Fisheries and Oceans Canada | Pêches et Océans Canada
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Canadian Science Advisory Secretariat (CSAS)

Research Document 2025/022

Newfoundland and Labrador Region

Assessment of Capelin (*Mallotus villosus*) in NAFO Divisions 2J + 3KL to 2023

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May 2025

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.

Published by:

Fisheries and Oceans Canada
Canadian Science Advisory Secretariat
200 Kent Street
Ottawa ON K1A 0E6

http://www.dfo-mpo.gc.ca/csas-sccs/
DFO.CSAS-SCAS.MPO@dfo-mpo.gc.ca

ISSN 1919-5044
ISBN 978-0-660-76424-5 Cat. No. Fs70-5/2025-022E-PDF

Correct citation for this publication:

Murphy, H.M., Adamack, A.T., Lewis, R.S., and Bourne, C.M. 2025. Assessment of Capelin (*Mallotus villosus*) in NAFO Divisions 2J + 3KL to 2023. DFO Can. Sci. Advis. Sec. Res. Doc. 2025/022. iv + 39 p.

Aussi disponible en français :

*Murphy, H.M., Adamack, A.T., Lewis, R.S. et Bourne, C.M. 2025. Évaluation du capelan (*Mallotus villosus*) dans les divisions 2J et 3KL de l'OPANO jusqu'en 2023. Secr. can. des avis sci. du MPO. Doc. de rech. 2025/022. iv + 41 p.*

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ABSTRACT

Fishery-independent (spring acoustic survey, larval survey, biological characteristics from the spring acoustic and fall bottom-trawl surveys, and citizen science beach spawning diary program) and fishery-dependent survey data were used to assess the status of Capelin (*Mallotus villosus*) in Northwest Atlantic Fisheries Organization (NAFO) Divisions (Div.) 2J3KL up to and including 2023. In 2023, the 2J3KL Capelin acoustic biomass index was 331.3 kt which was similar to the 2018–22 period (median: 282 kt), but well below the most recent stock high of 2013–14 and a fraction of the 1980s median. Capelin were feeding well in 2023 with immature fish growing rapidly with a high proportion maturing at age-2; spawning timing was delayed; and the Bellevue Beach larval index was similar to the time series mean. Capelin fall relative condition was the fourth highest value of the time series. Based on the Capelin forecast model, the Capelin acoustic biomass index in 2024 is expected to be similar to or slightly lower than the 2023 biomass index. Since Div. 2J3KL Atlantic Cod's Limit Reference Point (LRP) was revised in 2023 and is now based on 40% B_{msy} (biomass at maximum sustainable yield), the LRP for Capelin has also changed. The LRP of the Capelin stock is 155 kt based on the spring acoustic biomass index. The Capelin stock in 2023 is above its LRP and has been since 2007, except for 2010 and 2017; however, due to the stagnation in stock size since 2018, Science advises management actions that encourage stock growth in the short term. The boundary between the cautious and healthy zones has not been determined for this stock.

INTRODUCTION

Capelin is a small, short-lived pelagic schooling species with a circumpolar sub-Arctic distribution in the Northwest Atlantic, waters around Iceland, in the Barents Sea, and in the North Pacific (Gjøsæter 1998, Anderson & Piatt 1999, Carscadden et al. 2013). Capelin is the dominant forage fish species in the Newfoundland and Labrador (NL) ecosystem, providing a vital energetic link between zooplankton and numerous higher trophic level predators, including seals, whales, Atlantic Cod (*Gadus morhua*), Greenland Halibut (*Reinhardtius hippoglossoides*), Atlantic Salmon (*Salmo salar*), and seabirds (Templeman 1948, Carscadden et al. 2001, Davoren & Montevecchi 2003, Buren et al. 2014b).

In 1992, as a result of accumulated biological evidence (Nakashima 1992), it was recommended that Capelin in Northwest Atlantic Fisheries Organization (NAFO) Subarea 2 + Div. 3K and Div. 3L be considered one stock complex (hereafter referred to as 2J3KL Capelin; Fig. 1). There are three other Capelin stocks in the Northwest Atlantic: NAFO Div. 4RST; NAFO Div. 3Ps; and NAFO Div. 3NO. Of these four stocks, the 2J3KL Capelin stock is the largest. 2J3KL Capelin spend most of their adult life offshore on the NL shelves. The center of Capelin distribution changes seasonally, typically with Capelin found feeding further north (NAFO Div. 2J3K) in the fall, moving southward along the shelf break in the spring (NAFO Div. 3L), and turning in across the shelf and migrating back up the northeast coast of Newfoundland into bays and northwards to coastal Labrador to spawn at beaches and coastal deep-water (demersal) sites in the summer. Capelin is a facultative semelparous species.

The 2J3KL Capelin stock collapsed in the early-1990s with minimal recovery over the subsequent 30+ years (Buren et al. 2019). While Capelin stock biomass has increased since 2007, population dynamics of this stock has remained changed since the collapse with faster growth by immature fish and maturation subsequently occurring at a younger age; an age-truncated spawning population with few fish age-4+ compared to the 1980s; and an abrupt and persistent delay in beach spawning timing. Year-class strength is set early in the life history of Capelin (Murphy et al. 2018), and delayed spawning is predicted to produce weak year-classes (Murphy et al. 2021).

FISHERY

Capelin have been extensively harvested for food, bait and fertilizer for multiple centuries in NL waters. An offshore commercial Capelin fishery started in 1972, and an inshore commercial fishery started in 1978. The offshore fishery closed in 1991 and the inshore fishery is the only ongoing commercial Capelin fishery. The inshore fishery uses mobile gear (purse seines) and fixed gear (traps and a modified bar seine called a tuck seine). Due to the short fishing season, changes in fishery timing, exploitation methods, and the effect of market forces on landings, Capelin commercial catch rates have not been used as an index of spawning stock biomass since 1993. However, biological data from commercial fishery samples collected during the season are used in the assessment to provide data on the age- and size-structure of the spawning stock (see Mowbray et al. 2023 for more details).

Samples from the commercial fishery are obtained from vessels as catches are unloaded at processing facilities. In each bay with landings in the stock area, up to ten samples of 200 fish each are collected and frozen. A total of 20 of these frozen samples are processed each year, apportioned among gear sectors, bays and season (weekly) as a function of the total 2J3KL landings. Length, sex, and maturity are determined for all fish sampled and additional detailed information (weight, gonad weight, stomach fullness, and age from otoliths) is collected for 2 fish per sex, per 5 mm length class in each sample. Catch at age is calculated separately for each catch cell. A catch cell is defined as a unique combination of gear sector and NAFO Division. Age-length keys are determined for each combination of Division and sex. These age-length keys are applied to the sexed length frequency (5 mm bins) of each sample, so that each fish is assigned an age based on length. Numbers of fish within each 5 mm length grouping are converted to biomass using length-weight regressions calculated by Division, sex, and month. Subsequent length and age frequencies from sampled fish are scaled to landings for each catch cell.

COMMERCIAL LANDINGS AND BIOLOGICAL CHARACTERISTICS

In 2023, the Total Allowable Catch (TAC) for the 2J3KL + 3Ps Capelin stock areas was 14,533 t of which 11,355 t was landed (78% of the TAC; Fig. 2). The fishery was prosecuted in Div. 3KL with no landings in Div. 2J (TAC: 58 t) and Div. 3Ps (TAC: 968 t). Median annual landings in the fishery was 20,406 t from 1991–2021 (there was no fishery in 2022). There has been a reduction in the TAC since 2017 to a low of 14,533 t in 2022–23.

In 2023, mean total lengths (TL) of Capelin were similar to 2018-2021 averages with males on average 168.5 mm TL and females on average 147.3 mm TL, pooled by Division (Fig. 3). Mean weights showed a similar pattern to lengths (Fig. 3). The average size of Capelin landed in the commercial fishery is largely a reflection of the age distribution of the catch with larger fish landed in the 1980s compared to the post-1991 period.

SPAWNING

Since 1991, Capelin beach spawning has been monitored throughout the province by paid citizen scientists who check their local beaches every day during the Capelin spawning period (June – August) and fill out a spawning diary with their observations of Capelin spawning behaviour (Murphy 2022). There has been consistent monitoring of beaches during this program, with each beach having been monitored an average of five years (range 1–32 years). Participation in this program has varied inter-annually with an average of 18 beaches monitored each year, with the majority of beaches monitored being in Div. 3L (Fig. 4). In 2023, 16 beaches were monitored with four beaches recording no spawning behaviour (Fig. 5). Median peak (high intensity) beach spawning was July 21, 2023, which is delayed compared to the post-collapse median (July 9 for years 1991–2022). Median first day of spawning was July 7, 2023 but spawning intensity was considered low to moderate by citizen scientists. The spawning period lasted on average 11.5 days (median duration is 11 days from 1991–2022). Year-class strength is predicted to be weaker than the post-collapse average in 2023 based on delayed beach spawning timing (Murphy et al. 2021).

In 2023, spawning Capelin were collected from two beaches in subdivisions Div. 3Ps and 3Pn in June, three beaches in Div. 3L in July, and two beaches in Div. 3K in July. The collections of spawning fish followed the northeasterly spawning migration. At all beach sites, 200 fish were collected with a cast net at the beach, and length, sex, and maturity were determined for all fish sampled and additional detailed information (weight, gonad weight, stomach fullness, and age from otoliths) was collected for two fish per sex per 5 mm length class in each sample. An age-length key was constructed based on these 2023 data and was used to assign ages to all lengths. Almost all of these sampled fish were male (97%), which is likely due to males arriving first at beaches to spawn. The majority of sampled fish across all beaches were age-3 (on average 62%; Fig. 6) and mean lengths were similar amongst divisions, with marginally smaller fish in Div. 3L (166.8 ± 10 mm TL) compared to the other two divisions (3Ps/3Pn: 172.6 ± 11 mm TL; 3K: 174.1 ± 8 mm TL). Error is standard deviation (SD) in this section.

At Bellevue beach, Trinity Bay (Div. 3L) spawning fish were sampled throughout the spawning period using a cast net. A total of nine samples were collected between June 24 – July 30, 2023. At this beach, each sample was composed of a maximum of 25 females and 25 males (n = 430) and detailed sampling was conducted on all fish collected. This sampling method resulted in data on female fish, and we found that the majority of female fish were age-2 in both months (June: 53%; July: 66%) while the majority of male fish were age-3 (June: 76%; July: 52%) (Fig. 7). Spawners in June (pooled for sex) were on average older (2.75 years) and larger (165.6 ± 17 mm TL) compared to spawners in July (2.61 years; 161.3 ± 16 mm TL). The female component of the spawning population being composed of predominately age-2 spawners is impacting the dynamics of this stock in regards to spawning timing, age-truncation of the stock, and productivity (Buren et al. 2019).

EARLY LIFE HISTORY

BELLEVUE BEACH LARVAL INDEX

Larval surface tows using a 75 cm diameter ring net with 270 μm mesh have been conducted at five fixed stations in nearshore waters (<20 m) off Bellevue Beach (BB), Trinity Bay (TB) since 2001 (Fig. 8; see Mowbray et al. 2023 for more details). This survey was designed to sample larvae emerging from a variety of sources including BB itself, nearshore deep-water Capelin spawning beds, and four smaller spawning beaches along the western shore of BB. Sampling takes place over a prolonged period (~6 weeks each summer) in order to cover the entire emergence period. The larval samples were predominately composed of newly emerged larvae (4.77 ± SD 0.74 mm standard length (SL) for the years 2001–16). While older larvae were occasionally sampled in the BB area, their densities were low and their inclusion had a negligible impact on total annual larval density estimates (H. Murphy, unpublished data). Capelin larvae were preserved in a 5% formalin and saltwater solution buffered with sodium borate, and samples were processed in the laboratory, see Mowbray et al. (2023) for more details.

Annual density of larvae per m^3 (N) was estimated using the trapezoidal integration method in equation 1:

$$N = \sum (t_n - t_{n-1}) \tfrac{1}{2} [X(t_n) + X(t_{n-1})] \qquad \textbf{(1)}$$

where t is the day of the year, n is the number of sampling days, and X(t) is the daily average number of larvae per m^3 from the five stations sampled on day t. Only days when all five stations were successfully sampled were included in the analysis. If a station was missed due to adverse sea conditions or for any other reason, the average of the estimates on the adjacent days is substituted. If sampling was missed for three or more days then the missing values are set to 0.

Variance of the annual densities of larvae (var(N)) is estimated using equation 2 based on Millar and Jordan (2013) and Irvine et al. (1992):

$$var(N) = 0.25 \sum (t_n - t_{n-1})^2 \, var(c_n) \qquad \textbf{(2)}$$

where t is the day of the year, n the sampling day, and var(c_n) is the variance of larval densities from the five stations per sampling day.

In 2023, the BB larval index was 1,391.6 ± standard error (SE) 316.9 ind. m^{-3} which was similar to 2022 and the time series mean (1,436.1 ind. m^{-3}; 2001–22) (Fig. 9). This suggests an average 2023 year-class relative to the post-collapse period. However, since peak spawning timing was delayed in 2023 relative to the post-collapse average, the 2023 year-class may be weaker than expected if there is poor larval survival. This cohort will be sampled at age-2 in the 2025 spring acoustic survey.

The age-2 recruitment index from the offshore spring acoustic survey, which was lagged by two years in order to compare survivors of the same cohort, was positively related to the BB surface tow index (Murphy et al. 2018). This relationship has weakened with the addition of additional year-classes to the model since there has been better-than-expected recruitment from low larval abundance years. However, the BB larval index is a parameter in the most parsimonious forecast model (see Forecast Model section below), providing support for the importance of survival in the first few weeks of life to Capelin population dynamics.

TRINITY BAY LARVAL INDEX

The TB Capelin larval surveys began in 2002, building on prior work conducted in TB from 1982 to 1986 where 52 stations were sampled in July and August using oblique bongo tows (mesh 333 µm) to a maximum depth of 200 m (Dalley et al. 2002). In 2002, 52 stations were sampled across the bay, while in 2003–18, 19 stations were sampled in the center of the bay. In 2019–23, sampling effort increased once again, and 32 stations were sampled across the entire bay (Fig. 10). This sampling program occurs at a fixed date for one week in both August and September. During years when only one survey was conducted, it was targeted for September. For further details on this sampling program, see Mowbray et al. (2023).

In the laboratory, larval samples are sorted and Capelin density per square meter was calculated for each station using equation 3:

$$\rho_i = C_i * D_i / V_i \qquad \textbf{(3)}$$

where ρ is the density of Capelin larvae per square meter, i is the station, *C* is the number of Capelin caught, *D* is the maximum tow depth at station i in meters, and *V* is the filtered volume in m^3. Mean annual densities are calculated using only the 19 core stations.

The 2023 TB larval index, pooled for month, was 18.0 ± SE 3.3 ind. m^{-2}, which was below the time series mean (2002 – 2022; 26.5 ind. m^{-2}). By month, the August 2023 larval density was 21.8 ± 6.2 ind. m^{-2} and September 2023 larval density was 14.2 ± 1.9 ind. m^{-2} , and both these indices were below the time series mean (August 2008–22: 37.4 ind.m^{-2} ; September 2002–22: 24.8 ind.m^{-2}) (Fig. 11). Only the September TB larval index was positively related to the BB larval index (linear regression $R^2 = 0.22$, $p = 0.016$; Fig. 12), which may be due to timing of the TB larval survey since larval emergence is still occurring in August. The positive relationship between the BB and September TB indices supports the use of BB as an index beach for TB.

SPRING ACOUSTIC SURVEY METHODS

The acoustic survey is typically conducted in May and covers the majority of Div. 3L, an area of particular importance for juvenile and non-migratory age-1+ Capelin. Since 1982, the spring Capelin acoustic survey has taken place annually with approximately the same temporal and spatial coverage, except for 1983–84 and 2021, and there were no acoustic surveys in 1993–95, 1997–98, 2006, 2016, and 2020. Since 1996, the lower portion of Div. 3K (<50°N) has been included in the survey (Fig. 13). The inclusion of areas further north (>50°N) are precluded due to the presence of sea ice in May.

The spring acoustic survey produces a biomass index that is used as a proxy of stock status. Empirical support for the use of this index as a proxy is extensive (Murphy et al. 2018, Buren et al. 2019, Koen-Alonso et al. 2021, Regular et al. 2022). Interannual variability in the proportion of maturing age-2 fish since the stock collapse prevents the survey from being able to produce a spawning stock biomass estimate for the following summer. Details on the acoustic survey methods, sampling details, and calculation of abundance and biomass indices can be found in Mowbray (2013), Mowbray et al. (2023) and Murphy et al. (2024).

SPRING ACOUSTIC SURVEY ABUNDANCE AND BIOMASS

During the 2023 acoustic survey (conducted May 6–21), all of the core strata were surveyed (Fig. 14). Capelin were most dense along the middle latitudes of Div. 3L (47°00'N – 49°00'N) with higher concentrations in coastal strata (B, C & T) and in Conception Bay, but also relatively high density in stratum H to the east of stratum B. Capelin density diminished on the southern, northern and eastern extents of the survey area with the exception of some density along the shelf break. This distribution is consistent with most years during the past decade. In 2023, the biomass index was 333 kt (90% confidence interval (CI): 235 – 568 kt), which was similar to the 2018–22 time period (median: 282 kt) suggesting stability in the stock in recent years (Fig. 15). Since the collapse of the stock in 1991, the median annual Capelin acoustic biomass index is 174 kt (1991–2022), well below the pre-collapse 1985–90 median (3,704 kt). The spring acoustic abundance index in 2023 was 34.4 billion fish, which was higher than the 1991–2022 median (18.5 billion fish) (Fig. 16).

SPRING AGE, MATURATION, GROWTH, AND DIET

In the 2023 spring acoustic survey, age-2 fish dominated the catch (83%) followed by age-3 fish (13%) (Fig. 17). Age-1 fish are poorly recruited to the Campelen 1800 trawl so there is no reliable index of this age group. Similar to recent years, very few age-4+ fish were sampled in the 2023 spring acoustic survey.

In 2023, 55.7% of female age-2 fish were maturing and would have spawned that summer, which was similar to 2022 (Fig. 18). A high proportion of age-2 fish maturing in the spring acoustic survey is typical of lower biomass index years; however, this is a phenotypic response since in recent higher biomass years (2013–15), Capelin grew slower resulting in 18–33% of female age-2 fish maturing in those years. In the late-1980s (1985–90), on average 3.7% of female age-2 fish were maturing in the spring. Due to facultative semelparity, the high proportion of age-2 fish maturing has resulted in an age-truncated stock.

Since timing of maturation is linked to growth, year-classes with fast juvenile growth mature at a younger age. For the 2J3KL Capelin stock, fast immature growth and an increased proportion of the stock maturating at age-2 is a characteristic of the post-collapse period. In the post-collapse period, age-1 and age-2 fish were longer and heavier than ages 1 and 2 Capelin in the 1980s (Fig. 19, 20). In 2023, age-2 fish were similar in length and weight to fish sampled in 2022. Mean weights and lengths of ages 3 and 4 fish have remained the same or decreased since the 1980s likely because maturation at a younger age results in Capelin putting more energy into reproduction than allometric growth (Fig. 19, 20). Age-5+ fish are predominantly absent from the survey post-1991. As expected, the proportion of Capelin mature at age-2 is strongly related to the mean length of the cohort at age-2 (beta regression, Pseudo $R^2 = 0.77$, $p = 0.01$) (Fig. 21).

In spring 2023, 28% of sampled Capelin had empty stomachs, which was lower than the post-collapse time series mean of 47% empty stomachs. At all lengths, Capelin diet was dominated by copepods with no obvious ontogenetic shift at ~120 mm TL to larger prey taxa like euphausiids (Dalpadado & Mowbray 2013) (Fig. 22). Mean percent body weight (%BW) of Capelin was used as a measure of stomach fullness (see equation 4 where WS is the weight of the stomach contents [g] and WB is whole body weight [g]). In 2023, Capelin mean %BW was 0.92 ± SD 1.12% which was below the time series (1999–2022) mean of 1.17%.

$$\%BWi = \left(\frac{WS}{WBi - WSi}\right) * 100 \qquad \textbf{(4)}$$

Frequency of occurrences (FO) of Capelin prey taxa were calculated using equation 5 where S_i is number of stomachs containing prey category i and S_{total} is the total number of stomachs containing prey. The top three prey taxa in Capelin spring diet based on FO were copepods (93.6%), the appendicularian *Oikopleura* spp. (43.2%), and hyperiid amphipods (35.0%). *Oikopleura* spp. is considered a low quality prey taxa for Capelin in the Barents Sea and does not replace euphausiids in their diet (Orlova et al. 2009, 2010). Euphausiids were the fifth most important prey item based on FO (9.5%). The copepod category can be further divided: *Calanus* sp. stages IV - VI; *Calanus* sp. stages I – III; *Metridia* spp.; and Copepods (no species id). The Copepods (no species id) category includes small copepod species like *Pseudocalanus* spp. as well as copepod pieces. *Calanus* sp. stages IV-VI had the highest FO (79.8%) followed by *Metridia* spp. (61.3 %) (Fig. 23). These diet data suggest that Capelin are feeding well on large copepods in the ecosystem but their diet appears to be lacking in other prey taxa like euphausiids as they grow larger, which may be impacting their %BW and, more generally, the productivity of the stock.

$$FO = (S_i / S_{total}) * 100 \qquad \textbf{(5)}$$

FALL MULTISPECIES BOTTOM-TRAWL SURVEYS

Fall multispecies bottom trawl surveys (hereafter bottom trawl surveys) are conducted annually by the DFO NL Region in NAFO Div. 2GHJ3KLNO (Fig. 1). For a detailed account on the methodology and design of these surveys see Rideout and Ings (2018). Bottom trawl survey data are not used to estimate Capelin biomass due to the diel vertical distribution of Capelin and the selectivity of the trawl gear, which is biased against smaller sized fish – in particular those less than 10 cm (Mowbray 2002). Sampling of Capelin caught during the bottom trawl survey focuses on attaining samples from the full geographic distribution of the species (see Mowbray et al. 2023 for more details).

In 2023, the bottom trawl survey covered the entire survey area. However, timing of the survey was up to a month earlier in some divisions (namely Div. 2J3K). Furthermore, some samples from Div. 2J3K were lost due to a freezer mishap. The Pelagic Section conducted a fall acoustic research cruise in December 2023 in Div. 2HJ3KL, and a selection of the midwater and bottom trawl samples collected during the research cruise were used to replace some of these lost samples from northern divisions (Fig. 24).

FALL CONDITION AND DIET

Fall condition in 2023 was calculated using data from all sets where detailed sampling was available, including four extra samples from the December research cruise in Div. 2J3K. Data were first pooled by NAFO Division. A condition index (LeCren 1951) was then calculated by sex and age class (ages 1 and 2) and the resultant values averaged. Capelin fall relative condition in 2023 was lower than in 2022 and similar to 2020 (Fig. 25). Capelin fall condition has been high since 2020. There were no age-1 and age-2 fish sampled in Div. 2J in 2023 (Fig. 26).

Stomach fullness data is available for fall Capelin where stomach fullness is ‘called’ for fish undergoing detailed sampling. Stomachs are categorized into five categories: 0 (empty), 1 (¼ full), 2 (½ full), 3 (¾ full), and 4 (full). In 2023, 424 Capelin had stomach fullness data. 42% of Capelin had empty stomachs which is lower than the post-collapse average (54% empty stomachs; Fig. 27). When only considering stomachs called full (categories 3 and 4), 11% of Capelin had full stomachs in 2023, compared to the post-collapse mean of 10%. The stomach fullness data support the observed high condition of these fall sampled fish.

FORECAST MODEL

The Capelin forecast model suite (Lewis et al. 2019) builds on two prior Capelin models (Buren et al. 2014a, Murphy et al. 2018) by combining key features of the models within a common Bayesian framework which is then used to generate predictions of the Capelin biomass index from the spring acoustic survey. In Lewis et al. (2019), the most parsimonious Capelin forecast model (CSAM3) included the BB larval index; day of year (DOY) of the most southerly position of contiguous sea ice (sea ice retreat; t_{ice}) which is related to the timing of the annual spring plankton bloom; and the fall relative condition index of age-1 and age-2 Capelin. The model uses a combination of time-lags for the different indices in order to account for when the individual indices are expected to affect Capelin biomass for the year being forecast.

The Capelin forecast model was refit with 2023 data and up-to-date t_{ice} data (February 28, 2024). Similar to the original paper and previous assessments, the most parsimonious model was CSAM3, which includes the BB larval index, fall condition, and t_{ice} parameters (Table 1) (Lewis et al. 2019, DFO 2022, 2024). The model forecast suggests that the Capelin acoustic biomass index in 2024 will be similar to or slightly lower than the 2023 biomass index (Fig. 28).

In the 2023 assessment, the Capelin forecast model was found to be sensitive to fall condition (DFO 2024). For the 2024 assessment, as the forecast model is refit each year using the updated values, the observed 2022 condition value might unduly influence the prediction for 2024 and 2025. To investigate this possibility, the forecast model was fit with three different values for condition: the observed value of relative condition for 2022 (1.13); the second highest condition value from the condition time series (1.074); and the midpoint value (1.1) between the highest and second highest condition values. The value used for condition in 2022 had little effect on the predicted biomass indices for 2024 and 2025 (Fig. 29).

LIMIT REFERENCE POINT

The capcod model (Koen-Alonso et al. 2021) is the basis for the LRP for Capelin. This model accurately predicts Atlantic Cod biomass based in part on Capelin biomass. This model was used successfully in both the NL and Barents Sea ecosystems. In 2022, using the capcod model, the Capelin acoustic biomass index required to maintain Northern Cod at its own LRP, i.e., levels last observed in 1983–89, was 640 kt (DFO 2024). Northern Cod serves as an indicator finfish species in the NL ecosystem since the finfish community has a positive relationship with the status of Northern Cod and Capelin. Therefore, setting a LRP for Capelin that considers Northern Cod's dependence on Capelin is expected to benefit the entire finfish community. In the fall of 2023, the Northern Cod LRP underwent a framework assessment and, as a result, the Northern Cod LRP is now based on 40%B_{msy}. This resulted in Capelin's LRP changing as well. Using the same model configuration and data as the 2023 Capelin assessment (i.e., Northern Cod biomass up to 2020) (DFO 2024) and 40%B_{msy} for the Northern Cod LRP (internally estimated by the capcod model), the capcod model estimated a Capelin LRP of 155 kt based on the spring acoustic biomass index (Fig. 30). Below this level, the Capelin stock is likely at risk of serious harm. This is also the level of Capelin in the ecosystem required to maintain Northern Cod at its LRP. In 2023, the Capelin stock is currently above its LRP; however, this does not mean there are more Capelin in the ecosystem, rather fewer Capelin are required to maintain Northern Cod at its LRP. The boundary between the cautious and healthy zones has yet to be determined for the 2J3KL Capelin stock.

ECOSYSTEM CONTEXT

Capelin compose the middle trophic level of a 'wasp-waist' ecosystem (Cury et al. 2000) where a few forage species transfer energy from lower trophic levels (zooplankton) to higher trophic level predators. Capelin population dynamics are influenced by bottom-up drivers such as climate and zooplankton population dynamics (Buren et al. 2014a); and Capelin, in turn, play a vital role in the larger ecosystem by influencing the population dynamics of their predators (Buren et al. 2014b, Koen-Alonso et al. 2021).

The NL climate experiences fluctuations at decadal time scales, with known impacts on ecosystem productivity. The warmer and potentially more productive period emerging since 2018 has continued in 2023 (Fig. 31). While the impact of large-scale variations in ocean climate on 2J3KL Capelin is largely unknown, recent research found that the summer North Atlantic Oscillation index and the Newfoundland and Labrador Climate Index (NLCI) were predictors of Capelin spawning timing (Murphy et al. 2021), and inter-annual variability in prey availability associated with changes in the timing of the spring phytoplankton bloom and sea ice retreat was hypothesized to influence adult Capelin and, by extension, biomass (Buren et al. 2014a, Cyr et al. 2023).

Overall conditions of the past four years are indicative of improved productivity at the lower trophic levels in the NL bioregion (NAFO Divs. 2HJ3KLNOPs) (Fig. 32). This includes earlier phytoplankton blooms, higher nutrient concentrations, and above-average zooplankton biomass with a high abundances of both small and large energy-rich *Calanus* copepods. These zooplankton community changes suggest improved foraging conditions for larval (Murphy et al. 2018) and adult (Buren et al. 2014a) Capelin.

Despite these positive signals at the lower trophic levels, the NL bioregion continue to experience overall low productivity conditions, likely driven by bottom up processes (e.g., food limitation) (Fig. 33). The groundfish rebuilding that started in the mid-2000s stalled, and declines were observed in the mid-2010s. Ecosystem trends in recent years (e.g., biomass trends, stomach content weights) indicate improvements from the lows in the late-2010s, but overall biomass has yet to reach the early-2010s level.

Both consumption estimates of Capelin by fish predators and predictions of Capelin biomass from the probability of Capelin in predators' stomachs indicate that Capelin have shown recent improvements from the late-2010s levels (Fig. 34). This positive trend would be expected to persist in the 2024 Capelin spring acoustic survey, but the precise magnitude of this expected improvement remains unclear.

The examination of Capelin per capita productivity strength in relation to environmental conditions shows positive Capelin responses to increases in the NLCI (Fig. 35). This further consolidates the idea that Capelin is bottom-up regulated and emphasizes the importance of stock size to capitalize on the occurrence of good environmental conditions.

SUMMARY AND CONCLUSIONS

The 2J3KL Capelin stock has shown limited signs of recovery from its collapse in 1991. Persistent changes in Capelin population dynamics post-collapse are likely due to density-dependent factors, resulting in fast immature growth and maturation at a younger age. This trend continued in 2023 with a high proportion of Capelin maturing at age-2. Due to semelparity and early age at maturation, the stock is age-truncated compared to the 1980s. Post-1991, the Capelin stock is also characterized by delayed spawning and low recruitment. Spawning timing in 2023 was delayed; and while the BB larval index was similar to 2022, it was only average compared to the post-collapse time series mean. This suggests that 2023 was an average year-class compared to the post-collapse period but the 2023 year-class could be weaker than expected due to delayed spawning. Capelin fall relative condition was above average in 2023. In 2023, the 2J3KL Capelin acoustic biomass index was similar to the 2018–22 median, but well below the recent stock high of 2013–14 and a fraction of the 1980s median. The Capelin forecast model predicted that the Capelin acoustic biomass index in 2024 would be similar to or slightly lower than 2023. The Northern Cod LRP changed in 2023 and is now based on 40%B_{msy}; as a result, the Capelin LRP was also revised. Using the capcod model, the Capelin LRP was 155 kt based on the spring acoustic biomass index. In 2023, the Capelin stock is above its LRP, and the boundary between the cautious and healthy zones has not been determined for this stock. While the 2J3KL Capelin stock is above its LRP, the stock is facing challenges such as late spawning, maturing at earlier ages, and a population that is dominated by relatively young fish. Furthermore, the stock remains well below the 1985–90 productive period. These factors indicate reduced stock productivity, and Science advises a management approach that focuses on short-term stock growth.

AREAS OF UNCERTAINTY

The spring acoustic survey does not provide an estimate of total spawning stock biomass so the impact of fishing on the Capelin stock is unknown.

The BB larval index may not be representative of larval densities from areas with a high proportion of deep-water (demersal) spawning. However, trends in larval indices were similar between a site in Notre Dame Bay with a high proportion of deep-water spawning and the BB larval index (Tripp et al. 2023). The BB larval index is included in the most parsimonious Capelin forecast model.

The estimated envelope of Capelin consumption by fishes remains large and is highly dependent on how well these species represent overall predation. While order of magnitude analyses indicated that fishes are the main consumers of Capelin, consumption of Capelin by marine mammals and seabirds remains an important source of uncertainty.

The impact of fishing mortality on the Capelin stock is not quantified and is generally poorly understood, particularly its targeted impact on pre-spawning, egg-bearing females that have already survived predation and other sources of natural mortality.

There are currently limited abundance and biomass data for age-1 Capelin from the spring acoustic survey. Using a smaller meshed pelagic trawl on the spring acoustic survey may increase data on this life stage and potentially fine-tune the recruitment forecast from the larval stage to age-2.

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TABLES

Table 1. Model selection statistics for the Capelin forecast models in 2023 using the observed value of fall relative condition for 2022 (1.13). Model details are provided in Lewis et al. (2019)[1]. DIC: deviance information criterion; ΔDIC: difference between change in DIC from the most parsimonious model; R^2 are for Bayesian analyses (Gelman et al. 2019).

Model type	DIC	ΔDIC	R^2
CSAM3	36.39075938	0	0.547
CSAM1	38.33352816	1.942768774	0.442
AM0	40.28240179	3.891642403	0.188
CSAM2	41.8968585	5.506099118	0.378
AM1	43.60151904	7.210759658	0.315
CS1	45.12243678	8.731677397	0.309
CS0	45.77759602	9.386836632	0.275

[1]CS1 (BB larval index and zooplankton index); AM0 (t_{ice}); AM1 (t_{ice} and condition); CS0 (BB larval index); CSAM1 (BB larval index and fall condition); CSAM2 (BB larval index, t_{ice}); CSAM3 (BB larval index, t_{ice}, fall condition)

FIGURES

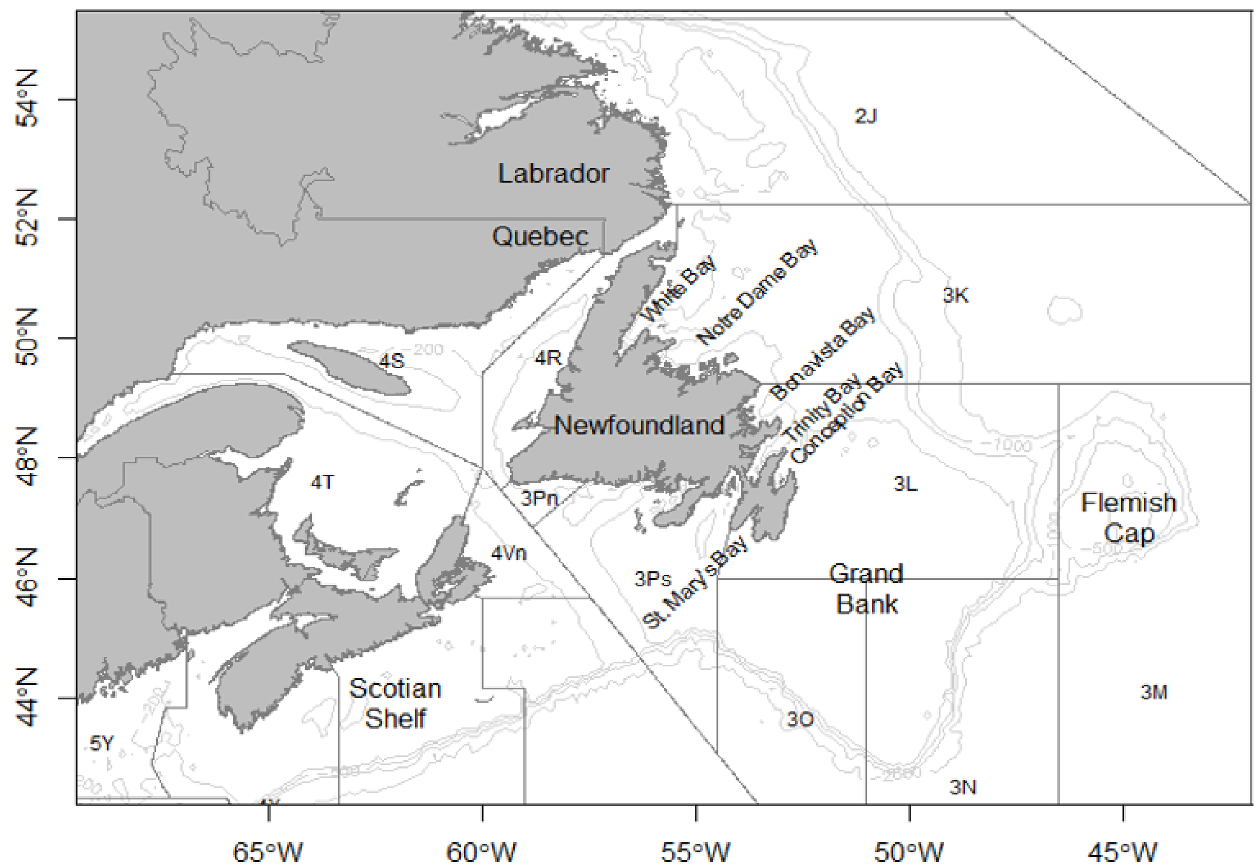

Figure 1. Stock area of NAFO Divisions 2J3KL Capelin.

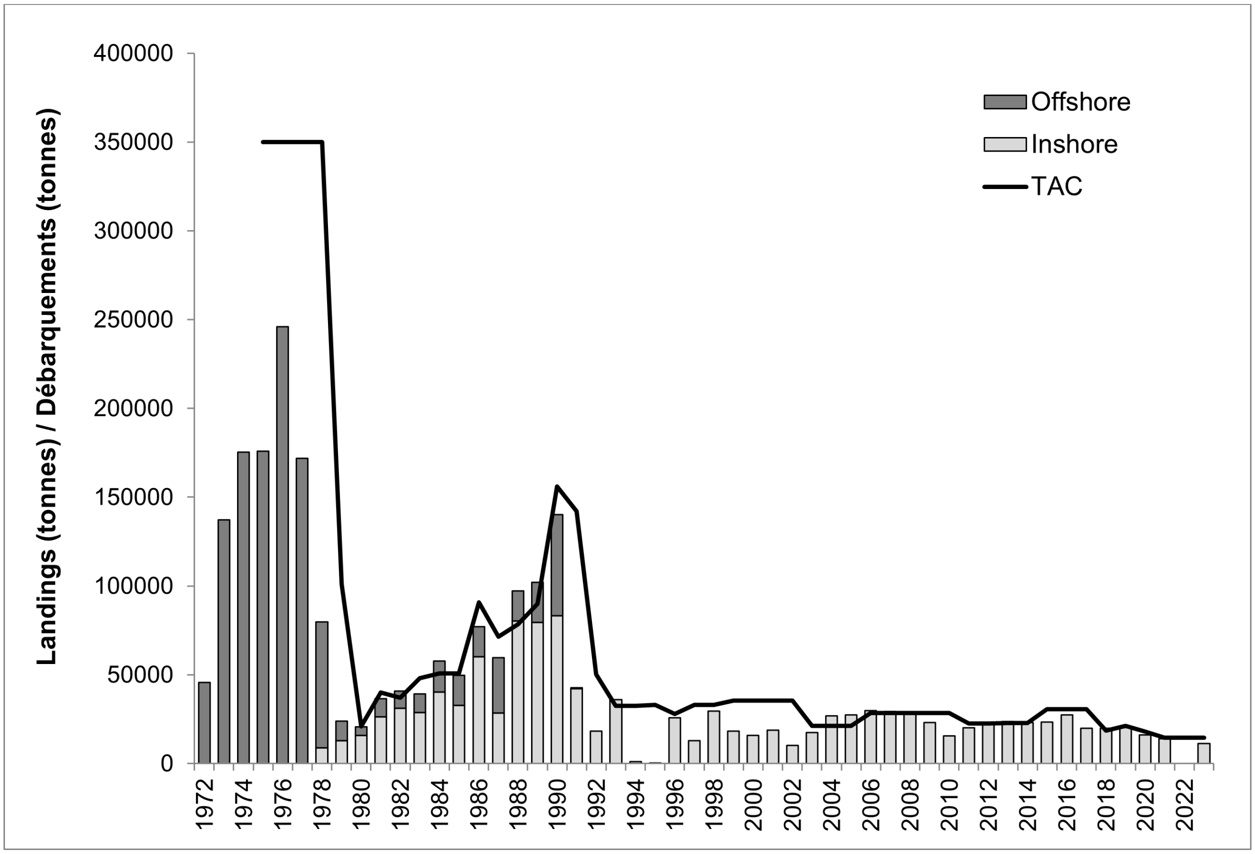

Figure 2. Inshore landings (light grey bars), offshore landings (dark grey bars), and Total Allowable Catch (TAC) (line) for Capelin in Divs. 2J3KL from 1972 to 2023. Note that annual inshore landings were likely greater than 0 t between 1972 and 1977, but they were not recorded prior to 1978. There was no commercial fishery in 1994, 1995, and 2022.

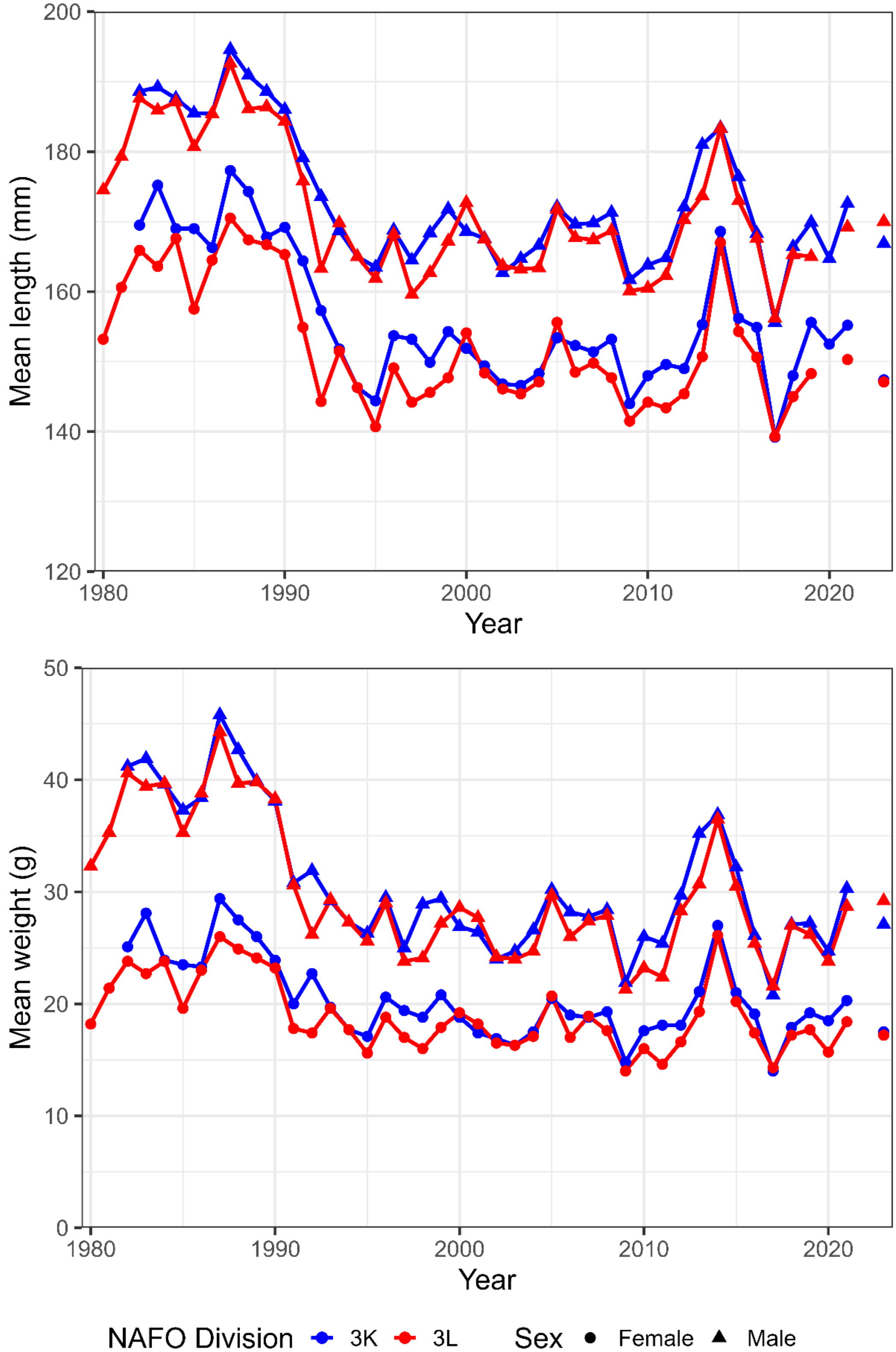

Figure 3. Mean length and weight of Capelin caught in NAFO Divisions 3K and 3L in inshore commercial landings from 1980–2023.

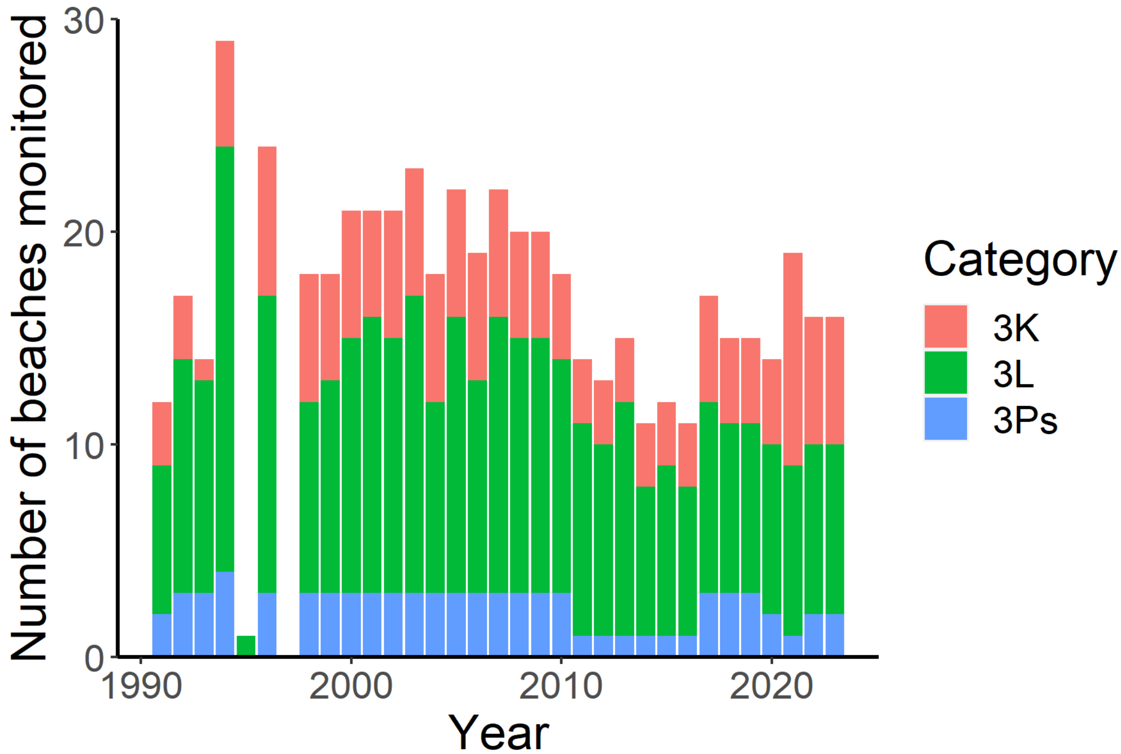

Figure 4. Number of Capelin spawning beaches monitored by Division by DFO's Capelin spawning diary citizen science program since 1991.

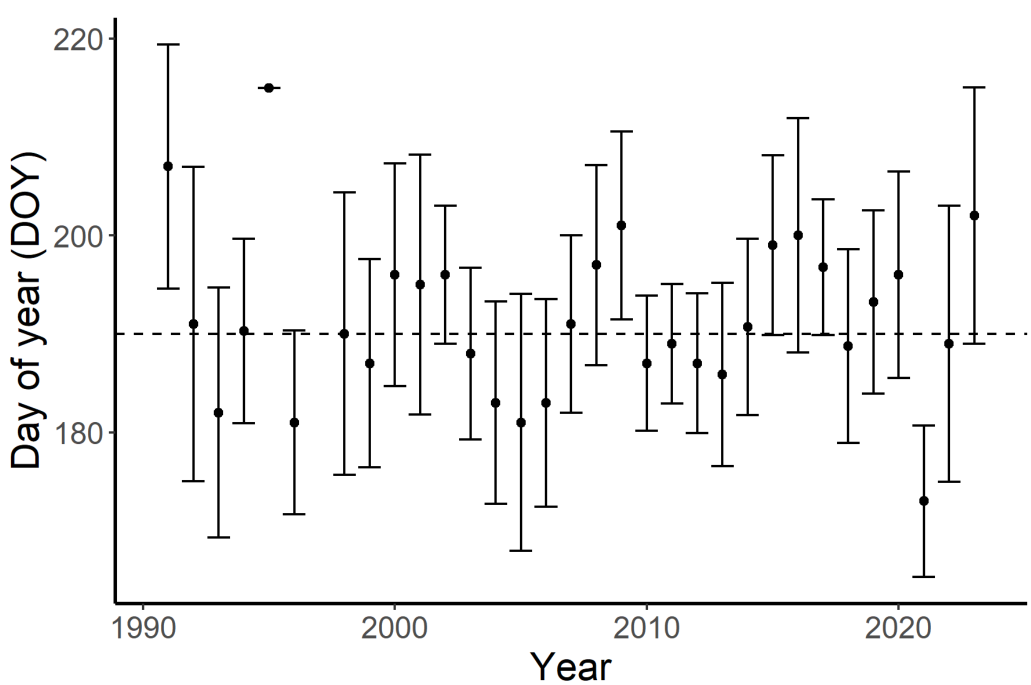

Figure 5. Median peak beach spawning timing for 2J3KL Capelin in 2023 was July 21 (Day of year [DOY]: 202) based on 16 beaches monitored in the Capelin citizen science spawning diary program. The dashed line is the median of the time series (1991–2022; July 9, DOY 190). The error bars are standard deviation.

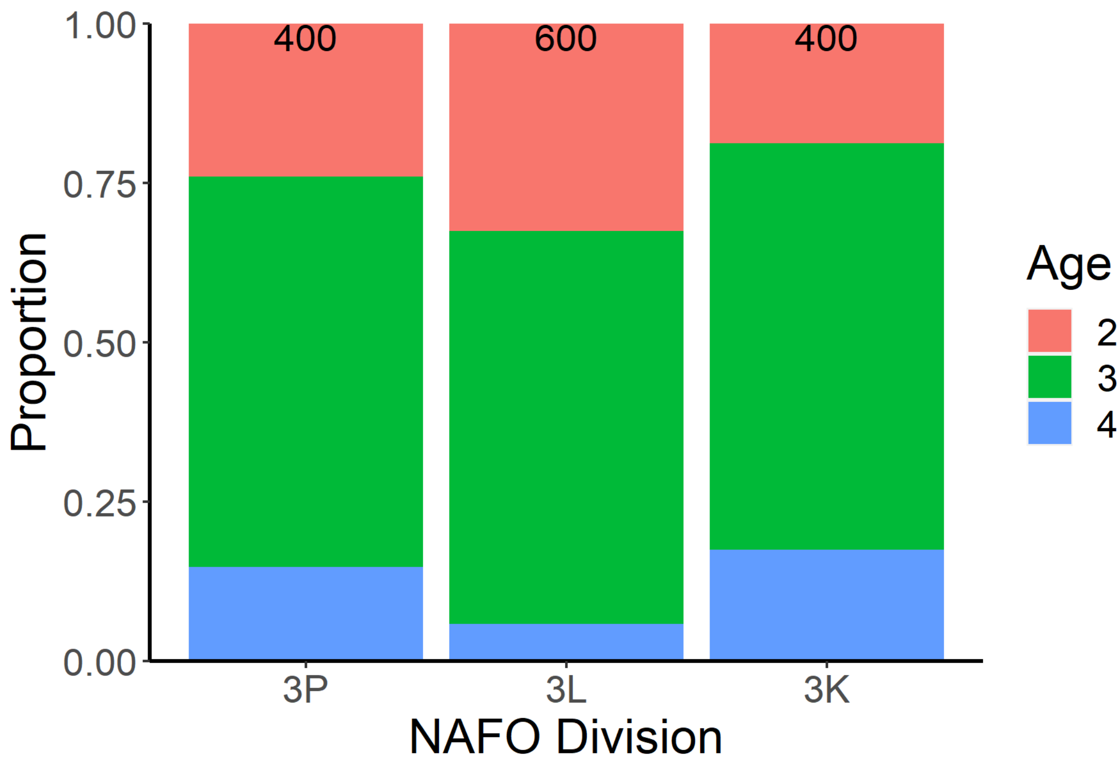

Figure 6. Age composition of beach spawning Capelin at beaches in NAFO Divisions 3KLP in June and July 2023. Fish were sampled with cast nets at seven beaches. Sample size is at the top of each bar.

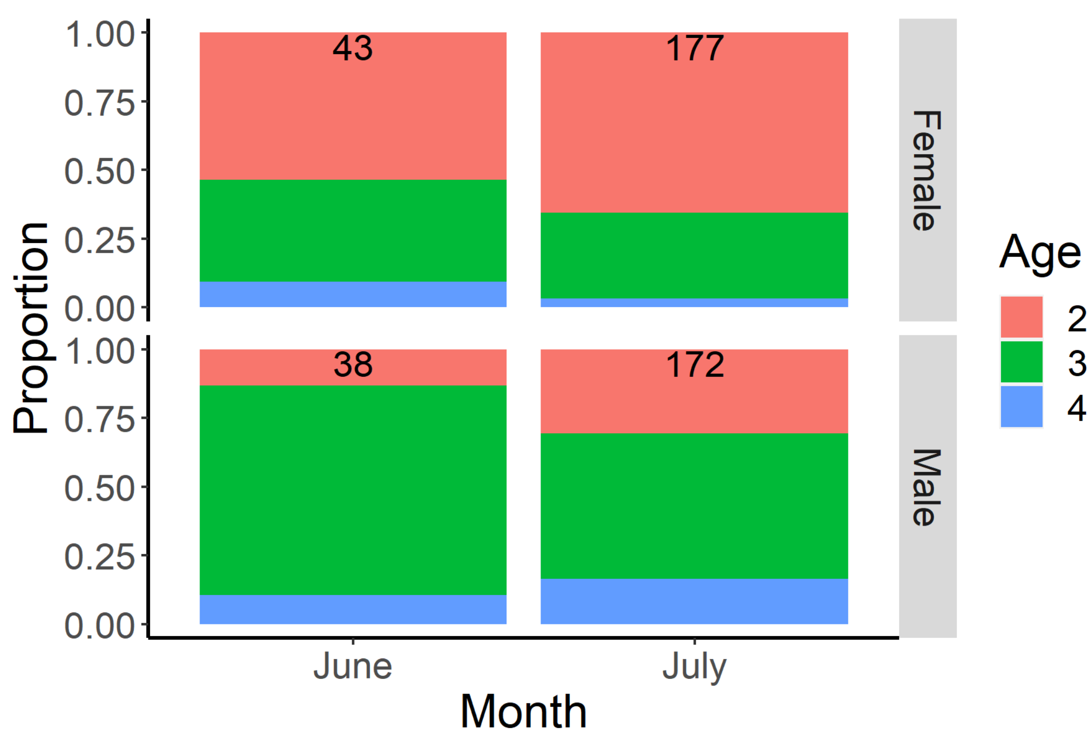

Figure 7. Age and sex composition of beach spawning Capelin at Bellevue beach in NAFO Division 3L in June and July 2023. Fish were sampled with cast nets. Sample size is at the top of each bar.

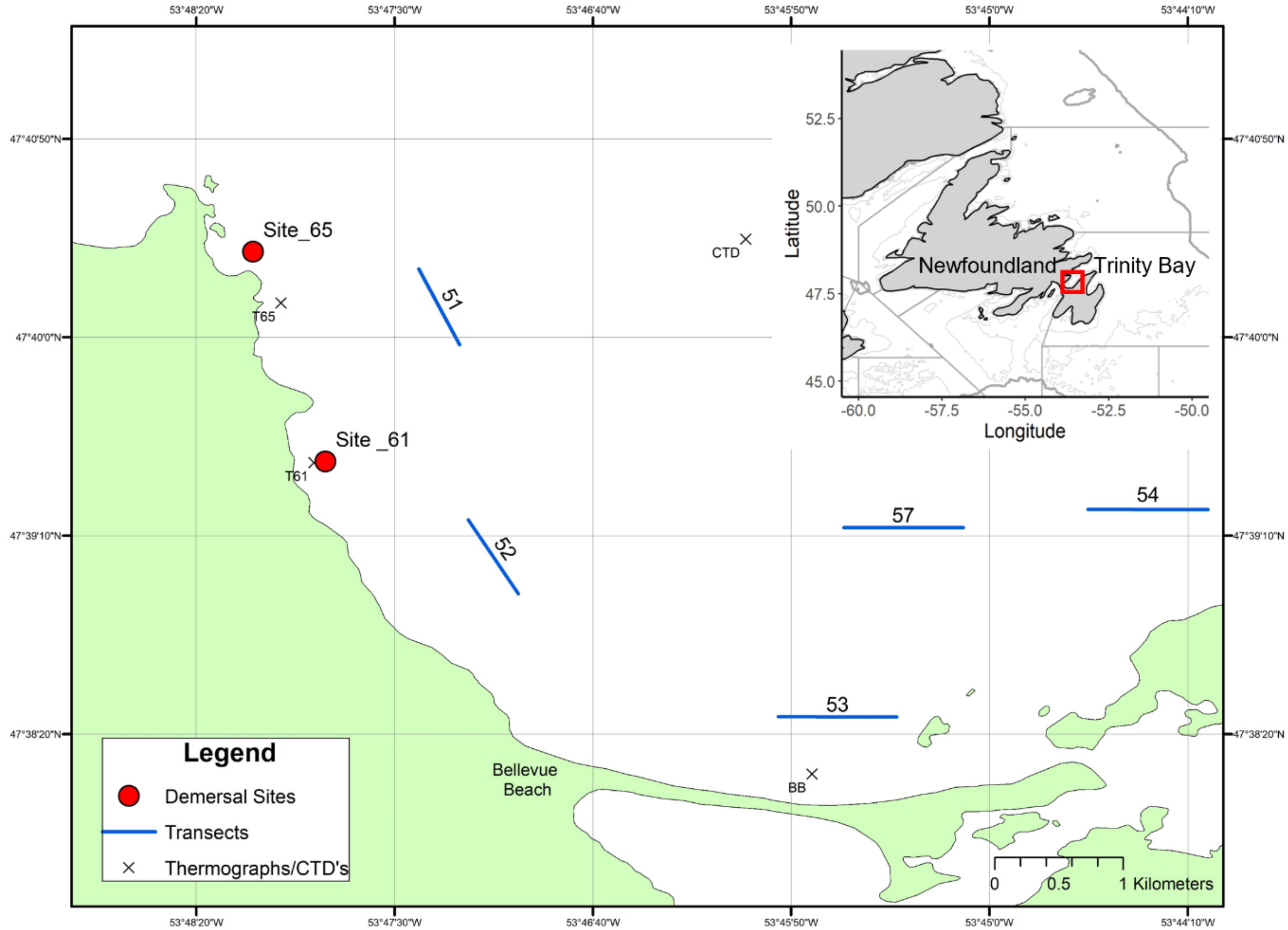

Figure 8. Bellevue Beach sampling area in Trinity Bay (Div. 3L). Demersal sites are in red (depths of 12–14 m). The numbered transects are fixed stations for larval surface tows. X indicates fixed stations for CTD data collected each sampling day. The red box in the inlay figure is the location of Bellevue Beach at the bottom of Trinity Bay.

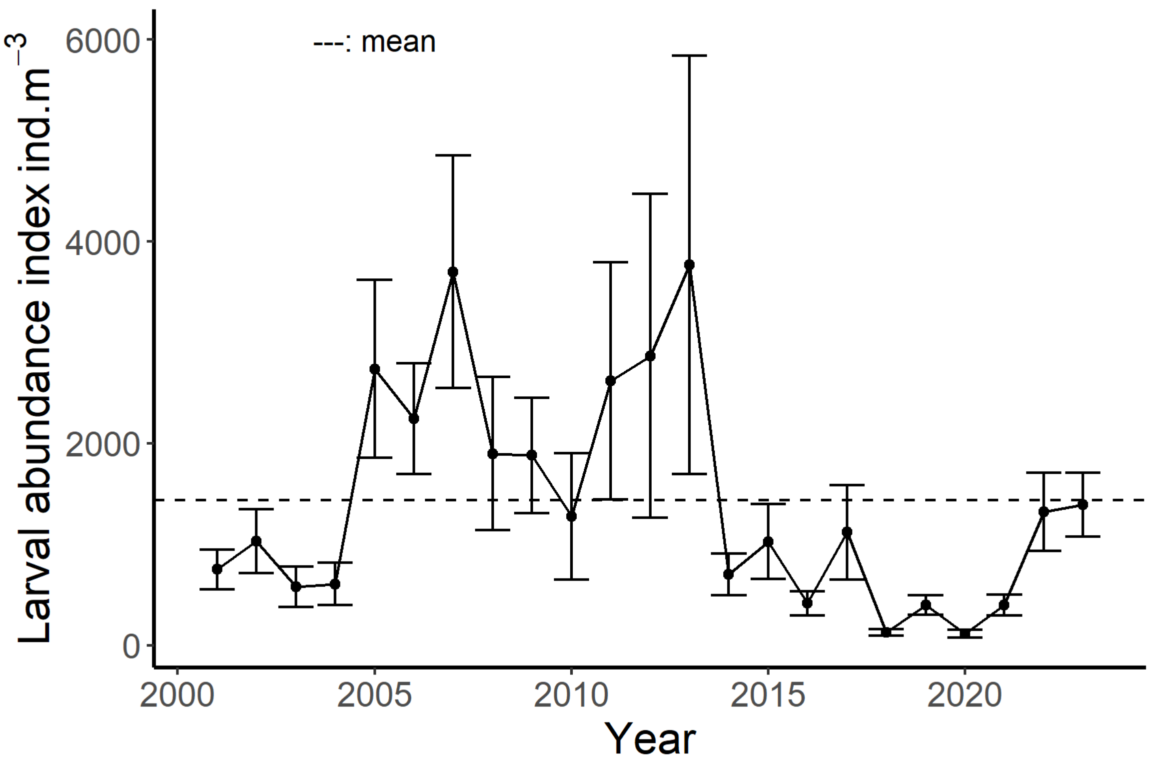

Figure 9. Bellevue Beach larval index (2001–23) ± standard errors. The dashed line is the mean larval abundance index (2001–22).

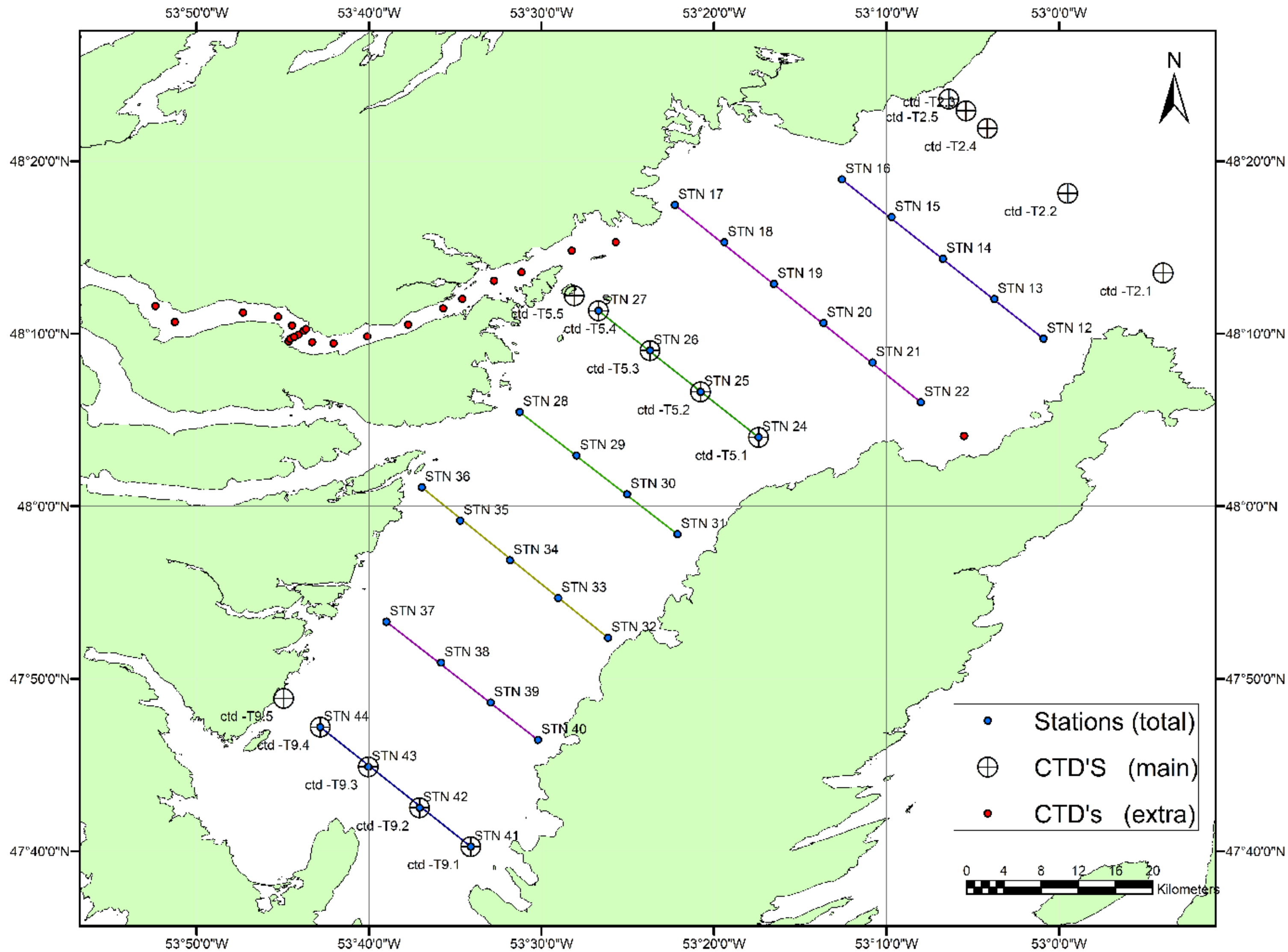

Figure 10. Trinity Bay larval survey. The core stations sampled are in the center of the bay (Stations 17–36).

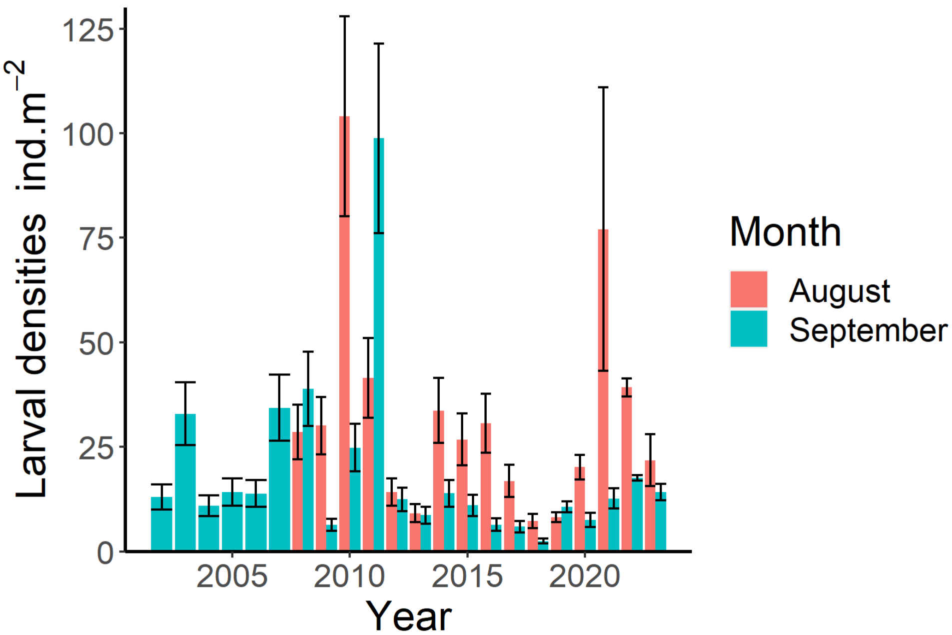

Figure 11. Trinity Bay (TB) larval densities sampled at 19 core fixed stations in the center of TB in August and September. Error bars are ±SE.

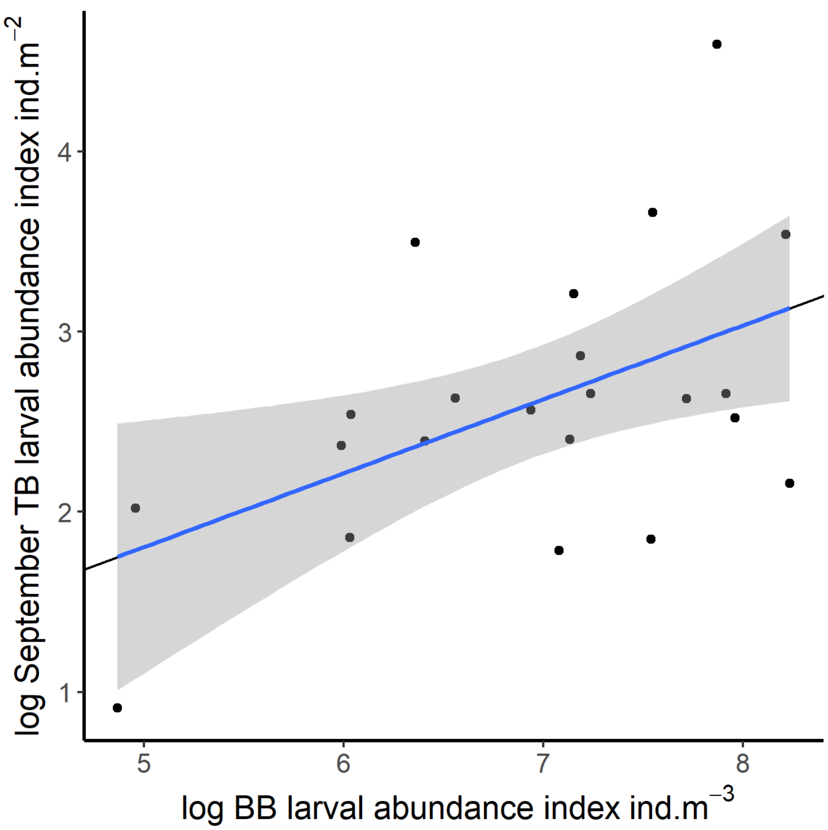

Figure 12. The Trinity Bay (TB) larval densities in September are positively related to the Bellevue Beach larval index sampled in July and August (2002–23; linear regression $R^2 = 0.22$, $p = 0.016$).

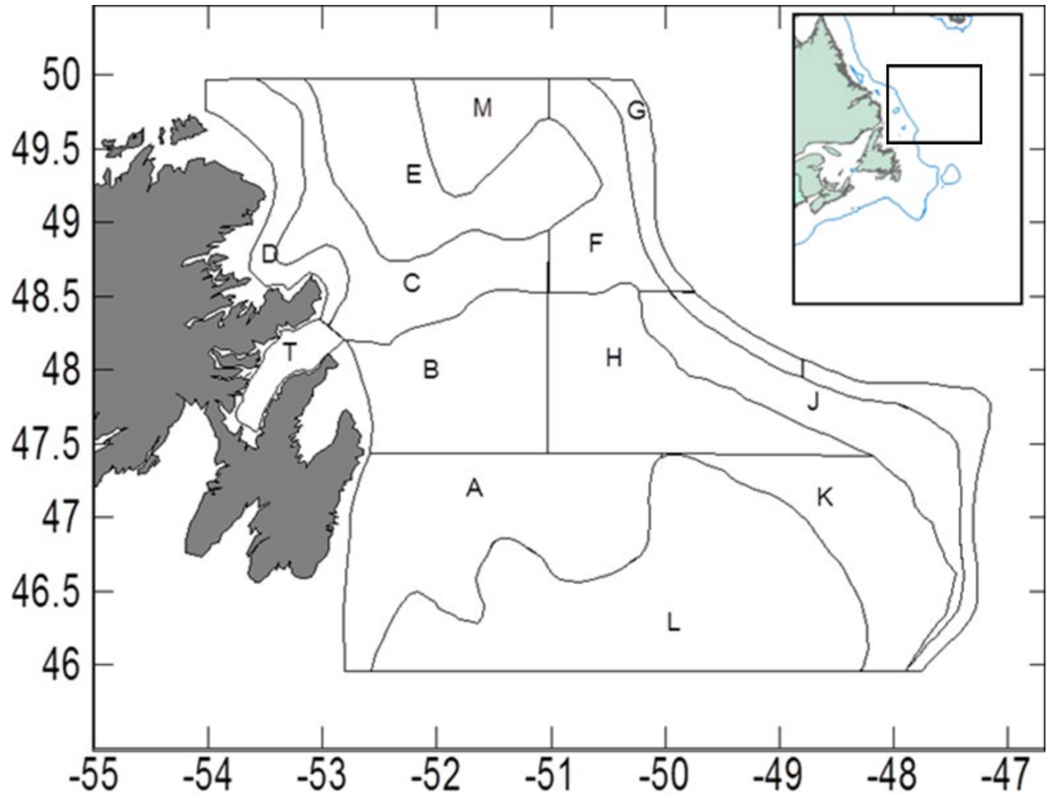

Figure 13. Spring acoustic survey strata in NAFO Divisions 3KL.

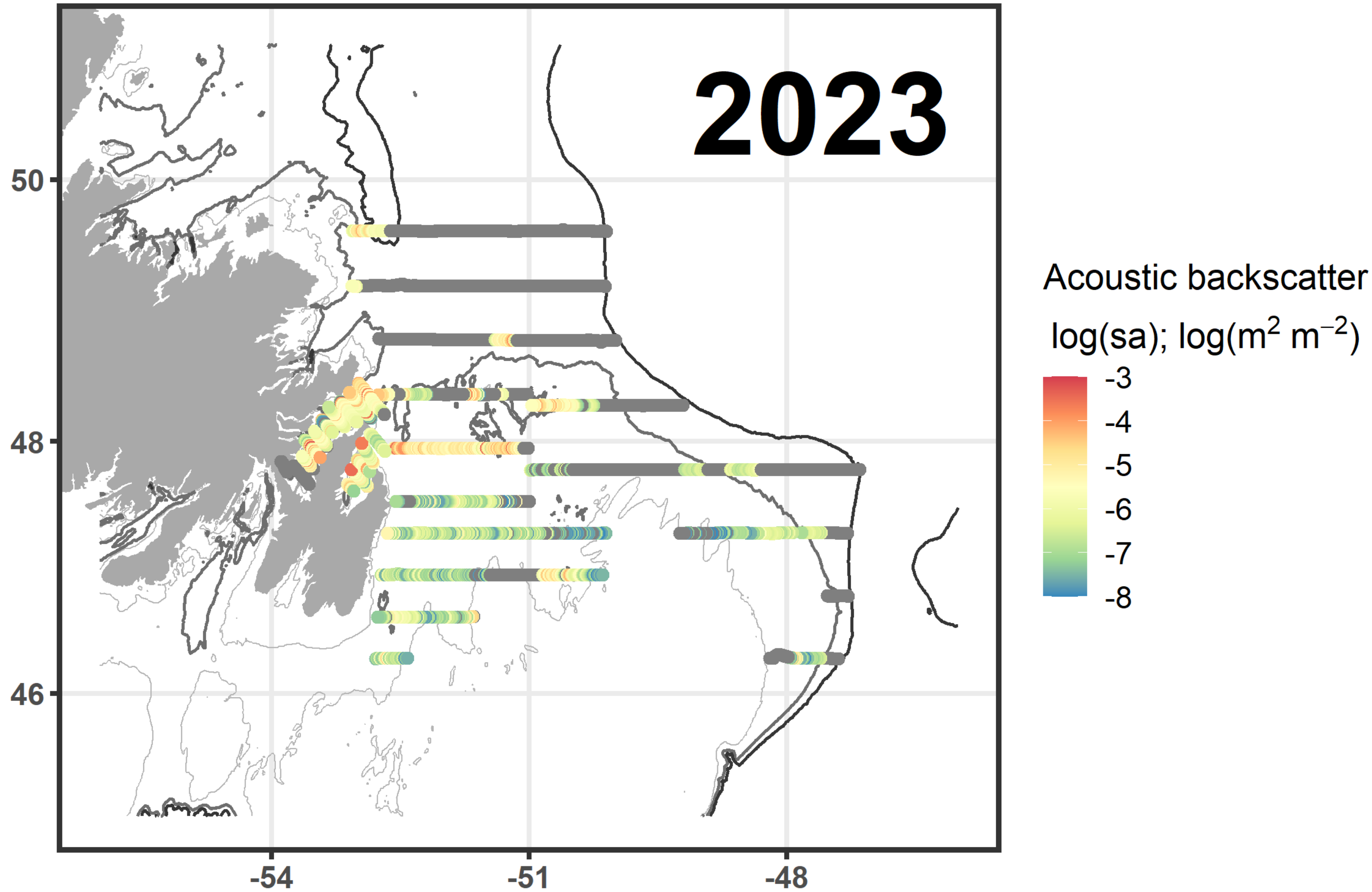

Figure 14. Spring acoustic survey tracks in 2023. Consecutive colour increments indicate an order of magnitude difference in acoustic backscatter with colder colours (blue) indicating lower acoustic biomass. Grey indicates no Capelin acoustic backscatter.

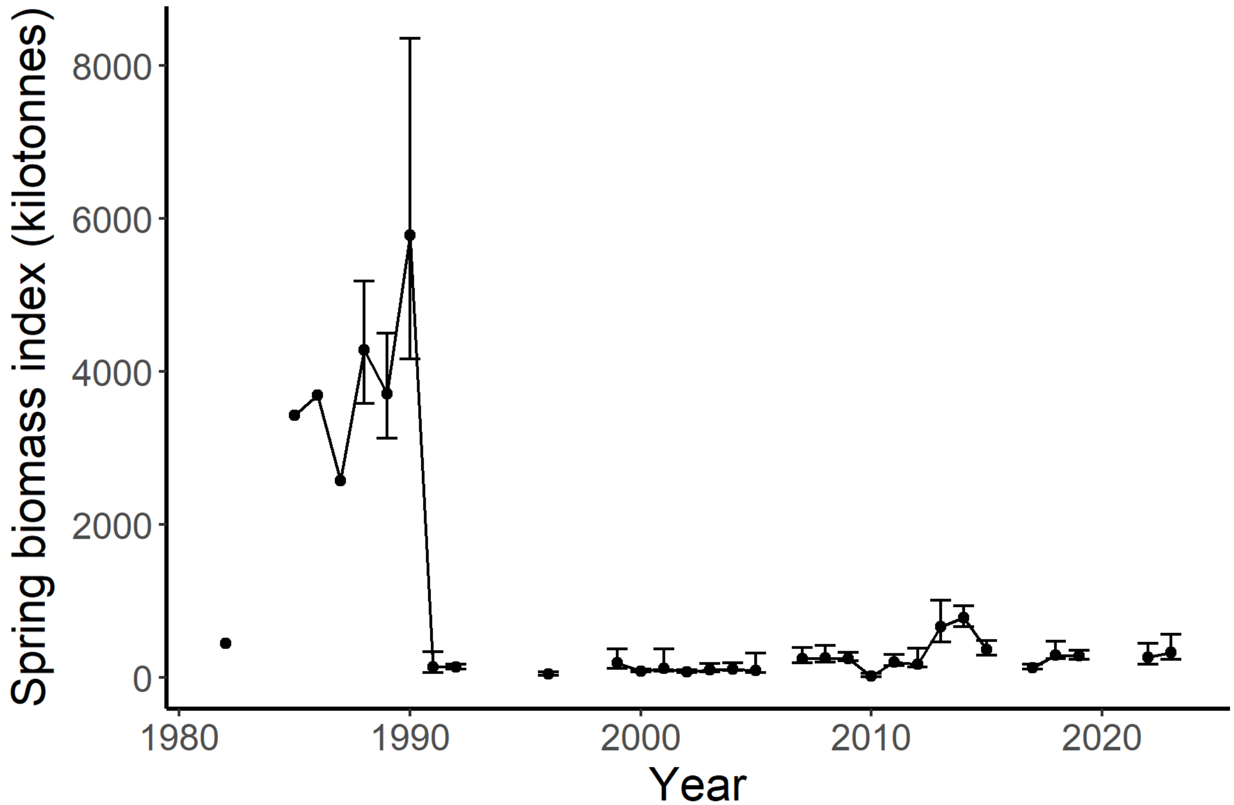

Figure 15. Capelin spring acoustic biomass index from 1982–2023. Error bars are 90% confidence intervals, ranging from the 5th to the 95th percentiles of the estimate. Error bars could not be calculated for 1982–87.

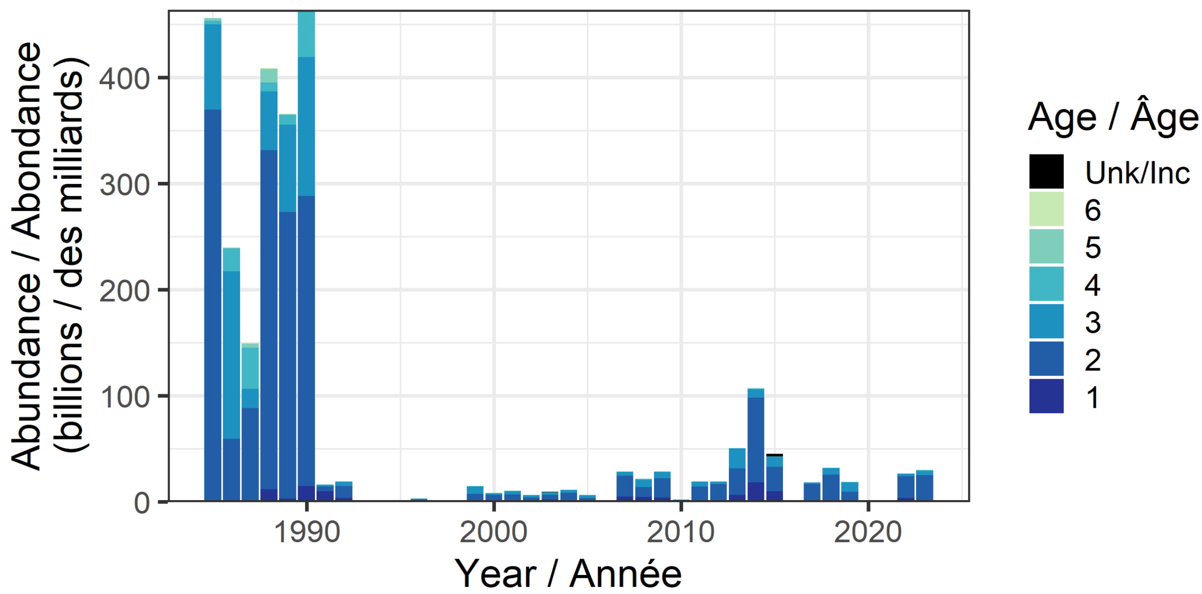

Figure 16. Capelin spring acoustic age disaggregated abundance index from 1985–2023.

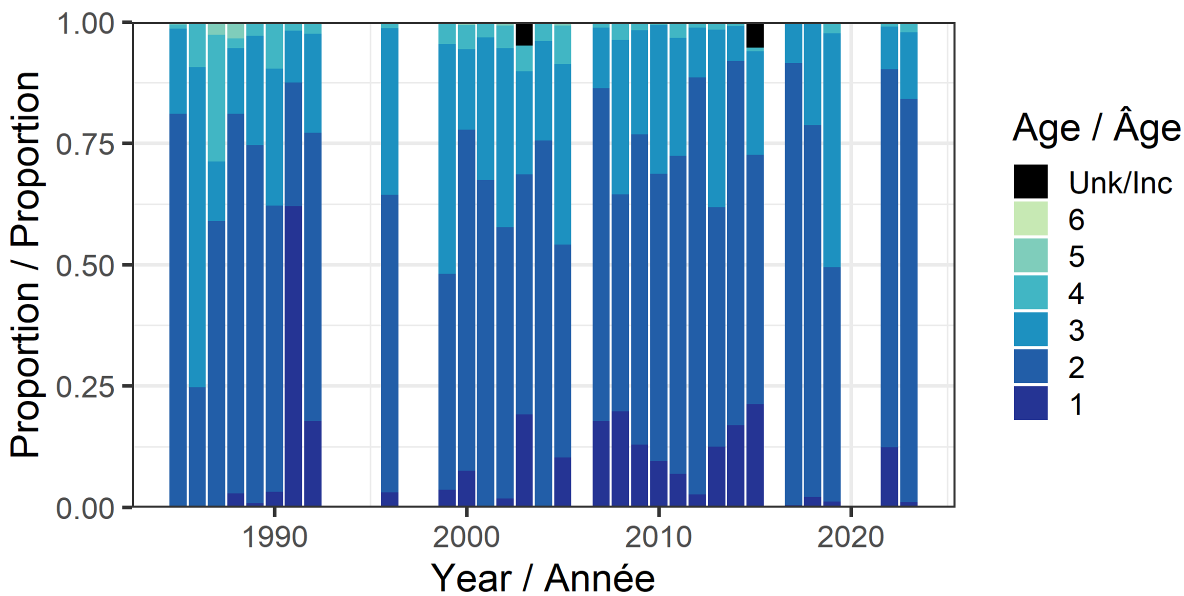

Figure 17. Age composition of 2J3KL Capelin in the spring acoustic survey since 1985.

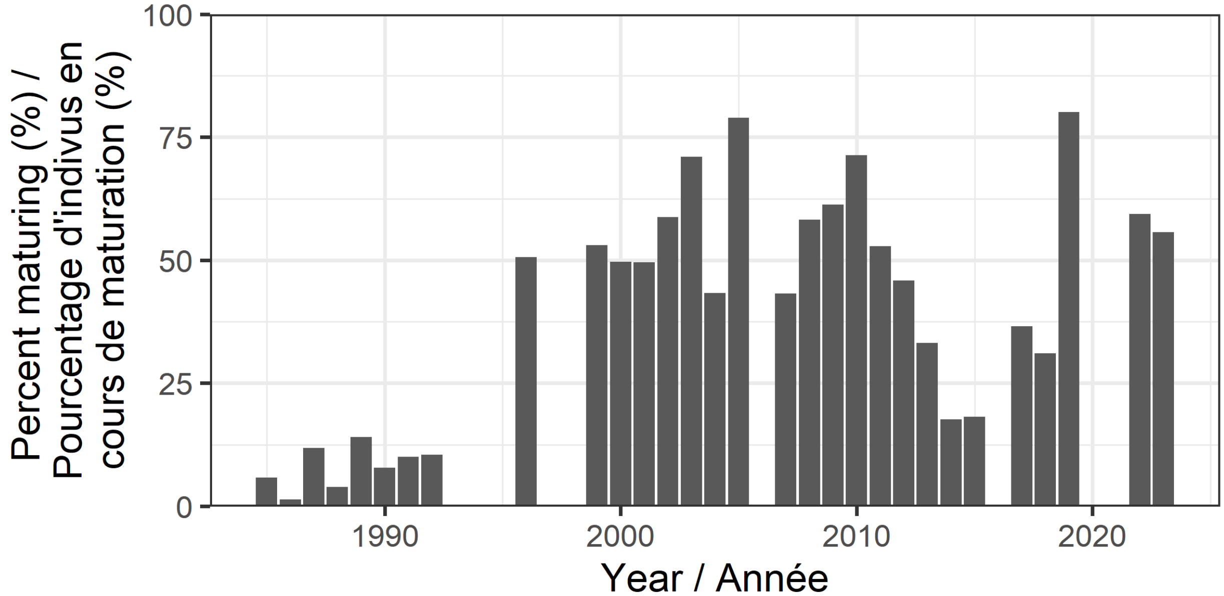

Figure 18. Percentage maturing of female age-2 Capelin in the spring acoustic survey since 1985.

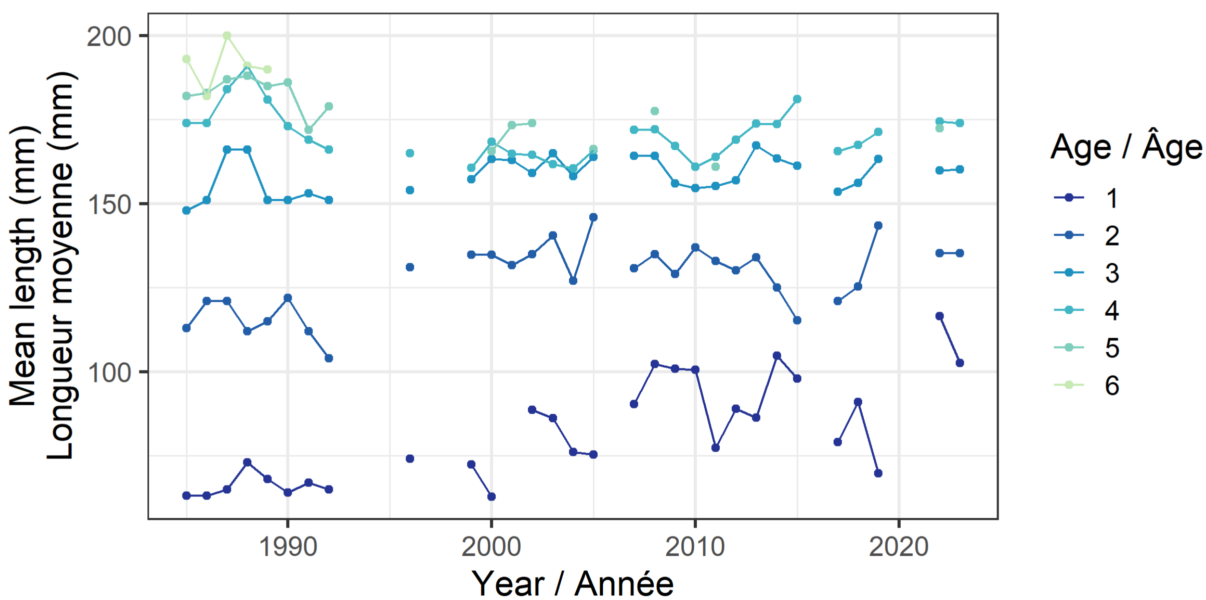

Figure 19. Mean lengths of 2J3KL Capelin sampled in the spring acoustic survey (ages 1–6) from 1985–2022.

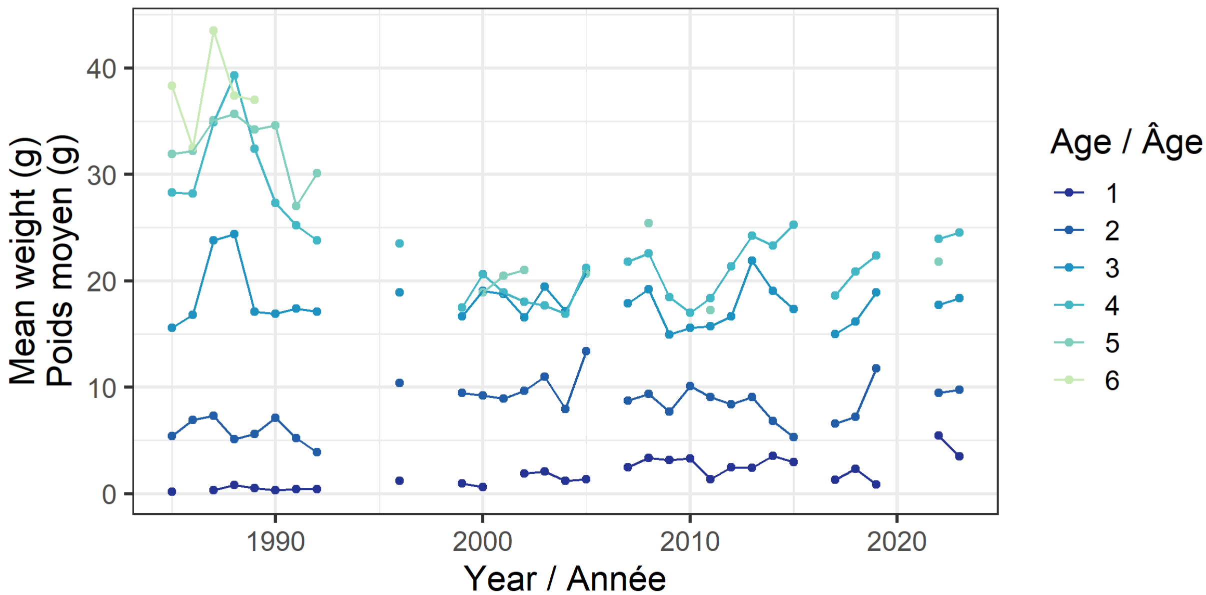

Figure 20. Mean weights of 2J3KL Capelin sampled in the spring acoustic survey (ages 1–6) from 1985–2022.

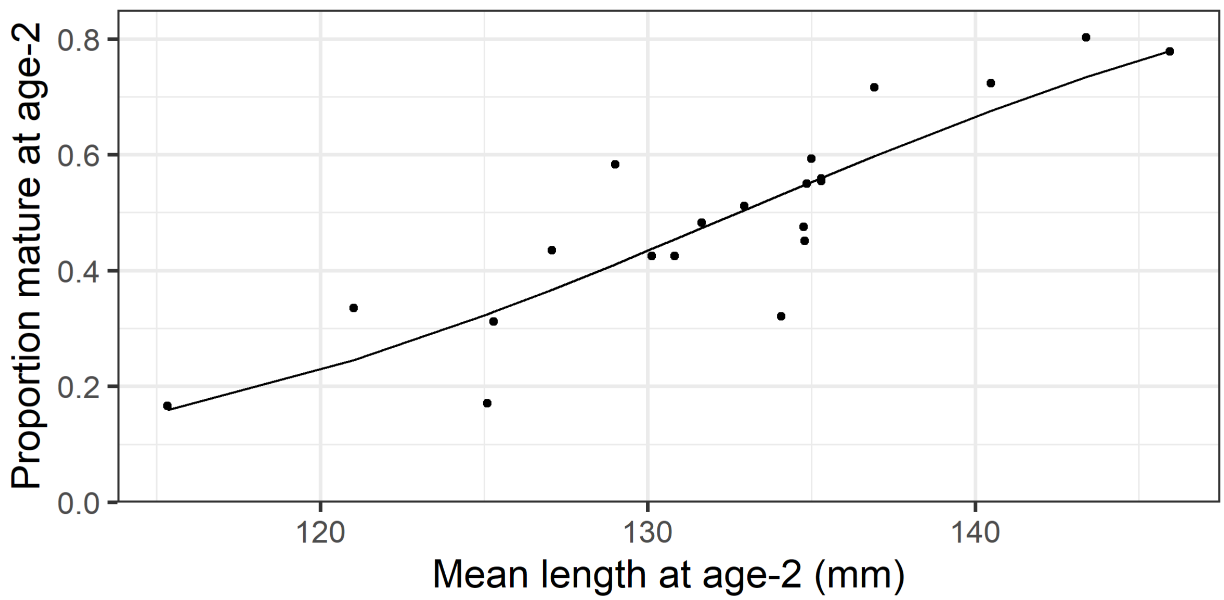

Figure 21. Proportion of Capelin mature at age-2 was positively related to mean length at age-2 (beta regression Pseudo R^2=0.77, p=0.001).

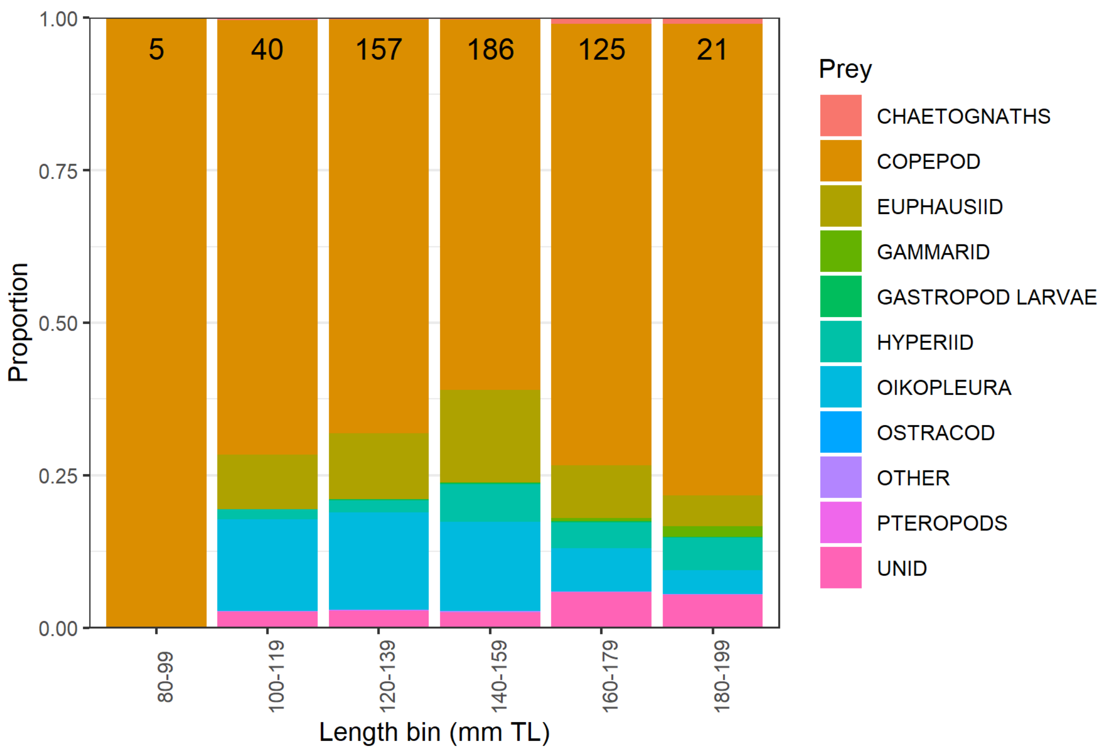

Figure 22. Proportion of main prey taxa in Capelin diet in spring 2023. The other category includes rare prey taxa like cirripedia and polychaetes, and the unid category includes digested material. The numbers at the top of each bar are the number of stomachs analyzed.

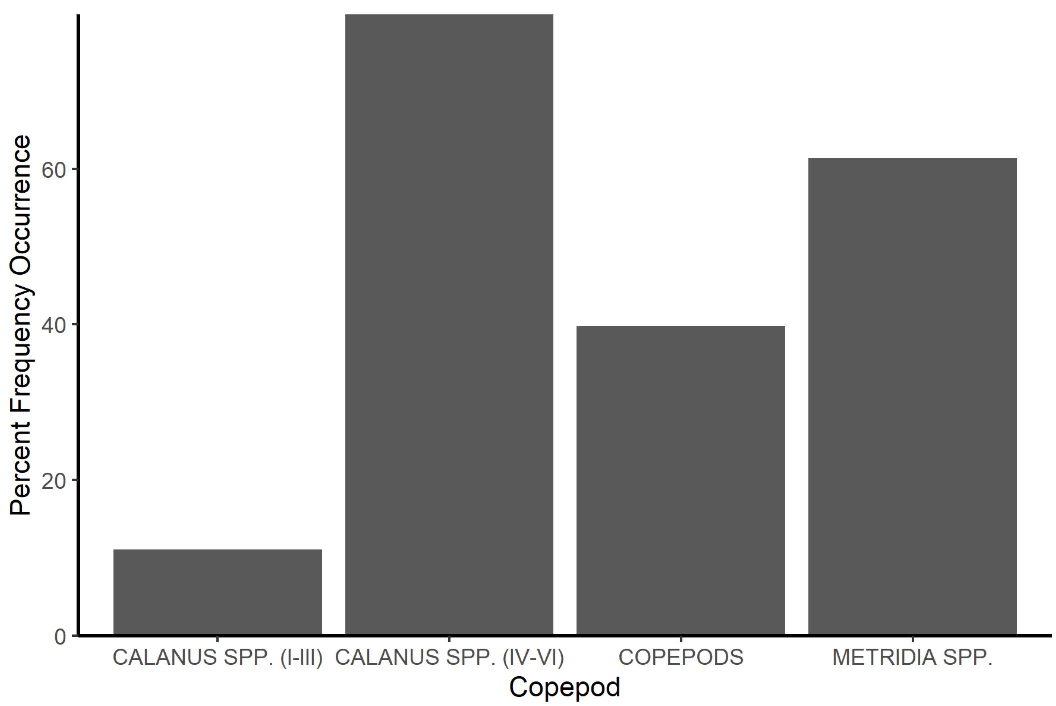

Figure 23. Frequency of occurrence of copepod categories in Capelin diet in spring 2023. 'Copepods' category includes small copepods like Pseudocalanus spp. as well as copepod pieces.

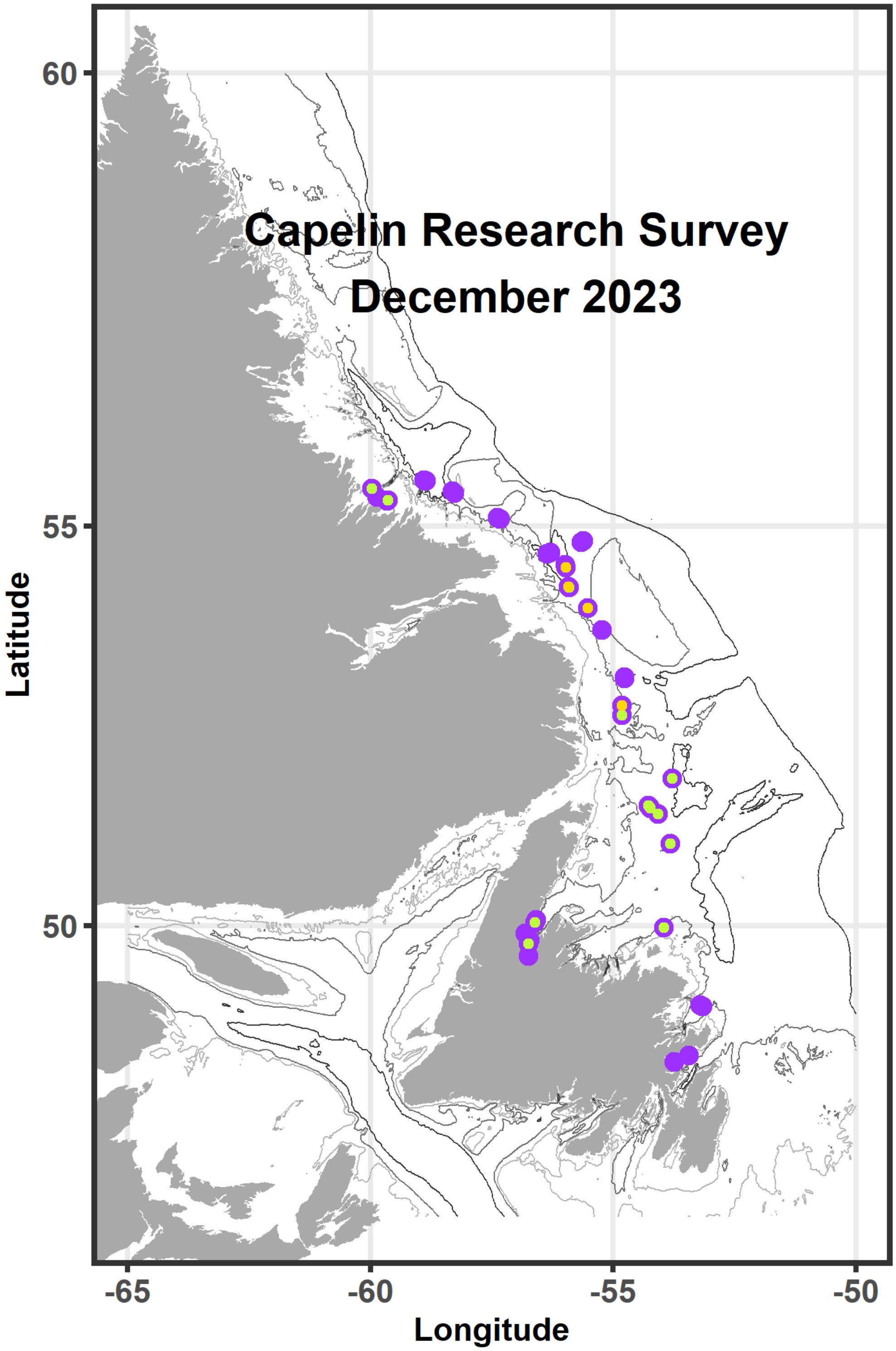

Figure 24. Fishing set locations (purple) for the Capelin Acoustic Research Survey conducted from Nov 30 – Dec 15, 2023. Depending on the presence or absence of strong acoustic signal in the water column, fishing sets were either conducted in pairs (pelagic and demersal tow) or solo (demersal tow only). Locations where Capelin were captured are indicated by purple/green and purple/gold. Purple/gold indicates Capelin samples contributing to the fall condition index.

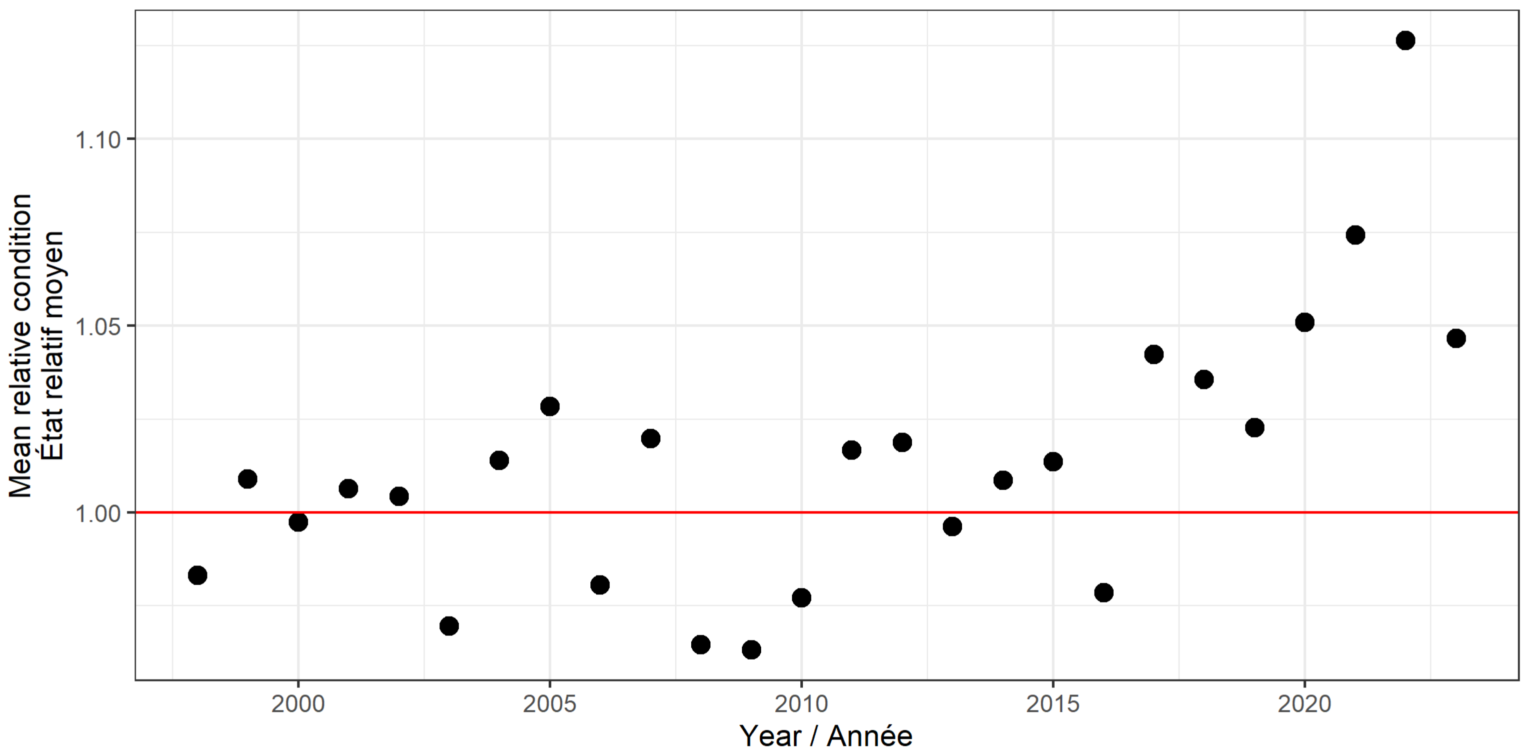

Figure 25. Fall relative condition of ages-1 and -2 male and female Capelin in Div. 2J3KL from 1999–2023. Red horizontal line is the mean relative condition.

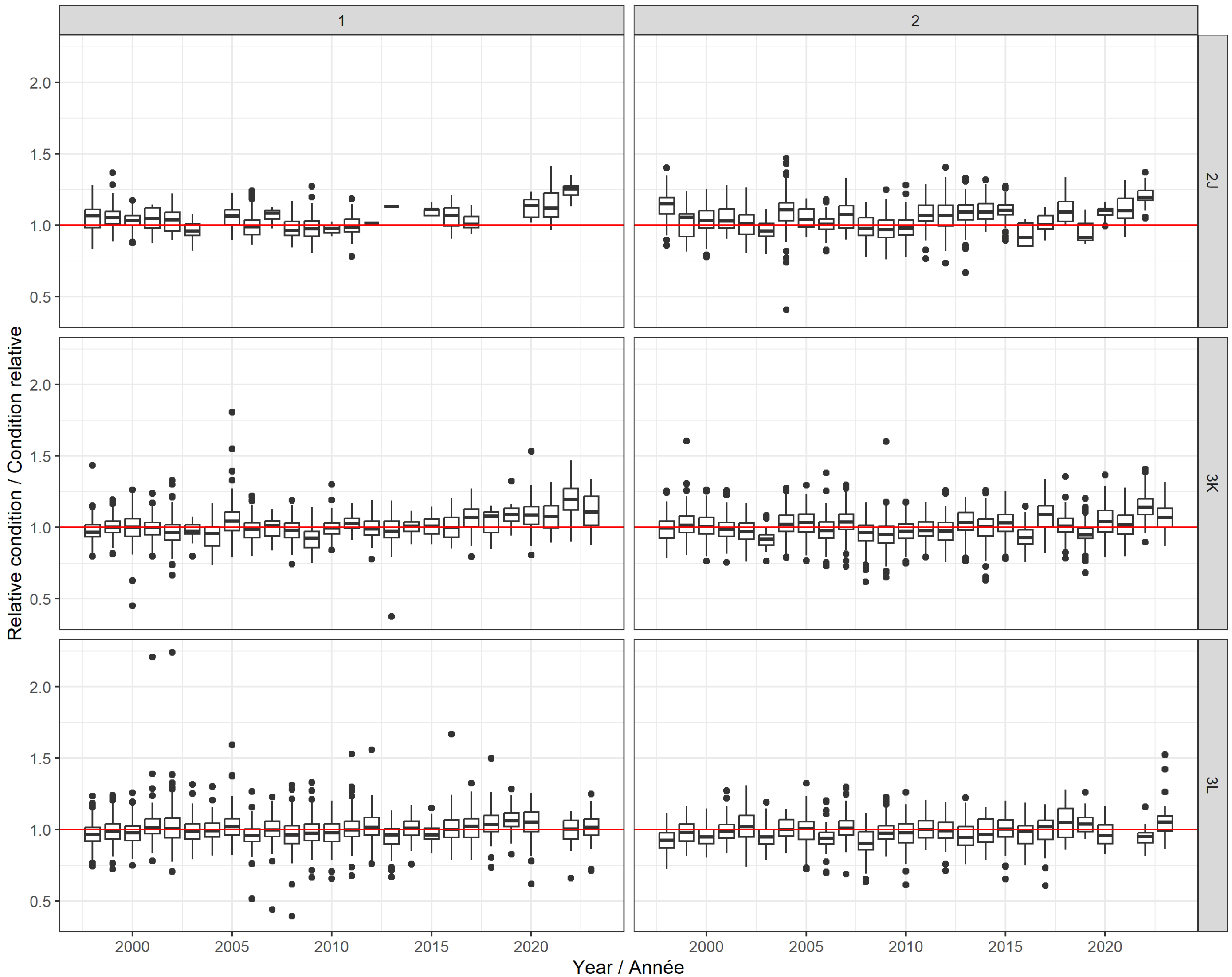

Figure 26. Fall relative condition of ages-1 and -2 Capelin (pooled for sex) by NAFO Division from 1999–2023. Red horizontal line is the mean relative condition.

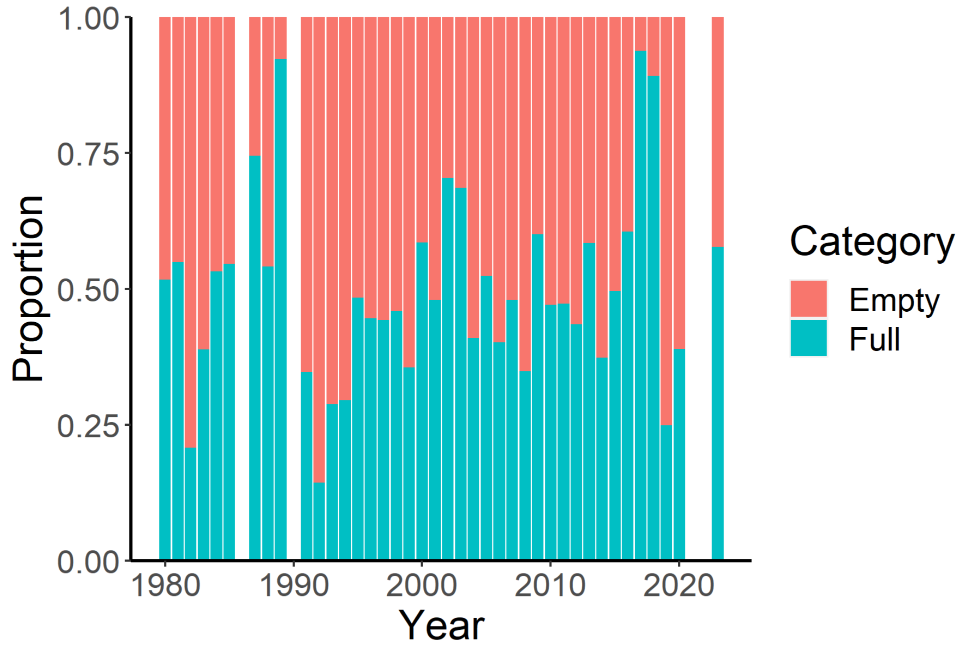

Figure 27. Proportion of empty (category 0) and full (categories 1–4 on stomach fullness scale, pooled) of undissected 'called' Capelin stomachs in the fall multi-species bottom-trawl survey in Divs. 2J3KL (1980–2023). Data from 2021 and 2022 are not included due to changes in survey coverage in these two years. Gear change from Engel to Campelen bottom trawls occurred in 1996.

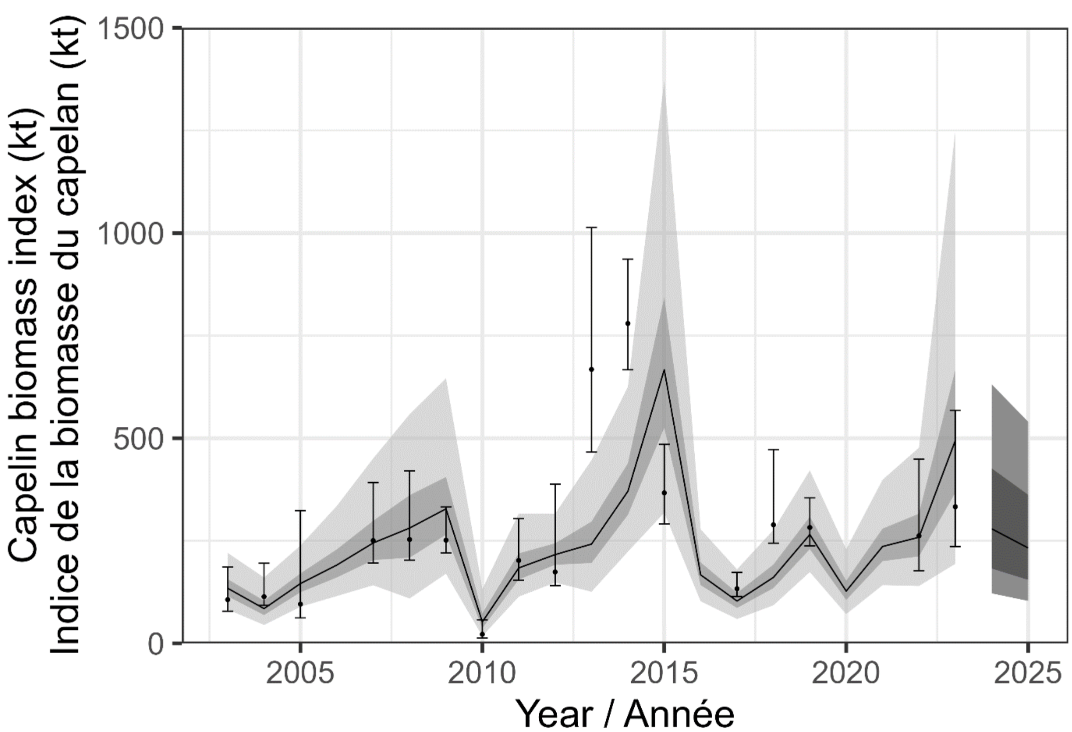

Figure 28. Results for the Capelin forecast model including the 95% credible (light grey) and 80% prediction (dark grey) intervals for expected values of the spring acoustic capelin biomass index (solid line). Observed biomass index values (circles) with 95% confidence intervals are also plotted. Condition value from 2022 was used in this final model run.

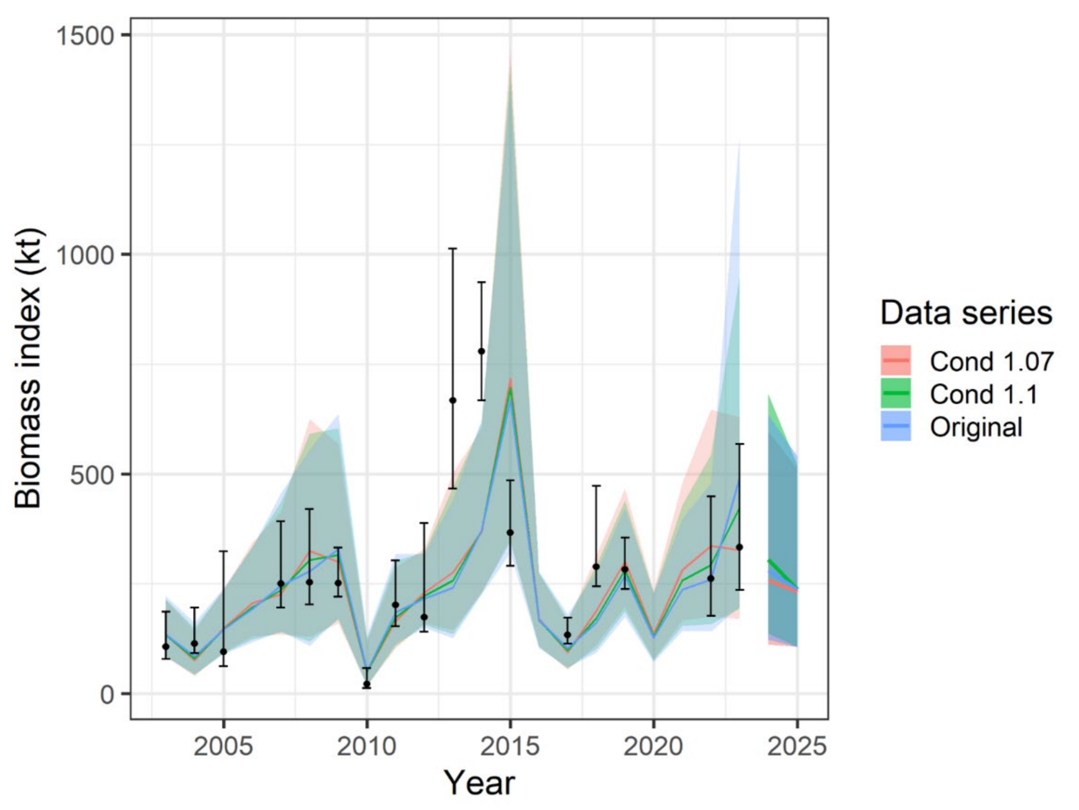

Figure 29. Forecast model credible intervals (2.5th to 97.5th percentiles) from 2003–23, and prediction intervals (10th to 90th percentiles) from 2024 to 2025 using three different values for fall condition in 2022. Solid lines show the median of the credible or prediction intervals. The original condition value for 2022 was 1.13 and is shown with blue lines and shading. The 2nd highest relative condition value was 1.07 and is shown with red lines and shading while the midpoint relative condition value for 2022 was 1.1 and is shown with the green lines and shading. Observed biomass index values (black circles) with 90% confidence intervals (black lines with whiskers) are also shown.

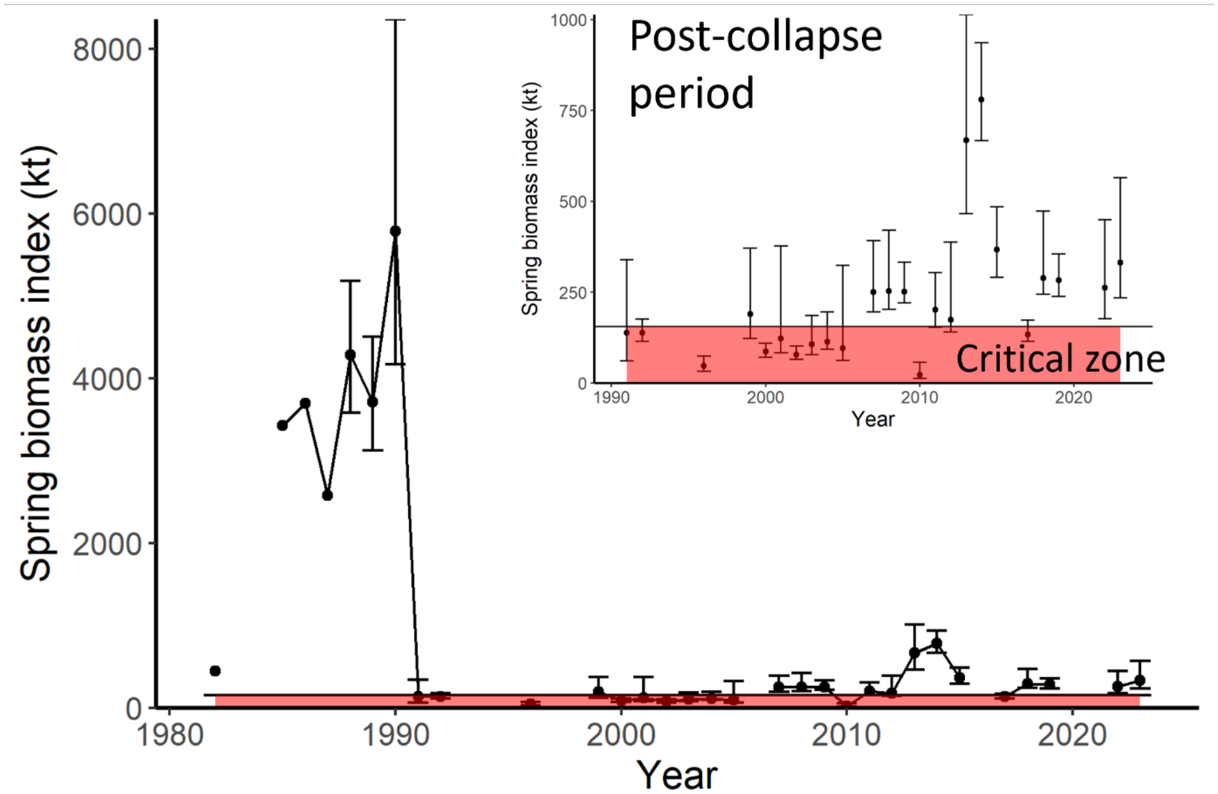

Figure 30. The Capelin LRP is 155 kt and was updated at the 2024 assessment in response to an update in the Northern Cod LRP. Using the capcod model (Koen-Alonso et al. 2021) and 40%B_{msy} Northern Cod LRP, a 155 kt acoustic biomass index is the Capelin LRP, below which the 2J3KL Capelin stock and the Northern Cod stock are likely at risk of serious harm. The inset figure shows the post-collapse years only (1991–2023).

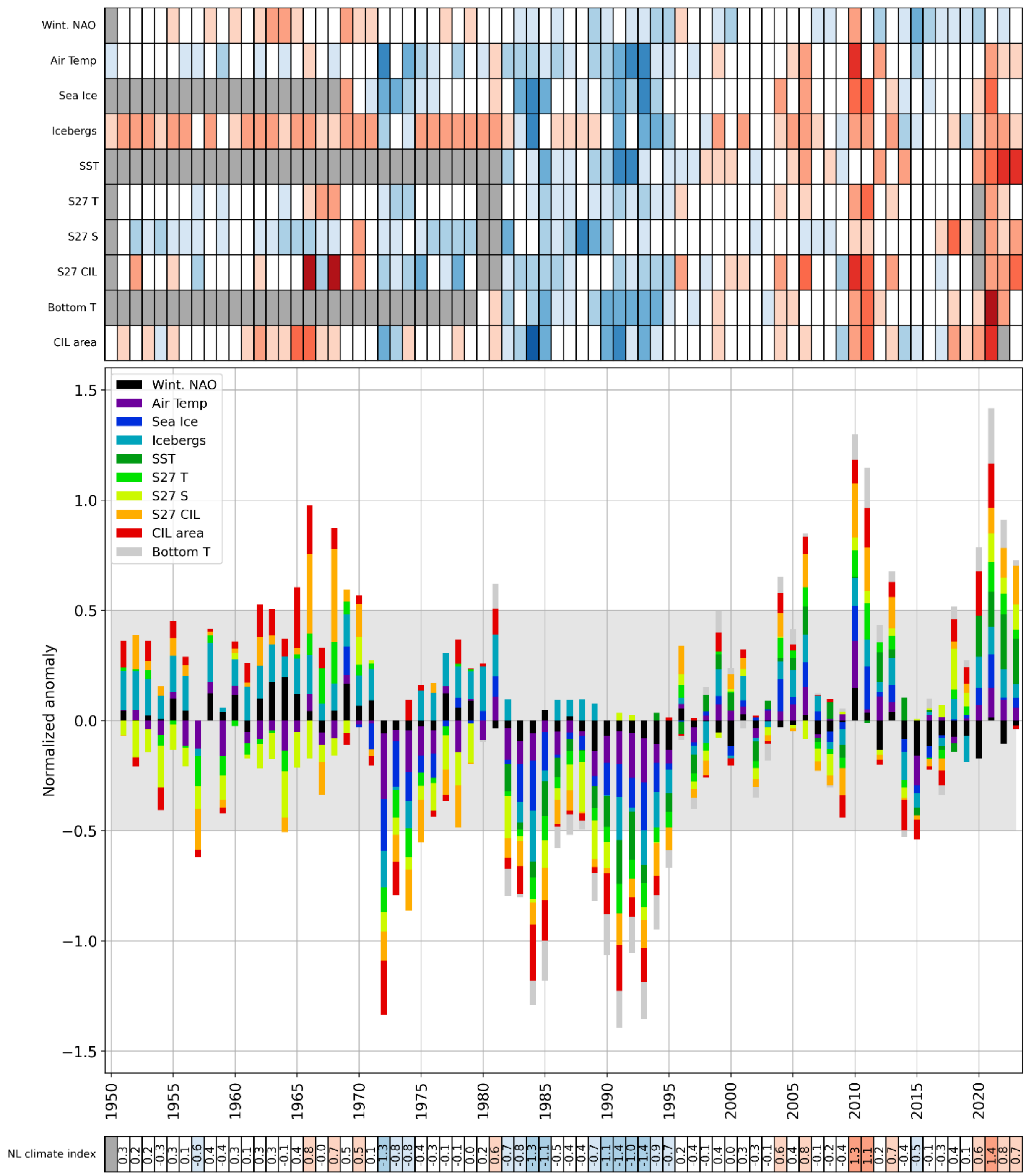

Figure 31. The Newfoundland and Labrador Climate Index updated to 2023. The index is made up of 10 subindices: winter NAO index; air temperature at five sites; sea ice season duration and maximum area for northern and southern Labrador and Newfoundland shelves; number of icebergs; sea surface temperatures in NAFO Divisions 2GHJ3KLNOP; vertically averaged temperature and salinity at Station 27; Cold Intermediate Layer (CIL) core temperature at Station 27; summer CIL areas in hydrographic sections Seal Island, Bonavista Bay, and Flemish Cap; spring and fall bottom temperatures in NAFO Divisions 3LNOPs and 2HJ3KLNO, respectively. The length of the stacked-bar is the average of the respective subindices in which their relative contribution to the average is adjusted proportionally. The scorecard at the bottom of figure shows the colour-coded numerical values of the climate index (blue negative, red positive, white neutral).

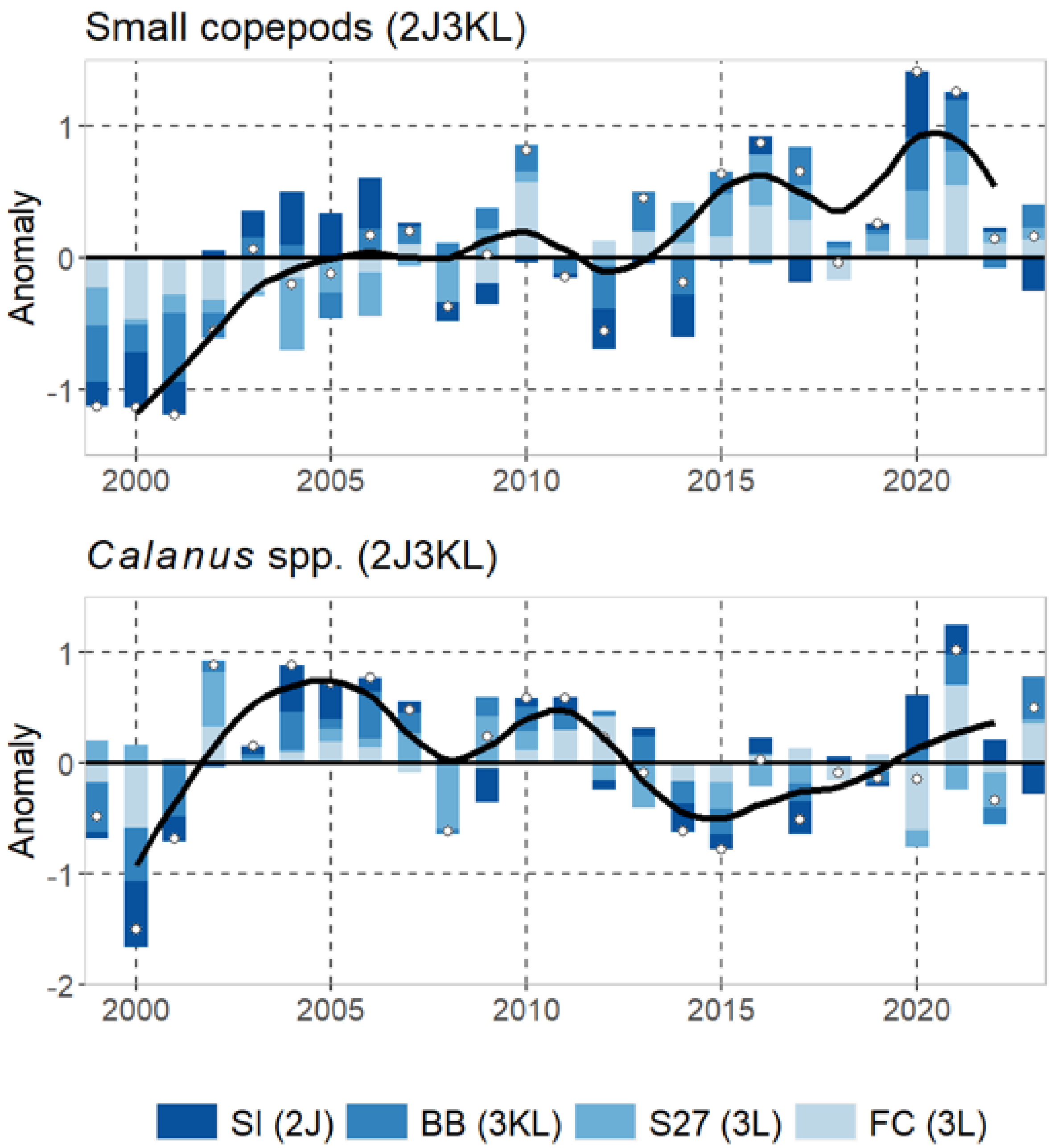

Figure 32. Zooplankton abundance anomalies for small copepods (top panel) and Calanus spp. (bottom panel) from 1999–2023. Colour shades indicate the relative contribution of AZMP section/NAFO Division to the annual mean anomaly (open circles) for the region. Small copepod taxa include Pseudocalanus spp., Oithona spp., and Temora longicornis . SI is Seal Island section, BB is Bonavista Bay section, S27 is Station 27, and FC is Flemish Cap section.

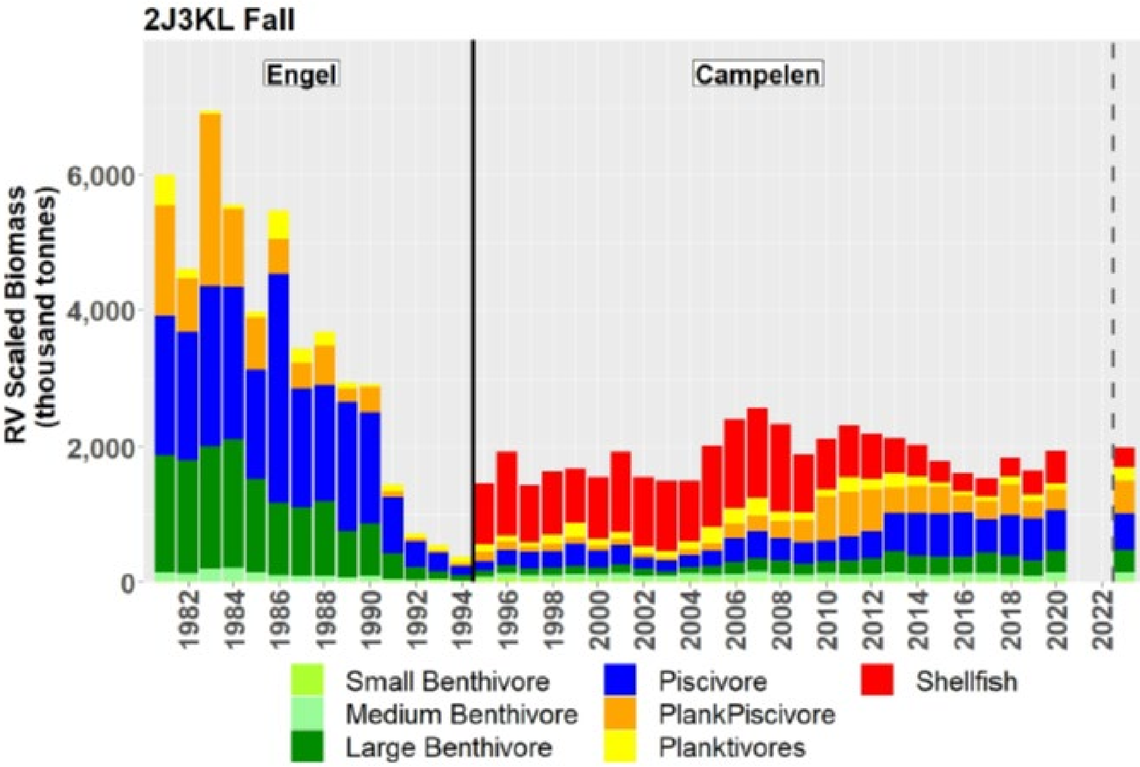

Figure 33. Total Fall RV Biomass index trend of the fish community in the Newfoundland Shelf and northern Grand Bank (Divs. 2J3KL) discriminated by fish functional groups. Indices for the Engel period (solid vertical line: 1981–95) have been scaled to be comparable to the Campelen period (1996–2022) (Koen-Alonso and Cuff 2018). New Science Research Vessels started operation in 2023 (vertical dashed line). Shellfish data were not consistently collected during the Engel period; the index for this functional group is not available prior to 1995.

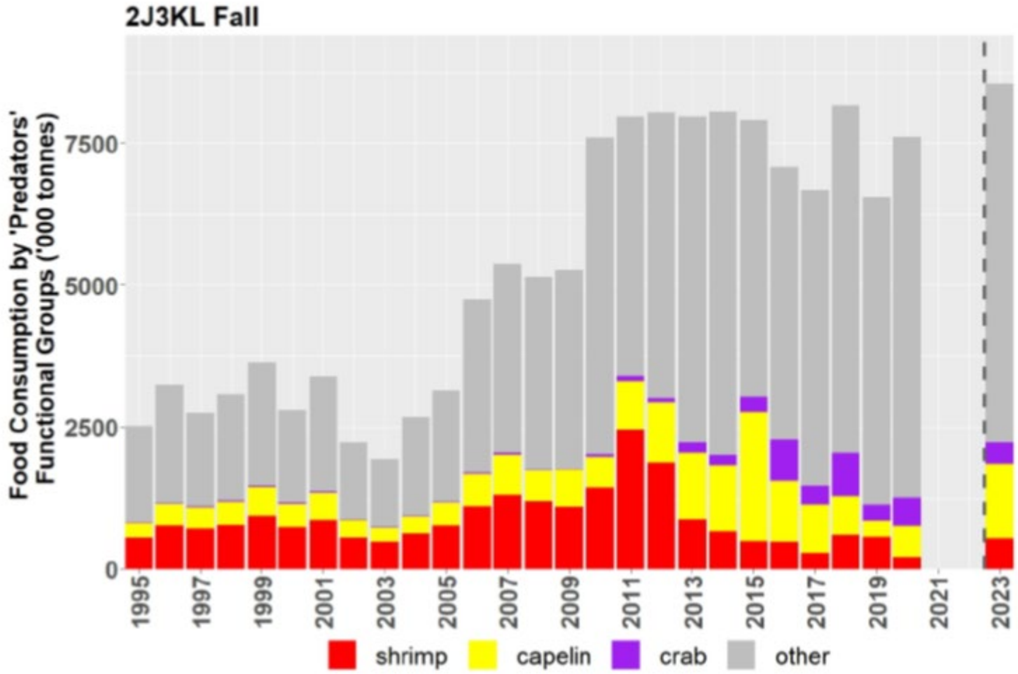

Figure 34. Consumption of shrimp, Capelin and crab by fish predators in NAFO Div. 2J3KL in the fall (1995–2023). New Science Research Vessels started operation in 2023 (vertical dashed line).

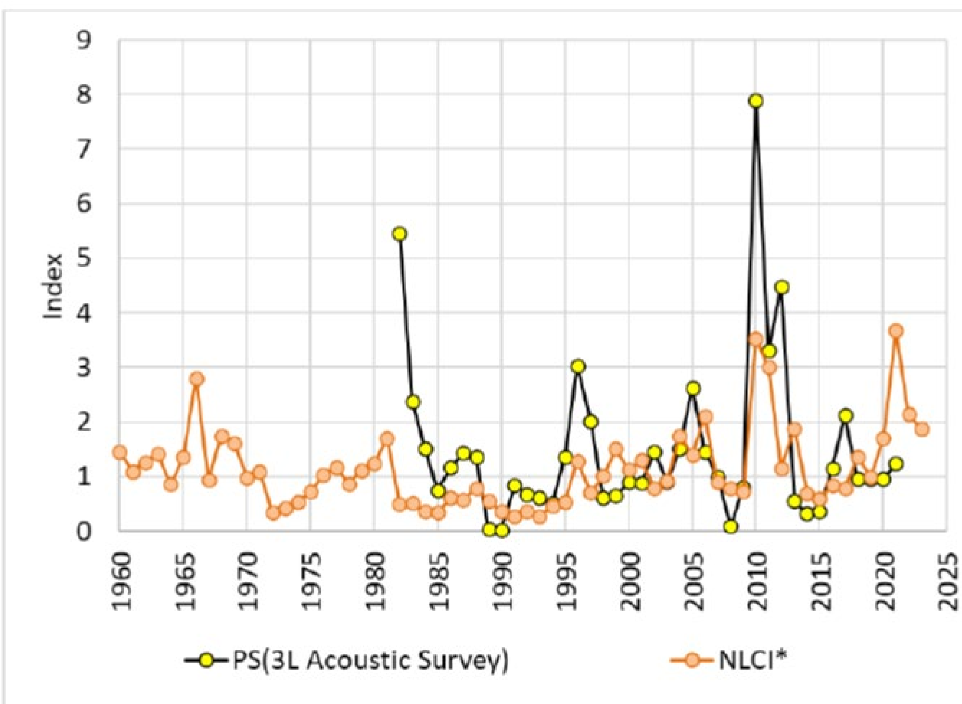

Figure 35. Capelin per capita recruitment (P) is related to the NL Climate Index (NLCI=exp(NLCI)) (Spearman Rho=0.32, p=0.046). P was calculated using linear interpolated values for the Capelin spring acoustic index when needed.*