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Assessment of Capelin (*Mallotus villosus*) in 2J3KL to 2019

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Foreword

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

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ABSTRACT

The assessment of the 2J3KL Capelin (*Mallotus villosus*) stock included fisheries and ecosystem data to the fall of 2019, and the sea ice data available to March 2020. Data sources reviewed included spring 3L acoustic surveys, inshore larval surveys, multispecies bottom trawl surveys and fishery catches, state of the ecosystem, predatory fish diets and consumption of Capelin by fishes. Following the collapse of this stock in the early 1990s, the spring acoustic survey abundance index declined by an order of magnitude. Coincidentally the size at age of younger Capelin increased and the age at maturity decreased. There have been no strong indications of recovery of the stock since. The 2019 spring acoustic abundance index was at a similar level to 2017 and was consistent with values observed during the period of lowest values during the early 2000s. Age-3 fish comprised a larger than usual portion of the spring survey abundance and fishery catches in 2019. Patterns in Capelin distribution, growth and maturation were consistent with the interpretation that the surveyed cohorts were weak (2018) to moderate (2017) in strength. Due to the high proportion of maturing age-2 fish and the usual high rates of post-spawning mortality few age-3 spawners are expected in 2020. The larval index has indicated poor production for the last 5 years including the two cohorts entering the fishery in 2020. However fewer empty stomachs in adults suggests that feeding success has improved moderately in the last 3–4 years, which may lead to an improvement in post larval survival. The forecast model predicts that Capelin biomass index for the 2020 spring acoustic survey will likely decline compared to 2019, returning to low biomass levels similar to that seen in 2017. The increases in groundfish observed in the late-2000s and early-2010s appear associated with bottom-up processes, including an improved prey field, with modest increases in Capelin availability in comparison with the 1990s. Capelin and shrimp are key forage species in the ecosystem. More recent declines in total finfish biomass may be associated with simultaneous reductions in Capelin and shrimp availability.

STOCK STRUCTURE

Capelin (*Mallotus villosus*) is a small, short-lived pelagic schooling species with commercially important populations occurring in the Northwest Atlantic, waters around Iceland, in the Barents Sea, and in the North Pacific. 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, 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 DFO Newfoundland and Labrador Region currently assesses.

Capelin are a key forage fish in the Newfoundland ecosystem, providing a vital energetic link between zooplankton and numerous higher trophic level predators, including seals, whales, Atlantic cod, Greenland halibut, salmon, and seabirds. 2J3KL Capelin spend most of their adult life in offshore waters. 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 deep-water (demersal) sites close to beaches in the summer. Capelin are a short-lived species, maturing at age-2 or 3. Post spawning Capelin have a high rate of mortality, near 100% for males and likely in excess of 50% for females. There is no evidence of a stock-recruitment relationship for this Capelin stock, probably due to highly variable, environmentally driven, egg and post-hatch larval mortality. However, larval year class strength is an important factor in subsequent adult abundance (Murphy et al. 2018).

FISHERY

FISHERY OVERVIEW

Capelin have historically been an important part of the Newfoundland inshore fishery and culture, with fish gathered from spawning beaches largely being used for food, bait, and fertilizer. Commercial harvests are mostly directed to roe markets and consequently the fishery targets pre-spawning fish, removing spawners subsequent to most predation within the ecosystem. Total annual removals prior to the commercial fishery were estimated to be about 25,000 tonnes (t). In the early 1970s, an offshore fishery began in Div. 2J3KL which peaked at nearly 250,000 t in 1976; an inshore commercial fishery began in the same areas in 1978, peaking at 71,000 t in 1990 (Fig. 1). The offshore fishery was closed in Div. 3L in 1979 and in Div. 2J3K in 1992; the inshore fishery has continued through to today with recent landings of between 20,000 and 30,000 t (Fig. 2). Due to the short fishing season, as well as changes in fishery timing and exploitation methods, 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 fishery removals.

Participation in the Capelin fishery depends largely 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 2019a). 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 a fishery be opened until the test fishery finds that Capelin are of high quality. 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. The fixed gear component consists of traps, cast-nets, dip-nets, and tucks 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 collected across bays are processed each year, apportioned among gear sectors, bays and season (weekly) as a function of the total 2J3KL landings. Length, sex, and maturity are determined for all fish sampled and additional detailed information (weight, gonad weight, stomach fullness, and age [from otoliths]) is collected for 2 fish per sex, per 5 mm length class in each sample. Catch-at-age is calculated separately for each catch cell. A catch cell is defined as a unique combination of gear sector and NAFO Division (Division hereafter). Age-length keys are determined for each combination of Division and sex. These age-length keys are applied to the sexed length frequency (0.5 cm bins) of each sample, so that each fish is assigned an age based on length. Numbers of fish within each 0.5 cm length grouping are converted to biomass using length-weight regressions calculated by Division, sex, and month. Subsequent length and age frequencies from sampled fish are scaled to landings for each catch cell.

ECOSYSTEM CONTEXT

NL climate experienced cold conditions between the mid-1980s and the mid-1990s, and from about 2012 to 2017. These cold conditions were associated with positive phases of the North Atlantic Oscillation (NAO) and changes in large-scale ocean circulation (e.g., increased Labrador Current transport along the NL shelf edge) (Cyr et al. 2020). At this point in time, the impact of large scale variations in ocean climate on Capelin is unknown, but it has been shown that mismatches in prey availability associated with changes in the timing of spring sea ice retreat impacts the biomass of adult Capelin (Buren et al. 2014).

Primary (chlorophyll) and secondary (zooplankton biomass) production indices have improved over the past 3–4 years. Recent changes in zooplankton community structure have resulted in fewer large, lipid-rich copepods, which are an important energy source for adult Capelin, and increased abundance of small copepods (DFO 2019b), which indicate poor foraging conditions for adults (Buren et al. 2014), but improved foraging conditions for larval Capelin (Murphy et al 2018).

Information on the 2J3KL fish community is available from the fall bottom trawl survey (1981–2019). The fish community on the Newfoundland Shelf and Northern Grand Bank (NAFO Divs. 2J3KL) was dominated by finfishes in the 1980s. The ecosystem changes observed in the 1990s involved the collapse of the groundfish community and an increase in shellfish (Koen-Alonso et al. 2010, Pedersen et al. 2017, Koen-Alonso and Cuff 2018; Fig. 3). Capelin also collapsed during this period (Buren et al. 2019).

Ecosystem conditions continue to be indicative of limited overall productivity of the fish community. Total research vessel (RV) biomass levels remain much lower than prior to the 1990s collapse. The increases in groundfish observed in the late-2000s and early-2010s appear associated with bottom-up processes, including an improved prey field, with modest increases in Capelin availability in comparison with the 1990s (Buren et al. 2019).

Capelin and shrimp are key forage species in the NL shelf ecosystem. Declines in total finfish biomass observed in 2016–17 may be associated with simultaneous reductions in Capelin and Shrimp availability.

Capelin and Shrimp consumption by those fish functional groups considered to be predators of these forage species(i.e., medium and large benthivores, plankpiscivores, and piscivores) was estimated by combining total food consumption and diet composition of key species within those functional groups. An envelope for total food consumption was estimated as the range from a suite of consumption models, and using the median of these estimates as a summary statistic for total consumption. All consumption models were based on the combination of fish biomass estimated from the fall multispecies survey, and consumption rates per unit of biomass which were estimated by:

1. Allometric methods. Two different models were used here:
    a. a bioenergetic-allometric consumer-resource modelling framework, based on empirical allometric scaling relationships (Yodzis and Innes 1992), and
    b. an allometric framework derived from growth principles based on the Von Bertallanfy equation and rationale (Wiff and Roa-Ureta 2008).
2. Daily ration. These estimates are based on assuming daily prey consumption as a percent fraction of predator body weight. We assumed two generic daily ration scenarios of 1% and 2% based on the typical range of values for fishes from literature reports (Macdonald and Waiwood 1987, Adams and Breck 1990).

The combined diet composition of key species weighted by their total consumption by NAFO division was used to estimate the overall consumption of Capelin and Shrimp by predatory fishes. The key species considered were Atlantic cod, Greenland halibut, American plaice, yellowtail flounder, and redfish because they represent a major fraction of the combined biomass of the selected function groups, and dominate the overall consumption signal.

Both consumption of Capelin by fishes (Fig. 4) and the predation mortality index (estimated Capelin consumption/Capelin acoustic estimate) declined from 2017 to 2019, suggesting reduced availability of Capelin in the system.

COMMERCIAL LANDINGS AND BIOLOGICAL CHARACTERISTICS

Following the 2019 stock assessment (DFO 2019a), the overall Total Allowable Catch (TAC) for the 2J3KL stock area was increased from 18,506 t to 21,277 t, 90% of which was landed in 2019 (Fig. 1). As per sector allocations, fixed gear continued to account for the majority of landings in 2019 (Fig. 2), although landings were made by both gear sectors in all areas, except Southern Shore and St. Mary's Bay where Capelin were taken with fixed gear only. This is the first time since 2009 that commercial landings have occurred in these two areas. Div. 3K was the only area in 2019 where the full quota was not taken, largely due to a lack of landings in the mobile gear sector in this area. No landings occurred in White Bay in 2017 due to issues with timing of Capelin migration along the northeast coast and processing capabilities (Fig. 2). Landings in Div. 3L in 2019 increased over 2018 with most of the gains made in Bonavista Bay, which did not attain its quota in 2018 (Fig. 2).

Average total lengths of Capelin reached a post-collapse maximum in 2014 and then proceeded to decline over the next few years to a time series minimum in 2017. Since 2018, the average lengths of landed fish have increased to sizes similar to those observed during the late 1990s and 2000s (Fig. 5). Mean weights showed a similar pattern to lengths (Fig. 5). The average size of Capelin landed in the commercial fishery is largely a reflection of the age distribution of the catch. Compared with the 1980s, there has been a higher proportion of age-2 Capelin and declines in the proportion of older age classes (ages 4–6) since the early 1990s (Fig. 6). Overall average lengths and weights of spawners are larger when the proportion of age-2 spawners is low, such as in 2014–16 and low when age-2 fish dominate the spawning population (2017).

SPAWNING

For Capelin, earlier beach spawning is generally associated with the formation of a stronger cohort at age-2 (Fig.7). This may be due to earlier spawning times improving the chance of a match between larval emergence and ideal environmental and biological conditions. Data on peak beach spawning timing has been collected at two reference beaches on the Avalon Peninsula: Bryant's Cove, Conception Bay (1978–present) and Bellevue Beach, Trinity Bay (1990–present). The timing of Capelin beach spawning has experienced a persistent shift from June to July since 1991. From 1978–1990, average peak spawning day at Bryant's Cove was Day of the year (DOY) 171 (June 20; Standard deviation [SD] ± 7 days). From 1991–2019, average peak spawning day at Bryant's Cove was DOY 193 (July 12; SD ± 7 days) and at Bellevue Beach was DOY 198 (July 17; SD ± 11 days) (Fig. 8). In 2019, peak spawning at Bryant's Cove was July 10 and Bellevue Beach was July 15.

Since 1991, Capelin beach spawning has been monitored throughout the province by paid spawning diarists who checked their local beaches every day during the Capelin spawning period (June-August). Participation in this program has varied inter-annually and has decreased in recent years. Generally, spawning occurs earlier in the south with similar peak beach spawning in Divs. 3KL, which was seen in 2019 with mean peak spawning on July 15 in Div. 3L and July 14 in Div. 3K (Fig. 9). Capelin occupied all but one of the monitored beaches in 2019 (Fig. 9). Timing of commercial catches of Capelin in the bays corresponded with peak beach spawning timing with the Northeast (NE) coast fishery completed between July 17–26 2019, depending on the bay and gear type. Conception and Trinity Bays closed before the northern bays.

Samples of spawning Capelin are collected using a cast net once a week at Bellevue beach and another six beaches on the Avalon Peninsula during the spawning season. Samples are comprised of 25 males and 25 females randomly selected. These samples are used to examine within season variation in spawner composition with a general pattern of larger fish arriving first to spawn followed by smaller fish. There are exceptions to this trend. In 2010, the size of spawners increased at the end of the season, and in a few recent years (2013, 2018, 2019) there was little variation in spawner size throughout the spawning season (Fig. 10). The impact of this change in spawning composition on egg and larval production is unknown.

BELLEVUE LARVAL SURFACE TOWS

The age-2 recruitment index, which was lagged by 2 years in order to compare survivors of the same cohort, is positively related to the Bellevue surface tow index (Murphy et al. 2018). This relationship is an important driver of Capelin population dynamics.

Larval surface tows have been conducted at 5 stations in nearshore waters (<20 m) off Bellevue Beach, Trinity Bay since 2001. This survey was designed to sample larvae emerging from demersal Capelin spawning beds and off Bellevue beach and 4 smaller spawning beaches along the western shore of Bellevue. Since 2003 this work has been 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). Only one of the nets collects a larval sample. A General Oceanics 2030 Series mechanical flow meter positioned in the opening of one net measures the volume of water filtered. Capelin larvae are preserved in a 5% formalin and saltwater solution buffered with sodium borate. In the laboratory, when less than 500 Capelin larvae are present in a sample all larvae are enumerated, otherwise a sub-sampling technique is used (van Guelpen et al. 1982). Fifty larvae from each sample are measured for length 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 post-hatch (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 rings in their otoliths until approximately 12 days post-hatch (Ivarjord et al. 2008), and few of these larvae have formed rings in their otoliths at the time of sampling (Murphy, unpublished data).

Total annual production of larvae per m^3 (N) is estimated using the trapezoidal integration method:

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

where t is the day of the year, n is the number of sampling days, and X(t) is the number of larvae per m^3 on day t. Only days when all 5 stations were successfully sampled are 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 3 or more days, then the missing values are set to 0.

Since 2014, the emergent larval index has been below the long-term average (2001–13) of 1,977 ind/m^{-3}, with recent annual production of Capelin larvae of 1,115 m^{-3} (2017), 129 ind/m^{-3} (2018), and 399 ind/m^{-3} (2019) (Fig.11). The 2019 Bellevue surface tow index is the second lowest in the time series, which suggests that the 2019 year class will be weak. Generally, the standardized anomalies (standardized to years 2001–13) of the age-2 recruitment and emergent larval indices have the same trend (Fig. 12).

ADULT SURVEYS METHODS

SPRING ACOUSTIC SURVEY

The spring Capelin acoustic survey has taken place annually since 1982, except in 1993–95, 1997–98, 2006 and 2016 (Mowbray 2013). The acoustic survey is typically conducted in May and covers the majority of Div. 3L, an area of particular importance for juvenile Capelin. Since 1996, the lower portion of Div. 3K (<50ºN) was also included in the survey, but the inclusion of areas further north are sometimes precluded due to the presence of heavy sea ice. The main objective of the spring acoustic survey is to produce an abundance estimate of the non-migratory, immature portion of the Capelin stock (primarily age-2s) that will be recruited to the spawning population the following year. However, with an increasing proportion of age-2s maturing in the 2000s, the survey now also captures a proportion of the pre-spawning Capelin population. The spring acoustic survey does not provide an estimate of the total spawning stock biomass because the surveyed area only covers a portion of the population range of Capelin. All age classes acoustically surveyed are included in the annual index of Capelin abundance.

A stratified survey design is conducted each year, although the transect design, stratum boundaries and areas covered have changed over time. Prior to 1989, transects were laid out in equidistant parallel or zigzag patterns. From 1989 to 1992, randomly 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 point of the initial 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 (Fig. 13). The methodology and original strata for each survey from 1982 to 1996 are presented in annual stock assessment documents (Miller 1991, 1992, 1997).

During acoustic surveys, backscatter is attributed to species using echogram characteristics and biological characteristics of the catches from fishing trawls. Targeted trawl sets (both bottom and mid-water) are conducted as required to investigate the species composition of the acoustic backscatter and to confirm the absence of fish signal. A minimum of one trawl set is conducted every 12 hours. Since 1996, a Campelen 1800 trawl has been used on the acoustic survey. 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 to be verified. The total number and weight of all species caught during the spring acoustic surveys is recorded. When Capelin are caught, the length, sex, and maturity for a maximum of 200 randomly selected fish per set is recorded. Additional detailed sampling (weight, gonad weight, stomach fullness, and age from otoliths) is conducted on two Capelin of each sex per 5 mm length group. Since 1999, stomachs have been removed from each fish for prey content analysis. From 1999 to 2007, stomachs were preserved in 10% formalin; as of 2008, stomachs were frozen until diet analyses could be performed. Since 1999, length measurements have also been recorded for all other potential acoustic targets including Arctic cod, Atlantic Cod, Atlantic Herring, Redfish, and Sandlance to assist with classifying mixed aggregations.

A Capelin abundance index is generated from the survey by combining information from acoustics with that from directed biological sampling. The associated variance of the abundance index is calculated using a Monte Carlo approach which incorporates potential variability in Capelin abundance derived from four factors: calibration uncertainty (associated with technological advances); target strength (TS) (resulting from variations in length composition and catchability); acoustic detectability (resulting from variations in Capelin vertical migration); and 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-backscattering coefficient (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 correction factor, TS (derived from a range of lengths), and a detectability correction. This process is repeated 1,000 times for each 2 km segment within each stratum. The median value of the resultant distribution is then used to estimate the areal density of fish in each stratum while the 5th and 95th percentiles are used as lower and upper confidence limits (Mowbray 2013). Two abundance indices are generated from the spring acoustic survey, one for the offshore area (all strata except Trinity Bay) and one for an inshore area (Trinity Bay).

FALL MULTISPECIES SURVEYS

Multispecies (MS) bottom trawl surveys (hereafter bottom trawl surveys) are conducted by the DFO NL Region each fall in NAFO Div. 2J3KL and each spring in NAFO Div. 3LNOPs (Fig. 14). For a detailed account on the methodology and design of these surveys see Brodie (2005). Bottom trawl survey data are not used to estimate Capelin abundance due to the diel vertical distribution of Capelin and the selectivity of the trawl gear (Mowbray 2001); however, the bottom trawl survey data are used to describe Capelin distribution, diet, and biological characteristics.

Capelin caught during bottom trawl surveys are collected at sea and later processed in the laboratory to determine length, sex, and maturity. Samples of up to 200 randomly selected fish are frozen from each set during the spring MS survey while the sorted catch, up to 25 randomly selected fish, are retained from each set during the fall surveys. For spring catches, one sample (of 200 fish) is processed for each superstrata (stratum grouping) from the set with the highest catch in the superstrata. Detailed sampling is conducted on two fish per sex per 5 mm length class in each sampled catch. For fall catches, length, sex, and maturity are recorded for all frozen fish, but detailed sampling is conducted on only one sample (25 fish representing the set with the highest Capelin catch). Detailed sampling consists of additional measurements of whole weight and gonad weight, recording of stomach fullness and age (as determined from otoliths).

Approximately 400–500 Capelin stomachs are collected and analyzed from each of the fall (since 2008) and spring (since 2013) bottom trawl surveys. Total stomach content weight is recorded, and the dominant prey type is identified, and its proportion of the total stomach contents recorded. Since 2009, one in every 10 stomachs has been subjected to a detailed prey weight analysis, where the first non-empty stomach in every group of 10 stomachs is examined in detail from each set. Prey is classified to species level where possible and total prey weight is recorded.

ADULT SURVEYS DISTRIBUTION AND ABUNDANCE RESULTS

SPRING ACOUSTIC SURVEY

Despite poor weather, acoustic transects were realised in all offshore spring acoustic survey strata during the 2019 survey, although transect spacing in stratum L was larger than usual (40 vs 20 nautical miles). Trinity Bay was also surveyed. Unlike 2018, when Capelin were observed near shore and in the bays both by the survey and by industry, Capelin distributions in 2019 were more typical with Capelin distributed throughout the northern portion of the surveyed area and along the shelf break (Fig. 15).

Distribution in 2019 was contrasted with that observed when the spring acoustic survey abundance index was classified as low (<10 billion individuals), moderate (10–50 billion individuals) and high (>50 billion individuals) (Fig 16). Distribution patterns in 2019 were most consistent with those exhibited during years of low to moderate Capelin abundance, typical during the late 1990s and 2000s.

Marked changes in vertical migration of Capelin have been observed over the course of the time series, particularly between pre and post collapse periods. Vertical distribution of Capelin may impact detectability by acoustic survey techniques. Vertical distribution may also be linked to overall Capelin school density and the presence of predators (Mowbray 2002). Historically, Capelin underwent diel vertical migrations; however, starting in the spring of 1991, the pattern of vertical migration changed, with Capelin remaining deeper in the water column throughout the day (Mowbray 2002). Diel vertical migrations were observed again to some extent from 2011–15, but reverted to near bottom distributions again in 2017. In 2019 Capelin were distributed further off bottom than in recent years (Fig. 17).

Significant changes in the offshore Capelin abundance index have occurred during the past four decades (Fig. 18). The index dropped by more than an order of magnitude from 400–600 billion individuals (4–7 million t) in the late 1980s to between 3.4 and 30 billion individuals (<200,000 t) during the period of 1991 to 2005. Low abundances persisted since the early 2000s despite an increase in surveyed area from 2000 onward and a general warming in oceanographic conditions from 1995–2010 (Cyr et al. 2020). This persistent low abundance contrasts with previous hypotheses that the index collapse was related to changes in migrations patterns resulting from record cold oceanographic conditions as opposed to an actual decline in abundance (Buren et al 2019).

An initial post-collapse improvement in the Capelin abundance index occurred between 2007 and 2009 with the index improving slightly to 22–29 billion individuals (260,000–300,000 t), but fell again to less than 1% of the historic high in 2010 with only 2 billion fish (23,000 t) observed. The dramatic decline in Capelin in 2010 included a steep drop in the abundance index for 2 year classes (2007 and 2008), similar to the circumstances in the 1991 fall and spring acoustic surveys when the 1988 and 1989 year classes disappeared from the survey. The 2010 survey abundance index estimate is now considered to be an underestimate as the 2007 and 2008 year classes were stronger than expected in the subsequent 2011 spring acoustic survey. It should be noted that the within season trend in the length composition of spawners in 2010 was also anomalous (Fig.10) , which may indicate a change in the distribution or migration pattern in that year.

From 2013–15, the spring abundance index was at its highest levels since the 1980s , ranging from 53.6 to 121.9 billion individuals, with a peak in the abundance index in 2014. Since 2015, the Capelin abundance index has ranged from 18.5 to 32.1 billion individuals, levels similar to the 2000s. The abundance index in 2019 was 18.5 billion, which is 15% of the 2014 peak.

The offshore Capelin biomass index from the survey generally tracks the abundance index trend but exhibits greater variability due to inter-annual variations in the relative year class strengths of ages 2 and 3 Capelin, and consequently the mean weight of Capelin in a given strata. The biomass index for the offshore area in 2019 was 283,841 t, approximately 21% of the recent peak in biomass in 2014 (Fig. 18).

Abundance of Capelin in the surveyed inshore area (Trinity Bay) is generally less dynamic than the offshore and has at times shown contrasting trends. However, it cannot be established if this relationship was upheld during the recent abundance peak (2013–15) as Trinity Bay was not surveyed. In 2019, Capelin abundance in Trinity Bay (1.7 billion individuals) was 67% of that surveyed in 2018, although substantially higher abundance than observed in 2017 (0.3 billion) and similar to levels observed in the early 2000s.

FALL MULTISPECIES SURVEY

The fall bottom trawl survey occurs from September to December while Capelin are feeding in preparation for overwintering. During the fall, the 2J3KL Capelin stock tends to be distributed in the northern portion of their range, centered in 3K. However, in years of high abundance when age range is more extensive Capelin distributions expand into 2J. Fall 2019 Capelin distributions were compared with fall surveys in three years that were categorized as low (2009), medium (2006) and high recruitment (2013), based on the spring acoustic survey index the following spring (Fig. 19 and Fig. 20). Capelin in Fall 2019 were more dispersed and further south than any of the examples shown.

Buren et al. (2019) used a center of gravity (CG) analysis that accounted for both inertia (i.e., spatial dispersion of the population around its center of gravity) and changes in sampling effort (cf. Woillez et al. 2007). The CG trend in most decades was a pronounced shift along the north-south axis rather than the east-west axis, with an exception in the 2000s when there was a westward shift in the CG. From 2010–16, the CG was offshore with shifts along the north-south axis, similar to the CG of the late 1980s. In 2017 and 2018, the CG was orientated toward the inshore with a westward shift in distribution similar to what was observed in the 2000s. For 2019, the CG was again offshore and south, similar to other years with lower to moderate abundance. (Fig. 21).

ADULT SURVEYS BIOLOGICAL CHARACTERISTICS

AGE, MATURATION AND GROWTH

Capelin captured in the spring acoustic survey trawl sets range from 5 to 20 cm in length 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. In most years, age-2s account for the majority of the surveyed Capelin, with age-3s being the second most abundant age group. The trawls used to sample Capelin during the spring acoustic survey (Diamond IX: 1982–96 and Campelen: 1999-present) are biased against smaller sized fish – in particular, those less than 10 cm; this has resulted in a poor representation of age-1 (typically 5 to 8 cm total length in May) Capelin in the survey. However, ages 2+ Capelin are well sampled by both gear types (Mowbray, 2001). The number of age-1s sampled by the survey has been very low since 2015, while the age-2 index has been similar in magnitude to that of the late 2000s (Fig. 22). Age-3 Capelin comprised an unusually large proportion of Capelin surveyed in 2019. Most Capelin cohorts tracked well in the acoustic survey index, with the exception of the 2008 and 2009 cohorts which were notably underrepresented at ages 2 and 1 respectively in the 2010 survey (Fig. 23). The 2017 cohort (age-2s in 2019 survey) was only moderate in strength, and the 2018 cohort (age-1) appears weak.

The spring acoustic survey was designed to sample the immature, non-migratory portion of the Capelin stock; however, as a result of a decrease in age of maturation in the early 1990s, the proportion of maturing age-2 Capelin sampled during the spring acoustic survey has increased significantly since the survey's inception. (Fig. 24). Pre-1991, a period of high stock abundance, the proportion of Capelin maturing at age-2 was low (~4%) compared to post-1991 where ~40–80% of age-2 fish were maturing. In 2012–14, when the acoustic survey abundance index increased to 25% of pre-1991 values, the proportion of maturing age-2s declined to less than 40%. In 2017 and 2018, the proportion of maturing age-2s remained relatively low (~ 30%) even though the abundance index decreased to a level similar to the 2000s. The proportion of maturing age-2s in 2019 was the highest in the time series.

Younger age of maturation has been associated with decreased stock size in Barents Sea Capelin (reviewed in Gjøsæter 1998). Younger maturation is also associated with changes in Capelin growth, namely increased size at age for younger (age-1 and 2) Capelin and decreased size at age of older fish (Fig. 25). Observed changes in the rate of maturing age-2 fish in 2019 are consistent with size at age information (Fig. 26). Size of age-2 fish in 2019 was the second highest in the time series, while the size of older fish (4 and 5) were consistent with those observed during the last decade. In contrast, age-1 fish were small compared to recent years, similar to sizes observed in the early 2000s.

CONDITION, ROE CONTENT AND FEEDING

Le Cren's condition was estimated by first fitting a length-weight regression to the $\log_{10}$ transformed lengths and weights of male Capelin across the dataset (Le Cren 1951). The observed weight of each fish was then divided by its predicted weight given the observed length and the fitted length-weight regression equation. Seasonal condition was calculated for maturing female Capelin taken during the spring acoustic survey and for male Capelin taken during the fall multispecies survey. Maturing females were examined in the spring to investigate the relationship between spring condition and spawning time. Only male Capelin were examined in the fall as the effects of energy re-allocation to gonads and mixed spawning history can make interpreting female condition during the fall post-spawning season problematic.

Trends in Spring condition were similar among 3 size classes (12–13.99, 14–15.99, 16–17.99 cm) which roughly correspond to maturing female Capelin ages 2, 3 and 4. Spring condition in 2019 was lower than average and similar to condition trends exhibited since 2010 (Fig. 27). Fall condition of male age-1s and 2s were considered separately (Fig. 28). No male Capelin samples were available from Div. 2J in 2019. The relative condition index of age-1 males in Divisions 3K and 3L continues to be higher than average, whereas condition of age-2 fish in Div. 3K and 3L declined in 2019, approaching the long term average. Fewer fish were sampled in 2018 and 2019 than previous years due to lower catches.

FEEDING - SPRING AND FALL

Stomach fullness is recorded using a scaler value of 0–4, where 0 is empty, 1 is ¼ full, 2 is ½ full, 3 is ¾ full, and 4 is full. The proportion of empty stomachs has decreased in the spring for the last four years and in the fall for the last three years (Fig. 29). In 2019, the proportion of ¼ full stomachs increased and full stomachs decreased. Changes in prey composition and relative abundance of various prey types needs to be investigated in order to understand the reason for these changes.

FORECAST MODEL

A Capelin forecast model (Lewis et al. 2019) was used to predict the Capelin biomass for the 2020 spring acoustic survey and to provide a partial forecast for the 2021 spring acoustic survey. The model builds on two prior Capelin models (Buren et al. 2014, 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 indices used in this Capelin forecast model are the Bellevue Beach larval index, DOY of the most southerly position of contiguous sea ice (sea ice retreat; t_{ice}) which is related to the annual spring plankton bloom, and fall condition index of adult 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 effect Capelin biomass for the specific forecast year.

The 2020 forecast is based on the 2018 larval index (a 2-year lag), 2019 adult fall condition index (a 1-year lag), and t_{ice} in 2020 (no lag). The 2021 partial forecast is based on the 2019 larval index (2-year lag), and the average values for the adult fall condition index and t_{ice}. The 80% prediction interval for the 2020 spring acoustic survey biomass index ranges from 59.0 to 341 kt with a median estimate of 144 kt (Fig. 30). The partial forecast for 2021 suggests that the biomass index for 2021 will be similar to that of 2020. The 2021 partial Capelin forecast will be updated at the next assessment, after the required data becomes available.

CONCLUSIONS

The acoustic abundance index declined slightly from 2018 to 2019. Current Capelin abundance levels are typical of those found during the late 2000s and constitutes only 15% of the abundance (20% of the biomass) observed during the post-collapse (1990–91) high observed in 2014 (Fig. 19). The Capelin age composition from the spring acoustic survey was similar to the age composition of the spawners captured in the commercial fishery. Patterns in Capelin distribution, growth and maturation were consistent with the interpretation that the cohorts surveyed are weak (2018) to moderate (2017) in strength. The high proportion of maturing age-2 fish suggests that few age-3 Capelin will be present in the stock next year. This finding is consistent with the southerly distribution of Capelin, as northerly distributions are linked to a higher percentage of immature or surviving age-2 and 3 fish. The larval index has indicated poor production for the last 5 years. However, feeding success has improved moderately in the last

3–4 years, possibly leading to an improvement in post larval survival. The forecast model predicts that Capelin biomass in the 2020 spring acoustic survey will likely decline from 2019, to levels similar to those seen in 2017. Capelin and shrimp are key forage species in the ecosystem. The increases in groundfish observed in the late-2000s and early-2010s appear associated with bottom-up processes, including an improved prey field, with modest increases in Capelin availability in comparison with the 1990s. More recent declines in total finfish biomass may be associated with simultaneous reductions in Capelin and shrimp availability.

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.

Larval productivity in the Bellevue Beach inshore area may not be representative of larval production in other bays although previous work showed a correlation between Bellevue Beach and other bays.

Three bottom-up drivers of Capelin recruitment and survival have been identified and are being used in a Capelin forecast model; however, there is unexplained variability in the model and the influence of top-down processes on the Capelin stock have not been investigated.

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APPENDIX I: FIGURES

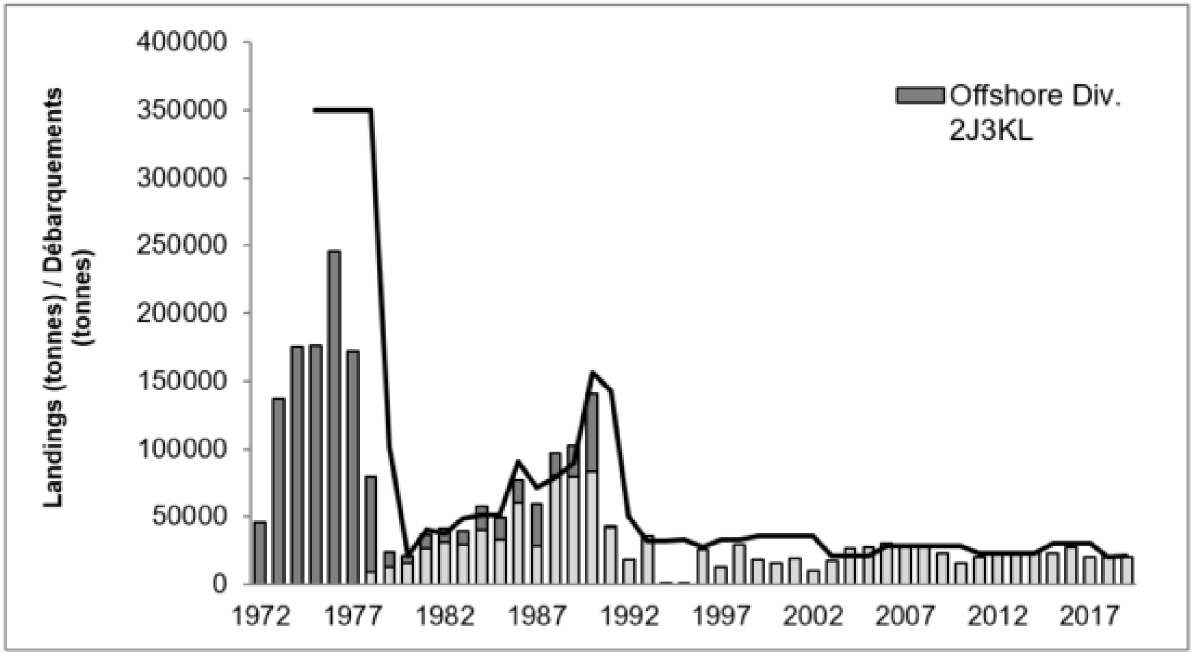
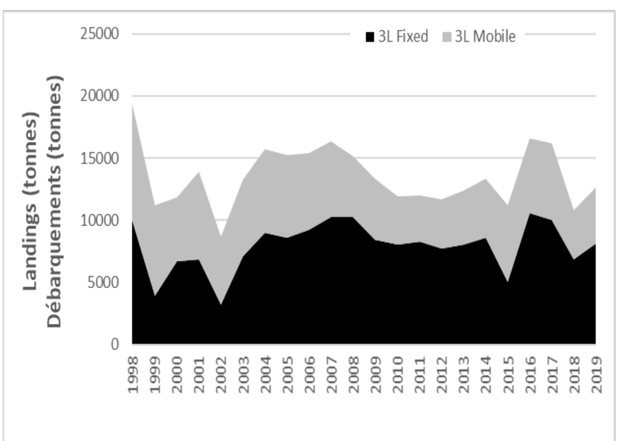


Figure 1: Capelin landings (tonnes) in NAFO Divisions 2J3KL from offshore (dark bars) and inshore (light bars) gear sectors from 1972–2019. Solid line indicates total Capelin TAC for the combined sectors.*
**2017–19 landings preliminary.*



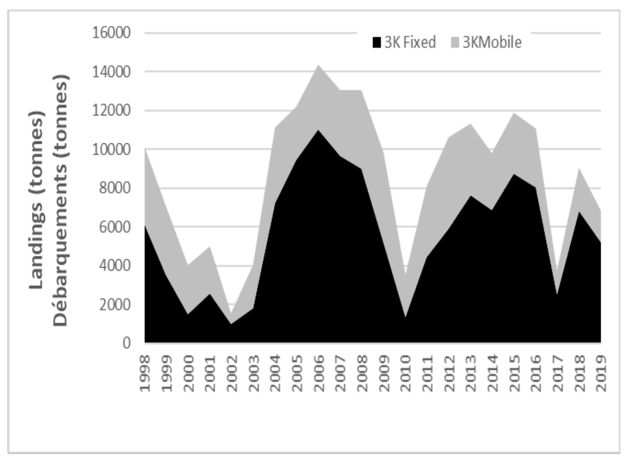


Figure 2: Inshore commercial Capelin landings by NAFO division and gear sector from 1998–2019.*
**2016–19 landings considered preliminary.*

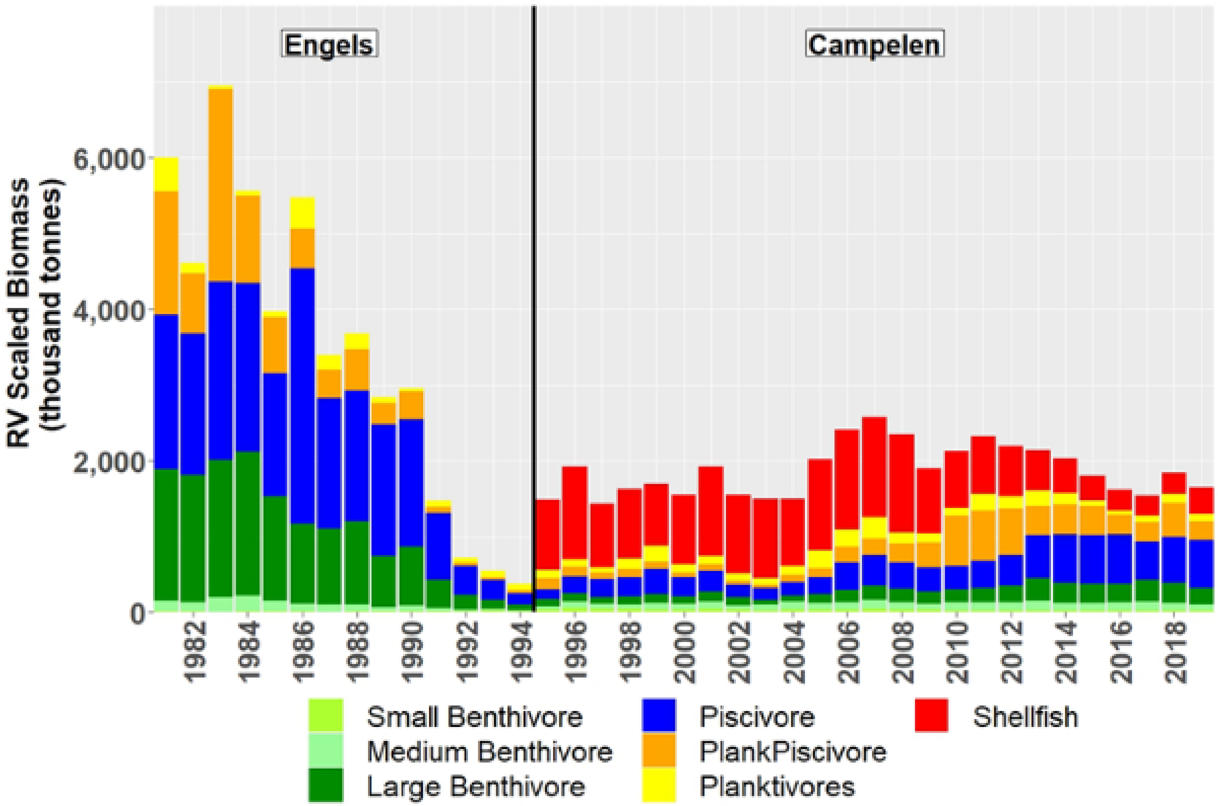


Figure 3: Total RV Biomass index trend of the fish community in the Newfoundland Shelf and northern Grand Bank (Divs. 2J3KL) discriminated by fish functional groups. Indices for the Engel period have been scaled to be comparable to the Campelen series (Koen-Alonso and Cuff 2018). Shellfish data were not consistently collected during the Engel period; the index for this functional group is not available prior to 1995.

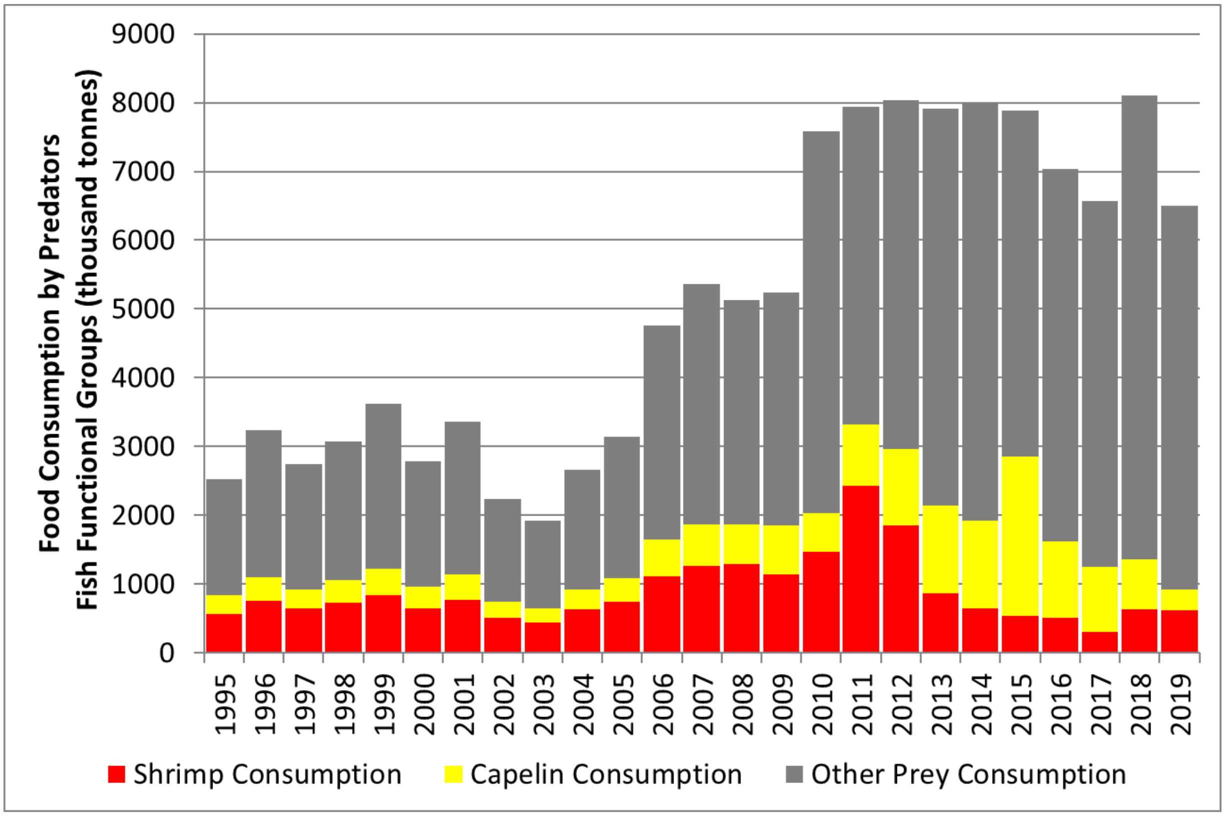


Figure 4: Estimated magnitude of consumption of Capelin, Shrimp, and other prey by the fish functional groups considered predators of these key forage species (i.e., medium, and large benthivores, plankpiscivores, and piscivores) from 1995–2019. The estimated magnitudes of consumption are based on a suite of model estimates of total food consumption/requirements and stomach contents data of key groundfish species sampled during the fall RV survey.

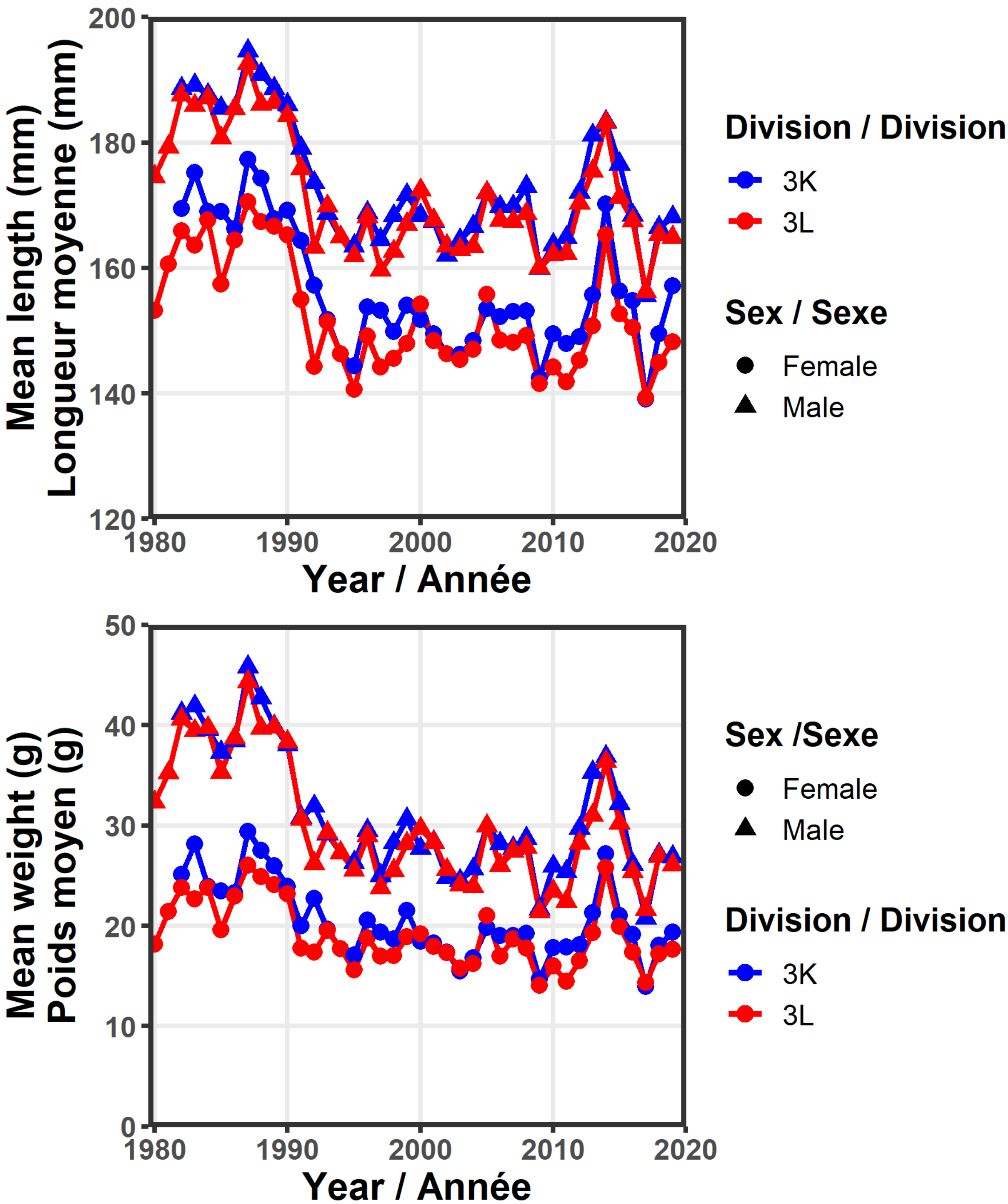


Figure 5: Mean length and weight of Capelin caught in NAFO Divisions 3K and 3L in inshore commercial fisheries from 1980–2019.

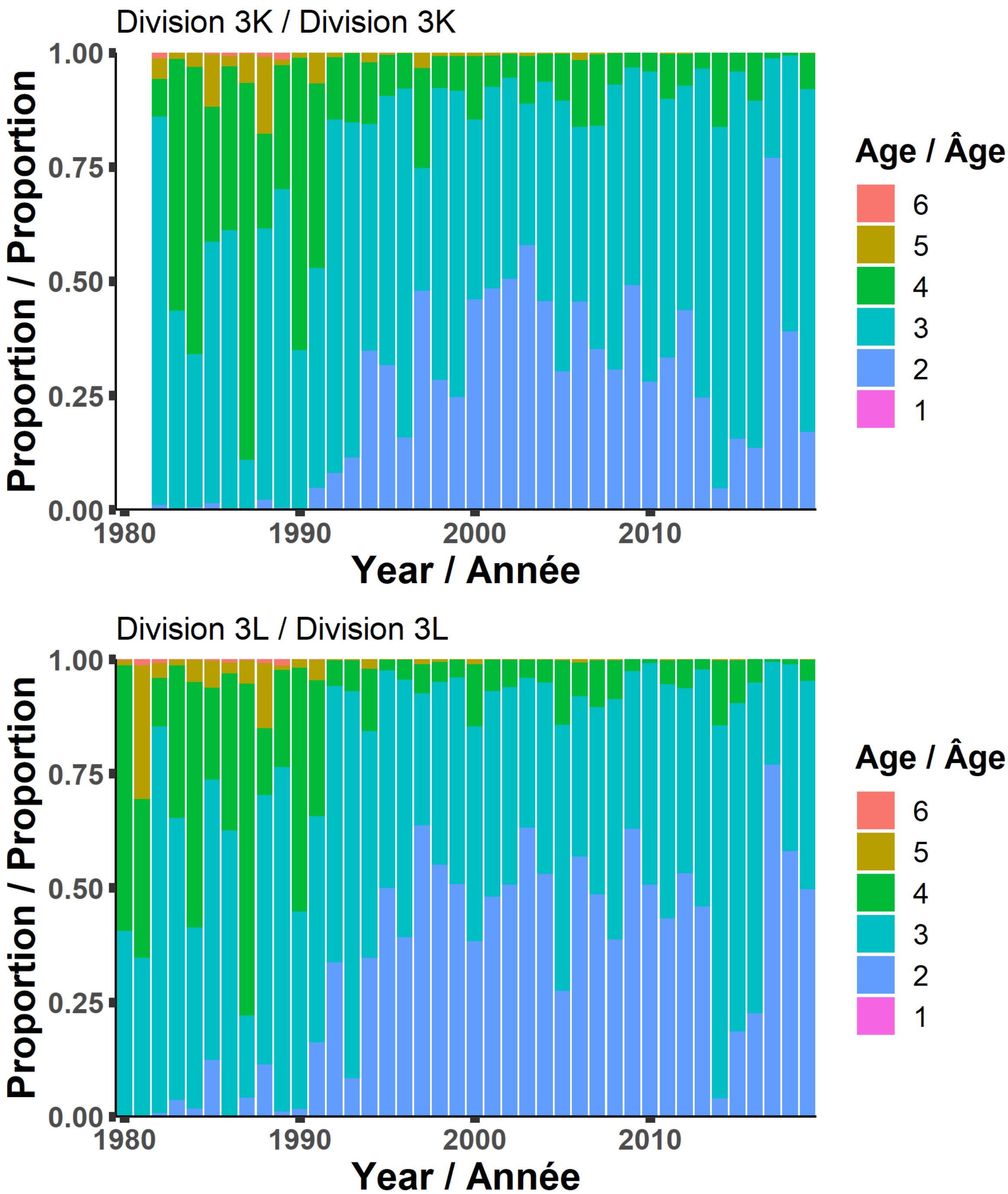


Figure 6: Age composition of samples collected from inshore commercial fisheries in NAFO Divisions 3K (top panel; 1982–2019) and 3L (lower panel;1980–2019).

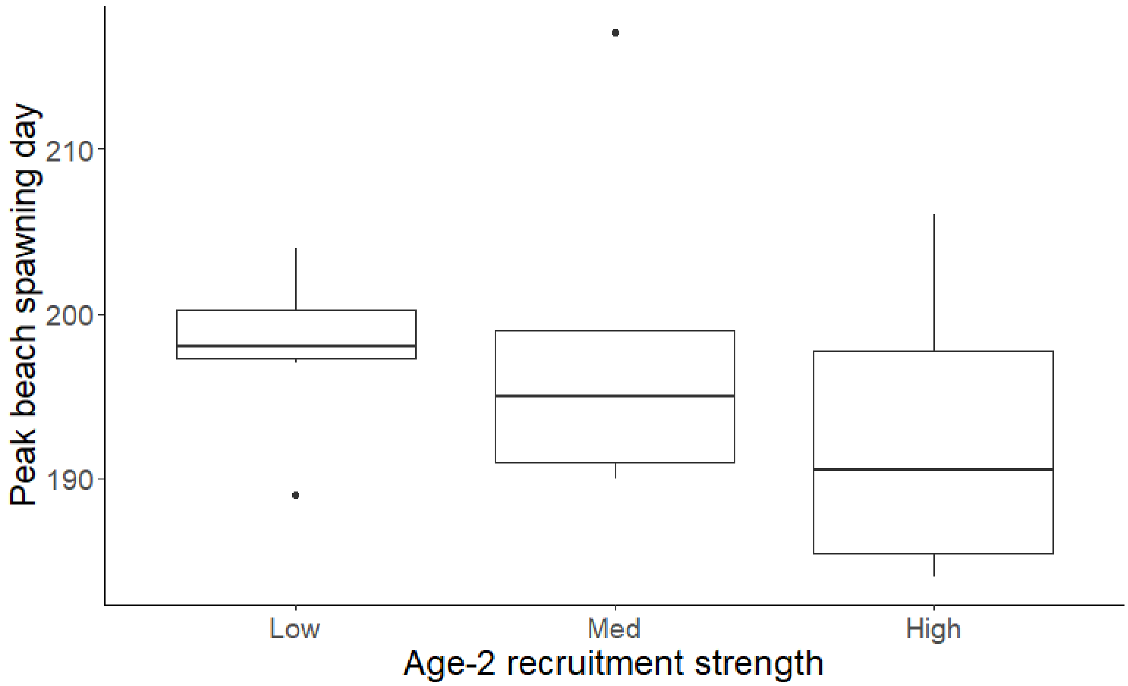


Figure 7: The relationship between peak beach spawning day at Bellevue Beach, Trinity Bay and age-2 recruitment strength from the spring acoustic survey suggests earlier spawning is beneficial for year-class (recruitment) strength. Low: <10 billion individuals; medium (med): 10–20 billion individuals; and high: >20 billion individuals.

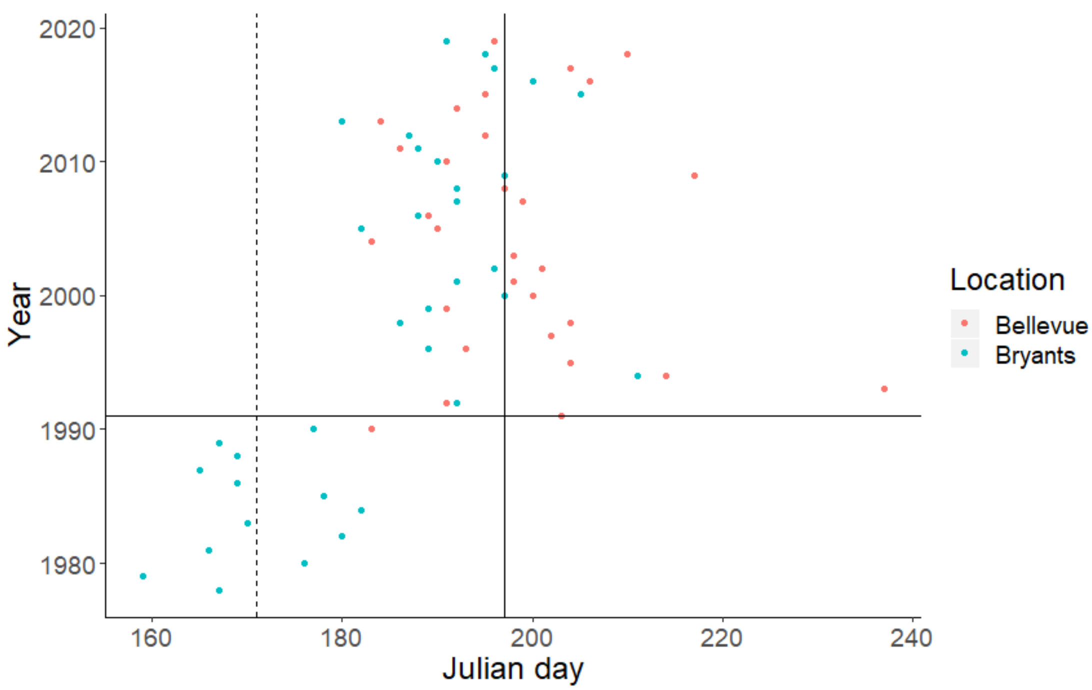


Figure 8: Peak spawning times at Bryant's Cove, Conception Bay (1972–2019) and Bellevue Beach, Trinity Bay (1990–2019) determined by citizen science (spawning diaries) and scientific monitoring. The horizontal line is 1991, approximately the timing of collapse in the Capelin population. The vertical dashed black line is the average spawning day pre-1991 and the vertical solid black line is the average spawning day post-1990.

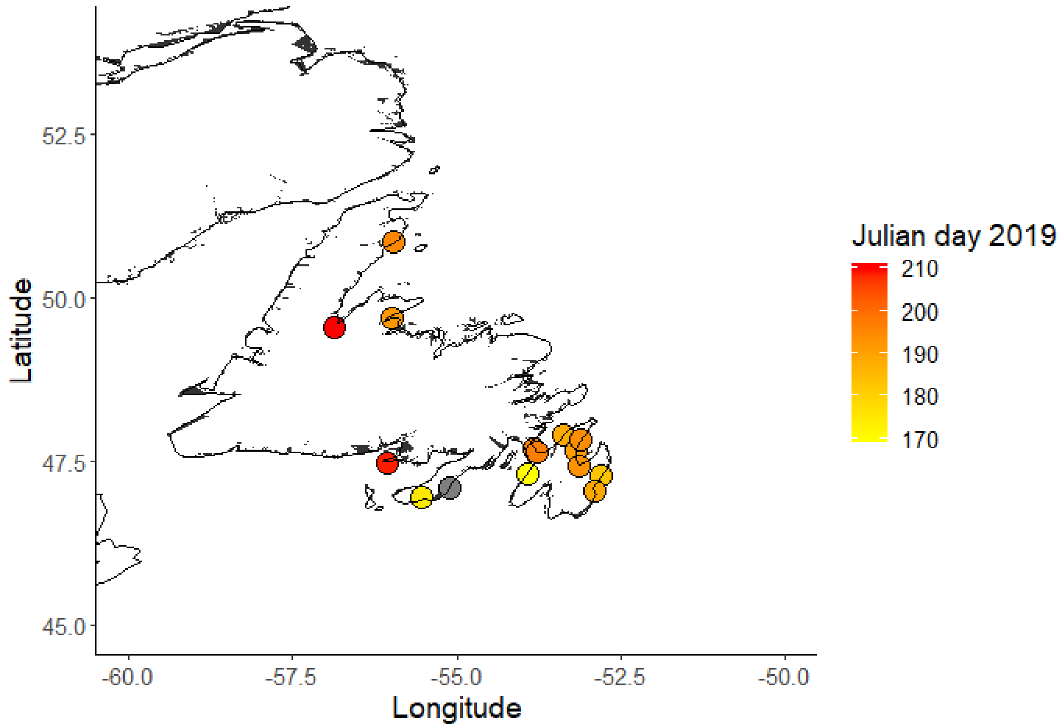


Figure 9: Timing of Capelin peak beach spawning monitored by citizen scientists in 2019.

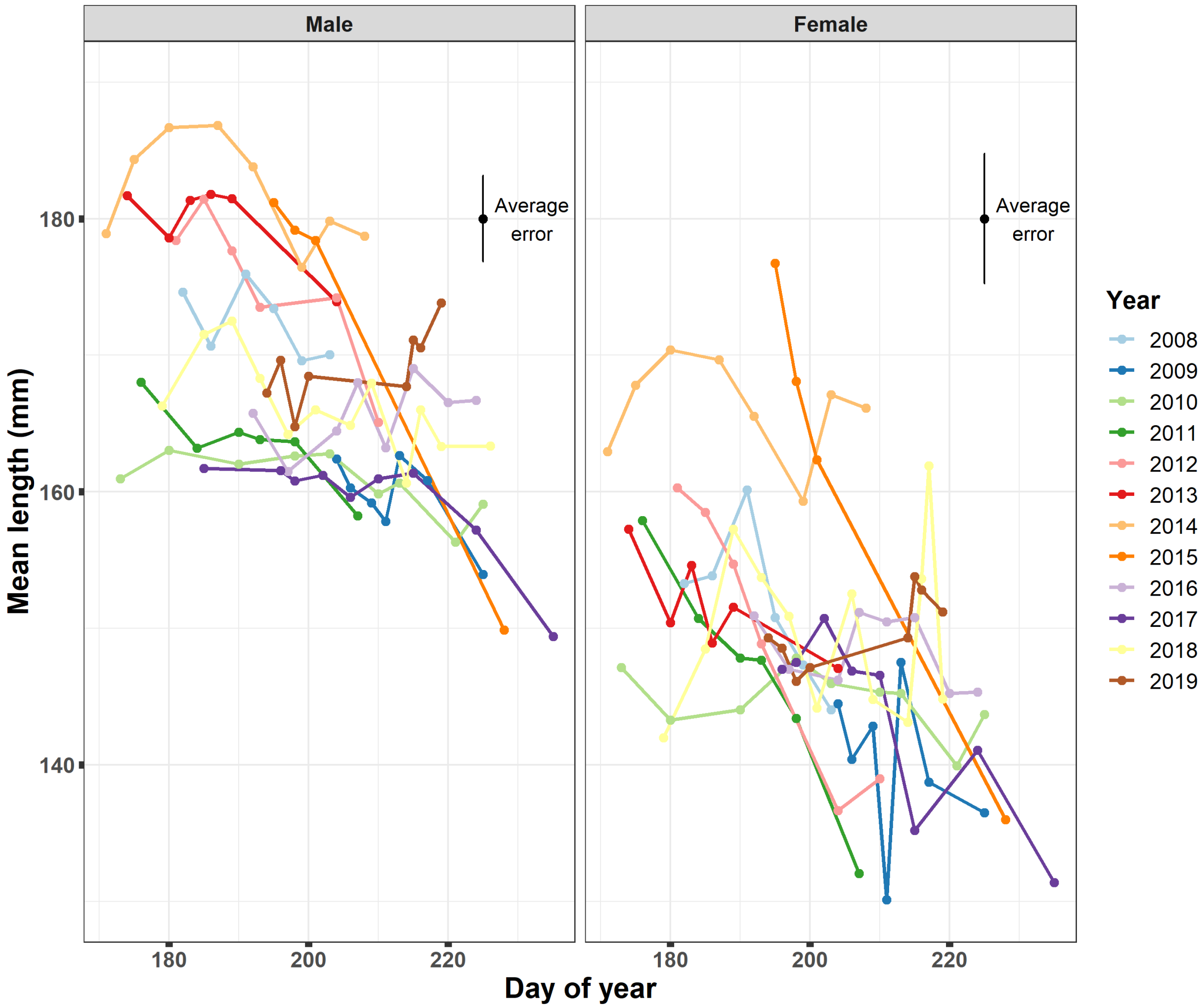


Figure 10: Mean length of Capelin arriving for spawning at seven monitored beaches on the Avalon Peninsula, three north of St. John's (Middle, Outer and Torbay), one in Conception Bay (Chapel's) and three near Bellevue, Trinity Bay (not all beaches are sampled in all years).

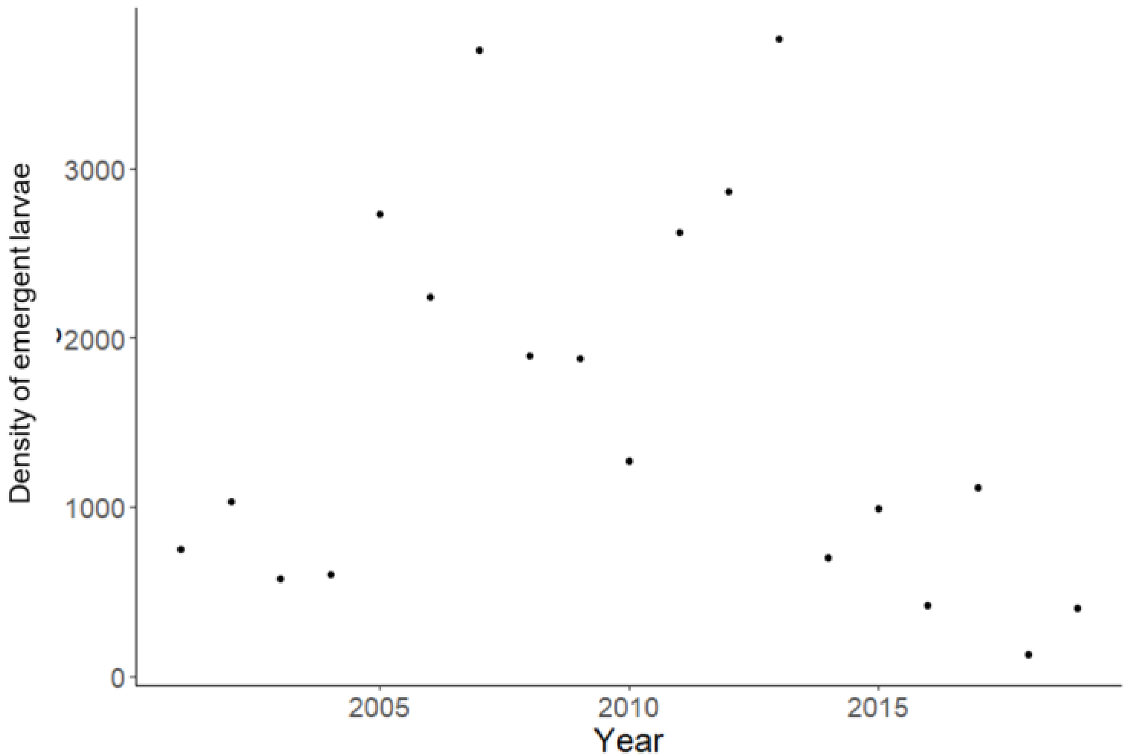


Figure 11: Annual emergent larval densities (ind. m^{-3}) from surface tows at Bellevue Beach, Trinity Bay (2001–19).

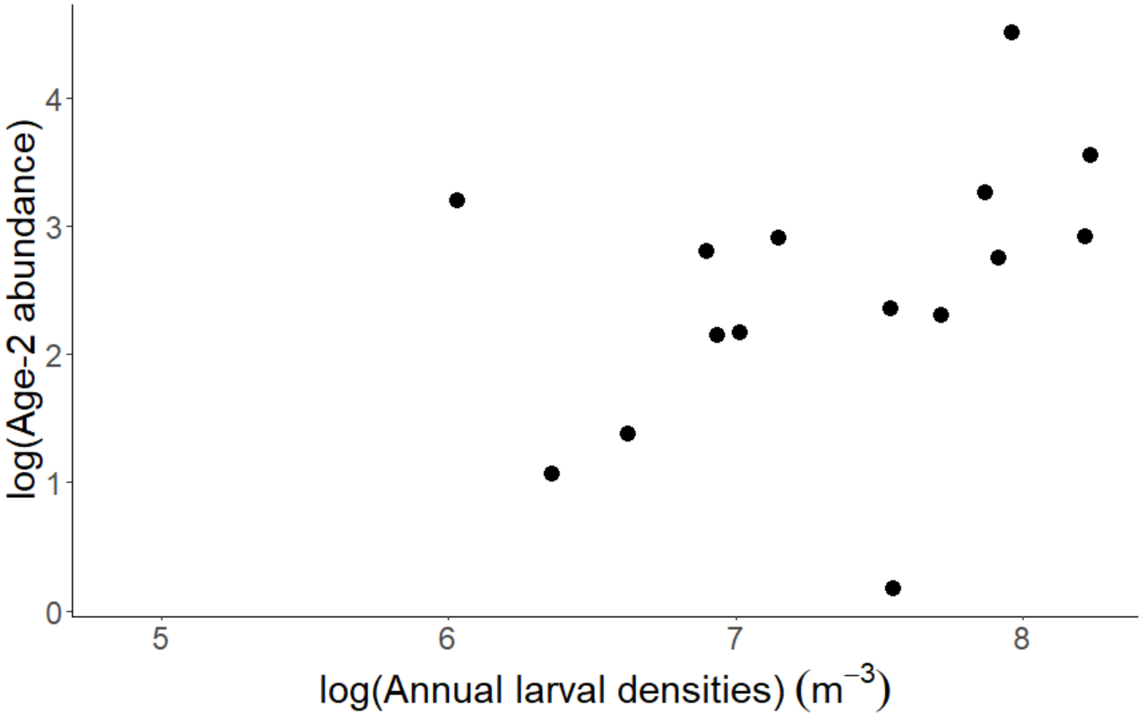


Figure 12: The relationship between the emergent larval and the age-2 recruitment indices is non-significant (p = 0.161) when additional years were added to the relationship (2014–19). The age-2 recruitment index was lagged by two years to compare cohorts from the same year classes.

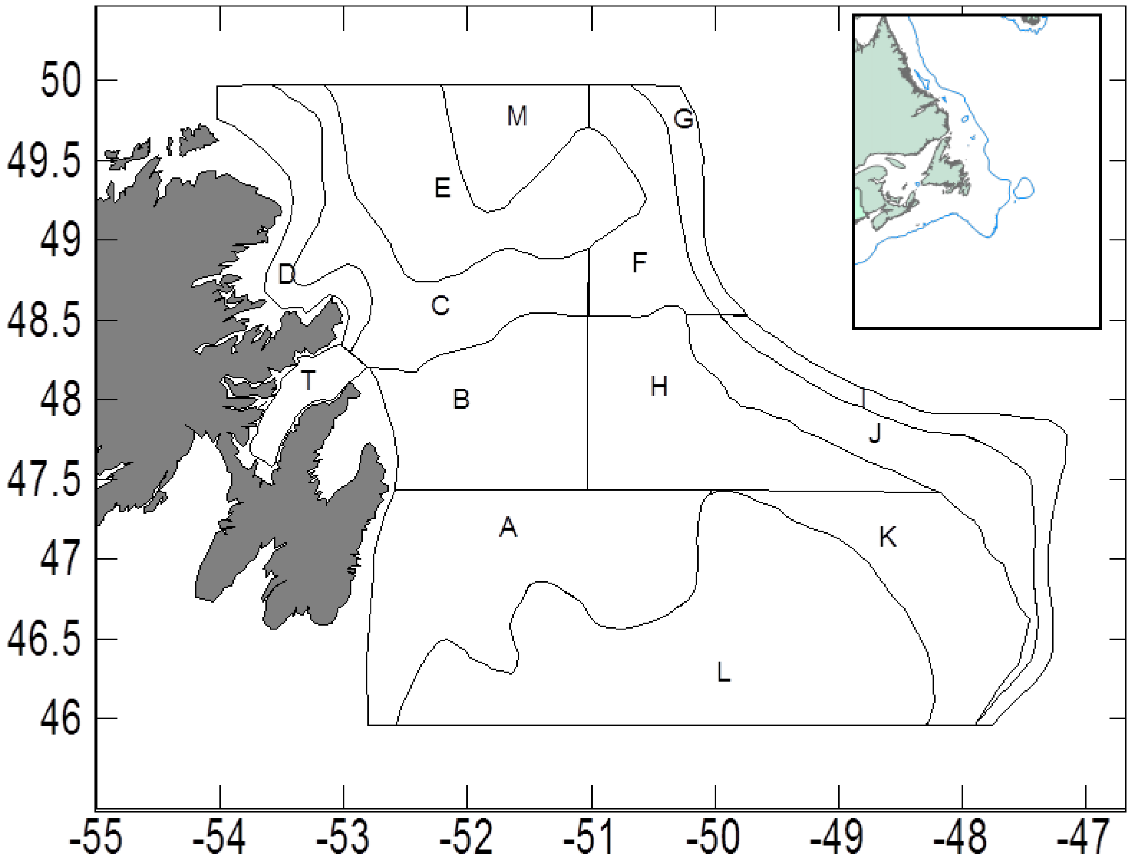


Figure 13: Map of survey area showing boundaries of depth-delimited strata used in the spring Capelin acoustic survey since 1999.

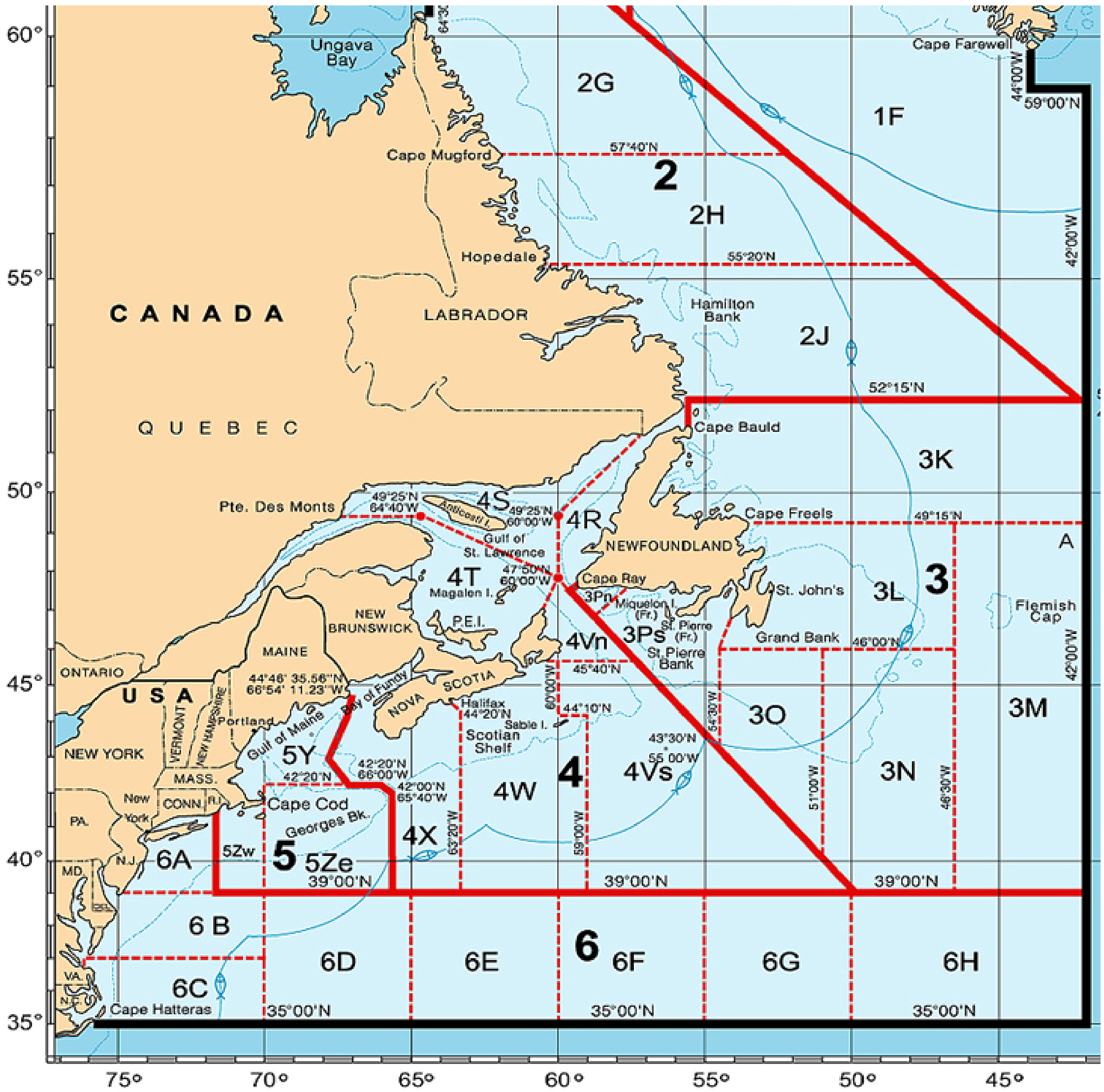


Figure 14: Map of NAFO divisions 2J3KLNO.

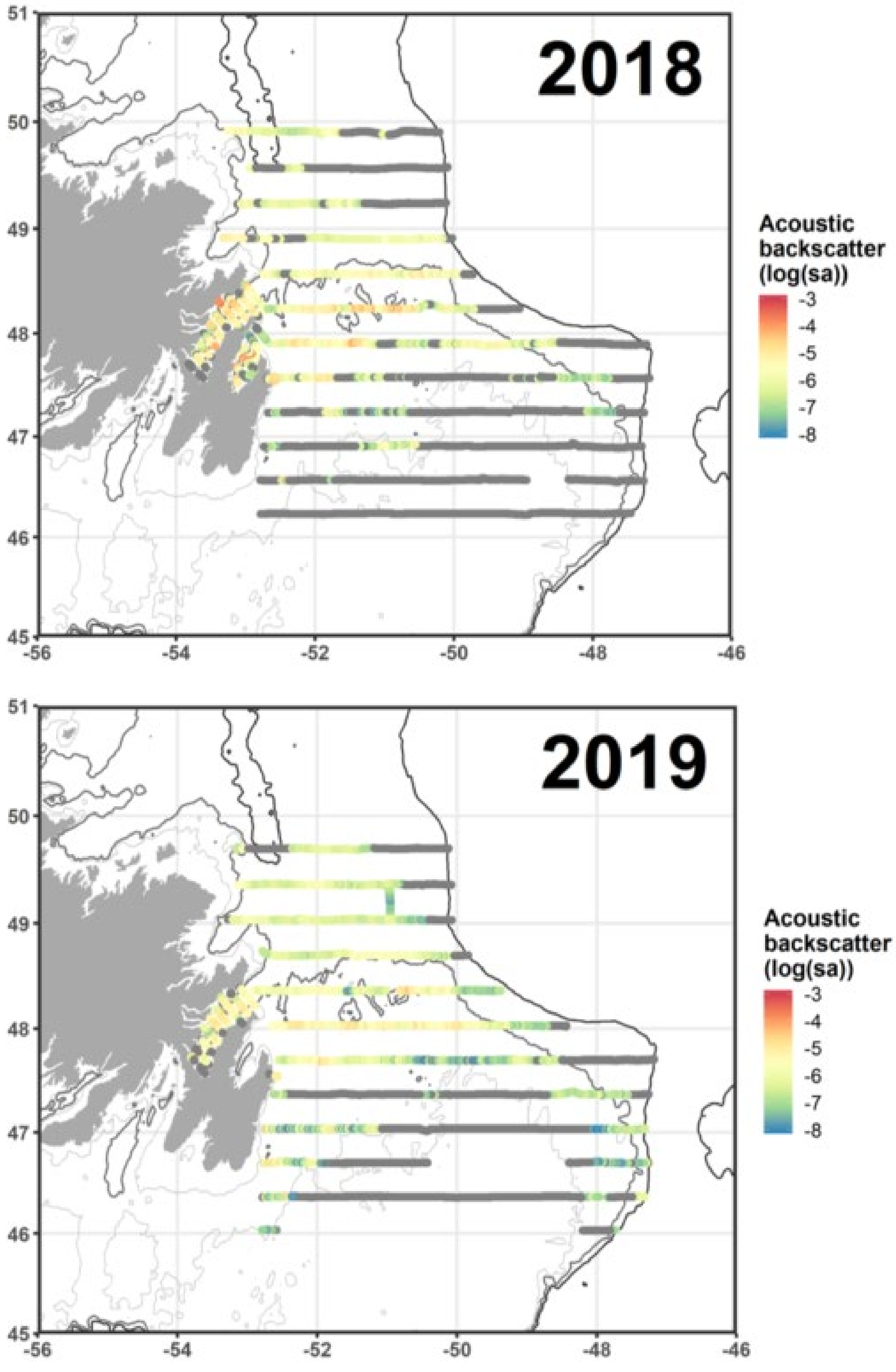


Figure 15: Distribution and intensity of Capelin backscatter during the 2018 and 2019 spring acoustic surveys (blue is low intensity and red is high).

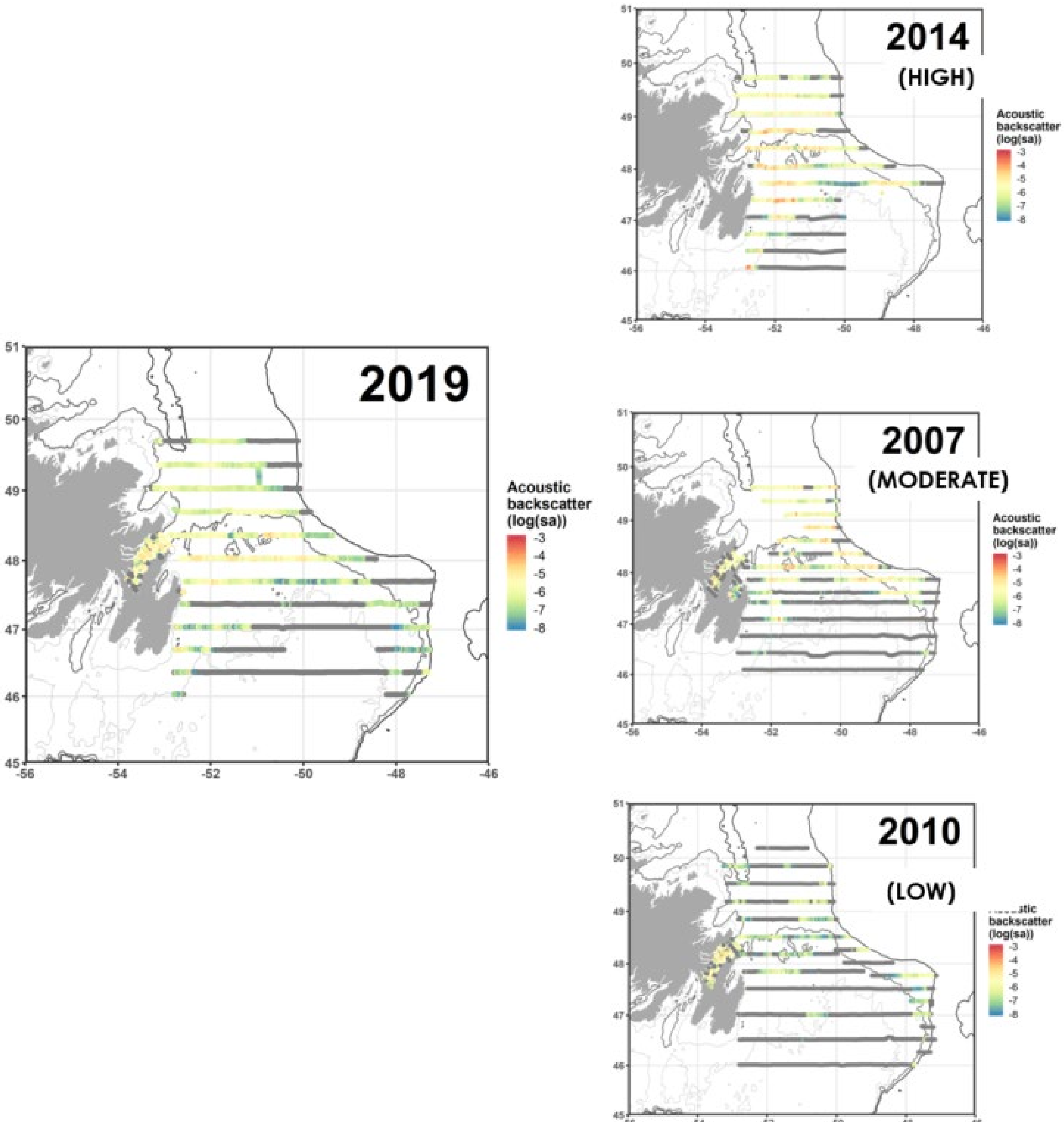


Figure 16: Distribution and intensity of Capelin backscatter during the 2019 spring acoustic surveys relative to years of low (2010), medium (2007) and high (2014) abundance.

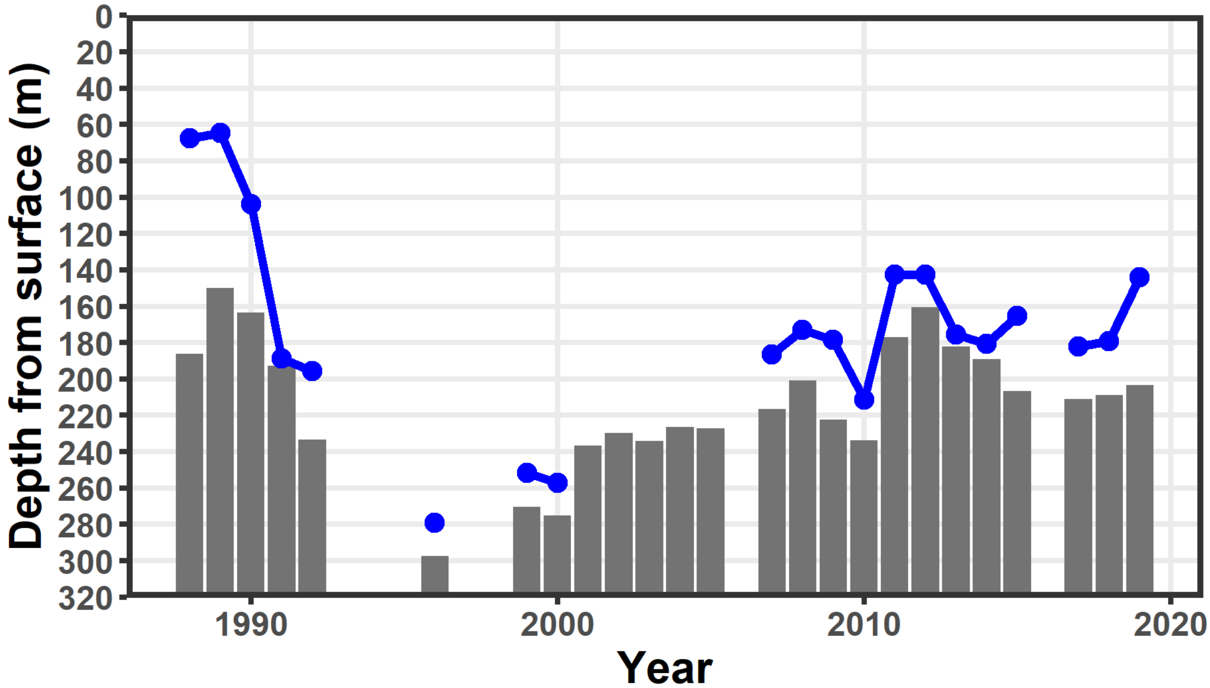
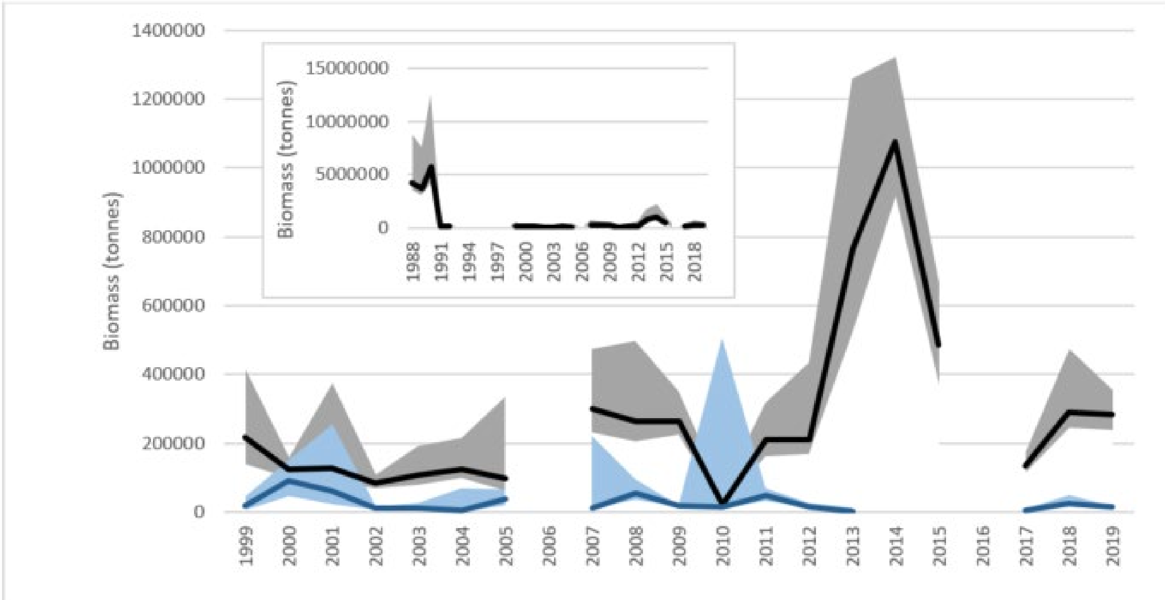


Figure 17: Annual mean bottom depth (bars) of areas occupied by Capelin and the mean depth of Capelin backscatter during spring acoustic surveys from 1988–2019. Both values are weighted by the total backscatter of Capelin in the water column in each integration bin.



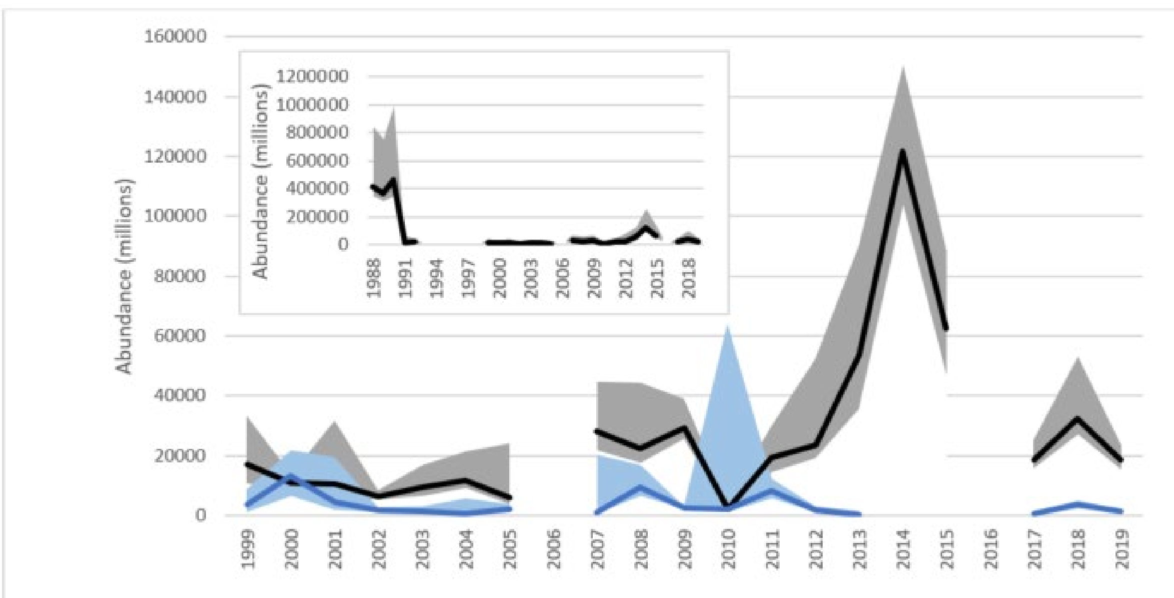


Figure 18: Index of estimated biomass (top) and abundance (bottom) of Capelin from the spring acoustic survey in the offshore area. Shaded areas give upper and lower confidence limits, insets show post-collapse period (post 1990). Grey lines and shaded area are from the offshore index, blue are estimates from Trinity Bay.

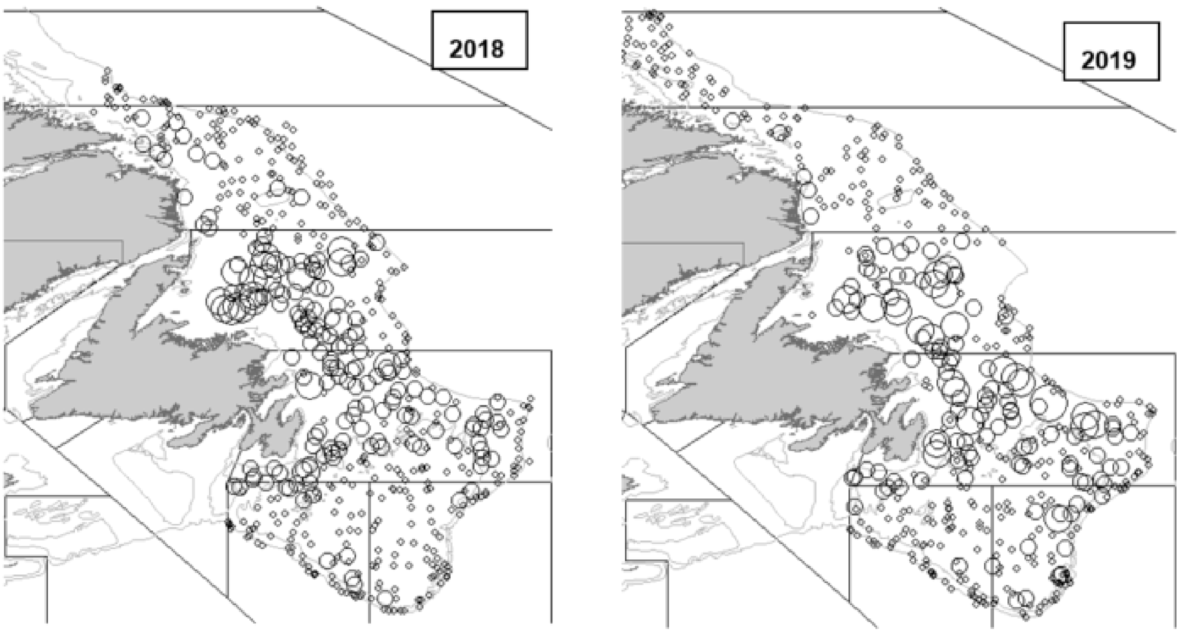


Figure 19: Distribution of Capelin catch from the 2018 and 2019 fall (October – December) bottom trawl survey. Circle sizes are proportional to the weight of Capelin caught in standardised 15 minute bottom tows. Five levels of catch weight are plotted: 0, 0.01–1, 1.01–10.00, 10.01–100.00, 100.01–1,000.00, 1,000.01–10,000.

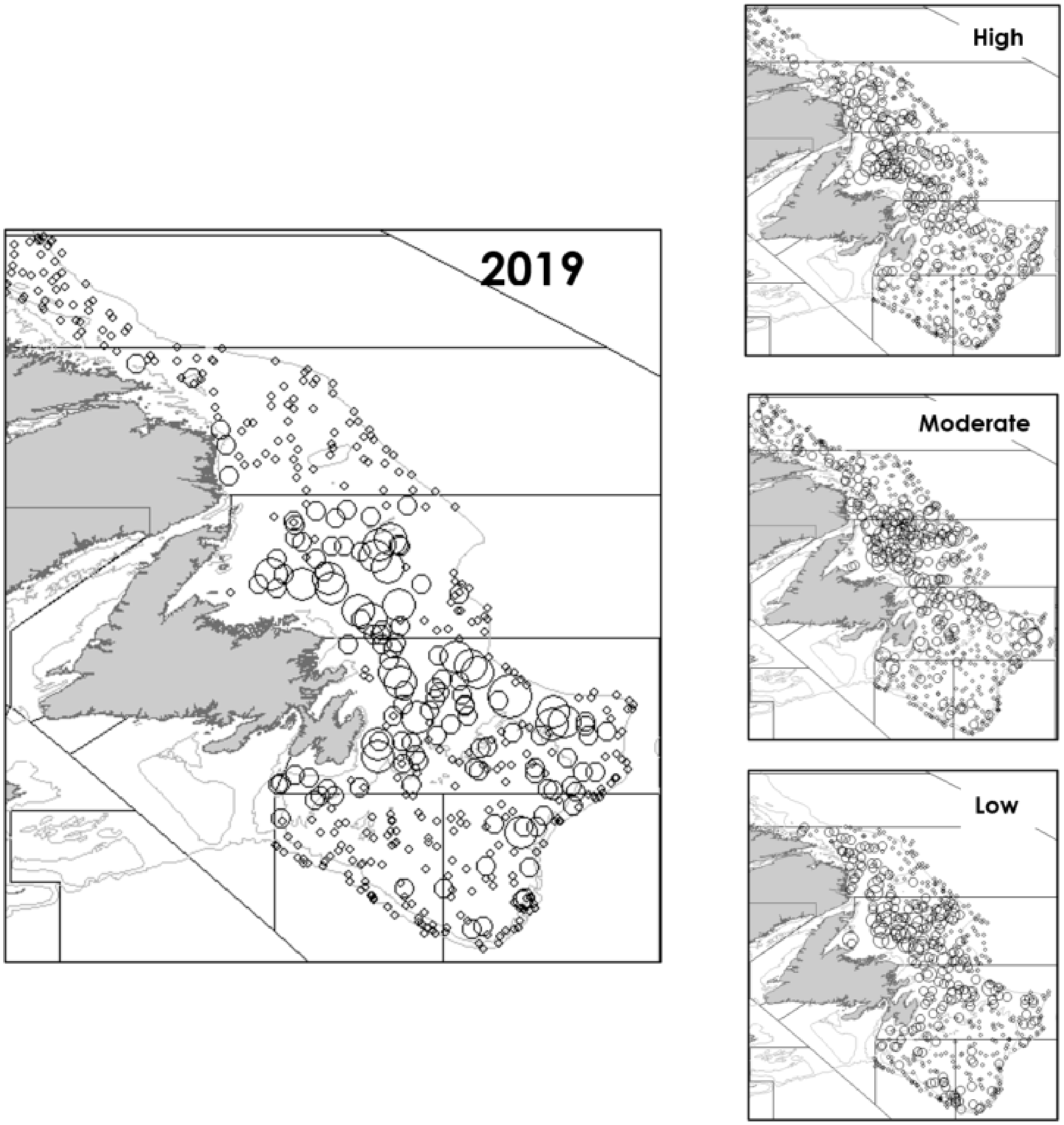


Figure 20: Distribution of Capelin catch from the 2019 fall (October – December) bottom trawl survey contrasted with observed distributions in periods of high, moderate, and low abundance. Circles sizes are proportional to the weight of Capelin caught in standardised 15 minute bottom tows. Five levels of catch weight are plotted: 0, 0.01–1, 1.01–10.00, 10.01–100.00, 100.01–1,000.00, 1,000.01–10,000).

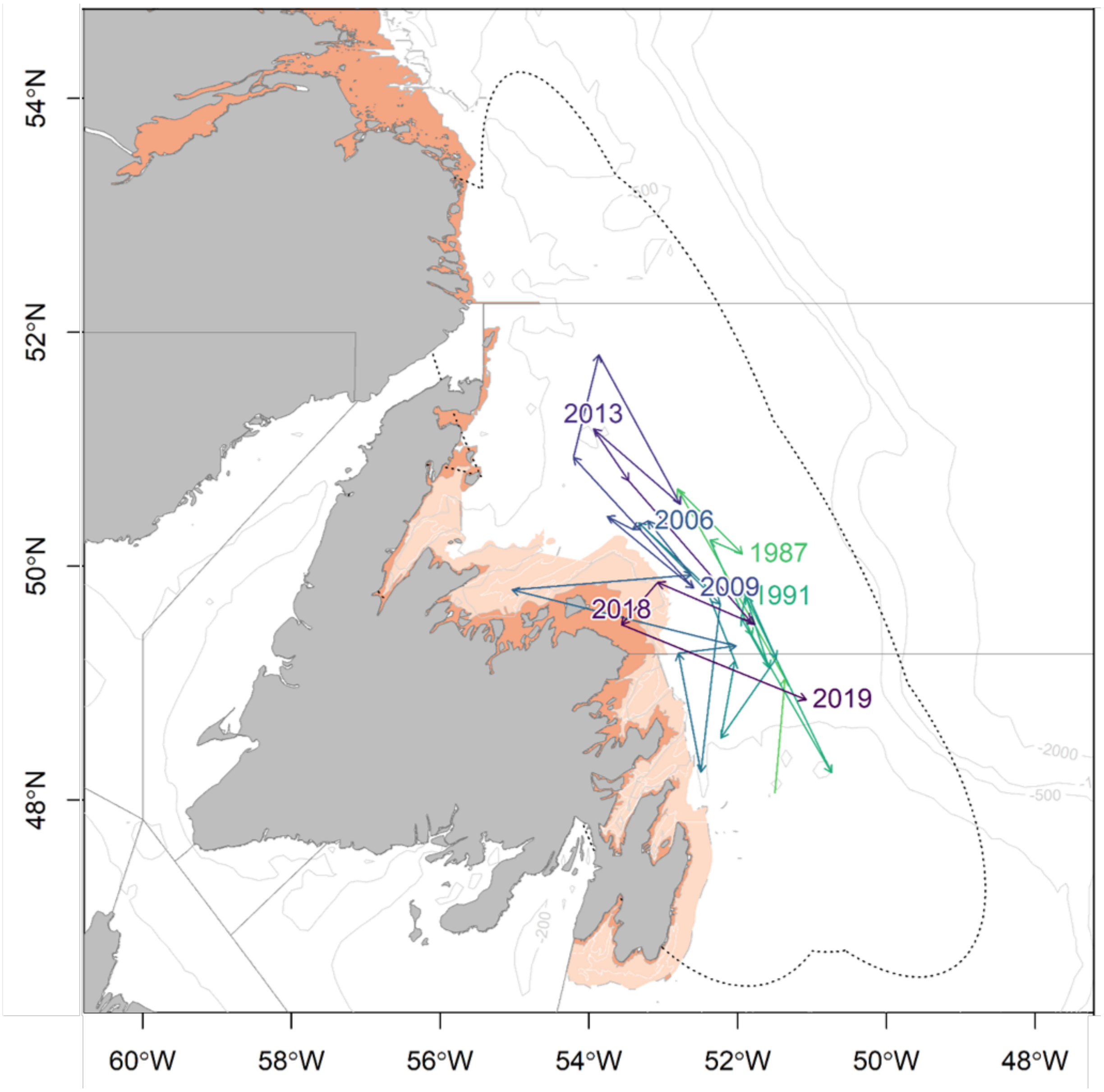
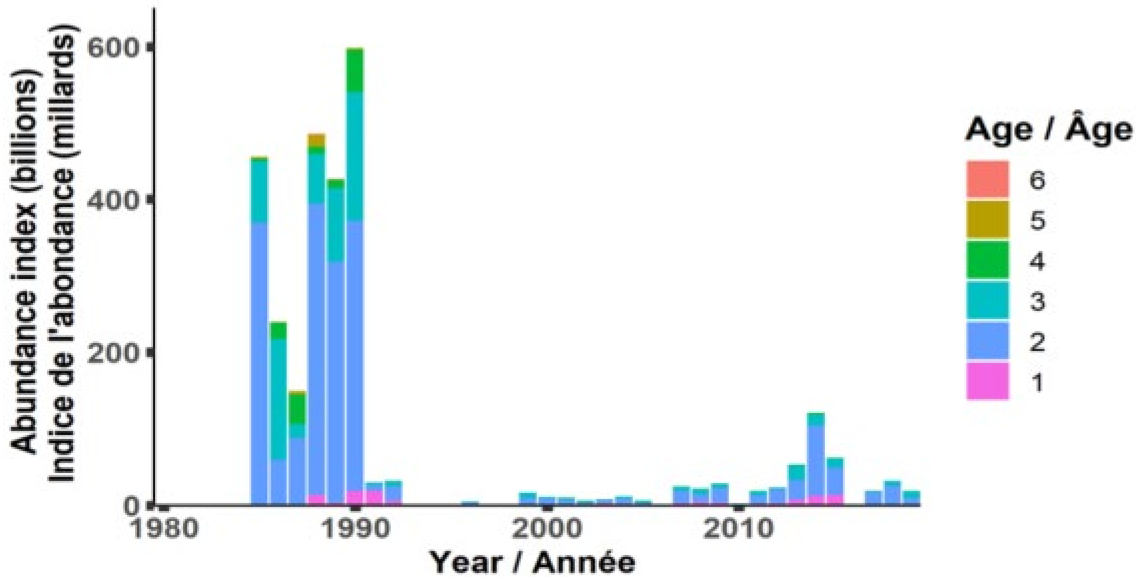


Figure 21: Center of gravity of Capelin from the fall bottom trawl surveys in NAFO Divisions 2J3KL from 1983–2019 (updated from Buren et al. 2019). Annual center of gravity estimates are connected by lines through time, and composite ellipses of deviation around these estimates (i.e., inertia) are indicated by the dotted black line. Center of gravity and inertia were calculated using equations found in Woillez et al. (2007). The red area indicates areas not covered by the survey and the light pink area indicates inshore strata that are poorly covered by the fall bottom-trawl survey.



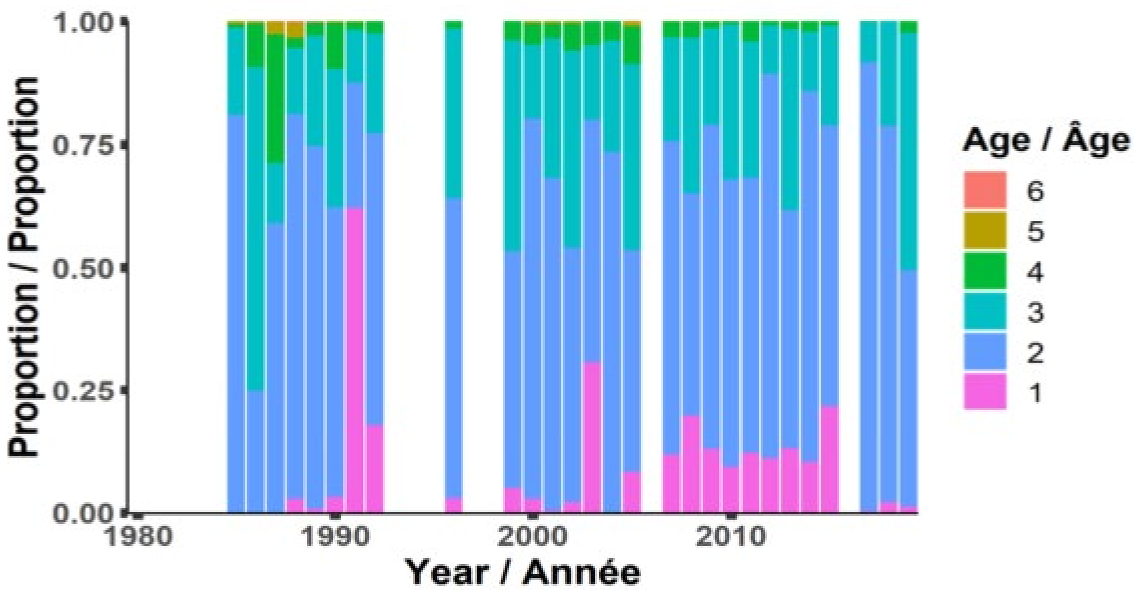


Figure 22: Age distribution of Capelin sampled during the spring acoustic survey by number (upper) and proportion (lower) 1985–2019.

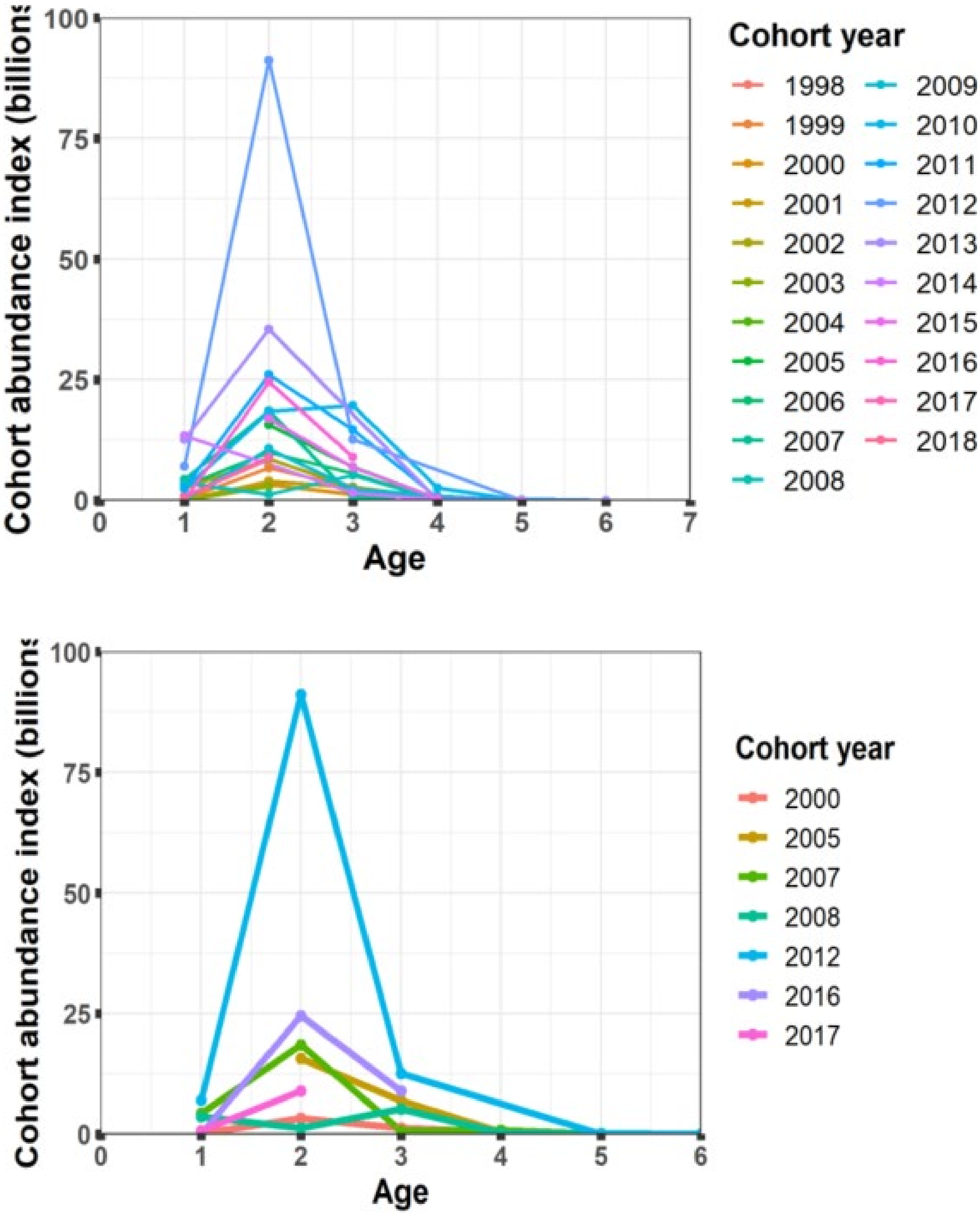


Figure 23: Cohort strength (abundance) of Capelin in spring acoustic surveys conducted between 1999 and 2019 (upper panel). Lower panel presents the most recent cohort (2017), and selected others which deviated from the typical pattern.

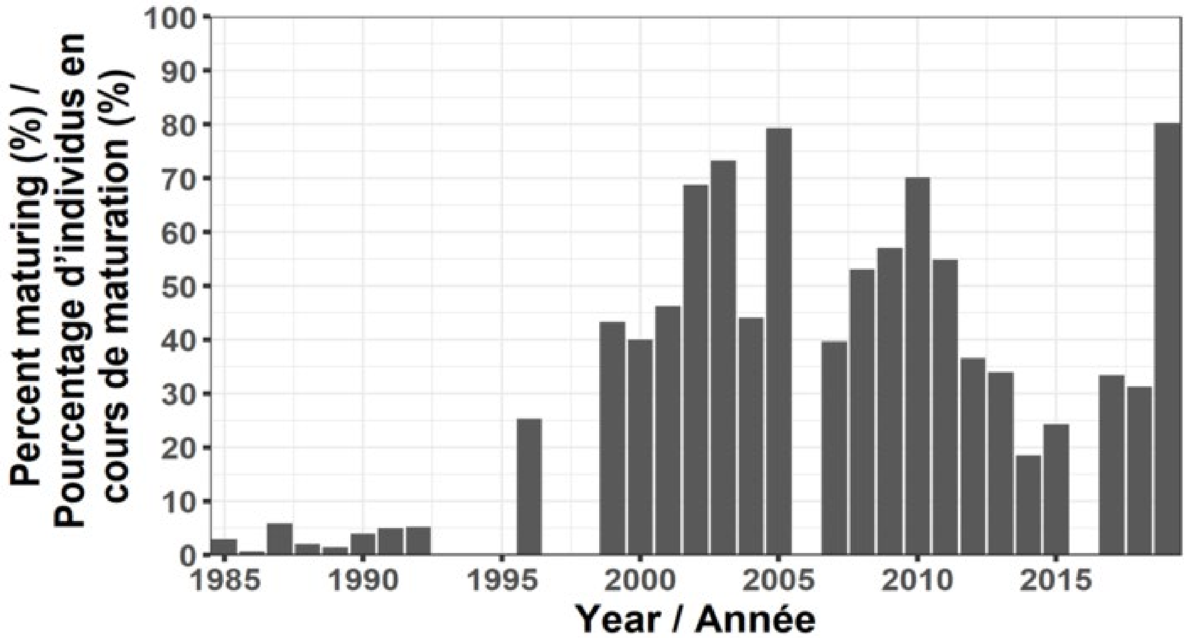


Figure 24: Proportion of age-2 Capelin sampled during the spring acoustic survey that were maturing (1985–2019

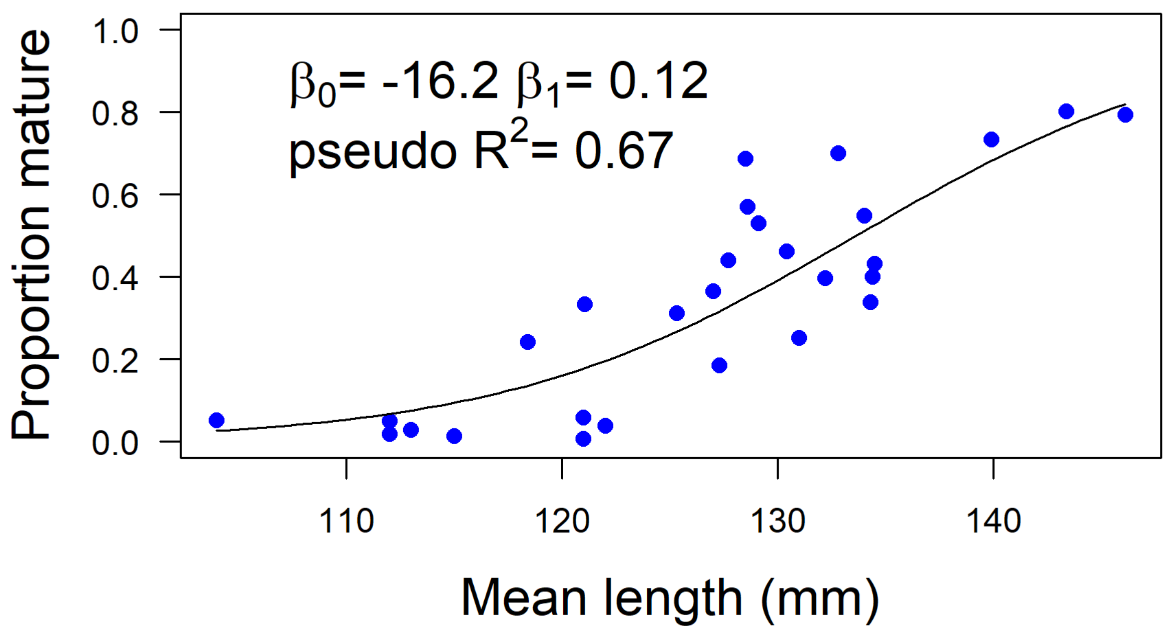


Figure 25: A comparison of mean length of age-2 Capelin from the spring acoustic survey to the proportion of age-2 Capelin that were mature (1985–2019). The beta regression fitted between mean length and proportion mature (solid line) has a pseudo R^2 = 0.67.

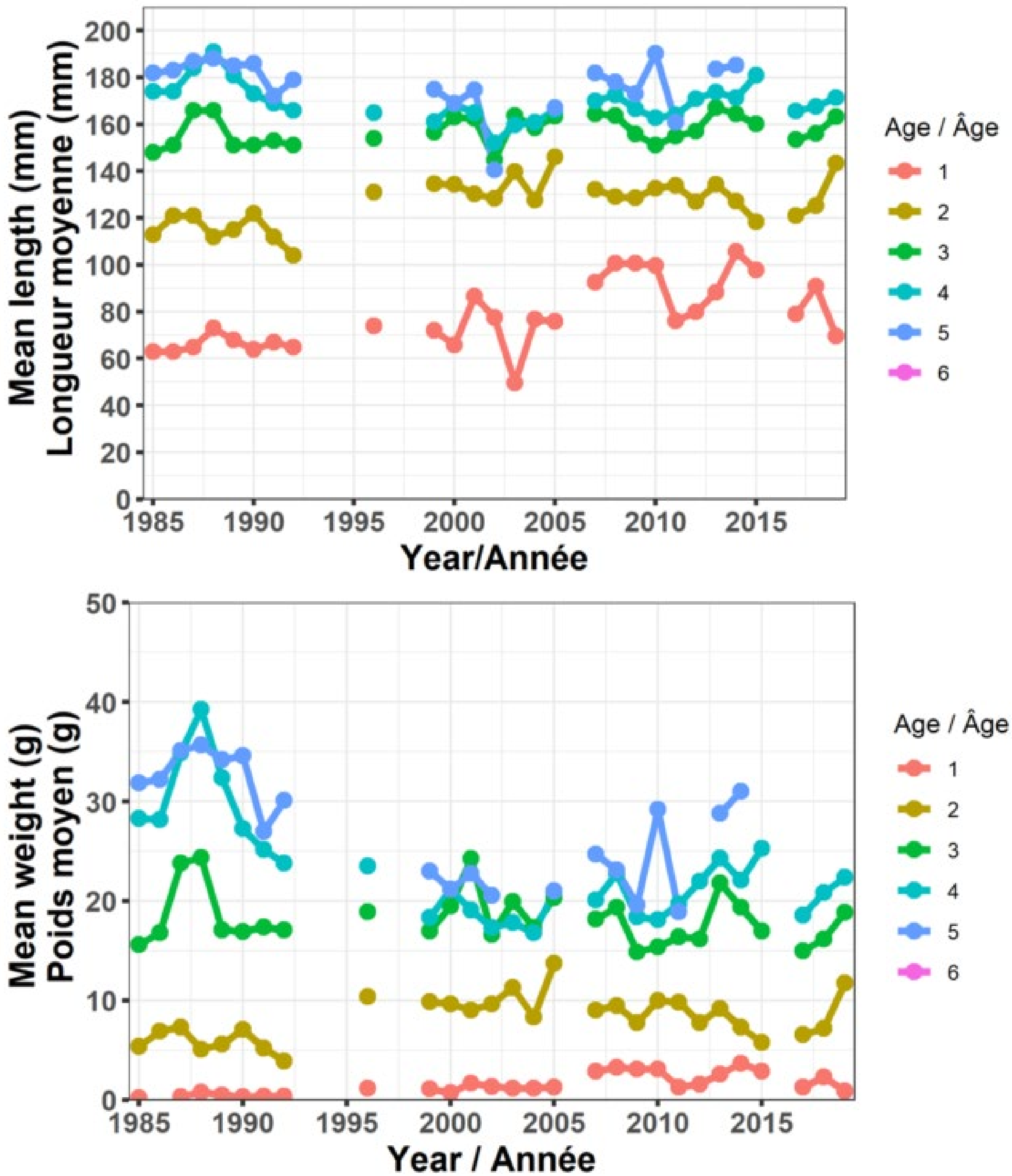
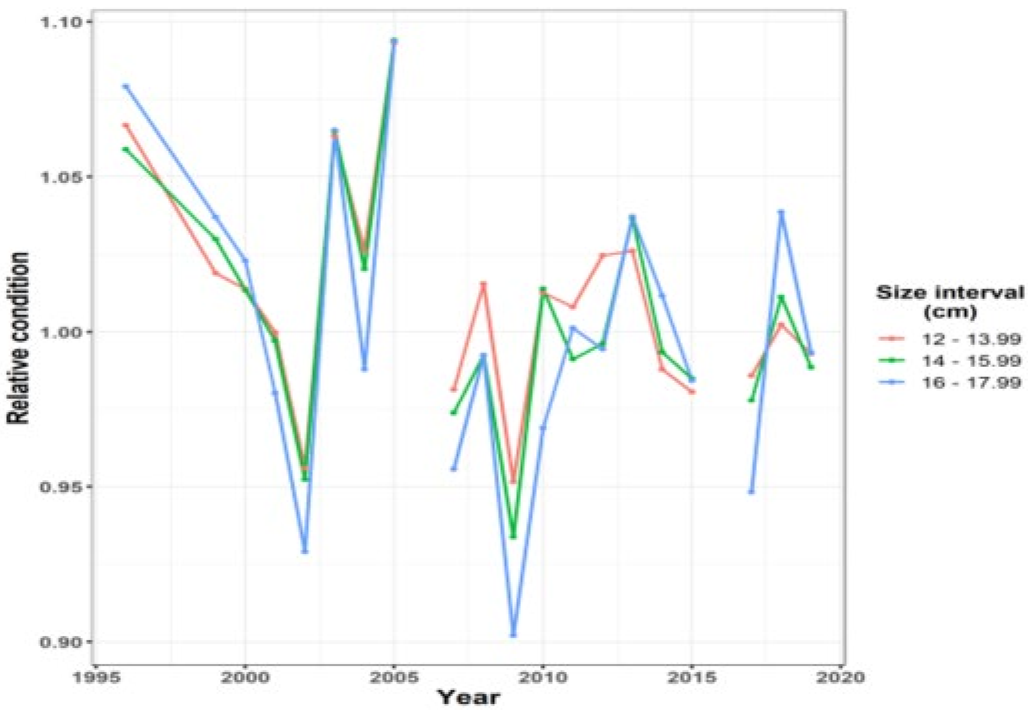


Figure 26: Mean length (upper) and weight (lower) of Capelin sampled during the spring acoustic surveys (1985–2019).



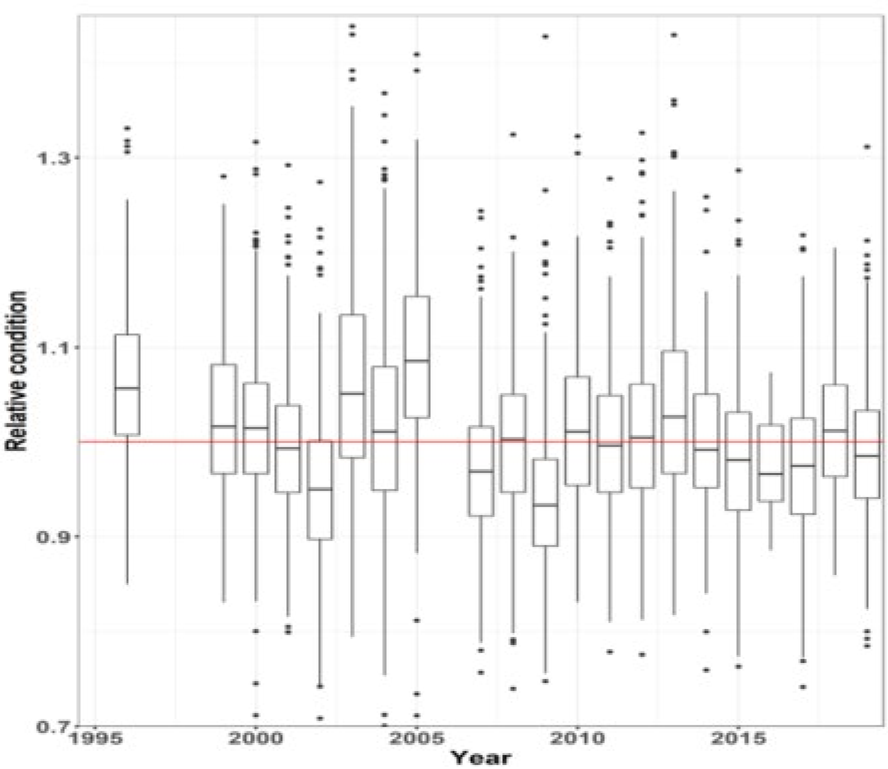


Figure 27: Relative condition of maturing female Capelin sampled during the spring acoustic survey by length group (upper) and pooled by year of sampling (lower).

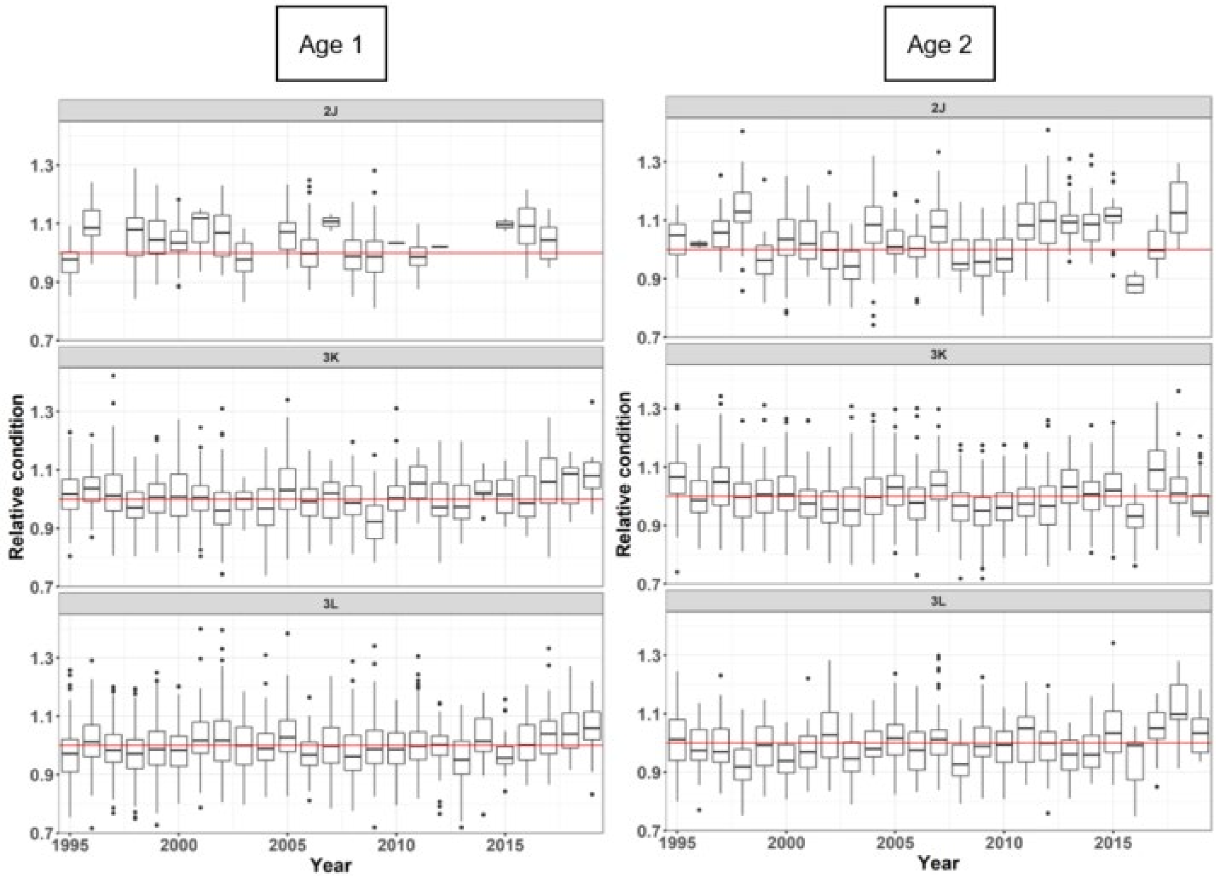
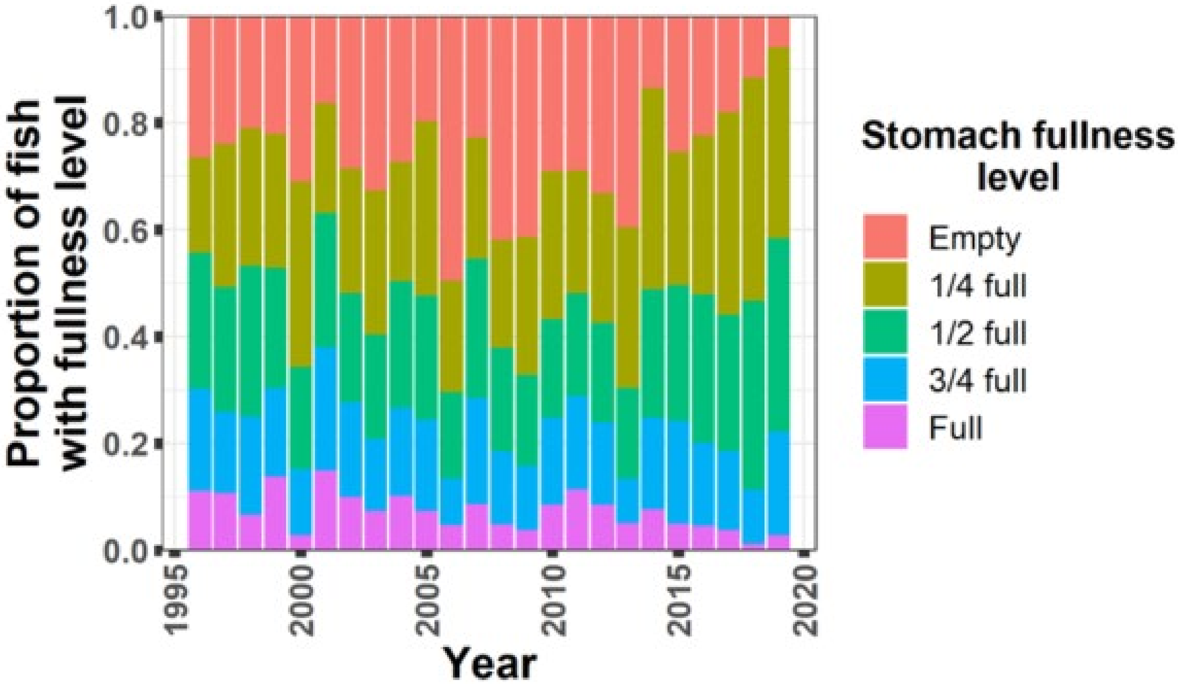


Figure 28: Le Cren condition of age 1 (left) and age-2 (right) male Capelin during the fall multispecies survey (1995–2019).



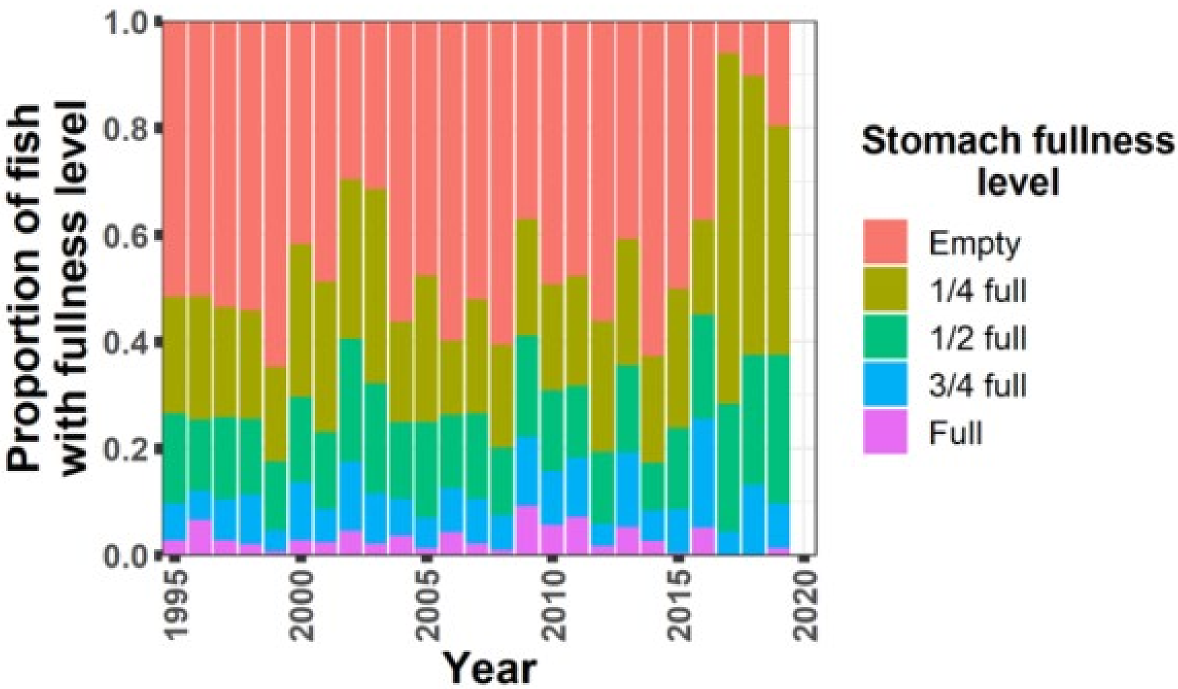


Figure 29: Observed scalar stomach fullness of Capelin sampled during spring (upper) and fall (lower) multispecies surveys (lower). Values are quarters where 0 = empty and 4 = full.

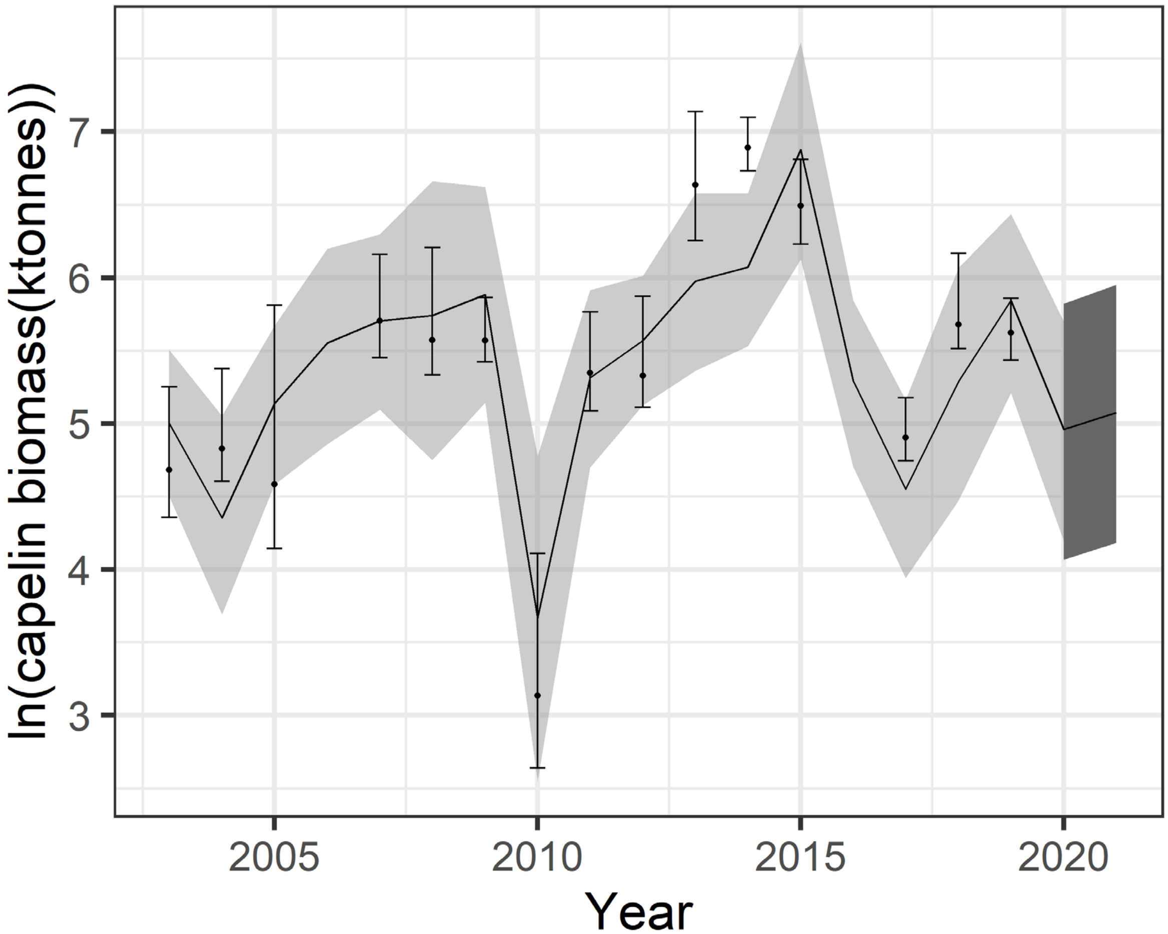


Figure 30: Results for the Capelin forecast model including the 95% credible (light grey) and 80% prediction (dark grey) intervals for expected values of the spring acoustic Capelin biomass index (solid line). Observed biomass index values (circles) with 95% confidence intervals are also plotted.