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Southern Gulf of St. Lawrence Atlantic Rock Crab (*Cancer irroratus*) Stock Review to 2023

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Foreword

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

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ABSTRACT

The Atlantic rock crab commercial fishery in the southern Gulf of St. Lawrence (sGSL) began in the 1960s, when bycatch from the lobster fishery started being sold to registered buyers. A directed exploratory fishery was launched in 1974 on a modest scale, and more significant development followed in the 1980s with the issuance of exploratory licences across the five management areas: Lobster Fishing Areas (LFAs) 23, 24, 25, 26A, and 26B.

The most recent stock assessment was conducted in 2013; however, at that time no Limit Reference Point (LRP) was set. Subsequent updates to Fishery Status Indicators in 2018 and 2022 provided fisheries management with updated information from key data sources.

This research document provides an overview of the fishery-dependent and fishery-independent data available for the rock crab stock in the sGSL. It also proposes candidate data sources and methods to support the establishment of an LRP.

Fishery-dependent indicators presented include landings from the directed and bycatch fisheries, standardized catch per unit effort (CPUE), and the estimated number of fishing days required to land 9,000 kg. Fishery-independent indicators include a trap survey CPUE, a dockside length-frequency monitoring program, and a bio-collector program to assess recruitment. In addition, results from a lobster predator abundance model are discussed.

Based on the standardized CPUE, an LRP is proposed at 5.02 kg/trap, which is below the current CPUE level of 7.38 kg/trap. This LRP would place the stock in the Cautious zone.

INTRODUCTION

Atlantic rock crab (*Cancer irroratus,* hereafter referred to as just rock crab) is a decapod crustacean distributed along the Atlantic coast of North America, from South Carolina and Florida, where it can occur at depths of up to 575 m (Williams 1965), to Labrador, where it is more typically found in shallower waters, including the intertidal zone (Department of Fisheries and Aquaculture 1999). While rock crab shows a preference for sandy substrates, it is also found on a variety of bottom types. In the southern Gulf of St. Lawrence (sGSL, Figure 1), rock crab plays a key ecological role as a prey species for lobster and large benthic fishes such as Atlantic cod, rays, and skates (Hanson et al. 2014). It is also a commercial species in the region.

Rock crab exploitation in the sGSL began in the early 1960's (Wilder 1973), initially as bycatch in the lobster (*Homarus americanus*) fishery. An exploratory fishery was launched in 1974 and gradually evolved into a directed commercial fishery by the year 2000. The number of licence holders peaked at 255 in 2002 but has since decreased and is now approximately 225. Bycatch sales continue to be permitted from the lobster fishery and a considerable amount of overlap exists in terms of participants between the rock crab and lobster fisheries. Virtually all holders of directed rock crab licences are also licenced lobster harvesters.

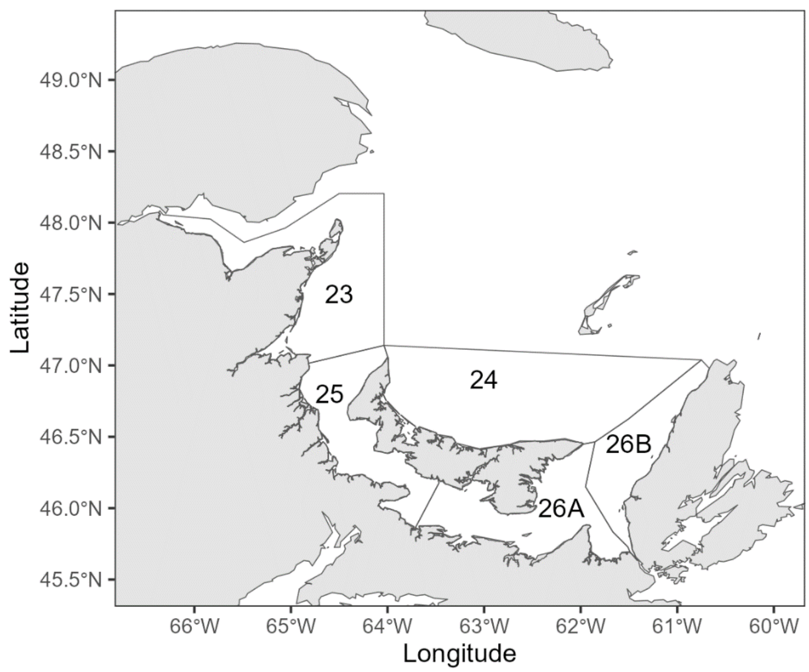

Figure 1. Lobster fishing areas (LFA) used in the management of the directed rock crab fishery in the sGSL.

BIOLOGY

Rock crab (*Cancer irroratus*) is a decapod crustacean with an oval-shaped carapace that is typically yellowish-brown to reddish-purple in colour on the dorsal side and whitish-tan on their ventral side (Bigford 1979). Like other decapod crustaceans, it has four pairs of walking legs and one pair of chelipeds (claws) used for feeding and defence. The front edge of its carapace has 9 pairs of small points while the rear edge of its carapace features only a single pair of points.

In the sGSL, rock crabs hatch in mid-June and pass through six planktonic larval stages before settling on the bottom in mid-September. Growth occurs through moulting, during which the hard outer shell is periodically shed to allow the vulnerable soft-bodied crab to swell before a new, larger shell is formed. Moulting frequency decreases with age, particularly after reaching sexual maturity.

Male rock crabs take about six years to reach commercial size in the sGSL (DFO 2013). On average, female mature at 49 mm carapace width (Campbell and Eagles 1983) and the size at 50% maturity was estimated to be 48.8 mm CW for male rock crab in the Northumberland Strait. Full male maturity (≥ 95%) is reached at 73 mm CW (Rondeau 2014). Mating occurs in late summer and fall, shortly after females moult and while their carapace is still soft. Males typically moult earlier (winter/spring), ensuring they have hardened shells during the mating season. Females typically extrude eggs soon after mating and carry them on their abdomen for roughly 10 months, with hatching occurring the following June.

FISHERY MANAGEMENT

The rock crab fishery in the sGSL consists of two main components: the directed fishery, conducted during the designated rock crab fishing season by licence holders, and the bycatch fishery, where lobster harvesters retain rock crab during the lobster season. Fishing is managed separately within five lobster fishing areas (LFAs, Figure 1), although activity in LFA 26B has historically been minimal due to low catches and has ceased entirely since 2011.

The directed fishery is managed primarily through input controls, including limitations on the number of licences, traps limits per licence, gear restrictions, defined fishing seasons, a minimum legal size, and a prohibition on landing females (Table 1). Output controls are also in place in the form of individual allocations. Landings from the directed fishery are subject to a 100% dockside monitoring program and harvesters are required to keep logbooks detailing daily catch, fishing effort (number of traps and soak time), and location.

Only male rock crab can be retained as bycatch during the lobster fishery, but few other additional measures apply, beyond those already in place for the lobster fishery (e.g. trap limits, fishing seasons, see Asselin et al. 2024 for more details). From 1999 to 2003, a daily bycatch limit was enforced along with a minimum legal size, however, these restrictions were rescinded due to conflict with the Atlantic Fishery Regulations (Canada 1985). From 2004 to 2021, lobster harvesters were permitted to keep any size of male rock crab for use as bait or to land as bycatch. In 2021, lobster licence conditions were amended to impose a 102 mm size limit for bait-use rock crabs (DFO 2021). This size limit was further increased to 108 mm in LFA 26A, aligning with the directed fishery (DFO 2024). No size restrictions apply to rock crab sold as bycatch to licensed buyer and, while sales slips are required for such transactions, logbook records of rock crab used as bait or sold as bycatch are often incomplete.

Table 1. Key management measures in the directed rock crab fishery in the sGSL in 2023.

LFA	Minimum Legal Size (mm)	Trap Limit	Fishing Season	Individual Allocation (kg)	Licences Issued	Licences Active
23	102	100	Aug 7-Nov 18	35,000	52	21
24	102	150	Jul 8-Oct 29	20,000	10	4
25	102	100	Jun 26-Jul 29 Oct 23-Dec 3	25,000[1]	66	38
26A	108	90	Aug 7-Nov 25	23,913	95	53
26B	108	100	-	27,216	5	-

[1] Community and commercial communal licences have a limit of 35 000 kg

In the directed fishery, harvesters primarily use conical crab traps; although modified lobster traps and pyramidal crab traps are also permitted. All traps must be equipped with escape vents consisting of rigid circular openings measuring 63.5 - 76.2 mm in diameter, which helps to minimize bycatch of lobsters or undersized rock crab. Traps must also contain a biodegradable mechanism to reduce ghost fishing in the event that gear is lost at sea. While traps are typically hauled daily, harvesters are permitted to leave gear deployed for up to 72 hours (Canada 1993).

Licences in the directed fishery fall into four categories: commercial (individual), commercial communal (allocated to Indigenous groups), partnerships, and community, the latter representing multiple harvesters from the same community. Individual catch allocations vary by LFA and licence type and have remained unchanged since 2000 (Table 1). In some cases – such as partnerships and community licences – allocations may increase by as much as 50% per partner, though such arrangements are rare and are not considered in this document. Additionally, commercial communal licences in LFA 25 are allocated 35,000 kg annually as opposed to 25,000 kg as per commercial licences in the same area. This distinction was accounted for when calculating allotment attainment rates.

DATA SOURCES

FISHERY DEPENDENT DATA

Official Statistics

Landings data from the directed rock crab fishery are monitored through a dockside monitoring program with 100% coverage. Harvesters are required to hail in and report catch and effort information to a certified dockside monitoring company. Details on fishing effort - including the number of traps hauled, soak time, and fishing locations - are recorded in mandatory logbooks and submitted to dockside monitoring companies, which compile and forward the information to DFO’s Statistics and Economic Services division.

Catch, price, and buyer details are documented in sales slips generated for all landings from the directed fishery and for rock crab sold as bycatch and are submitted to DFO’s Statistics and Economic division. Information on the number, type, and licence conditions (e.g., trap limitations, individual allocations) for rock crab is obtained from DFO’s Licensing.

Dockside Length Frequency Program

In 2021, a dockside length frequency monitoring program was established in collaboration with industry partners (the Prince Edward Island Fisherman’s Association and the Maritime Fisherman’s Union) to collect carapace width data on commercial rock crab catches during the directed fishery. Field technicians employed by the industry partners conduct sampling according to a standardized protocol designed to ensure spatial coverage across all LFAs and temporal coverage of the entire fishing season. A random sample (pan) is selected from among the landed catch and the carapace widths (to the nearest mm) of all crabs within that pan are measured. If the randomly selected pan contained fewer than 150 crabs, a second randomly selected pan will be sampled. Sampling is conducted dockside as crab are unloaded or as crabs arrive at a processing plant. The goal is to measure 200 crabs per landing while also recording the date of the catch, the fishing area, port landed, licence details, and trap and bait type used. The target sampling frequency for each fishing area is every two weeks.

FISHERY INDEPENDENT DATA

Scientific Trap Survey

In 2021, a rock crab trap survey was initiated with the primary objective of collecting fishery-independent data on rock crab abundance, sex ratios, and size distributions using gear comparable to that used in the commercial fishery. One study area was selected within each LFA (Figure 2), representing a range of fishing intensities as determined by logbook location data and associated catches from sales slips. An additional site was added to LFA 23 to account for potential differences in population dynamics between the Baie de Chaleur area and the main Gulf. The spatial extent of each area ranged from 394 to 464 km^2, with traps set at stations spaced ~4.5 km from each other.

During each survey, traps are deployed in a grid pattern covering the entire study area and fished over a 4-day period. Due to resource constraints, not all study areas are sampled every year; instead, areas are sampled on a rotational basis.

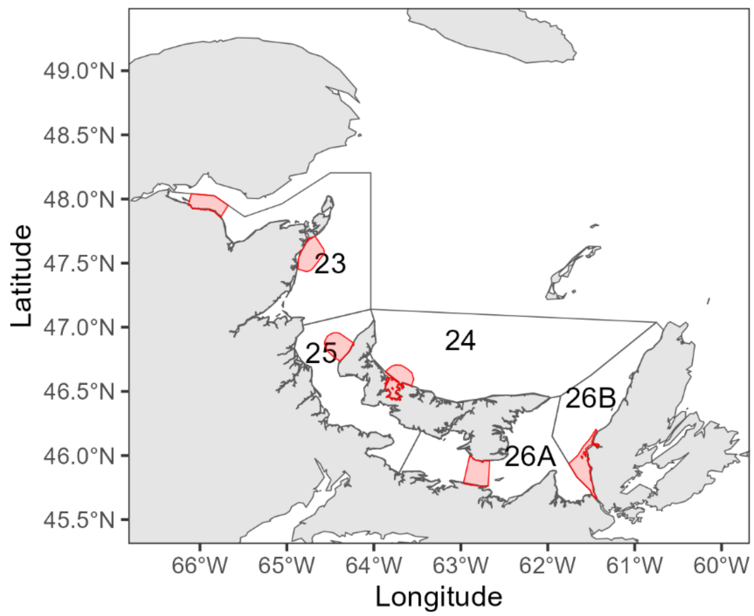

Figure 2. The locations of trap survey study areas within the sGSL from 2021 to 2024.

Sampling is conducted using standard conical rock crab traps similar to those used by most commercial harvesters, but with a finer mesh size (knot-to-knot stretched mesh width of 25 mm) compared to commercial standard of 63 mm (2.5 inches). In 2022, to increase the capture of small crabs (<60 mm), small, rectangular traps (610 mm x 610 mm x 229 mm) with 25 mm wire mesh were deployed in several survey areas (Table 2). However, results did not show improved catch efficiency for small crabs, and their use was discontinued. Beginning in 2023, the sampling stations originally created to test the smaller traps were retained and fished using additional conical scientific traps, increasing the total number of traps used in the survey (Table 2). Each trap is baited with ~2.25 kg (5 lbs) of frozen herring suspended above the trap floor.

Table 2. Sampling details for the annual rock crab trap survey. Numbers indicate the number of 24 hour trap sets completed within each survey area.

Year	LFA	Mission Goal	Commercial Traps	Scientific Traps	Rectangular Traps
2021	24	trap survey	-	40	-
2021	23C	trap survey	-	66	-
2021	26A	trap survey	-	59	-
2021	26B	trap survey	-	24	-
2022	25	comparative survey	20	20	20
2022	25	trap survey	-	54	28
2022	23A	trap survey	-	59	44
2023	24	trap survey	-	117	-
2023	25	trap survey	-	111	-
2023	23A	repeat survey	-	152	-
2023	23A	trap survey	-	152	-
2023	23C	trap survey	-	152	-
2023	26A	trap survey	-	159	-
2024	24	trap survey	-	148	-
2024	23C	trap survey	-	156	-
2024	26A	trap survey	-	157	-

DATA ANALYSIS

ABUNDANCE INDICATORS

Landings – Directed Fishery

Landings data were first classified as originating from the directed fishery by cross-referencing the licence number, landing date, and, when available, the stated target species. These landings were then aggregated by fishery type, year, and LFA. Licence numbers were also used to match each harvester with their corresponding individual allocation. Temporal trends in total landings and allocation attainment were assessed annually and by LFA.

Landings – Bycatch

Bycatch landings of rock crab were identified based on sales slips alone. Sales slips were considered to represent bycatch if they were associated with lobster licence numbers, had landing dates outside the rock crab fishing season, or listed lobster as the target species. As bycatch data are derived solely from sales slips, they include only rock crab sold as bait or to processing plants via registered buyers. These data do not include information on fishing effort or the volume of rock crab retained and used directly as bait by lobster harvesters.

Individual Allotment Attainment

The percentage of rock crab licence holders landing their full individual allotment was calculated annually for LFAs 23, 25, 26A and 26B for 2000 to 2023 and for LFA 24 from 2015 to 2023 (individual allotments were implemented in LFA 24 in 2015). Few harvesters land their entire allotment, likely due to hesitancy in making a final trip when the risk of exceeding the allocation is high. For this reason, the attainment threshold was set at ≥ 90% of the individual allocation.

These proportions were modelled using a binomial generalized linear model (GLM), with year and LFA as explanatory variables. Significant differences among years within each LFA were identified through post hoc comparisons using the contrast() function from the emmeans package in R (Length 2020). Only active licences (licences associated with at least one fishing trip in a given season) were included in the analysis. All licence types were considered, and results were also summarized by licence category (commercial vs. commercial communal).

Harvest Limit Rates

As with allotment attainment, the rate at which harvesters land rock crab varies among individuals, across LFAs, and over time, as shown by cumulative landings between 2021 and 2023 (Figure 3). The number of days required for harvesters to reach their individual allocation can be modelled using a time-to-event framework, specifically an accelerated failure time (AFT) model. AFT models are useful for quantifying the influence of factors such as year and LFA on the time required to reach an allocation, while accounting for repeated measurements from individual harvesters through clustering (Wei 1992; Saikia and Barman 2017).

Figure 3 illustrates that while some harvesters in each LFA land their full allocation, others stop harvesting before reaching the limit. AFT models accommodate this right-censored data by assuming that, given sufficient time, all harvesters could potentially reach their full allotment. The likelihood of reaching this threshold can be modelled using a survival distribution such as Weibull, exponential, or log-normal.

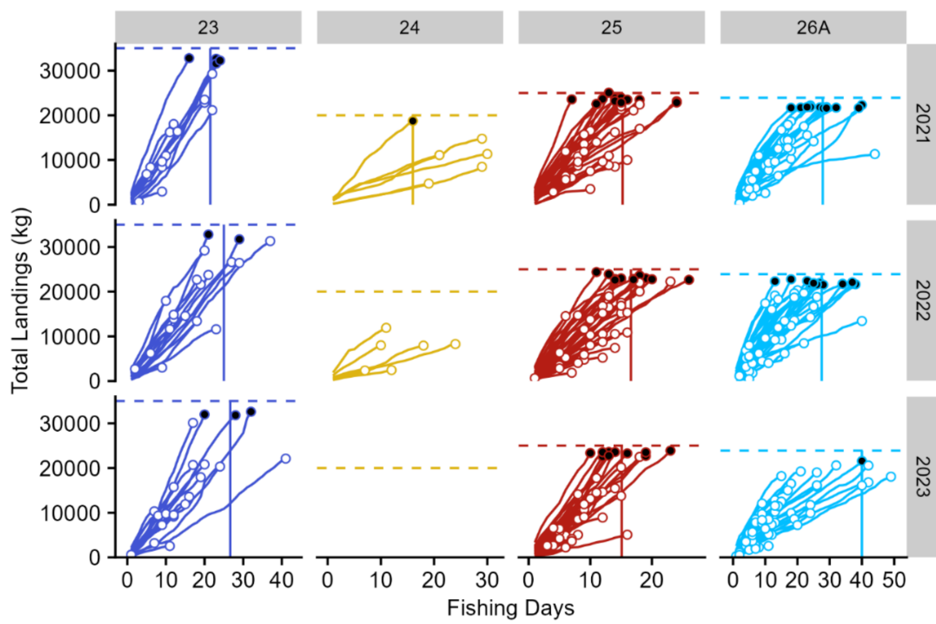

Figure 3. Cumulative rock crab landings between 2021 and 2023 by individual harvesters. Circles represent total seasonal catches while filled circles indicate total catches >= 90% of the harvester's individual allotment. Data are not shown for LFA 24 in 2023 due to fewer than 5 harvesters participating in the fishery that year.

As noted with the attainment analysis, few harvesters land their entire allotment, especially in more recent years in LFA 24, resulting in a high proportion of censored observations. To improve statistical power, an arbitrary catch limit of 9,000 kg was set as the event threshold, thereby increasing the number of events per year and LFA. All active licence holders were included as the sample population. An AFT model was then used to quantify variation in time-to-event by year and LFA, with harvester ID included as a clustering variable to account for individual variability. The average number of traps used per harvester per year was included as a covariate to adjust for differences in fishing effort.

Estimates were only generated for year–LFA combinations with at least five observed events to ensure statistical reliability. Time was measured as the number of active fishing days rather than calendar days to control for gaps in fishing activity, an important consideration in LFA 25, where the rock crab season is interrupted by the fall lobster fishery. Preliminary survival curve analyses indicated that the log-normal distribution provided the best fit to the data.

Fishery-dependent CPUE

Catch per unit effort (CPUE) for the directed rock crab fishery was calculated using landings data (kg) from sales slips and corresponding effort data (trap numbers, soak times) from harvester logbooks. When logbook entries were missing, incomplete, or clearly erroneous (e.g., number of traps = 0), values were imputed using the following rules: missing trap numbers were replaced with the maximum allowed under the licence conditions, and missing soak times were set to 24 hours (the most commonly reported soak duration in the sGSL).

Despite these validation steps, implausible CPUE values (e.g., 102 kg/trap or 0.0007 kg/trap) remained. To minimize the influence of such outliers on model estimates, only records with raw CPUE values between the 2.5th and 97.5th percentiles (1.47 < x < 25.43 kg/trap- red lines in Figure 4) were retained for analysis. CPUE values were not calculated for LFA 26B due to insufficient landings data.

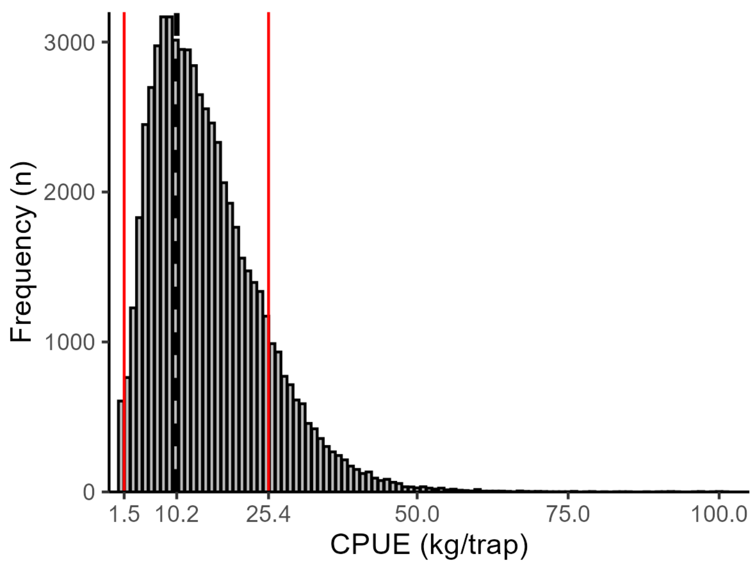

Figure 4. Distribution of raw catch per unit effort (CPUE) values calculated from landings and logbook effort values for a single trap and a 24 hour soak time. Vertical lines identify the central range (red lines) as well as the mean (black dashed line).

To obtain standardized CPUE values, landings were modelled using a generalized additive mixed-effects model (GAMM). To reduce computational demands, each LFA was modelled separately, with CPUE expressed as a function of year and fishing day. A smoothing spline with a maximum of 15 knots was applied to the fishing day variable; this level of flexibility was validated using the gam.check() function from the mgcv package in R (Wood 2017). The smoothing term was allowed to vary by year.

To account for spatial heterogeneity within LFAs, statistical district was included as a random effect on the intercept. Fisher-specific differences in motivation and harvest efficiency were addressed by including fisher identification numbers (FINs) as a second random intercept. Soak time was included as a continuous covariate using a separate smoothing spline. The number of traps used was incorporated as an offset term (ln(traps)). The error structure was specified as a Tweedie distribution with a log link to accommodate the semi-continuous nature of catch data.

The model can be written as:

$$\ln(C_{lfa}) = \beta_0 + \beta_{year} + f_1(fishing\ day, year) + f_2(soak\ time) + \ln(traps) + b_{district} + b_{FIN} + \varepsilon_{year}$$

where the model components can be interpreted as:

- C_{lfa} is the recorded catch (kg) from a given lfa,
- β_0: the mean catch (kg) per trap,
- β_{year} is the year coefficient,
- $f_1(fishing\ day, year)$ is a smoothing spline over the day of the fishing season which varies by year,
- $f_2(soak\ time)$ is a smoothing spline over gear soak time,
- $\ln(traps)$ is an offset to account for the number of traps used,
- $b_{district}$ and b_{FIN} are random effects on the intercept term applied across statistical districts and harvesters with $b \sim N(0, \sigma^2)$ in both cases, and
- ε_{lfa} is the residual error assumed to follow a Tweedie distribution.

The standardized CPUE was estimated as the predicted catch (kg) from a single trap fished for 24 hours on the 8th day of the season. This day was selected because, historically, it corresponds to the highest number of active harvesters in the sGSL (see Appendix).

Fishery-independent CPUE

CPUE from the scientific rock crab trap survey was estimated using a generalized additive model (GAM), with the number of crabs caught per trap as the response variable. In contrast to the fishery-dependent CPUE estimates, these were based on count data rather than catch weight. Catches were modelled as a function of year interacting with survey area (e.g., LFA 24, LFA 23A), along with a suite of covariates spanning environmental, temporal, spatial, methodological, and ecological factors.

Environmental covariates included water temperature and depth. Water temperatures were recorded every 15 minutes at a subset of 10 randomly selected survey stations within each area. For unsampled stations, temperatures were estimated using an inverse distance weighted (IDW) model based on the daily mean temperatures from the eight nearest stations, which also accounted for the possibility of temperature logger loss. To address multicollinearity between temperature and depth, temperature deviation (in °C) was used in the model; this was defined as the difference between the expected temperature at a given depth and the observed (or estimated) temperature (see Appendix for methodological details, Figure A2). Depth itself was also included as a covariate, centred around 20 m, which corresponds to the most common depth at which rock crabs are harvested according to logbook data. In the event that catches were affected by meteorological conditions air temperature and precipitation (treated as a binary variable) were included in the model, however air temperature subsequently removed due to strong correlation with the sampling week.

Temporal covariates included the week of the year in which each survey area was sampled. Survey timing varied across years and sites (Table 3), depending on when the lobster season ended and before the rock crab season began. Soak times also varied due to logistical and weather constraints. Although the average soak time was 24.03 hours, values ranged from 15.3 to 47.9 hours, with 90% of trap sets falling between 19.6 and 26.5 hours.

Table 3. Weeks during which rock crab trap surveys were conducted within each LFA.

Year	23A	23C	24	25	26A	26B	Mean
2021	-	29	27	-	30	31	29.2
2022	29	-	-	24	-	-	26.5
2023	29, 31	30	27	25	28	-	28.3
2024	-	29	28	-	27	-	28
Mean	29.7	29.3	27.3	24.5	28.3	31	28.3

To account for spatial differences in catch rates within LFA 24, stations inside Malpeque Bay (14 in total) were treated separately from those located offshore (25 stations), resulting in two sub-areas: 24a (Malpeque Bay) and 24b (Gulf). Methodological variation in the gear used during the first four years of the survey was addressed by including a gear type variable distinguishing between the standard scientific conical traps (with 1-inch stretched mesh) and smaller rectangular metal traps (also with 1-inch mesh).

Ecologically, the presence of lobsters in traps was hypothesized to reduce the efficiency of rock crab capture, potentially due to predator avoidance. Although the sequence of entry into the trap could not be determined, the presence of a lobster was used as a proxy to represent localized predation pressure.

The distribution of trap catches was examined using the descdist() function from the *fitdistrplus* package in R (Delignette-Muller and Dutang 2015, bootstrap n = 1,000), and was found to most closely follow a negative binomial distribution. A negative binomial GAM was therefore constructed, expressed as:

$$\ln(C_{year,area}) = \beta_0 * \beta_{year} + \beta_{gear} + \beta_{week} + \beta_{lobster} + \beta_{precipitation} + f_1(depth) + f_2(temp) + f_3(duration) + f_4(week) + \varepsilon_{year,area}$$

The model components are interpreted as follows:

- $C_{year,area}$; the number of crabs caught in a particular fishing area and year
- β_0: the mean catch per trap,
- β_{area}: Effect of survey area,
- β_{year}: Effect of survey year,
- β_{gear}: Effect of trap type,
- β_{week}: Effect of the week in which sampling occurred,
- $\beta_{lobster}$: Effect of lobster presence in traps,
- $\beta_{precipitation}$: Effect of rain on the day traps were hauled,

- $f_1(depth)$: Smoothing spline for trap deployment depth,
- $f_2(temp)$: Spline for difference between expected and observed temperatures,
- $f_3(duration)$: Spline for soak duration,
- $f_4(week)$: Spline for sampling week, and
- $\varepsilon_{year,area}$: Error term following a negative binomial distribution.

Model selection was performed using full-subset Akaike Information Criterion (AIC) comparisons to identify the best-fitting model, followed by further simplification to determine whether linear covariates could replace smoothers without loss of explanatory power. Final model adequacy was evaluated using simulated quantile residuals (DHARMa residuals; Hartig 2024).

Standardized CPUE estimates were then produced for each survey area. These were corrected to reflect a 24-hour soak duration, on week 28 of the year, using a standard scientific trap set at 20 m depth, at the standardized temperature for that depth, year, and area, and assuming lobster presence within the trap, as this was the more commonly observed condition. For LFA 24, separate standardized estimates were produced for Malpeque Bay and the offshore Gulf area. However, data limitations currently preclude the reliable estimation of CPUE in years or areas where surveys were not conducted.

FISHING PRESSURE INDICATORS

Fishing Effort

To characterize trends in fishing effort over time, the number of active licences in each LFA was calculated annually. In addition to tracking the number of active licences, effort was also measured by the number of fishing trips and trap hauls recorded in harvester logbooks, calculated on an annual basis for each LFA.

Fishery-dependent Size-frequency Distributions

In 2021, a commercial length-frequency monitoring program was initiated through a partnership between DFO and industry stakeholders, including the Prince Edward Island Fishermen’s Association (PEIFA) and the Maritime Fishermen’s Union (MFU). The objective of this initiative is to complement the dockside monitoring program, which documents total landings across the Gulf, by generating length-frequency data from a subset of commercial catches sampled across the sGSL throughout the fishing season. During the season, trained technicians visited selected wharves (Figure 5) to collect carapace width measurements from landed commercial catches.

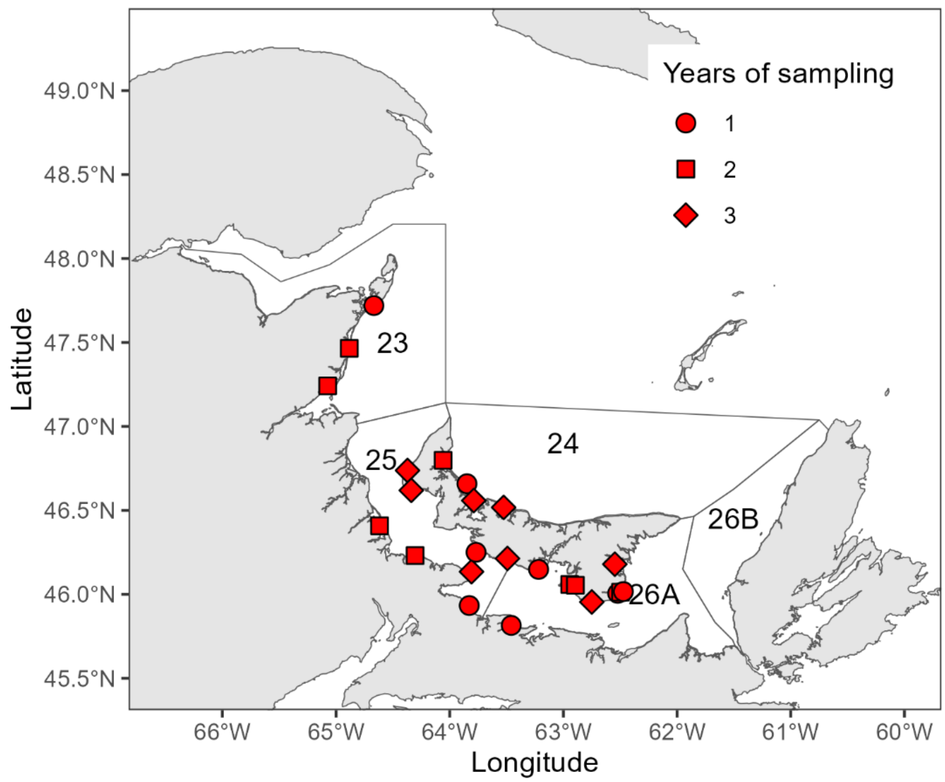

Figure 5. Wharfs at which sampling of the length frequencies from commercial rock crab landings have occurred between 2021 – 2023.

The resulting size-frequency data were analysed using a generalized linear model (GLM) to evaluate whether rock crab sizes declined significantly as the fishing season progressed. The model used a Gamma error distribution with a log link function to detect negative slopes in carapace width over time. The analysis also accounted for variability across years and among fishing areas. The model was expressed as:

$$\ln(carapace\ width) = \beta_0 + \beta_{area} * \beta_{year} * \beta_{fishing\ day} + \varepsilon$$

where model components are represented by:

- β_0: the mean carapace width,
- β_{area}: the effect of fishing area on the intercept,
- β_{year}: the effect of year on the intercept,
- $\beta_{fishing\ day}$: the slope of the carapace size according to the day of the season, and
- ε: error term following a normal distributed.

where the three main effects and their interactions allowed for the estimation of trends in size over time within each area and year. The model outputs were examined to identify LFA–year combinations that exhibited statistically significant negative slopes, indicating within-season declines in crab size in the commercial fishery.

Fishery-independent Size-frequency Distributions

If commercial fishing exerts sufficient pressure to deplete local rock crab populations, one would expect the size-frequency distribution of legally sized crabs late in the fishing season to shift toward smaller sizes compared to pre-season distributions. To assess this, commercial size-frequency data collected during the latter part of the season (i.e., after 45 days) were compared to fishery-independent size-frequency distributions obtained from the annual trap survey, which takes place prior to the opening of the commercial fishery.

This comparison was conducted for each LFA where data were available. In LFA 23, only observations from a subarea were included, as no commercial size-frequency data were collected in the whole LFA 23. Carapace widths from legal-sized crabs were modelled using GLM with a Gamma error distribution and a log link function. The model incorporated LFA, year, and sampling time (pre-fishery vs. late fishery) as explanatory variables and was formulated as follows:

$$\ln(carapace\ width) = \beta_0 + \beta_{LFA} * \beta_{year} * \beta_{sampling\_period} + \varepsilon$$

where the model components represent:

- β_0: is the mean carapace width,
- β_{LFA}: the effect of fishing area (LFA),
- β_{year}: annual variation, treated as a categorical variable,
- $\beta_{sampling\_period}$: the effect of pre-season and late-season samples, and
- ε: the error term, assumed to follow a Gamma distribution.

To evaluate whether carapace size distributions differed significantly between pre-fishery and late-season samples, estimated marginal means were computed and contrasted using the emmeans package in R, while controlling for variation across LFAs and years.

PRODUCTIVITY INDICATORS

Bio-collectors

Since 2008, bio-collectors have been deployed annually across the sGSL to assess juvenile rock crab densities (Rondeau et al. 2014, 2015; Asselin et al. 2024). Originally developed to monitor post-larval lobster settlement (Wahle et al. 2009, 2013), bio-collectors have proven effective for sampling a range of small demersal organisms, including juvenile rock crab and fish species (Wittig 2007; Hunt et al. 2017).

Each bio-collector is constructed from 10-gauge vinyl-coated wire (38 mm mesh) and measures 61.0 × 91.5 × 15.0 cm, for a total surface area of 0.55 m². The internal structure is lined with 2 mm rugged plastic mesh (PetMesh™) to retain small fauna during retrieval. Gravel (10–20 mm) is layered at the bottom of each unit, followed by cobble (10–15 cm) to simulate natural substrate. Collectors are deployed horizontally using bridles and are retrieved in the same orientation to minimize sample loss (Wahle et al. 2009).

In collaboration with the PEIFA, the Prince Edward Island Department of Fisheries, Tourism, Sport and Culture, and the Gulf Nova Scotia Fleet Planning Board, 30 collectors were deployed by commercial harvesters at each of eight coastal sites, at depths ranging from 7.5 to 11 m (Figure 6). Collectors were deployed in July and retrieved in September–October. Upon retrieval, collectors were transported to nearby wharfs, where contents were sorted. Lobsters were measured to the nearest 0.1 mm, and those over 20 mm in carapace length were also sexed and released. Crabs and fishes were frozen for later processing in the laboratory, where they were identified and measured. Rock crab carapace widths were recorded to the nearest 0.1 mm.

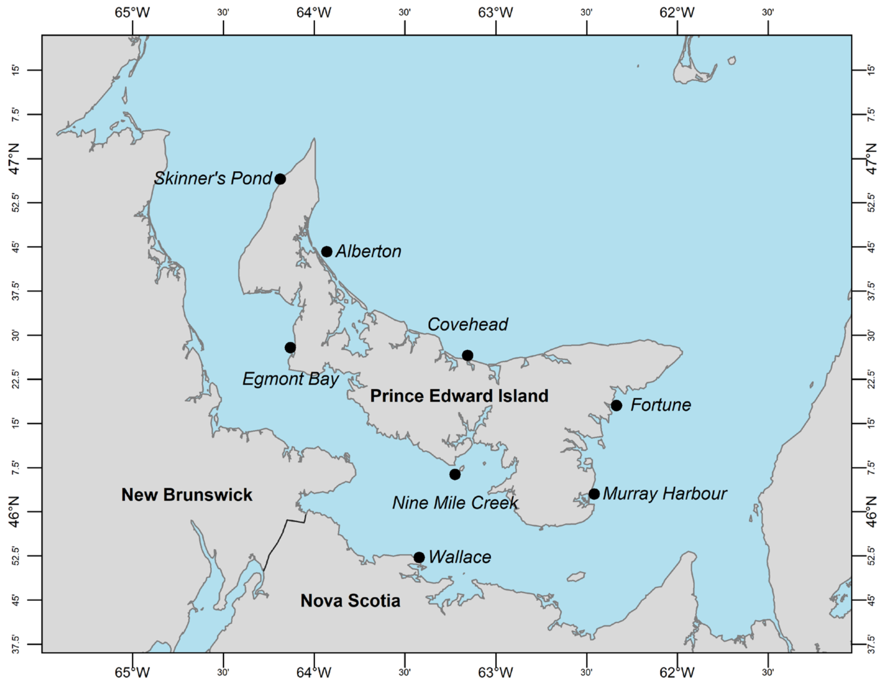

Figure 6. The locations of bio-collectors deployed annual between July and September-October.

As in previous publications (Rondeau et al. 2014; DFO 2017, 2019, 2023), only individuals measuring less than 16 mm in carapace width were considered juvenile rock crabs. Juvenile density was estimated at each site and year using a GLM with a negative binomial error distribution. This full-interaction model accounted for spatial and temporal variability across sites and years. The model is defined as follows:

$$\ln(\mu_{site,year}) = \beta_0 + \beta_{site} * \beta_{year} + \epsilon$$

where the model components are interpreted as:

- $\mu_{site,year}$: the density of juvenile rock crab for a given site and year,
- β_0: the mean number of juvenile rock crabs per collector at site *s* in year *y*,
- β_{site}: the effect of site,
- β_{year}: the effect of year, and
- ϵ: the error term assumed to follow a negative binomial distribution.

To standardize across studies, all juvenile densities were scaled to a square metre by dividing by the effective surface area of the collectors (0.55 m²).

ECOSYSTEM INDICATORS

Predator Abundance Index

Rock crab are considered a principal prey of American lobster in the sGSL (Hanson 2009; Hanson et al. 2014) and are important for lobster reproduction (Gendron et al. 2001). In a stomach-content study completed from 1999 to 2006, rock crab consumption by lobster was found to vary by season, substrate, and lobster size, varying from as little as 29% to as much as half of all stomach contents by weight (Table 4).

To assess the potential predation pressure exerted by lobster on rock crab populations, an index of total lobster biomass was developed for LFAs 25 and 26A, two of the most productive regions in the sGSL. Biomass estimates were derived from the Northumberland Strait multi-species trawl survey.

Table 4. Percentages of lobster diet comprised of rock crab according to lobster size classes (sizes are carapace lengths measured in mm). Adapted from Hanson 2009.

Size Class	% of Diet
< 50.0	41.7
50.0 - 59.9	29.0
60.0 - 69.9	40.7
70.0 - 80.9	41.6
>= 81.0	50.5

Following methods presented in Asselin et al. (2023), data from 2001 to 2009 and 2012 to 2023 were standardized for fishing gear. The sdmTMB package (Anderson et al. 2022), implemented in R (R Core Team 2016), was then used to fit a spatio-temporal random effects model. Depth measurements were centered and scaled and included as a covariate with its coefficients allowed to vary by year. A k-means triangulated mesh was used, with 300 knots and a barrier to limit correlation between survey areas separated by land.

Models considered included those with linear and non-linear depth relationships, with depth coefficients considered either fixed in time or allowed to vary annually, modelled as a random walk. For annually varying depth coefficients, three to six B-spline basis functions were tested, obtained from the bs function from the splines R package. For the spatio-temporal effect, a Matérn covariance function and a first-order auto-regressive process (AR-1) were assumed for the spatial and temporal components, respectively. A Tweedie distribution was assumed for the observation error term.

Models were compared using AIC and k-fold cross validation. For the cross-validation, five folds were used, wherein 80% of the data were used to predict the remaining 20% for five model runs. Model predictions were compared using mean absolute error (MAE) and root mean squared error (RMSE). In contrast to the model used in Asselin et al. (2024), the number of B-spline basis functions was reduced from six to five based on assessments of the model's AIC, MAE and RMSE. Formally, the statistical model is:

$$\ln(\mu) = \alpha + \sum_{j=1}^{5} \beta_{(j,y)} B_j(d) + \Omega_y(p) + \epsilon_{(y,p)} + \ln(a)$$

where:

- α is an intercept parameter,
- $\beta_{(j,y)}$ are time-varying coefficients, indexed by 5 B-spline basis functions,
- B_j indexed by j and year y over water depth d,
- $\Omega_y(p)$ is a time-varying spatial process defined over coordinate space p,
- $\epsilon_{y,p}$ is an independent Gaussian error term over time y and space p. and,
- $\ln(a)$ is an offset term for trawl swept area a, in square meters.

Annual model residuals were examined for systematic spatial bias. Biomass was predicted using a 0.5 km grid.

Climate Considerations

Beyond changes in predator abundance, rising seafloor water temperatures may also influence rock crab populations in the sGSL. A time series of modelled seafloor water temperatures is available at a 500 m resolution across the region (Chassé et al. 2014), based on observations collected with Conductivity-Temperature-Depth (CTD) sensors during annual DFO research surveys. Using this modelled dataset, average annual bottom temperatures were estimated for each LFA during the months of June and September.

These temperature data were analyzed in two ways: Independently, to test for significant long-term trends in bottom temperature within each LFA during the fishing season; and in conjunction with standardized catch-per-unit-effort (CPUEstd) values, to explore potential correlations between temperature and rock crab abundance.

To evaluate temperature trends, a generalized linear model (GLM) was fitted in R, using temperature as the response variable and a three-way interaction between year, month, and LFA as the explanatory terms. The model was used to determine whether statistically significant trends in temperature existed over time. These relationships were assessed using the emtrends() function from the emmeans package (Length 2020).

RESULTS

ABUNDANCE INDICATORS

Landings – Directed Fishery

Before 2000, rock crab landings were not differentiated by fishery type and reflected a combination of bycatch from the lobster fishery and removals from the developing directed rock crab fishery. During the exploratory phase, annual landings averaged around 500 t, increasing to approximately 1,000 t between 1984 and 1992. Beginning in the mid-1990s, exploratory licence holders began transitioning to permanent licences, resulting in a steady increase in landings, which rose to roughly 5,000 t by the time the directed fishery was formally established in 2000.

The directed rock crab fishery peaked in 2001, reaching its maximum recorded catch of 5,670 t. Landings remained relatively stable at approximately 5,000 t annually until 2011 (Figure 7). Since then, landings have declined steadily at an average rate of about 7% per year, reaching 1,438.2 t in 2023.

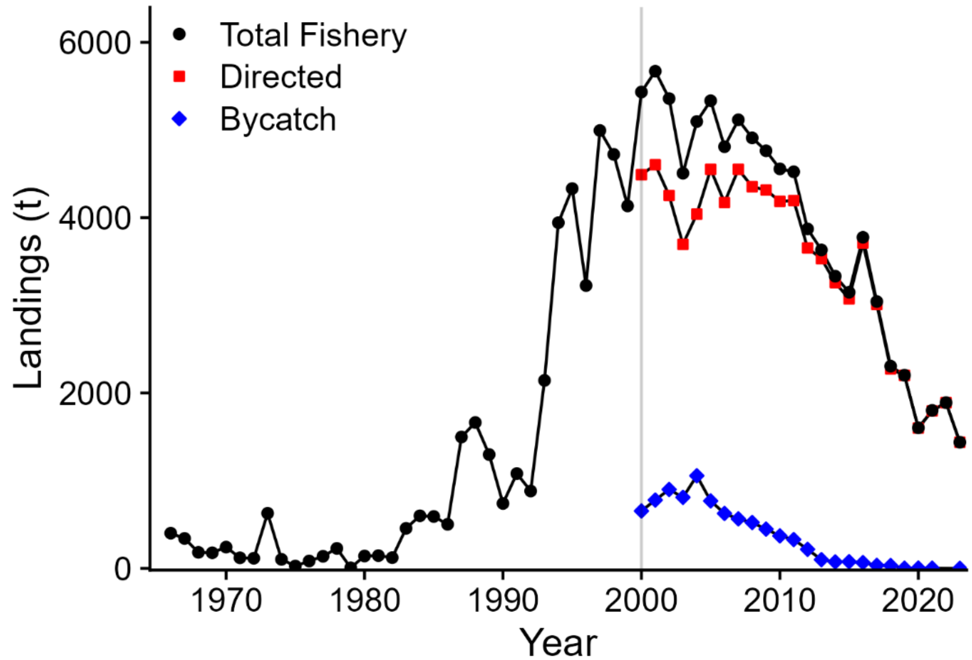

Figure 7. Annual landings separated by fishery. Landings prior to 2000 were not classified as either bycatch or directed.

Landings from the directed fishery have primarily originated from LFA 26A (Figure 8), which contributed 44.4% of total landings in 2000 and has remained the dominant source throughout most of the fishery. In 2023, LFA 26A accounted for 35.1% of total directed landings. LFA 25, the second largest contributor, accounted for 25.6% of landings in 2000 but has increased steadily over time, surpassing LFA 26A in 2023 with 39.8% of total landings. Landings from LFA 23 have remained relatively stable, contributing approximately 20% annually. In contrast, LFA 24 consistently accounts for a small proportion of the catch, averaging about 4% of total directed landings. Landings from LFA 26B have been negligible since the start of the fishery and are not considered further in this report (see appendix, Table A1).

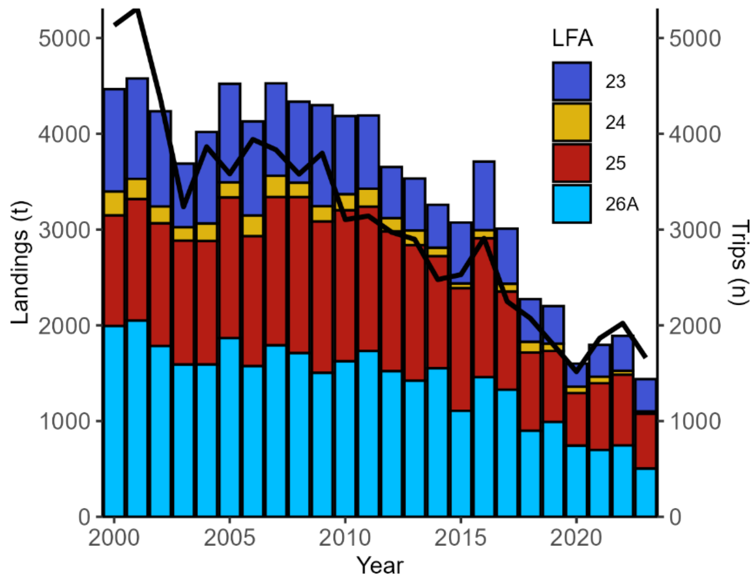

Figure 8. Landings from the directed fishery separated by LFA. Black line represents the total number of trips recorded by the directed fishery per year.

Landings – Bycatch

When the directed fishery was established in 2000, bycatch sales represented 12.0% of the total landed weight of rock crab in the sGSL (Figure 9). This proportion increased to a peak of 20.7% in 2004 before gradually decreasing to its current negligible level relative to total registered landings. The majority of rock crab bycatch sold originated from LFA 26A, followed by LFAs 23 and 25. Bycatch sales from LFA 24 have remained minimal throughout the history of the directed fishery, while LFA 26B has contributed negligibly since the outset (see Appendix, Table A2).

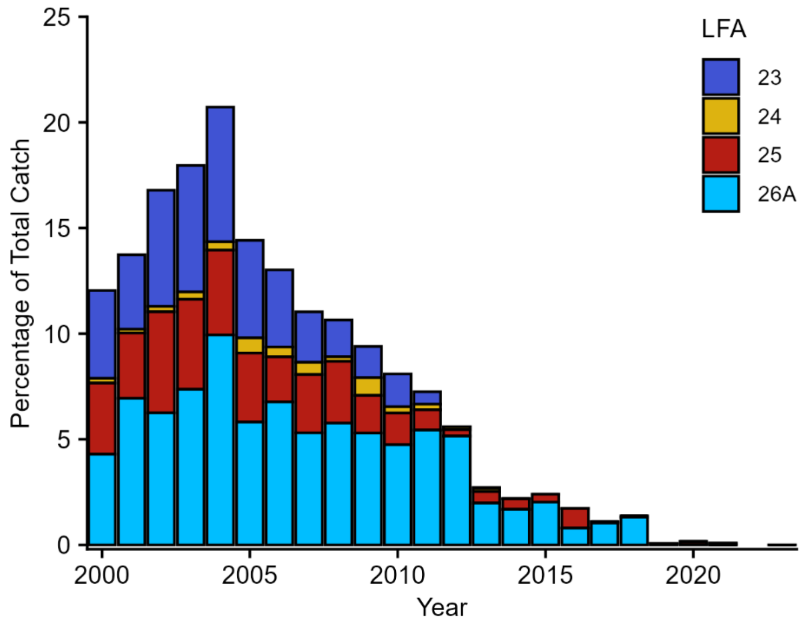

Figure 9. Bycatch as a percentage of the total annual landings of rock crab in the sGSL.

However, the quantity of rock crab collected and retained for use as bait by lobster harvesters remains unknown. A recent bycatch study on the sGSL lobster fishery (Boudreau and Hanley 2023) assessed all species captured in lobster traps over two seasons (spring and summer). Over the sampling period, the most common bycatch species was rock crab and male rock crabs eligible to be used as bait represented 3.5% (by weight) of the total legal-sized lobster landings (as defined by 2015 regulations). Though rock crab bycatch is influenced by numerous factors such as trap type, fishing effort, and lobster abundance, the extent to which rock crabs are caught as bycatch and subsequently used as bait remains poorly quantified and may be substantial, despite bycatch sales dropping to negligible levels in recent years.

Individual Allotment Attainment

The proportion of harvesters achieving their individual allotment has declined substantially since the onset of the directed fishery. In 2000, an average of 49% of licence holders in LFAs 23, 25, 26A, and 26B reached their allotments (note that LFA 24 was excluded, as individual allotments were not included in licence conditions until 2015). By 2023, this proportion had dropped to an average of just 10% across these LFAs (Figure 10). The sharpest decline occurred in LFA 24, where allotment attainment fell from a peak of 33% in 2016 to 0% by 2023. A similar trend was observed in LFA 26A, where only one harvester met their allotment in 2023, down from nearly 80% in 2000 (Figure 10).

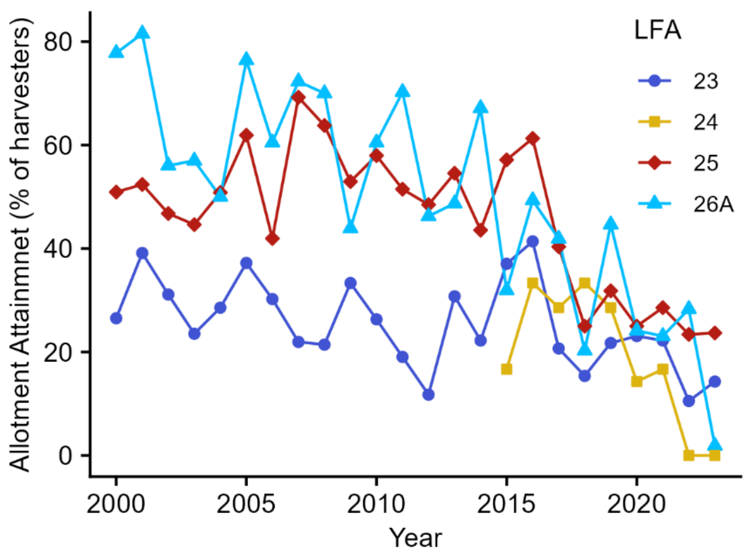

Figure 10. The percentage of active rock crab licence holders in each LFA that reached 90% of their individual allotment.

Harvest Limit Rates

An accelerated failure time model was used to evaluate the number of fishing days required to harvest 9,000 kg of rock crab, accounting for differences in trap limits across LFAs. Clear differences emerged in the fitted event times among LFAs (Figure 11). On average, harvesters in LFA 24 required the most time to reach the 9,000 kg threshold (16.2 days), while those in LFA 26A required the fewest (6.7 days). These rates, however, were not consistent throughout the time series.

Across most LFAs, catch rates were fastest between 2004 and 2017, with both earlier and more recent years requiring more fishing days to reach the harvest limit. The most stable rates were observed in LFA 23, where harvesters initially needed ~11 days but quickly improved to ~8 days, a level that remained relatively constant over time. LFAs 24 and 25 showed an initial decline in the number of days required to reach the harvest limit within the first 3–5 years, followed by a stable period lasting over a decade. In both LFAs, harvest rates have since increased to levels similar to those observed at the start of the series. In LFA 26A, harvest rates remained stable at ~7 days for the first 17 years, before increasing by approximately 75%, reaching 11.5 days in 2023.

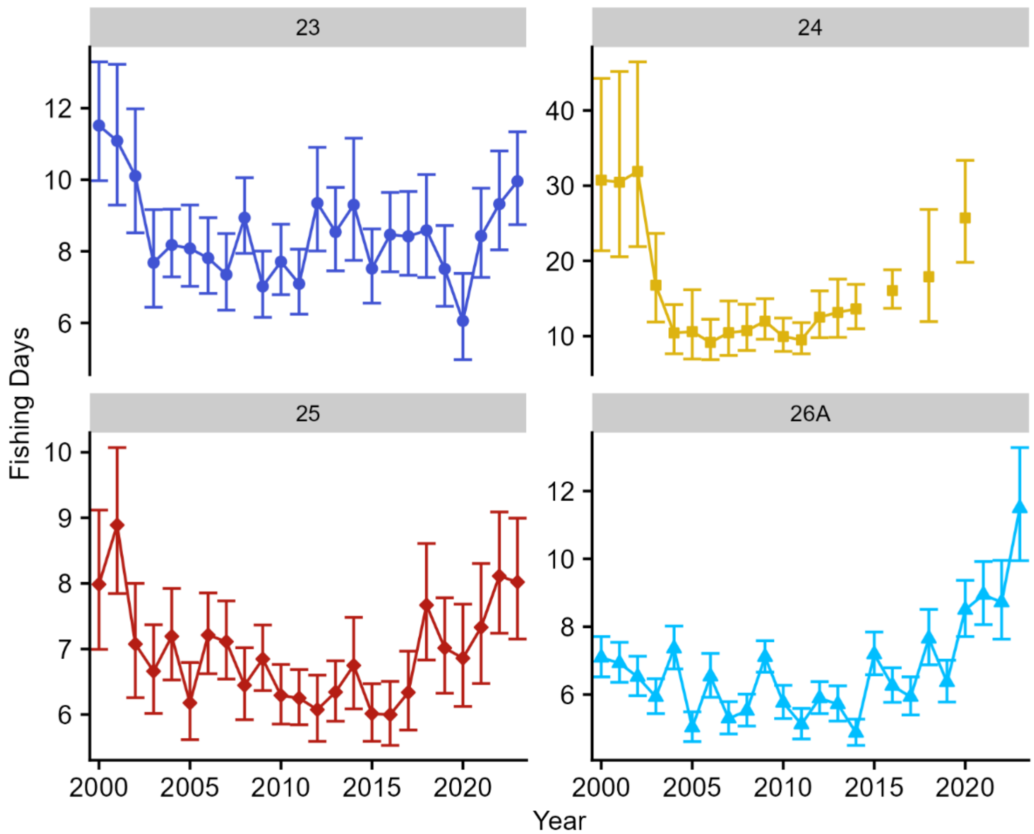

Figure 11. Estimated time (active fishing days) required for rock crab harvesters to land 9,000 kg using 100 traps. Error bars represent 95% confidence intervals.

Fishery-dependent CPUE

Each of the LFA specific GAMMs fit the data well, producing the expected residual distribution (Figure A3 through Figure A6). Standardizing fishery-dependent CPUE estimates were then produced by controlling for factors such as soak time (Figure A7), day of the fishing season (Figure A8), number of traps, fishing district, and harvester ID, the $CPUE_{std}$ values show a common pattern across LFAs. Initially, $CPUE_{std}$ increases over 2 to 3 years before stabilizing for approximately 9 to 10 years (Figure 12).

Following this stable period, trends diverge among LFAs. In LFAs 23 and 25, inter-annual variation increases, with $CPUE_{std}$ eventually declining to levels comparable to the beginning of the time series. In contrast, LFAs 24 and 26A exhibit a downward trend in $CPUE_{std}$, with values in recent years falling below those observed at the start of the series. While greater uncertainty in the 2023 estimates for LFA 24 limits confidence in asserting a significant decline since 2000, the decrease in $CPUE_{std}$ for LFA 26A in 2023 is statistically significant compared to 2000.

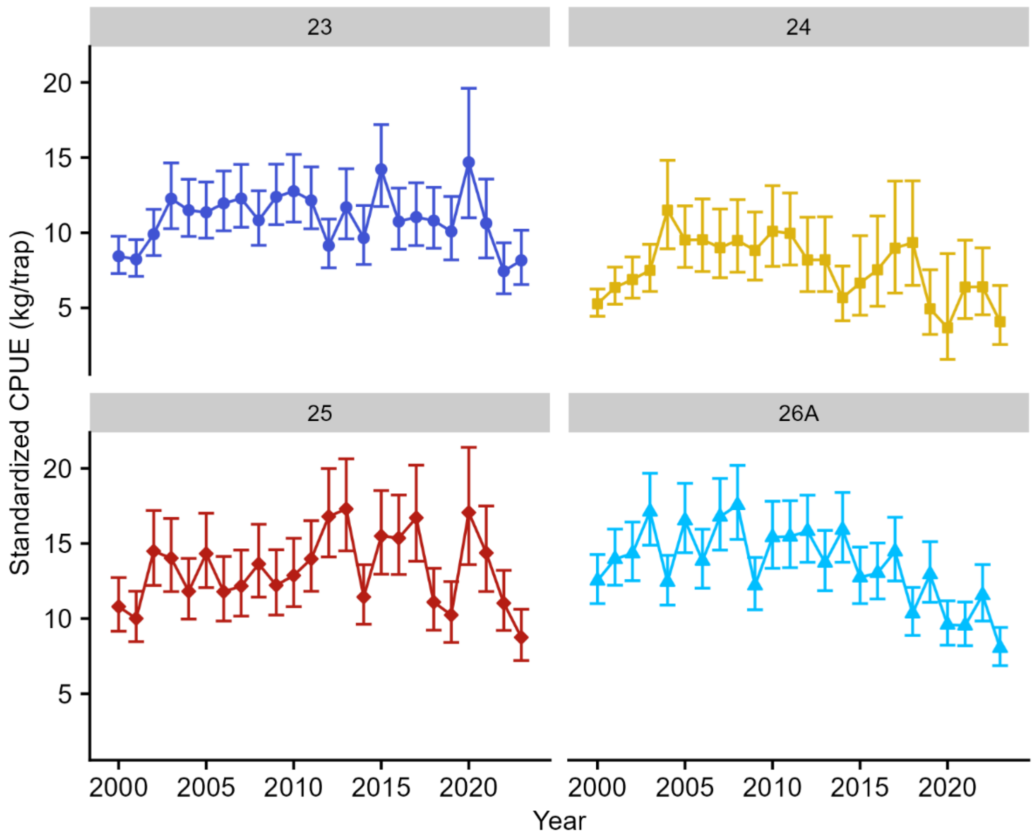

Figure 12. Standardized rock crab CPUE for each LFA within the sGSL.

Fishery-independent CPUE

During model selection for the $CPUE_{std}$ GAM, precipitation was found not to improve model fit and was removed. Similarly, trap soak time did not affect catch rates, likely because soak times showed little variation. Traps were typically retrieved after 24 hours whenever possible. The resulting best-fitting model exhibited well behaved residuals and provided an good description of the variation observed in the trap catches (see appendix, Figure A9)

The best-fitting model included an interaction between year and area, as well as the covariates lobster presence, gear type, week, water temperature residuals, and depth (Figure A10). For parsimony, week was modeled as a linear effect rather than non-linear. In this simplified model, lobster presence in traps significantly reduced rock crab catches by over half (beta = -0.98), while using smaller square traps reduced catches by more than 95 percentage points (beta = -3.1).

Catch rates per trap increased significantly as the fishing season progressed (week effect), and catches were significantly higher in LFA 24 within Malpeque Bay compared to open Gulf waters (Figure 13). Among environmental variables, the highest catches occurred at shallower depths, with catch rates declining sharply below 40 meters (see Appendix). For water temperature deviations, catches peaked at temperatures about 2.5 °C above the expected values for a given depth, LFA, and year, but decreased substantially when temperatures deviated more than ~5 °C in either direction (see Appendix).

After controlling for these covariates, the $CPUE_{std}$ showed an overall negative trend across most LFAs over time. In LFA 23A (Baie des Chaleurs), catches declined by 58%, from 9.1 crabs/trap in 2022 to 3.8 crabs/trap in 2023. Similarly, in LFA 23C, catch rates dropped 96% from 6.4 crabs/trap in 2021 to 0.2 crabs/trap in 2023. Although catch rates more than doubled in 2024, they remained low at 0.68 crabs/trap.

In LFA 25, catch rates decreased by 25%, from 3.0 crabs/trap in the first year sampled to 2.2 crabs/trap in 2023. In LFA 24, catches were initially high in Malpeque Bay (12.7 crabs/trap) but declined 31% to 8.7 crabs/trap and remained stable through 2024 (8.5 crabs/trap). A similar decline occurred in the open water section of LFA 24, where catches fell 34% from 2.5 crabs/trap in 2021 to 1.7 crabs/trap in 2023. Unlike Malpeque Bay, catch rates in open waters continued to decline by 62% from 2023 to 2024, reaching 0.6 crabs/trap.

LFA 26A experienced a 46% decrease between 2021 and 2023, with catches dropping from 8.9 to 4.8 crabs/trap. However, catches rebounded sharply in 2024, increasing 210% to 14.9 crabs/trap.

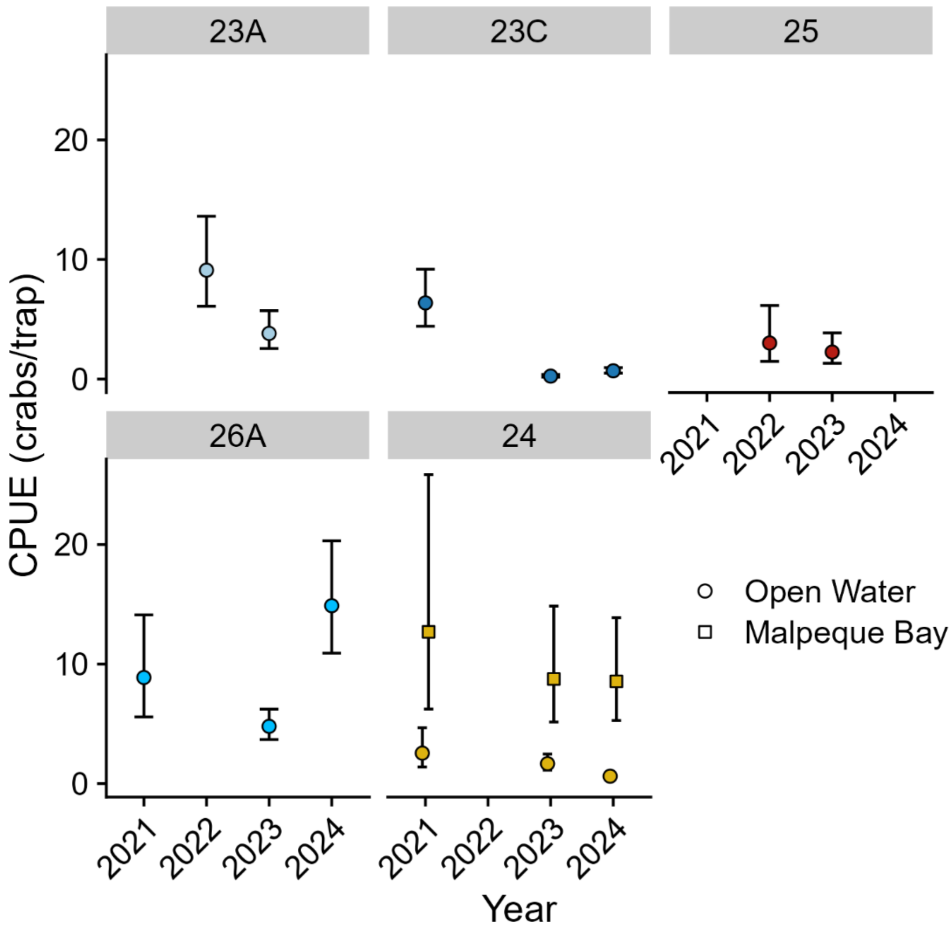

Figure 13. Standardized fishery-independent CPUE estimates in survey areas within the sGSL.

FISHING PRESSURE INDICATORS

Fishing Effort – Active Licences

Although the number of licences issued for the directed fishery has gradually decreased across all LFAs over the past two decades, the most notable reductions have occurred in LFAs 24 and 26B (Figure 14). At the same time, not all licence holders have remained active in the fishery.

The proportion of active licences has declined significantly over time (binomial GLM, overall $\beta_{year} = -0.11$, $p < 0.01$).

This downward trend varied in slope across LFAs but remained statistically significant in all areas except LFA 24. The lack of significance in LFA 24 is likely due to the removal of several inactive licences between 2013 and 2015, following a DFO management decision not to renew inactive licences in that area. This action may have incentivized remaining harvesters to maintain active licence status in order to retain access to the fishery.

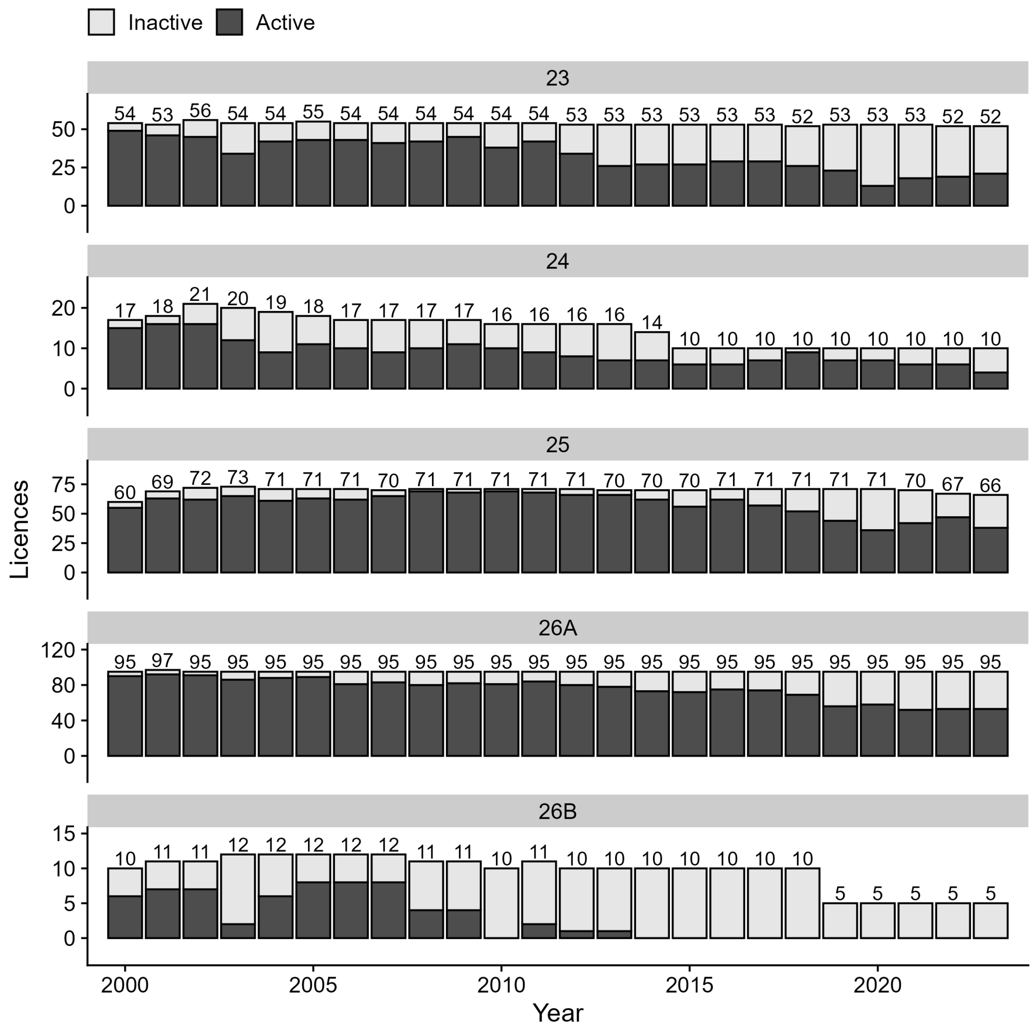

Figure 14. Rock crab licences issued annually within the sGSL. Active licences represent licence holders with at least one recorded landing.

Fishing Effort – Trips and Trap Hauls

Two clear patterns emerge from the time series of fishing trips and total annual trap hauls by LFA. First, the number of trips is closely correlated with the number of trap hauls (Figure 15), which is expected given the stability of LFA-specific trap limits throughout the history of the directed fishery. Most harvesters use the maximum number of traps allowed. The exceptions are LFAs 24 and 26B, where harvesters are permitted to use 150 and 100 traps per trip, respectively, but typically use fewer, averaging 130 traps in LFA 24 and 86 in LFA 26B.

The second notable trend is a steady decline in both effort measures over the course of the fishery. A linear regression of trip numbers over time shows the steepest annual decline in LFA 23, where trips decreased from 1,608 in 2000 to just 342 in 2023. A reduction of approximately 51 trips per year. In contrast, LFA 24 exhibited a more gradual decline, from 406 trips in 2000 to 76 in 2023, averaging a decrease of 8 trips per year.

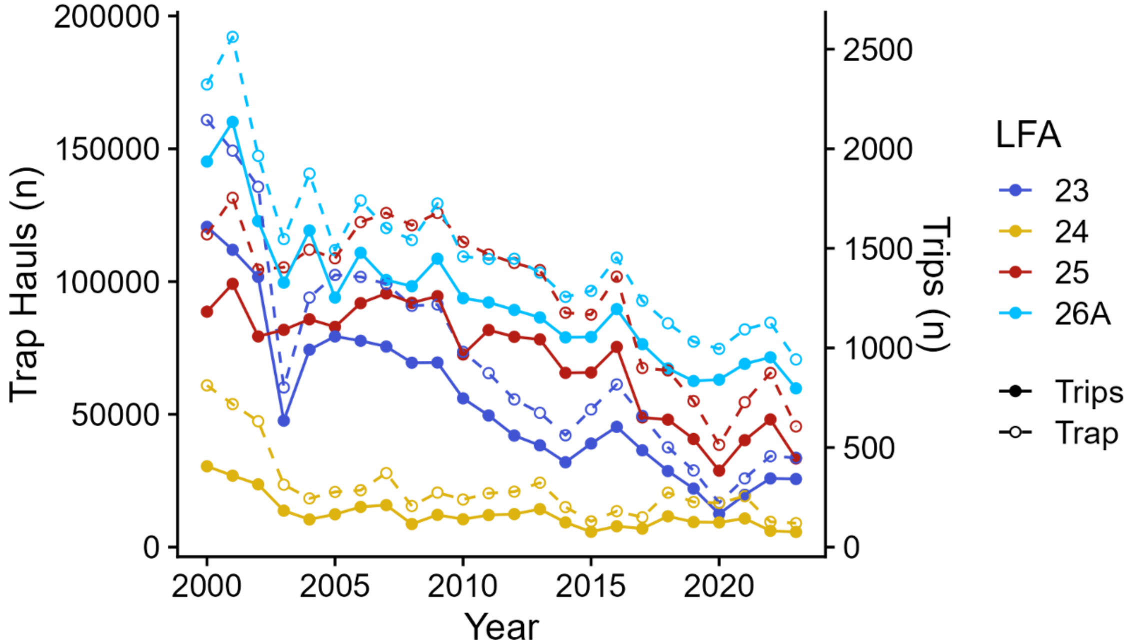

Figure 15. The number of trips and trap hauls completed within each LFA over the course of the directed rock crab fishery.

Fishery-dependent Size-frequency Distributions

A minimum of five sampling events was conducted in each designated LFA, except for LFA 23 in 2022, where logistical constraints and low harvester participation prevented sampling. Similarly, declining harvest activity in the Baie des Chaleurs in recent years has meant that recent LFA 23 samples have been limited to the Gulf side of the Acadian Peninsula (LFA 23C).

The model fitted to the size-frequency distributions of commercial rock crabs indicated that, in most cases, the size of landed crabs did not decline consistently over the course of the fishing season. In fact, in LFAs 23, 24, and 25, the average size of commercial rock crabs increased as the season progressed, suggesting no evidence of localized depletion of legal-sized crabs in the sGSL (Table 5).

While significant negative trends were detected in three LFAs (23, 25, and 26A), only LFA 26A showed a consistent pattern across years. Even in this case, however, the magnitude of the seasonal decline was relatively minor, with the average size of landed commercial crabs decreasing by less than 1 mm over the fishing season.

Table 5. Summary of dockside length-frequency program. Trends, and their associated 95% CI, are the modelled relationships between carapace widths and day of the season (GLM) and represent the change in average carapace width (CW) per year.

LFA	Year	Sampling Events	First Sample	Size Range (mm)	Mean CW (mm)	Sample size	Trend	LCL	UCL
23	2021	5	Aug 11 - Oct 18	102 - 130	114.5	1072	0.0006	0.00046	0.00074
23	2022	NA	-	NA	NA	NA	NA	NA	NA
23	2023	5	Aug 28 - Oct 12	102 - 136	116	932	-0.00035	-0.00055	-0.00015
24	2021	8	Jul 14 - Sept 24	102 - 131	108.2	1325	0.00015	0.00002	0.00027
24	2022	10	Jul 14 - Sept 08	102 - 138	111.8	1936	0.00138	0.00126	0.00149
24	2023	7	Jul 21 - Oct 06	102 - 132	108.6	1268	0.00031	0.00021	0.00041
25	2021	27	Jul 01 - 11-18	102 - 140	112.1	7192	-0.00012	-0.00018	-0.00006
25	2022	18	Jun 29 - 11-23	102 - 135	111.1	3809	0.0004	0.00031	0.00049
25	2023	15	Jun 27 - 11-30	102 - 136	113.3	4270	0.00076	0.00068	0.00084
26A	2021	23	Aug 03 - Oct 05	108 - 139	114.5	7466	-0.00008	-0.00016	-0.00001
26A	2022	30	Aug 02 - 11-03	108 - 137	116.9	8336	-0.00012	-0.00017	-0.00008
26A	2023	21	Aug 08 - 11-23	108 - 135	115.5	5032	-0.00007	-0.00011	-0.00002

Fishery-independent Size-frequency Distributions

In contrast to the fishery-dependent analysis, comparisons of pre- and late-season size-frequency samples revealed a greater number of significant differences (Figure 16). However, these differences were generally small in magnitude and did not consistently indicate a decline in size.

In LFA 23, significant decreases in mean carapace width were observed in both 2021 and 2023, by 1.9 mm and 3.5 mm respectively. No significant changes were detected in LFA 24. In LFA 25, results were mixed: in 2022, the mean size increased by 2.8 mm, whereas in 2023 it decreased by 1.1 mm. LFA 26A, similar to LFA 23, showed small but significant decreases in mean size between the pre- and late-season samples in both 2021 (0.8 mm) and 2023 (1.4 mm).

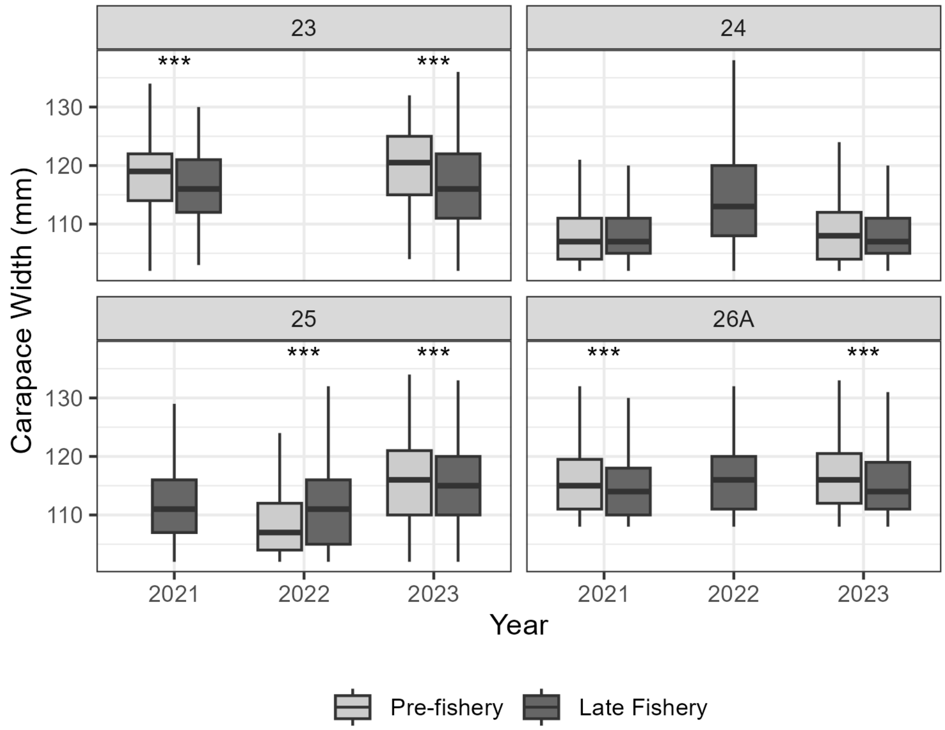

Figure 16. Rock crab carapace widths from rock crabs sampled during the rock crab trap survey (pre-fishery) and during the second half of the commercial fishing season (late fishery). Asterisks identify significant differences between the pre- and late fishery samples according to P-values adjusted for multiple comparisons.

PRODUCTIVITY INDICATORS

Bio-collectors

The highest juvenile rock crab densities and inter-annual variability were observed in Alberton and Covehead (LFA 24) between 2008 and 2017. The maximum recorded density occurred in Alberton in 2012, with 145.3 crabs per m² (95% CI: 122.1–172.8; Figure 17). Since 2017, juvenile densities in LFA 24 have decreased and become less variable, with a maximum of only 26.9 crabs per m² (95% CI: 22.5–32.1) recorded in Covehead in 2017.

In LFA 26A, juvenile densities at Nine Mile Creek and Wallace were consistently low, remaining below 1.1 crabs per m² throughout the time series. Like Alberton and Covehead in LFA 24, sites in LFA 26A such as Murray Harbour and Fortune showed high inter-annual variability in juvenile densities until around 2015, after which densities stabilized. At Fortune, this stabilization occurred at a lower level than in earlier years, while Murray Harbour stabilized at a slightly higher density of approximately 5.3 crabs per m².

In LFA 25, juvenile densities also varied across sites. Juvenile rock crabs were never detected at Cape Egmont throughout the study period, whereas at Skinner's Pond, located on the west coast of PEI, densities have remained relatively stable at approximately 6.2 crabs per m² since 2013.

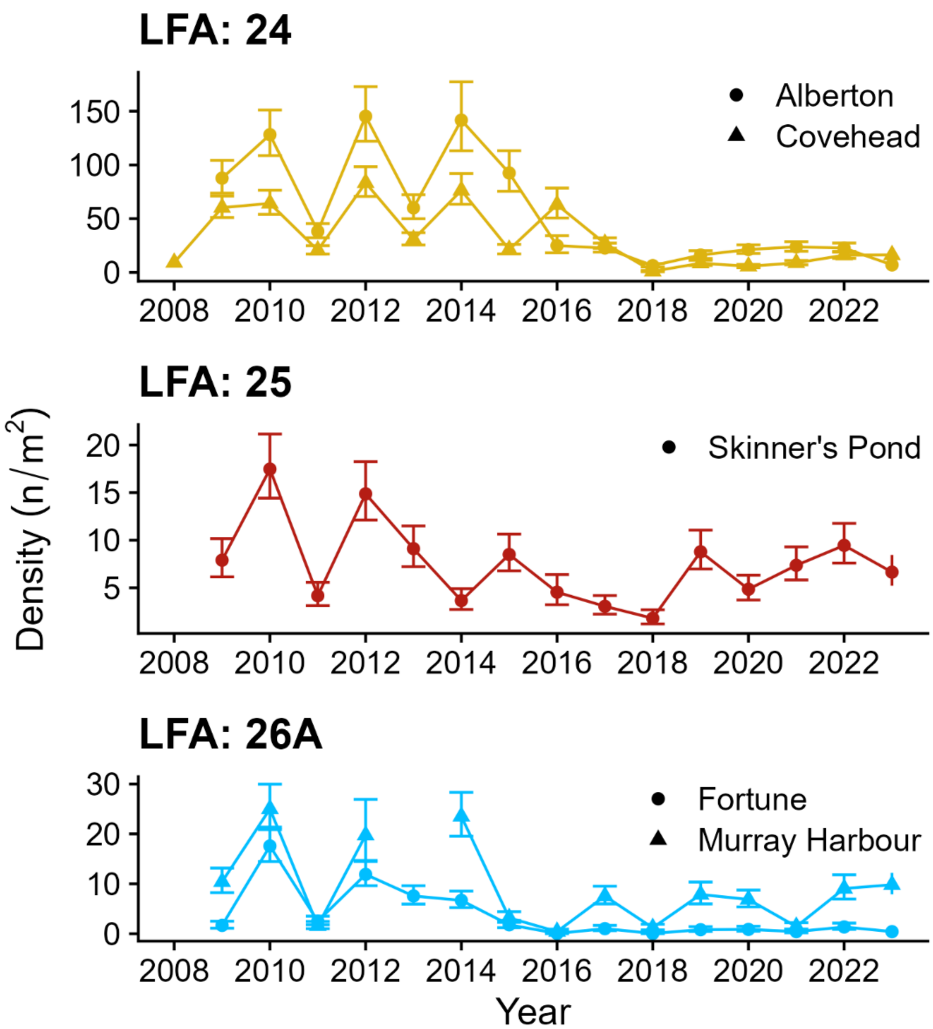

Figure 17. Mean densities of rock crab observed in biocollectors deployed annually between July and September-October.

ECOSYSTEM INDICATORS

Predator Abundance Index

Model results indicate that lobster biomass has steadily increased in LFAs 25 and 26A, rising from a low of approximately 6,500 t in 2003 (95% CI: 5,000–9,000) to a peak of 99,000 t in 2021 (95% CI: 82,500–119,000; Figure 18). This increase reflects both higher lobster densities and an expansion of their spatial distribution within each LFA (Figure 19). Notably, the most pronounced density increases have occurred in the central regions of the Northumberland Strait. Areas that previously supported sparse lobster populations now exceed 250 kg/km² in density. These findings suggest that natural mortality of rock crab in the most productive areas of the sGSL (LFAs 25 and 26A) is likely increasing due to elevated predation pressure from lobster.

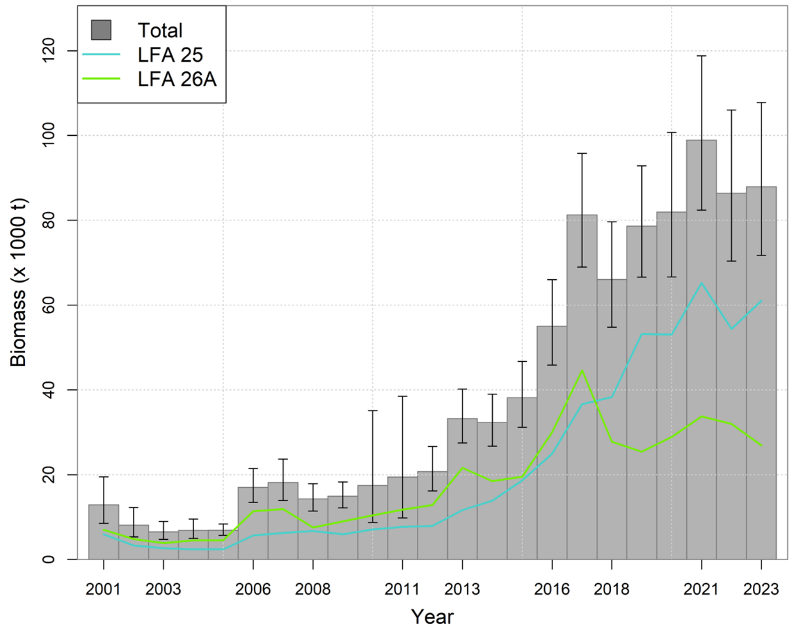

Figure 18. Estimated lobster biomass within LFAs 25 and 26A based on data from the Northumberland Strait multi-species trawl survey and a spatial-temporal random effects model with sdmTMB.

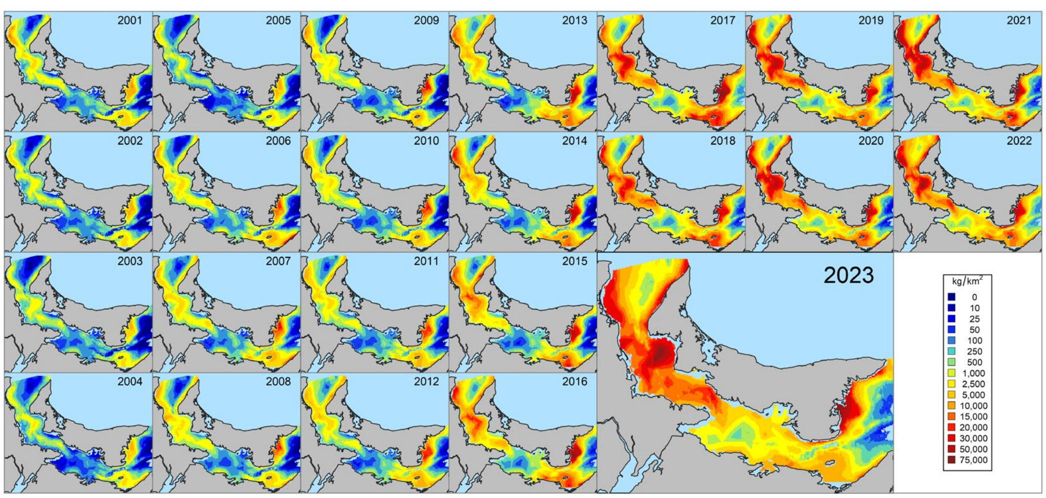

Figure 19. Estimated lobster densities based on data from the Northumberland Strait multi-species trawl survey and a spatial-temporal random effects model with sdmTMB.

Climate Considerations

Throughout the temperature time series, LFAs 24 and 26B consistently emerged as the coolest regions within the sGSL, with overall mean bottom temperatures ranging from 1.26 °C to 3.01 °C and 1.93 °C to 4.05 °C in June and September, respectively (Table 6). In contrast, LFAs 25 and 26A were the warmest, with mean temperatures ranging from 8.84 °C and 6.55 °C in June to 14.01 °C and 12.23 °C in September respectively. These two LFAs also exhibited the greatest seasonal increase in temperature between June and September. By comparison, LFA 23 showed a smaller increase, rising from a mean of 4.11 °C in June to 7.41 °C in September.

Trend analysis revealed only one statistically significant temperature increase over time: LFA 25 in September, which showed a positive slope, with bottom temperatures rising by approximately 0.25 °C per year.

Table 6. Mean and slope for linear regressions of a sea bottom temperatures time-series spanning 1985-2023. Significant slopes are indicated by an asterisk. Lagged correlation coefficients between sea bottom temperatures and annual $CPUE_{std}$ estimates for the rock crab directed are provided for time-lags of 0-7 years.

Season	LFA	Mean Temperature (°C)	Slope	Lagged Correlation Coefficient (r)							
				0 yr	1 yr	2 yr	3 yr	4 yr	5 yr	6 yr	7 yr
June	23	4.11	-0.019	-	-	-	-	-	-	-	-
September	23	7.41	0.028	-	-	-	-	-	-	-	-
June	24	1.26	0.011	-	-	-	-	-	-	-	-
September	24	3.02	0.022	-	-	-	-	-	-	0.54	-
June	25	8.84	-0.005	-	-	-	-	-	-	-	-
September	25	14.01	0.046*	-	-	-	-	-	-	0.45	-
June	26A	6.55	0.019	-0.43	-	-	-0.46	-	-	-	-
September	26A	12.23	0.01	-	-	-	-	-	0.51	-	-
June	26B	1.93	0.022	-	-	-	-	-	-	-	-
September	26B	4.05	0.023	-	-	-	-	-	-	-	-

An analysis of correlations between fishery-dependent $CPUE_{std}$ and bottom temperatures in June and September showed no consistent patterns across LFAs or seasons. For instance, $CPUE_{std}$ values in LFAs 24 and 25 were positively correlated with mean September bottom temperatures from six years earlier (Table 6), while in LFA 26A, a positive correlation was observed with September bottom temperatures from five years prior. Additionally, $CPUE_{std}$ in LFA 26A during June were negatively correlated with bottom temperatures from three years prior, as well as with non-lagged temperatures. No significant correlations were detected for LFA 23 in either season.

Overall, the lack of consistent relationships between $CPUE_{std}$ and bottom temperatures across LFAs and time lags suggests that rock crab abundance indices in the sGSL are not strongly influenced by interannual variations in bottom water temperature.

SOURCES OF UNCERTAINTY

Until recently, all available information on the rock crab fishery was exclusively fishery-dependent, derived from harvester logbooks and sales records collected by dockside monitoring companies. These two data sources are combined to produce the primary index of abundance: CPUE. This process is subject to delays in data availability and presents numerous opportunities for errors or omissions, particularly in the logbook data.

Moreover, trends in CPUE may not directly reflect changes in rock crab abundance. They are influenced by a range of external factors including management decisions, market conditions, and socio-economic considerations. For instance, since many rock crab licence holders also possess lobster and/or snow crab licences, outcomes in these other fisheries can significantly affect their participation in the rock crab fishery. A strong lobster season may lead a harvester to forgo fishing rock crab, while in other years, a harvester may engage in the rock crab fishery only partially, with no intention of harvesting their full allocation but simply to supplement income in the short term.

CPUE as an index of abundance is inherently uncertain. It may be affected by phenomena such as hyperstability (Hutchings 1996), or by direct and indirect external biases. While standardising CPUE (e.g., Restrepo et al. 1998) can mitigate some of these concerns, such estimates should be interpreted cautiously in the absence of ground-truthing to confirm a linear relationship between CPUE and true abundance.

The dockside length-frequency monitoring program only samples landed crabs, theoretically providing an accurate size profile of commercial landings, but offering no insight into the broader population structure. Still, it remains a useful indicator of seasonal shifts in commercial crab sizes and provides a reference point for comparisons with pre-season size distributions. Future analyses of size-frequency distributions would benefit from an at-sea sampling program, which would expand spatial coverage and include females and sub-legal size classes.

Currently, the only source of juvenile abundance data comes from the bio-collector program. Although these collectors have proven effective in capturing juvenile crabs, the program was originally designed to monitor lobster recruitment. As such, sampling sites were chosen for their suitability for juvenile lobsters, which may not coincide with optimal habitats for rock crab. Sites with persistently low juvenile crab densities may reflect sub-optimal habitat for rock crab rather than an indication of losses in recruitment and could be excluded from analyses.

CANDIDATE INDICES FOR AN LRP

As outlined above, the available information for the rock crab stock is largely fishery-dependent. While new fishery-independent (e.g., the rock crab trap survey) and semi-independent (e.g., dockside length-frequency monitoring) data collection programs are now underway, their datasets are not yet sufficiently established to inform the development of a Limit Reference Point (LRP). As such, any candidate LRP at present must rely on fishery-dependent data.

Among the available indices, landings and allotment attainment rates are unsuitable for defining an LRP, as they are highly influenced by external drivers such as market conditions, pricing, and the availability of more lucrative species. This leaves only the abundance indices, harvest limit rate and $CPUE_{std}$, as viable candidates.

The harvest limit rate, defined as the average number of days required for an LFA to reach 9,000 kg of landings, shows potential as an indicator of stock abundance. However, its reliance on harvester-level data results in small sample sizes and high uncertainty, particularly in LFAs with low participation such as LFA 24. In contrast, the $CPUE_{std}$, calculated from trip-level data, provides a larger dataset and benefits from greater statistical power. The inclusion of random effects (harvester FIN and statistical district) in the CPUE model facilitates information sharing across years and areas, improving the accuracy of estimates even in strata with sparse data. For these reasons, $CPUE_{std}$ is currently the most robust index on which to base an LRP.

Under the one-stock-one-LRP principle outlined in the Fish Stock Provisions of the Fisheries Act (s.6.1(2)), $CPUE_{std}$ values from individual LFAs must be aggregated into a single index representative of the stock as a whole in the sGSL. This was done using a predict-then-aggregate approach (Campbell 2015; Hoyle et al. 2024), whereby LFA-specific CPUE estimates were combined into an area-weighted average, based on the extent of optimal rock crab habitat (10–40 m depth; Rondeau et al. 2014) in each LFA (Figure 20). Confidence intervals were generated via bootstrapping.

The resulting sGSL-wide CPUE trend shows a 30% increase during the first three years (from ~9 kg/trap to ~12 kg/trap), followed by an 11-year plateau, and then a gradual decline to a 2023 value of 7.38 kg/trap.

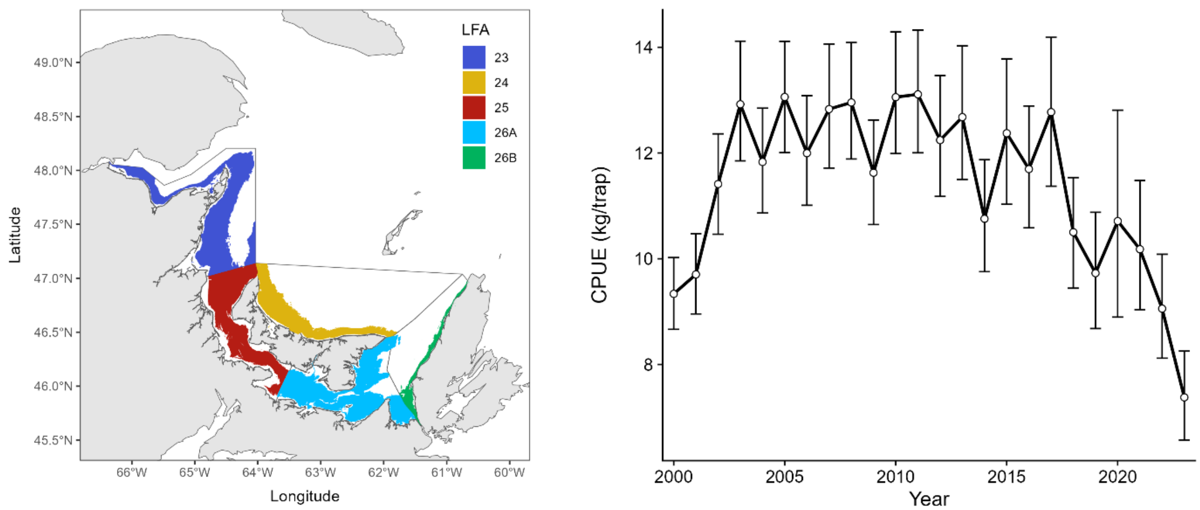

Figure 20. Left: Areas within the sGSL within the optimal depth range for rock crab (10 – 40 m) according to trawl surveys between 2010 – 2011 (Rondeau et al. 2014). Right: Area-weighted CPUE estimates with bootstrapped confidence intervals for rock crab in the sGSL.

Because $CPUE_{std}$ is a relative index of abundance, it cannot directly provide a biomass estimate, which is often preferred to set formal reference points. However, assuming constant catchability (q) and a proportional relationship between CPUE and biomass (Schaefer 1954), a stable period of CPUE and landings may indicate that removals are being offset by recruitment, thereby approximating CPUE of maximum sustainable yield ($CPUE_{MSY}$). Following DFO's Precautionary Approach (DFO 2009), an LRP can be set at 40% of this estimated maximum sustainable yield (MSY)-level CPUE.

Between 2004 and 2011, landings and CPUE remained relatively stable and catches averaged ~4,300 t while aggregated $CPUE_{std}$ held near 12.56 kg/trap (Figure 21). Using this period to estimate $CPUE_{MSY}$, the proposed LRP would be 5.02 kg/trap (i.e., 40% of 12.56 kg/trap). This is below the 2023 aggregated $CPUE_{std}$ of 7.38 kg/trap.

Applying DFO's reference point framework, the Upper Stock Reference (USR) is set at 80% of the $CPUE_{MSY}$ proxy, or 10.05 kg/trap. Based on this framework, the sGSL rock crab stock would be considered to fall within the Cautious Zone in both 2022 and 2023, with $CPUE_{std}$ values between the LRP and the USR.

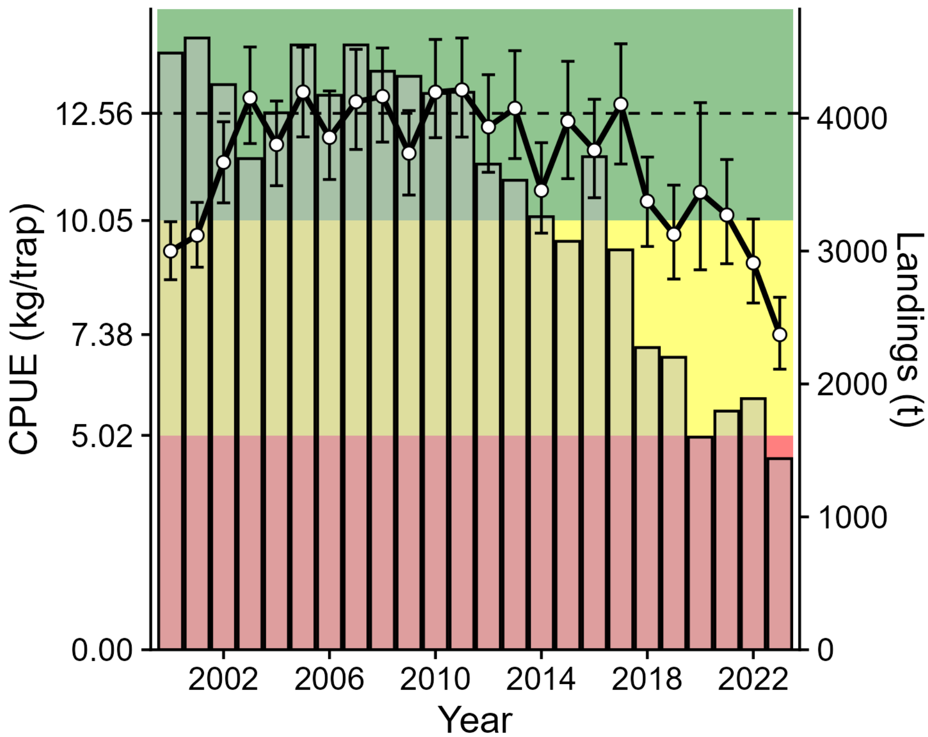

Figure 21. Area-weighted mean CPUEstd values for sGSL rock crab (lines) and total catches from the directed fishery (bars). The dashed line represents a proxy for B_{MSY} while the colored zones represent the stock status zones according precautionary approach: red, Critical; yellow, Cautious; green, Healthy.

DISCUSSION AND CONCLUSION

If current trends in licence activation persist, approximately half of all purchased rock crab licences will remain inactive each year. This represents a substantial source of latent fishing pressure. In years when lobster harvests are suboptimal, a significant number of fishers may activate their rock crab licences to compensate, potentially leading to a sharp increase in removals. Such increases would likely coincide with a greater proportion of harvesters fishing until their individual allotments are reached. At present, only about 10% of active licence holders reach their full allotment. However, absent a major change in market conditions (e.g., a sustained increase in rock crab prices or a significant reduction in operating costs like fuel) a large-scale expansion of the rock crab harvest appears unlikely.

One factor that could alter this outlook is volatility in the bait market. Between 2021 and 2023, a surge in demand for rock crab as lobster bait led to a temporary 300–400% increase in rock crab prices recorded in the sales slips and statistic unit personal communication. This underscores the potential influence of external markets, particularly bait availability and cost, on fishing effort in the rock crab fishery. Such dynamics should be considered in future management planning.

Trends in fishery-dependent data show that declines in rock crab landings have occurred in parallel with reductions in the number of active licences and the proportion of harvesters reaching their allotment. On the surface, this could suggest that the directed fishery has reduced rock crab abundance to levels that are no longer economically viable for the fleet. However, the abundance indices - specifically, the time required to reach 50% of allotment and standardised CPUE - suggest otherwise. These indicators show that commercial rock crab abundance has remained relatively stable, with some evidence of decline in recent years, particularly in LFA 26A.

Size-frequency data from dockside sampling also do not support a pattern of overexploitation. There is no consistent trend toward decreasing average size of harvested crabs over the course of the fishing season, again with the exception of LFA 26A. Similarly, while bio-collector data suggest a decline in juvenile abundance across much of the Gulf, these data are spatially limited and must be interpreted with caution. Juvenile densities have stabilized at roughly half the levels observed a decade ago, which may reflect broader ecological changes rather than direct effects of the fishery.

Taken together, these findings point to several key considerations, first, the increasing abundance and profitability of lobster may be reducing the incentive for licence holders to actively fish for rock crab. As a result, declines in landings may reflect decreased fishing effort rather than a true decline in stock size. Second, lobster are known predators of juvenile rock crab. The threefold increase in lobster biomass over the past decade is likely contributing to increased juvenile mortality and reduced recruitment into the rock crab fishery. Finally, once rock crabs reach a size refuge from lobster predation, their early maturation and low observed fishing mortality may support the establishment of a new equilibrium density within the Gulf. This could signal a broader ecological shift, where the rock crab population stabilises at a lower level under current predation regimes.

In conclusion, while some indicators suggest localized declines (notably in LFA 26A), the broader evidence does not support a stock-wide decrease in abundance. Rather, observed trends in landings and effort may reflect shifting fisher behaviour in response to changing ecological and economic conditions. Future management of the rock crab fishery should account for these interacting factors, particularly the role of lobster as both a predator and a competing fishery, and the sensitivity of fishing effort to market fluctuations.

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APPENDIX

DIRECTED FISHERY LANDINGS

Table A1. Annual landings (tonnes) from the directed rock crab fishery in the southern Gulf of St. Lawrence separated by fishing area (LFA).

Year	23	24	25	26A	26B	Total
2000	1119.5	248.9	1212.1	2038	24	4642.5
2001	1112.5	211.4	1304.4	2065.5	25.3	4719.1
2002	1008.3	175.8	1303.9	1795.8	17.5	4301.3
2003	663.8	139.4	1294.5	1590.4	7.6	3695.7
2004	955.6	182.9	1289.9	1590.9	21.2	4040.5
2005	1041.8	158.7	1469.1	1866.3	28.6	4564.5
2006	993	215.1	1358.2	1573.7	43	4183
2007	965.2	220.9	1549.8	1790.8	24.4	4551.1
2008	880	148.8	1629	1711.2	17.8	4386.8
2009	1054.5	158.5	1582.2	1503.3	16.7	4315.2
2010	816.6	166.8	1578.3	1624.3	NA	4186
2011	764.5	186.6	1509.1	1730.9	3.8	4194.9
2012	532.6	139.5	1460.1	1520.7	1.5	3654.4
2013	542.3	152.5	1416.5	1421.4	0.1	3532.8
2014	447.9	88.4	1170.6	1551.6	NA	3258.5
2015	636	49.2	1281.4	1106.9	NA	3073.5
2016	716.7	84.4	1451	1458.1	NA	3710.2
2017	575.4	81.3	1025.4	1327.2	NA	3009.3
2018	445.5	112	817.4	899	NA	2273.9
2019	392.6	76.6	741.4	990.3	NA	2200.9
2020	242	65.3	549.3	743.3	NA	1599.9
2021	332.1	72.8	696.3	698.2	NA	1799.4
2022	364.3	40.9	738.8	745.7	NA	1889.7
2023	338.3	23.7	571.9	504.3	NA	1438.2
Total	**16941**	**3200.4**	**29000.6**	**33847.8**	**231.5**	**83221.3**

ROCK CRAB BYCATCH LANDINGS FROM LOBSTER FISHERY

Table A2. Bycatch rock crab landings in tonnes. The Total column represents annual sums while the % of Total column represents total bycatch as a percentage of the combined bycatch and by the directed fishery landings.

Year	23	24	25	26A	26B	Total	% of Total
2000	226	12	183	233	<0.1	654.267	12
2001	200	10	175	394	<0.1	778.928	13.7
2002	295	14	256	335	<0.1	899.611	16.8
2003	270	16	192	332	<0.1	809.671	18
2004	325	20	205	507	<0.1	1056.023	20.7
2005	246	38	174	310	<0.1	768.884	14.4
2006	175	23	103	326	0.12	626.21	13
2007	122	30	141	271	<0.1	564.584	11
2008	85	11	144	283	<0.1	522.833	10.6
2009	70	40	85	252	<0.1	447.456	9.4
2010	71	14	68	216	1.4	370.256	8.1
2011	27	12	43	246	<0.1	328.242	7.3
2012	0.29	5.3	12	200	<0.1	216.818	5.6
2013	1.8	5.3	20	72	<0.1	98.962	2.7
2014	<0.1	0.56	16	56	<0.1	73.416	2.2
2015	<0.1	0.15	12	64	<0.1	75.714	2.4
2016	<0.1	0.26	35	30	<0.1	65.443	1.7
2017	<0.1	0.34	1.8	32	<0.1	33.732	1.1
2018	<0.1	<0.1	1.4	30	<0.1	31.84	1.4
2019	0.24	<0.1	0.57	0.81	<0.1	1.622	0.1
2020	<0.1	<0.1	2.2	0.36	0.23	2.89	0.2
2021	0.47	<0.1	1.3	<0.1	<0.1	1.777	0.1
2023	<0.1	<0.1	<0.1	<0.1	<0.1	0.096	0

STANDARDIZED CPUE PREDICTION DATES

As the CPUE model incorporated a seasonal variable (i.e., day of season) to generate a single standardized catch per unit effort ($CPUE_{std}$) estimate for each year, predictions were made for a common date across LFAs and years. To insure the predictions were not disproportionately influenced by the data from a small group of harvesters, the prediction date was chosen based on the median number of active harvesters per fishing day across LFAs and years (2000 – 2023, Figure A1). This analysis identified the eighth day of the fishing season as the day with the highest harvester activity across the sGSL. Consequently, $CPUE_{std}$ estimates for each LFA were produced for this date.

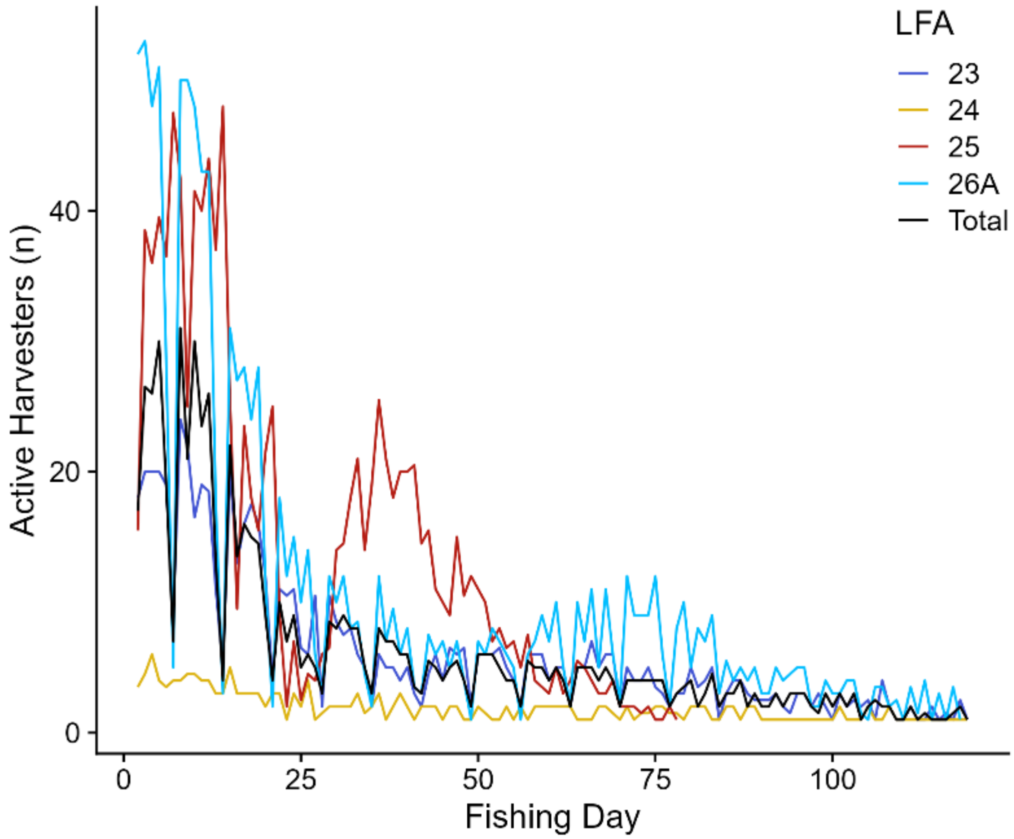

Figure A1. The median number of active harvesters per fishing day in the sGSL rock crab fishery. Medians are calculated across years for the period of 2000 – 2023. The black line represents the median across LFAs and years for each fishing day.

STANDARDIZED BOTTOM TEMPERATURES BY DEPTH

In order to account for temperature differences within the fishery independent survey CPUE model, temperature was included, but as there was a strong correlation between temperature and depth, this collinearity needed to be dealt with. This was done by fitting a loess model to each LFA's annual temperature – depth relationship and using the resulting temperature residuals (or deviations) in the CPUE model. In this way, temperature was included in the model as a function of deviations from the expected temperature at any given depth. For the loess models, a span of 0.75 was used and two separate models were fit to both the LFA 24 data within Malpeque Bay and stations outside the bay due to the warming effect of the shallower bay waters.

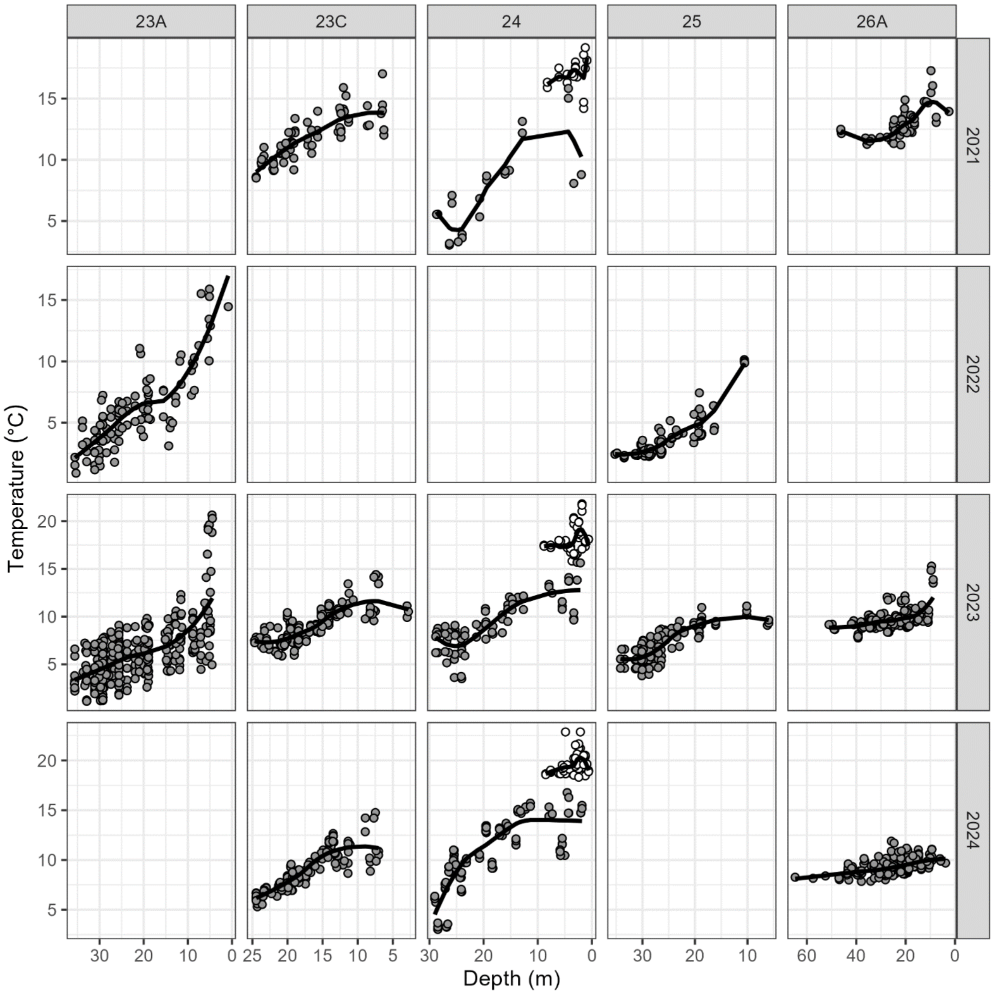

Figure A2. Loess models fit to estimates of sea-floor temperature according to depth in each of the survey areas targeted during the annual rock crab trap survey. Separate models were fit to the temperature estimates for LFA 24 in Malpeque Bay (white circles).

FISHERY DEPENDENT CPUE MODEL: RESIDUAL PLOTS

Model fit was assessed using the mgcViz package in R (Fasiolo et al. 2020) which provides visualization tools for GAM modesl fit with the mgcv package (Wood 2011). Diagnostic plots were produced using deviance residuals to assess normality, homoscedasticity, and potential model misspecification.

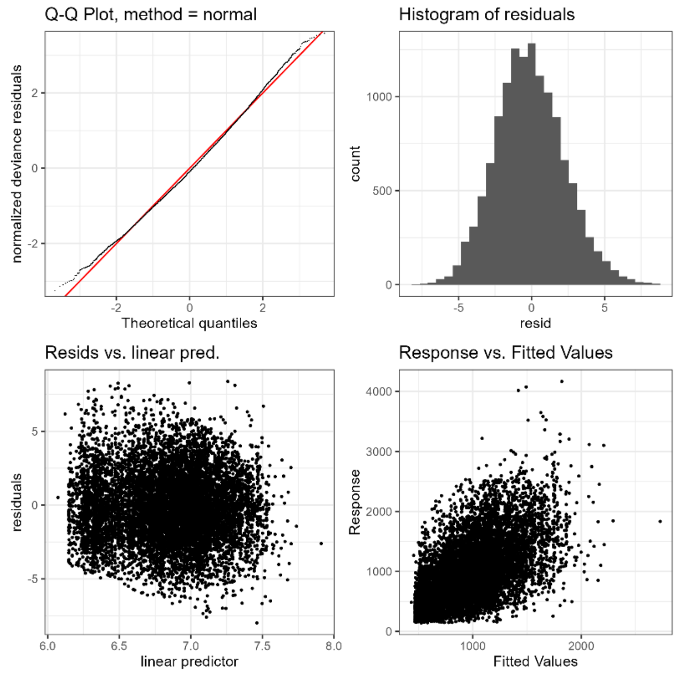

Figure A3. Model diagnostics plots for the LFA 23 fishery dependent CPUE model.

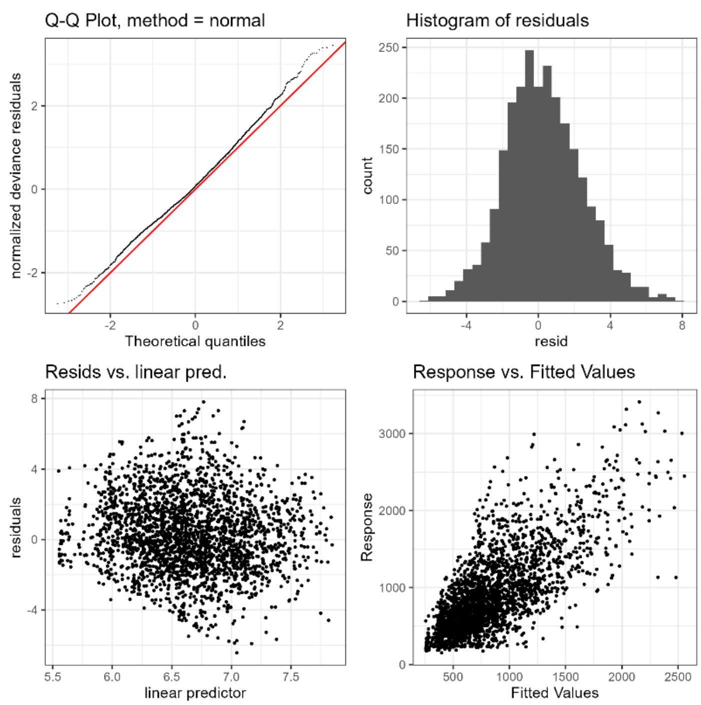

Figure A4. Model diagnostics plots for the LFA 24 fishery dependent CPUE model based.

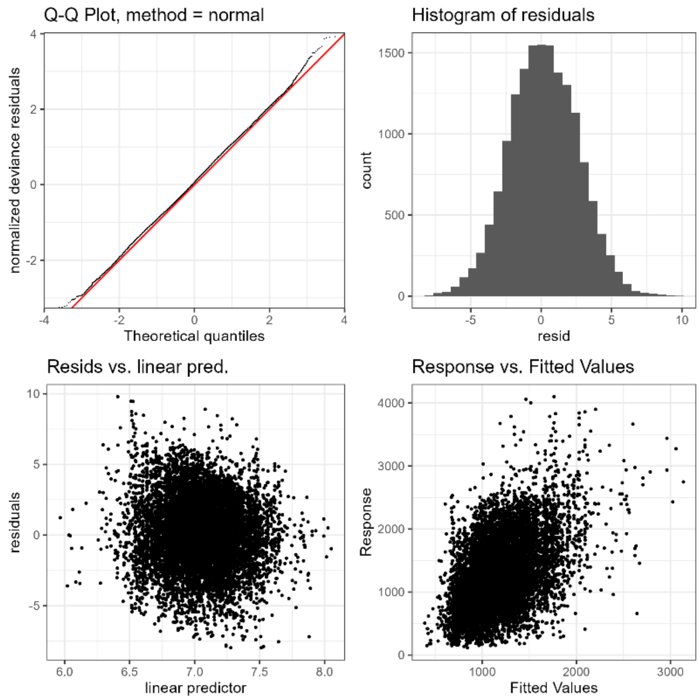

Figure A5. Model diagnostics plots for the LFA 25 fishery dependent CPUE model.

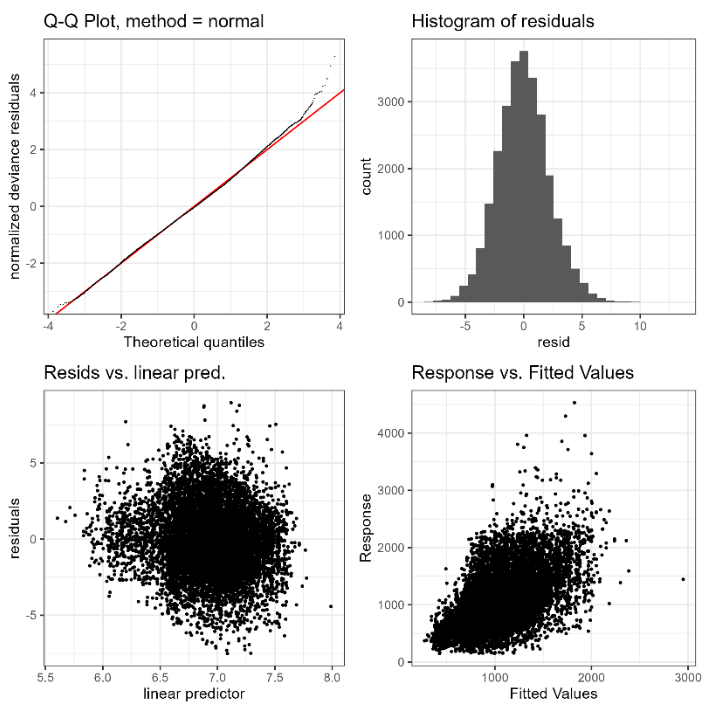

Figure A6. Model diagnostics plots for the LFA 26A fishery dependent CPUE model.

FISHERY DEPENDENT CPUE MODEL: PARTIAL EFFECT CURVES

The GAMM models fit to the directed fishery CPUE data indicated a significant non-linear effect of the gear soak time on catch (Figure A7). This saturating effect of the gear soak time was expected as crab traps can become full, leaving little room for new crabs to enter, or bait can become depleted either from individuals within the trap, from smaller invertebrates (i.e., sand flies), consuming the bait. When this happens, the traps ability to attract more crabs becomes seriously limited. In most cases, the trapping efficacy seems to saturate after around 35 – 40 hours.

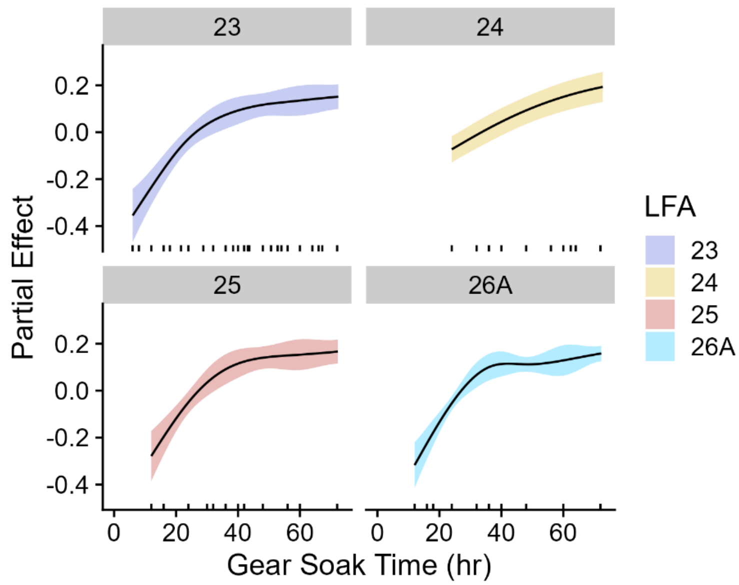

Figure A7. Partial effect plots for the effect of gear soak time on commercial catches of rock crab by the directed fishery in the southern Gulf of St. Lawrence.

With the seasonal fishing day variable, a general negative trend is observed. This trend was expected as the local populations in each fishing area are depleted, resulting in lower catches for the same amount of effort. Notably, however, there are instances, particularly in LFA 25, where catches seem to increase towards the end of the fishery. This is likely due to the fact that, in LFA 25, the fishery is separated into two periods, with an active lobster fishing season in the middle. This period when harvesters are not actively seeking rock crab may provide the local populations to disperse and reinhabit areas which had previously been fished during the first season.

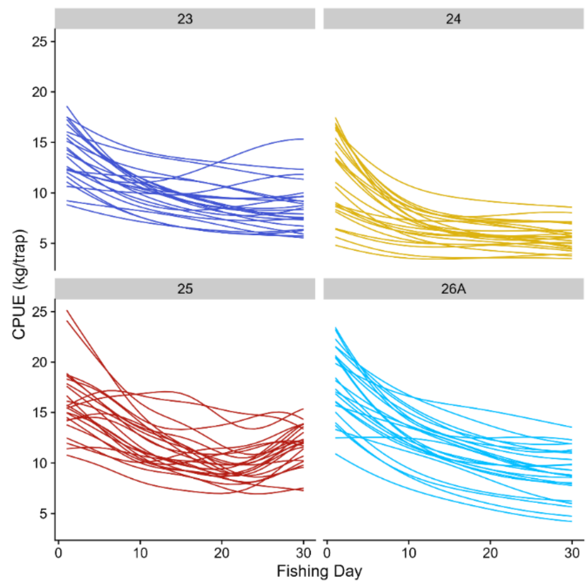

Figure A8. Partial effect plots for the effect of seasonal fishing day on the catches of rock crab by the directed fishery in the southern Gulf of St. Lawrence. Individual lines represent estimated effects for each year.

FISHERY-INDEPENDENT CPUE MODEL: RESIDUAL PLOTS

To assess model fit, simulated quantile standardized residuals (or DHARMa residuals, Hartig 2024) were used as they provide a robust and intuitive diagnostic tool for evaluating the fit of complex models like Generalized Additive Models (GAMs), especially when using non-Gaussian distributions such as the negative binomial. Unlike traditional residuals, which can be difficult to interpret in the presence of nonlinearity, overdispersion, or non-normal error structures, DHARMa residuals are generated by simulating response values from the fitted model and comparing each observed value to its corresponding simulated response distribution. This process transforms residuals onto a uniform scale, facilitating the detection and interpretation of patterns.

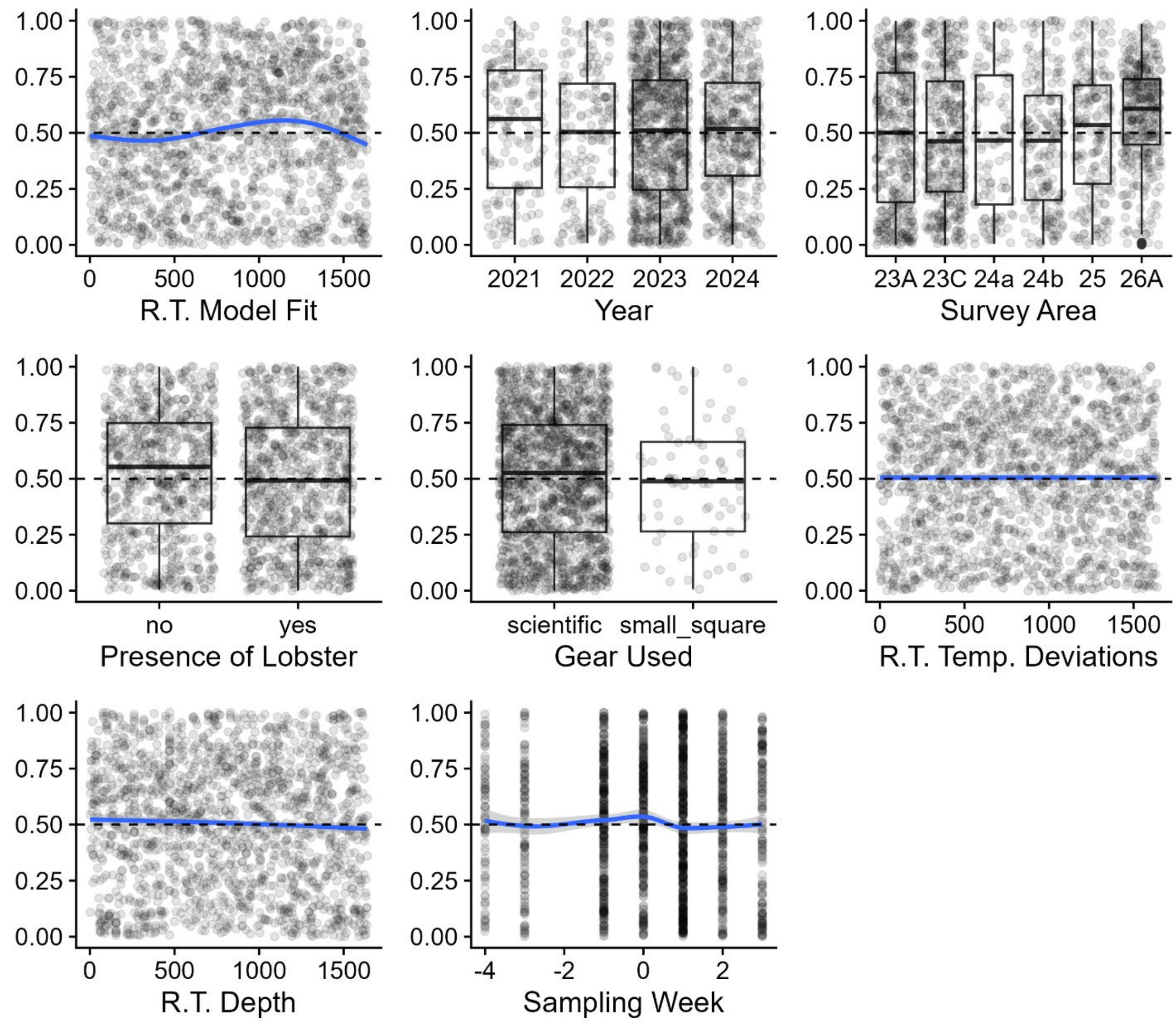

Figure A9. Simulated quantile residuals from a Generalized Additive Model of rock crab catches in annual trap survey. "R.T." indicates that the x-axis variable is rank transformed. A total of 1,000 simulations were used in producing the rank.

FISHERY-INDEPENDENT CPUE MODEL: PARTIAL EFFECT CURVES

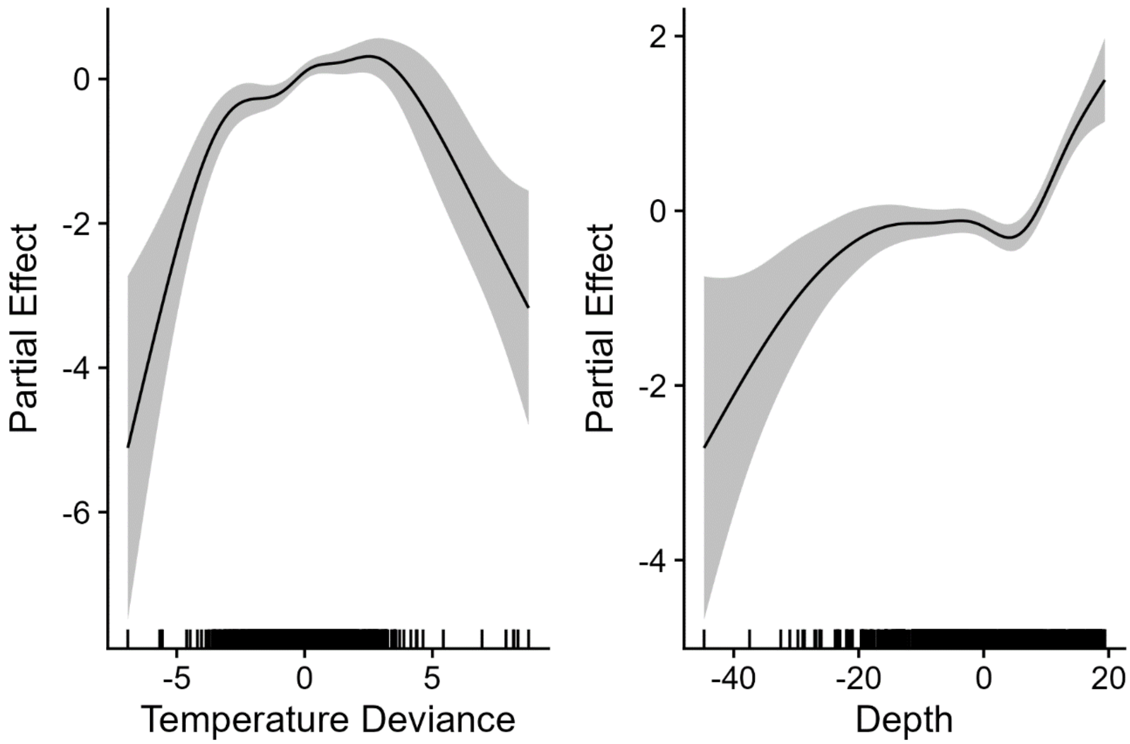

Figure A10. Partial effect plots for a negative binomial GAM model fit to trap survey catches. The smoothed variables included in the model were depth (relative to a standard depth of 20 m) and temperature deviations (°C relative to estimated temperatures at depth for each LFA annually).