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### **Assessment of Capelin (*Mallotus villosus*) in NAFO Divisions 2J + 3KL to 2022**

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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

Fishery-independent survey data (spring acoustic survey, larval survey, biological characteristics from the spring acoustic and fall bottom-trawl surveys, and citizen science beach spawning diary program) were used to assess the status of Capelin (*Mallotus villosus*) in Northwest Atlantic Fisheries Organization (NAFO) Divisions (Div.) 2J3KL up to and including 2022. There was no commercial Capelin fishery in 2022 due to market reasons. In 2022, the 2J3KL Capelin acoustic biomass index was above the post-collapse median and similar to 2018 and 2019, but well below the recent stock high of 2013–14 and a fraction of the 1980s median; Capelin were feeding well but immature fish were growing fast with a high proportion maturing at age-2; spawning timing was typical of the post-collapse period; and the Bellevue Beach (BB) larval index improved compared to recent years and was similar to the time series mean. Capelin fall relative condition was the highest in the time series, but the 2022 condition value may not be directly comparable to prior years due to an earlier than usual sampling time in Div. 3K in 2022 due to the Comparative Fishing Program. Therefore, the Capelin forecast model results can only be described qualitatively due to uncertainty in the 2022 condition value. The Capelin acoustic biomass index in 2023 is expected to be at or above the level of 2022. A 640 kt Capelin acoustic biomass index was selected as the Limit Reference Point (LRP) below which the Capelin stock is likely at risk of serious harm and is the level necessary to support the growth of the Northern cod (*Gadus morhua*) stock to levels last seen in 1983–89 (reference period for the Northern cod LRP). Since 1991, with the exception of 2013 and 2014, the Capelin stock has been in the critical zone. Consistent with the Fisheries and Oceans Canada (DFO) decision-making framework, incorporating the precautionary approach requires that removals from all sources must be kept at the lowest possible level until the stock clears the critical zone.

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## STOCK STRUCTURE

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 and Piatt 1999, Carscadden et al. 2013). Historically, Fisheries and Oceans Canada (DFO) Newfoundland and Labrador (NL) Region assessed and provided advice on three Newfoundland Capelin stocks: Northwest Atlantic Fisheries Organization (NAFO) Subarea (SA) 2 + Division (Div.) 3K; NAFO Div. 3L; and NAFO Div. 3NO. In 1992, as a result of accumulated biological evidence (Nakashima 1992), it was recommended that Capelin in NAFO SA 2 + Div. 3K and Div. 3L be considered one stock complex (hereafter referred to as 2J3KL Capelin). This is the only Capelin stock that the NL Region currently assesses (Fig. 1). There are two other assessed Capelin stocks in Canadian waters: the Gulf of St. Lawrence (Div. 4RST; assessed by DFO) and the Southeast Shoal (Div. 3NO; assessed by NAFO), and one unassessed stock on the south coast of Newfoundland (Subdivision [Subdiv.] 3Ps).

Capelin is the dominant forage fish in the NL ecosystem, providing a vital energetic link between zooplankton and numerous higher trophic level predators, including seals, whales, Northern cod, Greenland Halibut (*Reinhardtius hippoglossoides*), Atlantic Salmon (*Salmo salar*), and seabirds (Templeman 1948, Carscadden et al. 2001, Davoren and Montevecchi 2003, Buren et al. 2014b). 2J3KL Capelin spend most of their adult life offshore on the Newfoundland and Labrador shelves. The center of Capelin distribution changes seasonally, typically with Capelin found feeding further north (NAFO Div. 2J and 3K) 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 to spawn at beaches and coastal deep-water (demersal) sites in the summer.

The 2J3KL Capelin stock collapsed in the early-1990s with minimal recovery over the subsequent 30+ years (Buren et al. 2019). Historically, Capelin matured and spawned at ages-3–4. Following the collapse of the stock, immature Capelin experienced faster growth and now mature at a younger age, suggesting a compensatory growth response due to lower stock abundance and relaxation of resource competition (Engelhard and Heino 2004). Since the majority of 2J3KL Capelin die after spawning (i.e. semelparous; Winters and Carscadden 1978, Shackell et al. 1994, Flynn et al. 2001), a significant proportion of Capelin maturing at age-2 results in an age-truncated spawning population with few fish age-4+ compared to the 1980s. Following the stock collapse, Capelin experienced an abrupt and persistent delay in beach spawning timing, with spawning occurring approximately 18 days later during the post-collapse period (1991–2019; and continuing through to today) compared to much of the 20<sup>th</sup> century (1919–90), and there has been minimal beach spawning in Labrador since the stock collapse (Murphy et al. 2021). The predictors of delayed spawning were small size of spawners (related to the change in age structure of the population to a younger age at maturation) and negative anomalies in the summer North Atlantic Oscillation index and the Newfoundland and Labrador Climate Index (Murphy et al. 2021). This persistent delay in beach spawning timing has resulted in an observed increase in the use of coastal deep-water spawning sites by fishers (Nakashima and Clark 1999) since beaches are often too warm (>12°C) later in the summer for spawning (Templeman 1948, Dodson et al. 1991, Davoren 2013). Embryo development and larval emergence are delayed at deep-water spawning sites due to colder water temperatures at these sites compared to beach sites, but recent research suggests that these spawning habitats can produce similar larval densities as beach sites (Tripp et al. 2023) in contrast to an earlier study (Nakashima and Wheeler 2002). Year-class strength is set early in the life history of Capelin

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(Murphy et al. 2018), and delayed spawning is predicted to produce weaker year-classes (Murphy et al. 2021).

## FISHERY

### FISHERY OVERVIEW

Capelin have historically been an important part of the NL inshore fishery and culture, with fish gathered from spawning beaches for food, bait and fertilizer. In the early-1970s, an offshore fishery of immature and maturing fish in primarily autumn (August-December) began in Div. 2J3KL and peaked at nearly 250,000 tonnes in 1976. An inshore summer (June-August) commercial roe-fishery began in 1978, peaking at 71,000 tonnes in 1990 (Fig. 2). The offshore fishery was closed in Div. 3L in 1979 and in Div. 2J3K in 1992; the inshore fishery is the only ongoing commercial Capelin fishery and has median annual landings of 20,406 t from 1991–2021. There has been a decline in the Total Allowable Catch (TAC) since 2017 to a low of 14,533 t in 2022. Due to the short fishing season, changes in fishery timing and 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.

Participation in the Capelin fishery depends on market conditions and processing sector capacity both for Capelin and for other species. Currently, the Capelin Integrated Fishery Management Plan (IFMP) splits the overall quota between mobile and fixed gear sectors (DFO 2019). Limits on the window of time during which the fishery occurs are set forth in the IFMP, but opening dates for each gear sector within each bay are determined annually in consultation with industry and are dependent on the availability and quality of Capelin. Prior to the opening of the fishery, test fishery permits are allocated to monitor the biological characteristics of Capelin. In most cases, industry will not request the fishery within a bay be opened until the test fishery finds that Capelin are of high quality (i.e., large size, high proportion of females, low occurrence of 'red' feed (copepods) in the stomachs). The mobile gear sector opens 24 hours in advance of the fixed gear sector. The mobile sector is comprised solely of purse seiners, which are permitted to harvest quota throughout the stock area (i.e., across multiple fishing areas). The fixed gear component consists of traps, cast-nets, dip-nets and tuck seines (modified bar seines). Fishers holding fixed gear licenses are limited to harvesting within one Capelin fishing area.

Samples from the commercial fishery are obtained from vessels as catches are unloaded at processing facilities. Up to ten samples of 200 fish each are collected and frozen from landings in each bay. A total of 20 of these frozen samples are processed each year, apportioned among gear sectors, bays and week as a function of the total 2J3KL Capelin landings. Length, sex, and maturity are determined for all fish sampled and additional detailed information (weight, gonad weight, stomach fullness, and age from otoliths) are collected for two fish per sex, per 5 mm length class in each sample. Catch at age is calculated separately for each catch cell, which 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 to 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. The resulting length and age frequencies from sampled fish are scaled to landings for each catch cell.

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## Commercial Landings and Biological Characteristics

In 2022, the TAC for the 2J3KL + 3Ps Capelin stock areas was 14,533 t; however, the fishery was not opened due to market reasons (Fig. 2). This is the third time in the post-collapse period where the fishery was not opened due to market reasons (test fishery landed 960 t in 1994 and 116 t in 1995). In 2021, the commercial fishery in Div. 2J3KL landed 13,945 t (96% of the 14,533 TAC for Divs. 2J3KL+ 3Ps; Fig. 2).

Age and size structure of spawning fish is usually inferred from commercial catches. But with no commercial fishery in 2022, biological data from the fishery were not available. However, DFO staff and citizen scientists used cast nets to collect spawning Capelin from beaches on the southern and the northeastern coasts of the island of Newfoundland at a rate of approximately one sample per week during the period of active spawning. Spawning fish were collected from one beach in Div. 3Ps in June (Lawn), five beaches in Div. 3L in June and July (Middle Cove, Holyrood, Chapels Cove, Long Beach, and Bellevue Beach [BB] and one beach in Div. 3K in July (Jackson's Cove). The collections of spawning fish followed the northeasterly spawning migration. At all beach sites except BB, 200 fish were randomly sampled 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. At BB, 25 females and 25 males were collected, and detailed sampling was conducted on the full sample. A total of 989 fish were analyzed for age, length, weight, and sex, with the majority sampled in Div. 3L ( $n = 905$ ), followed by Div. 3Ps ( $n = 63$ ) and Div. 3K ( $n = 21$ ). In the 2022 beach samples, the majority of spawners were age-3 (54%) (Fig. 3a), and mean length and standard deviation (pooled by sex and age) ranged from  $162 \pm 17.7$  mm Total Length (TL) in Div. 3Ps to  $173 \pm 16.9$  mm TL in Div. 3K. In Div. 3L, where the majority of samples were obtained, there was evidence of a change in age structure and length from June to July (data were pooled by sex; Fig. 3b). Proportion of age-2 spawners increased from 0.18 to 0.28 and mean length (pooled by age and sex) decreased from  $172 \pm 12.4$  mm TL to  $165 \pm 15.1$  mm TL from June to July. These data document the presence of two spawning waves in Div. 3L. It is unknown how these beach samples relate to the commercial samples.

## SPAWNING

Capelin beach spawning timing changed abruptly in 1991 and this change has persisted with beach spawning occurring on average 18 days later compared to earlier in the 20<sup>th</sup> century (Murphy et al. 2021). Delayed beach spawning timing is predicted to produce weak year-classes (Murphy et al. 2021), which may be due to a combination of factors including later spawners are generally smaller, younger, and produce fewer eggs and there is now a mismatch between larval emergence and ideal environmental conditions for larval survival in the post-collapse period (Leggett et al. 1984, Murphy et al. 2018).

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) (Murphy 2022). There has been consistent monitoring of beaches during this program, with each beach monitored on average five years (range 1–32 years) (Murphy 2022). Participation in this program has varied inter-annually with on average 18 beaches monitored each year (Fig. 4). In 2022, 16 beaches were monitored with three beaches recording no spawning behaviour (one beach in 3Ps and two beaches in 3K) (Fig. 5). Median peak (high intensity) beach spawning was July 8, 2022, which is similar to the long-term median (July 9 from 1991–2020) but was approximately two weeks later than in 2021 (median peak spawning day: June 22). However, median first day of spawning was June 22, 2022, which is earlier than

average (July 4), but spawning intensity was considered low to moderate by citizen scientists. Two waves of spawning were observed in 2022, with the spawning period lasting on average 17 days (median duration is 11 days from 1991–2021; Murphy 2022). This documentation of two spawning waves is supported by the beach spawning samples collected in Div. 3L (Fig. 3b) which showed differences in age composition between June and July. Spawning started first in Div. 3Ps (June 26; only two beaches monitored) followed by Div. 3L (July 8) and Div. 3K (July 17) (Fig. 5). Year-class strength is predicted to be weak in 2022 based on beach spawning timing that was similar to the post-collapse median.

## EARLY LIFE HISTORY

### BELLEVUE BEACH LARVAL INDEX

Larval surface tows have been conducted at five fixed stations in nearshore waters (<20 m) off BB, Trinity Bay (TB) since 2001 (Fig. 6a). This survey was designed to sample larvae emerging from BB, nearshore deep-water Capelin spawning beds, and four smaller spawning beaches along the western shore of BB. This monitoring program is conducted from a 27-foot fiberglass boat using two 75 cm diameter ring nets with 270 µm mesh which are towed for a duration of 10 minutes at 2.1 knots every 24–48 hours (weather permitting) from the start to the end of larval emergence (~6 weeks each summer). Only one of the nets collects a larval sample; the second net is used for balance and does not have a codend. A General Oceanics 2030 Series mechanical flow meter, positioned in the opening of the net with the codend, measures the volume of water filtered. Capelin larvae are preserved in a 5% formalin and saltwater solution buffered with sodium borate, and samples are processed in the laboratory. When less than 500 Capelin larvae are present in a sample, they are all enumerated; otherwise, a sub-sampling technique is used (Van Guelpen et al. 1982). From each sample, 50 larvae are measured and the presence/absence of their yolk sac is recorded. If the yolk sac is present, then its diameter is measured. Capelin larvae sampled in this index range in age from newly emerged to <12 days (size range 3–10 mm Standard Length [SL]). This estimate of age is based on the presence/absence of the yolk sac and larval length. Capelin do not form daily increments in their otoliths until approximately 12 days post-hatch (Ivarjord et al. 2008), and few of these larvae have formed daily increments at the time of sampling (Murphy, unpublished data).

Total annual production of larvae per m<sup>3</sup> (N) is estimated using the trapezoidal integration method in equation 1:

$N = \sum (t_n - t_{n-1}) \frac{1}{2} [X(t_n) + X(t_{n-1})]$	<b>1</b>
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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<sup>3</sup> from the five stations sampled on day t. Only days when all five stations were successfully sampled were included in the analysis. If a sample 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 total annual production of larvae (var(N)) is estimated using equation 2 based on Millar and Jordan (2013) and Irvine et al. (1992):

$\text{var}(N) = 0.25 \sum (t_n - t_{n-1})^2 \text{var}(c_n)$	<b>2</b>
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where t is the day of the year, n the sampling day, and var(c<sub>n</sub>) is the variance of larval densities from the five samples per sampling day.



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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, is positively related to the BB surface tow index (Murphy et al. 2018). However, this relationship has weakened in recent years and is no longer significant due to recent better-than-expected age-2 recruitment from years with low BB larval index values (Fig. 6b). This may be due to a variety of potential factors such as a shift in distribution of spawning to deep-water spawning habitats or BB no longer representing typical larval production in TB. However, the BB larval index is a parameter in the most parsimonious forecast model (see Forecast Model section below), and the trends in larval indices were similar between a site in Notre Dame Bay, which has a high proportion of deep-water spawning, and the BB larval index (Tripp et al. 2023).

In 2022, the BB larval index ( $1,322 \pm 387.7$  ind.  $m^{-3}$ ) reached its highest level since 2013 and was similar to the time series mean ( $1,439.5$  ind.  $m^{-3}$ ; 2001–21) (Fig. 6c). This is the ninth consecutive low larval abundance year (2014–22) and includes all year-classes available to the fishery in 2023 (Fig. 6d).

## **IMMATURE AND MATURING STOCK SURVEYS**

### **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, although all age classes acoustically surveyed are included in the annual Capelin biomass index. 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. In 1982, the spring acoustic survey occurred in April, but it is included in the time series as the survey had good spatial coverage of Div. 3L. In 1983–84, the spring acoustic surveys were focused in southern Div. 3L in April and were not comparable to the typical spring acoustic survey so were excluded from the time series. In 2021, there was a spring acoustic survey in June that surveyed only a portion of strata in Div. 3L and was not comparable to other years so was excluded from the time series. Since 1996, the lower portion of Div. 3K (<50°N) has been included in the survey (Fig. 7). The inclusion of areas further north (>50°N) are precluded due to the presence of sea ice in May.

Originally, the main objective of the spring acoustic survey was to produce an abundance estimate of the non-migratory, immature portion of the Capelin stock (primarily age-2 fish) that would be recruited to the spawning population the following year. However, with an increased proportion of age-2 fish maturing since the collapse in the stock, the survey now also captures a proportion of the maturing, pre-spawning Capelin population. This variable proportion of maturing age-2 fish prevents the survey from being able to produce an estimate of the abundance of the spawning stock expected the following summer. The spring acoustic survey cannot provide an estimate of total spawning stock biomass because the surveyed area only covers a portion of the population range of Capelin and the spatial distribution of Capelin within that range varies from year to year. Previous surveys have shown that during the survey period larger and older Capelin were distributed north of the survey area, while a portion of the youngest Capelin (age-1 and age-2) can also be distributed in inshore areas. Details on the acoustic survey methods, sampling details, and calculation of abundance and biomass indices can be found in Mowbray (2013).

A stratified survey design is conducted each year, although the transect design, stratum boundaries, and areas covered have changed over time (Mowbray 2013, 2014). Prior to 1989, transects were laid out in equidistant parallel or zigzag patterns. From 1989 to 1992, randomly

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spaced parallel transects were surveyed following protocols set out in O'Boyle and Atkinson (1989). A randomly spaced transect design was thought preferable as it would allow for calculation of variance on abundance estimates based on transect means. However, a decline in offshore Capelin densities and a change in distribution patterns led researchers to revert back to the equidistant parallel line design in 1993, as this design was considered to have the greatest probability of intersecting Capelin aggregations. Since 1999, the start latitude of the initial survey transect has been randomly generated for each survey. Prior to 1999, strata were generally rectangular and extended from the coastline across the shelf, but not as far as the shelf break. Since 1999, stratum have been depth-delimited. The methodology and original strata for each survey from 1982 to 1996 are presented in annual stock assessment documents (Miller 1991, 1992, 1997). A more detailed description of survey changes is documented in Mowbray (2013) and all changes in survey design are accounted for in the biomass index calculations.

Capelin abundance is derived from the acoustic backscatter measurements for the entire water column. Echograms are edited in two steps:

1. application of an automated bottom detection algorithm and manual review of the results to adjust the chosen bottom so as to exclude all signals generated by bottom substrate;
2. acoustic backscatters are reviewed by trained analysts and assigned species-specific regions based on targeted fishing sets, acoustic frequency response, target strength information, signal shape/appearance, and previously acquired information on habitat and area associations.

An acoustic backscatter signal associated with a trawl catch comprised of 80% or more (by weight) of Capelin is assigned 100% to Capelin. When two predominant backscattering species are present in the catch (e.g., Capelin and Arctic cod [*Boreogadus saida*]), and Capelin comprised less than 80% of the catch, the acoustic backscatter is classified into regions proportional to the catch of each species. Demersal acoustic signals associated with trawl catches that are a mix of groundfish and/or shrimp are assigned 'mixed demersal' species. Since 1985, the classified acoustic records are integrated from the surface exclusion depth (11 m) to the bottom line, in 100 m elementary distance sampling units (EDSU). If any portion of a transect (E-W lines) was covered twice, only the first pass is used for Capelin abundance analyses. This is necessary because acoustic data started to be acquired continuously during each survey in 1999. Areal backscatter ( $s_a$ ) from each EDSU is allocated to an event (transect, inter-transect, fishing over previously surveyed area, fishing along un-surveyed transect, and other) using logbook entries that track event types associated with consecutive time periods. EDSU midpoint times are subsequently linked to event times in the logbook.

Survey instructions request a minimum of one trawl be conducted every 12 hours. Trawls are deployed on bottom and mid-water to investigate the species composition of the acoustic backscatter. Often the one trawl per 12-hour rate is exceeded, particularly when acoustic signal appearances change rapidly or in circumstances where there is a need to verify the composition of more than one concurrent vertical layer of signal. In some circumstances, a trawl every 12 hours may not be possible due to fishing gear in the water, vessel traffic, unsuitable bottom to set a trawl, or presence of ice bergs. Trawls are also deployed occasionally in the absence of fish signal to check the assumptions that Capelin are detectable and the gear is functioning as expected.

Prior to 1996, a large mid-water trawl (Diamond IX) was used for targeted fishing sets, and from 1996 to 2002, both mid-water (International Young Gadoid Pelagic Trawler [IYGPT]) and bottom trawls (Campelen 1800) were used. Since 2003, the Campelen 1800 trawl is used to conduct both mid-water and bottom trawls with the occasional IYGPT mid-water set occurring between

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2004–12. Length-based selectivity corrections were made to all IYGPT catches to produce Campelen equivalents, as the IYGPT trawl catches significantly more small capelin (<10 cm) and relatively fewer large capelin (>14 cm). The duration of trawl sets ranges from 15 to 120 minutes, depending on the mode of deployment (bottom or mid-water) and the intensity of the backscatter. The total number and weight of all species caught are recorded. When Capelin are caught, the length, sex, and maturity for a maximum of 200 randomly selected fish per set are recorded. Proportion of maturing females is calculated by dividing the number of age-2 females that are maturing by the total number of age-2 females in the catch. Detailed sampling (weight, gonad weight, stomach fullness, and age from otoliths) from each set is conducted on two Capelin of each sex per 5 mm length group. Since 1999, stomachs are collected for subsequent prey content analysis during the detailed sampling process, and all stomachs are subject to detailed prey identification and weighing. From 1999 to 2007, stomachs were preserved in 10% formalin; as of 2008, stomachs are frozen until diet analyses can be performed in the laboratory.

Abundance of other fish species surveyed during the acoustic surveys was not regularly calculated. But since 1999, length measurements have been recorded for all other potential acoustic targets including Arctic cod, Atlantic Cod, Atlantic Herring (*Clupea harengus*), Redfish (*Sebastes spp.*), and Sandlance (*Ammodytes spp.*) in order to assist analysts with the classification of mixed aggregations.

Acoustic backscatter attributed to Capelin is converted to Capelin densities using information from associated directed biological sampling obtained from trawl sets. In cases where no associated trawling was completed for a particular strata, biological data from the nearest strata with similar acoustic attributes were used. Prior to 1985, Capelin densities were extrapolated to the surveyed area using methods presented in O'Boyle and Atkinson (1989) and reported in Miller (1997). Since 1985, Capelin densities have been converted to a survey abundance index using a Monte Carlo approach which incorporates potential variation in Capelin density estimates due to four factors:

1. calibration uncertainty (associated with technological advances);
2. target strength (TS; resulting from variations in length composition and catchability);
3. acoustic detectability (resulting from variations in Capelin vertical migration); and
4. spatial variability (aggregation).

Using this technique, a re-sampled population of Capelin areal density estimates is derived for each stratum. To address issues of spatial autocorrelation, the survey track is divided into consecutive 2 km segments. For each segment, the mean area  $s_a$  value of Capelin is randomly selected from one of the 20 candidate 100 m horizontal bins. This value is then transformed into Capelin density by incorporating randomly selected values for three parameters: calibration uncertainty; TS; and acoustic detectability. This process is repeated 1,000 times for each 2 km transect segment within each stratum. The mean value of the Capelin density distribution for each strata from each iteration (including one value from each 2 km track segment) is used to give 1,000s of estimates of density for each stratum. The median density of the means from these iterations is used as an estimate of the areal density of fish in each stratum while the 5<sup>th</sup> and 95<sup>th</sup> percentiles are used as lower and upper confidence limits (Mowbray 2013). Areal densities for each strata is then multiplied by the stratum area to produce an abundance estimate and confidence limits.

Using annual information on age and sex composition, and lengths and weights derived from directed trawling, abundance estimates for each stratum ( $A_{\text{stratum}}$ ) is converted to biomass and partitioned into age classes ( $B_{\text{stratum, age; g}}$ ) using the following equation 3:

$$B_{stratum, age} = A_{stratum} \times p_{stratum, age} \times \bar{W}_{stratum, age}$$

3

Where  $p_{stratum, age}$  is the proportion of individuals in a stratum that are assigned to a particular age class and  $\bar{W}_{stratum, age}$  is the mean weight (g) of individuals in a stratum belonging to an age class.  $B_{stratum, age}$  is then converted from g to kilotonnes using appropriate conversion factors and can be summed as needed across age classes and strata to obtain annual biomass at age, annual biomass, or stratum biomass. As a part of this analysis, catch weighted estimates of proportion maturing at age, mean length at age, and mean weight at age are also generated.

Not all strata have been consistently covered in the spring acoustic survey time series. During the 2008 Capelin assessment, the impact of lost strata was examined and a recommendation was made to choose a subset of core strata to calculate the spring acoustic abundance and biomass indices (Mowbray 2013). However, the abundance and biomass indices derived from Core versus All Strata tracked very closely and the two have been used interchangeably over the years. In anticipation of Limit Reference Point (LRP) development, it was decided that a more standardized approach for calculating the spring acoustic biomass index was required.

The development of this revised spring acoustic biomass index included a review of previous abundance indices, areal coverage of the surveys, and the methodology used to convert abundance to biomass. Since both the total survey extent and strata boundaries varied over the time series, a visual summary of survey coverage was developed by overlaying previous years' survey tracks on the survey boundaries first implemented in 2000 (Fig. 8). Strata names as they appear in Fig. 8 relate only to the 2000 onward strata boundaries. These strata names were also used in previous years, but the boundaries were different. When calculating abundance and biomass indices, no attempt was made to estimate abundance for strata that do not have the 2000 onward strata boundaries. This is because interannual variations in Capelin distribution and differences in the habitat characteristics of adjacent strata preclude the invocation of suitable proxies.

When converting the revised abundance indices to biomasses, methodological changes were made to standardize the way at-sea sampling effort was applied. Prior to 1999, Capelin sampled at sea were not weighed; consequently, a length-weight regression was derived using May samples collected from the commercial Capelin fishery, Capelin tagging trips, spring multi-species bottom trawl surveys, and bycatch from other fishery-independent surveys and commercial fisheries such as shrimp, squid, and cod. This length-weight regression was used to convert the Capelin acoustic survey abundance to biomass. From 1999–2012, Capelin were weighed at sea, but the same method as described above was used to construct length-weight relationships. In 2013, a new catch-at-age program was developed which allowed for calculation and application of length-weight relationships from samples weighed at sea. In cases where a strata was surveyed acoustically but fish were not sampled, samples from a nearby stratum were used. In cases where more than one adjacent stratum was available, samples were chosen from the adjacent stratum with an acoustic signal most continuous with the unsampled stratum (Table 1).

The new catch-at-age application allowed for greater flexibility in how samples were chosen and applied to strata. This inadvertently resulted in discrepancies in application methods. These discrepancies stemmed from input of fishing set/stratum pairings and manual settings (groupings, minimum sample size) chosen by the analyst. For the 2023 Capelin assessment, fishing set/stratum values from 1999 onwards were reviewed and revised, and Capelin abundances and biomasses were re-calculated using a standard set of data subsets and

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groupings. The final groupings were chosen to replicate as closely as possible pre-1999 methodology, while minimizing losses of age classes when few fish were captured.

Median biomass estimates were quite similar between the Core and All Strata time series in most years and were generally well within the uncertainty range of one another except in 2000 (Fig. 9a). During this review and method standardization process, a cut and paste error was discovered for the 2014 acoustic survey analyses that resulted in a mismatch between acoustic densities, stratum areas, and mean weights which were used to calculate the Capelin abundance and biomass indices (Fig. 9b). The 2014 indices were presented at Capelin stock assessments since 2015 and used in the Capelin forecast model. A correction of this error resulted in a decrease of these indices for 2014. A second error impacting the 2015 survey results was also identified. In this case, preliminary values of the mean weight, calculated without weighing by the population length frequency of Capelin in the strata, were used. However, this error was only in a version of the biomass database used in the development of the Capelin forecast model, not in the biomass and abundance estimates as presented in the assessment documents. These errors did not impact the overall conclusions or advice that was provided at assessments in which the 2014 and 2015 acoustic biomass indices were presented (DFO 2015, 2018).

### **Spring Acoustic Survey Abundance and Biomass**

In 2022, the spring acoustic survey covered most of the survey area, but the survey was split into two portions. The first leg of the survey was conducted on the Canadian Coast Guard Ship (CCGS) Capt. Jacques Cartier (May 2–14) using an EK-80 echosounder, and the second leg completed on the CCGS Teleost (May 23–30) using an EK-60 echosounder. Normally, spring acoustic surveys are conducted during a continuous 14–20 day period, but in 2022 issues related to vessel availability resulted in a nine-day gap between survey legs. Since the survey targets the non-migratory portion of the stock and the survey ended prior to the spawning migration (June), this gap in survey coverage likely had a minimal impact on the survey estimates. The use of two vessels unlikely impacted comparability of acoustic data as both vessels' acoustic systems were fully calibrated and data were collected using the same frequencies. Similarly, as trawling is not conducted in a standardized manner during the Capelin acoustic survey (e.g., set time, trawl depth), biological sample collection was not impacted by the use of two separate vessels.

During the 2022 survey, the majority of strata were surveyed (except strata E and F; Figs. 8 and 10a), and Capelin were most dense in coastal strata with a second lower density band along the shelf break (Fig. 10a). This distribution is consistent with most years during the past decade. In order to understand the potential impact of missing strata E and F in 2022, the distribution of abundance during years when a full survey is realized was examined (Fig. 7). During these years, the combined coastal strata (A-C) accounted for on average 48% of the total abundance of core strata, while strata E and F accounted for on average 9% of total abundance. The contributions of strata E and F were higher during the early-2000s (2000–07, 14%) compared to subsequent years (2008–22, 6%). Based on this analysis, the impact of missing these two strata is considered minimal and no attempt was made to estimate biomass for these missed strata.

The Capelin acoustic biomass index in 2022 was 262 kt (90% confidence interval: 177–448 kt), which was similar to 2018 and 2019 (288.9 kt and 282.4 kt, respectively) (Fig. 10b). Since the collapse of the stock in 1991, the median annual Capelin acoustic biomass index was 156 kt, well below the pre-collapse 1985–90 median (3,704 kt). The spring acoustic abundance index in 2022 was 26.6 billion fish, which was higher than the 1991–2019 median (18.3 billion fish) (Fig. 10c).

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## Spring Age, Maturation, Growth, and Diet

Capelin captured in the spring acoustic survey trawl sets (Diamond IX, IYGPT, Campelen 1800) range from 5 to 20 cm TL and have historically been composed of ages 1 through 6, although ages 5 and 6 have only been present in limited numbers in a few years since the 1990s. Due to the design of the survey (i.e. targeting a known juvenile nursery area), age-2 fish account for the majority of surveyed Capelin, with age-3 fish being the second most abundant age group. The trawls used to sample Capelin during the spring acoustic survey are biased against smaller sized fish – in particular those less than 10 cm; this has resulted in a poor representation of age-1 fish (typically 5 to 8 cm TL) in the survey. However, ages-2+ Capelin are well sampled by all gear types (Mowbray 2001). In the 2022 spring acoustic survey, age-2 fish dominated the catch (~75%) with a similar proportion of age-1 and age-3 sampled (Fig. 11). Similar to recent years, very few age-4 and no age-5+ fish were sampled (Fig. 11).

In the 1980s, the proportion of male and female Capelin maturing at age 2 was low (~4%) compared to the proportion of age-2 fish maturing in the post-collapse period (~40–80%) (Fig. 12). In the 1980s, a variable proportion of age-3 fish were maturing in the spring while close to 100% of age-3 fish sampled since 1991 were maturing. This change in population dynamics is likely a compensatory response due to a relaxation in competition for resources when the stock collapsed. There is plasticity in this growth response as there was a decrease in proportion of age-2 fish maturing (~25%) in 2013–15 when the spring acoustic index increased. In 2022, 67% of age-2 fish were maturing and would have spawned in summer 2022 (Fig. 12). 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 maturing at age-2 is a characteristic of the post-collapse period. This change in population dynamics has been seen in other pelagic fish stocks that have decreased in abundance (i.e., density-dependent effects) (e.g., Gjøsæter 1998; Engelhard and Heino 2004). In 2022, age-1 and age-2 fish were heavier and longer than ages 1 and 2 Capelin in the 1980s (Fig. 13a, b). Mean weights and lengths of ages 3 and 4 fish have remained the same or decreased since the 1980s likely because maturing at a younger age results in Capelin putting more energy into reproduction than allometric growth (Fig. 13a, b). 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  $R^2 = 0.76$ ,  $p = 0.01$ ) (Fig. 14a). Furthermore, using the annual mean length data, we found evidence of density-dependent growth effects in this stock with fish from weaker cohorts (based on the age-2 abundance index) being longer at age-2 compared to years with stronger cohorts (linear regression  $R^2 = 0.25$ ,  $p = 0.0032$ ) (Fig. 14b).

From 1999–2022 (excluding the partial acoustic survey in 2021), length and sex stratified samples of stomachs were collected from all offshore strata in which fishable quantities of Capelin were observed. Median annual sample size was 417 stomachs. Total stomach content weight was recorded to the nearest 0.01 g from 1999–2006 and the nearest 0.001 g from 2007 until present, and all stomachs were subject to a detailed analysis. Prey is classified to species level where possible and total prey weight is recorded. Prior to 2007, all copepods were recorded under one prey type category (copepods), but intact specimens were recorded separately from copepod pieces. Since 2007, large copepods are further divided into four categories: ‘Calanoid ns’, ‘Calanus stages I-III’, ‘Calanus stages IV-VI’ and ‘Metridia’, while small copepods (i.e., *Oithona* spp., *Temora* sp.) are weighed along with any remaining copepod

pieces and entered as ‘Copepods’. Whenever possible, the species in each of these categories is identified. The count of stomachs containing large copepods are identified as those where a prey weight is present for at least one of the large copepod prey types. In 2007, the presence of at least one small copepod species in either the ‘Copepods’ or ‘Unidentified’ prey type categories is used to derive the count of stomachs containing small copepods. Only stomachs with prey content are used to calculate the Partial Fullness Index (PFI; equation 4) and Frequency of Occurrence (FO; equation 5) of specific prey, while the percentage of empty stomachs uses all sampled stomachs.

$PFI = \sum \frac{W_{i,k}}{L_k^3} \times 10^4$	<b>4</b>
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where  $W_i$  is the weight (g) of prey items  $i$  found in the stomach of Capelin  $k$ , and  $L_k$  is the length (cm) of Capelin  $k$ .

$FO = S_i / S_{total}$	<b>5</b>
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where  $S_i$  is the number of stomachs with prey item  $i$  and  $S_{total}$  is the total number of stomachs with prey.

Since 1999, a total of 8,367 Capelin stomachs have been examined of which 4,986 contained prey. The PFI was high from 2017–19 suggesting there were resources available for Capelin in the ecosystem (Fig. 15a). In all years, copepods were the dominate prey item by weight in Capelin diet (highest PFI), and the importance of amphipods (hyperiid) and euphausiids by weight varied interannually with the PFI of amphipods increasing since 2017. Overall, PFI in 2022 decreased compared to 2017–19, with large decreases in all prey categories except amphipods.

Copepods are the main prey item for 2J3KL Capelin. While there is interannual variability in FO of small and large copepods, large copepods typically dominate the diet (Fig. 15b). In 2017–19, there was a notable increase in FO of small copepods, while FO of small copepods decreased again in 2022.

In the post-collapse period during which stomachs were sampled (1999–2022), an increase in the proportion of empty stomachs in the spring was related to an increase in the spring acoustic biomass index (beta regression:  $\text{logit}(\mu_y) = 0.002x - 0.81$ , Pseudo  $R^2 = 0.31$ ,  $p = 0.003$ ) suggesting there may be increased competition for food in years with a higher spring acoustic biomass index (Fig. 15c).

## FALL MULTISPECIES BOTTOM-TRAWL SURVEYS

Fall multispecies bottom trawl surveys (hereafter bottom trawl surveys) are conducted by the DFO NL Region in NAFO Div. 2J3KL (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. In order to achieve this goal while maintaining a feasible workload, starting in 1999 the bottom trawl survey strata were grouped into superstrata. These groupings were based on strata bathymetry and adjacency, resulting in the realignment of 228 strata into 88 superstrata. Up to 25 Capelin are retained from the largest Capelin catches within a superstrata. In the laboratory, these samples are processed for length, sex and maturity, and detailed sampling is conducted on two fish per sex per 5 mm

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length class where additional measurements include whole weight and gonad weight, recording of stomach fullness, and age (as determined from otoliths). These data are used to describe Capelin diet and biological characteristics.

### **Fall Condition and Diet**

Inconsistencies in fall bottom trawl survey coverage during the last two years resulted in a lack of sampling in Div. 3L in 2021, and many unsampled strata in 2022 due to the Comparative Fishing Program. Consequently, a change in the way the Capelin condition index is calculated was required. Previously, data from all sets where detailed sampling was available were pooled by NAFO Division. A condition index (Le Cren 1951) was then calculated by sex and age class (ages 1 and 2) and the resultant values averaged. In this assessment, in order to accommodate for the unequal sampling effort across NAFO Divisions in the past two years, relative condition for Capelin was calculated separately by age class (ages 1 and 2), sex, and NAFO Division. Relative condition was averaged across sexes within each age class by NAFO Division and then across age classes by NAFO Division and then across NAFO Divisions. Where Div. 3L was not sampled in fall 2021, Capelin condition in 2021 was calculated by averaging across the observed relative conditions in Divs. 2J and 3K and by the average condition of Capelin in Div. 3L from 2011–20. The relative condition values were generally similar between the old and new approaches although there were some differences in the early-2010s and in recent years (Fig. 16).

In 2022, the fall relative condition value was the highest (1.11) in the time series (1998–2022). The previous high value for the time series was 1.06 (2021) and the mean relative condition value for the time series (1998–2021) is 1.01 with a standard deviation of 0.036. Given that the highest value of the time series coincided with the change in sampling protocol in 2022, its potential impact on condition warranted further investigation.

The 2022 condition value was investigated using three approaches. First, relative condition was re-calculated across the whole time series based on the reduced set of strata sampled in 2022. The 2022 relative condition was still the highest in the time series, and there were minor differences in annual condition when the number of strata was reduced (Fig. 17a). Second, fall condition data were restricted to Div. 3K only, since this is the core area of fall Capelin distribution and has been sampled in all years. In 2022, Div. 3K condition values were the highest in the time series and condition trends in Div. 3K were consistent with the full Divs. 2J3KL area (Fig 17b). Third, the potential impact of sampling timing in 2022 was examined, since sampling in Div. 3K was 30 days earlier in 2022. While a linear model investigating the effect of day of year, sex and NAFO Division was statistically significant, it was not considered biologically significant. Based on these three analyses, it appears likely that in 2022 fall relative condition of Capelin was likely at or near time series highs. The actual magnitude of the 2022 condition value is unclear due to changes in timing of sampling, which affects our estimate of relative condition by an unknown amount making it difficult to accurately compare this year's relative condition value to prior years.

From the fall bottom trawl time series (1980–2020), proportion of empty stomachs was calculated based on a scalar index of stomach fullness (0 = empty, 1–4 levels of fullness) recorded for undissected 'called' stomachs. During the Engel trawl period (1980–95), a median of 258 Capelin stomachs were 'called' annually, and during the Campelen 1800 trawl period (1996–2020), a median of 1001 stomachs were 'called' annually. The catchability of Capelin differs between these two trawl gears, with the Campelen trawl retaining more smaller sized organisms compared to the Engel trawl. Based on these called stomachs, the median proportion of empty stomachs increased in the post-collapse period (0.46 in pre-collapse period



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and 0.54 in post-collapse period). In 2017–18, the median proportion of empty stomachs was at an all-time low (0.08) but increased again in 2019–20 (Fig. 18).

## 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. The most parsimonious Capelin forecast model 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 (Lewis et al. 2019). 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.

A few changes were made to the input values and calculations of the Capelin forecast model in 2023. First, we revised the Capelin biomass index as a part of the process of preparing data for LRP development. Second, we identified two errors in how the Deviance Information Criterion (DIC), which is used to help select the best fit model, was calculated. The first error was that the DIC values were being calculated incorrectly. DIC values have a deviance component and a penalty component, and our calculation for the DIC values was not including the penalty component resulting in the DIC values not properly accounting for the number of parameters being used by the different models in the modeling suite. The second error was that only 2,000 iterations were being used to calculate DIC values rather than the full number of iterations that were assumed to be used (typically hundreds of thousands of iterations). Third, the chain setting was adjusted when fitting the models, reducing the number of iterations that are discarded as part of the burn-in process and the amount of thinning that is done on the chains (Link and Eaton 2012). Further, we increased the number of iterations being used to fit the models in order to ensure that all chains reached stability as a result of the adjustments to the number of burn-in iterations and the amount of thinning being done. None of these changes would have changed the science advice provided since 2019.

In 2023, the change in the biomass index time series resulted in a decline in the amount of variance explained by models using  $t_{ice}$  as a predictor. In the case of the CSAM3 model, which includes the BB larval index, fall condition, and  $t_{ice}$  parameters, the  $R^2$  decreased from 0.68 at the 2020 assessment to 0.51 at the 2023 assessment. The decline in  $R^2$  is due to the revision of the acoustic biomass index time series. For the first time, the CSAM1 model was the most parsimonious model, based on DIC values, but it was statistically equivalent to the CSAM3 model (Table 2). However, since the CSAM1 model only includes two parameters (BB larval index and fall condition) and has a lower  $R^2$  than CSAM3, the CSAM3 model was chosen for the provision of science advice.

Examining the responses of the CSAM3 model to different fall condition values found that the model is quite sensitive to fall condition. As the fall 2022 condition value is well outside the range of data used to fit the forecast model, the 2023 forecast model results can only be described qualitatively due to uncertainty in the 2022 condition value. Using the CSAM3 model, a range of plausible condition values were used to predict the general trend of the 2023 spring acoustic survey. Three sets of simulations using 2022 fall conditions of 1.11 (the observed value), 1.06 (the approximate value of the highest previously observed condition value), and 1.095 (an intermediate value between the observed value and the previous highest observed value) were used to determine the likely trend in the biomass index for spring 2023. Based on

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these simulations, the Capelin acoustic biomass index in 2023 is expected to be at or above the level of 2022 (Fig. 19).

## 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 potential impacts on ecosystem productivity. The warmer and potentially more productive period emerging since 2018 has continued in 2022 (Fig. 20). 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 NL Climate Index (NLCl) 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 sea ice retreat was hypothesized to influence adult Capelin and, by extension, biomass (Buren et al. 2014a).

Overall conditions of the past three years are indicative of improved productivity at the lower trophic levels in the NL bioregion (NAFO Divs. 2HJ3KLNOPs) (Fig. 21). This includes earlier phytoplankton blooms, higher chlorophyll concentrations, and increased zooplankton biomass with a higher abundance of larger, more 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.

The fish community on the Newfoundland Shelf and Northern Grand Bank (NAFO Divs. 2J3KL) was dominated by finfishes (Capelin and groundfish) in the 1980s but these populations collapsed in the early-1990s while shellfish increased (Koen-Alonso and Cuff 2018, Buren et al. 2019). Even with the increases in shellfish since the 1990s, total biomass is still far below pre-collapse levels (Fig. 22). In 2022, the fall bottom-trawl survey was re-deployed to conduct the Comparative Fishing Program. This re-deployment resulted in incomplete coverage of Div. 2J3KL. For the 2023 Capelin assessment, ecosystem data up to 2021 were presented.

Capelin consumption by fish functional groups that are considered predators of forage species (i.e., medium and large benthivores, planktivores, and piscivores) in Divs. 2J3K increased in 2020–21 compared to 2019 (Fig. 23). The proportion of Capelin in the diet of its main predators, Northern Cod and Greenland Halibut (Turbot), increased to almost one quarter and one half, respectively, in Div. 2J in 2021. Diet changes were relatively minor in Div. 3K and there was no diet data from Div. 3L in 2021 (see DFO 2023a for more details). If predators’ consumption and diets in the fall are an indicator of Capelin biomass the following spring, which these analyses suggest, an improvement in biomass in the 2022 Capelin acoustic survey would be expected. However, there was no evidence of an improvement in the 2022 biomass index with the 2022 spring acoustic biomass index (262 kt) being similar to 2018 (288.9 kt) and 2019 (282.4 kt).

Current evidence indicates that Capelin is primarily bottom-up regulated. Additional support for this perspective is provided by the examination of the relationship between NLCl and an index of per capita recruitment. The spring acoustic survey signal is dominated by age-2 Capelin, and when this index is used as an indicator of recruitment it is typically lagged two years. If we assume that the acoustic index also tracks relative changes in the spawning component of the stock (this assumption is generally consistent with the observed coherence between the

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Research Vessel (RV) fall survey in year t-1 and the spring acoustic survey in year t, the ratio between the Capelin spring acoustic biomasses in years t+2 and t would be an indicator of per capita recruitment for year t. This index is conceptually similar to the idea of recruits per spawner. Since the NLCI is an anomaly, considering  $NLCI^* = \exp(NLCI)$  provides a way to represent variations in climate condition as a positive only index where a value of 1 corresponds to the average ocean climate state. This re-scaling also highlights positive anomalies. The Capelin per capita recruitment index shows a really good match with  $NLCI^*$  (Spearman  $Rho = 0.38$ ,  $p\text{-value} = 0.016$ ), indicating clear Capelin responses to positive anomalies in  $NLCI^*$  (Fig. 24). This indicates that climate conditions corresponding to the NLCI in year t have an impact on either the survival of larvae during their first year, the condition of the spawning adults in year t, or both. Irrespective of the mechanism, this provides additional support for the hypothesis that Capelin is bottom-up regulated. Further, this analysis shows consistent positive responses to warmer/productive ocean climate conditions both before and after the stock collapse, suggesting that bottom-up regulation is likely a feature for Capelin and not just the result of a collapsed stock. This analysis also emphasizes the importance of Capelin having an increased stock size in order to be able to capitalize on the occurrence of good environmental conditions.

### LIMIT REFERENCE POINT

Revisions to the *Fisheries Act* (R.S.C., 1985, c.F-14) on June 21, 2019, resulted in new Fish Stock Provisions (FSP). Interpreted through the lens of the Sustainable Fisheries Framework and the Precautionary Approach Policy, the FSPs identify objectives for sustainable use of stocks including determining a single LRP per stock and the status of the stock relative to the LRP. A National Advisory Process (NAP; DFO 2023b) was held in June 2022 to provide guidance for LRPs that align with the FSPs. DFO (2023b) provided best practices for developing LRPs including how certain criteria should be considered, i.e., given a particular approach is feasible, the LRP should take into account the reliability of the data, parameters, and models used, as well as the plausibility of the LRP. For the 2J3KL Capelin LRP, only approaches that met all three criteria (feasible, reliable, plausible) were considered valid and subject to further scrutiny.

A suite of Capelin LRP approaches were considered, but only three were considered valid (see Lewis et al. [in prep<sup>1</sup>] for further details). The first approach was a  $B_{\text{recover}}$  based on the 1982 acoustic survey biomass index value (446 kt) which is the lowest observed biomass that led to stock recovery. The concern about the  $B_{\text{recover}}$  approach was that it was based on a single point (1982) without a measure of variation from a survey conducted in April rather than May, suggesting that it is an underestimate of the biomass index.  $B_{\text{recover}}$  also rests on the assumption that possible future recovery depends on the prevailing conditions relative to 1982. The second approach was a proxy for  $B_0$  (the unfished biomass) based on the median of the 1985–90 acoustic biomass index values, which are the highest in the spring acoustic survey time series. The  $B_0$  is typically multiplied by 0.2, which resulted in an LRP of 741 kt, but in the case of forage fish or unproductive stocks a multiplication by 0.3 is commonly used, which resulted in an LRP of 1,111 kt. The concerns about the  $B_0$  approach were the choice of a somewhat arbitrary multiplier, the wide variations in practice for selecting historical time periods, and the difficulty in justifying that 1985–90 was truly a proxy for  $B_0$ .

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<sup>1</sup> Lewis et al. In Prep. A Review and Evaluation of Potential Limit Reference Points For 2J3KL Capelin (*Mallotus villosus*). DFO Can. Sci. Advis. Sec. Res. Doc.

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The third approach was based on the capcod model (Koen-Alonso et al. 2021) that accurately predicts Atlantic Cod biomass based in part on Capelin biomass. This model was used successfully in both the NL and Barents Sea ecosystems. Using the capcod model, the Capelin biomass index required to maintain Northern cod at its own LRP, i.e., levels last observed in 1983–89, is 640 kt. Northern cod serves as an indicator species 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. The capcod LRP approach was considered to be the most robust of the three approaches, in part due to its ecosystem-based approach to fisheries management and its solid theoretical and analytical foundation (Koen-Alonso et al. 2021).

Using the 2J3KL Capelin LRP, the Capelin stock has been in the critical zone since 1991, with the exception of 2014 (Fig. 25). In 2013, the probability of the stock being in the critical zone was ~45%.

## **SUMMARY AND CONCLUSIONS**

The 2J3KL Capelin stock has not recovered from its collapse in 1991. Persistent changes in Capelin population dynamics post-collapse are likely due to density-dependent factors, resulting in faster immature growth and maturation at a younger age; and, due to semelparity, the stock is age-truncated compared to the 1980s. Delayed spawning and low recruitment are also characteristics of the 2J3KL Capelin stock since its collapse. While there was a brief recovery in stock size in 2013–14, it did not persist. In 2022, the 2J3KL Capelin acoustic biomass index was above the post-collapse median and similar to 2018 and 2019, but well below the recent stock high of 2013–14 and a fraction of the 1980s median; Capelin were feeding well and immature fish were growing fast with a high proportion maturing at age-2; spawning timing was typical of the post-collapse period; and the BB larval index improved and was similar to the time series mean. Capelin fall relative condition was the highest in the time series, but the 2022 condition value may not be directly comparable with prior estimates due to an earlier than usual sampling time in 2022. Since the Capelin forecast model is sensitive to fall condition, the results can only be described qualitatively due to uncertainty in the 2022 condition value. The Capelin acoustic biomass index in 2023 is expected to be at or above the level of 2022. A 640 kt Capelin acoustic biomass index was selected as the LRP below which the Capelin stock and the finfish community are likely at risk of serious harm. This is the level necessary to support the growth of the Northern cod stock to levels seen in the 1980s. Since 1991, with the exception of 2013 and 2014, the Capelin stock has been in the Critical Zone. Consistency with the DFO decision-making framework, incorporating the precautionary approach requires that removals from all sources must be kept at the lowest possible level until the stock clears the Critical Zone.

## **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

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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.

### **RESEARCH RECOMMENDATIONS**

1. Examine the effect of stomach fullness (weight) on condition.
2. Examine the frequency of empty stomachs in earlier years using the scalar stomach fullness indicator recorded at the time of sampling.
3. Gather more information on biomass levels in the 1980s from multiple data sets including diet studies and how Capelin can respond to improved feeding conditions.
4. Examine the role of the environment (climate, lower trophic levels) on the productivity of the stock including new research and a literature review.
5. Review and update the Capelin forecast model suite. Discuss ways to deal with out-of-range values and how to deal with them in a forecast, e.g., moving averages.
6. Understand the impact of constant parameters in capcod model and the value of natural mortality ( $mB^2$ ) on Capelin.
7. Continue the development of the Capelin age-structured model.

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## TABLES

*Table 1. Stratum substitutions by year. Unsampled stratum are stratum that were surveyed acoustically but were not physically sampled using a Campelen trawl or were physically sampled, but the trawl did not collect sufficient Capelin to generate an estimate of age composition and mean weight. The Source stratum was the stratum that was deemed to be the most likely to be similar to the unsampled stratum and was used to provide age composition, and mean weights and lengths at age for the unsampled stratum.*

<b>YEAR</b>	<b>UNSAMPLED STRATUM</b>	<b>SOURCE STRATUM</b>
1999	E, F	D
1999	C	B
2000	C	D
2001	K	J
2002	G	F
2002	I	J
2003	G	F
2003	I	J
2004	G	F
2004	K	J
2004	M	F
2005	M	E
2007	F, M	B
2007	G	B
2007	I, K	J
2008	G	F
2008	D	C
2008	I	J
2009	G	F
2010	K	J
2011	G	F
2012	G	F
2014	L	J
2015	F, M	C
2015	L	K
2017	G	F
2018	G	F
2018	L	K

Table 2. Model selection statistics for the capelin forecast models. Model details are provided in Lewis et al. (2019)<sup>1</sup>. DIC: deviance information criterion;  $\Delta$ DIC: difference between change in DIC from the most parsimonious model;  $R^2$  are for Bayesian analyses (Gelman et al. 2019).

Model type	DIC	$\Delta$ DIC	$R^2$
CSAM1	37.52	0	0.48
CSAM3	37.9	0.47	0.51
AM0	39.31	1.79	0.20
CSAM2	40.35	2.83	0.42
AM1	42.47	4.94	0.34
CS1	42.57	5.04	0.30
CS0	43.33	5.81	0.13

<sup>1</sup>CSAM3 (BB larval index,  $t_{ice}$ , condition), CSAM1 (BB larval index and condition), CSAM2 (BB larval index and  $t_{ice}$ ), CS1 (BB larval index and zooplankton index), AM0 ( $t_{ice}$ ), AM1 ( $t_{ice}$  and condition), CS0 (BB larval index)

FIGURES

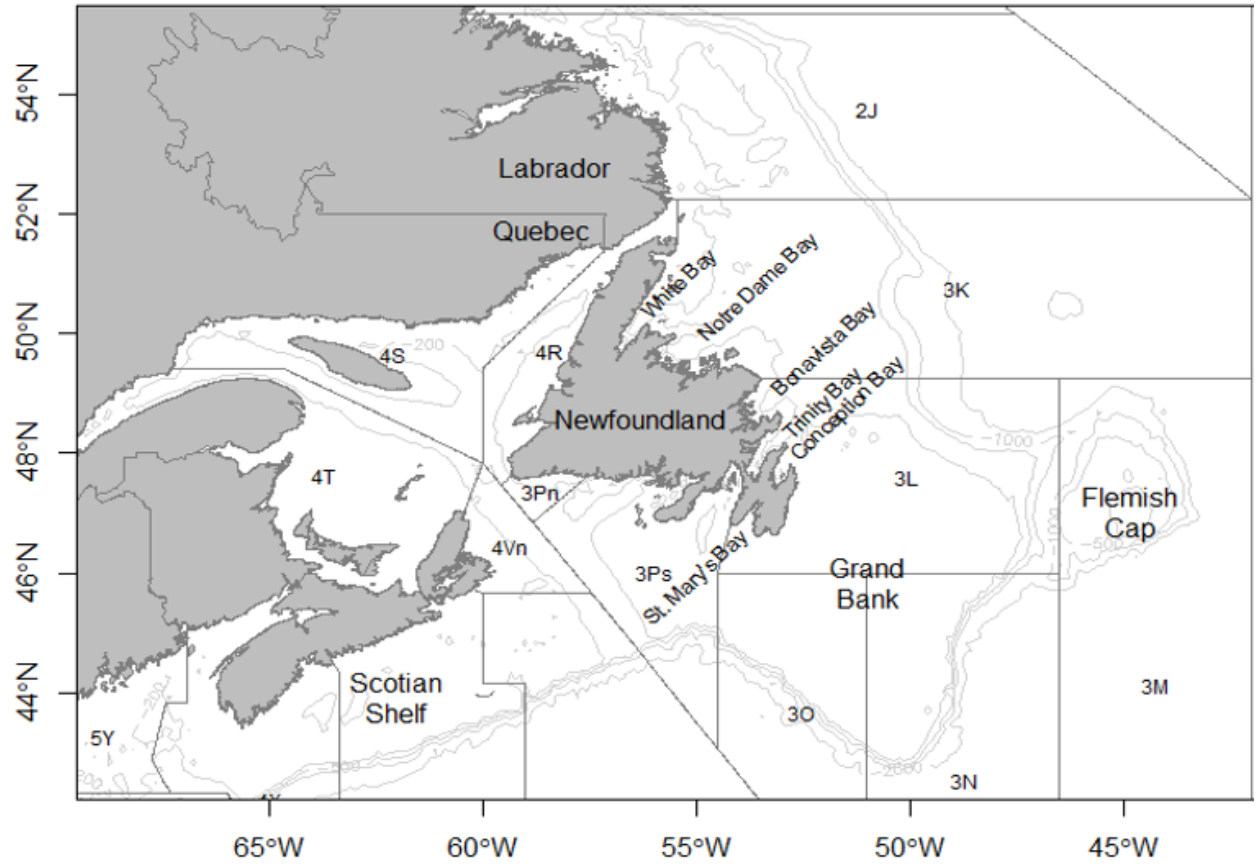


Figure 1. Stock area of NAFO Divisions 2J3KL Capelin.

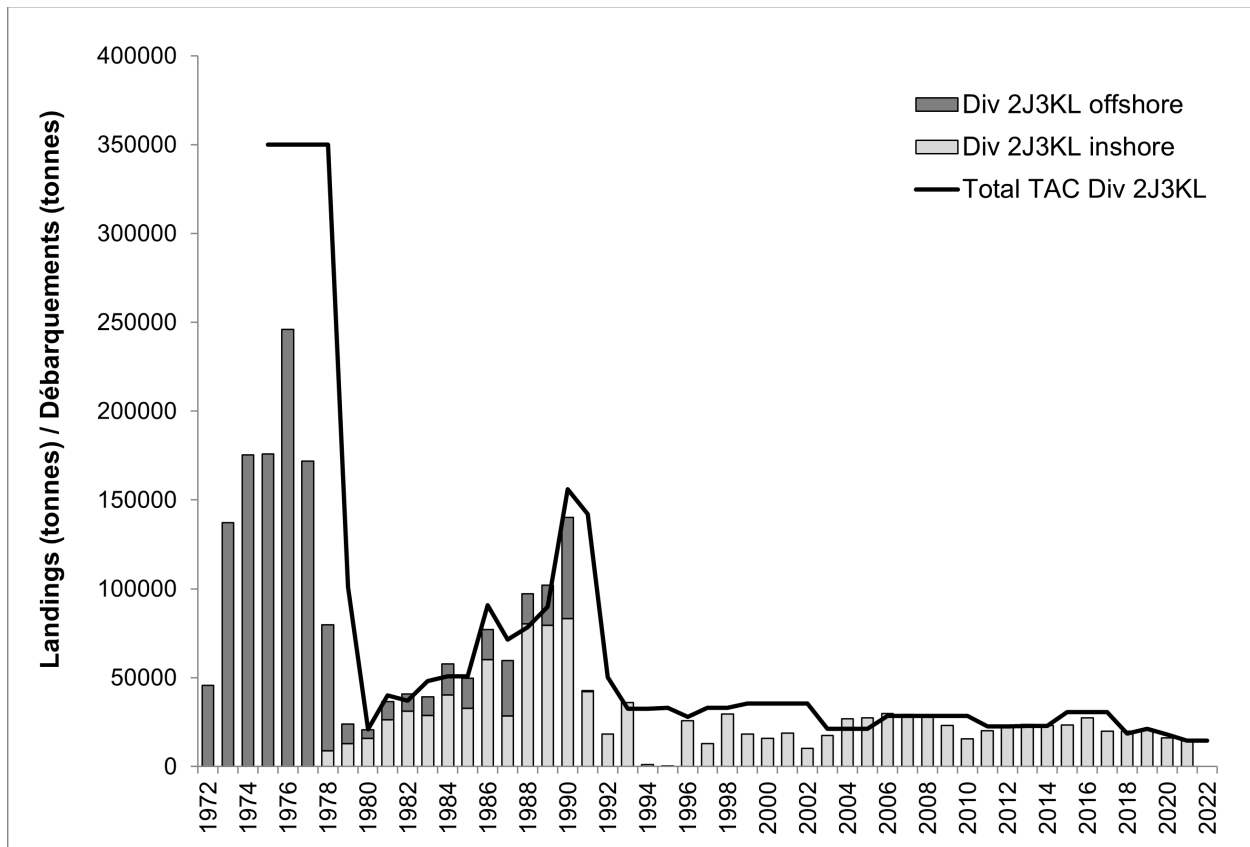


Figure 2. Inshore landings (light grey bars), offshore landings (dark grey bars) and TAC (line) for Capelin in Divs. 2J3KL from 1972 to 2022. Note that annual inshore landings were likely greater than 0 t between 1972 and 1977, but they were not recorded prior to 1978. There was no commercial fishery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

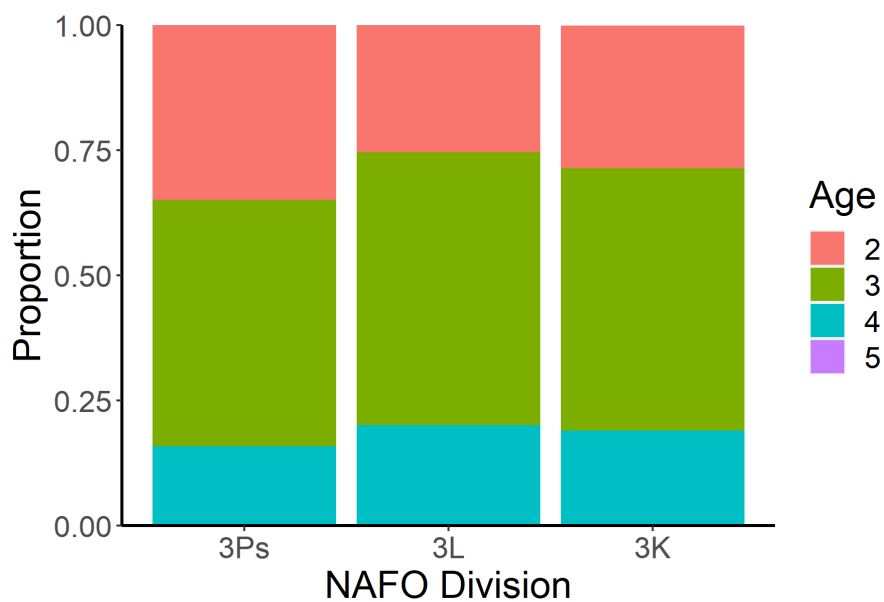


Figure 3a. Age composition of beach spawning Capelin in NAFO Divisions 3K (n = 21), 3L (n = 905), and 3Ps (n = 63) in June and July 2022. Fish were sampled using cast nets at seven beaches in southern and northeastern Newfoundland.

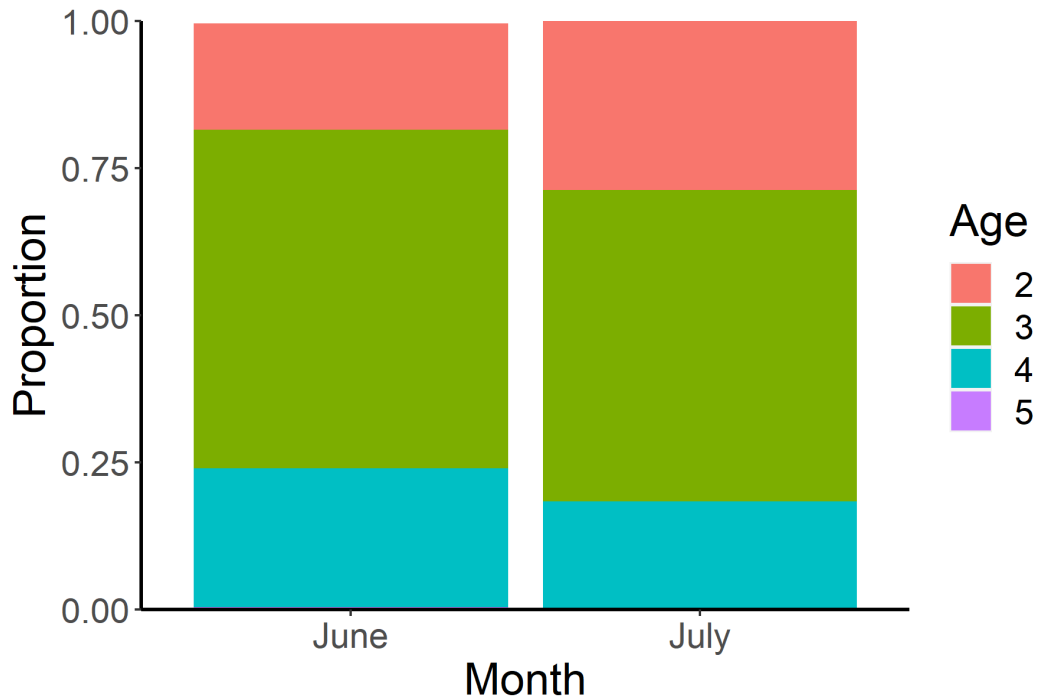


Figure 3b. Age composition of beach spawning Capelin in NAFO Division 3L in June (n = 288) and July (n = 617) 2022. Fish were sampled with cast nets at five beaches.

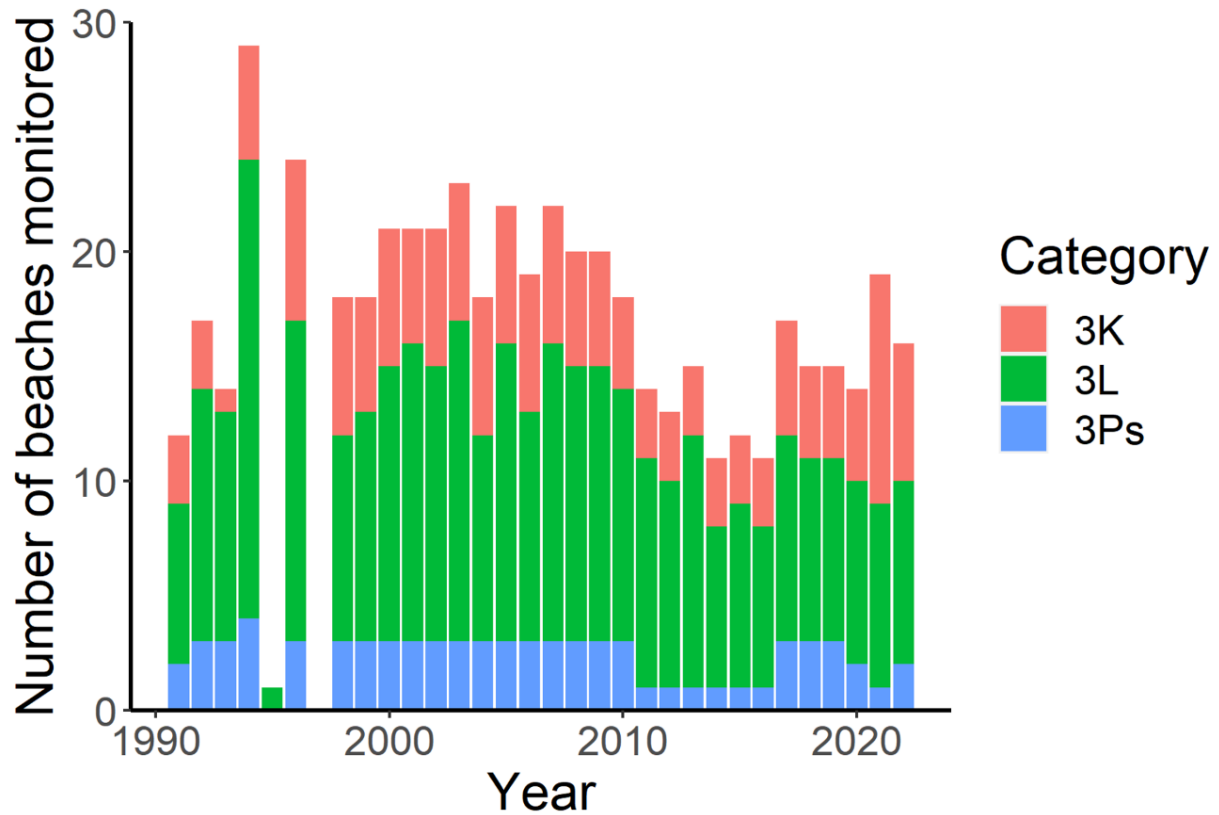


Figure 4. Capelin spawning beaches monitored by Division by DFO's Capelin spawning diary citizen science program since 1991.

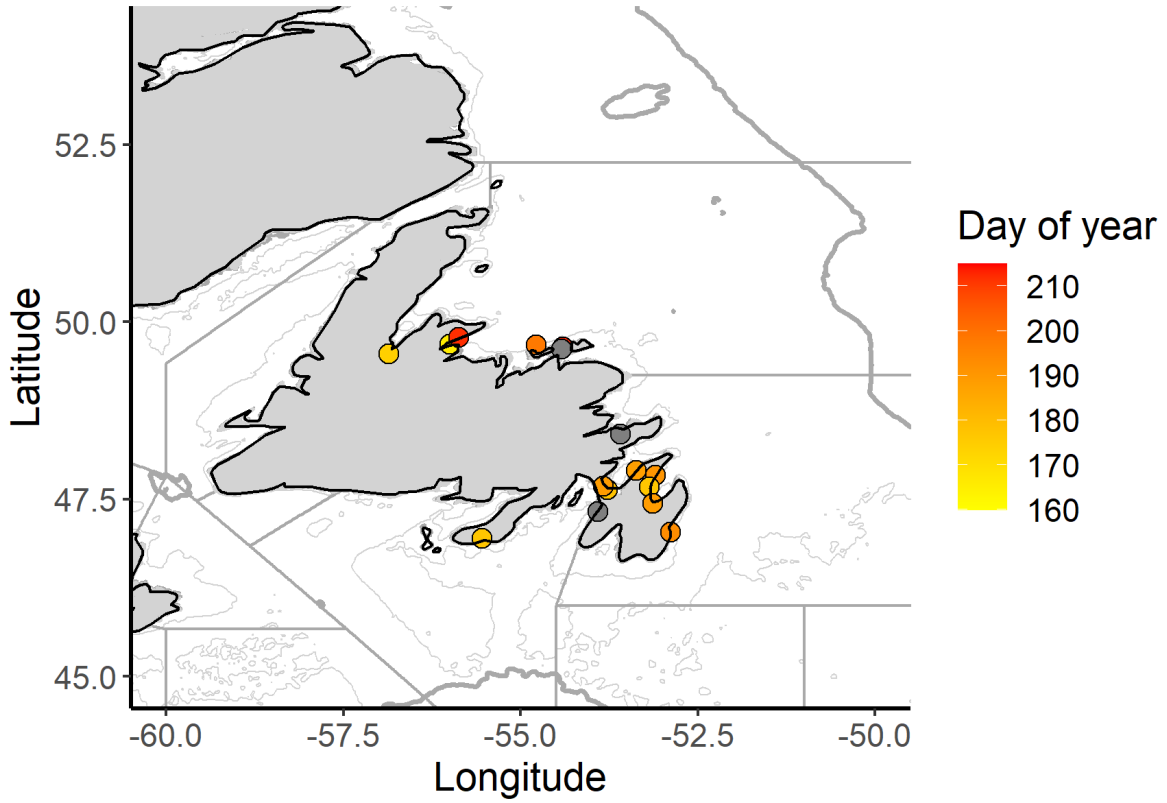


Figure 5. Median Capelin spawning timing in 2022 at the 16 beaches monitored in the Capelin citizen science spawning diary program. Grey dots indicate monitored beaches with no spawning recorded in 2022. Bathymetry: 100 m light grey and 500 m dark grey contour lines.

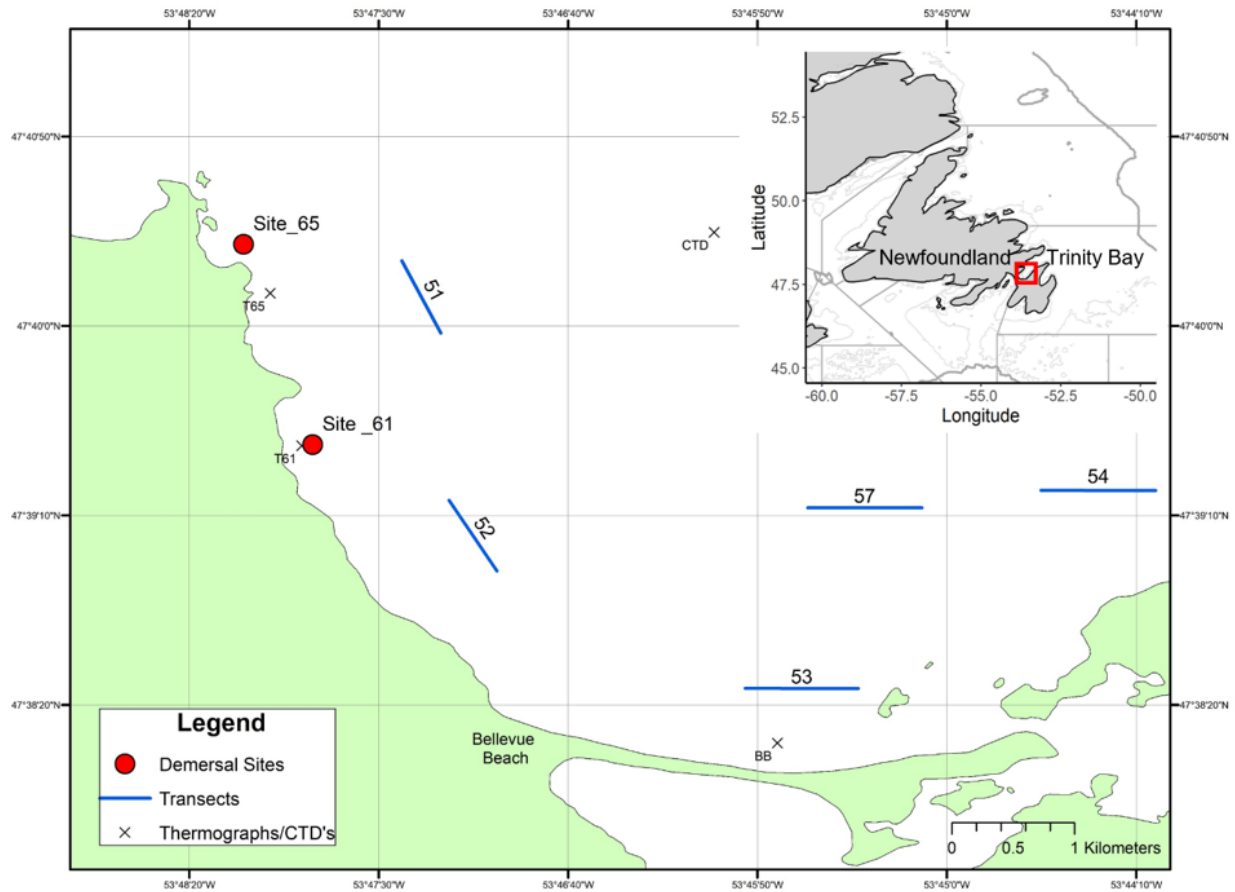


Figure 6a. BB sampling area in TB (Div. 3L). Demersal sites are in red (depths of 12–14 m). The numbered transects are fixed stations for larval surface tows. X indicates fixed stations for conductivity-temperature-depth (CTD) data collected each sampling day. The red box in the inlay figure is the location of BB at the bottom of TB.

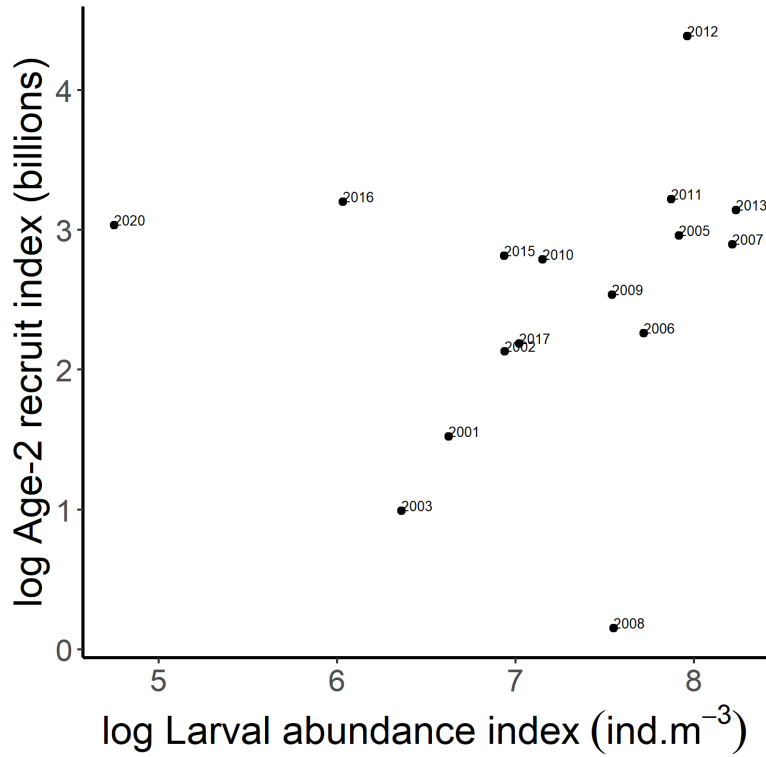


Figure 6b. Updated relationship between the age-2 recruit index and the BB larval index. This relationship is no longer significant with the addition of the 2015–17 and 2020 year-classes. The years in figure refer to the year class.

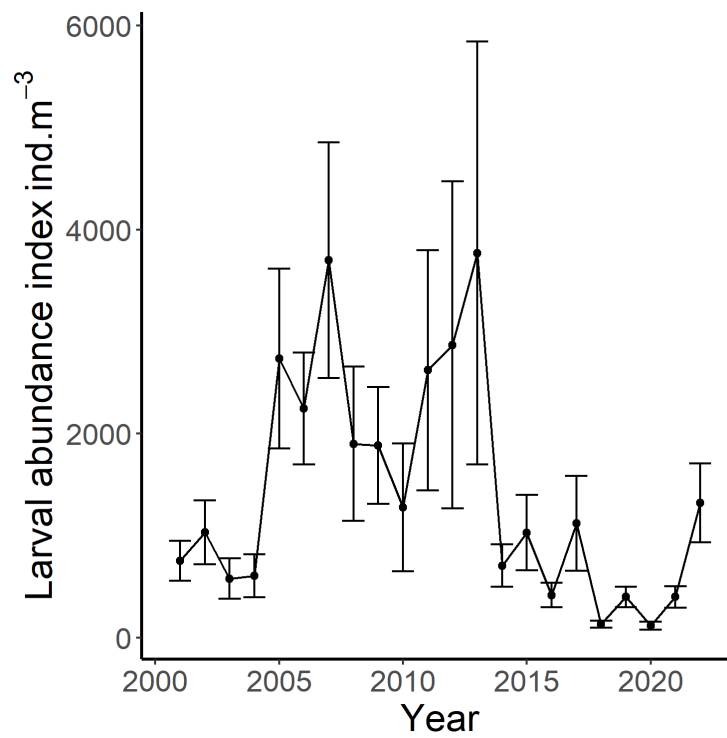


Figure 6c. BB larval index (2001–22) ± standard errors.



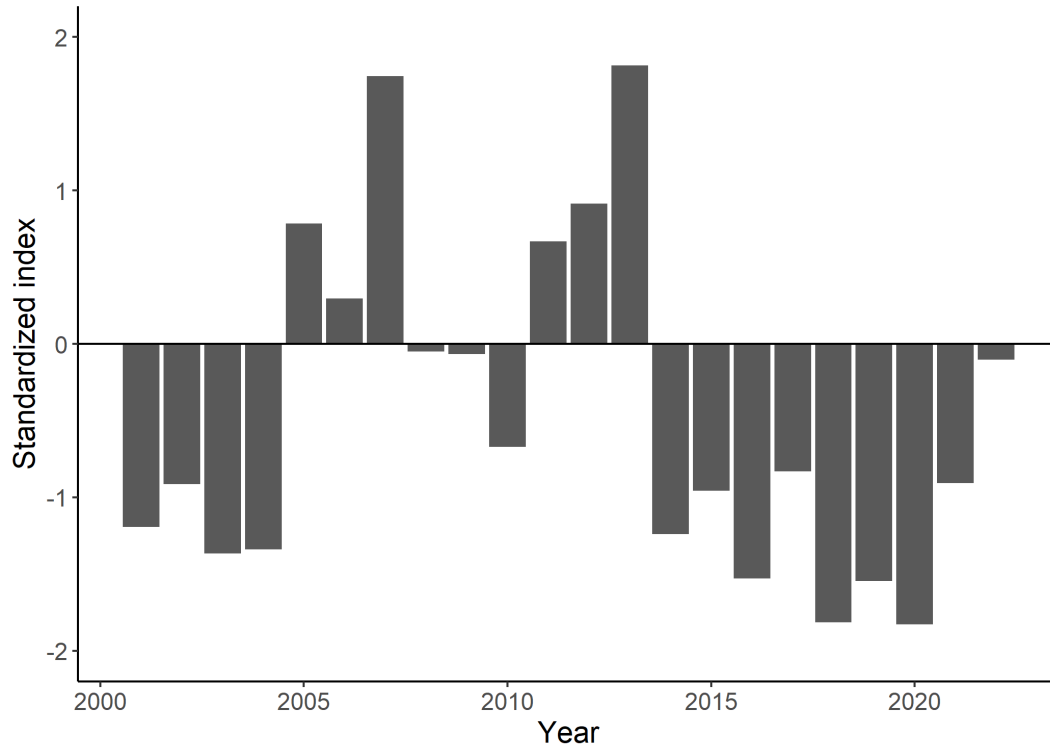


Figure 6d. Standardized anomalies of the BB Capelin larval index for the 2001 to 2022 year-classes. Anomalies were calculated using a 2001–21 reference period. Negative anomalies indicate below average annual larval production.

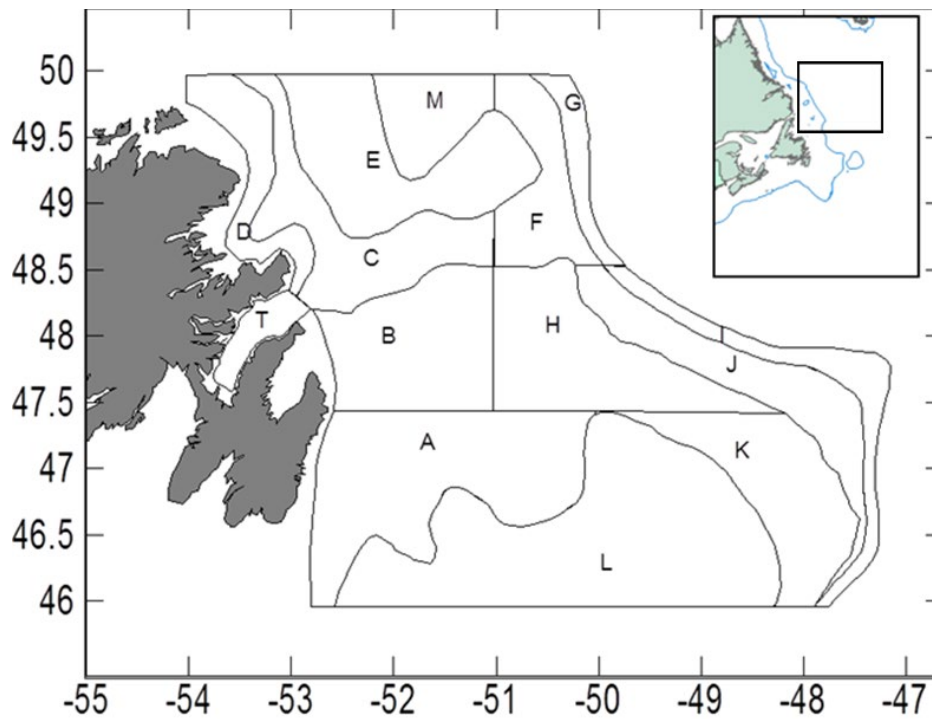


Figure 7. Spring acoustic survey strata in NAFO Divisions 3KL.

Standard Stratum (2001-2022)																							Core							
	1988	1989	1990	1991	1992	1996	1999	2000	2001	2002	2003	2004	2005	2007	2008	2009	2010	2011	2012	2013	2014	2015	2017	2018	2019	#	2021	2022	Strata	
A	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	X
B	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	X
C	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	X
D	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	
E	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	X
F	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	X
G	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	X
H	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	X
I	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	X
J	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	X
K	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	
L	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	
M	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	X
T	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	

Figure 8. Acoustic strata coverage for spring Capelin acoustic surveys from 1988–2022. Green indicates strata fully covered, orange indicates partial coverage, and red indicates missing or inadequate coverage. Note stratum names refer to strata boundaries as established in 2000.

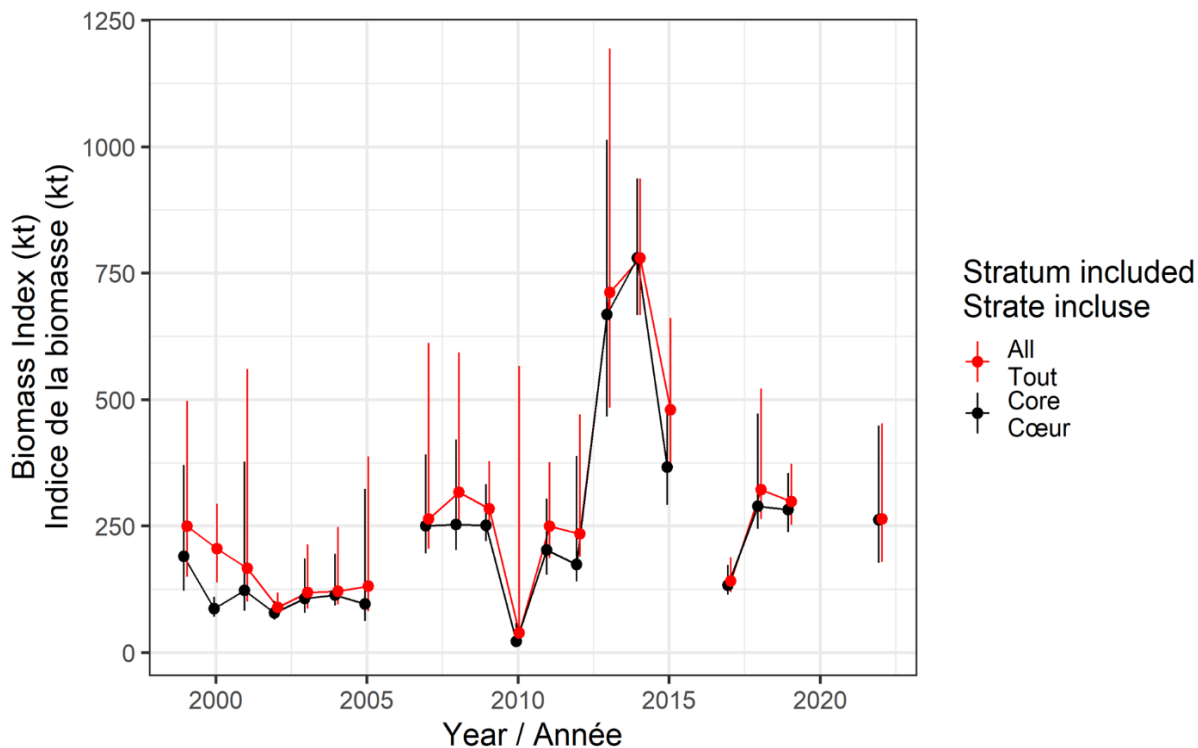


Figure 9a. Comparison of the Capelin biomass index calculated using All Strata survey (All; red line) vs. the biomass index calculated using only the Core Strata (Core; black line). For both time series, the points indicate the median biomass index estimate for each year while the vertical bars show the 90% confidence intervals for the year's biomass index estimate, ranging from the 5<sup>th</sup> to the 95<sup>th</sup> percentiles of the estimate.

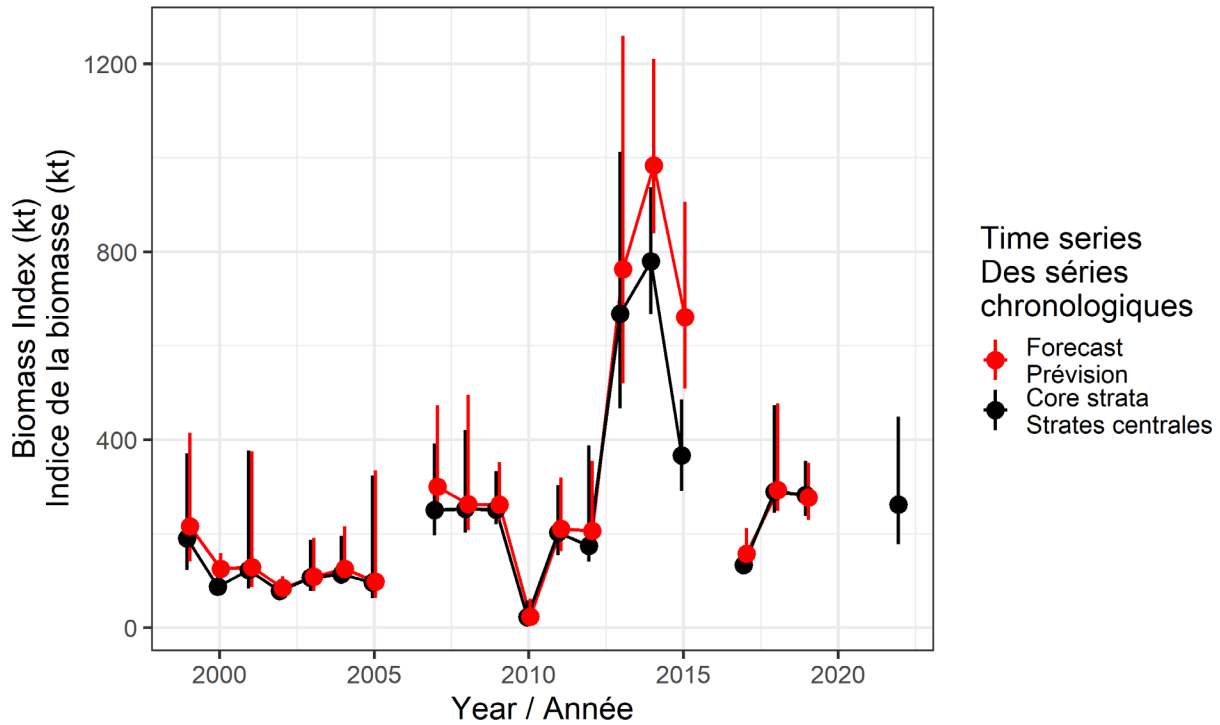


Figure 9b. Comparison of the revised Capelin biomass index based on the Core Strata (Core strata; black line) vs. the Capelin biomass index used in the Capelin forecast model from 2017–21 (Forecast; red line).

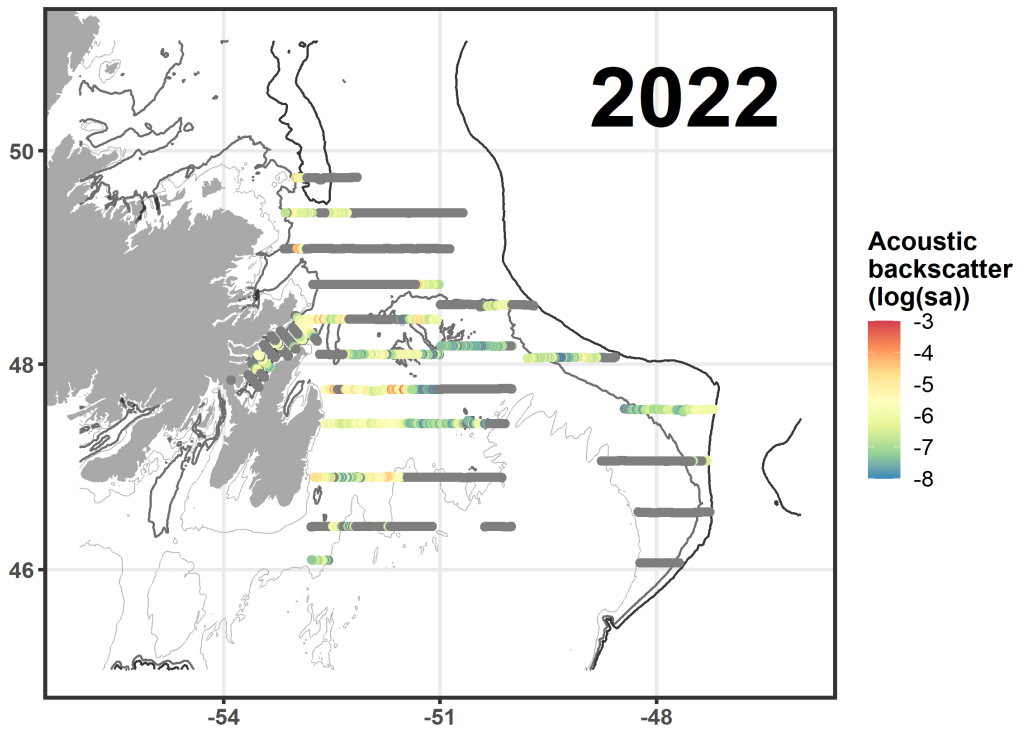


Figure 10a. Spring acoustic survey tracks in 2022. Consecutive colour increments indicate an order of magnitude difference in acoustic backscatter with colder colours (blue) indicating lower acoustic biomass. Grey indicates no Capelin acoustic backscatter.

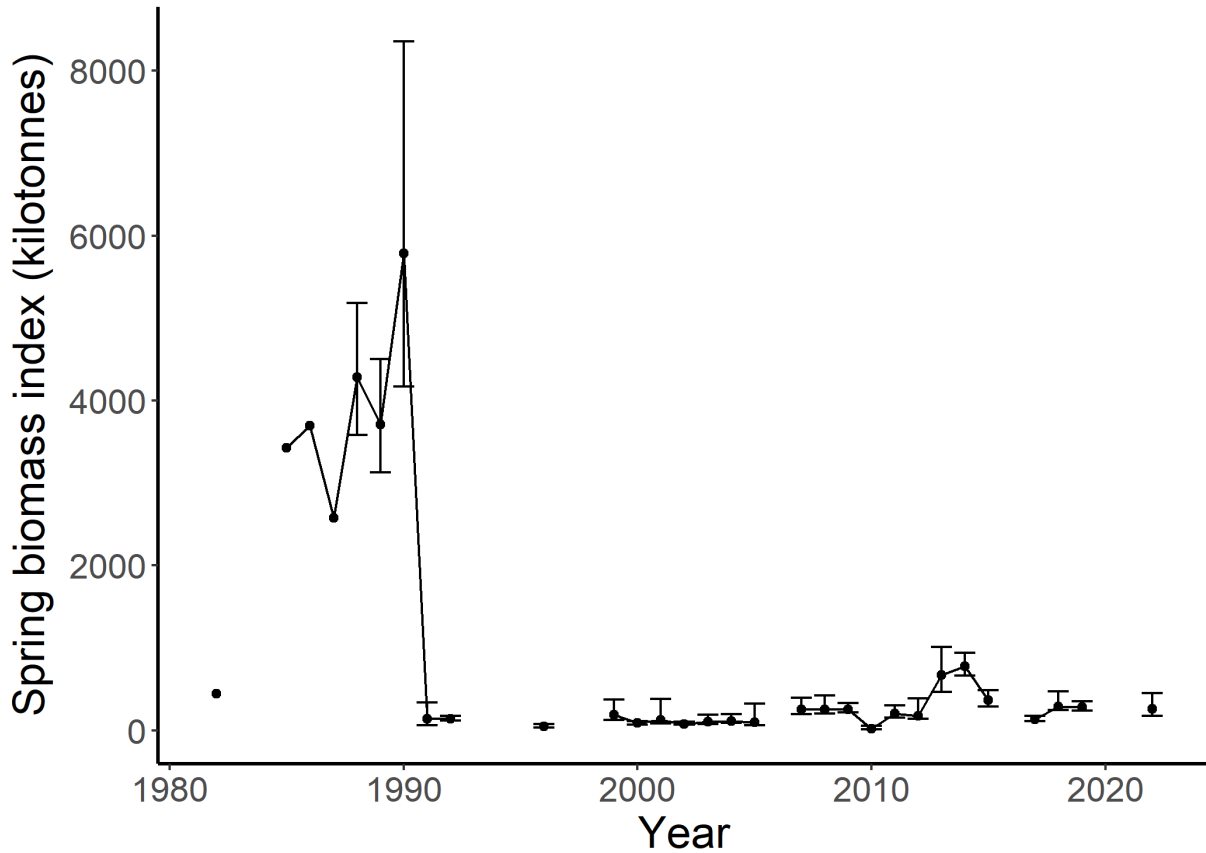


Figure 10b. Capelin spring acoustic biomass index from 1982–2022. Error bars are 90% confidence intervals, ranging from the 5<sup>th</sup> to the 95<sup>th</sup> percentiles of the estimate. Error bars could not be calculated for 1982–87.

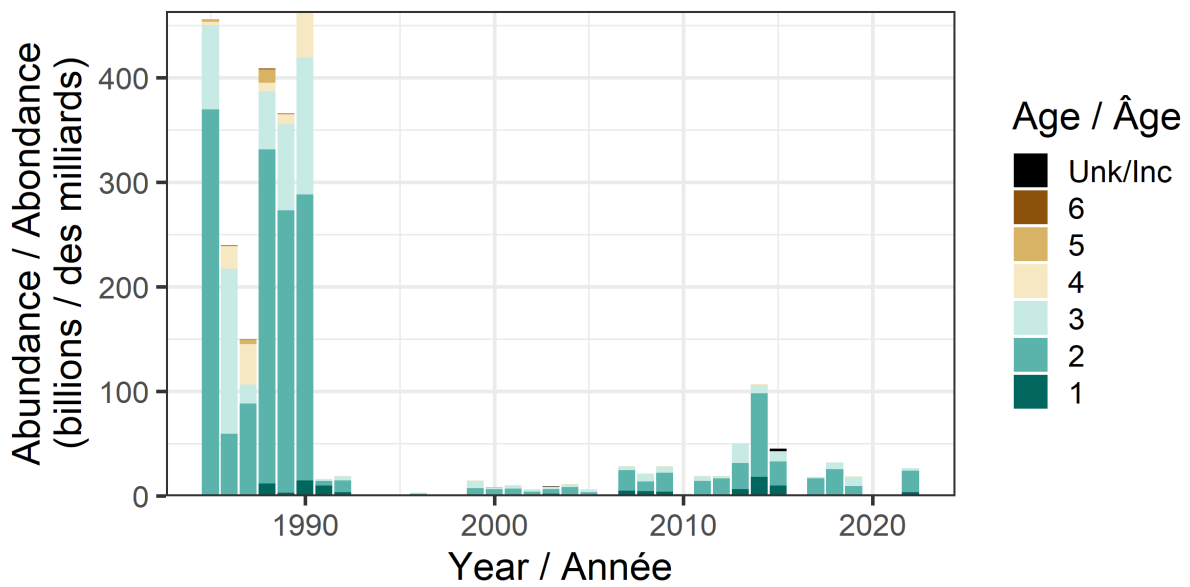


Figure 10c. Capelin spring acoustic age disaggregated abundance index from 1985–2022.

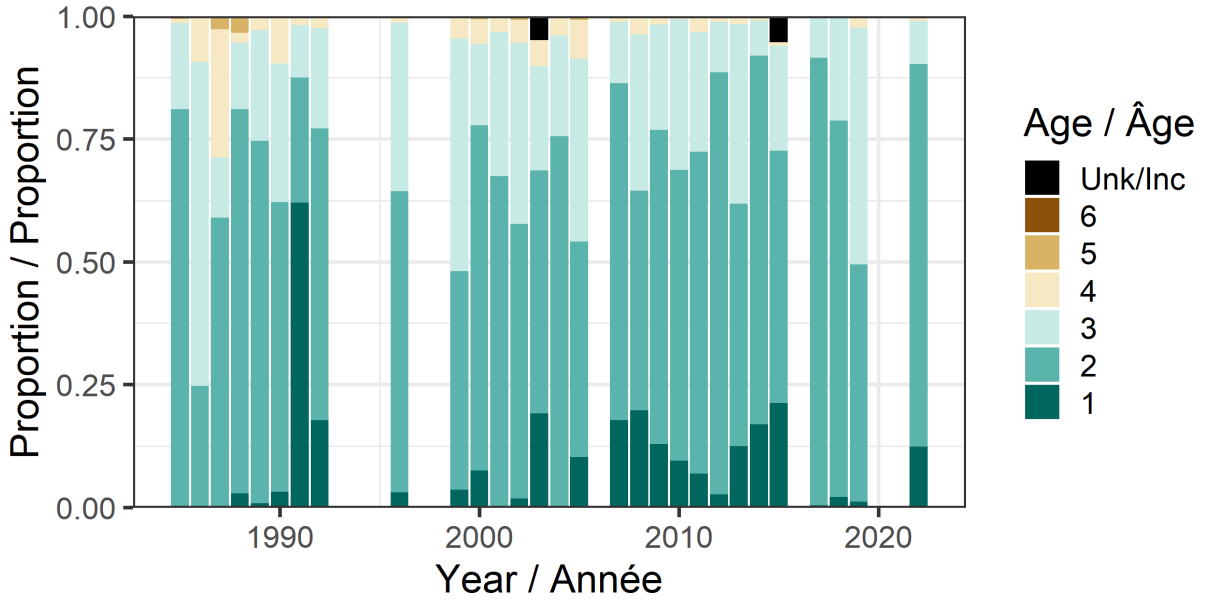


Figure 11. Age composition of 2J3KL Capelin in the spring acoustic survey since 1985.

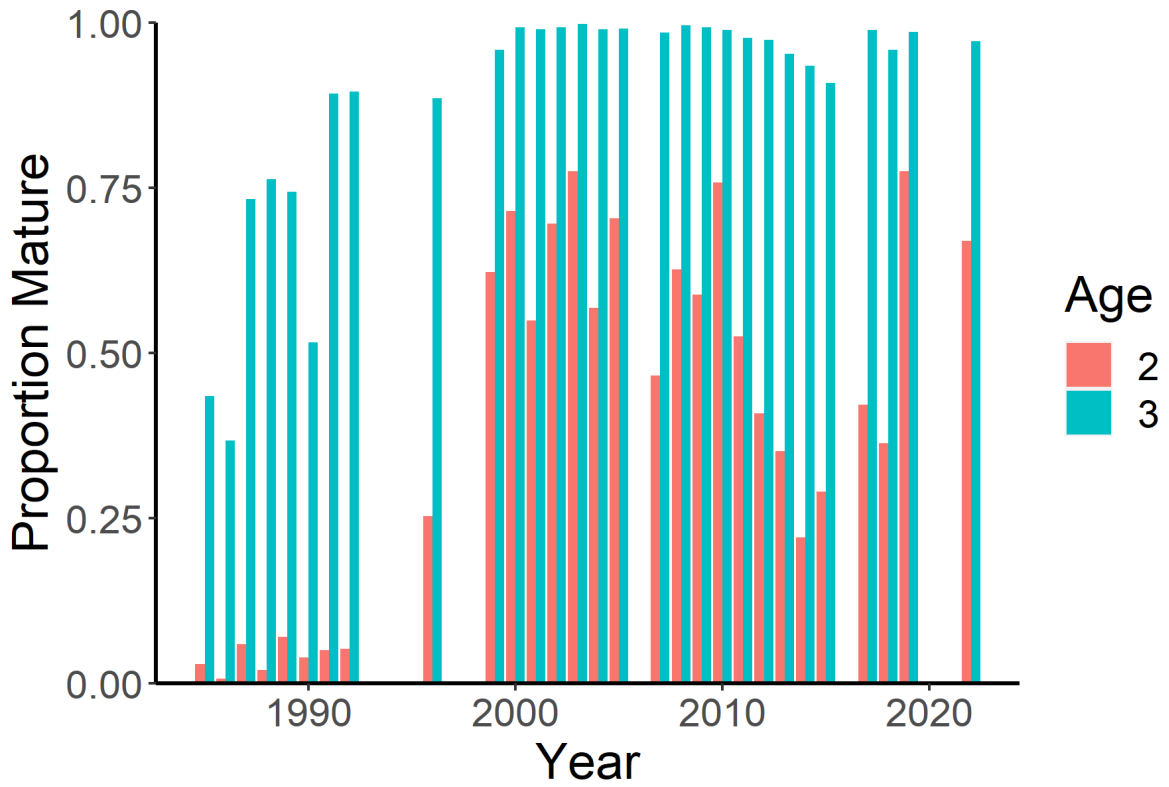


Figure 12. Proportion of Capelin mature (pooled by sex) at age-2 and age-3 since 1985.

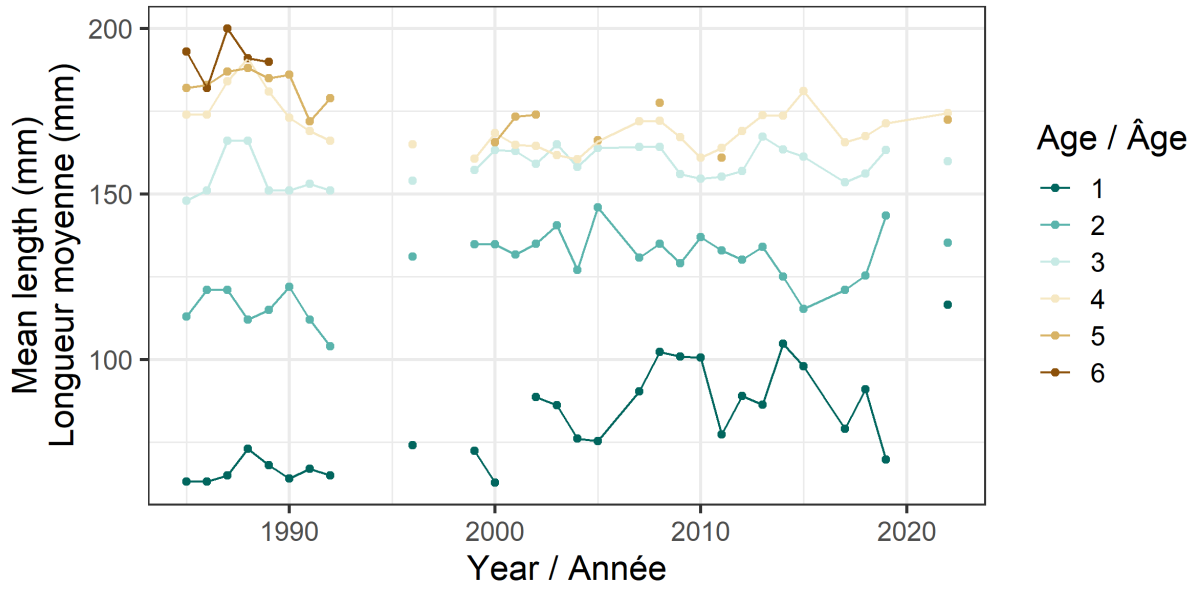


Figure 13a. Mean lengths of 2J3KL Capelin sampled in the spring acoustic survey (ages 1–6) from 1985–2022.

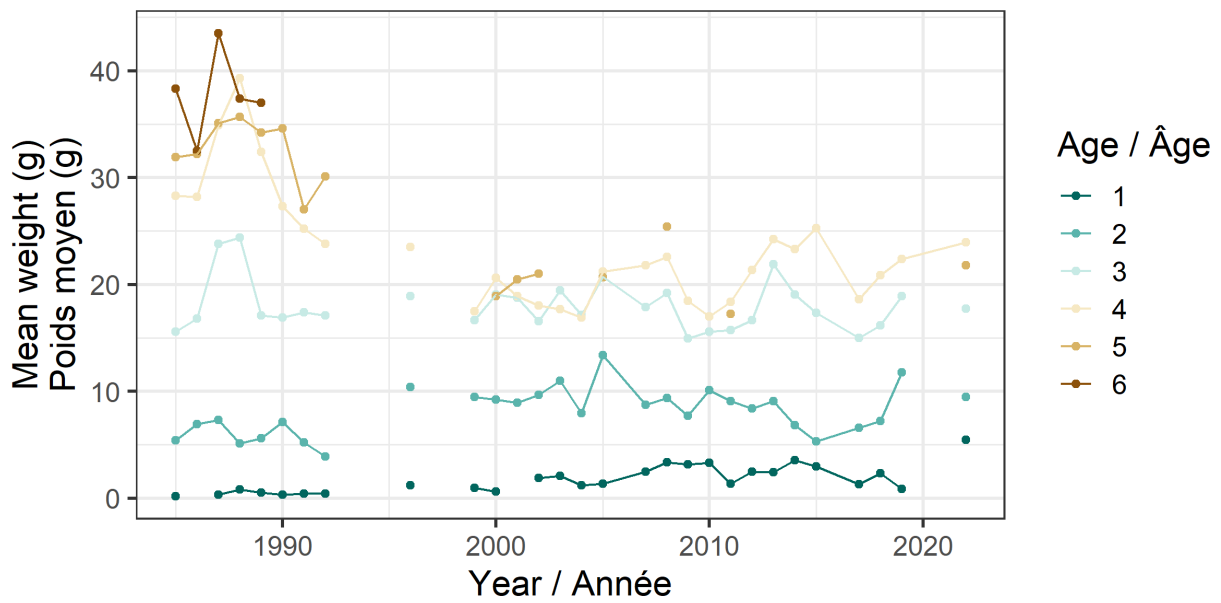


Figure 13b. Mean weights of 2J3KL Capelin sampled in the spring acoustic survey (ages 1–6) from 1985–2022.

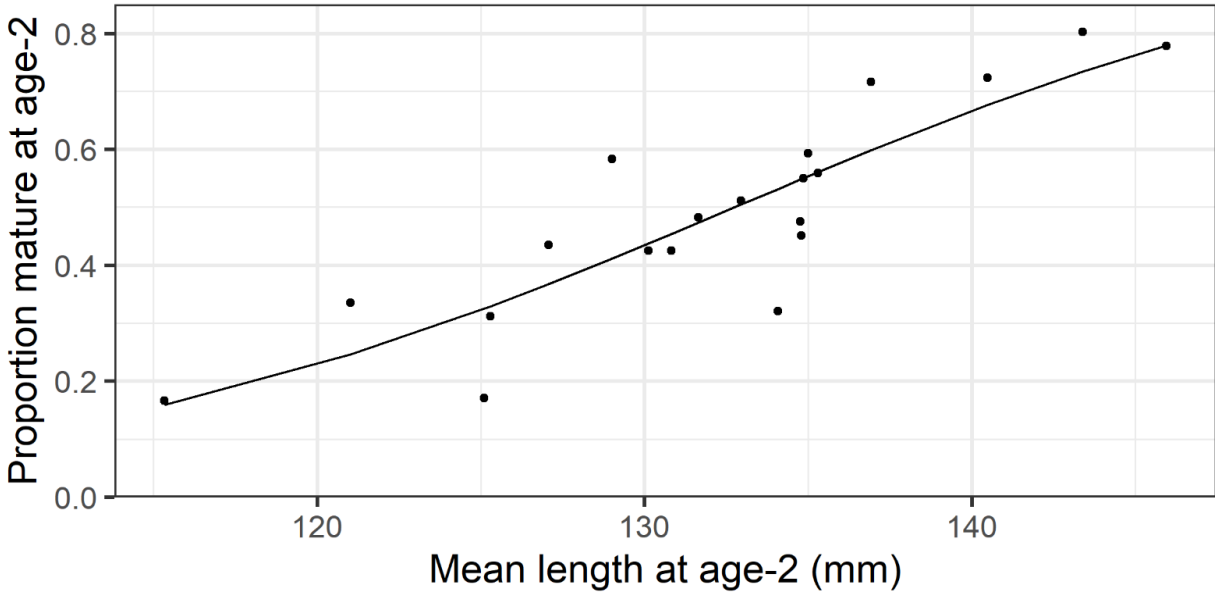


Figure 14a. Proportion of Capelin mature at age-2 was positively related to mean length at age-2 (beta regression Pseudo  $R^2 = 0.76$ ,  $p = 0.001$ ).

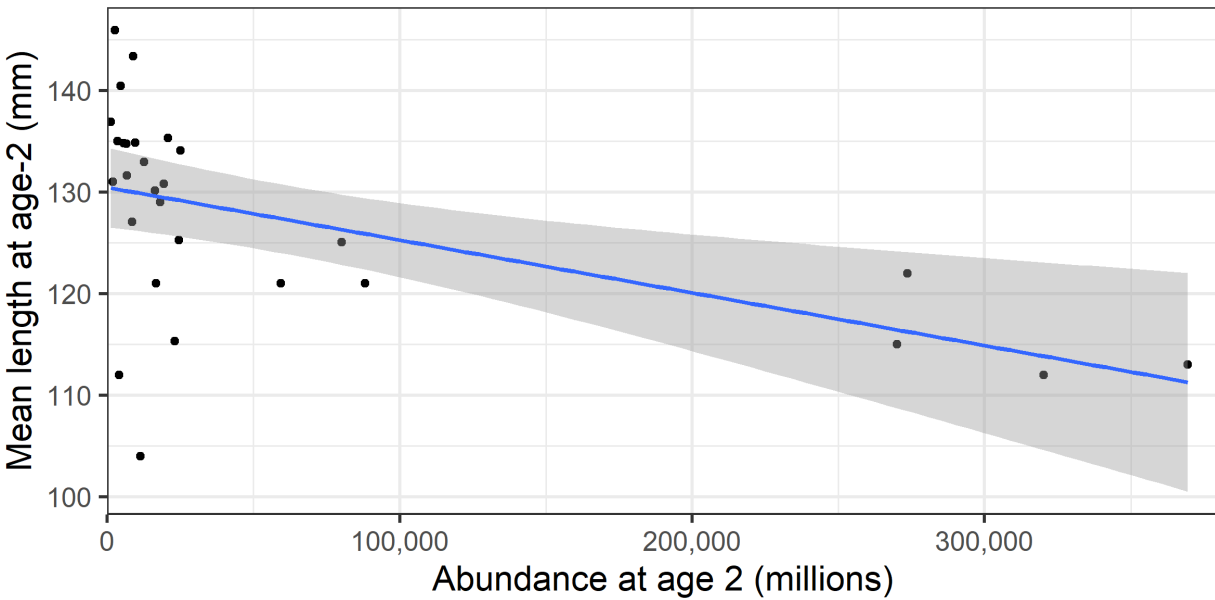


Figure 14b. Abundance of age-2 Capelin was negatively related to mean length at age (linear regression  $R^2 = 0.25$ ,  $p = 0.0032$ ).

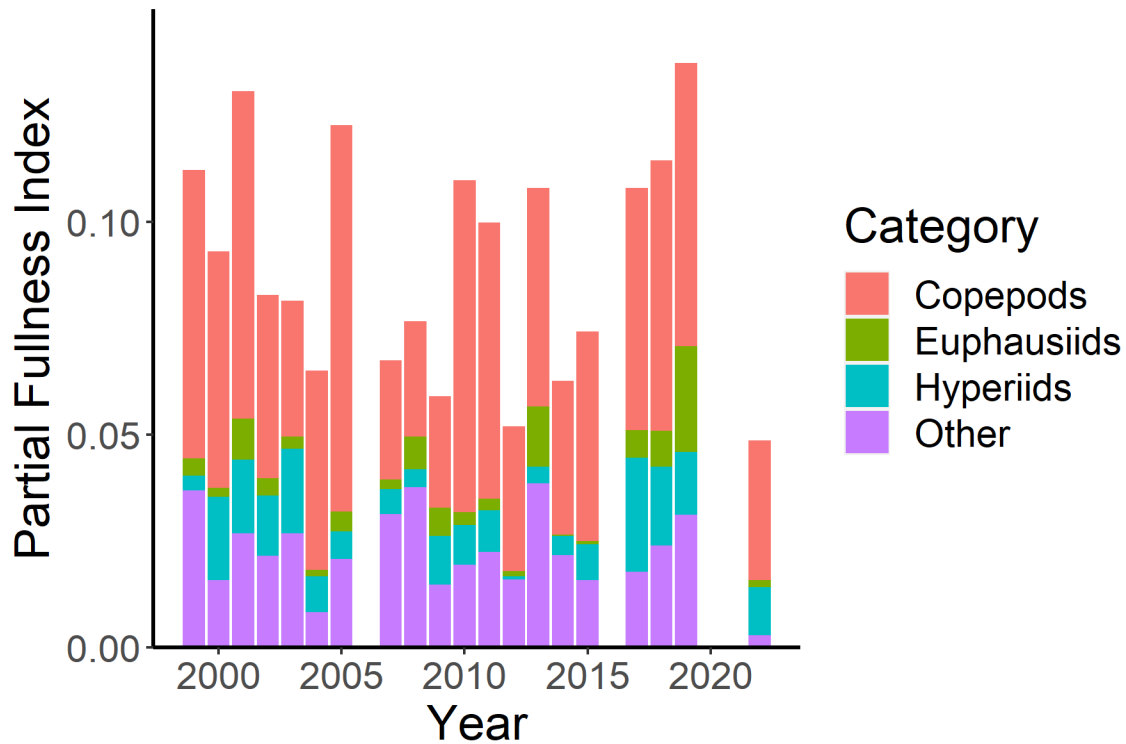


Figure 15a. Partial Fullness Index of 2J3KL Capelin (1999–2022). There was no acoustic survey in 2020 due to the COVID-19 pandemic, and 2021 was excluded because there was only partial coverage of the survey area in June.

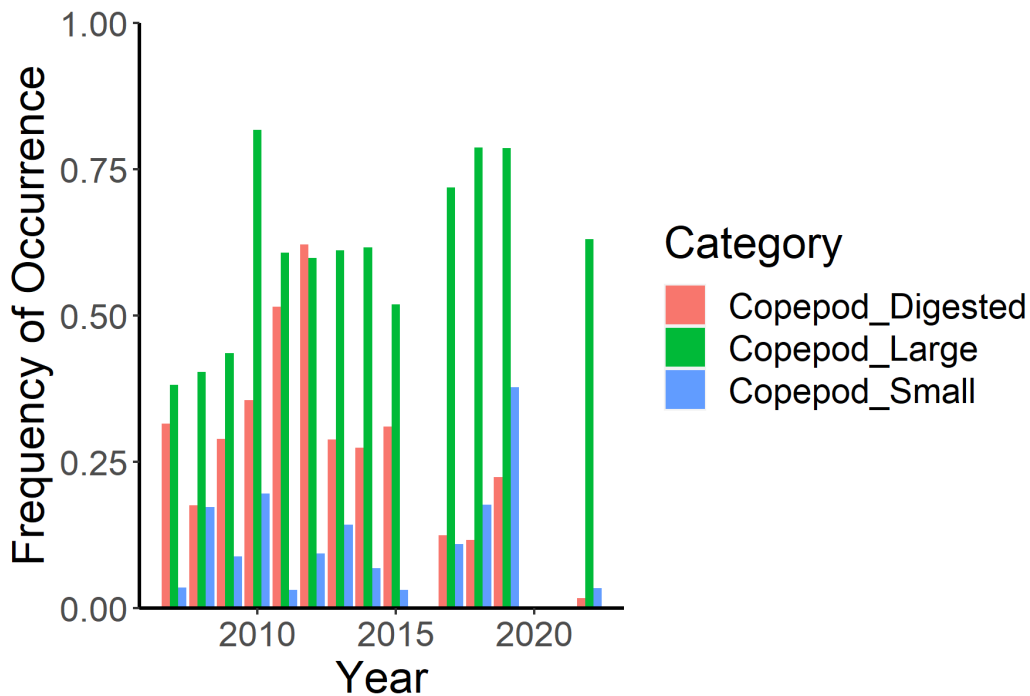


Figure 15b. Frequency of Occurrence of small, large and digested copepods in 2J3KL Capelin diets (2007–22). There was no acoustic survey in 2020 due to the COVID-19 pandemic, and 2021 was excluded because there was only partial coverage of the survey area in June.



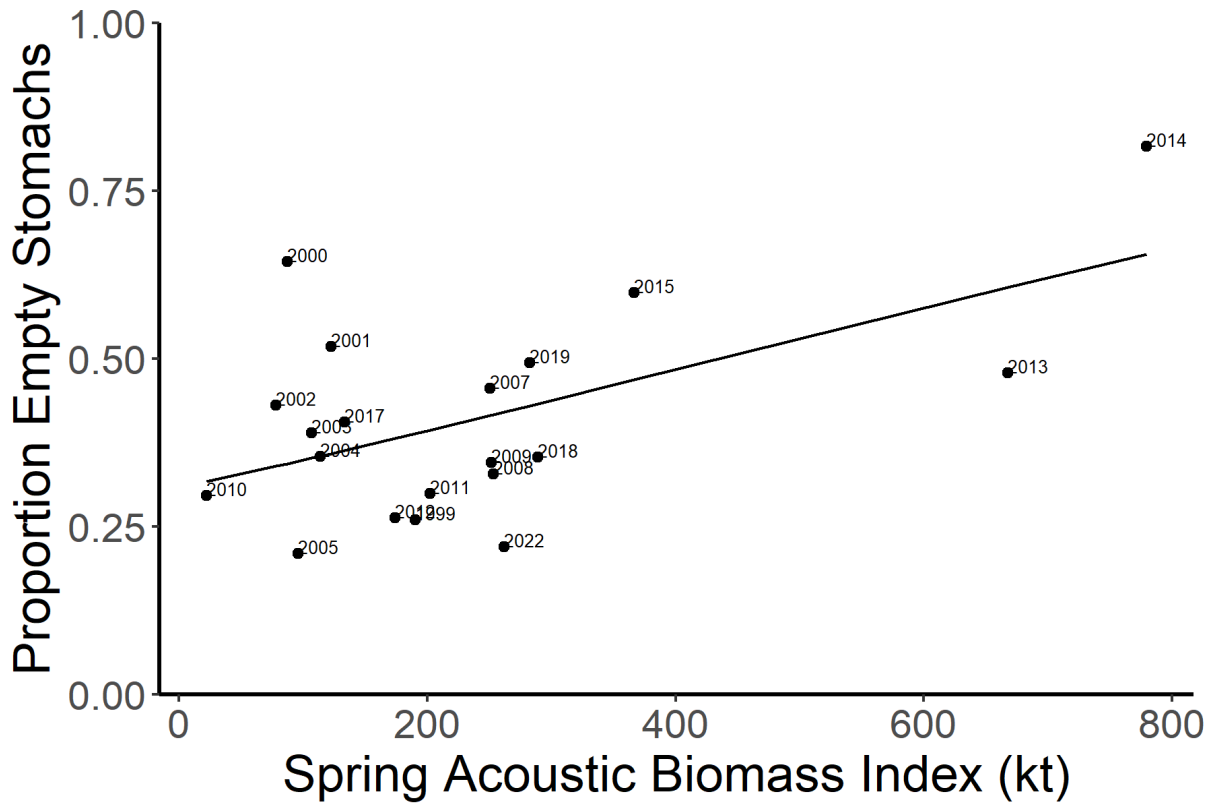


Figure 15c. Beta regression between proportion of empty stomachs in the spring (May) and the Capelin spring acoustic biomass index (1999–2022; beta regression: Pseudo  $R^2 = 0.31$ ,  $p = 0.003$ ).

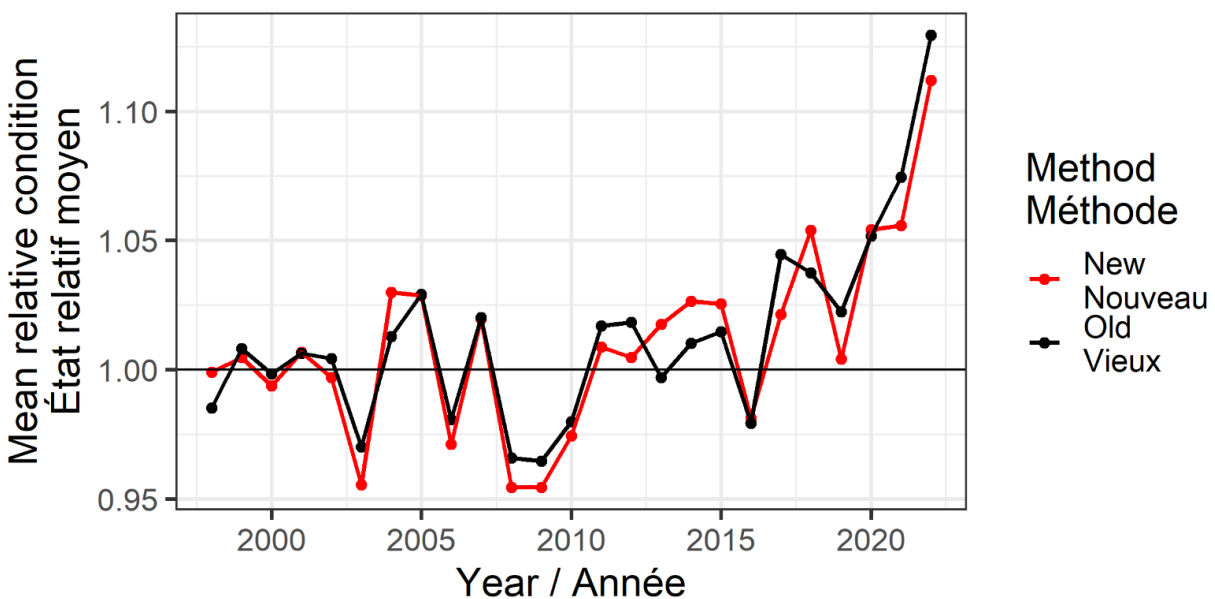


Figure 16. Comparison of old and new methods for calculating mean relative condition of male and female age-1 and -2 Capelin sampled in the fall multi-species bottom trawl survey by year (1998–2022) for NAFO Divisions 2J3KL. In 2021, 3L was not surveyed so the condition value used average 3L condition from 2011–20. In 2022, survey coverage was atypical due to the Comparative Fishing Program.

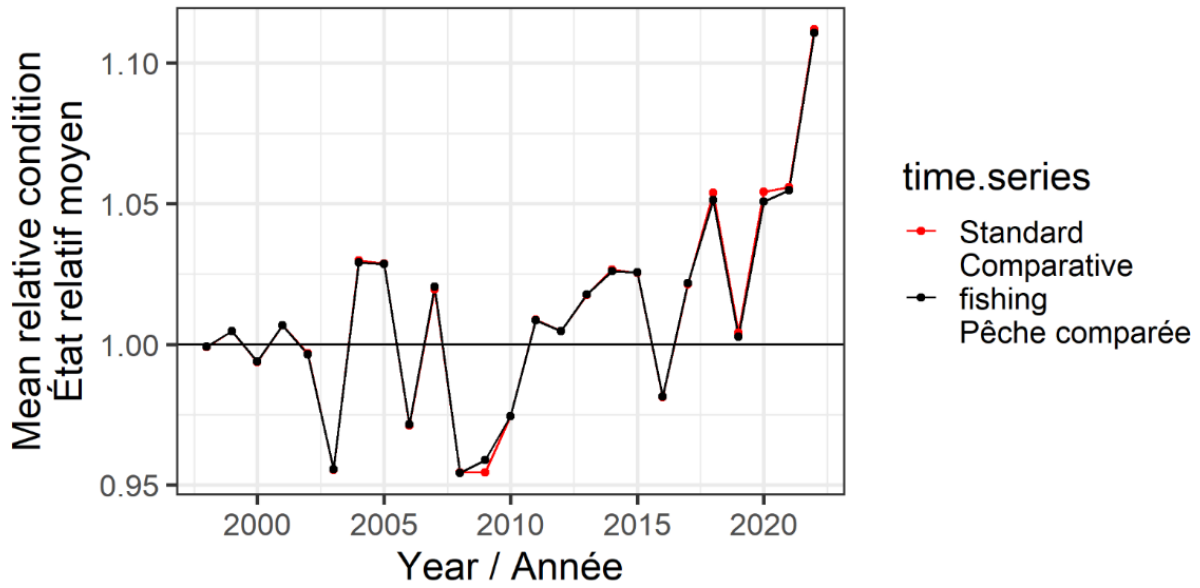


Figure 17a. Comparison of fall relative condition between a typical fall bottom-trawl survey design (Standard) from 1998–2022 and only strata surveyed during the Comparative Fishing Program (Comparative fishing) from 2022.

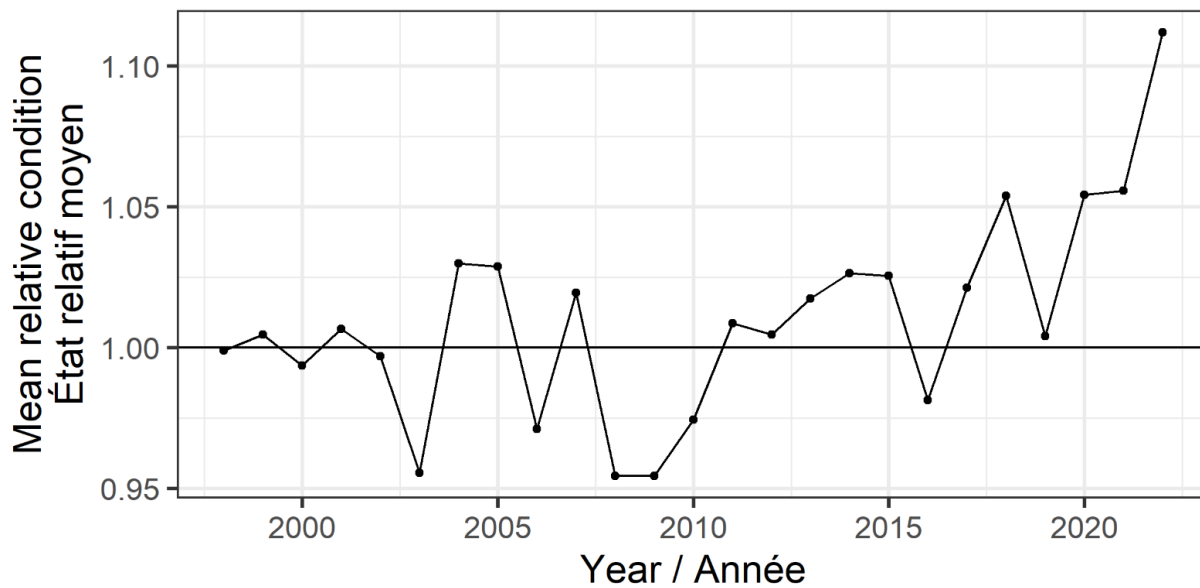


Figure 17b. Fall relative condition of ages-1 and -2 male and female Capelin in Div. 3K only from 1999–2022.

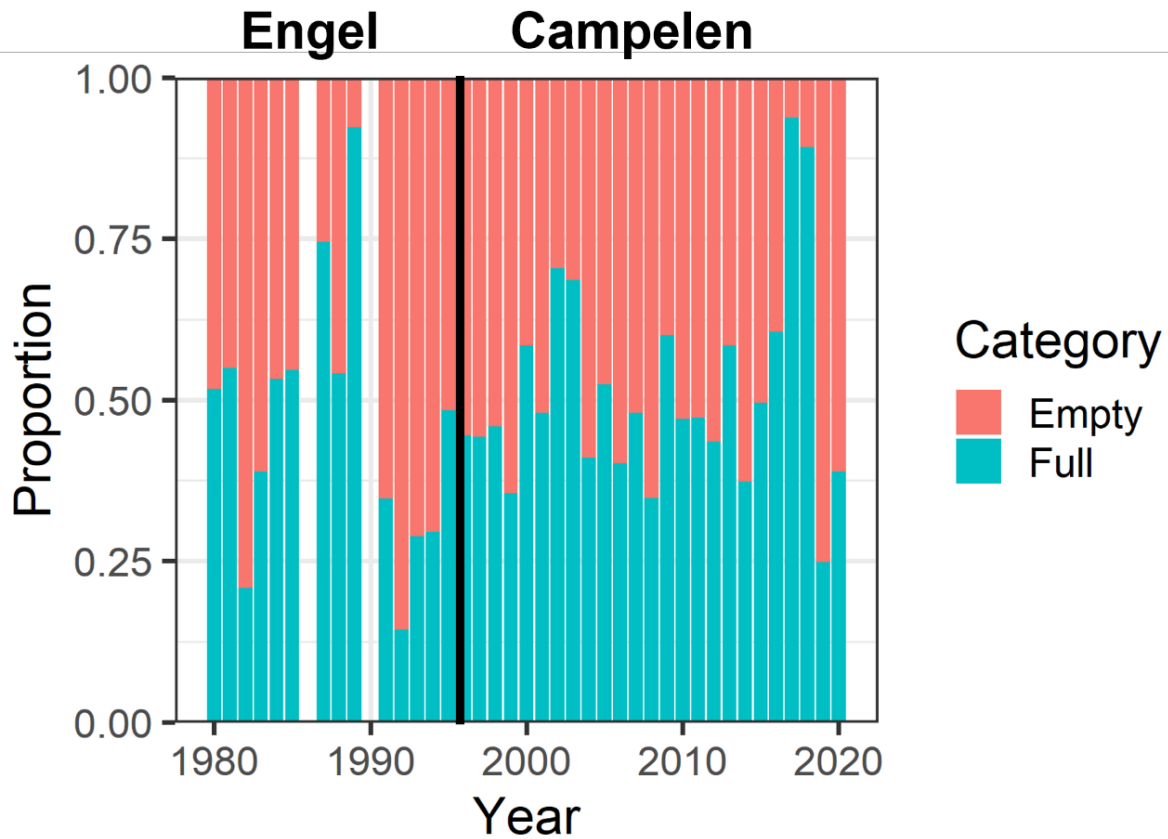


Figure 18. Proportion of empty (category 0) and full (categories 1–4 on stomach fullness scale, pooled) of undissected ‘called’ Capelin stomachs in the fall multi-species bottom-trawl survey in Divs. 2J3KL (1980–2020). Data from 2021 and 2022 are not included due to changes in survey coverage in these two years. Black vertical line delineates Engel and Campelen bottom trawl gear periods.

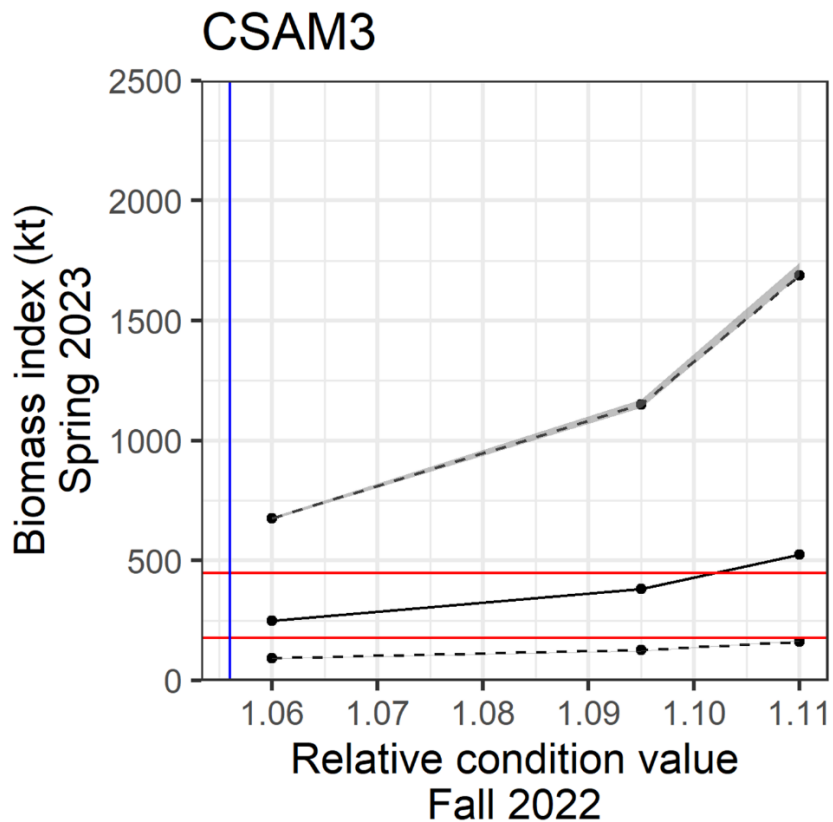


Figure 19. A comparison of predicted biomass index values for spring 2023 for a range of fall 2022 relative condition values using the CSAM3 forecast model. The vertical blue line shows the largest condition value used to fit the forecast model. The two horizontal red lines show the 5<sup>th</sup> and 90<sup>th</sup> percentiles of the biomass index for spring 2022. The black dashed lines show the 10<sup>th</sup> and 90<sup>th</sup> percentiles of the prediction interval for the forecast model while the shaded areas show the range between the lower and upper limits of the 10<sup>th</sup> and 90<sup>th</sup> percentiles when accounting for the model's sensitivity to the timing of sea ice retreat. The smallness of the shaded areas indicated that the model forecast was only slightly affected by the timing of the sea ice retreat.

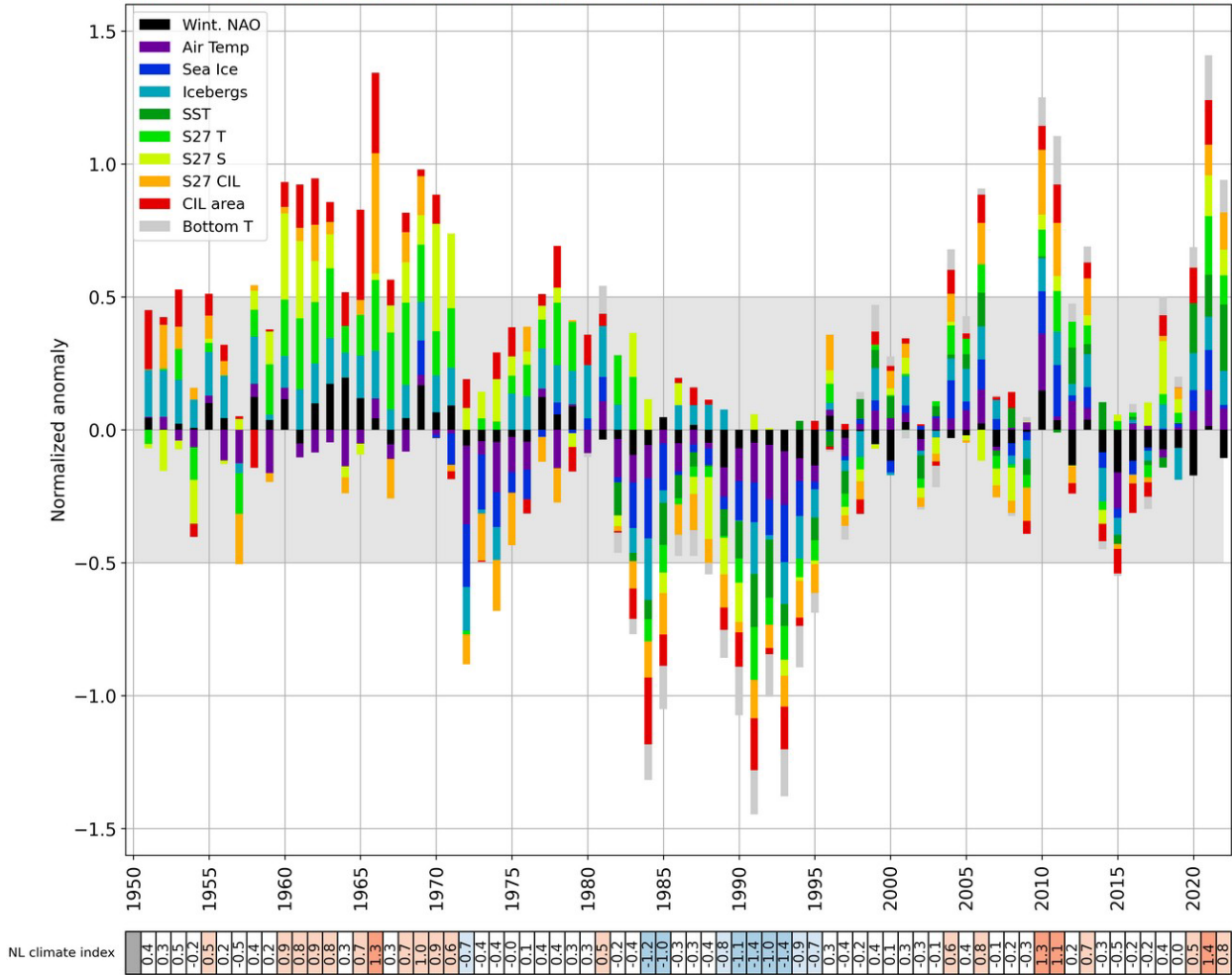


Figure 20. The Newfoundland and Labrador Climate Index is made up of 10 subindices: winter North Atlantic oscillation (NAO) index; air temperature at five sites; sea ice season duration and maximum area for northern and southern Labrador and Newfoundland shelves; number of icebergs; sea surface temperatures 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).

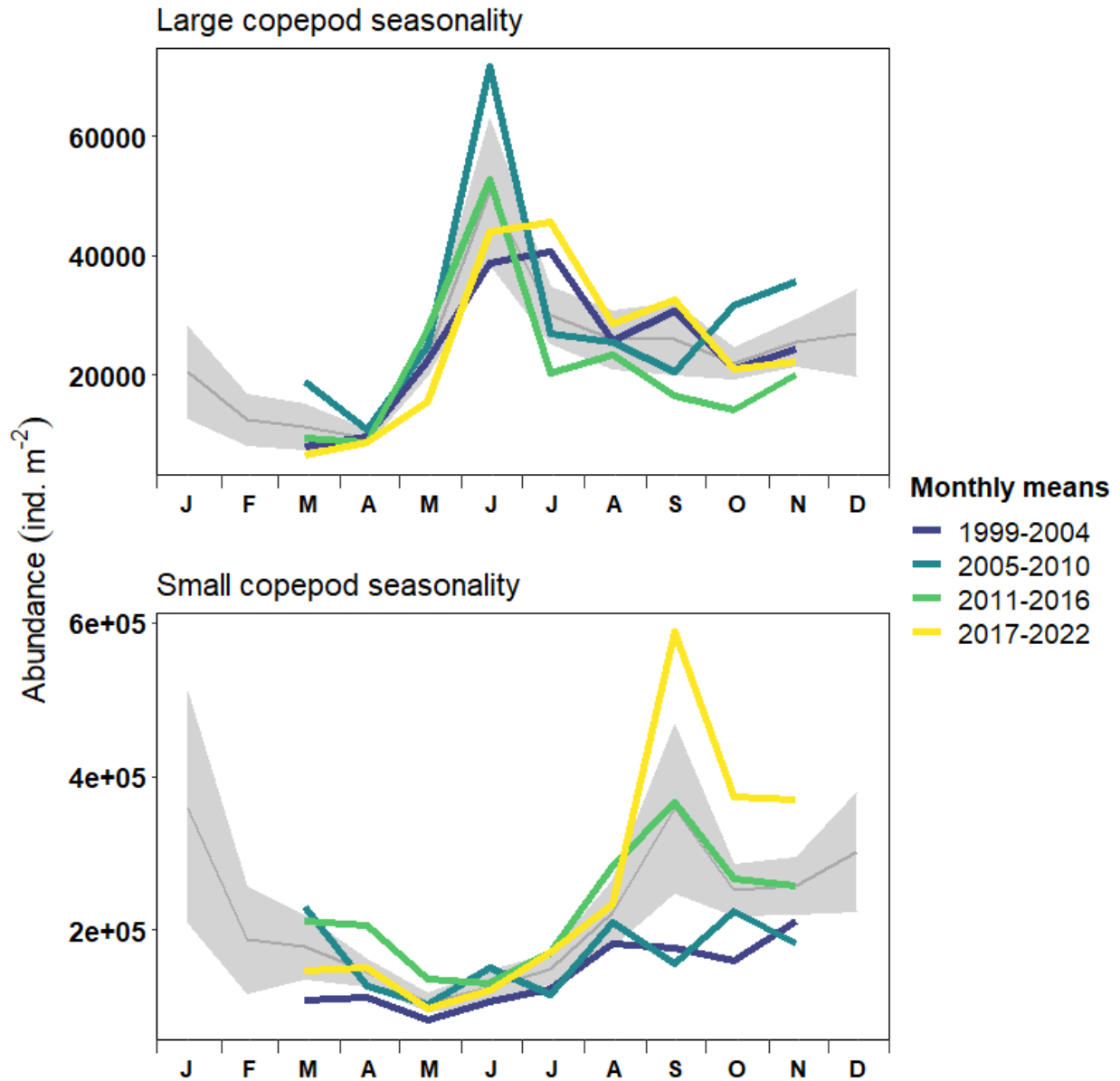


Figure 21. Seasonal large and small copepod abundance data sampled at Station 27. Monthly means were calculated using six-year bins (i.e., 1999–2004). The grey line and ribbon represent the mean and 95% confidence intervals for the entire data series (1999–2022). Months with no data were interpolated (December, January, February).

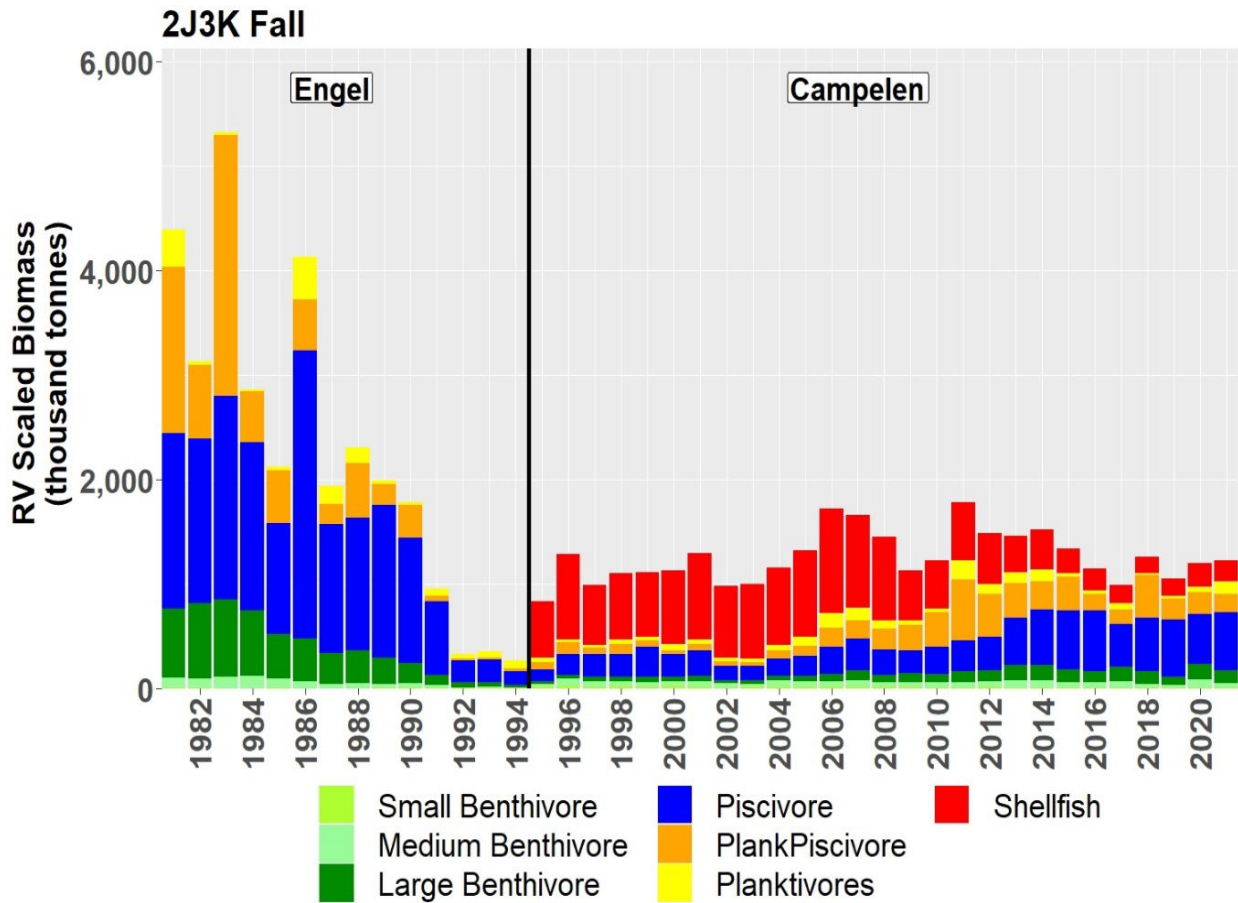


Figure 22. Total Fall RV Biomass index trend of the fish community in the Newfoundland Shelf and northern Grand Bank (Divs. 2J3K) discriminated by fish functional groups. Indices for the Engel period have been scaled to be comparable to the Campelen series (Koen-Alonso and Cuff 2018). Shellfish data were not consistently collected during the Engel period; the index for this functional group is not available prior to 1995. Note that this figure does not include data for Div. 3L due to lack of survey coverage in this division in 2021 (see DFO 2023a for more details).

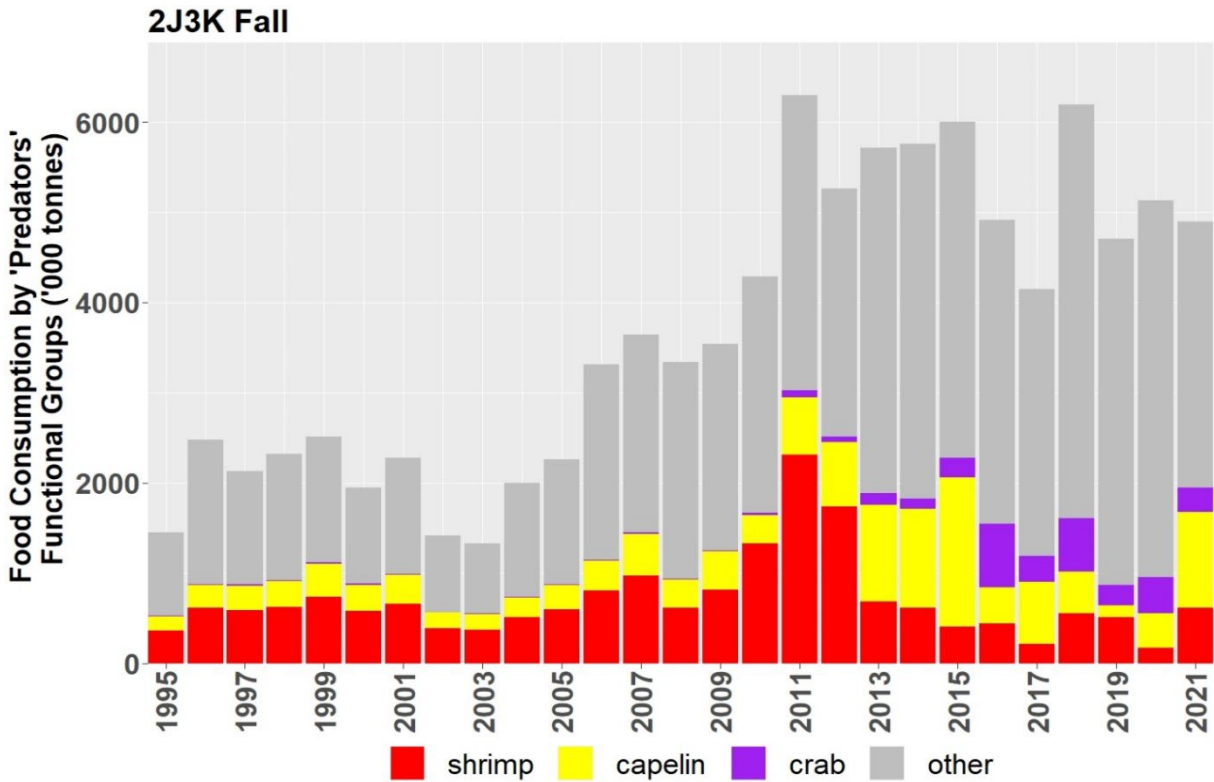


Figure 23. Consumption of shrimp, Capelin and crab by fish predators in NAFO Div. 2J3K only (1995–2021; data from Div. 3L excluded based on lack of survey coverage in 2021). See DFO (2023a) for more details.

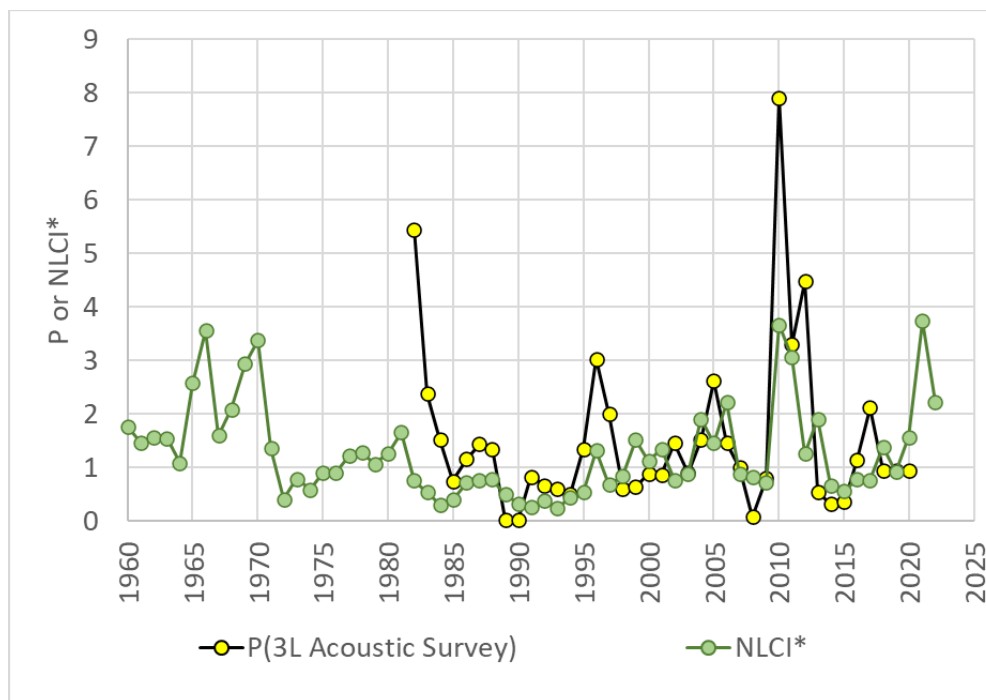


Figure 24. Capelin per capita recruitment ( $P$ ) is related to the NL climate index ( $NLCI^* = \exp[NLCI]$ ) (Spearman  $Rho = 0.38$ ,  $p = 0.016$ ).  $P$  was calculated using linear interpolated values for the Capelin spring acoustic index when needed.



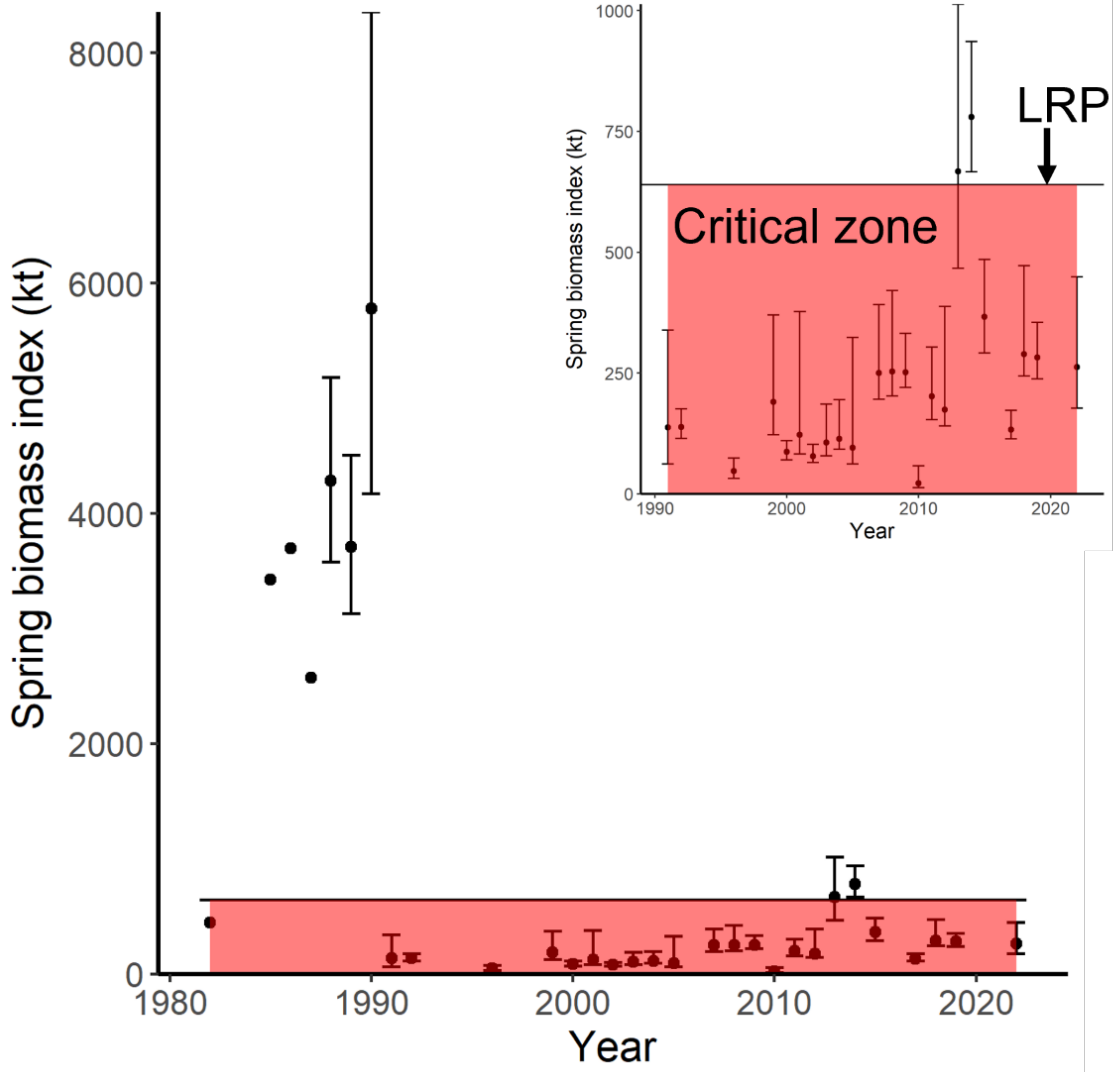


Figure 25. Capelin LRP was established based on its importance to the ecosystem. A 640 kt acoustic biomass index was selected as the LRP, below which the Capelin stock and the finfish community are likely at risk of serious harm. The inset figure shows the post-collapse years only (1991–2022).

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## APPENDIX

### TRINITY BAY RESEARCH PROGRAM

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 (Dalley et al. 2002). The objectives of the current survey are to track larval production at the bay scale and investigate how later spawning times affect larval survival and growth. In 2002, 52 stations were sampled across the bay, while in 2003–18, 19 stations were sampled in the center of the bay. In 2019–22, sampling effort increased once again, and 36 stations were sampled across the entire bay. This sampling program occurs at a fixed date for one week in August, September and/or October. During years when only one survey was conducted, it was targeted for September. The sampling stations are fixed along 4–7 northwest transect lines, spaced 6 nmi apart, with stations placed at 3 nmi intervals along each of the lines. The sampling methods are the same as Dalley et al. (2002). The bongo nets are composed of 333  $\mu\text{m}$  mesh nets and a constant bongo net descent and ascent rates are maintained at each station by real-time monitoring of gear depth using a net-mounted CTD. Target descent rate is 20 m/min and the ascent rate is 10 m/min. The filtered volume of each net is monitored using mechanical flow meters (General Oceanics 2030 Series). The bongo nets are towed at a speed of 2–2.5 knots. At each station, one bongo sample is preserved in 2% buffered formaldehyde and the other bongo sample is preserved in 99% ethanol or frozen. The different preservation methods are used to facilitate different types of analyses (counts vs. diet and growth studies).

CTDs casts of the entire water column are conducted across the head, center, and mouth of the bay when time and weather conditions permit (Fig. A1). Since 2013, zooplankton samples have been collected at each bongo station using a 50  $\mu\text{m}$  mesh net attached to the interior of one of the bongo nets and the zooplankton samples were preserved in 2% buffered formalin. In 2017–19, fresh zooplankton samples were analyzed onboard the Canadian Coast Guard (CCG) Vladykov using a FlowCam. From 2020, zooplankton samples were once again preserved in 2% buffered formalin or frozen.

Following the survey, the larval samples preserved in 2% buffered formaldehyde are strained, soaked in freshwater and then reconstituted to 1L volume. Successive 50 ml aliquots of the reconstituted sample were sorted and all fish larvae identified to species. The number of individuals of each species was recorded, and all Capelin and herring larvae measured for standard length. Aliquots were analyzed until either a minimum of 50 Capelin were counted or half the volume (500 mL) was sorted. In 2022, the entire larval sample was sorted and this is the new approach going forward. Capelin density per square meter was calculated for each station using equation S1:

$\rho_i = C_i * D_i / V_i$	<b>S1</b>
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where  $\rho$  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  $\text{m}^3$ . Mean annual densities are calculated using only the 19 core stations.

The second bongo sample preserved in ethanol was used for Capelin larval trophodynamics and growth studies to identify the mechanisms of recruitment variability in Capelin. Capelin larvae preserved in ethanol in 2002, 2006 and 2013 were <30 days old and experienced inter-annual variability in growth rates, which may be related to prey availability (Murphy et al. 2018).

In 2022, the TB larval index (pooled for month) was 28.4 ind.  $\text{m}^{-2}$  (Fig. A2). In the majority of years when there was a survey in August and September, TB larval densities were higher in

August than September (12 of 15 years) which may be a reflection of spawning timing and retention in TB (i.e., increased mortality and advection from bay between August and September) (Fig. A3). Similar to the BB larval index, the TB larval index has been below average (32.4 indiv. m<sup>-2</sup>; 2002–12) for an extended period of time (2015–20) (Fig. A2). In 2021, the TB larval index was above average, but the BB larval index was below average, suggesting that there was higher larval survival than expected in 2021 or that BB was not representative of productivity at other beaches in TB in 2021. Spawning was early in 2021, suggesting this may have provided an ideal environmental window for capelin larval survival compared to a typical spawning season in the post-collapse period. However, these two larval indices are not correlated, and the TB larval index is not related to the age-2 recruit index (Murphy et al. 2018). The lack of significant statistical relationships is likely due to the spatial and temporal limitations of this survey compared to the extended sampling protocol at BB that captures the start and end of larval emergence.

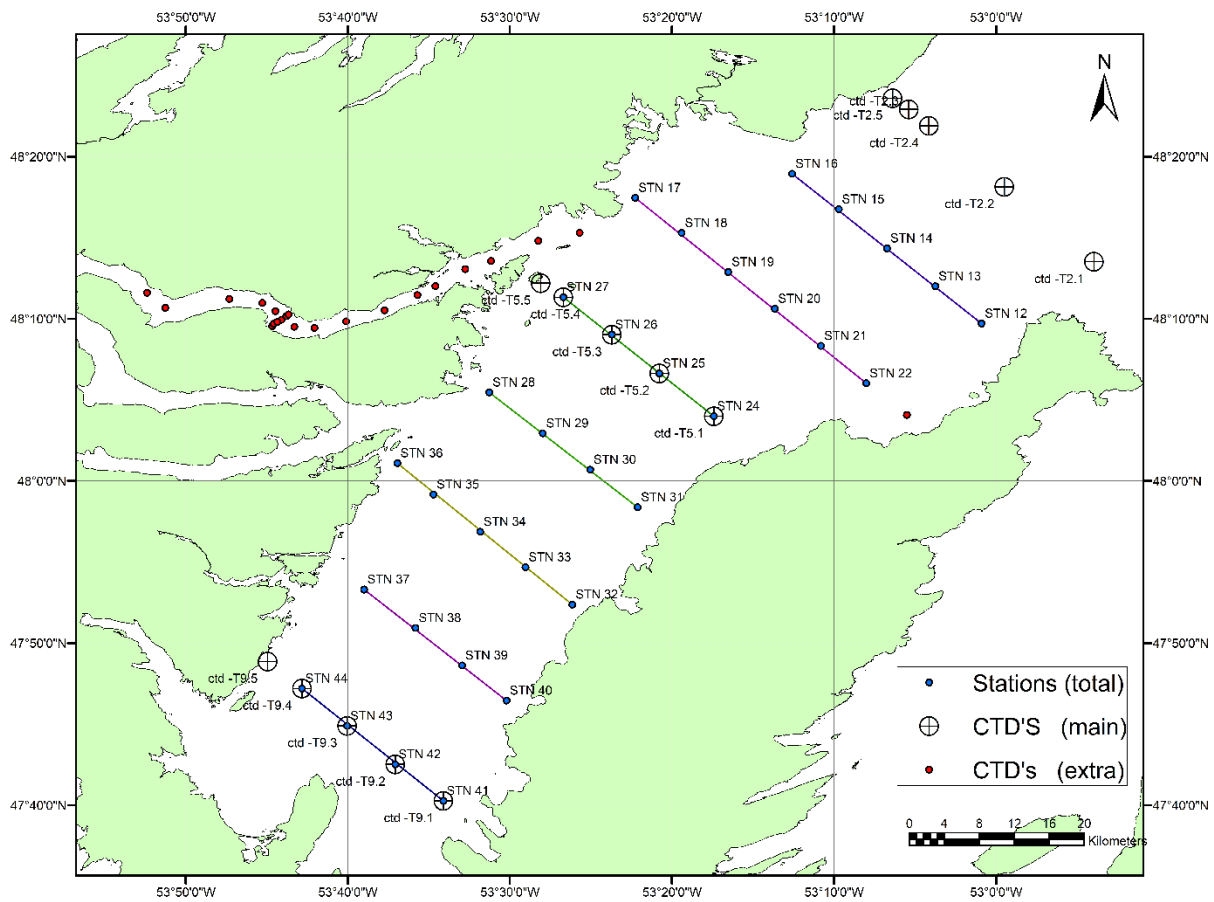


Figure A1. TB larval survey. The core stations sampled are in the center of the bay (Stations 17–36).

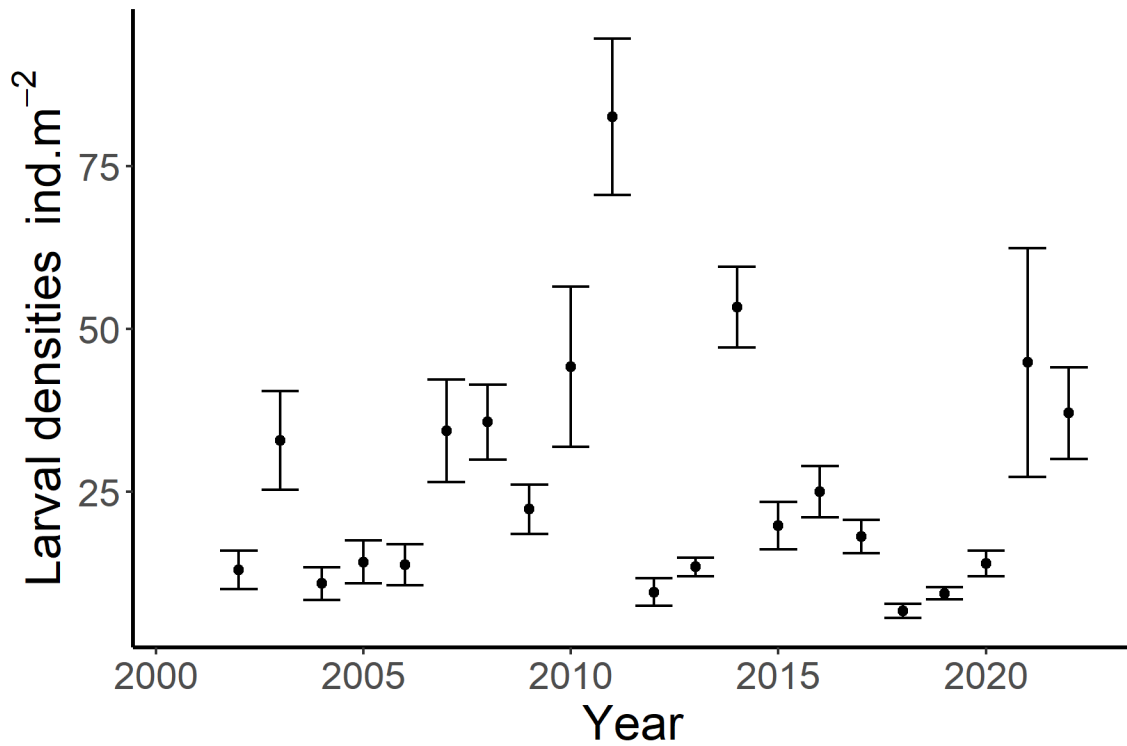


Figure A2. TB larval index (error bars are  $\pm$ SE), pooled for month (August and September). From 2002–07, this survey was only conducted in September.

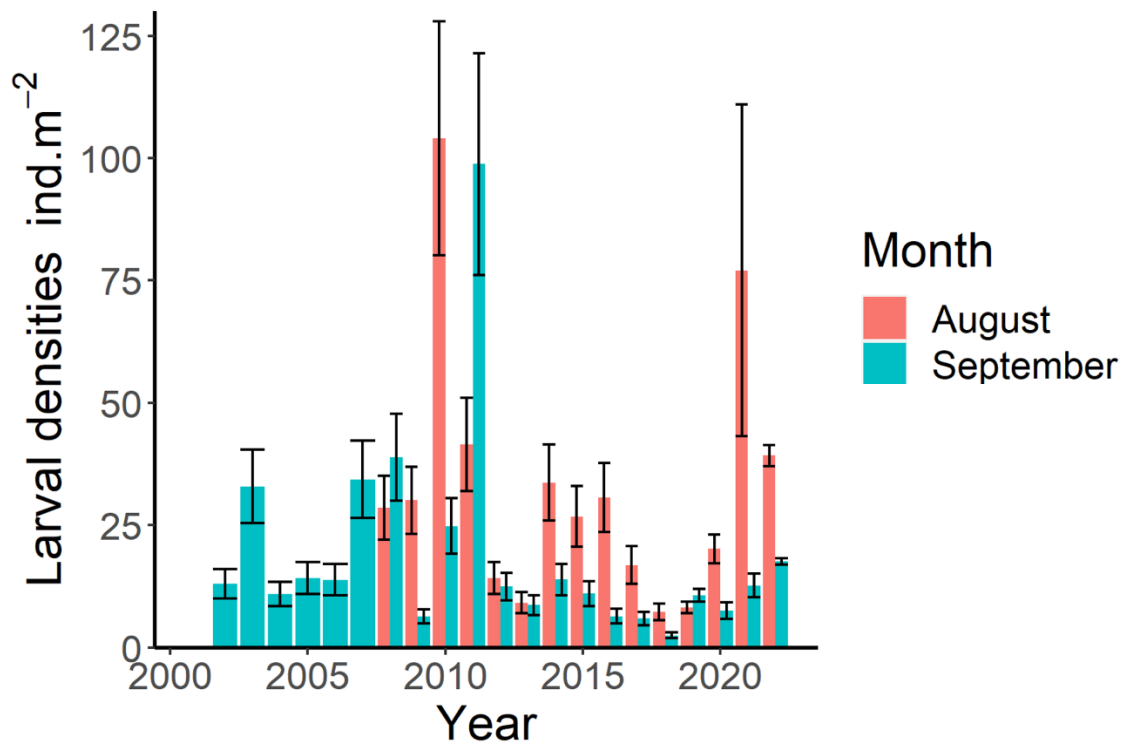


Figure A3. TB larval densities sampled at 19 core fixed stations in the center of TB in August and September. Error bars are  $\pm$ SE.