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Assessment framework for fall-spawning Atlantic herring (*Clupea harengus*) in the southern Gulf of St. Lawrence (NAFO Div. 4T): Population models and status in 2014

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Foreword

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ABSTRACT

The fall spawning component of Atlantic herring (*Clupea harengus*) in the southern Gulf of St. Lawrence has been assessed using virtual population analysis (VPA). A review of assessment inputs and models was undertaken due to poor model fit and unresolved model uncertainties. This document compares alternate model formulations (using revised data inputs described elsewhere) and presents status in 2014 based on the preferred model. The base model treated fall spawners as a single population and assumed that population dynamics parameters (e.g., natural mortality, M) and observation parameters (e.g., catchability) were stationary over time. A model incorporating process error in fully-recruited catchability to the gillnet fishery (q) provided the best fit to the data and eliminated the strong pattern in residuals. To address management requests, models treating fall spawners as three putative populations, based on three groups of spawning grounds (North, Middle and South), was examined. The greatest improvement in model fit and reduction in residual patterns occurred using a three-population model with process error in q, allowing q to vary independently among populations. This model was chosen as the preferred model for the provision of advice.

Cadre d'évaluation de la composante des reproducteurs d'automne du hareng de l'Atlantique (*Clupea harengus*) dans le sud du golfe du Saint-Laurent (division 4T de l'OPANO) : modèles de population et état en 2014

RÉSUMÉ

La composante de reproducteurs d'automne du hareng de l'Atlantique (*Clupea harengus*) dans le sud du golfe du Saint-Laurent a été évaluée au moyen d'une analyse de population virtuelle (APV). Un examen des intrants et des modèles d'évaluation a été réalisé en raison d'un mauvais ajustement du modèle et des incertitudes non résolues concernant le modèle. Le présent document permet de comparer d'autres formules de modèle (à l'aide de données révisées décrites ailleurs) et présente l'état en 2014 selon le modèle privilégié. Le modèle de base traitait les reproducteurs d'automne comme une population unique et supposait que les paramètres actuels de la dynamique des populations (p. ex., mortalité naturelle, *M*) et les paramètres d'observation (p. ex., capturabilité) avaient été stationnaires au fil du temps. Un modèle intégrant les erreurs dues au processus dans la capturabilité des spécimens pleinement recrutés dans la pêche au filet maillant (*q*) a produit le meilleur ajustement aux données et a éliminé la forte tendance associée aux données résiduelles. Pour répondre aux demandes de gestion, les modèles traitant les reproducteurs d'automne en tant que trois populations présumées, en fonction de trois groupes de frayères (nord, centre et sud), ont été examinés. La plus grande amélioration de l'ajustement du modèle et la réduction des tendances résiduelles ont été obtenues à l'aide d'un modèle à trois populations avec une erreur de processus dans *q*, qui a permis de faire varier *q* de façon indépendante parmi les populations. Ce modèle a été choisi comme modèle privilégié pour formuler cet avis.

INTRODUCTION

At the March 2014 peer review meeting examining the assessment of Atlantic herring (*Clupea harengus*) in the southern Gulf of St. Lawrence (sGSL), Northwest Atlantic Fishery Organization (NAFO) Division 4T, issues were identified with the indices of abundance from the fall gillnet fishery and with the population models used to assess status of fall-spawning herring (LeBlanc et al. 2015). It was suggested that the catchability of 4 and 5 year old herring to the gillnet fishery may be decreasing due to the observed declines in weight-at-age. Two assessment models were examined, one allowing a trend in the catchability of 4 and 5 year olds to the gillnet fishery since 2004 and one assuming that catchability has been constant since the start of the time series in 1986. Estimates of recent biomass and catch advice differed substantially between the two models, though no evidence was available to determine whether one model was preferable (DFO 2015). Furthermore, both produced strong retrospective patterns and patterns in model residuals that indicated poor model fit to the data. Thus, a framework review of the assessment approach was held in April 13-15, 2015.

This document examines revised population models for fall-spawning herring in the sGSL. These models incorporate revised abundance indices based on catch rates in the fall gillnet fishery (Benoît et al. 2016) and new indices based on monitoring by experimental gillnets (Surette et al. 2016) and the annual research vessel (RV) bottom-trawl survey of the sGSL (Surette 2016). The data for all indices are summarized in Benoît et al. (2016) and are not presented here. Possible process error associated with non-stationarity in natural mortality or in catchability to the gillnet fishery was also examined. In response to requests from fisheries managers, models which treated herring from different spawning regions as independent populations were also examined.

PART 1: CANDIDATE MODELS

METHODS

All models were virtual population analyses (VPA) implemented in AD Model Builder (Fournier et al. 2011). Uncertainty in model estimates was evaluated based on MCMC sampling, with every 40th of 200,000 samples saved. Models extended from 1978 to 2014 and from age 2 to ages 11+ (i.e., 11 years and older). Plus group calculations followed the FRATIO method described by Gavaris (1999).

Two sets of analyses were conducted. In the first, the fall spawning component was treated as a single, fully mixed population (Type-1 Models). In the second, this component was treated as three independent populations corresponding to the North, Middle and South spawning grounds (Type-2 Models; Fig. 1). A number of alternative formulations were compared for each of these model types.

Single-population models

Data inputs were fishery catches at ages 2 to 11+ (in numbers), fishery catch per unit effort (CPUE) in numbers at ages 4 to 10 years from 1986 to 2014, catch rates at age in experimental nets (ages 3 yo 10, 2003 to 2013), abundance indices at ages 2 and 3 from the fall acoustic survey (1994 to 2014), and catch rates at ages 4 to 6 in the September RV survey. Catchability (q) to the fishery was adjusted for changes in mesh size and fish length-at-age as follows:

$$q'_a = (p_1\, Sr_{1,a,t} + (1 - p_1) Sr_{2,a,t}) q_a \qquad (1)$$

where p_1 is the proportion of nets with a mesh size of $2^5/_8$" (as opposed to $2^3/_4$"), $Sr_{1,a,t}$ is the relative selectivity of a $2^5/_8$" mesh net for age *a* in year *t* taking into account the changes in length at age *a* over time, $Sr_{2,a,t}$ is the corresponding relative selectivity for $2^3/_4$" mesh nets, and q_a is catchability at age to the fishery without accounting for changes in relative selectivity. q_a was freely estimated for each age, with the exceptions described below.

Three models were compared. Model 1A assumed that process error was negligible. This model is comparable to the models used in previous assessments, with the following two exceptions. First, in previous models, catchability to the fishery was not adjusted for changes in fish length-at-age or changes in mesh size. Second, the experimental net and RV survey indices were not available in previous assessments. Parameters for model 1A were abundance at ages 3 to 11+ at the start of 2015, $\log_e$ catchability at age to the fishery (*a* = ages 4 to 10), to the experimental nets (ages 3 to 10), to the acoustic survey (ages 2 to 3) and to the RV survey (ages 4 to 6), and the standard deviations of observation error at age for the fishery cpue, the experimental nets, the acoustic survey and the RV survey. The instantaneous rate of natural mortality (*M*) was assumed to be constant at 0.2 for all ages (the assumption used in previous assessments).

In recent assessment reviews for NAFO 4T herring, fish harvesters have reported that their fishing protocols have changed over time including the timing of fishing relative to the tidal cycle, and the searching procedures. It has not been possible to incorporate these changes into the effort standardization when estimating CPUE. Other components of effort (e.g., number of net hauls per night) are based on average values from an end-of-season telephone survey and are not likely to be fully accounted for in the effort standardization. In order to investigate possible effects of changes in fishing effort that are not accounted for in the effort standardization, Model 1B allowed for process error in catchability to the fishery. Catchability to the fishery was modelled as logistic selectivity at age (S_a) times fully recruited *q*:

$$q'_a = (p_1\, Sr_{1,a,t} + (1 - p_1)Sr_{2,a,t})S_a q \qquad (2)$$

q was allowed to vary over time following a random walk:

$$q_{1986} = q_1 \text{ and } q_t = q_{t-1}e^{Qdev_t} \text{ if } t>1986 \qquad (3)$$

q_{1986} was freely estimated whereas values of $Qdev_t$ were assumed to be normally distributed with a mean of 0 and a standard deviation of 0.1. The objective function included a term penalizing departures of $Qdev_t$ from 0:

$$0.5 \cdot (\textstyle\sum_t Qdev_t^2)/\sigma^2 \text{ where } \sigma = 0.1 \qquad (4)$$

Similar to Model 1A, *M* was assumed to be constant at 0.2 in Model 1B. Catchability at age to the experimental nets was assumed to be constant over time because effort was standardized and effects of size-dependent changes in q are accounted for in the index, which is based on catches in a range of mesh sizes (Surette et al. 2016).

In Model 1C, fishery catchability was assumed to be constant over time but process error was allowed in *M*. *M* was allowed to differ between ages groups 2 to 5 years and 6+ years. For each age group, the prior for initial *M* in 1978 had a mean of 0.2 and a standard deviation of 0.05. After 1978, *M* of each age group followed independent random walks (like in equation 3). The *M* deviations were assumed to be normally distributed with a mean of 0 and a standard deviation of 0.05. The objective function included four penalty terms associated with the random walks in *M*, terms for the departures of the $Mdev_t$ values from 0 for each age group, and terms for the departures of initial *M* of each age group from its prior.

Multiple-population models

In these models, fall spawners using the North, Middle and South spawning grounds were treated as three separate populations. Separate fishery catches at age, CPUE indices from the gillnet fishery and indices from the experimental nets were derived for each of the three regions. The acoustic and RV survey indices were considered abundance indices for the sum of the three populations. Models were similar to the single-population models, except that population dynamics were independent for each of the three populations. Initial trials assumed that catchability was the same among populations for the gillnet fishery and for the experimental nets. However, it was clear from the results that these catchabilities differed between regions for both indices, and this was incorporated in models. Unlike in the single-population models, it was not possible to reliably estimate abundance at age 2 in 2013, at ages 2 and 3 in 2014 and at ages 2, 3 and 4 in 2015. This was because the only indices available for age 2 in 2013 and ages 2 and 3 in 2014 were from the acoustic index, an index for the three populations combined. In the future, it may be possible to estimate these ages in these years if the experimental net index is available in the most recent year. At the time of the assessment framework meeting the values of this index for 2014 were not available.

As in the single-population models, three basic models were examined:

- Model 2A, assuming negligible process error;
- Model 2B, allowing process error in fully-recruited *q* to the gillnet fishery; and
- Model 2C, allowing process error in *M*.

Variants of models 2B and 2C included:

- Model 2Ba and 2Ca, process error was assumed to be common among the three populations; and
- Model 2Bb and 2Cb, process error was assumed to be independent among the three populations.

RESULTS

Single-population models

Residuals between observed and predicted values were similar between models for the experimental nets, acoustic survey and RV survey, both in terms of the patterns over time and age and the sum of squared residuals (Fig. 2). Residual patterns were not extreme for these indices. However, the fishery CPUE index displayed an extreme residual pattern in Model 1A (no process error). Residuals were almost all negative prior to 1996 and all positive since then (Fig. 2a). The 2014 Model showed a similar extreme pattern in residuals (LeBlanc et al. 2014). This pattern was greatly improved in Model 1B (process error in fishery *q*), along with a 45% reduction in the sum of squared residuals. Model 1C (process error in *M*) showed a lesser improvement in residuals for the fishery CPUE index. Although substantially reduced, the tendency for residuals to be negative prior to 1996 and positive since then persisted, and the reduction in sum of squared residuals was not as great (28%).

Both Model 1B and Model 1C indicated a non-stationarity in the data beginning in about 1995. In Model 1B, fully-recruited *q* to the fishery began to increase in about 1995, reaching a level over three times higher than the 1986-1994 level by 2014 (Fig. 3). In Model 1C, there was no change over time in estimated *M* for ages 2-5, but estimated *M* for ages 6+ increased threefold between 1990 (0.189) and 2010 (0.596) (Fig. 4).

In Models 1A and 1C, catchability at age (q_a' in equation 2) decreased over time for ages recruiting to the gillnet fishery (Fig. 5). This reflected decreasing length at age, and occurred despite increases in the proportion of small ($2^5/_8$") mesh nets in the fishery. In Model 1B, this effect was opposed by the increasing trend in fully-recruited *q* after 1995, resulting in increasing *q* for the older ages.

The temporal trend in estimated spawning stock biomass (SSB) was similar between Model 1A, Model 1B, and Model 1 in 2014 (Fig. 6). Estimated SSB since 2011 was higher in Model 1A than in Model 1B due to the lower catchability estimated for Model 1A. Estimated SSB after 1995 was much higher in Model 1C than in the other models, reflecting the high 6+ *M* estimated in this period in Model 1C.

The estimated instantaneous rate of fishing mortality (*F*) for ages 5 to 10 diverged between Model 1C and the other models beginning about 1995 and between Models 1A and 1B beginning in about 2009 (Fig. 7). Recent estimates of *F* were lowest in Model 1C, reflecting the high *M* and thus high population size, and greatest in Model 1B, reflecting the higher *q* and thus lower population size.

Temporal patterns in recruitment were similar among models, except that recent levels of recruitment were higher in Model 1C, reflecting the recent high *M* in this model (Fig. 8). All models estimated the 2010 year-class to be the lowest on record and the 2012 year-class to be the highest on record. The estimate for the 2012 year-class is based entirely on the 2014 acoustic index of age-2 abundance, and is highly uncertain.

There were strong retrospective patterns in the estimates of fully-recruited gillnet fishery *q* in Model 1B (Fig. 9) and of 6+ *M* in Model 1C (Fig. 10). Retrospective patterns in SSB and *F* were most severe for models 1A and 1C and somewhat less severe for Model 1B (Fig. 11).

Multiple-population models

For Model 2A (no process error), residuals from the gillnet fishery CPUE indices showed patterns similar to the pattern observed in the single-population model. Residuals were mostly negative prior to 1995 and positive since then (Fig. 12). This pattern was not as severe as in the single-population model, particularly in the North population. It was largely eliminated in models with a random walk in *q* (2Ba, 2Bb), particularly in the model with independent random walks between regions (2Bb). Models with random walks in *M* (2Ca, 2Cb) showed only modest improvements in the residual patterns in the fishery CPUE indices.

Differences between models in the residual patterns for the experimental nets were minor (Fig. 13). Residuals from this index showed a fairly strong pattern in the North population, with most residuals negative early in this short series and positive in more recent years. This temporal pattern was evident for all the multiple-population models, but did not occur in the single-population models.

For the acoustic and RV surveys, residual patterns were very similar between all the multi-population models (Fig. 14) and between these models and the single population models.

In Model 2Ba, which allowed a common trend in *q* to the gillnet fishery among populations, the trend was similar to that in the single-population model, with *q* increasing beginning in the mid-1990s (Fig. 15a). However, while the trend was similar, the extent of the increase was considerably less, about two-fold compared to over three-fold in the single-population models. The gillnet fishery *q* in the Middle population was about twice the level in the other populations.

Model 2Bb allowed independent trends in fishery *q* between populations (Fig. 15b). Fishery *q* showed moderate change over time in the North. In the South, *q* began to increase in the mid-1990s, with the increase becoming more sharp in the mid-2000s. The overall increase in the

South was over five-fold. In the Middle population, *q* was relatively low in the early 1990s and high since the late 1990s. Fishery *q* was highest in the Middle population, except since about 2010 when estimated *q* was higher in the South.

Models 2Ca and 2Cb incorporated random walks in *M* which were independent between age groups 2 to 5 and 6+ (Fig. 16). In Model 2Ca, which assumed a common trend in *M* for all populations, estimated *M* of 2 to 5 year old herring remained steady near 0.2 for the entire time series, whereas *M* of 6+ herring increased slightly over time, from 0.1 prior to the mid-1990s to about 0.2 since about 2005 (Fig. 16a). Model 2Cb allowed independent trends between populations, but the estimated *M* differed little between the populations (Fig. 16b, 16c); for all populations, estimated *M* remained near 0.2 for 2 to 5 year-olds and near 0.1 for 6+ fish over the entire time series. Estimated changes in *M* were slight and resulted in minor improvements in model fit compared to changes in *q*. Thus, Models 2Ca and 2Cb are not considered further below.

Estimated catchability at age to the gillnet fishery was considerably greater in the Middle region than in other regions (Fig. 17). In Model 2A, which did not incorporate a random walk in *q*, catchability tended to decline over time in all regions for ages younger than about 9 years. This reflected decreasing herring length-at-age. In Model 2Ba, which incorporated a random walk in *q* common to all populations, catchability at age increased in the mid-1990s for all populations, but declined in recent years. In Model 2Bb, which incorporated independent random walks in *q* in each population, patterns in catchability differed between populations. In the North population, catchability increased in the early to mid-1990s for older ages and decreased for all ages starting in about 2005. In the Middle population, catchability increased in the mid to late 1990s and then showed a decreasing trend beginning in about 2000. In the South population, catchability of the older fish increased progressively over time beginning in the mid-1990s whereas catchability of younger fish remained roughly stable. These patterns in catchability at age appear to reflect the opposing effects of declining herring length-at-age and increasing fishing efficiency in the gillnet fishery.

As in the gillnet fishery, catchability to the experimental nets was estimated to be considerably greater for the Middle population than for the other populations (Fig. 18). Estimated catchability at age 10 in the Middle population was unusually high in all three models.

Although the long-term trends in SSB were similar among models, recent estimates of SSB were highest from Model 2Bb and lowest from Model 2Ba (Fig. 19). Average total SSB over the last 5 years was 17% higher in Model 2A and 21% higher in Model 2Bb compared to Model 2Ba. These differences are primarily due to differences in the North population. North SSB was 49% higher in Model 2Bb and 26% higher in Model 2A compared to Model 2Ba. In contrast, South SSB was 20% lower in Model 2Bb than in Model 2A and 15% lower than in Model 2Ba. Differences in Middle region SSB were slight between models. Estimates of *F* averaged over ages 5 to 10 years ($F_{5\text{-}10}$) were similar between Models 2A and 2Ba, except that recent estimates for the North population averaged about 30% higher for Model 2Ba. Recent estimates of $F_{5\text{-}10}$ diverged most for Model 2Bb, with estimates of North and South *F* averaging 65% and 128% respectively of the Model 2Ba estimates.

Like in the single-population models, estimates of the strength of the 2010 year-class by all three models were the weakest on record for the North population, the South population and all three populations combined (Fig. 20). For the Middle population, the 2010 year-class was estimated to be weak, but not as weak as the 2008 year-class and some year-classes in the 1980s and late 1970s. No estimates of the strengths of the 2011 and 2012 year-classes are available for the multiple-population models.

Retrospective patterns in the estimates of fishery *q*, SSB and $F_{5\text{-}10}$ are shown in Figures 21 to 23. Overall, retrospective patterns in SSB were worst for Model 2A and best for Model 2Bb.

Retrospective patterns in F_{5-10} also tended to be worst for Model 2A and best for either Model 2Ba or Model 2Bb, depending on the population.

DISCUSSION

The severe residual pattern in Model 1A indicates a non-stationarity in the dynamics of this stock or in its fishery beginning in the early to mid-1990s. This non-stationarity could reflect an increasing trend in catchability to the gillnet fishery (Model 1B) or increasing natural mortality of herring 6 years and older (Model 1C).

Of the single-population models examined here, Model 1B provided the best fit to the data, with little blocking in its residuals with respect to age and year and with the least severe retrospective pattern. This model accounted for non-stationarity by allowing catchability to the fishery to vary over time. An increasing trend in catchability was estimated, beginning in the mid-1990s. Catchability to commercial fisheries is expected to increase over time as technological improvements are implemented. Herring harvesters have reported changes in fishing procedures which have not been incorporated in effort standardization. Increases in fishing efficiency resulting from these changes in fishing procedures may underlie the estimated increase in catchability.

Model 1C accounted for non-stationarity by allowing *M* to vary. This model estimated a large increase in 6+ *M* between the early 1990s and about 2009. The estimated trend in *M* is not consistent with estimates of consumption of herring by fish, seabirds and marine mammals (Benoît and Rail 2016). Estimated consumption increased sharply in the early 1980s as cod biomass increased and decreased sharply in the late 1980s as cod biomass collapsed. Since then, Benoît and Rail (2016) estimated that declining consumption by demersal fishes (cod and white hake) has been offset by increasing consumption by gannets and grey seals. Tuna abundance increased sharply in the southern Gulf between 2003 and 2012, resulting in an increasing trend in the estimated consumption of herring, though the magnitude of this increase is uncertain due to high uncertainty in absolute tuna abundance. Given the trend in herring biomass estimated by Model 1C (Fig. 6), these consumption estimates imply changes in *M* that are quite different from those estimated by Model 1C. This model also did not fit the data as well as Model 1B, showing substantial blocking of residuals and a more severe retrospective pattern.

Model 1B is recommended as the preferred single-population VPA model based on its superior fit to the data (e.g., no severe residual patterns) and the plausibility of non-stationary catchability to the fishery. Implementation of a Statistical Catch-at-age version of this model is also recommended as a possible solution to the retrospective problem.

Splitting the fall spawning component into three separate populations improved the residual patterns for the gillnet fishery CPUE index. Nonetheless, a tendency for residuals prior to 1996 to be negative and those since then to be positive persisted within each of the three populations. Unlike in the single-population model, allowing process error in *M* did not result in substantial improvements in this residual pattern. Moreover, estimated changes in *M* were slight, even when changes were permitted to be independent between populations. On the other hand, allowing process error in fishery *q* resulted in substantial improvements in the residual pattern as well as the best overall fit to the data (i.e., the greatest reductions in sum of squared residuals). The improvement was greatest when *q* was allowed to vary independently between populations (Model 2Bb). It is plausible that *q* may vary independently between populations due to regional variation in the fisheries and trends in population abundance. For example, catchability to fisheries may be density-dependent, increasing as population size decreases (Winters and Wheeler 1985). Model 2Bb estimated that SSB of the South population has declined sharply since about 2005. Thus, the sharp rise in fishery *q* in this area since 2005 may partly reflect increasing *q* due to decreasing population abundance. Model 2Bb is recommended as the preferred multiple-population model.

PART 2: STATUS BASED ON THE PREFERRED MODEL

DATA UPDATES

A number of data updates became available after fitting and comparing the models above. The fishery catch-at-age was updated to include winter catches in NAFO subdivision 4Vn. These catches, averaging 14% of the annual totals, had been omitted from the 1978 to 1997 data. In addition, revised fishery CPUE indices and relative selectivity matrices (which account for effects of changes in fish length-at-age) became available during the assessment framework meeting as a result of issues identified during the review.

The main change to the fishery catch-at-age (CAA) was the addition of the winter catches in 4Vn, which had been excluded in the original 1978 to 1997 CAA. These catches were mostly added to the CAA for the North region (Fig. 24; for details see Benoît et al. 2016). The update also corrected a problem in 1994, when some mobile gear catches of North fish had been incorrectly assigned to the Middle CAA (indicated by the filled circles in Fig. 24). The update to the CPUE indices revised the age-aggregated trends for the North and Middle populations (Fig. 25). In the South, the revised index was greater than the original index by a factor that varied little over time. The revision to the relative selectivity matrices tended to increase selectivity for young fish and decrease it for older fish (Fig. 26).

The preferred model (Model 2Bb) was fitted to these updated data and results were compared to those from the initial model fit. Changes in the estimates of fully-recruited catchability (*q*) to the gillnet fishery were minor for the North and Middle regions (Fig. 27). There was a substantial increase in estimated *q* for the South region but there was little change in its trend over time. There was negligible change to the estimates of SSB, except for an increase in the estimates for the North population in the 1980s and early 1990s (Fig. 28). This increase, averaging 14% from 1980 to 1993, resulted from the increased catch attributed to the North in the updated data (Fig. 24). There was also a 5% increase in SSB for the North in 2012 to 2014. All changes to the SSB estimates for the Middle and South populations were negligible, and most are not discernible in Figure 28. Changes in estimated fishing mortality were also negligible, except in 1981 and 1983 for the Middle population (Fig. 29). In summary, these changes associated with the updated data do not result in any substantial changes to conclusions about stock status in relation to SSB and F.

SENSITIVITY ANALYSES

The value chosen for the standard deviation in process error (e.g., σ in equation 4) is meant to strike a reasonable compromise between an undue influence of noise in the input data when the standard deviation is set too high and a poor fit to the data when process error is too severely constrained. Results from the preferred model were compared with σ set at 0.02, 0.05 or 0.10. With σ set at 0.02, blocking in the residuals from the CPUE index remained severe for the Middle and South populations, with most residuals negative prior to 1995 or 1996 and positive since then (Fig. 30). Increasing σ to 0.05 resulted in a substantial reduction in the sum of squared residuals, particularly for the South population, but the residual pattern remained severe for the Middle population. Increasing σ further to 0.10 resulted in a further reduction in the sum of squared residuals, though this reduction was modest except for the Middle population. The residual pattern was also less severe for the Middle population with σ set at 0.10. These results suggest that σ must be increased to 0.10 to provide a good fit to the CPUE data with acceptable residual patterns, though it could be argued that a lower value between 0.05 and 0.10 may be adequate.

Estimated trends in *q* were negligible in all regions with σ set at 0.02 (Fig. 31), consistent with the negligible improvement in model fit at this level of σ. Trends in *q* remained comparatively minor at all levels of σ in the North population. In the Middle population, there was strong variation in *q* with σ set at 0.1, and intermediate variation with σ at 0.05. In the South population, the estimated change in *q* was much greater with σ at 0.10 than at the lower levels. The estimated trends in q were fairly smooth even at σ = 0.1, suggesting that the influence of noise in the data on the estimated trend was not undue even at this level of process error. Estimates of fishery *q* and their uncertainty are compared among populations in Figure 32, based on the preferred model fit to the updated data with σ = 0.1.

Effects of the choice of σ on estimates of SSB and $F_{5\text{-}10}$ were minor in most cases (Figs. 33 and 34). For both variables, the level chosen for σ had a negligible effect on estimates for the Middle population. For the North population, there were negligible differences in estimates of SSB and $F_{5\text{-}10}$ between σ = 0.02 and σ = 0.05, but estimates were somewhat higher since 2009 for SSB and slightly lower for $F_{5\text{-}10}$ in recent years with σ = 0.1. For the South population, estimates of SSB and $F_{5\text{-}10}$ differed very little between σ = 0.02 and σ = 0.05 but were slightly higher for SSB and lower for $F_{5\text{-}10}$ in recent years with σ = 0.1. In conclusion, estimates of SSB and $F_{5\text{-}10}$ were not very sensitive to the value chosen for σ (within the range examined), and conclusions about stock status were in general the same at all three levels.

STOCK STATUS

Estimated SSB has been at a high level since 2009 for the North population (Fig. 35; Table 1). For the South population, estimated SSB was at a high level from the mid-1980s to the mid-2000s, but has declined sharply in recent years and is now approaching the lowest levels on record (Fig. 35; Table 2). SSB of the Middle population increased from 1980 to the late 2000s but has declined in recent years to an intermediate level (Fig. 35; Table 3). Summed over all three putative populations, estimated SSB was firmly in the healthy zone in 2009 (Fig. 35; Table 4) but has declined steadily since then and is now estimated to be at the border between the healthy and cautious zones (the upper stock reference or USR). The probability that total SSB was below the USR at the beginning of 2014 is estimated to be 63%.

Estimated adult (ages 4+) abundance increased sharply in the early 1980s in the North population and the mid-1980s in the South population (Fig. 36; Tables 5 and 7). Adult abundance increased gradually over the 1978 to 2014 period in the Middle population (Fig. 36; Table 6). In the South population adult abundance remained high from the late 1980s to 2010 but has declined sharply since then. In the North population, estimated adult abundance declined in the early 1990s to an intermediate level where it remained until the mid-2000s. It began to increase in 2007 and has been at a high level since 2009. Summed over all three putative populations, adult abundance has been at a high level since the early to mid-1980s (Table 8). Total adult abundance is estimated to have been at the highest level on record in 2011 but has declined since then. For most of the time series estimated adult abundance was highest in the North and lowest in the Middle population. However, with the recent sharp decline in the South population, estimated adult abundance was lowest in this population for the first time in 2014.

Estimated abundance-weighted average *F* over ages 5-10 was high in the late 1970s for the North population, the late 1970s and early 1980s for the Middle population, 1980 for the South population and 1978 to 1980 for the abundance-weighted average over all three populations (Fig. 37; Tables 9 to 12). Estimated $F_{5\text{-}10}$ was at a relatively low level between the early or mid-

1980s and the early 1990s but then increased to an intermediate level. In recent years, estimated $F_{5\text{-}10}$ has been declining for the North population, stable for the Middle population and increasing for the South population.

The management goal for this stock is to restrict fishing mortality to below F0.1, which for fall-spawning herring in the southern Gulf is estimated to be 0.32 for abundance averaged *F* over ages 5 to 10 (LeBlanc 2016). Average ages 5-10 *F* for the total fall-spawning component is estimated to have been above this level in all but one year from 1994 to 2008 but then declined below this level (Fig. 37). The probability that *F* was above this level in 2014 is estimated to be only 1.5%.

Estimated recruit abundance was relatively high in 2006 to 2009 (2004 to 2007 year-classes) in the North population and in 2006 to 2008 in the Middle and South populations (Fig. 38). In contrast, the 2010 year-class, the most recent year-class for which there is an estimate (observed in 2012), is estimated to be the weakest on record in the North and South populations, and summed over all populations.

PROJECTIONS AND RISK

The populations were projected forward to obtain estimates of SSB at the beginning of 2015. This required predictions of abundance at age-2 in 2013 and age-3 in 2014. Predictions were obtained using the estimates of SSB in 2011 and 2012 and recruitment rates (the number of age-2 recruits divided by the SSB that produced them) randomly sampled from the five most recent estimates of recruitment rate (the rates for the 2006 to 2010 year-classes). Projections were based on the MCMC samples (200,000 samples with each 40^{th} sample saved), which propagated uncertainty in the model estimates into the projections. Summed over all populations, estimated SSB at the beginning of 2015 was 182,000 t, just above the USR (Fig. 39). However, uncertainty was high, with a 95% confidence interval of 109,000 to 295,000 t and a 47% chance that SSB was below the USR.

The populations were projected further to the start of 2016 assuming various catch levels in 2015. The total annual catch of the three populations was varied from 10,000 t to 50,000 t in steps of 2,000 t. Total catch was divided among populations based on the observed catch proportions in the last five years, using a randomly-selected year for each MCMC iteration. For each population and iteration, a partial recruitment vector was randomly selected from the five most recent estimates (2008 to 2012) and a vector of catch weights-at-age was randomly selected from the four most recent years (2011 to 2014). Fewer years were used for weights-at-age because of the declining trend in weight-at-age (Benoît et al. 2016). The abundance of age-2 recruits was predicted as described above. Estimates of SSB and $F_{5\text{-}10}$ are shown in Figures 40 and 41 for catches of 29,000 and 30,000 t in 2015, respectively. Predicted SSB in 2016 is very uncertain in this example, with a 95% confidence interval spanning from 97,000 to 350,000 t. This stems mostly from uncertainty in SSB of the North population, which is estimated to currently have much greater SSB than both the other populations (Fig. 40). With a catch of 29,000 t in 2015, the estimated probability that total SSB will be less than the USR at the start of 2016 is 39%. With a total catch of 30,000 t in 2015, $F_{5\text{-}10}$ in 2015 is expected to remain low for the North population, increase above the 0.32 level for the Middle population and rise to a very high level in the South population (Fig. 41), assuming that the catch is distributed among populations in the proportions observed in recent years. Under these conditions, the probability that the average $F_{5\text{-}10}$ over all populations equals or exceeds the 0.32 limit is estimated to be 56%.

Under the conditions of these projections, the estimated probabilities that $F_{5\text{-}10}$ will equal or exceed 0.32 in 2015 and that total SSB will be below the USR at the start of 2016 are shown in Figures 42 and 43 and Table 13 for catch levels of 10,000 to 50,000 t in 2015. The probability that the weighted average $F_{5\text{-}10}$ of the three populations will exceed the target maximum level of 0.32 in 2015 is estimated to be 38% with a total catch of 28,000 t, 56% with a catch of 30,000 t, and 95% with a catch of 38,000 t (Table 13). At these levels of catch the estimated probabilities that SSB will be below the USR at the beginning of 2016 are 38.5%, 39.5% and 43.1%, respectively.

The uncertainty in estimated SSB in these projections is very high (Figs. 39 and 40). This is in part due to high uncertainty in recruitment levels in the near future (Fig. 44). The recruitment rates used in the projections were sampled from the most recent five values, which varied between a high value for the 2006 year-class (particularly in the North population) to the lowest values observed (the 2011 year-class). Estimated recruitment rates show a declining trend from the 2006 to the 2011 year-classes. If the recent low values persist for the projected year-classes, then these projections are overly optimistic. Estimates of recruitment for the 2011 and 2012 year-classes are available only from the single-population model. Based on this model, year-class strength remained very low in 2011 but was at the highest level observed in 2012. However, these estimates, particularly the 2012 estimate, are very uncertain (Fig. 8). If the 2012 year-class is indeed very strong, then projections may be overly pessimistic.

CONCLUSIONS

PART 1: CHOICE POPULATION MODEL

The model historically used for the fall spawning component of herring in the southern Gulf of St. Lawrence treats this component as a single population. This model assumes that population dynamics parameters (e.g., natural mortality) and observation parameters (e.g., catchability) are stationary over time. However, a severe pattern in the residuals from the gillnet fishery CPUE index indicates a non-stationarity that is not accounted for in this model. This problem can be addressed by allowing process error in fully-recruited *q* to the gillnet fishery. Estimated *q* showed a strong increasing trend beginning in 1995. A model allowing process error in *M* does not perform as well in terms of residual patterns and fit to the data. Furthermore, the estimated trend in *M* is not consistent with the trend expected from estimated temporal variation in consumption of herring by predators.

There is a desire for finer scale assessment of southern Gulf herring for management purposes. Models treating fall spawners as three populations were examined. The populations corresponded to fall spawners using the North, Middle and South spawning grounds. Residual patterns were improved but the tendency for residuals to be negative early and positive late in the time series persisted. Allowing process error in *M* did little to improve residual patterns. The greatest improvement in model fit and reduction in residual patterns occurred using a three-population model with process error in *q*, allowing *q* to vary independently among populations. This model was chosen as the preferred model for providing advice. Estimated fishery *q* varied little over time in the North but increased over time in the South. Estimated *q* in the Middle region resembled that in the South until the late 2000s, when it remained stable at a level below that in the South. Implementation of a Statistical Catch-at-Age version of this model is recommended as a possible solution to the retrospective problem.

PART 2: STATUS IN 2014

Based on the preferred multi-population model, status in 2014 varied between populations. Estimated SSB in 2014 was high for the North population. Estimated SSB of the South population has been declining since 2009 and is now approaching record low levels, with SSB in 2014 estimated to be 20% of the level in the North population. In the Middle population, estimated SSB has shown an increasing trend since 1980, with SSB in 2014 estimated to be

20% of the level in the North. Populations were projected forward to estimate status at the beginning of 2015 and 2016. Projections were very uncertain due to uncertainties in the abundance of age-2 recruits in 2013 to 2015, which have not yet been observed. Summing over all three populations, projected total SSB at the beginning of 2015 was estimated to be 182,000 t, with a 47% chance of being below the USR of 172,000 t. A management goal for this stock is to limit *F* for ages 5-10 years to levels below 0.32. Under the conditions of these projections, the probability of exceeding this limit in 2015 is estimated to be 38%, 56% or 95% with catches of 28,000, 30,000 or 38,000 t, respectively.

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TABLES

Table 1. Estimated beginning-of-year biomass (t) at age and for ages 4+ (SSB) of fall-spawning herring in the North population of the southern Gulf of St. Lawrence.

	Age (years)										
Year	2	3	4	5	6	7	8	9	10	11+	SSB
1978	5370	6416	5638	7379	1841	1997	5927	653	248	7216	30899
1979	27859	7952	7789	2232	2235	732	990	1196	243	1366	16783
1980	15411	26969	7481	6089	653	818	262	491	268	298	16360
1981	27206	22035	27830	6628	5141	377	202	76	248	149	40650
1982	28313	34615	26749	28454	6307	5010	287	91	47	280	67226
1983	17213	42270	38670	23687	20955	4686	4058	112	16	110	92293
1984	13956	24891	54823	37043	20202	15863	3828	3316	58	58	135192
1985	22330	22978	30445	54669	32043	16847	12690	3067	2835	17	152614
1986	30896	35671	29709	30004	45933	25599	12767	8673	1283	2023	155991
1987	15515	37688	47856	26472	24950	33020	16372	7944	5565	2097	164276
1988	13211	20431	38422	43824	20680	18136	21841	9632	4437	4744	161716
1989	46621	19327	24412	31803	33150	15378	12341	15197	6394	5162	143836
1990	32633	69965	24970	21200	22627	22199	9590	8324	9956	6951	125815
1991	8455	35798	83844	20860	14621	13553	12002	5018	4335	9874	164109
1992	13722	10429	38842	70228	15519	10694	8354	6928	3098	8691	162354
1993	6284	20346	11704	37523	50890	10099	6949	4606	3408	4941	130120
1994	17631	9088	26101	11658	28200	36637	7285	4916	2712	4730	122239
1995	11072	19702	11600	25306	8115	16310	18203	3650	2024	3179	88387
1996	12536	16762	24176	11165	15088	3426	5725	5993	1126	1369	68067
1997	26055	16824	22156	23110	6782	7090	1422	2186	2126	894	65764
1998	14844	33442	20259	21049	13463	3585	3537	702	805	1244	64644
1999	11650	20740	42194	18372	13645	6201	1548	1195	350	418	83924
2000	10895	17396	26375	40500	10280	4728	2494	569	534	284	85764
2001	10626	15047	23035	23655	22992	4958	2254	1067	234	338	78533
2002	28913	16816	19384	19905	14602	12807	3038	1313	692	363	72103
2003	20613	39324	21356	15273	11689	8110	8033	1765	871	547	67643
2004	12521	27161	47596	16953	7033	5466	3405	2242	308	212	83216
2005	8537	16011	31401	42922	11073	3834	3294	1785	1053	121	95482
2006	26065	11809	19751	30474	26287	4527	1269	1643	724	365	85040
2007	47527	34347	14230	18838	20008	13537	2271	585	532	359	70361
2008	28750	40646	39613	11436	11626	8201	5117	617	241	353	77204
2009	47361	45510	74100	40883	10842	9055	5538	1694	155	129	142396
2010	22284	49770	39471	52191	25610	5897	4505	2772	923	104	131473
2011	23357	23457	52283	37157	39414	16215	2999	2429	1258	355	152110
2012	2191	21837	23391	52149	32946	28117	8642	1823	1281	458	148807
2013	na	2135	25527	25256	47278	25752	18517	4826	1004	560	148720
2014	na	na	2336	26449	23294	36710	18102	13721	3574	1316	125502
2015	na	na	na	2296	25300	18258	26269	13305	9636	4465	na

Table 2. Estimated beginning-of-year biomass (t) at age and for ages 4+ (SSB) of fall-spawning herring in the South population of the southern Gulf of St. Lawrence.

	Age (years)										
Year	2	3	4	5	6	7	8	9	10	11+	SSB
1978	3862	10266	6720	3727	1491	1860	2145	312	434	3523	20213
1979	13009	5569	10512	5315	2758	1040	1350	927	88	1468	23457
1980	8418	12927	6236	9937	3995	1928	795	1012	648	595	25147
1981	11508	12136	10233	3867	4083	1135	317	229	106	25	19996
1982	16851	14500	13012	7612	3242	3697	796	177	112	64	28712
1983	9199	25228	16953	10907	5968	1840	2318	363	28	105	38482
1984	15671	13302	32647	15445	8429	4308	1302	1532	143	33	63839
1985	17251	25852	16343	30715	13162	6424	3136	907	1200	108	71995
1986	15795	27587	33848	15976	24753	10414	4794	1983	589	954	93311
1987	8179	19217	37160	28648	13576	18665	8064	3563	1496	1167	112339
1988	5234	10880	20508	36281	23492	10395	12069	4791	1485	1031	110052
1989	17234	7830	13190	18139	29198	18332	7670	8112	3013	1496	99151
1990	17581	25900	10211	12963	16098	23801	14710	6015	6069	3469	93336
1991	4483	19291	31334	8581	9747	11843	9285	9160	3513	5325	88787
1992	8762	5531	21381	28870	7087	7935	9518	6328	6877	6234	94231
1993	3214	12994	6240	21549	23743	5619	6344	7286	3901	9631	84313
1994	13605	4663	17066	6625	18702	19738	4627	5368	5927	10647	88700
1995	3524	15203	5970	17399	5699	12852	11781	3361	3514	8589	69164
1996	15696	5333	18785	6293	14536	4396	8060	7024	2065	6566	67726
1997	18038	21109	7171	20270	4904	9591	2400	3638	2870	3171	54015
1998	15074	23168	26101	6807	13192	3668	5804	1636	2105	3046	62358
1999	8900	21065	29382	24771	5293	7947	2157	2598	886	1610	74645
2000	24861	13334	27738	30196	14776	3218	3355	778	920	728	81708
2001	16900	34478	17939	27826	20497	8356	1964	1768	436	732	79517
2002	18734	26850	45918	18762	19942	12455	3484	851	839	465	102717
2003	10300	25392	34054	44903	14445	12535	6544	1665	378	504	115028
2004	10195	13553	30585	31229	28878	10011	6344	2357	527	343	110274
2005	5595	13002	15564	29251	25238	18836	6949	3807	1016	242	100903
2006	18873	7787	16393	16224	24253	17780	8855	4511	1614	474	90103
2007	12706	24901	9506	16451	13800	16323	10242	3787	2378	797	73284
2008	15609	10898	30098	8602	11235	7833	7279	4703	1960	1596	73306
2009	9051	24797	20225	33557	10036	11691	6038	4122	2750	1360	89780
2010	2229	9515	21812	15158	23394	5409	4326	3001	2378	1547	77024
2011	5142	2347	10029	20848	11705	13825	2765	1287	890	1670	63021
2012	577	4827	2348	10064	18034	8580	6636	566	152	525	46904
2013	na	564	5653	2533	9198	13483	4355	2336	96	67	37720
2014	na	na	628	5718	1978	5923	6943	1824	879	19	23913
2015	na	na	na	548	4734	989	2890	2381	595	384	na

Table 3. Estimated beginning-of-year biomass (t) at age and for ages 4+ (SSB) of fall-spawning herring in the Middle population of the southern Gulf of St. Lawrence.

	Age (years)										
Year	2	3	4	5	6	7	8	9	10	11+	SSB
1978	881	1649	2257	2350	694	1297	2291	650	153	4964	14656
1979	4069	1303	2020	1127	1589	413	953	920	519	2860	10401
1980	2040	4045	1449	1332	513	364	100	189	147	150	4244
1981	3612	2940	4448	1270	692	320	247	12	60	168	7216
1982	4621	4596	3477	3546	824	326	160	16	0	71	8420
1983	2051	6917	5383	2966	2813	649	227	89	12	42	12181
1984	2213	2940	7960	3096	1627	925	248	94	5	4	13960
1985	2919	3649	3610	7843	2148	1185	484	103	52	1	15426
1986	4814	4668	4778	3651	7015	1710	895	242	16	29	18335
1987	1404	5880	6321	4350	3099	5574	1139	620	134	9	21247
1988	2574	1867	6283	6401	3617	2335	3972	876	427	10	23921
1989	11223	3853	2120	5133	5188	2531	1704	3007	436	364	20483
1990	9924	16866	5025	1953	4325	4291	1995	1327	2435	558	21909
1991	1739	10889	20468	4534	1373	3346	2854	1500	967	2362	37404
1992	5001	2146	12067	18286	3572	816	2270	1678	793	1944	41426
1993	1239	7417	2424	11579	14068	2741	543	1790	1279	2077	36501
1994	5215	1797	9741	2530	8986	10257	2012	298	1372	2405	37602
1995	2214	5828	2302	10153	2042	6288	6537	1466	151	2836	31775
1996	5441	3352	7228	2429	7536	1062	2531	2850	868	1003	25508
1997	9001	7318	4505	7512	1839	4066	688	1339	1447	1015	22410
1998	6653	11564	9072	3916	4604	1191	2557	404	883	1546	24172
1999	4367	9297	14654	8193	2564	1656	551	1327	137	679	29761
2000	5791	6543	12302	14242	4647	1110	646	128	368	186	33629
2001	6142	8037	8945	11234	8542	2276	355	186	0	293	31832
2002	10513	9788	10865	8730	7484	5444	1270	147	102	163	34204
2003	7173	14301	12481	9853	6118	4817	2993	752	80	116	37209
2004	4689	9452	17545	11151	6078	3966	3231	1561	405	83	44019
2005	2786	5999	11042	16978	8020	3668	2209	1605	606	106	44234
2006	13192	3863	7380	9695	11108	3841	2103	1010	677	241	36055
2007	14486	17420	4741	7318	7572	6543	2083	1147	337	215	29955
2008	8354	12425	21059	4092	5106	3883	2920	814	587	141	38603
2009	6210	13271	22863	21842	4382	4954	3157	1039	393	180	58809
2010	1762	6528	11688	16207	15024	2600	2117	1566	518	295	50014
2011	5714	1855	6886	11185	12231	9615	1135	800	712	225	42788
2012	2692	5364	1856	6881	10007	8139	5000	305	152	132	32473
2013	na	2628	6281	1988	6123	7249	4595	2527	52	12	28827
2014	na	na	2938	6562	1786	4200	4263	2643	1628	0	24020
2015	na	na	na	3011	6151	1092	2365	1903	1849	1355	na

Table 4. Total estimated beginning-of-year biomass (t) at age and for ages 4+ (SSB) of fall-spawning herring of the southern Gulf of St. Lawrence.

	Age (years)										
Year	2	3	4	5	6	7	8	9	10	11+	SSB
1978	10113	18330	14615	13456	4026	5154	10363	1616	835	15704	65768
1979	44936	14825	20321	8673	6582	2185	3293	3043	850	5693	50640
1980	25868	43942	15167	17358	5161	3110	1157	1691	1063	1044	45751
1981	42326	37111	42511	11764	9917	1832	767	316	413	342	67862
1982	49785	53711	43239	39613	10372	9033	1243	284	159	415	104358
1983	28463	74416	61006	37561	29736	7174	6603	563	55	256	142955
1984	31840	41133	95430	55584	30259	21096	5378	4942	206	95	212991
1985	42501	52478	50398	93227	47354	24456	16310	4077	4087	126	240035
1986	51505	67926	68335	49631	77700	37723	18456	10898	1888	3005	267637
1987	25098	62784	91336	59470	41625	57259	25575	12127	7195	3273	297861
1988	21019	33179	65213	86507	47789	30866	37881	15299	6349	5785	295689
1989	75077	31011	39722	55074	67536	36241	21715	26317	9843	7022	263470
1990	60138	112732	40205	36116	43050	50290	26294	15667	18460	10978	241060
1991	14678	65978	135646	33975	25742	28742	24141	15678	8815	17561	290299
1992	27485	18106	72290	117384	26177	19445	20142	14935	10768	16869	298010
1993	10737	40756	20368	70652	88701	18459	13836	13681	8588	16649	250934
1994	36451	15548	52908	20814	55888	66632	13924	10583	10011	17782	248541
1995	16810	40733	19873	52858	15856	35450	36521	8477	5690	14603	189327
1996	33672	25447	50189	19888	37160	8884	16316	15867	4059	8938	161302
1997	53094	45251	33832	50891	13524	20748	4510	7163	6443	5079	142190
1998	36570	68174	55432	31771	31259	8443	11899	2742	3792	5836	151174
1999	24916	51102	86230	51335	21503	15804	4256	5120	1373	2708	188330
2000	41548	37273	66415	84938	29703	9056	6495	1476	1821	1198	201101
2001	33668	57562	49919	62716	52031	15590	4573	3022	670	1363	189883
2002	58160	53454	76166	47397	42028	30705	7792	2311	1633	991	209024
2003	38087	79017	67891	70028	32252	25461	17569	4183	1329	1167	219880
2004	27405	50167	95726	59334	41989	19443	12980	6160	1240	638	237509
2005	16918	35012	58007	89151	44331	26338	12452	7197	2675	468	240619
2006	58130	23459	43523	56393	61648	26147	12228	7163	3014	1080	211198
2007	74718	76668	28477	42607	41380	36403	14596	5518	3248	1371	173600
2008	52714	63969	90769	24130	27968	19917	15317	6134	2788	2090	189113
2009	62623	83577	117188	96282	25260	25700	14733	6856	3299	1669	290986
2010	26275	65813	72971	83556	64028	13906	10948	7339	3819	1945	258511
2011	34213	27658	69198	69190	63349	39655	6899	4516	2861	2250	257918
2012	5461	32028	27595	69094	60987	44836	20278	2694	1584	1116	228184
2013	na	5327	37460	29777	62600	46484	27468	9688	1152	639	215267
2014	na	na	5902	38729	27058	46834	29309	18187	6082	1335	173435
2015	na	na	na	5856	36185	20340	31524	17588	12079	6205	na

Table 5. Estimated beginning-of-year abundance (thousands) at age of fall-spawning herring in the North population of the southern Gulf of St. Lawrence.

	Age (years)										
Year	2	3	4	5	6	7	8	9	10	11+	4+
1978	72572	55308	28765	31005	6742	7369	18237	2042	846	18551	113557
1979	248738	59346	41431	9111	8068	2480	3065	3350	693	3903	72100
1980	185673	198304	40439	25160	2463	2754	808	1319	698	755	74398
1981	295718	149900	144198	27615	17428	1201	586	216	577	352	192175
1982	404469	242063	118886	106172	20021	13726	756	231	124	618	260535
1983	223551	330235	188632	89050	70083	14071	10822	302	42	263	373264
1984	208304	183020	270066	145839	69424	49110	10574	8481	152	140	553786
1985	348914	170204	148513	210267	108990	51364	35847	7824	6766	40	569611
1986	257463	285367	137542	116748	153621	75962	34979	22944	3130	4715	549641
1987	176312	210547	231187	101426	84008	100671	45226	20687	14342	4946	602493
1988	188727	142873	162806	165375	68932	55633	61350	25414	11232	11830	562573
1989	638641	150995	114609	117788	110132	46458	35060	40743	16146	12652	493588
1990	336427	522127	122400	80917	74677	67065	27089	22436	25593	16829	437006
1991	112729	275366	421327	84797	51666	41832	34589	13786	11590	24686	684273
1992	258911	92294	220692	302705	59232	36373	25316	20141	8728	23363	696549
1993	110243	211938	75025	170561	202750	36859	22935	13789	10111	13763	545794
1994	238263	89978	169488	57145	116527	137218	25034	15364	7930	13324	542029
1995	208911	195073	73420	127167	35435	62731	64322	11550	5919	8709	389253
1996	179082	171042	158011	53939	65600	13705	20087	19778	3342	3689	338150
1997	400851	146296	137614	108496	28024	27694	5059	7096	6483	2422	322887
1998	255932	327862	115763	99759	55634	13375	12863	2266	2478	3513	305650
1999	219810	209493	267052	84275	57576	23578	5412	4093	1054	1216	444256
2000	184662	179342	164845	191037	42478	18326	8811	1892	1727	812	429929
2001	189747	150472	142192	111580	97014	19067	8165	3618	754	1073	383463
2002	444812	154273	116771	91726	60840	49068	10890	4406	2253	1115	337069
2003	322084	364112	124886	69739	48504	31433	28688	5984	2705	1663	313601
2004	195642	263700	293805	83104	30313	21777	12565	7758	1017	650	450989
2005	142289	160114	213610	211436	49215	15712	12478	6351	3570	382	512754
2006	420403	115771	128250	162096	115803	18708	4978	5866	2505	1202	439407
2007	565792	343474	93006	96604	91782	57117	9159	2248	1922	1235	353073
2008	429109	461885	267654	67269	62845	41421	24026	2627	919	1278	468038
2009	584705	350074	370499	197503	43025	33913	19779	5987	576	483	671765
2010	289409	478554	281938	277610	124925	25420	18164	10661	3370	372	742460
2011	311429	236943	390171	222496	194157	75419	12547	9487	4803	1286	910366
2012	28092	253914	193316	316052	174319	132628	39104	7471	4946	1710	869546
2013	na	22962.0	207537	157850	250149	126233	84554	21447	4015	2147	853932
2014	na	na	18396	166343	119457	176492	83420	59140	15273	4767	643289
2015	na	na	na	14441	129742	87781	121055	57348	41180	16179	na

Table 6. Estimated beginning-of-year abundance at age (thousands) of fall-spawning herring in the Middle population of the southern Gulf of St. Lawrence.

	Age (years)										
Year	2	3	4	5	6	7	8	9	10	11+	4+
1978	11901	14212	11515	9872	2542	4784	7050	2031	523	12761	51079
1979	36328	9726	10747	4598	5737	1401	2950	2577	1478	8170	37658
1980	24575	29743	7833	5506	1935	1224	307	507	384	381	18078
1981	39261	19999	23046	5290	2345	1018	716	34	139	399	32986
1982	66009	32140	15455	13233	2616	893	420	40	0	156	32813
1983	26630	54040	26260	11152	9407	1949	606	239	32	99	49745
1984	33036	21615	39212	12188	5593	2864	685	241	14	10	60807
1985	45616	27030	17612	30164	7307	3612	1368	262	125	2	60452
1986	40120	37347	22120	14207	23460	5073	2451	641	39	67	68057
1987	15952	32848	30535	16668	10434	16994	3146	1616	345	22	79760
1988	36767	13059	26621	24155	12058	7162	11157	2312	1082	24	84571
1989	153736	30102	9955	19010	17237	7648	4841	8063	1100	891	68744
1990	102306	125869	24631	7454	14273	12963	5636	3578	6260	1351	76145
1991	23193	83761	102854	18432	4852	10326	8226	4120	2585	5904	157299
1992	94363	18989	68563	78821	13632	2777	6879	4879	2233	5225	183007
1993	21736	77258	15536	52633	56048	10003	1793	5358	3796	5785	150952
1994	70475	17796	63253	12404	37134	38414	6914	933	4012	6776	169839
1995	41776	57700	14570	51020	8917	24186	23099	4639	442	7769	134641
1996	77727	34203	47241	11736	32766	4250	8881	9405	2575	2705	119559
1997	138473	63635	27982	35266	7598	15885	2449	4347	4411	2749	100687
1998	114699	113372	51843	18557	19024	4443	9300	1304	2716	4366	111551
1999	82391	93908	92746	37580	10821	6296	1928	4545	412	1973	156302
2000	98158	67456	76885	67181	19203	4303	2283	426	1191	530	172003
2001	109685	80365	55217	52992	36043	8754	1287	632	0	930	155855
2002	161735	89802	65451	40232	31184	20858	4550	492	331	499	163597
2003	112084	132417	72986	44989	25385	18670	10688	2550	249	352	175869
2004	73270	91767	108303	54662	26197	15801	11923	5400	1336	255	223875
2005	46431	59988	75119	83636	35644	15033	8366	5712	2055	334	225899
2006	212770	37876	47921	51569	48936	15870	8249	3606	2342	793	179286
2007	172456	174200	30985	37529	34735	27610	8398	4410	1217	737	145620
2008	124686	141195	142289	24073	27600	19612	13710	3462	2241	512	233499
2009	76670	102084	114313	105516	17388	18554	11274	3671	1462	675	272854
2010	22881	62772	83489	86207	73288	11206	8535	6021	1890	1056	271692
2011	76185	18733	51386	66974	60249	44722	4748	3125	2718	816	234738
2012	34515	62375	15337	41706	52948	38392	22626	1251	585	493	173338
2013	na	28259	51062	12424	32399	35536	20983	11231	209	45	163888
2014	na	na	23130	41273	9158	20193	19647	11391	6958	1	131751
2015	na	na	na	18937	31546	5251	10898	8201	7900	4910	na

Table 7. Estimated beginning-of-year abundance at age (thousands) of fall-spawning herring in the South population of the southern Gulf of St. Lawrence.

	Age (years)										
Year	2	3	4	5	6	7	8	9	10	11+	4+
1978	52189	88501	34284	15658	5462	6865	6599	976	1481	9058	80384
1979	116150	41561	55915	21692	9956	3525	4180	2597	250	4194	102308
1980	101420	95053	33710	41063	15077	6491	2455	2720	1687	1507	104709
1981	125089	82556	53020	16114	13842	3615	920	657	247	59	88473
1982	240733	101400	57832	28404	10291	10129	2095	448	297	141	109637
1983	119472	197096	82700	41004	19961	5525	6180	980	74	251	156675
1984	233891	97811	160821	60809	28966	13338	3598	3918	373	78	271900
1985	269554	191494	79721	118133	44770	19585	8860	2313	2864	249	276495
1986	131629	220692	156702	62163	82785	30903	13135	5247	1436	2223	354594
1987	92943	107356	179516	109762	45709	56905	22277	9279	3856	2752	430056
1988	74774	76087	86900	136911	78305	31886	33901	12640	3760	2572	386876
1989	236078	61174	61925	67180	97004	55384	21790	21749	7609	3668	336308
1990	181250	193284	50055	49476	53128	71906	41553	16214	15602	8400	306335
1991	59779	148395	157457	34881	34443	36551	26757	25164	9393	13312	337958
1992	165316	48943	121485	124441	27050	26991	28841	18395	19371	16759	383334
1993	56387	135349	40002	97950	94593	20506	20936	21813	11576	26829	334205
1994	183848	46166	110815	32478	77282	73924	15902	16775	17330	29991	374497
1995	66485	150522	37786	87432	24887	49430	41628	10636	10275	23531	285604
1996	224224	54414	122780	30402	63202	17582	28281	23182	6129	17699	309256
1997	277503	183554	44541	95163	20263	37467	8542	11813	8750	8593	235131
1998	259888	227141	149150	32259	54513	13685	21105	5277	6476	8606	291070
1999	167920	212778	185964	113627	22332	30218	7542	8898	2670	4681	375931
2000	421376	137461	173363	142432	61058	12472	11857	2586	2976	2079	408821
2001	301783	344780	110734	131257	86484	32139	7116	5994	1400	2323	377446
2002	288220	246328	276612	86461	83093	47719	12489	2856	2734	1427	513391
2003	160942	235113	199149	205036	59939	48584	23370	5646	1174	1532	544428
2004	159296	131587	188796	153085	124476	39883	23409	8156	1739	1052	540596
2005	93244	130016	105875	144093	112167	77198	26322	13549	3443	766	483413
2006	304405	76342	106445	86300	106840	73470	34726	16111	5584	1558	431033
2007	151256	249009	62132	84365	63301	68874	41297	14564	8587	2738	345858
2008	232976	123838	203364	50598	60732	39560	34173	20013	7482	5783	421705
2009	111744	190745	101126	162113	39825	43787	21566	14566	10224	5093	398300
2010	28950	91488	155798	80630	114116	23313	17445	11544	8677	5544	417066
2011	68557	23702	74846	124841	57659	64303	11571	5029	3398	6050	347697
2012	7402	56130	19405	60997	95417	40470	30026	2318	586	1960	251178
2013	na	6061	45955	15830	48666	66093	19887	10380	385	255	207452
2014	na	0	4949	35962	10143	28477	31997	7863	3758	70	123217
2015	na	na	na	3449	24277	4754	13318	10262	2541	1392	na

Table 8. Total estimated beginning-of-year abundance at age (thousands) of fall-spawning herring in the southern Gulf of St. Lawrence.

	Age (years)										
Year	2	3	4	5	6	7	8	9	10	11+	4+
1978	136662	158021	74564	56536	14747	19018	31886	5049	2850	40370	245020
1979	401216	110633	108093	35401	23760	7405	10195	8525	2421	16267	212067
1980	311668	323100	81982	71728	19475	10470	3570	4546	2769	2643	197184
1981	460068	252455	220264	49018	33616	5834	2222	907	963	810	313634
1982	711211	375603	192172	147809	32928	24748	3271	719	422	914	402984
1983	369653	581371	297592	141206	99451	21544	17608	1521	148	613	579685
1984	475231	302446	470099	218836	103983	65312	14856	12640	539	228	886493
1985	664084	388728	245846	358564	161067	74561	46075	10400	9755	291	906558
1986	429212	543406	316364	193118	259866	111938	50565	28832	4605	7004	972293
1987	285207	350751	441238	227856	140151	174570	70649	31582	18543	7719	1112309
1988	300267	232019	276327	326441	159296	94681	106408	40367	16074	14426	1034020
1989	1028455	242271	186489	203978	224374	109490	61691	70554	24855	17210	898640
1990	619983	841280	197086	137847	142078	151934	74278	42228	47454	26581	819486
1991	195701	507522	681638	138109	90961	88709	69572	43070	23569	43902	1179530
1992	518590	160226	410740	505967	99914	66141	61036	43414	30331	45347	1262889
1993	188366	424545	130563	321144	353391	67368	45664	40960	25483	46377	1030950
1994	492586	153940	343556	102027	230942	249557	47850	33072	29271	50091	1086366
1995	317172	403295	125776	265618	69240	136346	129049	26825	16636	40009	809498
1996	481033	259659	328032	96077	161567	35537	57249	52365	12046	24092	766965
1997	816827	393485	210137	238925	55885	81046	16050	23256	19644	13764	658706
1998	630519	668375	316756	150574	129170	31503	43268	8846	11669	16485	708271
1999	470121	516179	545762	235482	90728	60092	14882	17536	4136	7871	976489
2000	704196	384259	415093	400650	122739	35101	22951	4904	5894	3422	1010753
2001	601215	575617	308143	295829	219541	59961	16568	10243	2154	4326	916764
2002	894767	490403	458834	218419	175118	117645	27930	7754	5318	3040	1014058
2003	595110	731642	397021	319764	133828	98686	62746	14180	4128	3547	1033899
2004	428208	487054	590904	290851	180986	77461	47898	21313	4091	1957	1215460
2005	281965	350118	394604	439165	197026	107943	47166	25612	9069	1482	1222067
2006	937578	229989	282616	299965	271579	108047	47952	25583	10430	3554	1049726
2007	889504	766683	186123	218497	189818	153601	58854	21222	11725	4711	844550
2008	786771	726918	613307	141940	151177	100593	71909	26102	10642	7573	1123242
2009	773119	642903	585938	465132	100238	96254	52618	24225	12262	6251	1342919
2010	341240	632814	521225	444447	312329	59939	44144	28226	13937	6972	1431219
2011	456172	279379	516403	414311	312065	184444	28866	17642	10918	8152	1492801
2012	70009	372419	228059	418754	322684	211489	91755	11039	6117	4164	1294061
2013	na	57281	304554	186104	331215	227863	125424	43057	4609	2447	1225272
2014	na	na	46475	243577	138758	225162	135064	78394	25990	4837	898256
2015	na	na	na	36828	185565	97786	145271	75811	51621	22481	na

Table 9. Estimated instantaneous rates of fishing mortality (F) at age and for fully-recruited ages 5 to 10 (F5-10) of fall-spawning herring in the North population of the southern Gulf of St. Lawrence.

	Age (years)										
Year	2	3	4	5	6	7	8	9	10	11+	*F*5-10
1978	0.0012	0.0889	0.9497	1.1463	0.8002	0.6773	1.4944	0.8808	1.4035	1.4035	1.1498
1979	0.0266	0.1836	0.2988	1.1080	0.8747	0.9214	0.6429	1.3685	1.6056	1.6056	1.0126
1980	0.0140	0.1186	0.1814	0.1672	0.5180	1.3475	1.1175	0.6262	1.2173	1.2173	0.3545
1981	0.0002	0.0318	0.1061	0.1216	0.0388	0.2629	0.7303	0.3544	0.2092	0.2092	0.1044
1982	0.0028	0.0494	0.0890	0.2154	0.1527	0.0378	0.7191	1.4970	0.8361	0.8361	0.1945
1983	0.0000	0.0011	0.0573	0.0490	0.1556	0.0857	0.0437	0.4822	0.5810	0.5810	0.0928
1984	0.0020	0.0089	0.0503	0.0912	0.1013	0.1148	0.1011	0.0259	1.7879	1.7879	0.0971
1985	0.0010	0.0131	0.0407	0.1139	0.1610	0.1842	0.2462	0.7161	0.1670	0.1670	0.1580
1986	0.0012	0.0106	0.1046	0.1291	0.2226	0.3186	0.3252	0.2699	0.2614	0.2614	0.2255
1987	0.0103	0.0571	0.1350	0.1862	0.2121	0.2953	0.3764	0.4107	0.2888	0.2888	0.2623
1988	0.0231	0.0204	0.1237	0.2065	0.1946	0.2617	0.2093	0.2536	0.4004	0.4004	0.2215
1989	0.0014	0.0100	0.1481	0.2557	0.2960	0.3394	0.2464	0.2650	0.3372	0.3372	0.2822
1990	0.0003	0.0145	0.1670	0.2486	0.3795	0.4621	0.4755	0.4605	0.3414	0.3414	0.3741
1991	0.0000	0.0213	0.1307	0.1588	0.1510	0.3022	0.3408	0.2571	0.2400	0.2400	0.2183
1992	0.0002	0.0072	0.0577	0.2008	0.2743	0.2612	0.4075	0.4891	0.6466	0.6466	0.2483
1993	0.0031	0.0235	0.0722	0.1810	0.1904	0.1869	0.2007	0.3533	0.3833	0.3833	0.1963
1994	0.0000	0.0034	0.0873	0.2779	0.4193	0.5577	0.5736	0.7538	0.6922	0.6922	0.4807
1995	0.0000	0.0107	0.1083	0.4619	0.7499	0.9388	0.9793	1.0402	1.1776	1.1776	0.7365
1996	0.0022	0.0175	0.1760	0.4548	0.6623	0.7966	0.8405	0.9154	0.8659	0.8659	0.6618
1997	0.0010	0.0341	0.1217	0.4679	0.5397	0.5669	0.6034	0.8522	0.7300	0.7300	0.5219
1998	0.0002	0.0051	0.1175	0.3497	0.6585	0.7048	0.9452	0.5650	1.3946	1.3946	0.5249
1999	0.0035	0.0397	0.1350	0.4851	0.9448	0.7843	0.8510	0.6628	0.8278	0.8278	0.6930
2000	0.0047	0.0321	0.1903	0.4776	0.6010	0.6085	0.6902	0.7204	0.6615	0.6615	0.5165
2001	0.0070	0.0536	0.2384	0.4065	0.4817	0.3601	0.4169	0.2735	0.2938	0.2938	0.4312
2002	0.0002	0.0113	0.3155	0.4372	0.4604	0.3367	0.3988	0.2877	0.5056	0.5056	0.4169
2003	0.0000	0.0145	0.2073	0.6332	0.6008	0.7169	1.1078	1.5724	1.7045	1.7045	0.7572
2004	0.0004	0.0107	0.1290	0.3239	0.4571	0.3569	0.4823	0.5761	1.2734	1.2734	0.3857
2005	0.0062	0.0219	0.0760	0.4020	0.7673	0.9495	0.5547	0.7305	0.9902	0.9902	0.5114
2006	0.0021	0.0190	0.0834	0.3688	0.5068	0.5142	0.5948	0.9159	0.8989	0.8989	0.4474
2007	0.0029	0.0494	0.1240	0.2299	0.5956	0.6660	1.0488	0.6951	0.7040	0.7040	0.4924
2008	0.0036	0.0205	0.1039	0.2469	0.4169	0.5392	1.1895	1.3177	1.3141	1.3141	0.4941
2009	0.0003	0.0165	0.0886	0.2580	0.3262	0.4244	0.4181	0.3747	0.8454	0.8454	0.3005
2010	0.0000	0.0042	0.0368	0.1576	0.3047	0.5060	0.4495	0.5974	0.8684	0.8684	0.2437
2011	0.0042	0.0035	0.0107	0.0440	0.1811	0.4569	0.3185	0.4514	1.0696	1.0696	0.1789
2012	0.0016	0.0017	0.0027	0.0338	0.1228	0.2502	0.4006	0.4209	0.9314	0.9314	0.1315
2013	na	0.0217	0.0213	0.0787	0.1488	0.2142	0.1575	0.1395	0.0568	0.0568	0.1447
2014	na	na	0.0421	0.0485	0.1082	0.1771	0.1747	0.1620	0.0140	0.0140	0.1235

Table 10. Estimated instantaneous rates of fishing mortality (F) at age and for fully-recruited ages 5 to 10 (F5-10) of fall-spawning herring in the Middle population of the southern Gulf of St. Lawrence.

	Age (years)										
Year	2	3	4	5	6	7	8	9	10	11+	*F*5-10
1978	0.0019	0.0795	0.7179	0.3428	0.3959	0.2834	0.8062	0.1183	0.2861	0.2861	0.4410
1979	0.0000	0.0164	0.4688	0.6656	1.3444	1.3170	1.5602	1.7041	3.0322	3.0322	1.3923
1980	0.0061	0.0551	0.1926	0.6535	0.4424	0.3367	2.0101	1.0946	0.4509	0.4509	0.6299
1981	0.0001	0.0578	0.3548	0.5043	0.7652	0.6842	2.6910	4.2472	1.0387	1.0387	0.7727
1982	0.0001	0.0021	0.1263	0.1412	0.0941	0.1880	0.3632	0.0100	0.2518	0.2518	0.1416
1983	0.0086	0.1208	0.5676	0.4902	0.9891	0.8462	0.7204	2.6358	2.4260	2.4260	0.7511
1984	0.0007	0.0049	0.0623	0.3116	0.2373	0.5388	0.7591	0.4603	2.3340	2.3340	0.3397
1985	0.0000	0.0004	0.0148	0.0514	0.1649	0.1876	0.5583	1.7121	0.4420	0.4420	0.1097
1986	0.0000	0.0014	0.0830	0.1086	0.1224	0.2776	0.2168	0.4194	1.3706	1.3706	0.1456
1987	0.0001	0.0102	0.0344	0.1237	0.1763	0.2208	0.1081	0.2010	2.5383	2.5383	0.1869
1988	0.0000	0.0714	0.1368	0.1374	0.2554	0.1916	0.1248	0.5429	0.0159	0.0159	0.1802
1989	0.0000	0.0006	0.0893	0.0866	0.0850	0.1053	0.1023	0.0531	0.1879	0.1879	0.0871
1990	0.0000	0.0019	0.0899	0.2293	0.1237	0.2549	0.1132	0.1250	0.0539	0.0539	0.1635
1991	0.0000	0.0002	0.0661	0.1017	0.3582	0.2061	0.3224	0.4127	0.2854	0.2854	0.2231
1992	0.0000	0.0007	0.0644	0.1410	0.1095	0.2374	0.0499	0.0509	0.0540	0.0540	0.1280
1993	0.0000	0.0000	0.0252	0.1488	0.1778	0.1694	0.4538	0.0893	0.1464	0.1464	0.1646
1994	0.0000	0.0000	0.0149	0.1300	0.2288	0.3086	0.1989	0.5460	0.1283	0.1283	0.2441
1995	0.0000	0.0000	0.0163	0.2428	0.5411	0.8018	0.6985	0.3886	0.9105	0.9105	0.4893
1996	0.0000	0.0008	0.0923	0.2347	0.5240	0.3513	0.5145	0.5571	0.4525	0.4525	0.4653
1997	0.0000	0.0049	0.2107	0.4172	0.3367	0.3354	0.4303	0.2705	0.2947	0.2947	0.3735
1998	0.0000	0.0008	0.1217	0.3394	0.9057	0.6348	0.5158	0.9516	1.0779	1.0779	0.6381
1999	0.0000	0.0000	0.1225	0.4714	0.7221	0.8145	1.3089	1.1395	1.3035	1.3035	0.6316
2000	0.0000	0.0002	0.1722	0.4227	0.5855	1.0068	1.0847	7.0021	0.4155	0.4155	0.5279
2001	0.0000	0.0053	0.1166	0.3302	0.3470	0.4543	0.7613	0.4474	0.4230	0.4230	0.3535
2002	0.0000	0.0073	0.1749	0.2605	0.3130	0.4686	0.3792	0.4817	0.6570	0.6570	0.3297
2003	0.0000	0.0010	0.0891	0.3408	0.2741	0.2484	0.4828	0.4465	0.6588	0.6588	0.3257
2004	0.0000	0.0002	0.0585	0.2276	0.3554	0.4358	0.5359	0.7659	1.3605	1.3605	0.3554
2005	0.0037	0.0246	0.1762	0.3360	0.6091	0.4002	0.6417	0.6914	0.9025	0.9025	0.4453
2006	0.0000	0.0008	0.0445	0.1952	0.3723	0.4364	0.4262	0.8865	1.2476	1.2476	0.3435
2007	0.0000	0.0023	0.0524	0.1073	0.3716	0.5001	0.6862	0.4769	1.1391	1.1391	0.3511
2008	0.0000	0.0112	0.0990	0.1253	0.1971	0.3536	1.1176	0.6620	1.2061	1.2061	0.3937
2009	0.0000	0.0011	0.0822	0.1645	0.2393	0.5765	0.4272	0.4640	0.5051	0.5051	0.2500
2010	0.0000	0.0001	0.0204	0.1583	0.2939	0.6588	0.8046	0.5955	1.0838	1.0838	0.2943
2011	0.0000	0.0000	0.0087	0.0350	0.2506	0.4814	1.1340	1.4755	1.7689	1.7689	0.2946
2012	0.0000	0.0001	0.0107	0.0525	0.1988	0.4042	0.5005	1.5885	2.9846	2.9846	0.2748
2013	na	0.0003	0.0128	0.1051	0.2728	0.3926	0.4109	0.2788	5.5637	5.5637	0.3282
2014	na	na	0.0000	0.0688	0.3561	0.4168	0.6737	0.1660	0.1487	0.1487	0.2824

Table 11. Estimated instantaneous rates of fishing mortality (F) at age and for fully-recruited ages 5 to 10 (F5-10) of fall-spawning herring in the South population of the southern Gulf of St. Lawrence.

	Age (years)										
Year	2	3	4	5	6	7	8	9	10	11+	*F*5-10
1978	0.0277	0.2592	0.2577	0.2529	0.2381	0.2962	0.7325	1.1613	0.7214	0.7214	0.3868
1979	0.0005	0.0094	0.1087	0.1638	0.2277	0.1616	0.2298	0.2314	0.8817	0.8817	0.1936
1980	0.0058	0.3838	0.5381	0.8874	1.2280	1.7540	1.1186	2.1991	3.7882	3.7882	1.1722
1981	0.0100	0.1559	0.4241	0.2484	0.1124	0.3458	0.5192	0.5920	0.5774	0.5774	0.2208
1982	0.0000	0.0039	0.1439	0.1527	0.4221	0.2940	0.5592	1.6044	0.3585	0.3585	0.2643
1983	0.0001	0.0034	0.1075	0.1476	0.2032	0.2290	0.2558	0.7677	1.2217	1.2217	0.1871
1984	0.0000	0.0045	0.1085	0.1062	0.1914	0.2091	0.2416	0.1133	0.3927	0.3927	0.1464
1985	0.0000	0.0005	0.0488	0.1556	0.1707	0.1995	0.3239	0.2766	0.1370	0.1370	0.1721
1986	0.0038	0.0065	0.1560	0.1075	0.1749	0.1273	0.1475	0.1079	0.0849	0.0849	0.1417
1987	0.0001	0.0114	0.0709	0.1377	0.1601	0.3179	0.3666	0.7033	0.7437	0.7437	0.2344
1988	0.0007	0.0060	0.0574	0.1446	0.1463	0.1807	0.2439	0.3076	0.3461	0.3461	0.1697
1989	0.0000	0.0006	0.0244	0.0347	0.0994	0.0873	0.0956	0.1322	0.0944	0.0944	0.0831
1990	0.0000	0.0050	0.1612	0.1622	0.1740	0.7886	0.3015	0.3459	0.3895	0.3895	0.3961
1991	0.0000	0.0001	0.0353	0.0542	0.0438	0.0369	0.1747	0.0617	0.1036	0.1036	0.0715
1992	0.0000	0.0017	0.0153	0.0742	0.0770	0.0540	0.0793	0.2632	0.0977	0.0977	0.0889
1993	0.0000	0.0000	0.0084	0.0370	0.0465	0.0543	0.0216	0.0301	0.0473	0.0473	0.0404
1994	0.0000	0.0003	0.0370	0.0662	0.2469	0.3743	0.2022	0.2902	0.4986	0.4986	0.2808
1995	0.0004	0.0037	0.0174	0.1245	0.1475	0.3584	0.3854	0.3513	0.4471	0.4471	0.2526
1996	0.0001	0.0002	0.0548	0.2057	0.3229	0.5219	0.6730	0.7743	0.8199	0.8199	0.4612
1997	0.0003	0.0076	0.1226	0.3572	0.1925	0.3739	0.2816	0.4011	0.5008	0.5008	0.3485
1998	0.0000	0.0000	0.0720	0.1678	0.3900	0.3958	0.6637	0.4814	0.9699	0.9699	0.4119
1999	0.0002	0.0049	0.0667	0.4211	0.3825	0.7355	0.8706	0.8953	1.0631	1.0631	0.5180
2000	0.0006	0.0162	0.0782	0.2989	0.4418	0.3611	0.4822	0.4132	0.5776	0.5776	0.3537
2001	0.0030	0.0203	0.0474	0.2572	0.3946	0.7452	0.7130	0.5849	0.7592	0.7592	0.3838
2002	0.0037	0.0126	0.0994	0.1664	0.3367	0.5139	0.5939	0.6893	0.7991	0.7991	0.3333
2003	0.0014	0.0194	0.0631	0.2991	0.2074	0.5302	0.8527	0.9777	0.7447	0.7447	0.3661
2004	0.0031	0.0174	0.0702	0.1110	0.2777	0.2155	0.3468	0.6624	1.0927	1.0927	0.2155
2005	0.0000	0.0000	0.0044	0.0991	0.2231	0.5989	0.2909	0.6865	0.7937	0.7937	0.2793
2006	0.0009	0.0060	0.0325	0.1099	0.2391	0.3761	0.6689	0.4293	0.7586	0.7586	0.3004
2007	0.0000	0.0025	0.0054	0.1287	0.2701	0.5008	0.5244	0.4660	0.4721	0.4721	0.3379
2008	0.0000	0.0026	0.0267	0.0394	0.1271	0.4067	0.6528	0.4716	0.7572	0.7572	0.2974
2009	0.0000	0.0024	0.0265	0.1511	0.3355	0.7203	0.4250	0.3180	0.8163	0.8163	0.3134
2010	0.0000	0.0008	0.0215	0.1353	0.3736	0.5005	1.0438	1.0230	0.6547	0.6547	0.3946
2011	0.0000	0.0000	0.0046	0.0688	0.1540	0.5616	1.4079	1.9498	1.3727	1.3727	0.3161
2012	0.0000	0.0000	0.0037	0.0258	0.1672	0.5105	0.8622	1.5957	2.1017	2.1017	0.3003
2013	na	0.0027	0.0452	0.2451	0.3359	0.5254	0.7280	0.8159	2.0178	2.0178	0.4880
2014	na	na	0.1610	0.1929	0.5578	0.5599	0.9372	0.9296	0.8118	0.8118	0.5828

Table 12. Estimated instantaneous rates of fishing mortality (F) at age and for fully-recruited ages 5 to 10 (F5-10) of fall-spawning herring of the southern Gulf of St. Lawrence. Values are abundance weighted averages of the values in each region.

	Age (years)										
Year	2	3	4	5	6	7	8	9	10	11+	*F*5-10
1978	0.0114	0.1834	0.5958	0.7585	0.5223	0.4406	1.1846	0.6282	0.8439	0.8972	0.7865
1979	0.0166	0.1034	0.2174	0.4720	0.7170	0.6346	0.7390	1.1235	2.4016	2.1355	0.6997
1980	0.0107	0.1908	0.3292	0.6168	1.0602	1.4813	1.1951	1.6194	2.6775	2.5725	0.8835
1981	0.0029	0.0745	0.2087	0.2045	0.1198	0.3877	1.2747	0.6712	0.4233	0.6444	0.2178
1982	0.0016	0.0331	0.1085	0.1967	0.2322	0.1481	0.5710	1.4817	0.4990	0.6630	0.2074
1983	0.0007	0.0130	0.1163	0.1124	0.2440	0.1912	0.1415	1.0050	1.3003	1.1420	0.1722
1984	0.0009	0.0072	0.0712	0.1077	0.1337	0.1527	0.1655	0.0613	0.8379	1.3312	0.1228
1985	0.0006	0.0060	0.0414	0.1224	0.1639	0.1884	0.2704	0.6435	0.1617	0.1431	0.1591
1986	0.0019	0.0083	0.1286	0.1206	0.1984	0.2639	0.2738	0.2437	0.2157	0.2159	0.1946
1987	0.0064	0.0387	0.1020	0.1583	0.1925	0.2954	0.3613	0.4860	0.4253	0.4574	0.2463
1988	0.0147	0.0186	0.1041	0.1754	0.1755	0.2291	0.2115	0.2871	0.3618	0.3901	0.1975
1989	0.0009	0.0064	0.1039	0.1672	0.1948	0.1955	0.1818	0.1998	0.2563	0.2777	0.1884
1990	0.0002	0.0104	0.1559	0.2166	0.2770	0.5989	0.3507	0.3881	0.3193	0.3420	0.3655
1991	0.0000	0.0116	0.0989	0.1248	0.1214	0.1817	0.2747	0.1578	0.1907	0.2048	0.1648
1992	0.0001	0.0047	0.0463	0.1603	0.1984	0.1756	0.2121	0.3441	0.2524	0.3754	0.1836
1993	0.0018	0.0117	0.0471	0.1318	0.1499	0.1439	0.1285	0.1466	0.1954	0.1593	0.1427
1994	0.0000	0.0021	0.0577	0.1925	0.3310	0.4650	0.3960	0.5128	0.5003	0.5000	0.3792
1995	0.0001	0.0066	0.0704	0.3088	0.5065	0.7041	0.7375	0.6544	0.7194	0.6961	0.5247
1996	0.0009	0.0116	0.1186	0.3491	0.5015	0.6074	0.7072	0.7886	0.7541	0.7857	0.5472
1997	0.0006	0.0170	0.1337	0.4163	0.3862	0.4323	0.4057	0.5143	0.5301	0.4999	0.4254
1998	0.0001	0.0027	0.0968	0.3094	0.5816	0.5607	0.7156	0.5721	1.0852	1.0890	0.5015
1999	0.0017	0.0181	0.1096	0.4520	0.7798	0.7629	0.9203	0.9043	1.0270	1.0870	0.6074
2000	0.0016	0.0208	0.1401	0.4049	0.5194	0.5694	0.6220	1.1046	0.5695	0.5724	0.4542
2001	0.0037	0.0269	0.1479	0.3266	0.4253	0.5803	0.5709	0.4665	0.5964	0.5715	0.3976
2002	0.0013	0.0112	0.1652	0.2974	0.3755	0.4320	0.4829	0.4479	0.6659	0.6682	0.3659
2003	0.0004	0.0137	0.1132	0.3778	0.3626	0.5363	0.9063	1.1331	1.3685	1.1861	0.4750
2004	0.0013	0.0105	0.0973	0.1937	0.3190	0.3002	0.4294	0.6572	1.2251	1.1876	0.2842
2005	0.0038	0.0142	0.0758	0.2901	0.4289	0.6222	0.4229	0.6985	0.8957	0.8689	0.3935
2006	0.0012	0.0117	0.0576	0.2645	0.3772	0.4089	0.6195	0.6053	0.9021	0.9152	0.3674
2007	0.0019	0.0235	0.0725	0.1698	0.4461	0.5621	0.6291	0.4926	0.5793	0.6373	0.4014
2008	0.0019	0.0156	0.0772	0.1523	0.2604	0.4509	0.9207	0.5820	0.8998	0.8816	0.3928
2009	0.0003	0.0098	0.0766	0.1995	0.3148	0.5883	0.4228	0.3541	0.7806	0.7850	0.2949
2010	0.0000	0.0033	0.0296	0.1537	0.3273	0.5325	0.7530	0.7711	0.7645	0.7311	0.2969
2011	0.0029	0.0030	0.0096	0.0500	0.1895	0.4993	0.8893	1.0600	1.3380	1.3646	0.2385
2012	0.0007	0.0012	0.0033	0.0345	0.1484	0.3279	0.5763	0.7998	1.2399	1.7256	0.1893
2013	na	0.0091	0.0235	0.0946	0.1884	0.3323	0.2903	0.3389	0.4703	0.3615	0.2275
2014	na	na	0.0338	0.0732	0.1574	0.2470	0.4279	0.2396	0.1654	0.0256	0.2080

Table 13. Probabilities that average F for ages 5-10 years will exceed the target level of 0.32 and that SSB will be below the Upper Stock Reference given various catch levels in 2015 for fall-spawning herring in the southern Gulf of St. Lawrence. SSB is the sum over the North, Middle and South populations and F is the abundance weighted average over the three populations.

Catch (1,000 t)	*F* > 0.32	SSB < USR
10	0.000	0.284
12	0.000	0.300
14	0.000	0.311
16	0.000	0.319
18	0.002	0.330
20	0.012	0.341
22	0.044	0.352
24	0.114	0.363
26	0.235	0.372
28	0.379	0.385
30	0.557	0.395
32	0.711	0.406
34	0.830	0.415
36	0.907	0.424
38	0.951	0.431
40	0.975	0.440
42	0.985	0.448
44	0.992	0.455
46	0.996	0.463
48	0.998	0.470
50	0.999	0.476

FIGURES

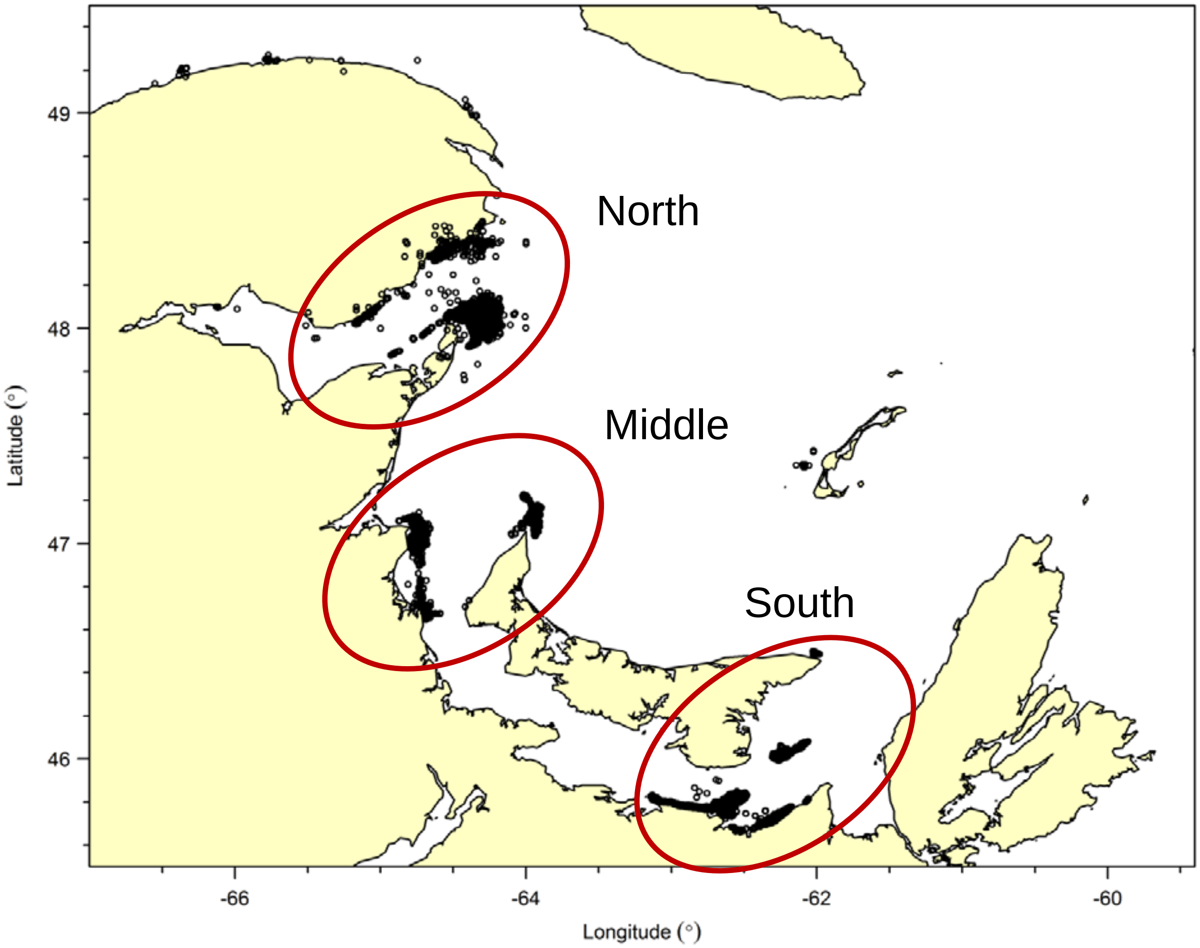

Figure 1. Fall herring spawning grounds (black circles) in the southern Gulf of St. Lawrence and their grouping (large red ellipses) into North, Middle, and South putative populations for assessment and management purposes.

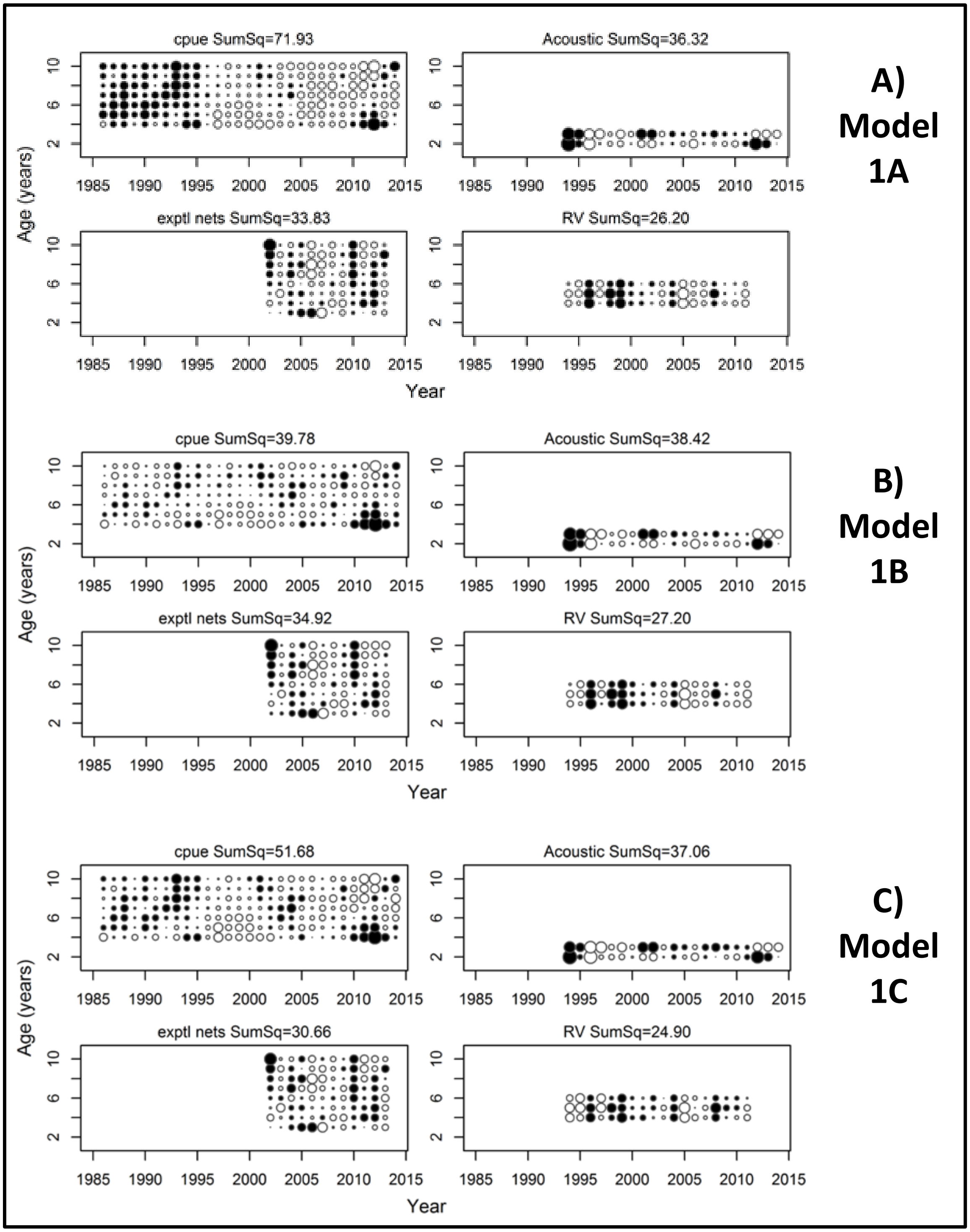

Figure 2. Residuals (observed – predicted indices) for variants of Model 1 assuming a single fall-spawning population. Circle radius is proportional to the absolute value of residuals. Black circles indicate negative residuals (i.e., observed < predicted).

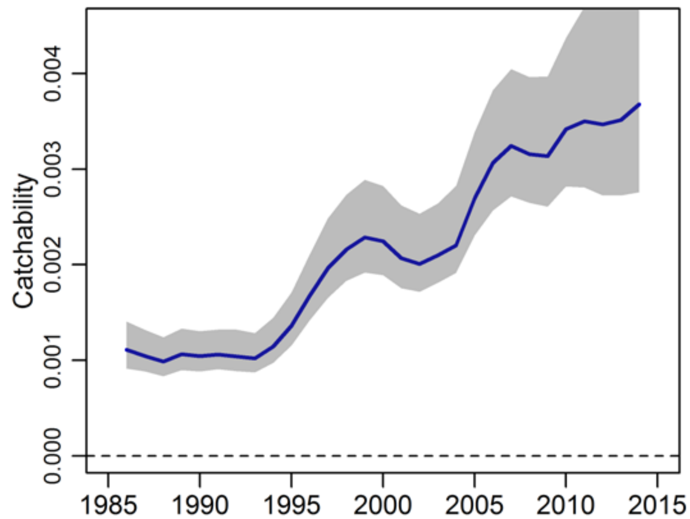

Figure 3. Estimated trend in fully recruited catchability to the fishery in Model 1B. The line is the maximum likelihood estimate (MLE) and the shading shows 95% confidence intervals based on MCMC sampling.

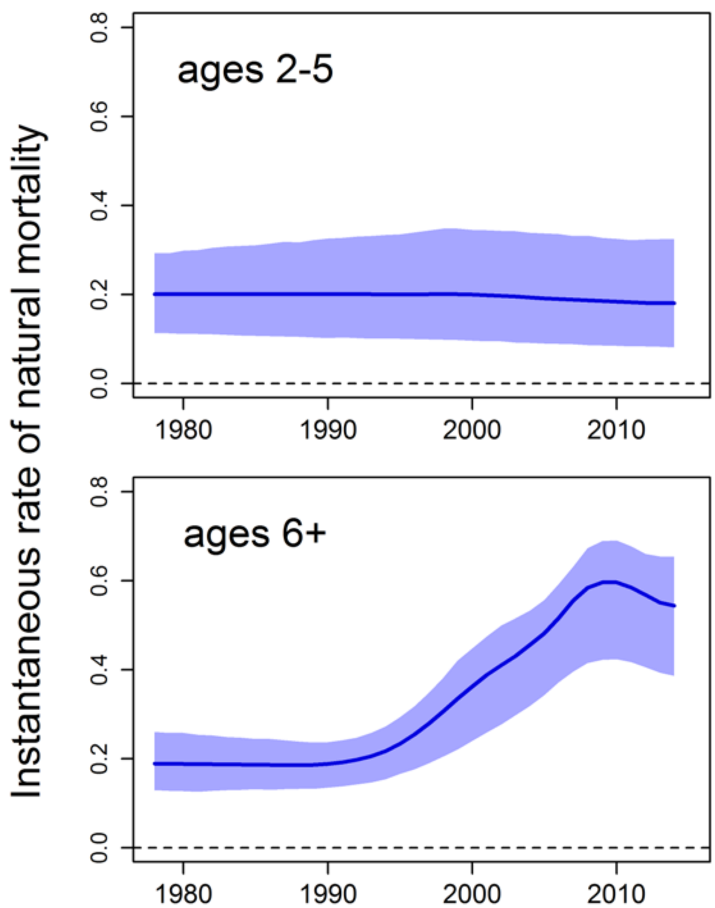

Figure 4. Estimated trend in M of ages 2 to 5 and 6+ in Model 1C. Lines are the MLEs and shading shows 95% confidence intervals based on MCMC sampling.

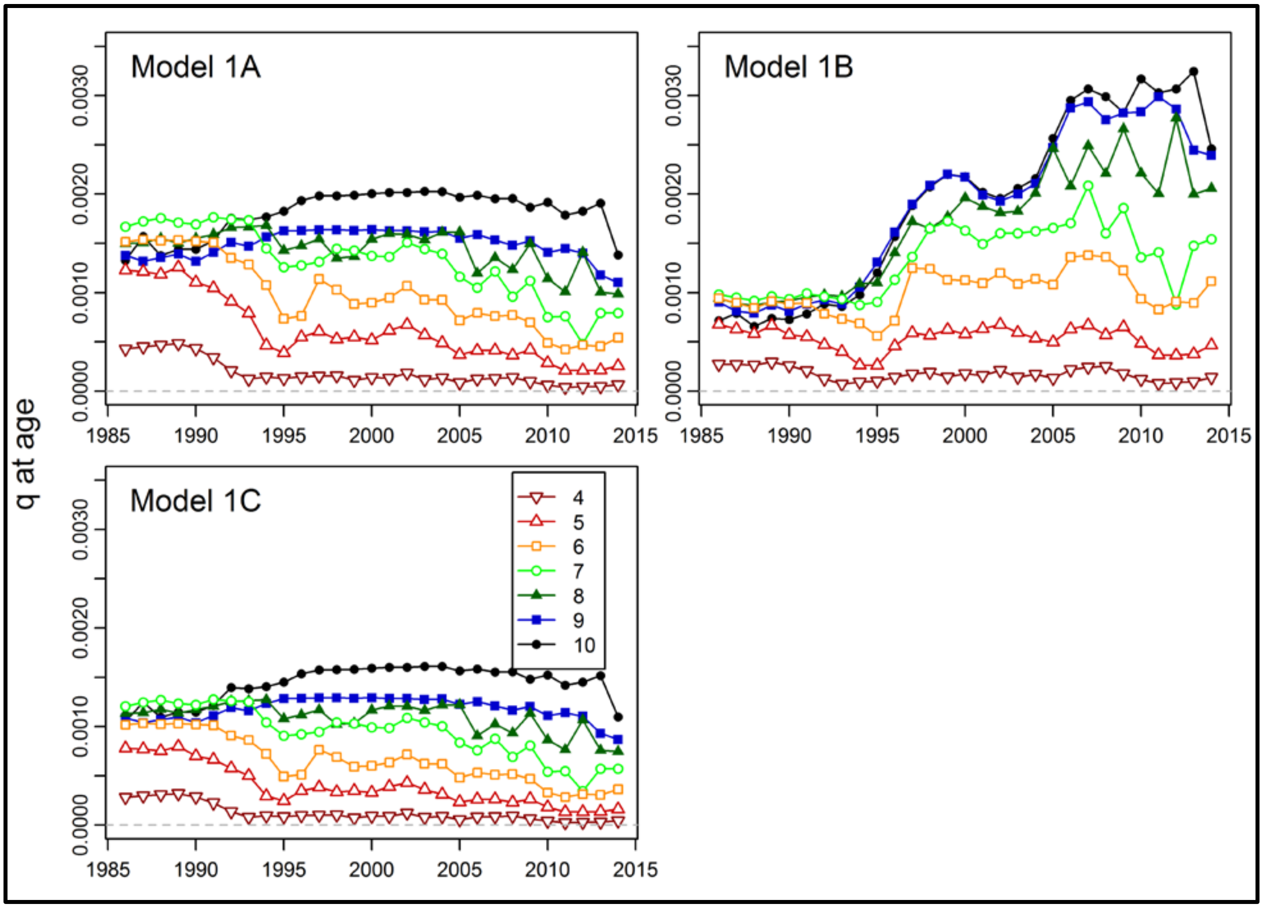

Figure 5. Estimated catchability at age (qa′ in equation 2) to the gillnet fishery for variants of Model 1. qa′ takes into account changes in mesh size and length at age, as well as non-stationarity in fully recruited q in the case of Model 1B.

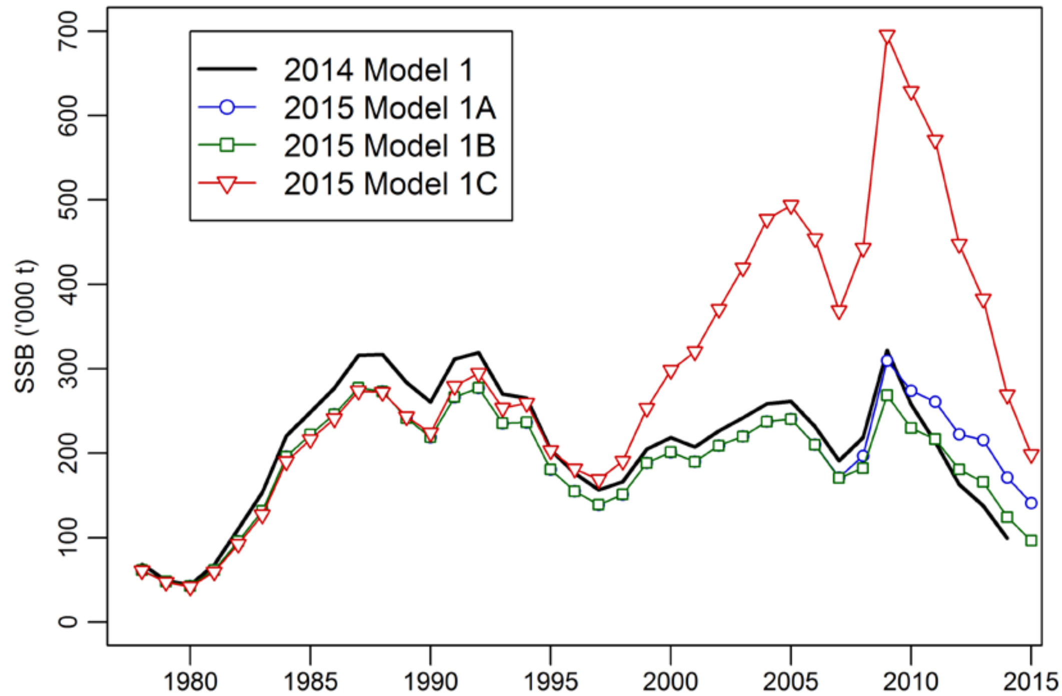

Figure 6. Estimated spawning stock biomass (SSB) based on Model 1 from the 2014 assessment and from Model 1A (stationarity), Model 1B (non-stationary fishery CPUE q) and Model 1C (non-stationary M).

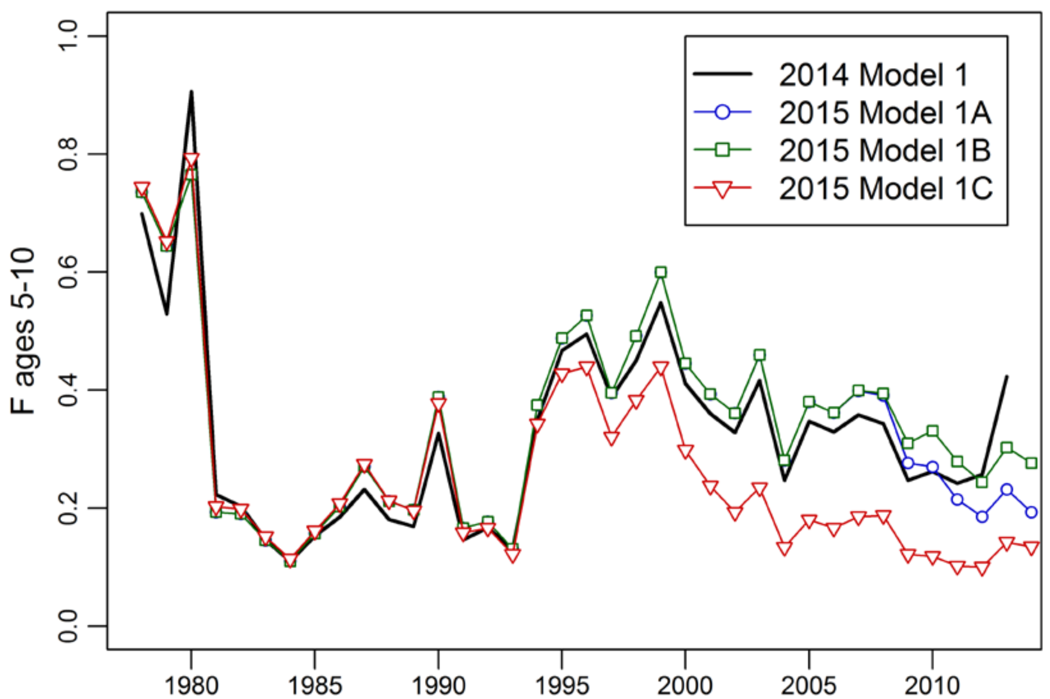

Figure 7. Estimated fishing mortality (F, ages 5 to 10) based on Model 1 from the 2014 assessment and from Model 1A (stationarity), Model 1B (non-stationary fishery CPUE q) and Model 1C (non-stationary M).

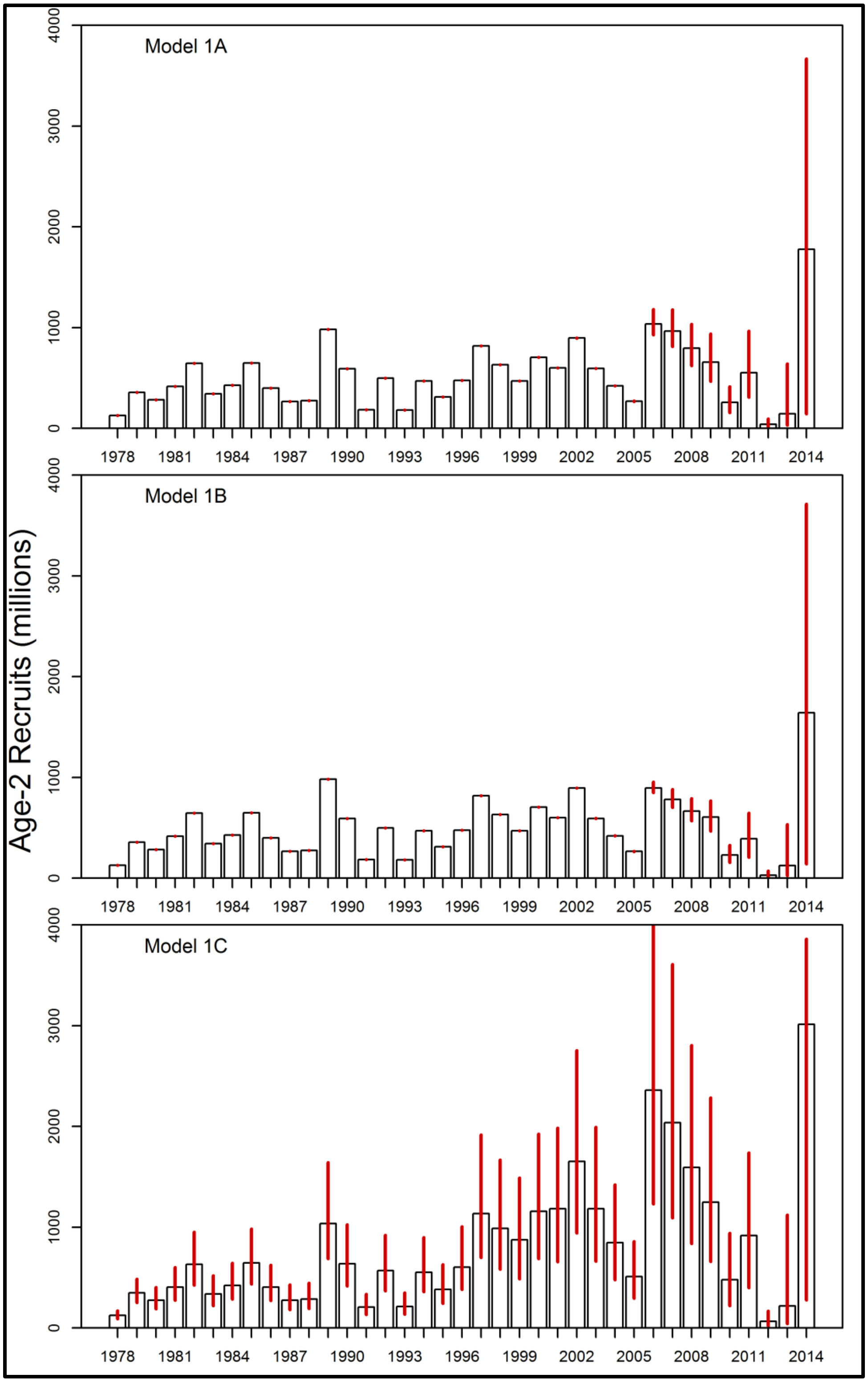

Figure 8. Estimated recruit abundance (millions) at age 2 based on Models 1A, 1B and 1C. Vertical lines are 95% confidence intervals based on MCMC sampling.

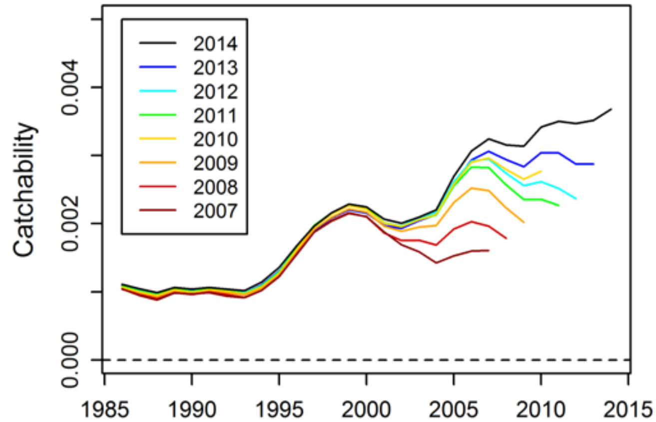

Figure 9. Retrospective pattern in fully-recruited catchability to the fishery based on Model 1B.

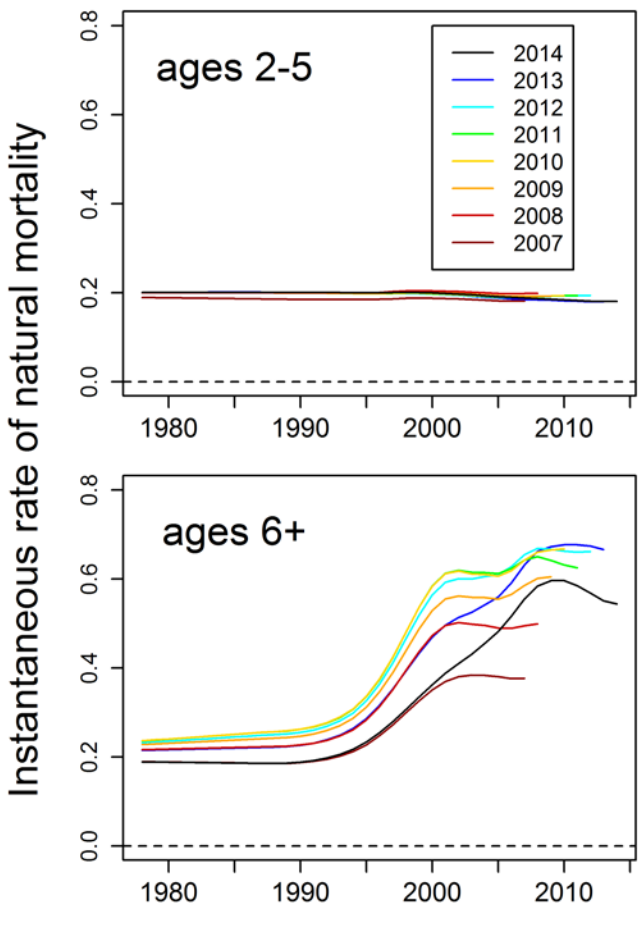

Figure 10. Retrospective pattern in the instantaneous rate of natural mortality (M) based on Model 1B.

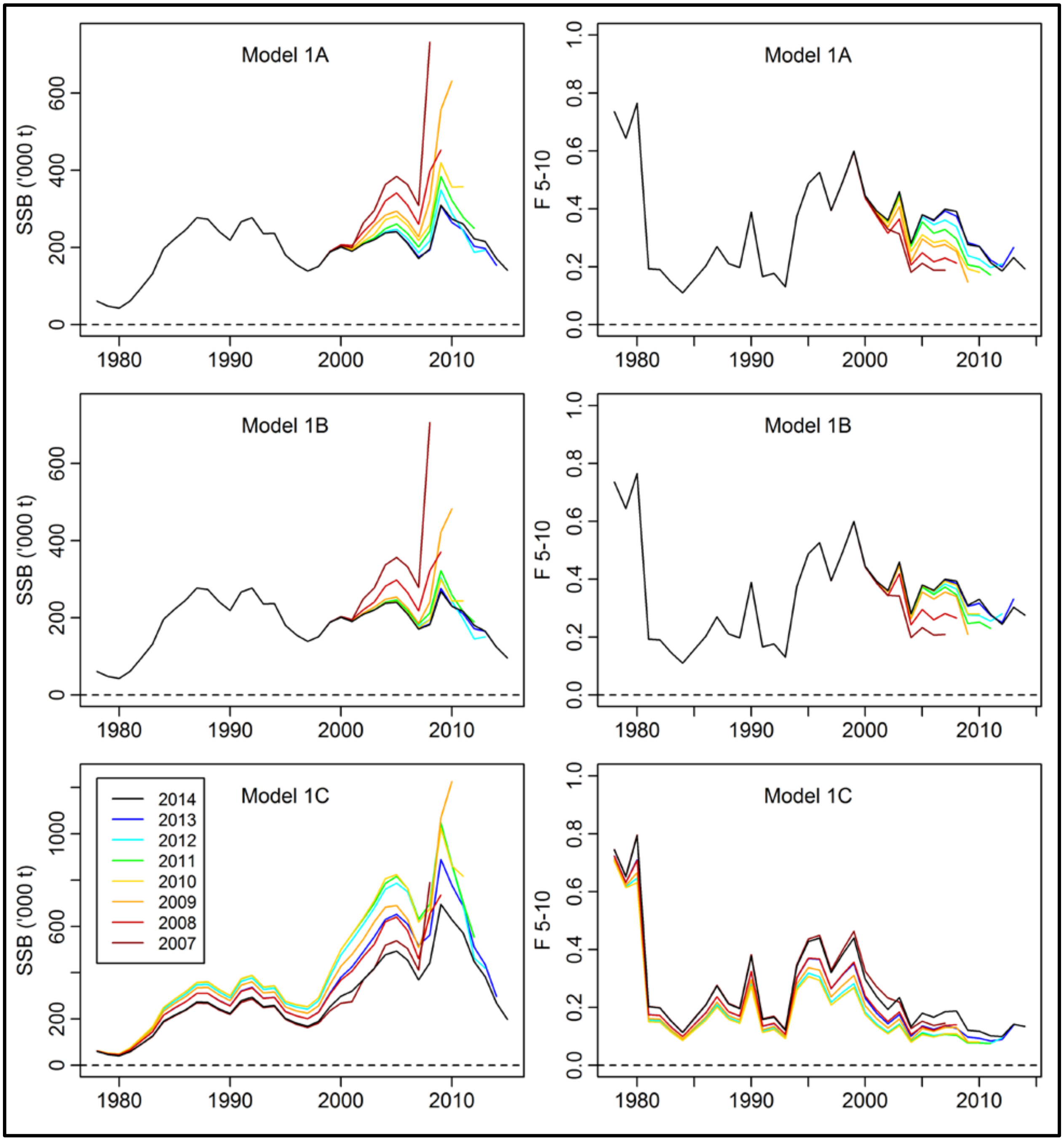

Figure 11. Retrospective patterns in estimated spawning stock biomass (SSB; left column) and the instantaneous rate of fishing mortality (F; right column) for ages 5-10 for variants of Model 1 (which assumes a single fall-spawning population of Atlantic herring in the southern Gulf of St. Lawrence).

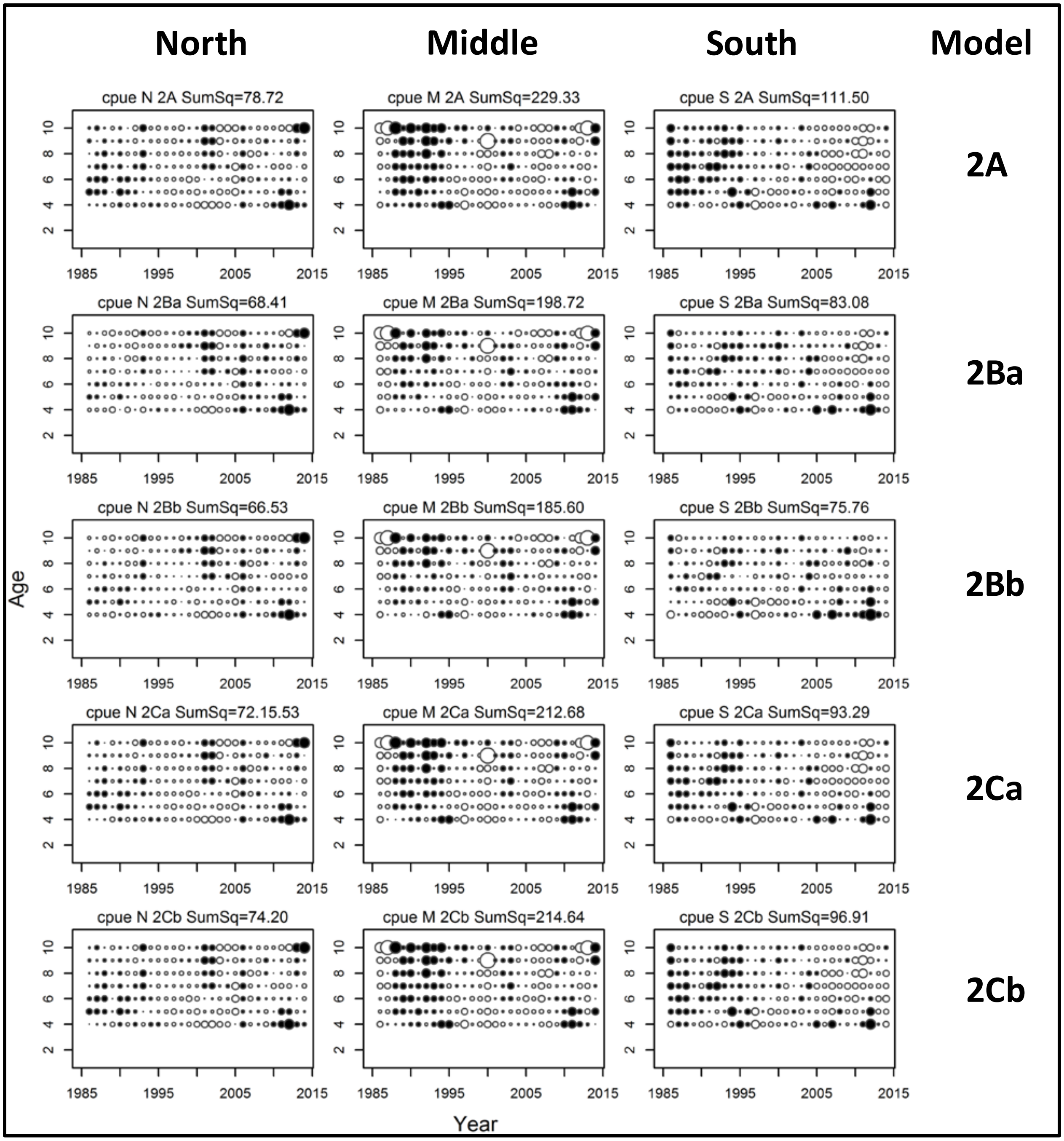

Figure 12. Residuals from the CPUE index for the gillnet fishery by population (North – left column; Middle – middle column; South – right column) and variants of Model 2. Circle radius is proportional to residual magnitude. Black circles indicate negative residuals (i.e., observed < predicted).

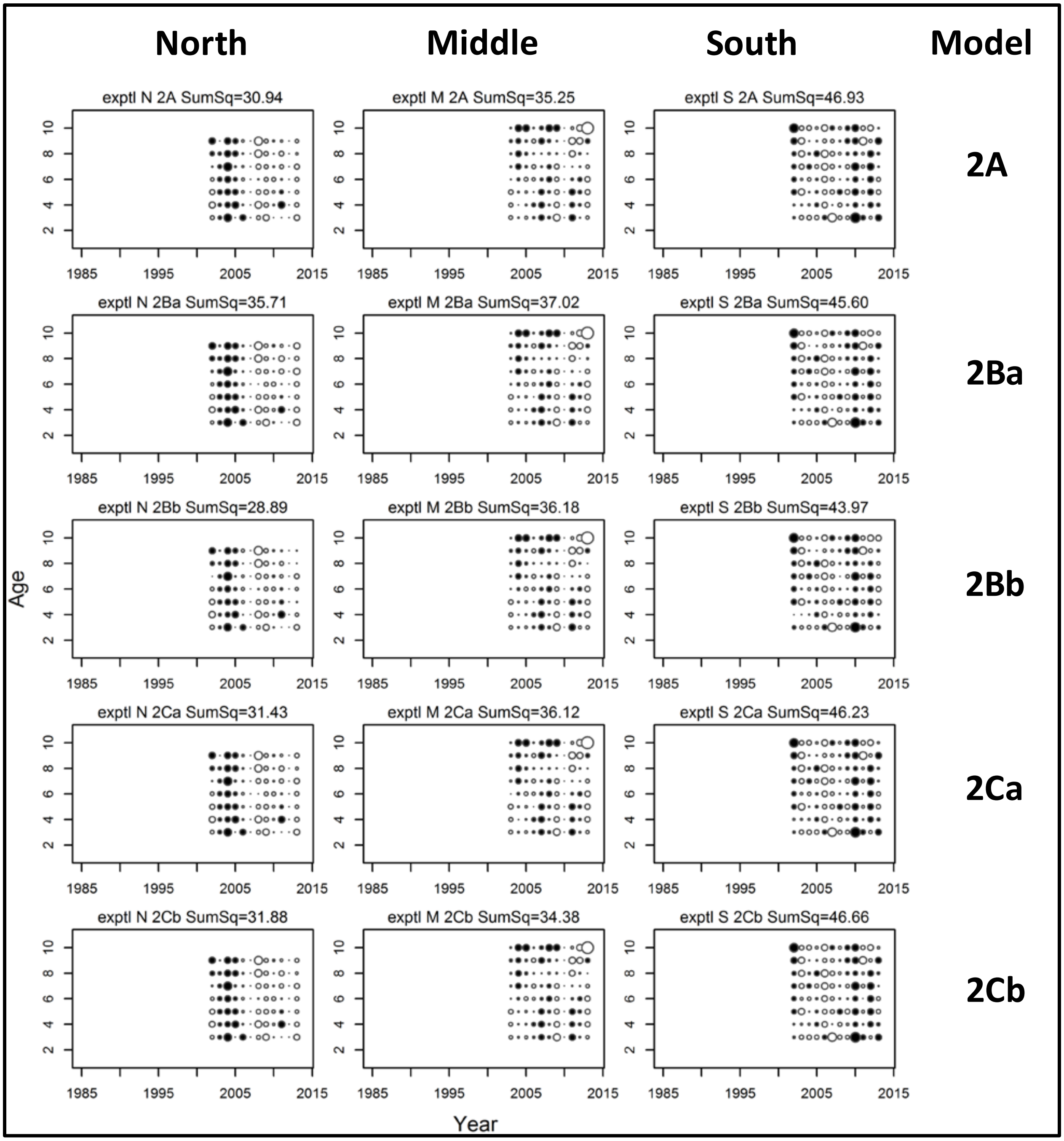

Figure 13. Residuals from the experimental nets index by population (North – left column; Middle – middle column; South – right column) and variants of Model 2. Circle radius is proportional to residual magnitude. Black circles indicate negative residuals (i.e., observed < predicted).

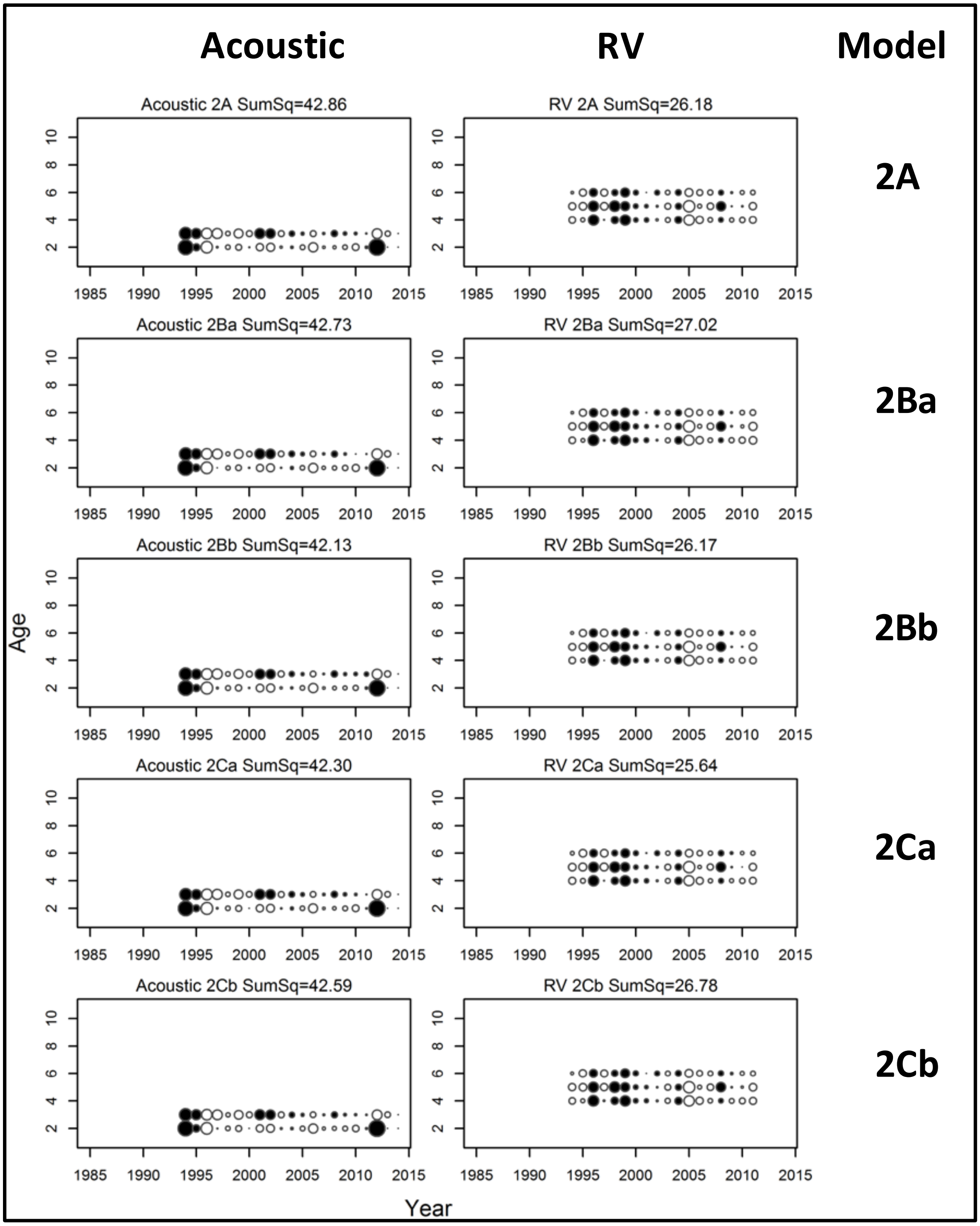

Figure 14. Residuals from the acoustic (left column) and RV survey (right column) indices for the entire southern Gulf of St. Lawrence for variants of Model 2. Circle radius is proportional to residual magnitude. Black circles indicate negative residuals (i.e., observed < predicted).

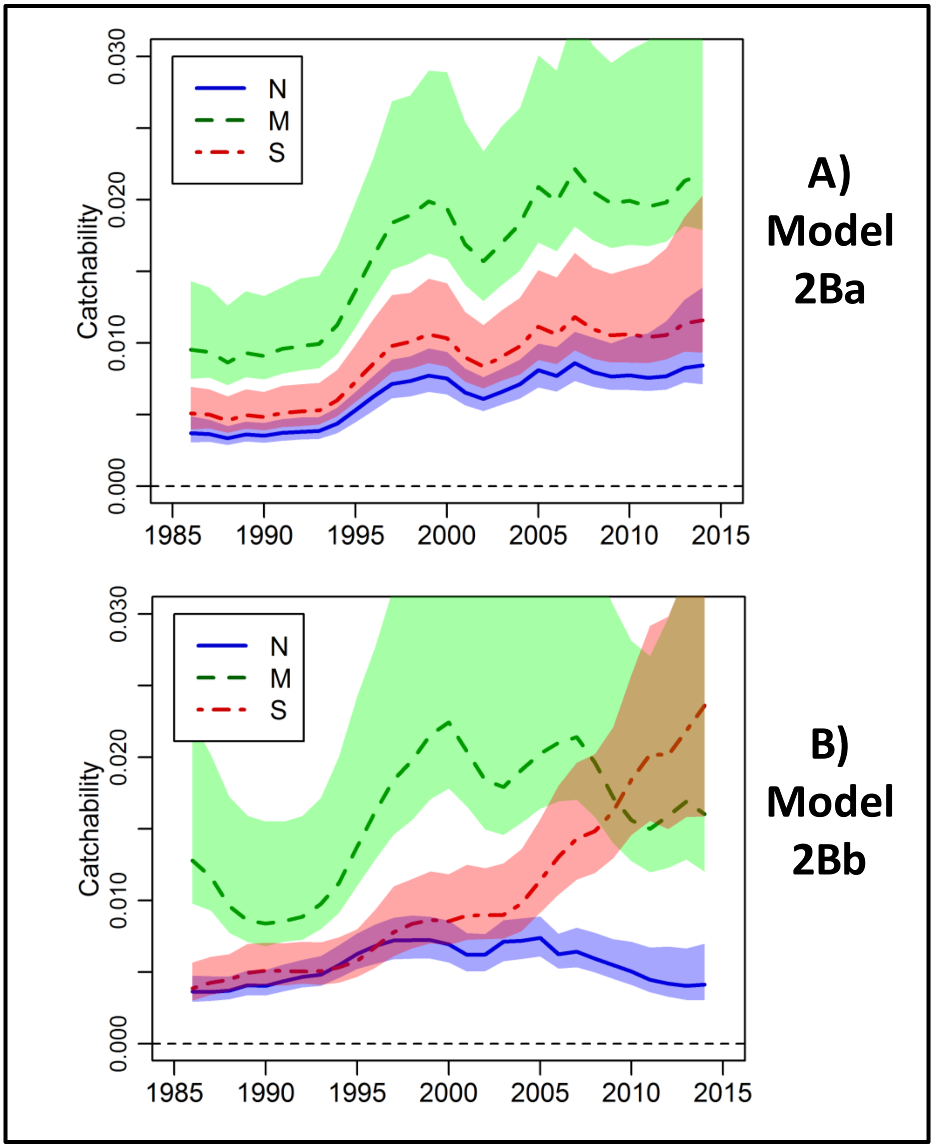

Figure 15.Estimated trends in fully recruited catchability to the gillnet fishery by population (North = N; Middle = M; South = S) for Model 2Ba (A, upper panel; common trend among populations) and Model 2Bb (B, lower panel; independent trends between populations). Lines show the MLEs and shading the 95% confidence bands based on MCMC sampling.

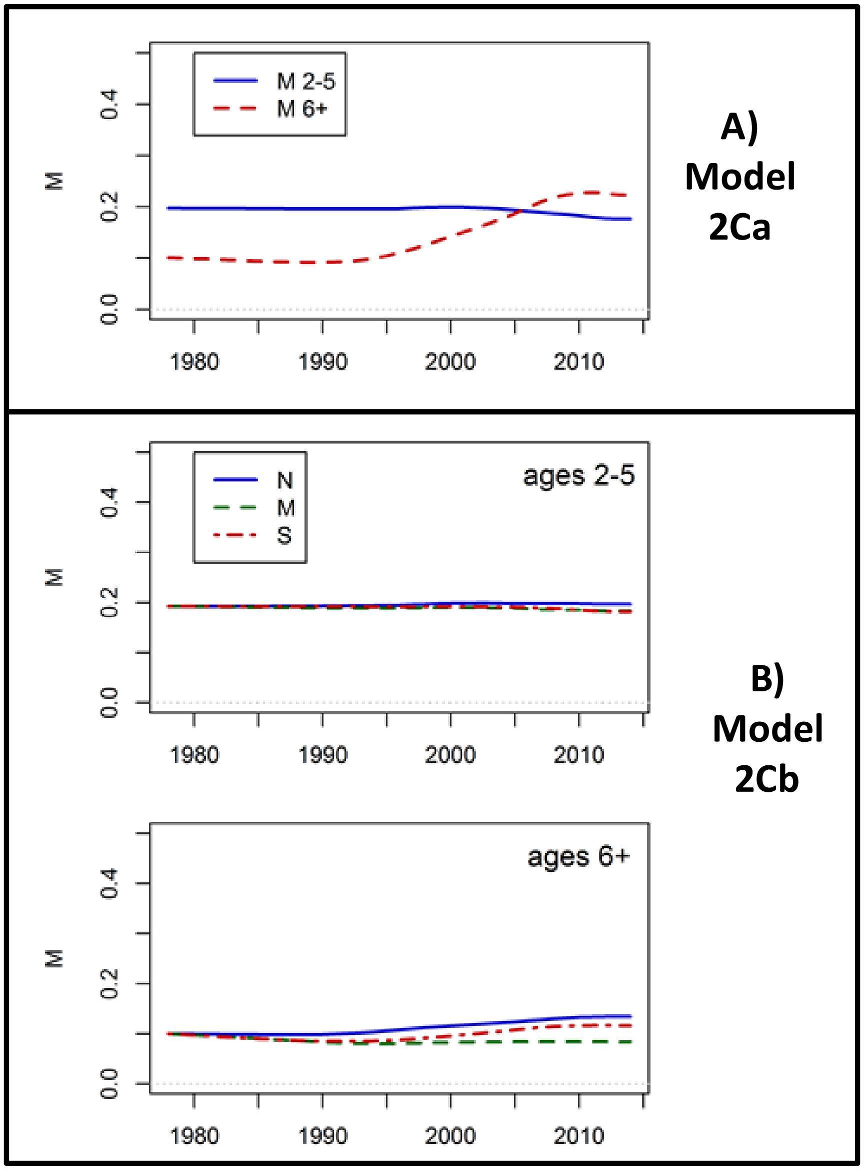

Figure 16.Estimated trends in the instantaneous rate of natural mortality (M) by age group (ages 2 to 5 and ages 6+) for Model 2Ca (A, upper panel; common trend among populations) and Model 2Cb (B, middle and lower panels; independent trends between populations with North = N, Middle = M, and South = S).

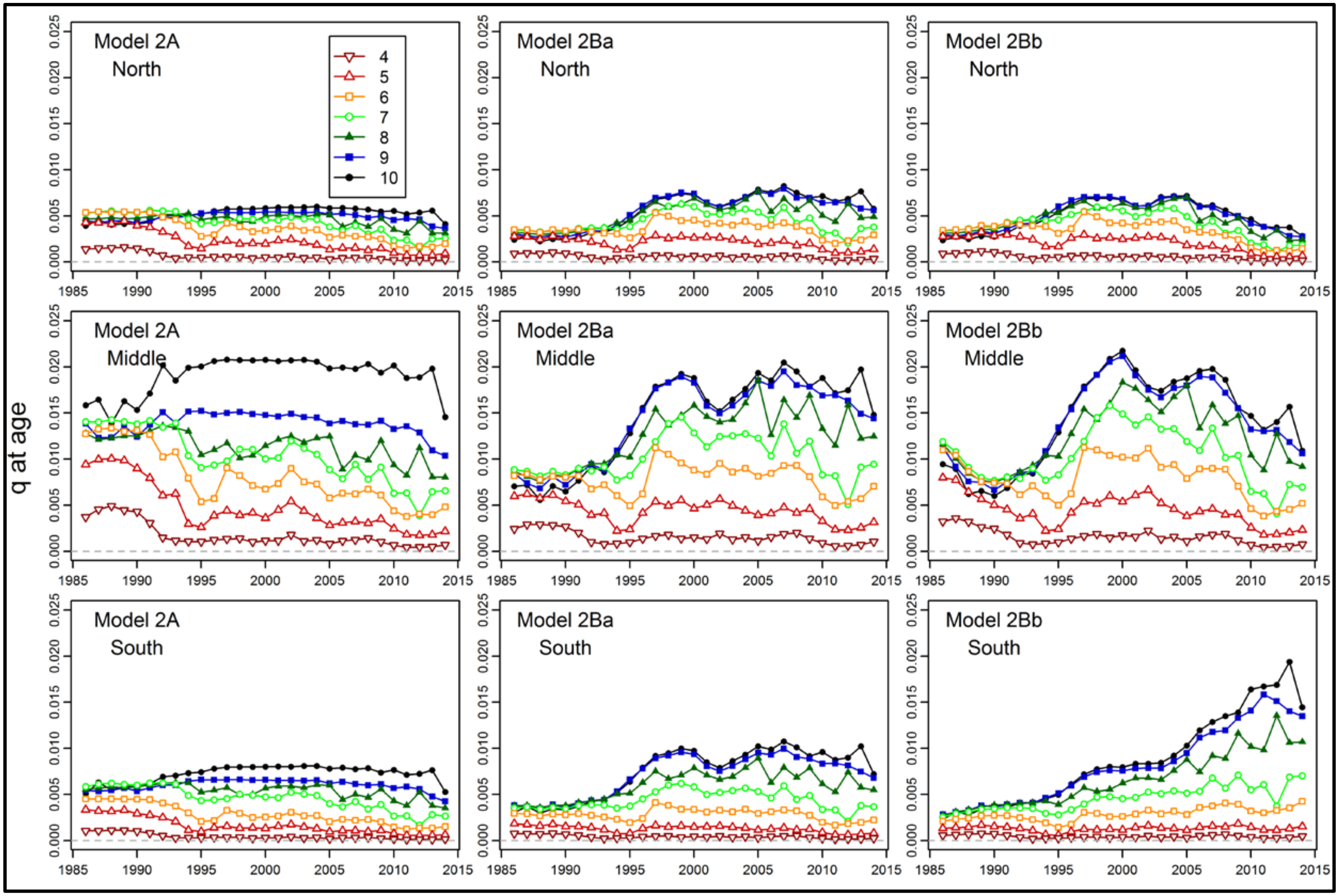

Figure 17. Estimated catchability (q) at age (q_a' in equation 2) to the gillnet fishery for variants of Model 2 that treat fall spawning herring as three populations (North – upper row; Middle – middle row; South – lower row). q_a' takes into account changes in mesh size and length at age, as well as non-stationarity in fully recruited q in the case of Models 2Ba and 2Bb. Fully recruited q is constant in Model 2A (left column), varies in common among populations in 2Ba (middle column), and varies independently between populations in 2Bb (right column).

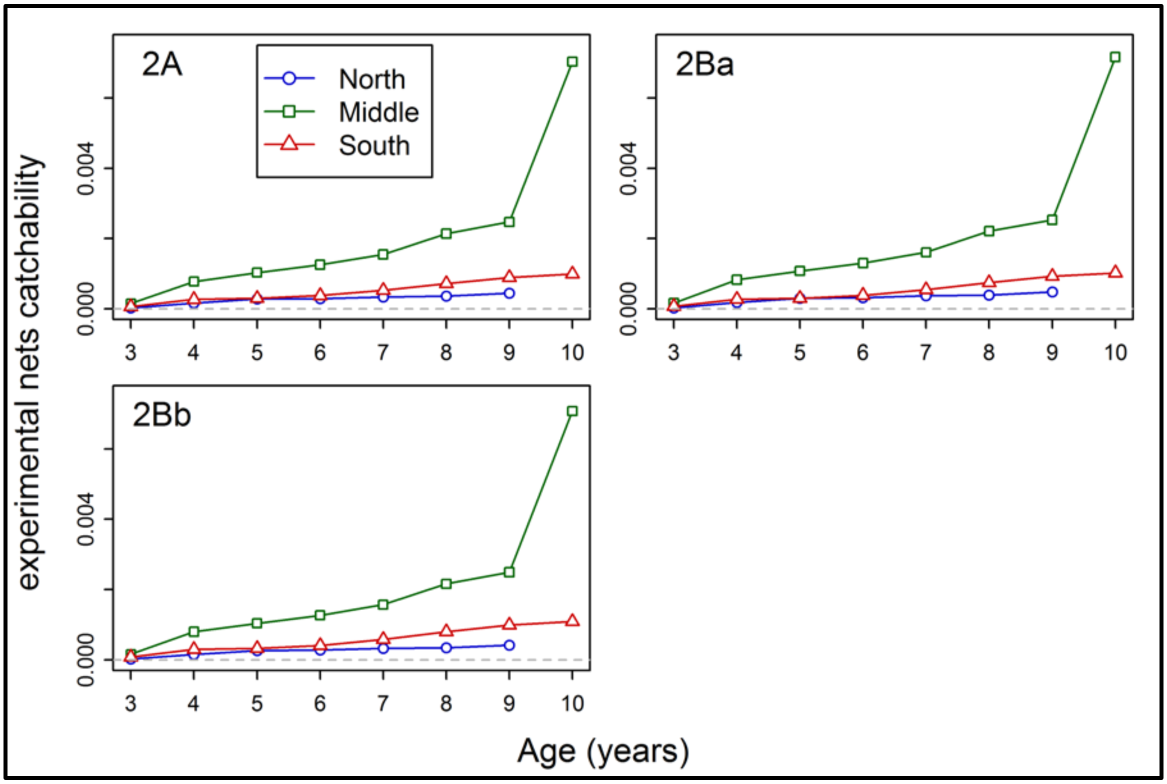

Figure 18. Catchability at age to the experimental nets by population (North, Middle, South) for variants of Model 2.

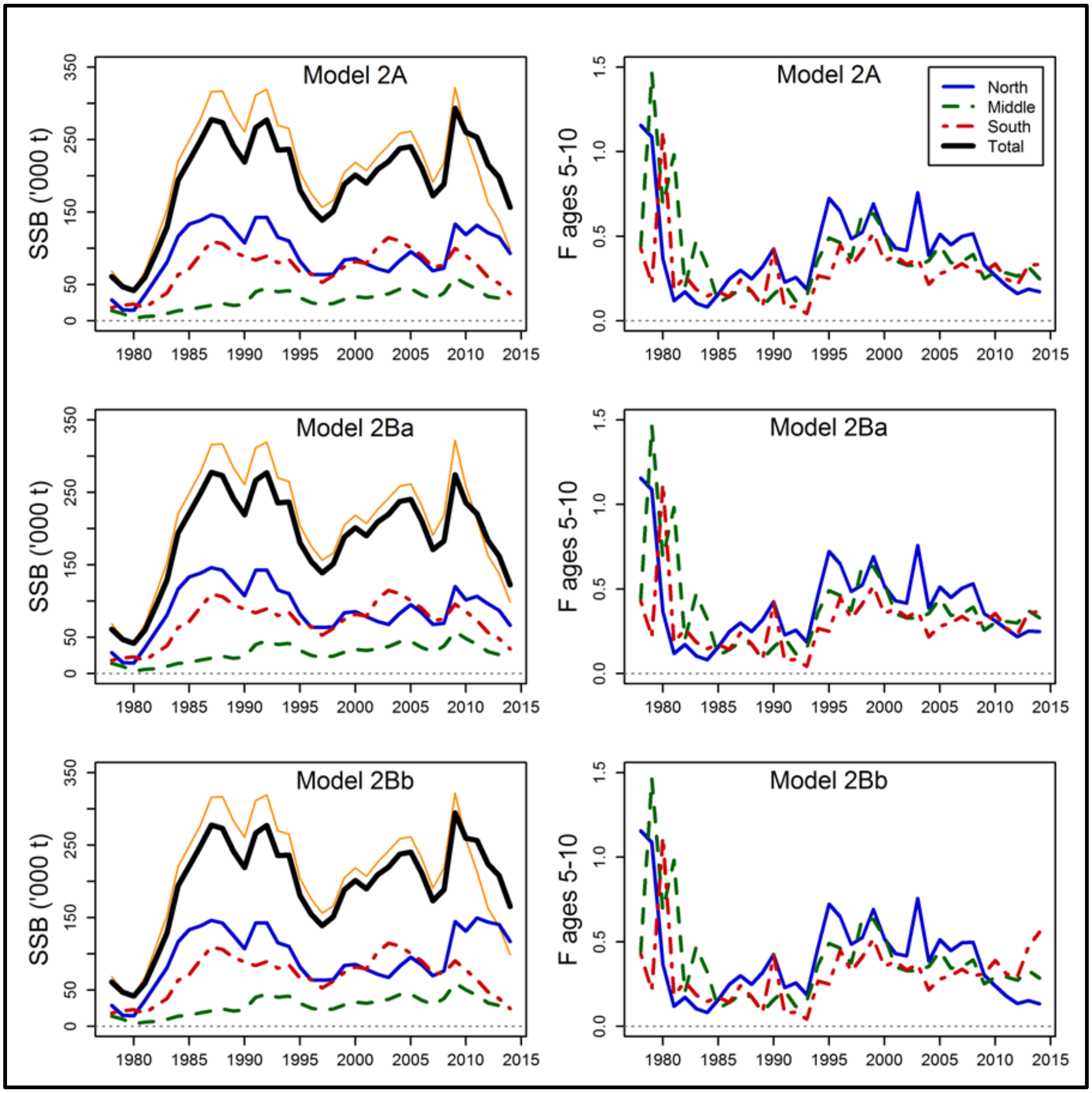

Figure 19. Estimated spawning stock biomass (SSB; left column) and average F for ages 5-10 years (right column) for variants of Model 2 that treat fall spawners as three separate populations (North, Middle and South). The thin orange line in the right column panels shows SSB estimated by Model 1 in the 2014 assessment. Model 2A (upper row) assumes constant fully-recruited q (prior to adjustments for changes in mesh size and fish length). Model 2Ba (middle row) allows q to vary in common among populations over time. Model 2Bb (lower row) allows q to vary independently between populations over time. Total (thick solid black line in the right column) is the SSB for the southern Gulf of St. Lawrence.

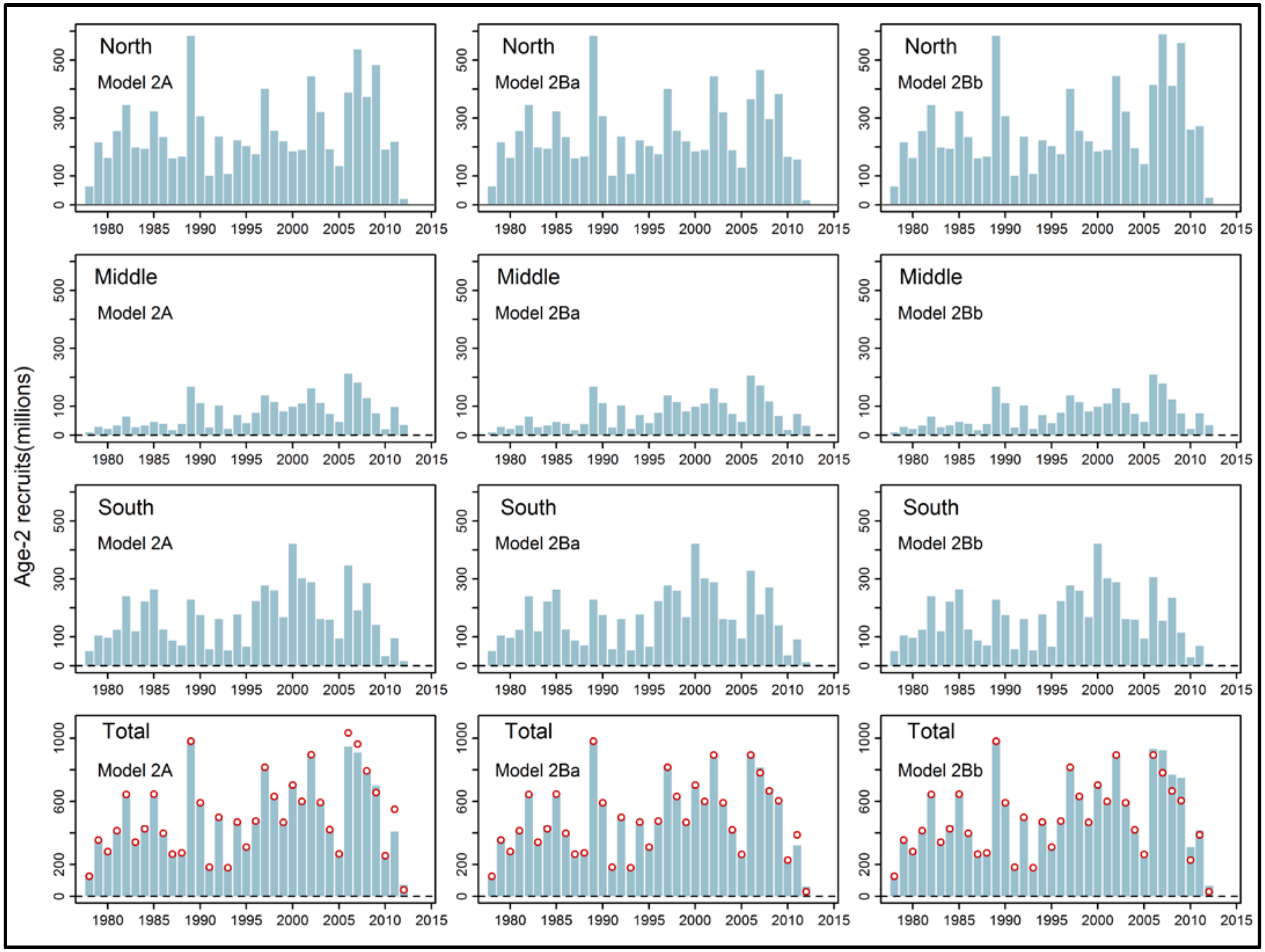

Figure 20. Estimated abundance of recruits at age-2 by population (North in upper row; Middle in second row; South in third row) and the total for the southern Gulf of St. Lawrence (bottom row) summed over populations. Circles in the panels of the bottom row are the recruit abundances estimated by single-population models (Model 2A is compared with Model 1A, and Models 2Ba and 2Bb with Model 1B.)

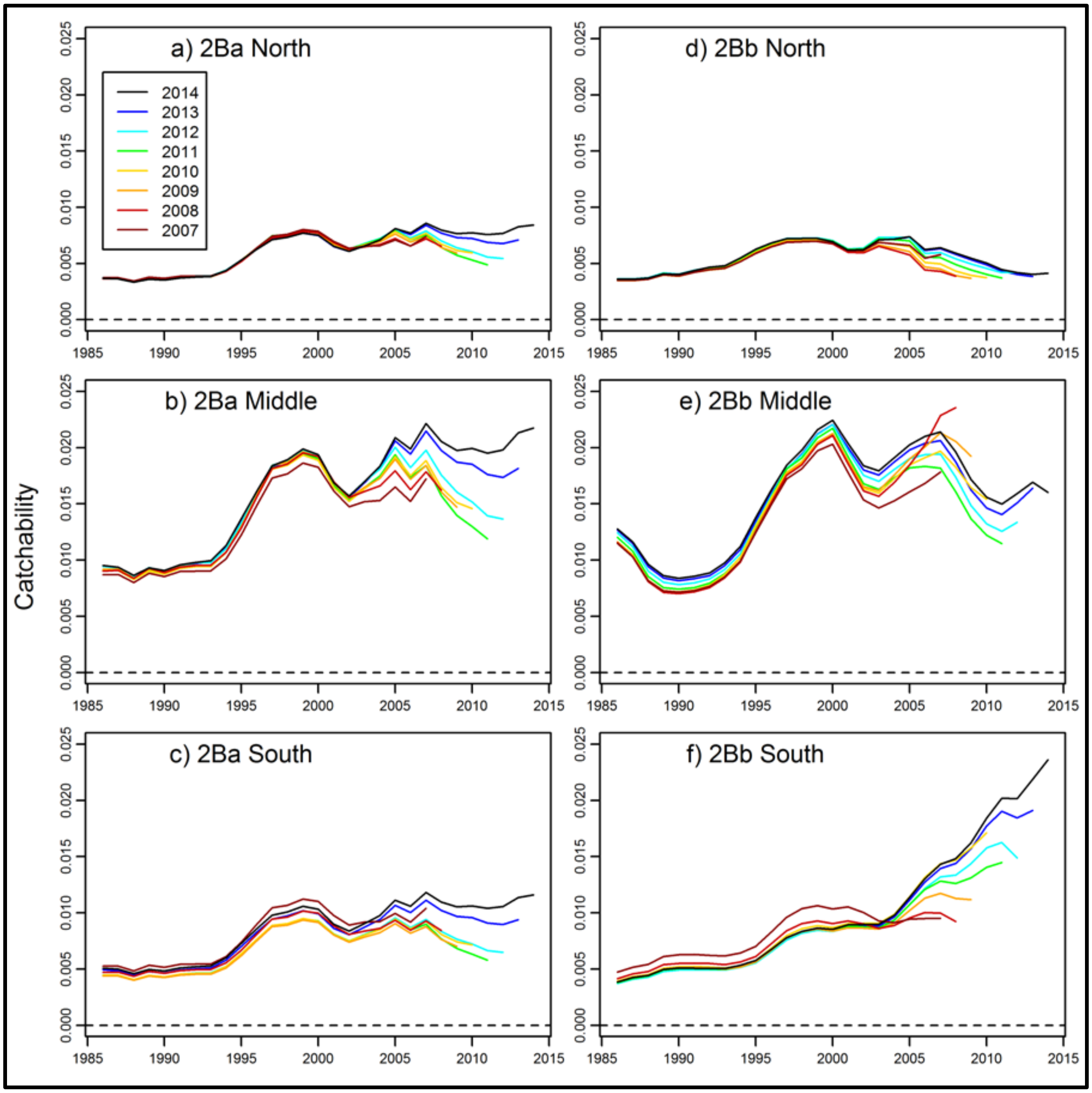

Figure 21. Retrospective patterns in fully-recruited catchability to the gillnet fishery from variants of Model 2 (Model 2Ba left column; Model 2Bb right column) for the North (upper row), Middle (middle row) and South (bottom row) populations of fall spawing Atlantic herring of the southern Gulf of St. Lawrence.

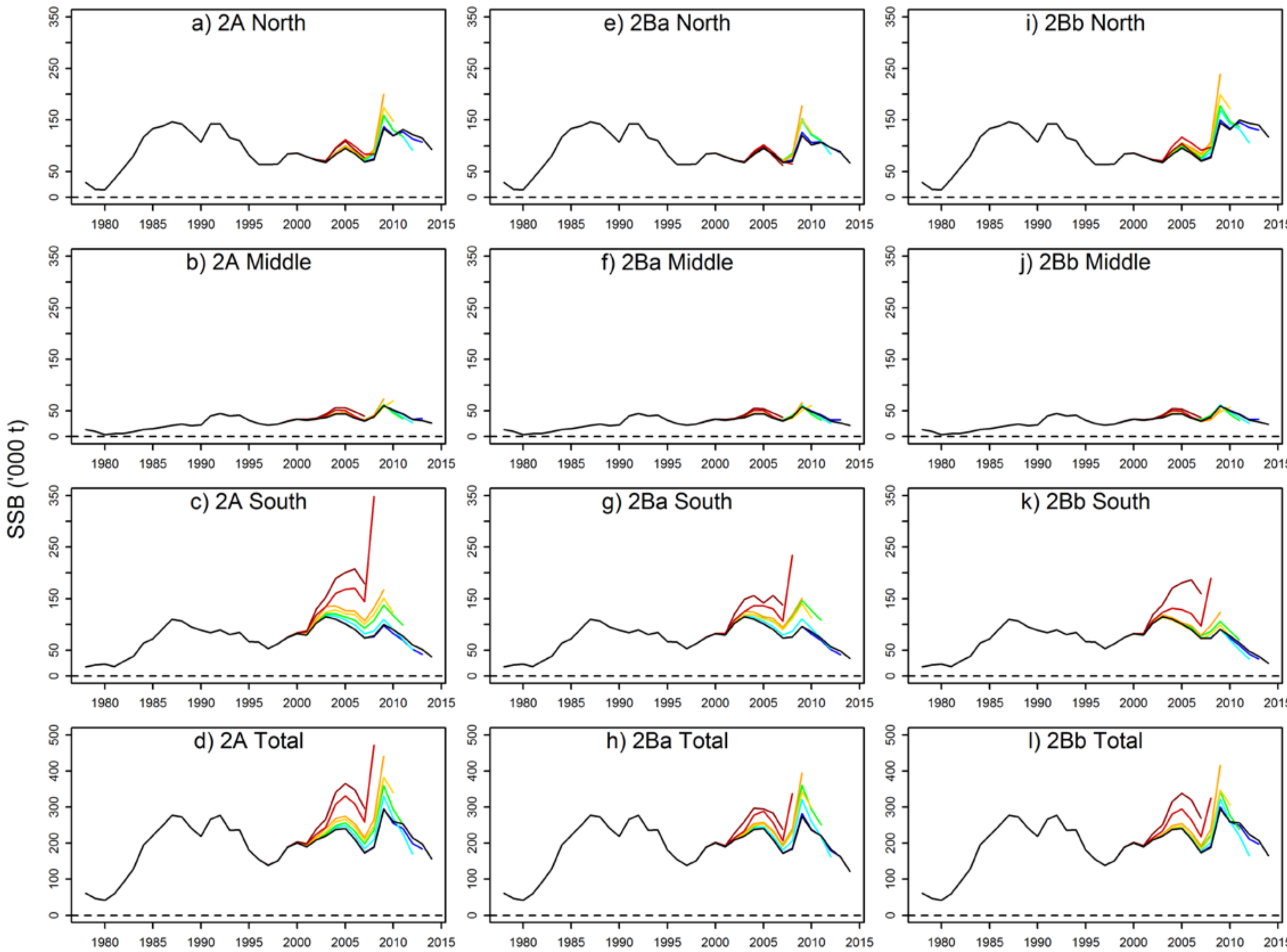

Figure 22. Retrospective patterns in spawning stock biomass (SSB) of fall spawning Atlantic herring from variants of Model 2 for the three populations (North, Middle, South) and for the entire southern Gulf of St. Lawrence. Lines are interpreted as per legend in Figure 21.

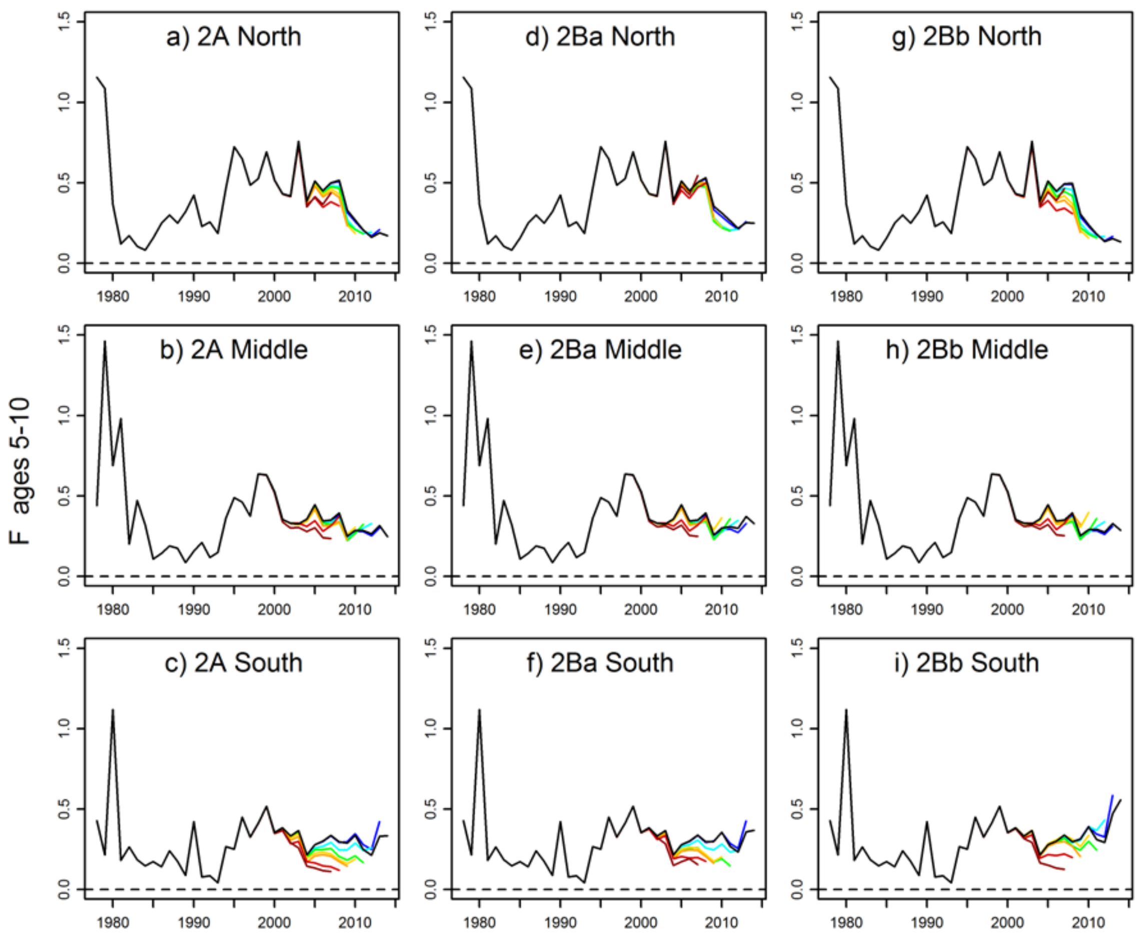

Figure 23. Retrospective patterns in the instantaneous rate of fishing mortality (F) averaged over ages 5 to 10 years of fall spawning Atlantic herring from variants of Model 2 for the three populations (North, Middle, South) of the southern Gulf of St. Lawrence. Lines are interpreted as per legend in Figure 21.

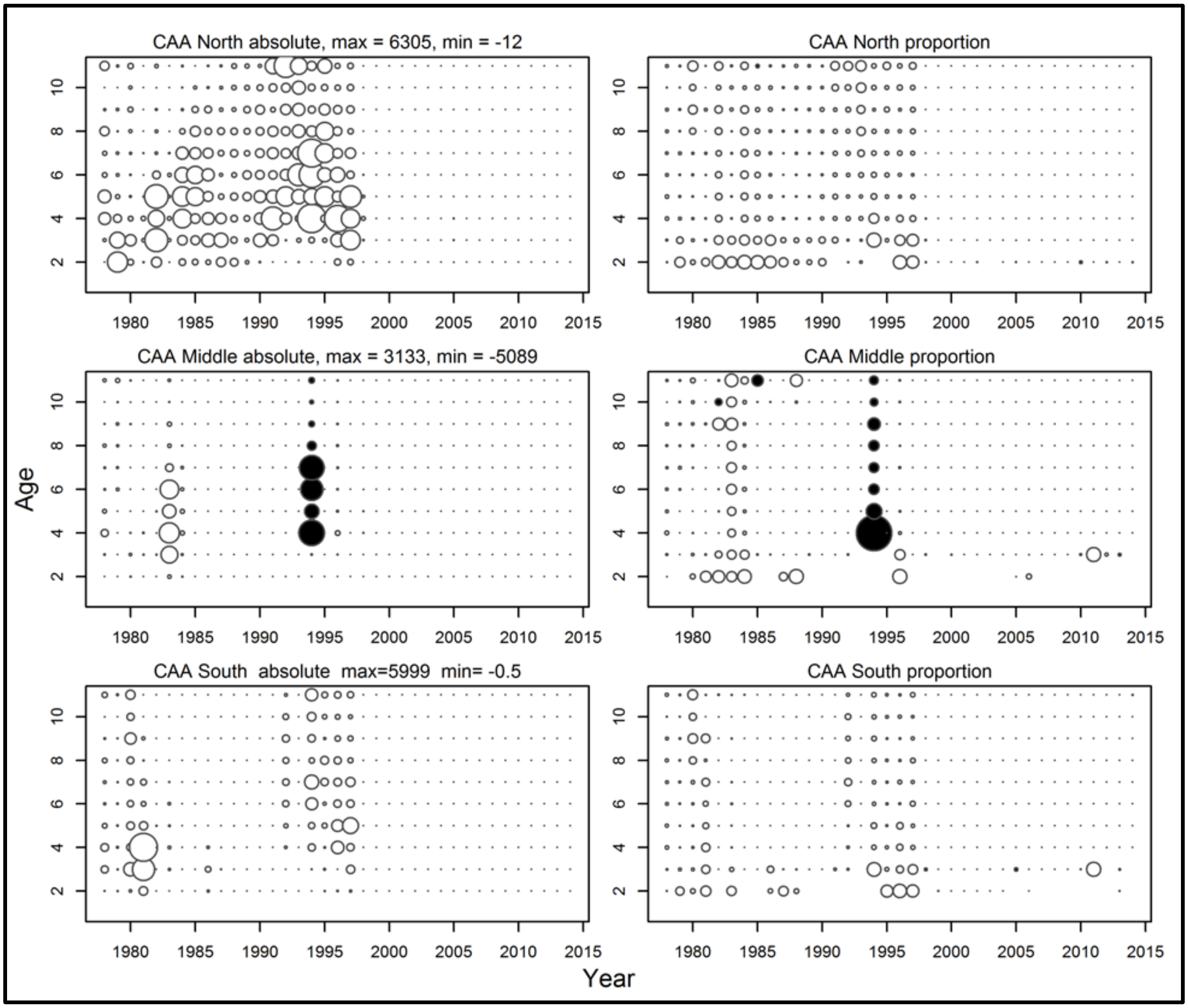

Figure 24. Comparison between the revised and original fishery catch-at-age (CAA) data of fall spawning Atlantic herring for the three populations of the southern Gulf of St. Lawrence. Circle size is proportional to the difference (new data – old data). The left panels show the absolute difference. The right panels show the difference as a proportion of the new values. Filled circles indicate negative values (old data > new data).

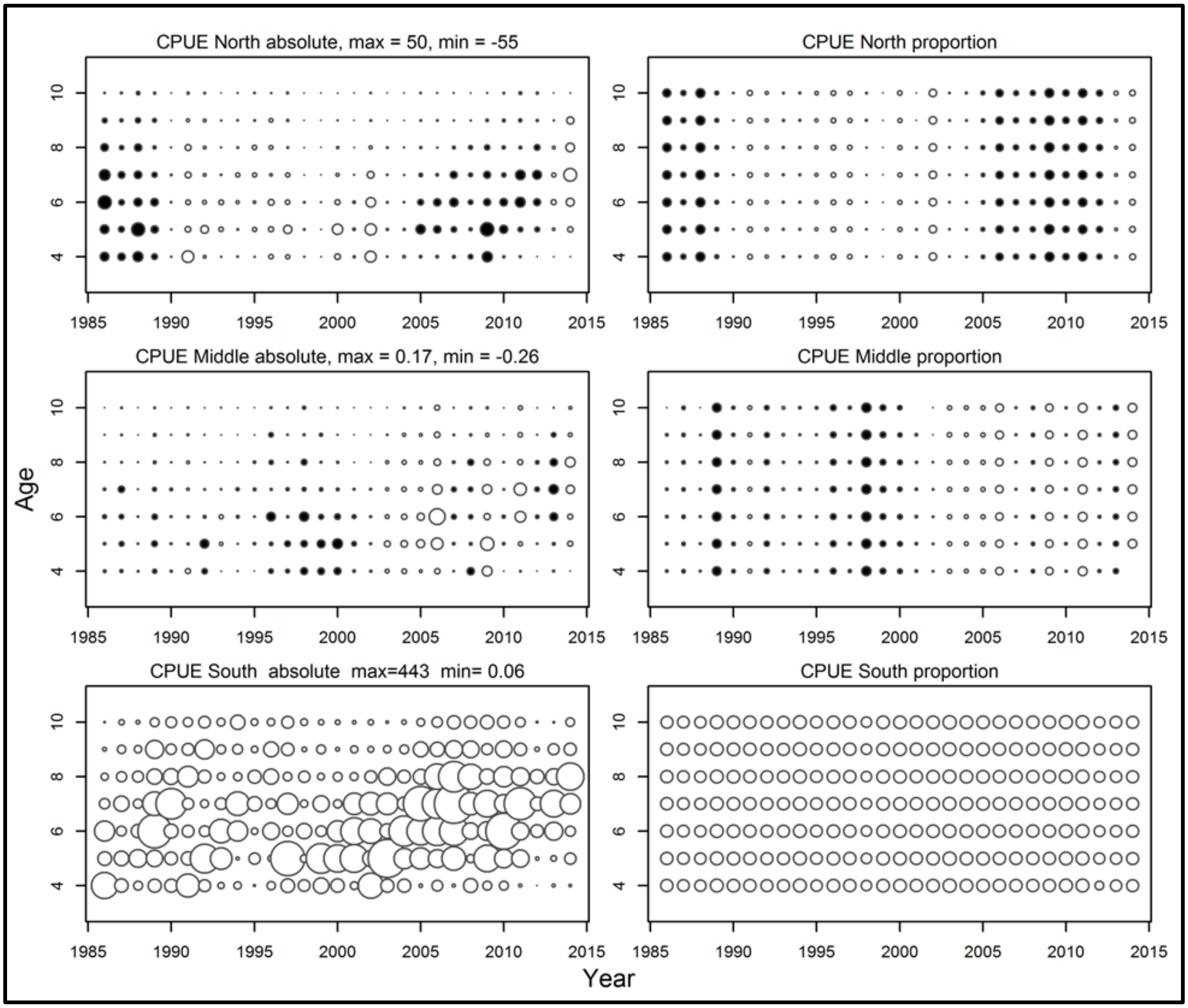

Figure 25. Comparison between the revised and original fishery CPUE indices of fall spawning Atlantic herring for the three populations of the southern Gulf of St. Lawrence. Circle size is proportional to the difference (new data – old data). The left panels show the absolute difference. The right panels show the difference as a proportion of the new values. Filled circles indicate negative values (old data > new data).

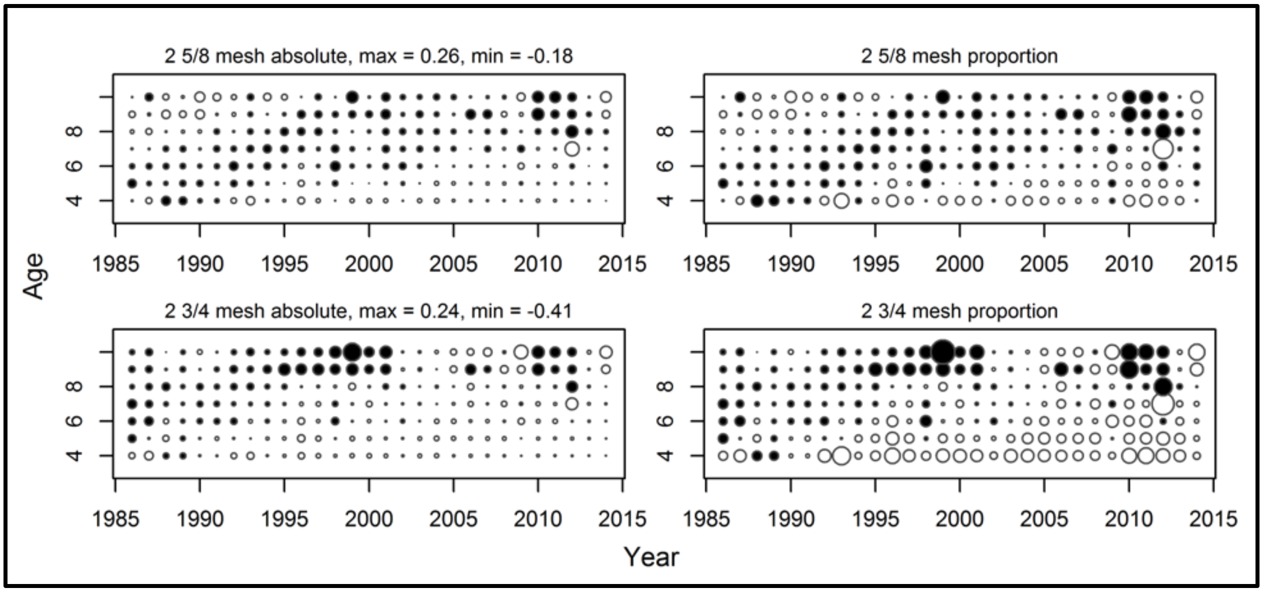

Figure 26. Comparison between the revised and original relative selectivity matrices for mesh sizes $2^5/_8$ inches (top row) and $2^3/_4$ inches (bottom row). Circle size is proportional to the difference (new data – old data). The left panels show the absolute difference. The right panels show the difference as a proportion of the new values. Filled circles indicate negative values (old data > new data).

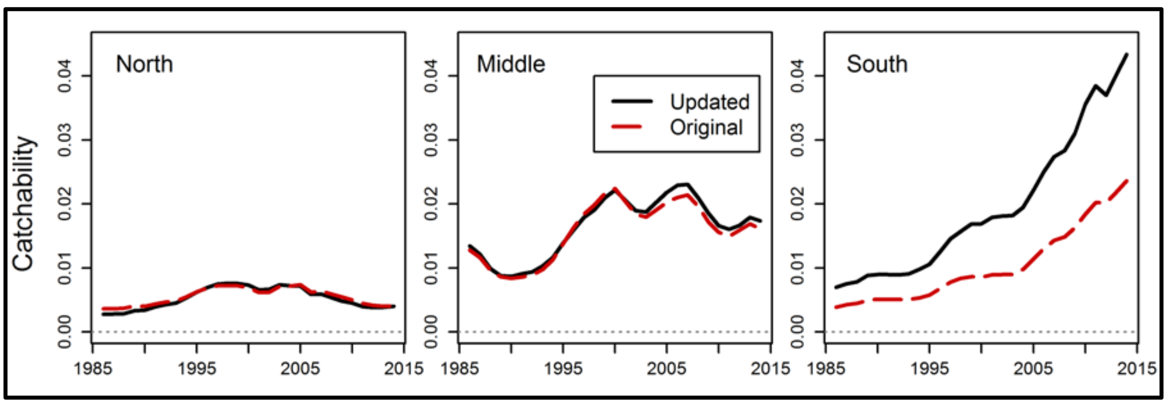

Figure 27. Estimates of fully-recruited catchability to the gillnet fishery from Model 2Bb for the three populations based on the original and updated data.

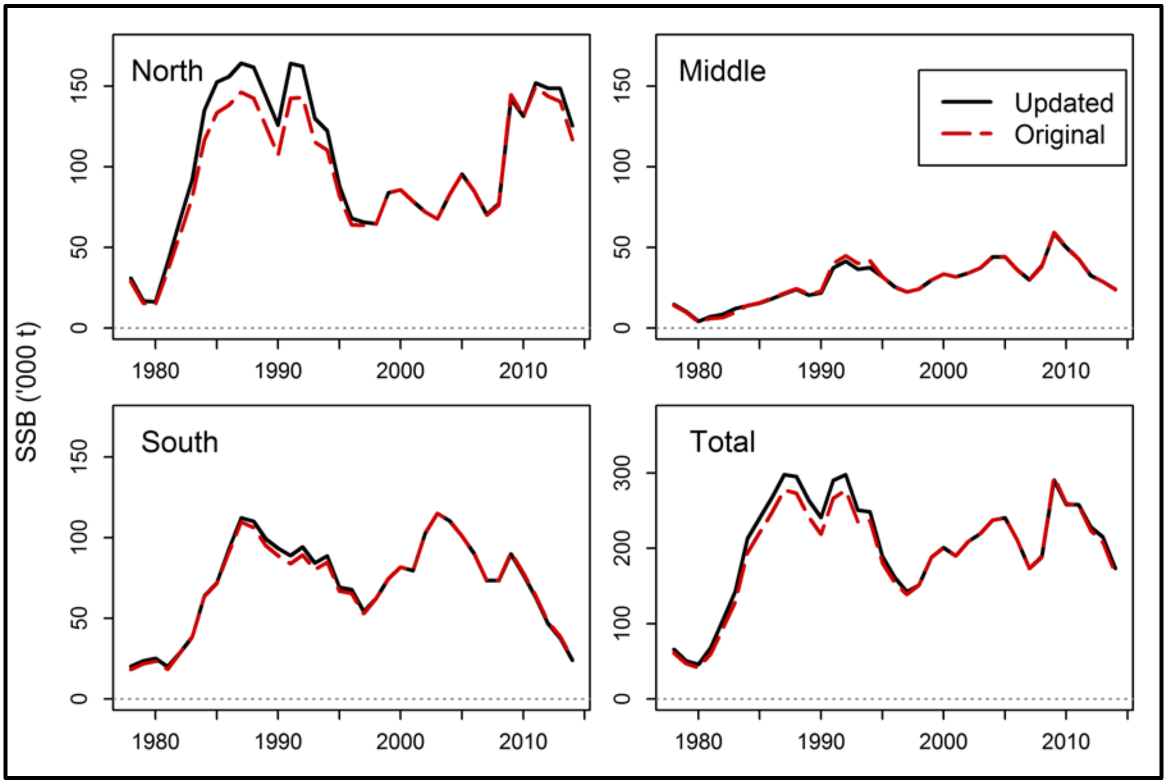

Figure 28. Estimates of SSB from Model 2Bb for the three populations (North, Middle, South) and overall for the southern Gulf of St. Lawrence, based on the original and updated catch-at-age data.

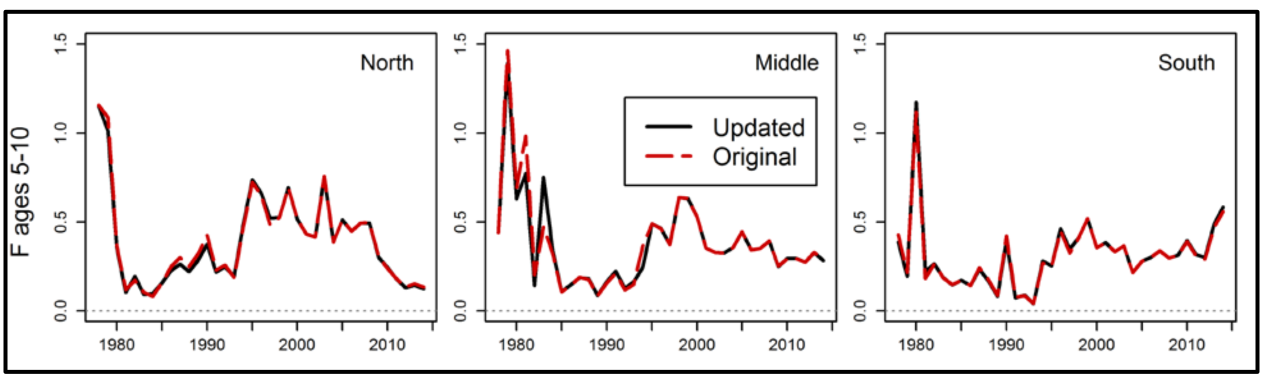

Figure 29. Estimates of the instantaneous rate of fishing mortality F for ages 5-10 from Model 2Bb for the three populations based on the original and updated data.

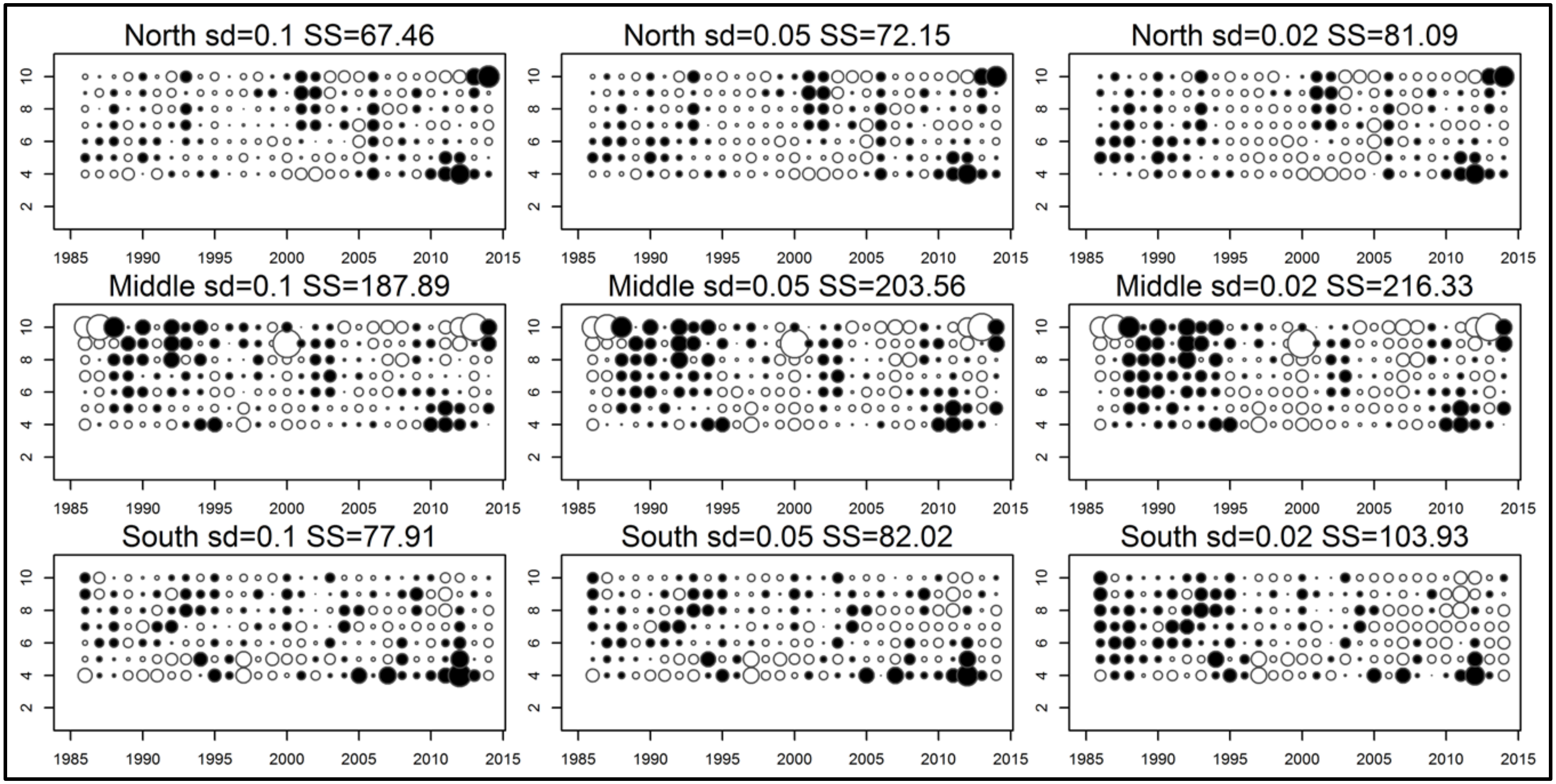

Figure 30. Residuals from the CPUE index for the gillnet fishery at different assumed levels for the σ (sd) of process error in fishery q, by population (North in upper row; Middle in middle row; South in lower row). Circle radius is proportional to residual magnitude. Closed circles indicate negative residuals (i.e., observed < predicted).

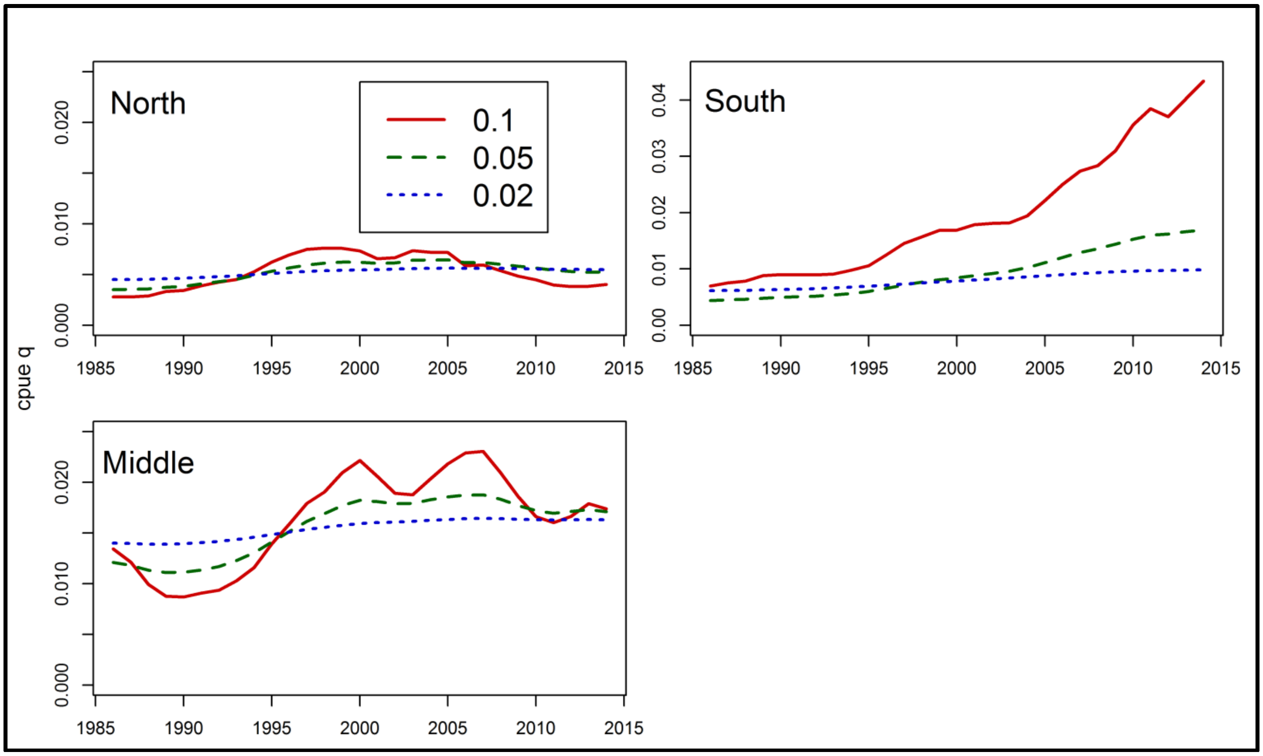

Figure 31. Effect of the value assumed for the σ of process error in fishery q on estimated trends in q by population (North, Middle, South).

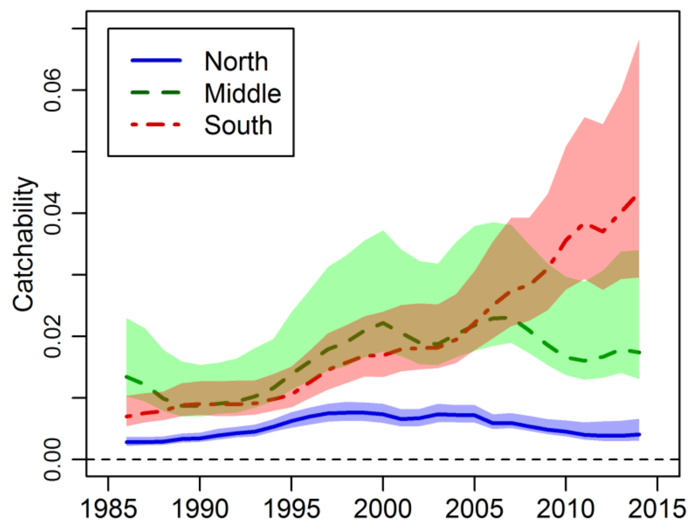

Figure 32.Estimated trends in fully recruited catchability to the gillnet fishery of fall spawning herring by population (North, Middle, South) in the southern Gulf of St. Lawrence based on Model 2Bb fit to the updated data with σ = 0.1. Lines show the MLEs and shading the 95% confidence bands based on MCMC sampling.

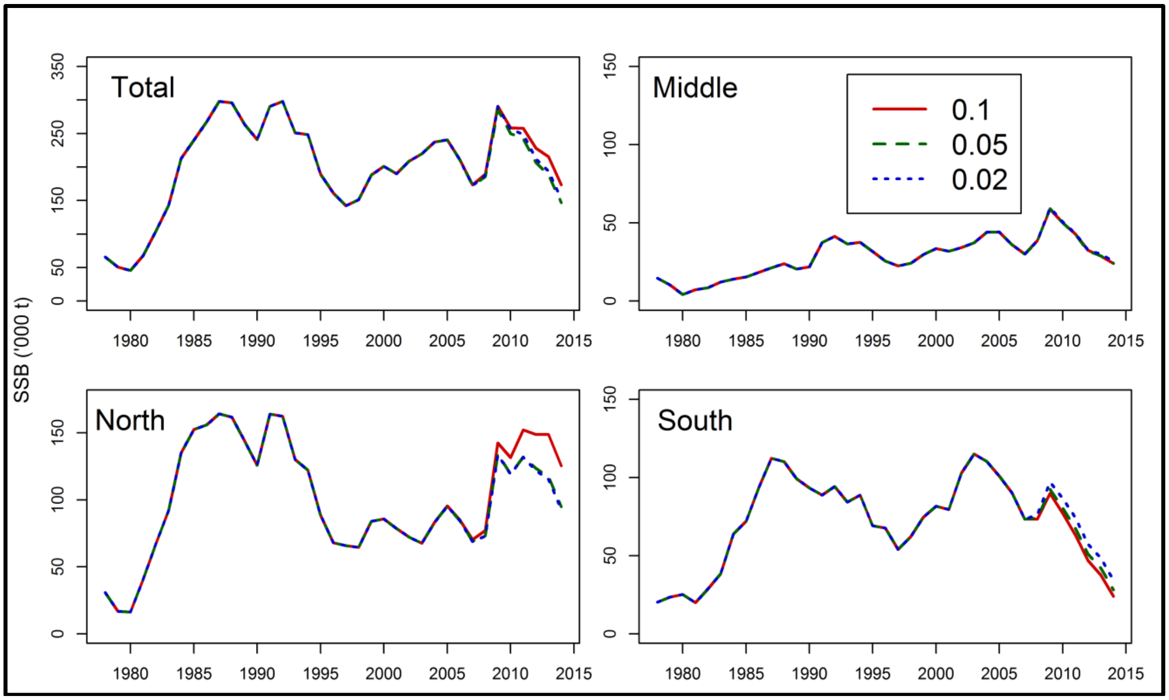

Figure 33. Effect of the value assumed for the σ of the process error in fishery q on estimated SSB of fall spawning herring by population (North, Middle, South) and overall for the southern Gulf of St. Lawrence.

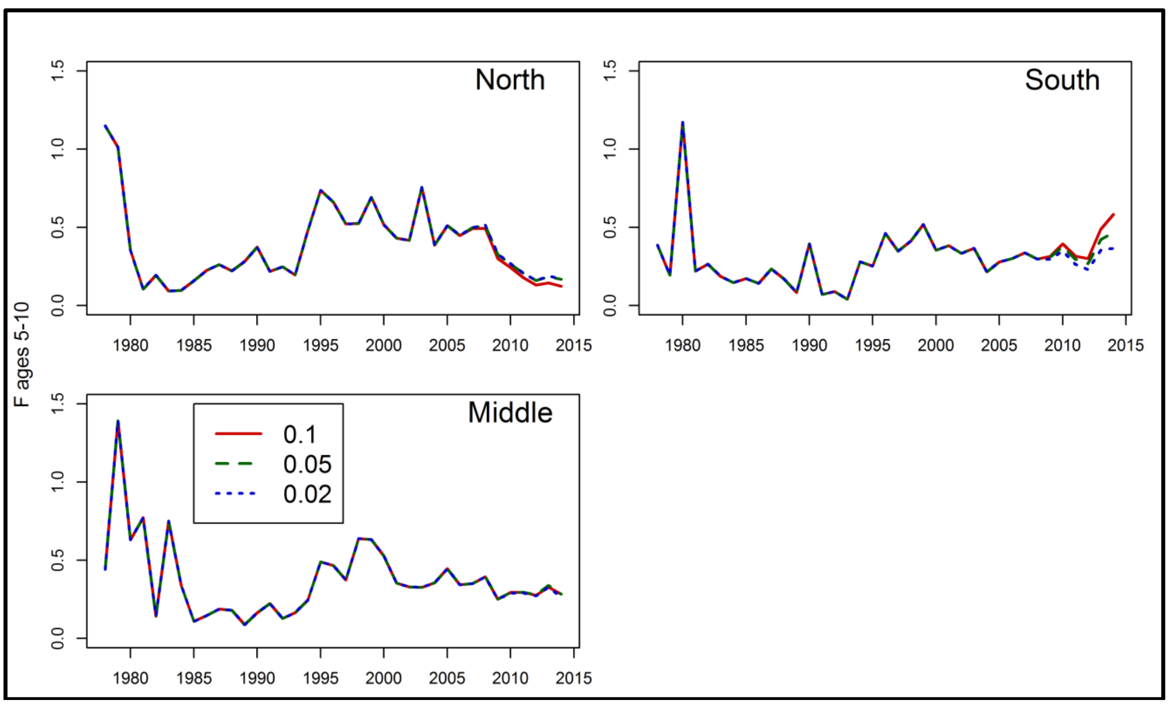

Figure 34. Effect of the value assumed for the σ of the process error in fishery q on estimated F averaged over ages 5 -10 years of fall spawning herring by population (North, Middle, South) of the southern Gulf of St. Lawrence.

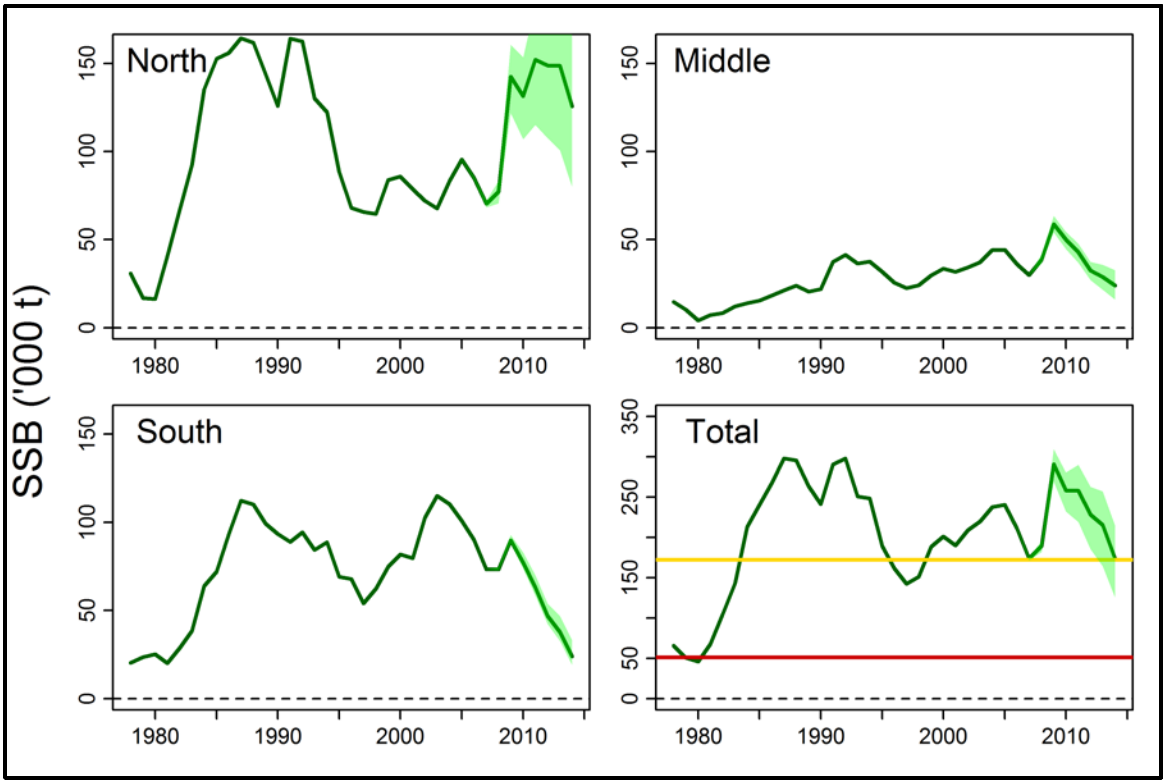

Figure 35. Estimated spawning stock biomass (SSB) of fall-spawning herring in the southern Gulf of St. Lawrence, by putative population (North, Middle, South) and summed over populations (Total). Line shows the MLE and shading the 95% confidence intervals based on MCMC sampling. In the lower right panel, the gold line is the upper stock reference (USR) and the red line the limit reference point (LRP).

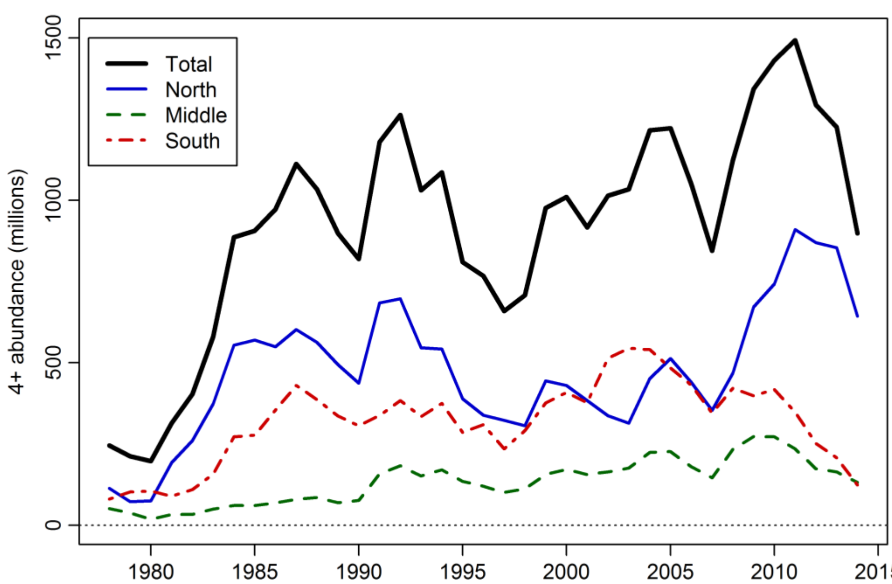

Figure 36. Estimated abundance of fall-spawning herring 4 years and older in the southern Gulf of St. Lawrence, by putative population (North, Middle, South) and summer over populations (Total).

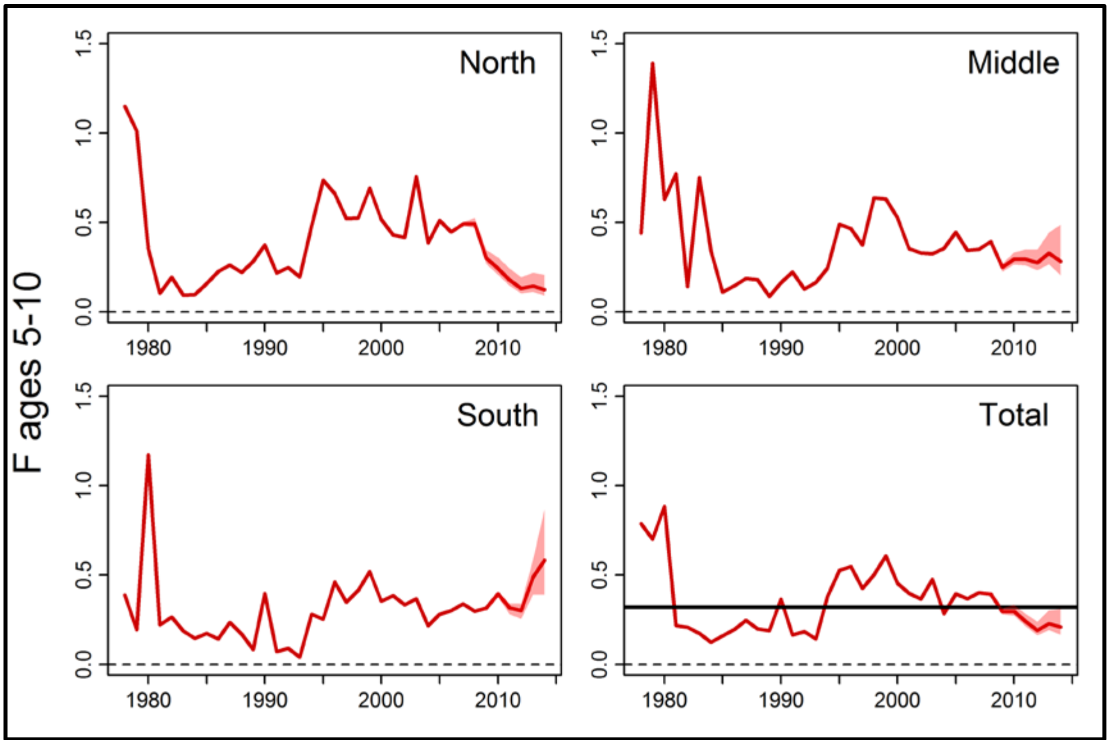

Figure 37. Estimated abundance-weighted average F for ages 5-10 years for fall-spawning herring in the southern Gulf of St. Lawrence, by putative population (North, Middle, South) and averaged over populations (Total, weighting by abundance). Line shows the MLE and shading the 95% confidence intervals based on MCMC sampling. The black horizontal line in the lower right panel is the target F of 0.32.

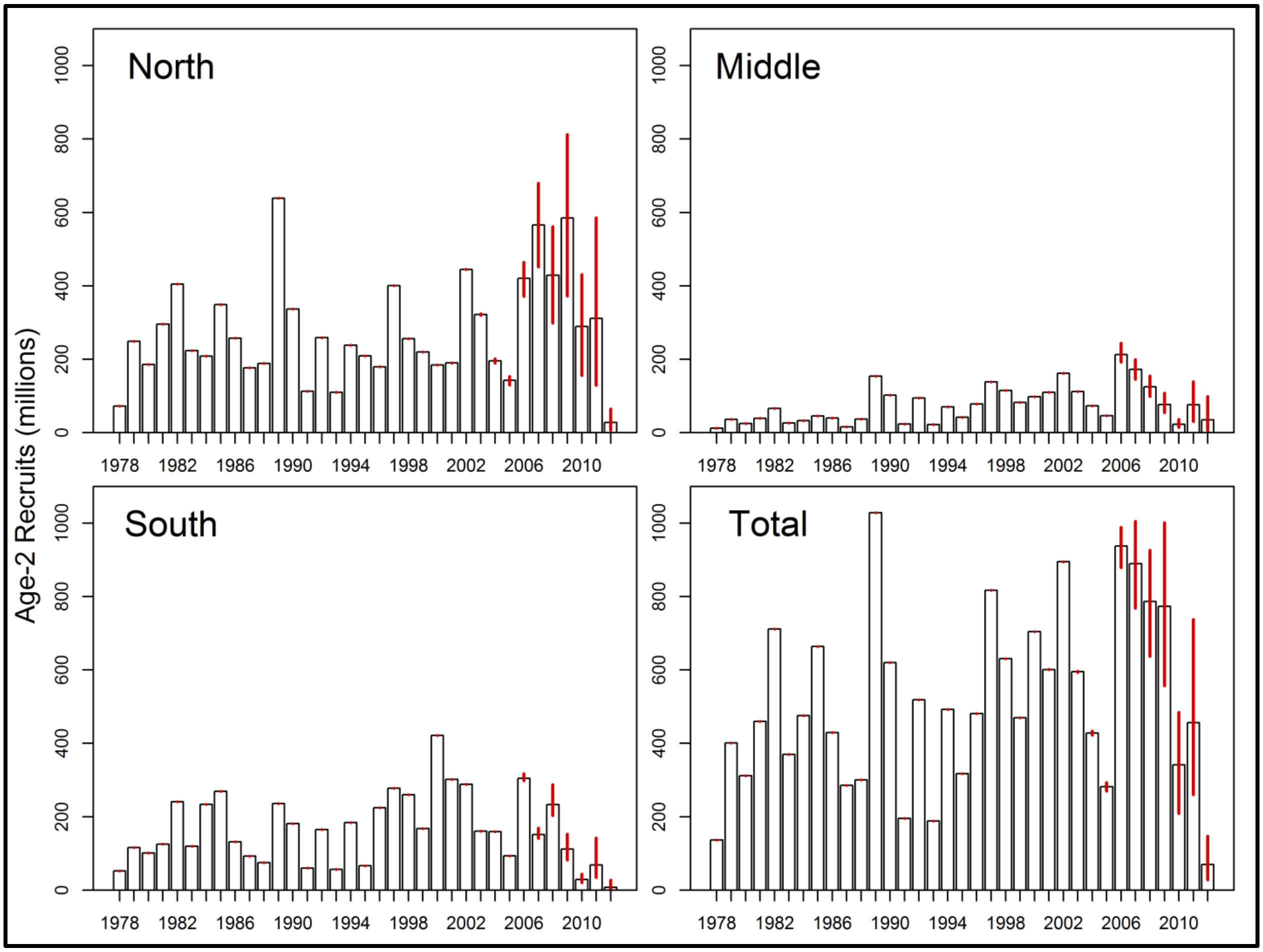

Figure 38. Estimated abundance of recruits at age 2 of fall spawning Atlantic herring in each putative population (North, Middle, South) and summed over populations (Total) of the southern Gulf of St. Lawrence. Vertical lines show 95% confidence intervals.

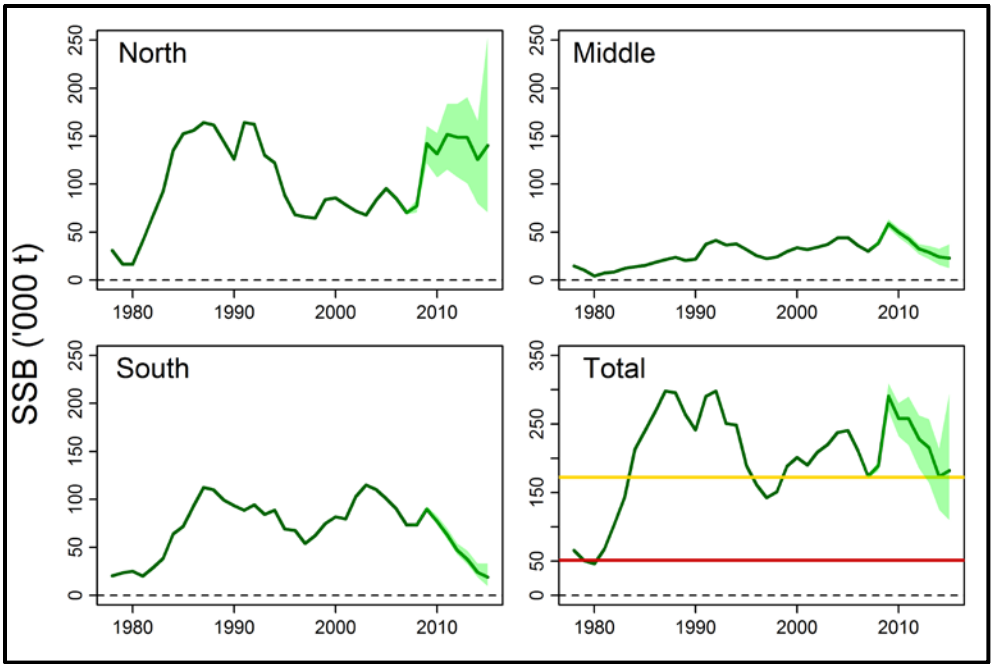

Figure 39. Estimated spawning stock biomass (SSB) of the fall-spawning component of southern Gulf of St. Lawrence herring projected forward from 2014 to the beginning of 2015. Results are shown by putative population (North, Middle, South) and summed over populations (Total). Lines show the MLEs and shading the 95% confidence intervals based on MCMC sampling. In the lower right panel, the gold line is the upper stock reference (USR) and the red line the limit reference point (LRP).

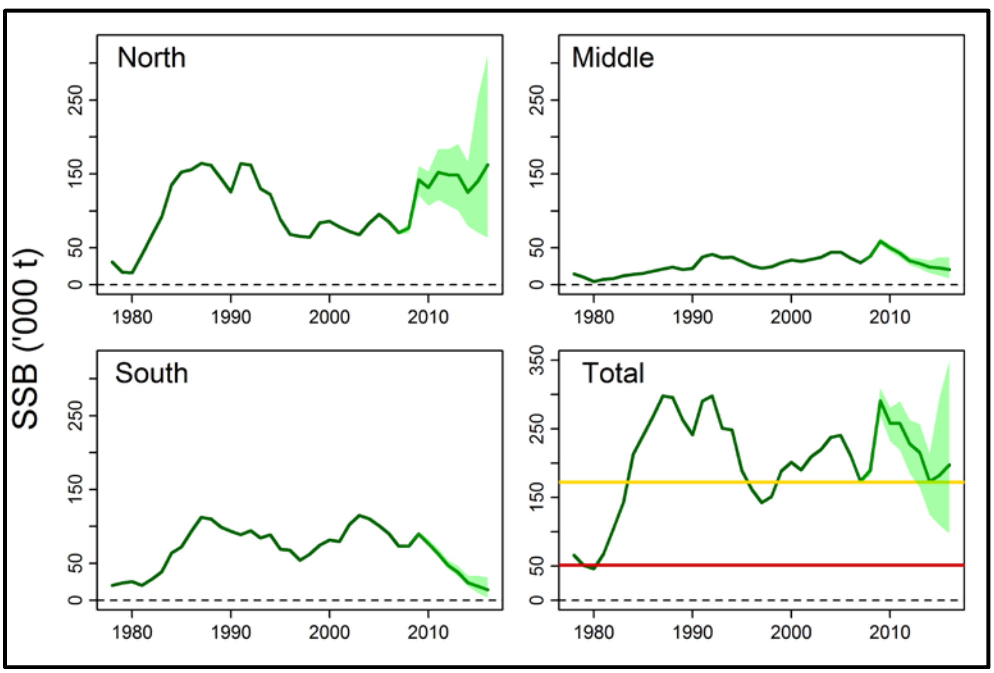

Figure 40. Estimated SSB projected forward to the start of 2016 assuming a catch of 29,000 t in 2015. See the caption to Figure 39 for further details.

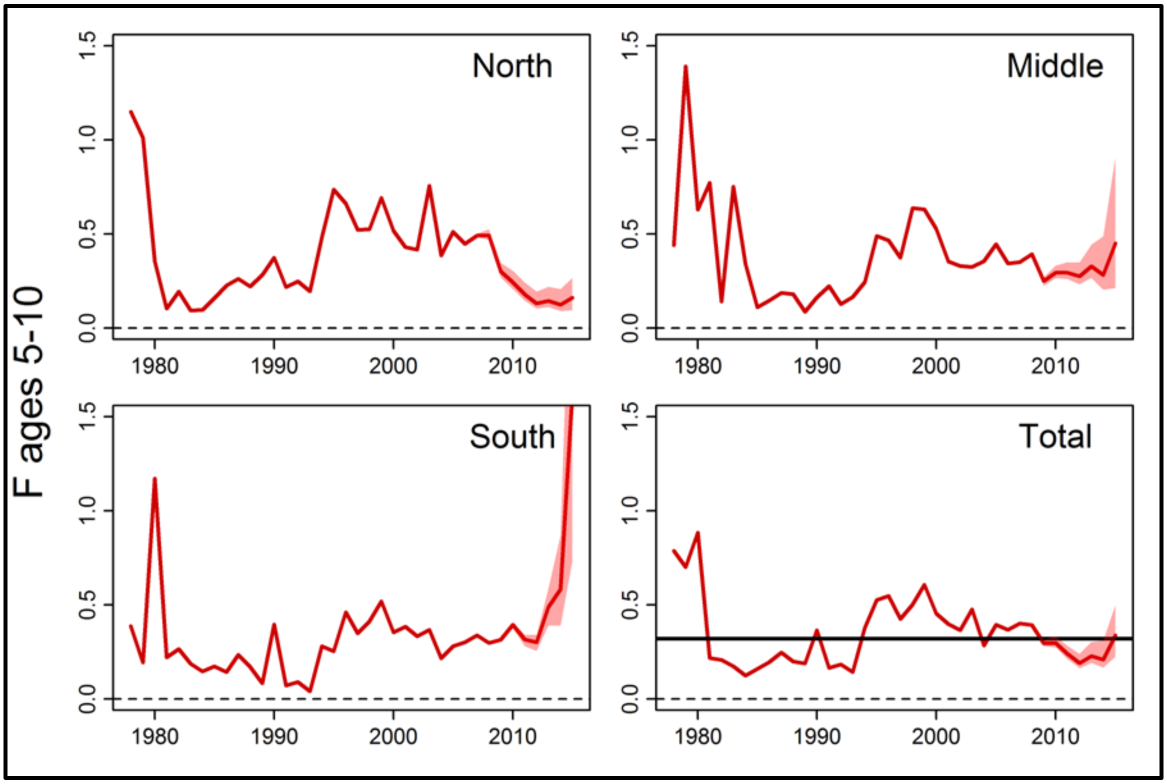

Figure 41. Estimated fully recruited F at ages 5 to 10 (F_{5-10}) of fall spawning Atlantic herring by population (North, Middle, South) and for the southern Gulf of St. Lawrence (Total) projected forward to 2015 assuming a total catch of 30,000 t in the southern Gulf of St. Lawrence in 2015. The F_{5-10} for the aggregate of the three populations (Total) is an abundance-weighted average. Lines show the MLE and shading the 95% confidence interval. In the lower right panel, the solid black horizontal line is F=0.32, the target upper limit for F_{5-10}.

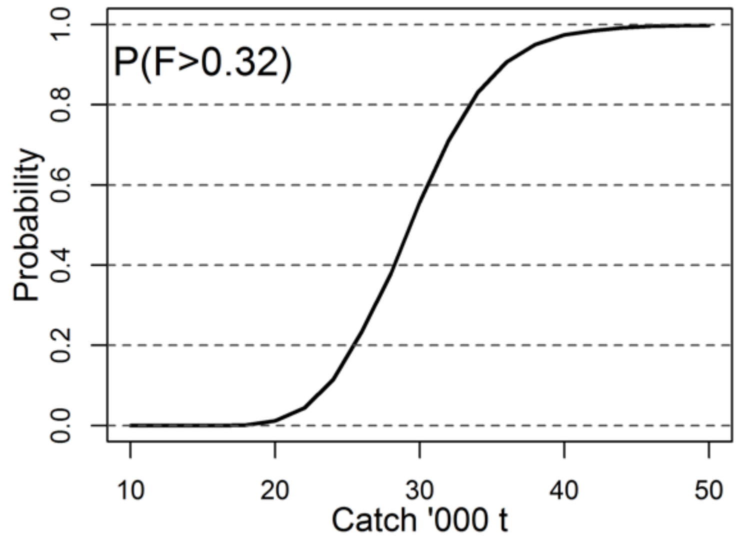

Figure 42. Estimated probability that the abundance-weighted $F_{5\text{-}10}$ averaged over all three putative populations will exceed the estimated $F_{0.1}$ level of 0.32 in 2015 at total catch levels of 10,000 to 50,000 t, assuming that the catch is distributed among populations in the recently observed proportions.

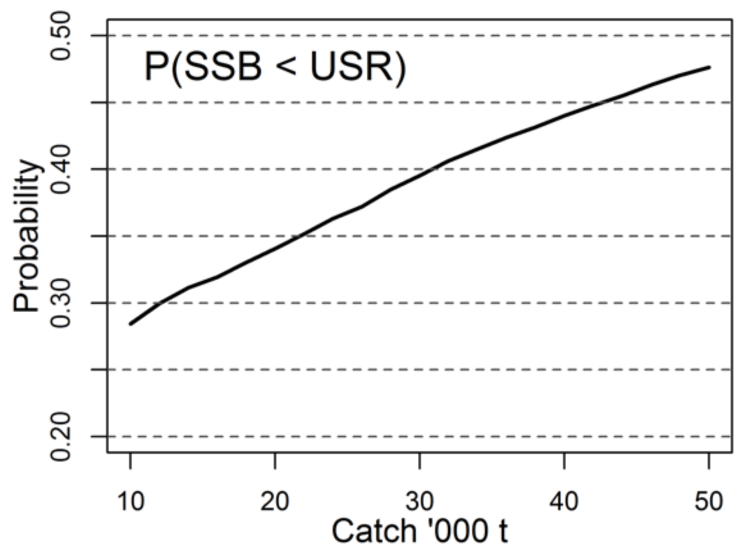

Figure 43. Estimated probability that SSB summed over the three putative populations of fall-spawning herring in the southern Gulf will fall below the USR of 172,000 t at the start of 2016 given various catch levels in 2015.

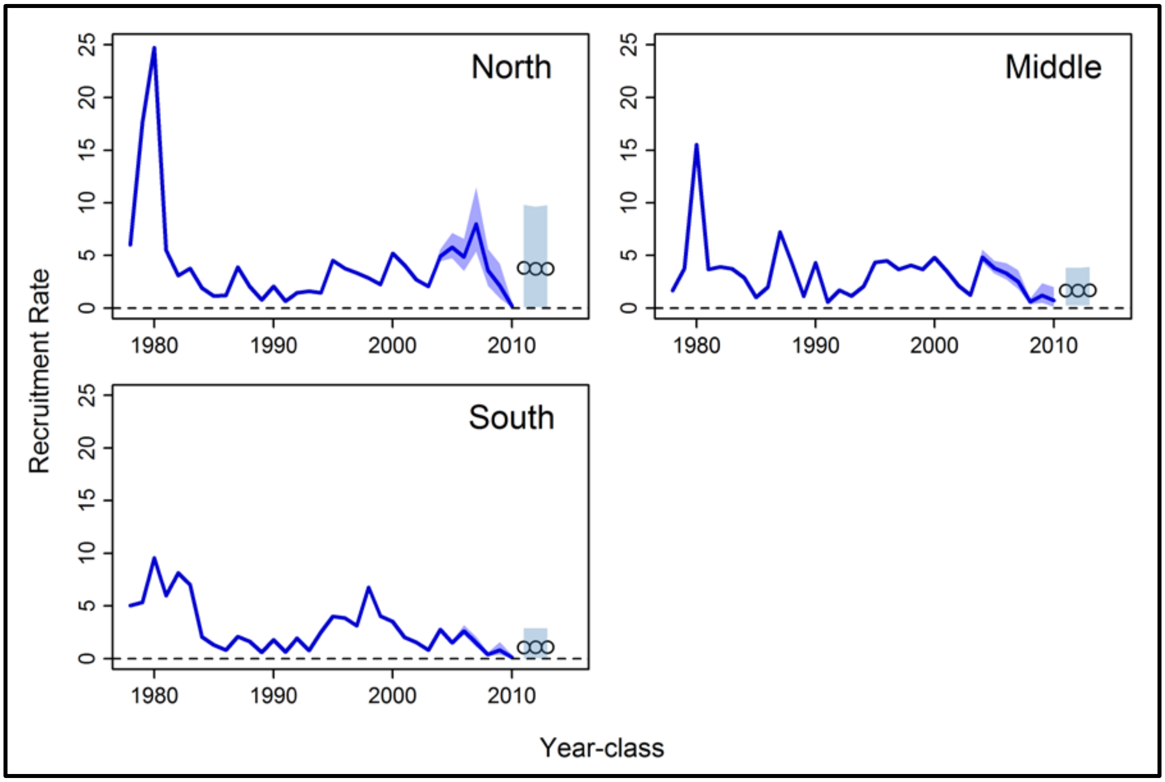

Figure 44. Estimated recruitment rates (at age 2) of fall-spawning herring by putative population (North, Middle, South) in the southern Gulf of St. Lawrence. The line shows the mean and the shading the 95% confidence intervals based on the MCMC samples. The circles and light shading indicate the mean and central 95% of the values used in the projections.