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The 2022 assessment of the snow crab (*Chionoecetes opilio*) stock in the southern Gulf of Saint Lawrence (Areas 12, 12E, 12F and 19)

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Canada

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

Stock status of southern Gulf of Saint Lawrence (sGSL) snow crab (*Chionoecetes opilio*) in 2022 is in the healthy zone, based on defined reference points. A commercial biomass of 85,532 tonnes (t) is projected for 2023. Fishery recruitment biomass is estimated at 68,348 t, while the residual biomass was estimated at 17,388 t. Based on the harvest decision rule the commercial biomass estimate corresponds to a target exploitation rate of 41.79% and a catch option of 35,745 t for the 2023 fishery. For this catch option, a risk analysis indicates that there is a very low likelihood that the residual biomass would be below the limit reference point and a very high likelihood that the 2023 commercial stock biomass would remain above the upper stock reference point. Population recruitment and spawning stock abundance remain at high levels. Warming bottom temperatures remain a cause for concern, with crab densities in areas along the margins of the sGSL showing marked declines in recent years.

1. INTRODUCTION

The snow crab, *Chionoecetes opilio*, is a common cold-water species found in many northern regions from Greenland, northern Europe, Japan, the Bering Sea, and eastern Canada. Canadian snow crab populations are found off the coasts of Nova Scotia and Newfoundland, as well as the northern and southern portions of the of the Gulf of Saint Lawrence.

The southern Gulf of Saint Lawrence (sGSL) snow crab population is naturally bounded by warm coastal temperatures to the south and west, and by warm deep waters of the Laurentian channel to the northeast (Figure 1), residing within an area of cold intermediate water layer. The snow crab population in the sGSL is considered as a single stock unit, with limited exchanges with northern and southern snow crab populations (Biron et al. 2008) and some free-floating larval inputs from the Quebec population to the north (Puebla et al. 2008).

1.1. BIOLOGY

The snow crab is a crustacean with a flat, almost circular body and five pairs of legs. The hard outer shell is periodically shed in a process called moulting, after which crabs have a relatively soft shell for a period of 8 to 10 months.

Snow crab do not moult throughout their lifespan, but rather undergo a final, terminal moult after which they attain full sexual maturity (Conan and Comeau 1986; Comeau and Conan 1992). Sexually mature males have larger claws and span a large range of sizes from 40 and 150 mm CW (carapace width). Sexually mature females develop a wider abdomen for carrying eggs, and range in size from 40 mm to 95 mm CW. Females produce eggs that are carried beneath the abdomen for approximately two years in the sGSL (Moriyasu and Lanteigne 1998). Eggs hatch in late spring or early summer and the newly-hatched larvae spend 12-15 weeks in the water column, then settle on the bottom. It takes at least 8-9 years (post-settlement) for males to grow to the commercial size.

1.2. FISHERY AND MANAGEMENT

Since its beginnings in the mid-1960s, the sGSL snow crab fishery has grown to be a commercially important fishery with landings generally in excess of 20,000 tonnes (t) annually (Figure 2). Management of the fishery is based on annual quotas (attributed by management area and distributed among license holders) and effort controls (number of licenses, trap allocations, trap dimensions, and seasons). Landing of females is prohibited and only large, hard-shelled males with a minimum size of 95 mm CW are commercially exploited.

There are currently four crab fishing areas in the sGSL: 12, 12E, 12F and 19 (Figure 1), with Area 12 being the largest by area, number of participants, and landings. Area bounds are not based on biological considerations, but solely for management purposes (DFO 2009). The fishing season in Areas 12, 12E and 12F generally starts as soon as the sGSL is clear of ice in late April to early May and lasts until mid-July or when the area quota is caught. In Area 19, the fishing season starts in July and ends in mid-September or when the quota is caught. The number of traps per license varies by harvester group and management area.

There are two buffer zones within the sGSL where fishing is prohibited: one is a two nautical mile-wide strip located along the northern edge of Area 19 and the other is located along the south edge of Area 19. During the season, the fishery is subject to local area closures, usually in the form of 10’ x 10’ grids, to limit fishery impacts on soft-shelled crabs, as well as closures due to the detection of north Atlantic right whales (NARW) over fishing grounds.

1.3. RECENT CONCERNS AND RESEARCH DOCUMENT OBJECTIVES

Concerns in recent sGSL snow crab assessments included: an apparent increase in survey catchability which accompanied a change in survey vessel in 2019; the effect that relocating survey sampling stations to more trawlable areas may have had over time on abundance and biomass indices; and warming bottom temperatures.

Investigations regarding the increase in survey catchability led to a change in end-of-trawling practices since 2021. This eliminated latent trawling during winching as a possible source of bias in the 2021 and 2022 surveys (Surette and Chassé 2022). To monitor the effect of survey station relocations, a subset of stations have been reverted to their original locations since 2021 This provides a means of estimating the scale bias from particular source over time. Finally, a new analysis is presented which shows changes in snow crab distribution and its relation to warming temperatures.

This research document contains advice to support the implementation of two main objectives. The first is to ensure that a viable reproductive stock of commercial males remains after the fishery. The second aims to maintain a minimum quantity of commercial stock to sustain a commercial fishery. These objectives are achieved through survey-based estimation of commercial biomass and then evaluating risks associated with various catch options based on this estimate.

2. SURVEY METHODS

Stock status of snow crab is mainly assessed through trends in abundance and biomass indices calculated using data from a dedicated annual trawl survey. These data provide indices of recruitment, spawning stock, and other crab categories of biological or commercial interest.

2.1. SPATIAL DESIGN

The sGSL snow crab trawl survey has undergone changes in sampling design, survey area and sampling protocols since its inception in 1988. Originally, the extent of the survey area was smaller and concentrated over fishing grounds. The survey area was sub-divided using a lattice of 10’ x 10’ latitude-longitude grids and a small number of randomly selected sampling locations were then selected and held as fixed stations in subsequent surveys, though stations were often discarded and relocated over subsequent years due to trawl damage. Major methodological reviews occurred in 2005 (DFO 2006) and 2011 (DFO 2012a; Wade et al. 2014), which resulted in major design changes in the 2006 and 2012 surveys, respectively. In 2006, a large portion of survey stations were redistributed with the 10’x10’ lattice-grid design so that sampling stations would be more uniformly distributed within the survey area. In 2012, the 10’x10’ lattice-grid layout was discarded in favor of square grids, as defined using a Universal Transverse Mercator (UTM) (NAD 83) projection. This change was also accompanied by an expansion of the survey area boundaries to the 20 and 200 fathom isobaths. We consider that the survey area encompasses the vast majority of snow crab habitat in the sGSL.

As part of the implementation of the 2011 review, a new set of 325 sampling stations was generated for the 2012 survey and 355 new stations were generated for the 2013 survey. As was the common practice in previous surveys, it was decided that sampling locations generated for 2013 were to be retained as fixed stations in subsequent surveys.

However, not all regions within the survey area are amenable to trawling. About 20% of first tows in 2012 and 2013 failed due to damage to the trawl. The survey vessel was directed to a new, randomly-generated alternate sampling station within its assigned survey grid when significant trawl damage was incurred. The alternate location station would then be used as the reference fixed station for the following year's survey. At the time, it was felt that the fact that these alternate sampling locations were randomly generated would ensure that survey catches would remain as representative samples of their assigned grids, as was the intent of the original sampling design. However, this had the overall effect of a portion of stations being displaced to more trawlable areas within their respective sampling grids over time.

Since 2021, survey stations have been held at fixed locations from the 2020 survey, with the exception of an ongoing experiment involving a random subset of 100 of the survey sampling stations reverting to their original locations, as per the 2013 survey design. This experiment is being performed in an effort to monitor and assess possible bias due to stations being relocated to more trawlable areas over time with possibly higher catches of snow crab.

2.2. TRAWLING AND SAMPLING PROTOCOLS

Sampling stations are trawled during civil twilight hours using a Bigouden Nephrops bottom trawl net, originally developed for Norway lobster fisheries in France. The trawl has a 20 m opening and a 28.2 m footrope (Moriyasu et al. 2008). The vessel fishes at a target speed of 2 knots for 5 minutes. A 3:1 warp-to-depth ratio is used, up to a maximum warp length of 575 fathoms. Monitoring probes were attached to the trawl at various positions. eSonar ® acoustic probes (eSonar, St. John's, NL, Canada) relayed real-time measurements of trawl depth, headline height and wing spread. Star-Oddi ® DST centi-TD et DST tilt probes (Star-Oddi, Gardabaer, Iceland) recorded water pressure and temperature, along with tilt angle measurements from a tilt probe attached to the center of the footrope.

Survey catches were sorted by species or of taxonomic group and measured directly aboard the vessel. For every crab, carapace width, and carapace condition were recorded. Chela height (CH) was also measured for males while gonad and egg clutch characteristics were recorded for females (Hébert et al. 1997). Other species or taxonomic groups in the catch were identified, weighed and counted. Since 2010, fish species for a random subset of 100 survey sampling stations were measured for length using a Scilex electronic measuring board (Hallprint, Hindmarsh Valley, Australia).

2.3. 2022 SURVEY

The Avalon Voyager II, a 65-foot stern-trawling (850 HP) fiberglass boat performed the survey from July 13th and September 7th, 2022. A total of 343 sampling stations (Figure 3) were successfully trawled out of a target 355, with a total of 410 trawling attempts. In part due to the reversion of 100 survey stations to their original random locations from 2013 (Figure 4), there was a higher number of abandoned sampling stations (12) this year due to significant trawl damage. For logistical and efficiency considerations, it was decided that the number of trawling attempt was reduced from three to two to reduce the loss of time for net repairs. The regular survey captain was replaced by another captain from August 10th to the 26th, but resumed his duties on September 1st.

The overall trawling speed in 2022 was slightly faster than in previous years, with an average of 2.22 knots, compared to 2.17 knots in 2021 and 2.15 knots in 2020. The target trawling speed for the survey is 2.0 knots. Average trawl wing spread measurements were comparable to those of past years: about 8 meters once the trawl net is fully open. Wing spread measurements were somewhat noisier in 2022 than in previous years, likely due to less stringent noise filtering by the recording software or poorer relaying of the data between the trawl's probes and the survey vessel's acoustic receiver. Nonetheless, 298 tows had sufficient wing spread data to calculate trawl swept area, while swept areas for the remaining 45 tows were calculated as the average of the nearest 10 tows with available data, following the same method as in previous years. Trawl swept areas were an average of 2614 m^2 in 2022, which is comparable to those of 2021 (2670 m^2) and 2020 (2637 m^2). Following a change in end-of-trawling protocol in 2021, the duration of the passive trawling phase during the winching of the trawl has been greatly reduced, passing from ~90 seconds (secs) in 2019 and 2020, to 18 secs in 2021 and 13 secs in 2022.

3. METHODS

3.1. BIOLOGICAL CATEGORIES

The following definitions were used to specify the various snow crab categories used in this assessment. Crab maturity is assessed morphometrically using a chela height versus carapace width classifier in males (Conan and Comeau 1986), and carapace width and abdomen width classifier in females (Comeau and Conan 1992). Commercial crab are defined as mature male crab ≥ 95 mm CW. Commercial crab are divided into two groups: new recruits to the fishery (also called R-1 crab), identified as soft-shelled or white crab (carapace conditions 1 and 2); and remaining or residual crab, which represents the portion of the commercial crab that is left over after the previous fishing season, identified as hard-shelled crab (carapace conditions 3, 4 and 5). Adolescent male crab were grouped into size categories according to the time they are expected to recruit to the fishery. These categories are R-2 (> 83 mm CW), R-3 (69 to 83 mm CW), and R-4 (56 to 68 mm CW), which are expected to recruit to the fishery in two, three or four years' time, respectively.

3.2. FISHERY PERFORMANCE

Data on reported landings and fishing effort (number of trap hauls) were obtained from fishery logbooks and dockside monitoring data, compiled by the DFO Statistics Branches from the Quebec and Gulf Regions. Post-processing of these data by Science staff involves verification, correction or deletion of erroneous data. This includes corrections for fishing dates, fishing coordinates, landings and effort data.

Only data with reliable effort data were used for calculating catch-per-unit-of-effort (CPUE). Two types of CPUE were calculated: a seasonal CPUE representing an index of overall fishery performance, and a standardized CPUE using only the last six years of data. Total effort was estimated from the landings divided by the CPUE estimate, to account for missing effort in the data.

Standardized CPUE were calculated using fishery landings data from 2017 to 2022. We defined standardized CPUE as the average catches per trap 7 days after the opening of the fishery, after a 36-hour soak time for an average vessel within each fishing area. A 36-hour soak time was chosen because it is an intermediate value between the shorter soak times in Area 19 (1-2 days) and those of Areas 12, 12E and 12F which vary between 2 to 5 days. Nonlinear relationships were assumed between the log-scale landings and the day since the start of the fishery, as well as trap soak time. Log-scale landings were also assumed to vary by fishing and number of traps and fishing vessel. Formally the statistical model is

$$\ln L_{ijz} = \alpha_z + s_f(d_{ij}) + s_f(t_{ij}) + v_j + \ln n_{ij} + \varepsilon_{ij}$$

Where L_{ijz} is the recorded landings for fishing vessel i, and logbook entry j in fishing area z. The model components are: the intercept parameters by fishing zone α_z for fishing fleet *f*, $s_f(d_{ij})$ is a smoothing spline over fishing day d_{ij} for fishing fleet *f*, $s_f(t_{ij})$ is a smoothing spline over trap soak time t_{ij}, v_j is a vessel a random effect for each fishing vessel $v_j \sim N(0, \sigma_v^2)$, $\ln n_{ij}$

is an offset term for the number of traps fished and $\varepsilon_{ij} \sim N(0, \sigma^2)$ is an error term. Data analysis was performed using the GAMM (Generalized Additive Mixed Models) function from the R package mgcv package, version 1.8 (Wood 2017). This model was fit separately for each year.

3.3. CATCH STANDARDIZATION

Survey catches were standardized by trawl swept area, calculated using wing spread measurements and vessel speed, integrated over the time interval defined by the trawl touchdown, calculated using tilt probe angle data, and the stop time, which signals the start of trawl winching and end-of-tow procedures.

3.4. STOCK COMPOSITION

Annual size-frequency distributions were determined from standardized survey catches, separated by sexual maturity. For surveys prior to 2012, size-frequencies within each 10'x10' grid (the survey design used at the time) were averaged prior to calculating the annual average. This step was performed to spatially disaggregate survey catches for these older surveys. Means and interquartile ranges of crab sizes were calculated for fishery recruits (legal-sized, new-shelled mature males) and mature females from their corresponding spatially disaggregated size-frequency distributions for each year.

3.5. ABUNDANCE AND BIOMASS

The survey bounds are defined by a polygon with a surface area of 57,842.8 km^2. The portions of the management areas and buffer zones which overlap with the survey polygon were used to define corresponding sub-polygons which partition the survey area (Figure 5).

Kriging with external drift was used to estimate all abundance and biomass indices (DFO 2012a). For biomass estimates, crab counts at each tow were first converted to weights using the size-weight equation $w = (2.665 \times 10^{-4})\ CW^{3.098}$, where w is the weight in grams and CW is the carapace width in mm (Hébert et al. 1992).

3.6. SURVIVAL AND EXPLOITATION RATES FOR COMMERCIAL CRAB

An index for annual exploitation rates (F_t) was defined as a proportion of fishery landings (L_t) for fishing year t over the commercial biomass B_{t-1} estimate from the previous year:

$$F_t = L_t / B_{t-1}$$

An index of the survival rate of commercial crab from post-fishery survey in year $t-1$ to the post-fishery survey in the following year was calculated as the ratio of the landings (L_t) plus the residual biomass (R_t) in year t after the fishery over the commercial crab estimate (B_{t-1}) from year $t-1$:

$$S_t = (L_t + R_t) / B_{t-1}$$

Annual survival rates projection are variable, being subject to estimation error, changes in survey catchability and misidentification of carapace conditions. Also note that this estimate assumes that discard mortality from the fishery is negligible.

3.7. RISK ANALYSIS AND CATCH OPTIONS

The risk analysis calculated the probabilities of two events following the 2023 fishery: that the residual biomass would be below the Limit Reference Point (LRP) of 10,000 t, and/or that the total commercial biomass from the 2023 survey would be below the Upper Stock Reference (USR) of 41,400 t. Inputs to the risk analysis were the projected recruitment biomass to the fishery (R-1) for 2023, using a Bayesian model (Surette and Wade 2006; Wade et al. 2014). A range of catch options were considered, including the one prescribed by the Harvest Decision Rule for sGSL snow crab (DFO 2014). Risk probabilities were then calculated for each catch option, with an assumed natural mortality equal to the observed rate from the survey for the past 5-years.

3.8. CHANGES IN CRAB DISTRIBUTION AND WARMING TEMPERATURES

Changes in the depth, temperature, and spatial distribution of snow crab were examined to investigate the potential effects of warming bottom temperatures in the sGSL. Snow crab survey data from 1997 to 2022 were used, along with interpolated water temperature data for the month of September (Galbraith et al. 2021). The choice September bottom temperatures data was based on the availability of reliable temperature observations for the over the study period, as well as serving as a proxy for peak temperatures of the year, although temperatures may rise even further later in the fall. The distribution of three crab categories of interest were examined: 1) mature females, an index of reproductive stock, 2) instar VIII crab, the index of population recruitment, and 3) commercial crab.

Depth distributions for each crab category was obtained by first calculating the average survey catches, grouped by 1-meter depth bins, then scaling by the depth distribution within the survey area, based on GEBCO (General Bathymetric Chart of the Oceans) bathymetry (Becker et al. 2009). Quantiles of the resulting depth distribution were then calculated and displayed as a whisker plots by crab category and survey year. Similarly, the temperature distributions occupied by each crab category was calculated by calculating average densities by 0.1-degree temperature bins, then scaling by the September temperature distribution within the survey area for the corresponding year. Quantiles of the resulting temperature distribution were then calculated and displayed as a whisker plots by crab category and survey year. To account for the different survey design prior to 2012, standardized catches, depth and temperature data were averaged by 10’x10’ grid prior to analysis.

Density maps were interpolated using kriging for each year and snow crab category for each year between 1997 and 2022. The survey time series was divided into an early period (1997-2012) and a recent period (2013-2022) and the spatial distribution between these two periods were compared. These periods were defined to average over the population fluctuations between the two periods. The annual density maps were then averaged for each of the two study periods, and the relative change in density was then calculated.

4. RESULTS

4.1. FISHERY PERFORMANCE

The seasonal average of CPUE, an index of overall fishery performance, was calculated directly from landings and effort data, compiled from crab harvesters’ logbook data. These CPUE values were not standardized. In Area 12, the seasonal average CPUE decreased by 10.5% to 51.4 kilograms per trap haul (kg/th) in 2022, slightly below the long-term mean of 54.9 kg/th (average from 1998 to 2022). In Area 19, the seasonal average CPUE decreased by 6.9% to 112.6 kg/th, which was slightly above the long-term mean of 108.0 kg/th. CPUE by management area are shown in Figure 6.

Generally, standardized CPUE were very similar to seasonal values (Table 1), with differences generally less than 10% between the two values. The CPUE standardization model also produces estimates of the relationship between CPUE and day of the fishing season, as well as soak time. As expected, CPUE tend to decrease with day of the fishery. For example, CPUE in

Areas 12, 12E and 12F in 2022 decrease by about half between the start of the fishery and after two weeks of fishing. The decrease is even more pronounced in Area 19 (Figure 7). Soak time trends for the 2022 fishery (Figure 8) shows that CPUE increases by moderate amounts for Areas 12, 12E and 12F while the soak time effect is much more pronounced in Area 19.

4.2. STOCK COMPOSITION

4.2.1. Survey size distribution

Crab size distributions were standardized by trawl swept area for each tow, then averaged across all tows from the survey and the resulting densities scaled to the survey area. Size-frequency distributions by maturity are shown for male crab in Figure 9 and female crab in Figure 10. Size distributions for males in 2022 show a marked decrease of about 30% among sub-legal males, notably among immatures, with respect to 2021. Large abundances of instars VII (~28 mm CW) and VIII instars (~38 mm CW) in 2021, have yielded corresponding increases in instars VIII and IX (~50 mm CW), but these are much less pronounced than expected. In contrast, the abundance of legal-sized males has remained similar for the past five years. Size distributions for females in 2022 show a decrease in abundance among immatures and a slight increase among matures. The strong peak in instar VIII (~38 mm CW) immature crabs in 2021 yielded only a modest corresponding increase in instar IX (~50 mm CW) for mature females, despite the ostensible increase in trawl catchability associated with the size increase.

Annual variation in mean crab sizes was examined for legal-sized new-shelled mature males (i.e. fishery recruits). Mean size among these recruits have varied from a low of 108.3 mm CW in 2001 to high of 115.1 mm in 2008. The mean size then decreased to 109 mm CW in 2011-2012, increased to 113.0 mm CW in 2015, then decreased to 108.8 mm CW in 2018 and has since remained at this level (Figure 11), and stands currently at 110.0 mm CW in 2022.

Mean sizes among mature females have varied from 57.4 mm CW in 1997, to a high of 60.7 mm CW in 2005. Since 2005, mean size has gradually decreased to 56.7 mm CW in 2019, 56.9 mm CW in 2020, 56.7 mm in 2021, and 55.5 mm in 2022, the lowest in the series (Figure 11). The size range among mature females has also been steadily decreasing over the period from 1997 to 2021, with the interquartile range (IQR) decreasing from 13.0 mm CW to 10.0 mm CW from 1997 to 2005, and decreased to record lows of 9.4 mm in 2020 and 2021 and increasing slightly to 10.6 mm in 2022.

4.2.2. Commercial biomass

Commercial biomass for the sGSL is estimated at 85,532 t, with a 95% confidence interval of (74,658 - 97,535) (Table 2, Figure 12). Commercial biomass estimates have been comparable for the past five years, with 77,748 t in 2020 being the lowest and the 2022 estimate being the highest. The spherical variogram model used for interpolating the commercial biomass had a nugget value of 0, a sill at 4.4×10^6 and a range of 11.3 km.

Fishery recruitment in 2022 increased by 9.5% to 68,348 t (58,894 to 78,880 t), representing 80% of the commercial biomass (Table 2, Figure 12). Residual biomass (i.e. commercial crab with carapace conditions 3, 4 and 5) decreased by 9.0% and was estimated at 17,388 t (14,040 to 21,292 t) (Table 2, Figure 12). Residual biomass was dominated by carapace condition 3, representing 80% of survey catches, with 18% made up of carapace condition 4 crab and 2% carapace condition 5 crab (Table 3). The large proportion of carapace condition 3 in the residual biomass shows that the post-fishery population is young and does not show signs of an ageing population.

A breakdown of the commercial biomass by crab fishing area and buffer zone is shown in Table 4. The 2022 trawl survey estimate of commercial biomass for Area 12 was 75,742 t (66,447 - 85,966 t) representing 89.3% of the biomass located within the four fishing areas. In Area 12E, the commercial biomass from the 2022 trawl survey was estimated at 685 t (74 - 2,721 t), representing 0.8% of the biomass located within the four fishing areas. In Area 12F, the commercial biomass from the 2022 trawl survey was estimated at 4,320 t (2,949 - 6,113 t), representing 5.1% of the biomass located within the four fishing areas. The 2022 post-fishery trawl survey estimate of the commercial biomass for Area 19 was 4,094 t (2,465 - 6,408 t), representing 4.8% of the biomass located within the four fishing areas. An estimated 732 t of commercial crab lie within the unassigned zone above Areas 12E/12F and the two buffer zones (Figure 5).

4.2.3. Spatial distribution of commercial crab

The spatial distribution of commercial crab in 2022 was similar to that from 2018 to 2021, with crab concentrations south of Bradelle Bank, to the south and west of the Magdalen Islands and moderate concentrations in Shediac Valley (Figure 13). Densities in the Baie des Chaleurs remained high relative to previous years and increased slightly in 2022. Densities within Area 12F were similar to those of last year. Densities within the northern and middle portions of Area 19 showed a strong decrease, relative to 2021 (Figure 13).

The spatial distribution of the residual portion of commercial crab is shown in Figure 14. The residual stock is most abundant in Area 12F, with some a few small areas between the Magdalen Islands and PEI. The density of residual crab is low in Area 19, the Baie des Chaleurs, Shediac Valley and the Bradelle Banks.

4.2.4. Spawning stock

Total mature male abundance from the survey had a period of high abundance from 1999 to 2004 with a high of 401 million animals in 1999, then declined to 160 million in 2009 (Table 3). Abundance then increased to 299 million in 2012, decreasing to lower levels of about 235 million from 2013 to 2015. Since 2016, total abundance of mature males has increased to highs of 420 million in 2021 and 425 million in 2022. Over the past five years, the quantity of legal-sized mature males has been fairly constant at 144 to 154 million crab, and the overall increase in total mature males is due to the increased abundance of sub-legal sized mature crab, passing from 173 million in 2018 to 271 million in 2021 and 2022.

Mature female abundance from the survey was over 600 million animals from 1999 to 2002, then declined to 237 million in 2006 (Figure 15). Since then, female abundance has gradually increased to a high of 777 million in 2020, then declined by 25% to 585 million crab in 2021 and rose by 3.7% to 602 million crab in 2022.

Primiparous abundance from the survey was high from 1997 to 2001, with a sudden drop from 233 million in 2001 to 51 million in 2002, which gradually increased to 152 million in 2010, followed by a decrease to 79 million in 2011, which grew to 201 million in 2018 and 197 million in 2019, followed by a decrease to 139 million in 2020, 123 million in 2021 and 138 million in 2022. Primiparous females represent an average of 25% of the spawning stock.

The 6 mm CW decrease in mature females size (Figure 11) from 2005 to 2022 translates to a 28% decrease in individual fecundity. However, this decrease is more than offset by the increase in mature female abundance over the same period.

4.2.5. Population recruitment

The population recruitment index is defined as the abundance of small male crabs (34-44 mm CW), which roughly corresponds to instar VIII crabs. Last year's survey had a record 329 million crab, which decreased by 38.8% to 202 million crab in 2022 (Figure 16). The index for 2022 is remains the fifth highest in the series, and the record abundance last year was due to a strong cohort growing though the population, which has grown to instar IX in 2022, a stage where a small proportion of males and a majority of females moult to maturity. We note that the error associated with this index is higher than for larger crab, in part due to the lower catchability of the trawl at these sizes, as well as the occasional very large catches of such crab. Male instar VIII crab is expected to reach commercial size in 5-6 years, though some portion may skip a moult and/or mature at sizes smaller than commercial sizes.

4.2.6. Fishery recruitment

Fishery recruitment biomass (R-1) was relatively stable over the period from 2018 to 2021, with a low of 58,438 t in 2020 to a high of 62,473 t for the 2021 survey, but increased by 9.5% in 2022 to 68,348 t (58,894 t to 78,880 t) (Table 2). One-year predictions from a Bayesian model (Surette and Wade 2006; Wade et al. 2014), over-estimated recruitment by 21.3% in 2020 and 21.8% in 2021, but the 2022 prediction improved at only 6.4% above the observed recruitment from the survey (Figure 17). Although predictions are well within the 95% credibility interval, we note that the uncertainty associated with the prediction is fairly high. The predicted fishery recruitment for 2023 is estimated at 57,280 t (39,220 to 80,840 t), using the Bayesian model. This would represents a 16.3% decrease from the observed recruitment in 2022.

Fishery pre-recruit indices declined significantly in 2022 relative to 2021, with R-4s declining by 30.1% to 94.7 million crab, R-3s by 39.6% to 93.1 million and R-2s by 30.1% to 131.8 million. R-4s and R-3s are now below their respective long-term averages (1997-2021) of 127.2 million and 122.6 million crab (Table 3). The spatial distribution of fishery pre-recruits in 2022 follows the declines observed in the abundance indices, with decreases in adolescent male crab in the Shediac Valley, Bradelle Banks and around the Magdalen Islands, and especially strong decreases in Areas 12F and Area 19. Baie des Chaleurs is among the few areas with an increase (Figure 18).

4.3. COMMERCIAL EXPLOITATION AND SURVIVAL RATES

The exploitation rate for the 2022 fishery was estimated at 39.1%, based on the 2021 survey commercial biomass estimate (Table 2). Exploitation rates have varied between 21.0% and 44.7% from 1998 to 2022, with an average of 35.0% over the period from 1998 to 2022.

Estimates of annual survival rates had been declining ~ 5% annually, from 69.5% in 2018, to 64.4% in 2019, to 59.8% in 2020, to 56.1% in 2021, but increased slightly to 60.6% in 2022 (Table 2). The average survival rate was 66.6% over the period from 1998 to 2022. The low survival rates in recent years may be due to increases in mortality processes (natural and/or fishery-induced), though it also be due to misattribution of crab among recruitment and residual groups.

4.4. ENVIRONMENTAL CONDITIONS

Environmental factors, such as water temperature, can affect the timing of moulting and reproduction, as well as the movement of snow crab. Bottom temperatures over most of the sGSL are typically between less than 3 °C, a temperature range suitable for snow crab habitat. Bottom temperatures in deeper waters of Areas 12E and 12F are higher (1 to 7 °C) than in snow crab grounds in Area 12 while bottom temperatures in Area 19 are usually 1 to 2 °C warmer than on the traditional crab grounds in Area 12 (Chassé and Pettipas 2009).

Overall, bottom temperatures for the sGSL during 2022 were still much warmer than normal except for the coastal area north of PEI and on the eastern side of Northumberland Strait, including St. Georges Bay (Figure 19). Bottom temperatures in September 2022 were compared to the average temperatures over the period from 1991 to 2021 using data from surveys. Temperatures for Area 12 in 2022 were 0.5 to 1 °C (or more) above normal in Baie des Chaleurs and over a large area between the Acadian Peninsula, the Magdalen Islands and the Gaspe Peninsula. This area includes the Orphan’s and Bradelle Banks. Bottom temperatures near the coast of PEI were significantly colder than normal in some areas. Bottom temperatures in Area 12E, 12F and 19 were 1 to 2 °C above normal. Areas with below normal temperatures were around PEI, the southern area of the Magdalen Islands and the western part of Baie des Chaleurs. An oceanographic buoy off the northeast coast of PEI registered a sudden increase in bottom temperatures, which corresponds to a temperature anomaly of +1.3 °C, relative to September.

The surface area of the sGSL with bottom temperatures less than 3 °C in September, an index of snow crab habitat, rose slightly in 2022 from 2021, but remained low. The temperature within this area, at an average 1.4 °C, is still well above the long term average (1991-2020) representing a decrease of 0.2 °C from 2021 (1.6 °C), a 0.8 °C increase from the latest significant minimum observed in 2014 (0.6 °C). The 2022 average temperature within the snow crab habitat is the second highest of the 1971-2022 time series (Figure 20). The highest value was observed in 2021.

Starting in May 2022, surface waters in the sGSL were significantly warmer than normal except for July and a few weeks in September-October when temperatures were close to normal. Over the Magdalen Shallows, the temperature anomaly was +2.0 °C in September. These warmer surface temperatures lasted until the end of December. At the same time, the deep waters of the Laurentian channel continued their warming trend and were much warmer than normal. The temperature at 200 m near Cabot Strait reached 7.26 °C, which is 2.04 °C warmer than the long term average of 5.22 °C. The above conditions led to the water volume of the Cold Intermediate Layer (CIL), defined as waters < 1 °C, being one of the four lowest on record for September, from 1971 to 2022, with minimums in 1980, 2012 and 2021. The CIL water volume for 2022 was ~480 km^3, about 5 times lower than normal, and may in fact be the lowest on record, as the data for 1980 was scarce.

4.5. CHANGES IN CRAB DISTRIBUTION AND WARMING TEMPERATURES

4.5.1. Depth distribution

Figure 21 shows the depth distribution for mature females, male instar VIII and commercial snow crab from 1997 to 2022 from the trawl survey.

Mature females show a slight change in their depth distribution between the first part of the survey series from 1997 to 2012 and the later part from 2013 to 2022, with median depths have decreasing by about 4 meters, going from 70 meters down to 66 meters between the two periods. The proportion of crab in waters deeper than 100 meters has also decreased, going from an average of 4.6% of the population prior to 2013, down to 1.5% afterwards. The range of depths occupied by the mature female stock has also decreased: the interquartile range, i.e. the range of depths containing 50% of survey catches, has decreased from an average of 17 meters prior to 2013 down to 13 meters afterwards.

The pattern for male instar VIII crab was similar to those of mature females, with a slight shift away from deeper waters from 62 meters prior to 2013 down to 58 meters afterwards. Although depth distributions for male instar VIII are more variable, the median depths which they inhabit are 8-10 meters shallower than those of mature females. There were small proportions of the population in waters deeper than 100 meters from 2002 to 2009.

Commercial crab show a fairly uniform depth distribution through time. Median depths however are around 63 meters, which are about 8 meters less than those of mature females.

4.5.2. Temperature distribution

Figure 22 shows the September temperature distribution occupied by mature females, male instar VIII and commercial snow crab from 1997 to 2021 in the sGSL.

September temperatures occupied by mature females have fluctuated from lower to higher temperatures about four times from 1997 to 2021, with warm temperature periods in 2000, 2006, 2010, and 2012. The most recent increase in the temperature regime that mature females occupy began in 2014 at 0.20 °C and is currently at the highest value in the series at 1.21 °C in 2021, compared to the mean of 0.61 °C for the series. Minimum temperatures that mature females occupy, using the 2.5th percentile values, are also currently at their highest values at 0.81 °C for 2021, compared to the average 0.0 °C for the series. Mature females prior to 2015 had an average of 3.6% (up to 10%) of their population in bottom temperatures exceeding 3 °C in September, likely because a small portion of the population existed in deeper warmer waters. Since 2015 the proportions of females bottom temperatures exceeding 3 °C has been negligible.

Male instar VIII show more variability in their September temperature distribution, with an average proportion of 6.7% occupying waters exceeding 3 °C than those observed in mature females. The median temperatures for instar VIII crab was very high in 2021 at 1.76 °C, the highest in the series, though this value is likely strongly influenced by a single large tow of these crab in a warmer water area east of PEI. As was the case for females, the minimum temperatures for instar VIII crab had an increasing trend from -0.39 °C in 2014 to a high of 0.89 °C in 2021, the highest in the series.

Commercial crab occupation temperatures in September were relatively warm in 2000 and 2009-2014, and has since warmed from a median 0.17 °C in 2014 to 1.23 °C in 2021, the warmest in the series. As was the case for the other two categories, minimum temperatures occupied by commercial crab went from -0.45 °C in 2015 to series highs of 0.45 °C in 2020 and 0.35 °C in 2021.

The distribution of September bottom temperatures for the survey area is shown as a boxplot in Figure 23. The trends and fluctuations observed between the temperatures occupied by the three snow crab categories and the bottom temperatures of the survey are very similar overall. For instance, there is a close correspondence between the minimum (i.e. 2.5th percentile) and median temperatures within the survey area and those occupied by each of the three snow crab categories considered. As expected, snow crab do not occupy the warmest portions of the survey area, resulting in an average 2.7 °C difference between the survey area temperature distribution and those of the three snow crab categories.

4.5.3. Spatial distribution

Figure 24 shows a series of maps representing, for each of the three snow crab categories, the average kriged densities for the early period (1997-2012), the current period (2013-2022) and the relative differences between the two periods.

For all three crab categories, crab densities in the American Bank, notably the western portion, are markedly reduced in the current period, with more moderate decreases apparent to the south and east of the American Bank for all three categories, down to the 48th parallel. With the exeption of Area 12F, a decrease is also apparent along the Laurentian Channel, although we note that the survey had fewer stations in this area prior to 2006.

Mature female snow crab have shifted to more southern portions of the sGSL in the past ten years, with strong overall increases in the Shediac Valley, all around the Magdalen Islands, especially in the area north of PEI and Area 12F. In contrast, strong decreases in mature females are apparent in the Cape Breton Troughs, with current densities restricted to shallower western and southern portions of the area.

The pattern observed in mature females is very much the same for instar VIII males, with the exception of strong increases in the area south of Area 19, between PEI and southwestern Cape Breton.

Commercial crab also showed a strong decrease in the American Bank, but by more moderate manner than those observed for mature females and instar VIII crab. In contrast to mature females and instar VIII males, Area 19 commercial crab showed no overall decrease between the two study periods. As for the other two categories, commercial male crab saw a large increase in abundance in Area 12F from 2014 onward. Large concentrations of commercial crab are now found in more southern areas and south and west of the Magdalen Islands.

4.5.4. Temperature changes

Figure 25 shows the change in average temperatures between the current period from 2013 to 2021 and the early period from the survey from 1997 to 2012. A general warming trend is observed for most of the sGSL, but there are regions of moderate warming (Baie des Chaleurs, the central portion of the sGSL, the south and west of the Magdalen Islands) and even regions which saw some cooling between the two periods (the northern coast of PEI, the area between PEI and Cape Breton, and to the north and west of Magdalen Islands).

Areas with significant warming in September temperatures were found in and along the Laurentian Channel and the American Bank, the Shediac Valley, the far end and the edges of the Baie des Chaleurs, the coastal areas of the Magdalen Islands, and Area 19, notably in the Cape Breton Troughs.

Regions of relative cooling neatly explain some of the population recruitment and redistribution patterns that were observed, including the large increase of the crab population explosion in Area 12F, the southward shift if the population towards the north coast of PEI and the explosion of population recruitment south of Area 19. Conversely, regions with strong warming trends generally saw declines in crab abundance, notably the American Bank, along the Laurentian Channel, and the Cape Breton Troughs. These deeper areas form bathymetric connections with the deep, warming water mass of the Laurentian Channel. Water stratification temperatures show that the 3-degree isobath, considered as a traditional upper limit for favourable snow crab habitat, is being pushed into shallower areas by this deep water mass entering these regions of the sGSL (Figure 26).

5. PRECAUTIONARY APPROACH

5.1. REFERENCE POINTS

Reference points conforming to the Precautionary Approach (PA) (DFO 2009) were developed for sGSL snow crab in 2010 (DFO 2010). These reference points, in conjunction with appropriate stock parameters, are used to classify stock status as belonging to the critical, cautious or healthy zones, with each zone being assigned its particular management or harvest decision rules.

The sGSL snow crab stock has three defined reference points (Figure 27). A limit reference point (LRP) = 10,000 t, was defined according to the lowest survey residual biomass observed from 1997 to 2008. An upper stock reference (USR) point = 41,400 t, was defined as 40% of the maximum commercial biomass (i.e. recruitment plus residuals) from the 1997 to 2008 surveys. A removal rate reference F_{lim} = 34.6% (DFO 2012b; Figure 28), was set corresponding to the average annual exploitation rate for fishery years 1998 to 2009. See DFO (2010) for further details on the specification of these reference points.

The commercial biomass estimate for the 2023 sGSL fishery is 85,532 t (Tables 2 and 4), which is well within the healthy zone of the PA framework (Figures 27 and 28). The residual biomass after the 2022 fishery was at 17,388 t (Table 2), which was above its limit reference point of 10,000 t, and is thus also considered to be in the healthy zone.

F_{lim} is not currently treated as a limit reference point in the management of sGSL snow crab, in that the target exploitation rate given by the harvest decision rule generally exceeds F_{lim}, up to a maximum of 45%. The limit removal rate prescribed by the harvest decision rule is only applied when commercial biomass falls below 45,500 t, a situation which has not occurred since 2010.

5.2. RISK ANALYSIS

Inputs to the risk analysis were the commercial biomass from the 2022 survey (85,532 t), the projected fishery recruitment from the Bayesian model (57,280 t), and the 5-year average annual survival rate of 62%. A provisional catch option of 35,745 t, corresponding to an exploitation rate of 41.79%, as per the harvest decision rule, was used for the 2023 fishery (Figure 29).

The risk analysis indicates that this catch option results in a very low probability of the commercial biomass would be below USR despite the decrease in fisheries recruitment, which remains at a relatively high level. Similarly, the residual biomass has a low probability of 1.3% that it would fall below LRP after the 2023 fishery. Thus, the snow crab stock is projected to remain in the healthy zone of the PA in 2023 using that catch option (Table 5, Figure 29).

6. DISCUSSION

6.1. STOCK STATUS INDICATORS UNCERTAINTIES

The sGSL snow crab survey was developed to provide quality abundance and biomass indices for its resident snow crab population: it uses a bottom trawl with high catchability for commercial crab, contains a fairly large number stations which are sampled annually, and a sampling area that covers most of the crabs' habitat. Although progressive improvements in the spatial sampling design and protocols have been applied to the survey over the years, sources of uncertainty remain which were not accounted for when estimating indices.

One source of uncertainty relates to swept area estimates, which are used to standardize survey catches. Although these estimates are calculated for each individual tow using trawl monitoring data, the error associated with these estimates were not considered when calculating abundance and biomass indices. This does not necessarily constitute a source of bias for these indices, but rather implies that their reported error is under-estimated.

A second source of potential uncertainty were the set of 12 (out of 355) stations abandoned during the 2022 survey. The possible impact of removing these stations in 2022, commercial biomass estimates from previous years were recalculated by removing these 12 stations and then compared to their original values. This showed that the impact was minimal: biomass estimates differed only slightly, with increases of +0.6% in 2020 to +2.4% in 2021. Impacts on other population indices were on a comparable scale.

A third source of uncertainty is the impact of survey station relocations have had on indices over the years. The current experiment of setting 100 survey stations to their original, randomly selected locations from 2013 has yielded a few insights. Commercial biomass using only these stations were calculated for 2021 and 2022 and compared to those from the entire survey. The difference in commercial biomass was -16.3% in 2021 and +3.9% using the data subset. Thus far, these two estimates lack sufficient power to provide a reliable estimate of station relocation bias, the scale of the supposed bias will become clearer over time as the experiment is repeated in future surveys.

Another source of uncertainty is the variation in trawl and survey catchability apparent in certain years of the survey, notably the unexplained increase in sub-legal crab in 2019 relative to 2018. Changes brought to end-of-trawling procedures in 2021 yielded no obvious change in the scale of standardized size distributions, relative to 2019 and 2020. These procedures effectively eliminated unaccounted trawling during the winching of the trawl net as an explanation of the survey catch increases in 2019. Examination of trawl mensuration data such as headline height, wind spread, the tilt touchdown probe, and vessel speed, showed no apparent variation over the last five years. Thus, the cause of the increase in trawl catchability among sub-legal sized crab in 2019 remains unknown, with variation in trawl symmetry or the quality of bottom contact of the trawl proposed as likely candidates.

In light of the uncertainty associated with survey catchability, the decrease of survey catches among sub-legal males in 2022 is due either to a decrease in trawl catchability or an increase in natural mortality. It is not clear which of these two factors possibilities is at play. Monitoring and measurement of trawl symmetry during the survey remains limited. Direct observation of trawling via cameras require some time and effort to configure, and would likely slow down regular survey operations. Conversely, if the observed decline is due to mortality, it appears to have occurred in immature crab much more than mature ones at the same size, although maturation rates are known to vary from year to year. Rising temperatures in recent years may be leading increased mortality among sub-legal males. Indeed, natural mortality among commercial crab was relatively high at an average 38% over the last five years, although the natural mortality rate was not observed to have increased in 2022.

6.2. STANDARDIZED CPUE AND COMMERCIAL BIOMASS

A discussion on the hypotheses that standardized CPUE could shed some light on recent concerns regarding survey catchability issues, notably the increases in survey catchability in 2020 is the focus of this section and it will concentrate mainly on the patterns observed in Area 12, since biomass estimates in other areas have much higher uncertainty in their biomass estimates.

The high CPUE in Area 12 for the 2017 fishing season were in line with a correspondingly high projected total biomass of 98,384 t. However, standardized CPUE in other areas were not markedly higher. The following year, projected biomass declined by 33%, and standardized CPUE in Area 12 fell by 46% from the previous year. In 2019, biomass increased by 23% and standardized CPUE increased by 39% in Area 12. Starting in 2019, projected commercial biomasses remained relatively constant, at around 80,000 t.

For the 2020 fishing season, concern regarding the survey catchability increase raised the possibility that the commercial biomass was overestimated. Indeed, despite a quota reduction, CPUE in 2020 saw sizeable decreases in all fishing areas, perhaps indicating that the underlying biomass had declined relative to 2019. However, area closures due to NARW likely also negatively impacted CPUE in 2020. Following a change in the end-of-tow fishing protocol during the 2020 and 2021 surveys, the commercial biomass remained almost constant, but standardized CPUE generally increased in 2021 by 20-30%, and have remained at comparable levels in 2022. The reasons for these CPUE increases are unclear, but factors such as the earlier start of the fishing season in April in 2021 and 2022 could have influenced this increase.

Although CPUE should scale to some degree with the underlying commercial crab density, CPUE are much more subject to variations in scale than surveys, as they are not subject to monitoring or controls to account for many important factors which would be useful for standardizing (Maggs et al. 2016). However, the standardization variables included here do adjust for certain nuisance factors, such as soak time and time of fishing, many others such as changing fishing practices and the areas that fish harvesters target were not considered when standardizing. Interpreting changes in the underlying commercial biomass through the optic of standardized CPUE remains a difficult task, and sheds little light on recent changes in survey catchability. Thus, the proper standardization of the survey time series remains an on-going issue.

6.3. CHANGES IN CRAB DISTRIBUTION AND WARMING TEMPERATURES

Many aspects of snow crab biology, including feeding, metabolism and reproduction, have characteristically narrow temperature ranges. A laboratory study involving male snow crab from the sGSL showed that metabolic costs above 7 °C exceeded caloric intake and that caloric intake decreased when passing the 5 °C threshold (Foyle et al. 1989). In terms of egg development, optimal temperatures range from 0 to 3 °C (Webb et al. 2007). An experimental study from the sGSL showed that incubating females held in warmer temperatures (between 1.8 and 3.2 °C) passed from a 2-year to a 1-year reproductive cycle (Moriyasu and Lanteigne 1998). Similarly, in eastern Nova Scotia, around 80% of mature females were shown to have a 1-year reproductive cycle, with this region having higher temperatures than in the sGSL (Kuhn and Choi 2011). In terms of recruitment, another laboratory study showed that small benthic recruits favoured temperatures of 0 °C to 1.5 °C, which explained some of the depth distribution patterns observed in the northwestern portions of the Gulf of Saint Lawrence (Dionne et al. 2003).

Most recently, the collapse of eastern Bering Sea snow crab fishery in Alaska in 2021 was preceded by average temperatures of occupancy stood at 2.5 °C during their 2018 survey. The temperatures for immature male snow crab stood was about 2 °C during the 2021 survey, just prior to the collapse of the fishery (Fedewa et al. 2020, Fedewa et al. 2021).

For sGSL snow crab, September temperature distributions for the three snow crab categories favoured temperatures less than 3 °C, with less than 10% of their respective populations lying above this threshold over the history of the survey (Figure 22). Median temperatures occupied by sGSL snow crab have inched upwards since 2014 to all-time highs in 2021, ranging from 1.2 °C (mature female and commercial crab) to 1.7 °C (instar VIII males), closely mirroring increases in bottom temperatures in the sGSL during September.

7. CONCLUSION

Current indicators for the sGSL snow crab stock continue to be positive, positioning the stock within the healthy zone of the PA, with relatively high commercial biomass, spawning stock, population recruitment and projected fishery recruitment. The commercial stock biomass from the post-fishery survey is estimated at 85,532 t, composed of 80% new recruitment and 20% of residual biomass. Based on the harvest decision rule, this commercial stock biomass estimate corresponds to an exploitation rate of 41.79%, and a catch option of 35,745 t for the 2023 sGSL snow crab fishery. A risk analysis indicates that such catch option in 2023 would result in a very low likelihood that the residual stock biomass would fall below the LRP and a very high likelihood that the 2023 commercial stock biomass would remain above the USR, as defined by the PA.

However, warming temperatures in the sGSL are a cause of concern. The volume of the CIL has been very low in recent years, associated with a decrease in the area of snow crab habitat. Similarly, analysis of survey data has shown concurrent decreases in snow crab densities in areas along the margins of the Laurentian Channel, where a mass of warming, deep waters have been observed over the past decade. In light of this, some portions of the stock may be approaching known thermal limits for egg incubation, larval settlement and metabolic tolerances, which may lead to lower recruitment, increased mortality and emigration, should temperatures keep increasing in the future.

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10. TABLES

Table 1. Seasonal average and standardized catch-per-unit-of-effort (kg / trap haul) by year and management area. Standard errors are shown in parentheses.

Year	12		12E		12F		19	
	Average	**Standard.**	**Average**	**Standard.**	**Average**	**Standard.**	**Average**	**Standard.**
2017	72.0	78.3 (1.0)	60.9	54.0 (1.2)	72.6	51.4 (1.1)	142.8	154.0 (1.0)
2018	44.2	42.0 (1.0)	46.6	45.5 (1.2)	69.1	61.5 (1.1)	156.1	144.0 (1.0)
2019	55.5	58.2 (1.0)	65.7	44.3 (1.2)	64.5	68.0 (1.1)	112.7	124.6 (1.0)
2020	44.1	42.7 (1.0)	45.9	48.6 (1.2)	45.2	46.9 (1.1)	101.7	97.8 (1.1)
2021	57.4	55.7 (1.0)	55.7	48.9 (1.2)	59.1	54.4 (1.1)	121.0	112.9 (1.0)
2022	51.4	56.6 (1.0)	78.5	77.8 (1.4)	76.4	69.8 (1.1)	112.6	115.9 (1.0)

Table 2. Annual recruitment, residual and total commercial biomass (in tonnes) of southern Gulf of Saint Lawrence snow crab, based on trawl survey data. Parentheses show 95% confidence intervals. Also shown are annual landings, annual and five year average survival rates of commercial crab and exploitation rate.

Year	Recruitment (t)		Residual (t)	Commercial (t)	Landings (t)	Survival (%)		ER (%)
	Observed	Predicted				Annual	5-year	
1997	37,910 (30,911-46,018)	-	27,688 (21,982-34,422)	64,518 (54,105-76,345)	17,249	-	-	26.7
1998	30,603 (22,695-40,384)	-	28,295 (21,497-36,566)	57,813 (45,856-71,931)	13,575	64.9	-	21.0
1999	26,015 (20,709-32,265)	-	31,177 (25,044-38,356)	56,757 (47,641-67,102)	15,110	80.1	-	26.1
2000	40,734 (33,592-48,942)	-	9,979 (6,987-13,827)	50,621 (41,843-60,692)	18,712	50.6	-	33.0
2001	42,358 (33,800-52,422)	-	17,612 (13,853-22,077)	60,328 (49,851-72,351)	18,262	70.9	-	36.1
2002	66,076 (55,416-78,180)	-	13,060 (10,793-15,662)	79,228 (67,983-91,791)	25,691	64.2	66.1	42.6
2003	58,270 (50,270-67,175)	-	26,993 (22,124-32,613)	84,448 (73,486-96,574)	21,163	60.8	65.3	26.7
2004	83,764 (74,392-93,981)	-	21,259 (17,343-25,794)	103,146 (92,426-114,758)	31,675	62.7	61.8	37.5
2005	59,939 (53,551-66,870)	60,500 (38,800-86,000)	23,496 (18,902-28,868)	82,565 (73,514-92,415)	36,118	57.8	63.3	35.0
2006	54,541 (48,235-61,438)	49,700 (33,200-73,000)	19,621 (16,697-22,907)	73,645 (65,681-82,302)	29,121	59.0	60.9	35.3
2007	40,048 (35,286-45,269)	35,200 (21,300-55,000)	26,829 (23,232-30,821)	66,371 (59,971-73,264)	26,867	72.9	62.6	36.5
2008	32,241 (27,929-37,027)	29,000 (18,500-42,000)	20,981 (17,989-24,327)	52,921 (47,167-59,178)	24,458	68.5	64.2	36.9
2009	20,618 (17,747-23,818)	27,700 (17,800-38,000)	10,454 (8,687-12,474)	31,015 (27,519-34,829)	23,642	64.4	64.5	44.7
2010	20,477 (17,815-23,423)	25,900 (17,100-37,000)	15,490 (13,022-18,289)	35,929 (32,049-40,147)	9,549	80.7	69.1	30.8
2011	29,643 (25,676-34,045)	33,700 (22,900-47,000)	33,679 (28,430-39,613)	62,841 (55,985-70,299)	10,708	-	71.6	29.8
2012	49,010 (40,382-58,931)	40,700 (31,300-52,400)	25,615 (21,607-30,147)	74,778 (64,881-85,748)	21,956	75.7	72.3	34.9
2013	39,988 (31,504-50,055)	40,380 (31,670-50,380)	27,092 (22,041-32,952)	66,709 (54,294-81,108)	26,049	71.1	73.0	34.8
2014	44,285 (37,440-52,014)	37,893 (28,568-49,114)	23,863 (20,356-27,799)	67,990 (59,802-76,978)	24,479	72.5	75.0	36.7
2015	34,982 (29,145-41,643)	42,300 (32,760-51,840)	24,106 (20,290-28,429)	58,927 (51,368-67,278)	25,911	73.6	73.2	38.1
2016	74,124 (64,811-84,392)	50,000 (36,400-66,900)	24,309 (20,876-28,143)	98,394 (87,150-110,677)	21,725	78.1	74.2	36.9
2017	51,127 (43,976-59,103)	46,200 (31,400-64,230)	14,650 (12,134-17,534)	65,738 (57,221-75,157)	43,656	59.3	70.9	44.4
2018	59,609 (51,755-68,310)	47,700 (33,800-64,880)	21,432 (17,271-26,291)	80,746 (70,984-91,467)	24,260	69.5	70.6	36.9

Year	Recruitment (t)		Residual (t)	Commercial (t)	Landings (t)	Survival (%)		ER (%)
	Observed	Predicted				Annual	5-year	
2019	58,995 (50,215-68,863)	49,820 (33,790-70,970)	20,291 (16,940-24,109)	79,066 (69,072-90,091)	31,707	64.4	69.0	39.3
2020	58,438 (49,759-68,189)	74,280 (49,300-107,400)	19,107 (16,235-22,239)	77,748 (67,706-88,852)	28,156	59.8	66.2	35.6
2021	62,473 (53,650-71,590)	79,870 (52,760-115,700)	19,144 (15,997-22,726)	80,950 (70,543, 92,451)	24,479	56.1	61.8	31.5
2022	68,348 (58,894-78,880)	73,120 (48,590-105,200)	17,388 (14,040-21,292)	85,532 (74,658, 97,535)	31,661	60.6	62.1	39.1
2023	-	57,280 (39,220-80,840)	-	-	-	-	-	-

Table 3. Annual abundance (in millions) of crab categories based on southern Gulf of Saint Lawrence trawl survey data. Parentheses show standard errors.

Year	Pre-recruits			Recruits	Residual		
	R-4	R-3	R-2	CC 1 & 2	CC 3	CC 4	CC 5
1997	114.0 (12.5)	98.2 (10.5)	59.7 (6.6)	59.3 (6.5)	28.3	17.7	5.2
1998	135.3 (14.9)	91.3 (11.6)	60.3 (7.3)	50.9 (7.6)	24.9	16.0	8.6
1999	195.6 (21.5)	151.1 (16.6)	112.9 (14.6)	48.1 (5.4)	32.7	16.8	7.8
2000	237.5 (26.1)	159.1 (13.8)	88.4 (9.0)	68.4 (5.9)	10.3	7.4	2.5
2001	310.8 (34.2)	227.3 (17.5)	136.3 (12.8)	76.4 (8.4)	28.1	5.4	1.6
2002	164.3 (17.3)	242.2 (20.1)	202.2 (16.9)	112.3 (9.2)	21.7	4.3	0.9
2003	133.2 (15.8)	202.3 (16.2)	178.5 (14.0)	100.3 (7.5)	38.0	11.7	1.8
2004	85.8 (8.2)	122.9 (9.3)	144.1 (10.5)	143.3 (8.4)	28.2	9.9	1.2
2005	62.2 (5.7)	79.8 (6.3)	117.2 (9.7)	99.1 (5.6)	30.0	10.5	0.6
2006	54.1 (5.4)	49.6 (3.2)	65.7 (5.9)	84.2 (4.9)	29.2	5.8	1.0
2007	56.5 (5.0)	47.6 (3.5)	55.4 (4.9)	62.8 (3.8)	31.5	14.0	1.0
2008	80.6 (6.5)	54.6 (4.2)	45.8 (5.2)	49.1 (3.4)	23.0	11.4	3.0
2009	88.5 (5.9)	69.3 (5.5)	43.8 (4.8)	31.7 (2.3)	12.5	5.3	1.3
2010	140.8 (7.7)	110.3 (7.4)	72.5 (7.0)	32.8 (2.2)	20.6	4.2	1.6
2011	91.4 (6.0)	99.2 (6.5)	88.2 (5.9)	53.0 (3.7)	44.3	9.8	1.8
2012	95.7 (8.7)	86.4 (9.9)	80.5 (7.4)	86.6 (8.3)	37.9	5.7	1.2
2013	103.1 (9.3)	85.1 (9.6)	79.4 (8.1)	63.7 (7.3)	30.1	18.3	0.7
2014	105.1 (10.9)	93.6 (9.8)	117.2 (12.1)	73.3 (6.3)	29.6	13.1	0.6
2015	107.1 (7.6)	124.7 (12.3)	127.5 (11.1)	56.2 (5.2)	27.2	17.3	0.5
2016	113.1 (7.1)	124.8 (9.7)	101.6 (6.8)	125.9 (8.6)	30.6	14.7	0.1
2017	113.0 (7.7)	119.6 (9.2)	103.3 (7.2)	90.0 (6.9)	21.6	6.1	0.4
2018	135.6 (7.6)	116.5 (7.2)	108.3 (8.4)	115.6 (7.9)	34.6	4.5	0.8

Year	Pre-recruits			Recruits	Residual		
	R-4	R-3	R-2	CC 1 & 2	CC 3	CC 4	CC 5
2019	190.7 (11.8)	186.0 (13.0)	185.7 (16.0)	105.1 (7.8)	28.8	9.3	0.8
2020	180.9 (11.2)	170.3 (12.0)	203.0 (17.2)	103.5 (8.3)	29.8	7.2	0.6
2021	135.9 (7.6)	154.4 (9.5)	188.9 (15.3)	112.0 (8.1)	29.7	6.4	1.5
2022	94.7 (6.5)	93.1 (7.8)	131.8 (11.0)	119.6 (8.7)	27.6	6.2	0.7

Table 4. Commercial biomass by management area and buffer zones based on 2022 southern Gulf of Saint Lawrence survey data. Parentheses show 95% confidence intervals. Labels are from Figure 5.

Areas	Area (km^2)	Biomass (t)	
Southern Gulf	57,842.8	**85,532**	(74,658 - 97,535)
Area 12	48,074.0	**75,742**	(66,447 - 85,966)
Area 12E	2,436.9	**685**	(74 - 2,721)
Area 12F	2,426.8	**4,320**	(2,949 - 6,113)
Area 19	3,813.0	**4,094**	(2,465 - 6,408)
Sum of management areas[1]	56,750.7	**84,841**	
Unassigned zone above 12E/F **(A)**	667.9	**43**	(0 - 292)
Buffer zone 19/12F **(B)**	134.2	**137**	(26 - 436)
Buffer zone 12/19 **(C)**	289.5	**552**	(184 – 1,293)
Sum of total areas and zones	57,842.7	**85,573**	

[1] Small difference in the sum of all individual area estimates compared to the southern Gulf estimates is due to rounding of intermediate calculations.

Table 5. Risk analysis for different catch options for the 2023 southern Gulf of Saint Lawrence snow crab fishery showing the probability that the residual commercial biomass (B_{res}) would be below limit reference point (LPR), the probability that the total commercial biomass (B) would be below the upper stock reference (USR), and the expected biomass for the 2023 survey. In bold is the catch option corresponding to an exploitation rate of 41.79%, the rate as per the harvest decision rule.

Catch option (t)	Probability		Predicted biomass for 2023 (t)
	B_{res} < LRP	B < USR	
30,000	0.0%	0.0%	80,640 (61,258 – 104,924)
31,000	0.0%	0.0%	79,640 (60,258 – 103,924)
32,000	0.0%	0.0%	78,640 (59,258 – 102,924)
33,000	0.1%	0.0%	77,640 (58,258 – 101,924)
34,000	0.3%	0.0%	76,640 (57,258 – 100,924)
35,000	0.7%	0.0%	75,640 (56,258 – 99,924)
35,745	1.3%	0.0%	74,896 (55,513 – 99,179)
36,000	1.6%	0.0%	74,640 (55,258 – 98,924)
37,000	3.4%	0.0%	73,640 (54,258 – 97,924)
38,000	6.5%	0.0%	72,640 (53,258 – 96,924)
39,000	11.3%	0.0%	71,640 (52,258 – 95,924)
40,000	18.0%	0.1%	70,640 (51,258 – 94,924)
41,000	26.5%	0.1%	69,640 (50,258 – 93,924)
42,000	36.7%	0.1%	68,640 (49,258 – 92,924)
43,000	47.5%	0.2%	67,640 (48,258 – 91,924)
44,000	58.4%	0.3%	66,640 (47,258 – 90,924)
45,000	68.5%	0.5%	65,640 (46,258 – 89,924)
50,000	96.1%	2.6%	60,640 (41,258 – 84,924)
60,000	100.0%	20.7%	50,640 (31,258 – 74,924)
70,000	100.0%	55.9%	40,640 (21,258 – 64,924)
80,000	100.0%	83.8%	30,640 (11,258 – 54,924)

11. FIGURES

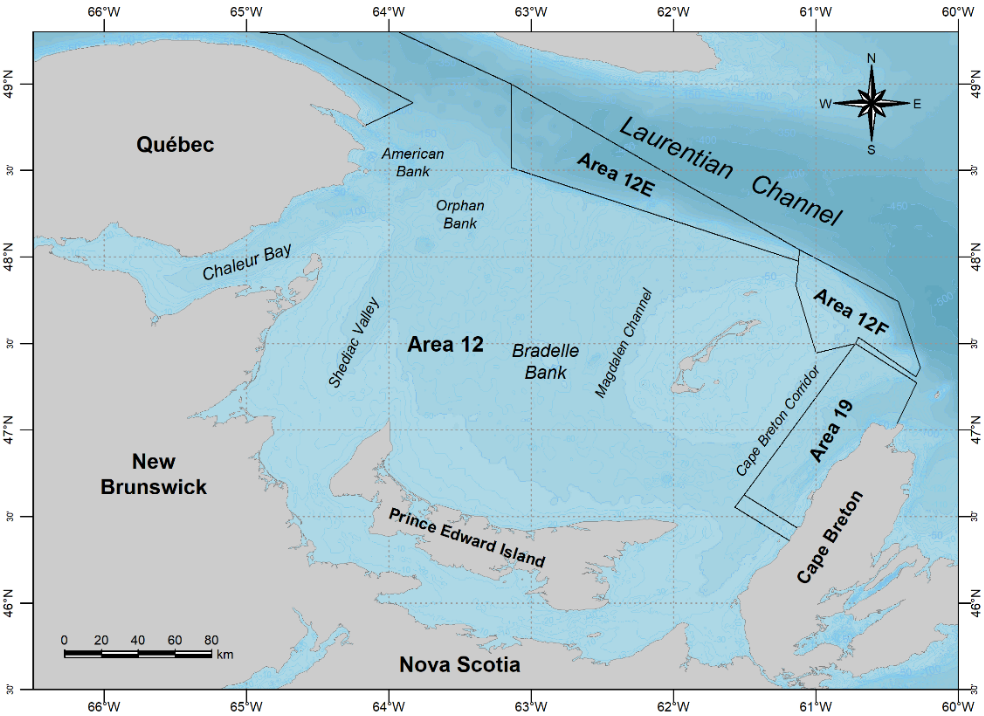

Figure 1. Map of the southern Gulf of Saint Lawrence showing snow crab fishery areas (12 12E, 12F and 19) and common names for fishing grounds.

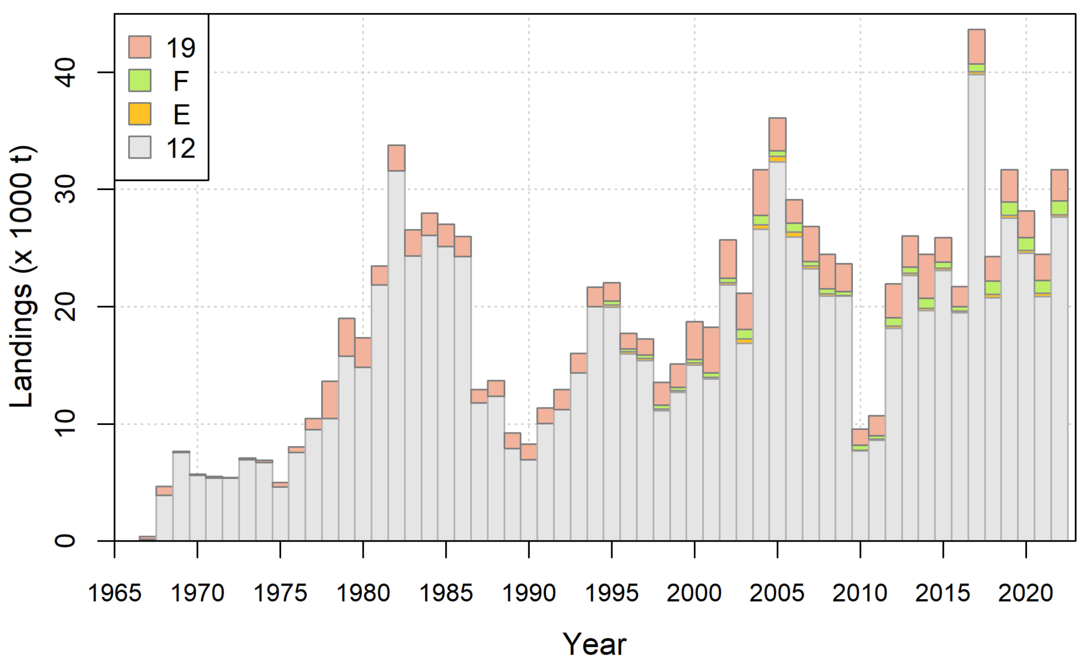

Figure 2. Annual landings (in tonnes) of southern Gulf of Saint Lawrence snow crab by fishing area.

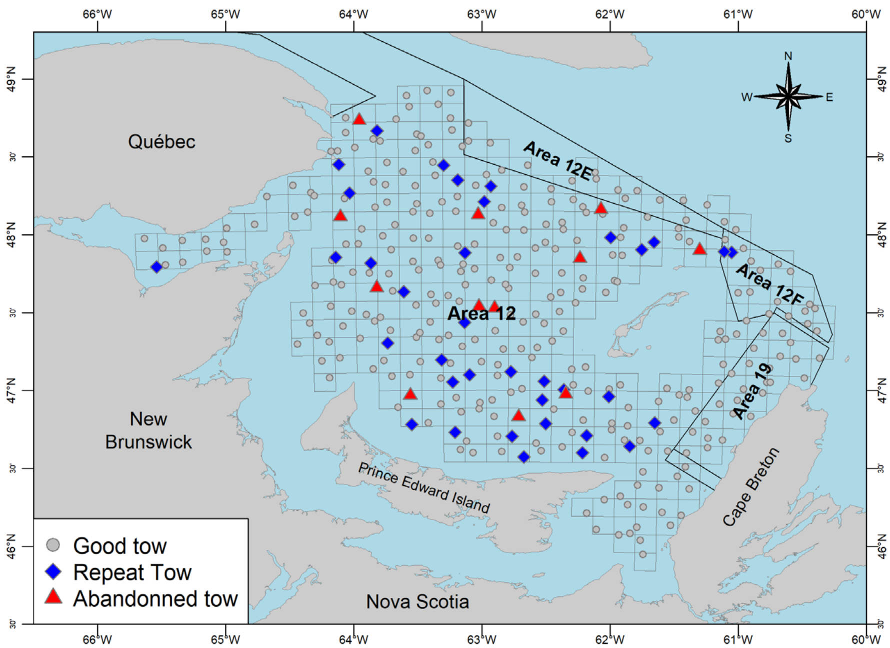

Figure 3. Locations of the 2022 snow crab trawl survey stations. Grey circles points are tows successfully trawled on the first try, blue diamonds show tows repeated and successfully trawl at the same station, and red triangles are abandoned tows. Survey sampling grids are shown in grey.

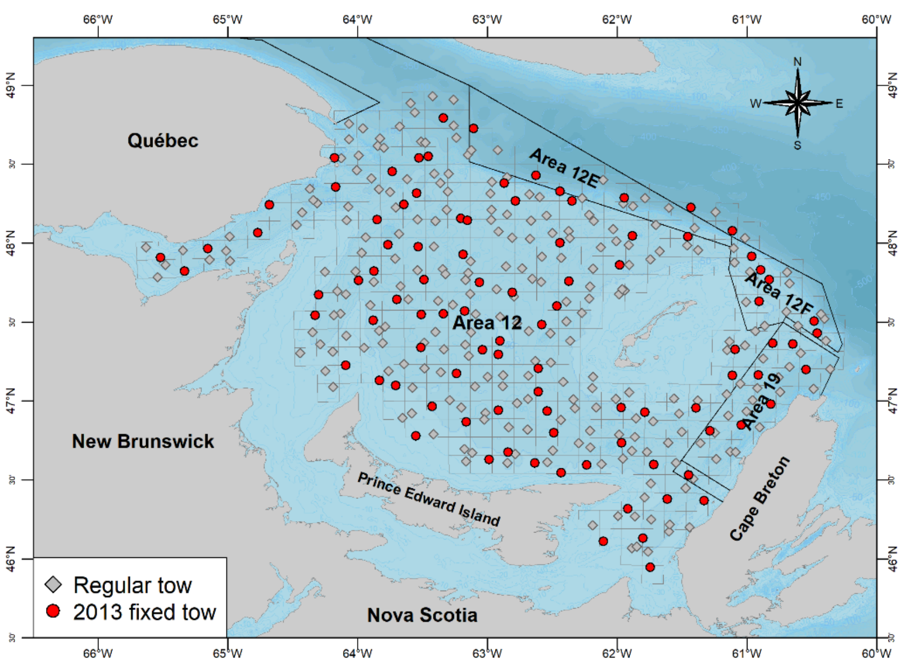

Figure 4. Map showing the 100 stations which were moved to their original 2013 positions (red circles) during the 2022 survey, along with the 255 remaining stations (grey diamonds). Survey sampling grids are shown in grey.

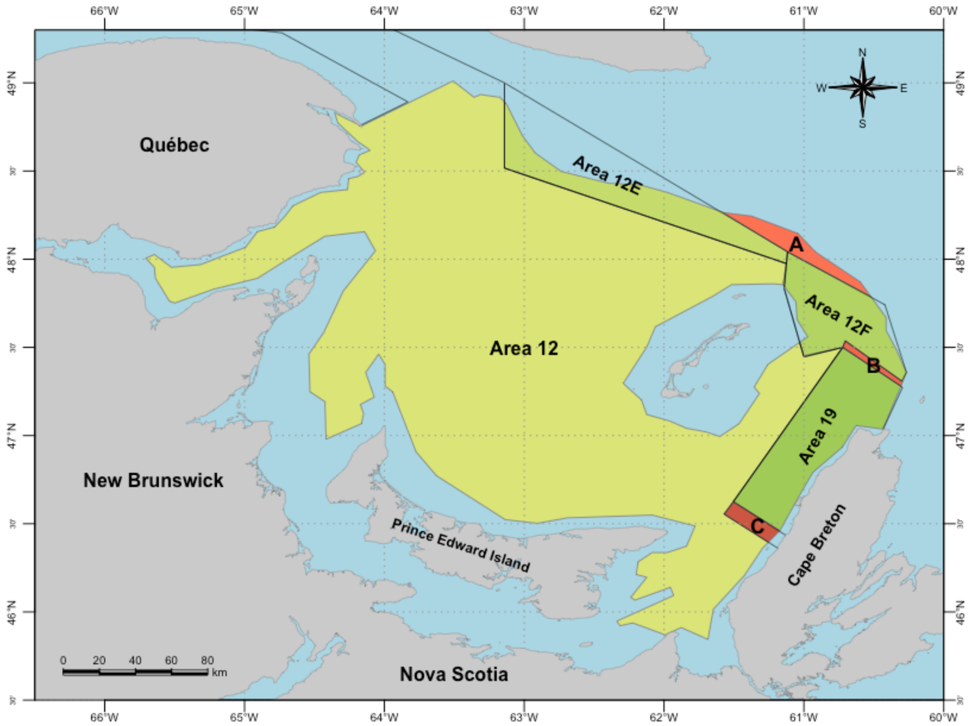

Figure 5. Polygons used for estimating survey stock indices. The unassigned zone north of Areas 12E and 12F (label A) and buffer zones (labels B and C) are also shown.

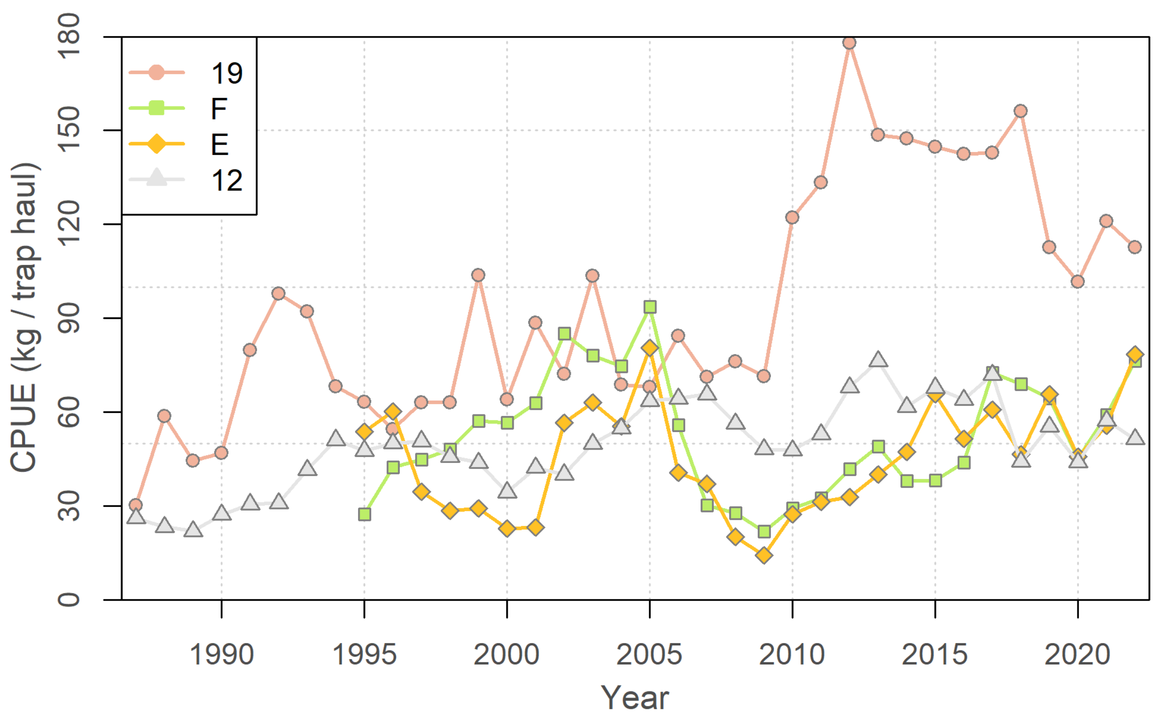

Figure 6. Seasonal average catch-per-unit-of-effort (CPUE; kg/th) by fishing management area in the southern Gulf of Saint Lawrence, based on fishery logbook data (not currently updated for 2022).

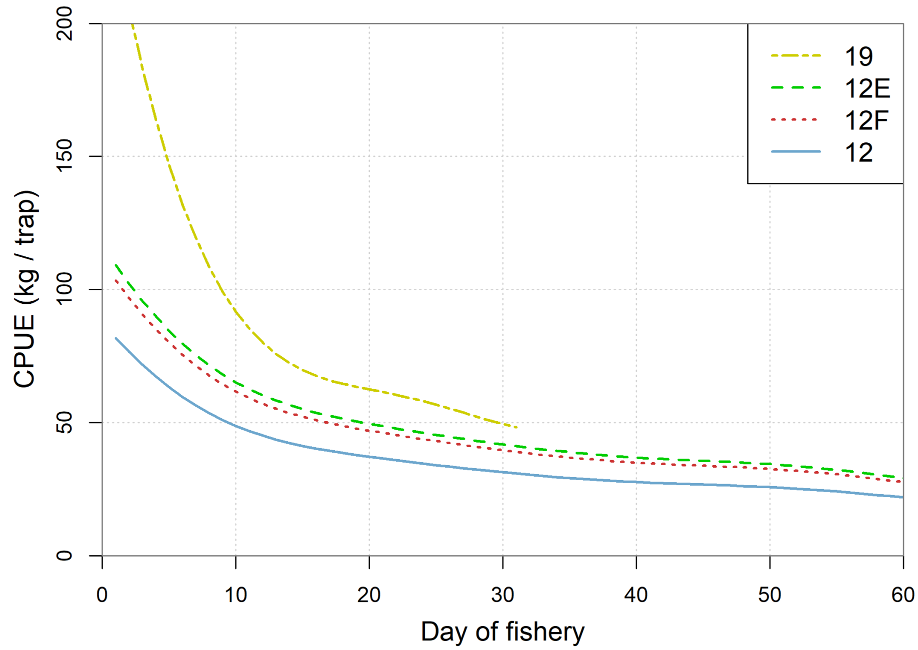

Figure 7. Catch-per-unit-of-effort versus fishing day for the 2022 fishery, as estimated from the catch-per-unit-of-effort standardization model, evaluated for 36-hour soak time for an average fishing vessel in each fishing area.

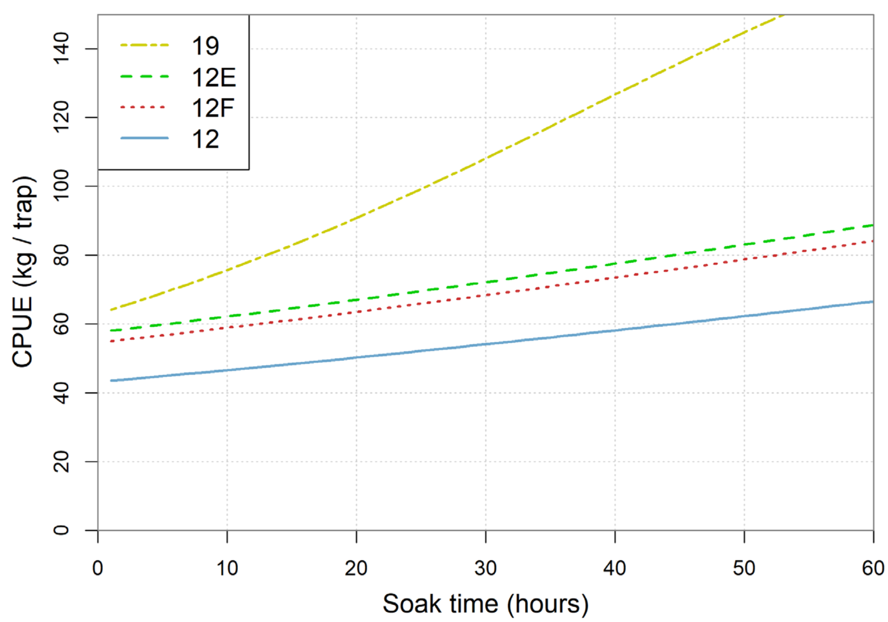

Figure 8. Catch-per-unit-of-effort versus trap soak time for the 2022 fishery, as estimated from the catch-per-unit-of-effort standardization model, evaluated at the 7th day of the fishery for an average fishing vessel in each fishing area.

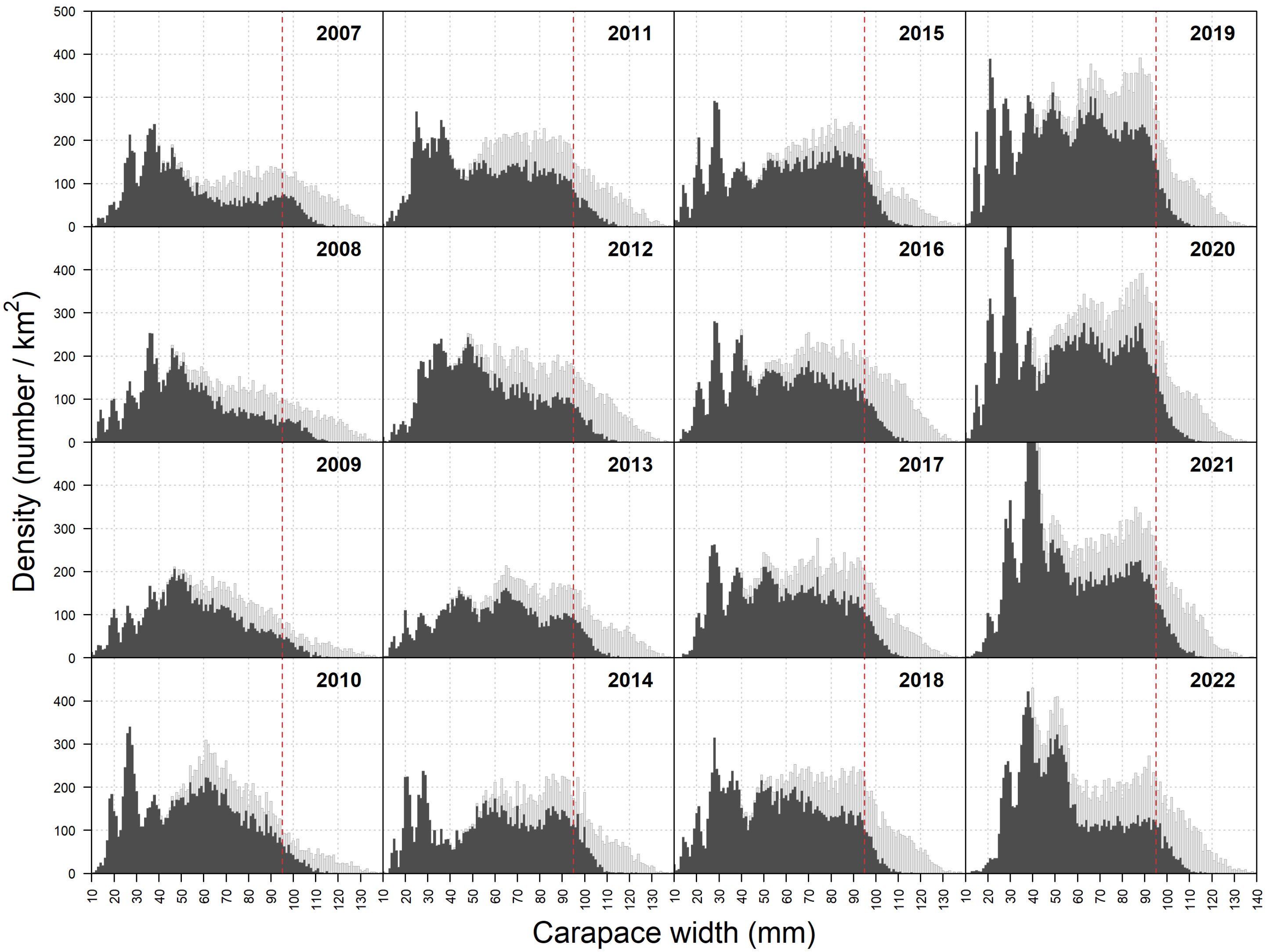

Figure 9. Annual size-frequency distributions of immature and adolescent (dark grey bars) and mature male (light grey bars) snow crab from the trawl surveys. The red dotted line shows the minimum legal size of 95 mm carapace width. Note that abundances for small crab for 2020 and 2021 exceed the scale of the plot.

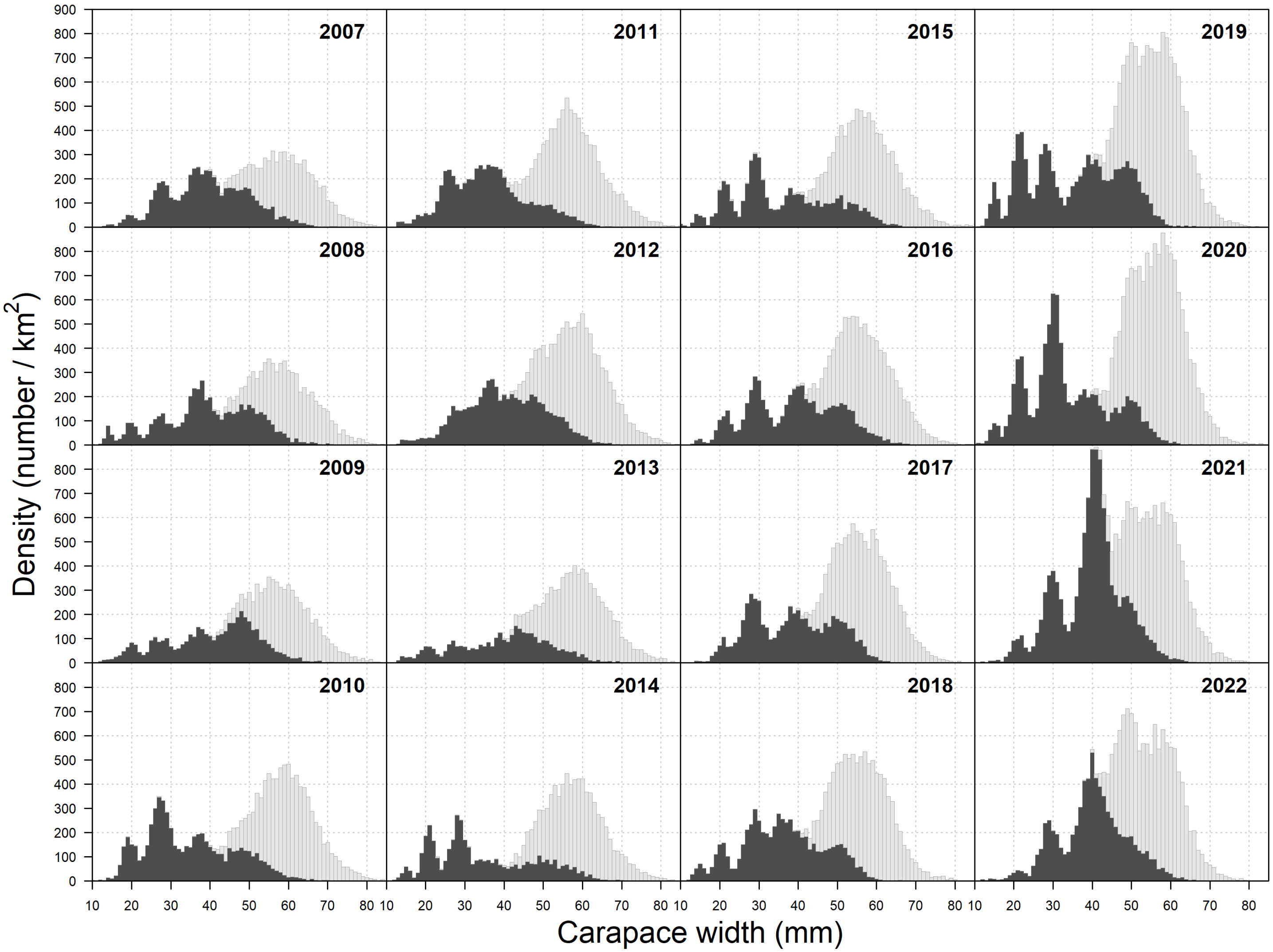

Figure 10. Annual size-frequency distributions of immature and pubescent (black bars) and mature female (grey bars) snow crab from the trawl surveys.

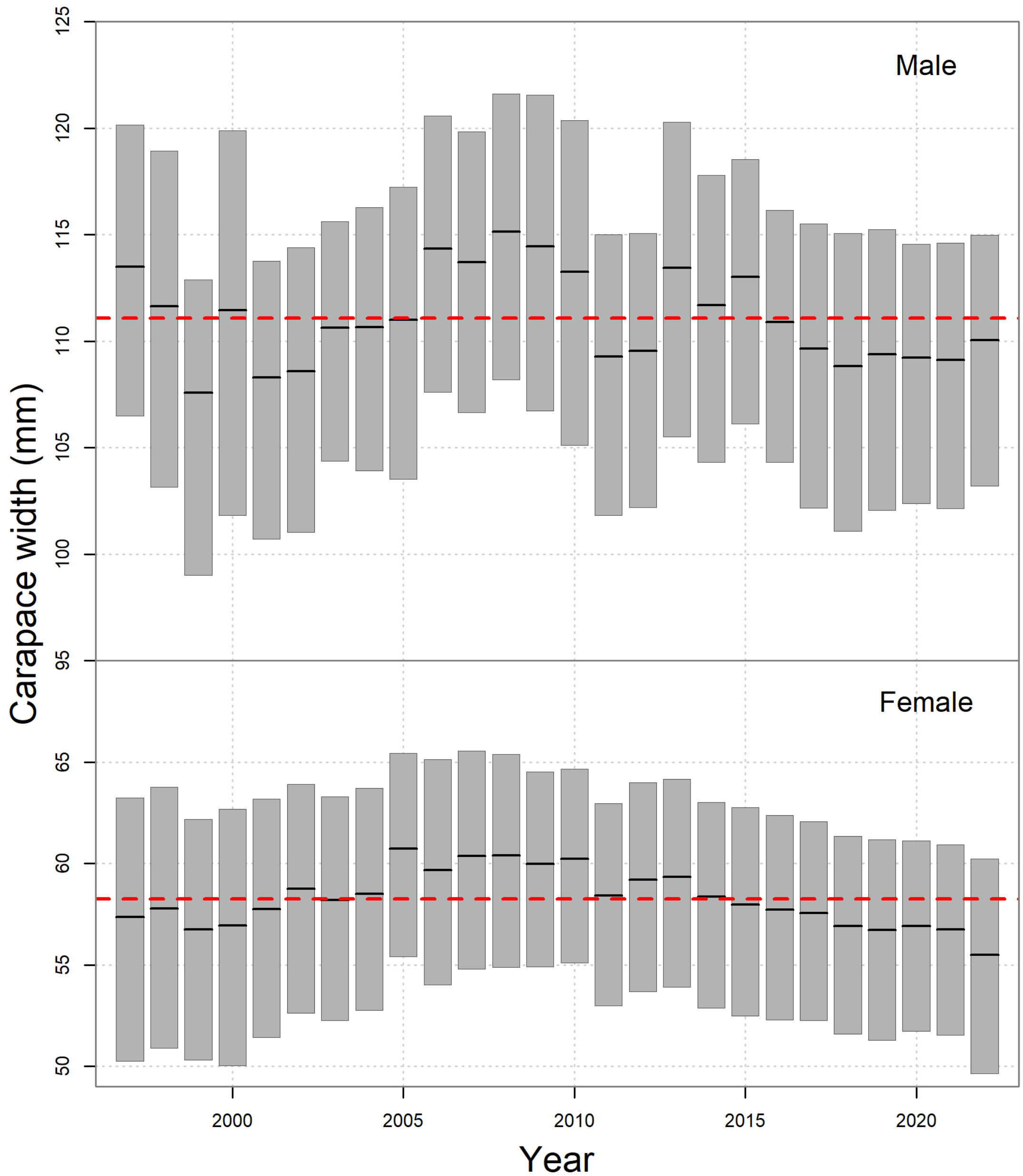

Figure 11. Size variation of mature legal-sized male (top panel) and mature female (bottom panel) snow crab observed in trawl survey data. Middle line shows the mean carapace width and grey bars show interquartile size range. The overall mean is shown as red dashed lines for reference.

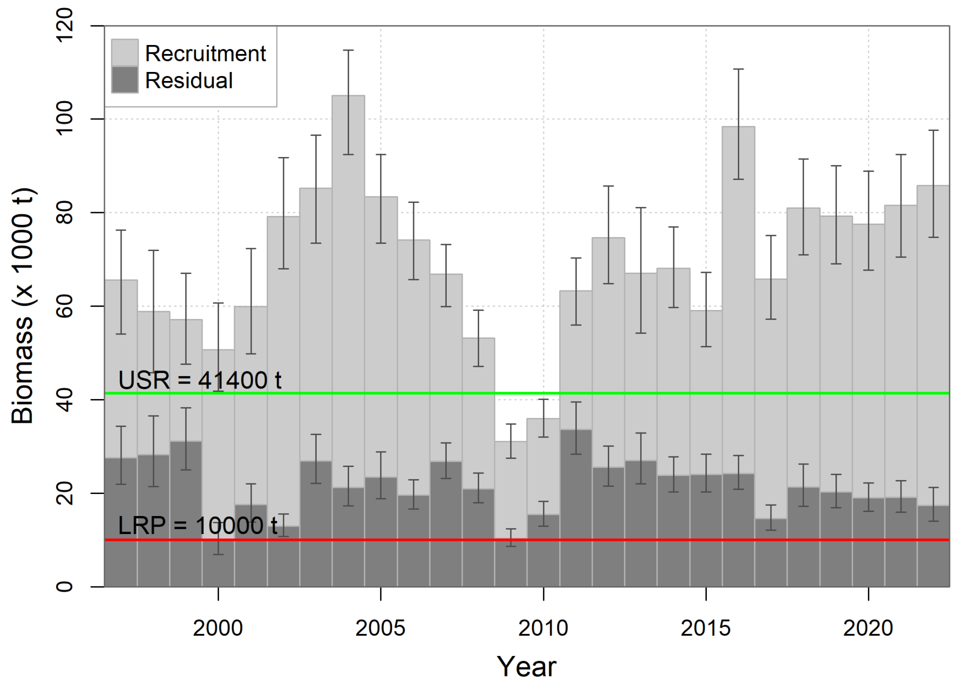

Figure 12. Biomass of commercial recruitment (light grey bars) and residual (dark grey bars), as estimated from trawl survey data. Error bars show 95% confidence intervals. Also shown are the corresponding limit reference point (LRP) for the residual biomass (red line) and upper stock reference (USR) (green line).

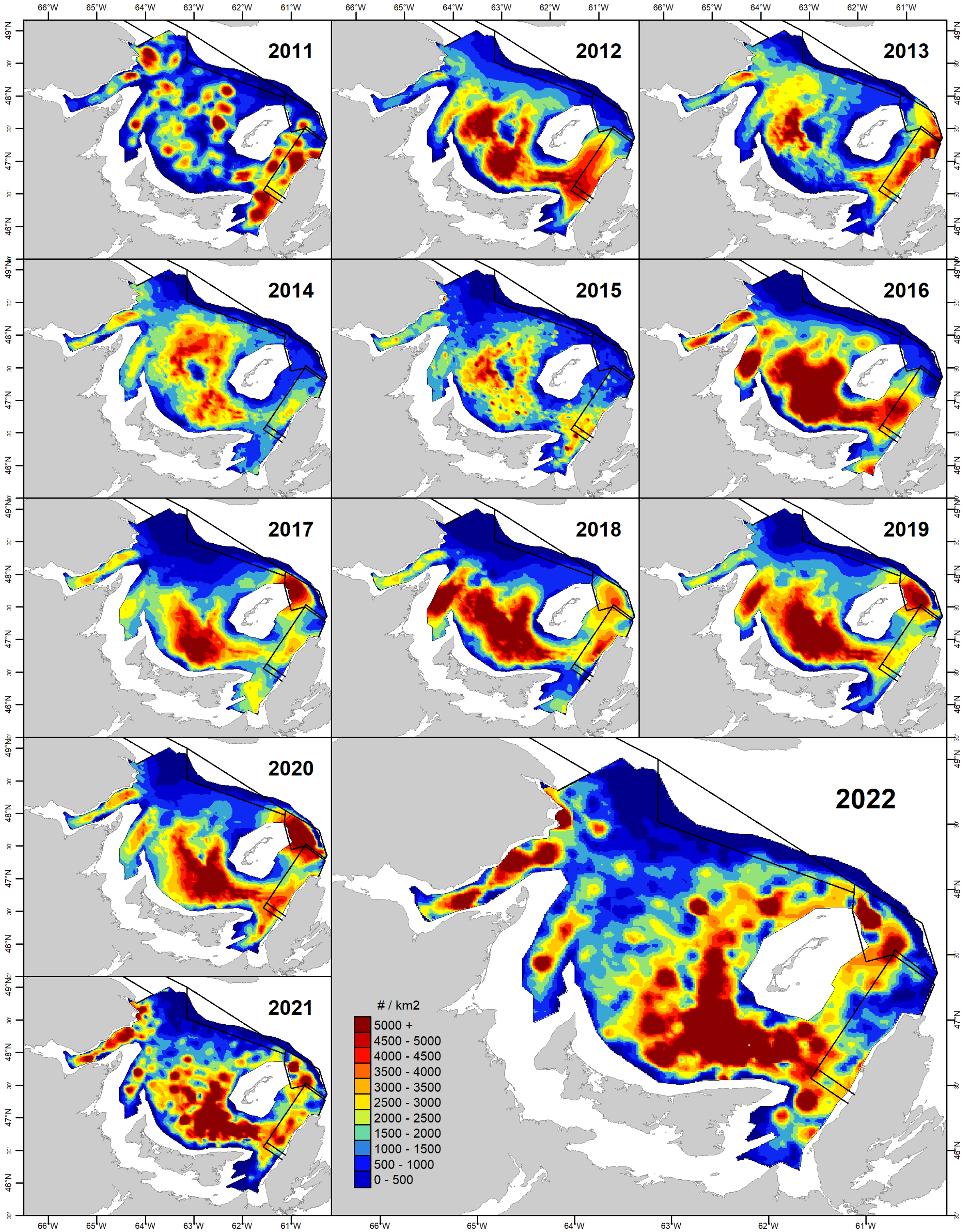

Figure 13. Density (number per km²) contours of commercial crab in the southern Gulf of Saint Lawrence from 2011 to 2022, based on the snow crab trawl survey, interpolated using kriging.

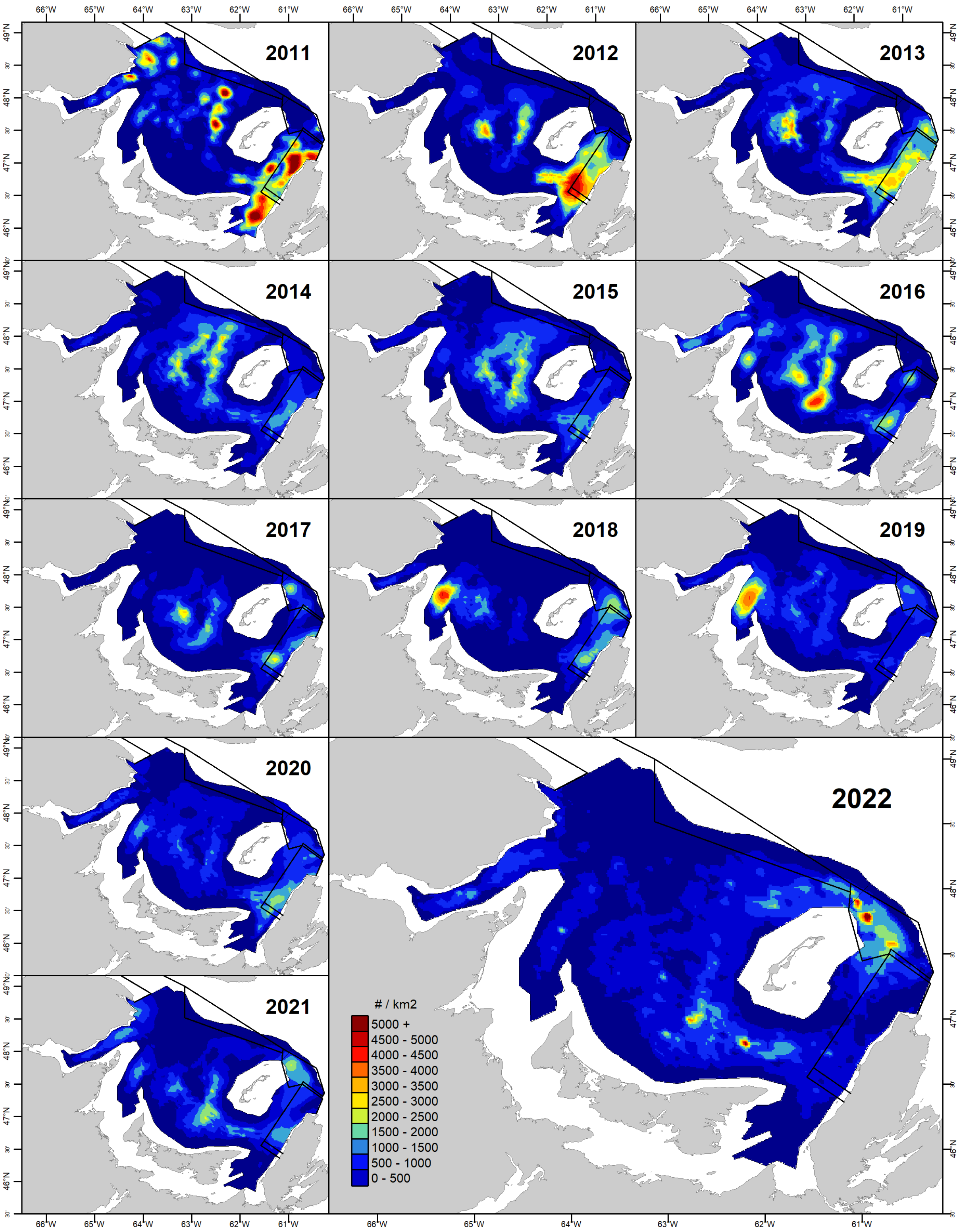

Figure 14. Spatial distribution of the residual component of commercial snow crab (carapace conditions 3,4, and 5) from 2011-2022 based on southern Gulf of Saint Lawrence trawl survey data, interpolated using kriging.

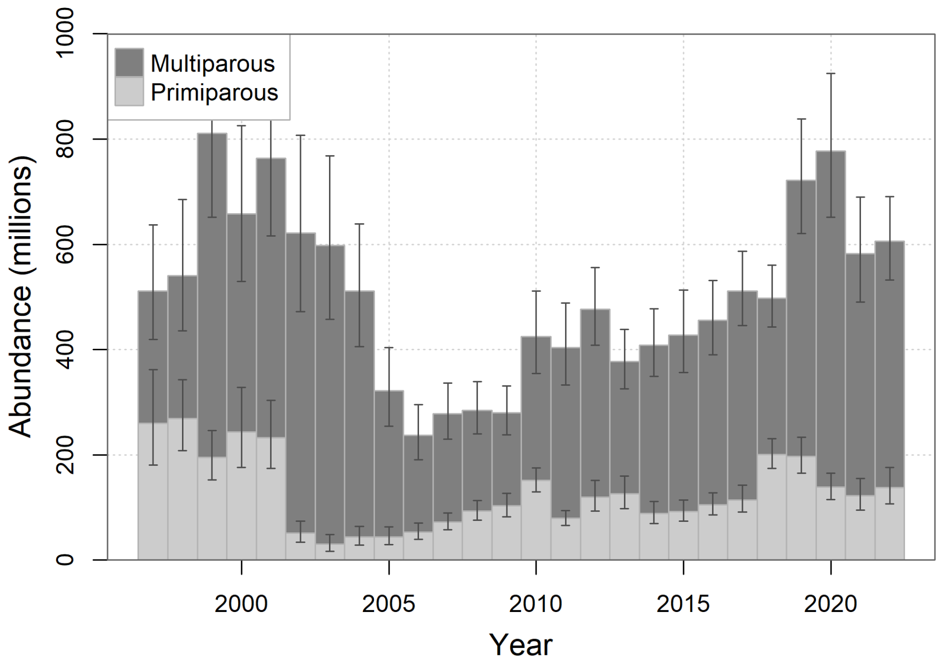

Figure 15. Survey abundance of primiparous and multiparous female snow crab in the southern Gulf of Saint Lawrence.

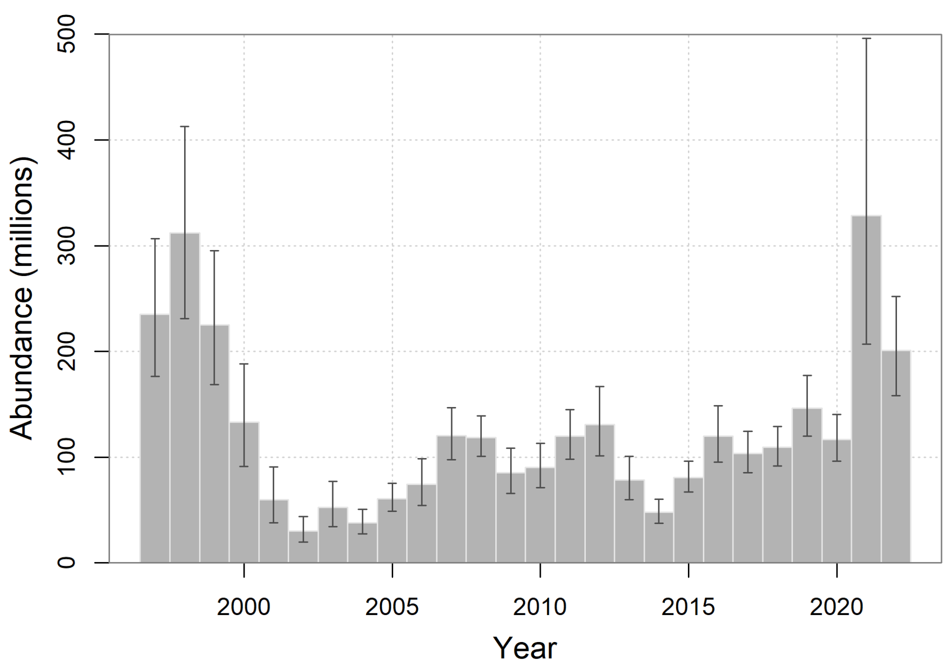

Figure 16. Annual abundance (in millions; means with 95% confidence intervals) of small male crabs of 34 to 44 mm of carapace width, based on the trawl survey data.

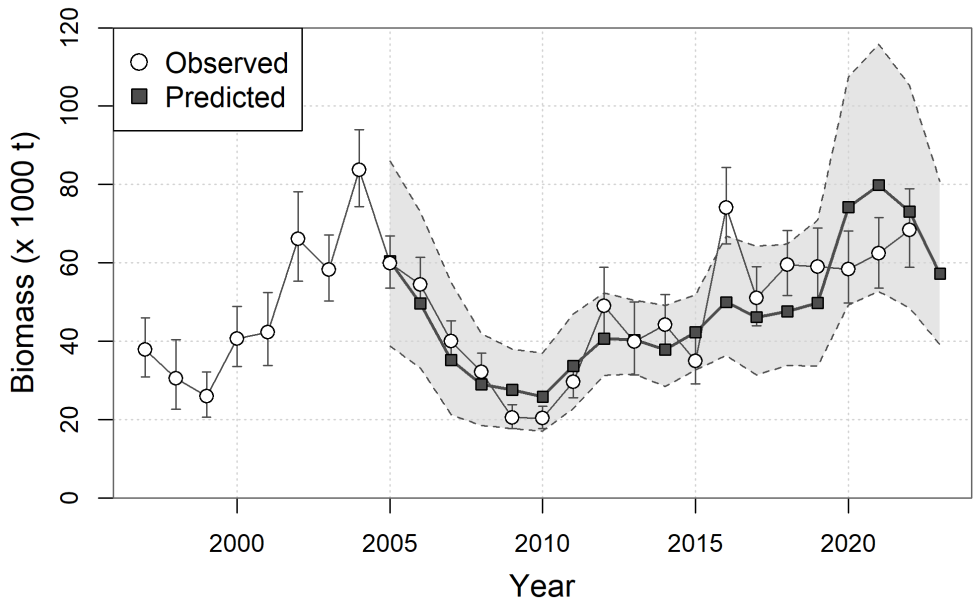

Figure 17. Estimated (open circles are the means with 95% confidence interval vertical bars) and predicted (black squares are the means with the 95% confidence interval bands as dashed lines) fishery recruitment biomasses of R-1 snow crab (adult male crabs >= 95 mm carapace width of carapace conditions 1 and 2) in the year of the survey, 1997 to 2022. The predicted abundances are based on a relationship to the estimated abundances of R-2 (adolescent male crabs with a carapace width larger than 83 mm) in the previous year.

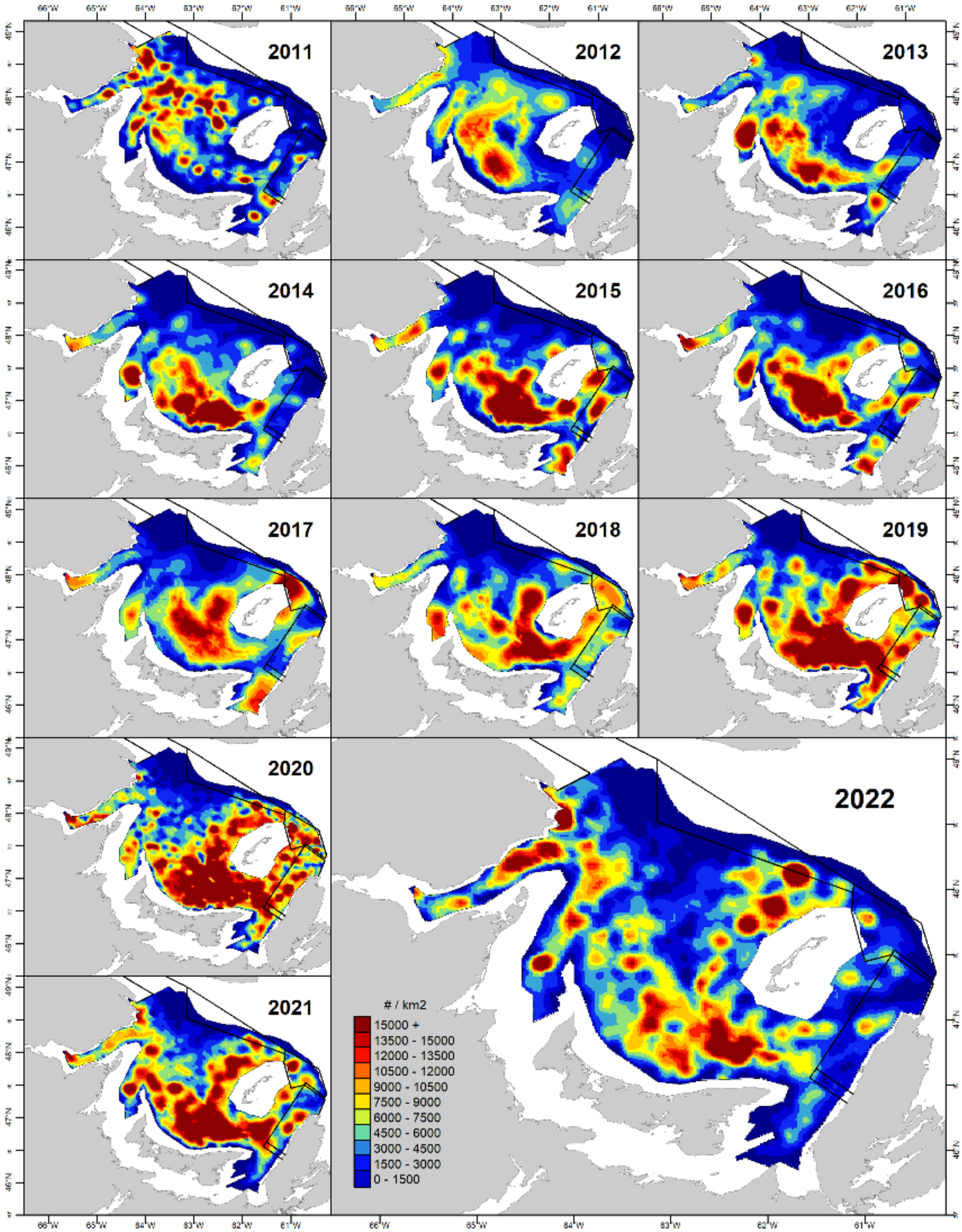

Figure 18. Adolescent male snow crab spatial distribution by year based on southern Gulf of Saint Lawrence trawl survey data, interpolated using kriging. Adolescents are made up of future recruits to the fishery (i.e. R-4, R-3 and R-2s).

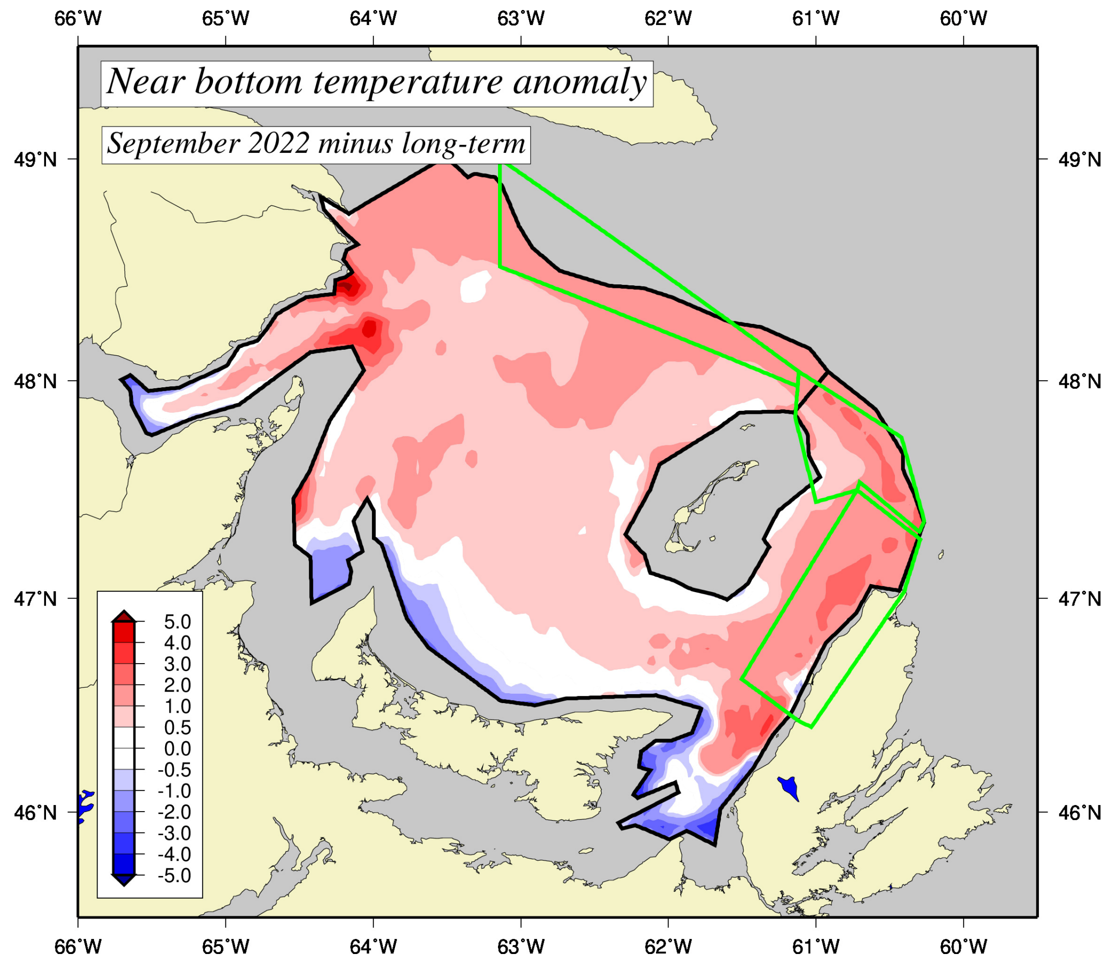

Figure 19. Difference between September 2022 local bottom temperatures and their long-term means from the period from 1991 to 2021. Blue areas represent colder-than-normal temperatures while red regions represent warmer-than-normal conditions. Differences are in °C.

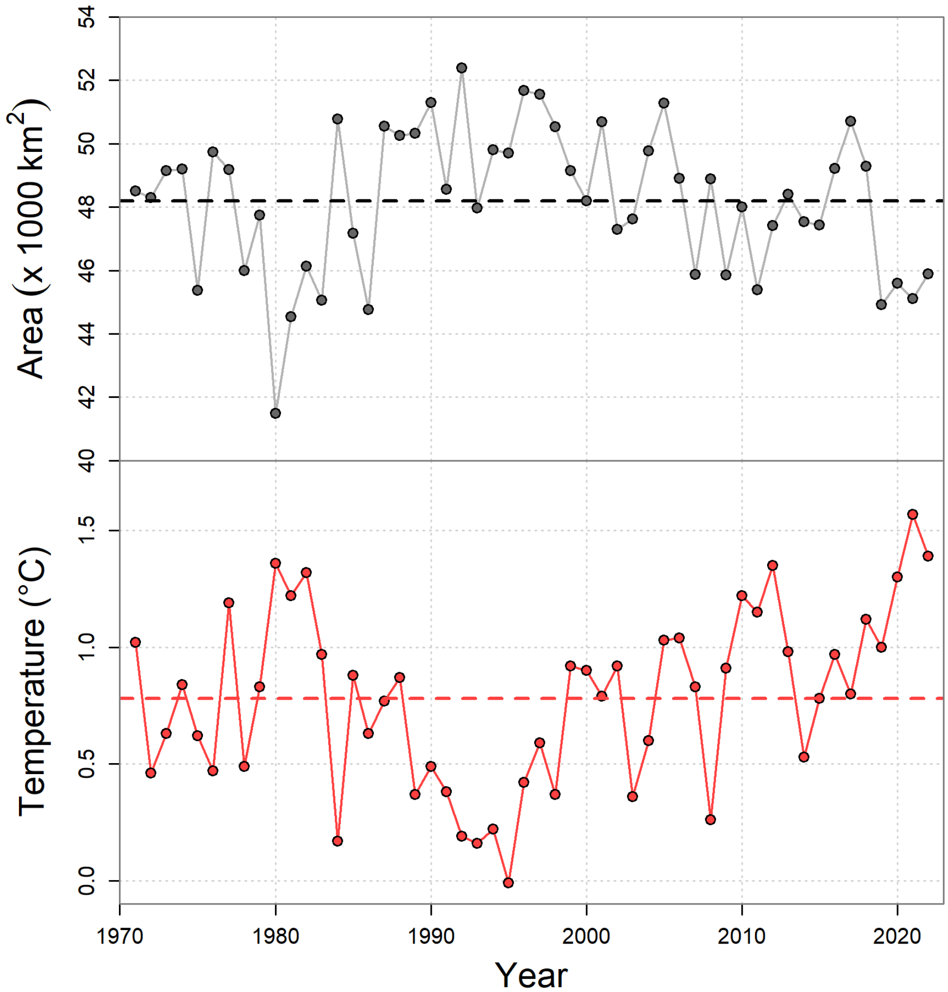

Figure 20. Habitat index of the southern Gulf of Saint Lawrence snow crab (extent of area with bottom temperatures less than 3 °C, (top panel)) and the mean temperature within the area (bottom panel). Horizontal dashed lines represent the means over the series.

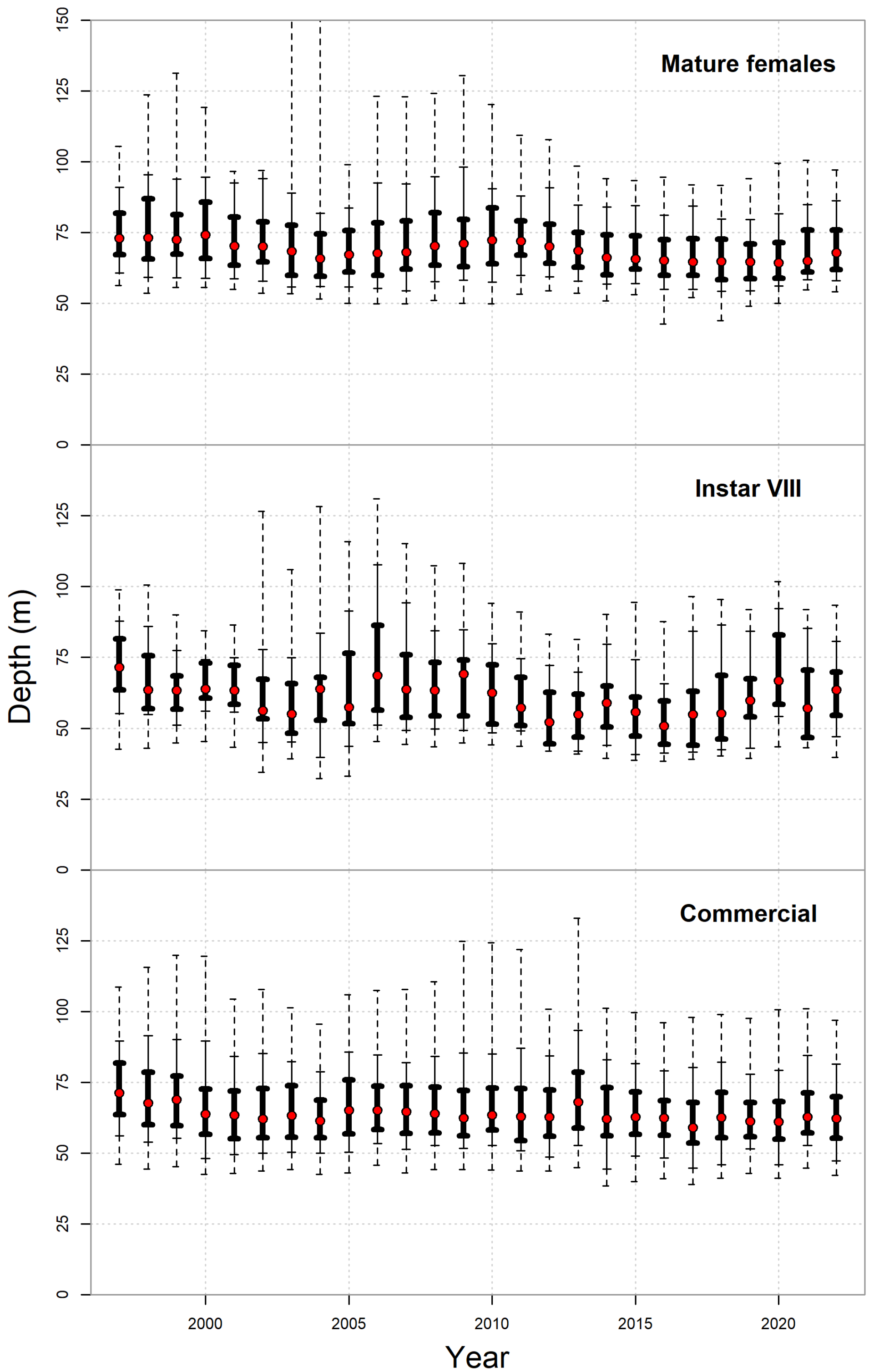

Figure 21. Annual depth distribution for mature female (top panel), instar VIII (middle panel) and commercial (bottom panel) snow crab from the trawl survey. Red dots show the median, the thick black bars show the interquartile range, the thin solid black lines show the range between the 10% and 90% percentiles and the dashed lines show the 2.5% and 97.5% percentiles.

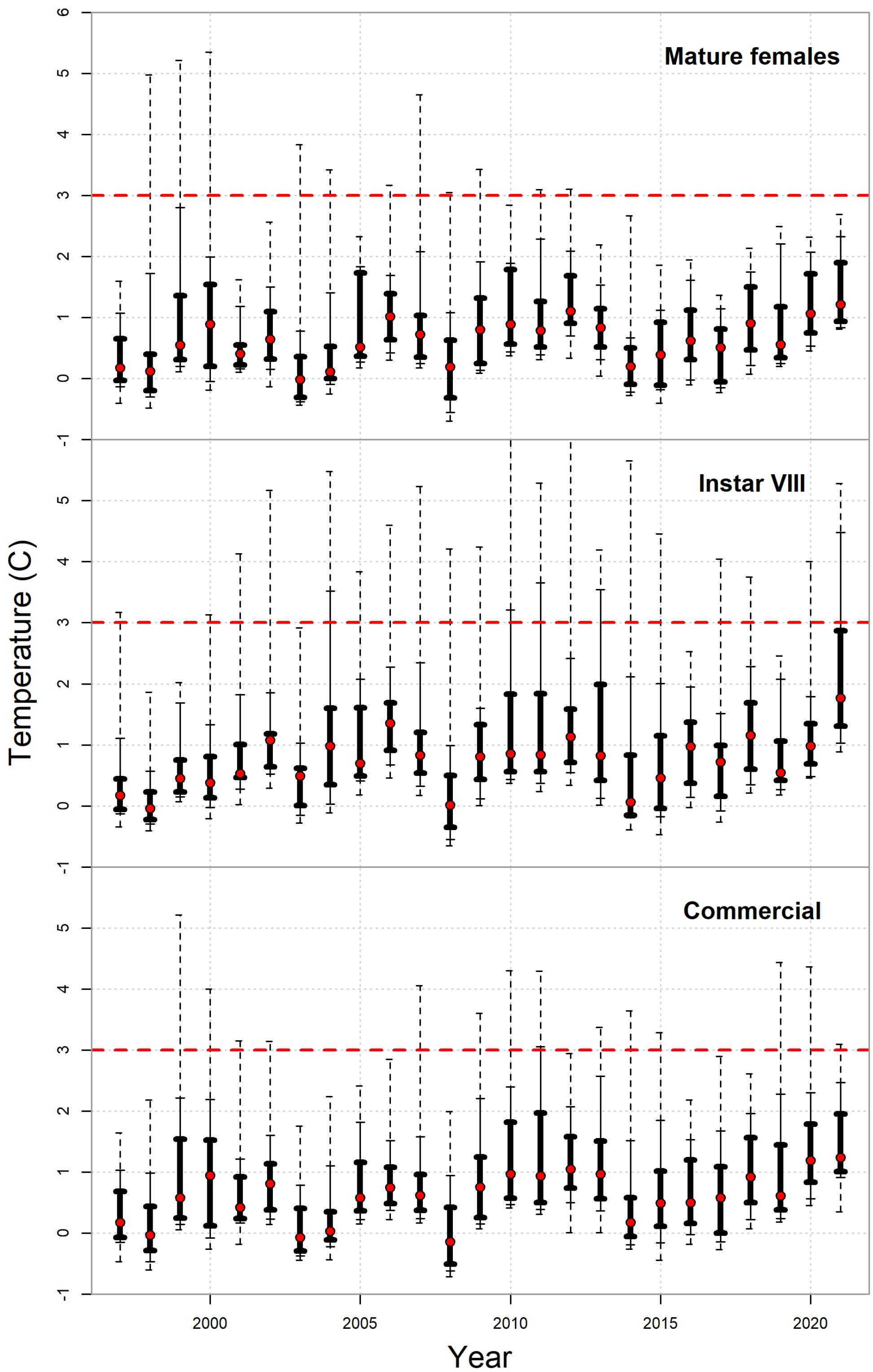

Figure 22. Annual temperature distribution in September for mature female (top panel), instar VIII (middle panel) and commercial (bottom panel) snow crab from the trawl survey. Red dots show the median, the thick black bars show the interquartile range, the thin solid black lines show the range between the 10% and 90% percentiles and the dashed lines show the 2.5% and 97.5% percentiles.

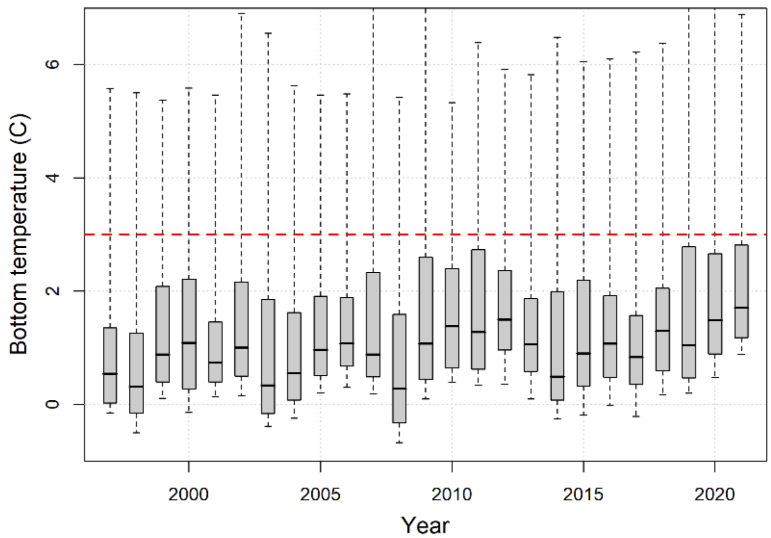

Figure 23. Boxplot of annual bottom temperatures in September within the snow crab survey area from 1997 to 2021. Central dark line indicates the median, boxes indicate the interquartile range, and dashed lines indicate the 2.5th and 97.5th percentiles.

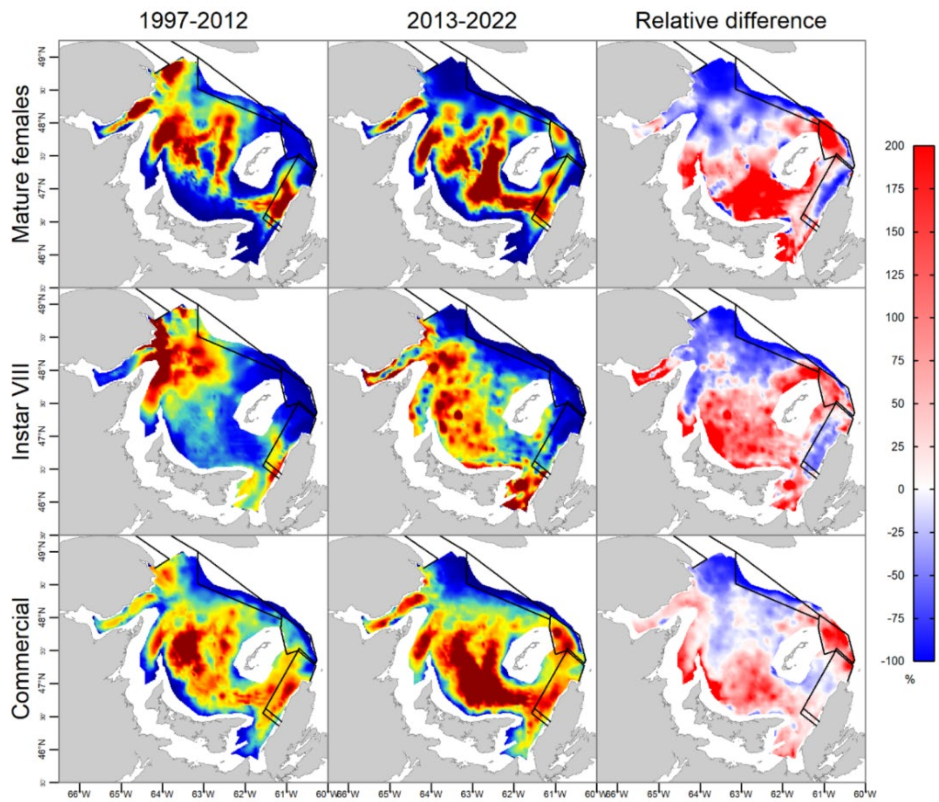

Figure 24. Comparison of the average densities for three categories of snow crab from two periods of the trawl survey: 1997 to 2012 (first column) and 2013 to 2022 (second column). The third column shows the relative differences between the two periods, with blue areas indicating a decrease and red areas indicating an increase in the observed densities.

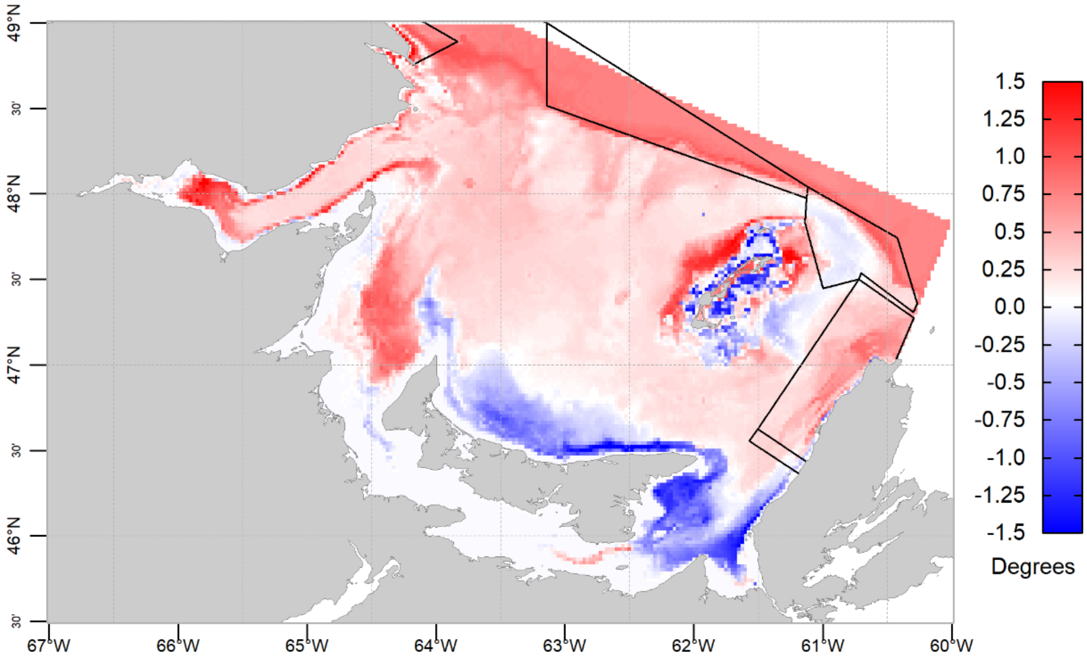

Figure 25. Average difference in September temperatures between the current period from 2013 to 2021 and the early period from the survey from 1997 to 2012.

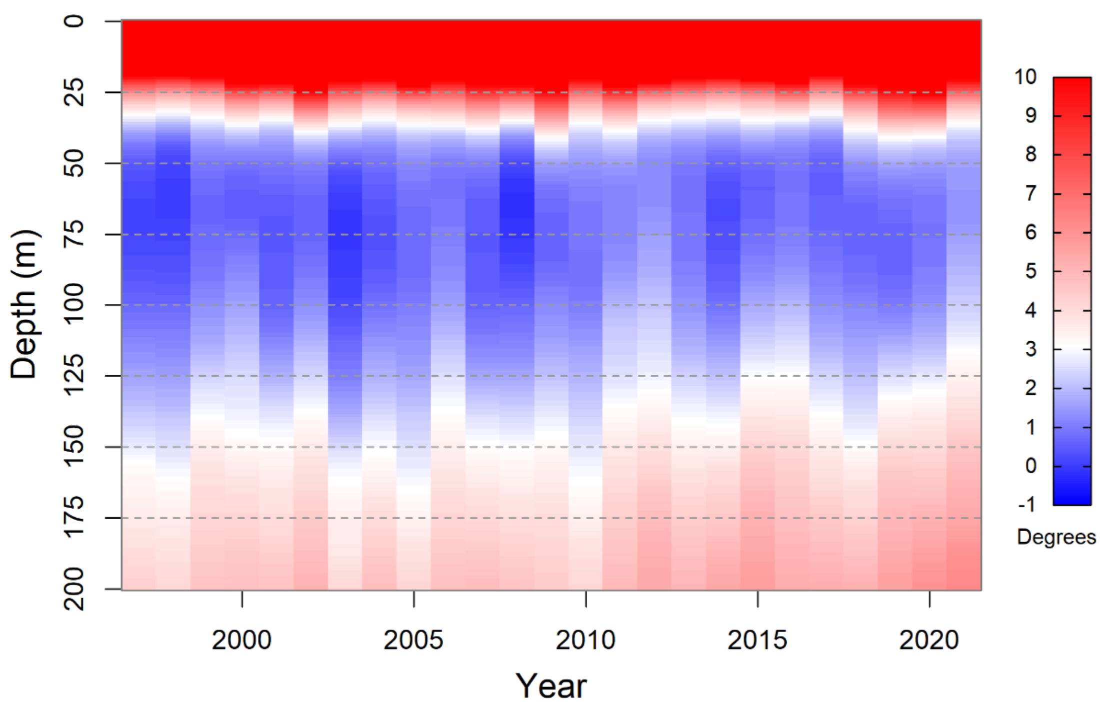

Figure 26. Average temperature stratification in September within the snow crab survey area by year. Blue areas are colder than 3 °C (the Cold Intermediary Layer), white areas are approximately 3 °C, and red areas are warmer than 3 °C. The top red layer corresponds to warm surface waters, while the bottom red layer corresponds to the deep, warm water mass of the Laurentian Channel.

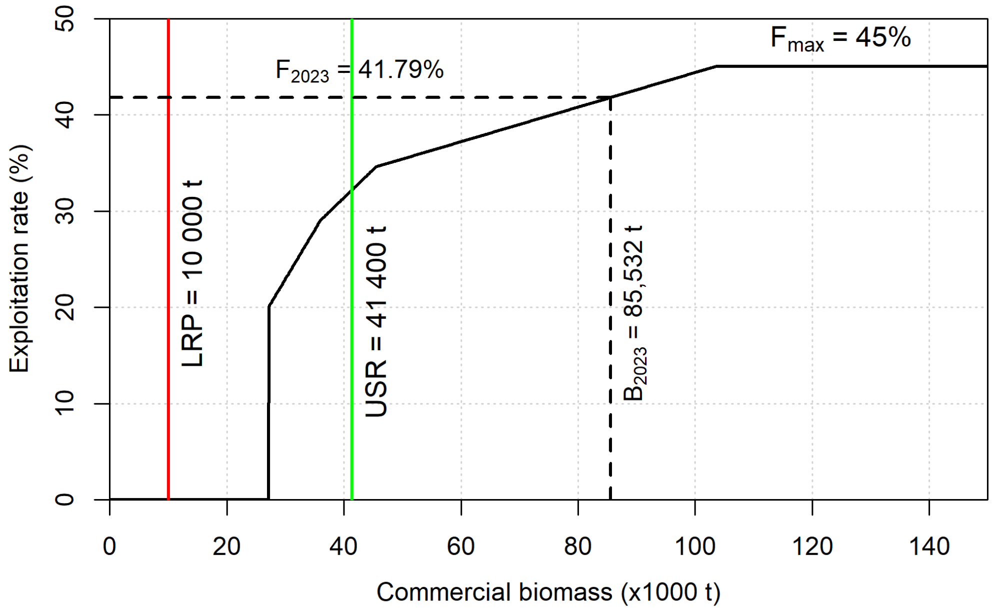

Figure 27. Harvest decision rule used for the southern Gulf of Saint Lawrence snow crab fishery (DFO 2014), expressed as exploitation rate versus commercial biomass (black line). Coloured lines represent reference points: LPR (red line) is the limit reference point for residual biomass and USR (green line) is the upper stock reference point for commercial biomass. F_{max} represents the maximum exploitation rate harvest decision rule. The dashed line shows the projected biomass estimate for 2023 along with the corresponding targe exploitation rate.

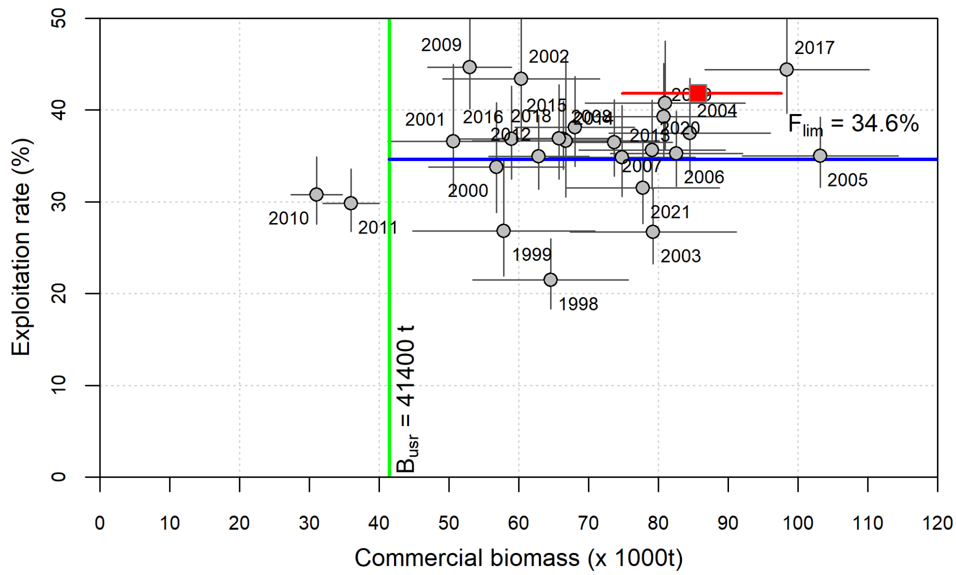

Figure 28. Exploitation rate versus the commercial biomass, with 95% confidence intervals. Year labels represent the fishery year. Coloured lines represent reference points, F_{lim} (blue line) is the limit reference point for fishing removal rate, and USR (green line) is the upper stock reference point for commercial biomass. Red square corresponds to the commercial biomass estimate with the target exploitation rate of 41.79% for the 2023 fishery.

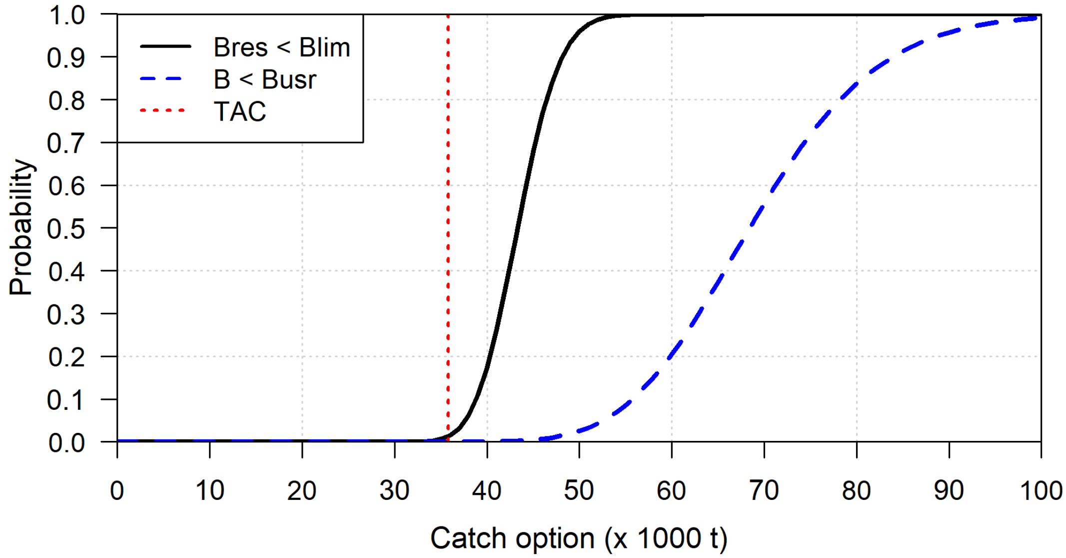

Figure 29. Risk analyses showing the probability that the residual commercial biomass falls below limit reference point (black solid line) or that the total commercial biomass falls below the upper stock reference (blue dashed line) point after the 2023 fishing season. TAC for 2023 is shown by the dashed red line.