Fisheries and Oceans Canada
Canada

Pêches et Océans
Canada

Ecosystems and
Oceans Science

Sciences des écosystèmes
et des océans

Canadian Science Advisory Secretariat (CSAS)

Research Document 2022/046

Gulf Region

Biomass indices of NAFO Division 4TVn fall spawning Atlantic Herring (*Clupea harengus*) from hydroacoustic surveys on spawning grounds

François Turcotte, Jenni L. McDermid, Rachel A. DeJong, Lysandre Landry and Nicolas Rolland

Fisheries and Oceans Canada
Gulf Fisheries Center
343 University Avenue, P.O. Box 5030
Moncton, New Brunswick, E1C 9B6

July 2022

Canada

Foreword

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

Published by:

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

http://www.dfo-mpo.gc.ca/csas-sccs/
csas-sccs@dfo-mpo.gc.ca

ISSN 1919-5044
ISBN 978-0-660-44142-9 Cat. No. Fs70-5/2022-046E-PDF

Correct citation for this publication:

Turcotte, F., McDermid, J.L., DeJong, R.A., Landry, L. and Rolland, N. 2022. Biomass indices of NAFO Division 4TVn fall spawning Atlantic Herring (*Clupea harengus*) from hydroacoustic surveys on spawning grounds. DFO Can. Sci. Advis. Sec. Res. Doc. 2022/046. iv + 18 p.

Aussi disponible en français :

*Turcotte, F., McDermid, J.L., DeJong, R.A., Landry, L. et Rolland, N. 2022. Indices de biomasse des reproducteurs d'automne du hareng de l'Atlantique (*Clupea harengus*) de la division 4TVn de l'OPANO selon le relevé hydroacoustique sur les frayères. DFO Secr. can. de avis sci. du MPO. Doc. de rech. 2022/046. iv + 19 p.*

TABLE OF CONTENTS

ABSTRACT

Atlantic Herring in the southern Gulf of St. Lawrence (sGSL) are found in the area extending from the north shore of the Gaspé Peninsula to the northern tip of Cape Breton Island, including the Magdalen Islands. Fall spawning Herring in the sGSL are assessed using regionally-disaggregated assessment models (North, Middle, South regions). Since 2015, hydroacoustic surveys were conducted annually on six major Herring fall spawning grounds in the sGSL. To account for missing samples, a predictive model of nightly Herring biomass was used to obtain a complete data grid and derive unbiased biomass indices. The covariates included in the negative-binomial model allowed to predict data for missing values in the observed data set. The trends in Herring biomass generated from this hydroacoustic survey closely match the trends observed in other population indices and stock status estimates from the population model. The North region biomass showed a decline to very low values in 2021. However, the Middle region decline in biomass seemed to be slower and with more interannual variation. Finally, a declining trend in the South region seemed to have reversed and biomass levels in 2021 were as high as in the beginning of the time series. The quality of the sampling and potential biases are discussed.

INTRODUCTION

Atlantic Herring in the southern Gulf of St. Lawrence (sGSL) are found in the area extending from the north shore of the Gaspé Peninsula to the northern tip of Cape Breton Island, including the Magdalen Islands (North Atlantic Fisheries Organization (NAFO) Division 4T). Herring is a pelagic species that schools particularly during feeding, spawning, annual migrations and overwintering. The Herring population in the sGSL consists of two spawning components: spring spawners and fall spawners. Spring spawning occurs primarily in April-May in shallow waters. Fall spawning occurs from mid-August to mid-October at depths of 5 to 20 m, but can occur as early as July 1. The spring and fall spawners of 4TVn Herring are genetically distinct stocks and are assessed separately. Herring also show high spawning site fidelity (Wheeler and Winters 1984; McQuinn 1997; Brophy et al. 2006) and local stocks are targeted by a gillnet fishery that takes place on the spawning grounds and a purse seine fishery that takes place on the feeding grounds and migration corridor. Fall spawning Herring in the sGSL are therefore assessed using regionally-disaggregated assessment models (North, Middle, South regions).

NAFO Division 4TVn fall spawning Atlantic Herring (hereafter, Herring) is assessed using a statistical catch-at-age (SCA) population model since 2020 (Turcotte et al. 2021). The new SCA model and the former Virtual Population Analysis (VPA) model both generate retrospective patterns in model estimates. A potential solution to this problem is to use additional indices of Herring biomass to better inform the estimations by the model. Due to its extensive spatial and temporal coverage of biomass dynamics on all major fall spawning grounds in the sGSL, the spawning grounds acoustic survey is probably the best data source to improve the population model performance. Hydroacoustic techniques are frequently used to assess the abundance and biomass of fish (Simmonds and MacLennan 2005). These techniques are well suited for use on pelagic species such as mackerel, salmonids, anchovies, and herring (Simmonds and MacLennan 2005), including Atlantic Herring (e.g. Axelsen et al. 2000; Surette et al. 2015; Singh et al. 2020). Atlantic Herring is known to spawn at specific times of year, aggregating in defined geographic locations (Stephenson et al. 2009). Surveys conducted over their spawning grounds have been used to estimate stock biomass in locations such as the Bay of Fundy (Singh et al. 2020), Gulf of St. Lawrence (Surette et al. 2015), off the coast of Ireland (O'Malley et al. 2021) and in the Gulf of Maine (Wurtzell et al. 2016).

This survey is the result of a partnership between Fisheries and Oceans Canada (DFO) and fishery associations. The sampling effort varied between regions and years, generating non-random missing values in the data, which can create biased biomass estimates when the mean annual value is calculated. To account for missing samples, a predictive model of nightly Herring biomass could be used to obtain a complete data grid and derive unbiased biomass indices. The objectives of this document are to (1) build a predictive model of fall spawning Atlantic Herring nightly biomass in the three assessment regions, (2) use the model to predict missing values in the sampling grid of the acoustic survey, and (3) derive a biomass index per region for years 2015 to 2021. The indices of biomass are to be used in the 2022 stock assessment of fall spawning Atlantic Herring.

METHODS

Since 2015, hydroacoustic surveys were conducted annually on six major Herring fall spawning grounds in the sGSL (Gaspé (QC), Miscou (NB), Escuminac (NB), West PEI, East PEI and Pictou (NS), Figure 1). Strata were defined on each spawning ground using the acoustic information collected in the previous industry partnership studies. Strata were designed to be large enough to encompass the historical spawning grounds in each region and the transects were randomly generated within a stratum at a minimum of 400 m apart, following a stratified random design.

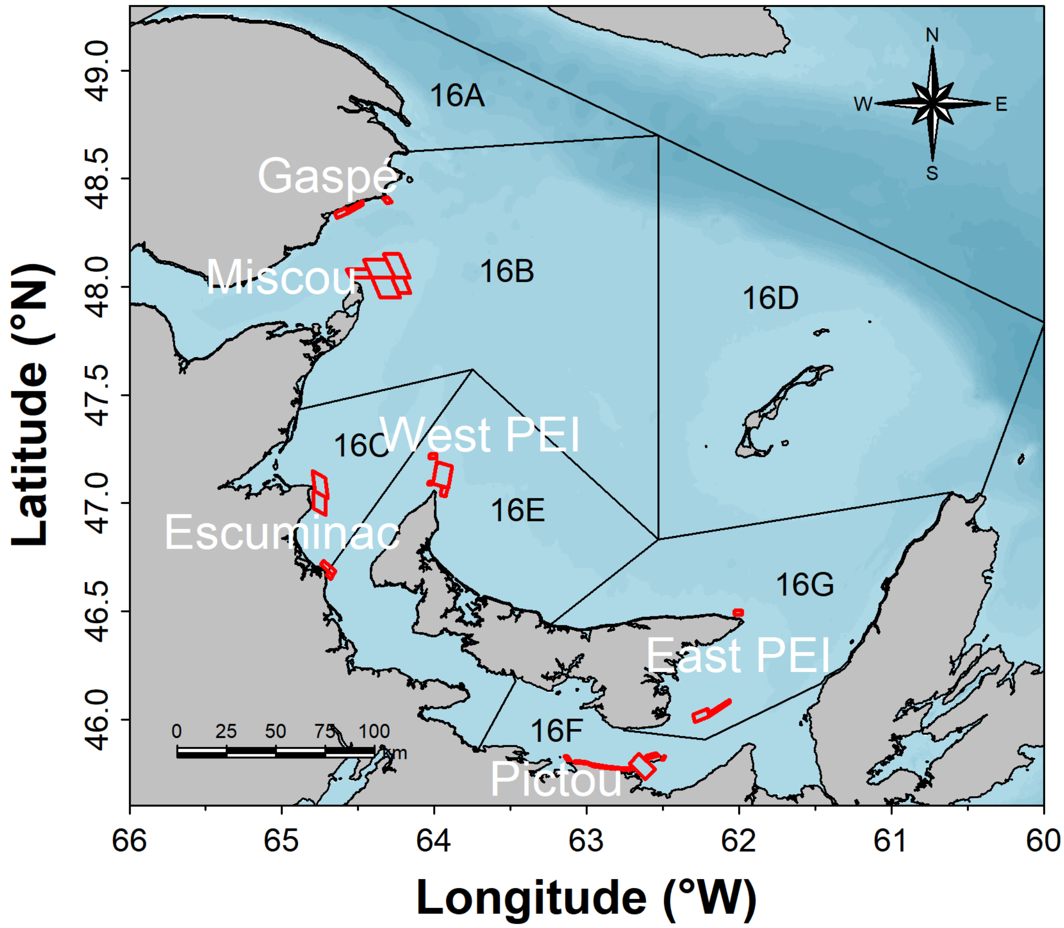

Figure 1: General map of strata (red lines) during the annual spawning ground acoustics surveys.

The vessels were equipped with either a DE9320 digital echo-sounder and a 120 kHz, 14 degree beam angle single beam transducer (Femto Electronics Limited) calibrated as described by Clay and Claytor (1998), or a calibrated (Demer et al. 2015) SIMRAD ES80 transceiver and ES120-7C transducer. The ES80 echosounders gradually replaced the DE9320, and all vessels have been using ES80 echosounders since 2020. Sampling was conducted between dusk and dawn at less than or equal to 10 knots while on transects. The whole sampling area was to be surveyed in one night, or in two consecutive nights if necessary.

One or two fishing vessels per spawning ground (See Appendix 1 for boat and gear details) collected acoustic data up to a week prior to the fishing season, during the weekend closures and up to a week following the closure of the fishing season. Generally, a maximum of five surveys were performed per spawning ground per year (Table 1). Sampling effort varied between spawning ground and years, as a result of participant availability, weather dependence, weekend fishery closures and equipment or vessel malfunctions.

Table 1: Number of hydroacoustic samples per region and per spawning ground per year.

Region	Ground	2015	2016	2017	2018	2019	2020	2021
North	Gaspé	5	5	1	5	7	5	5
North	Miscou	5	5	4	5	5	6	4
Middle	Escuminac	2	2	1	0	1	6	3
Middle	West PEI	2	1	2	6	4	7	4
South	Pictou	5	5	4	4	5	5	5
South	East PEI	0	3	5	2	2	3	0

Echograms were processed using the Echoview software. Herring size frequency data to convert the acoustic data into biomass estimates were obtained from the experimental gillnet surveys conducted on the spawning grounds during the commercial fishing activities in each week (Surette et al. 2016). See McDermid et al. (2018) and Turcotte et al. (2021) for detailed descriptions of yearly methods and results.

Data exploration was done following Zuur et al. (2010), while model selection and validation were done following Zuur et al. (2013). Preliminary modeling showed that the low number of samples and unbalanced data did not allow for the modeling of the biomass using the spawning ground and the stratum covariates. Hence, the finest level of spatial aggregation possible was at the region level (North, Middle and South), which corresponds to the level of spatial aggregation for the fall spawning Herring stock assessment population model.

As the model using the Poisson distribution was over-dispersed, a negative-binomial general linear model (GLM) with a log link function was used to model the nightly Herring biomass as a function of the covariates (Year, Region, Julian day). The log link function ensures positive fitted values and the negative binomial distribution is typically used for count data. Model fit was tested for statistical overdispersion and sources of overdispersion considered were missing covariates, missing interaction terms, outliers, non-linear patterns, and variation larger than the distribution allows. Model assumptions were verified by plotting the residuals against the fitted values. Independence was assessed by plotting the Pearson’s residuals against each of the covariates. Autocorrelation was estimated to be weak (0.8%) and an autocorrelation term did not improve a generalized least square model. Hence, no auto-correlation term was added to the model. The MASS package (Venables and Ripley 2002) in the software R (R Core Team 2021) was used to fit the models. The full predictive model reads as follows:

$$Biomass_{ij} = \beta_1 + \beta_2 fYear_{ij} \colon \beta_3 fRegion_{ij} + \beta_4 Jday_{ij}$$

Where $Biomass_{ij}$ is the jth observation from the ith year-region combination, $fYear_{ij}$ is a categorical variable for the fixed year effect (2015 to 2021), $fRegion_{ij}$ is a categorical variable for the fixed region effect (North, Middle, South) and $Jday_{ij}$ is the Julian day of the year effect (222 to 309).

For each region, the sampling season length was defined using the first and last Julian day of samples from all years combined. This season length was divided in five bins of equal length, defining the time periods where samples were expected (the sampling protocol asked for five samples per spawning ground per year). Two samples were expected per bin, since each region contains two spawning grounds, for a total of 10 samples per region per year. The predictive model was used to obtain data for bins where samples were missing. Using the complete data grid composed of observed data and predicted data for missing samples, the biomass indices to be used in the stock assessment were calculated as the average biomass per region per year. For comparison, the biomass indices were also calculated as 1) the average of the observed data without replacing the missing values and 2) replacing the missing values by the average observed biomass per region and year (Appendix 2).

RESULTS

Observed biomass generally declined as Julian day progressed when all years and regions were pooled (Figure 2A) and also declined within regions over pooled years (Figure 2B). The linear regression of the biomass by Julian day over all years and regions was statistically significant, although it only explained a small portion of the variation ($R = 0.05$, $F = 7.742$, $p = 0.00607$). Linear regressions of the biomass by Julian day were not statistically significant within each regions across years.

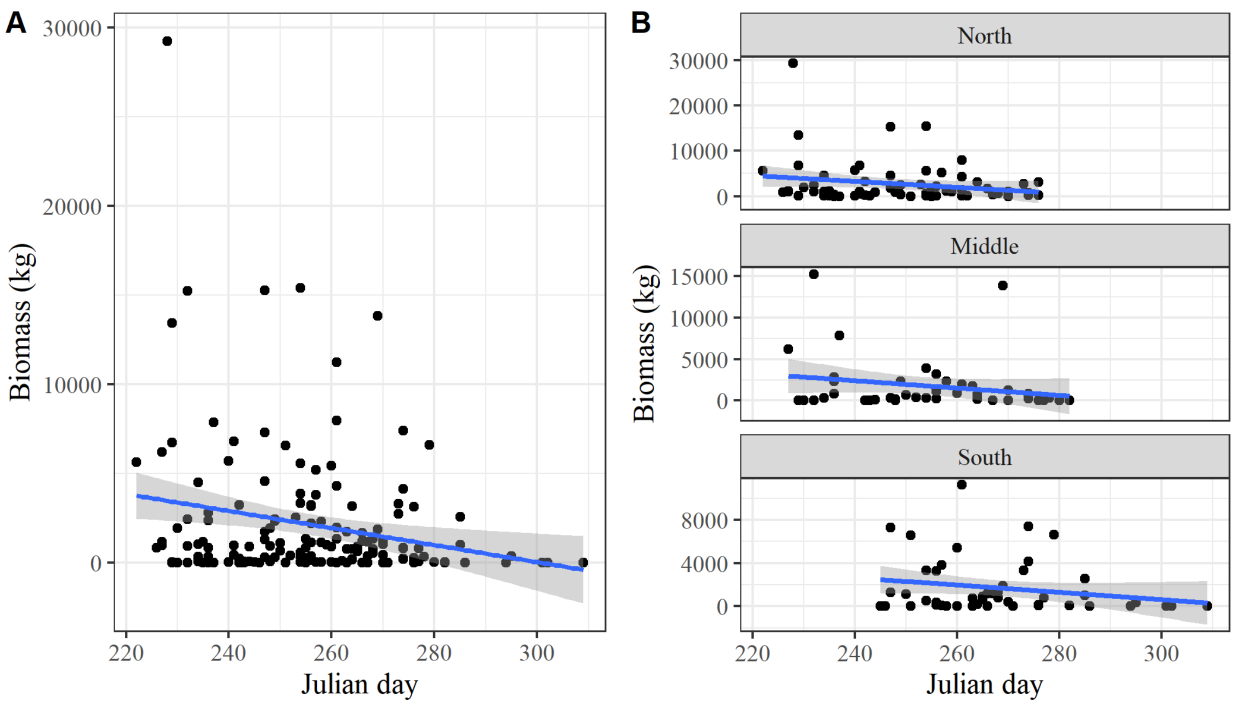

Figure 2: Observed Herring biomass over years and regions (A) and over years for three regions (B, North, Middle, South), blue line is a linear regression and grey shading is 95% confidence interval.

Model validation did not indicate any reason for concern (Figure 3). The residuals plotted against the fitted values showed that the homoscedasticity of residuals was acceptable. Independence was assessed by plotting the Pearson's residuals against each of the covariates, which showed no clear non-linear patterns. The Cook's distance analysis did not show any outliers in the data.

The negative-binomial model was slightly underdispersed (dispersion parameter = 0.73) as a few extreme high values could not be predicted by the model. As shown in Figure 4, the model could not predict most of the values over 15000 metric tons of biomass. However, the remainder of the values are spread homogeneously around the 1:1 line, showing no bias in the predictions made by the model. As seen in Figure 5, the variance in observed values was greater than the variance in predicted values for most years and regions.

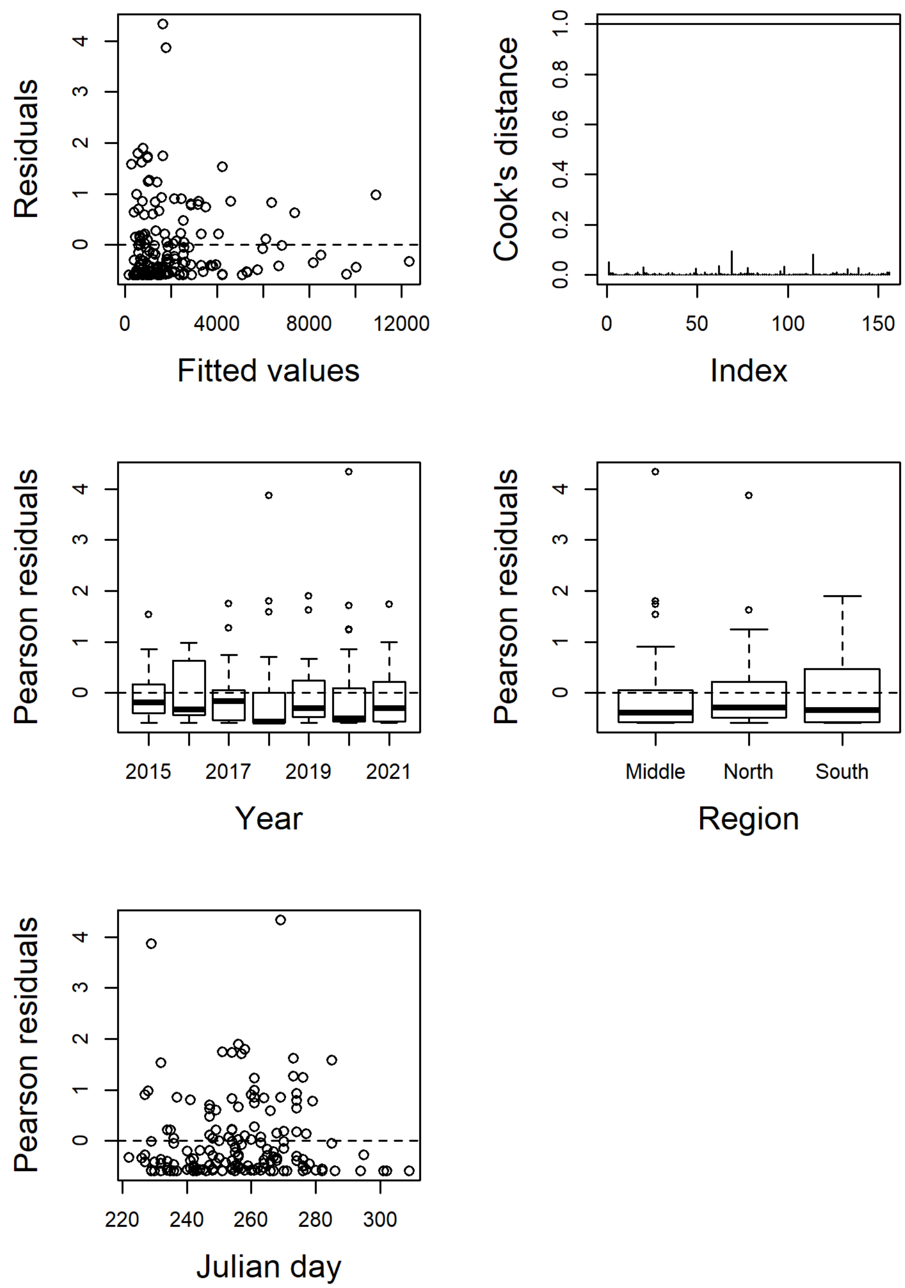

Figure 3: Pearson residuals versus fitted values (top left), Cook's distance values (top right), Pearson residuals versus Year, Region and Julian day.

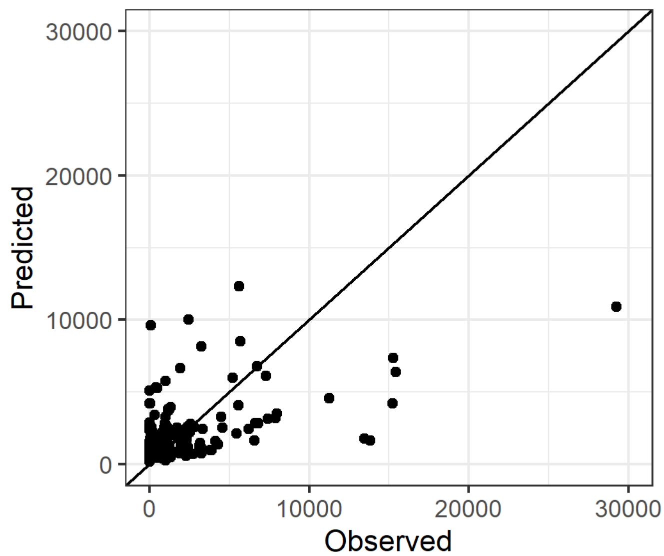

Figure 4: Observed versus predicted values, diagonal line is the 1:1 line.

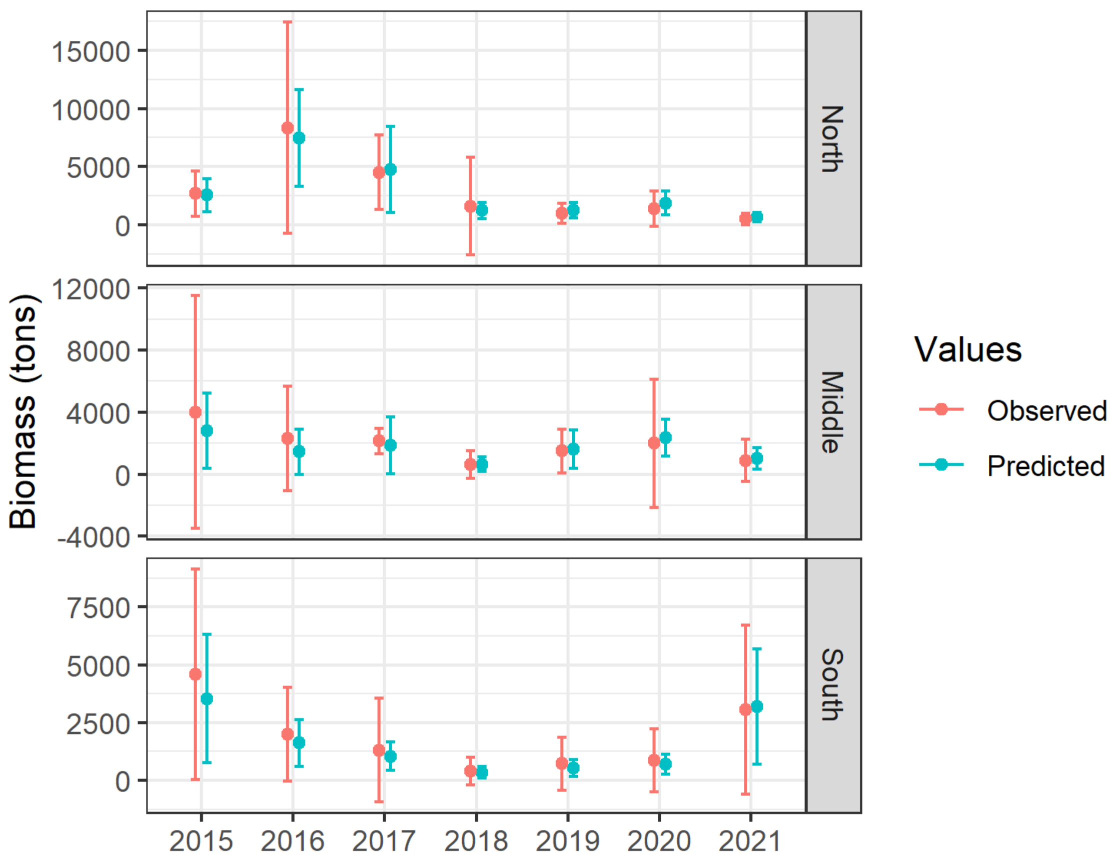

Figure 5: Observed and model predicted biomass values (units of metric tons) comparison per region and year, points are means and bars are standard errors.

Figure 6 shows the observed and model predicted data per region, year and Julian day. Most of the observed data points are close to the standard error intervals. The predicted data across regions and years show a decline in predicted biomass values as Julian day increases, as seen in most year-regions.

Figure 7 shows the results of the data prediction for missing samples. For specific regions and years, the predicted biomass values on individual Julian days fall within the range of the observed biomass values, and the trend through Julian days generally concur with the trend in observed biomass, which declines as the Julian day increases. The calculated biomass indices showed different trends across regions (Figure 8). In the North region, biomass increased between 2015 and 2016 before gradually decreasing to the lowest level in 2021. In the Middle region, biomass decreased between 2015 and 2016 and remained at that level afterwards, with some variation. In the South region, biomass declined continuously between 2015 and 2018, before increasing from 2019 to 2021.

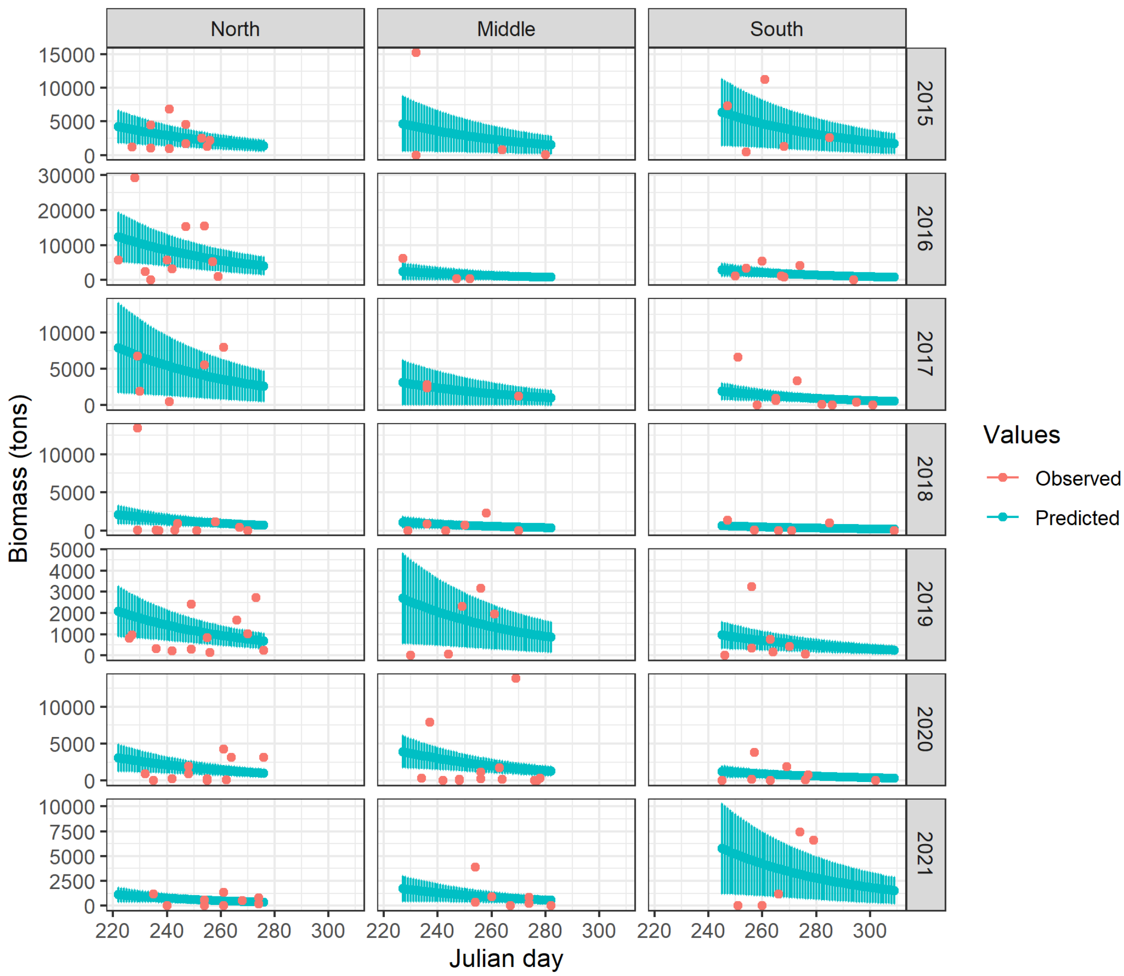

Figure 6: Observed and model predicted biomass values (units of metric tons) comparison per region, year and Julian day. Red points are observed values, green points and error bars are predicted values and standard errors.

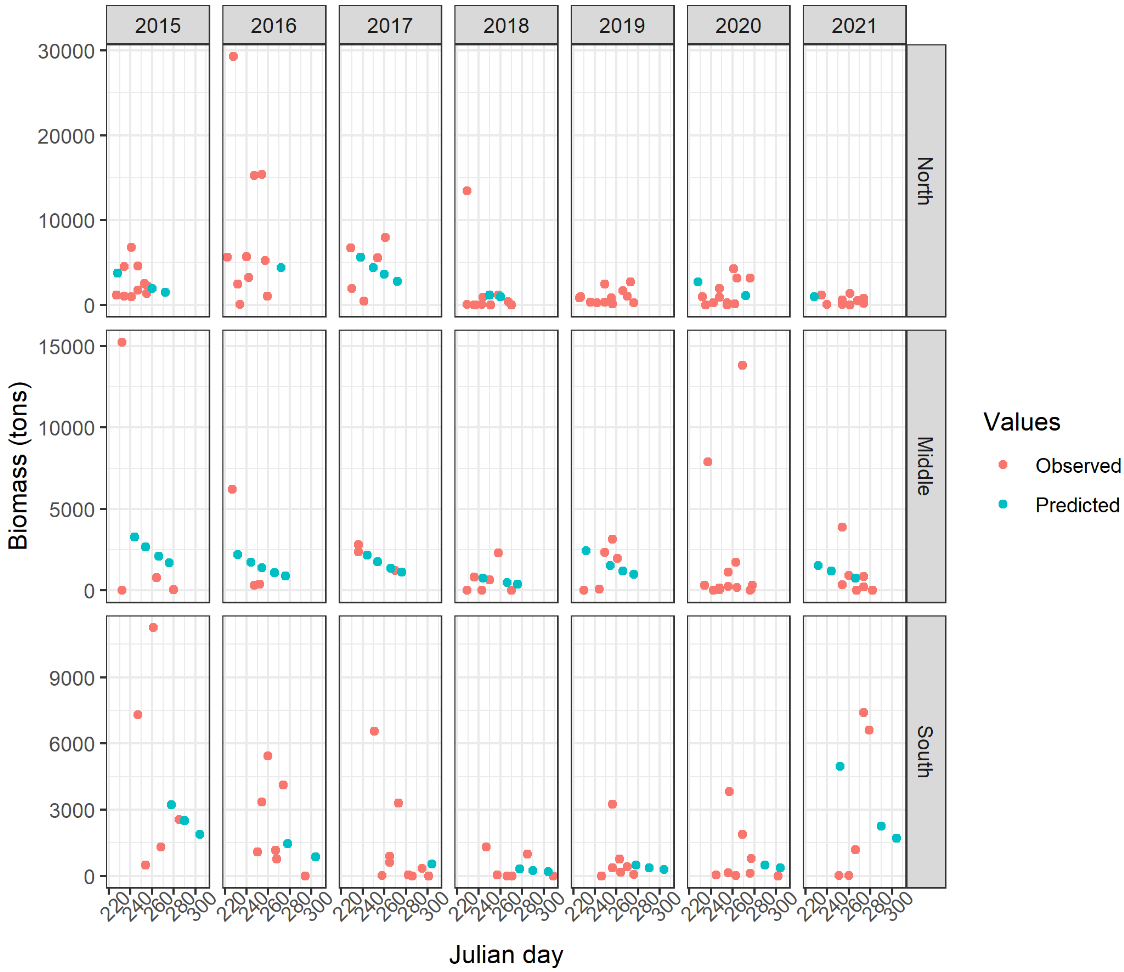

Figure 7: Data used to generate the biomass indices, showing observed and model predicted biomass data (units of metric tons) per region, year and Julian day.

The yearly average biomass values ranged from 338 metric tons in the South in 2018 to 7,667 metric tons in the North in 2016 (Table 2). The average biomass values are similar across regions, with no region showing an overall greater or lower biomass. Over all years, average biomass in the North region was 2,672 metric tons (SE = 462 metric tons), 1,661 metric tons (SE = 252 metric tons) in the Middle region and 1,536 metric tons (SE = 252 metric tons) in the South region.

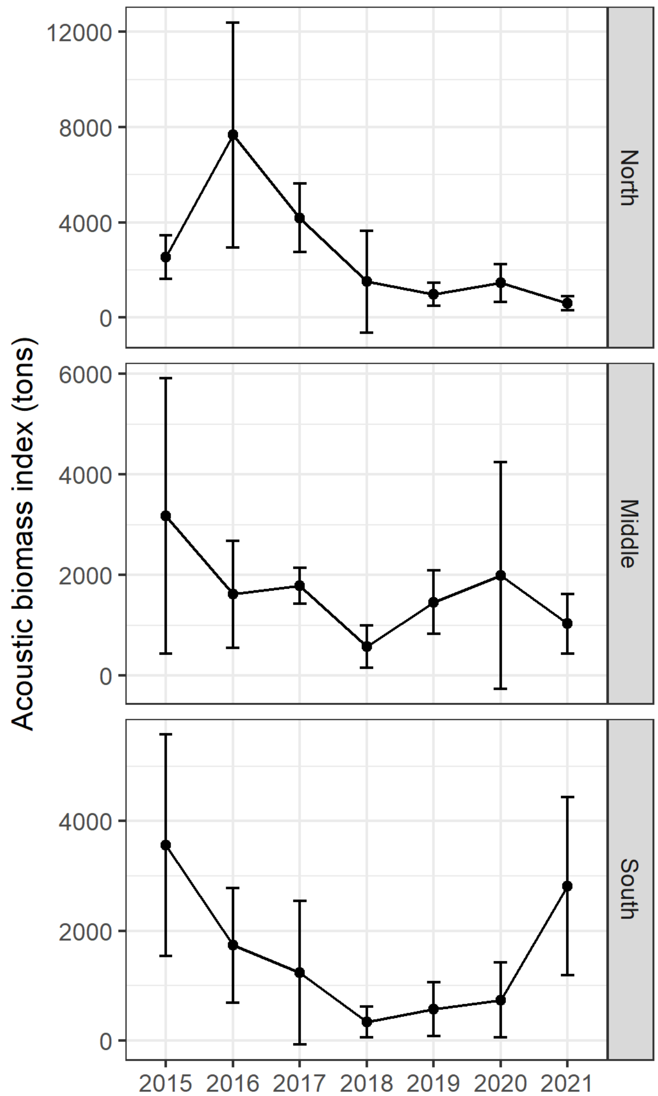

Figure 8: Acoustic biomass indices (units of metric tons) of NAFO Division 4T fall spawning Atlantic Herring in the North, Middle and South regions between 2015 and 2019. Points are averages and vertical lines are 95% confidence intervals.

Table 2: Average biomass (metric tons) of NAFO Division 4T fall spawning Atlantic Herring in the North, Middle and South regions between 2015 and 2021.

Region	2015	2016	2017	2018	2019	2020	2021
North	2531.39	7667.64	4180.55	1503.72	975.00	1449.03	600.13
Middle	3175.44	1616.30	1786.29	576.92	1463.08	1995.85	1036.41
South	3563.53	1737.44	1236.30	338.45	569.38	740.42	2816.26

DISCUSSION

BIOMASS INDICES

The trends in Herring biomass from this survey were in general agreement with the trends observed in other population indices and stock status estimates from the population model (Turcotte et al. 2021). Both the bottom trawl and the juvenile acoustic survey indices of abundance showed a continuous decline between the mid-2000s and 2019, a trend that is reflected in the population model SSB estimates (Turcotte et al. 2021). From this survey, the North region biomass showed a decline to very low values in 2021. However, the biomass decline in the Middle region seemed to be slower, with more interannual variation. Finally, the declining trend in the South region seemed to have reversed and biomass levels in 2021 were as high as in the beginning of the time series. Although the time series from the spawning grounds acoustic survey is short, it shows clear trends and will more than likely be informative to the population modeling. This survey has the widest spatial and temporal coverage when compared to the other indices. It uses consistent methodology and frequent sample collection throughout the spawning season to collect relevant region specific information on biomass. Moreover, since Atlantic Herring spawn at known times of the year and exhibit homing behaviour (Wheeler and Winters 1984; Stobo 1987; Stephenson et al. 2009), the survey allows the targeting of a specific age group in the population (spawners) at a predictable time and location.

The covariates included in the negative-binomial model allowed for the prediction of missing values in the observed data set. The region and year interaction allowed the model to predict different trends across years among regions, which was consistent to the pattern in the observed data. The Julian day covariate allowed the model to predict data for missing samples specifically for the time in the sampling season for which they were missing. As the observed biomass generally declined through the sampling season (more specifically, the highest biomass is often observed on the first sampling night), predicting values specifically for the julian day reduced the bias in the calculated biomass index.

Model performance was acceptable even if the model was slightly underdispersed. The few and infrequent very high observed biomass values could not be predicted by the model. This was expected, as these were rare occurrences in the observed data. This is reflected in the smaller variance around the predicted mean than around the observed mean. The consequence of this underdispersion is that the model will never predict values as high as the rare high observed values. However, as the model is predicting values for missing samples, it is more advised to obtain conservative predicted values.

While the wide spatial and temporal coverage of the survey is a major advantage when attempting to characterize Herring spawner biomass, it is still subject to potential biases. These mostly reside in uncertainties about (1) the residency time on spawning grounds and temporal spacing of surveys and (2) the sampling methods.

SURVEY SAMPLING SCHEDULE

One uncertainty with the predictive model used here is that it assumes a linear relationship between the covariates and the response variable. Atlantic Herring spawn in waves, with several waves occurring within the same spawning season (Lambert and Messieh 1989; McPherson et al. 2003; Stephenson et al. 2009). Shortly after spawning, a spent school leaves the spawning ground, allowing for the next wave to arrive on the spawning grounds (Stephenson et al. 2009). A model that would account for the aggregation and disaggregation processes occurring on the spawning grounds could potentially explain more of the variation in the data. However, there is no information available on these processes for the sGSL Herring, and attempts to account for this process have shown to be challenging in other jurisdictions.

If attempting to perform a census, assuming that fish present on a spawning ground during one hydroacoustic survey are not present for the next survey is important to ensure that fish are not double-counted (see Melvin et al. 2014). On the other hand, spacing surveys too far apart could result in missing some of the spawning fish. Other studies on Atlantic Herring with a similar design have been spaced out seven days (Wurtzell et al. 2016), 10-14 days (Singh et al. 2020), and 14 days (Melvin et al. 2014). Spawning wave frequency, as measured by spacing between larval cohorts, has been estimated as short as six (McPherson et al. 2003) to eight days (Lambert 1984); however, one tagging study found that some fish tagged on the spawning ground remained after five to six weeks (Clark 2006), demonstrating the wide range in estimated residency times. An estimated 81-87% spawner turnover was found in one study after 14 days, with the turnover rate being region dependent (Melvin et al. 2014). Another study estimated a 90% turnover rate at 13 to 18 days (Martin 2014). A 50% turnover rate has been estimated at four to five days (Martin 2014); this would suggest that at a study spacing of seven days, there is likely some double-counting of fish.

Correction factors could be applied to the estimated biomass to account for residency time (Melvin et al. 2020). However, without certainty about sGSL Herring specific residency time, and with the potential for region specific differences and/or changes in turnover rates through time, it is probably more advisable to use a fixed sampling grid each year and allow the population model to estimate the catchability to the survey. This would allow for variation in year to year sampling error, but the high frequency of within season sampling is assumed to produce a mean biomass that is representative of the biomass in each year and region. Allowing the population model to estimate the catchability coefficient to the survey (a standard practice in fish stock assessment, see Wilberg et al. (2009)) would account for potential double-counting and/or missing fish. In this survey, acoustic sampling was consistently spaced six to eight days apart as this survey frequency is allowed by weekend closures of the commercial fishery in the region.

Hydroacoustic data are often collected opportunistically throughout fishing operations (e.g. references within ICES 2007; Surette et al. 2015). Surveys such as this one, that are specifically designed to collect data to estimate abundance or biomass, are better than opportunistically gathered data (ICES 2007). Other studies of Atlantic Herring have also used grids with randomized transects, collected by multiple vessels (e.g. Wurtzell et al. 2016; O’Malley et al. 2021).

SURVEY SAMPLING METHODS

Hydroacoustic surveys conducted by fishing industry harvesters can be an efficient and cost-effective method of conducting acoustic surveys, relative to scientific research vessels, increasing both the amount of concurrent work that can be conducted in a set time frame, and the spatial distribution of this work (ICES 2007; Surette et al. 2015; Wurtzell et al. 2016). Studies comparing hydroacoustic data collected from different acoustic setups, including equipment from different manufacturers, different frequencies and, in some cases, using different analysis methods found that estimated biomass values (Wanzenböck et al. 2003; Draštík and Kubečka 2005), or Sa values (ICES 1998) were statistically similar. One such comparison study did find a significant difference between data collected by two vessels, although this difference was small (Simmonds and MacLennan 2005). The transition from FEMTO to SIMRAD equipment in these surveys is unlikely to have significant effect on biomass estimates given the similarity of all set ups, which used the same frequency transducer, the same software for data analysis and the same data analysis methods.

In some cases, vessels used for acoustic surveys have been shown to affect fish behavior, including that of Herring (ICES 2007). In response to vessel noise, Herring have been shown to elicit predator-avoidance behavior such as tighter schooling, increasing depth, and increased swim speed (e.g. van der Knaap et al. 2022). Vessels built to ICES noise-reduced vessel standards may still lead to Herring avoidance at depths less than 20 m (see ICES 2007 and references within). When vessels pass by, pre-spawning or overwintering Herring have been observed to go deeper in the water column, as a result of one or both factors of vessel noise and vessel lights (Olsen 1979; Ona and Toresen 1988; Vabo et al. 2002; Skaret et al. 2006); the same has been observed in schools on a spawning migration (Misund 1990). These studies were conducted at depths as shallow as 30-40 m, and as deep as 200-400 m. The depths at which Herring is typically observed in the sGSL spawning grounds surveys is 20-30 m. In contrast, a survey of spawning Herring (30-40 m study depth) did not result in significant reactions to vessel noise, which was suggested to be a result of the increased importance of spawning behavior (Skaret et al. 2005). The sGSL surveys were conducted on industry vessels that were not noise-reduced. However, since surveys took place during spawning and most fish schools were observed on the ocean floor, it is likely that fish did not react overly to vessel presence.

Other sources of noise include electrical interference, interference from other echosounders, and noise from bubbles. Data were checked after the first survey in each year and region to correct any electrical interference if observed, to ensure that no other sounder was operating at the same or an interfering frequency at the time of the survey, and data less than five meters were ignored in data analysis, unless obvious fish were present on the echogram.

The potential for noise induced biases within spawning grounds in this survey is small. The same boat/captain has been used in all years in West PEI, and in most years in Miscou, Gaspé, and Pictou. If present, differences in noise biases could be more important between regions rather than within regions, due to relatively few changes in vessels within a region. Within the East PEI and Escuminac spawning grounds, however, where the boat/captains have changed more regularly through the time series, differences in noise biases may be expected to be larger than in other regions. Potential for vessel noise biases will be measured in the next survey seaons by recording passive noise on all sampling vessels. If significant differences in noise among vessels are found, the data will be corrected in order to improve comparability among regions.

ACKNOWLEDGMENTS

This work was supported by the Fisheries Science Collaborative Program of Fisheries and Oceans Canada. We thank all industry participants, harvesters and associations. Authors would also like to thank DFO technicians for conducting the port and laboratory sampling.

REFERENCES CITED

Axelsen, B.E., Nottestad, L., Ferno, A., Johannessen, A., and Misund, O.A. 2000. ‘Await’ in the pelagic: Dynamic trade-off between reproduction and survival within a herring school splitting vertically during spawning. Marine Ecology Progress Series 205: 259–269.

Brophy, D., Danilowicz, B.S., and King, P.A. 2006. Spawning season fidelity in sympatric populations of Atlantic herring (*Clupea harengus*). Can. J. Fish. Aquat. Sci. 63(3): 607–616.

Clark, K.J. 2006. An Examination of Turnover Rate of Herring on the Spawning Grounds of Scots Bay and German Bank using Tagging Data. DFO Can. Sci. Advis. Sec. Res. Doc. 2006/47.

Clay, A., and Claytor, R. 1998. Hydroacoustic Calibration Techniques used for southern Gulf of St . Lawrence Herring Fishing Vessels - 1997. DFO Can. Sci. Advis. Sec. Res. Doc. 1998/96.

Demer, D.A., Berger, L., Bernasconi, M., Bethke, E., Boswell, K., Cgu, D., Domokos, R., Dunford, A., Fassler, S., Gauthier, S., Hufnagle, L.T., Jech, M.J., Bouffant, N., Lebourges-Dhaussy, A., Lurton, X., Macaulay, G.J., Perrot, Y., Ryan, T., Parker-Stetter, S., Stienessen, S., Weber, T., and Williamson, N. 2015. Calibration of acoustic instruments. ICES Coop. Res. Rep. (326): 130.

Draštík, V., and Kubečka, J. 2005. Fish avoidance of acoustic survey boat in shallow waters. Fisheries Research 72(2-3): 219–228.

ICES. 1998. Report of the planning group for herring surveys. ICES CM 1998/G:4, Bergen, Norway.

ICES. 2007. Collection of Acoustic Data From Fishing Vessels. *Edited by* W.A. Karp. ICES Cooperative Research Report No. 287.

Lambert, T.C. 1984. Larval cohort succession in herring (*Clupea harengus*) and capelin (*Mallotus villotus*). Canadian Journal of Fisheries and Aquatic Sciences 41(11): 1552–1564.

Lambert, T.C., and Messieh, S.N. 1989. Spawning Dynamics of Gulf of St . Lawrence Herring (*Clupea harengus*). Canadian Journal of Fisheries and Aquatic Sciences 46: 2085–2094.

Martin, J.R. 2014. Turnover time and annual migration of (*Clupea harengus*) Atlantic herring on the German Bank and Scot's Bay spawning grounds : a mark and recapture study. PhD thesis, University of New Brunswick.

McDermid, J.L., Swain, D.P., Turcotte, F., Robichaud, S.A., and Surette, T. 2018. Assessment of the NAFO Division 4T southern Gulf of St. Lawrence Atlantic herring (*Clupea harengus*) in 2016 and 2017. DFO Can. Sci. Advis. Sec. Res. Doc. 2018/052. xiv + 122 p

McPherson, A.A., Stephenson, R.L., and Taggart, C.T. 2003. Genetically different Atlantic herring. Marine Ecology Progress Series 247: 303–309.

McQuinn, I.H. 1997. Metapopulations and the Atlantic herring. Rev. Fish Biol. Fish. 7: 297–329.

Melvin, G.D., Martin, R., and Power, M. J. 2014. Estimating German Bank and Scots Bay Herring Spawning Ground Turnover Rates from Tag Returns. DFO Can. Sci. Advis. Sec. Res. Doc. 2014/068. iv + 22 p.

Melvin, G.D., Singh, R., Martin, R., and Power, M.J. 2020. Updated herring spawning biomass estimates for German Bank and Scots Bay based on spawning ground turnover rates from tag returns. DFO Can. Sci. Advis. Sec. Res. Doc. 2020/008. iv + 24 p

Misund, O.A. 1990. Sonar observations of schooling herring: school dimensions, swimming behavior, and avoidance of vessel and purse seine. Rapp. P.-v. Réun. Cons. int. Explor. Mer 189: 135–146.

Olsen, K. 1979. Observed avoidance behaviour in herring in relation to passage of an echo survey vessel. C.M. 1979/B:18. International Council for the Exploration of the Sea, Bergen, Norway.

O'Malley, M., Mullins, E., and Nolan, C. 2021. FEAS Survey Series : Industry Acoustic Atlantic Herring in 6aS / 7b , Industry Acoustic Survey Cruise Report November-December 2020 and January 2021. Marine Institute.

Ona, E., and Toresen, R. 1988. Avoidance reactions of herring to a survey vessel, studied by scanning sonar. C.M. 1988/H:46 Pelagic Fish Committee: 8.

R Core Team. 2021. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.

Simmonds, J., and MacLennan, D. 2005. Fisheries Acoustics. *In* 2nd editions. Blackwell Science Ltd, Oxford, UK.

Singh, R., Knox, D., MacIntyre, A., and Melvin, G.D. 2020. 2018 Evaluation of Northwest Atlantic Fisheries Organization (NAFO) Divisions 4VWX Herring. DFO Can. Sci. Advis. Sec. Res. Doc. 2020/062. v + 157 p.

Skaret, G., Axelsen, B.E., Nøttestad, L., Fernö, A., and Johannessen, A. 2005. The behaviour of spawning herring in relation to a survey vessel. ICES Journal of Marine Science 62(6): 1061–1064.

Skaret, G., Slotte, A., Handegard, N.O., Axelsen, B.E., and Jørgensen, R. 2006. Pre-spawning herring in a protected area showed only moderate reaction to a surveying vessel. Fisheries Research 78(2-3): 359–367.

Stephenson, R.L., Melvin, G.D., and Power, M.J. 2009. Population integrity and connectivity in Northwest Atlantic herring: A review of assumptions and evidence. ICES Journal of Marine Science 66(8): 1733–1739.

Stobo, W.T. 1987. Atlantic herring (*Clupea harengus*) movement along the Scotian Shelf and management considerations. *In* Proceedings of the conference on forage fishes of the southeastern Bering sea. US Department of the Interior, Minerals Management Services, Alaska OCS Region, Anchorage, Alaska. pp. 55–60.

Surette, T.J., LeBlanc, C.H., and Mallet, A. 2016. Abundance indices and selectivity curves from experimental multi-panel gillnets for the southern Gulf of St. Lawrence fall herring fishery. DFO Can. Sci. Advis. Sec. Res. Doc. 2016/067. vi + 23 p.

Surette, T., LeBlanc, C.H., Claytor, R.R., and Loots, C. 2015. Using inshore fishery acoustic data on Atlantic herring (*Clupea harengus*) spawning aggregations to derive annual stock abundance indices. Fisheries Research 164: 266–277. Elsevier B.V.

Turcotte, F., Swain, D.P., McDermid, J.L., and DeJong, R.A. 2021. Assessment of the NAFO Division 4TVn southern Gulf of St. Lawrence Atlantic Herring (*Clupea harengus*) in 2018-2019. DFO Can. Sci. Advis. Sec. Res. Doc. 2021/030. xiv + 158 p.

Vabo, R., Olsen, K., and Huse, I. 2002. Vessel avoidance of wintering Norwegian spring spawning herring. The Journal of the Acoustical Society of America 103(5): 3035–3035.

van der Knaap, I., Ashe, E., Hannay, D., Bergman, A.G., Nielsen, K.A., Lo, C.F., and Williams, R. 2022. Behavioural responses of wild Pacific salmon and herring to boat noise. Marine Pollution Bulletin 174: 113257.

Venables, W.N., and Ripley, B.D. 2002. Modern applied statistics with s. *In* Fourth. Springer, New York.

Wanzenböck, J., Mehner, T., Schulz, M., Gassner, H., and Winfield, I.J. 2003. Quality assurance of hydroacoustic surveys: The repeatability of fish-abundance and biomass estimates in lakes within and between hydroacoustic systems. ICES Journal of Marine Science 60(3): 486–492.

Wheeler, J.P., and Winters, G.H. 1984. Homing of Atlantic Herring (*Clupea harengus*) in Newfoundland Waters as Indicated by Tagging Data. Canadian Journal of Fisheries and Aquatic Sciences 41: 108–117.

Wilberg, M.J., Thorson, J.T., Linton, B.C., and Berkson, J. 2009. Incorporating time-varying catchability into population dynamic stock assessment models. Reviews in Fisheries Science 18(1): 7–24.

Wurtzell, K.V., Baukus, A., Brown, C.J., Jech, J.M., Pershing, A.J., and Sherwood, G.D. 2016. Industry-based acoustic survey of Atlantic herring distribution and spawning dynamics in coastal Maine waters. Fisheries Research 178: 71–81.

Zuur, A.F., Hilbe, J.M., and Ieno, E.N. 2013. A begginer's guide to GLM and GLMM with R. Highland Statistics Ltd.

Zuur, A.F., Ieno, E.N., and Elphick, C.S. 2010. A protocol for data exploration to avoid common statistical problems. Methods in Ecology and Evolution 1(1): 3–14.

APPENDIX 1

Table A1.1. Details on captains, vessels, and equipment used to conduct industry acoustic surveys. FEMTO indicates FEMTO equipment with 120 kHz transducer, and SIMRAD indicates SIMRAD ES80 with 120 kHz transducers.

Spawning ground	Year	Vessel	Equipment
Gaspé	2015	Mary David	FEMTO
Gaspé	2016	Mary David	FEMTO
Gaspé	2017	Mary David	FEMTO
Gaspé	2018	Miss Amy Lynn	SIMRAD
Gaspé	2019	Miss Amy Lynn	SIMRAD
Gaspé	2020	Miss Amy Lynn	SIMRAD
Gaspé	2021	NigNag	SIMRAD
Miscou	2015	Autumn Breeze / B-Carll	FEMTO
Miscou	2016	B-Carll	FEMTO
Miscou	2017	Hebert Boys	FEMTO
Miscou	2018	Hebert Boys	SIMRAD
Miscou	2019	Hebert Boys	SIMRAD
Miscou	2020	Hebert Boys	SIMRAD
Miscou	2021	Hebert Boys	SIMRAD
Escuminac	2015	Alicia G	FEMTO
Escuminac	2016	Alicia G	FEMTO
Escuminac	2017	Alicia G	SIMRAD
Escuminac	2018	N/A	N/A
Escuminac	2019	Miss Tate	SIMRAD
Escuminac	2020	Sea Princess No. 1	SIMRAD
Escuminac	2021	Sea Princess No. 1	SIMRAD
West PEI	2015	Sting Rae	FEMTO
West PEI	2016	Sting Rae	FEMTO
West PEI	2017	Sting Rae	FEMTO
West PEI	2018	Sting Rae	FEMTO
West PEI	2019	Sting Rae	FEMTO
West PEI	2020	Sting Rae	SIMRAD
West PEI	2021	Sting Rae	SIMRAD
East PEI	2015	N/A	N/A
East PEI	2016	Sunrise Sail II	FEMTO
East PEI	2017	Sunrise Sail II	FEMTO
East PEI	2018	Sunrise Sail II	SIMRAD
East PEI	2019	Katherine Maureen	FEMTO
East PEI	2020	Katherine Maureen	SIMRAD
East PEI	2021	N/A	N/A
Pictou	2015	Northport Lady II / Slack Tide	FEMTO
Pictou	2016	Northport Lady II	FEMTO
Pictou	2017	Slack Tide	FEMTO
Pictou	2018	Slack Tide	SIMRAD
Pictou	2019	Slack Tide	SIMRAD
Pictou	2020	Slack Tide	SIMRAD
Pictou	2021	Slack Tide	SIMRAD

APPENDIX 2

Figure A2.1 shows a comparison of the acoustic biomass indices for the North, Middle and South regions, between 2015 and 2021, using three analysis options to deal with missing data. The first option is to ignore the missing data and use the mean of all observed values per region and year ("Mean" in figure legend). The second option is to use replace the missing values by the mean value of the observations in the region-year ("Missing mean" in figure legend). The third option is the predictive model developed in this research document ("Model" in figure legend).

As there are very few missing data in the North region, there is almost no difference in the average or error values between the three methods. For the Middle and South regions, where the number of missing values is higher, some differences appear, although minor. In general, using the mean of observed values generates higher error estimates around the mean values. This is to be expected, as this data set contains fewer samples than the data sets of the two other methods. The mean biomass values obtained using the mean method or the missing mean method are almost identical for all years and regions. The missing mean and model methods produced similar error around the average values, as the number of samples from these two data sets are the same. In some years and regions, the average values using the model method are different than the other two methods. For example, in the South region in 2015, the model method average value is lower than the mean and missing methods average. In that region-year, the three missing samples were all from the end of the season (Figure 7). The model thus predicted lower values, which generated a lower average biomass value than the other methods.

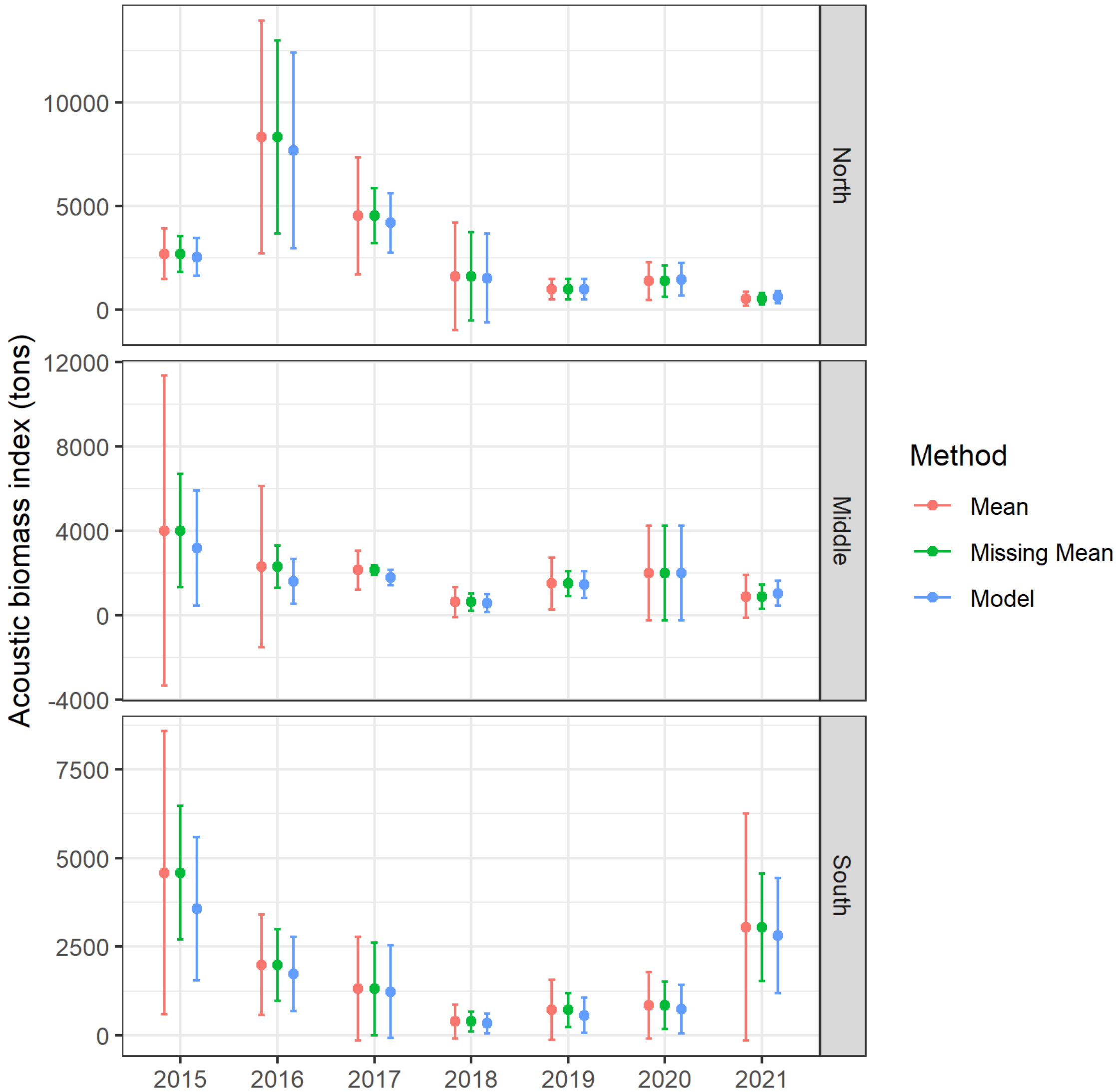

Figure A2.1: Acoustic biomass index (metric tons) of fall spawning Atlantic Herring in the North, Middle and South regions between 2015 and 2021, calculated as the mean of the observed values (in red), by replacing the missing values by the mean of the region-year combination (in green), or by using the predictive model from this research document (in blue).