Fisheries and Oceans Canada | Pêches et Océans Canada
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Quebec Region
Canadian Science Advisory Secretariat
Science Response 2023/044

REVIEW OF THE PRECAUTIONARY APPROACH AND ASSESSMENT OF THE NORTHERN SHRIMP STOCKS IN THE ESTUARY AND GULF OF ST. LAWRENCE IN 2023

Context

The review of the Precautionary Approach (PA) of northern shrimp (*Pandalus borealis*) stocks in the Estuary and Gulf of St. Lawrence (EGSL) began in 2020-2021. A working group, made up of representatives from Fisheries and Oceans Canada (DFO, Science and Fisheries Management [FM] sectors), industry, provincial governments of Quebec and the Atlantic provinces as well as indigenous groups, was created in spring 2021 to develop a PA proposal. This proposal was to include limit, upper and target reference points (LRP, USR and TRP), as well as scenarios of harvest control rules (HCR).

In parallel, a review of stock assessment units and a new assessment model were completed on June 28, 2023 during a Canadian Science Advisory Secretariat (CSAS) meeting held in Mont-Joli (Smith and Bourdages 2023, In press, Bourdages et al. 2023). The development of the present PA is based on this work.

The FM Branch asked DFO Science to determine the PA compliance of the proposed reference points and decision rules. In addition, FM requested a recommendation for the management of these stocks for the 2024 fishing season based on this new PA.

This Science Response results from the regional peer review of October 25, 2023 on the review of the precautionary approach and projected harvest level options for northern shrimp stocks in the Estuary and Gulf of St. Lawrence.

Background

A first PA for the four northern shrimp stocks of the EGSL was adopted in 2012 (DFO 2011). However, during the last stock assessment in winter 2022 (DFO 2022a), it was concluded that the PA should be revised by the next assessment. This revision was justified since current ecosystem conditions were not the same as during the development of the PA in the early 2010s and a bias was observed in the main stock status indicator.

Northern shrimp is a cold water species. The Gulf of St. Lawrence is near the southern limit of its distribution area and water temperatures in its habitat are near the upper level of its thermal preference. With warming and the depletion of oxygen in deep waters, northern shrimp are now exposed to environmental conditions that are increasingly unfavorable for them.

Results from a recent genomics study suggest that northern shrimp from the EGSL form a different population from adjacent populations on the Scotian Shelf and

Newfoundland/Labrador/Arctic (Bourret et al., In prep.[1], Bourdages et al. 2023). These results show reduced connectivity between these three populations.

Other results also suggest that there are isolated biological components within the EGSL. The results of the population genomics study show that connectivity seems limited between certain management units in the EGSL, and more particularly between Esquiman and the other management units further west (Bourdages et al. 2023a). Furthermore, sites where shrimp abundance is higher are spatially isolated from each other in the EGSL.

In light of historical information on fishing effort distribution, shrimp distribution and the study on population genomics, it was agreed, at the SCAS meeting on June 28, 2023, to modify the stock assessment units in EGSL. This modification allows for a better spatial match between stock status indicators and biological units (Bourdages et al. 2023). In summary, a first modification consisted of enlarging the Estuary assessment unit following the addition of new, shallower strata from 2008. For this assessment unit, the time series of the biomass index begins in 2008 and the study area corresponds to depths of more than 37 m. A second modification was to move the border separating the units of Sept-Iles and Anticosti from the south center of Anticosti island to the eastern tip of the island. The Sept-Iles assessment unit is therefore enlarged towards the east in the Laurentian Channel and the Anticosti unit is reduced to correspond mainly to the Anticosti Channel, i.e. the north of the island. Analyzes presented in this document were carried out based on these new delineations of stock assessment units (Figure 1).

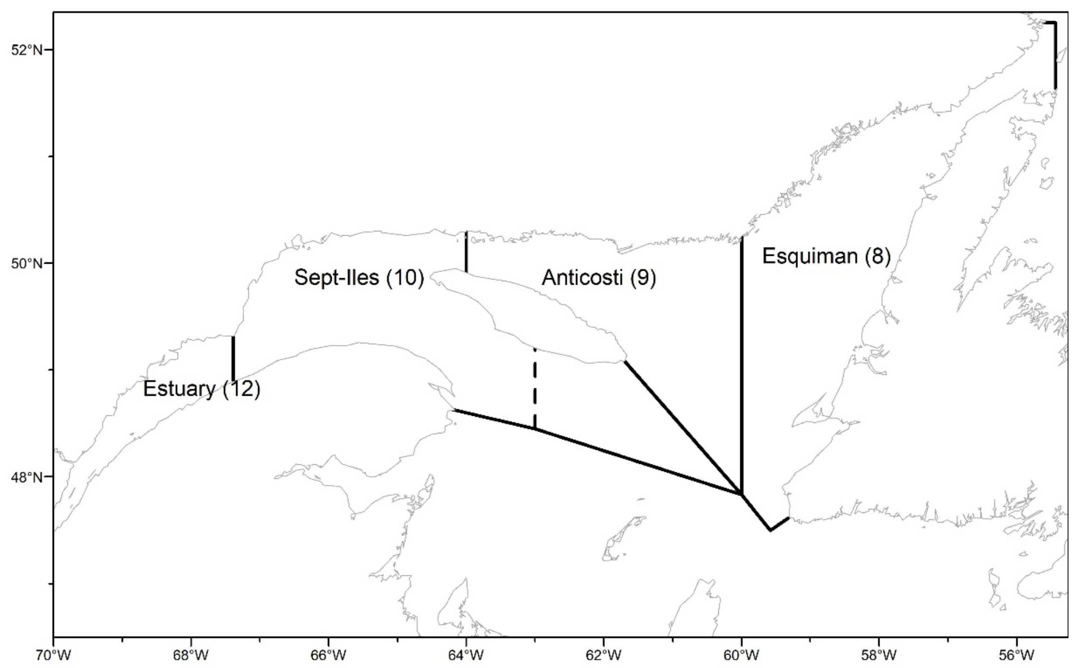

Figure 1. New delineations of stock assessment units (solid line). The dotted line south of Anticosti island corresponds to the previous boundary between the Sept-Iles and Anticosti assessment units.

[1] Bourret, A., Leung, C., Puncher, G., Le Corre, N., Deslauriers, D., Skanes, K., Bourdages, H., Di Cassista Ross, M., Walkusz, W., Jeffery, N. W., Stanley, R. E. E. and Parent, G. J. 2023. Diving into large scale genomics to decipher drivers of structure and climatic vulnerability in a widespread marine shrimp. In preparation.

Description of the fishery

The northern shrimp fishery began in the Gulf of St. Lawrence in 1965. The exploitation is conducted by trawlers in four shrimp fishing areas (SFA): Estuary (SFA 12), Sept-Iles (SFA 10), Anticosti (SFA 9) and Esquiman (SFA 8).

Landings of northern shrimp in the EGSL gradually increased from nearly 1,000 metric tons (t) at the start of exploitation in the 1970s to more than 35,000 t at the end of the 2000s (Figure 2). Landings subsequently decreased to reach 5,505 t in 2023 (preliminary data as of October 15) out of an overall total allowable catch (TAC) of 14,524 t. In 2022 and 2023, the proportion of the overall TAC landed was 79% and 38% respectively.

In 2022 and 2023, the projected harvests from the PA were revised downwards by applying a conditioning approach to scientific advice (Roux et al. 2022) based on evidence demonstrating that decision-making now operates at the outside the environmental framework that prevailed when the PA was developed (Bourdages et al. 2022). The TACs were then successively reduced by 13% and 11% in the Estuary, by 18% and 12% in Anticosti, and by 19% and 12% in Esquiman. In Sept-Iles, the TAC increased by 4% in 2022 and remained unchanged in 2023. Preliminary statistics indicate landings, in 2022 and 2023, of 496 t and 424 t in Estuary (TAC of 530 t and 473 t), 3,906 t and 1,369 t in Sept-Iles (TAC of 5,304 t), 3,788 t and 2,041 t in Anticosti (TAC of 5,153 t and 4,525 t) and 4,276 t and 1,672 t in Esquiman (TAC of 4,825 t and 4,222 t). As of October 15, 2023, the TAC was reached at 90% in Estuary, 26% in Sept-Iles, 45% in Anticosti and 40% in Esquiman. As the fishing season is not yet over, these landings could be revised upwards.

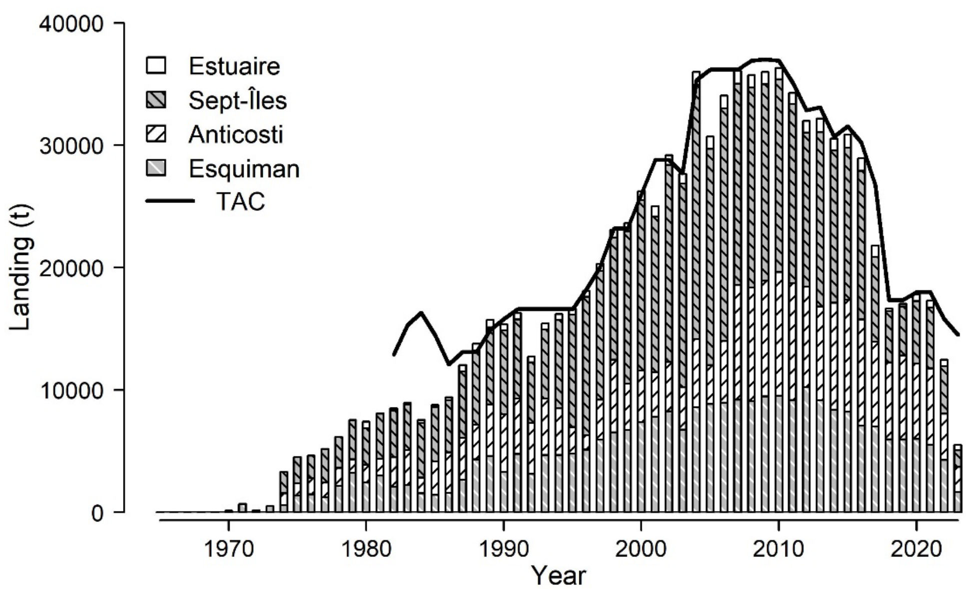

Figure 2. Annual landing per assessment unit and total allowable catches (TAC). The 2022 and 2023 data are preliminary as of October 15.

Annual commercial fishing catch per unit effort (CPUE) is standardized to account for changes in fishing capacity and seasonal patterns of fishing activity. CPUE has varied greatly over time and has experienced the same major trends since 1982 in the four zones (Figure 3). From 1982 to 1995, CPUEs were low. They increased from 1995 to reach a maximum around 2007. Then, they remained high for a few years and began to decrease thereafter. A downward trend has been observed since 2015 with the exception of the Estuary where CPUE increased again from

2017 to 2022. In 2023, CPUE decreased in the four zones, i.e. by 49% in Estuary, 54% in Sept-Iles, 42% in Anticosti, and 31% in Esquiman. The CPUE of the Estuary in 2023 compares to the average values observed in the 2000s. The CPUE of Sept-Iles and Anticosti compares to the lowest values of the historical series, i.e. to the values observed in the 1980s. Finally, the Esquiman CPUE compares to low values observed in the early 1990s.

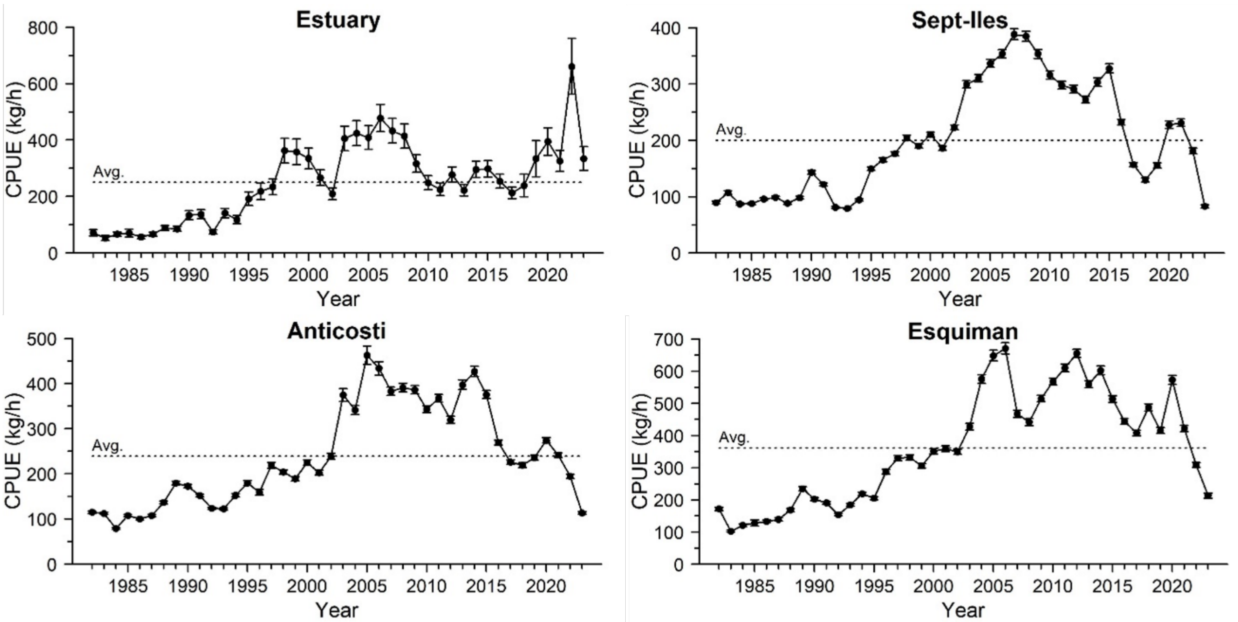

Figure 3. Standardized catch per unit of effort (CPUE kg/h) in the fishery (95% confidence interval) per stock assessment unit. The dotted line represents the average. The 2023 data are preliminary as of October 12.

The use of the vessel monitoring system (VMS) since 2012 has made it possible to describe the spatial distribution of fishing effort. The area where trawling activities took place decreased constantly, from 15,000 km^2 to 8,000 km^2 between 2012 and 2023. Fishing effort is now concentrated on smaller surfaces within each fishing areas. In addition, some fishing sectors have been neglected in recent years due to the low abundance of shrimp. These sectors include the sector east of the Manicouagan Peninsula in the Estuary, the northeastern tip of Gaspé Peninsula, the south of Anticosti island and the southwestern of Esquiman Channel (Figure 4).

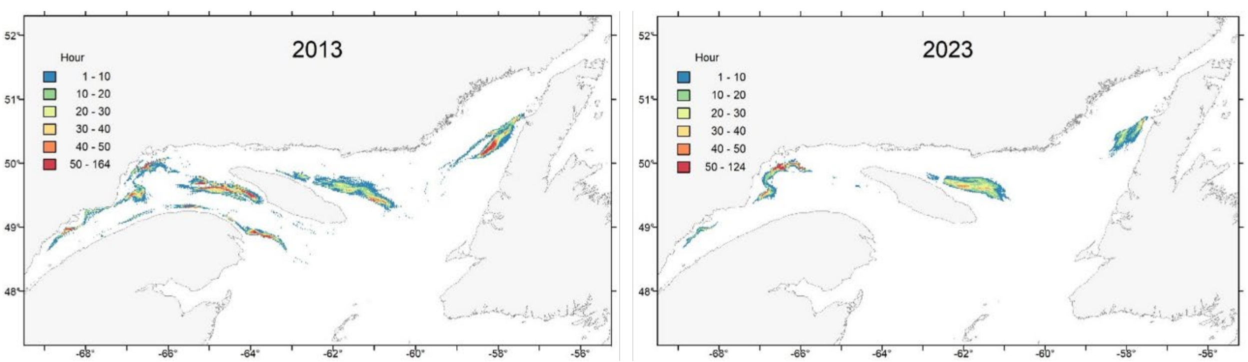

Figure 4. Spatial distribution of the annual fishing effort of shrimpers in the estuary and Gulf of St. Lawrence for the years 2013 and 2023 (number of hours per 1-minute square) based on data from the vessel monitoring system.

Analysis and Response

Research survey indicators

Due to operational issues with the CCGS *John Cabot* in August 2023, the time at sea for the DFO survey was reduced by a third and the study area could not be fully covered. Consequently, two sectors were not sampled, namely the Strait of Belle Isle and the St. Lawrence estuary west of Pointe-des-Monts. Additionally, sampling coverage was reduced in coastal areas. For this assessment, as the Estuary stock was not sampled in 2023, it is not possible to update the stock status indicator. For the three other stocks, the sampling coverage in 2023 is representative of the distribution areas of higher shrimp concentrations. However, it is likely that the biomass indices are slightly overestimated, since the sampling effort was reduced in shallow areas where shrimp abundance is very low.

DFO research survey data indicate that northern shrimp are present throughout the EGSL (Figure 5). Shrimp are found at depths varying from 150 to 350 m, i.e. under the cold intermediate layer (CIL), in the bottom layer. Currently, northern shrimp are mainly concentrated in smaller areas at the head of the channels.

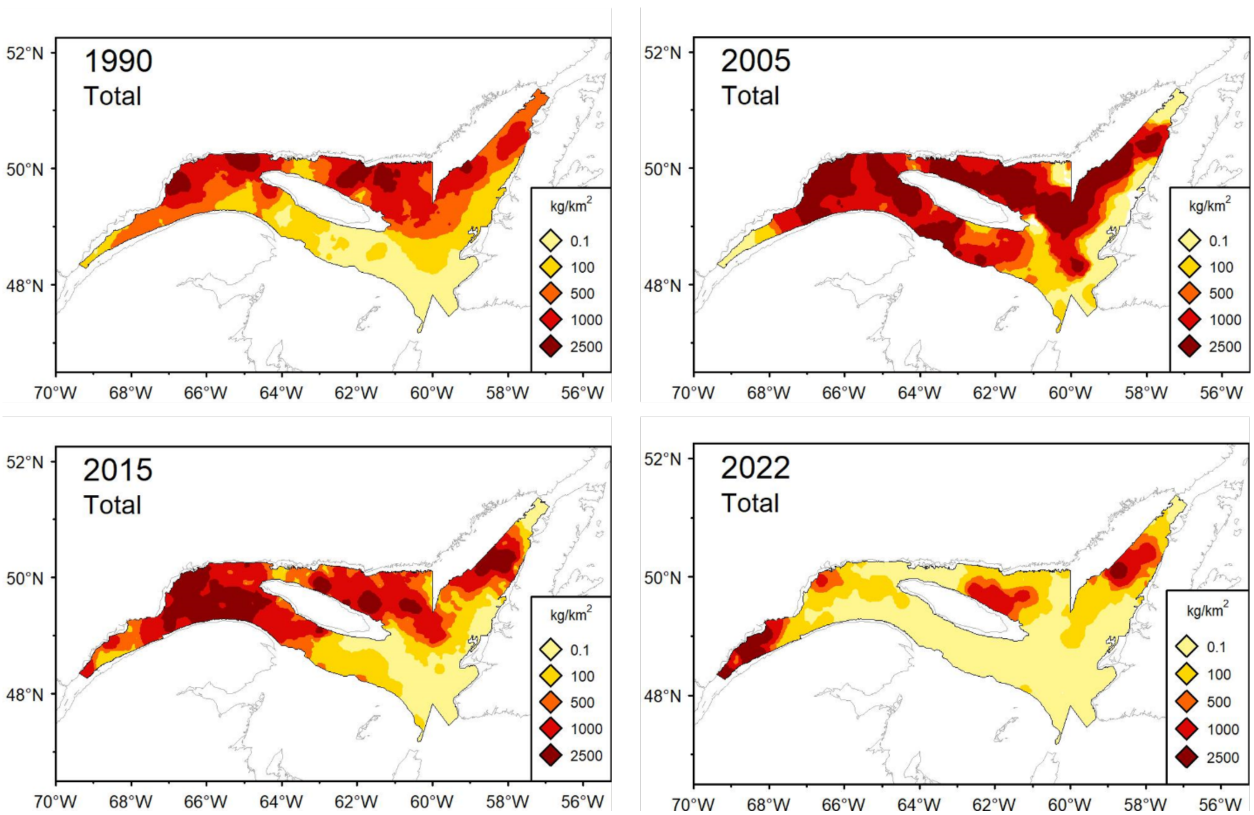

Figure 5. Northern shrimp biomass (kg/km²) distribution in the DFO survey obtained by kriging for 1990, 2005, 2015, and 2022.

The total biomass indices of the Sept-Iles, Anticosti and Esquiman stock assessment units showed increasing trends from 1990 to 2003, but decreasing trends since then (Figure 6). The biomasses observed in Sept-Iles and Anticosti in 2022 and 2023 are the lowest of their historical series beginning in 1990, while the biomass of Esquiman has been stable since 2020 at low values comparable to those of the early 1990s.

For the Estuary, the observed biomasses showed a downward trend from 2008 to 2020, then increased significantly in 2021 and 2022, to reach the highest value in 2022. However, the confidence interval for the biomass estimate of 2022 is very large and is influenced by a single tow which, by itself, more than doubled the average biomass estimated from the 17 tows carried out for this stock. Sampling this unit was not possible in 2023.

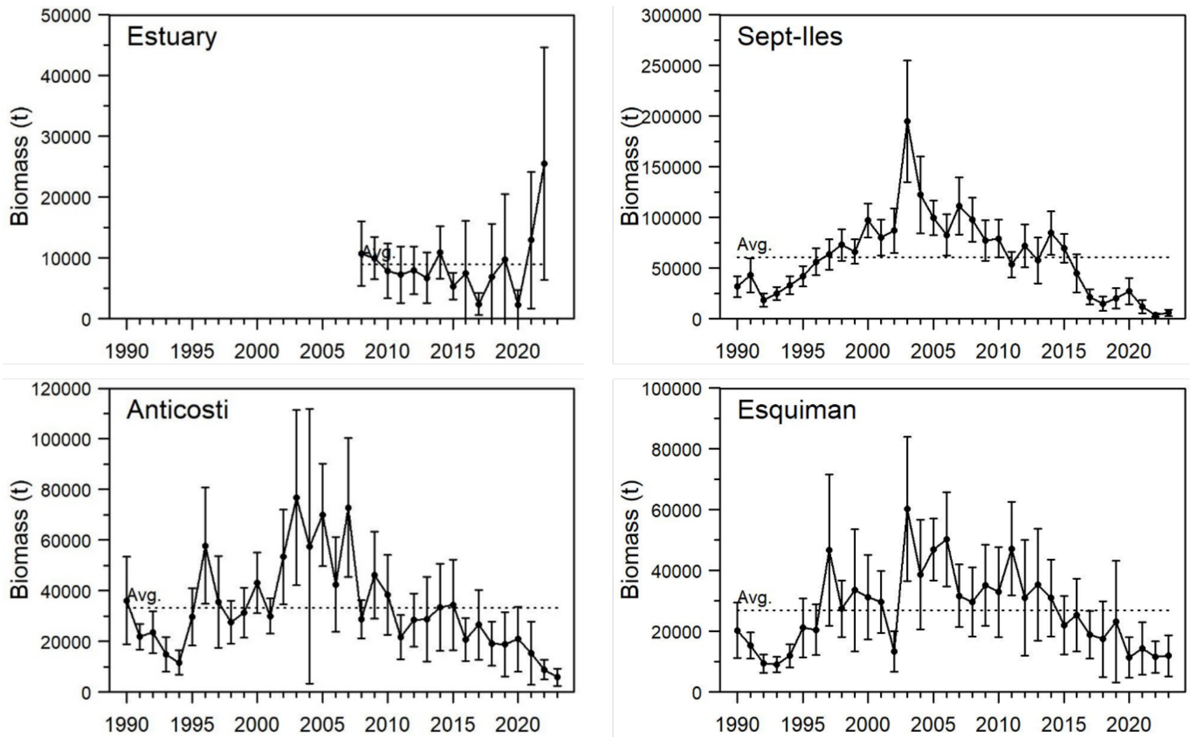

Figure 6. Biomass index from DFO survey (95% confidence interval) per stock assessment unit. The dotted line represents the average. The Estuary assessment unit could not be sampled in 2023.

The demographic structures of the populations of Sept-Iles, Anticosti and Esquiman obtained in 2022 and 2023 show that the abundances of the different components of the population are lower than the average of the series beginning in 1990 (Figure 7). In Sept-Iles, males, regardless of their size, were almost absent over the last two years. In Anticosti and Esquiman, males will remain present but in low abundance in 2022 and 2023 compared to the average. The abundance of primiparous (first year of spawning) and multiparous (second year of spawning) females in Sept-Iles and Anticosti was very low in 2022 and 2023 while it was only slightly below average in Esquiman.

For Estuary in 2022, the abundances of males and females were higher than the average for the series beginning in 2008. Among females, the multiparous, which lay eggs for a second year, were dominant in 2022. According to the known life cycle, these females should have survived until spring 2023, when larvae are hatching, before suffering a significant natural mortality.

A recruitment index is obtained by estimating the abundance of juveniles, i.e. shrimp whose cephalothorax length is less than 12.5 mm. Those individuals are approximately fifteen months old. Since 2020, the annual abundance of juveniles has been very low in the Estuary, Sept-Iles and Esquiman, while in Anticosti, 2020 and 2023 each produced average recruitment (Figure 8).

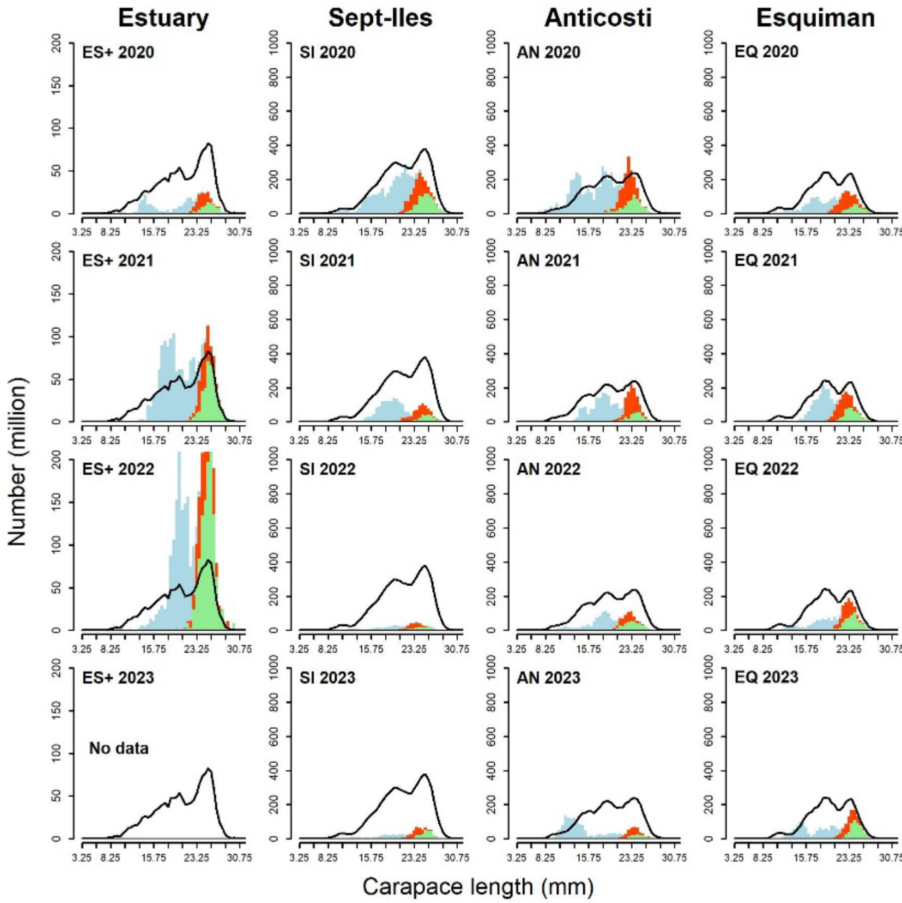

Figure 7. Northern shrimp abundance (in millions) by sex and by assessment unit based on their size in the 2020–2023 DFO survey. The histograms represent males (in blue), primiparous females (in red) and multiparous females (in green). The solid line represents the mean for the years 1990–2023 (2008–2022 for the Estuary). Note the difference in scale between Estuary and the other assessment units.

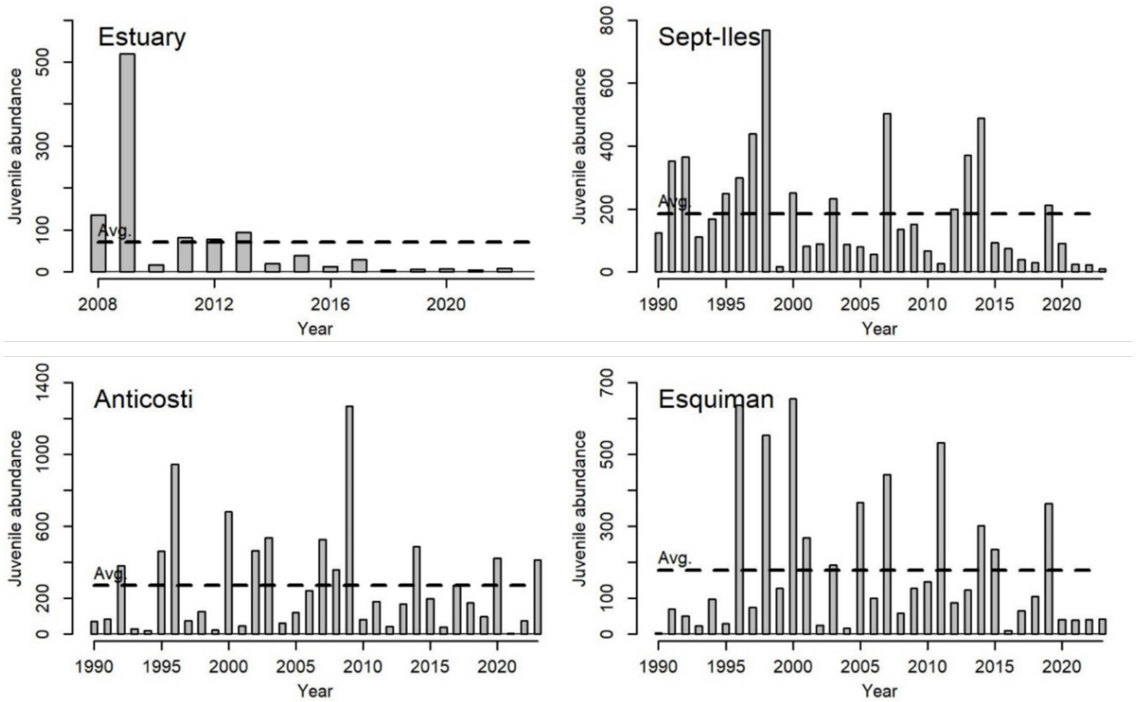

Figure 8. Abundance of juveniles (in millions) by assessment unit and by year. The dotted line represents the average.

Review of the precautionary approach

The decision-making framework for fisheries integrating the PA (Policy on the precautionary approach, DFO 2009) requires the definition of a stock status indicator, limit reference (LRP) and upper stock reference (USR) points delineating critical, cautious and healthy zones, a reference exploitation rate and harvest decision rules (hereafter referred to as harvest control rules; HCR). The HCRs determine the maximum authorized removals based on the stock status indicator.

Stock status indicators and reference points

A surplus production model (SPM) was used to describe the shrimp stocks trajectory over time. This model does not integrate information on the size or age structure of the population, and simplifies the productivity processes (recruitment, growth, natural mortality, etc.) to the estimated parameters *r* and *K*, which determine, respectively, the population growth rate and the support capacity of the environment. Essentially, next year's biomass is equal to this year's biomass, plus stock productivity, minus fishery catches.

Shrimp productivity has changed significantly over the past 30 years, with an initial increase in productivity that allowed the growth of the stock, followed by a significant decrease in productivity over the past decade that has greatly contributed to shrimp decline (Tamdrari et al. 2018). These changes are only partially captured by the model’s process error. As a result, the SPM is used heuristically to estimate the biomass that produces a maximum sustainable yield (MSY) from the fishery or B_{MSY}, and an exploitation rate at MSY or F_{MSY}. The B_{MSY} corresponds to a biomass at which the stock was productive, while the F_{MSY} corresponds to the approximate exploitation rate which prevailed when the stocks were at high abundance. The absolute annual values of biomass (B) and exploitation rate (F) estimated by the SPM do not make it possible to distinguish the effects of changes in productivity and fishing on stock dynamics, and are therefore considered unreliable and should not be overinterpreted. Only their trajectory over the entire series is informative, and the relationship between the relative biomass (B/B_{MSY}) and the relative exploitation rate (F/F_{MSY}) can serve as a guide to establish fishing removals which will reduce the risk of overfishing. The model is, however, not suitable for understanding future medium- and long-term responses of the stock to fishing on stock dynamics.

This model used was fitted using the shrimp biomass index estimated by DFO survey and commercial fishing landings. The SPM was fitted independently to data for each of the four stock assessment unit for the 1990-2023 period. The model adjustment is done with the JABBA application (Winker et al. 2018), i.e. a Bayesian state-space SPM. Details of model fitting are described in Smith and Bourdages (2023, In press).

Model estimated parameters sensitivity analyzes and removal of years of data showed that the absolute value of the MSY and therefore the quantities derived for B_{MSY} and F_{MSY} were variable. However, when we considered the relative trajectories of B_{MSY} and F_{MSY}, the latter showed the same trends in the different analyses. It was therefore decided to use the ratio between annual biomass (B) and B_{MSY} as the indicator of stock status.

Consistent with DFO PA framework, a standard approach was used to establish reference points based on the B_{MSY}. The limit reference point (LRP) is set at 0.4 (40%) of B_{MSY}, the proposed upper stock reference point (USR) is 0.8 (80%) of B_{MSY} and the proposed target reference point (TRP) corresponds to B_{MSY}. These reference points are valid for all four assessment units.

The relative biomasses estimated for Sept-Iles, Anticosti and Esquiman have experienced a constant decline since 2004 (Sept-Iles) or 2007 (Anticosti and Esquiman, Figure 9). In 2023, these stocks reached the lowest values of the time series starting in 1990 at respective values of 0.05, 0.17 and 0.37 of the B_{MSY} (respectively at 13%, 42% and 93% of the LRP). These stocks are therefore in the critical zone with probabilities in 2023 of 100%, 99% and 57%, respectively.

The reference points were based on the longest period of available data, from 1990 to 2023. During this period, EGSL shrimp stocks demonstrated significant variations in productivity, notably having been more productive at the end of the 1990s than actually. The reference points were therefore estimated from a series of years that included different levels of productivity.

The ecological mechanisms that influence these changes in stock productivity have not been quantified and explicitly incorporated into the model. Additionally, environmental conditions continue to change in a directional, non-stationary manner. It is therefore not justified to set the reference points on the recent low productivity regime (DFO 2013).

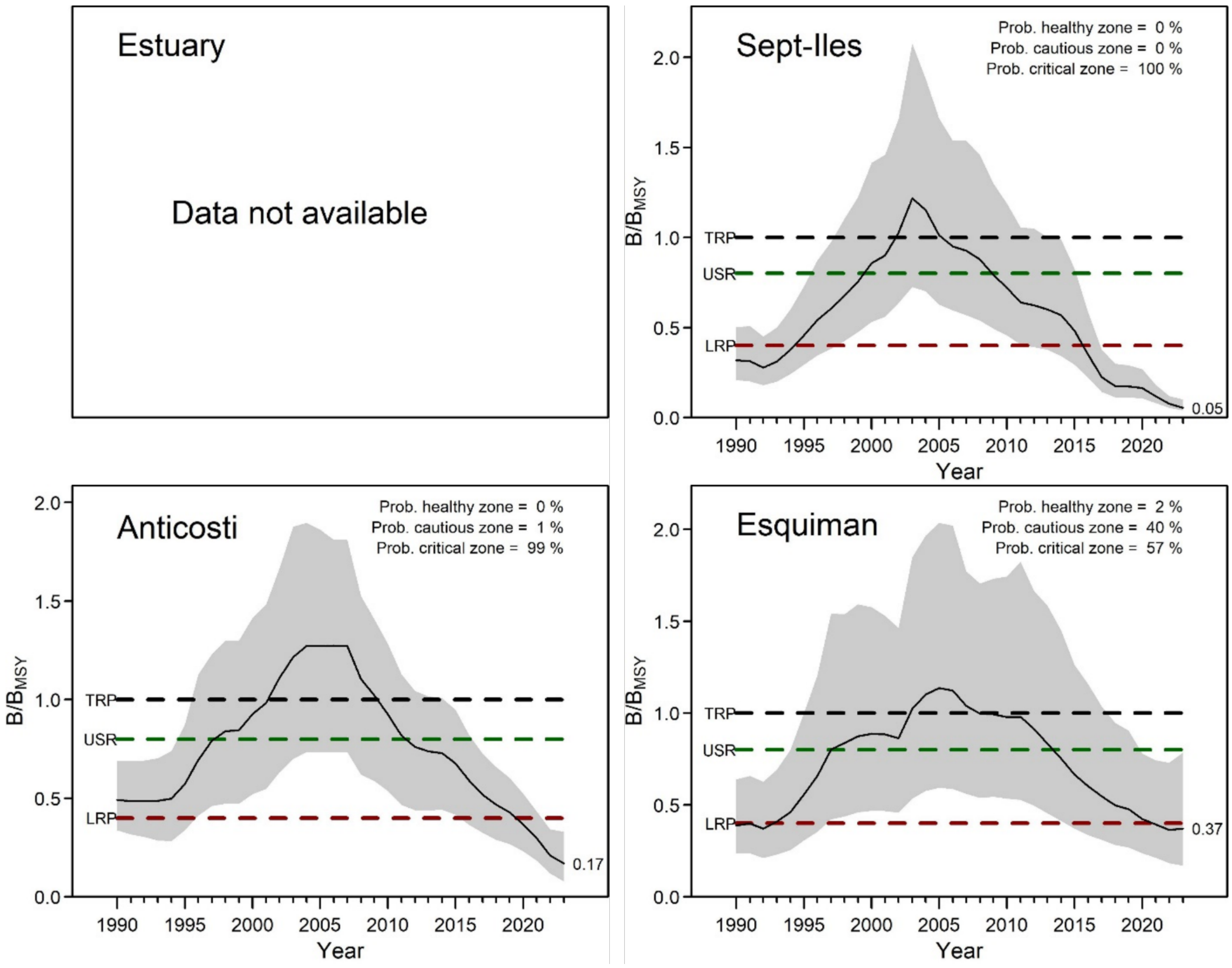

Figure 9. Ratio between biomass (B) and B_{MSY} value per stock according to the SPM. The solid line indicates the median value of B/B_{MSY} and the shaded area indicates the 95% credible interval. The dotted lines represent LRP, USR and TRP. The estimated value of B_{2023}/B_{MSY} and the probability to be in the critical, cautious and healthy zone are indicated in each panel.

Proposed decision rules for establishing the projected harvest

HCR can be developed in accordance with PA principles using the stock biomass indicator and reference exploitation rates. In this case, it was agreed to develop “status-based” type HCR, where projected exploitation rates and corresponding removals are a function of stock status (Kronlund et al. 2014).

The reference exploitation rate used for the review of the PA is the F_{MSY} derived from the SPM. The exploitation rate trajectories of the three stocks followed the same trends over time (Figure 10). By the early 1990s, exploitation rates were declining. In the late 1990s and early 2000s, exploitation rates were either lower than or comparable to F_{MSY}. Since 2005, exploitation rates have been increasing and are above F_{MSY}. The increasing exploitation rates trend was reversed in 2023. The exploitation rates decreased significantly with the reduction in preliminary landings.

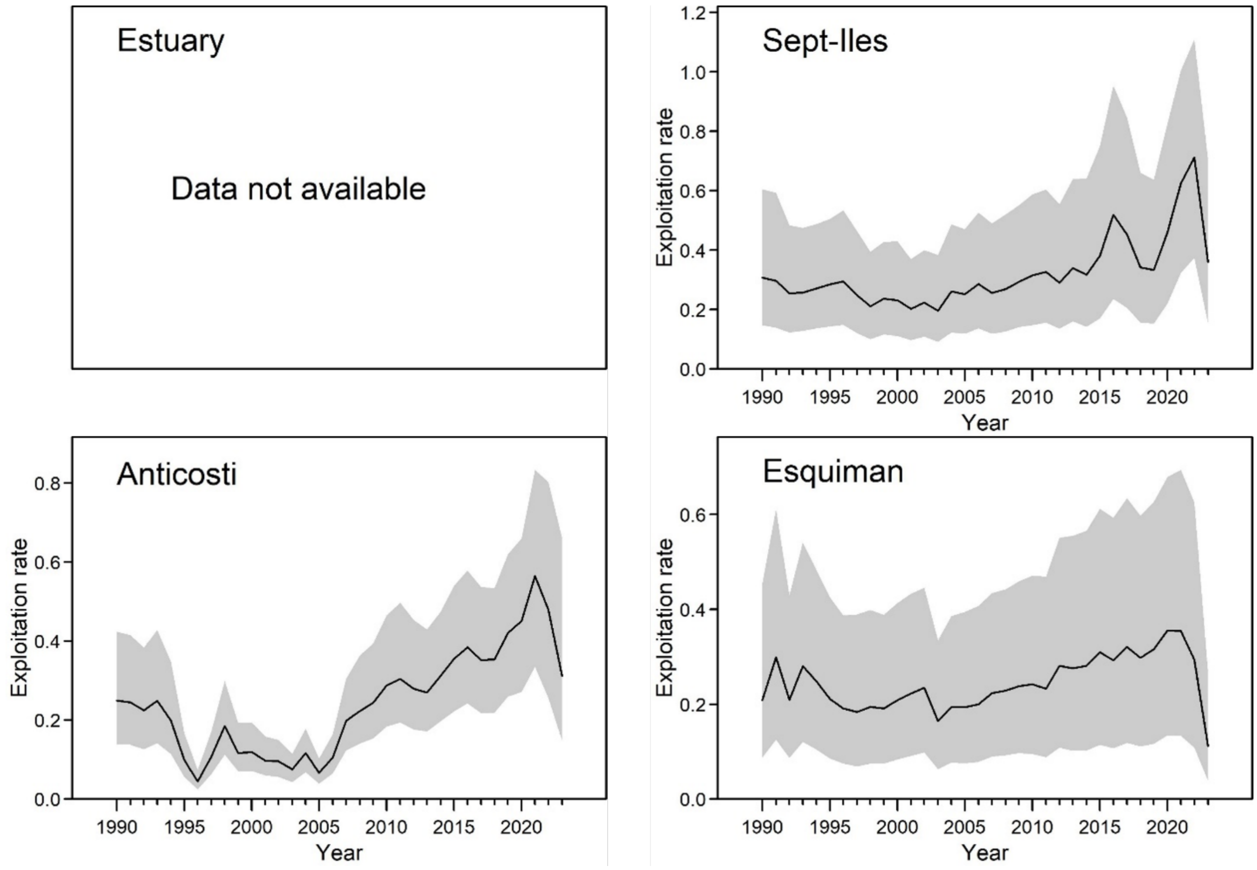

Figure 10. Relative exploitation rate per stock assessment unit according to the SPM. The solid line indicates the median exploitation rate and the shaded area indicates the 95% credible interval.

The decision-making framework for fisheries integrating the PA mentions that, in the healthy zone, the exploitation rate must not exceed the pre-established maximum harvest level and that management measures must react to a downward trend when the stock status is approaching the cautious zone. The maximum exploitation rate proposed for the four HCR proposals is set at F_{MSY} when the stock is above the USR (Figure 11).

In the cautious zone, the decision-making framework mentions that the exploitation rate should increase only gradually depending on the stock status until the pre-established maximum level is reached. This approach should promote the recovery of the stock so that it returns to the healthy zone. Management measures must encourage stock growth in the short term. If the stock status is in the lower part of the zone, the tolerance risk for avoidable decline should be very low to low. Thus, for the different HCRs proposed, the exploitation rate decreases proportionally to the stock status decrease, to reach exploitation rate values of 0.5 (scenarios A and B), 0.25 (scenario C) or 0% (scenario D) of F_{MSY} when the stock status reaches the LRP.

In the critical zone, the decision-making framework requires that management measures must promote growth and removals from all sources must be maintained at the lowest possible level until the stock leaves this zone. The proposed exploitation rates in the critical zone vary according to the different HCRs. In scenario A, the exploitation rate is constant and should not exceed 0.5 of F_{MSY}. In scenario B, the exploitation rate gradually decreases from 0.5 F_{MSY} to zero when the stock reaches 0.2 B_{MSY}. The exploitation rate of scenario C gradually decreases from 0.25 F_{MSY} to zero when the stock reaches 0. Finally, it is proposed with scenario D that no directed fishing is permitted when the stock is in the critical zone.

The proposed HCRs determine the exploitation rate based on stock status indicator. Then, this exploitation rate is converted into a projected harvest, i.e. a recommended catch limit. The relative projected harvest presented in figure 11 must be rescaled to the fishing harvest scale by multiplying it by the MSY specific to each stock. Determining the TAC is a matter for FM and is not covered in this document. Additionally, amendments to the *Fisheries Act* in 2019 require that a rebuilding plan is developed when a stock falls to or below the LRP (DFO 2021).

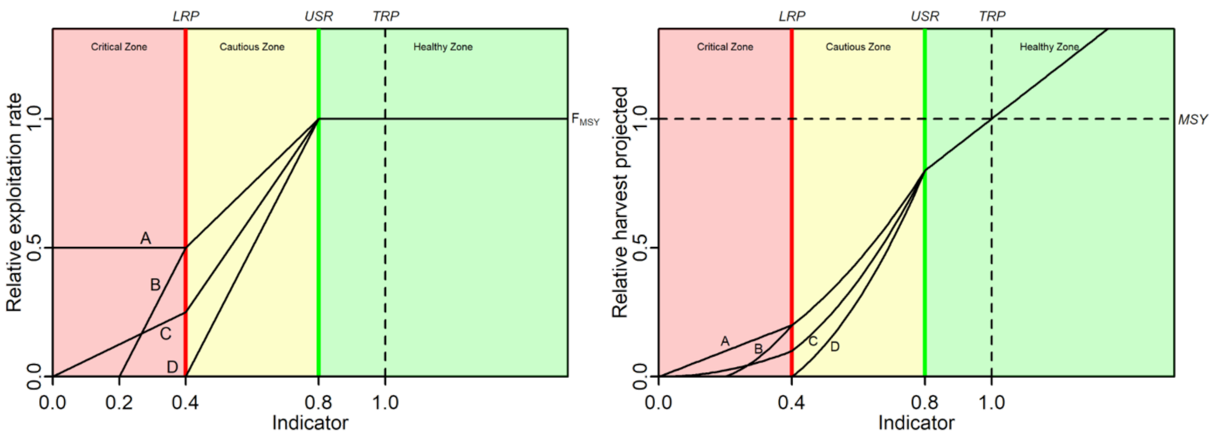

Figure 11. Four proposed harvest control rules (HCR) presenting relative exploitation rate (F/F_{MSY}, left) and relative projected harvest (right) as a function of the stock status indicator (B/B_{MSY}). The reference points are presented on the panels by the vertical lines which define the three zones of the PA.

To determine the projected harvests for the coming year, it is first necessary to make a projection of the stock status indicator (B/B_{MSY}) for the year 2024. The projection is made following the adjustment of the SPM with the JABBA application. The projected median value of the indicator determines the relative exploitation rates (F/F_{MSY}) under the four HCR scenarios. Then, the distribution of predicted catches corresponding to these different scenarios is calculated for the year 2024. The uncertainties in the model estimates were propagated in the projection with the variance of the process error. It should be noted that due to its heuristic nature, the current SPM was not used to make projections beyond one year.

The PA preconizes prudent management strategies that include scientific uncertainty. Simulation work demonstrates that the use of a percentile lower than 50th percentile of predicted catches distribution would make it possible to maintain a higher biomass in the short term, without a substantial reduction in catches in the longer term (Mildenberger et al. 2022). For stocks assessed with an SPM, the International Council for the Exploration of the Sea (ICES) recommends HCRs which take into account estimation uncertainties. It suggests using the 35th percentile of the projected catch distribution rather than the median value (50th percentile) (ICES 2021, 2022). In addition, it is suggested to refit and review the SPM annually in order to update the recommendation for projected harvests.

Depending on the HCR that will be retained, the projected harvests for 2024, according to the 35th percentile rule, could vary between 0 and 342 t for Sept-Iles, between 0 and 488 t for Anticosti, and between 320 and 1,757 t for Esquiman (Table 1).

Table 1. Median and 35th percentile of projected harvests distribution for 2024 (t) per stock assessment unit under different harvest control rules (HCR).

HCR	F_{2024}/F_{MSY}	Projected harvest 2024 (t)	
		Median	35th percentile
Sept-Iles (B_{2024}/B_{MSY} = 0.06)			
A	0.50	407	342
B	0.00	0	0
C	0.04	30	25
D	0.00	0	0
Anticosti (B_{2024}/ B_{MSY} = 0.17)			
A	0.50	587	488
B	0.00	0	0
C	0.11	125	104
D	0.00	0	0
Esquiman (B_{2024}/ B_{MSY} = 0.44)			
A	0.55	2,092	1,757
B	0.55	2,092	1,757
C	0.33	1,237	1,038
D	0.10	381	320

The four HCR proposals are simple and consistent with the PA policy for fisheries management since:

- Exploitation rate does not exceed the maximum reference value in the healthy zone.
- In the cautious zone, the HCRs reduce the exploitation rate according to the decrease in the stock status indicator.
- In the critical zone, harvest are kept to the minimum possible or at low values.

The choice of one HCR proposal over another is difficult to justify scientifically in the absence of quantitative tools with the capacity test the performance of HCR scenarios. However, if any of the four HCRs proposed here had been used in recent years, the projected harvests would have been more conservative than the actual allowed TACs.

Future work will attempt to develop one or more population dynamics models that take into account significant changes in stock productivity and have the capacity to make reliable projections. That work may lead to modifications of the PA.

The elements of the PA, including the rule adopted for harvest control, will be implemented by FM. Likewise, the TAC will be determined by FM based on the estimate of the projected harvest based on the HCR of the PA which will have been retained.

Estuary stock

The biomass index used to adjust the SPM for the Estuary stock could not be updated in 2023. The SPM adjusted to the Estuary stock data from 2008 to 2022 (Smith and Bourdages 2023, In press) showed that the adjustment was very sensitive to the biomass observed in 2022. This increase in biomass in 2022 was also observed in the commercial fishing CPUE. However, the latter decreased by almost 50% in 2023. This recent decrease could be explained by the fact that the majority of the biomass in 2022 was made up of multiparous females (females who spawn eggs for a second year) not having survived beyond spring 2023, which is plausible based on our knowledge of shrimp life cycle. Due to the high uncertainty associated with the biomass index for the Estuary in 2022 and the lack of information for 2023, the status of this stock is considered uncertain. It is therefore not possible to use the SPM to make a harvest projection for 2024. However, we recommend adopting a cautious approach given the situation of the three other stocks and the environmental and ecosystem conditions reported in the next section.

Ecosystem considerations and stock productivity

Shrimp are forage species and play a key role in the ecosystem as an intermediary in the transfer of energy from lower trophic levels (e.g. phytoplankton and zooplankton) to higher predators such as fish. They constitute an important food source for several demersal predators and generally experience high predation mortality. The low abundances of northern shrimp stocks recently observed in EGSL could negatively affect the productivity or survival of demersal species for which northern shrimp is an important prey.

In 2022, the condition observed for Atlantic cod (*Gadus morhua*) and Greenland halibut (*Reinhardtius hippoglossoides*) in the EGSL, two predators of northern shrimp, was particularly low (DFO 2023a, 2023b). It was then observed that stomach fullness indices were low and that the contribution of northern shrimp to their diet was lower compared to previous years. A high natural mortality has already been observed in the past at this condition level with cod (Lambert et Dutil 1997). This deterioration of cod and Greenland halibut condition should be studied in more detail over the coming years, particularly in relation to the effect of changing ecosystem conditions in the EGSL.

Furthermore, the deepwater redfish (*Sebastes mentella*), another northern shrimp predator, has made a comeback in recent years in the EGSL (DFO 2022b). The 2011 cohort, which is the most abundant ever measured, now has a modal size of 24 cm and is distributed throughout the deep channels of the northern Gulf and to a lesser extent in the estuary (Figure 12). Small redfish primarily consume zooplankton but switch to consuming more shrimp and fish as they grow (Ouellette-Plante et al. 2020). northern shrimp become an important prey for redfish over 25 cm. Estimated redfish predation on northern shrimp has increased significantly over the past seven years and is a significant factor contributing to the decline of northern shrimp. The total estimated biomass of *S. mentella* in the EGSL in 2021 was 2.8 million t whereas it was less than 100,000 t before 2013 (DFO 2022b).The situation is not expected to improve in the coming years.

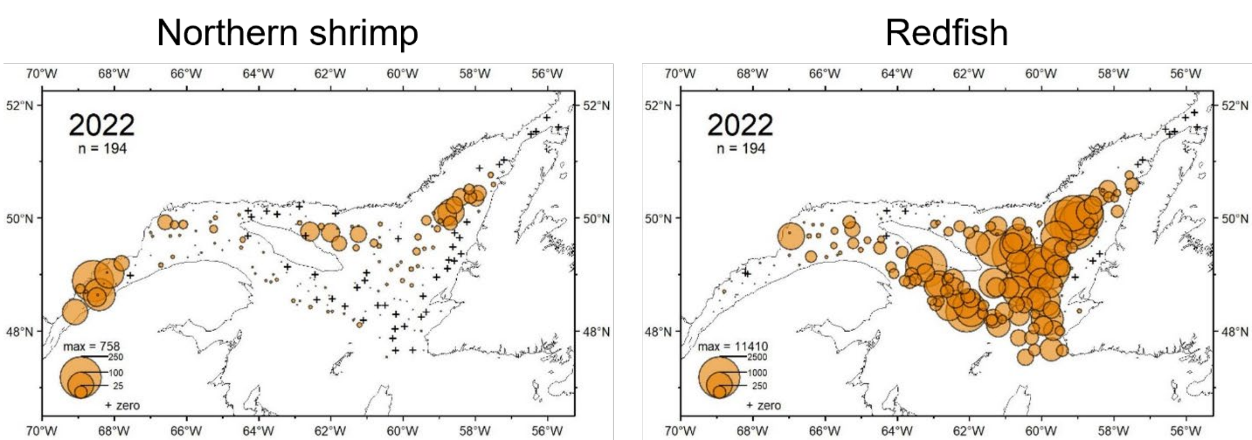

Figure 12. Distribution of northern shrimp and redfish catch rates (kg/15 minutes tow) in the August 2022 DFO survey in the Estuary and northern Gulf of St. Lawrence.

In the EGSL, northern shrimp are found in a hypoxic habitat (depth of more than 150 m and dissolved oxygen (DO) saturations of 18 to 40%). The impact of hypoxia on adult shrimp, male and female, has been studied in the laboratory (Dupont-Prinet et al. 2013, Pillet et al. 2016). The results show that females are less tolerant than males to hypoxia and that the tolerance of both sexes decreases with increasing temperature. The critical DO thresholds for females increase from 15 to 22% when the temperature increases from 5 to 8°C, while for males, the thresholds increase from 9 to 15%.

For 15 years, the northern shrimp of the EGSL has been facing warming and a depletion of DO in its habitat. In 2022-2023, 50% of the biomass of female shrimp from the Sept-Iles, Anticosti and Esquiman stocks was exposed to DO levels below 27% or 24%, while a quarter of the biomass was exposed to levels DO of less than 23%, 20% and 22%, respectively, and at temperatures above 6.5°C, or even 7°C in some locations (Figure 13). A significant proportion of the stocks is therefore exposed to DO levels corresponding to the critical thresholds observed in the laboratory. Recent studies (Guscelli et al. 2023), where the impact of warming, acidification and hypoxia was assessed in the laboratory, show that the survival and aerobic performance of shrimp could decrease considerably when exposed to these factors combined (Guscelli et al., In prep[2]).

The sustained warming and loss of DO in the deep waters of the EGSL inhabited by northern shrimp are well documented by the Atlantic zonal monitoring program (Galbraith et al. 2023, Blais et al. 2023). Future projections also show general warming across the entire EGSL under different models of climate changes (Lavoie et al. 2020). It is therefore unlikely that current environmental conditions will improve in the short or medium term, and could on the contrary continue to deteriorate in the long term. The favorable conditions for northern shrimp productivity observed in the late 1990s and early 2000s in the EGSL are unlikely to return in the future given projected climate change. The stocks would then be exposed to conditions where their productivity would remain low.

The lack of genetic variation that can express thermal plasticity suggests limited adaptability in this species' response to ongoing environmental changes (Leung et al. 2023). These results, along with the higher mortality observed at the highest temperatures, indicate that the distribution of northern shrimp will likely be limited to higher latitudes in the future.

Already, there is evidence that the stock productivity is negatively affected. The observed low abundance of juveniles and males in recent years, as well as the downward trend in female size, indicate lower stock productivity. In addition, with warming and the depletion of DO in deep waters, we observe a loss of habitats suitable for northern shrimp. More precisely, the deeper part of its distribution area has been abandoned in the Estuary, Sept-Iles and Anticosti (Figure 13). This change in distribution, depending on bottom depth, is very marked in the Estuary. In fact, shrimp are now found closer to the CIL in colder and more oxygenated waters. Despite these changes in environmental conditions, we do not observe a change in depth for shrimp in Esquiman.

These changes expose part of the population to environmental conditions approaching the limits of tolerance of the species. This exposure likely affects stock productivity. To survive, northern shrimp will have to find favorable conditions locally, such as using shallower bottom, therefore closer to the CIL. As a result, future favorable habitat for shrimp will likely be diminished. Shrimp stocks will therefore be less productive and more vulnerable to predation and fishing pressures.

[2] Guscelli, A. 2023. Survival and aerobic capacity of the northern shrimp are threatened by exposure to combined ocean global change drivers. In preparation.

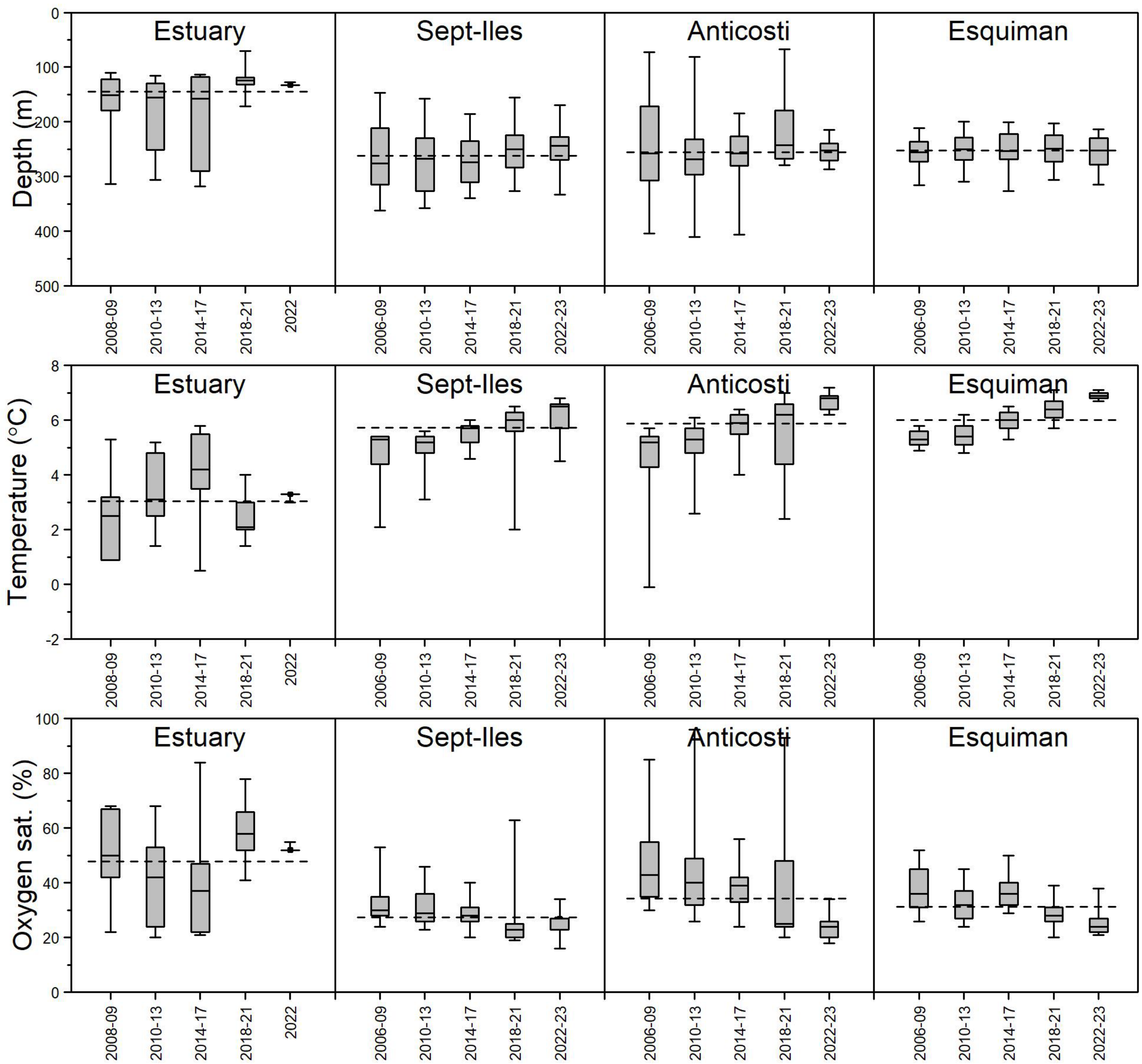

Figure 13. Female shrimp biomass distributions based on depth, temperature and dissolved oxygen saturation in bottom water per four-year period observed during the August DFO survey in the Estuary and the northern Gulf from 2006 to 2023 (2008 to 2022 in the Estuary).

The changes observed in the ecosystem indicate an increased risk of undesirable biological and ecological consequences for the sustainability of shrimp stocks and, consequently, for the ecosystem that shrimp is part of through its role as a forage species (Table 2). The risk to the sustainability of shrimp stocks is currently greater than in the 1990s and early 2000s.

Table 2. Evaluation of the risk and anticipated consequences for northern shrimp stocks due to ecosystem changes observed over the last decade.

Observations	Anticipated consequence	Risk evaluation
↓ Shrimp distribution range	↑ Shrimp vulnerability to predation	↑
↑ Predation (Redfish)	↑ Natural mortality	↑
↑ Water temperature	↓ Productivity	↑
↓ Dissolved oxygen	↓ Productivity	↑

The perspectives for these stocks depends on northern shrimp sensitivity to environmental changes, predation pressure and fishing pressure. The warming and oxygen depletion observed in deep waters, as well as the strong predation pressure by redfish, are not expected to improve in the short and medium term.

Conclusions

The elements necessary for northern shrimp PA in the EGSL have been revised. New LRP have been adopted and other PA elements have been proposed and will be implemented by FM. In 2023, Sept-Iles, Anticosti and Esquiman stocks are in the critical zone with probabilities of 100%, 99% and 57% respectively, while the status of the Estuary stock is uncertain.

Following the guidelines used by ICES for stock assessments based on SPM, the 35th percentile was chosen to determine projected harvests under the HCR. Projected harvests for 2024 could vary between 0 and 342 t for Sept-Iles, between 0 and 488 t for Anticosti, and between 320 and 1,757 t for Esquiman.

The EGSL northern shrimp ecosystem is experiencing major changes induced by climate changes. These changes represent an additional, unquantified risk for northern shrimp stocks associated with the application of the proposed HCR.

The perspectives for these stocks depend on the sensitivity of northern shrimp to environmental changes, predation pressure from redfish and fishing pressure. The status of northern shrimp stocks in the EGSL is therefore not expected to improve in the short and medium term and could continue to deteriorate. Since the northern shrimp plays a key role as a forage species in the EGSL ecosystem, caution should be exercised regarding the exploitation of this resource. The low abundance of northern shrimp observed recently in the EGSL could have negative consequences for other species that depend on them as a food source and finally for its rebuilding potential.

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Appendix 1

Median of parameters estimated by the SPM and derived quantities for the four stock assessment units.

Parameter	Estuary (2008-2022)	Sept-Iles (1990-2023)	Anticosti (1990-2023)	Esquiman (1990-2023)
K	8,649	138,433	77,032	81,992
r	0.516	0.397	0.357	0.419
B_{1990}/K	0.534	0.170	0.238	0.194
F_{MSY}	0.258	0.198	0.179	0.210
B_{MSY}	4,324	69,217	38,516	40,996
MSY	1,049	13,875	6,867	8,489
B_{2023}/B_{MSY}	1.458	0.053	0.169	0.372
F_{2023}/F_{MSY}	0.333	1.833	1.751	0.540

Appendix 2

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