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Atlantic herring (*Clupea harengus*) stocks of the west coast of Newfoundland (NAFO Division 4R) in 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

This document presents the data and methods used to assess the status of the Northwest Atlantic Fisheries Organization (NAFO) 4R spring and fall spawning herring stocks. Based on preliminary data, herring catches totalled 7,418 t in 2018 and 15,806 t in 2019, with an annual total allowable catch of 20,000 t. The fishery experienced difficulties due to weather, changes in herring distribution and management measures. The proportion of landings composed of the spring spawning stock increased from 1.5% in 2014 to 24.5% in 2019. Catches of spring-spawning herring were dominated by the 2013 cohort. Fall spawning herring age 11+ have dominated the landings since 2014. The 2008 cohort contributed to the fishery in recent years, but has been less important to the fishery than the previous 2000 year-class. Evidence from scientific sampling and the fishery indicates above average presence of young fish in recent years. Both of these stocks show a general downward trend in mean weight-at-age for ages 3+ beginning in the early 1980s, and a downward trend in condition since the early 2000s associated with changes in zooplankton abundance, phenology and community structure. The biomass of herring estimated from the 2019 fall acoustic survey was 47,522 t and 68,796 t for spring and fall spawning herring, respectively. There is evidence of changes in catchability of the acoustic survey in recent years indicating that the survey may not consistently provide a reliable index of abundance. Further investigation of the assessment model used as the basis of the advice confirmed existing concerns over model sensitivity to time-varying survey catchability and other input assumptions (constant natural mortality), and the inability to reliably estimate recruitment. As a result, the model was rejected as the basis of the advice. A review of the assessment framework for 4R herring is recommended. The available evidence up to 2019 (commercial catch-at-age, age and length at maturity, abundance of young fish, low exploitation rate in 2019) indicate that current harvest levels do not pose significant risk to herring stocks in 4R in the short term. This conclusion should be revisited following a review of the assessment framework.

1. INTRODUCTION

Atlantic herring (*Clupea harengus*) is a pelagic fish that inhabits the cold waters of the Atlantic Ocean. In Canada, its distribution extends from the coasts of Nova Scotia to those of Labrador. Herring move in tight schools to feed, to spawn near the coast, and to winter in deeper waters. The same spawning, feeding, and wintering grounds are visited by herring each year. When they are laid, herring eggs attach to the bottom forming a carpet a few centimetres thick. Egg incubation time and larval growth are related to the characteristics of the environment, including water temperature. Herring generally reach sexual maturity around four years of age, at a total length of about 25 cm, but these life history traits vary between ecosystems and in time.

In many of the Northwest Atlantic ecosystems, herring populations are characterized by the presence of two spawning groups or stocks. Spring spawners (SS) generally spawn in April-May and fall spawners (FS) in August and September. Historically, southern areas were dominated by FS and northern areas by SS, although this pattern has shifted over time (Melvin et al. 2009). SS and FS herring are considered separate stocks and, as such, are assessed separately in NAFO division 4R. Recent genetic studies have confirmed the genetic differentiation between these two spawning groups (Lamichhaney et al. 2017). On the west coast of Newfoundland (NAFO division 4R; Figure 1), the herring fishery is managed by a Total Allowable Catch (TAC) without distinction between the two spawning groups.

In NAFO division 4R, average annual herring landings have been around 16 000 metric tons (t) since 1975. The current TAC of 20 000 t was established following scientific advice in the early 2000s (DFO 2002, DFO 2003). The sharing of the TAC between the different fleets can be summarized as follows: 55% (11 000 t) for large purse seiners (≥65′), 22% (4 400 t) for small purse seiners (<65′) and 23% (4 600 t) for fixed gear (DFO 2017). Since 2018, an annual allocation of 50 t for the bait fishery has been taken in the fixed gear allocation (DFO 2018a). Fishing by large purse seiners is managed according to an Individual Transferable Quota (ITQ) regime and that of small purse seiners by an Individual Quota (IQ) regime. Fixed gear fishing regime is competitive with separate quotas for herring Fishing Areas 13 and 14 (Figure 2). In 2017, the minimum size limit for herring was 10.5 inches (26.5 cm, fork length) and a maximum of 10% small herring (by count) per fishing trip was allowed. In 2018 and 2019, the minimum size limit for herring decreased to 9.75 inches (24.76 cm; fork length) following an update of the mean length at maturity (DFO 2018b) and the tolerance for undersized fish increased to 20% (DFO 2017).

A first series of acoustic surveys was carried out between 1991 and 2002 to derive an estimate of herring abundance. A second series of surveys was initiated in the fall of 2009 and continued until 2019. Abundance indices are calculated from these two series and those indices, along with commercial fishery data, constitute the main source of information used to assess stocks state.

A peer review was conducted on November 18 to 20 2020 to provide the regional fisheries management with advice on the status of herring stocks on the west coast of Newfoundland, published in the ensuing Science Advisory Report (DFO 2021). This document details the data and analyses underlying the scientific advice. This includes the evaluation of the status of the herring stocks based on 1) commercial fishery data following the 2018 and 2019 seasons (breakdown by unit area, gear and month); 2) the updated biological indicators resulting from the commercial sampling program; 3) the biological characterization of the catches from the DFO multi-species research vessel bottom-trawl survey; 4) results of the 2019 summer and fall acoustic surveys and 5) results from Virtual Population Analysis (VPA) models with an emphasis on diagnostic plots to evaluate their validity. Analyses conducted on the effects of the environment on stock productivity indices (recruitment and relative condition factor) are also presented.

2. METHODS

2.1. LANDINGS

Data from the Atlantic herring commercial fisheries in NAFO division 4R (west coast of Newfoundland, Figure 1) were extracted in September 2020 from the ZIFF (Zonal Interchange File Format) files produced by the Department of Fisheries and Oceans Canada's (DFO) regional statistics bureau for the years 1985–2019. At the time of this assessment, landing data for the 2018 and 2019 fishing seasons were considered preliminary as landings were still being compiled or validated for some herring fisheries. Landings for the period 1965–1984 were compiled from different archived databases and reports (McQuinn 1987a, McQuinn and Lefebvre 1995, McQuinn et al. 1999).

Landing data were grouped by NAFO Division 4R unit area (Figure 1) and fishing gear. Large seiners are defined as seiners with a vessel length greater than or equal to 65 feet, whereas small seiners have a vessel length less than 65 feet. Infrequently, used gear types were grouped as "others" and include the beach and bar seine, hand line (baited), longline, gillnet (drift), pot, bottom otter trawl (stern), midwater trawl (stern), midwater trawl (side) and jigger.

Landing data by fishing fleet (large and small purse seiners and fixed gear) were compared to allocations for the period 1985–2019. Cumulative frequency distributions were used to describe seasonal patterns in landings in individual years or blocks of years for the period 1985–2019. Finally, the yearly spatial distributions of the catch for the three types of seine (large, small and "Tuck") were mapped.

The herring bait fishery was excluded from previous stock assessments, as no data prior to the implementation of logbooks (2017) were available and fisheries management believed that this fishery contributed only a minor fraction of the total removals. For the years 2017, 2018 and 2019, a total of 184 herring logbooks from the bait fishery were collected by the DFO NL region, 8 of which were from NAFO division 4R, 81 from unknown divisions and the remaining from other divisions. The home port name was used to infer the missing NAFO divisions, assuming that fishing activities occurred in the NAFO division corresponding to the home port.

2.2. COMMERCIAL AND BIOLOGICAL SAMPLING

Biological samples were collected from main landing ports through DFO's commercial sampling program. For a given landing, 150 herring were randomly selected and measured (total length) to the nearest 0.5 cm to obtain length-frequency information. Then, another sample of 55 fish was randomly selected and sent to the Maurice-Lamontagne Institute (MLI) for determination of the spawning component (spring or fall), total length (± 1 mm), mass (± 1 g), sex, gonad mass (± 0.1 g), stage of gonadal development, and age via the extraction and examination of otolith structure.

Individual herring were assigned a spawning stock component using the method established by McQuinn (1987b, 1989). Maturity stages 1, 2, 6 and 7 were determined by visual examination following McQuinn's (1987b) gonad maturity chart. Gonad maturity stages 3, 4, 5, and 8 were determined by a discriminant analysis using a gonadosomatic index. Immature herring (maturity stages 1 and 2) were assigned to a spawning component based on the visual examination of their otoliths (Messieh 1972, Cleary et al. 1982). Mature individuals (maturity stages 3 to 8) were assigned to a spawning component based on gonad maturity stage and month of capture (Cleary et al. 1982).

Total (W_t) and gonad (W_g) weight of frozen fish (W_{frozen}) samples were converted to fresh weight (W_{fresh}) using the following equations;

$$W_{g\ fresh} = 1{,}1253 \times W_{g\ frozen}{}^{0{,}977} \text{ (males)}$$

$$W_{t\ fresh} = 1{,}2258 \times W_{t\ frozen}{}^{0{,}96916} \text{ (males)}$$

$$W_{g,fresh} = 1.365 \times W_{g,frozen}{}^{0.916} \text{ (females)}$$

$$W_{t,fresh} = 1.1626 \times W_{t,frozen}{}^{0.97851} \text{ (females)}$$

When required, fork length (L_f) was converted to total length (L_t) as:

$$L_t = \left(1.0866 \times L_f\right) + 9.5632$$

Finally, frozen total length ($L_{T.frozen}$) was converted to fresh total length ($L_{T.fresh}$) as:

$$L_{T.fresh} = 1.02 \times L_{t.frozen}$$

Only the length frequencies of the purse seine fishery were presented because this gear represents the largest proportion of the total catch. Size frequency distributions were adjusted for sample size and calculated for unit areas 4Ra, 4Rb, 4Rc and 4Rd.

In 2018 and 2019, herring samples were collected on DFO’s annual northern Gulf of St. Lawrence (nGSL) multi-species bottom trawl survey in order to increase sample size for length and age at maturity estimations. In addition to the usual herring length and weight measurement procedure (Bourdages et al. 2020), for all tows with a minimum of 10 herrings, a random sample of up to 55 fish was frozen and sent to MLI for determination of biological characteristics. All fish with a total length less than 200 mm were added to the sample.

2.3. CATCH-AT-AGE

Catch-at-age was calculated using CATCH 2_4_3, an APL program developed at MLI and last updated in 2014. The program is based on methods and equations detailed in McQuinn (1987b). Briefly, the landings were tabulated by year, month, NAFO unit area and gear (hereafter strata) for pairing with the corresponding biological samples.

Where there was no biological sample for a given stratum, the landings were paired with the sample(s) judged to have the best representability. The following hierarchy was used to attribute biological samples to strata with insufficient samples:

1. Across months within a unit area and quarter (April to June, July to September and October to December).
2. Across unit areas within a month.
3. Across months and unit areas within a quarter.
4. Across months and quarters within the northern (4Ra) and southern zone (4Rb, 4Rc, 4Rd).

Based on the attributed biological samples, we calculated the stratum-specific catch proportion, age composition and mean weight-at-age for each spawning component. The total catch per stratum could hence be separated by spawning component, and transformed into catch-at-age (in numbers) for both the spring and fall components (landings per component x proportion-at-age / weight-at-age). The yearly 4R fishery catch-at-age by spawning component was obtained by summing over all strata. The yearly proportion of SS in the fishery was then computed by dividing the total number of SS by the total number of both spring and FS in the catch-at-age of the corresponding year.

2.4. LENGTH AT 50% MATURITY

Length at 50% maturity (L50) is a biological indicator that can reflect fishery-induced changes in maturation (Lappalainen et al. 2016), changes in environmental conditions, and density-dependence mechanisms (Cardinale and Modin 1999, Meyer et al. 2003); it can also be used to establish minimal legal sizes.

L50 maturity was computed by spawning components and cohort year (birth year). The computation by cohort year (longitudinal estimates) was preferred over year (cross-sectional estimates) because the maturation schedule reflects the conditions experienced by the cohorts (Enberg et al. 2012) and because the results are used as a biological index (not in a stock assessment model). All available biological data (commercial landings, acoustic and nGSL multi-species bottom trawl survey, hereafter commercial and research samples) were used in the computations. One generalized linear model (GLM) by spawning component and cohort year was fit with a Bernouilli distribution and a logit link function. Maturity stage (mature or immature) was used as the response variable and the explanatory variables were total length and month of capture (coded as a factor) in order to correct for any changes in the timing of the herring fishery. Month of capture was, however, not included as an explanatory variable for the SS models because of the insufficient availability of juveniles in the biological samples. Cohort L50 was calculated as the predicted L50 in November. Fitted models were bootstrapped over 999 iterations using the “car” package in R to produce 95% confidence intervals (Fox and Weisberg 2011) when there were more than 5 immature fish. There was no significant difference between males and females maturity ogives.

2.5. AGE AT 50% MATURITY AND MATURITY-AT-AGE

Age at 50% maturity (age at which 50% of the individuals are mature, A50) and maturity-at-age (the proportion of mature fish at a given age, MAA) were computed using GLMs with a Bernouilli distribution and a logit link function on all the available biological data (commercial and research samples). One model by spawning component and year was fitted with maturity stage (mature or immature) as the response variable, and age as a numeric explanatory variable. For SS herring, maturity-at-age could not be estimated for some years due to insufficient numbers of immature herring in the samples. Hence, for each SS model, data from the given year as well as the two neighbouring years were included. Sex was not included as an explanatory variable in the GLMs because maturity-at-age was used as data input in the sex-pooled stock assessment models and because its effect size was not biologically relevant (although significant at an alpha level of 0.05). To account for the maturation of juvenile herring throughout the year of their first reproduction, age was calculated using the month of capture with the following equations:

$$Age_{spring} = \frac{8 + (Month - 1) + (Age - 1) \times 12}{12}$$

$$Age_{fall} = \frac{5 + (Month - 1) + (Age - 1) \times 12}{12}$$

Where Age_{spring} and Age_{fall} are respectively the SS and FS ages used in the Bernouilli GLM models, $Month$ is the month of capture and Age is the age determined by otolith reading. In doing so, it was assumed that all SS and FS herring hatched in May and August respectively. The models were then used to predict the yearly proportion of mature fish for each age as well as age at fifty percent maturity (A50). Confidence intervals for the A50s were computed using the same methodology as for the L50s.

2.6. WEIGHT-AT-AGE

The SS and FS component's yearly mean weight-at-age were estimated using all available biological data (commercial and research samples). One standardizing model by spawning component and age class was fitted to account for seasonal, spatial and gear variability among samples. Total weight was used as the response variable and the following explanatory variables were considered as factors: year, month, NAFO unit area and gear type. Gaussian GLMs with the log link were used because the identity link predicted negative weights for some years in the age 2 models. Residuals were inspected for signs of overdispersion. For SS herring, weight-at-age was predicted for NAFO subunit 4Rd, August and small purse seiners (<65′) of each year, whereas for FS, reference levels were 4Ra, November and large purse seiners (>65′). The reference levels were chosen to maximize the number of years where weight-at-age could be predicted in these categories. Where the models could not provide estimates for the reference levels because of insufficient data, the mean value for that age class across all years was taken, specific to the spawning component. Annual weight-at-age matrices were used within the stock assessment models along with the maturity ogives to convert estimated population numbers-at-age to spawning stock biomass.

2.7. ACOUSTIC SURVEY INDEX

A first series of acoustic surveys off the west coast of Newfoundland, aimed at estimating herring biomass during the fall commercial fishery targeting pre-wintering aggregations, was completed in October and November of 1991, 1993, 1995, 1997, 1999, and in September 2002. A second series of surveys began in the fall of 2009 following recommendations from the Fisheries Resource Conservation Council (FRCC 2009) and was conducted in October and November of 2009, 2010, 2011, 2013, 2015, 2017 and 2019. This new survey covers a larger area as it always includes the northern strata (4Ra), which were previously skipped on occasion, as well as the Lower North Shore of Quebec (4Sw, not included in this assessment). It also begins with the northern strata and moves south, in contrast to the 1991–2002 survey series. In 2019, a second acoustic survey was conducted in August in addition to the fall survey. The details and results of the first series of acoustic surveys are presented in McQuinn and Lefebvre (1999), Beaulieu et al. (2010) as well as in Appendix A and will not be further discussed. The following sections describe the methodology used for the 2009–2019 surveys.

2.7.1. Survey Design

The survey spanned the entire west coast of Newfoundland, from Cape Anguille to the southern portion of the Strait of Belle Isle (in 4Ra), covering the 20 m to 60 m isobaths. The study area was stratified (10 strata) according to the major physical characteristics of the environment, the spatial distribution of commercial catches and the population distribution as observed in past surveys (McQuinn and Lefebvre 1999) (Figure 3). Transects surveyed by the hydroacoustic vessel were parallel, equidistant, and oriented perpendicular to the coast within each stratum. The location of and distance between transects varied annually due to logistic reasons. For every survey, the first transect within each stratum was placed randomly. The total number of transects for all strata was determined based on the allocated ship time minus 30%, as a margin for bad weather and mechanical breakdowns. Nevertheless, there was among year variation in the number of transects per stratum (Figure A57). The transects were surveyed at night-time only (17:00–07:00) because of the diurnal behaviour of herring as it generally migrates off the bottom at night (McQuinn and Lefebvre 1999), thus making them more distinct from the bottom echoes and reducing the “deadzone” problem (Mitson 1983).

2.7.2. Acoustic Data Acquisition and Analysis

A Simrad EK60 echo sounder was used to transmit and collect the acoustic signals. Up to five frequencies (38, 70, 120, 200, and 333 kHz) were used simultaneously, depending on the vessel performing the survey (Table A20). All data were saved in real time on a computer using Simrad’s ER60 software. The echosounder was calibrated each year before the survey using the standard target or sphere method (Demer et al. 2015).

The acoustic data was transformed into the HAC format (HydroACoustics, McQuinn et al. 2005) using ER60. The HAC files were subsequently scrutinized and integrated in 2 m (depth) by 25 m (horizontal distance) cells using CH2 software developed at MLI (Simard et al. 2000). Schools were classified as swim bladdered fish by comparing the mean backscattering volume strength (S_V) of the 38, 120 and 200 kHz frequencies. Most fish schools were considered to be herring as very few other swim bladdered fish species were present in the survey area in the fall (McQuinn and Lefebvre 1999). Herring 38 kHz S_V was than averaged by transect, transformed into area-backscattering coefficient (s_a) and converted into mean herring density (kg/m2) using the following equation for clupeids at 38 kHz:

$$TS_{cm} = 20(\log_{10} L) - 71.9 \text{ (Foote 1987)}$$

and by converting to target strength per unit weight:

$$TS_{kg} = TS_{cm} + 10(\log_{10} W^{-1})$$

where L is mean fish length (cm) and W is the mean fish weight (kg) (McQuinn and Lefebvre 1999). Biological samples provided the mean herring length and weight per stratum and spawning component, as well as proportion of each component by weight. Total biomass and variance per stratum were obtained following the equations described in O’Boyle and Atkinson (1989) for surveys with varying transect lengths (mean biomass density weighted by transect length, multiplied by stratum area and corresponding variance estimate). Although the application of classical statistics for a random-stratified design to a systematic-stratified survey may lead to a bias in the strata variance estimates, the variance should theoretically be overestimated (Cochran 1977). The variance estimates and corresponding standard errors presented in the results section are therefore considered conservative in terms of acoustic data, but do not account for the uncertainties related to biological sampling.

The total biomass per spawning component per stratum was transformed into number-at-age (biomass per component x proportion-at-age / weight-at-age). The age disaggregated abundance index was then obtained by summing over all the strata covered by the survey during a given year. However, some strata were not surveyed every year and the survey biomass estimates are limited to those that were.

2.7.3. 2019 Summer and Fall Surveys

The acoustic survey implies the calculation of a survey number-at-age independent from the commercial fishery and therefore relies on biological samples collected with an accompanying fishing vessel for herring spawning stock composition, length and weight information. The accompanying vessels (since 2009) was a small DFO research vessel, first Canadian Coast Guard Ship (CCGS) Calanus II and then the CCGS Leim. Both employed a large pelagic trawl, but catch efficiency was low and variable (see Table A21) as a result of a mismatch between the gear and the vessel capacities and lack of expertise from the crew. Commercial samples in the herring biological database corresponding to the closest spatiotemporal match were therefore used to get estimates of demographic composition of herring. The consequence of this shortcoming was that these samples now classified as “research samples” were excluded from the commercial fishery catch-at-age calculation to avoid inducing a correlation between the two sources of data in the assessment model. The biological samples used in the subsequent calculations thus originate from multiple gear types and have a time-varying coverage. In the fall 2019, the chartering of a fishing vessel, the Meridian 66, equipped with a pelagic trawl (50 mm codend) allowed the collection of biological samples independent from the commercial fishery during the acoustic survey (Table A21). The chartered vessel was provided with the coordinates of important acoustic signals so that they could be sampled with the closest temporal match, and up to 100 randomly selected fish per tow were frozen and sent to MLI for determination of biological characteristics.

Over the last decade, the 4R commercial fishery, which target pre-overwintering herring aggregations, generally occurred later in the year, suggesting a potential delay in the timing of herring migration in late fall (DFO 2018b). This change resulted in a temporal mismatch between the acoustic survey and the commercial fishery, a deviation from the initial acoustic survey design (McQuinn and Lefebvre 1999, DFO 2018b). Because of logistical constraints associated with the deployment of DFO’s small research vessels later in the fall, an additional acoustic survey was initiated in August 2019 (hereafter summer survey) in order to target spawning aggregations of fall herring deemed to occur in a more consistent manner. Strata were added in the Strait of Belle Isle (BI; Figure 3) as landings have been regularly reported in this area. The 2019 summer acoustic survey was carried out from August 11 to 23 with the CCGS Frederick G. Creed. A portion of the acoustic signals observed in the Bay of Islands stratum were considered to be capelin (*Mallotus villosus*), in concordance with the samples obtained by the chartered fishing vessel (the Steven Paul) fishing with the same pelagic trawl used in the 2019 fall survey. These signals, as well as occasional strong cloudlike signals only visible on the 38 kHz frequency, were excluded from the biomass computation in order for the estimates to be conservative. This survey is considered as the start of a new time series. Results are presented but are not used in this stock assessment.

2.7.4. Catch Curve Analysis

Selectivity-adjusted catch curves for estimated acoustic survey abundances for herring ages 3 to 10 years were examined for evidence of multi-year changes in catchability. Under constant catchability such catch curves should be declining for each cohort, reflecting their attrition due to mortality, although some variability is expected due to observation errors. Provided that age-dependent selectivity is correctly specified and catchability is constant, or at least stationary, the slope of the log catch curves provides an estimate of total mortality, Z (Sinclair, 2001).

Bias-corrected selectivities estimated in the 2004 assessment of the stocks were used because that assessment provided reasonable diagnostics suggesting adequacy of the model and its inputs (Grégoire et al. 2004). Estimated abundance for age 2 were excluded because these included many zeros, and those for age 11+ were excluded because that group is an accumulator that does not conform simply to cohort dynamics. Catch curves are based on log selectivity-adjusted abundance at age and year. To address a small number of zero values, half the minimum estimated positive abundance for each stock was added to all abundances prior to dividing by age specific selectivity and taking the logarithm.

2.8. STOCK ASSESSMENT MODELS

The SS and FS components (1965 to 2019) were assessed using Virtual Population Analysis (VPA) models fitted with the VPA/ADAPT software version 3.4.4 (NOAA fisheries toolbox, NFT 2014). VPA is a deterministic algorithm that back calculates the stock number-at-age and fishing mortality rate-at-age matrices. Data inputs to the models included:

- Fishery catch-at-age in numbers (ages 2 to 11+, years 1965 to 2019)
- Fall acoustic survey indices in numbers at age (ages 2 to 11+, years 1991 to 2002 and 2009 to 2019)

In addition to these matrices, the following estimates were used to convert the predicted number-at-age into spawning stock biomass (SSB):

- Maturity-at-age (in proportions)
- Weight-at-age (in kg)

The model equations are provided in Table A24 and the parameters used for the application in the ADAPT NFT program are presented in Appendix B. The estimated parameters are population numbers in 2020 ($N_{a,t}$, a = ages 3 to 11+ and t = 2020) and catchability coefficients (q_a, a = 2 to 11+).

The natural mortality rate (M) was fixed at 0.2 in the first SS and FS models (model 1a). In order to evaluate this assumption, the NFT toolbox was used to perform a sensitivity analysis on M by blocks of 5 years (1965–1969, 1970–1974, … 2015–2019) for ages 4 to 10, keeping all other M constant at 0.2. That is, for a given 5 year block, the residual sum of squares (RSS, Table A24, equation 17) was calculated for each model run with values of M going from 0.05 to 0.90 by steps of 0.05. The M value giving the lowest RSS for each 5-year block was chosen and used as an alternative model (model 2a), as in Brassard et al. (2020).

Historically, the acoustic survey number-at-age indices relied on commercial samples with an age composition influenced by fishermen actively avoiding small herring aggregations or discarding catches dominated by small fish. In 2019, the use of a chartered pelagic trawler during the acoustic survey resulted in less size-selective fishing. Although this could be considered an improvement, it nevertheless represented a departure from previous assessments. Because of this discrepancy in selectivity, we ran model simulations assuming a constant natural mortality (M = 0.2) with (model 1a) and without (model 1b) the age-2 class (SS models), and age-2 and 3 (FS models), in order to assess the impact of this change and ensure a model run similar to previous assessments (model 1b). Additionally, we ran a sensitivity analysis with both models assuming a 5-year block-wise M (models 2a and 2b) as in Brassard et al. (2020). Table 1 summarizes the distinctions between models 1a, 1b, 2a and 2b.

Model diagnostics were inspected in terms of residuals and retrospective patterns. Retrospective analysis was done by sequentially peeling off the last 5 years (last year removed = 2014), refitting the model to the truncated data, and averaging the relative bias ([retro-base]/base) of SSB, average F (annual arithmetic mean instantaneous fishing mortality rate for ages 2 to 11+) and recruitment computed with the truncated and the corresponding estimate of the full time series (Mohn's Rho, Mohn, 1999).

Within the precautionary approach (PA, DFO 2009), reference points were defined for the SS and FS components in McQuinn et al. (1999). The limit reference points (LRP) corresponded to 20% of the maximum spawning stock biomass from the entire time series and the upper stock reference point (USR) was defined as the lowest observed historical spawning stock biomass (> LRP) which produced good recruitment. Good recruitment was defined as recruiting year-classes observed at age 2 during the historical time series greater than the geometric mean of upper third best recruiting year classes (Schweigert et al. 1998, McQuinn et al. 1999). The LRP and USR calculated by McQuinn et al. (1999) were respectively 37 384 t and 57 468 t for the SS and 47 953 t and 61 074 t for the FS components.

2.9. ENVIRONMENTAL DRIVERS OF CONDITION

A previous study examining the links between 4T and 4R herring recruitment (R) and environmental variability done with multivariate environmental indices suggested that environmental variability did not seem to act uniformly on the recruitment of either stocks or their respective spawning components (Brosset et al. 2019). Moreover, high R in 4R SS herring was associated with cooler conditions (temperature, zooplankton), whereas high R in 4R FS herring was associated with warmer conditions. In this context, we assessed the relationships between recruitment and body condition, and environmental conditions using standard discrete environmental indices produced as part of the Gulf of St. Lawrence ecosystem approach (Duplisea et al. 2020). We used generalized additive models (GAMs) to assess the effect of variations in physical (temperature, timing of surface water warming and cooling) and biological (spring bloom dynamics, abundance and phenology of key zooplankton taxa, relative abundance of zooplankton groups as an indicator of average prey size, predation) environmental conditions known to be mechanistically linked with pelagic fish species recruitment and growth (Brosset et al. 2019, Ljungström et al. 2020). *Calanus* spp. and *Pseudocalanus* spp. are key taxa due to their importance in larval, juvenile and adult herring diets (see Darbyson et al. 2003).

We hypothesized that body condition would respond positively to warmer conditions/earlier timing of plankton and a greater availability of preferred/important prey. Likewise, we hypothesized that R should be favoured under conditions that would promote a faster growth (and improved survival) of larval herring.

2.9.1. Recruitment Indices (R, Rstrength)

Given the uncertainty associated with herring data and stock assessment models, we used two distinct recruitment indices: 1) R as the number of fish at age 2 estimated by the VPA model 1a and lagged two years and 2) Rstrength as a relative index of recruitment based on the proportion of ages 3–4 in the commercial catch-at-age. We removed data after 2017 for R because of the high uncertainty of R estimated in later years in a VPA. Rstrength was calculated using catch-at-age standardized at year (mean and variance of each year respectively equal to 0 and 1). Standardized catch-at-age were subsequently averaged for ages 3 and 4 of year x and x+1 and the resulting Rstrength was lagged 3 years. Rstrength was also calculated for ages 3 to 5 and was highly correlated ($r>0.95$) with Rstrength for ages 3 to 4. The latter was used in subsequent analyses because it could be calculated for one more year of the time series than the former.

2.9.2. Relative Condition Factor (Kn)

Le Cren's (1951) relative condition factor was estimated separately for the SS and FS herring using the following formula:

$$Kn = \frac{W}{aL^b}$$

Where W is the somatic weight (g), L the total length (mm) and a and b the parameters of the length-weight relationship estimated using a nonlinear model (nls function in R). The use of the log-log relationship was avoided because backtransforming the predictions (and/or the *a* parameter) on the original scale tends to underestimate the predicted weight (Ogle 2016). To account for seasonal, spatial and gear variability among samples, Kn were standardized using one gaussian glm with identity link for each combination of spawning component and age. The following explanatory variables were considered as factors: year, month, NAFO subunits and gear type. For SS herring, Kn was predicted for NAFO subunit 4Rd, August and small (<65′)

purse seiners of each year, whereas for FS herring, reference levels were 4Ra, November and small purse seiners. Kn of herring ages 4 to 9 was subsequently averaged for each year. This age range was selected because adult condition was of interest and condition at these age classes is highly correlated. In contrast, condition estimated for younger fish showed substantial interannual variability, potentially as a result of small sample size.

2.9.3. Environment Variables

Environmental indices were extracted from the Gulf of St. Lawrence (GSL) Ecosystem Matrix (Duplisea et al. 2020). They were chosen according to their potential role in herring feeding success and net energy gain and in recruitment. Predictors were classified into 3 categories: physical indices, spring bloom dynamics and key zooplankton taxa abundance, and phenology indices. Physical predictors (1982–2019) were sea surface temperature (SST) averaged over seasons or during specific months, spring (week of the year when SST warms up to 10 °C) and fall (week of the year when SST cools down to 10 °C) timing, and last day of ice. For each spawning component, SST was considered for the month used to standardize the Kn or averaged over the months between spawning and the month used to standardize Kn. Thus, for the SS component, SST in August and SST averaged over May–August were considered, while SST in November and averaged in August–November were considered for the FS herring. Spring bloom dynamics indices (1998–2018) included the timing and the duration of the bloom. Zooplankton indices (2001–2018) included the abundance of *C. finmarchicus*, *C. hyperboreus*, *Pseudocalanus* spp. and small Calanoida (dominated by *Pseudocalanus* spp.) in early summer and fall, the phenology (ratio between C1–C4 and other copepodites stages) of *C. finmarchicus* in early summer and fall and the phenology of *C. hyperboreus* (ratio of C4 on C1–C4) in early summer (used for SS herring only). *C. hyperboreus* abundance and phenology were not considered as predictors of recruitment because it is unlikely to be a prey of herring larvae. The ratio of the abundance of large calanoids/small calanoids was used to reflect changes in the average size of zooplankton taxa prey. Herring SSB calculated by the VPA model 1b (Table 1) was used in the recruitment model. The relationship between SSB and recruitment can be positive, indicative of a stock-recruitment relationship, or negative if predation on herring larvae is important. Predictors were extracted for regions 2, 3 and 4 of the ecosystem approach (EA) which correspond to the 4R region and the annual average was weighted by the area of each EA region (Duplisea et al. 2020).

2.9.4. GAMs

The effect of the environment on the variability of Kn was evaluated with GAMs assuming a Gamma error distribution. We used quantile GAMs to verify the effect of the environment on R and Rstrength using quantile 0.5 and 0.75 because of the high variability in recruitment data. We adopted a stepwise approach when considering environmental predictors of different categories:

1. physical indices representing the longest time series (1982–2019),
2. physical and spring bloom indices (1999–2018),
3. physical, spring bloom and zooplankton indices corresponding to the shorter time series (2001–2018).

Correlations and relationships were verified among predictors and correlated predictors (> 0.6) were not included in models. Outliers were investigated by dot plots and we removed the duration of the bloom in 2003. All models considering a maximum of three predictor variables were tested in order to minimize potential of overfitting and were ordered according to their Akaike Information Criterion corrected for small sample size (AICc). The basis dimension (k) was set to a maximum of three to avoid multimodal relationships. The R^2 between prediction and observation and the deviance explained were calculated and the model was evaluated using a Monte Carlo simulation and leave-one-out cross-validation (jackknife).

The Monte Carlo simulations were developed by generating normally distributed random predictors with mean and variance corresponding to the original predictors. The model was fitted using these randomized values and the deviance explained was calculated. The process was replicated 1000 times and the deviance of the selected model was compared with the distribution of the explained deviance obtained in the Monte Carlo simulations. To be selected, the deviance explained by a model had to be larger than the 95th quantile of the distribution of explained deviance with simulated datasets. That is, the probability that random erratic time series explain as much of the deviance as the selected variables needed to be below 5%. Each model was also tested using a jackknife procedure. For each model, we removed one year at a time, fitted the model and predicted the value. The predicted values were compared to the observed values and the R^2 was calculated. The final selected model had the lowest AICc (Δ <2), the highest R^2 (Δ <0.05), was significant (<0.05) in the Monte Carlo simulations and was robust against missing years (jackknife R^2 Δ <0.1). When two models had similar performances on all indicators, the most parsimonious model was selected. Model residuals were inspected for temporal autocorrelation using the acf function in R. All analyses were done in R version 4.0.2 (R Core Team 2020), GAMs were fitted using the mgcv (Wood, 2017) and quantile GAMS were calculated using the qgam (Fasiolo et al. 2017) packages.

3. RESULTS AND DISCUSSION

3.1. LANDINGS

During the 1980s and 1990s, Atlantic herring landings on the west coast of Newfoundland were variable and averaged 14 762 metric tons. Landings increased slowly but regularly between 1999 and 2008 and stabilized at around 20 000 t until 2016, limited by the TAC for those years. Landings have not reached the total allowable catch (TAC) since 2017 (Figure 4) and totalled 7 419 and 15 782 metric tons in 2018 and 2019 (preliminary data, Table 2). Since 2012, most landings have been reported from NAFO subunit 4Rb (Table 2, Figure 4).

The majority of the herring is usually landed by the large seiner fleet (Table 2, Figure 5). In 2018 and 2019 (preliminary data), the large seiners landed 4 077 t and 7 676 t respectively, lower than the 1985–2017 average of 10 472 t. The small seiners also landed less biomass in 2018 than in 2019 (966 t and 3 758 t respectively), while the 1985–2017 average was 3 418 t. The biomass landed with the “Tuck” seine, a modified bar seine considered as a fixed gear, totalled 1 440 in 2018 and 3 377 t in 2019 (Table 2). In 2018, less than half of the small and large seiners quotas were caught (Figure 6). In 2019, 68% of the large seiner quota was caught, and the small seiners and fixed gears landed more than 85% of their quota (Figure 6). A reduction in herring landings was also observed in NAFO division 4S in 2018 and attributed to either the management measures that were put in place in 2017 and 2018, adverse weather conditions for fishing activities, or a shift in the distribution of herring to greater depths. This latter phenomenon, which would reduce the availability of fish to fishing gear, was reported by members of the fishing industry and was also observed during the 4S acoustic survey conducted by DFO in the fall of 2018 (DFO 2019).

Spring fishing activity by the large and small purse seiners was greatly reduced following the implementation in 1999 of management measures aimed at protecting the spawning of SS. Since then, these fisheries, as well as the “Tuck” seine fishery, are mostly practised in the fall. Cumulative landings show that the large seiner fleet followed this pattern in 2018 and 2019, but a higher proportion (26.3%) of the landings occurred before July 1 in 2019 (Figure 7 and 8). The cumulative landing patterns of the small seiners show that this fishery occurred mostly in the fall, as was usually the case. Landings by the fixed gear fleet in 2018 and 2019 increased steadily throughout the season, as has generally been the case historically (Figure 8).

Landings by large and small purse seiners are concentrated near the coast and within large bays (Bonne Bay, Bay of Islands, Port au Port Bay and St. George Bay; Figure 9). Landings by the “Tuck” seine began in 2005 in unit area 4Ra and Bonne Bay. They then extended to the large bays located further south (the entry of fishing coordinates is incomplete for 2018 and 2019). The proportion of missing geographic coordinate values in the ZIFF data was less than 20% and often zero for the large seiners, and between 25% and 63% for small seiners in the early 2000s, then below 10% until 2017 when the percentage increased again (Figure 10). The “Tuck” seine data has the most missing coordinates, with percentages decreasing from 2005 to 2016 but increasing recently. The high occurrence of missing values in 2018 and 2019 was probably due to the fact that these data were still preliminary. Interpretation of the spatial distribution of the landings for the “Tuck” seine in 2018 and 2019, and to a lesser extent the small seine fleet, are therefore uncertain.

For the 2017–2019 period, the reported landings in the herring bait fishery in 4R ranged from 2.9 to 32.9 metric tons per year (0.04–0.20% of total landings) and the number of logbooks returned by year varied between 2 and 24 (Table 3). There were 567 and 565 bait licences in 2018 and 2019, respectively, in NAFO division 4R (Julia Sparkes, DFO Newfoundland and Labrador region, pers. comm., 2020)

3.2. COMMERCIAL AND BIOLOGICAL SAMPLING

Atlantic herring commercial samples were generally collected according to the distribution of the fisheries in space and time (Table 4). In 2018, individuals from the fixed and mobile gear fisheries were collected in the spring and in the fall, but most samples came from the more important mobile gear fishery in the fall. In 2019, no or very few fish were sampled from the fixed gear fishery in the spring or in the fall. There were numerous samples from the 2019 fall mobile gear fishery in all 4 NAFO subunits (Table 4).

The proportion of SS herring in the commercial biological samples varied between 30 and 80% between 1965 and 2005 (Figure 11). The proportion of SS herring decreased rapidly from 2005 and 2008 and reached 2.3% in 2014. Since 2014, the proportion of SS herring in the fishery increased to 27.6% and 30.0% in 2018 and 2019, respectively. The proportion of SS herring in the total landings (proportion in each sample weighted by the landings in the corresponding stratum) followed the same trends. SS herring represented 1.5% of the landings (in number of fish) in 2014, 12.4% in 2018, and 24.5% in 2019 (Figure 12). Interestingly, the increasing prevalence of FS since 2003 was predicted to some degree by Melvin et al. (2009) based on their conceptual model of environmentally driven reproductive success and the expected increasing mean water temperatures. It is worth noting, however, that proportions of FS in the samples (Figure 12) are representative of the proportions in the fishery (as opposed to stocks relative abundance) and consequently are influenced by the management measures implemented in 1999 aimed at protecting the SS, as well as fishery selectivity.

The fall purse seine length frequency distributions of SS and FS calculated from commercial biological samples are presented in Figure 13. The length frequencies of the SS from the fall purse seine fishery are characterized by the presence of modes which are associated to dominant cohorts (Figure 13A). These modes move over the years towards larger sizes. Between 2006 and 2010, the dominance of the 2002 cohort in the length frequencies was confirmed by the age readings. The mode in the length frequencies between 2016 and 2019 was caused by the 2013 cohort. The FS length frequencies are also characterized by the periodical presence of dominant year-classes (Figure 13B). The dominance of the 2000 and 2001 year-classes in the length frequencies between 2003 and 2013 was also confirmed by age readings. Since 2013 the FS length frequencies are dominated by the 2008 cohort and older individuals (Figure 13B).

Location and proportion of FS and SS in the DFO's nGSL multi-species bottom trawl survey in August 2018 and 2019 are presented in Figure 14. Samples were collected and sent to MLI for detailed biological examination from NAFO subunits 4Ra and 4Rb in both years because all tows with more than 10 herring were located in these areas. The SS component represented 21.2% (84 individuals) of the biomass of the 350 individuals sampled in 2018 and 13.3% (44 individuals) of the biomass of the 287 herring sampled in 2019.

3.3. 2019 ACOUSTIC SURVEYS

The summer 2019 survey covered all acoustic strata with the exception of stratum 4. Strata in the Strait of Belle Isle were partially covered because of mechanical problems (Figure 15, Figure A57).

During the 2019 fall survey, the southern strata (1, 2 and 4) as well as stratum 5 were not covered by the acoustic vessel due to adverse weather conditions (Figure 15). Within covered strata, transect density was lower than in previous years (Figure A57) because the vessel used to perform the acoustic transects was slower and less stable than the one used in previous years.

The biological samples used in the computation of the acoustic survey index were collected by various fishing gears since 2009. The majority of the samples were collected by the commercial purse seine fleet (Table A21), with the exception of 2019 when samples were collected with a pelagic trawl (50 mm codend). During the 2019 summer survey, a total of 15 midwater trawl samples (corresponding to 513 herring) were collected by the chartered pelagic trawler between August 11 and 22, and 13 samples were used in the computation of the acoustic biomass index (505 fish, Table A21). During the 2019 fall survey, a total of 15 midwater trawl samples were collected by the chartered pelagic trawler between October 31 to November 5 (corresponding to 1108 herring), and 11 samples were used in the computation of the acoustic biomass index (868 fish, Table A21). Samples that were not used in the computations of the acoustic index were from strata not covered by the acoustic survey.

The proportion of SS and FS in the pelagic trawl samples in 2019, as well as their spatial distribution, are illustrated in Figure 16. The SS component represented 10.9% (114 individuals) of the biomass of the 513 individuals sampled by the Steven Paul and 29.0% (450 individuals) of the biomass of the 1108 herring sampled with the Meridian 66 in October and November 2019. Interestingly, the proportion of the samples biomass from the 2019 nGSL bottom trawl survey represented by SS (13.3%) was similar to the proportion of SS observed in the Steven Paul during the same period.

The length frequency distributions of SS herring used in the computation of the fall 2009 to 2019 age disaggregated acoustic index, as well as the samples from the 2019 summer survey, are shown in Figure 17A. For the fall surveys, the mode of the length frequency distributions was variable from one survey to the other and the progression of modes associated with different cohorts was hardly discernable because few SS were present in the biological samples. The 2019 summer and fall samples used in the calculation of the index show a mode at around 200–225 mm total length and a less pronounced one at around 325 mm, while the samples captured during the nGSL bottom trawl survey and assigned to the SS component were mostly individuals larger than 275 mm.

The length frequency distributions of the FS herring used in the computation of the fall 2009 to 2019 age disaggregated acoustic index, as well as the samples from the 2019 summer survey are shown in Figure 17B. The mode of the length frequency distribution was around 325–350 mm from 2009 to 2015, not clearly discernable in 2017, and did not seem to follow the growth of cohorts over time. The 2019 samples from the summer and fall surveys both showed an important number of fish less than 250 mm, while the individuals from the nGSL bottom trawl survey assigned to the FS component were mostly larger than 280 mm (Figure 17B).

3.4. CATCH CURVE ANALYSIS

Catch curves for cohorts of both SS and FS for the period 1991 to 2009 were largely declining, consistent with attrition and stationary catchability (Figure 18). In contrast, catch curves for 2009–2011 for SS and 2009–2013 for FS show increasing or asymptotic survey abundances across numerous cohorts indicating increased catchability to the survey. Similarly, estimated survey abundance of numerous cohorts in both stocks increased considerably from the 2017 to 2019 survey, indicating an important increase in catchability. Time varying catchability prior to 2009 and during the mid 2010s cannot be ruled out, but is very likely of much smaller magnitude compared to the periods mentioned above. Temporal variability in catchability means that the acoustic survey does not provide a consistent index of relative abundance for these stocks. If it can be assumed that natural mortality (M) for SS and FS herring is constant, it might be possible in the future to explicitly model catchability as time-varying in the assessment model (e.g., McDermid et al. 2018). Otherwise, de-confounding temporal variation in M from variation in catchability will be very difficult and likely impossible unless there is external information for one of the two parameters or if one or more additional reliable indices of abundance are available.

3.5. SPRING SPAWNER COMPONENT ASSESSMENT

3.5.1. Catch-at-Age

The catch-at-age of SS in the 2018 and 2019 fishing seasons was characterized by the dominance of the 2013 cohort (Figure 19). This cohort accounted for 45.4% and 44.1% of all landings (in numbers) respectively in 2018 and 2019. The estimated number of fish at age 2 in the commercial fishery in 2019 was the highest for that age group since 1965. This may reflect an abundant year class, changes in management measures beginning in 2018 which favour the catch of smaller herring, or both. Specifically, the regulated minimum size was decreased from 26.5 cm to 24.8 cm (fork length) beginning in 2018, based on a review of age at maturity (DFO 2018b), and the tolerance level for landing small herring was increased from 10 to 20 percent in 2019. Other dominant cohorts for this stock were those of 1968, 1974, 1980, 1982, 1987, 1990, 1996, 1997, 1999 and 2002 (Figure 19; Table 5).

3.5.2. Length at 50% Maturity

The L50s for SS declined from 1962 to 1993 (cohort years) and increased towards the overall mean for the 1993–1997 cohorts (Figure 20). For the 1999 to 2016 cohorts, the length at maturity was variable and showed no consistent trend. The 2000–2008 cohorts were characterized by L50s around the overall mean while the L50 for the 2009–2014 cohorts were mostly below the mean. It was not possible to estimate L50 for the 1998 cohort because no immature fish were sampled. Large bootstrapped confidence intervals for some cohorts were associated with small sample sizes. The arithmetic mean of the L50 for the 1962–2016 cohorts is 271 mm (total length).

3.5.3. Age at 50% Maturity

Age at fifty percent maturity varied between 2.4 and 4.0 years of age between 1965 and 2019 with a mean of 3.27 years (Figure 21). Periods of higher and lower than average values were observed, the 2005–2017 period being characterized by a decline in A50 followed by the 2 highest values of the data series in 2018 and 2019. The 2018 and 2019 MAA and A50 were identical since they were both computed with the last 3 years of data. The 95% bootstrapped confidence intervals are larger since 2007, which was related to the smaller sample sizes (Table 4).

3.5.4. Maturity-at-Age

SS herring MAA was estimated using the same models as for A50, and showed annual variation for ages 2 to 4 (Figure 22). Proportion mature for these ages increased from 1965 to 2001, then rapidly declined to reach low values in the 2004–2014 period, peaked again in 2015–2016 and then rapidly declined to reach the 2 lowest values of the data series in 2018 and 2019 (Figure 22, Table 6).

3.5.5. Weight-at-Age

Weight-at-age could not be estimated for age 2 and age 11+ SS herring for 11 and 3 years respectively, because of missing samples for the reference levels in the standardization model (section WEIGHT-AT-AGE). The arithmetic mean of the standardized weight-at-age over all years used for these two age classes were respectively 0.064 kg and 0.411 kg. Age 2 standardized weight-at-age showed no consistent trend through time. Weight at ages 3 to 11+ increased from the beginning of the data series to the early 1980s and showed a variable yet clearly declining trend afterwards (Figure 23 and Table 7).

3.5.6. Acoustic Survey Index

The biomass of SS herring was estimated at 20 125 t for the August 2019 survey while the biomass was estimated at 47 522 t in October and November. The 2019 summer and fall acoustic biomass estimates were the highest since the survey restarted in 2009 (Figure 24). The spatial distribution of herring biomass during these two surveys is shown in Figure 15 and biomass estimated in different strata in tables 8 and 9. The ratio of the biomass fished in 2019 and the biomass estimated during the 2019 fall acoustic survey corresponds to an exploitation rate of 8.1% (F = 0.085). This exploitation rate is considered a maximum estimate, but is subject to change since the 2019 landings are preliminary.

The age-disaggregated survey index for SS herring did not follow the most dominant cohorts present in the commercial fishery catch-at-age (Table 10, Figure 25). This discrepancy with the commercial catch-at-age (Table 5, Figure 19) could be explained by low sample sizes for SS herring in the acoustic samples and/or the time-varying survey catchability. The 2019 age-disaggregated survey index for SS herring showed the highest number of age-2 fish since the beginning of the survey in 1991. The age-2 SS herring accounted for 64.0% of the individuals and 51.2% (24 330.9 t) of the biomass in the 2019 fall survey (Table 10 and Figure 25).

3.5.7. Stock Assessment Models

Model 1a estimated SSB to have varied substantially over the first three decades of the time series, increasing from less than 60 kt to over 120 kt in the early 1970s and in the mid 1980s (Figure 26A, Table 11). However, the SSB remained at lower levels (<50 kt) following the decrease observed during the 1990s. Several important recruitment peaks were estimated prior to these increases in SSB (e.g., 1970, 1971, 1982 and 1984, Figure 26A). The recruitment during the last year was estimated to be extremely high and is likely a model artefact caused by the over-estimation of age 2 abundance in the 2019 acoustic survey index. Generally, the age structure predicted by model 1a closely followed the cohorts observed in the fishery catch-at-age (Figure 26B), but cohort abundances decreased more sharply over time in the former, which is not inconsistent given that the fishery tend to select for larger (older) individuals. Estimated fishing mortality, averaged over ages 2 to 11+, remained relatively low and constant from 1966 to 2011 (generally <0.4 or an exploitation rate of <33%). A subsequent increase in 2013 and 2014 (F~1.1, exploitation rate ~67%) resulted from the decrease in SSB while landings remained similar to previous years (Figure 26C). The estimated survey catchability (q) increased almost linearly with age (starting around 0.1 for age 2) to reach a maximum value at ages 10 and 11+ (around 1.4; Figure 26D). The fully recruited catchability>1 appears unrealistic given that the acoustic survey does not fully cover the distributional area for 4R herring and suggests that other aspects of the model may be misspecified (e.g., M).

Retrospective patterns, residual plots and predicted versus observed abundance plots for SS model 1a are shown in figures 27 and 28. A retrospective pattern was observed for SSB without a consistent trend. The strong positive retrospective pattern for average F was caused by the large retrospective pattern in abundance relative to the commercial landings; small changes in the estimation of the former are impactful on the perception of F (Figure 27). The positive Monh's rho value suggests a potential underestimation of F in recent years. The positive strong retrospective pattern in recruitment for recent years is caused by its unrealistic estimate for the final year and illustrates that recruitment cannot be reliably estimated by the model. Estimated survey abundance-at-age was highly correlated with observed survey abundances (Pearson's r = 0.71, p <0.001), but the model consistently underestimated the highest observed survey abundances (Figure 27D). Residual plots thus showed negatively skewed residuals (Figure 28). They did not show clear patterns by age or year (Figure 28A), although some grouping was present (e.g., the 2009–2011 negative residuals for ages 5 to 7).

SS model 1b, parameterized without the age-2 abundance index, produced very similar SSB, age structure, average F, and catchability coefficients to those of model 1a (Figure 29). However, final year recruitment was estimated at a level that appears more realistic (Figure 30C). Retrospective patterns were similar to those of model 1a, with the exception that recruitment retrospective patterns were not influenced by the substantial 2017 cohort (high numbers of age 2 in 2019) observed in model 1a (Figure 30). Predicted values were also highly correlated with observed survey indices (Pearson's r = 0.70, *p* <0.001) but the model underestimated the highest observed values (Figure 30D). Residuals from SS model 1b showed the same block of negative residuals for ages 5 to 7 in 2009–2011 as in model 1a, but were less asymmetric to the left than the ones from model 1a (Figure 31).

Models 2a and 2b differed from the previously presented models in their assumptions of M. A sensitivity analysis was run to determine the natural mortality for each block of five years resulting in the best model fit, based on the RSS. Note that the RSS of both scenarios (with and without age-2 survey data) cannot be compared because of dissimilarity in the number of data points and parameters (Figure 32). The sensitivity analysis clearly identified alternative values of M improving model fit only for the 1995–1999, 2000–2004 and 2005–2009 periods (Figure 32). The highest natural mortality rate was identified for the 1995–1999 period, whereas the lowest rate occurred just after (2000–2009; Figure 33). The natural mortality values leading to an optimal model fit cannot be explained by our current knowledge of the ecosystem. For instance, the abundance of numerous large groundfish that could be predators of herring declined considerably in the early 1990s, which all else being equal should have reduced M. This incoherent natural mortality pattern could denote problems in the model input, or more likely some confounding with changes in catchability. The SS VPA models 2a and 2b (with values of

M selected presented in Figure 33) were nonetheless fitted in an ultimate attempt to solve the residual and/or retrospective patterns of models 1a and 1b (Figures A59, A60, A62 and A63). However, both models showed instability as a retrospective analysis resulted in non-convergence after (model 2a) or at the first (model 2b) peel. Residual patterns remained skewed to the left (Figure A61 and Figure A64).

3.6. FALL SPAWNER COMPONENT ASSESSMENT

3.6.1. Catch-at-Age

The catch-at-age of the FS herring showed a dominance of age 11+ individuals in recent years and allowed to track dominant cohorts over time most clearly from age 4 onwards (Figure 34). In 2018, herring of the 2008 cohort (age 10) accounted for 26.9% of the total landings (in numbers) and the 11+ group totalled 31.5%. The 2019 fishing season was characterized by the dominance of individuals age 11 and older, representing 40.8% of the total landings (Figure 34). Previous dominant cohorts for this stock were those of 1979, 1990, 1995, 2000, and 2001 (Figure 34; Table 12). One of the highest number of age 3 fish was observed in 2019. Similar to the SS age 2 fish in 2019, it could be caused by an abundant year class, recent change in regulations or both.

3.6.2. Length at 50% Maturity

The L50 for FS varied between 256 mm and 316 mm for the 1961 to 2016 cohorts (Figure 35). The L50 was higher for cohorts born in the 1960s, lower for those from the 1970s, 1980s, and early 1990s, then around the time series mean of 284 mm for the 1995 to 2016 cohorts. The L50 for the 1963, 1964, 1971, 1975, 1976, 1983, and 1984 cohorts could not be estimated for November because there were no samples available for that month. The large bootstrapped 95% confidence intervals for some cohorts were associated with small sample sizes of juveniles and/or mature fish. The arithmetic mean of the L50 for the 1962–2016 cohorts is 284 mm (total length).

3.6.3. Age at 50% Maturity

The standardized A50 for FS varied between 2.7 and 5.6 years of age between 1965 and 2019 and the mean was 4.0 years (Figure 36). The A50 declined from 1965 to 1986, fluctuated below average until the mid 2000s and has since increased to above average. The large bootstrapped 95% confidence intervals were associated with small numbers of juvenile fish in commercial and research samples.

3.6.4. Maturity-at-Age

FS herring MAA was estimated using the same models as for A50, and showed an annual variation for ages 3 to 5. Proportion mature for these ages increased from 1965 to the mid 1980s, then showed a general decreasing trend until 2006 and remained at low values until 2019 (Figure 37, Table 13).

3.6.5. Weight-at-Age

Weight-at-age could not be estimated for the reference levels for age 2 and age 3 FS herring for a period of 24 years and 2 years respectively (Figure 38). The mean of the standardized weight-at-age for these two age classes were respectively 0.320 kg and 0.118 kg. Weight-at-age 2 remained constant over time whereas weight at age 3 declined over the last decade. Weight-at-age 4 to 11+ increased from the beginning of the data series to the early 1980s and showed a variable yet clearly declining trend, which continued until 2012 for ages 7 to 11+, and until 2018 or 2019 for ages 3 to 6 (Figure 38, Table 14).

3.6.6. Acoustic Survey Index

The acoustic biomass varied little between 1991 and 2002, while the 2009–2017 period showed greater among-year variability (Figure 39). The biomass of FS herring was estimated at 117 656 t during the August 2019 survey, but at 68 796 t in October and November of the same year (Figure 39). The spatial distribution of herring biomass during these two surveys is shown in Figure 15 and the biomass estimated per strata in Tables 8 and 9. The ratio of the biomass fished in 2019 and the biomass estimated during the 2019 fall acoustic survey corresponds to an exploitation rate of 17.3% (F = 0.190). This exploitation rate is considered a maximum estimate, but is subject to change since the 2019 landings are preliminary.

The age-disaggregated survey index for FS herring seemed to follow earlier dominant cohorts present in the commercial fishery catch-at-age (e.g., 1990, 1995, 2000, and 2001 cohorts; Figures 34 and 40), but patterns in the acoustic survey number-at-age after 2008 are more inconsistent and include year effects in which abundance was high across a range of ages (e.g., 2010 and 2013) (Figure 40, Tables 12 and 15). The 2019 age-disaggregated survey index showed the highest number of age 3 fish since the beginning of the survey in 1991 (Table 15 and Figure 40) and accounted for 32.4% of the survey abundance and 16.4% (11 313.6 t) of the survey biomass. Although this high contribution of young fish could be an indication of a strong 2016 cohort, its high value could at least be partly associated to a change in survey catchability based on biological samples independent from commercial fishery. Biomass per year and stratum for the 1991–2019 surveys are presented in tables A21 and A22.

3.6.7. Stock Assessment Models

The first model for FS herring (model 1a) estimated a sharp drop in SSB that occurred at the beginning of the time series (Figure 41A). Subsequently, estimated SSB remained relatively stable until a substantial increase in the late 2000s to SSB values comparable to those of the early 1970s. Between 2009 and 2017, SSB declined sharply from 187 510 t to 58 210 t. SSB is estimated to have increased recently, although the confidence intervals for this estimate are very wide (Figure 41A). Recruitment at age 2 was estimated to be highly variable, with certain periods (notably 2000–2010) of sustained higher levels (Figure 41B). An extreme peak was estimated in 2018, which might again be related to uncertainty in the observed lower age classes present in the recent survey index (2019 age 3). There were no signs of age truncation in the estimated abundance-at-age but, as SS model 1 predicted, cohort abundances tended to deplete more rapidly than in the fisheries catch-at-age data (Figures 34 and 41B). This difference between the catch-at-age and estimated abundance-at-age is not inconsistent given that the fishery tend to select for larger and older individuals. Estimated average fishing mortality was low to moderate throughout the time series (average F<0.2, Figure 41C). Estimated survey catchability increased with age, reaching a value of 1.7 for ages 11+ (Figure 41D).

Retrospective patterns, residual plots and predicted versus observed plots for FS model 1a are shown in Figure 42. A minor retrospective pattern for all but the last peel was estimated for SSB but did not show a consistent trend (Figure 41A). The retrospective analysis for average F showed a large value in 2014, which was caused by a lower SSB and landings of around 20 000 t. (Figures 41B, 42A and B). The positive Monh’s rho value for average F suggests an underestimation of this variable in recent years. The strong negative retrospective pattern in recruitment for recent years was caused by the model’s sensitivity to a probable over-representation of young age classes in the 2019 acoustic index.

The FS herring model 1a predicted survey abundance at age matching well the survey observations along the 1:1 line (Figure 42D). Residuals were normally distributed and did not show patterns across age classes (Figure 43B, C and D). However, there was a clear temporal residual pattern, with mostly positive residuals for the first block of surveys (1991–2002) and negative ones for the second block starting in 2009 (Figure 43A).

FS herring model 1b, parameterized without the ages 2 and 3 abundance indices, produced very similar SSBs, age structures, average Fs, and catchability coefficients to those of model 1a (Figure 44). Retrospective analysis could only be performed with one peel (fatal nonlinear least square error; Figure 45A, B and C). Predicted survey abundance at age matched the survey observations well along the 1:1 line (Figure 45D). FS herring model 1b residuals showed the same blocks of positive and negative residuals in the 1990–2002 and 2009–2014 periods as in model 1a (Figure 45). Residuals were also normally distributed and did not show patterns when plotted against predicted values or year (Figure 46B, C and D).

Sensitivity analyses on M performed for both model configurations (a and b) resulted in the identification of alternative M values from 1990 onwards, although the difference in RSS was generally minimal, except for 2010–2014 where an M of 0.05 produced a much smaller RSS (Figure 47). For both models, the selected natural mortality rate was highest during the 2000–2004 period, and lowest afterwards (2005–2019; Figure 48). The natural mortality values leading to an optimal model fit cannot be explained by our current ecosystem knowledge. For instance, the abundance of numerous large groundfish that could be predators of herring declined considerably in the early 1990s, which all else being equal should have reduced M. This incoherent natural mortality pattern could denote problems in the model inputs, or more likely some confounding with changes in catchability. The FS VPA models 2a and 2b (with values of M selected presented in Figure 48) were nonetheless fitted in an ultimate attempt to solve the residual and/or retrospective patterns of models 1a and 1b (Figures A65, A66, A68 and A69). Both models showed strong positive SSB and average F retrospective patterns (Figure A66 and Figure A69). The negative residuals pattern in the 2009–2014 period was also present in models 2a and 2b but to a lesser extent than in models 1a and 1b (Figure A67 and Figure A70).

3.7. ENVIRONMENTAL DRIVERS OF CONDITION

The Kn of SS and FS herring followed similar inter-annual variations. Kn for both stocks were low in the early 1970s, started to increase at the end of the 1970s and stayed high until the 2010s when the Kn of SS and FS herring started to decrease (Figure 49). The Kn of the SS herring reached a minimum in 2016. Indices describing the physical environment and the spring bloom showed high inter-annual variations without a consistent trend (Figure 50, 51). *Calanus* abundances were in general higher in the spring than in the fall (Figure 52). *C. finmarchicus* abundance peaked in 2008, 2012 and 2017. *C.hyperboreus* abundance peaked in 2003, 2009 and 2014. *Pseudocalanus* spp., small calanoids started to increase around 2010 which led to a decrease in the ratio of large and small calanoids. The phenology index for *C. finmarchicus* (C1–C4/C1–C6) in early summer showed a variable yet steady increase from 2001 to 2018, whereas the fall phenology index varied around the mean with no temporal trend. *C. hyperboreus* phenology index (C4/C1–C4) was low in 2001–2003, high during the 2004–2013 period and varied around mid-range values afterwards (Figure 49).

For the Kn of SS herring, the best models considering either only the physical environmental indices or the physical and spring bloom dynamics indices explained a lower deviance in Kn than the 95th percentile of the distribution of deviance explained by random values and were rejected (Table 17). The best model considering zooplankton abundance and phenology indices, however, explained 82.6% of deviance in Kn. The model was robust against missing years; the R^2 between observed and predicted Kn (0.80) during the jackknife is similar to the r^2 obtained with all data (0.78). According to this model, Kn of SS was higher when *Calanus* phenology was early in spring (more advanced development as indicated by a lower proportion of early stages CI–CIV) and when the ratio of large Calanoids copepods abundance (mainly *Calanus* species) relative to small Calanoid copepods abundance was high (Figure 53). Large Calanoids provide more energy per unit than small Calanoids, which could favour a higher net energy gain by herring during years of greater abundance of large Calanoids (Ljungström et al. 2020). Small Calanoids are becoming more abundant in the Gulf of St. Lawrence since 2014 (Blais et al. 2019), suggesting that herring may acquire less energy in recent years for the same foraging effort.

For the Kn of FS herring, the best model considering only physical indices showed strong temporal autocorrelation in residuals for lag 1–5 and was therefore rejected (Table 17). The best model included *C. finmarchicus* abundance and phenology indices in the fall and explained 61.4% of deviance in Kn. The model was robust against missing years, the R^2 between observed and predicted Kn (0.68) during the jackknife is similar to the r^2 obtained with all data (0.56). Kn of FS herring was greater when *C. finmarchicus* was more abundant and when the ratio C1–C4/C1–C6 (phenology) was lower, indicative of an earlier development of the second generation (Figure 54).

For the Rstrength, most models were rejected because the deviance explained was not superior to the distribution of deviance generated by the Monte Carlo simulations (Table 18). Models for the spring component showed better deviance than the Monte Carlo simulation. However, both low and high SSB had a positive effect on recruitment, this U-shape effect not in accordance with either a positive effect of SSB on R nor a potential negative effect through density-dependent processes. Since this relationship was against our hypothesis and was most likely due to correlation between SSB and environmental predictors, particularly zooplankton abundance and phenology, the models were rejected. Other models that did not include SSB did not explain more deviance than the Monte Carlo simulations.

The fall commercial fishery in 4R targets herring aggregations occurring off the western Newfoundland coast presumably before their migration to the overwintering habitats (Figure 55; McQuinn 1997). The timing of this fishery appeared variable among years but also showed a tendency to occur later during the second part (2009–2019) than the first part (1991–2002) of the acoustic survey time series (Figure 56). As the timing of herring migrations could be influenced by various factors including body condition (e.g., Slotte and Fiksen 2000 and references therein), we qualitatively explored the hypothesis that variations in the timing of herring aggregation in the fall could be associated to variations in body condition. In the absence of an explicit index of herring migration timing, we used the timing (week number) when late summer-autumn commercial landings of SS and FS components reach 50% and 75% of their total values as a potential proxy of the timing of herring migration/aggregation (Figure 55). Standardized Kn of SS (August) and FS (November) herring increased from low values during the 1970s to high values in the early 1980s and remained high until the mid-2000s; Kn then decreased between 2005 and 2019 (Figure 55, upper panels). The timing of the fishery in the fall apparently mirrored these changes with the fishery occurring generally earlier during the period of high Kn (1980–2004) than during periods with low Kn (before 1980, 2005–2019) (Figure 55, lower panels). The timing of the acoustic surveys occurred during the bulk of the commercial fisheries (as indicated by the 50%–75% timing) during the first period of the acoustic survey (1991–2002), but since 2009 the acoustic survey occurred mainly before the bulk of the fishery (Figure 55). This change in the relative timing of the acoustic survey and commercial fishery represented a deviation from the initial design of the survey aimed at targeting herring fall aggregations during the commercial fishery. An alternative hypothesis would be that a lower (higher) Kn could result from a commercial fishery occurring later (earlier) and capturing fish after (during) the seasonal peak in Kn. Explicitly testing these hypotheses and improving our understanding of factors driving observed changes in the timing of the commercial fishery in the fall and its correspondence with the acoustic survey nevertheless warrant more work in the future.

3.8. QUALITY OF THE ASSESSMENT

In previous peer review meetings (DFO 2016 and 2018b), concerns were raised related to some aspects of the acoustic survey. An assessment index requires estimates of one year to be comparable to the next, so that trends in abundance or biomass can be identified and ascribed to either natural processes and commercial fisheries activities. However, as shown in the catch curve analysis, the catchability of the hydroacoustic survey is likely to have varied over time. This change is possibly related to the timing of the survey (end of October to beginning of November) which remained relatively constant, whereas peak fishing activity shifted over time (around the end of September to beginning of December), which could be indicative of a change in fish behaviour and hence its availability to the survey. Additionally, sampling effort and coverage varied between years as well, with transect density (zero, sparse or high, Figure A57) and distance from shore being among the identified concerns. Finally, the biological sampling used to split the biomass between SS and FS herring and to convert the biomass into number-at-age was done with varying gear from year to year, which could result in changes in the relative catchability of different ages or spawning groups, was dependent on the commercial fishery samples for most of the recent years, and sample sizes were frequently very small in the case of SS herring.

In this document we aimed to refit the VPA model while attempting to address some of these concerns, and a detailed analysis of the model diagnostics was presented. The diagnostics and sensitivity analyses performed assuming basic population dynamic equations (VPA model) confirmed inconsistencies (residual patterns, sensitivity to M, which is confounded with and may be aliasing variability in q) and uncertainty in the recent stock state. Consequently, the SS and FS herring VPA models were rejected during the peer review meeting

SS and FS herring in 4R are relative data-rich stocks, although there are key uncertainties in the fishery independent data. The available information for 4R spring and fall herring used to assess stock state and fishing pressure is summarized in Table 19, and advice is provided based on the amount and quality of each data source combined.

4. CONCLUSION AND ADVICE

The likely change in catchability of the acoustic survey which led to the rejection of the population model for the two herring stocks on the west coast of Newfoundland prevents a quantitative assessment of the stocks states. However, there are several biological indications that herring populations on the west coast of Newfoundland are not presently overfished.

The commercial fishery catch-at-age follows the progression of the cohorts in the fishery up to age 11+ for the two spawning stocks, indicating low overall mortality. The catch-at-age is also dominated by old individuals for the FS stock which is subject to the majority of landings. In an overexploited stock, cohorts would likely disappear before reaching advanced ages and landings would be dominated by young individuals (Berkeley et al. 2004).

The length at 50% maturity in the two spawning stocks shows variable trends around the mean for the 1962 to 2016 cohorts. The age at 50% maturity is variable around the mean for the SS and has increased over the past decade in FS. Excessive fishing pressure would have been expected to reduce the L50 and A50 (Kuparinen and Merilä 2007).

The abundance of juvenile fish observed in the 2019 acoustic surveys, by commercial fishermen and in the commercial catch-at-age for spring and fall spawners is an encouraging sign for the future, but will need to be monitored and validated.

Although the acoustic survey presents uncertainties hindering the interpretation of temporal trends and absolute values of abundance, the calculated biomass in 2019 represents a minimum estimate of the quantity of fish available at the time of the survey. The maximum exploitation rates estimated from this biomass and the 2019 commercial fishery were low, but could be revised since 2019 landings are preliminary.

In conclusion, the information available up to 2019 (commercial catch-at-age, age and length at maturity, abundance of young fish, low exploitation rate in 2019) indicate that current catch levels do not pose a significant short-term risk to herring stocks in 4R. There is evidence that the SS herring stock state was relatively low during the last decade and that the FS stock state was moderate in recent years. There is a sign of recent increase for both stocks, but this needs to be confirmed with additional years of data. This conclusion will need to be reconsidered following the review of the evaluation framework.

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TABLES

Table 1. Differences between VPA models 1a, 1b, 2a and 2b. SS and FS: respectively spring and fall spawning herring.

Model	Including age 2 in survey NAA	Including age 3 in survey NAA	M
SS Model 1a	Yes	Yes	0.2
SS Model 1b	No	Yes	0.2
SS Model 2a	Yes	Yes	Sensitivity analysis
SS Model 2b	No	Yes	Sensitivity analysis
FS Model 1a	Yes	Yes	0.2
FS Model 1b	No	No	0.2
FS Model 2a	Yes	Yes	Sensitivity analysis
FS Model 2b	No	No	Sensitivity analysis

Table 2. Annual landings (t) and Total Allowable Catch (TAC) of herring per fishing gear and unit area in NAFO Division 4R from 1966 to 2019. 2018 and 2019 data are preliminary.

YEAR	4Ra							4Rb						
	Large seiner	Small seiner	Gillnet	Tuck seine	Trap	Other*	TOTAL	Large seiner	Small seiner	Gillnet	Tuck seine	Trap	Other*	TOTAL
1966	0	-	45	-	-	-	**45**	5 491	-	39	-	-	-	**5 530**
1967	0	-	40	-	-	-	**40**	5 464	-	76	-	-	-	**5 540**
1968	0	-	11	-	-	-	**11**	3 776	-	67	-	-	-	**3 843**
1969	0	-	68	-	-	-	**68**	2 344	-	201	-	-	-	**2 545**
1970	0	-	407	-	-	-	**407**	2 939	-	534	-	-	-	**3 473**
1971	356	-	1 598	-	-	-	**1 954**	725	-	338	-	-	-	**1 063**
1972	0	-	3 628	-	-	-	**3 628**	1 330	-	214	-	-	-	**1 544**
1973	3 453	-	5 760	-	-	-	**9 213**	1 763	-	305	-	-	-	**2 068**
1974	1 071	-	1 972	-	-	-	**3 043**	439	-	479	-	-	-	**918**
1975	0	-	1 764	-	-	22	**1 786**	0	-	240	-	-	26	**266**
1976	184	-	2 143	-	-	140	**2 467**	0	-	226	-	-	20	**246**
1977	2 155	-	2 028	-	-	183	**4 366**	0	-	158	-	-	31	**189**
1978	1 834	-	3 795	-	-	22	**5 651**	0	-	288	-	-	81	**369**
1979	0	-	3 258	-	-	7	**3 265**	2 829	-	1 048	-	-	121	**3 998**
1980	428	-	3 810	-	-	5	**4 243**	2 002	-	879	-	-	88	**2 969**
1981	342	-	1 600	-	-	27	**1 969**	2 037	-	913	-	-	140	**3 090**
1982[2]	0	-	1 695	-	-	1	**1 696**	3 973	-	519	-	-	58	**4 550**
1983[2]	787	-	1 438	-	-	34	**2 259**	3 223	-	226	-	-	108	**3 557**
1984[2]	15	-	790	-	-	4	**809**	4 166	-	554	-	-	2	**4 722**
1985[2]	0	-	295	-	-	6	**301**	9 718	-	348	-	-	4	**10 070**
1986[2]	0	-	337	-	-	0	**337**	15 830	-	468	-	-	0	**16 298**
1987	164	-	829	-	-	0	**993**	10 164	-	327	-	-	5	**10 496**
1988	44	-	509	-	-	0	**553**	1 093	-	256	-	-	0	**1 349**
1989	13	-	337	-	-	0	**350**	947	-	69	-	-	0	**1 016**
1990	0	0	323	0	54	0	**377**	1 145	0	174	-	13	0	**1 332**
1991	0	151	368	-	56	1	**576**	6 567	270	103	-	7	0	**6 947**
1992	0	347	440	-	115	-	**902**	3 954	145	47	-	1	0	**4 147**
1993	362	332	55	-	103	-	**852**	1 899	299	0	-	0	0	**2 198**
1994	72	406	394	-	145	1	**1 017**	4 063	1 487	161	-	0	0	**5 711**
1995	464	580	1 215	-	24	0	**2 284**	2 138	930	101	-	104	0	**3 273**
1996	226	404	1 883	-	70	0	**2 584**	1 896	886	143	-	27	0	**2 951**
1997	0	617	1 765	-	189	1	**2 571**	2 192	1 097	8	-	154	0	**3 451**
1998	577	647	2 793	-	110	2	**4 129**	4 750	1 455	1 398	-	123	3	**7 729**
1999	610	379	600	-	64	-	**1 653**	3 409	1 060	269	-	28	0	**4 766**
2000	414	307	1 231	-	29	0	**1 981**	1 776	1 149	40	-	30	0	**2 995**
2001	1 228	223	1 157	-	5	0	**2 613**	1 076	1 360	58	-	145	4	**2 643**
2002	247	233	1 103	-	9	13	**1 604**	1 407	1 029	121	-	64	-	**2 621**
2003	-	23	1 193	-	74	-	**1 290**	110	148	426	-	30	-	**714**
2004	-	185	429	-	99	0	**712**		169	53	-	28	2	**252**
2005	-	110	537	72	329	90	**1 137**	733	1 340	467	502	191	340	**3 574**
2006	18	81	446	12	400	0	**957**	1 830	1 841	171	1 673	99	31	**5 645**
2007	14	148	43	0	680	0	**884**	106	322	78	382	26	-	**915**
2008	-	31	-	0	700	-	**731**	2 679	523	1	83	-	-	**3 286**
2009	-	97	0	-	725	0	**821**	1 516	732	-	2 179	147	0	**4 573**
2010	-	-	451	-	533	0	**984**	3 310	838	69	1 411	23	-	**5 651**
2011	-	51	2 017	-	625	0	**2 694**	5 486	469	89	345	0	0	**6 389**
2012	-	103	1 362	65	862	4	**2 396**	5 150	3 509	421	169	-	0	**9 249**
2013	-	86	718	87	1 087	-	**1 977**	5 051	2 663	145	648	144	0	**8 651**
2014	-	445	92	135	1 414	43	**2 129**	9 171	4 226	4	371	26	0	**13 798**
2015	140	500	680	75	928	-	**2 322**	10 936	3 738	0	1 241	-	-	**15 915**
2016	742	522	623	179	1 129	-	**3 195**	9 576	3 473	-	1 103	3	99	**14 253**
2017	852	447	545	252	746	-	**2 842**	7 048	2 375	1	265	-	37	**9 727**
2018[1]	-	117	511	514	423	-	**1 566**	3 551	526	1	281	1	-	**4 360**
2019[1]	1 362	585	671	1 544	289	-	**4 452**	5 446	1 758	9	573	-	-	**7 786**
MEAN (1966–2017)							**1 878**							**4 674**

**Includes shrimp trawl, bar seine, pelagic trawl and bottom trawl*
[1]Preliminary data; [2]Adjusted landings for purse seine based on industry data (McQuinn 1987a)

Table 2 (continued).

YEAR	4Rc							4Rd						
	Large seiner	Small seiner	Gillnet	Tuck seine	Trap	Other	TOTAL	Large seiner	Small seiner	Gillnet	Tuck seine	Trap	Other	TOTAL
1966	0	-	103	-	-	-	**103**	0	-	216	-	-	-	**216**
1967	0	-	66	-	-	-	**66**	0	-	215	-	-	-	**215**
1968	0	-	59	-	-	-	**59**	0	-	156	-	-	-	**156**
1969	0	-	46	-	-	-	**46**	241	-	36	-	-	-	**277**
1970	12	-	15	-	-	-	**27**	28	-	51	-	-	-	**79**
1971	2 239	-	185	-	-	-	**2 424**	3 287	-	543	-	-	-	**3 830**
1972	727	-	135	-	-	-	**862**	4 743	-	178	-	-	-	**4 921**
1973	2 740	-	122	-	-	-	**2 862**	12 112	-	429	-	-	-	**12 541**
1974	756	-	101	-	-	-	**857**	2 465	-	159	-	-	-	**2 624**
1975	0	-	112	-	-	16	**128**	3 221	-	116	-	-	3	**3 340**
1976	1 956	-	111	-	-	2	**2 069**	6 067	-	499	-	-	3	**6 569**
1977	2 009	-	193	-	-	3	**2 205**	5 289	-	272	-	-	7	**5 568**
1978	1 037	-	931	-	-	16	**1 984**	6 252	-	522	-	-	33	**6 807**
1979	2 774	-	2 267	-	-	2	**5 043**	4 387	-	1 642	-	-	3	**6 032**
1980	3 703	-	3 224	-	-	17	**6 944**	3 499	-	1 558	-	-	41	**5 098**
1981	3 277	-	1 622	-	-	0	**4 899**	2 269	-	1 368	-	-	2	**3 639**
1982[2]	5 575	-	1 572	-	-	11	**7 158**	0	-	1 463	-	-	3	**1 466**
1983[2]	3 269	-	873	-	-	46	**4 188**	0	-	1 410	-	-	2	**1 412**
1984[2]	3 023	-	902	-	-	0	**3 925**	0	-	1 006	-	-	1	**1 007**
1985[2]	1 733	-	164	-	-	0	**1 897**	1 720	-	398	-	-	0	**2 118**
1986[2]	1 586	-	1 069	-	-	0	**2 655**	1 854	-	273	-	-	0	**2 127**
1987	3 183	-	1 137	-	-	0	**4 320**	222	-	550	-	-	0	**772**
1988	13 197	-	592	-	-	0	**13 789**	2 019	-	435	-	-	0	**2 454**
1989	6 589	-	444	-	-	0	**7 033**	9 111	-	177	-	-	0	**9 288**
1990	824	248	187	-	0	0	**1 259**	3 275	1 768	152	-	0	0	**5 196**
1991	1 577	741	175	-	0	0	**2 494**	14 961	1 326	133	-	0	0	**16 420**
1992	1 271	82	37	-	0	0	**1 391**	7 589	1 279	27	-	1	0	**8 896**
1993	740	276	9	-	0	4	**1 029**	8 634	2 333	55	-	0	0	**11 022**
1994	2 026	951	75	-	0	0	**3 053**	1 472	1 010	117	-	0	0	**2 599**
1995	5 457	1 680	179	-	5	1	**7 321**	2 755	201	163	-	12	1	**3 134**
1996	6 751	1 332	84	-	5	1	**8 173**	600	450	65	-	0	0	**1 114**
1997	4 237	1 042	11	-	7	2	**5 300**	1 322	296	19	-	0	0	**1 638**
1998	3 712	2 173	5	-	0	1	**5 891**	428	160	21	-	0	0	**609**
1999	2 195	891	0	-	0	0	**3 087**	932	269	0	-	0	0	**1 201**
2000	4 766	1 697	5	-	0	0	**6 469**	1 470	0	0	-	0	0	**1 470**
2001	4 708	1 578	-	-	-	93	**6 379**	1 332	257	-	-	-	-	**1 589**
2002	5 929	1 721	9	-	-	-	**7 660**	809	400	23	-	-	0	**1 232**
2003	2 192	401	1	-	-	0	**2 593**	8 788	1 735	10	-	-	0	**10 533**
2004	5 673	489	-	-	-	-	**6 162**	5 426	2 131	17	-	-	-	**7 574**
2005	4 693	925	-	269	-	2	**5 889**	5 579	1 543	27	65	9	103	**7 326**
2006	3 029	991	3	433	-	-	**4 457**	6 224	1 028	82	182	-	22	**7 538**
2007	10 834	1 866	4	1 119	-	8	**13 831**	-	323	7	45	-	-	**375**
2008	4 165	666	-	837	-	-	**5 668**	4 341	3 137	2	3 578	-	-	**11 058**
2009	8 306	1 839	-	562	-	-	**10 707**	1 349	1 748	-	1 037	-	-	**4 134**
2010	3 352	715	3	272	-	-	**4 342**	3 556	3 397	2	1 270	4	-	**8 228**
2011	2 770	1 399	2	609	-	120	**4 899**	2 004	3 510	-	929	-	46	**6 489**
2012	1 821	866	7	280	-	19	**2 994**	3 076	694	-	828	-	114	**4 712**
2013	2 643	2 063	51	1 564	-	-	**6 322**	2 291	93	1	38	-	-	**2 424**
2014	303	287	-	49	-	-	**640**	520	546	-	520	-	-	**1 585**
2015	92	170	-	358	-	17	**637**	-	63	-	356	-	127	**546**
2016	681	336	-	1 105	-	89	**2 211**	-	66	-	207	-	-	**273**
2017	1 272	350	-	480	-	-	**2 102**	456	140	-	170	-	-	**767**
2018[1]	275	238	-	94	-	-	**607**	250	86	-	550	-	-	**885**
2019[1]	869	1 324	-	881	-	-	**3 073**	-	91	-	380	-	-	**470**
MEAN (1966–2017)							**4 010**							**4 082**

**Includes shrimp trawl, bar seine, pelagic trawl and bottom trawl*
[1]Preliminary data; [2]Adjusted landings for purse seine based on industry data (McQuinn 1987a)

Table 2 (continued).

YEAR	TOTAL												TAC
	Large seiner	Small seiner	Gillnet	Tuck seine	Trap	Other*	Total	4Ra	4Rb	4Rc	4Rd	4R	
1966	5 491	0	403	0	0	0	5 894	68	2 545	46	277	2 936	-
1967	5 464	0	397	0	0	0	5 861	407	3 473	27	79	3 986	-
1968	3 776	0	293	0	0	0	4 069	1 954	1 063	2 424	3 830	9 271	-
1969	2 585	0	351	0	0	0	2 936	3 628	1 544	862	4 921	10 955	-
1970	2 979	0	1 007	0	0	0	3 986	9 213	2 068	2 862	12 541	26 684	-
1971	6 607	0	2 664	0	0	0	9 271	3 043	918	857	2 624	7 442	-
1972	6 800	0	4 155	0	0	0	10 955	1 786	266	128	3 340	5 520	-
1973	20 068	0	6 616	0	0	0	26 684	2 467	246	2 069	6 569	11 351	-
1974	4 731	0	2 711	0	0	0	7 442	4 366	189	2 205	5 568	12 328	-
1975	3 221	0	2 232	0	0	67	5 520	5 651	369	1 984	6 807	14 811	-
1976	8 207	0	2 979	0	0	165	11 351	3 265	3 998	5 043	6 032	18 338	-
1977	9 453	0	2 651	0	0	224	12 328	4 243	2 969	6 944	5 098	19 254	12 000
1978	9 123	0	5 536	0	0	152	14 811	1 969	3 090	4 899	3 639	13 597	12 500
1979	9 990	0	8 215	0	0	133	18 338	1 696	4 550	7 158	1 466	14 870	12 500
1980	9 632	0	9 471	0	0	151	19 254	2 259	3 557	4 188	1 412	11 416	18 000
1981	7 925	0	5 503	0	0	169	13 597	809	4 722	3 925	1 007	10 463	16 000
1982[2]	9 548	0	5 249	0	0	73	14 870	301	10 070	1 897	2 118	14 386	10 000
1983[2]	7 279	0	3 947	0	0	190	11 416	337	16 298	2 655	2 127	21 417	10 000
1984[2]	7 204	0	3 252	0	0	7	10 463	993	10 496	4 320	772	16 581	10 000
1985[2]	13 171	0	1 205	0	0	10	14 386	553	1 349	13 789	2 454	18 145	10 000
1986[2]	19 270	0	2 147	0	0	0	21 417	350	1 016	7 033	9 288	17 687	17 000
1987	13 733	0	2 843	0	0	5	16 581	377	1 332	1 259	5 196	8 164	30 600
1988	16 353	0	1 792	0	0	0	18 145	576	6 947	2 494	16 420	26 437	30 600
1989	16 660	0	1 027	0	0	0	17 687	902	4 147	1 391	8 896	15 336	37 000
1990	5 245	2 016	836	0	66	0	8 164	852	2 198	1 029	11 022	15 100	35 000
1991	23 106	2 488	779	0	62	1	26 437	1 017	5 711	3 053	2 599	12 380	35 000
1992	12 815	1 853	552	0	117	0	15 336	2 284	3 273	7 321	3 134	16 012	35 000
1993	11 634	3 240	119	0	103	4	15 100	2 584	2 951	8 173	1 114	14 823	35 000
1994	7 634	3 854	747	0	145	1	12 380	2 571	3 451	5 300	1 638	12 960	35 000
1995	10 815	3 392	1 658	0	145	2	16 012	4 129	7 729	5 891	609	18 359	22 000
1996	9 472	3 072	2 175	0	102	1	14 823	1 653	4 766	3 087	1 201	10 707	22 000
1997	7 751	3 052	1 803	0	350	3	12 960	1 981	2 995	6 469	1 470	12 916	22 000
1998	9 468	4 434	4 217	0	233	6	18 359	68	2 545	46	277	2 936	22 000
1999	7 146	2 599	869	0	92	0	10 707	407	3 473	27	79	3 986	13 000
2000	8 427	3 153	1 277	0	59	0	12 916	1 954	1 063	2 424	3 830	9 271	15 000
2001	8 344	3 418	1 215	0	150	97	13 224	2 613	2 643	6 379	1 589	13 224	15 000
2002	8 392	3 383	1 256	0	73	13	13 117	1 604	2 621	7 660	1 232	13 117	15 000
2003	11 090	2 307	1 630	0	104	0	15 131	1 290	714	2 593	10 533	15 130	20 000
2004	11 099	2 974	499	0	127	2	14 701	712	252	6 162	7 574	14 700	20 000
2005	11 005	3 918	1 031	908	529	535	17 926	1 137	3 574	5 889	7 326	17 926	20 000
2006	11 101	3 941	702	2 300	499	53	18 596	957	5 645	4 457	7 538	18 597	20 000
2007	10 954	2 659	132	1 546	706	8	16 005	884	915	13 831	375	16 005	20 000
2008	11 185	4 357	3	4 498	700	0	20 743	731	3 286	5 668	11 058	20 743	20 000
2009	11 171	4 416	0	3 778	872	0	20 237	821	4 573	10 707	4 134	20 235	20 000
2010	10 218	4 950	525	2 953	560	0	19 206	984	5 651	4 342	8 228	19 205	20 000
2011	10 260	5 429	2 108	1 883	625	166	20 471	2 694	6 389	4 899	6 489	20 471	20 000
2012	10 047	5 172	1 790	1 342	862	137	19 350	2 396	9 249	2 994	4 712	19 351	20 000
2013	9 985	4 905	915	2 337	1 231	0	19 373	1 977	8 651	6 322	2 424	19 374	20 000
2014	9 994	5 504	96	1 075	1 440	43	18 152	2 129	13 798	640	1 585	18 152	20 000
2015	11 168	4 471	680	2 030	928	144	19 421	2 322	15 915	637	546	19 420	20 000
2016	10 999	4 397	623	2 594	1 132	188	19 933	3 195	14 253	2 211	273	19 932	20 000
2017	9 628	3 312	546	1 167	746	37	15 436	2 842	9 727	2 102	767	15 438	20 000
2018[1]	4 076	966	512	1 439	424	0	7 417	1 566	4 360	607	885	7 418	20 000
2019[1]	7 445	3 989	681	3 378	289	0	15 782	4 452	7 786	3 073	470	15 782	20 000
MEAN (1966–2017)	9 797	1 974	2 027	546	245	54	14 644	1 878	4 674	4 010	4 082	14 644	

*Includes shrimp trawl, bar seine, pelagic trawl and bottom trawl

[1]Preliminary data; [2]Adjusted landings for purse seine based on industry data (McQuinn 1987a)

Table 3. Reported landings and number of logbooks returned by year for the Atlantic herring bait fishery in NAFO Division 4R.

Year	Landings (t)	Number of logbooks
2017	32.93	24
2018	2.86	2
2019	8.56	6

Table 4. Number of Atlantic herring sampled by year, season, gear type and NAFO unit area from the commercial port sampling program and sent to MLI for further inspection of their biological characteristics. Fish sampled before and after August 1 are considered from the spring and fall fishery, respectively.

YEAR	Spring fishery								Fall fishery									TOTAL
	fixed				mobile				fixed				mobile					
	4Ra	4Rb	4Rc	4Rd	4Ra	4Rb	4Rc	4Rd	4Ra	4Rb	4Rc	4Rd	4R	4Ra	4Rb	4Rc	4Rd	
1965	0	0	0	0	0	0	0	0	0	100	0	0	0	0	465	0	0	565
1966	0	0	0	0	0	0	0	0	0	48	48	0	0	0	252	0	250	598
1967	0	100	0	94	0	163	0	88	50	277	78	0	0	0	545	0	0	1395
1968	0	0	0	0	0	50	26	300	0	0	0	24	0	0	350	0	0	750
1969	0	0	0	0	0	0	0	50	0	50	0	0	0	0	496	0	0	596
1970	100	0	0	0	0	0	0	200	248	350	0	0	0	0	149	0	0	1047
1971	200	0	0	0	0	0	300	150	0	550	0	0	0	50	150	0	0	1400
1972	150	50	0	100	0	0	97	350	400	400	0	0	0	0	1375	150	0	3072
1973	50	288	0	0	0	450	436	545	739	697	0	0	0	400	450	0	0	4055
1974	30	100	0	0	0	0	50	797	745	150	0	0	0	300	300	0	0	2472
1975	199	250	0	50	48	0	0	600	0	0	0	0	0	0	0	0	0	1147
1976	350	100	19	29	0	0	150	1190	150	0	0	0	0	447	0	0	0	2435
1977	535	140	0	0	0	0	695	1439	1048	50	0	0	0	200	290	0	0	4397
1978	750	276	0	100	0	94	94	721	350	0	0	0	0	1224	100	0	0	3709
1979	300	100	499	250	0	248	374	1069	750	100	0	0	0	300	150	0	0	4140
1980	1149	200	900	477	648	500	347	849	800	99	0	0	0	0	500	1085	0	7554
1981	500	259	1499	175	59	516	823	1375	396	37	0	0	0	0	1117	0	0	6756
1982	149	0	344	47	0	55	592	210	0	154	0	0	0	50	582	150	0	2333
1983	53	0	0	56	0	127	889	0	2099	343	0	0	0	274	1082	793	0	5716
1984	50	0	302	101	0	798	494	0	2006	247	100	0	0	106	2918	0	0	7122
1985	0	0	543	352	0	506	1328	282	1049	0	0	0	0	0	3747	349	0	8156
1986	149	0	845	890	0	129	364	401	1237	90	150	0	0	0	1650	50	0	5955
1987	0	0	943	795	0	105	241	167	1535	92	0	0	0	58	971	204	47	5158
1988	344	0	1061	699	50	101	101	1267	1253	220	0	0	0	57	1137	102	0	6392
1989	178	0	1071	448	0	462	191	622	755	194	0	0	0	118	838	358	81	5316
1990	148	0	513	338	0	2	159	508	883	50	0	0	0	2	1045	85	97	3830
1991	200	0	299	296	0	127	216	315	440	50	0	0	0	93	831	278	1	3146
1992	200	0	329	399	0	313	218	185	247	0	0	0	0	155	948	203	177	3374
1993	422	0	745	500	0	389	133	1010	1312	0	0	0	0	200	597	246	0	5554
1994	337	0	730	600	0	358	1207	636	1119	69	0	0	0	187	1250	757	232	7482
1995	420	50	399	699	0	100	366	255	1236	0	0	0	190	254	515	765	264	5513
1996	300	50	346	848	100	0	450	0	1259	250	0	0	192	200	100	600	100	4795
1997	150	0	578	900	0	0	150	250	633	0	0	0	68	250	400	600	150	4129
1998	200	0	197	486	50	0	649	50	800	50	0	0	100	100	250	50	50	3032
1999	200	0	278	848	150	315	67	0	100	0	0	0	339	732	380	1151	0	4560
2000	250	0	278	650	50	0	250	100	200	50	0	0	88	100	550	250	0	2816
2001	350	0	395	400	200	50	100	50	50	50	0	0	0	350	349	450	99	2893
2002	150	50	287	497	150	208	250	150	0	50	0	0	47	250	484	349	183	3105
2003	150	0	310	399	100	125	550	0	0	0	0	0	0	0	100	50	1199	2983
2004	50	0	345	399	0	0	100	0	0	0	0	0	0	0	0	600	750	2244
2005	0	0	164	247	0	0	192	0	0	0	0	0	0	0	93	49	901	1646

YEAR	Spring fishery								Fall fishery									TOTAL
	fixed				mobile				fixed					mobile				
	4Ra	4Rb	4Rc	4Rd	4Ra	4Rb	4Rc	4Rd	4Ra	4Rb	4Rc	4Rd	4R	4Ra	4Rb	4Rc	4Rd	
2006	0	0	264	109	50	0	50	50	0	50	0	0	0	0	450	50	1000	2073
2007	0	0	0	0	100	0	0	0	0	50	99	0	0	0	98	1252	0	1599
2008	0	0	0	0	0	0	0	0	0	0	0	100	0	0	428	250	578	1356
2009	0	0	0	0	0	0	349	0	0	350	0	0	0	0	919	1482	441	3541
2010	150	0	0	0	0	0	150	0	0	298	0	0	182	0	299	443	350	1872
2011	150	0	0	0	0	50	199	0	0	198	0	0	0	231	299	208	785	2120
2012	107	0	0	0	0	0	0	0	0	53	0	0	0	55	1104	0	603	1922
2013	220	0	0	0	0	0	110	0	0	0	0	0	0	67	1331	479	359	2566
2014	218	0	0	0	0	0	0	0	110	55	0	0	0	0	1537	0	330	2250
2015	0	0	0	0	0	0	0	0	110	48	0	0	0	111	1265	0	110	1644
2016	0	0	0	0	55	0	0	0	0	0	0	0	0	275	1154	317	0	1801
2017	164	0	0	0	110	0	0	0	0	0	0	0	0	277	759	165	276	1751
2018	165	0	0	0	0	323	0	0	0	0	0	0	0	56	831	0	330	1705
2019	0	0	0	0	55	0	0	0	0	11	0	0	0	596	1538	415	238	2853

Table 5. Commercial catch-at-age (000's) of spring spawning herring in NAFO Division 4R from 1965 to 2019.

YEAR	AGE									
	2	3	4	5	6	7	8	9	10	11+
1965	630	73	13	693	1 602	1 293	651	461	305	509
1966	115	283	276	520	1 822	4 176	2 090	1 652	382	638
1967	0	18	459	139	318	3 403	2 745	1 265	742	847
1968	84	163	302	549	203	569	1 120	2 049	420	358
1969	366	1 730	2 778	1 026	500	264	703	1 259	1 185	117
1970	1 067	570	297	435	182	75	116	565	1 615	61
1971	0	2 527	303	841	720	651	340	350	2 412	255
1972	284	220	8 189	1 308	1 461	1 245	1 115	1 377	1 034	2 013
1973	1 833	435	1 063	27 872	2 570	3 222	3 232	2 598	4 789	5 696
1974	141	261	130	371	9 445	318	851	774	490	2 175
1975	57	996	420	100	1 063	8 431	317	336	244	665
1976	484	680	846	201	350	2 802	15 567	759	3 136	3 588
1977	10	534	541	409	304	348	4 362	15 959	1 694	6 003
1978	0	47	1 987	207	679	241	2 162	8 208	15 260	5 062
1979	167	25	214	10 828	617	1 075	547	2 772	7 404	14 032
1980	300	854	106	355	13 872	407	1 344	247	1 427	20 574
1981	40	417	2 114	129	354	8 872	188	515	283	13 181
1982	594	2 374	693	2 452	421	2 153	6 488	704	950	12 863
1983	34	2 965	3 562	1 131	1 091	293	713	2 990	798	7 975
1984	198	433	7 773	3 809	595	814	209	672	755	4 226
1985	362	4 587	787	21 642	3 993	445	381	255	380	1 764
1986	323	2 348	13 762	3 349	28 781	5 241	465	167	260	1 661
1987	455	329	2 781	15 257	3 507	12 952	1 736	182	37	806
1988	702	539	402	2 461	15 064	3 677	13 616	2 527	423	2 060
1989	305	574	763	461	3 036	18 704	3 072	10 910	779	1 380
1990	114	2 136	670	405	997	5 010	16 296	3 773	6 432	2 187
1991	577	2 233	9 849	1 285	768	3 018	6 955	21 327	2 366	6 579
1992	90	1 243	1 707	8 538	998	998	2 781	2 168	11 879	3 902
1993	79	1 592	3 802	3 409	6 784	1 509	2 102	2 727	2 800	8 804
1994	14	332	2 597	3 183	3 762	3 434	1 642	1 589	1 757	1 945
1995	12	247	1 219	5 750	5 807	2 152	7 126	185	3 083	4 577
1996	1 347	248	1 156	4 056	7 712	4 211	551	3 291	419	1 597
1997	36	1 006	131	259	1 303	6 598	1 684	580	2 554	1 588
1998	80	859	7 836	393	579	2 143	7 683	1 146	994	3 174
1999	152	1 815	3 501	4 583	202	156	749	1 532	378	943
2000	0	3 106	7 182	2 207	3 971	108	248	765	857	773
2001	189	184	3 627	6 440	4 045	3 794	146	338	766	1 651
2002	0	6 545	515	6 643	8 770	3 672	3 525	179	411	869
2003	0	1 016	5 576	1 367	5 085	6 021	1 924	931	204	569
2004	1 048	722	2 224	4 829	2 307	8 375	5 591	1 113	320	841
2005	149	2 935	2 504	653	3 439	809	4 282	5 182	1 984	2 155
2006	63	391	4 973	4 891	1 402	1 643	1 529	2 011	919	575
2007	0	45	332	3 055	1 492	527	385	381	574	1 060
2008	57	62	141	857	5 078	740	635	361	345	475
2009	94	422	469	206	1 339	7 141	2 735	908	1 453	2 612
2010	0	32	248	232	404	1 473	3 301	1 143	445	1 437
2011	0	95	222	161	159	449	1 570	1 256	463	642
2012	0	63	195	462	1 018	748	591	2 918	3 259	499
2013	0	69	520	1 300	207	871	1 259	2 961	1 905	564
2014	0	50	111	169	172	124	126	113	17	150
2015	377	1 150	308	210	333	55	138	0	72	0
2016	0	1 569	1 232	476	188	99	290	131	71	851
2017	0	228	3 484	1 941	442	585	702	596	134	375
2018	0	506	346	1 980	614	306	65	406	93	41
2019	3732	290	1257	838	8523	2771	795	143	277	691

Table 6. Spring spawning herring maturity-at-age in NAFO Division 4R from 1965 to 2019.

YEAR	AGE									
	2	3	4	5	6	7	8	9	10	11+
1965	0.009	0.105	0.606	0.953	0.996	1.000	1.000	1.000	1.000	1.000
1966	0.009	0.105	0.606	0.953	0.996	1.000	1.000	1.000	1.000	1.000
1967	0.016	0.155	0.668	0.957	0.996	1.000	1.000	1.000	1.000	1.000
1968	0.070	0.291	0.690	0.924	0.985	0.997	0.999	1.000	1.000	1.000
1969	0.068	0.296	0.707	0.933	0.988	0.998	1.000	1.000	1.000	1.000
1970	0.068	0.298	0.712	0.935	0.988	0.998	1.000	1.000	1.000	1.000
1971	0.002	0.083	0.805	0.995	1.000	1.000	1.000	1.000	1.000	1.000
1972	0.004	0.105	0.787	0.992	1.000	1.000	1.000	1.000	1.000	1.000
1973	0.005	0.115	0.771	0.989	1.000	1.000	1.000	1.000	1.000	1.000
1974	0.021	0.199	0.745	0.972	0.998	1.000	1.000	1.000	1.000	1.000
1975	0.030	0.211	0.697	0.952	0.994	0.999	1.000	1.000	1.000	1.000
1976	0.024	0.211	0.746	0.970	0.997	1.000	1.000	1.000	1.000	1.000
1977	0.017	0.217	0.819	0.987	0.999	1.000	1.000	1.000	1.000	1.000
1978	0.010	0.190	0.844	0.992	1.000	1.000	1.000	1.000	1.000	1.000
1979	0.141	0.594	0.929	0.992	0.999	1.000	1.000	1.000	1.000	1.000
1980	0.113	0.684	0.973	0.998	1.000	1.000	1.000	1.000	1.000	1.000
1981	0.137	0.714	0.975	0.998	1.000	1.000	1.000	1.000	1.000	1.000
1982	0.117	0.481	0.866	0.978	0.997	1.000	1.000	1.000	1.000	1.000
1983	0.035	0.354	0.892	0.992	0.999	1.000	1.000	1.000	1.000	1.000
1984	0.005	0.194	0.920	0.998	1.000	1.000	1.000	1.000	1.000	1.000
1985	0.011	0.375	0.970	0.999	1.000	1.000	1.000	1.000	1.000	1.000
1986	0.012	0.343	0.958	0.999	1.000	1.000	1.000	1.000	1.000	1.000
1987	0.044	0.519	0.963	0.998	1.000	1.000	1.000	1.000	1.000	1.000
1988	0.035	0.449	0.948	0.998	1.000	1.000	1.000	1.000	1.000	1.000
1989	0.050	0.418	0.908	0.993	0.999	1.000	1.000	1.000	1.000	1.000
1990	0.039	0.406	0.920	0.995	1.000	1.000	1.000	1.000	1.000	1.000
1991	0.043	0.333	0.849	0.984	0.999	1.000	1.000	1.000	1.000	1.000
1992	0.042	0.351	0.871	0.988	0.999	1.000	1.000	1.000	1.000	1.000
1993	0.063	0.402	0.870	0.985	0.999	1.000	1.000	1.000	1.000	1.000
1994	0.220	0.584	0.874	0.972	0.994	0.999	1.000	1.000	1.000	1.000
1995	0.267	0.625	0.884	0.972	0.994	0.999	1.000	1.000	1.000	1.000
1996	0.126	0.439	0.809	0.958	0.992	0.999	1.000	1.000	1.000	1.000
1997	0.052	0.354	0.846	0.982	0.998	1.000	1.000	1.000	1.000	1.000
1998	0.064	0.347	0.805	0.970	0.996	0.999	1.000	1.000	1.000	1.000
1999	0.101	0.431	0.837	0.972	0.996	0.999	1.000	1.000	1.000	1.000
2000	0.088	0.440	0.865	0.981	0.998	1.000	1.000	1.000	1.000	1.000
2001	0.339	0.766	0.954	0.993	0.999	1.000	1.000	1.000	1.000	1.000
2002	0.267	0.816	0.982	0.998	1.000	1.000	1.000	1.000	1.000	1.000
2003	0.120	0.718	0.979	0.999	1.000	1.000	1.000	1.000	1.000	1.000
2004	0.005	0.146	0.849	0.995	1.000	1.000	1.000	1.000	1.000	1.000
2005	0.040	0.245	0.717	0.952	0.994	0.999	1.000	1.000	1.000	1.000
2006	0.110	0.308	0.616	0.853	0.954	0.987	0.996	0.999	1.000	1.000
2007	0.135	0.337	0.625	0.845	0.947	0.983	0.995	0.998	1.000	1.000
2008	0.098	0.273	0.564	0.817	0.939	0.981	0.995	0.998	1.000	1.000
2009	0.119	0.386	0.745	0.931	0.984	0.997	0.999	1.000	1.000	1.000
2010	0.083	0.343	0.750	0.945	0.990	0.998	1.000	1.000	1.000	1.000
2011	0.027	0.210	0.715	0.960	0.996	1.000	1.000	1.000	1.000	1.000
2012	0.063	0.280	0.692	0.929	0.987	0.998	1.000	1.000	1.000	1.000
2013	0.175	0.447	0.754	0.921	0.978	0.994	0.998	1.000	1.000	1.000
2014	0.172	0.441	0.749	0.919	0.977	0.994	0.998	1.000	1.000	1.000
2015	0.056	0.487	0.939	0.996	1.000	1.000	1.000	1.000	1.000	1.000
2016	0.387	0.585	0.760	0.876	0.941	0.973	0.988	0.994	0.997	0.999
2017	0.285	0.554	0.795	0.924	0.974	0.992	0.997	0.999	1.000	1.000
2018	0.007	0.074	0.478	0.913	0.992	0.999	1.000	1.000	1.000	1.000
2019	0.007	0.074	0.478	0.913	0.992	0.999	1.000	1.000	1.000	1.000

Table 7. Standardized Weight-at-age (kg) of spring spawning herring in NAFO Division 4R from 1965 to 2019. The reference levels used in standardization are: NAFO subunit = 4Rd, Month = August, gear = small purse seiner (<65').

YEAR	AGE									
	2	3	4	5	6	7	8	9	10	11+
1965	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
1966	0.064	0.185	0.214	0.261	0.258	0.262	0.286	0.305	0.368	0.078
1967	0.076	0.160	0.212	0.267	0.273	0.302	0.314	0.322	0.383	0.365
1968	0.062	0.141	0.233	0.268	0.268	0.297	0.308	0.319	0.366	0.322
1969	0.074	0.181	0.240	0.252	0.255	0.284	0.308	0.326	0.351	0.078
1970	0.052	0.177	0.252	0.263	0.278	0.298	0.351	0.348	0.375	0.404
1971	0.078	0.160	0.221	0.253	0.262	0.283	0.305	0.325	0.348	0.402
1972	0.066	0.165	0.209	0.244	0.275	0.301	0.305	0.321	0.363	0.372
1973	0.063	0.165	0.217	0.233	0.249	0.295	0.333	0.329	0.369	0.376
1974	0.069	0.188	0.247	0.243	0.254	0.294	0.327	0.347	0.357	0.393
1975	0.059	0.185	0.250	0.263	0.257	0.293	0.312	0.360	0.386	0.431
1976	0.060	0.185	0.227	0.256	0.258	0.273	0.309	0.324	0.341	0.374
1977	0.048	0.170	0.237	0.261	0.272	0.286	0.302	0.317	0.368	0.368
1978	0.078	0.198	0.243	0.300	0.307	0.310	0.332	0.345	0.367	0.399
1979	0.073	0.192	0.266	0.284	0.324	0.337	0.370	0.368	0.382	0.420
1980	0.081	0.225	0.278	0.315	0.329	0.368	0.389	0.396	0.406	0.447
1981	0.069	0.224	0.278	0.354	0.355	0.386	0.420	0.437	0.486	0.488
1982	0.079	0.210	0.280	0.296	0.347	0.383	0.402	0.417	0.450	0.460
1983	0.081	0.185	0.265	0.305	0.328	0.369	0.410	0.398	0.459	0.466
1984	0.064	0.198	0.251	0.297	0.336	0.367	0.408	0.406	0.437	0.486
1985	0.076	0.185	0.264	0.284	0.318	0.361	0.385	0.423	0.433	0.464
1986	0.073	0.182	0.239	0.271	0.300	0.320	0.392	0.401	0.424	0.466
1987	0.056	0.173	0.249	0.280	0.323	0.341	0.372	0.393	0.411	0.481
1988	0.070	0.206	0.251	0.274	0.302	0.334	0.372	0.379	0.446	0.484
1989	0.059	0.214	0.262	0.307	0.317	0.348	0.388	0.389	0.421	0.483
1990	0.063	0.183	0.257	0.317	0.336	0.355	0.376	0.400	0.428	0.450
1991	0.065	0.199	0.241	0.280	0.325	0.358	0.382	0.398	0.426	0.451
1992	0.047	0.158	0.231	0.270	0.299	0.373	0.395	0.401	0.435	0.448
1993	0.055	0.164	0.209	0.263	0.285	0.343	0.377	0.391	0.417	0.434
1994	0.042	0.151	0.198	0.231	0.273	0.303	0.359	0.369	0.397	0.395
1995	0.043	0.179	0.205	0.236	0.273	0.307	0.335	0.380	0.384	0.400
1996	0.070	0.170	0.222	0.246	0.270	0.309	0.358	0.359	0.431	0.447
1997	0.045	0.141	0.187	0.252	0.277	0.298	0.344	0.359	0.386	0.446
1998	0.088	0.142	0.187	0.252	0.294	0.303	0.334	0.371	0.392	0.433
1999	0.045	0.162	0.206	0.230	0.280	0.313	0.343	0.349	0.397	0.431
2000	0.078	0.173	0.201	0.256	0.265	0.329	0.363	0.370	0.384	0.451
2001	0.062	0.206	0.231	0.243	0.275	0.296	0.361	0.362	0.381	0.415
2002	0.034	0.194	0.237	0.266	0.286	0.315	0.347	0.412	0.420	0.463
2003	0.078	0.157	0.225	0.279	0.293	0.313	0.341	0.348	0.413	0.432
2004	0.070	0.153	0.247	0.266	0.297	0.317	0.345	0.365	0.406	0.426
2005	0.066	0.140	0.195	0.263	0.276	0.304	0.322	0.329	0.344	0.385
2006	0.101	0.150	0.189	0.226	0.264	0.296	0.322	0.318	0.346	0.360
2007	0.100	0.140	0.179	0.204	0.212	0.268	0.302	0.307	0.329	0.365
2008	0.073	0.142	0.236	0.241	0.248	0.268	0.301	0.308	0.335	0.362
2009	0.078	0.150	0.208	0.211	0.250	0.273	0.273	0.309	0.358	0.375
2010	0.051	0.162	0.200	0.232	0.267	0.288	0.304	0.334	0.381	0.389
2011	0.078	0.158	0.187	0.205	0.218	0.271	0.275	0.298	0.335	0.342
2012	0.078	0.118	0.167	0.195	0.241	0.299	0.300	0.346	0.374	0.383
2013	0.078	0.127	0.180	0.190	0.211	0.279	0.312	0.338	0.352	0.369
2014	0.078	0.136	0.186	0.210	0.226	0.266	0.319	0.313	0.346	0.357
2015	0.060	0.142	0.179	0.199	0.189	0.174	0.252	0.272	0.331	0.078
2016	0.078	0.136	0.176	0.193	0.206	0.233	0.253	0.279	0.283	0.338
2017	0.078	0.126	0.162	0.187	0.226	0.262	0.282	0.294	0.326	0.356
2018	0.042	0.127	0.183	0.197	0.222	0.244	0.311	0.336	0.356	0.360
2019	0.038	0.137	0.161	0.193	0.209	0.236	0.250	0.279	0.267	0.345

Table 8. Herring biomass densities and estimates by stratum from the fishery-independent acoustic survey conducted in August 2019. Standard error (S.E.) and coefficient of variation (C.V.) of the biomass estimates were computed based on the variance of transects biomass by stratum (O'Boyle and Atkinson 1989).

2019	**Stratum**				**All herring area backscattering coefficient (s_a)**					**Fall spawning herring**				**Spring spawning herring**			
Summer survey Name	**Number**	**Area** (***km²***)	**No. transects**	**Mean length** (***m***)	**Sampling dens.** (***km/km²***)	**Tot. Scattering** (**s_a * area; m²**)	**Weighted mean s_a** (***m²/m²***)	**S.E.**	**C.V.**	**Biom. dens.** (***kg/m²***)	**Biomass** **Tot. (*t*)**	**S.E.**	**C.V.**	**Biom. dens.** (***kg/m²***)	**Biomass** **Tot. (*t*)**	**S.E.**	**C.V.**
St-Georges S	1	407.7	3	8552.0	0.063	1514.1	3.71E-06	3.76E-06	101.4	0.008	3443.9	3491.4	101.4	0.001	536.9	544.3	101.4
St-Georges N	2	302.7	6	7417.8	0.147	1098.3	3.63E-06	2.89E-06	79.6	0.008	2509.2	1988.2	79.2	0.001	391.2	310.0	79.2
Port-au-Port G	3	806.3	5	10795.3	0.067	733.2	9.09E-07	5.58E-07	61.3	0.002	1664.7	1022.7	61.4	0.000	259.5	159.4	61.4
Port-au-Port	4	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Bay of Islands G	5	474.5	4	16250.8	0.137	4973.1	1.05E-05	8.09E-06	77.2	0.031	14521.7	11204.1	77.2	0.003	1370.4	1057.3	77.2
Bonne Bay B	6	1148.2	11	12843.5	0.123	3417.2	2.98E-06	1.10E-06	37.0	0.007	7613.7	2825.1	37.1	0.002	2209.5	819.9	37.1
Bay of Islands G	7	335.4	7	10821.8	0.226	12367.5	3.69E-05	1.49E-05	40.3	0.067	22563.3	9382.7	41.6	0.017	5774.5	2401.3	41.6
Bonne Bay	8	58.5	6	3328.6	0.341	965.5	1.65E-05	5.29E-06	32.0	0.035	2045.1	656.1	32.1	0.010	612.1	196.4	32.1
Hawk's Bay	9	499.8	6	9672.9	0.116	454.2	9.09E-07	2.24E-07	24.7	0.002	1120.9	276.8	24.7	0.001	261.4	64.5	24.7
St John Bay	10	996.9	7	17100.8	0.120	19479.2	1.95E-05	1.22E-05	62.6	0.052	51768.9	32401.4	62.6	0.008	7668.6	4799.7	62.6
Belle Isle S.	11	312.0	7	5885.9	0.132	3419.8	1.10E-05	4.95E-06	45.1	0.028	8653.3	3911.0	45.2	0.003	865.7	391.3	45.2
Belle Isle N.	12	626.8	7	9748.5	0.109	690.9	1.10E-06	4.84E-07	43.9	0.003	1751.3	768.7	43.9	0.000	175.2	76.9	43.9
Average / Total:		5968.8	69	10338.1	0.120	49113.0	1.08E-04	2.27E-05	21.1	0.020	117656.0	36124.6	30.7	0.003	20125.1	5586.8	27.8

Table 9. Herring biomass densities and estimates by stratum from the fishery-independent acoustic survey conducted in October and November 2019. Standard error (S.E.) and coefficient of variation (C.V.) of the biomass were computed based on the transects biomass variance by stratum (O'Boyle and Atkinson 1989).

2019	**Stratum**				**All herring area backscattering coefficient (s_a)**					**Fall spawning herring**				**Spring spawning herring**			
Fall survey Name	**Number**	**Area** (***km²***)	**No. transects**	**Mean length** (***m***)	**Sampling dens.** (***km/km²***)	**Tot. Scattering** (**s_a * area; m²**)	**Weighted mean s_a** (***m²/m²***)	**S.E.**	**C.V.**	**Biom. dens.** (***kg/m²***)	**Biomass** **Tot. (*t*)**	**S.E.**	**C.V.**	**Biom. dens.** (***kg/m²***)	**Biomass** **Tot. (*t*)**	**S.E.**	**C.V.**
St-Georges S	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
St-Georges N	2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Port-au-Port G	3	730.0	3	11777.4	0.048	2792.9	3.83E-06	1.49E-06	39.0	0.010	7568.0	998.4	38.8	0.004	2573.9	998.4	38.8
Port-au-Port	4	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Bay of Islands G	5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Bonne Bay B	6	972.8	7	11869.2	0.085	12230.8	1.26E-05	3.91E-06	31.1	0.025	23866.1	4044.9	31.1	0.013	13021.7	4044.9	31.1
Bay of Islands G	7	299.9	3	18479.7	0.185	672.9	2.24E-06	6.38E-07	28.4	0.005	1417.4	191.1	27.7	0.002	689.7	191.1	27.7
Bonne Bay	8	58.5	4	2867.0	0.196	161.8	2.77E-06	7.77E-07	28.1	0.005	315.8	48.4	28.1	0.003	172.3	48.4	28.1
Hawk's Bay	9	499.9	5	10602.4	0.106	3954.8	7.91E-06	4.72E-06	59.7	0.008	4097.0	3574.2	59.8	0.012	5977.2	3574.2	59.8
St John Bay	10	996.9	6	16279.4	0.098	21733.0	2.18E-05	2.59E-06	11.9	0.032	31531.2	2987.1	11.9	0.025	25087.9	2987.1	11.9
Belle Isle S.	11	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Belle Isle N.	12	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Average / Total:	-	3557.9	28	12000.4	0.094	41546.2	5.11E-05	6.90E-06	13.5	0.019	68795.5	6252.5	13.2	0.013	47522.7	6252.5	13.2

Table 10. *Spring spawning herring number-at-age from the fall acoustic surveys.*

YEAR	AGE									
	2	3	4	5	6	7	8	9	10	11+
1991	5252	14241	78462	216	13484	43972	26318	48683	8773	44080
1993	15591	36865	32008	26686	41341	1567	6965	6965	5398	12879
1995	1000	4627	5587	32838	12184	6786	18560	5301	12356	14334
1997	128	18951	2380	4341	17636	29299	12529	343	27038	5618
1999	4597	44622	24176	29285	725	0	988	8243	1786	8323
2002	1217	8112	909	16287	33965	23812	19822	238	4709	1190
2009	0	1346	0	485	3769	10014	2423	1938	969	3284
2010	2900.2	5996.2	62616	920	1518	12254	17779	4280	1311	1047
2011	0	8838.9	3086	3364	3225	279	5951	5952	5923	5255
2013	0	0	16396	3560	848	3392	3110	0	173	0
2015	0	508.3	3962	1321	0	0	0	0	364	0
2017	0	0	4879	18292	0	0	0	1424	0	1424
2019	314759	37518	4450	7082	90861	10034	24389	153	0	2695

Table 11. *Spring and fall spawning stock biomass (SSB) estimated by VPA model 1a from 1966 to 2019 in NAFO Division 4R.*

YEAR	Spring SSB	Fall SSB	YEAR	Spring SSB	Fall SSB
1966	37824	210408	**1993**	49326	55032
1967	43843	209912	**1994**	42511	58011
1968	49476	215845	**1995**	40843	64634
1969	55661	194592	**1996**	32101	59047
1970	63017	187375	**1997**	25080	50847
1971	74240	157995	**1998**	23690	44884
1972	130634	121001	**1999**	24683	41982
1973	180844	95534	**2000**	32948	45819
1974	181226	83120	**2001**	41156	46276
1975	165588	73449	**2002**	40637	48472
1976	142633	60414	**2003**	34978	48545
1977	122036	50118	**2004**	28422	85919
1978	120789	44461	**2005**	22084	117829
1979	114854	36403	**2006**	18625	137742
1980	96519	30233	**2007**	18553	137856
1981	72370	31479	**2008**	18592	177051
1982	54214	41377	**2009**	18908	187510
1983	48545	70802	**2010**	14151	179715
1984	78789	82651	**2011**	10965	169742
1985	95241	80241	**2012**	9273	161504
1986	125950	76661	**2013**	7913	147395
1987	131265	70586	**2014**	6689	131238
1988	118842	65686	**2015**	9407	114228
1989	103584	61033	**2016**	16266	85989
1990	87899	58279	**2017**	19055	58210
1991	77220	55913	**2018**	19348	58472
1992	60448	52225	**2019**	21731	70067

Table 12. Commercial catch-at-age (000's) of fall spawning herring in NAFO Division 4R from 1965 to 2019.

YEAR	AGE									
	2	3	4	5	6	7	8	9	10	11+
1965	17	655	476	235	271	303	1 010	653	355	722
1966	44	76	682	318	348	232	1 181	931	845	2 517
1967	0	112	181	790	369	124	433	934	1 011	3 108
1968	0	170	108	209	935	223	174	284	998	1 913
1969	34	299	711	364	876	736	200	142	214	1 859
1970	0	466	187	33	51	251	90	71	89	1 688
1971	40	0	112	440	638	2 150	3 485	2 071	1 073	14 138
1972	10	96	115	1 310	1 345	2 852	2 165	3 577	2 173	28 342
1973	0	1 798	1 180	1 114	2 626	1 527	2 631	3 830	8 265	17 653
1974	0	20	393	530	325	592	258	308	313	5 610
1975	0	19	40	865	925	107	157	147	218	3 371
1976	0	48	272	290	422	561	325	253	88	4 818
1977	0	3	169	134	404	721	405	342	293	6 646
1978	0	10	27	545	393	1 108	1 689	503	341	6 051
1979	0	7	116	345	2 689	520	1 287	1 847	468	6 286
1980	15	181	136	86	176	1 729	250	675	308	5 243
1981	0	33	524	245	90	295	1 234	153	124	3 369
1982	101	567	1 824	956	509	140	377	972	315	2 609
1983	15	83	2 330	1 356	1 309	506	159	467	618	2 824
1984	0	55	668	6 259	1 147	908	220	146	268	3 091
1985	15	235	1 340	1 907	9 678	902	622	115	36	468
1986	35	426	1 431	2 671	2 292	8 421	794	384	66	227
1987	0	156	487	1 354	2 009	1 728	5 927	474	163	196
1988	484	207	511	481	1 240	1 740	1 667	4 165	705	777
1989	43	599	539	923	807	749	828	961	2 873	983
1990	27	530	1 568	424	306	429	384	839	481	4 718
1991	73	832	1 278	5 763	674	1 501	919	649	2 144	7 124
1992	0	337	1 446	1 448	1 236	775	543	779	390	3 928
1993	21	210	672	1 957	1 015	1 661	558	911	877	4 608
1994	0	61	994	2 777	4 032	3 104	2 435	1 630	1 179	3 999
1995	65	91	1 419	6 159	3 512	3 905	1 211	3 189	411	4 246
1996	0	1 969	1 358	2 531	8 573	2 304	3 927	828	1 968	3 130
1997	0	593	1 726	877	1 086	7 649	2 193	4 949	562	4 200
1998	0	597	4 802	8 820	2 995	2 029	13 268	1 251	4 289	4 493
1999	0	989	10 785	4 245	4 103	1 178	858	4 238	1 096	2 222
2000	572	359	3 154	10 673	3 175	2 854	998	352	5 329	3 807
2001	83	2 503	589	4 829	9 608	3 647	2 607	532	546	2 265
2002	0	216	6 476	831	2 147	3 660	958	502	110	1 305
2003	227	8 782	3 910	4 227	2 130	6 168	4 305	1 212	441	2 674
2004	51	776	7 653	2 889	2 368	2 252	6 841	1 859	318	2 510
2005	181	734	2 668	21 815	4 036	2 825	1 113	2 252	2 577	2 610
2006	0	440	1 318	9 622	30 865	5 447	3 620	2 673	2 925	3 509
2007	34	871	3 007	4 355	13 677	30 979	3 083	1 928	577	2 594
2008	76	1 666	2 503	1 978	5 327	17 332	31 643	5 561	1 535	4 184
2009	139	402	6 271	2 710	2 530	4 146	11 850	24 999	2 685	3 274
2010	0	86	481	3 491	2 463	3 877	9 354	24 053	10 584	3 304
2011	0	871	883	1 596	3 837	4 047	5 040	15 725	24 198	9 639
2012	0	194	3 435	2 140	2 886	5 905	5 398	9 070	17 350	14 875
2013	6	421	2 106	10 581	4 307	4 768	8 565	8 951	12 192	11 657
2014	63	769	960	1 445	11 580	4 894	6 104	10 515	10 642	18 242
2015	42	3 961	4 967	1 782	2 037	12 376	5 151	6 817	9 913	23 145
2016	52	325	2 878	4 069	1 488	2 559	13 341	5 678	6 366	31 838
2017	0	152	899	4 809	3 428	1 061	3 697	11 233	7 280	17 404
2018	23	222	395	733	1 718	1 391	1 769	3 129	6 059	7 114
2019	50	2 814	881	1 094	1 815	4 134	5 373	3 513	5 141	17 088

Table 13. Fall spawning herring maturity-at-age in NAFO Division 4R from 1965 to 2019.

YEAR	AGE									
	2	3	4	5	6	7	8	9	10	11+
1965	0.000	0.001	0.088	0.898	0.999	1.000	1.000	1.000	1.000	1.000
1966	0.001	0.012	0.204	0.848	0.992	1.000	1.000	1.000	1.000	1.000
1967	0.000	0.002	0.077	0.818	0.996	1.000	1.000	1.000	1.000	1.000
1968	0.011	0.068	0.319	0.752	0.951	0.992	0.999	1.000	1.000	1.000
1969	0.003	0.022	0.124	0.475	0.853	0.974	0.996	0.999	1.000	1.000
1970	0.045	0.199	0.566	0.873	0.973	0.995	0.999	1.000	1.000	1.000
1971	0.013	0.089	0.426	0.849	0.977	0.997	1.000	1.000	1.000	1.000
1972	0.000	0.001	0.092	0.946	1.000	1.000	1.000	1.000	1.000	1.000
1973	0.000	0.001	0.111	0.939	0.999	1.000	1.000	1.000	1.000	1.000
1974	0.029	0.164	0.566	0.897	0.983	0.997	1.000	1.000	1.000	1.000
1975	0.014	0.180	0.778	0.982	0.999	1.000	1.000	1.000	1.000	1.000
1976	0.019	0.293	0.899	0.995	1.000	1.000	1.000	1.000	1.000	1.000
1977	0.001	0.052	0.804	0.997	1.000	1.000	1.000	1.000	1.000	1.000
1978	0.008	0.126	0.717	0.978	0.999	1.000	1.000	1.000	1.000	1.000
1979	0.005	0.081	0.596	0.961	0.998	1.000	1.000	1.000	1.000	1.000
1980	0.001	0.046	0.639	0.985	1.000	1.000	1.000	1.000	1.000	1.000
1981	0.047	0.358	0.862	0.986	0.999	1.000	1.000	1.000	1.000	1.000
1982	0.004	0.395	0.990	1.000	1.000	1.000	1.000	1.000	1.000	1.000
1983	0.012	0.352	0.961	0.999	1.000	1.000	1.000	1.000	1.000	1.000
1984	0.050	0.611	0.979	0.999	1.000	1.000	1.000	1.000	1.000	1.000
1985	0.020	0.289	0.890	0.994	1.000	1.000	1.000	1.000	1.000	1.000
1986	0.157	0.660	0.953	0.995	1.000	1.000	1.000	1.000	1.000	1.000
1987	0.018	0.208	0.791	0.982	0.999	1.000	1.000	1.000	1.000	1.000
1988	0.026	0.215	0.740	0.967	0.997	1.000	1.000	1.000	1.000	1.000
1989	0.001	0.053	0.707	0.990	1.000	1.000	1.000	1.000	1.000	1.000
1990	0.006	0.090	0.613	0.962	0.998	1.000	1.000	1.000	1.000	1.000
1991	0.002	0.080	0.760	0.991	1.000	1.000	1.000	1.000	1.000	1.000
1992	0.018	0.123	0.511	0.886	0.983	0.998	1.000	1.000	1.000	1.000
1993	0.004	0.073	0.600	0.966	0.998	1.000	1.000	1.000	1.000	1.000
1994	0.005	0.080	0.606	0.964	0.998	1.000	1.000	1.000	1.000	1.000
1995	0.169	0.545	0.876	0.976	0.996	0.999	1.000	1.000	1.000	1.000
1996	0.010	0.167	0.792	0.986	0.999	1.000	1.000	1.000	1.000	1.000
1997	0.008	0.109	0.649	0.965	0.998	1.000	1.000	1.000	1.000	1.000
1998	0.076	0.373	0.811	0.969	0.996	0.999	1.000	1.000	1.000	1.000
1999	0.011	0.111	0.591	0.944	0.995	1.000	1.000	1.000	1.000	1.000
2000	0.007	0.090	0.590	0.954	0.997	1.000	1.000	1.000	1.000	1.000
2001	0.001	0.038	0.739	0.995	1.000	1.000	1.000	1.000	1.000	1.000
2002	0.010	0.163	0.793	0.987	0.999	1.000	1.000	1.000	1.000	1.000
2003	0.001	0.028	0.597	0.987	1.000	1.000	1.000	1.000	1.000	1.000
2004	0.002	0.069	0.703	0.987	1.000	1.000	1.000	1.000	1.000	1.000
2005	0.001	0.022	0.384	0.945	0.998	1.000	1.000	1.000	1.000	1.000
2006	0.003	0.034	0.271	0.798	0.977	0.998	1.000	1.000	1.000	1.000
2007	0.002	0.018	0.127	0.530	0.897	0.985	0.998	1.000	1.000	1.000
2008	0.002	0.025	0.220	0.759	0.972	0.997	1.000	1.000	1.000	1.000
2009	0.000	0.005	0.122	0.786	0.990	1.000	1.000	1.000	1.000	1.000
2010	0.006	0.034	0.173	0.558	0.884	0.979	0.996	0.999	1.000	1.000
2011	0.002	0.019	0.147	0.608	0.933	0.992	0.999	1.000	1.000	1.000
2012	0.003	0.043	0.444	0.934	0.996	1.000	1.000	1.000	1.000	1.000
2013	0.011	0.064	0.300	0.729	0.944	0.991	0.998	1.000	1.000	1.000
2014	0.007	0.037	0.177	0.545	0.870	0.974	0.995	0.999	1.000	1.000
2015	0.000	0.009	0.179	0.837	0.992	1.000	1.000	1.000	1.000	1.000
2016	0.003	0.033	0.291	0.829	0.983	0.999	1.000	1.000	1.000	1.000
2017	0.001	0.007	0.044	0.236	0.675	0.933	0.989	0.998	1.000	1.000
2018	0.008	0.056	0.305	0.764	0.960	0.994	0.999	1.000	1.000	1.000
2019	0.000	0.010	0.195	0.859	0.994	1.00	1.00	1.00	1.00	1.00

Table 14. Standardized Weight-at-age (kg) of fall spawning herring in NAFO Division 4R from 1965 to 2019. The reference levels used in standardization are: NAFO subunit = 4Ra, Month = November, gear = small purse seiner (<65').

YEAR	AGE									
	2	3	4	5	6	7	8	9	10	11+
1965	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
1966	0.010	0.144	0.209	0.255	0.250	0.291	0.276	0.321	0.352	0.421
1967	0.032	0.132	0.189	0.254	0.273	0.328	0.336	0.374	0.374	0.439
1968	0.032	0.125	0.241	0.258	0.297	0.343	0.321	0.349	0.362	0.428
1969	0.020	0.119	0.214	0.241	0.279	0.329	0.352	0.366	0.368	0.420
1970	0.032	0.126	0.218	0.251	0.276	0.320	0.360	0.365	0.370	0.443
1971	0.014	0.118	0.234	0.247	0.286	0.328	0.354	0.369	0.395	0.439
1972	0.017	0.118	0.195	0.236	0.288	0.323	0.346	0.354	0.377	0.422
1973	0.032	0.119	0.223	0.255	0.288	0.350	0.392	0.389	0.407	0.450
1974	0.033	0.128	0.234	0.272	0.280	0.308	0.382	0.378	0.416	0.470
1975	0.032	0.122	0.212	0.262	0.300	0.312	0.342	0.388	0.408	0.492
1976	0.030	0.129	0.208	0.220	0.286	0.313	0.302	0.317	0.407	0.478
1977	0.032	0.202	0.228	0.274	0.291	0.354	0.363	0.343	0.342	0.462
1978	0.032	0.128	0.244	0.275	0.331	0.384	0.399	0.382	0.395	0.493
1979	0.032	0.138	0.246	0.292	0.336	0.405	0.443	0.461	0.463	0.525
1980	0.013	0.165	0.257	0.319	0.359	0.420	0.453	0.470	0.474	0.558
1981	0.032	0.142	0.285	0.313	0.368	0.449	0.480	0.510	0.523	0.574
1982	0.032	0.136	0.253	0.315	0.340	0.451	0.486	0.494	0.515	0.547
1983	0.032	0.158	0.246	0.287	0.327	0.376	0.419	0.476	0.498	0.547
1984	0.032	0.135	0.261	0.289	0.340	0.392	0.441	0.467	0.523	0.567
1985	0.032	0.133	0.240	0.287	0.323	0.382	0.403	0.431	0.462	0.527
1986	0.032	0.104	0.258	0.271	0.322	0.375	0.407	0.416	0.429	0.520
1987	0.032	0.121	0.253	0.309	0.331	0.397	0.427	0.423	0.456	0.510
1988	0.014	0.111	0.228	0.278	0.309	0.355	0.415	0.445	0.451	0.498
1989	0.021	0.110	0.248	0.293	0.346	0.408	0.441	0.467	0.480	0.526
1990	0.032	0.118	0.231	0.274	0.332	0.393	0.397	0.414	0.469	0.486
1991	0.039	0.132	0.242	0.268	0.319	0.387	0.426	0.446	0.467	0.493
1992	0.027	0.111	0.212	0.246	0.290	0.348	0.396	0.429	0.461	0.491
1993	0.013	0.102	0.211	0.238	0.288	0.346	0.379	0.427	0.453	0.496
1994	0.041	0.107	0.166	0.215	0.259	0.322	0.360	0.411	0.421	0.464
1995	0.048	0.116	0.210	0.227	0.283	0.347	0.394	0.410	0.462	0.471
1996	0.032	0.117	0.194	0.241	0.264	0.314	0.362	0.399	0.418	0.485
1997	0.030	0.123	0.188	0.226	0.268	0.313	0.333	0.390	0.422	0.462
1998	0.032	0.120	0.185	0.210	0.248	0.286	0.331	0.343	0.382	0.464
1999	0.019	0.115	0.193	0.245	0.269	0.341	0.370	0.397	0.425	0.483
2000	0.055	0.124	0.200	0.231	0.293	0.334	0.360	0.387	0.389	0.466
2001	0.048	0.119	0.198	0.239	0.267	0.325	0.346	0.385	0.406	0.436
2002	0.016	0.118	0.218	0.257	0.288	0.335	0.377	0.385	0.442	0.465
2003	0.036	0.112	0.181	0.251	0.282	0.335	0.360	0.397	0.419	0.462
2004	0.032	0.124	0.199	0.237	0.286	0.332	0.357	0.373	0.373	0.442
2005	0.031	0.097	0.181	0.232	0.253	0.306	0.328	0.354	0.376	0.410
2006	0.032	0.114	0.178	0.222	0.252	0.292	0.321	0.351	0.368	0.399
2007	0.027	0.115	0.191	0.213	0.238	0.281	0.295	0.320	0.363	0.370
2008	0.030	0.120	0.191	0.233	0.249	0.287	0.309	0.342	0.350	0.380
2009	0.031	0.117	0.184	0.222	0.249	0.291	0.309	0.329	0.346	0.393
2010	0.032	0.114	0.192	0.238	0.260	0.301	0.324	0.344	0.354	0.395
2011	0.032	0.093	0.170	0.208	0.237	0.280	0.305	0.326	0.340	0.370
2012	0.032	0.108	0.151	0.194	0.214	0.256	0.286	0.312	0.326	0.342
2013	0.064	0.108	0.177	0.200	0.226	0.272	0.299	0.329	0.350	0.364
2014	0.027	0.097	0.186	0.216	0.230	0.275	0.306	0.335	0.357	0.379
2015	0.033	0.093	0.173	0.230	0.254	0.278	0.301	0.332	0.357	0.380
2016	0.134	0.091	0.154	0.197	0.230	0.266	0.278	0.304	0.318	0.355
2017	0.032	0.059	0.155	0.188	0.213	0.276	0.299	0.313	0.335	0.368
2018	0.021	0.073	0.149	0.183	0.204	0.274	0.333	0.345	0.354	0.388
2019	0.017	0.070	0.143	0.179	0.222	0.262	0.290	0.338	0.336	0.372

Table 15. Fall spawning herring number-at-age from the fall acoustic surveys.

YEAR	AGE									
	2	3	4	5	6	7	8	9	10	11+
1991	0	8841	37546	29664	12515	4207	12515	16616	4101	106938
1993	3054	42610	25955	33590	14213	36785	9533	5601	8996	31228
1995	0	7365	15411	59905	12296	20719	8609	16702	5713	36515
1997	119	3334	29209	12209	13805	69256	7892	17097	1849	36207
1999	838	19431	83377	42889	44183	10165	4585	52314	7335	26596
2002	1422	4451	66684	4943	24607	85516	32926	20979	3156	17721
2009	2986	673	21474	8761	9336	26564	82666	77087	4429	20410
2010	0	20190	18109	97164	61536	36405	89921	142890	90500	41651
2011	0	54138	27071	19456	37160	23192	31018	86786	134727	40555
2013	2889	18088	49418	91576	86103	42062	67059	62379	67008	158837
2015	0	7980	13717	5862	14624	40698	15915	28025	48126	137759
2017	0	0	1598	10201	25127	8303	13970	39303	31859	50105
2019	1872	137301	12790	93318	57651	18335	27253	4261	8471	61928

Table 16. Variables tested in the GAMs are indicated by x in the spring and fall column. Fall spawning (FS) herring models did not include variables related to the spring bloom. For spring spawning herring, the abundance and phenology of zooplankton in early summer (June) was used whereas we used the abundance and phenology of zooplankton in fall (October) for FS herring. SST: sea surface temperature; SSB: spawning stock biomass; R: recruitment estimated by VPA model 1a; Kn: relative condition factor.

Period	Variable	Reference	Kn4-9y		R and Rstrength	
			Spring	Fall	Spring	Fall
1982–2019	SST May–November	Galbraith et al. 2019	-	-	x	x
	SST May–August		x	-	x	-
	SST August		x	-	-	-
	SST August–November		-	x	-	x
	SST November		-	x	-	-
	Spring timing (10 °C)		x	-	x	-
	Fall timing (10 °C)		-	x	-	x
	Timing of the last appearance of ice		x	-	x	-
	Herring SSB	VPA model 1b	-	-	x	x
1999–2018	Bloom timing	Blais et al. 2019	x	-	x	-
	Bloom duration		x	-	x	-
2001–2018	Abundance of *C. finmarchicus*	Blais et al. 2019	x	x	x	x
	Abundance of *C. hyperboreus*		x	x	-	-
	Abundance of *Pseudocalanus* spp.		x	x	x	x
	Abundance of small Calanus		x	x	x	x
	Phenology of *C. finmarchicus*		x	x	x	x
	Large Calanoid / Small Calanoid		x	x	x	x
	Phenology of *C. hyperboreus*	Plourde, DFO, pers. comm.	x	-	-	-

*Table 17. Best Kn 4–9 y. models for each time series and components. Phys serie: Physical indices, bloom: Spring bloom + physical indices, zoo: zooplankton + spring bloom + physical indices. The effect of each selected predictor on the response variable can be positive (+), negative (-), bell-shaped (⌒) or U-shaped (◡). Non-significant effect are noted with n.s. The performance of each model is evaluated with the R^2 between observed and predicted values, % of deviance explained (%DEV), the comparison of deviance explained with Monte Carlo simulation (MCs, * for significantly higher than the distribution obtained by MCs and n.s. otherwise) and the R^2 between predicted and observed values during the Jackknife procedure. The status of the models is either selected or rejected. In case of rejection, the reason is given. Selected models are in bold.*

Component	Series	Selected predictors	Effect	R^2	%DEV	MCs	Jackknife	Status
Fall	phys.	SST November	-	0.21	23	*	0.4	rejected: temporal autocorrelation
	zoo.	***C. finmarchicus* abundance (fall)** ***C. finmarchicus* phenology (fall)**	**+** **-**	**0.56**	**61**	*****	**0.68**	**selected**
Spring	phys.	SST August Spring timing	- - n.s.	0.12	17	n.s.	0.28	rejected: failed MCs
	bloom.	Spring timing Last ice Bloom duration	- n.s. - +	0.32	42	n.s.	0.43	rejected: failed MCs
	zoo.	***C. finmarchicus* phenology (early summer)** **Large Cal/Small Cal. (early summer)**	**-** **+**	**0.78**	**83**	*****	**0.8**	**selected**

*Table 18. Best recruitment models for each time series and components. Phys serie: Physical indices and SSB, bloom: Spring bloom + physical indices, zoo: zooplankton + spring bloom + physical indices. The effect of each selected predictor on the response variable can be positive (+), negative (-), bell-shaped (⌢) or inverse bell-shaped (⌣). Non-significant effect are noted with n.s. The performance of each model is evaluated with the R^2 between observed and predicted values, % of deviance explained (%DEV), the comparison of deviance explained with Monte Carlo simulation (MCs, * for significantly higher than the distribution obtained by MCs and n.s. otherwise) and the R^2 between predicted and observed values during the Jackknife procedure. The status of the models is either selected or rejected. In case of rejection, the reason is given.*

Response variables	Component	Series	Selected predictors	Effect	R^2	%DEV	MCs	Jackknife	Status
Rstrength 3–4y	Fall	phys.	SST November Fall timing Fall SSB	+ n.s. -n.s. -	0.09	22	n.s.	0.24	rejected: failed MCs
		zoo.	Fall timing C. finmarchicus phenology (fall) Pseudocalanus spp. abundance (fall)	+ ⌢ -	0.48	60	n.s.	0.29	rejected: failed MCs
	Spring	phys.	Spring SSB	- n.s.	0	11	n.s.	NA	rejected: failed MCs
		bloom	Spring timing Last ice Spring SSB	n.s. - ⌣	0.67	77	*	0.16	rejected: did not support hypothesis for SSB
		zoo.	Last ice Spring SSB	- ⌣	0.5	52	*	0.24	rejected: did not support hypothesis for SSB
R (NAA2y)	Fall	phys.	Fall timing	n.s.	-0.04	13	n.s.	-0.44	rejected: failed MCs
		zoo.	Fall timing C. finmarchicus abundance (fall) Fall SSB	n.s. +n.s. -n.s.	-0.02	34	n.s.	0.08	rejected: failed MCs
	Spring	phys.	Spring SSB	+n.s.	0.01	16	n.s.	0.02	rejected: failed MCs
		bloom	Spring timing Last ice Spring SSB	⌢n.s ⌢ ⌣	0.76	79	*	0.35	rejected: did not support hypothesis for SSB
		zoo.	SST August C. finmarchicus abundance (early summer) Pseudocalanus spp. abundance (early summer)	- n.s. +n.s. +n.s.	0.4	31	n.s.	-0.1	rejected: failed MCs

Table 19. Trends, limitations and consequences for the assessment of the main biological and stock state indicators. WAA: weight-at-age. CAA: catch-at-age.

Type of indicator	Indicator	Stock	Trend	Limitations	Consequences for the assessment
Biological	L50	Spring	Decrease for the 1963 to 1993 cohorts, variable around the mean thereafter	Small sample size in biological data since 2007	-
		Fall	Decrease for the 1963 to 1993 cohorts, variable around the mean thereafter	-	-
	A50	Spring	No prominent temporal trend	Small sample size in biological data since 2007	-
		Fall	Decrease (1965 à 1986), increase (1965–2007), stable (2007–2019)	-	-
	WAA	Spring	Decreasing since 1981 for most ages	Small sample size in biological data since 2007	-
		Fall	Decreasing since 1981 for most ages	-	-
Stock state	Fishery CAA	Spring	Possibility of following cohorts over time, the last 3 being 1999, 2002, 2013	Small sample size in biological data since 2007	The presence of many older fish is not consistent with current overfishing.
		Fall	Possibility of following cohorts over time, the last 3 being 2000, 2001, 2008	-	
	Abundance index	Spring	The total biomass estimate declined from 1991 to 2015, and increased in 2019.	Total biomass: change in the catchability of the survey possibly related to the timing of the survey (decoupled from the timing of the fishery) and in the spatial coverage (variable from one survey to another).	Important limitations in interpreting the trends
			The abundance-at-age index shows little consistent signal.	Abundance-at-age: change in catchability (samples from variable gear) and representability (low quantity of samples from variable places and times).	
		Fall	Decrease for the 1963 to 1993 cohorts, variable around the mean thereafter	Total biomass: change in the catchability of the survey related to the timing of the survey (decoupled from the timing of the fishery) and the spatial coverage (variable from one survey to another)	
			The abundance at age index shows a noisy signal.	Abundance-at-age: change in catchability (samples from variable gear) and representability (samples from variable locations and times)	

FIGURES

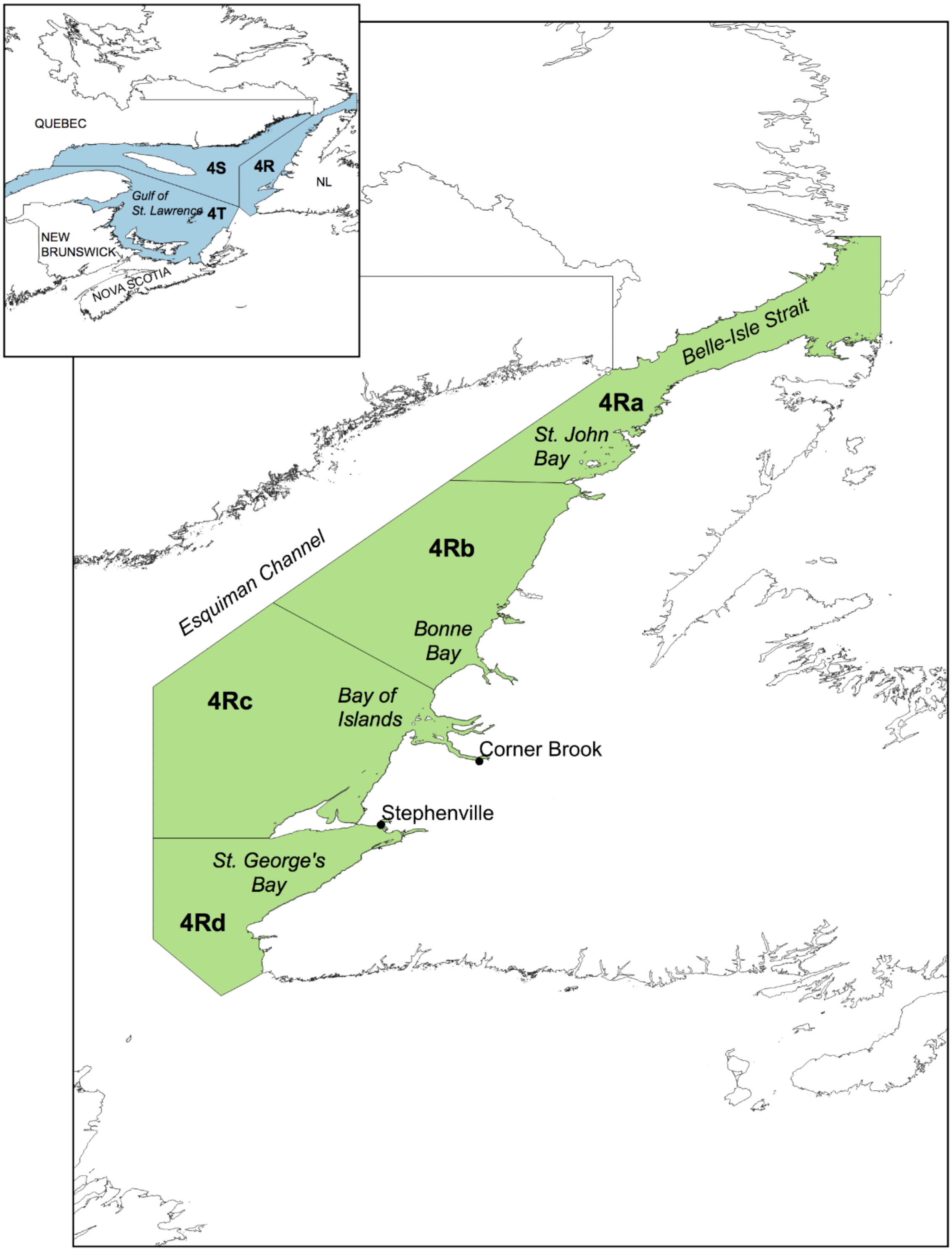

Figure 1. Map of the West Coast of Newfoundland and of NAFO Division 4R herring fishing unit areas with major bays indicated.

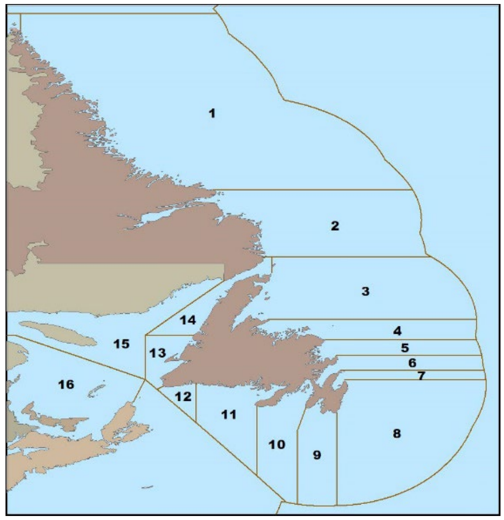

Figure 2. Map of Herring Fishing Areas around Newfoundland and Labrador.

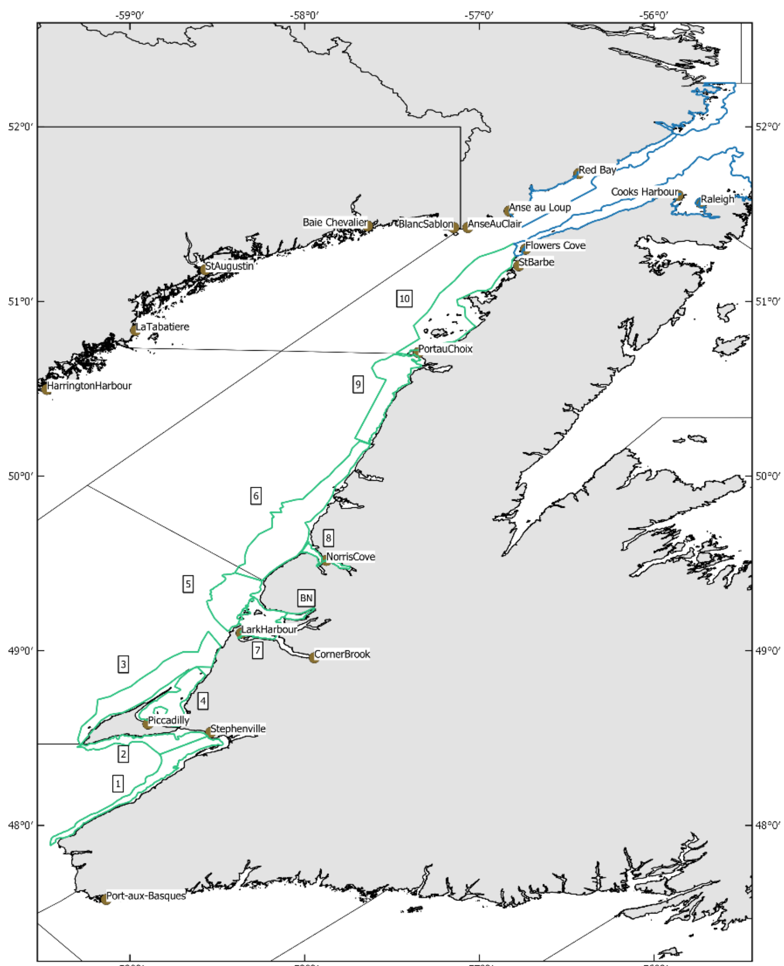

Figure 3. Map of the acoustic survey stratification scheme. Blue polygons are strata added to the survey area for the August 2019 survey.

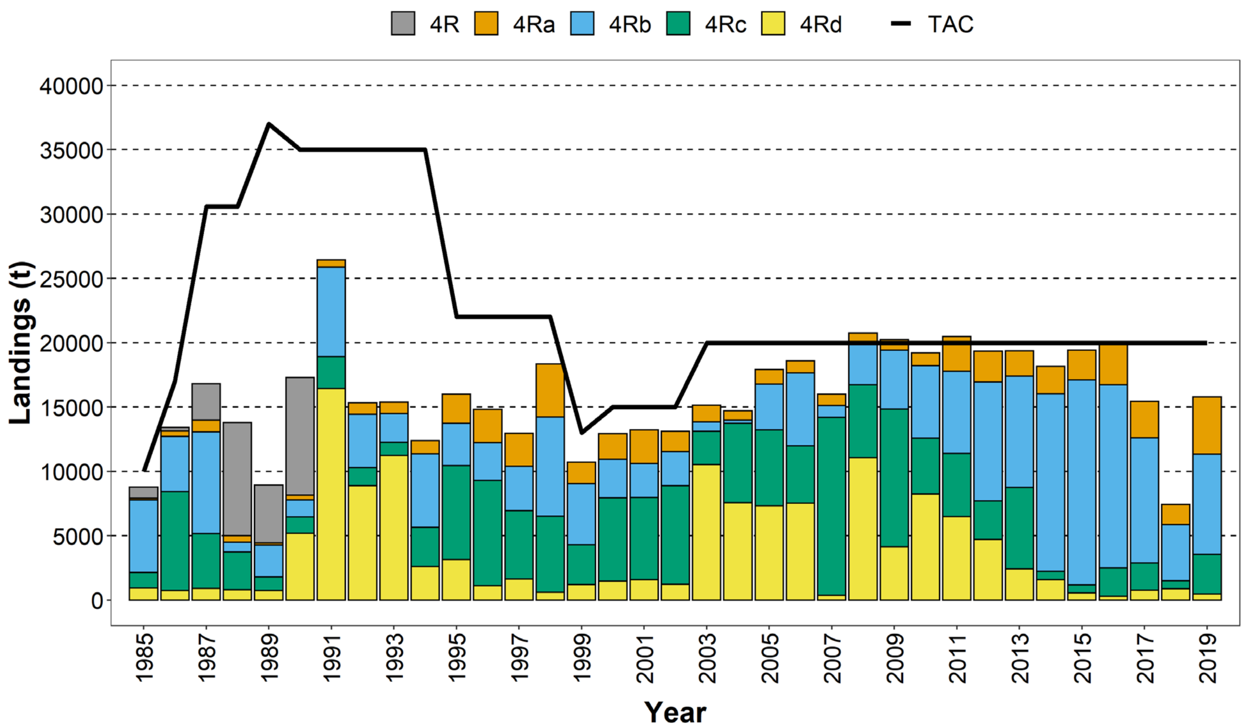

Figure 4. Total commercial herring landings (t) by unit area in NAFO Division 4R from 1985 to 2019. Total Allowable Catch (TAC) is represented by the solid black line. Landings for 2018 and 2019 are preliminary.

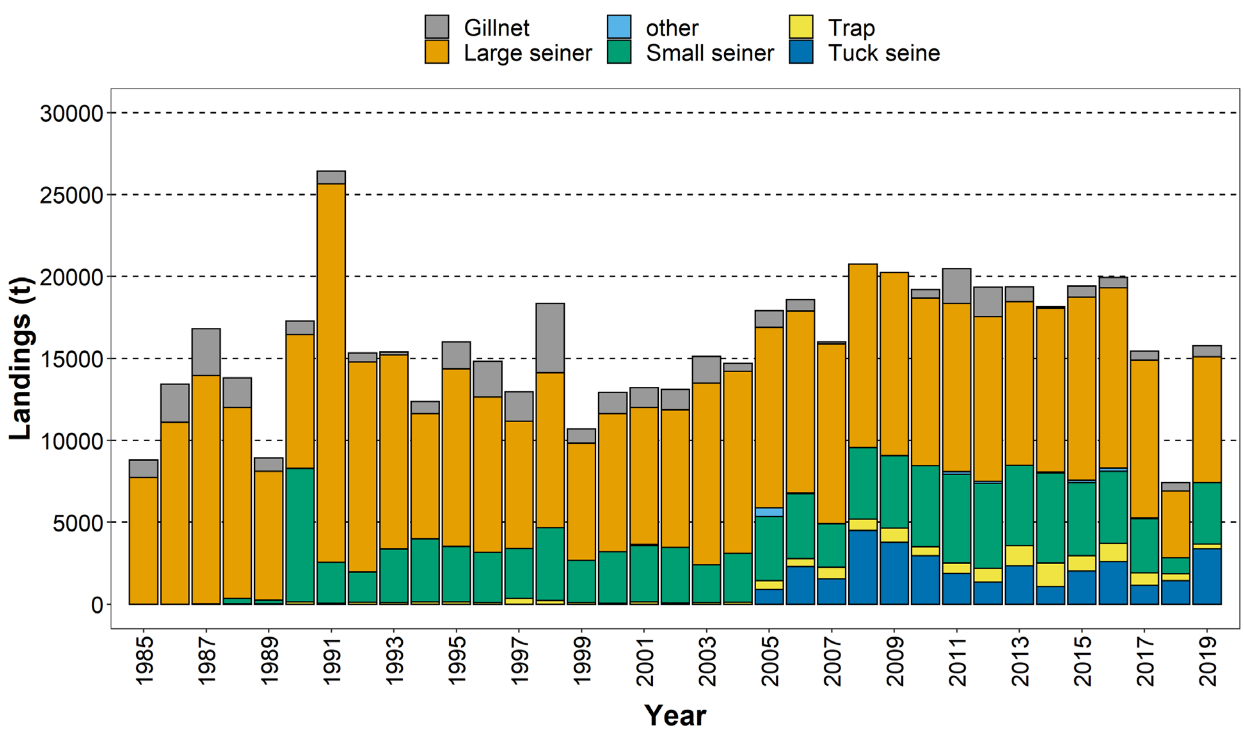

Figure 5. Commercial herring landings (t) by fishing gear used in NAFO Division 4R from 1985 to 2019. Landings for 2018 and 2019 are preliminary.

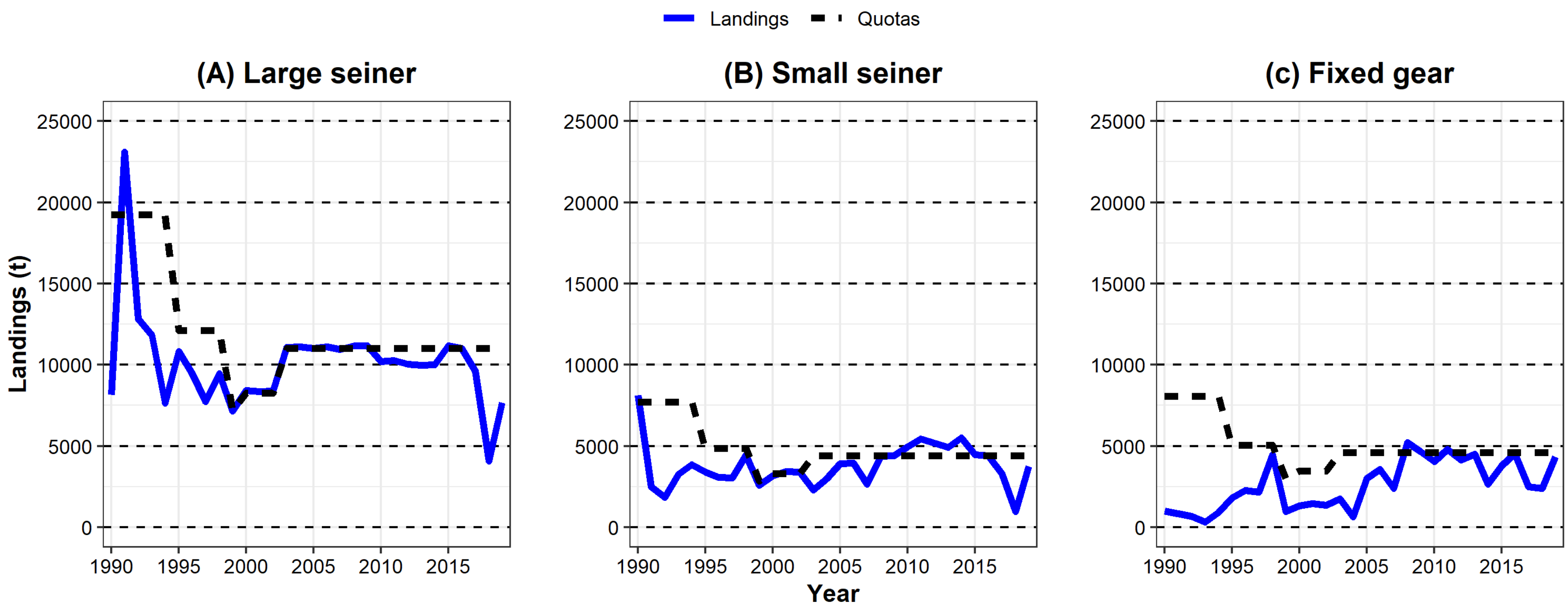

Figure 6. Commercial herring landings (t; solid blue line) and quotas (t; dashed black line) per fishing fleet in NAFO Division 4R: A) large seiner ≥65', B) small seiner <65', and C) fixed gear.

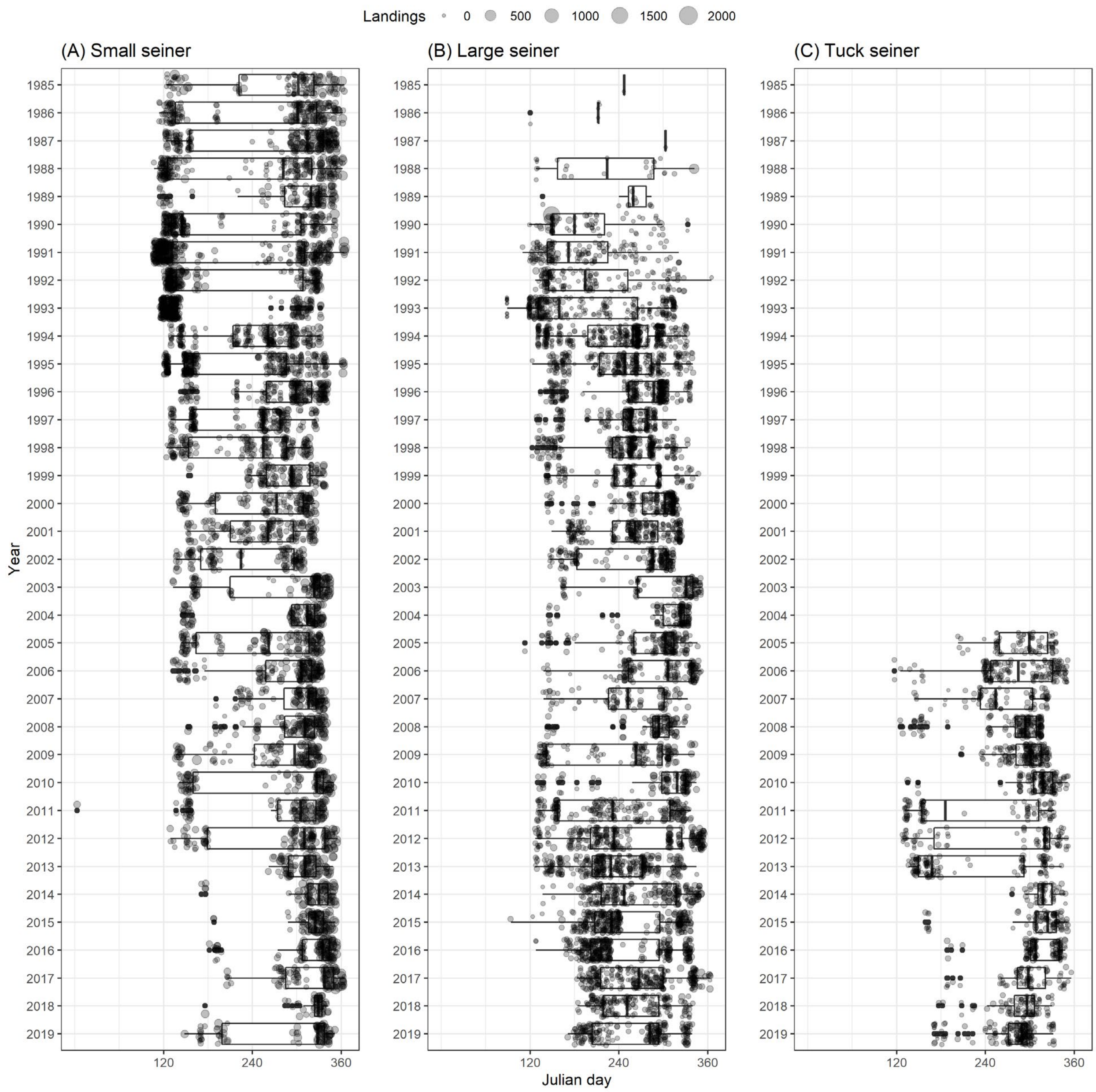

Figure 7. Boxplot representing commercial herring landings (t) per year and Julian day for large seiners >65' and small seiners <65' from 1985 to 2019, and for Tuck seines from 2005 to 2019 in NAFO Division 4R. Individual landings are plotted with circle size proportional to landed weight and jittered for visual representation.

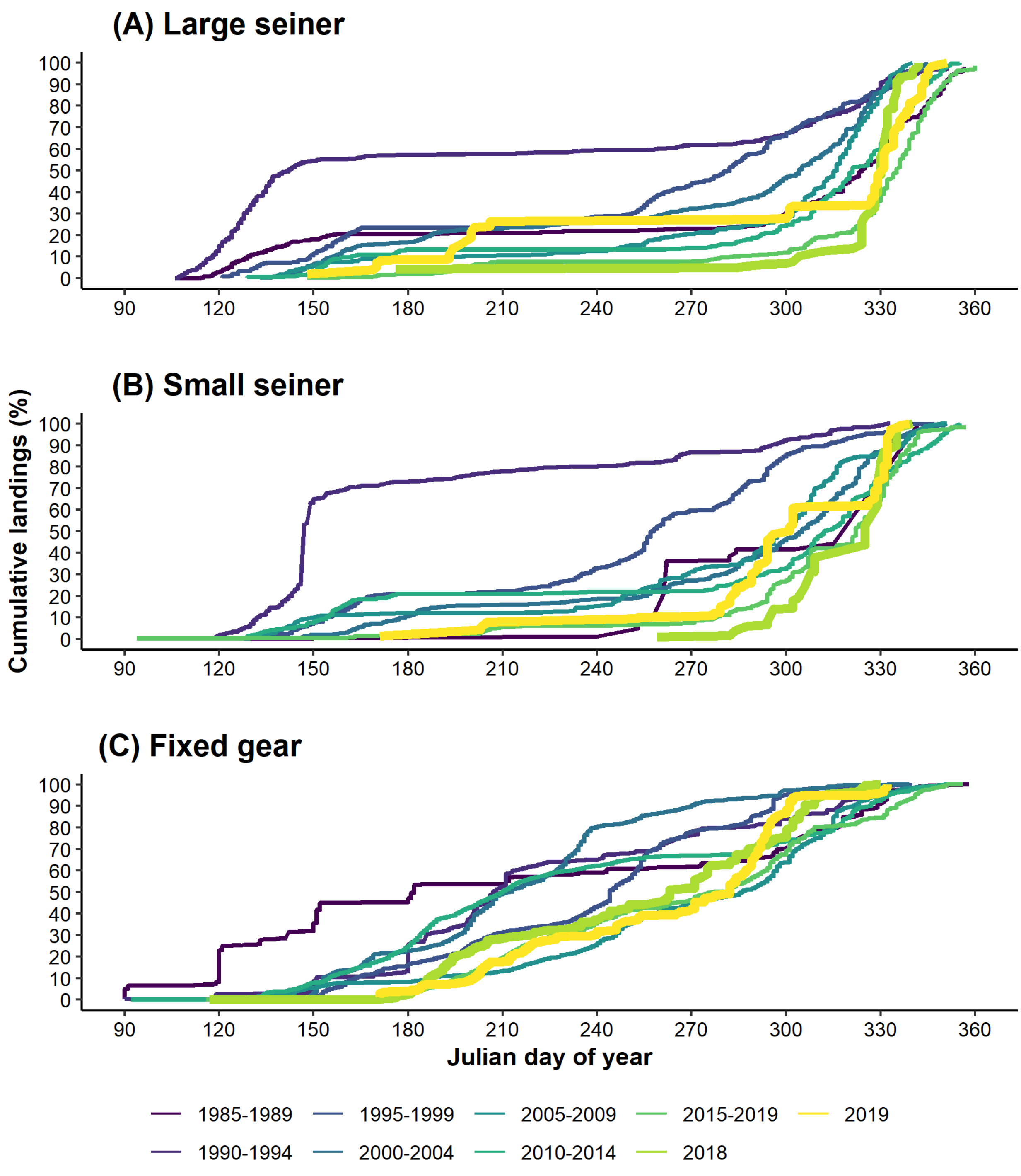

Figure 8. Cumulative commercial landings (%) over the fishing season by 5 year periods according to the day of year and by fishing fleet in NAFO Division 4R: A) large seiner >65', B) small seiner <65', and C) fixed gear. The last 2 years of available data are also plotted individually.

A)

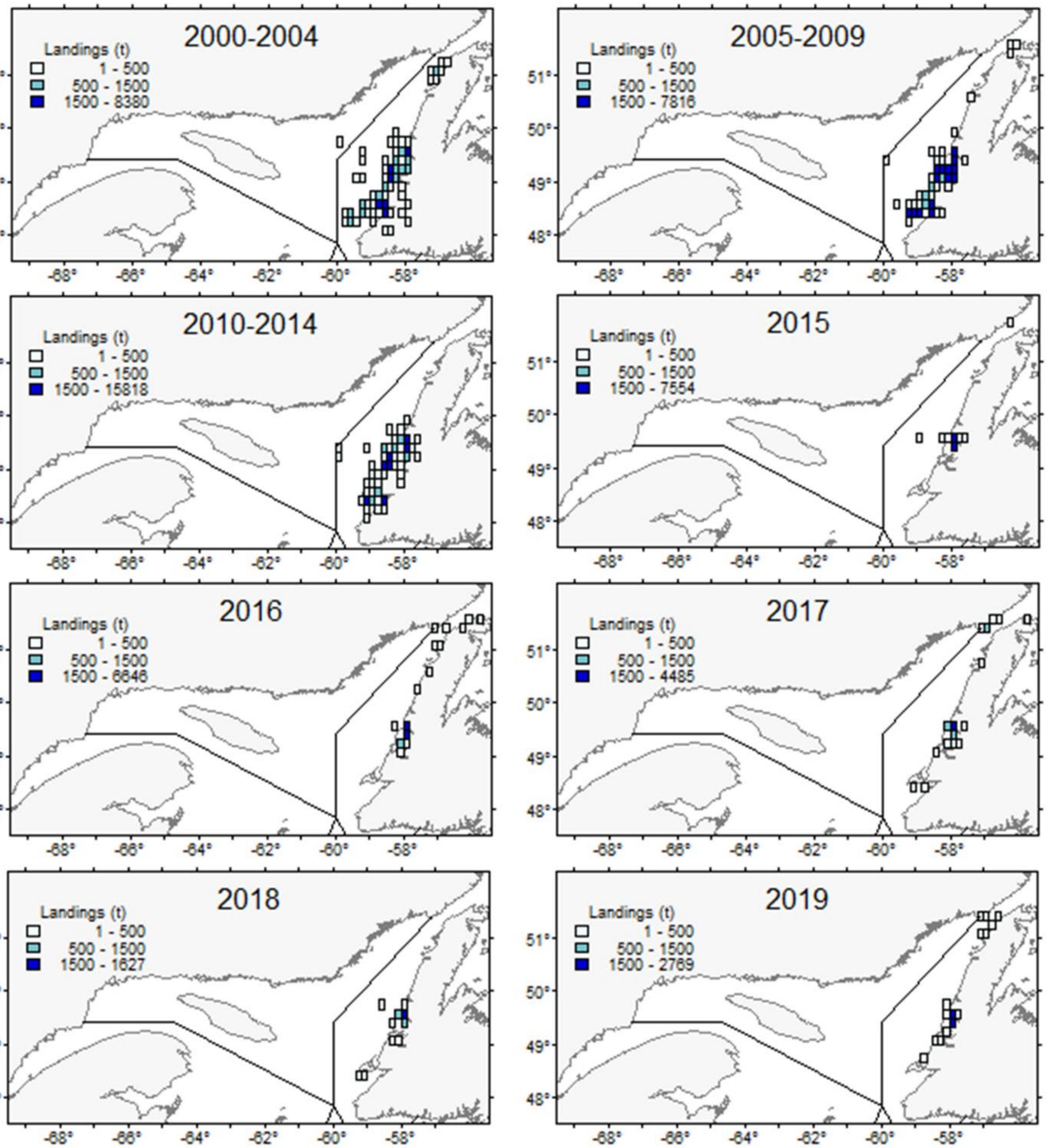

Figure 9. Location of commercial herring landings (t) by A) large seiners >65', B) small seiners <65) from 2000 to 2019, and by C) Tuck seiners from 2005 to 2019 in NAFO Division 4R.

B)

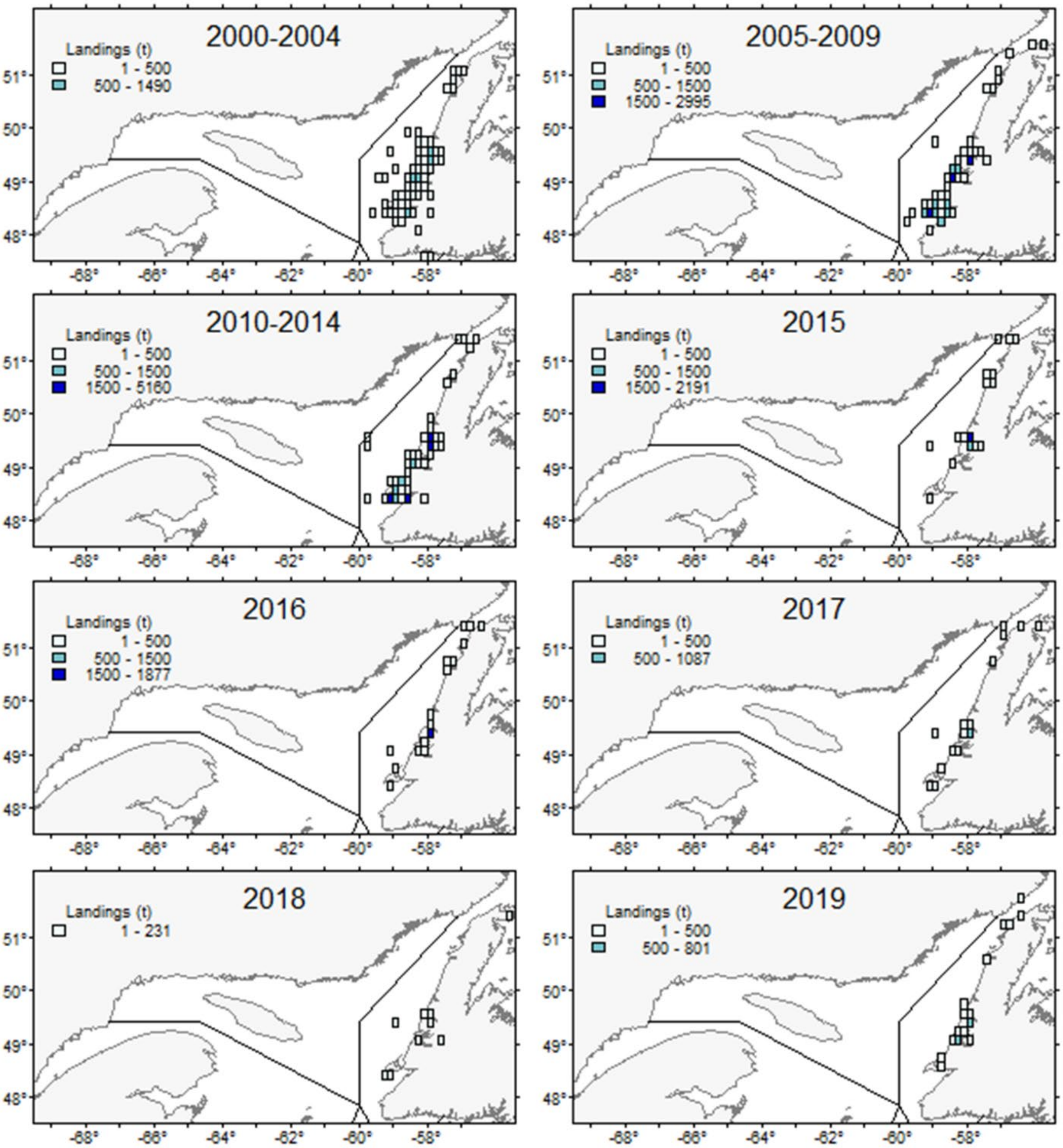

Figure 9 (continued).

C)

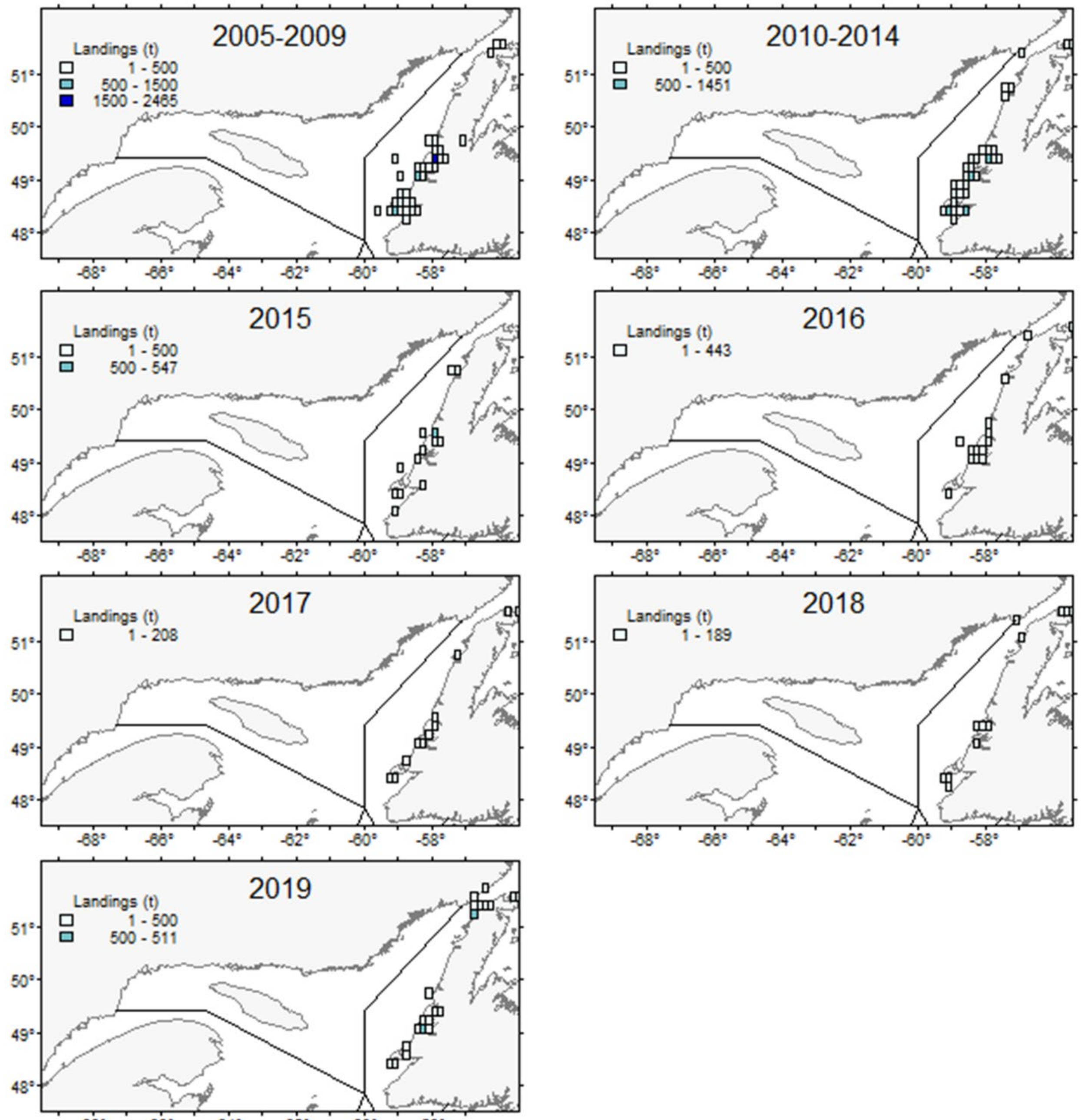

Figure 9 (continued).

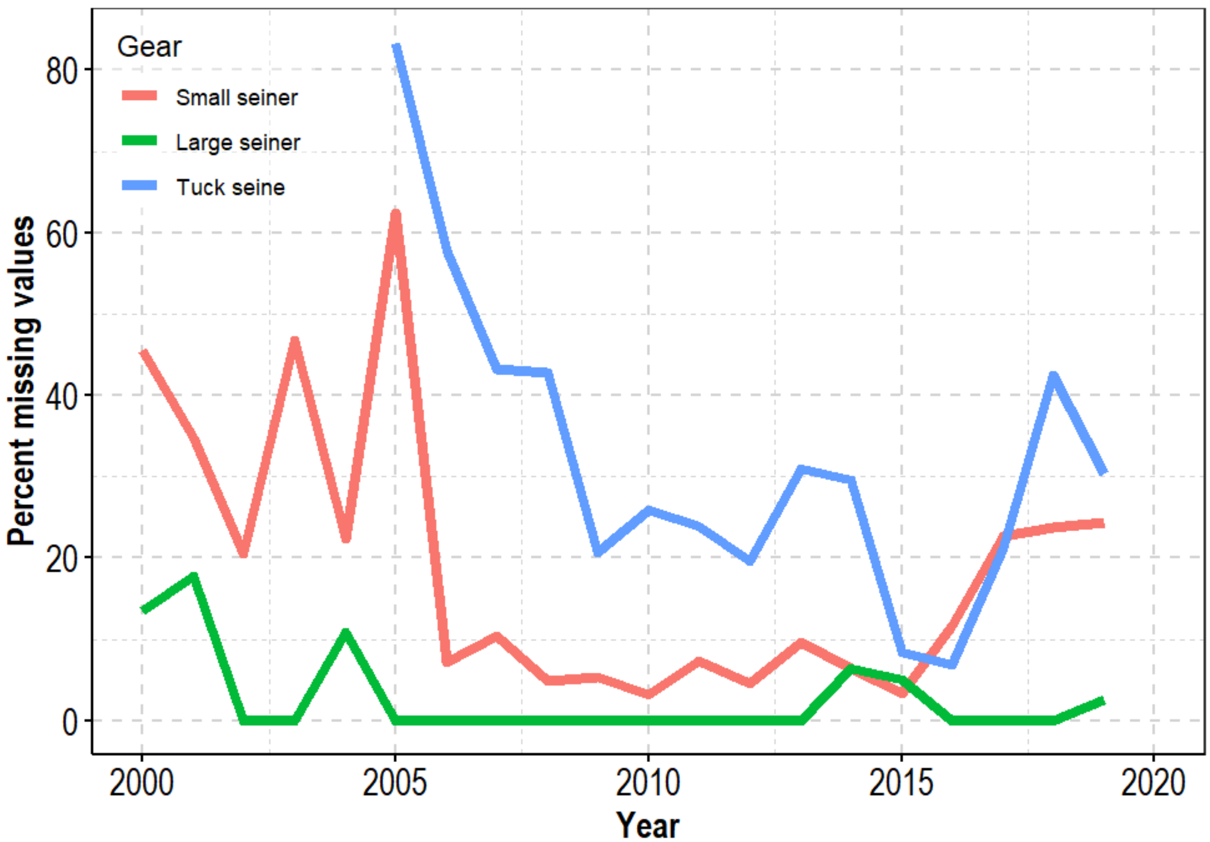

Figure 10. Percent missing latitude and longitude in the NAFO Division 4R herring ZIFF data for large, small and "Tuck" seiners. 2018 and 2019 data are preliminary.

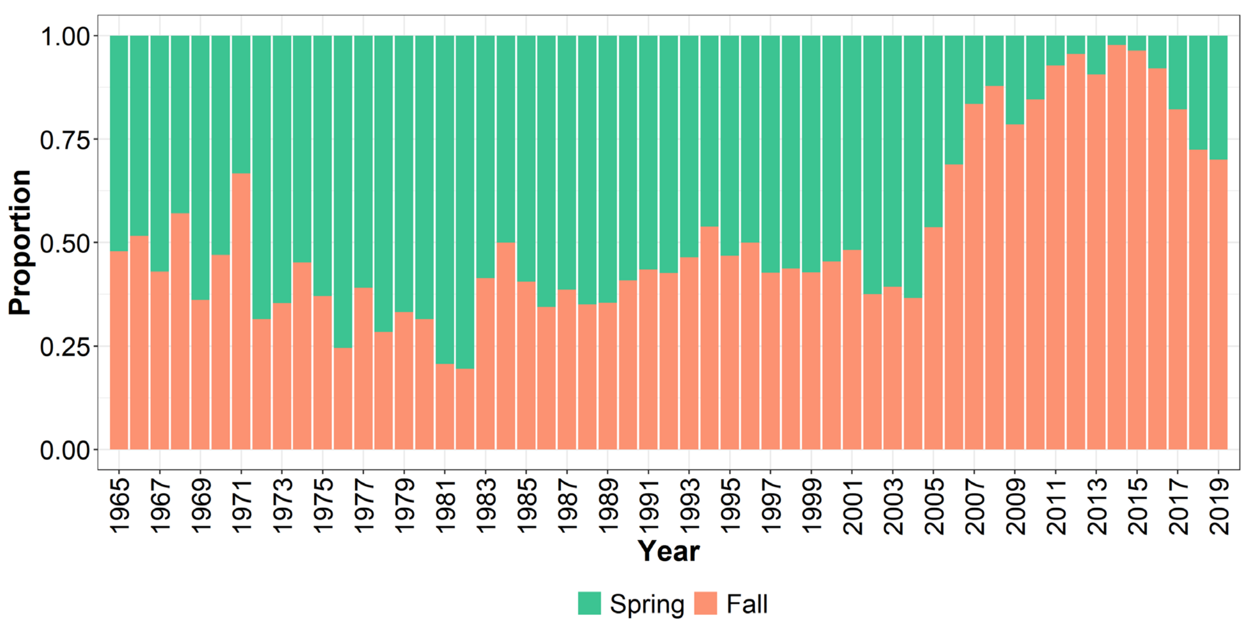

Figure 11. Proportion of spring and fall spawning herring (number of individuals) in the commercial biological samples from NAFO Division 4R from 1965 to 2019.

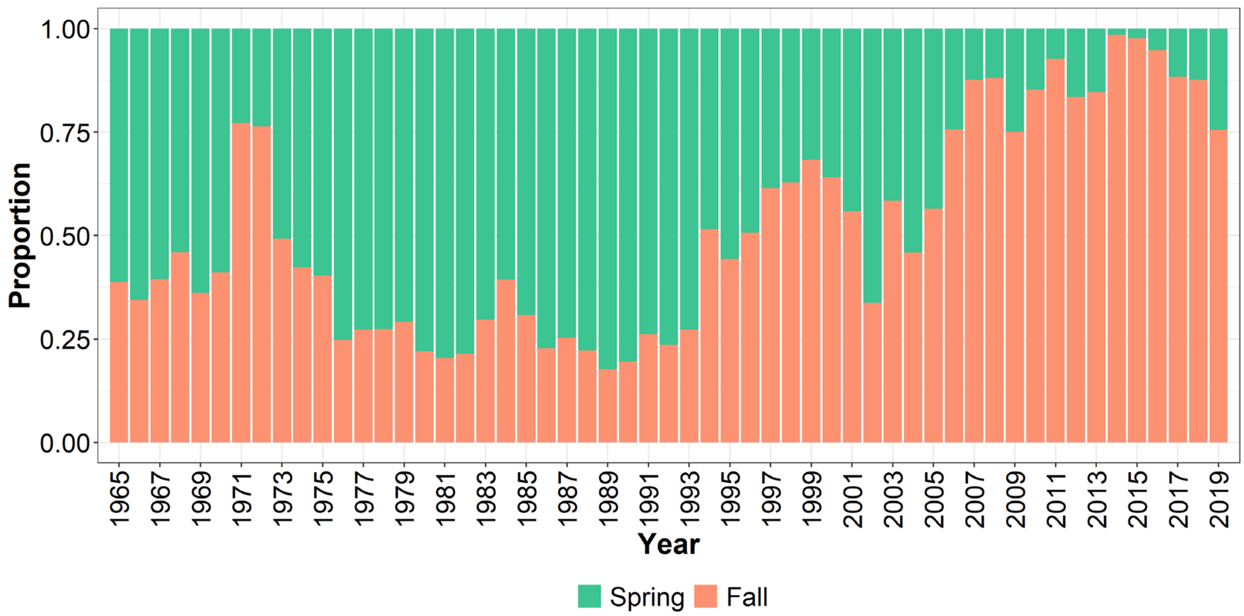

Figure 12. Proportion of spring and fall spawning herring (number of individuals) in commercial landings in NAFO Division 4R from 1965 to 2019.

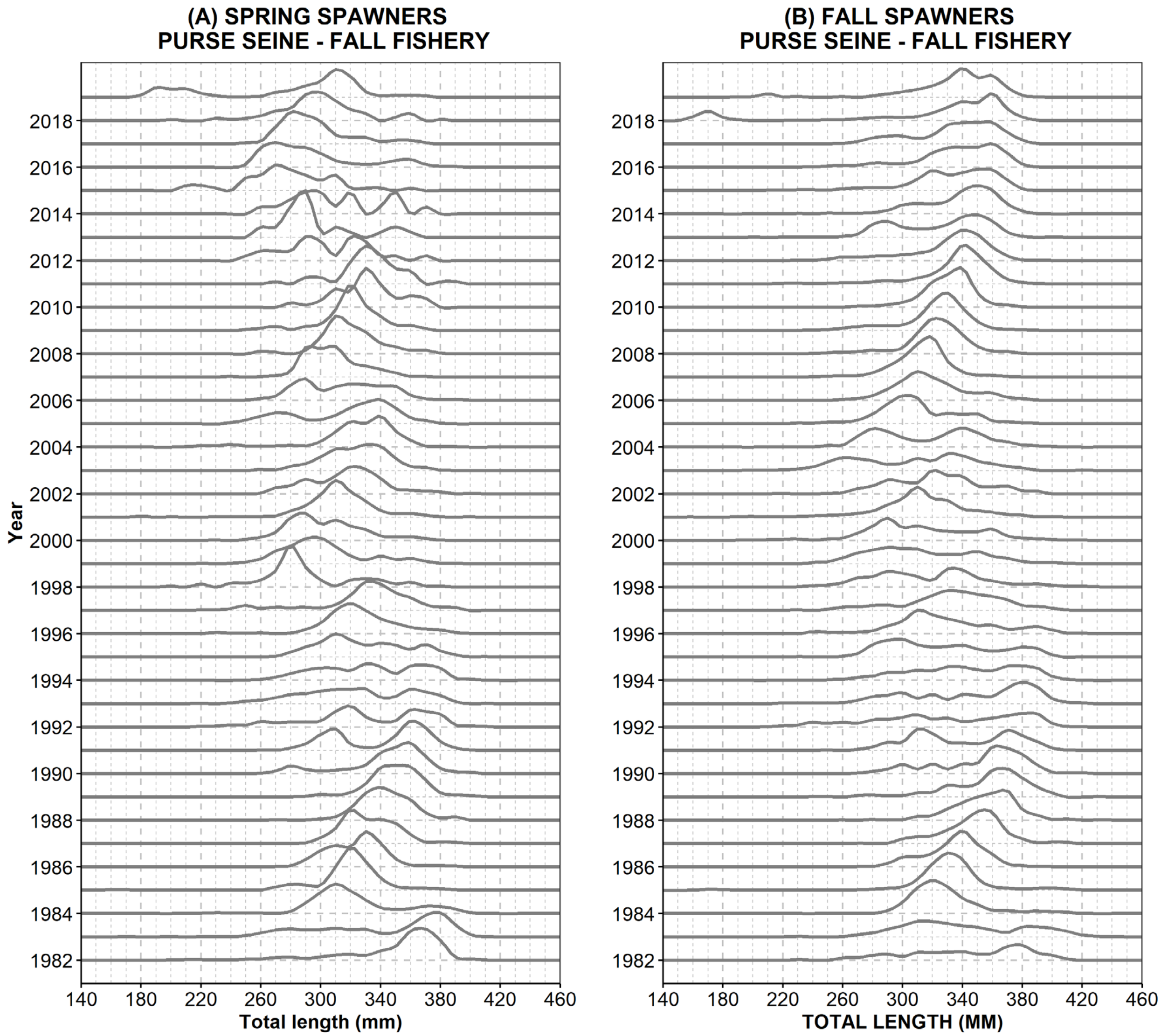

Figure 13. Fall purse seine relative total length (mm) frequency distributions in NAFO Division 4R for spring (A) and fall (B) spawning Atlantic herring, from 1982 to 2019

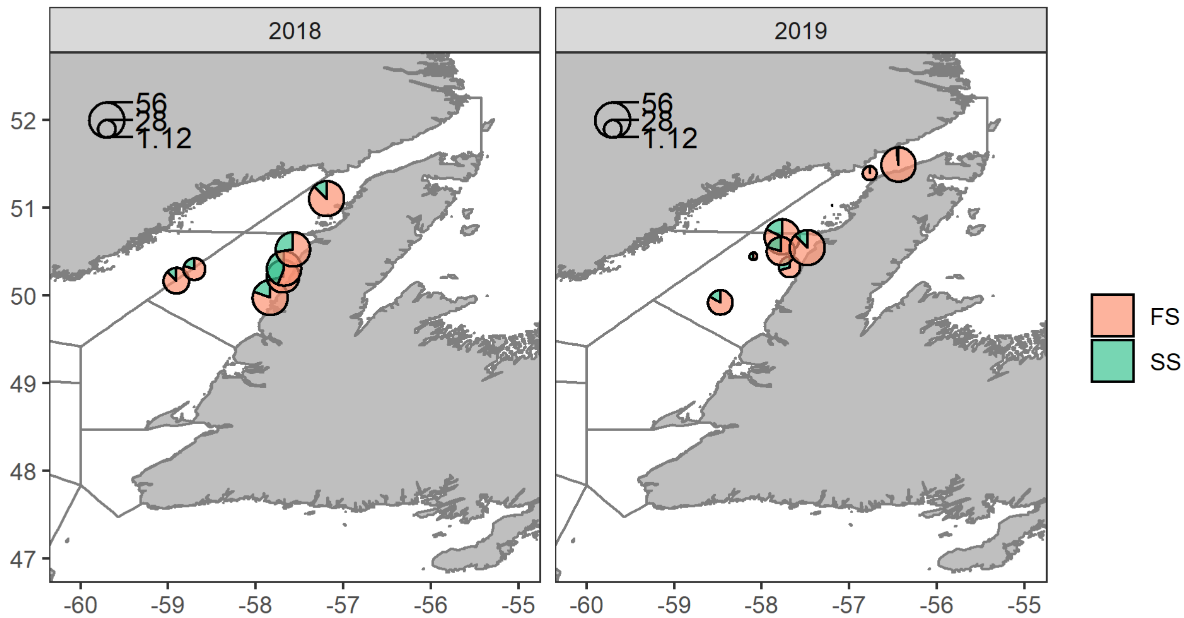

Figure 14. Pie charts representing the proportion (in number of individuals) of spring (SS) and fall spawning (FS) herring in the biological samples collected during the 2018 and 2019 August northern Gulf multi-species bottom trawl survey and sent to Maurice-Lamontagne Institute for detailed biological characterization. Circle radius is proportional to sample size.

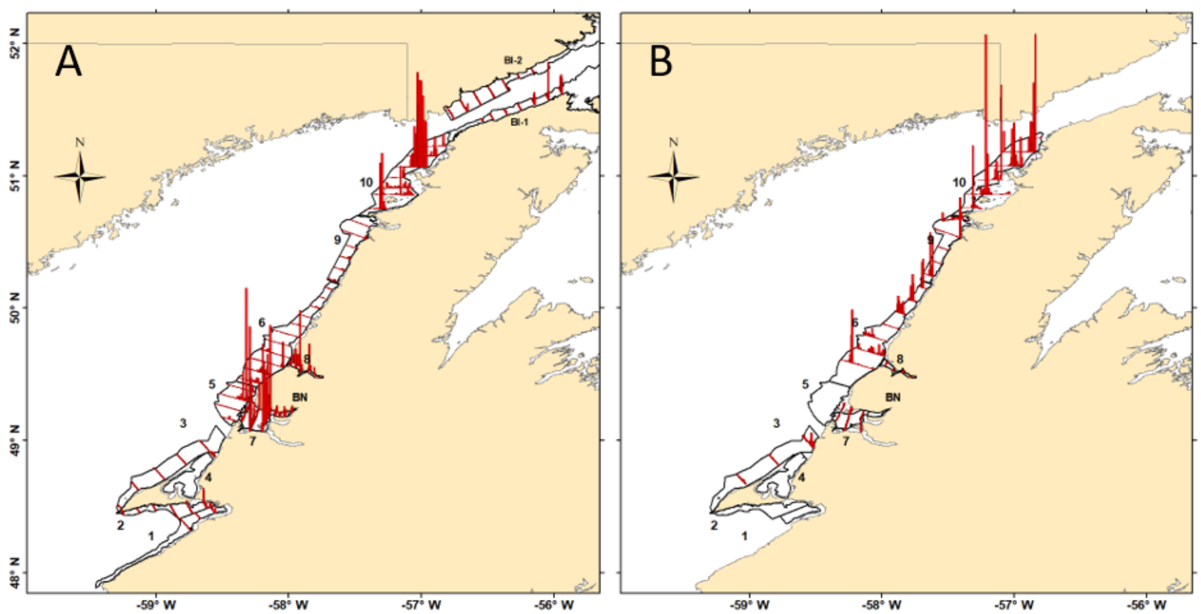

Figure 15. Distribution of herring biomass measured during the August (A) and fall (B) 2019 hydroacoustic surveys. Biomass is proportional to the height of the red bars. Survey strata names are identified (numbers, BI: Belle Isle, BN: Bras Nord).

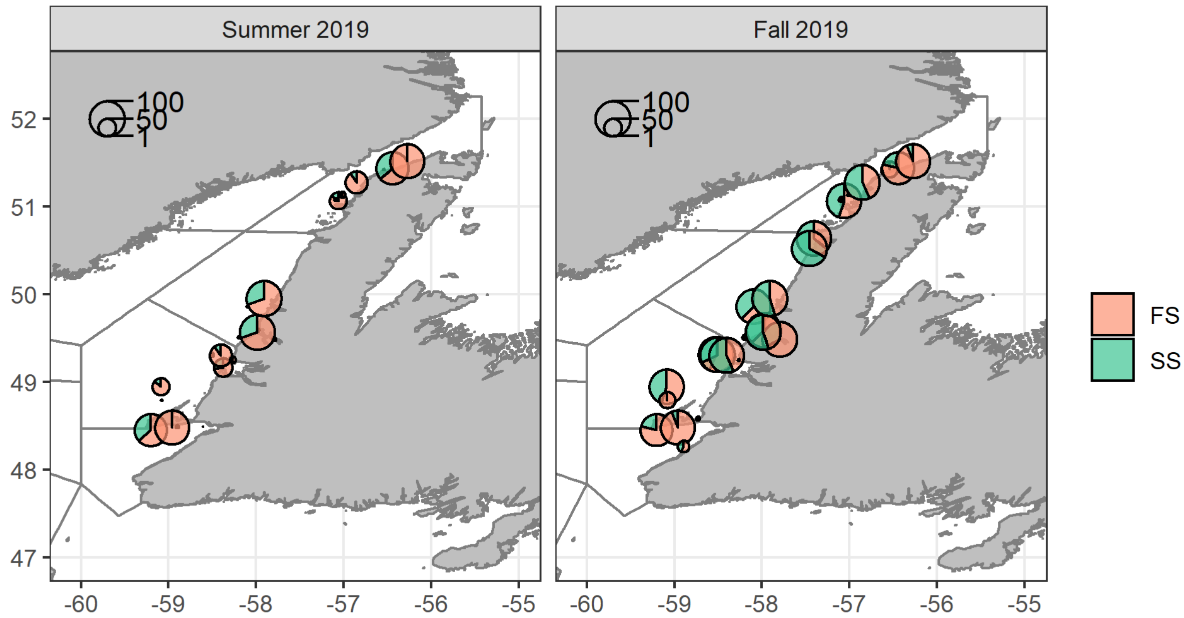

Figure 16. Pie charts representing the proportion (in number of individuals) of spring (SS) and fall spawning (FS) herring in the biological samples collected by the chartered pelagic trawlers during the 2019 acoustic surveys. Circle radius is proportional to sample size (not total catch abundance).

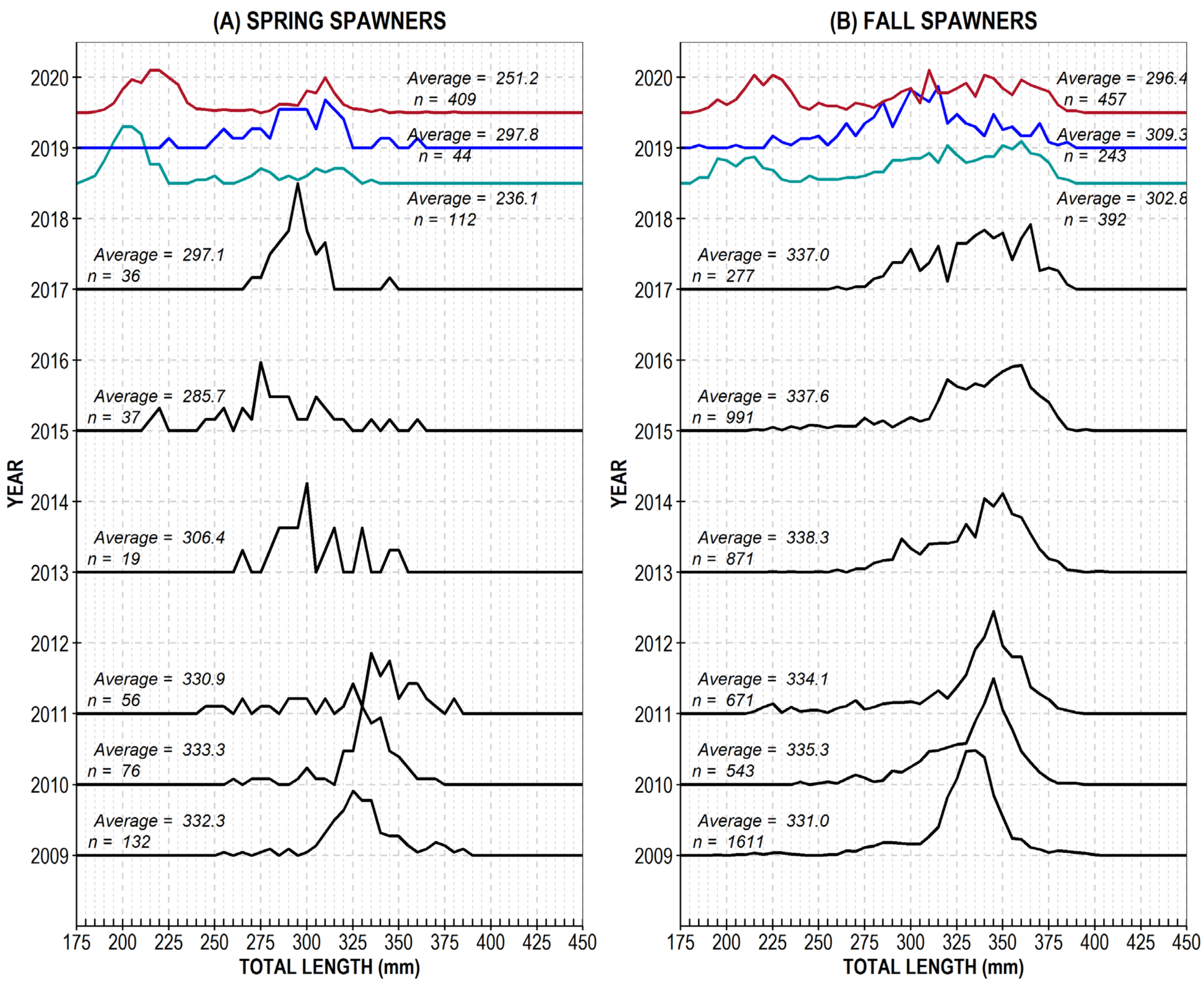

Figure 17. Total length relative frequency distributions of spring and fall spawning herring used in the computation of the age-disaggregated acoustic index. The lines below and above 2019 respectively represent the biological samples from the summer and fall acoustic surveys, while the blue lines represent the samples from the northern Gulf multi-species bottom trawl survey.

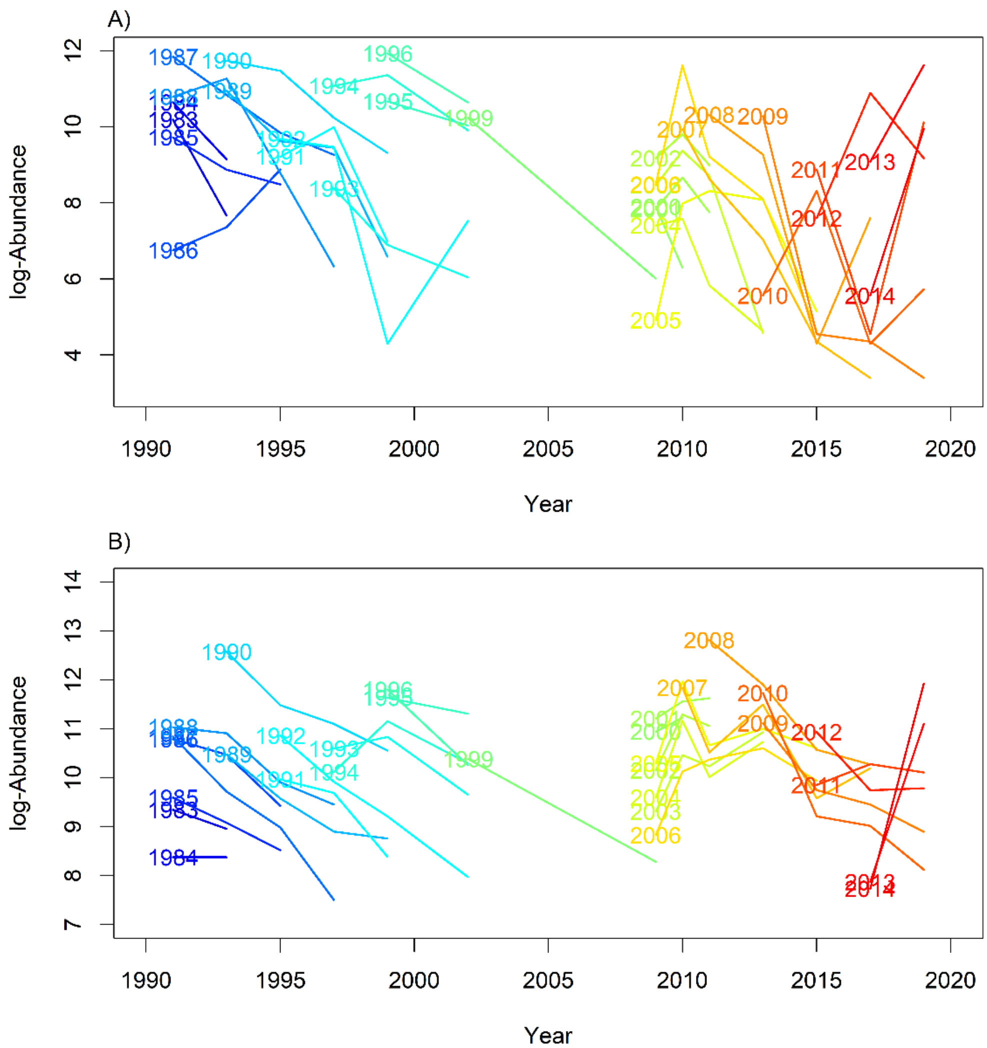

Figure 18. Selectivity-adjusted catch curves for acoustic survey abundances for a) spring and b) fall spawning herring ages 3 to 10 years. Individual lines display abundance trends for individual cohorts, identified by their year of birth. Age-dependent selectivities for each stock were taken from Grégoire et al. (2004).

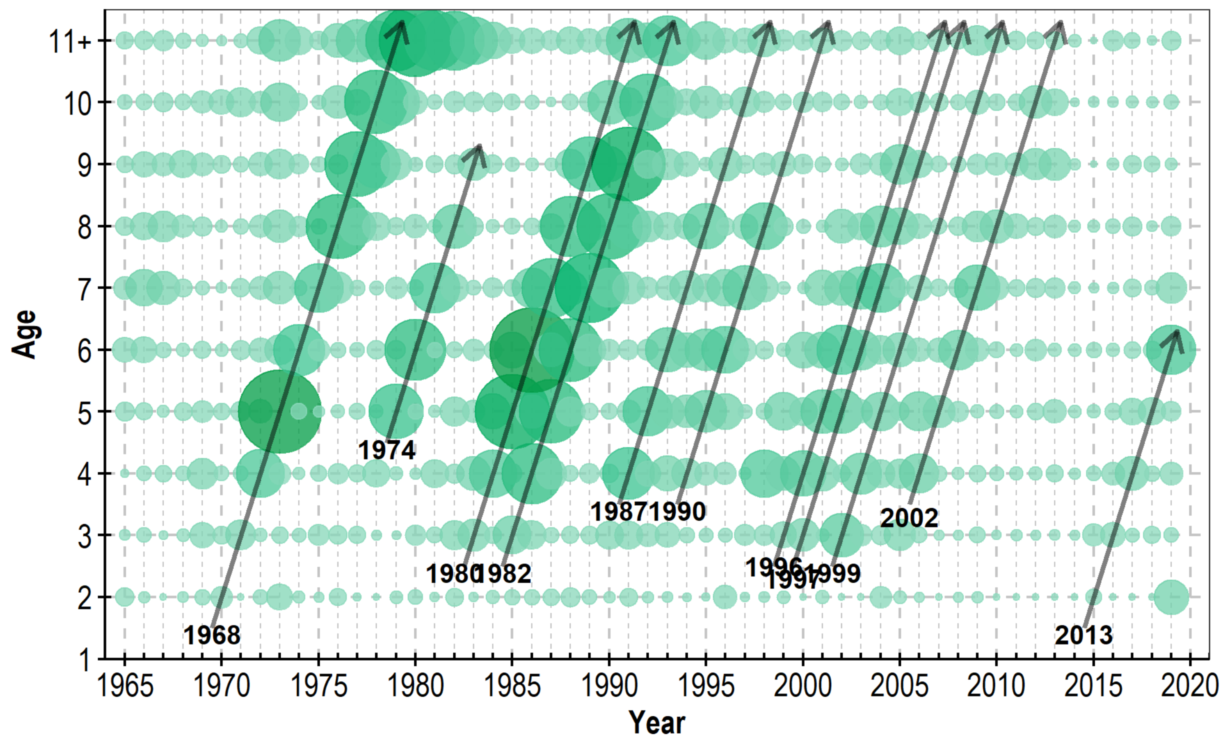

Figure 19. Bubble plot of spring spawning fishery catch-at-age, 1965–2019 in NAFO Division 4R. Circle area is proportional to the annual landing (number of fish). Arrows represent dominant cohorts.

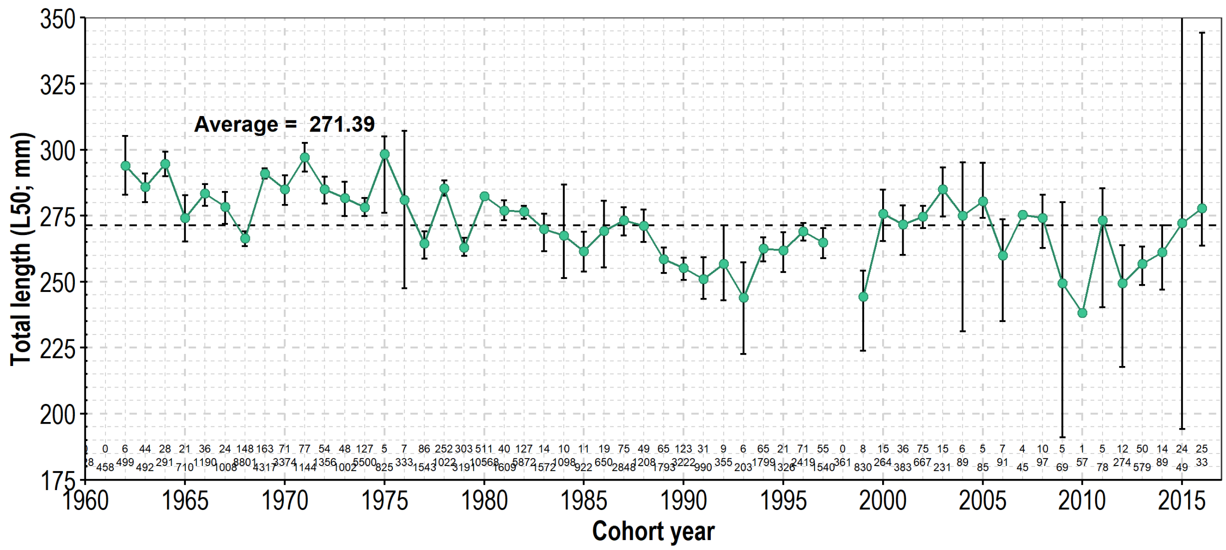

Figure 20. Total length at 50% maturity by cohort in NAFO Division 4R for spring spawning herring. Error bars represent bootstrapped 95% confidence intervals. The numbers above the x-axis represent total number of fish sampled by cohort (lower 2 lines) and the number of immature fish sampled by cohort (upper line). The horizontal dashed line is the arithmetic mean of the cohorts L50s.

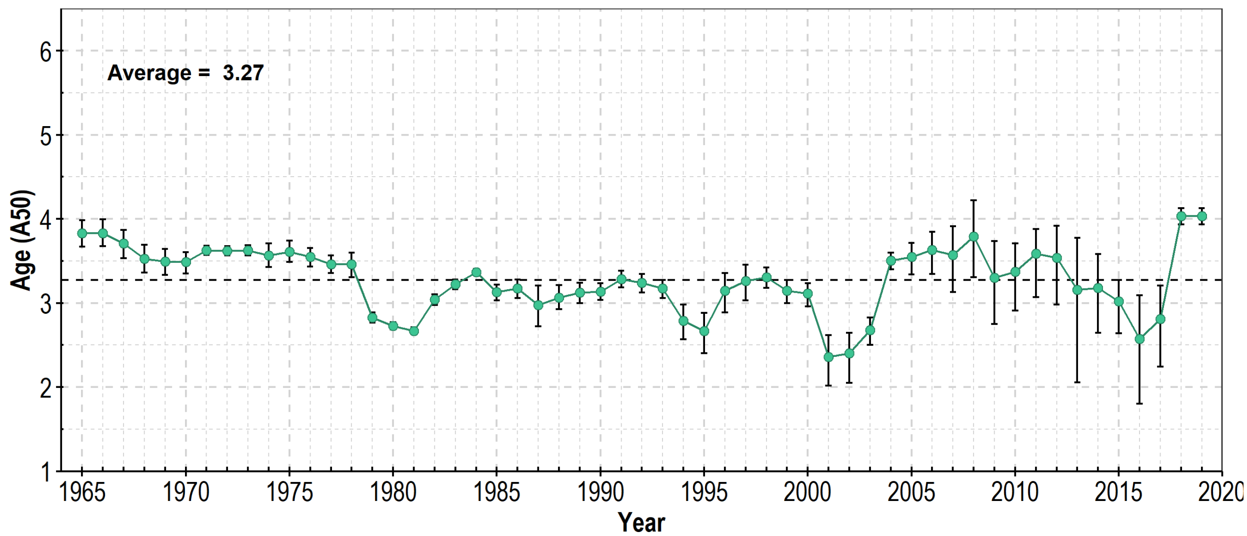

Figure 21. Age at 50% maturity by year in NAFO Division for 4R spring spawning herring. Error bars represent bootstrapped 95% confidence intervals. For each year, data were pooled with the 2 neighboring years because of insufficient number of immature fish. The horizontal dashed line is the arithmetic means of annual L50s.

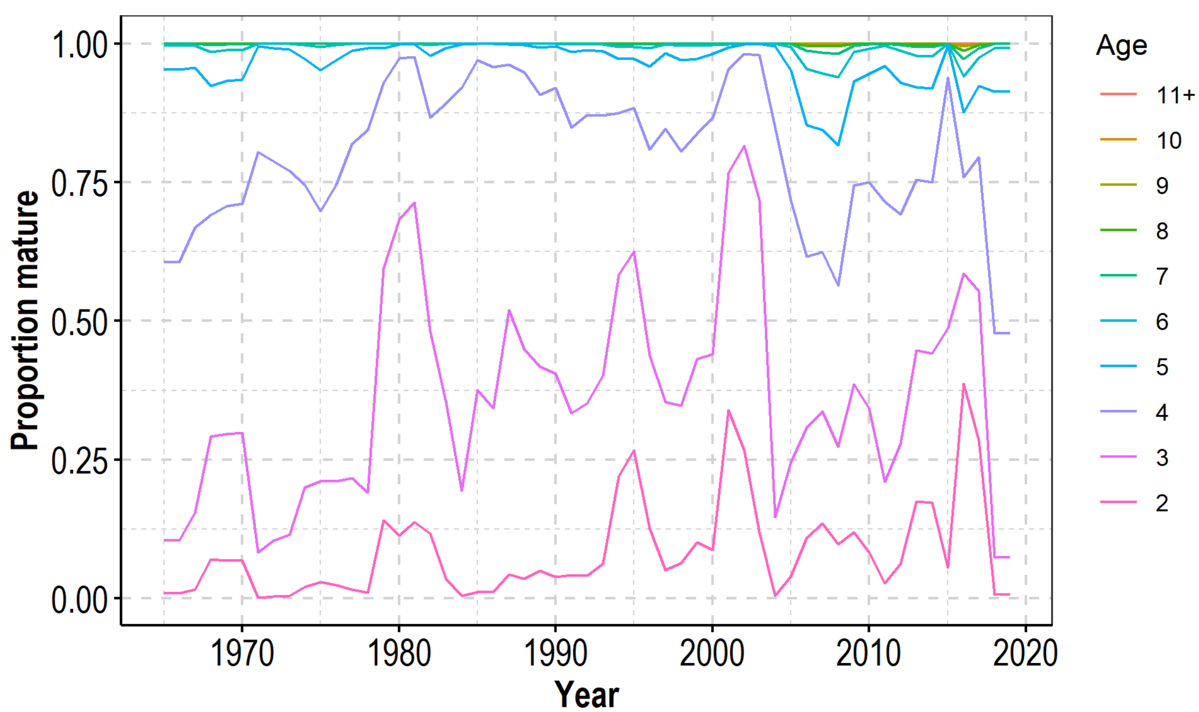

Figure 22. Maturity-at-age (proportion mature) in NAFO Division 4R for spring spawning herring.

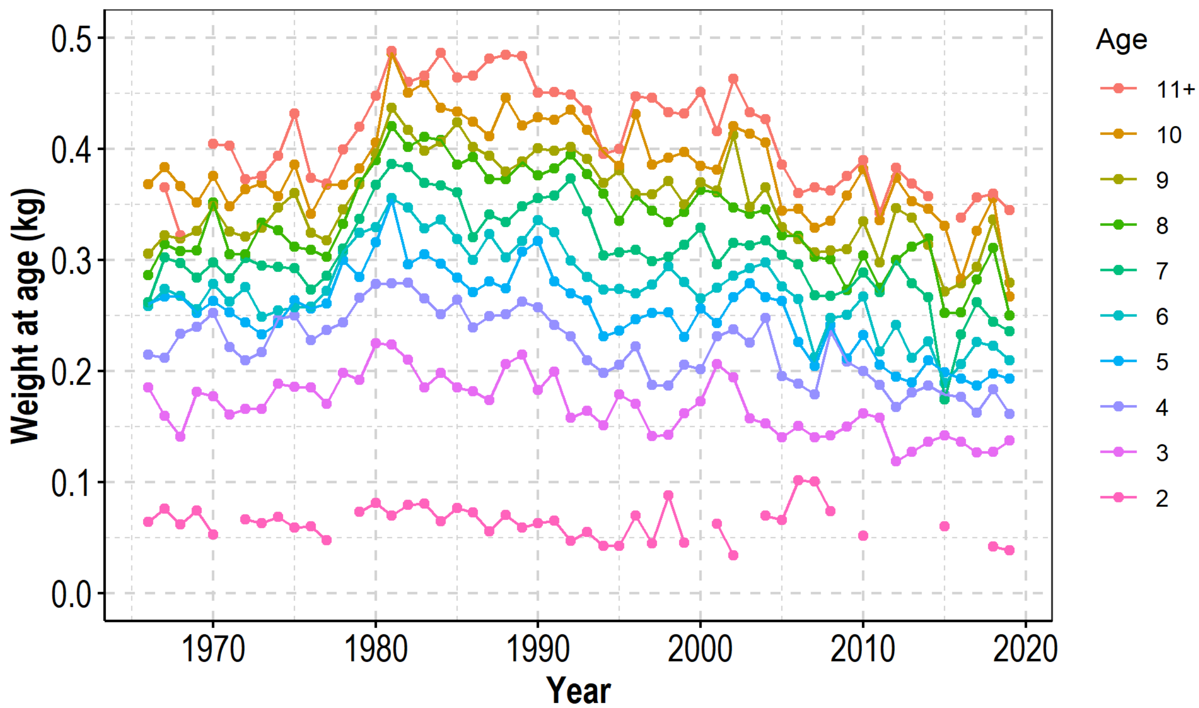

Figure 23. Predicted annual weight-at-age in NAFO Division 4R for spring spawning herring standardized for NAFO 4Rd, August and small purse seiners.

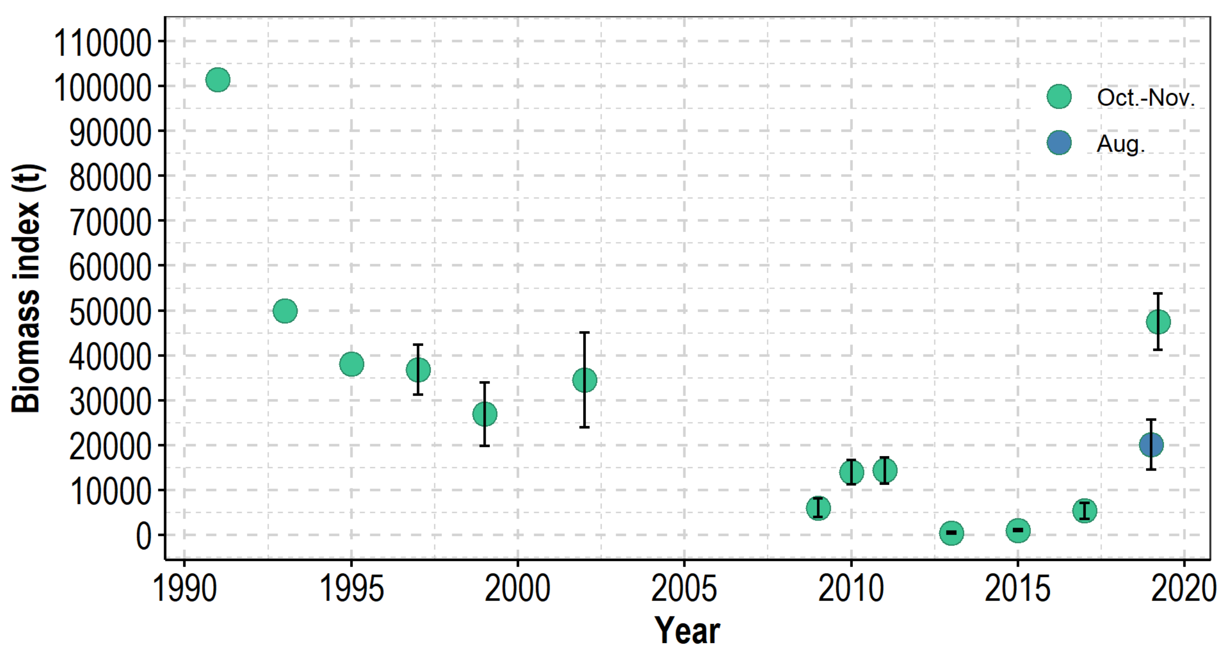

Figure 24. Fall and summer 2019 acoustic survey biomass indices for spring spawning herring. Error bars represent standard errors.

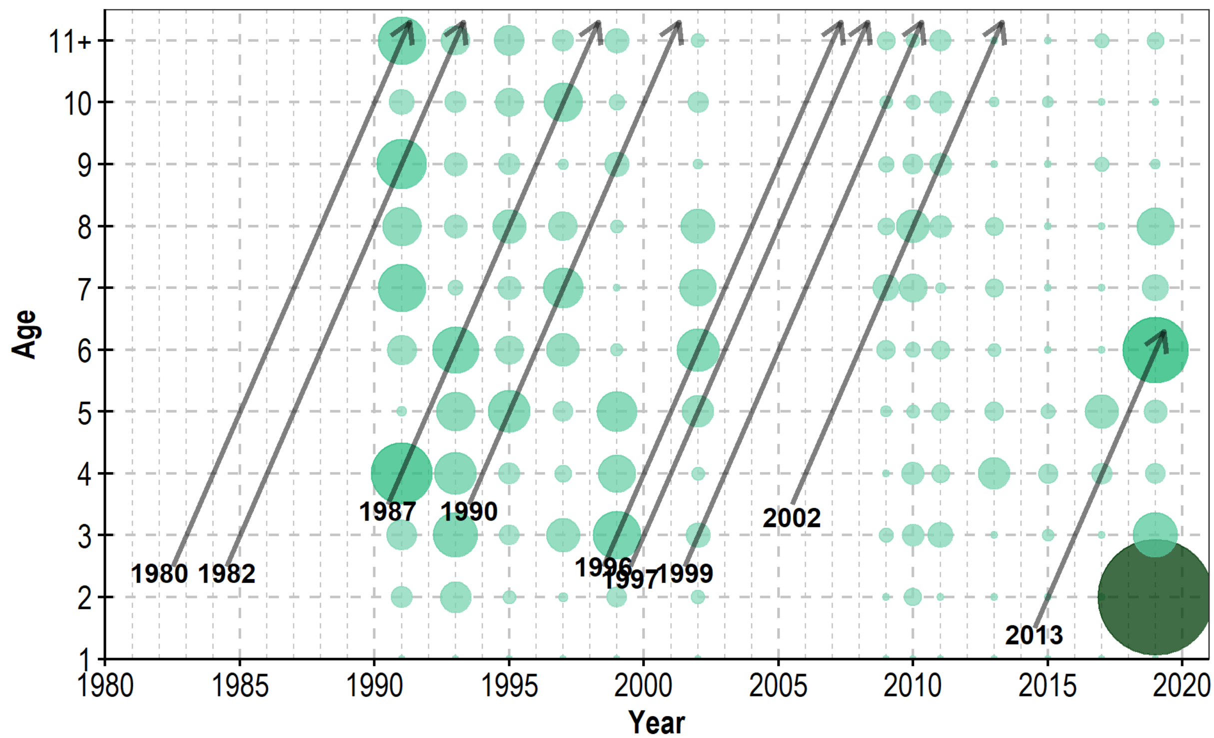

Figure 25. Bubble plot of the spring spawning herring number-at-age from the acoustic surveys. Circle area is proportional to estimated abundance (number of fish) in the survey. Arrows represent the same dominant cohorts indicated in Figure 19.

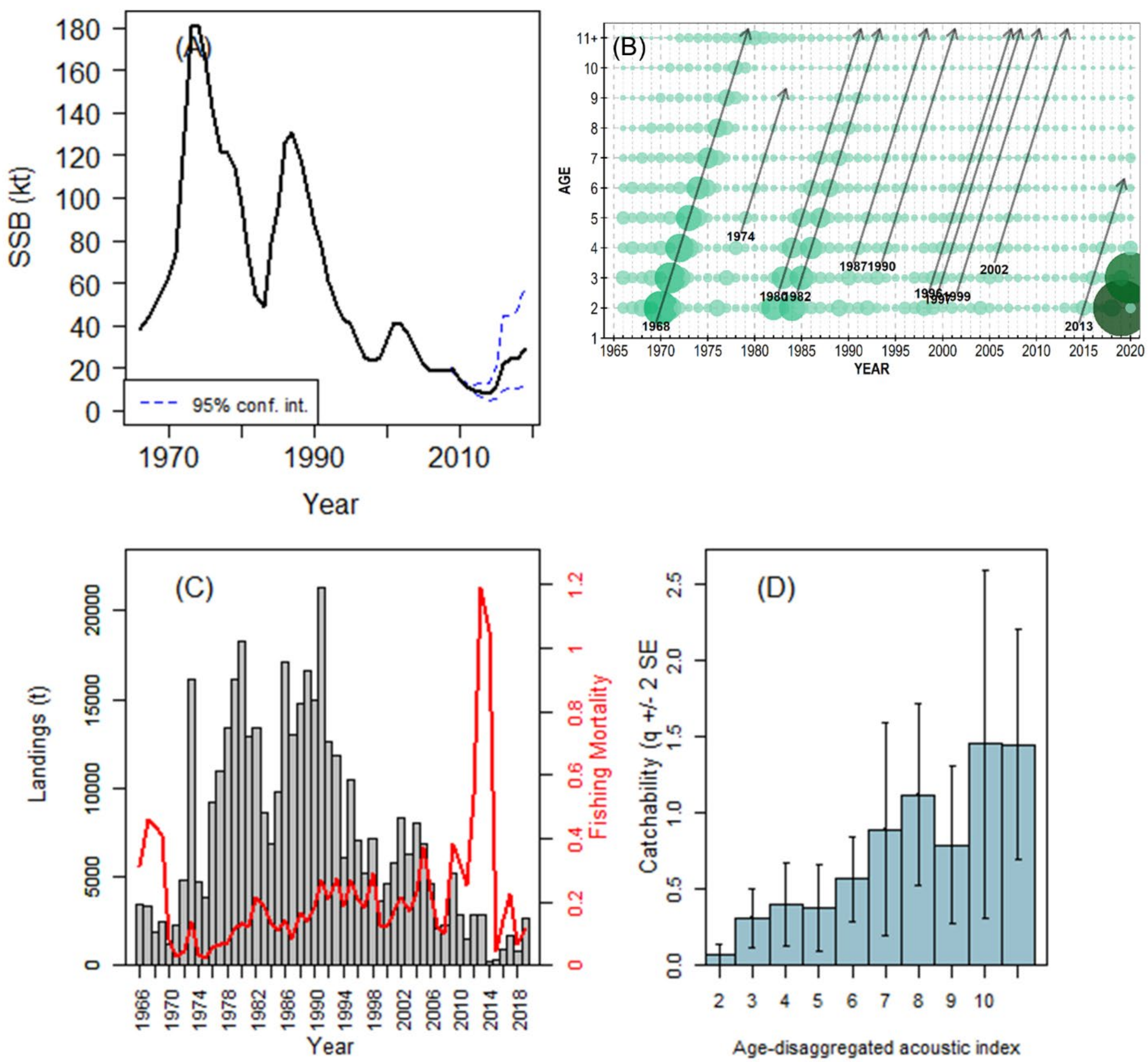

Figure 26. Spring spawning herring model 1a output: (A) estimated spawning stock biomass with 95% bootstrapped confidence intervals, (B) predicted number-at-age (arrows represent the same dominant cohorts indicated in Figure 19 and 25), (C) average F (2–11+) and annual landing, and (D) catchability coefficients.

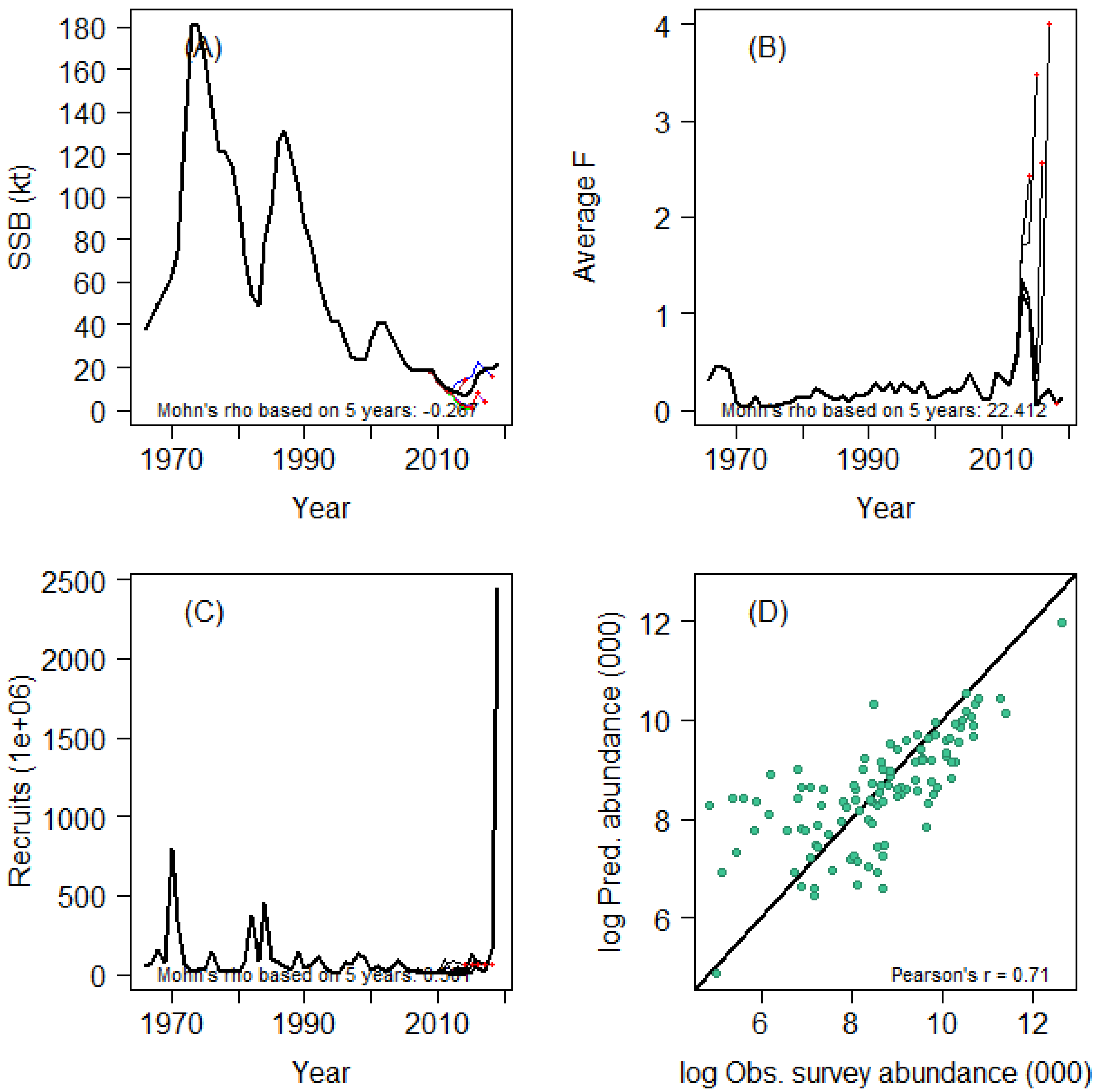

Figure 27. Spring spawning herring model 1a (A) SSB, (B) average F and (C) recruits retrospective plots, and (D) predicted and observed abundances.

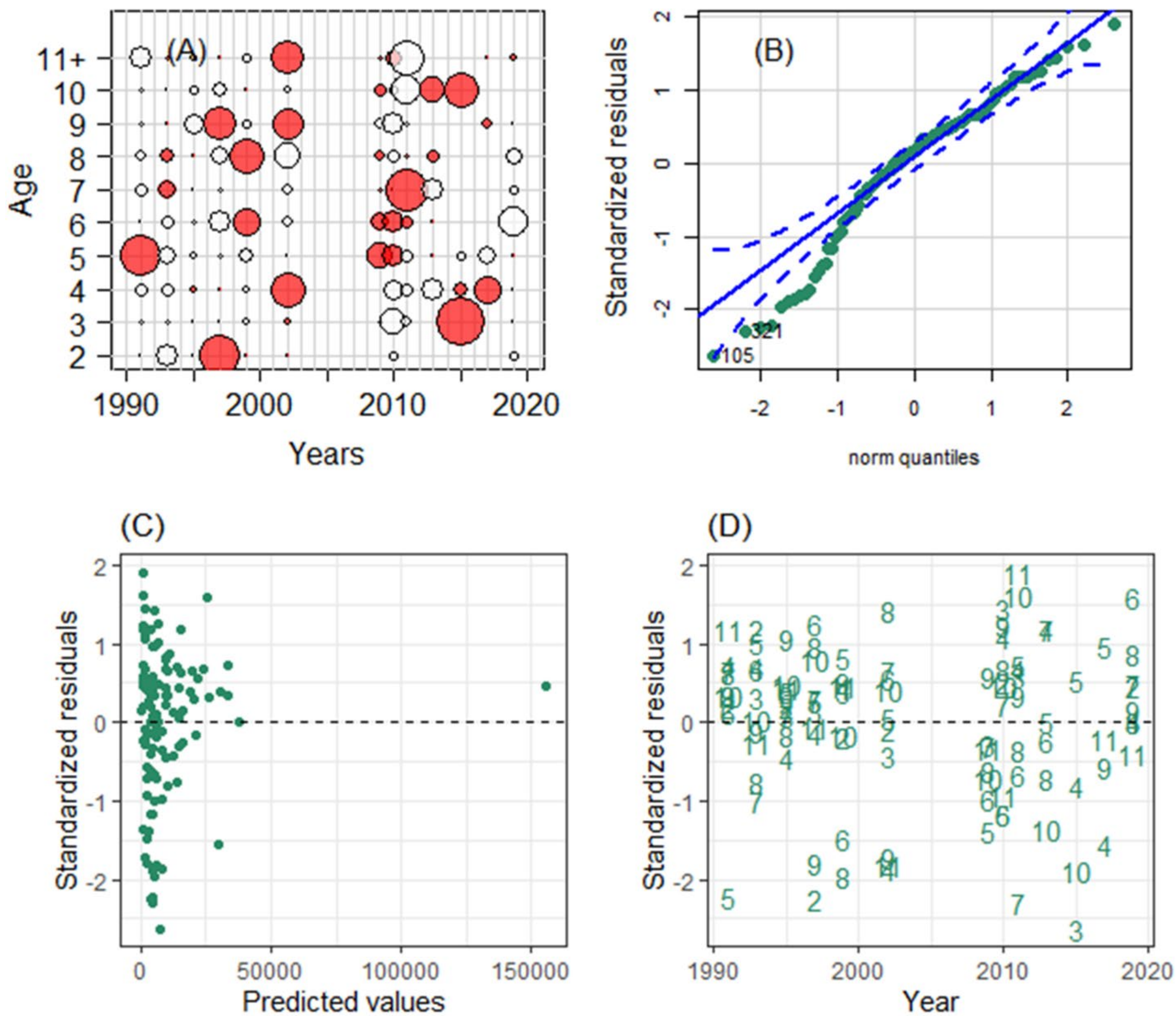

Figure 28. Spring spawning herring model 1a index residual plots: (A) bubble plot of residuals by age and year (open and red bubble respectively represent positive and negative residuals), (B) quantile-quantile plot (solid and dashed blue lines respectively represent theoretical quantiles and 95% confidence intervals), (C) standardized residuals and predicted values, and (D) standardized residuals as a function of year and age.

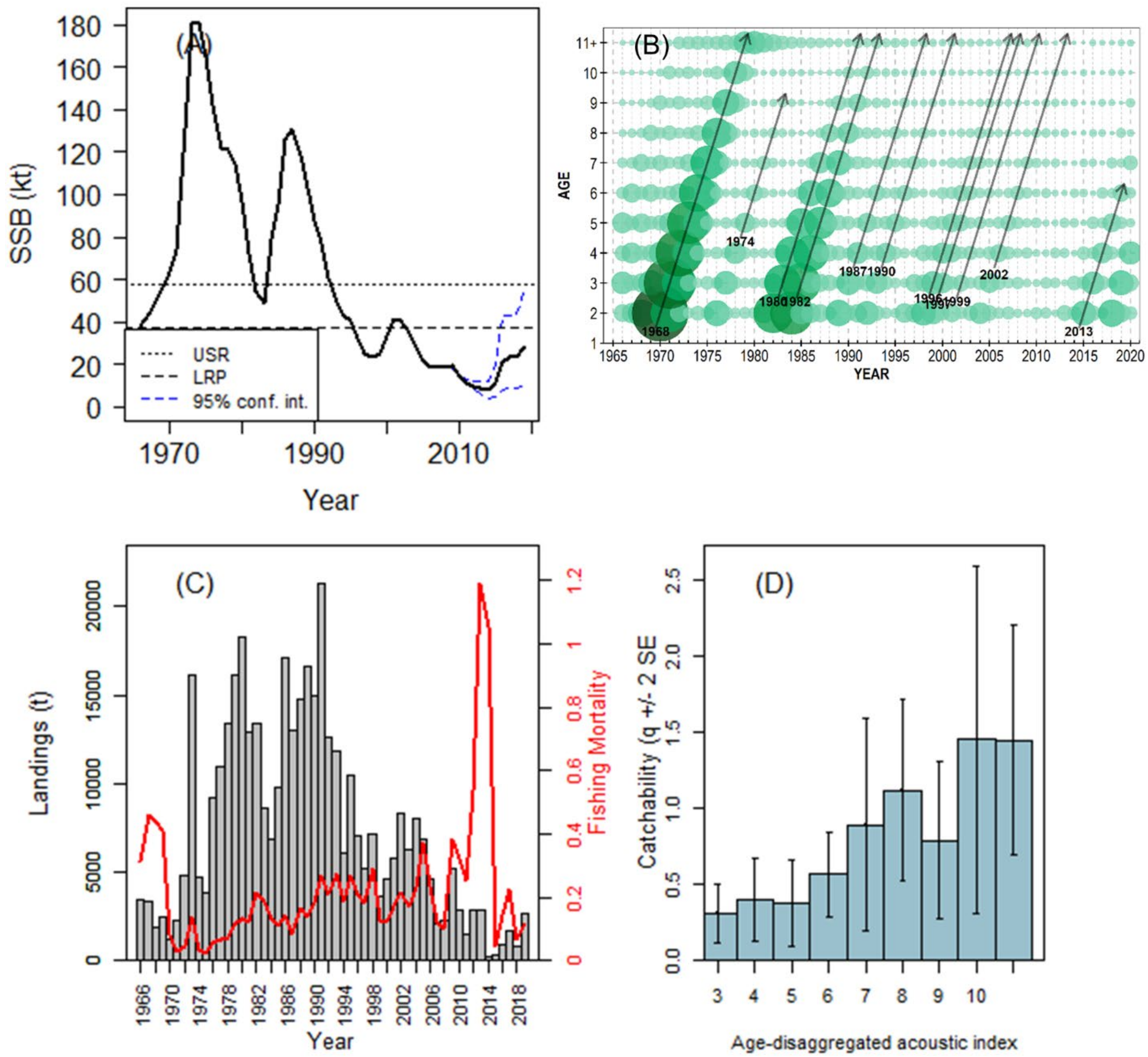

Figure 29. Spring spawning herring model 1b output: (A) estimated spawning stock biomass with USR, LRP and 95% bootstrapped confidence intervals, (B) predicted number-at-age (arrows represent the same dominant cohorts indicated in Figure 19 and 25), (C) average F (2–11+) and annual landings, and (D) catchability coefficients.

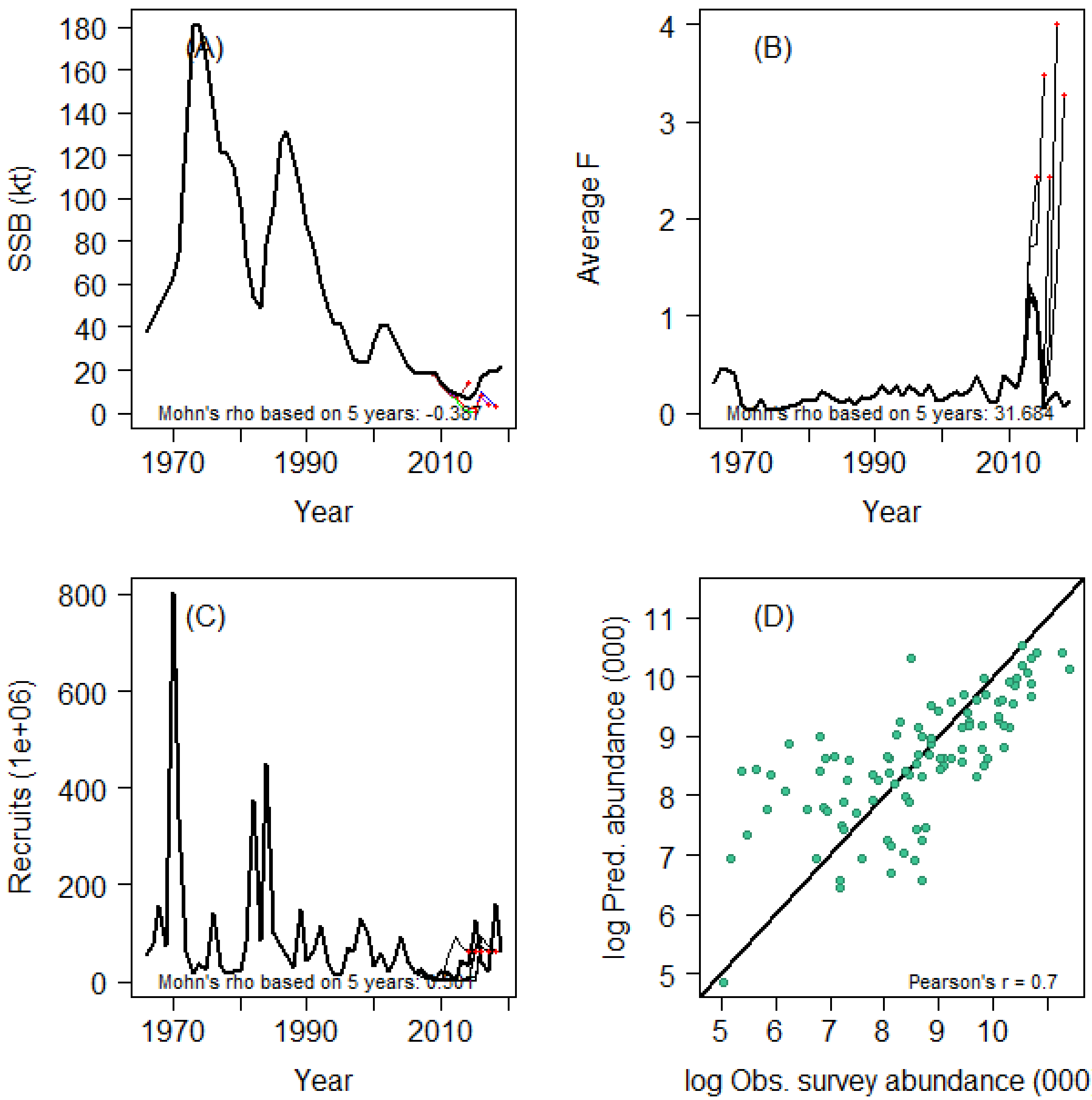

Figure 30. Spring spawning herring model 1b (A) SSB, (B) average F and (C) recruits retrospective plots, and (D) predicted and observed abundances.

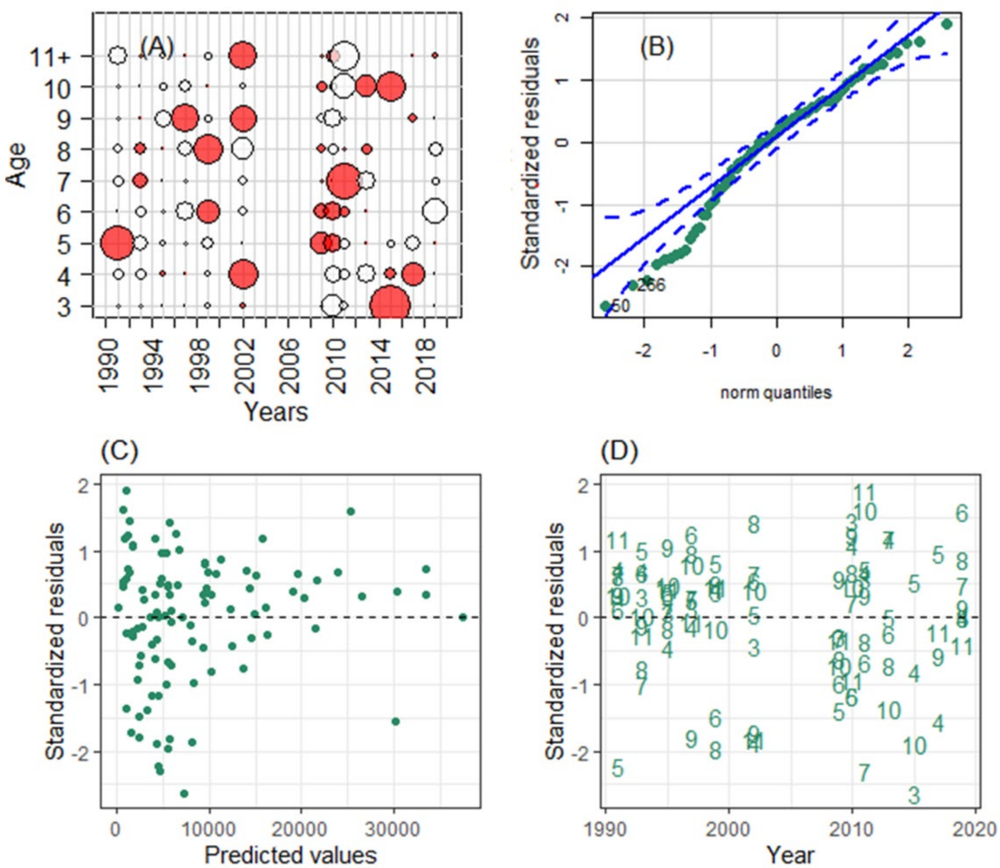

Figure 31. Spring spawning herring model 1b index residual plots: (A) bubble plot of residuals by age and year (open and red bubble respectively represent positive and negative residuals), (B) quantile-quantile plot (solid and dashed blue lines respectively represent theoretical quantiles and 95% confidence intervals), (C) standardized residuals and predicted values, and (D) standardized residuals as a function of year and age.

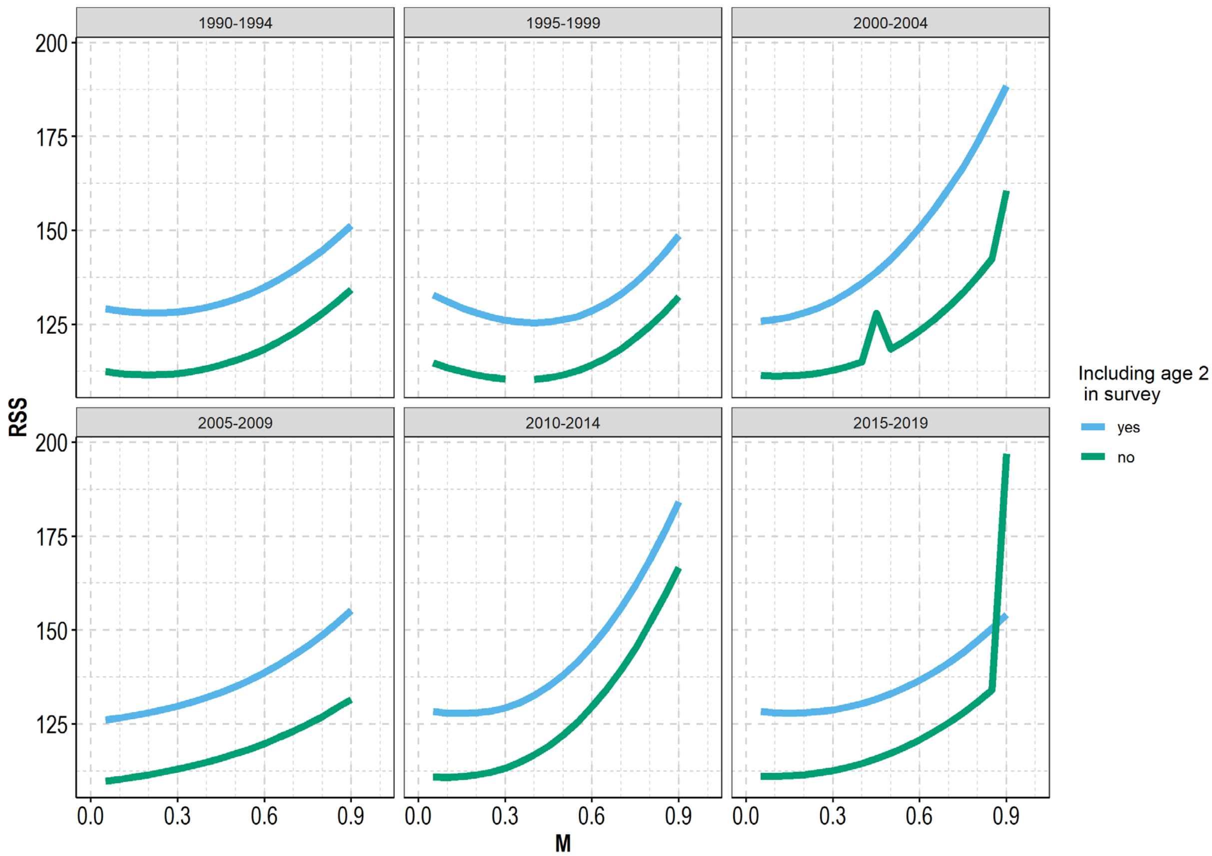

Figure 32. Sensitivity analysis used to select natural mortality (M) for Spring spawning herring models 2a (including age 2 survey index) and 2b (excluding age 2 survey index). RSS: residual sum of squares. Missing values indicate model non-convergence.

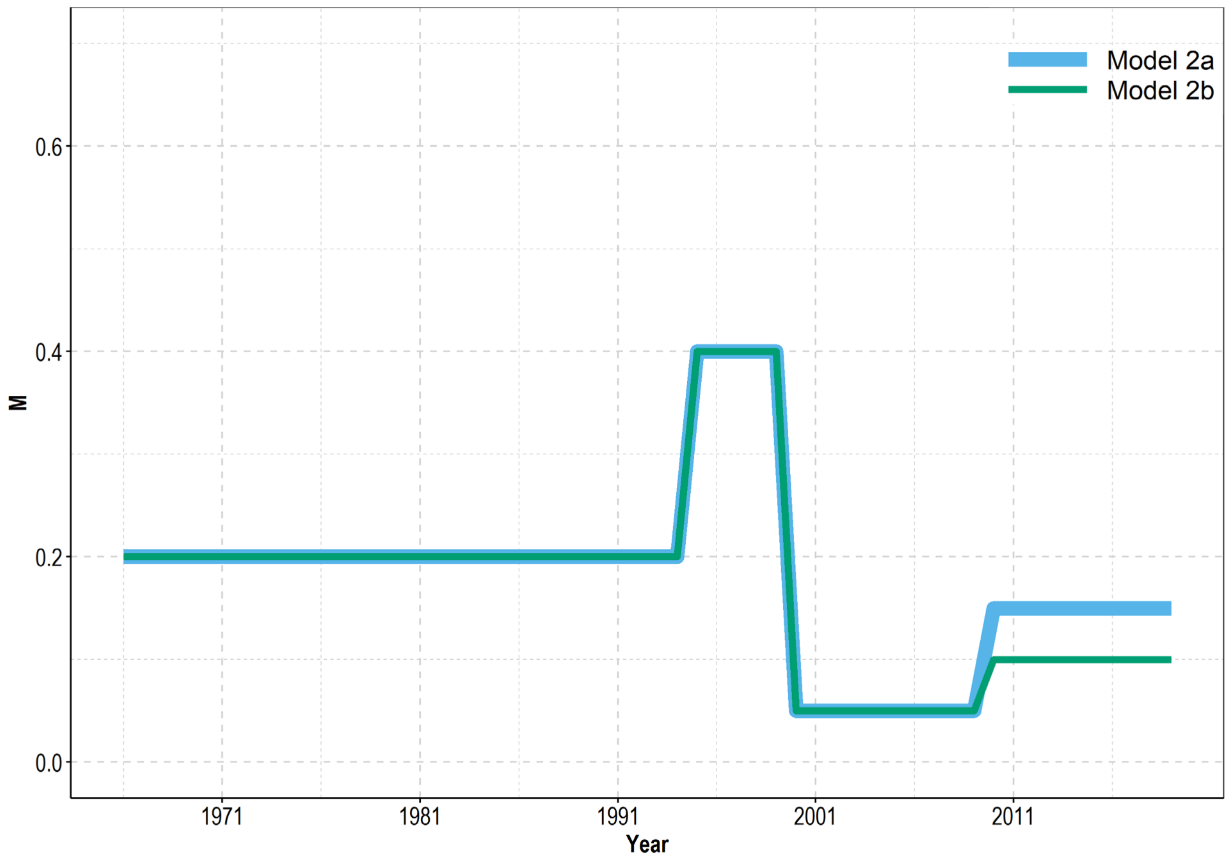

Figure 33. Natural mortality (M) selected by the sensitivity analysis and used in Spring spawning herring models 2a and 2b.

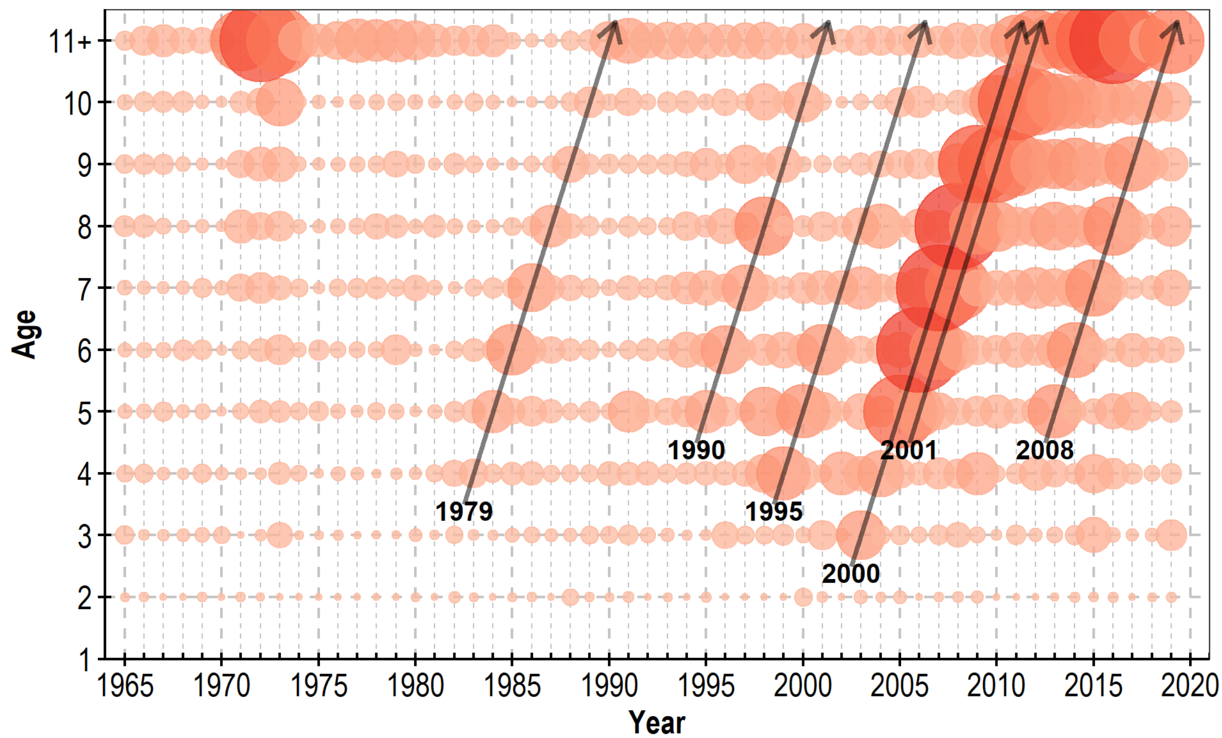

Figure 34. Bubble plot of fall spawning fishery catch-at-age in NAFO Division 4R, 1965–2019. Circle area is proportional to the annual landing (number of fish) of a given age class. Arrows represent dominant cohorts.

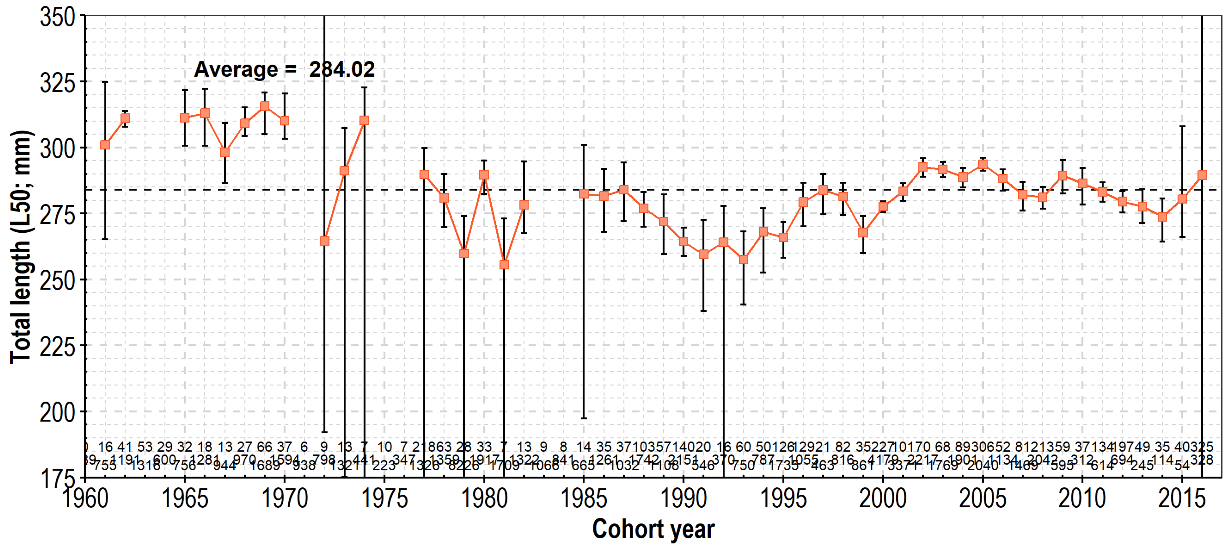

Figure 35. Total length at 50% maturity by cohort for fall spawning herring in NAFO Division 4R. Error bars represent bootstrapped 95% confidence intervals. The numbers above the x-axis represent total number of fish samples (lower 2 lines) and the number of immature fish samples by cohort (upper). The horizontal dashed line is the arithmetic mean of the cohorts L50s.

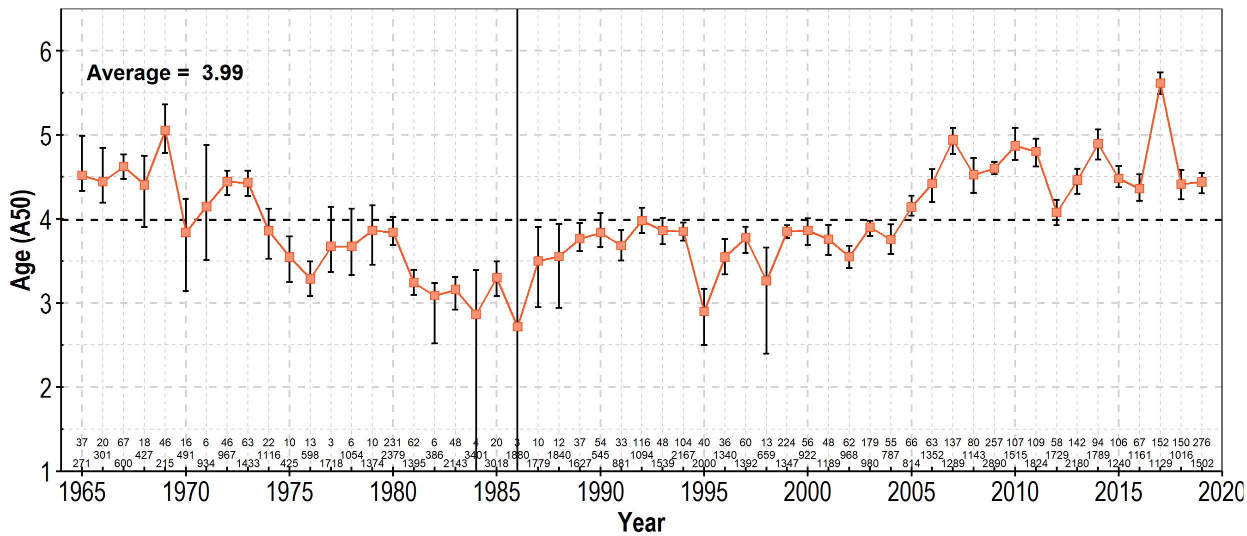

Figure 36. Age at 50% maturity by year for fall spawning herring in NAFO Division 4R. Error bars represent bootstrapped 95% confidence intervals. The horizontal dashed line is the arithmetic means of annual L50s. The numbers above the x-axis represent total number of fish by cohort (lower 2 lines of each figure) and the number of immature fish by cohort (upper line of each figure).

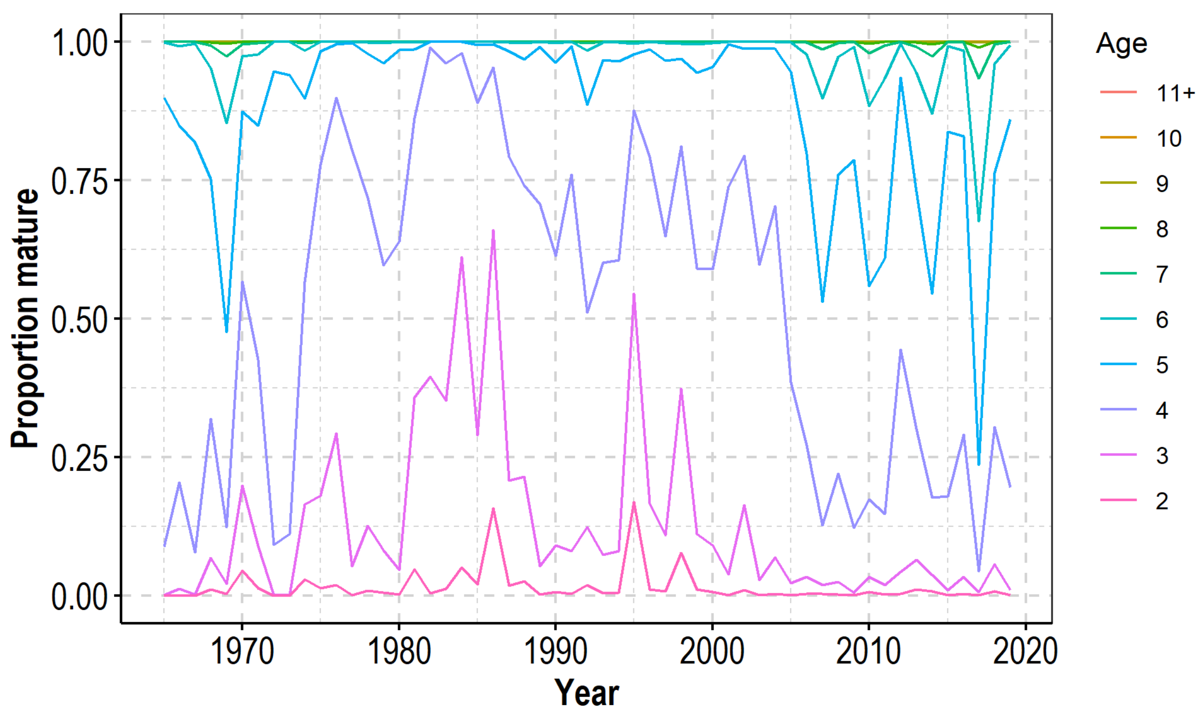

Figure 37. Maturity-at-age (proportion mature) for spring spawning herring in NAFO Division 4R.

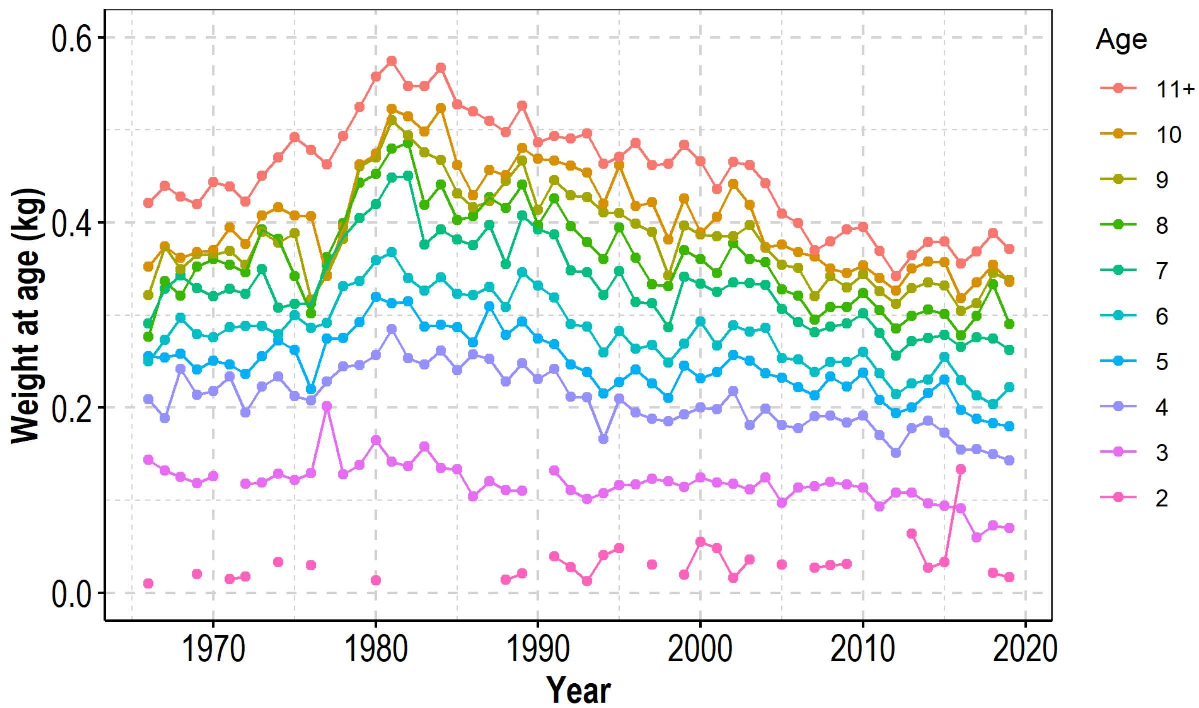

Figure 38. Weight-at-age by year for fall spawning herring in NAFO Division 4R. Weights were predicted from standardizing models for NAFO 4Ra, November and small purse seiners.

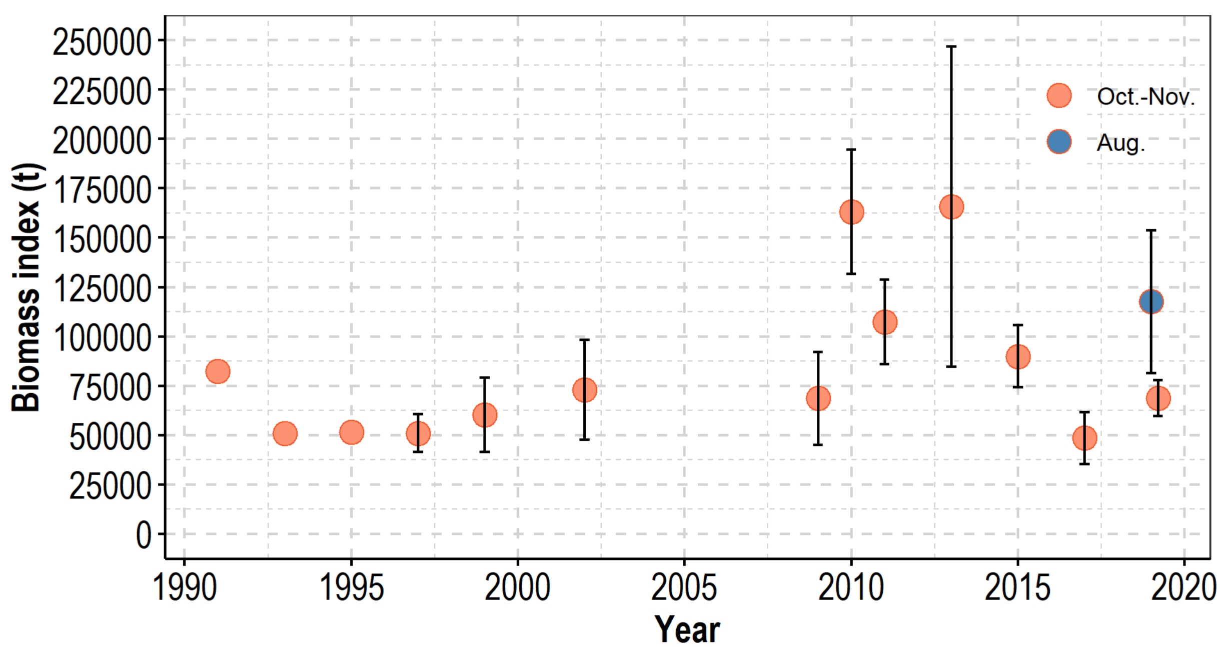

Figure 39. Fall and summer acoustic survey biomass indices for fall spawning herring. Error bars represent standard errors.

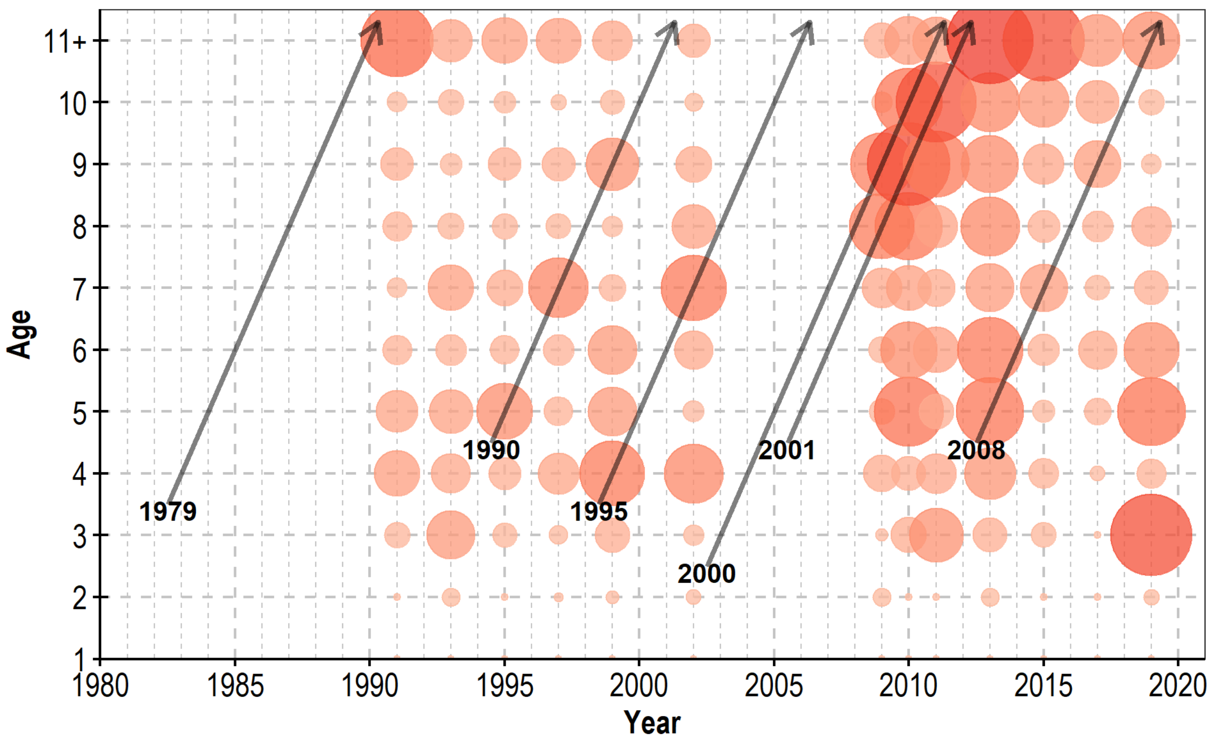

Figure 40. Bubble plot of the fall spawning herring number-at-age from the acoustic surveys. Circle area is proportional to the estimated abundance (number of fish) in the survey. Arrows represent the same dominant cohorts indicated in Figure 34.

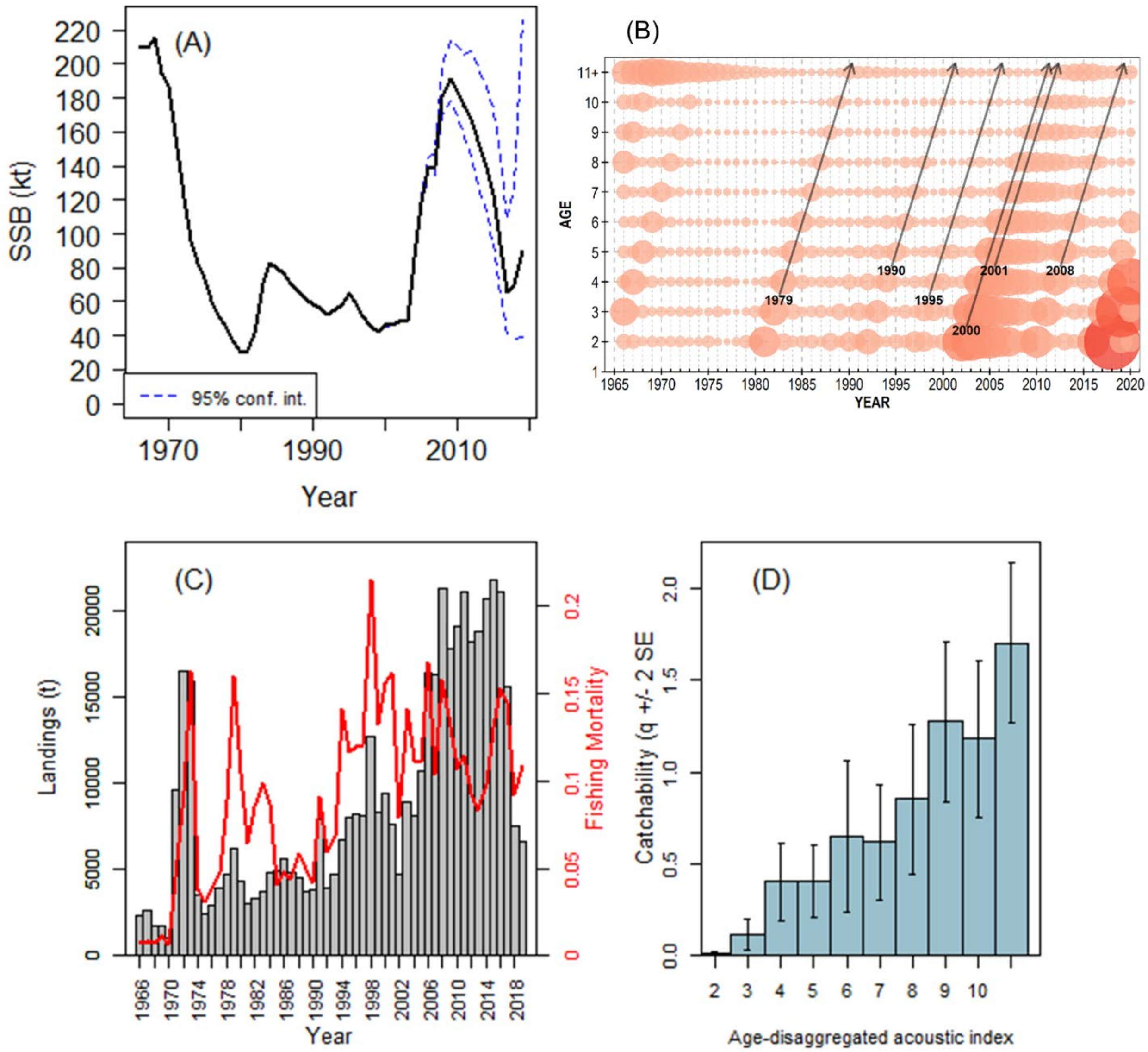

Figure 41. Fall spawning herring model 1a output: (A) estimated spawning stock biomass with 95% bootstrapped confidence intervals, (B) predicted number-at-age (arrows represent the same dominant cohorts indicated in Figure 34Figure 19 and 40), (C) average F (2–11+) and annual landings, and (D) catchability coefficients.

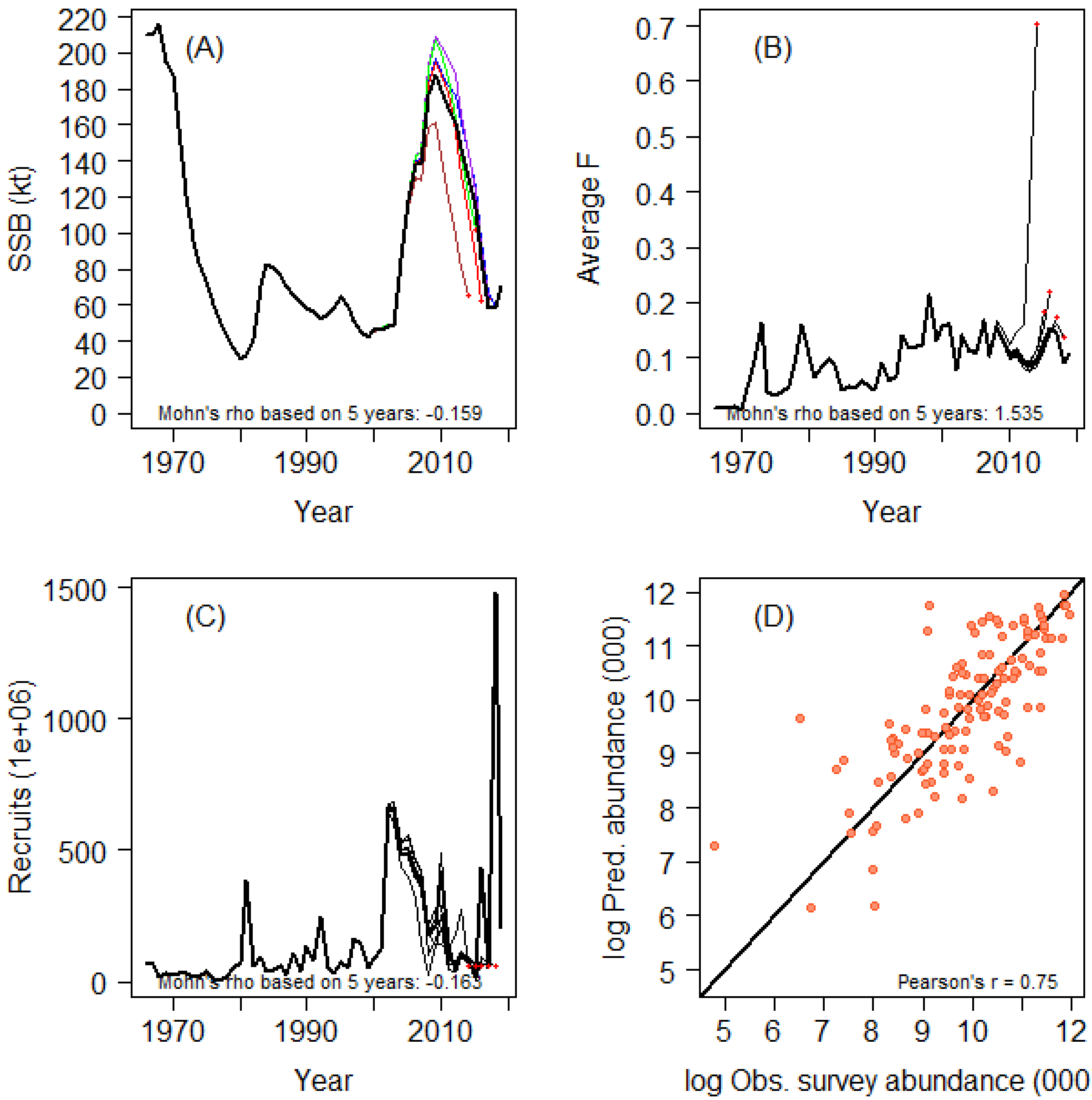

Figure 42. Fall spawning herring model 1a (A) SSB, (B) average F and (C) recruits retrospective plots, and (D) predicted and observed abundances.

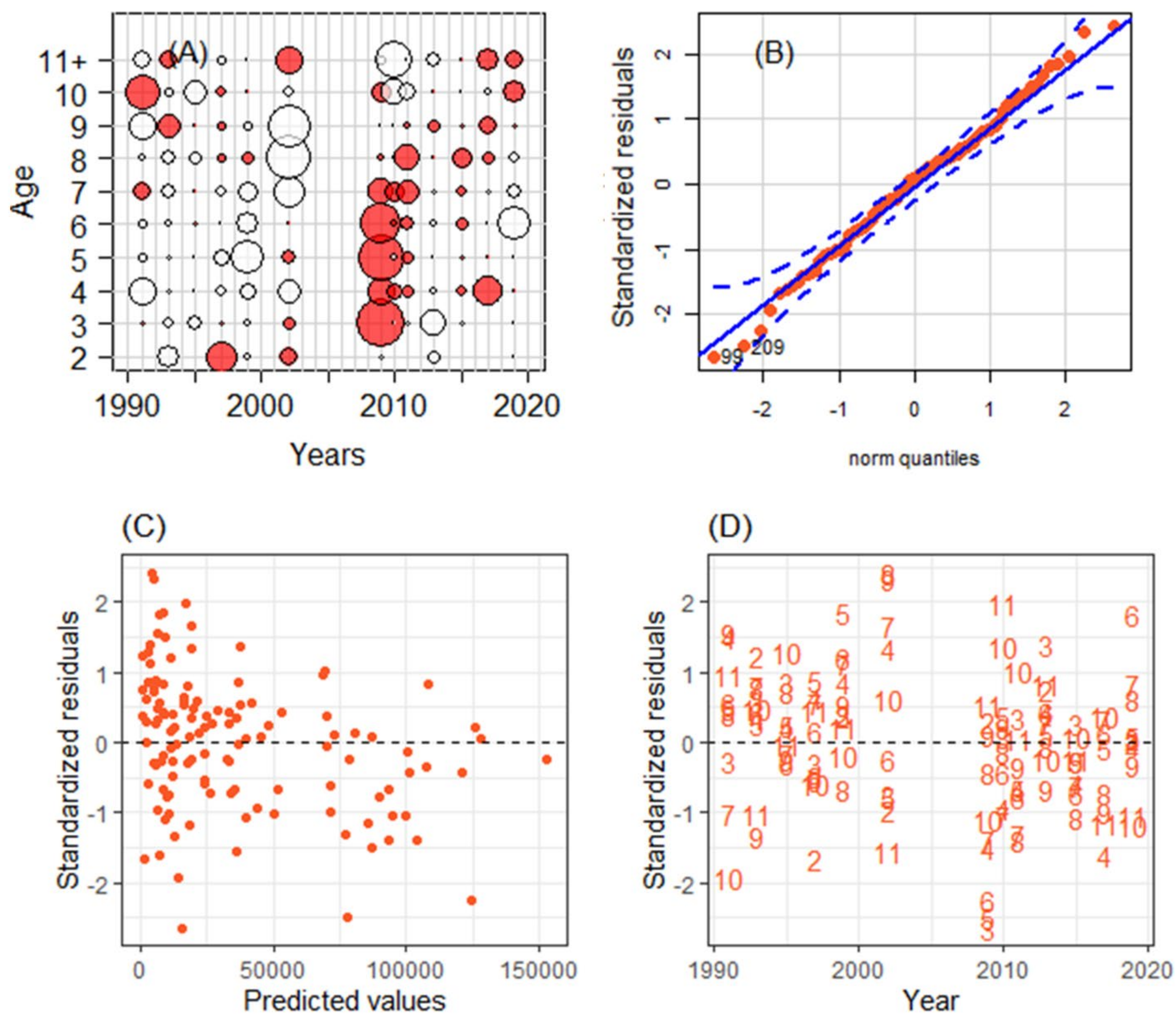

Figure 43. Fall spawning herring model 1a index residual plots: (A) bubble plot of residuals by age and year (open and red bubble respectively represent positive and negative residuals), (B) quantile-quantile plot (solid and dashed blue lines respectively represent theoretical quantiles and 95% confidence intervals), (C) standardized residuals and predicted values, and (D) standardized residuals as a function of year and age.

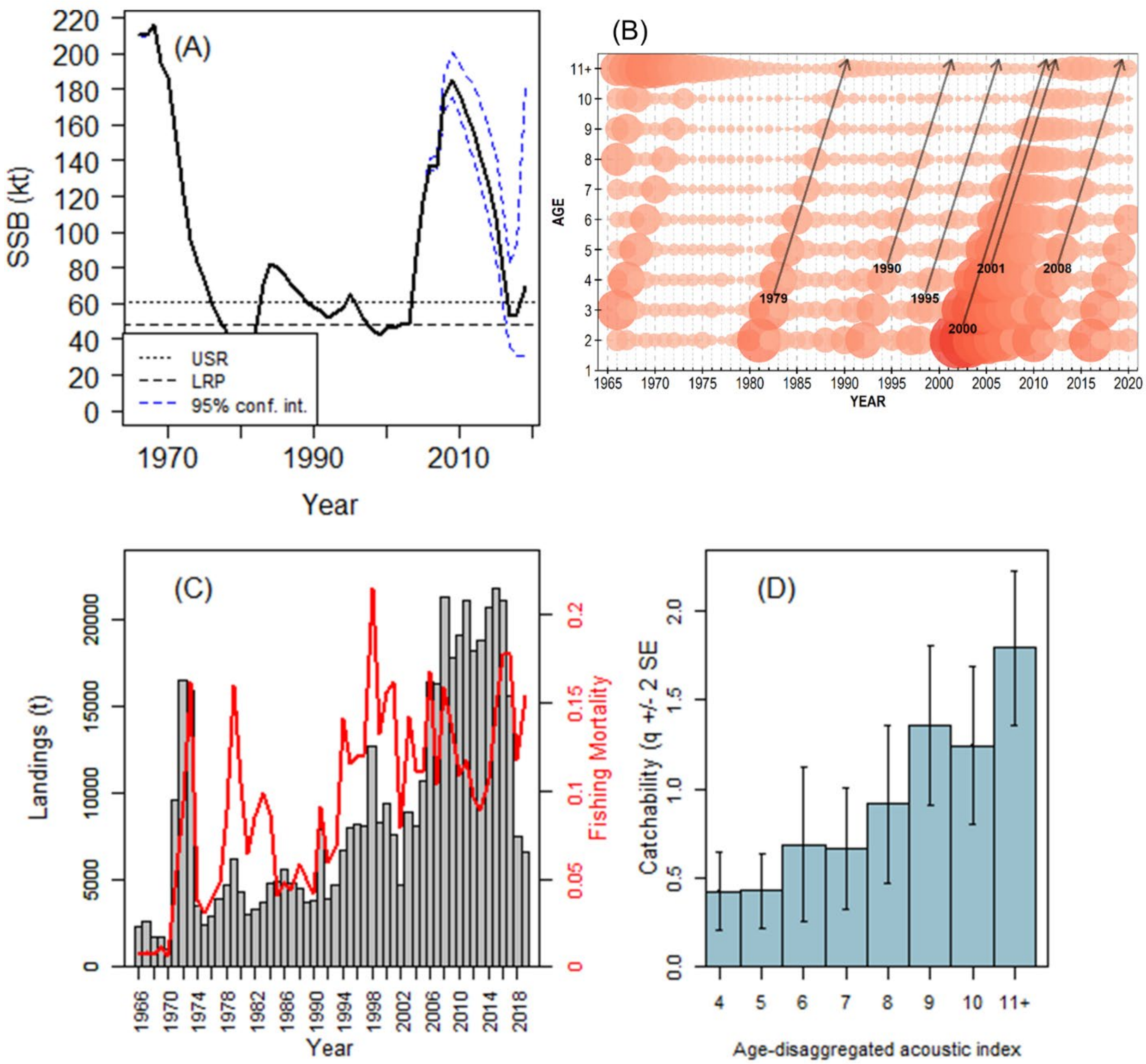

Figure 44. Fall spawning herring model 1b output: (A) estimated spawning stock biomass with USR, LRP and 95% bootstrapped confidence intervals, (B) predicted number-at-age (arrows represent the same dominant cohorts indicated in Figure 34Figure 19 and 40), (C) average F (2–11+) and annual landings, and (D) catchability coefficients.

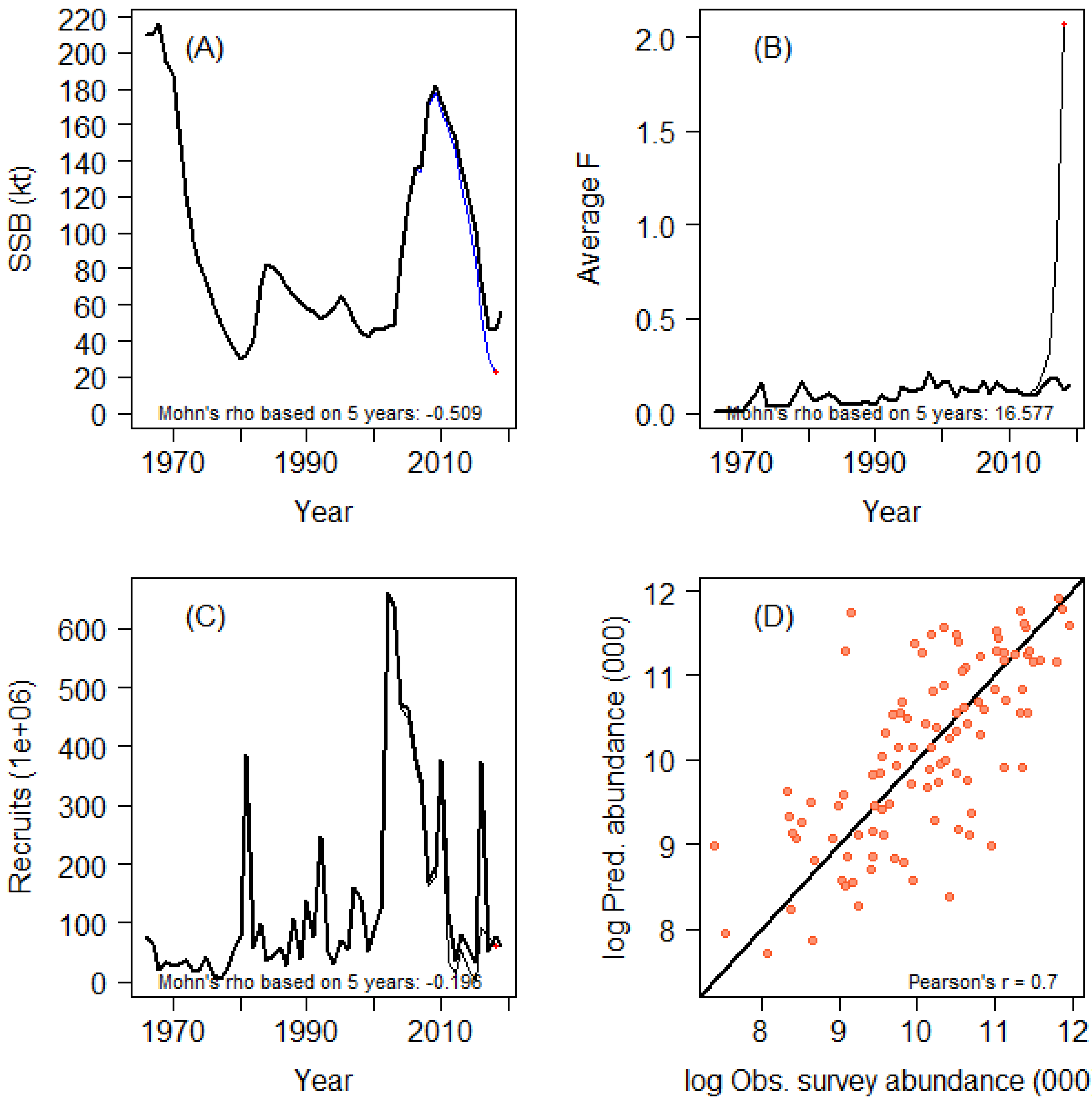

Figure 45. Fall spawning herring model 1b (A) SSB, (B) average F and (C) recruits retrospective plots, and (D) predicted and observed abundances.

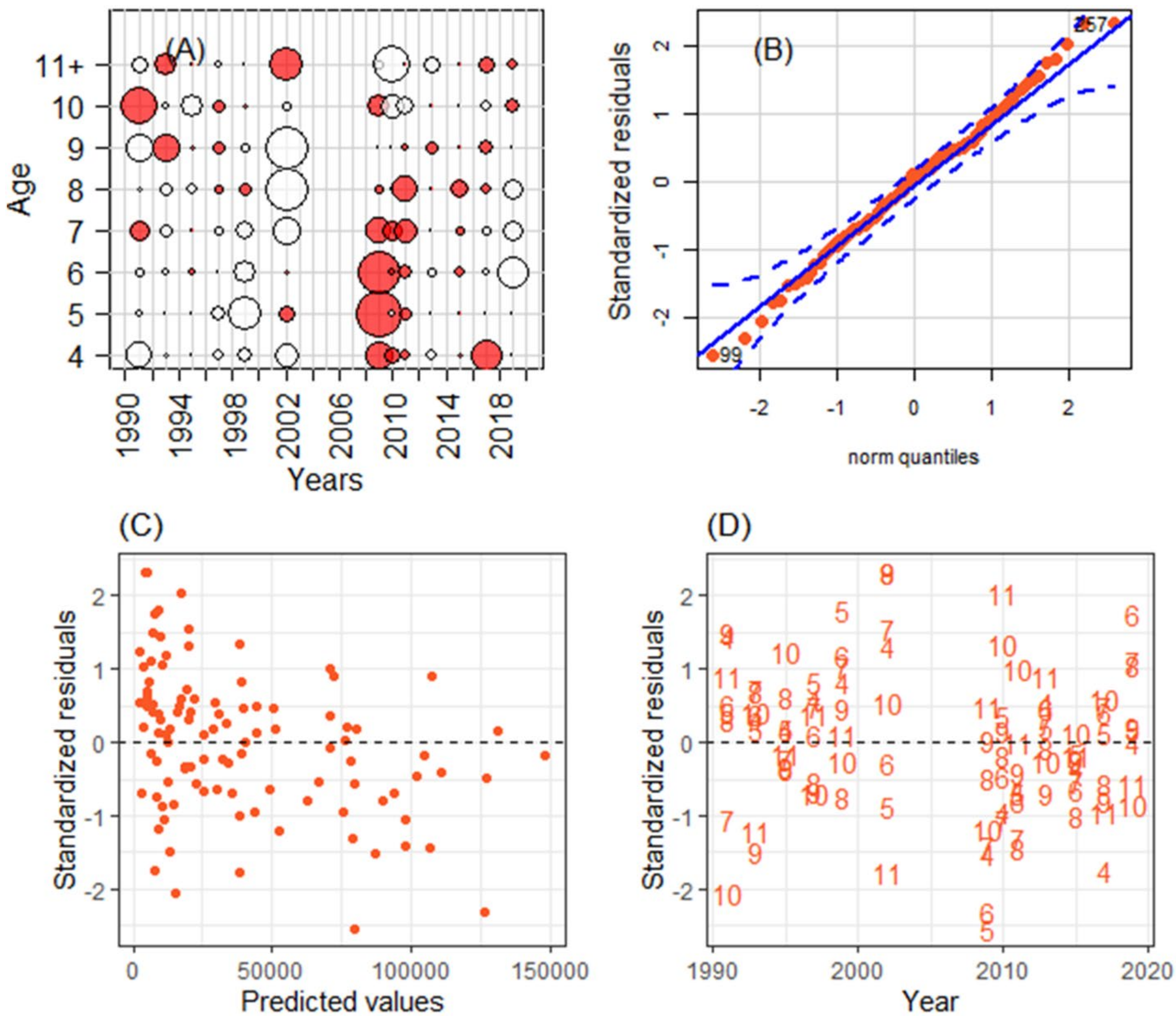

Figure 46. Fall spawning herring model 1b index residual plots: (A) bubble plot of residuals by age and year (open and red bubble respectively represent positive and negative residuals), (B) quantile-quantile plot (solid and dashed blue lines respectively represent theoretical quantiles and 95% confidence intervals), (C) standardized residuals and predicted values, and (D) standardized residuals as a function of year and age.

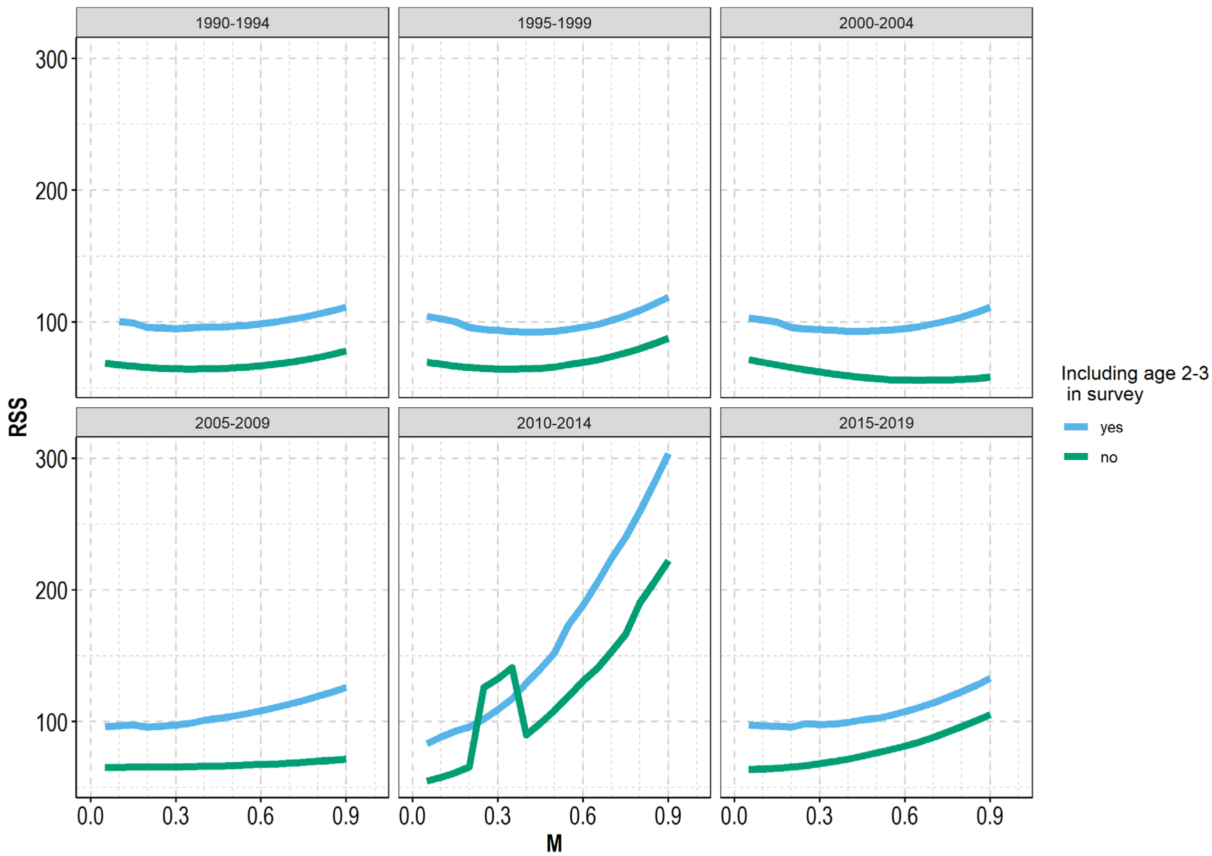

Figure 47. Sensitivity analysis used to select natural mortality (M) for Fall spawning herring models 2a (including age 2 and 3 survey indices) and 2b (excluding age 2 and 3 survey indices). RSS: residual sum of squares.

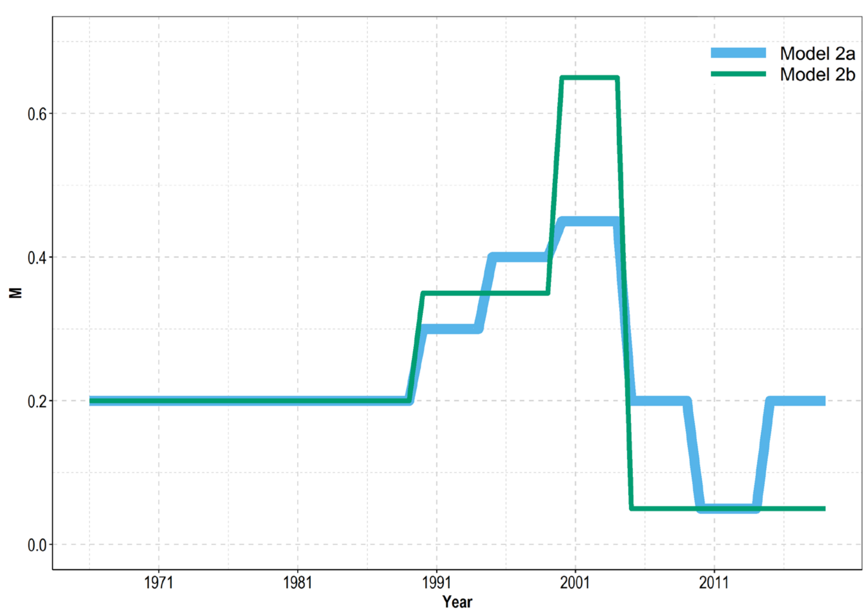

Figure 48. Natural mortality (M) selected by the sensitivity analysis and used in Fall spawning herring models 2a and 2b.

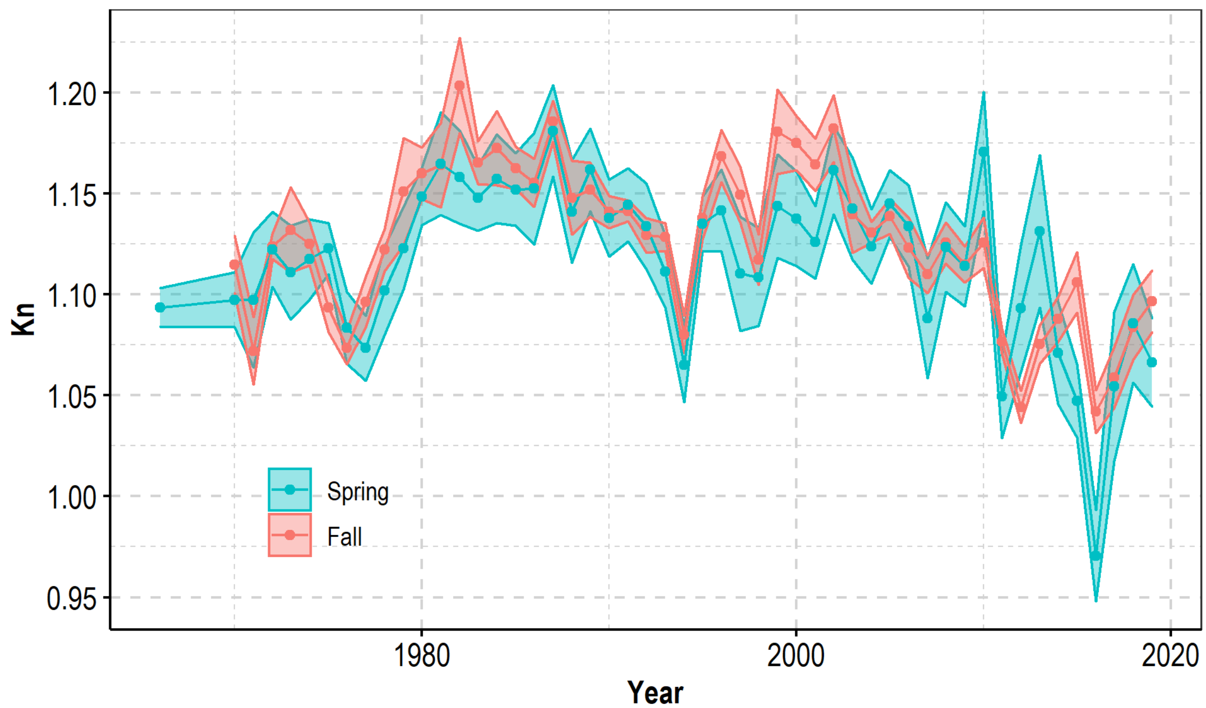

Figure 49. Interannual variability of standardized Kn averaged for age 4 to 9. Blue line: Kn for spring spawning herring, orange line: Kn for fall spawning herring, shaded area: standard error.

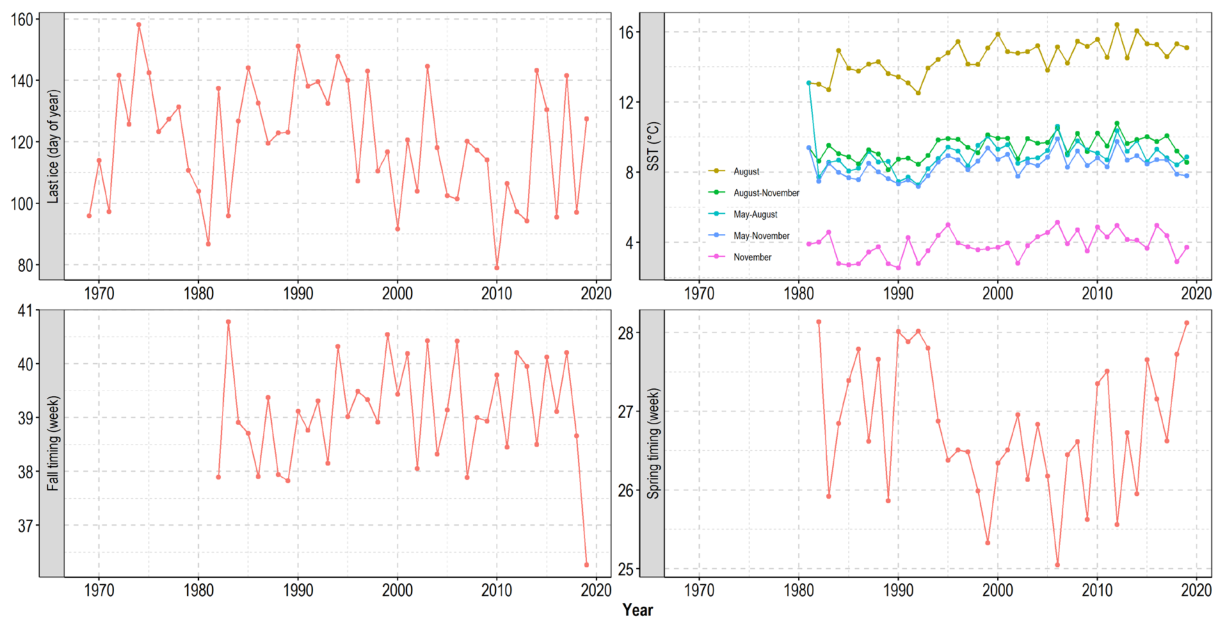

Figure 50. Interannual variability of the physical environment predictors included in model selection averaged for region 2, 3 and 4 of the ecosystem approach.

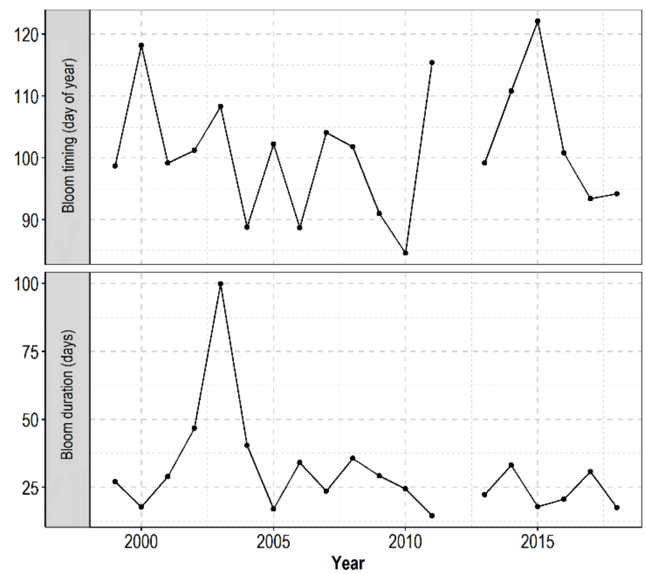

Figure 51. Interannual variability of phytoplankton productivity predictors included in model selection averaged for region 2, 3 and 4 of the ecosystem approach.

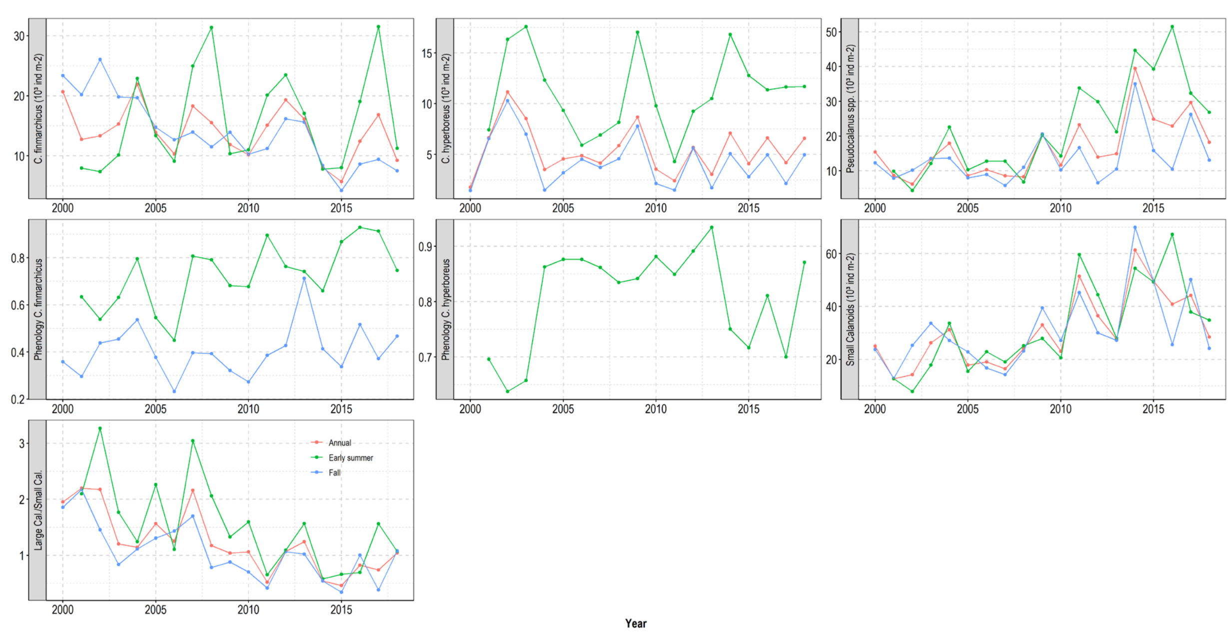

Figure 52. Interannual variability of zooplankton productivity predictors included in model selection averaged for region 2, 3 and 4 of the ecosystem approach.

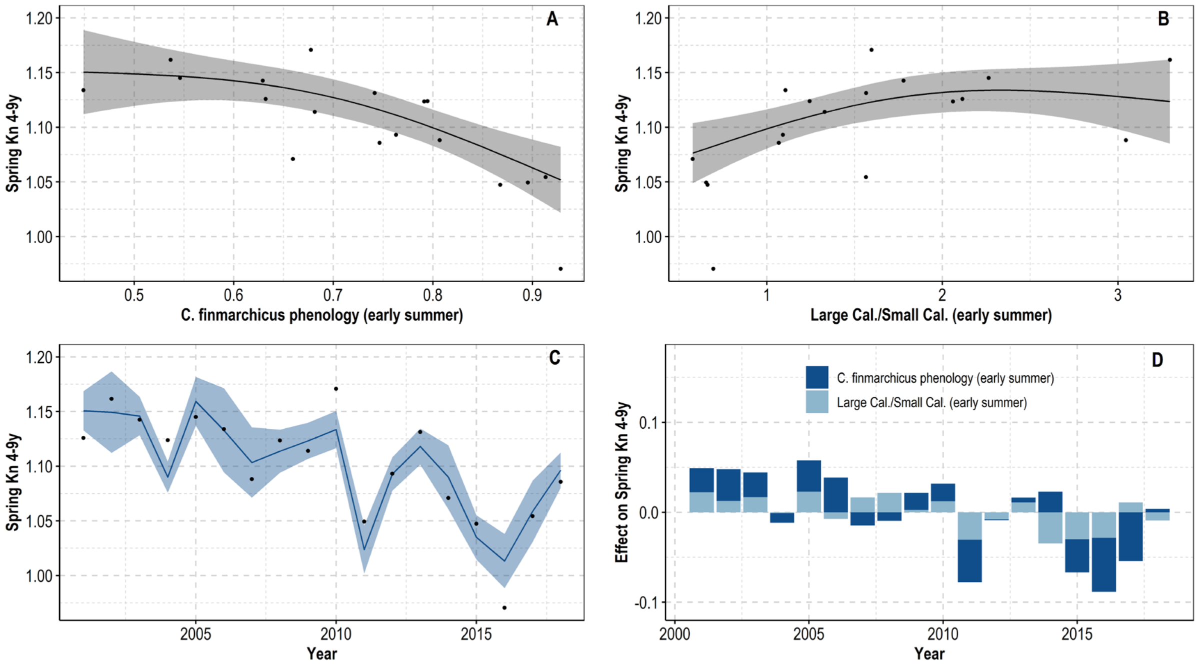

Figure 53. Results of GAMs for spring spawning herring. Relationship between Kn 4–9 years and C. finmarchicus phenology (A) and the ratio of large and small calanoids (B). Predicted Kn 4–9 years are compared to observations (C: blue line for predictions, shaded area 95% confidence intervals, black points for observations). The effect of each variable at each year is presented in D.

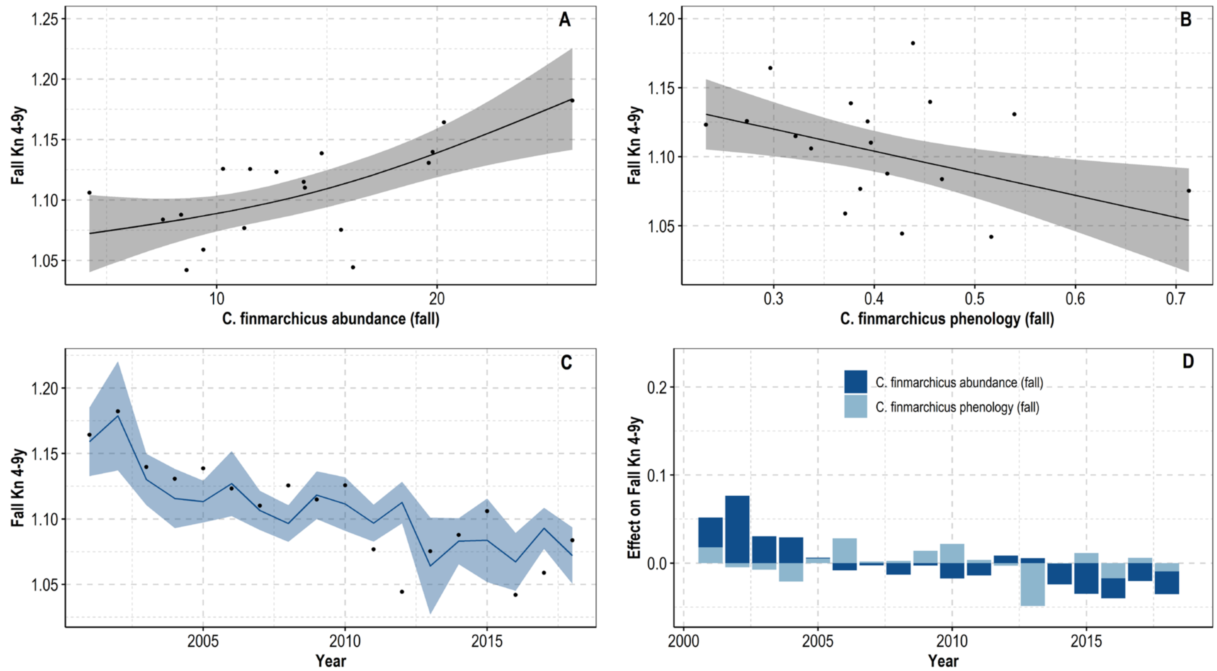

Figure 54. Results of GAMs for fall spawning herring. Relationship between Kn 4–9 years and C. finmarchicus abundance (A) and phenology (B). Predicted Kn 4–9 years are compared to observations (C: blue line for predictions, shaded area for 95% confidence intervals, black points for observations). The effect of each variable at each year is presented in D.

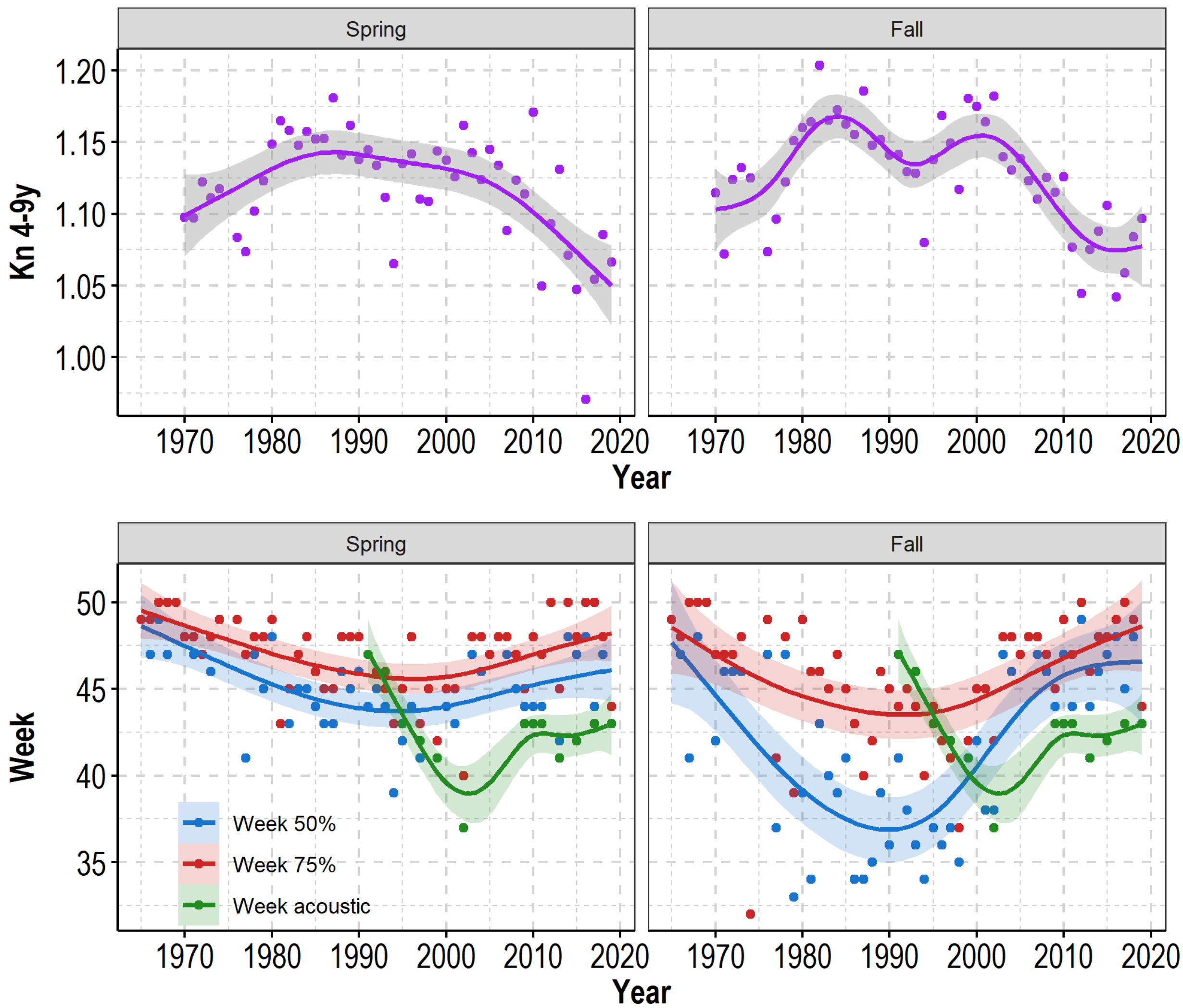

Figure 55. Variations in Kn (purple), week at which cumulative commercial landings of the late summer-autumn fishery reach 50% (blue) and 75% (red) for 4R fall spawning (right) and spring spawning herring (left) and median week of the acoustic survey (green). Lines: smoother function with confidence interval around the fit.

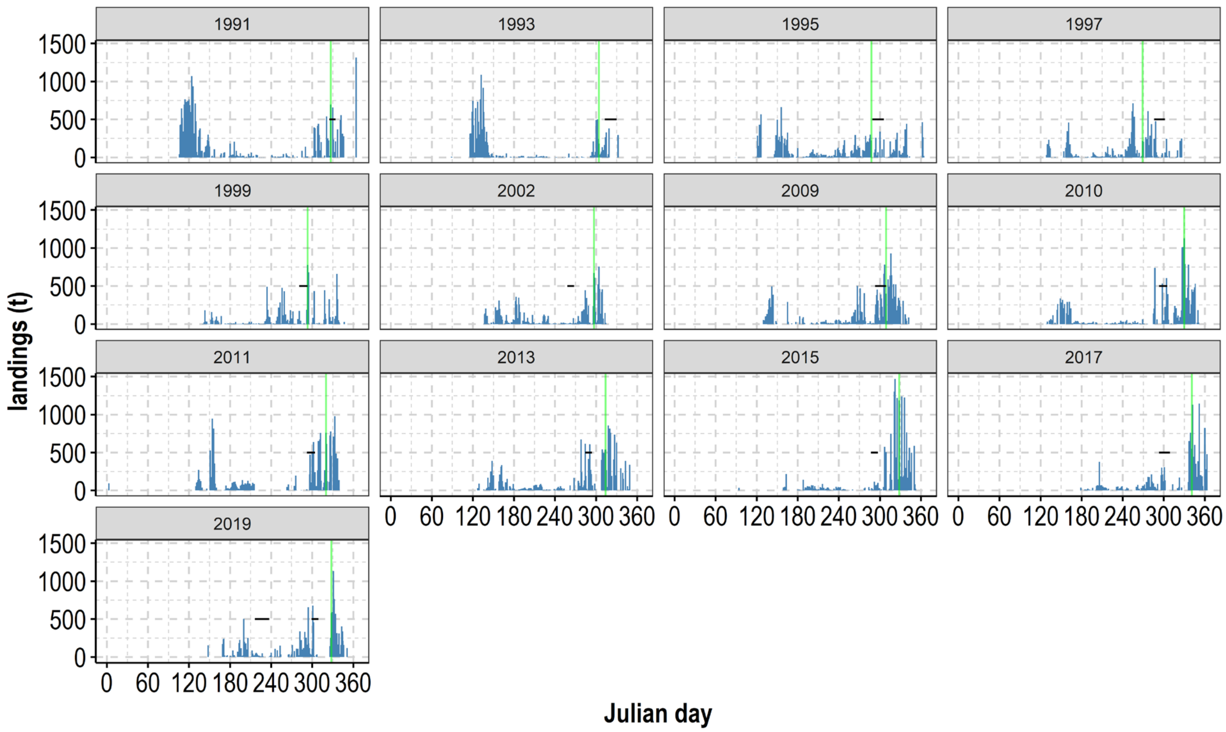

Figure 56. Temporal distribution of the landings (vertical bars) compared to the timing of the hydroacoustic survey (horizontal black lines). The date cumulative landings of the late summer-autumn fishery reach 50% is indicated by the green vertical bar.

APPENDIX A: SUMMARY OF 1991–2019 FISHERY-INDEPENDENT ACOUSTIC SURVEY RESULTS

Vessels used to perform the acoustic survey (Table A20), gear used to collect the biological samples used in the computation of the 2009–2019 abundance indices (Table A21), acoustic survey sampling effort (Figure A57), biomass per stratum and spawning component (Table A22 and Table A23), and spatial distributions of total biomass (2009–2017; Figure A58) are presented. The 1991 to 2002 acoustic biomass computations come from previous stock assessment documents (McQuinn and Lefebvre 1999, Grégoire et al. 2013, Légaré et al. 2014).

Table A20. Vessels used to perform the herring acoustic surveys.

Year	Vessel
1991	E.E. Prince
1993	F.G. Creed
1995	F.G. Creed
1997	F.G. Creed
1999	F.G. Creed
2002	F.G. Creed
2009	F.G. Creed
2010	F.G. Creed
2011	F.G. Creed
2013	F.G. Creed
2015	Vladykov
2017	F.G. Creed
2019 (August)	F.G. Creed
2019 (Oct.–Nov.)	Leim

Table A21. Number of Atlantic herring used by survey and gear for the computation of the acoustic biomass index.

Survey	Pelagic trawl	Tuck seine	Purse seine (>65’)	Purse seine (<65’)	Gillnet	Fishing vessel
2009	0	0	1743	0	0	Commercial
2010	0	0	625	0	0	Commercial
2011	231	0	497	0	0	Calanus & commercial
2013	0	0	566	324	0	Commercial
2015	0	110	442	441	48	Commercial
2017	93	0	166	55	0	Leim & commercial
2019 (August)	505	0	0	0	0	Steven Paul
2019 (Oct.–Nov.)	868	0	0	0	0	Meridian 66

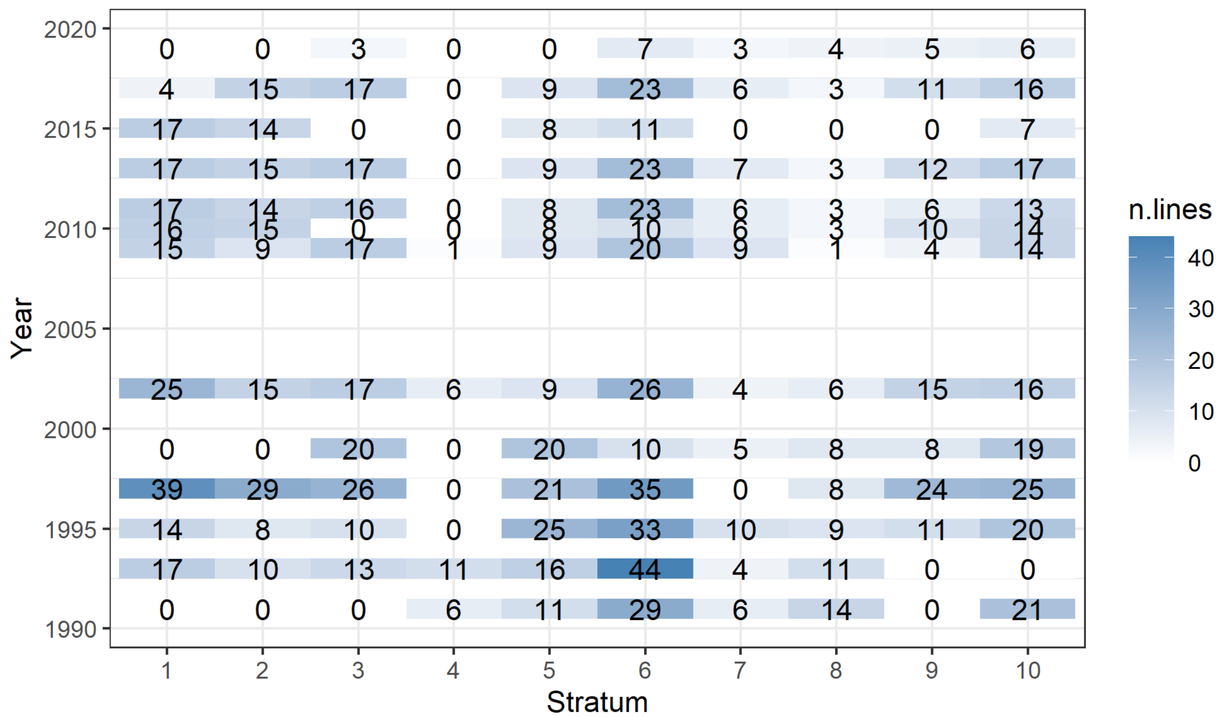

Figure A57. Number of lines per stratum for the 1991–2019 fall acoustic surveys.

Table A22. Herring biomass densities and estimates by stratum from the fishery-independent acoustic survey conducted in the fall of 1991, 1993, 1995, 1997, 1999 and 2002. Standard error (S.E.) and coefficient of variation (C.V.) of the biomass estimates were computed based on the variance of transects biomass by stratum (O'Boyle and Atkinson 1989).

1991	**Stratum**				**All herring area backscattering coefficient (s_a)**					**Fall spawning herring**				**Spring spawning herring**			
Name	**Number**	**Area (*km²*)**	**No. transects**	**Mean length (*m*)**	**Sampling dens. (*km/km²*)**	**Tot. Scattering (s_a * area; m²)**	**Weighted mean s_a (*m²/m²*)**	**S.E.**	**C.V.**	**Biom. dens. (*kg/m²*)**	**Biomass Tot. (*t*)**	**S.E.**	**C.V.**	**Biom. dens. (*kg/m²*)**	**Biomass Tot. (*t*)**	**S.E.**	**C.V.**
St. Georges S.	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
St. Georges N.	2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Port-au-Port G.	3	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Port-au-Port	4	437.4	6	10518.7	0.144	0.0	0.00E+00	0.00E+00	NA	0.000	0.0	0.0	0.0	-	0.0	0.0	-
B. of Islands G.	5	707.6	11	11898.6	0.185	1016.8	1.44E-06	1.41E-06	97.9	0.004	3014.0	2950.7	97.9	0.004	3683.0	3605.7	97.9
Bonne Bay Bank	6	682.5	29	12992.7	0.552	26307.3	3.85E-05	3.25E-05	84.4	0.114	77970.0	65650.7	84.2	0.099	95297.0	80240.1	84.2
Bay of Islands	7	295.7	6	14526.2	0.295	198.4	6.71E-07	6.92E-07	103.1	0.002	588.0	606.2	103.1	0.002	719.0	741.3	103.1
Bonne Bay	8	53.2	14	2158.5	0.568	451.1	8.47E-06	7.89E-06	93.2	0.017	877.0	816.5	93.1	0.019	1718.0	1599.5	93.1
Hawkes Bay	9	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.0	-
St. John Bay	10	1640.3	21	14503.1	0.186	0.0	0.00E+00	0.00E+00	NA	0.000	0.0	0.0	0.0	0.000	0.0	0.0	0.0
Average / Total:	-	3816.8	87	11410.7	0.260	27973.6	4.91E-05	3.35E-05	68.2	0.022	82449.0	816.5	79.5	0.019	101417.0	80626.5	79.5

1993	**Stratum**				**All herring area backscattering coefficient (s_a)**					**Fall spawning herring**				**Spring spawning herring**			
Name	**Number**	**Area (*km²*)**	**No. transects**	**Mean length (*m*)**	**Sampling dens. (*km/km²*)**	**Tot. Scattering (s_a * area; m²)**	**Weighted mean s_a (*m²/m²*)**	**S.E.**	**C.V.**	**Biom. dens. (*kg/m²*)**	**Biomass Tot. (*t*)**	**S.E.**	**C.V.**	**Biom. dens. (*kg/m²*)**	**Biomass Tot. (*t*)**	**S.E.**	**C.V.**
St. Georges S.	1	1157.4	17	10929.8	0.161	333.9	2.89E-07	2.77E-07	95.8	0.001	788.0	757.3	96.1	0.001	778.0	747.7	96.1
St. Georges N.	2	665.8	10	10732.0	0.161	0.0	0.00E+00	0.00E+00	NA	0.000	0.0	0.0	0.0	0.000			0.0
Port-au-Port G.	3	850.6	13	11531.0	0.176	933.6	1.10E-06	7.67E-07	69.7	0.003	2203.0	1539.9	69.9	0.002	2176.0	1521.0	69.9
Port-au-Port	4	437.4	11	7524.4	0.189	2.8	6.48E-09	6.43E-09	99.2	0.000	7.0	7.0	99.3	0.000	7.0	7.0	99.3
B. of Islands G.	5	707.6	16	10237.8	0.231	3141.8	4.44E-06	1.59E-06	35.8	0.010	7413.0	2653.9	35.8	0.008	7324.0	2622.0	35.8
Bonne Bay Bank	6	1035.5	44	10350.2	0.440	13206.5	1.28E-05	2.64E-06	20.6	0.038	39017.0	7725.4	19.8	0.029	38337.0	7590.7	19.8
Bay of Islands	7	295.7	4	14401.7	0.195	534.2	1.81E-06	1.73E-06	95.6	0.004	1260.0	1208.3	95.9	0.003	1245.0	1194.0	95.9
Bonne Bay	8	53.2	11	2200.5	0.455	51.2	9.62E-07	5.61E-07	58.3	0.003	159.0	92.7	58.3	0.002	125.0	72.9	58.3
Hawkes Bay	9	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
St. John Bay	10	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Average / Total:	-	5203.3	126	9736.7	0.236	18204.0	2.14E-05	3.67E-06	17.1	0.010	50846.0	8440.4	16.6	0.008	49993.0	8298.8	16.6

Table A22 (continued).

1995	Stratum				All herring area backscattering coefficient (s_a)					Fall spawning herring				Spring spawning herring			
Name	Number	Area (km^2)	No. transects	Mean length (m)	Sampling dens. (km/km^2)	Tot. Scattering (s_a * area; m^2)	Weighted mean s_a (m^2/m^2)	S.E.	C.V.	Biom. dens. (kg/m^2)	Biomass Tot. (t)	S.E.	C.V.	Biom. dens. (kg/m^2)	Biomass Tot. (t)	S.E.	C.V.
St. Georges S.	1	1156.7	14	10952.6	0.133	0.0	0.00E+00	0.00E+00	NA	0.000	0.0	0.0	0.0	0.000	0.0	0.0	0.0
St. Georges N.	2	666.5	8	10911.8	0.131	0.0	0.00E+00	0.00E+00	NA	0.000	0.0	0.0	0.0	0.000	0.0	0.0	0.0
Port-au-Port G.	3	866.8	10	1557.3	0.018	1640.6	1.89E-06	1.49E-06	78.8	0.002	1965.0	1548.4	78.8	0.003	4586.0	3613.8	78.8
Port-au-Port	4	-	-	-	-	-	-	-	-	-	-	-	-	0.000	-	-	-
B. of Islands G.	5	766.3	25	11957.9	0.390	2447.9	3.19E-06	1.38E-06	43.3	0.006	4573.0	1971.0	43.1	0.005	5312.0	2289.5	43.1
Bonne Bay Bank	6	1044.5	33	12481.3	0.394	3563.3	3.41E-06	7.67E-07	22.5	0.009	8942.0	2012.0	22.5	0.005	5717.0	1286.3	22.5
Bay of Islands	7	296.6	10	10005.6	0.337	0.0	0.00E+00	0.00E+00	NA	0.000	0.0	0.0	0.0	0.000	0.0	0.0	0.0
Bonne Bay	8	53.0	9	2404.3	0.408	11.9	2.24E-07	1.61E-07	71.9	0.000	10.0	7.5	74.5	0.000	39.0	29.1	74.5
Hawkes Bay	9	487.1	11	9065.9	0.205	1029.0	2.11E-06	1.21E-06	57.3	0.005	2607.0	1496.4	57.4	0.003	1650.0	947.1	57.4
St. John Bay	10	1786.5	20	17441.1	0.195	13028.9	7.29E-06	4.04E-06	55.4	0.019	33301.0	18448.8	55.4	0.012	20847.0	11549.2	55.4
Average / Total:	-	7124.0	140	10753.1	0.216	21721.6	1.81E-05	4.75E-06	26.2	0.007	51398.0	17783.7	34.6	0.005	38151.0	13200.2	34.6

1997	Stratum				All herring area backscattering coefficient (s_a)					Fall spawning herring				Spring spawning herring			
Name	Number	Area (km^2)	No. transects	Mean length (m)	Sampling dens. (km/km^2)	Tot. Scattering (s_a * area; m^2)	Weighted mean s_a (m^2/m^2)	S.E.	C.V.	Biom. dens. (kg/m^2)	Biomass Tot. (t)	S.E.	C.V.	Biom. dens. (kg/m^2)	Biomass Tot. (t)	S.E.	C.V.
St. Georges S.	1	328.0	39	5066.5	0.602	6885.3	2.10E-05	5.62E-06	26.8	0.026	8648.1	1944.2	22.5	0.061	20083.1	4515.0	22.5
St. Georges N.	2	305.0	29	5202.1	0.495	361.3	1.19E-06	8.06E-07	68.1	0.001	453.8	296.2	65.3	0.003	1053.9	687.9	65.3
Port-au-Port G.	3	1324.8	26	18525.9	0.364	64.2	4.85E-08	3.61E-08	74.5	0.000	102.3	73.1	71.4	0.000	78.8	56.3	71.4
Port-au-Port	4	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
B. of Islands G.	5	850.4	21	13496.7	0.333	1070.0	1.26E-06	6.09E-07	48.4	0.003	2167.6	1047.4	48.3	0.002	1969.5	931.6	47.3
Bonne Bay Bank	6	1156.2	35	11202.4	0.339	561.7	4.86E-07	1.77E-07	36.5	0.001	1135.8	390.0	34.3	0.001	1065.3	365.8	34.3
Bay of Islands	7	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Bonne Bay	8	52.0	8	2839.1	0.437	46.4	8.92E-07	5.67E-07	63.6	0.002	97.4	54.1	55.5	0.001	67.7	37.6	55.5
Hawkes Bay	9	550.3	24	8349.8	0.364	43.0	7.82E-08	7.03E-08	89.9	0.000	117.2	102.8	87.7	0.000	38.2	33.5	87.7
St. John Bay	10	1339.8	25	17821.4	0.333	14052.8	1.05E-05	2.59E-06	24.7	0.029	38276.1	9383.8	24.5	0.009	12488.0	3061.6	24.5
Average / Total:	-	5906.5	207	10503.8	0.368	23084.7	3.54E-05	6.30E-06	17.8	0.009	50998.0	9653.6	18.9	0.006	36844.0	5589.2	15.2

Table A22 (continued).

1999	**Stratum**				**All herring area backscattering coefficient (s_a)**					**Fall spawning herring**				**Spring spawning herring**			
Name	**Number**	**Area**	**No.**	**Mean length**	**Sampling dens.**	**Tot. Scattering**	**Weighted mean s_a**			**Biom. dens.**	**Biomass**			**Biom. dens.**	**Biomass**		
		(*km²*)	**transects**	**(*m*)**	**(*km/km²*)**	**(s_a * area; m²)**	**(*m²/m²*)**	**S.E.**	**C.V.**	**(*kg/m²*)**	**Tot. (*t*)**	**S.E.**	**C.V.**	**(*kg/m²*)**	**Tot. (*t*)**	**S.E.**	**C.V.**
St. Georges S.	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
St. Georges N.	2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Port-au-Port G.	3	1004.4	20	13863.9	0.276	3296.6	3.28E-06	9.86E-07	30.0	0.005	4856.1	1232.9	25.4	0.006	6213.7	1836.3	29.6
Port-au-Port	4	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
B. of Islands G.	5	850.4	20	12547.3	0.295	2443.1	2.87E-06	9.73E-07	33.9	0.005	4068.6	1246.2	30.6	0.005	3859.6	1174.7	30.4
Bonne Bay Bank	6	910.3	10	15935.3	0.175	11557.9	1.27E-05	7.35E-06	57.9	0.037	33948.2	18332.8	54.0	0.014	12541.4	6677.8	53.2
Bay of Islands	7	292.3	5	16727.3	0.286	71.7	2.45E-07	1.48E-07	60.5	0.000	96.4	49.9	51.7	0.000	0.0	0.0	-
Bonne Bay	8	52.0	8	1997.8	0.307	7.5	1.44E-07	1.36E-07	94.0	0.000	21.9	19.1	87.4	0.000	8.8	7.7	87.4
Hawkes Bay	9	320.4	8	7535.3	0.188	281.3	8.78E-07	8.29E-07	94.4	0.001	337.3	295.5	87.6	0.001	393.0	344.2	87.6
St. John Bay	10	1203.6	19	16720.3	0.264	8252.6	6.86E-06	1.62E-06	23.7	0.014	17034.4	3950.3	23.2	0.003	3912.4	674.6	17.2
Average / Total:	-	4633.4	90	12946.3	0.251	25910.8	2.70E-05	7.70E-06	28.5	0.013	60363.0	18837.7	31.2	0.006	26929.0	7065.3	26.2

2002	**Stratum**				**All herring area backscattering coefficient (s_a)**					**Fall spawning herring**				**Spring spawning herring**			
Name	**Number**	**Area**	**No.**	**Mean length**	**Sampling dens.**	**Tot. Scattering**	**Weighted mean s_a**			**Biom. dens.**	**Biomass**			**Biom. dens.**	**Biomass**		
		(*km²*)	**transects**	**(*m*)**	**(*km/km²*)**	**(s_a * area; m²)**	**(*m²/m²*)**	**S.E.**	**C.V.**	**(*kg/m²*)**	**Tot. (*t*)**	**S.E.**	**C.V.**	**(*kg/m²*)**	**Tot. (*t*)**	**S.E.**	**C.V.**
St. Georges S.	1	410.8	25	4331.2	0.264	876.5	2.13E-06	1.08E-06	50.8	0.006	2421.9	1162.8	48.0	0.003	1226.5	588.9	48.0
St. Georges N.	2	305.2	15	6059.0	0.298	1575.0	5.16E-06	4.77E-06	92.4	0.010	3048.9	2709.4	88.9	0.011	3364.1	2989.5	88.9
Port-au-Port G.	3	1697.0	17	18177.7	0.182	669.1	3.94E-07	3.00E-07	76.2	0.001	1222.1	893.0	73.1	0.001	1384.6	999.3	72.2
Port-au-Port	4	362.3	6	10516.5	0.174	4251.2	1.17E-05	1.04E-05	88.4	0.028	10199.3	8468.2	83.0	0.019	6743.0	5598.6	83.0
B. of Islands G.	5	482.3	9	13317.8	0.249	1576.1	3.27E-06	2.80E-06	85.7	0.007	3403.6	2750.5	80.8	0.005	2455.1	1984.0	80.8
Bonne Bay Bank	6	1089.0	26	11497.3	0.274	460.7	4.23E-07	3.02E-07	71.3	0.001	994.9	678.5	68.2	0.001	717.6	489.4	68.2
Bay of Islands	7	301.9	4	14287.0	0.189	1673.9	5.55E-06	3.76E-06	67.8	0.009	2655.6	1675.0	63.1	0.013	4043.0	2092.1	51.7
Bonne Bay	8	59.1	6	2918.7	0.296	37.8	6.40E-07	2.70E-07	42.1	0.001	79.1	27.8	35.1	0.001	68.6	24.1	35.1
Hawkes Bay	9	506.0	15	8643.0	0.256	25.6	5.07E-08	4.73E-08	93.3	0.000	79.6	71.5	89.8	0.000	24.0	21.5	89.8
St. John Bay	10	1477.6	16	20540.0	0.222	15657.5	1.06E-05	5.52E-06	52.1	0.033	48810.9	23293.2	47.7	0.010	14523.6	7841.7	54.0
Cape Ray	13	97.7	6	2932.3	0.180	0.0	0.00E+00	0.00E+00	NA	0.000	0.0	0.0	-	0.000	0.0	0.0	-
Average / Total:	-	6788.9	145	10624.9	0.211	26803.5	4.00E-05	1.36E-05	34.0	0.011	72916.0	25191.5	34.5	0.005	34550.1	10567.6	30.6

Table A23. Herring biomass densities and estimates by stratum from the fishery-independent acoustic survey conducted in the fall of 2009, 2010, 2011, 2013, 2015, and 2017. Standard error (S.E.) and coefficient of variation (C.V.) of the biomass estimates were computed based on the variance of transects biomass by stratum (O'Boyle and Atkinson 1989).

2009	**Stratum**				**All herring area backscattering coefficient (s_a)**					**Fall spawning herring**				**Spring spawning herring**			
Name	**Number**	**Area**	**No.**	**Mean length**	**Sampling dens.**	**Tot. Scattering**	**Weighted mean s_a**			**Biom. dens.**	**Biomass**			**Biom. dens.**	**Biomass**		
		(*km²*)	**transects**	**(*m*)**	**(*km/km²*)**	**(s_a * area; m²)**	**(*m²/m²*)**	**S.E.**	**C.V.**	**(*kg/m²*)**	**Tot. (*t*)**	**S.E.**	**C.V.**	**(*kg/m²*)**	**Tot. (*t*)**	**S.E.**	**C.V.**
St. Georges S.	1	410.8	15	3776.9	0.138	3819.36	9.30E-06	5.43E-06	58.4	0.031	12821.1	7490.2	58.4	0.003	1123.3	656.2	58.4
St. Georges N.	2	172.5	9	3787.4	0.198	10159.38	5.89E-05	3.57E-05	60.6	0.198	34103.7	20655.3	60.6	0.017	2987.9	1809.7	60.6
Port-au-Port G.	3	1697.0	17	12426.2	0.124	2746.33	1.62E-06	9.11E-07	56.3	0.005	9219.1	5189.9	56.3	0.000	807.7	454.7	56.3
Port-au-Port	4	0.0	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-
B. of Islands G.	5	482.3	9	17262.3	0.322	6.89	1.43E-08	1.35E-08	94.3	0.000	23.1	21.8	94.3	0.000	2.0	1.9	94.3
Bonne Bay Bank	6	1089.0	20	10848.0	0.199	1331.37	1.22E-06	5.92E-07	48.4	0.004	4469.2	2163.1	48.4	0.000	391.6	189.5	48.4
Bay of Islands	7	334.9	9	5414.1	0.145	2071.82	6.19E-06	5.57E-06	90.1	0.021	6954.8	6267.3	90.1	0.002	609.3	549.1	90.1
Bonne Bay	8	0.0	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Hawkes Bay	9	506.0	4	-	-	-	-	-	-	-	-	-	-	-	-	-	-
St. John Bay	10	1477.9	14	18871.1	0.179	324.80	2.20E-07	1.26E-07	57.2	0.001	1090.3	623.6	57.2	0.000	95.5	54.6	57.2
Average / Total:	-	6170.4	99	9972.0	0.160	20459.95	7.75E-05	5.18E-01	668358.3	0.011	68681.4	23537.8	34.3	0.001	6017.4	2062.2	34.3

2010	**Stratum**				**All herring area backscattering coefficient (s_a)**					**Fall spawning herring**				**Spring spawning herring**			
Name	**Number**	**Area**	**No.**	**Mean length**	**Sampling dens.**	**Tot. Scattering**	**Weighted mean s_a**			**Biom. dens.**	**Biomass**			**Biom. dens.**	**Biomass**		
		(*km²*)	**transects**	**(*m*)**	**(*km/km²*)**	**(s_a * area; m²)**	**(*m²/m²*)**	**S.E.**	**C.V.**	**(*kg/m²*)**	**Tot. (*t*)**	**S.E.**	**C.V.**	**(*kg/m²*)**	**Tot. (*t*)**	**S.E.**	**C.V.**
St. Georges S.	1	407.7	16	3944.1	0.155	3178.34	7.79E-06	5.68E-06	72.9	0.024	9789.7	7134.1	72.9	0.005	1945.2	1417.6	72.9
St. Georges N.	2	302.7	15	5305.0	0.263	3807.99	1.26E-05	5.88E-06	46.7	0.041	12321.5	5758.0	46.7	0.008	2329.6	1088.7	46.7
Port-au-Port G.	3	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Port-au-Port	4	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
B. of Islands G.	5	474.5	8	14578.1	0.246	7436.34	1.57E-05	3.05E-06	19.5	0.054	25397.8	4939.9	19.5	0.004	1745.0	339.4	19.5
Bonne Bay Bank	6	638.3	10	8390.4	0.131	6538.65	1.02E-05	2.49E-06	24.3	0.035	22331.9	5418.4	24.3	0.002	1534.4	372.3	24.3
Bay of Islands	7	245.4	6	9077.1	0.222	834.17	3.40E-06	1.01E-06	29.9	0.012	2849.0	850.7	29.9	0.001	195.7	58.4	29.9
Bonne Bay	8	35.3	3	3446.1	0.293	19.75	5.59E-07	2.25E-07	40.3	0.002	67.5	27.2	40.3	0.000	4.6	1.9	40.3
Hawkes Bay	9	412.8	10	8248.5	0.200	1832.98	4.44E-06	3.99E-06	89.9	0.015	6260.3	5627.7	89.9	0.001	430.1	386.7	89.9
St. John Bay	10	945.3	14	13079.0	0.194	24632.85	2.61E-05	8.82E-06	33.9	0.089	84130.3	28488.4	33.9	0.006	5780.4	1957.4	33.9
Average / Total:	-	3462.2	99	7561.1	0.195	48281.07	9.14E-05	1.33E-05	14.6	0.047	163147.9	31333.6	19.2	0.004	13965.1	2726.3	19.5

Table A23 (continued).

2011	Stratum				All herring area backscattering coefficient (s_a)					Fall spawning herring				Spring spawning herring			
Name	Number	Area	No.	Mean length	Sampling dens.	Tot. Scattering	Weighted mean s_a			Biom. dens.	Biomass			Biom. dens.	Biomass		
		(*km²*)	transects	(*m*)	(*km/km²*)	(s_a * area; m²)	(*m²/m²*)	S.E.	C.V.	(*kg/m²*)	Tot. (*t*)	S.E.	C.V.	(*kg/m²*)	Tot. (*t*)	S.E.	C.V.
St. Georges S.	1	410.8	17	4212.3	0.174	508.07	1.24E-06	4.58E-07	37.0	0.004	1709.7	632.5	37.0	0.000	146.4	54.2	37.0
St. Georges N.	2	305.2	14	4717.6	0.216	1040.63	3.41E-06	2.39E-06	70.2	0.011	3501.8	2457.1	70.2	0.001	299.9	210.4	70.2
Port-au-Port G.	3	812.0	16	7352.8	0.145	2603.19	3.21E-06	2.09E-06	65.3	0.011	8760.1	5718.5	65.3	0.001	750.3	489.8	65.3
Port-au-Port	4	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
B. of Islands G.	5	482.6	8	14926.8	0.247	712.19	1.48E-06	6.22E-07	42.1	0.005	2450.0	1032.4	42.1	0.000	119.4	50.3	42.1
Bonne Bay Bank	6	1148.1	23	11186.5	0.224	6623.12	5.77E-06	3.24E-06	56.1	0.020	22784.0	12780.9	56.1	0.001	1110.1	622.7	56.1
Bay of Islands	7	334.9	6	4134.5	0.074	20.50	6.12E-08	5.59E-08	91.3	0.000	70.5	64.4	91.3	0.000	3.4	3.1	91.3
Bonne Bay	8	30.6	3	3747.9	0.368	13.52	4.42E-07	2.46E-07	55.5	0.002	46.5	25.8	55.5	0.000	2.3	1.3	55.5
Hawkes Bay	9	506.0	6	6564.3	0.078	357.32	7.06E-07	2.66E-07	37.6	0.002	1022.6	384.7	37.6	0.000	179.5	67.5	37.6
St. John Bay	10	728.1	13	13477.1	0.241	23415.87	3.22E-05	7.60E-06	23.6	0.092	67013.7	15833.9	23.6	0.016	11761.3	2778.9	23.6
Average / Total:	-	4758.3	106	8326.8	0.185	35294.41	4.85E-05	8.89E-06	18.3	0.023	107359.0	21317.2	19.9	0.003	14372.6	2899.1	20.2

2013	Stratum				All herring area backscattering coefficient (s_a)					Fall spawning herring				Spring spawning herring			
Name	Number	Area	No.	Mean length	Sampling dens.	Tot. Scattering	Weighted mean s_a			Biom. dens.	Biomass			Biom. dens.	Biomass		
		(*km²*)	transects	(*m*)	(*km/km²*)	(s_a * area; m²)	(*m²/m²*)	S.E.	C.V.	(*kg/m²*)	Tot. (*t*)	S.E.	C.V.	(*kg/m²*)	Tot. (*t*)	S.E.	C.V.
St. Georges S.	1	407.7	17	4208.6	0.175	1123.15	2.75E-06	2.07E-06	75.2	0.009	3842.9	2891.3	75.2	0.000	33.7	25.3	75.2
St. Georges N.	2	302.7	15	6900.9	0.342	962.66	3.18E-06	1.65E-06	51.8	0.011	3293.8	1706.9	51.8	0.000	28.9	15.0	51.8
Port-au-Port G.	3	802.9	17	8214.5	0.174	362.95	4.52E-07	1.73E-06	382.1	0.001	1176.2	4753.0	404.1	0.000	10.0	41.7	417.1
Port-au-Port	4	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
B. of Islands G.	5	474.5	9	14540.4	0.276	498.14	1.05E-06	5.43E-07	51.7	0.003	1614.3	834.8	51.7	0.000	13.7	7.1	51.7
Bonne Bay Bank	6	1148.1	23	11327.6	0.227	41308.84	3.60E-05	2.02E-05	56.2	0.125	143041.0	80378.3	56.2	0.000	356.6	200.4	56.2
Bay of Islands	7	299.9	7	10057.7	0.235	839.27	2.80E-06	1.50E-06	53.7	0.009	2719.9	1460.8	53.7	0.000	23.1	12.4	53.7
Bonne Bay	8	58.5	3	2658.3	0.136	13.96	2.39E-07	1.84E-07	77.1	0.001	48.3	37.3	77.1	0.000	0.1	0.1	77.1
Hawkes Bay	9	499.8	12	9172.8	0.220	525.40	1.05E-06	3.14E-07	29.9	0.004	1819.3	543.9	29.9	0.000	4.5	1.4	29.9
St. John Bay	10	799.5	17	12469.0	0.265	2344.53	2.93E-06	2.66E-06	90.9	0.010	8118.4	7377.8	90.9	0.000	20.2	18.4	90.9
Average / Total:	-	4793.7	120	9221.1	0.231	47978.89	5.04E-05	2.07E-05	41.0	0.035	165674.4	80945.0	48.9	0.000	490.8	208.1	42.4

Table A23 (continued).

2015	**Stratum**				**All herring area backscattering coefficient (s_a)**					**Fall spawning herring**				**Spring spawning herring**			
Name	**Number**	**Area** (*km²*)	**No. transects**	**Mean length** (*m*)	**Sampling dens.** (*km/km²*)	**Tot. Scattering** (s_a * area; m²)	**Weighted mean s_a** (*m²/m²*)	**S.E.**	**C.V.**	**Biom. dens.** (*kg/m²*)	**Biomass** Tot. (*t*)	**S.E.**	**C.V.**	**Biom. dens.** (*kg/m²*)	**Biomass** Tot. (*t*)	**S.E.**	**C.V.**
St. Georges S.	1	407.7	17	4285.5	0.179	223.91	5.49E-07	4.35E-07	79.3	0.002	763.4	605.3	79.3	0.000	30.2	24.0	79.3
St. Georges N.	2	299.0	14	6038.1	0.283	466.63	1.56E-06	1.38E-06	88.6	0.005	1590.9	1409.0	88.6	0.000	63.0	55.8	88.6
Port-au-Port G.	3	0.0	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Port-au-Port	4	0.0	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
B. of Islands G.	5	464.5	8	14434.8	0.249	11794.07	2.54E-05	7.16E-06	28.2	0.090	41909.6	11812.2	28.2	0.001	387.6	109.2	28.2
Bonne Bay Bank	6	1132.5	11	11335.1	0.110	9470.43	8.36E-06	2.45E-06	29.3	0.030	33652.7	9875.1	29.3	0.000	311.2	91.3	29.3
Bay of Islands	7	0.0	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Bonne Bay	8	0.0	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Hawkes Bay	9	0.0	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
St. John Bay	10	876.7	7	15600.4	0.125	1837.21	2.10E-06	1.03E-06	49.1	0.007	6078.9	2983.2	49.1	0.000	190.9	93.7	49.1
Average / Total:	-	3180.5	57	8890.4	0.159	23792.25	3.80E-05	7.77E-06	20.5	0.026	83995.5	15757.4	18.8	0.000	983.0	180.9	18.4

2017	**Stratum**				**All herring area backscattering coefficient (s_a)**					**Fall spawning herring**				**Spring spawning herring**			
Name	**Number**	**Area** (*km²*)	**No. transects**	**Mean length** (*m*)	**Sampling dens.** (*km/km²*)	**Tot. Scattering** (s_a * area; m²)	**Weighted mean s_a** (*m²/m²*)	**S.E.**	**C.V.**	**Biom. dens.** (*kg/m²*)	**Biomass** Tot. (*t*)	**S.E.**	**C.V.**	**Biom. dens.** (*kg/m²*)	**Biomass** Tot. (*t*)	**S.E.**	**C.V.**
St. Georges S.	1	126.6	4	5623.7	0.178	39.07	3.09E-07	8.58E-08	27.8	0.001	116.9	32.5	27.8	0.000	0.0	10.3	1.61E+08
St. Georges N.	2	303.7	15	5280.6	0.261	1752.33	5.77E-06	4.81E-06	83.4	0.017	5243.7	4373.8	83.4	0.002	725.7	605.3	83.4
Port-au-Port G.	3	802.9	17	8261.2	0.175	2665.20	3.32E-06	4.17E-06	125.6	0.010	7975.4	10019.9	125.6	0.001	1103.7	1386.7	125.6
Port-au-Port	4	0.0	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
B. of Islands G.	5	474.5	9	13294.8	0.252	350.72	7.39E-07	2.46E-07	33.3	0.002	1163.1	386.8	33.3	0.000	58.5	19.5	33.3
Bonne Bay Bank	6	1148.1	23	10915.4	0.219	3240.25	2.82E-06	7.44E-07	26.4	0.009	10745.8	2834.2	26.4	0.000	540.5	142.6	26.4
Bay of Islands	7	192.7	6	7502.4	0.234	113.49	5.89E-07	4.50E-07	76.4	0.002	376.4	287.7	76.4	0.000	18.9	14.5	76.4
Bonne Bay	8	58.5	3	2930.6	0.150	28.62	4.89E-07	1.68E-07	34.4	0.002	94.9	32.7	34.4	0.000	4.8	1.6	34.4
Hawkes Bay	9	499.8	11	9055.1	0.199	705.54	1.41E-06	1.22E-06	86.6	0.005	2339.8	2026.1	86.6	0.000	117.7	101.9	86.6
St. John Bay	10	743.2	16	10331.2	0.222	5543.26	7.46E-06	2.74E-06	36.7	0.023	17257.5	6331.4	36.7	0.003	2459.6	902.4	36.7
Average / Total:	-	4349.9	104	8957.3	0.214	14438.47	2.29E-05	7.10E-06	31.0	0.010	45313.6	13114.4	28.9	0.001	5029.5	1770.6	35.2

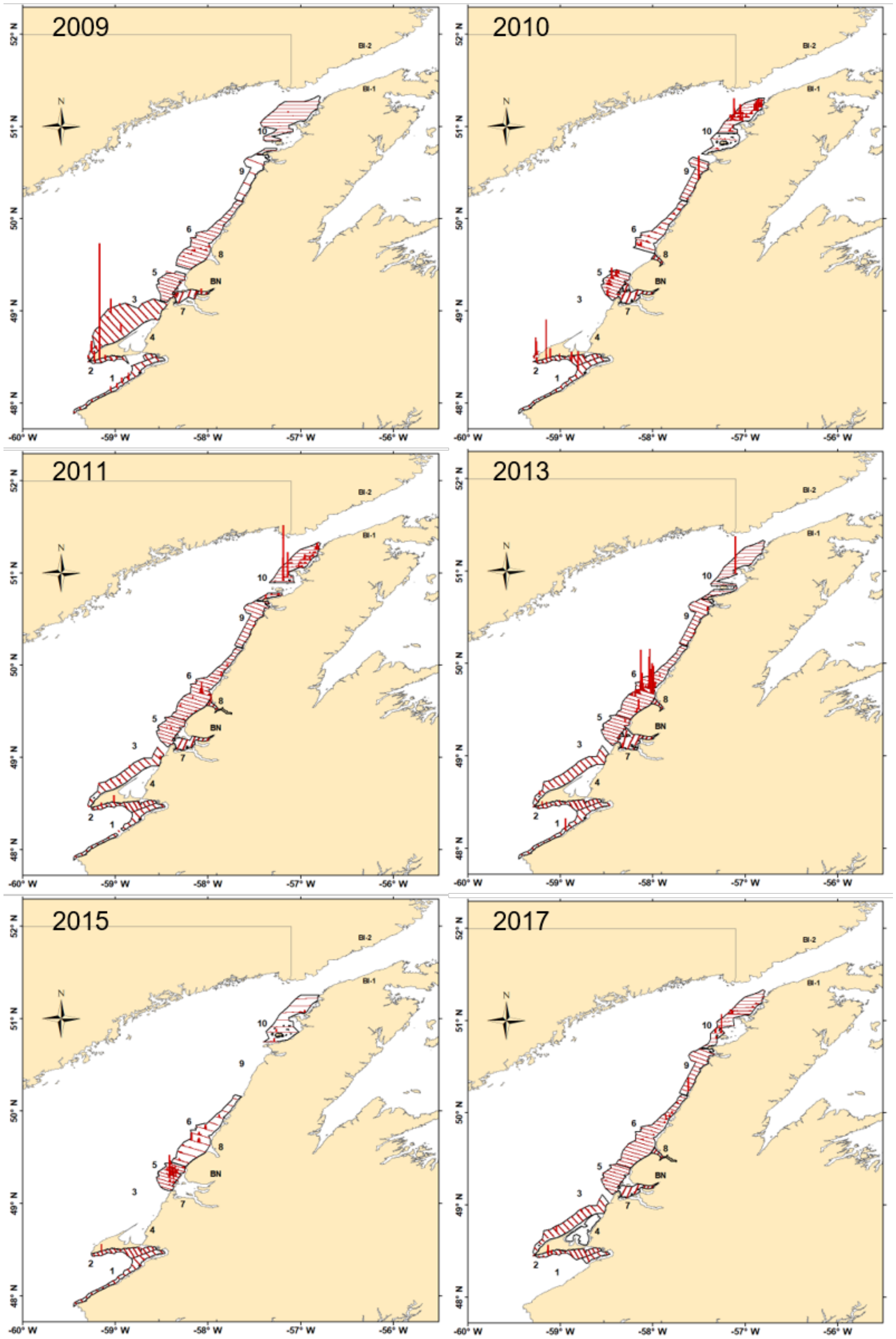

Figure A58. Distribution of herring biomass measured during the 2009 to 2017 hydroacoustic surveys. Biomass is proportional to the height of the red bars. Survey strata names are identified by numbers. The 2009 to 2013 and 2017 surveys were performed with the CCGS F.G. Creed and in 2015 the CCGS Vladykov was the designated platform. BN: Bras Nord.

APPENDIX B: VIRTUAL POPULATION ANALYSIS PARAMETERS AND EQUATIONS

The following structure was imposed to the VPA model fitted in VPA/ADAPT (NOAA fisheries toolbox 2014):

- January 1 weight at age: Rivard method.
- Natural mortality: fixed at 0.2 for spring and FS models 1a and b, adjusted by sensitivity analysis 5 years blocks for spring and FS models 2a and b. The results of the sensitivity analysis are presented in Figure 32, 33, 47, and 48.
- Starting values for stock number at age for ages 3 to 10: 50 000. Minimum and maximum stock estimates: 2 and 5 000 000.
- Estimation of earliest age (a = 2) in terminal year plus one (T+1 = 2020): geometric mean of stock numbers at earliest age for year 2009 to 2019.
- Partial recruitment (synonym: selectivity) for terminal year:
    - Age 2: 0.2
    - Age 3: 0.4
    - Age 4: 0.6
    - Age 5: 0.8
    - Age 6 to 10: 1.0
- Fully-recruited fishing mortality rate (F_{Full}) in the terminal year (T): Modified Heincke Method (Table A24, equation 11)
- Fishing mortality rate at oldest true age (a = 10) in the terminal year: The product of F and input partial recruitment.
- Fishing mortality rate and number (N) at oldest true age in year t < T: combined method (Table A24, equations 15 and 16).
- Ratio F-plus group and F-oldest true age: 1.
- Fraction of natural mortality and fishing mortality prior to spawning: 0 and 0.

Table A24. VPA/ADAPT model equations, from NFT (2014).

Parameter	Formula	No.
Cohort abundance	$N_{a+1,t+1} = N_{a,t}e^{-Z_{a,t}}$	1
	$N_{a,t} = \dfrac{C_{a,t}Z_{a,t}}{F_{a,t}(1-e^{-Z_{a,t}})}$	5
	$N_{A,t+1} = N_{A,t}e^{-Z_{A,t}} + N_{A-1,t}e^{-Z_{A-1,t}}$	12
	$N_{A+1,t+1} = \dfrac{C_{A+1,t}Z_{A+1,t}}{\alpha_t F_{A,t}(1-e^{-Z_{A+1,t}})} + \dfrac{C_{A,t}Z_{A,t}}{F_{A,t}(1-e^{-Z_{A,t}})}$	16
Mortality rates	$Z_{a,t} = F_{a,t} + M_{a,t}$	3
	$\mathrm{F_{A-1,T}} = \ln\left(\dfrac{\sum_{\mathrm{a\in R}} \mathrm{N_{a,T}e^{-M_{a,T}}}}{\sum_{\mathrm{a\in R}} N_{a+1,T+1}}\right)$	11
	$F_{A,t} = \alpha_t F_{A-1,t}$	15
Catch	$C_{a,t} = N_{a,t}\left(\dfrac{F_{a,t}}{Z_{a,t}}\right)(1-e^{-Z_{a,t}})$	2
	$C_{B,a,t} = C_{a,t}W_{C,a,t}$	32
Survey NAA	$N^*_{t,J} = \sum_{a\in G_J} N_{a,t}\dfrac{(1-e^{-Z_{a,t}})}{Z_{a,t}}$	20
	$Q_J = \exp\left(\left(\sum_{t\in I_J}\left(ln(I_{t,J}) - ln(N^*_{t,J})\right)\right) \div n_J\right)$	23
	$I^*_{t,J} = Q_J N^*_{t,J}$	24
Sum of squares	$SS(\Theta) = \sum_J \sum_{t\in I_j}\left(\ln(I_{t,J}) - \ln\left(I^*_{t,J}\right)\right)^2$	17
Residuals	$R_{t,J} = \ln(I_{t,J}) - \ln\left(I^*_{t,J}\right)$	25
Stock SSB	$SSB_{a,t} = N_{a,t}PropMature_{a,t}W_{SSB,a,t}e^{-(F_{a,t}F_{PROP}+M_{a,t}M_{PROP})}$	31

Table A25. Definition of variables used in Table A24.

Parameter / variable	Definition
$N_{a,t}$	Number at age *a*, time *t*
$Z_{a,t}$	Total mortality rate at age *a* in year *t*
$F_{A-1,T}$	Instantaneous fishing mortality rate at oldest true age and terminal year (2019).
$C_{a,t}$	Total catch in numbers of age *a* fish in year *t*
α_t	F plus-group ratio in year *t*
$M_{a,t}$	Natural mortality at age *a* in year *t*, *fixed at 0.2 or estimated by sensitivity analysis, depending on the model.*
R	Fully selected set of ages less than A
$C_{B,a,t}$	Catch biomass at age *a* in year *t*
$W_{C,a,t}$	Average catch weight of an age *a* fish in year *t*
$N^*_{t,J}$	Predicted stock size in year *t* and survey index *J*
G_J	Individual age class for survey *J*
Q_J	Catchability coefficient for survey index *J*
$I_{t,J}$	Observed survey index value in year *t* for survey *J*
$I^*_{t,J}$	Predicted survey index value in year *t* for survey *J*
n_J	Number of non-missing index values for survey *J*
$SS(\Theta)$	Sum of squares function to minimize
$R_{t,J}$	Calculated survey residual for year *t* and survey index *J*
$SSB_{a,t}$	Spawning stock biomass at age *a* in year *t*
$PropMature_{a,t}$	Proportion of fish mature at age *a* in year *t*
$W_{SSB,a,t}$	Average spawning weight of an age *a* fish in year *t*
F_{PROP}	Proportion of fishing mortality that occurs before spawning, fixed at 0 for both spring and fall spawning models
M_{PROP}	Proportion of natural mortality that occurs before spawning, fixed at 0.5 for both spring and fall spawning models

APPENDIX C: SPRING AND FALL SPAWNING HERRING VPA MODELS WITH M ADJUSTED BY A SENSITIVITY ANALYSIS

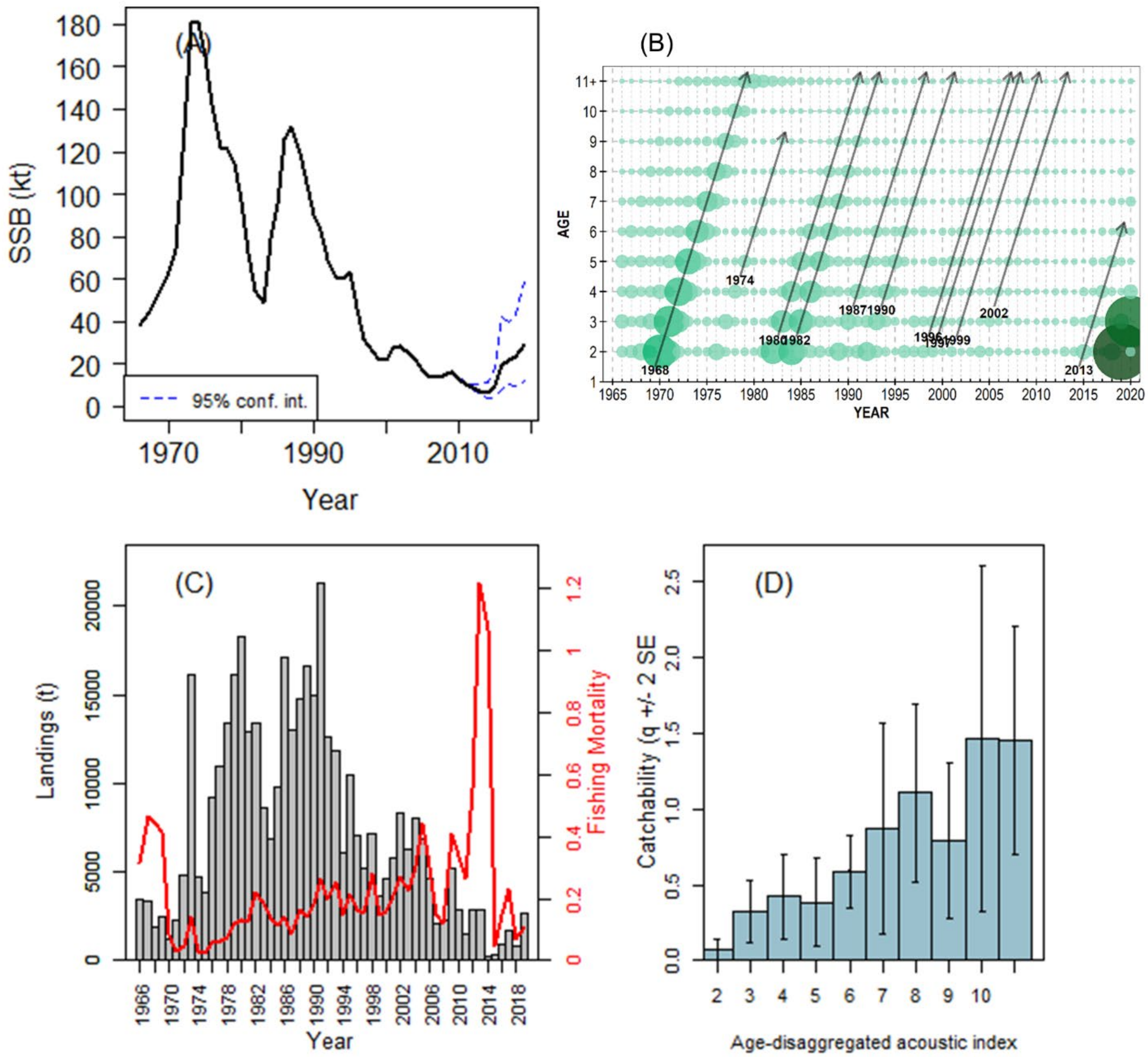

Figure A59. Spring spawning herring model 2a output: (A) estimated spawning stock biomass with 95% bootstrapped confidence intervals, (B) predicted number-at-age (arrows represent the same dominant cohorts indicated in Figure 19 and 25), (C) average F (2–11+) and annual landings, and (D) catchability coefficients.

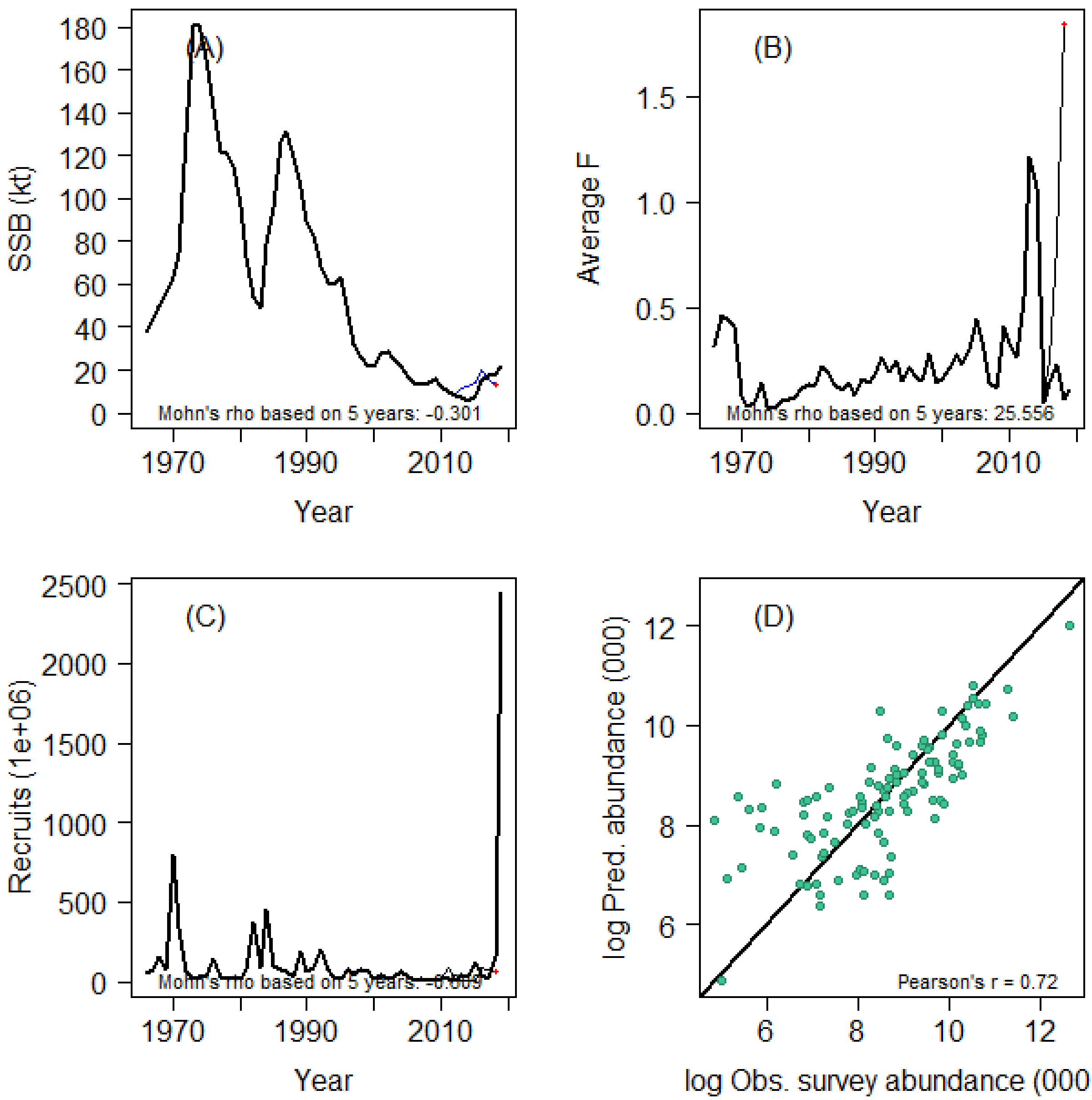

Figure A60. Spring spawning herring model 2a (A) SSB, (B) average F and (C) recruits retrospective plots, and (D) predicted and observed abundances.

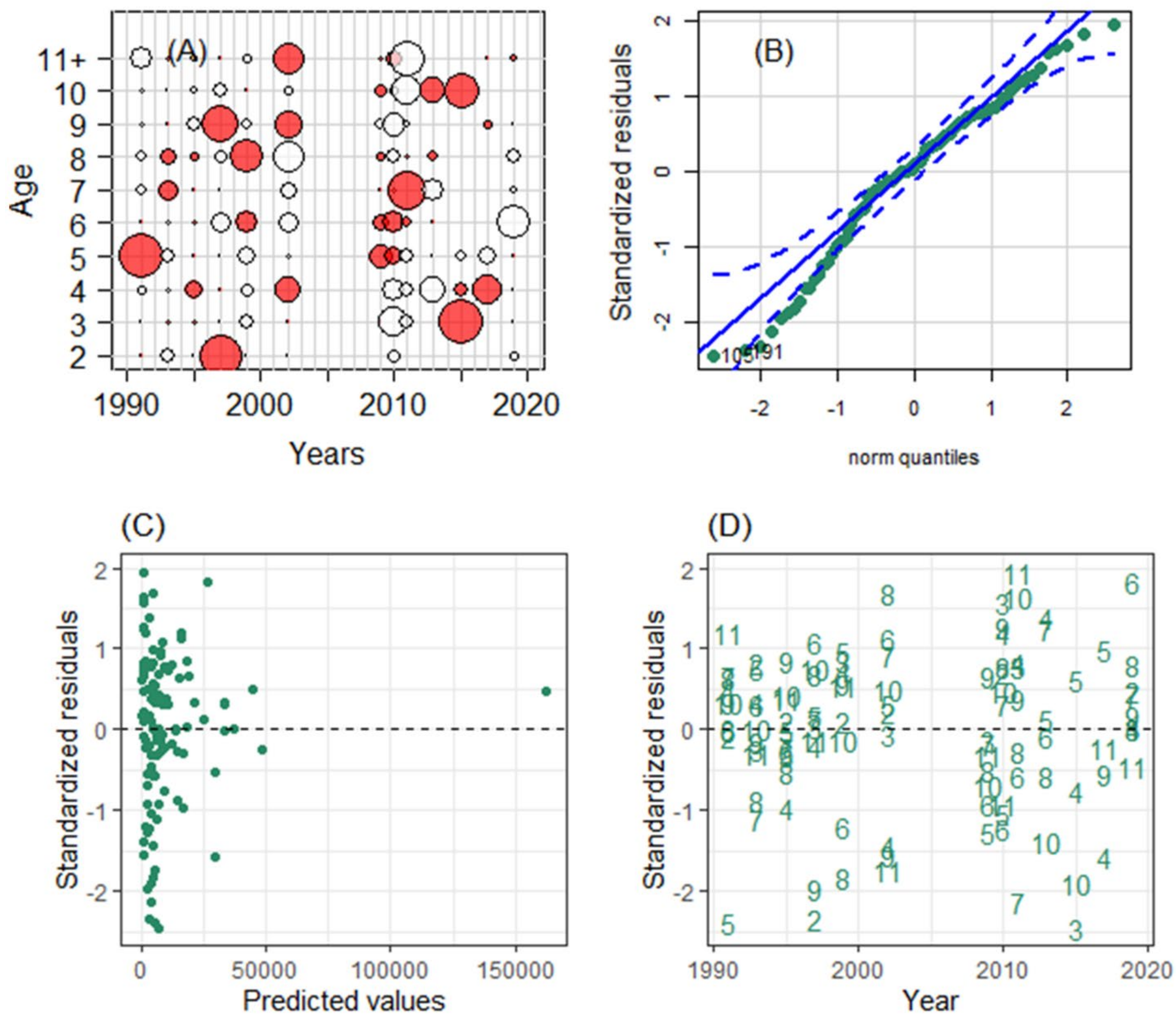

Figure A61. Spring spawning herring model 2a index residual plots: (A) bubble plot of residuals by age and year (open and red bubble respectively represent positive and negative residuals), (B) quantile-quantile plot (solid and dashed blue lines respectively represent theoretical quantiles and 95% confidence intervals), (C) standardized residuals and predicted values, and (D) standardized residuals as a function of year and age.

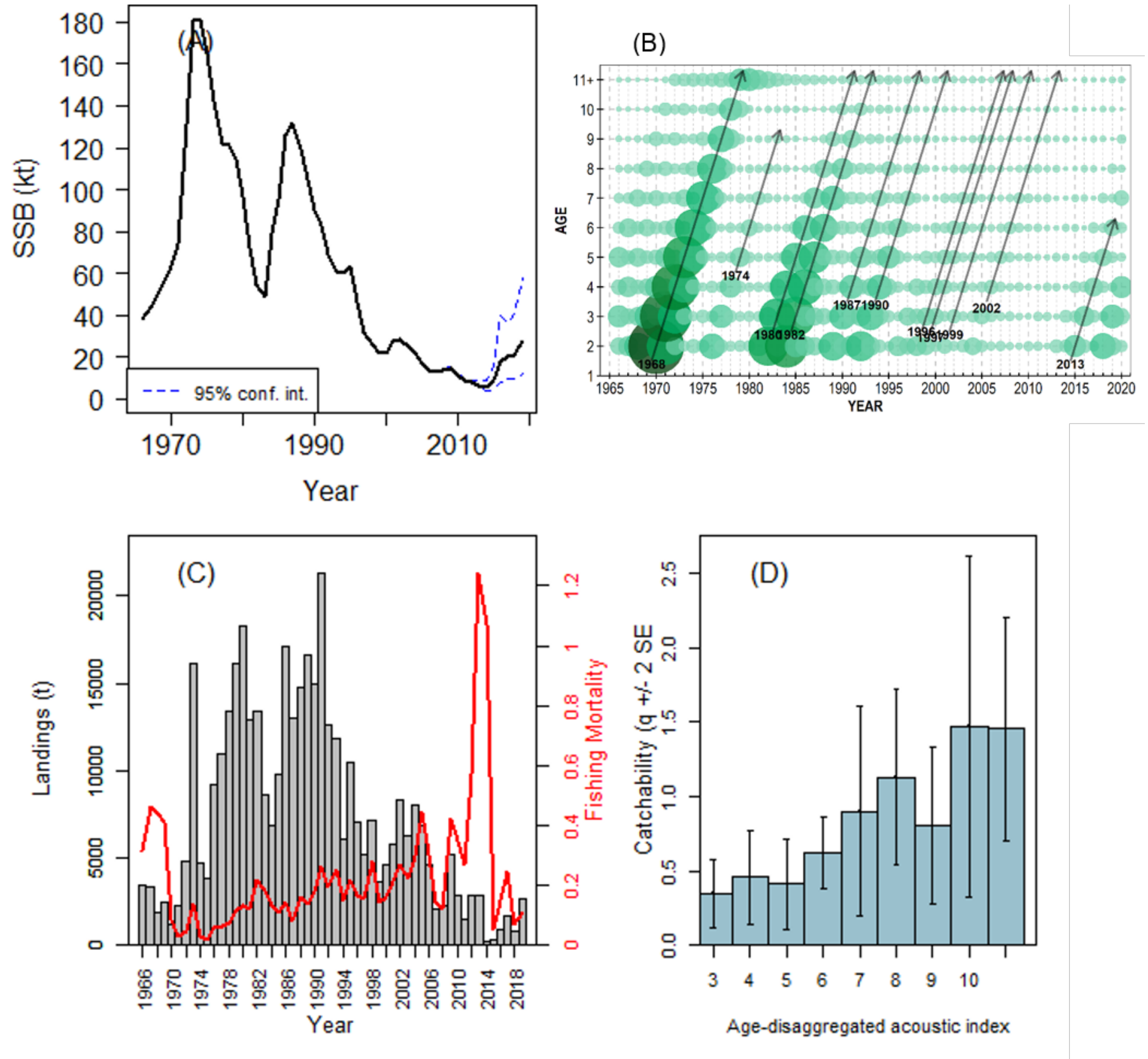

Figure A62. Spring spawning herring model 2b output: (A) estimated spawning stock biomass with 95% bootstrapped confidence intervals, (B) predicted number-at-age (arrows represent the same dominant cohorts indicated in Figure 19 and 25), (C) average F (2–11+) and annual landings, and (D) catchability coefficients.

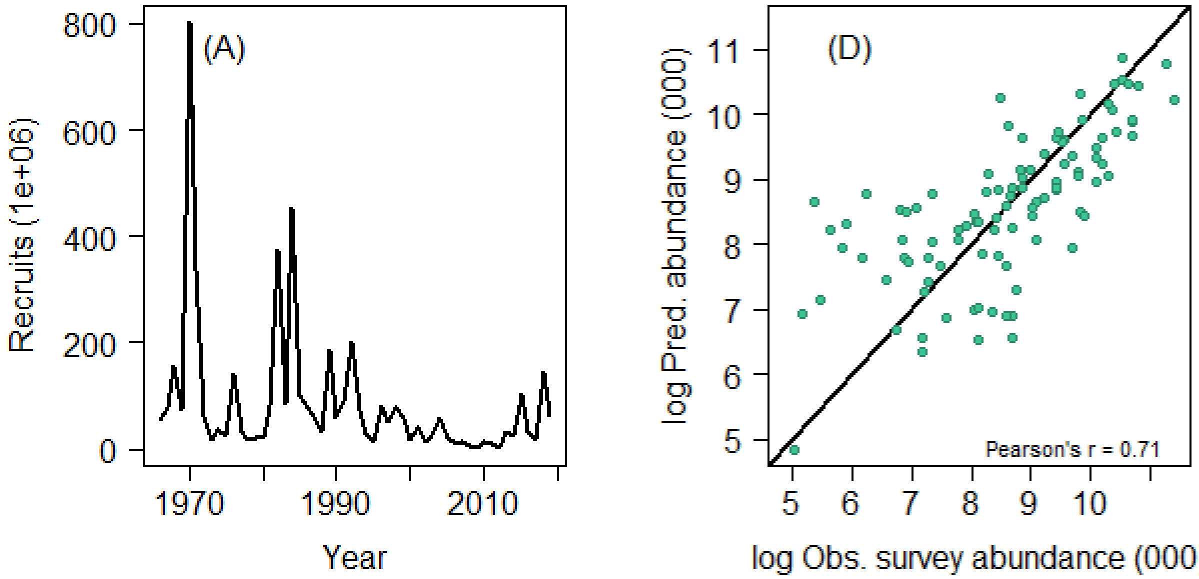

Figure A63. Spring spawning herring model 2b (A) recruits through time, and (D) predicted and observed abundances.

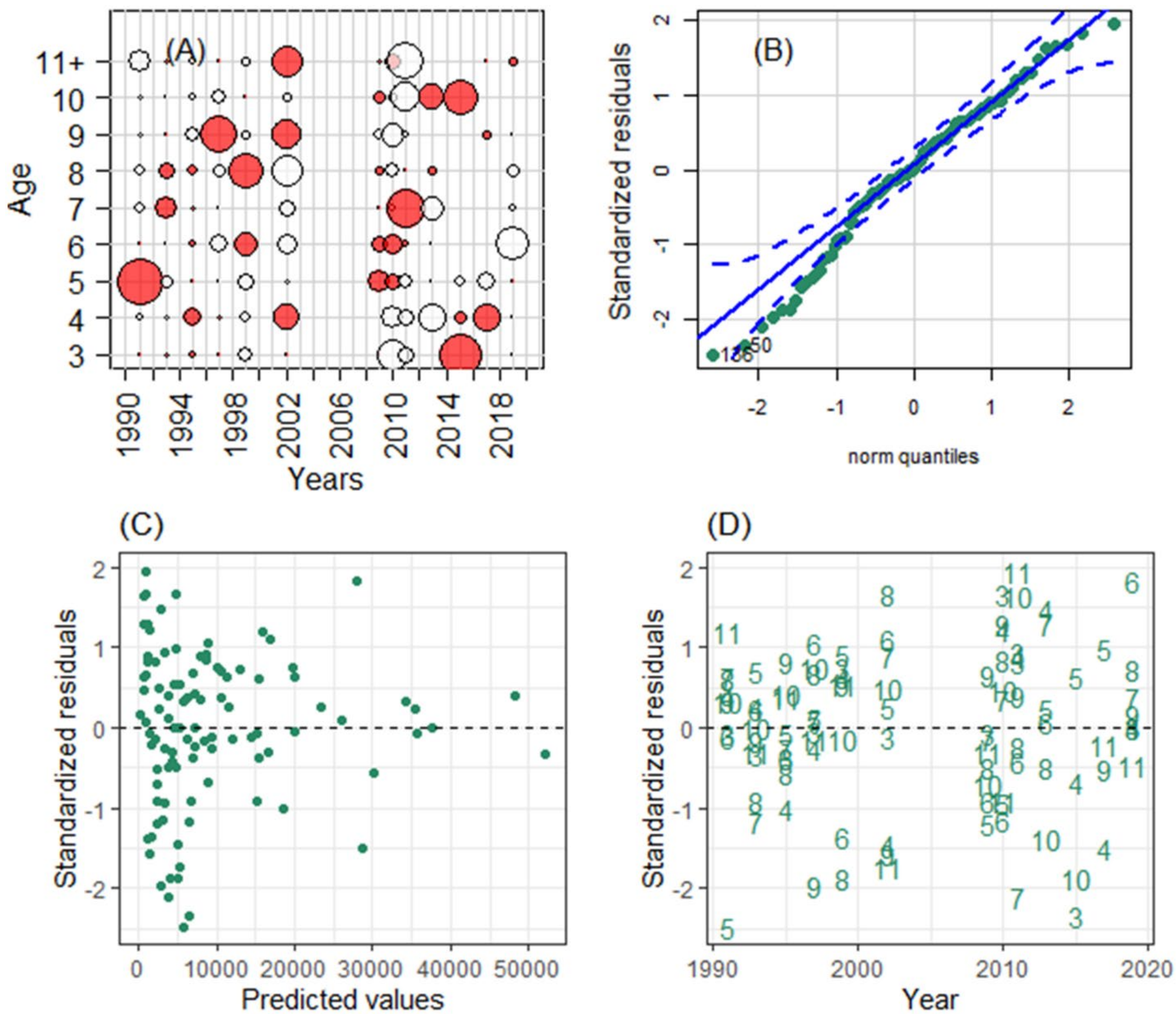

Figure A64. Spring spawning herring model 2b index residual plots: (A) bubble plot of residuals by age and year (open and red bubble respectively represent positive and negative residuals), (B) quantile-quantile plot (solid and dashed blue lines respectively represent theoretical quantiles and 95% confidence intervals), (C) standardized residuals and predicted values, and (D) standardized residuals as a function of year and age.

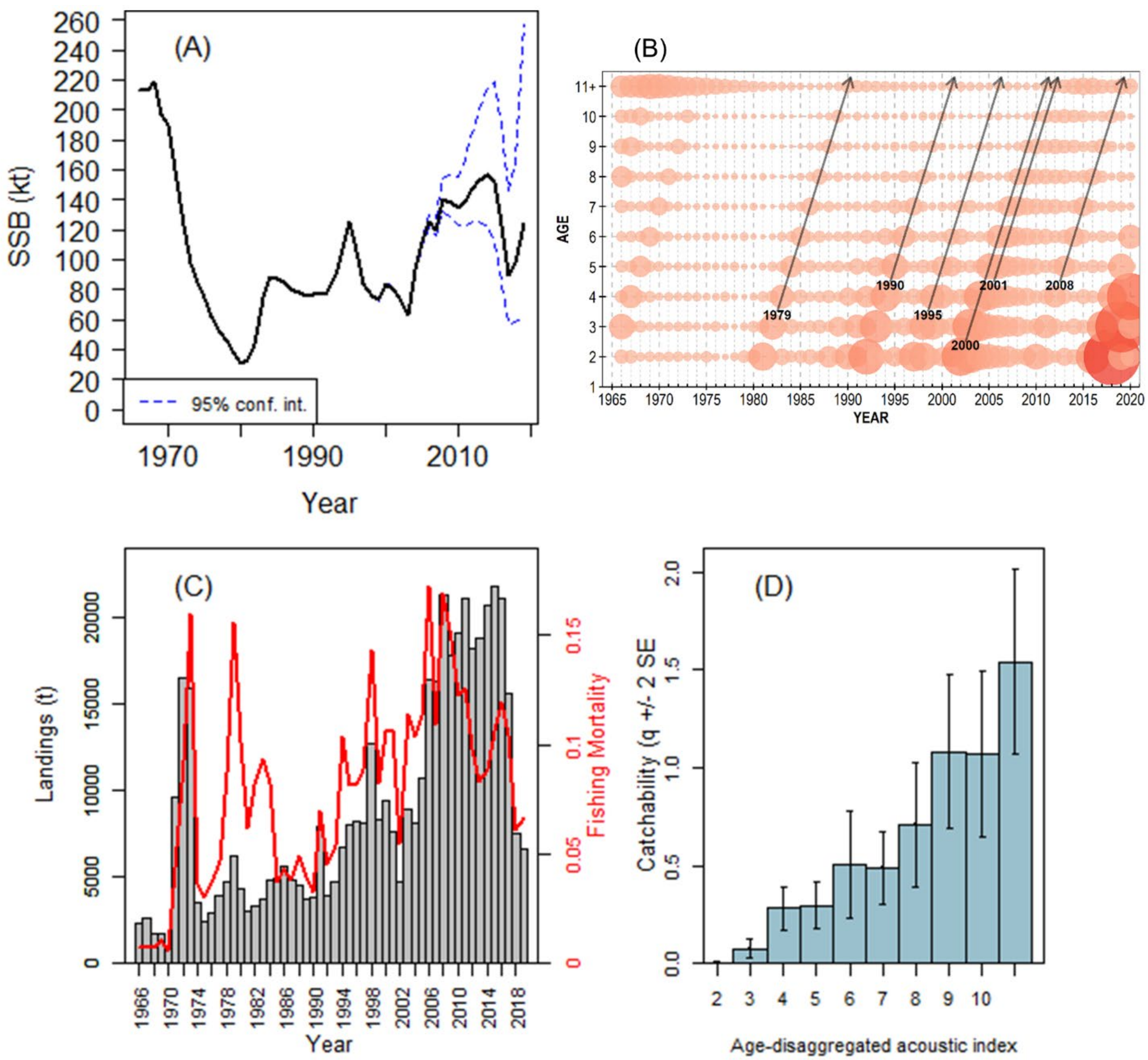

Figure A65. Fall spawning herring model 2a output: (A) estimated spawning stock biomass with 95% bootstrapped confidence intervals, (B) predicted number-at-age (arrows represent the same dominant cohorts indicated in Figure 34Figure 19 and 40), (C) average F (2–11+) and annual landings, and (D) catchability coefficients.

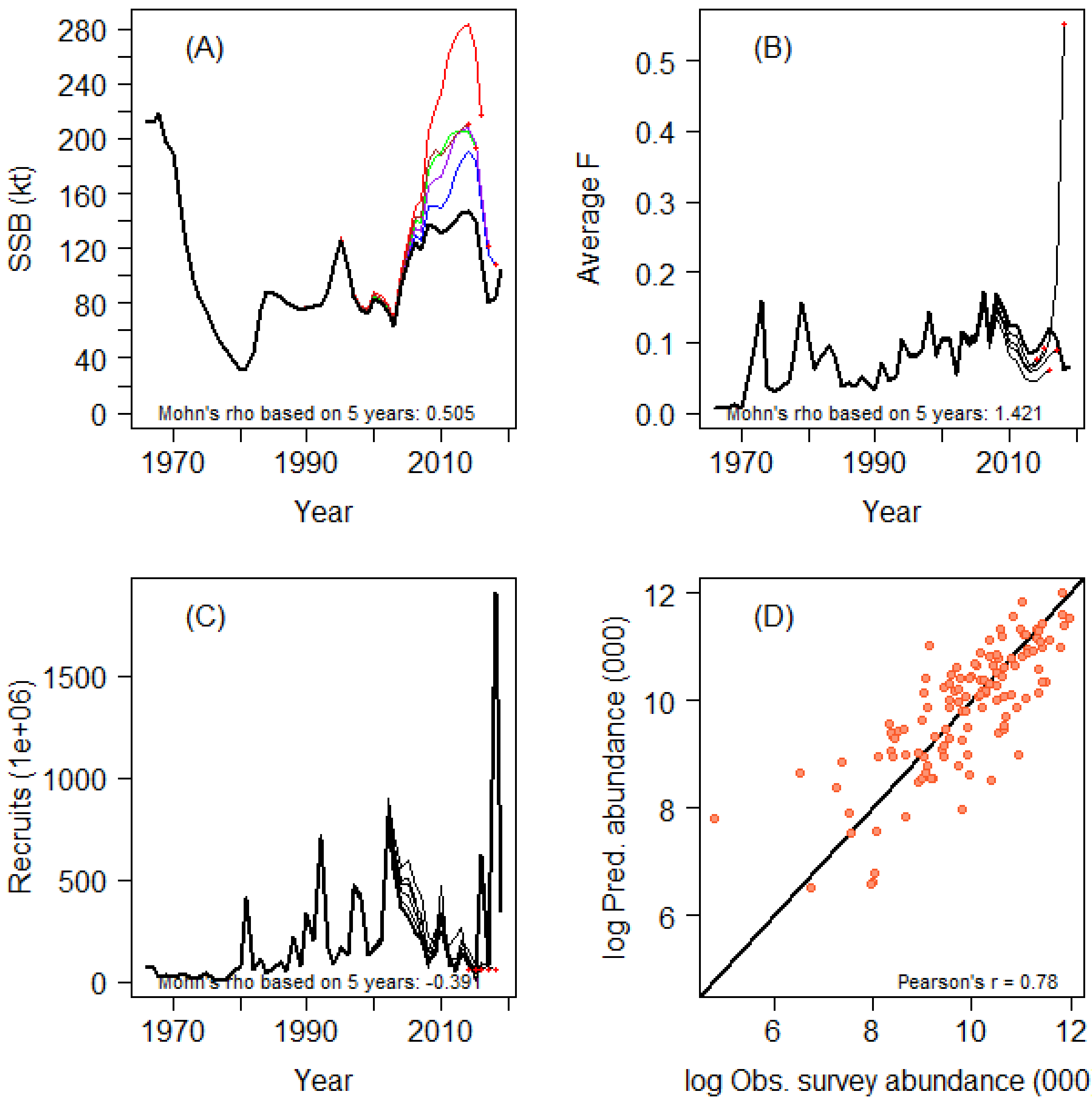

Figure A66. Fall spawning herring model 2a (A) SSB, (B) average F and (C) recruits retrospective plots, and (D) predicted and observed abundances.

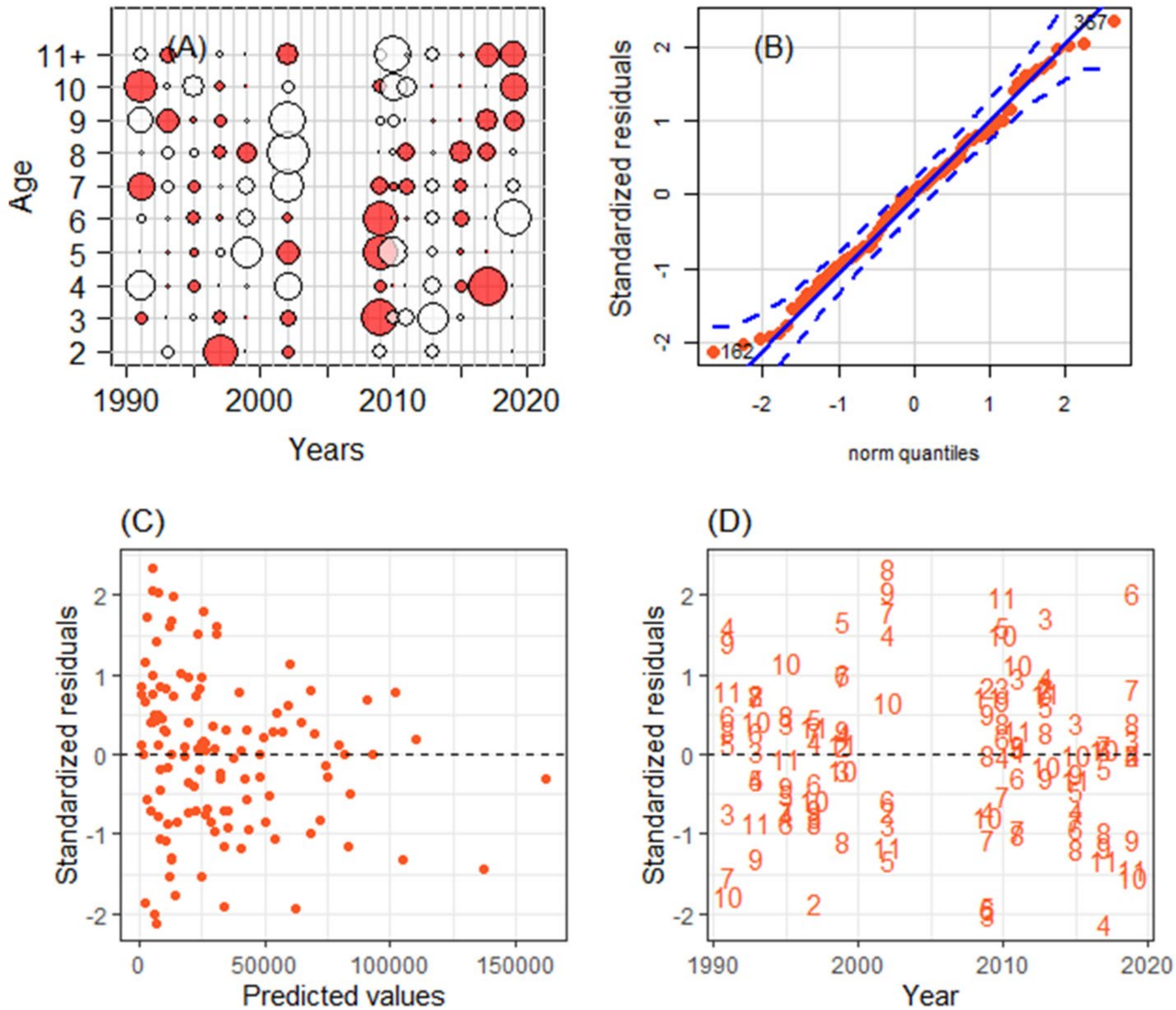

Figure A67. Fall spawning herring model 2a index residual plots: (A) bubble plot of residuals by age and year (open and red bubble respectively represent positive and negative residuals), (B) quantile-quantile plot (solid and dashed blue lines respectively represent theoretical quantiles and 95% confidence intervals), (C) standardized residuals and predicted values, and (D) standardized residuals as a function of year and age.

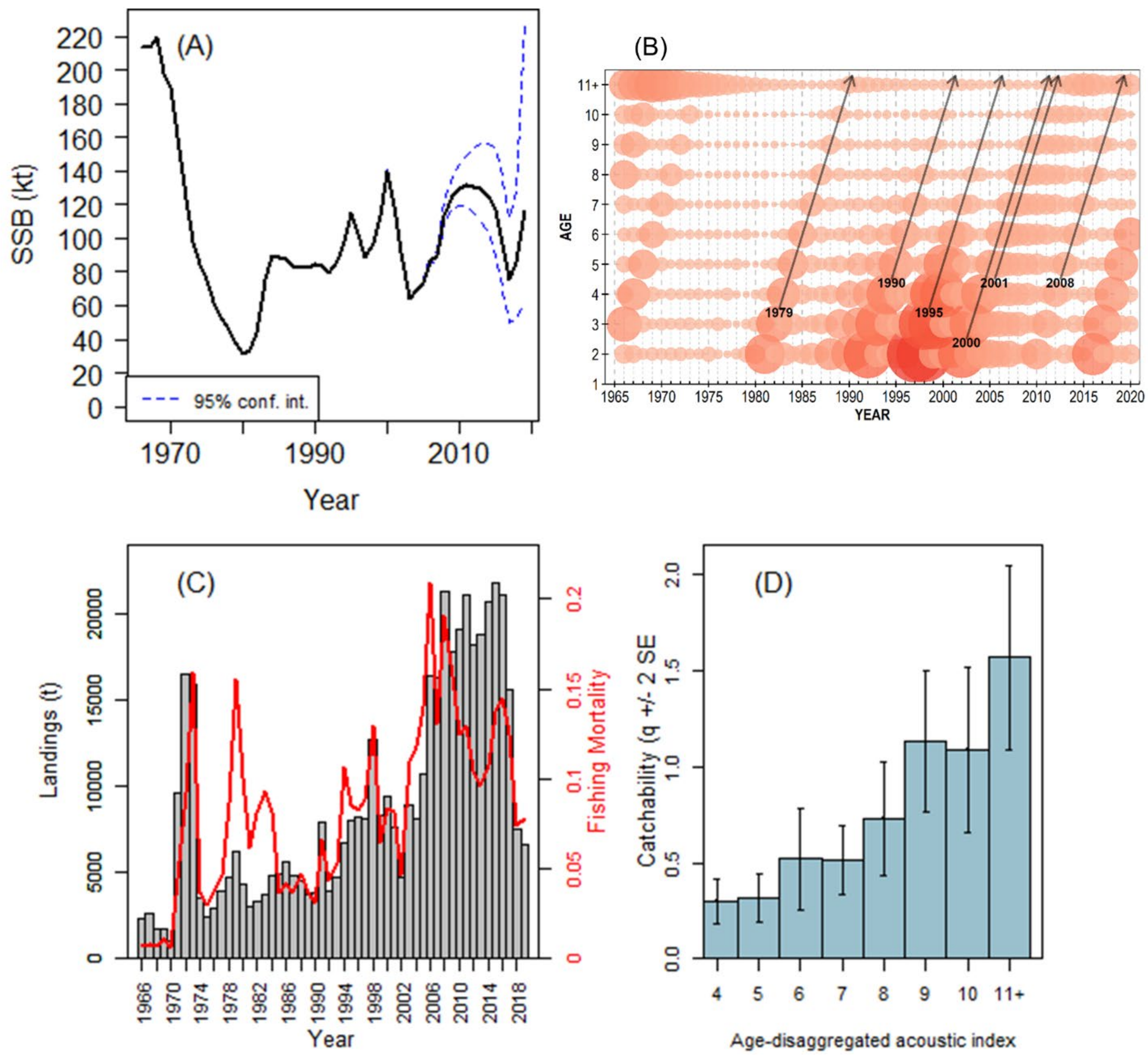

Figure A68. Fall spawning herring model 2b output: (A) estimated spawning stock biomass with 95% bootstrapped confidence intervals, (B) predicted number-at-age (arrows represent the same dominant cohorts indicated in Figure 34Figure 19 and 40), (C) average F (2–11+) and annual landings, and (D) catchability coefficients.

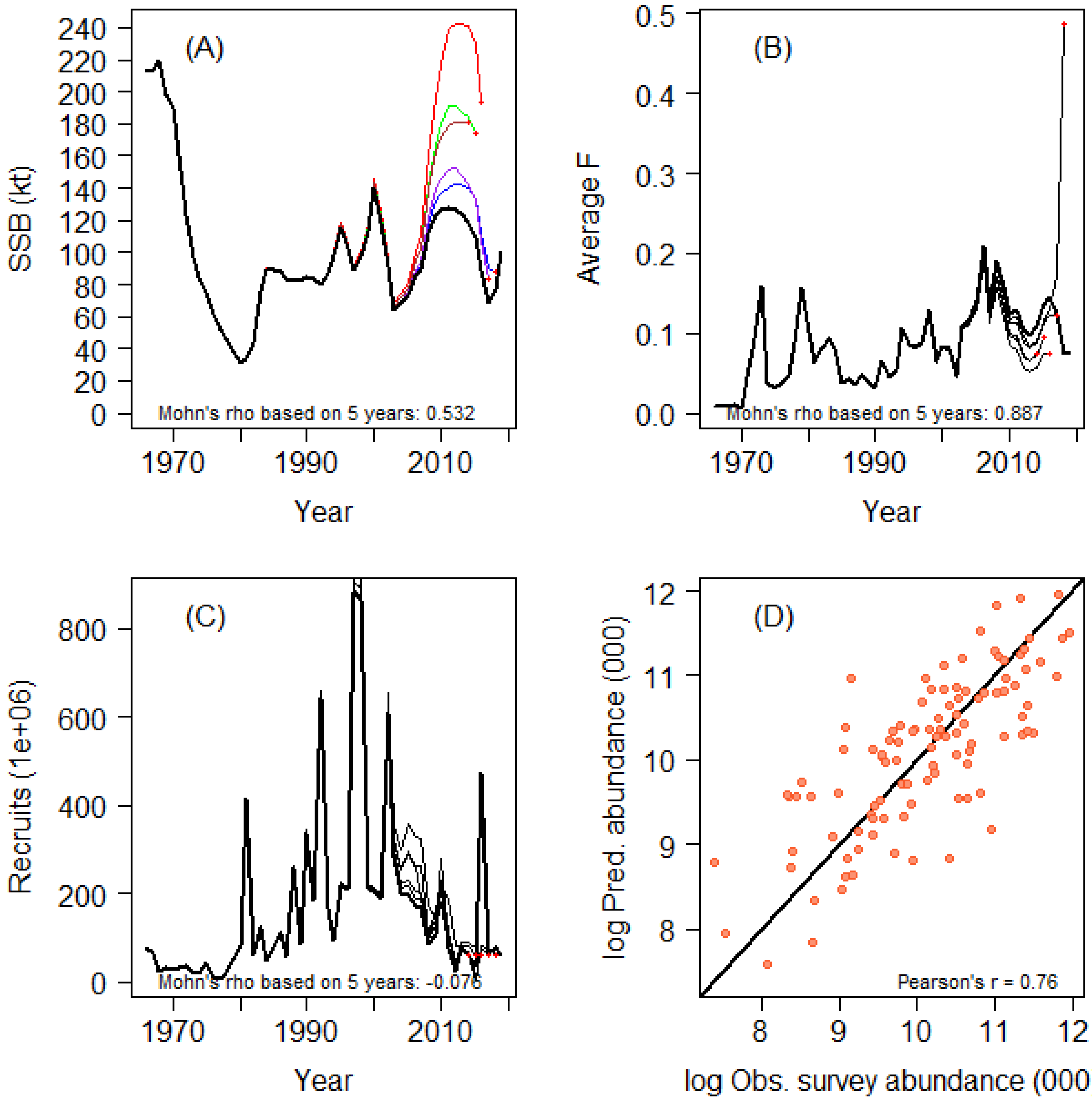

Figure A69. Fall spawning herring model 2b (A) SSB, (B) average F and (C) recruits retrospective plots, and (D) predicted and observed abundances.

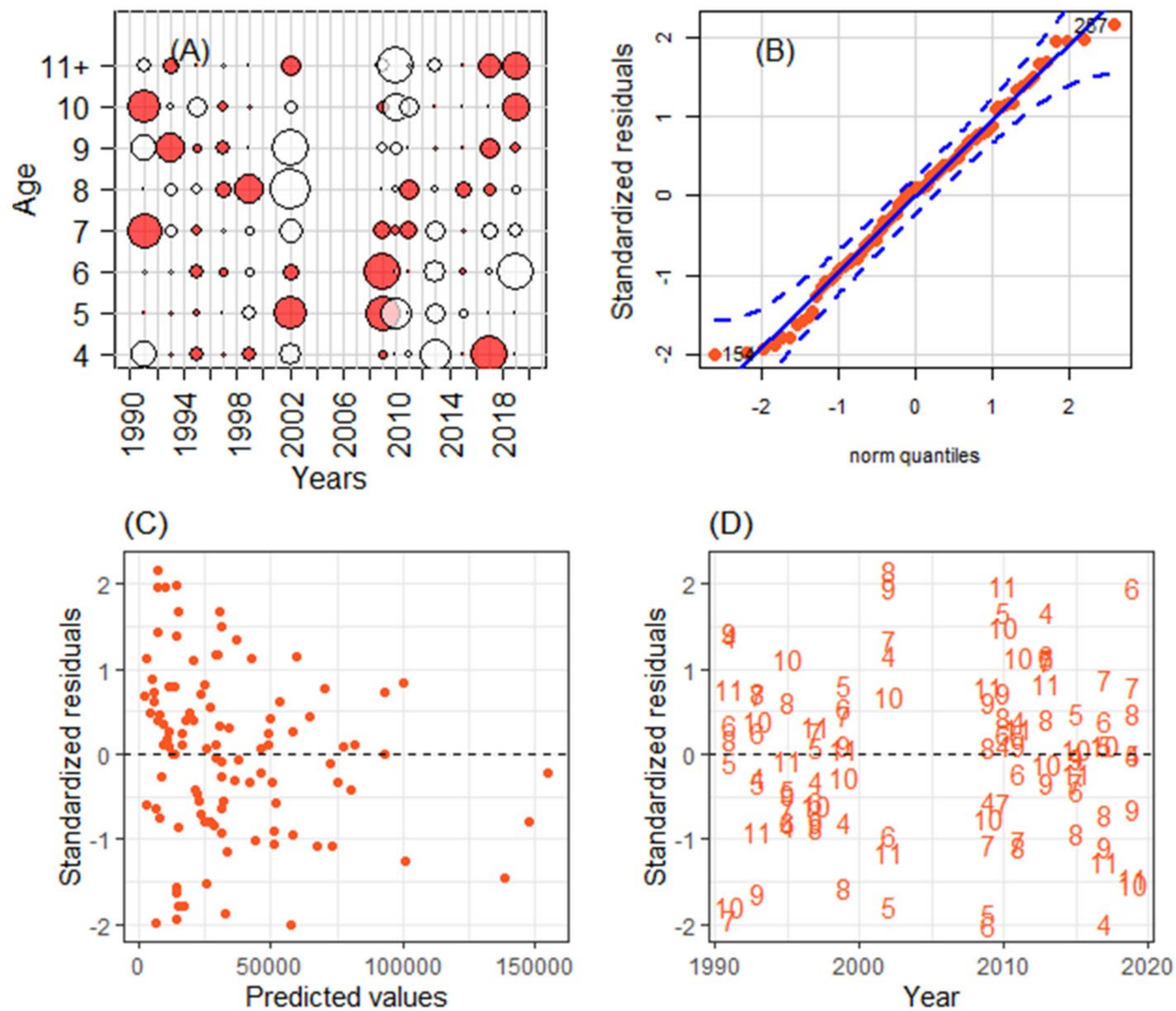

Figure A70. Fall spawning herring model 2b index residual plots: (A) bubble plot of residuals by age and year (open and red bubble respectively represent positive and negative residuals), (B) quantile-quantile plot (solid and dashed blue lines respectively represent theoretical quantiles and 95% confidence intervals), (C) standardized residuals and predicted values, and (D) standardized residuals as a function of year and age.