 (74,392-93,981)	21,259 (17,343-25,794)
2005	82,565 (73,514-92,415)	59,939 (53,551-66,870)	23,496 (18,902-28,868)
2006	73,645 (65,681-82,302)	54,541 (48,235-61,438)	19,621 (16,697-22,907)
2007	66,371 (59,971-73,264)	40,048 (35,286-45,269)	26,829 (23,232-30,821)
2008	52,921 (47,167-59,178)	32,241 (27,929-37,027)	20,981 (17,989-24,327)
2009	31,015 (27,519-34,829)	20,618 (17,747-23,818)	10,454 (8,687-12,474)
2010	35,929 (32,049-40,147)	20,477 (17,815-23,423)	15,490 (13,022-18,289)
2011	62,841 (55,985-70,299)	29,643 (25,676-34,045)	33,679 (28,430-39,613)
2012	74,778 (64,881-85,748)	49,010 (40,382-58,931)	25,615 (21,607-30,147)
2013	66,709 (54,294-81,108)	39,988 (31,504-50,055)	27,092 (22,041-32,952)
2014	67,990 (59,802-76,978)	44,285 (37,440-52,014)	23,863 (20,356-27,799)
2015	58,927 (51,368-67,278)	34,982 (29,145-41,643)	24,106 (20,290-28,429)
2016	98,394 (87,150-110,677)	74,124 (64,811-84,392)	24,309 (20,876-28,143)
2017	65,738 (57,221-75,157)	51,127 (43,976-59,103)	14,650 (12,134-17,534)
2018	80,746 (70,984-91,467)	59,609 (51,755-68,310)	21,432 (17,271-26,291)

Table 5. Abundance (number by 10^6; mean and 95% confidence interval) of commercial-sized adult male snow crabs by carapace condition (CC 1+2, CC3, CC4 and CC5) in the southern Gulf of St. Lawrence based on trawl survey data from 1997 to 2018.

Survey year	Carapace condition 1+2			Carapace condition 3			Carapace condition 4			Carapace condition 5		
	Mean	Confidence interval		Mean	Confidence interval		Mean	Confidence interval		Mean	Confidence interval	
1997	59.069	47.129	73.109	28.326	21.710	36.327	17.726	13.242	23.246	5.184	3.071	8.215
1998	51.382	38.994	66.464	24.903	18.569	32.709	16.030	11.367	21.975	8.608	5.213	13.411
1999	48.144	38.377	59.636	32.735	25.346	41.608	16.810	13.091	21.259	7.830	5.292	11.172
2000	68.440	57.669	80.631	10.295	7.750	13.410	7.406	4.336	11.845	2.522	1.701	3.605
2001	76.373	61.187	94.183	28.091	22.978	34.000	5.360	3.017	8.834	1.579	0.546	3.619
2002	112.257	95.352	131.282	21.725	18.201	25.730	4.308	2.925	6.125	0.892	0.477	1.529
2003	100.276	86.379	115.761	38.003	31.365	45.626	11.660	7.928	16.553	1.755	0.882	3.142
2004	143.279	127.523	160.430	28.162	22.442	34.895	9.862	7.794	12.311	1.156	0.785	1.643
2005	99.125	88.636	110.505	29.991	23.604	37.392	10.507	8.172	13.302	0.574	0.277	1.058
2006	84.164	74.958	94.181	29.213	24.788	34.197	5.762	4.408	7.402	1.009	0.636	1.523
2007	62.847	55.660	70.699	31.499	26.656	36.963	13.993	11.240	17.215	1.036	0.646	1.579
2008	49.118	42.877	56.008	23.030	19.338	27.219	11.420	9.172	14.052	3.034	2.099	4.245
2009	31.675	27.381	36.449	12.531	10.433	14.926	5.261	3.713	7.240	1.268	0.711	2.095
2010	32.789	28.700	37.294	20.640	16.940	24.906	4.179	3.271	5.260	1.565	1.012	2.314
2011	52.955	46.067	60.576	44.301	36.962	52.665	9.845	7.754	12.325	1.794	1.147	2.677
2012	86.737	71.647	104.057	37.886	31.920	44.640	5.706	4.192	7.590	1.195	0.678	1.957
2013	63.668	48.784	81.669	30.117	22.610	39.324	18.335	14.516	22.850	0.660	0.341	1.159
2014	73.424	59.839	89.165	29.594	23.955	36.160	13.078	10.490	16.110	0.646	0.335	1.132
2015	56.250	46.833	66.999	27.205	21.810	33.530	17.265	14.431	20.490	0.504	0.208	1.032
2016	125.923	109.938	143.565	30.564	25.904	35.817	14.700	11.999	17.826	0.071	0.011	0.245
2017	90.108	77.318	104.399	21.561	17.650	26.080	6.110	4.908	7.518	0.376	0.160	0.756
2018	105.779	91.984	121.047	34.588	28.017	42.233	4.493	3.326	5.939	0.765	0.437	1.247

Table 6. Data used in the risk analysis of catch options: point estimates of abundance (number x 10^6) of snow crab male prerecruits (R-4, R-3 and R-2), the estimated (with 95% confidence intervals) and forecast (from the Bayesian model with 95% credible intervals) values for recruitment biomass (t; R-1), estimated residual biomass (t) and estimated commercial biomass (t) in the southern Gulf of St. Lawrence based on trawl survey data, and survivorship rates (S) between years used for the forecast model of commercial biomass. S is calculated based on a 5-year moving average.

Survey Year	Prerecruits (number x 10^6)			Recruitment to the fishery (t)	Forecast recruitment (t)	Residual biomass (t)	Commercia biomass (t)	Survival rate
	R – 4	R - 3	R - 2	R - 1	R-1	Res	B	S
1997	114.0	98.2	59.7	37,910 (30,911-46,018)	na	27,688 (21,982-34,422)	64,518 (54,105-76,345)	na
1998	135.3	91.3	60.3	30,603 (22,695-40,384)	na	28,295 (21,497-36,566)	57,813 (45,856-71,931)	na
1999	195.6	151.1	112.9	26,015 (20,709-32,265)	na	31,177 (25,044-38,356)	56,757 (47,641-67,102)	na
2000	237.5	159.1	88.4	40,734 (33,592-48,942)	na	9,979 (6,987-13,827)	50,621 (41,843-60,692)	na
2001	310.8	227.3	136.3	42,358 (33,800-52,422)	na	17,612 (13,853-22,077)	60,328 (49,851-72,351)	na
2002	164.3	242.2	202.2	66,076 (55,416-78,180)	na	13,060 (10,793-15,662)	79,228 (67,983-91,791)	na
2003	133.2	202.3	178.5	58,270 (50,270-67,175)	na	26,993 (22,124-32,613)	84,448 (73,486-96,574)	na
2004	85.8	122.9	144.1	83,764 (74,392-93,981)	na	21,259 (17,343-25,794)	103,146 (92,426-114,758)	na
2005	62.2	79.8	117.2	59,939 (53,551-66,870)	60,500 (38,800-86,000)	23,496 (18,902-28,868)	82,565 (73,514-92,415)	na
2006	54.1	49.6	65.7	54,541 (48,235-61,438)	49,700 (33,200-73,000)	19,621 (16,697-22,907)	73,645 (65,681-82,302)	na
2007	56.5	47.6	55.4	40,048 (35,286-45,269)	35,200 (21,300-55,000)	26,829 (23,232-30,821)	66,371 (59,971-73,264)	na
2008	80.6	54.6	45.8	32,241 (27,929-37,027)	29,000 (18,500-42,000)	20,981 (17,989-24,327)	52,921 (47,167-59,178)	na
2009	88.5	69.3	43.8	20,618 (17,747-23,818)	27,700 (17,800-38,000)	10,454 (8,697-12,474)	31,015 (27,519-34,829)	na
2010	140.8	110.3	72.5	20,477 (17,815-23,423)	25,900 (17,100-37,000)	15,490 (13,022-18,289)	35,929 (32,049-40,147)	0.64
2011	91.4	99.2	88.2	29,643 (25,676-34,045)	33,700 (22,900-47,000)	33,679 (28,430-39,613)	62,841 (55,985-70,299)	0.64
2012	95.7	86.4	80.5	49,010 (40,382-58,931)	40,700 (31,300-52,400)	25,615 (21,607-30,147)	74,778 (64,881-85,748)	0.69
2013	103.1	85.1	79.4	39,988 (31,504-50,055)	40,380 (31,670-50,380)	27,092 (22,041-32,952)	66,709 (54,294-81,108)	0.72
2014	105.1	93.6	117.2	44,285 (37,440-52,014)	37,893 (28,568-49,114)	23,863 (20,356-27,799)	67,990 (59,802-76,978)	0.72
2015	107.1	124.7	127.5	34,982 (29,145-41,643)	42,300 (32,760-51,840)	24,309 (20,876-28,143)	58,927 (51,368-67,278)	0.73
2016	113.1	124.8	101.6	74,124 (64,811-84,392)	50,000 (36,400-66,900)	24,650 (21,369-28,793)	98,394 (87,150-110,677)	0.75
2017	113.0	119.6	103.3	51,127 (43,976-59,103)	46,200 (31,400-64,230)	14,759 (12,134-17,534)	65,738 (57,221-75,157)	0.74
2018	135.6	116.5	108.3	59,609 (51,755-68,310)	47,700 (33,800-64,880)	21,432 (17,270-26,291)	80,746 (70,984-91,467)	0.71
2019	na	na	na		49,820 (33,790-70,970)	na	na	0.71

Table 7. Estimated snow crab commercial biomass (t, mean and 95% confidence interval) in 2018 using kriging with external drift for the southern Gulf overall, by management areas 12, 19, 12E and 12F, and in buffer zones based on the trawl survey data.

		Commercial biomass (t)	
Area	Surface area (km^2)	Mean	95% confidence interval
Southern Gulf	57,842.8	80,746	(70,984-91,467)
Area 12	48,074	68,953	(60,344-78,439)
Area 19	3,813	6,825	(4,955-9,173)
Area 12E	2,436.9	425	(21-2,155)
Area 12F	2,426.8	3,883	(2,452-5,855)
Sum of management areas	56,750.7	80,086	na
Unassigned zone above 12E **(A)**	667.9	214	(11-1,074)
Buffer zone 19/12F **(B)**	134.2	234	(84-523)
Buffer zone 12/ 19 **(C)**	289.5	255	(35-923)
Sum of total areas and zones	57,842.7	80,789	na

Table 8. Data (from the trawl survey data, 1997 to 2008, using kriging in weights) used in the development of reference points for the snow crab fishery of the southern Gulf of St. Lawrence and exploitation rates for the fisheries in 1998 to 2018.

Year of the fishery	Landings (t)	Estimated commercial biomass (t) from survey in year-1	Estimated residual biomass (t) from survey in year-1	Exploitation rate (%) (landings fishery year t / commercial biomass fishery year t-1)
1998	13,575	64,518 (54,105-76,345)	27,688 (21,982-34,422)	21.0
1999	15,110	57,813 (45,856-71,931)	28,295 (21,497-36,566)	26.1
2000	18,712	56,757 (47,641-67,102)	31,177 (25,044-38,356)	33.0
2001	18,262	50,621 (41,843-60,692)	9,979 (6,987-13,827)	36.1
2002	25,691	60,328 (49,851-72,351)	17,612 (13,853-22,077)	42.6
2003	21,163	79,228 (67,983-91,791)	13,060 (10,793-15,662)	26.7
2004	31,675	84,448 (73,486-96,574)	26,993 (22,124-32,613)	37.5
2005	36,118	103,146 (92,426-114,758)	21,259 (17,343-25,794)	35.0
2006	29,121	82,565 (73,514-92,415)	23,496 (18,902-28,868)	35.3
2007	26,867	73,645 (65,681-82,302)	19,621 (16,697-22,907)	36.5
2008	24,458	66,371 (59,971-73,264)	26,829 (23,232-30,821)	36.9
2009	23,642	52,921 (47,167-59,178)	20,981 (17,989-24,327)	44.7
2010	9,549	31,015 (27,519-34,829)	10,454 (8,697-12,474)	30.8
2011	10,708	35,929 (32,049-40,147)	15,490 (13,022-18,289)	29.8
2012	21,956	62,841 (55,985-70,299)	33,679 (28,430-39,613)	34.9
2013	26,049	74,778 (64,881-85,748)	25,615 (21,607-30,147)	34.8
2014	24,479	66,709 (54,294-81,108)	27,092 (22,041-32,952)	36.7
2015	25,911	67,990 (59,802-76,978)	23,863 (20,356-27,799)	38.1
2016	21,725	58,927 (51,368-67,278)	24,309 (20,876-28,143)	36.9
2017	43,656	98,394 (87,150-110,677)	14,650 (21,369-28,793)	44.4
2018	24,260	65,738 (57,221-75,157)	14,759 (12,134-17,534)	36.9
2019	na	80,746 (70,984-91,467)	21,432 (17,270-26,291)	na

Table 9. Risk analyses for different catch options in 2019 for the southern Gulf of St. Lawrence snow crab fishery showing probabilities of the commercial-sized adult male biomass falling below the biomass limit reference point (B_{lim}) and being above the upper stock reference point (B_{USR}) after the fishery in 2019. In bold is the catch option (exploitation rate of 40.9% corresponding to the commercial biomass of 80,746 t) according to the agreed decision rule of the Precautionary Approach (variant 4, DFO 2014b).

Catch option (t) for 2018	Probability		Predicted commercial biomass for 2020 (t)
	< B_{lim} (10,000 t)	≥ B_{usr} (41,300 t)	
30,000	0	1	86,880 (75,840-97,900)
31,000	0	1	85,880 (74,840-96,900)
32,000	0	1	84,880 (73,840-95,900)
33,000	0	1	83,880 (72,840-94,900)
33,025	**0**	**1**	**83,850 (72,820-94,870)**
34,000	0	1	82,880 (71,840-93,900)
35,000	0	1	81,880 (70,840-92,900)
36,000	0	1	80,880 (69,840-91,900)
37,000	0	1	79,880 (68,840-90,900)
38,000	0	1	78,880 (67,840-89,900)
39,000	0	1	77,880 (66,840-88,900)
40,000	0	1	76,880 (65,840-87,900)
41,000	0	1	75,880 (64,840-86,900)
42,000	0.1	1	74,880 (63,840-85,900)
43,000	0.1	1	73,880 (62,840-84,900)
44,000	0.2	1	72,880 (61,840-83,900)
45,000	0.3	1	71,880 (60,840-82,900)
46,000	0.4	1	70,880 (59,840-81,900)
47,326	0.5	1	69,550 (58,510-80,570)
75,518	1	0.5	41,360 (30,320-52,380)

10.0 FIGURES

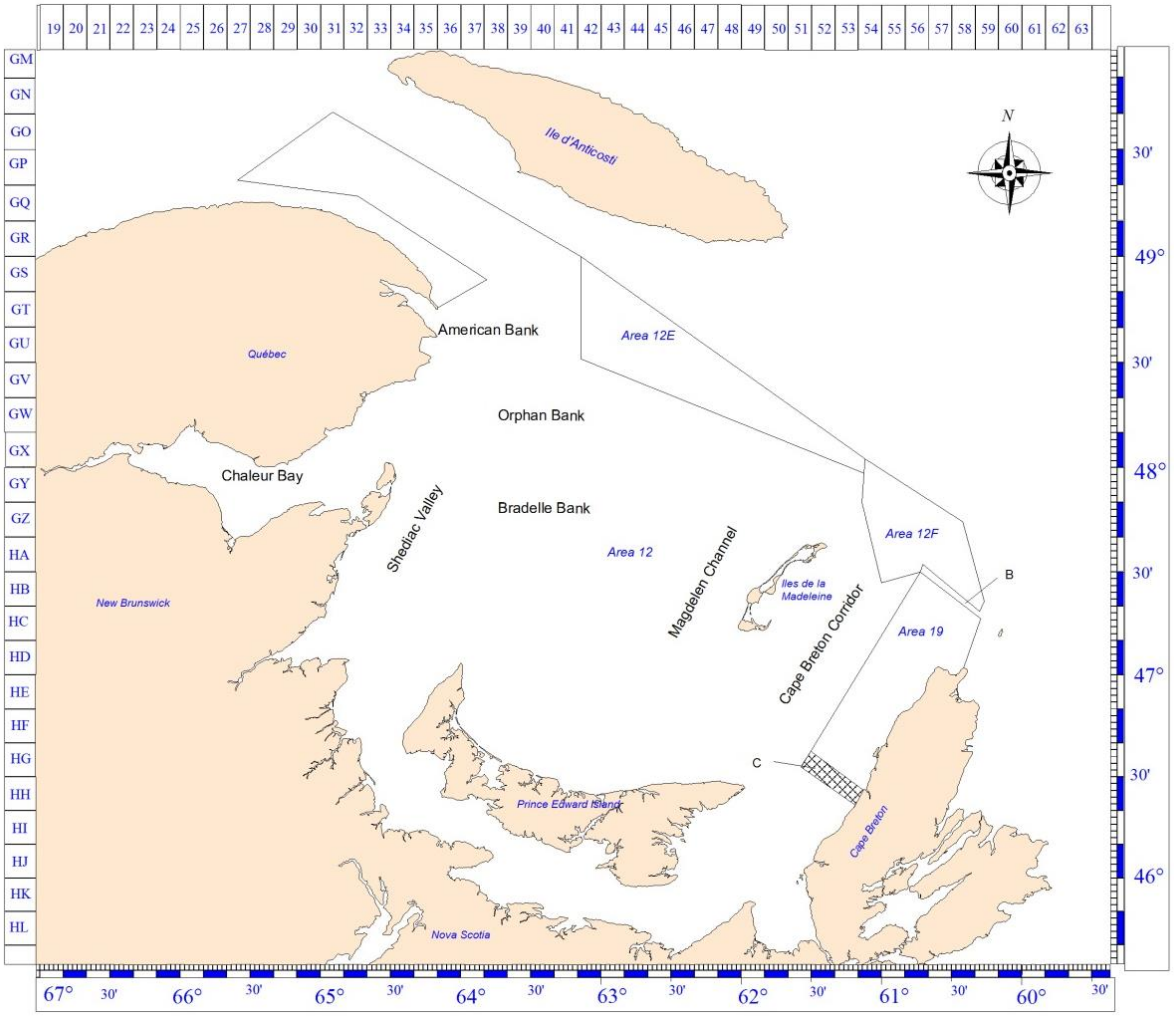

Figure 1. Map of the southern Gulf of St. Lawrence showing the snow crab (Chionoecetes opilio) fishing areas fishing grounds, and management buffer zones (labels B and C, shaded areas).

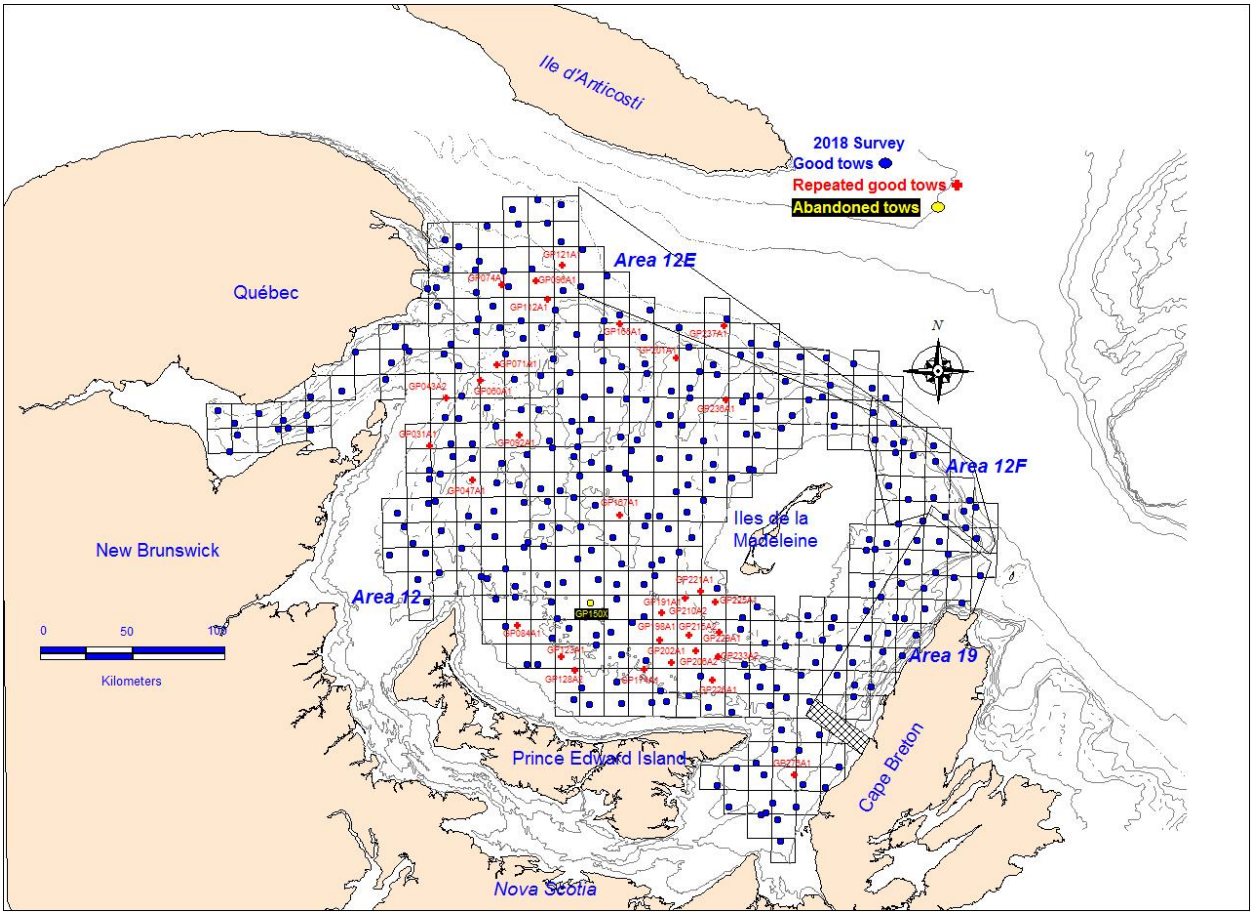

Figure 2. Locations of the 2018 snow crab (Chionoecetes opilio) trawl survey stations within the estimation polygon of 57,842.8 km^2 in the southern Gulf of St. Lawrence. The blue points are successful tows, red points are successful repeat tows and yellow points are abandoned tows.

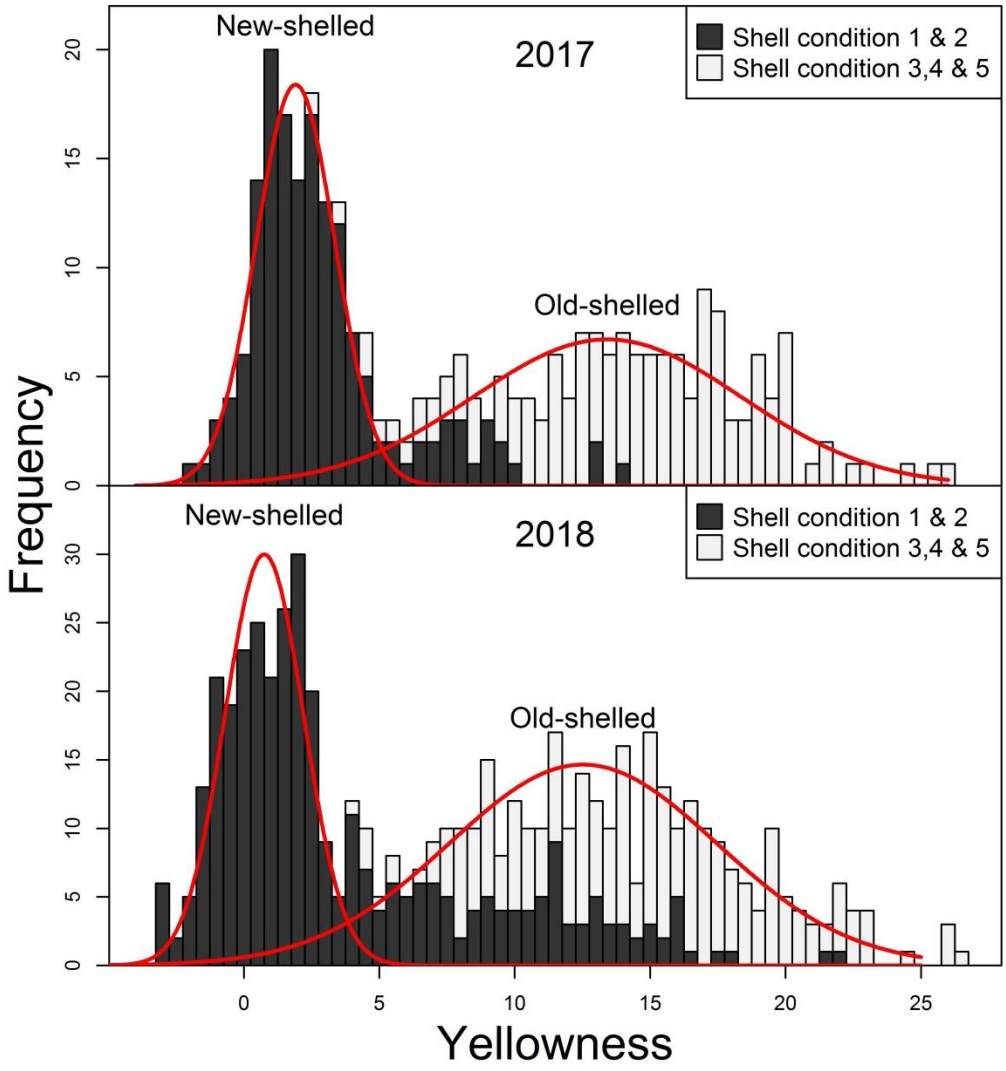

Figure 3. Frequency histogram of measured yellowness values (b value) as measured using a colorimeter on the underside of male chelae during August in 2017 (top panel) and in 2018 (bottom panel) trawl surveys. Red lines show the fit of the new-shelled (i.e. whiter shades) and old-shelled (yellow shade) components of a mixture model. For comparison, the bars are shaded according to the carapace condition class.*

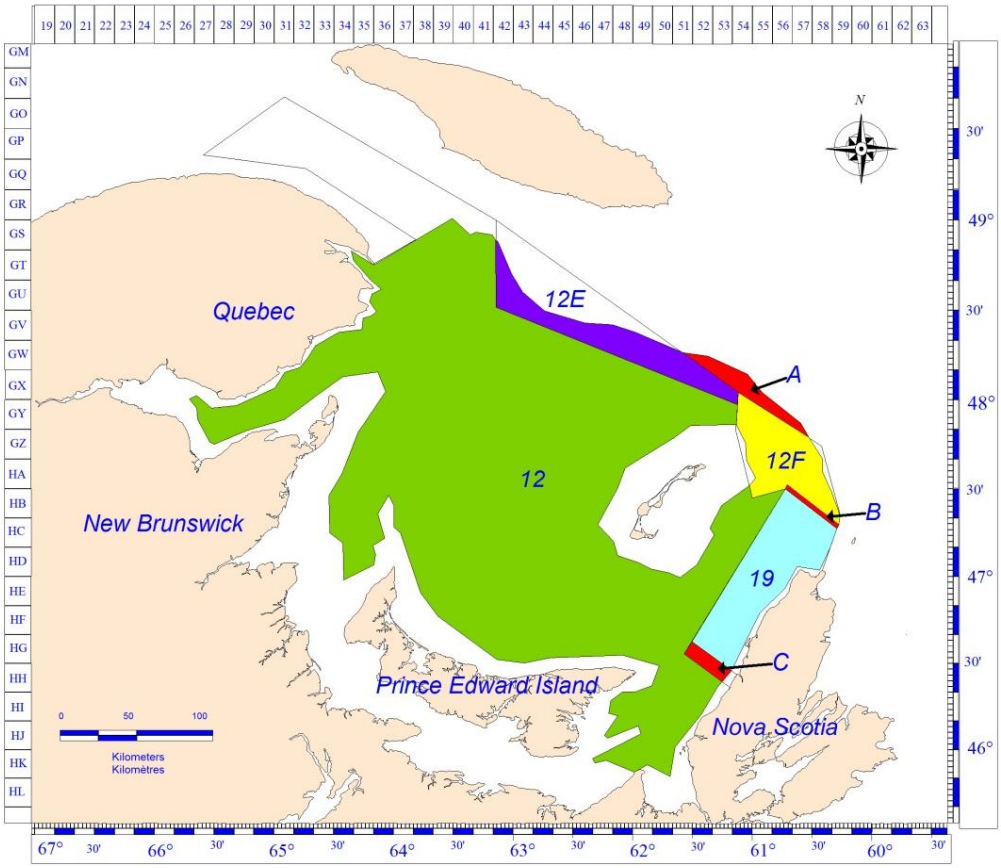

Figure 4. The estimation polygon of 57,842.8 km2 used for the 2018 snow crab (Chionoecetes opilio) stock assessment in the southern Gulf of St. Lawrence (all coloured areas) and corresponding estimation polygons for the four crab fishing areas (12, 12E, 12F and 19). The unassigned zone north of areas 12E and 12F (label A) and buffer zones (labels B and C) are also shown.

Figure

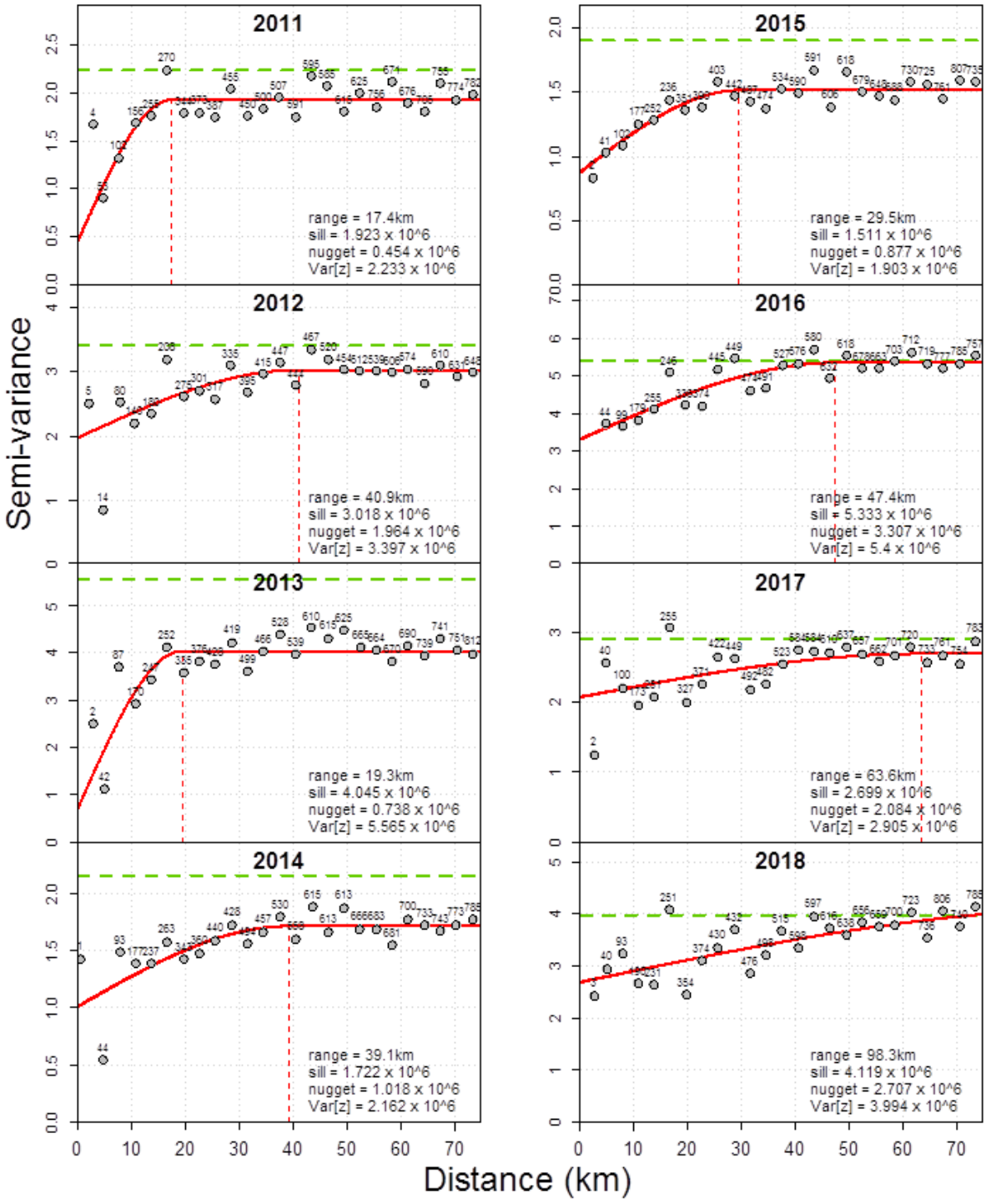

Figure 5. Three-year moving average variogram models for commercial-sized adult male snow crab (Chionoecetes opilio) in the southern Gulf of St. Lawrence, 2011 to 2018. Indicated is the number of paired observations used per distance lag semi-variance calculation. The red dashed lines indicate the range value on the abscise axis and the nugget and sill values on the y axis. The green dashed line indicates the variance on the y axis.

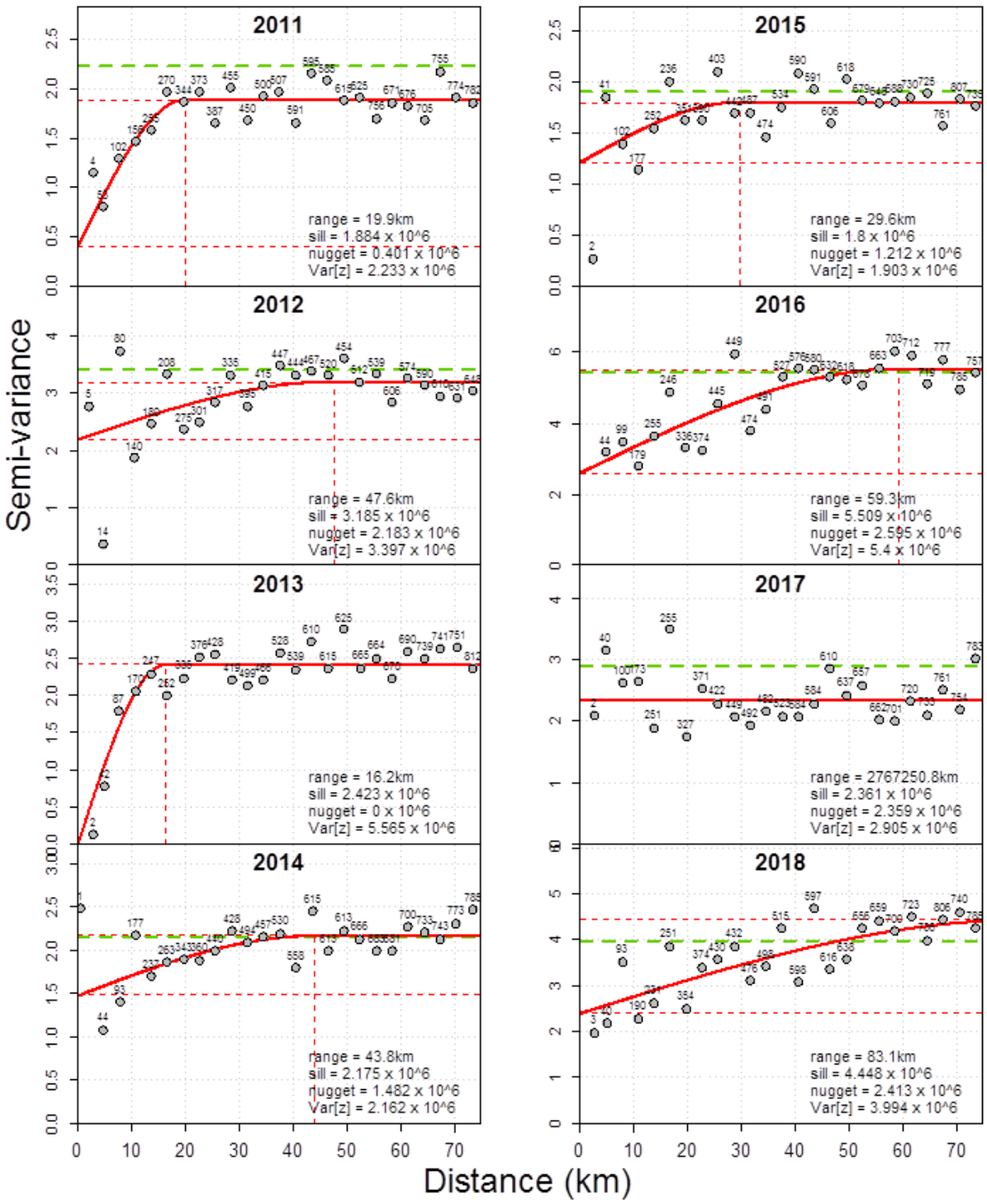

Figure 6. Annual variogram models for commercial-sized adult male snow crab (Chionoecetes opilio) in the southern Gulf of St. Lawrence, 2011 to 2018. Indicated is the number of paired observations used per distance lag semi-variance calculation. The red dashed lines indicate the range value on the abscise axis and the nugget and sill values on the y axis. The green dashed line indicates the variance on the y axis.

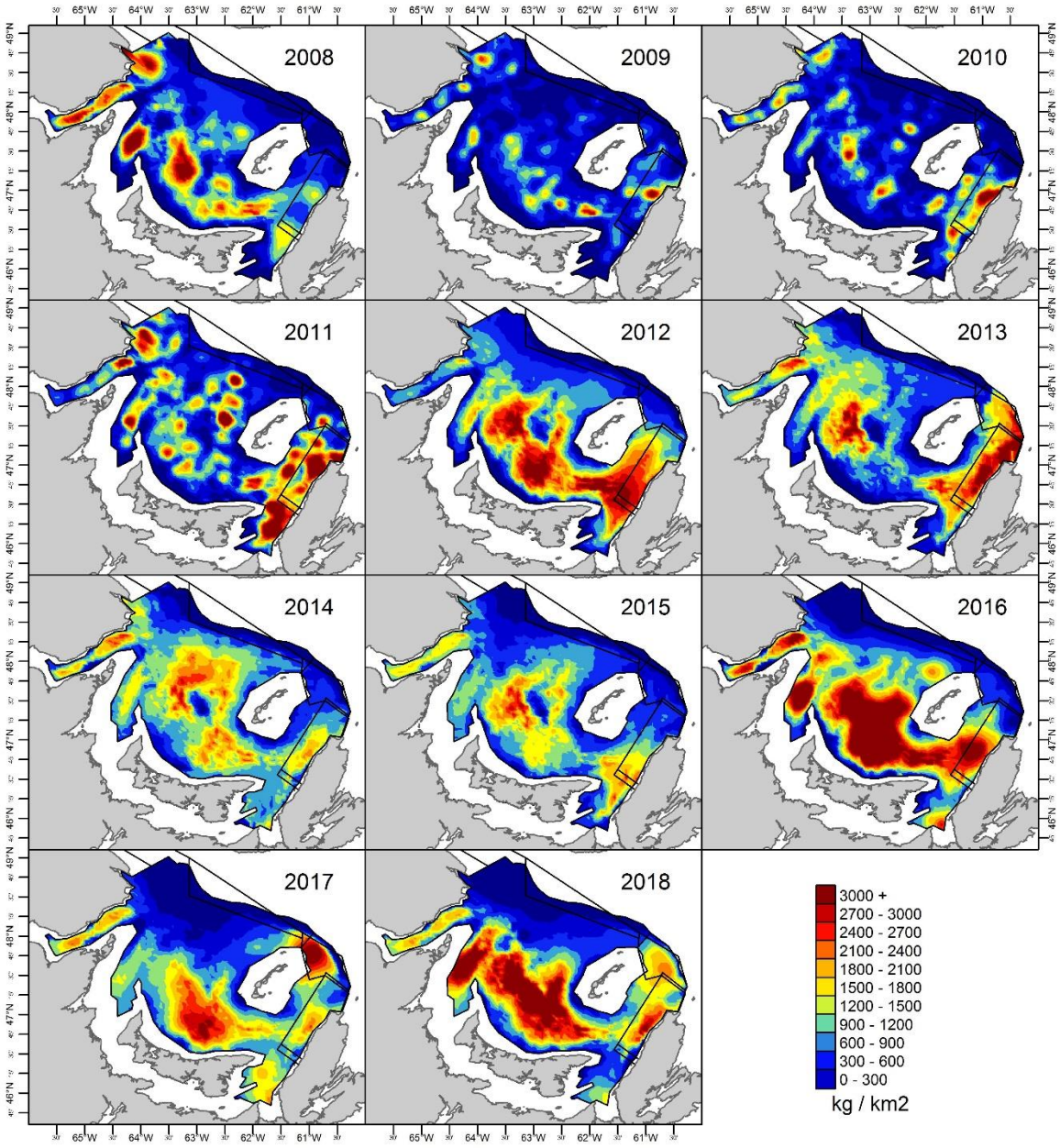

Figure 7. Density (kg per km²) contours of commercial-sized (≥ 95 mm of carapace width) adult male snow crab (Chionoecetes opilio) based on trawl survey data in the southern Gulf of St. Lawrence, 2008 to 2018.

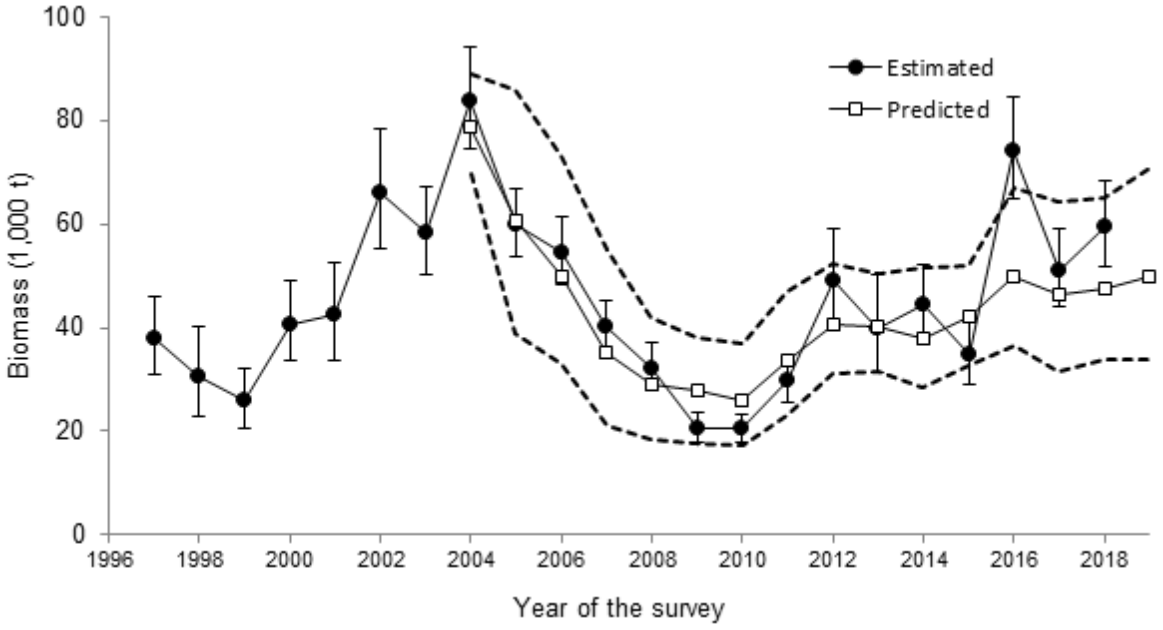

Figure 8. Comparison between the observed (mean with 95% confidence intervals) and forecasted (mean with 95% confidence intervals) recruitment (R-1) of male snow crab (Chionoecetes opilio) based on the Bayesian model on prerecruits (Surette and Wade 2006; Wade et al. 2014).

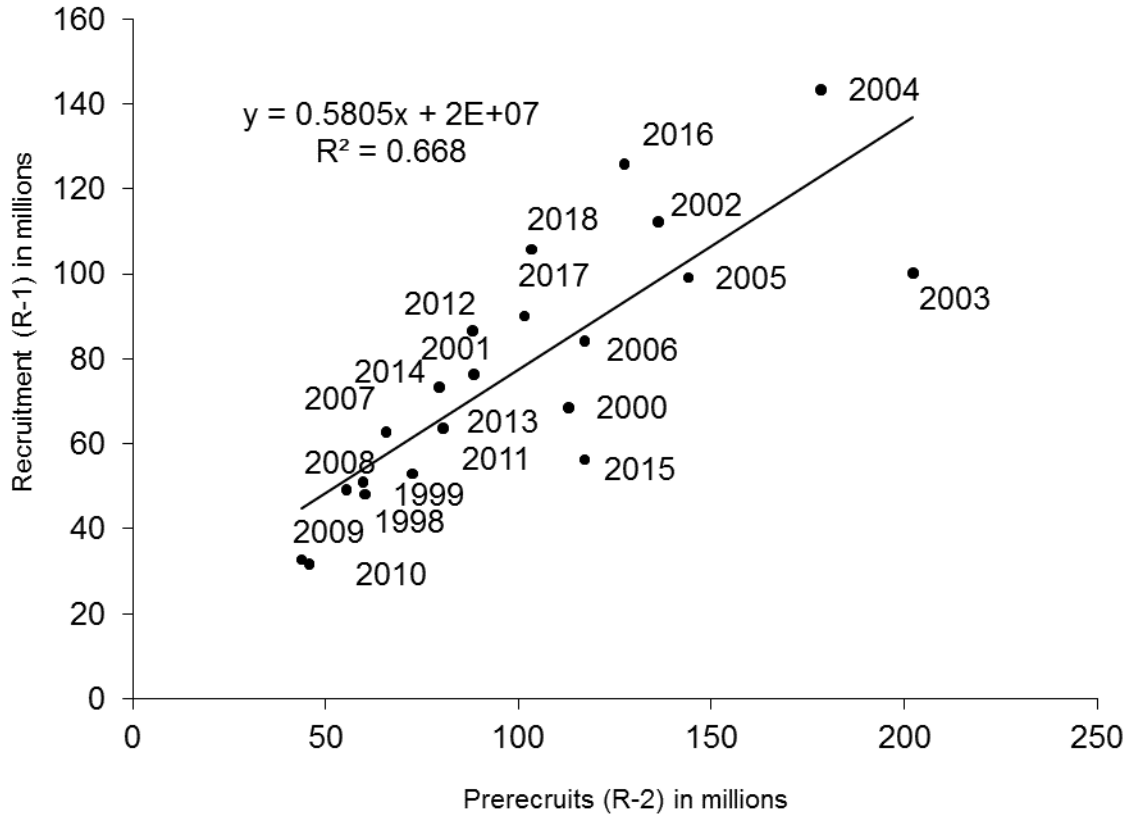

Figure 9. Relationship between the estimated abundance of prerecruits R-2 in year t and the estimated abundance of the recruitment to the fishery (R-1) in year t + 1 from the trawl survey data for the snow crab (Chionoecetes opilio) assessment in the southern Gulf of St. Lawrence.

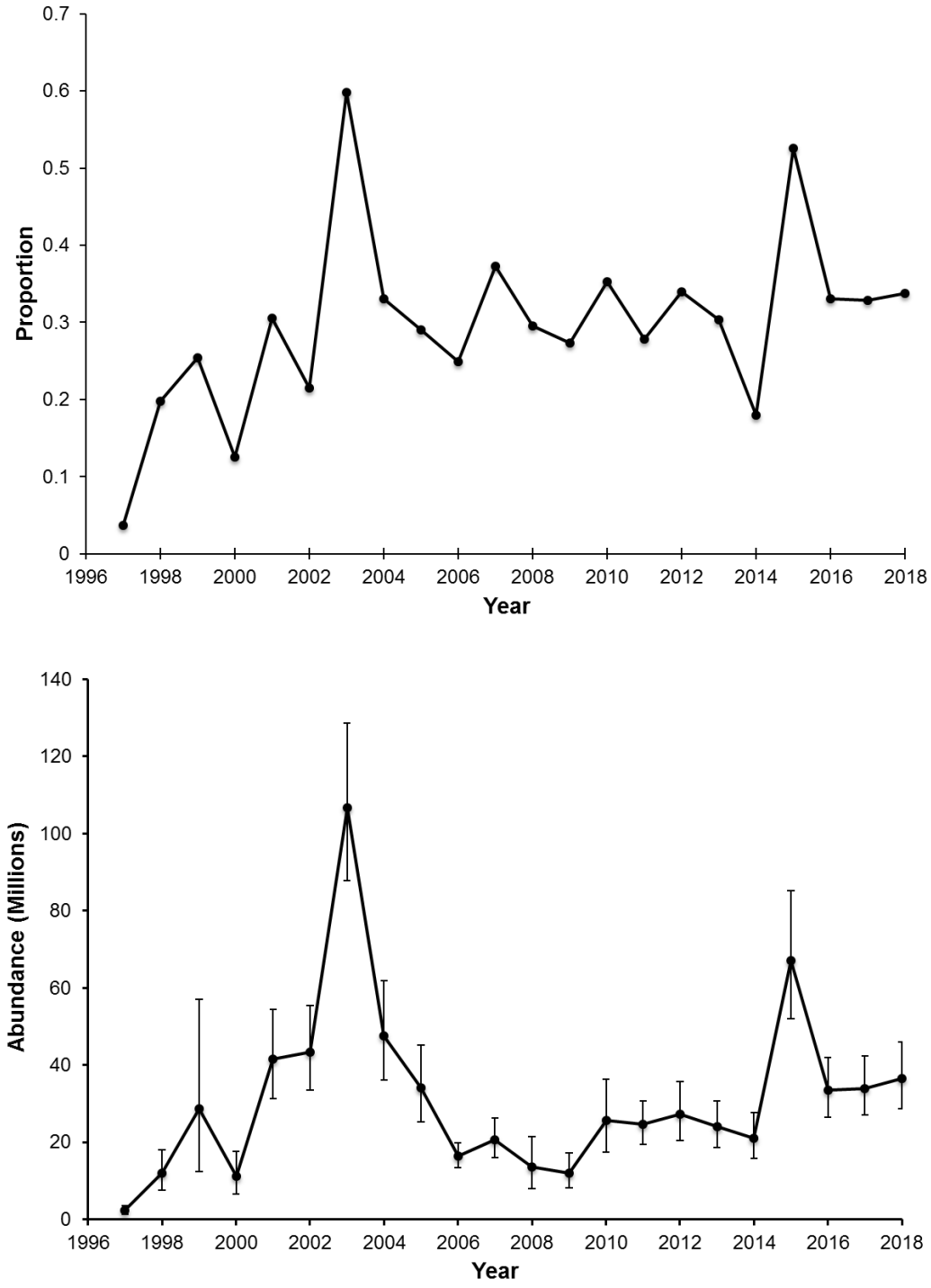

Figure 10. Abundance (in millions) (upper panel) and proportion (lower panel) of R-2 adolescent skip molters in the southern Gulf of St. Lawrence estimated from the trawl survey from 1997 to 2018.

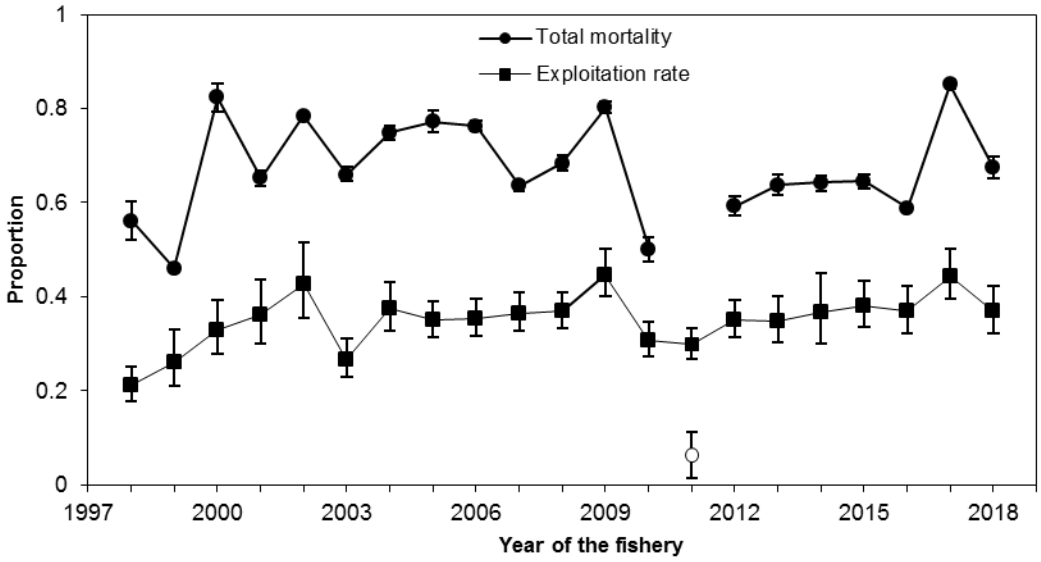

Figure 11. Estimated annual rates of exploitation and total loss of commercial-sized adult male snow crab (Chionoecetes opilio) in the southern Gulf of St. Lawrence, 1997 to 2018. The 2011 estimated total mortality value is not reliable (Hébert et al. 2012).

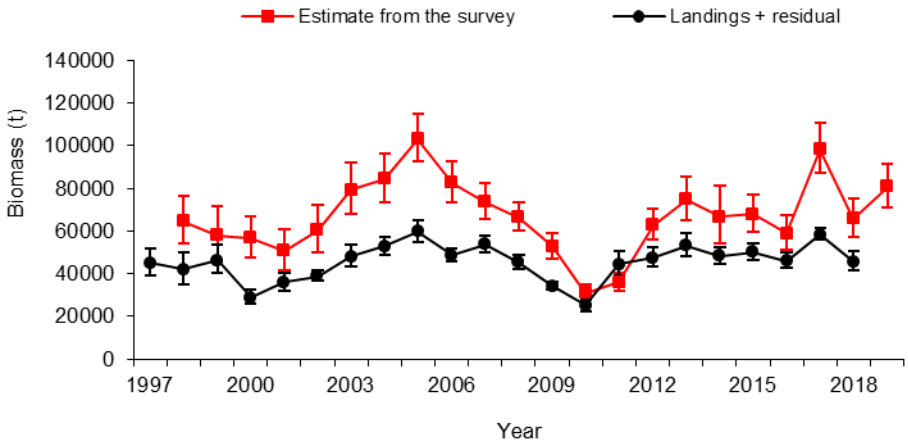

Figure 12. Comparison of the post-fishery calculated biomass (t; residual biomass plus the landings in year t+1) and the pre-fishery commercial-sized adult male snow crab (Chionoecetes opilio) biomass (t; recruitment plus residual biomass in year t) estimated from the trawl survey in the southern Gulf of St. Lawrence.

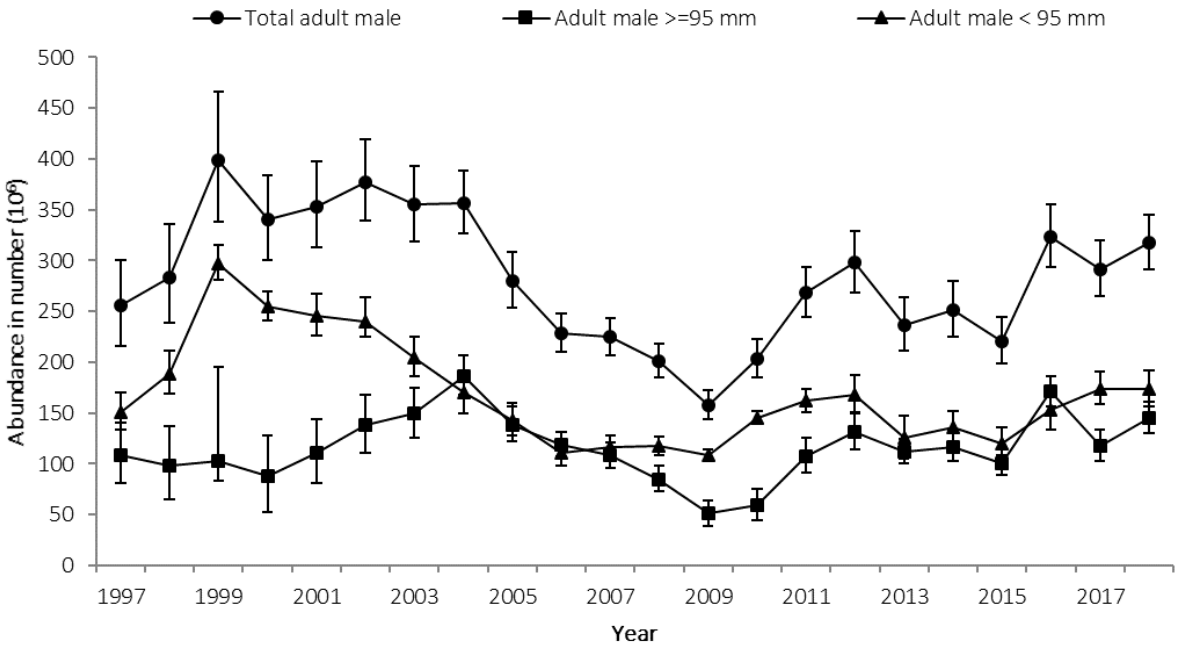

Figure 13. Estimated abundance (number in millions) of snow crab (Chionoecetes opilio) adult males in the southern Gulf of St. Lawrence, 1997 to 2018. CW = Carapace width.

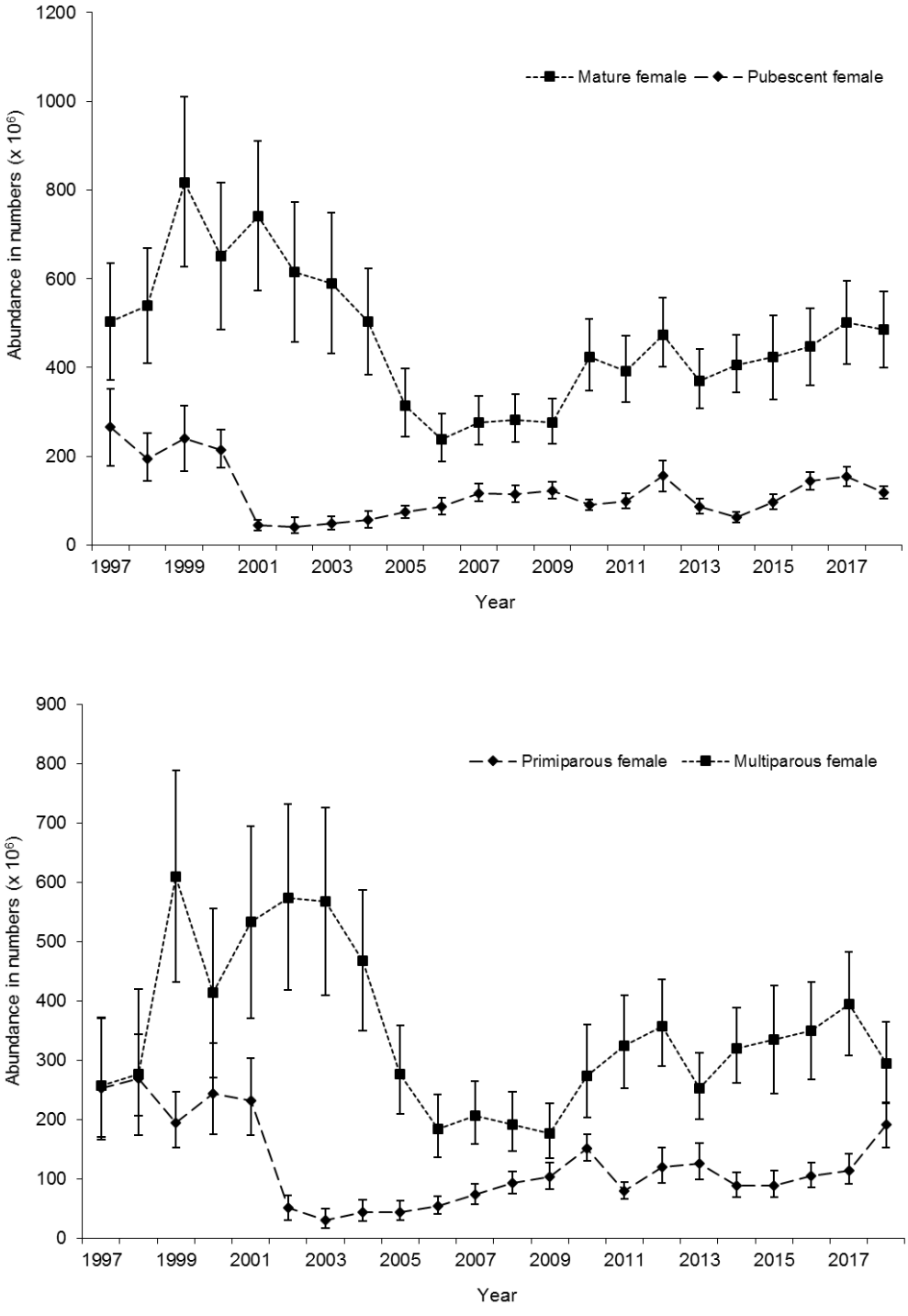

Figure 14. Abundance (number in millions) of mature and pubescent (above), and primiparous, and multiparous (i.e. mature; below) snow crab (Chionoecetes opilio) females in the southern Gulf of St. Lawrence, 1997 to 2018.

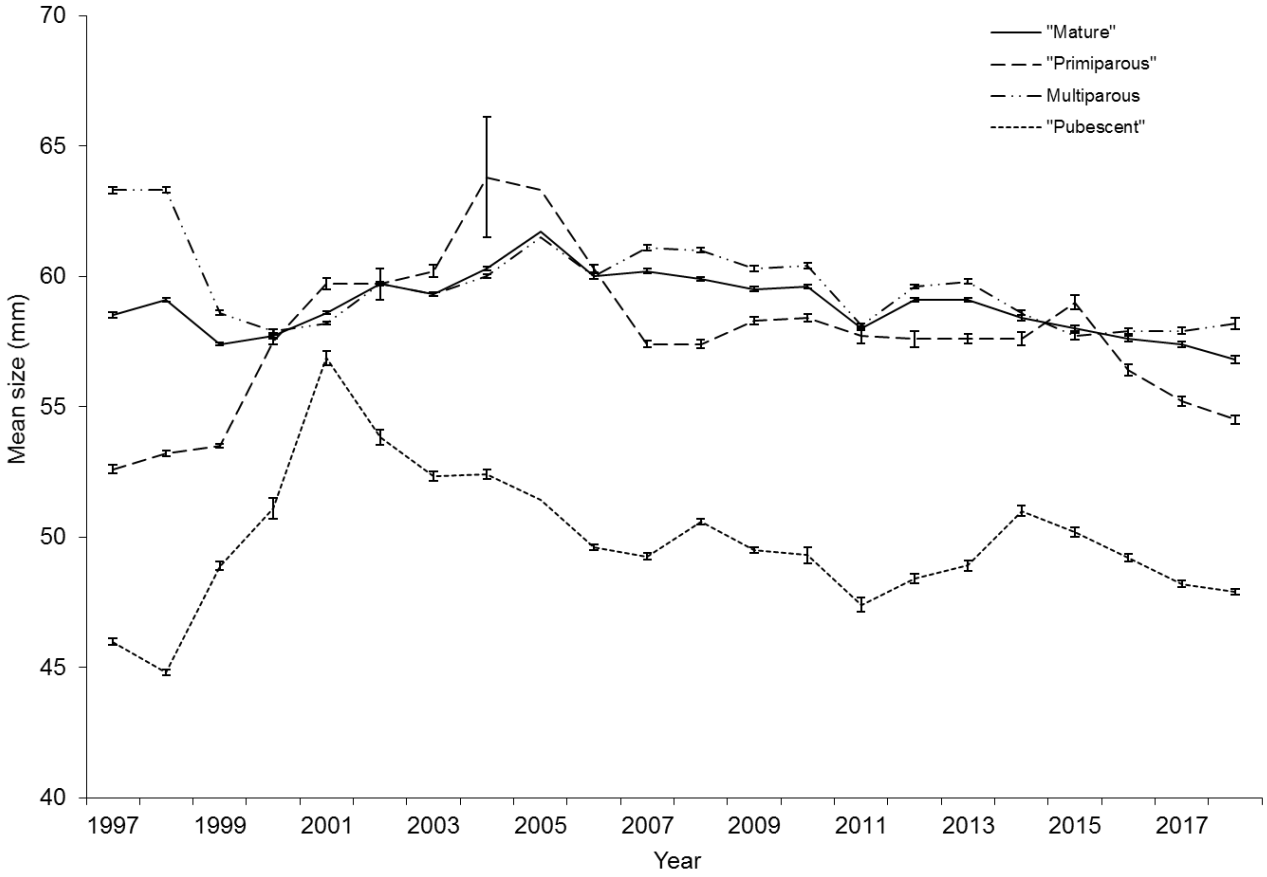

Figure 15. Mean size (carapace width in mm) with standard errors of pubescent, primiparous, multiparous and mature snow crab (Chionoecetes opilio) females based on samples from the trawl surveys, 1997 to 2018.

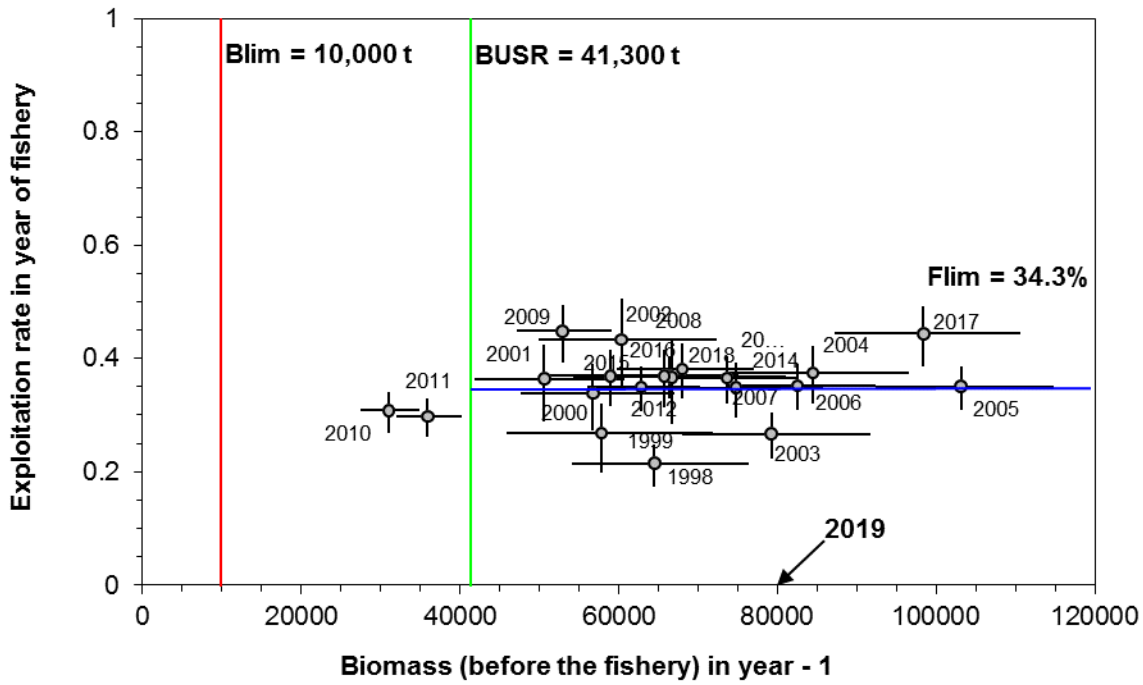

Figure 16. Trajectory of stock abundance (biomass of commercial-sized adult male snow crab (Chionoecetes opilio) as estimated from the trawl survey in year t – 1 versus exploitation rate of this biomass in the fishery of year t. Year of the fishery is labelled on the figure. B_{lim} = The limit reference point for biomass; Flim = Fishing removal rate limit reference point; B_{USR} = The upper stock reference point.

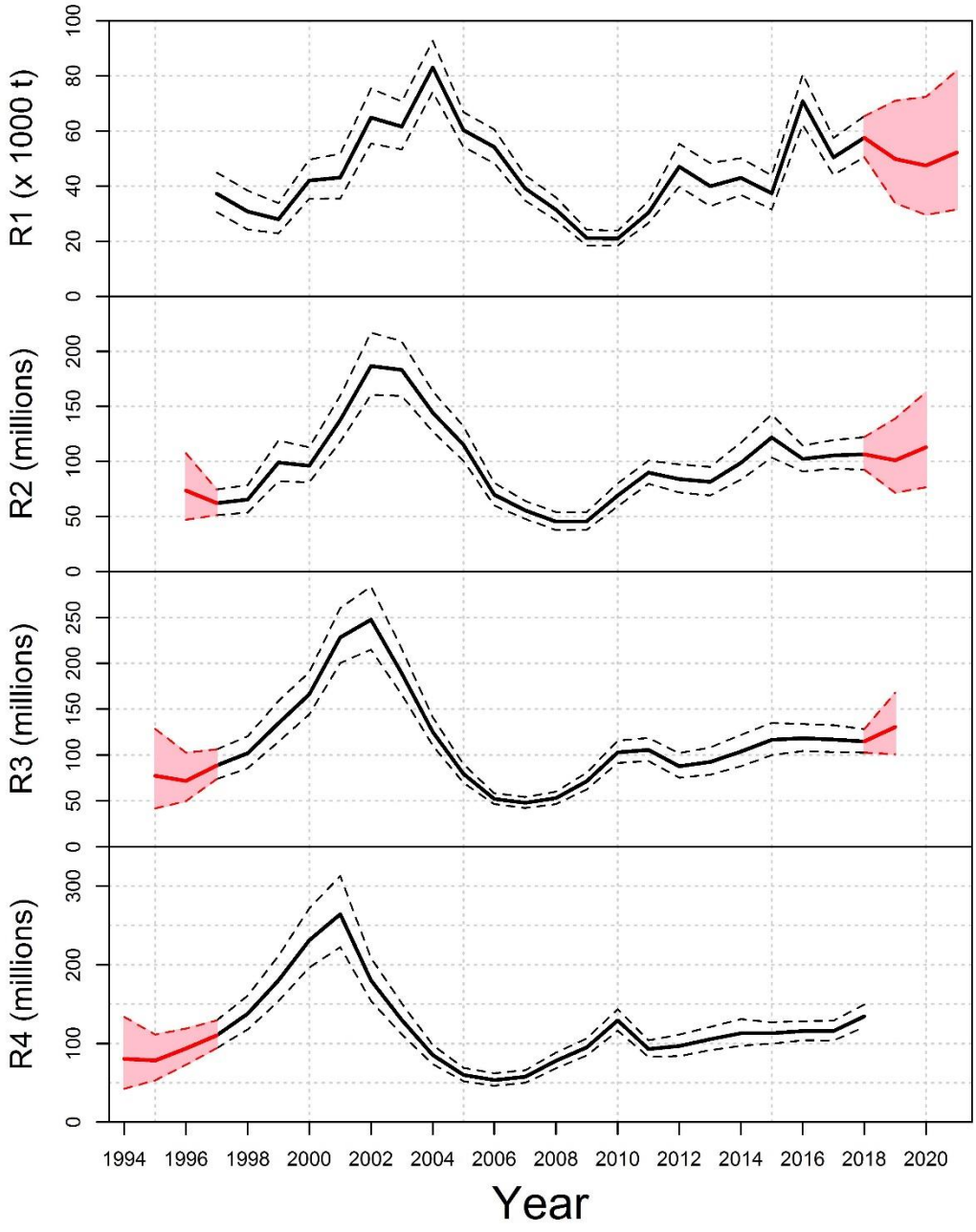

Figure 17. Snow crab (Chionoecetes opilio) recruitment (R) abundance (mean with 95% confidence intervals) by pre-recruit stages (Rj), where j =1,…,4 years until recruitment to the fishery based on the survey data estimates. Shaded areas are forecasted abundance from the Bayesian model (Wade et al. 2014).

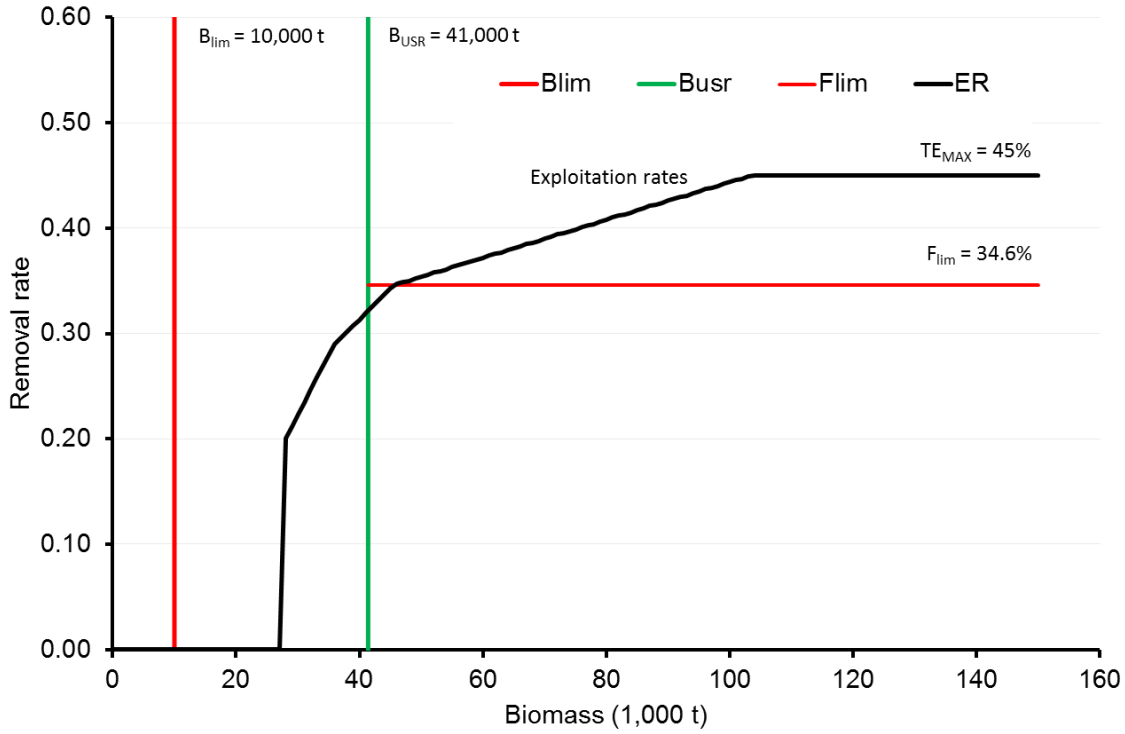

Figure 18. Harvest proportional decision rule (variant 4) compliant with the precautionary approach for the southern Gulf of St. Lawrence snow crab (Chionoecetes opilio) fishery (DFO 2014a). Blim = the biomass limit reference point; Flim = the maximum fishing removal rate (limit) reference in the healthy zone; BUSR = the biomass upper stock reference point; ER = the exploitation rates based on the proportional harvest decision rule; TEmax = The maximum exploitation rate based on the proportional harvest decision rule.

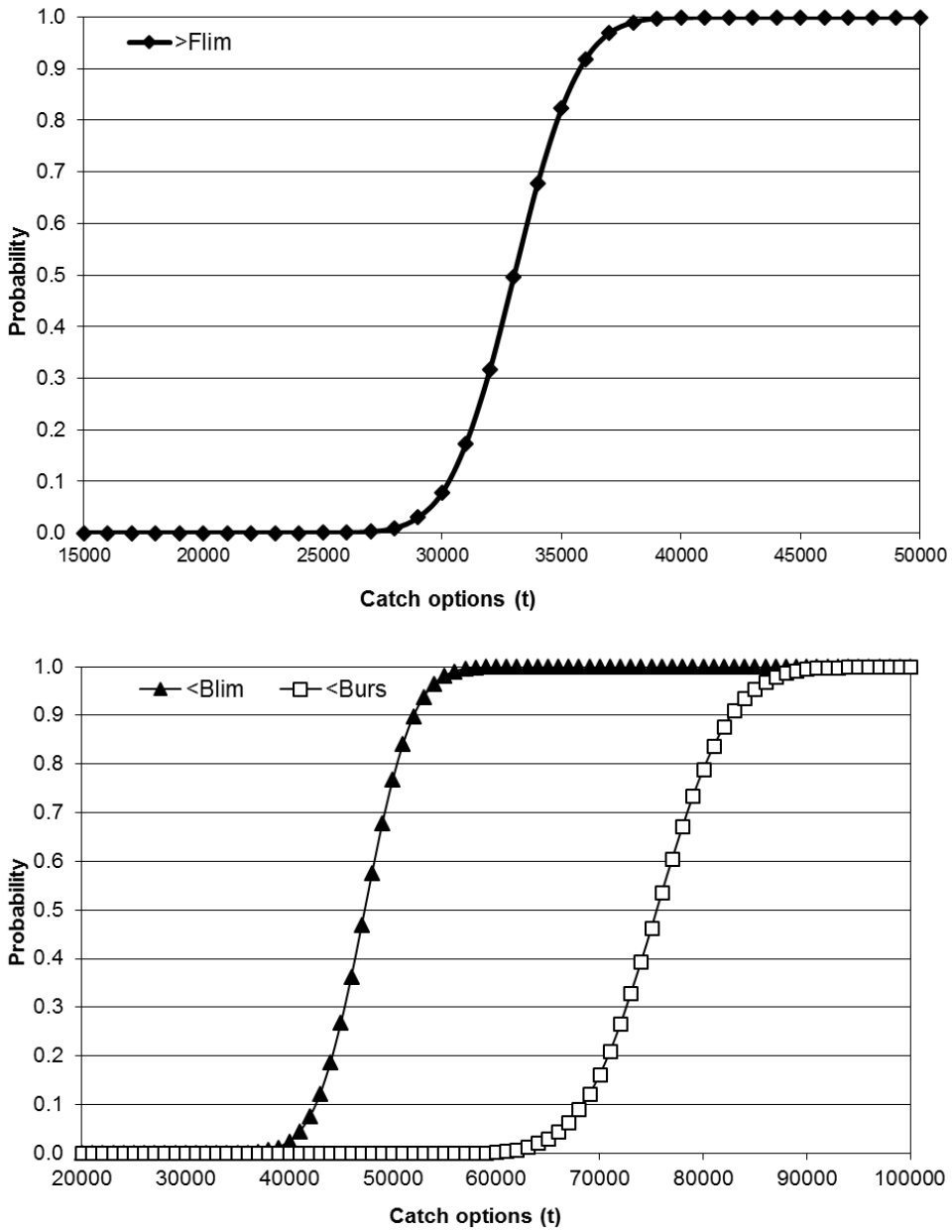

Figure 19. Risk analysis of catch options (t) for the 2019 fishery based on the expanded polygon for the southern Gulf of St. Lawrence snow crab, Chionoecetes opilio, showing probabilities of exceeding the fishing removal rate limit reference point (Flim), of the hard-shelled commercial-sized adult male residual biomass in 2019 falling below the limit reference point for biomass (Blim) and of the commercial-sized adult male biomass in 2019 will be below the upper reference point (BUSR) after the 2019 fishing season.

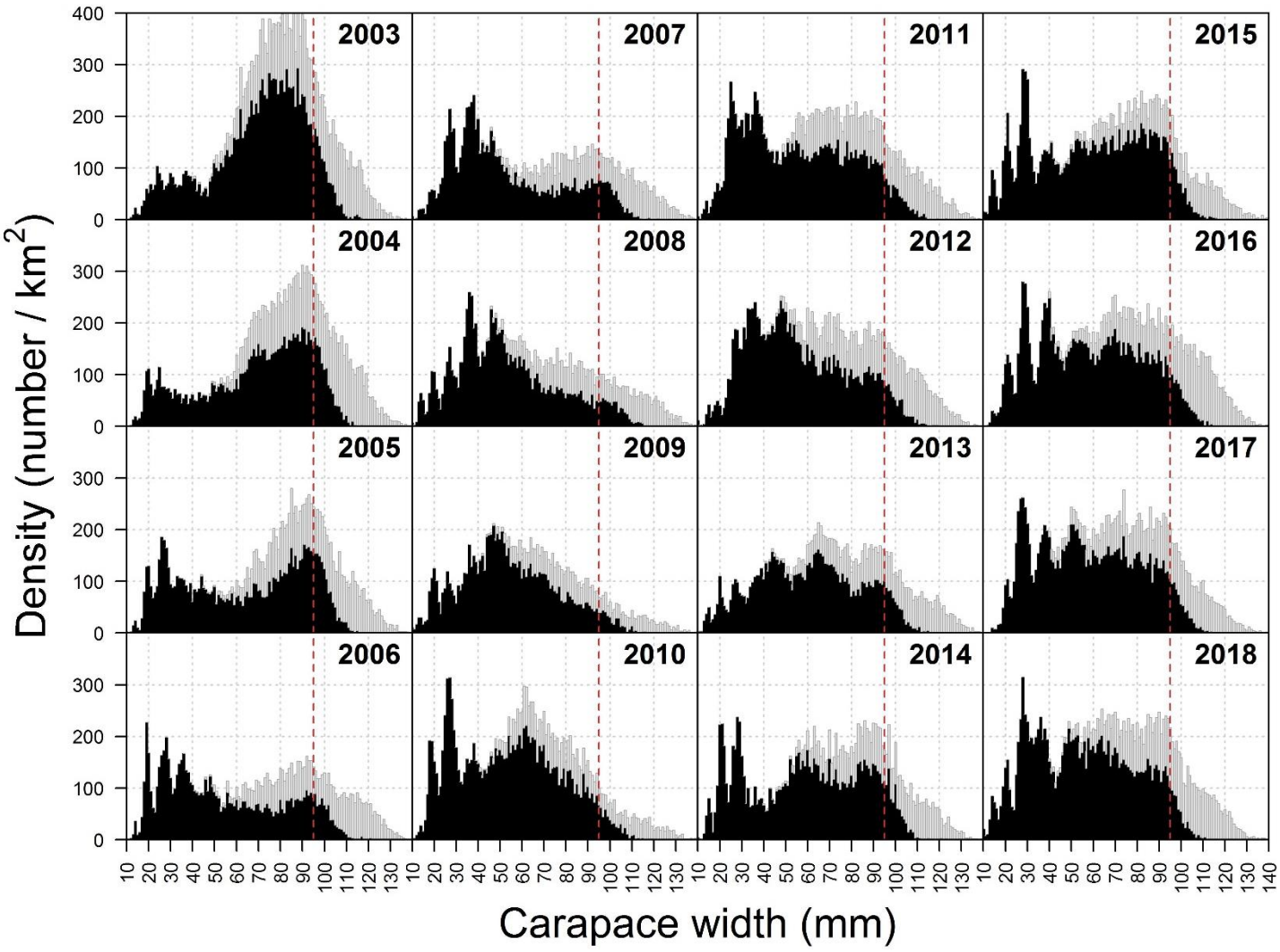

Figure 20. Size frequency distributions (by 1 mm carapace width interval) for male snow crabs (grey bars are adult males and black bars are adolescent males) based on samples from the post-fishery trawl surveys in the southern Gulf of St. Lawrence, 2003 to 2018. These size frequency distributions represent the mean number of male snow crab (Chionoecetes opilio) per km^2 based directly on samples in the trawl survey. The red dotted line represents the minimum legal size of 95 mm of carapace width.

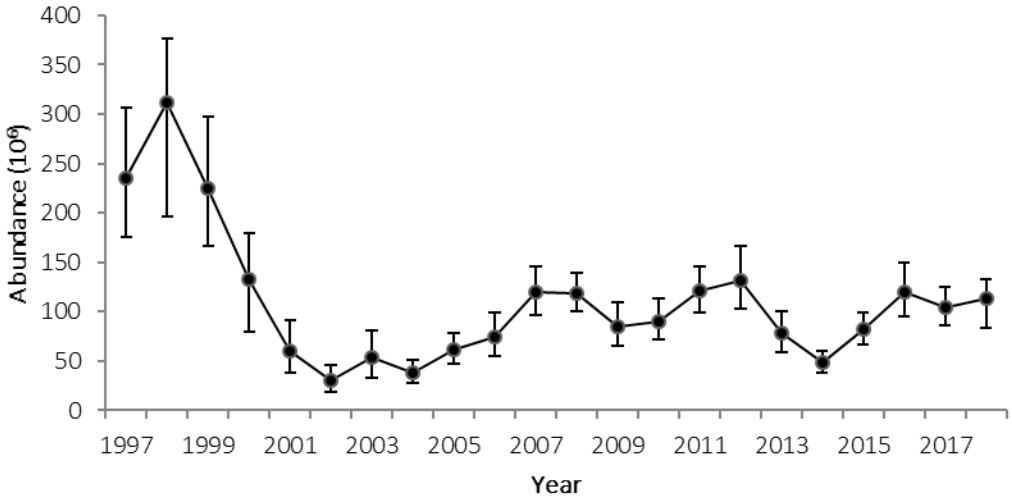

Figure 21. Abundance indices of small adolescent male snow crab (Chionoecetes opilio) with carapace width between 34 to 44 mm estimated from the trawl survey data in the southern Gulf of St. Lawrence, 1997 to 2018. These are crabs which reach legal size in approximately 6 years.

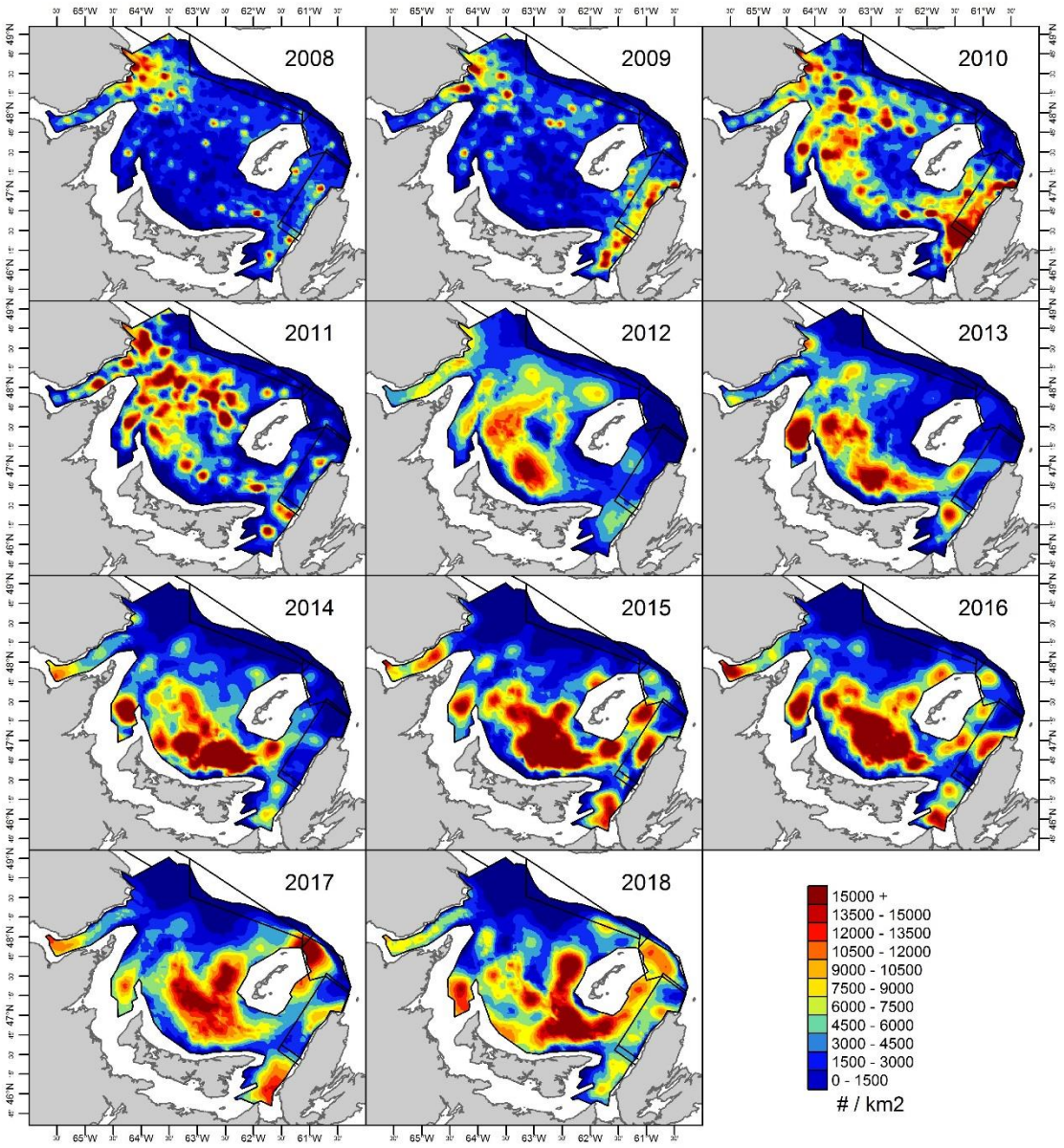

Figure 22. Density (number per km²) contours of adolescent male (R-4, R-3 and R-2) snow crab, (Chionoecetes opilio), ≥ 56 mm of carapace width, based on the trawl surveys conducted in the southern Gulf of St. Lawrence, 2008 to 2018.

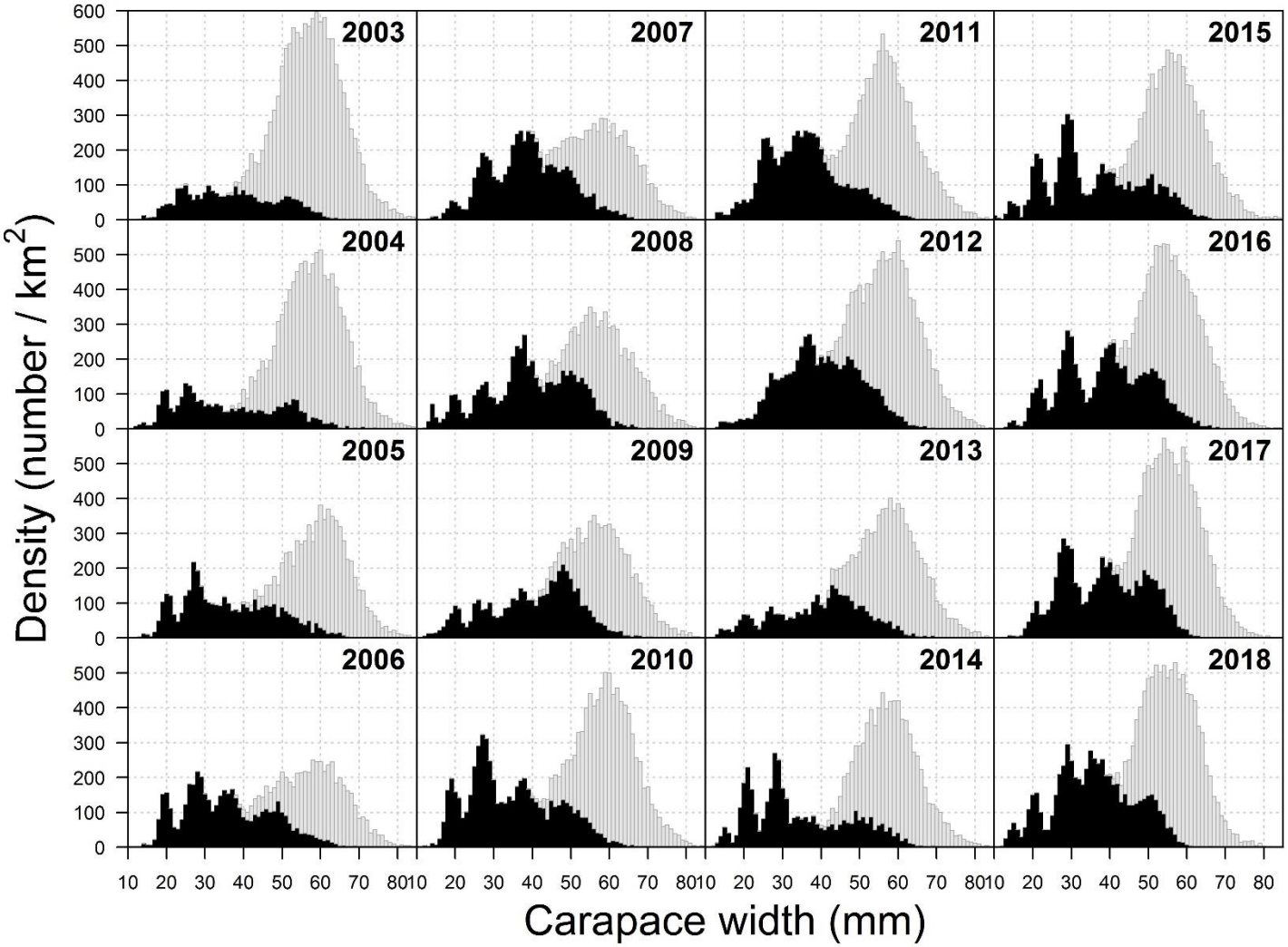

Figure 23. Size frequency distributions (carapace width by 1 mm interval) for female (white bars are mature females and black bars are pubescent and immature females) snow crab (Chionoecetes opilio) based on samples from the post-fishery trawl surveys in the southern Gulf of St. Lawrence, 2003 to 2018. These size frequency distributions represent the mean number of female crab per km² directly based on samples in the trawl survey.

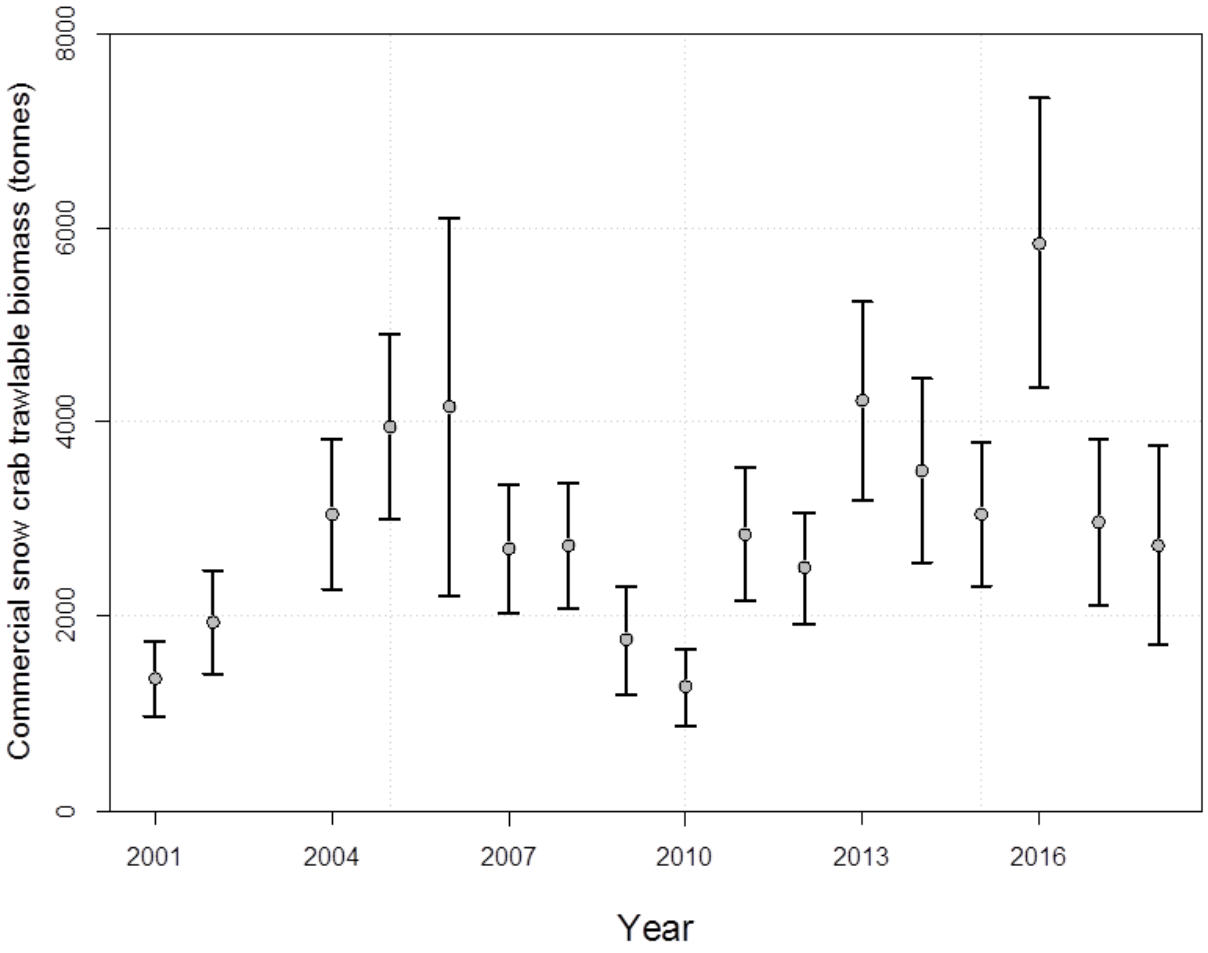

Figure 24. Index of trawlable biomass (in tonnes; means and 95% confidence intervals) of adult male snow crab ≥ 95 mm carapace width in the September multi-species bottom trawl survey for 2001 to 2018 excluding 2003, based on a geographic area comparable to that used for the current snow crab assessment.

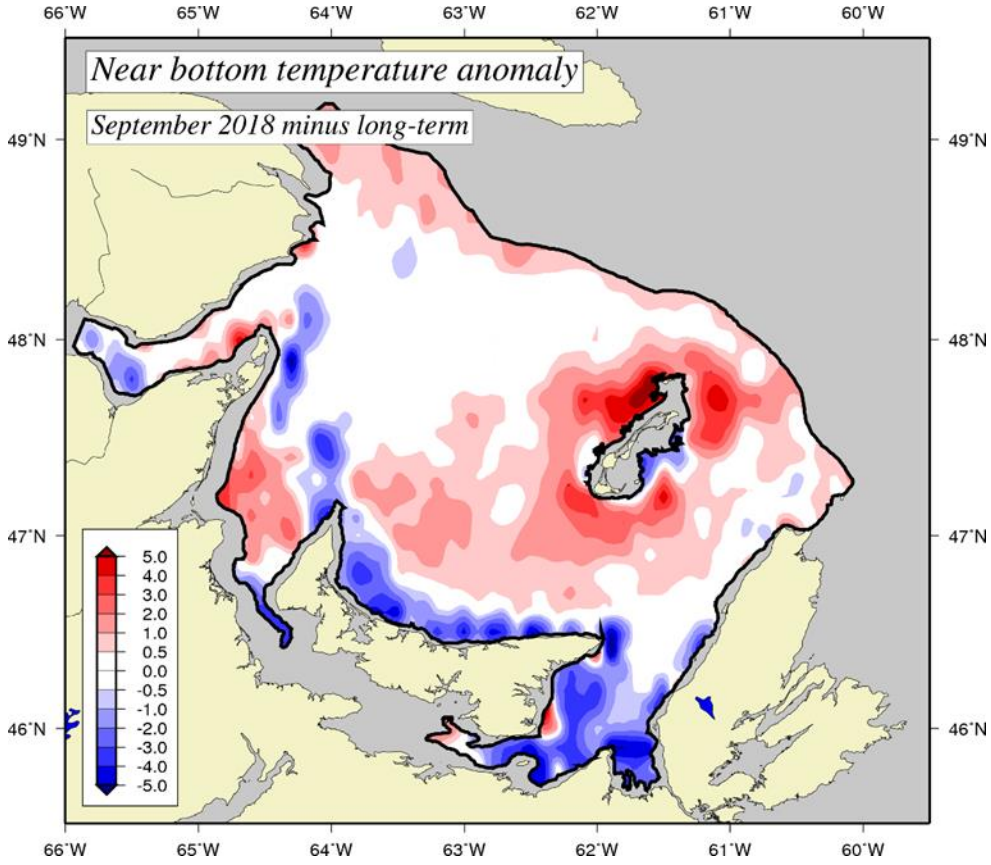

Figure 25. Near-bottom temperature departure (°C) from the long-term (1981-2010) mean in the southern Gulf of St. Lawrence during the 2018 September multi-species survey. Blue areas represent colder-than-normal temperatures while red regions represent warmer-than-normal conditions.

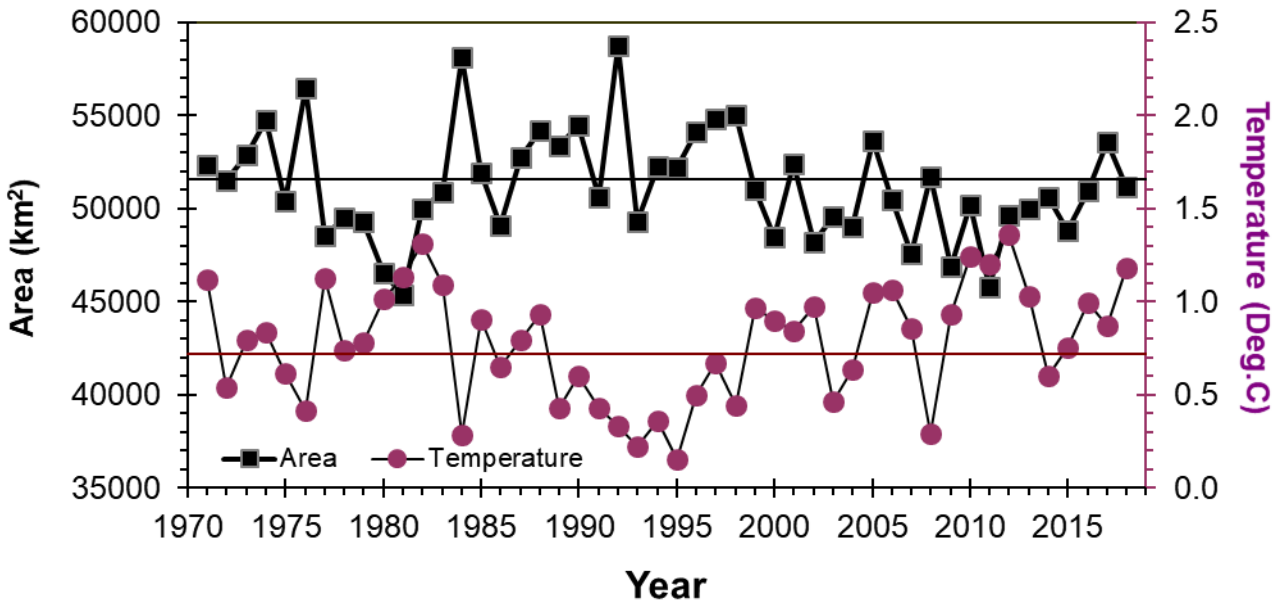

Figure 26. Snow crab temperature habitat area index (km^2) that encompasses water temperatures of -1 to 3°C (upper panel) and the mean temperature (°C) within the temperature area index (lower panel) in the southern Gulf of St. Lawrence, 1971 to 2018.