Northeast Fisheries Science Center Reference Document 15-16

doi:10.7289/V5CN71WS

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U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
National Marine Fisheries Service
Northeast Fisheries Science Center
Woods Hole, Massachusetts
August 2015

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Information Quality Act Compliance: In accordance with section 515 of Public Law 106-554, the Northeast Fisheries Science Center completed both technical and policy reviews for this report. These predissemination reviews are on file at the NEFSC Editorial Office.

This document may be cited as:

Deroba J. 2015. Atlantic herring operational assessment report 2015. US Dept Commer, Northeast Fish Sci Cent Ref Doc. 15-16; 30 p. Available at: http://www.nefsc.noaa.gov/publications/
doi:10.7289/V5CN71WS

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PREFACE

This document represents the findings of an operational assessment of Atlantic herring. The meeting was held April 8-9, 2015 at the Northeast Fisheries Science Center (NEFSC), National Marine Fisheries Service (NMFS), Woods Hole, MA. The meeting was chaired by Alexei Sharov (Maryland Department of Natural Resources [MD DNR]), with Jason MacNamee (Rhode Island Department of Environmental Management [RI DEM]) and Chris Legault (NEFSC) serving as reviewers. All reviewers are members of the New England Fishery Management Council (NEFMC) Scientific and Statistical Committee (SSC).

The Terms of Reference (TOR) were approved by the Assessment Oversight Panel (AOP), whose members are John Boreman (Mid Atlantic Fisheries Management Council [MAFMC] SSC), Jake Kritzer (NEFMC SSC), and Paul Rago (NEFSC). This group met via Webinar on December 22, 2014, and February 17, 2015. Preliminary analyses of the updated model performance suggested that the assessment model might not be a sufficient basis for estimating overfishing limits. The second meeting of the AOP in February 2015 was designed to review a "Plan B" option that would allow an alternative basis for setting overfishing limits. The Terms of Reference and Plan B option were approved by the AOP and used to guide the assessment team led by Jonathan Deroba.

Concerns about model performance and specification of Plan B helped clarify some ambiguities within the Northeast Regional Coordinating Council (NRCC) guidance memo on operational assessments. The guidance document (NRCC 2011) simultaneously gives the AOP and the Review Panel the authority to reject the primary assessment model and specify the use of an alternative. In the end it was decided to allow the Review Panel to determine the appropriate assessment approach. In view of the depth of the discussions by the Review Panel, it seems appropriate for the Review Panel, rather than the AOP, to make this determination. The Review Panel can review a greater range of material on model performance and weigh alternatives more thoroughly than possible during the much shorter meetings of the AOP.

In the case of Atlantic herring, the Review Panel judged that the original assessment model could be retained but that stock status would be based on a retrospective adjustment of terminal year stock size. This decision had the advantage of retaining accepted measures of overfishing and overfished condition, and allowing for multi-year projections. Values of biological reference points were updated in response to revised estimates of average weights-at-age, maturity-at-age, selectivity, and recruitment, but the basis of the reference points was unaltered.

Comments by the Review Panel are included in their entirety in this report. I wish to thank the assessment scientists and colleagues in the NEFSC Population Dynamics Branch for their efforts to implement the operational assessment of Atlantic herring. I also thank the Review Panel, and especially the Chair, for their timely and insightful reviews. This document is part of an overall program to streamline the stock assessment process and provide more timely information to the New England and Mid Atlantic Fishery Management Councils. I thank the executive staff of the NEFMC for their efforts to identify, coordinate, and support the peer Review Panel. All meetings of the AOP and Review Panel were open to the public and I appreciate the valuable input we received.

Paul Rago, Chief
Population Dynamics Branch
May 11, 2015

Northeast Regional Coordinating Council (NRCC). 2011. A new process for assessment of managed fishery resources off the Northeastern United States. Unpublished white paper; 26 p.

ATLANTIC HERRING OPERATIONAL ASSESSMENT REVIEWER RESPONSES TO TERMS OF REFERENCE

1. Update all fishery-dependent data (landings, discards, catch-at-age, etc.) and all fishery-independent data (research survey information) used as inputs in the baseline model or in the last operational assessment.

All data were updated to the terminal year of 2014, with the exception of the 2014 NEFSC fall survey age composition and 2014 consumption estimates. The components of the fishery-dependent data that were updated were the catches for the mobile gear fishery and fixed gear fishery, including biological sampling. Canadian fixed gear catches were combined with US fixed gear catches for the operational assessment.

Fishery-independent survey data were updated through the terminal year of 2014. All three fishery-independent surveys used in the assessment – namely, the NMFS spring and fall trawl surveys and the summer shrimp trawl survey – were updated and included in the assessment. The data were all processed and treated in a consistent manner to the 2012 benchmark assessment.

The Panel concludes this TOR was met.

2. Estimate fishing mortality and stock size for the current year, and update estimates of these parameters in previous years, if these have been revised.

The biological parameters as produced in the 2012 benchmark assessment were produced from this operational assessment. These include the F rate for the fully selected (age-5) fish and a SSB value for the stock. In addition to terminal year estimates, estimates for the entire time series were also produced. Given these historical estimates, and an ability to review this data through a retrospective analysis both internally to the model as well as through a historical comparison between this 2015 update and the 2012 benchmark, differences in estimation were determined between the update and the earlier benchmark. Due to the internal retrospective pattern, and the directionality of that pattern to both decrease retrospectively the SSB value and increase retrospectively the F rate (so SSB is overestimated in the terminal year, and F is underestimated in the terminal year), the Review Panel suggests using a retrospectively adjusted value for the terminal year estimates using Mohn's Rho. The retrospectively adjusted SSB and F were outside the joint 80% confidence intervals of the 2014 SSB and F estimates, leading the Panel to recommend applying the adjustment. The retrospective adjusted values for the 2014 F and SSB are 0.16 and 623,000 mt, respectively. The retrospective adjustments were approximately a 40% decrease in SSB and a 60% increase in F.

The Panel concludes this TOR was met.

3. Identify and quantify data and model uncertainty that can be considered for setting Acceptable Biological Catch limits.

The magnitude and trend of the increase in M from the benchmark assessment had less support in this update. The assessment update indicated a divergence between the model-predicted removals due to natural mortality and the independent estimates of consumption derived from food habits data. Additional sources of natural mortality beyond consumption may also vary through time.

The strength of the 2011 year class was also examined through the use of a sensitivity analysis. This sensitivity analysis reduced the 2011 year class to an average abundance, which was then used for projections. Results indicated that short-term catch was influenced by this cohort, but did not depend entirely on it.

Use of the retrospective adjustment for stock status and modifying the population abundance-at-age for projections was considered to be the appropriate response to the moderate retrospective pattern observed in the update assessment.

Additional sources of uncertainty are addressed in TOR 7.

The Panel concludes this TOR was met.

4. If appropriate, update the values of biological reference points (BRPs).

MSY-based reference points F_{MSY}, MSY, and B_{MSY} are estimated internally within the Age Structured Assessment Program (ASAP) model. These reference points were updated based on the model run with the addition of the years of data (2012-2014). The F_{MSY} value decreased slightly in the 2015 assessment update (F_{MSY} =0.24) compared to the 2012 SAW54 benchmark assessment (F_{MSY}=0.27). MSY and SSB_{MSY} increased in the 2015 assessment update (MSY= 77,247 mt, SSB_{MSY}= 311,145 mt) compared to the 2012 SAW54 benchmark assessment (MSY=53,000, SSB_{MSY}=157,000 mt). The reference points were not adjusted for the retrospective pattern as there is no standard accepted way to make such an adjustment.

The Panel concludes this TOR was met.

5. Evaluate stock status with respect to updated status determination criteria.

The Panel considered the results of the base run of the model update as well as the Mohn's Rho adjusted terminal year values of F and SSB. After the correction for retrospective bias, SSB 2014 is ~2 times the SSB_{MSY} and F2014 is ~half of F_{MSY} (Figure 9). This result indicates that the stock status is robust, which gave the Panel some comfort in continuing to use the assessment for stock status determination and catch advice. There are no signals indicating this stock is in danger of overfishing or becoming overfished.

The Panel concludes this TOR was met.

6. Perform short term projections

Short term projections (4 years) were performed using corrections for the retrospective pattern (based on the Mohn's Rho adjustment factor) resulting in a ~40% reduction of 2015 population abundance-at-age. All projections were conditioned on the annual catch limit (ACL) of 107,800 mt being caught in 2015. Projections were completed through 2018 for the following scenarios: F= F_{MSY}, F=0.75F_{MSY}, and constant catch =114,000 mt (the 2015 annual biological catch [ABC]) for years 2016-2018.

The Panel concludes this TOR was met.

7. Comment on whether assessment diagnostics—or the availability of new types of assessment input data—indicate that a new assessment approach is warranted (i.e., referral to the research track).

The two diagnostics in the benchmark that led to the use of an increased natural mortality rate in recent years did not perform as well with the updated data and fixed likelihood (See Section 6.1 of the update assessment report for more about the fixed likelihood). A greater increase in M would be required to reduce the retrospective pattern to near zero, but this decreases the match with the externally estimated consumption. A reduced M would be required to more closely match the externally estimated consumption, but this creates a much larger retrospective pattern. Thus, the benchmark approach that increased natural mortality by 50% from the base rates during 1996-2014 was considered to partially address both diagnostics, but not as well as it did previously.

The Panel discussed additional sources of uncertainty. The estimation of the stock recruitment relationship is not precise. An additional source of uncertainty is the highly variable maturity-at-age 3, which causes the SSB_{MSY} estimate to change at a constant F_{MSY}. The maturity information from the fishery-independent surveys was also examined during the review workshop, and it showed some differences from the maturity information derived from the commercial port samples used in the stock assessment model. None of these sources of uncertainty was considered sufficient to reject the assessment.

The Panel recommends referring this assessment to the research track in the hopes of identifying and accounting for the causes of diagnostic problems. Given the current good status of the stock and strong positive indicators of incoming recruitment, there is not an immediate need to develop a new model formulation. Research should be conducted during the next 3 to 6 years so that a new model is available for one of the next two specification periods. Topics that could be considered include: time dependent selectivity for the fishing fleets, time dependent availability for the surveys, spatial heterogeneity, ageing consistency, catch and consumption estimation, splitting natural mortality into components, and management strategy evaluations to evaluate harvest control rules (especially in the presence of retrospective patterns).

8. Should the baseline model fail when applied in the operational assessment, provide guidance on how stock status might be evaluated. Should an alternative assessment approach not be readily available, provide guidance on the type of scientific and management advice that can be.

The Panel concluded the baseline model did not fail. The Panel, however, did review alternative approaches for setting catch advice. Specifically, the Panel reviewed trends in fishery independent indices of abundance (NMFS spring and fall bottom trawl surveys and summer shrimp bottom trawl survey) and relative fishing mortality rates. Both indices of abundance and relative fishing mortality rates indicated trends similar to those presented in ASAP output, which provided additional confidence in the Panel's decision to continue the use of ASAP as the principle assessment method for this update. In general, the Panel supports the parallel consideration of update assessments and alternatives for review in operational update assessments. Alternatives might include depletion-based stock reduction analysis, depletion-corrected average catch, and abundance-based methods (e.g., Carruthers et al. 2014).

The Panel concludes this TOR was met.

9. References

Carruthers TR, Punt AE, Walters CJ, MacCall A, McAllister MK, Dick EJ, Cope J. 2014. Evaluating methods for setting catch limits in data-limited fisheries. Fish Res. 153: 48-68.

ATLANTIC HERRING *CLUPEA HARENGUS* OPERATIONAL ASSESSMENT UPDATE 2015

Jonathan J. Deroba

1. Introduction

The Atlantic herring stock was last assessed as a benchmark during the 54th Stock Assessment Workshop using data through 2011 (NEFSC 2012). Data were updated through 2014 for this operational assessment. The methods of data processing and the stock assessment model configuration were the same as those accepted at the previous benchmark (NEFSC 2012). Some assessment model sensitivities were also conducted to address model diagnostic problems.

2. Fishery

Catch data were separated into 2 aggregate gear types: fixed and mobile gears. New Brunswick, Canada weir catches were combined with US fixed gear catches for the assessment (Table 1).

Catch in the mobile gear fishery peaked in the late 1960s and early 1970s, largely due to efforts from foreign fleets (Figure 1). Catch in this fishery has been relatively stable since about 2000 and has accounted for most of the Atlantic herring catches in recent years. Catch in the fixed gear fishery has been variable, but has declined and has been relatively low since the mid-1980s (Figure 1).

Total catches during 1965-2014 ranged from 44,613 mt in 1983 to 477,767 mt in 1968 (Figure 1). Total catches during the past 5 years ranged from 79,413 mt in 2010 to 101,622 mt in 2013 and averaged 90,040 mt.

Portside sampling of the US mobile gear fishery has been relatively stable and averaged 126 trips per year from 2010-2014 (Table 2). Relatively little or no sampling has occurred for the US fixed gear fishery in several years, and the sampling levels of the Canadian weir fishery were not available. The age composition of the Canadian weir fishery was assumed to represent that of all fixed gear catches, US and Canadian.

The mobile gear fishery catches a relatively broad range of ages and some strong cohorts can be seen for several years, including the 2008 cohort that was estimated to be the largest in the time series at the last benchmark (NEFSC 2012; Figure 2). In contrast, the fixed gear fishery harvests almost exclusively age-2 herring (Figure 2).

3. Surveys

Abundances (i.e., arithmetic mean numbers per tow) from the NMFS spring, fall, and summer shrimp bottom trawl surveys were used in the assessment model along with annual coefficients of variation and age composition when they were available. The trawl door used on the spring and fall surveys changed in 1985 and likely altered the catchability of the survey gear.

Consequently, the spring and fall surveys were split into 2 time series between 1984 and 1985, and these were treated as separate indices in assessment models. Calibrations were applied to the spring and fall surveys to account for changes in survey methods, including changes in research vessels.

The NMFS spring survey indices of abundance declined from the time series high in 2011 to values in 2012-2014 that are similar to the average of the observations from 1985-2014 (Figure 3). The NMFS fall survey indices have varied without trend near the average of the observations from 1985-2014 for about 10 years (Figure 3). The indices from the NMFS summer shrimp survey have been near or below the time series average for about 8 years (Figure 3). The NMFS spring and fall surveys catch a relatively broad range of ages and some strong cohorts can be seen for several years, including the 2008 cohort that was estimated to be the largest in the time series at the last benchmark (NEFSC 2012; Figure 4). Age data are not available for the summer shrimp survey.

4. Natural Mortality and Consumption

Natural mortality was based on a combination of the Hoenig and Lorenzen methods, with the Hoenig method providing the scale of natural mortality and the Lorenzen method defining how natural mortality declined with age (Hoenig 1983; Lorenzen 1996). The natural mortality rates during 1996-2014 were increased by 50% from these base rates (e.g., Figure 5), as in NEFSC (2012).

Stomach contents data were used to estimate predatory consumption of Atlantic herring. Predatory consumption estimates of Atlantic herring through 2010 were used in justifying time varying natural mortality (i.e., the 50% increase from base rates) that partially resolved a retrospective pattern during the 2012 assessment (NEFSC 2012). Piscivorous fish consumption was estimated through 2013 using the same methods as in the previous benchmark assessment (NEFSC 2012). Consumption estimates for other predators (e.g., elasmobranchs, highly migratory species, whales, and seabirds) from 2011-2013 equaled the average consumption of these predators from 2006-2010, and the values for other years in the time series were the same as in the 2012 assessment. Total consumption equaled the sum of piscivorous fish and other predatory consumption estimates.

5. Weights and Maturity at Age

Weight- and maturity-at-age were estimated as in NEFSC (2012). Catch weights-at-age were estimated as the catch weighted mean weights-at-age among the strata used to develop the US catch-at-age matrices and ultimately among the mobile and fixed gear fisheries. Weights-at-age for spawning stock biomass (SSB) were estimated as the mean weights-at-age from the mobile gear fishery in quarter 3 (i.e., July-September) of each year. This data was used because the mobile gear fishery is relatively well sampled in all years, and quarter 3 is when herring typically begin spawning. January 1 weights-at-age were estimated by using a Rivard calculation of the SSB weights-at-age.

Maturity-at-age was developed using samples from commercial catches during quarter 3 (July to September). Fish caught during this time of year were used because they reflect the maturity condition of herring just prior to or during spawning, and therefore are best for calculations related to SSB. A general additive model with a logit link function (akin to a logistic regression) was fit to the proportion of mature fish-at-age in each year. The predicted maturity-at-age in each year from the general additive model was used in stock assessment modeling.

6. Assessment

6.1. Results

Since the previous assessment (NEFSC 2012), an issue with the contribution of recruitment to the negative log likelihood in the assessment framework, ASAP, was discovered. This issue was resolved for the assessment described here. Differences in results and diagnostics between NEFSC (2012) and this update are partially attributable to the likelihood issue. Resolving the likelihood issue had the effect of changing the scale of estimates (e.g., increasing abundance estimates), particularly in recent years. Regardless of the likelihood issue, diagnostic problems (e.g., retrospective patterns) were present in assessments done as part of this update. Resolving the likelihood issue only amplified these diagnostic problems (e.g., larger retrospective patterns). The model structure and all other model specifications were the same as in the NEFSC (2012) base model.

The point estimate of SSB in 1965 equaled 487,791 mt (Figure 6; Table 3). SSB generally declined from 1965 to a time series low of 56,509 mt in 1978. SSB generally increased from 1978 through the mid-1990s. SSB declined from 1997 to 347,675 mt in 2010, but then increased to the time series high of 1,041,500 mt in 2014. The point estimate of unexploited SSB equaled 845,176 mt.

Mean recruitment from 1965 to 2014 equaled 12.7 billion fish. As in the previous assessment (NEFSC 2012), the 2009 age-1 recruitment was estimated to be the largest in the time series, and equaled 62.4 billion fish (Figure 6; Table 3). The 2012 age-1 recruitment was estimated to be the second largest in the time series and equaled 42.4 billion fish. The point estimate of unexploited recruitment equaled 15.4 billion fish, and steepness equaled 0.44.

The 2012 benchmark assessment (NEFSC 2012) reported fishing mortality-at-age 5 because this age is the first fully recruited age in the mobile gear fishery, which represents the majority of the catch. Age-5 fishing mortality generally increased from 0.13 in 1965 to a time series high of 0.79 in 1971 (Figure 6; Table 3). Age-5 fishing mortality generally declined after 1971 to 0.11 in 1994, after which fishing mortality generally increased to a value of 0.29 in 2009. Since 2009, age-5 fishing mortality has been stable and low, equaling 0.13 in 2011-2013, and equaling the time series low of 0.10 in 2014.

6.2. Diagnostics

A major structural assumption in the base model from NEFSC (2012) was the increased natural mortality during 1996-2011. This time-varying natural mortality was included to reduce the internal retrospective pattern and create a greater consistency between implied levels of consumption based on the input natural mortality rates and the observed increases in estimated consumption of herring, based on stomach contents data. Consequently, the diagnostics focused on the degree of retrospective pattern and consistency between implied levels of consumption and estimated consumption.

The relative retrospective pattern for SSB had all positive peels (7 peels), and Mohn's Rho equaled 0.67 (Figure 7). The 2014 estimate of SSB adjusted for the retrospective pattern (1/[1+0.67]x1,041,500 mt) equaled 622,991 mt. The relative retrospective pattern for recruitment had all positive peels, except for 2 years, and Mohn's Rho equaled 0.44 (Figure 7). The relative retrospective pattern for age-5 fishing mortality had all negative peels and Mohn's Rho equaled -0.37 (Figure 7). The 2014 estimate of age-5 fishing mortality adjusted for the retrospective pattern (1/[1-0.37]x0.10) equaled 0.16. These results are in contrast to NEFSC (2012), when the retrospective patterns for SSB and fishing mortality had positive and negative peels, and Mohn's Rho equaled 0.13 and -0.07, respectively. The retrospective pattern for recruitment at that time, however, had all negative peels, and Mohn's Rho equaled -0.52.

Consumption based on the input natural mortality rates and estimates of consumption based on stomach contents were generally consistent from 1968-1988 (Figure 8), and this result was similar to NEFSC (2012). The time series are less consistent from 1989-2013, with the implied consumption based on input natural mortality rates generally higher than the estimates based on stomach contents, and the time series diverge in scale and trend during 2009-2014 (Figure 8).

6.3. Biological Reference Points (BRPs)

Maximum sustainable yield (MSY) reference points were based on the fit of the Beverton-Holt stock-recruitment relationship, estimated internally to the ASAP model, and inputs (e.g., weights-at-age, natural mortality) from the terminal year of the assessment (i.e., 2014). Point estimates of the MSY BRPs equaled: MSY = 77,247 mt, F_{MSY} = 0.24, and SSB_{MSY} = 311,145 mt. The values for these reference points during the previous benchmark assessment (NEFSC 2012) were: MSY = 53,000 mt, F_{MSY} = 0.27, and SSB_{MSY} = 157,000 mt.

6.4. Stock Status

In NEFSC (2012), a justification to increase natural mortality from 1996-2011 was a reduction in the retrospective pattern, and so no Mohn's Rho adjustments were applied to SSB or fishing mortality. The retrospective pattern has increased, however, and so stock status was considered here with and without Mohn's Rho adjustments.

Regardless of whether Mohn's Rho adjustments are made, the stock is not overfished and overfishing is not occurring (Figure 9).

6.5. Sensitivities

The 50% increase in the base natural mortality rates from 1996-2011 were justified in NEFSC (2012) to: 1) reduce the internal retrospective pattern, and 2) create a greater consistency between implied levels of consumption based on the input natural mortality rates and the observed increases in estimated consumption of herring based on stomach contents data. When the 50% increase in the base natural mortality rates was applied from 1996-2014, however, the justification deteriorated (see above).

Two sensitivities were conducted in response to this deterioration: 1) input natural mortality rates were increased from 1996-2014 until the retrospective pattern was similar in scale to that in NEFSC (2012); and 2) input natural mortality rates were changed during 2009-2014 until greater consistency was achieved in those years between the implied levels of consumption and the estimates of consumption based on stomach contents data (Figure 5). In each sensitivity run, all other model structures and specifications were unchanged.

Input natural mortality rates were increased 100% from base rates for 1996-2014 to reduce the retrospective pattern to a similar scale as that in NEFSC (2012; Figure 10). Implied consumption based on the input natural mortality rates diverged from the estimated consumption based on stomach contents data beginning in 1985, and from 1985-2013, implied consumption was on average 6 times higher than the estimates of consumption based on stomach contents (Figure 11). Trends in estimates of SSB, fishing mortality, and recruitment were similar between this sensitivity run and the base update assessment, but the scale of estimates differed (Figure 12). The steepness parameter also hit a lower bound (i.e., 0.2) during model fit, which led to unrealistic reference point estimates.

Input natural mortality rates were decreased by 30% from base rates for 2009-2014 to improve the consistency between the implied consumption based on input natural mortality rates and estimates of consumption based on stomach contents data (Figure 13). Retrospective patterns for SSB, fishing mortality, and recruitment for this sensitivity run were the largest of any model considered (Figure 14). Trends in estimates of SSB, fishing mortality, and recruitment were similar between this sensitivity run and the base update assessment, but the scale of estimates differed in some more recent years (Figure 15).

7. Projections

Short-term projections were conducted based on the results of the updated assessment. Numbers-at-age in 2015 were drawn from 1000 vectors of numbers-at-age produced from MCMC simulations of the updated assessment. These numbers-at-age were adjusted for the retrospective pattern by multiplying each value by the same adjustment as used for SSB (see above; 1/[1+0.67]). All projections assumed that catch in 2015 equaled 107,800 mt. Recruitment was simulated using the same methods as NEFSC (2012), but with parameters based on the updated stock assessment (Table 4). Vectors of natural mortality, weight, selectivity (total F-at-age rescaled to maximum of 1.0), and maturity-at-age all equaled the values for 2014.

Projections were done for 3 harvest scenarios, including F_{MSY}, 0.75 F_{MSY}, and the status quo allowable biological catch of 114,000mt. Results for each projection are summarized as the median of fishing mortality, catch, and SSB with 80% confidence intervals for each year (Table 5). The probability of fishing mortality exceeding F_{MSY}, and SSB going below SSB_{MSY}/2 was also reported for each year (Table 5).

One sensitivity projection was also conducted for the F_{MSY} harvest scenario, but with the size of the 2011 year class reduced to the level of the average recruitment over 1965-2014. The numbers-at-age for the 2011 year class were multiplied by 0.29 to achieve the appropriate reduction.

8. References

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Lorenzen K. 1996. The relationship between body weight and natural mortality in juvenile and adult fish: a comparison of natural ecosystems and aquaculture. J Fish Biol. 49: 627-647.

NEFSC (Northeast Fisheries Science Center). 2012. 54th Northeast Regional Stock Assessment Workshop (54th SAW) Assessment Report. US Department of Commerce, Northeast Fish Sci Cent Ref Doc. 12-18; 600 p.

9. Acknowledgements

I would like to thank the participants and reviewers of the 2015 Atlantic herring operational assessment update, especially, Matt Cieri, Brian Smith, Rabindra Singh, and Chris Legault. I would also like to acknowledge the work of the NEFSC Ecosystems Survey Branch and Fishery Biology Program, especially, Blanche Jackson and Eric Robillard. Lisa Pinkham of the Maine Department of Marine Resources also has worked diligently aging commercially caught herring.

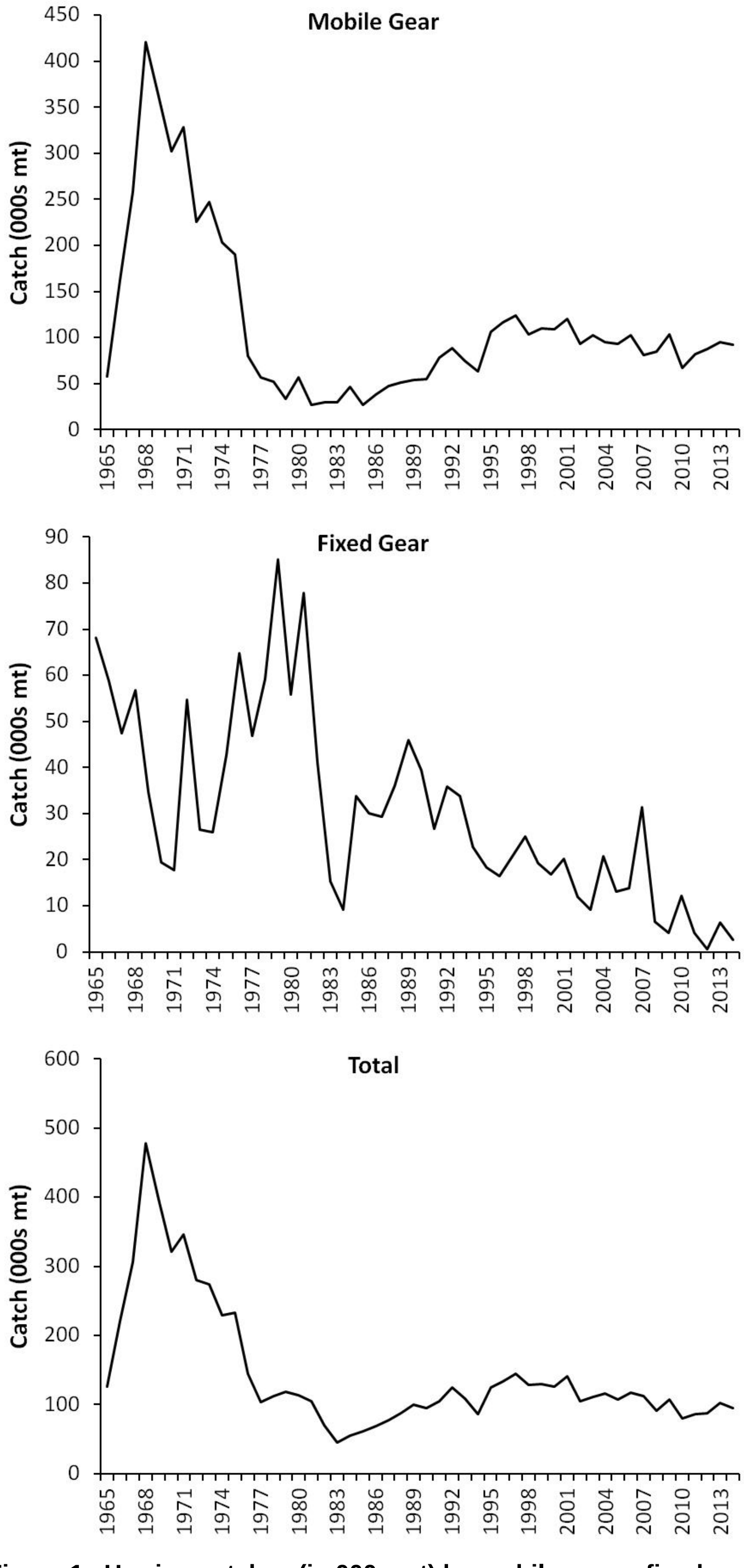
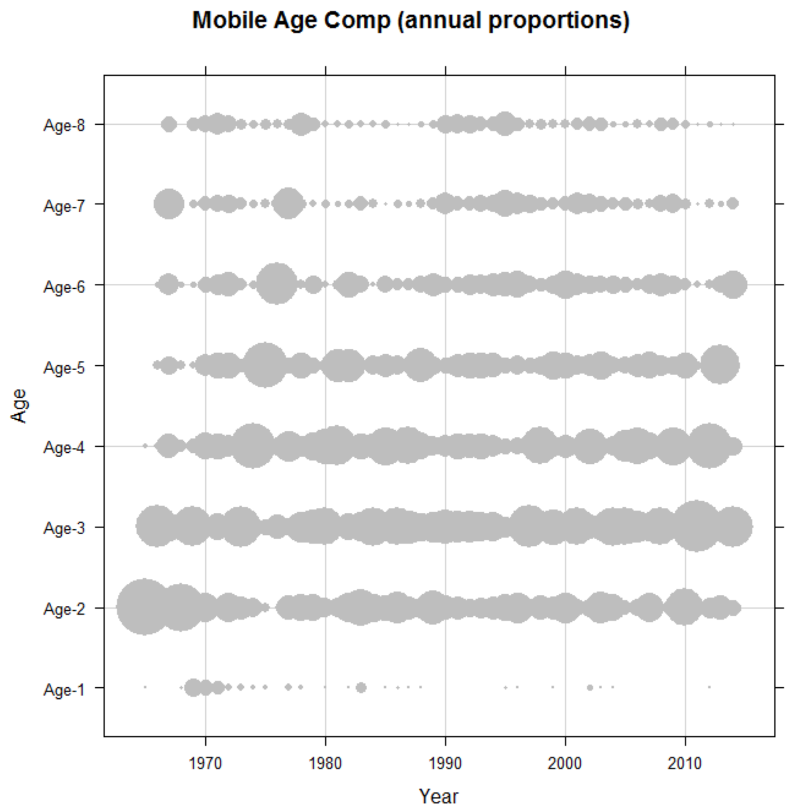


Figure 1. Herring catches (in 000s mt) by mobile gears, fixed gears, and total, 1965-2014.



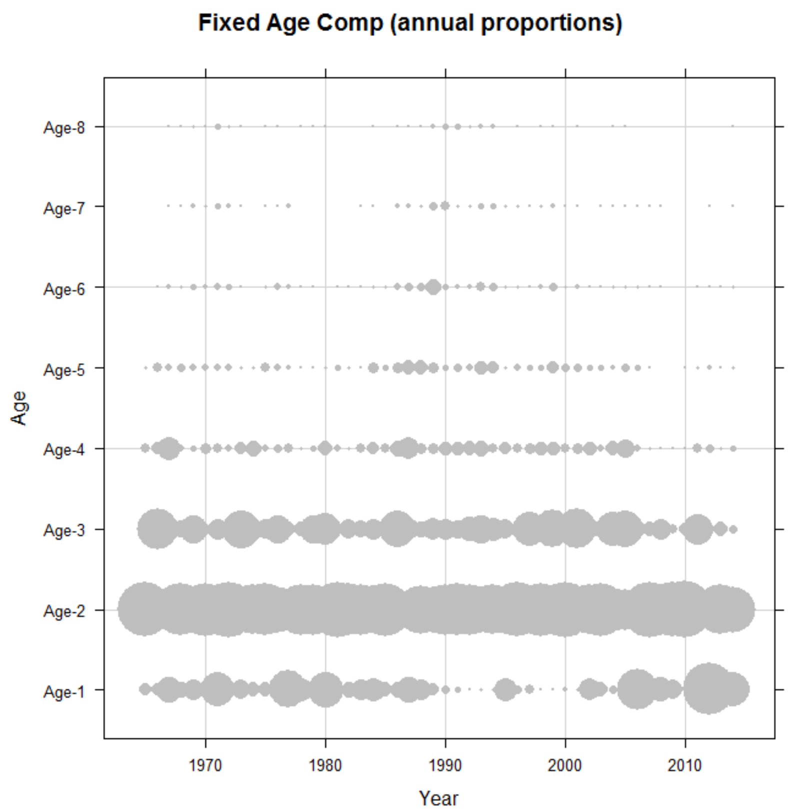


Figure 2. Mobile and fixed gear fishery age compositions for Atlantic herring, 1965-2014. (Values-at-age for each year sum to 1.0.)

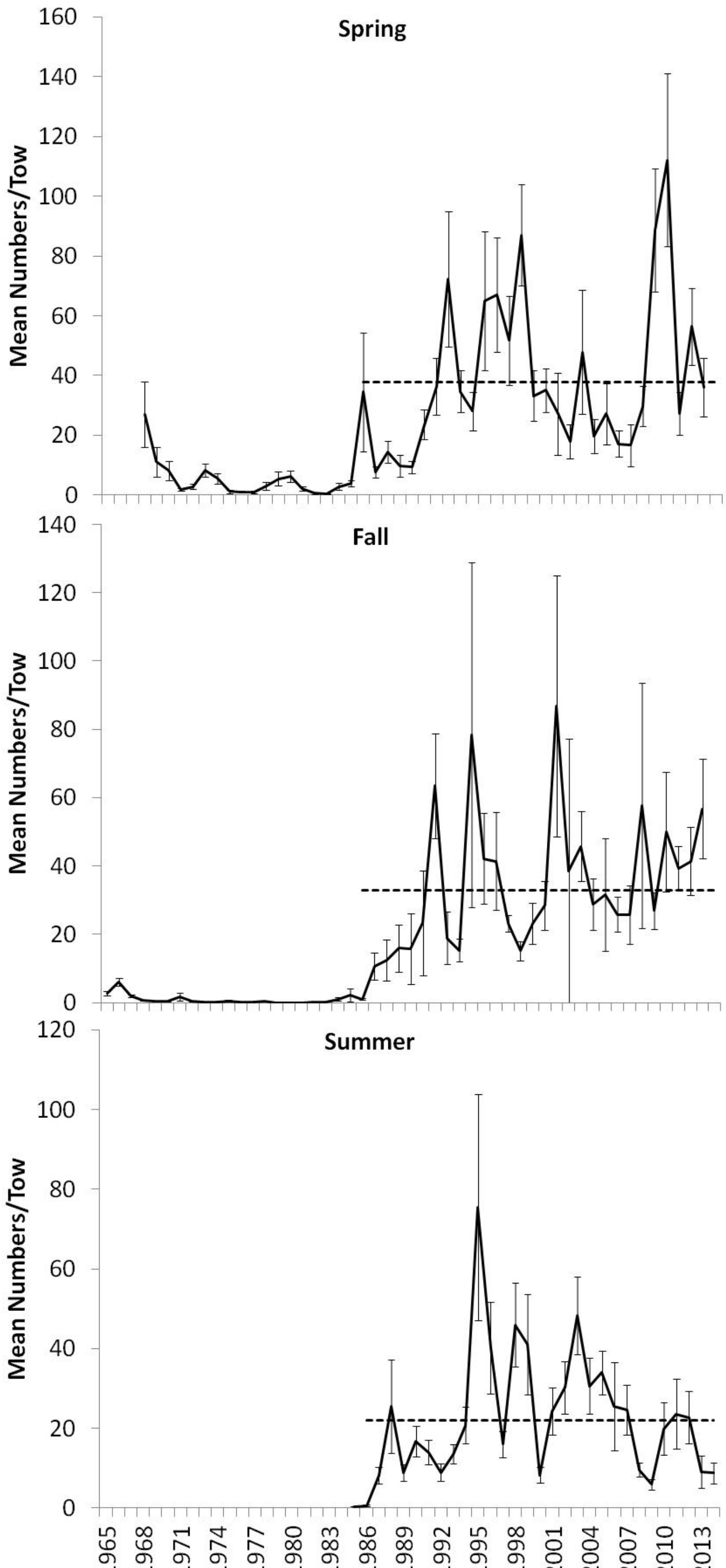
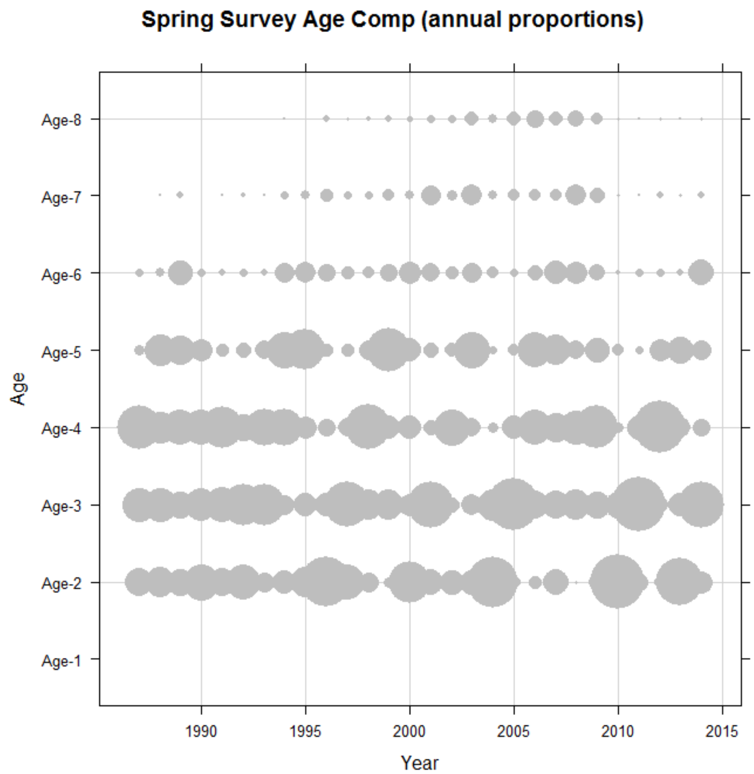


Figure 3. NMFS spring (1968-2014), fall (1965-2014), and summer shrimp (1983; 1985-2014) bottom trawl survey indices for Atlantic herring (plus/minus 1 standard deviation). The horizontal dashed line is the average value from 1985-2014 for each survey.



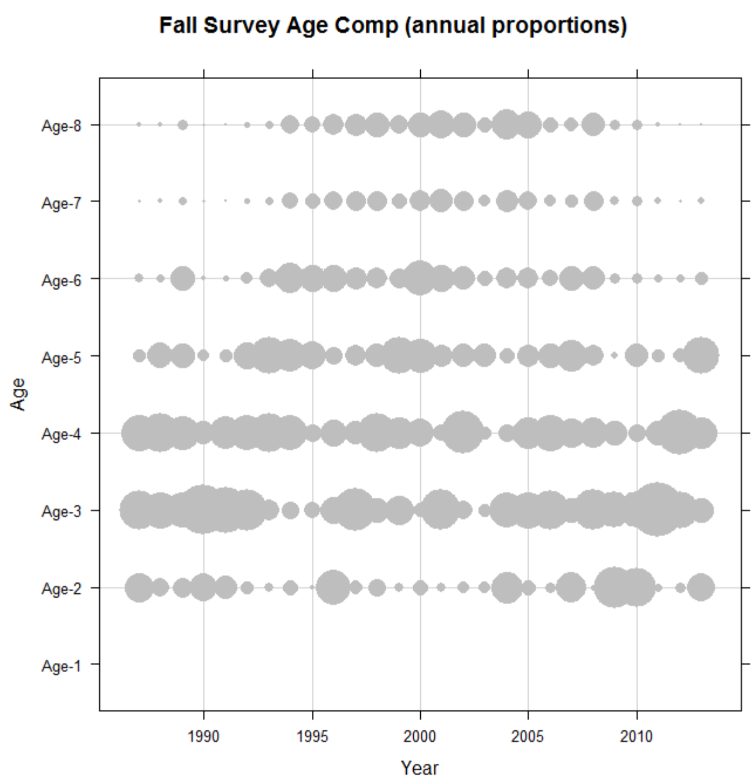


Figure 4. NMFS spring and fall bottom trawl survey age compositions for Atlantic herring, 1987-2014. (Values-at-age for each year sum to 1.0.)

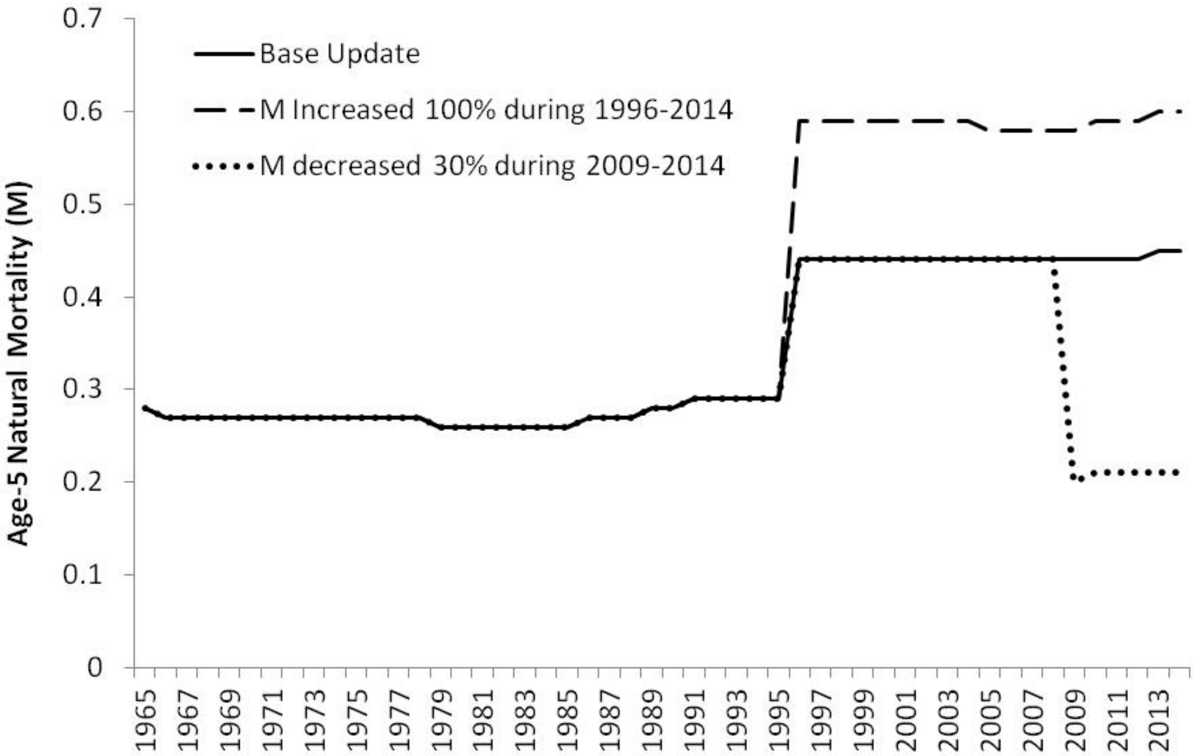


Figure 5. Age-5 natural mortality rates (M) for the base model operational update assessment for Atlantic herring, 1965-2014; a sensitivity run with M increased 100% from base rates during 1996-2014; and a sensitivity run with M decreased 30% from base rates during 2009-2014.

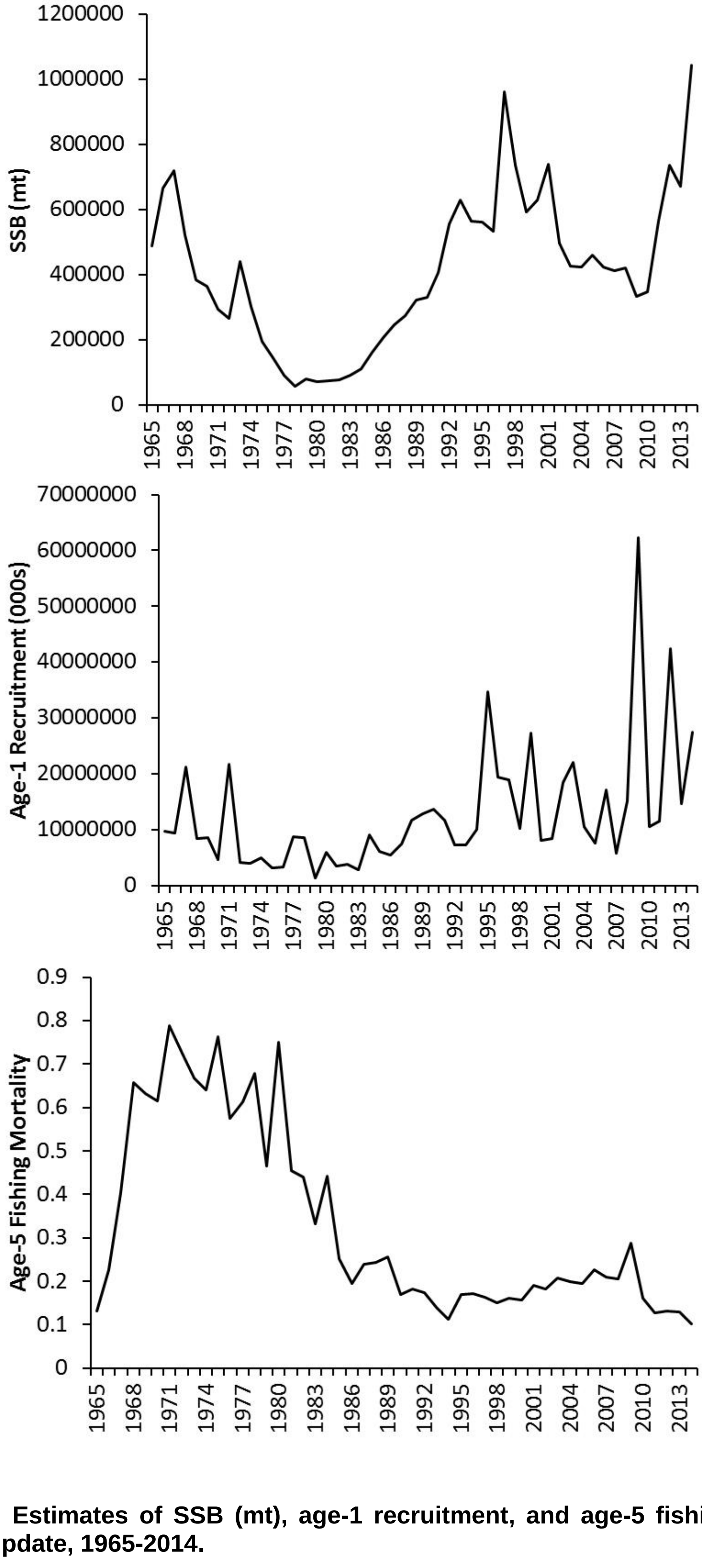


Figure 6. Estimates of SSB (mt), age-1 recruitment, and age-5 fishing mortality for the Atlantic herring update, 1965-2014.

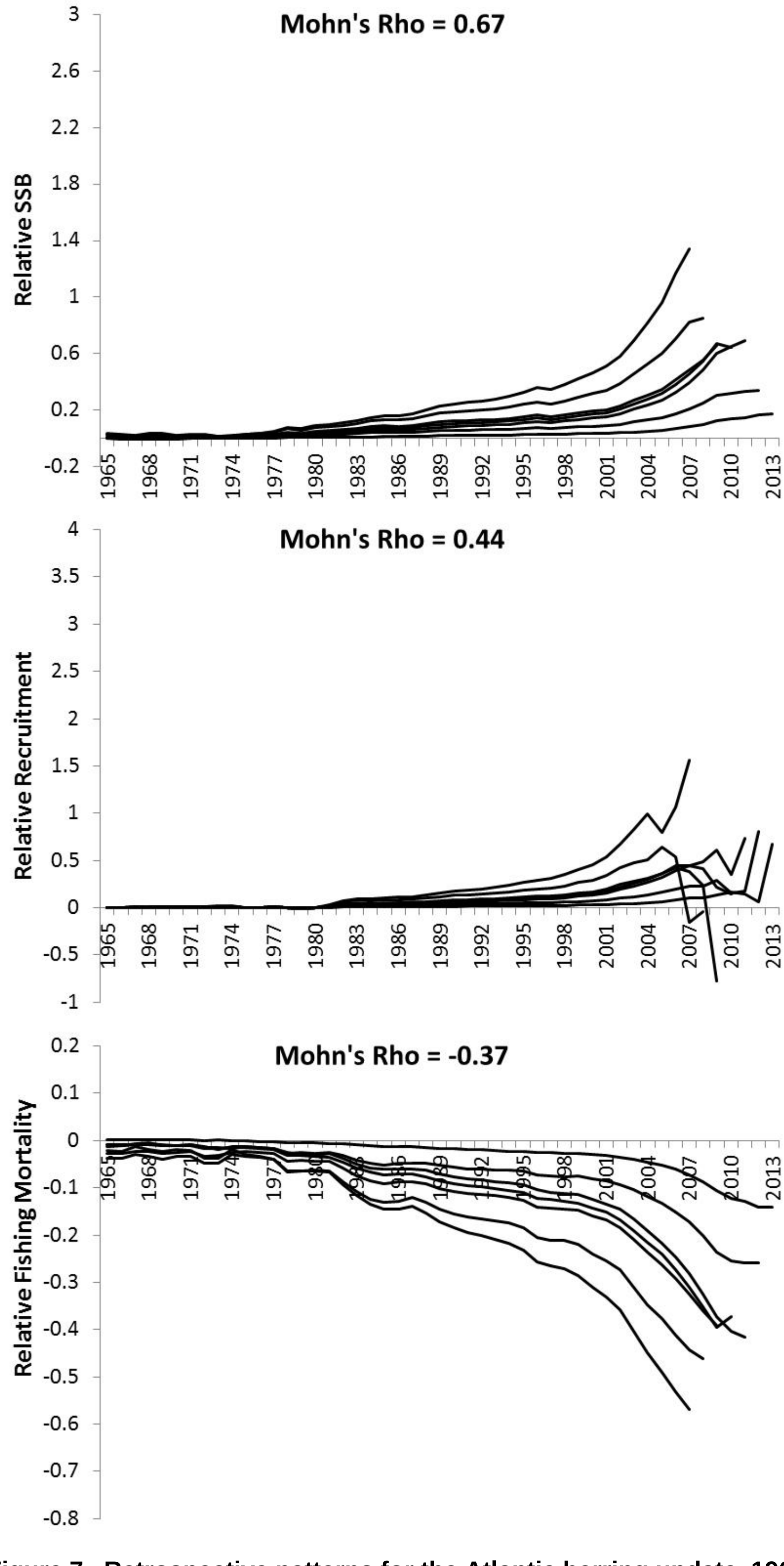


Figure 7. Retrospective patterns for the Atlantic herring update, 1965-2014.

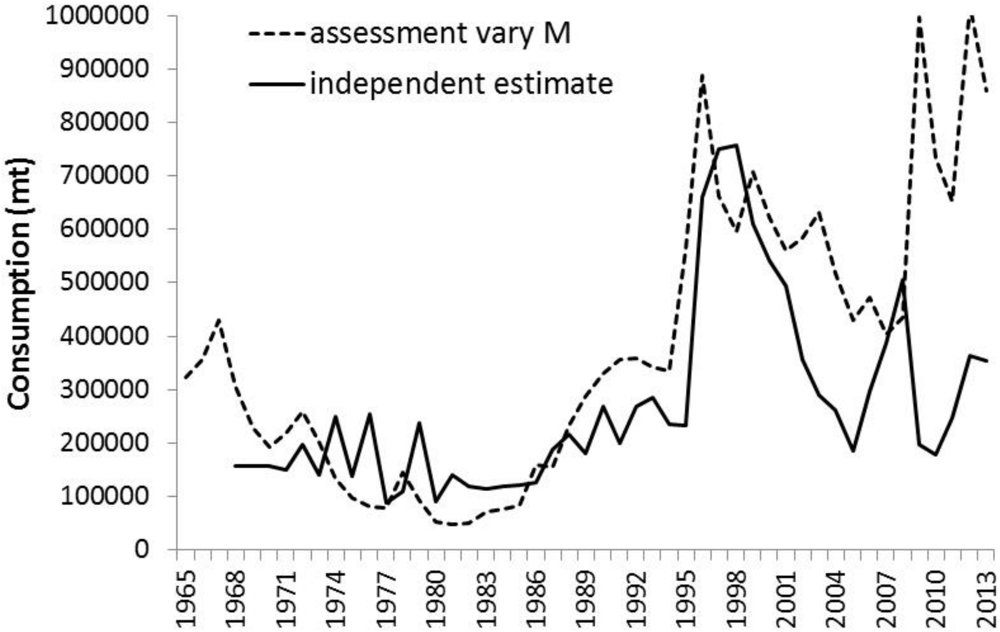


Figure 8. Total consumption of Atlantic herring by predators (solid black; "independent estimate") and the consumption of herring that would result based on input natural mortality rates in the updated stock assessment (dashed black, "assessment vary M"), 1965-2014.

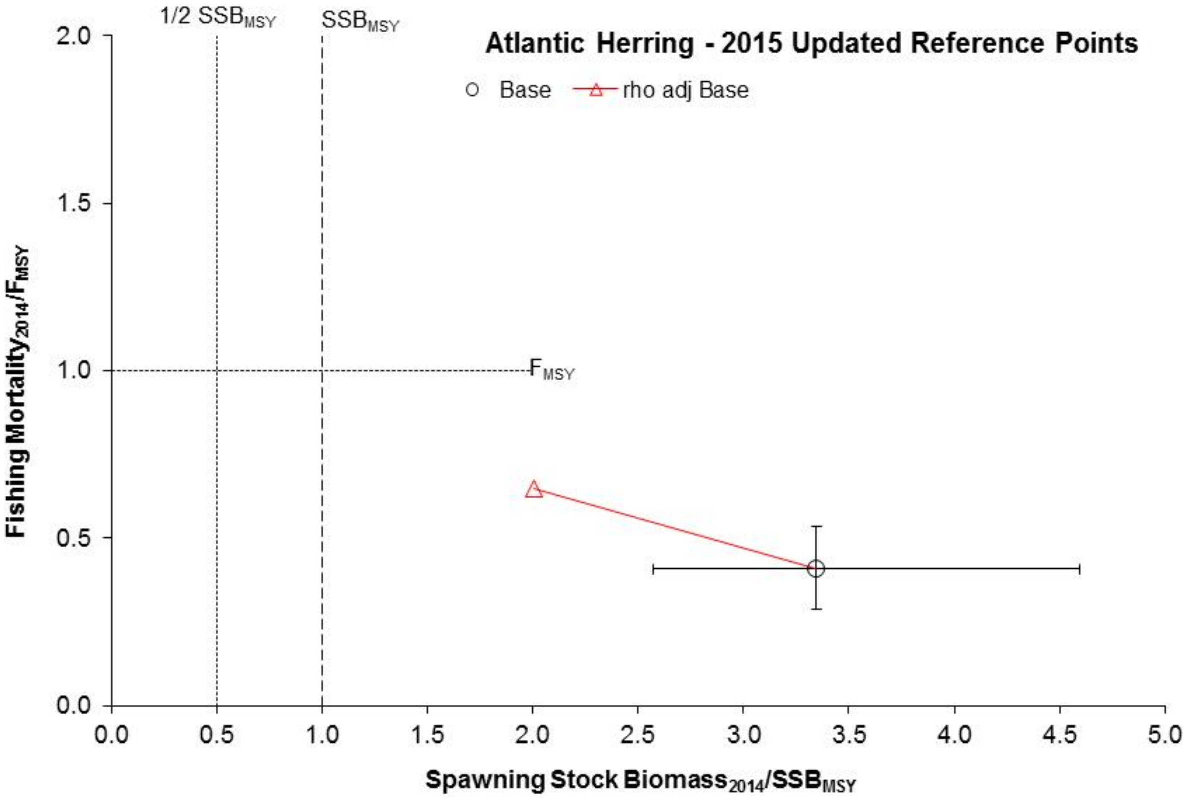


Figure 9. Fishing mortality in 2014 relative to F_{MSY} and SSB in 2014 relative to SSB_{MSY} (black circle; error bars are 10^{th} and 90^{th} percentiles based on MCMC of fishing mortality and SSB in 2014). The red line shows retrospective adjusted values.

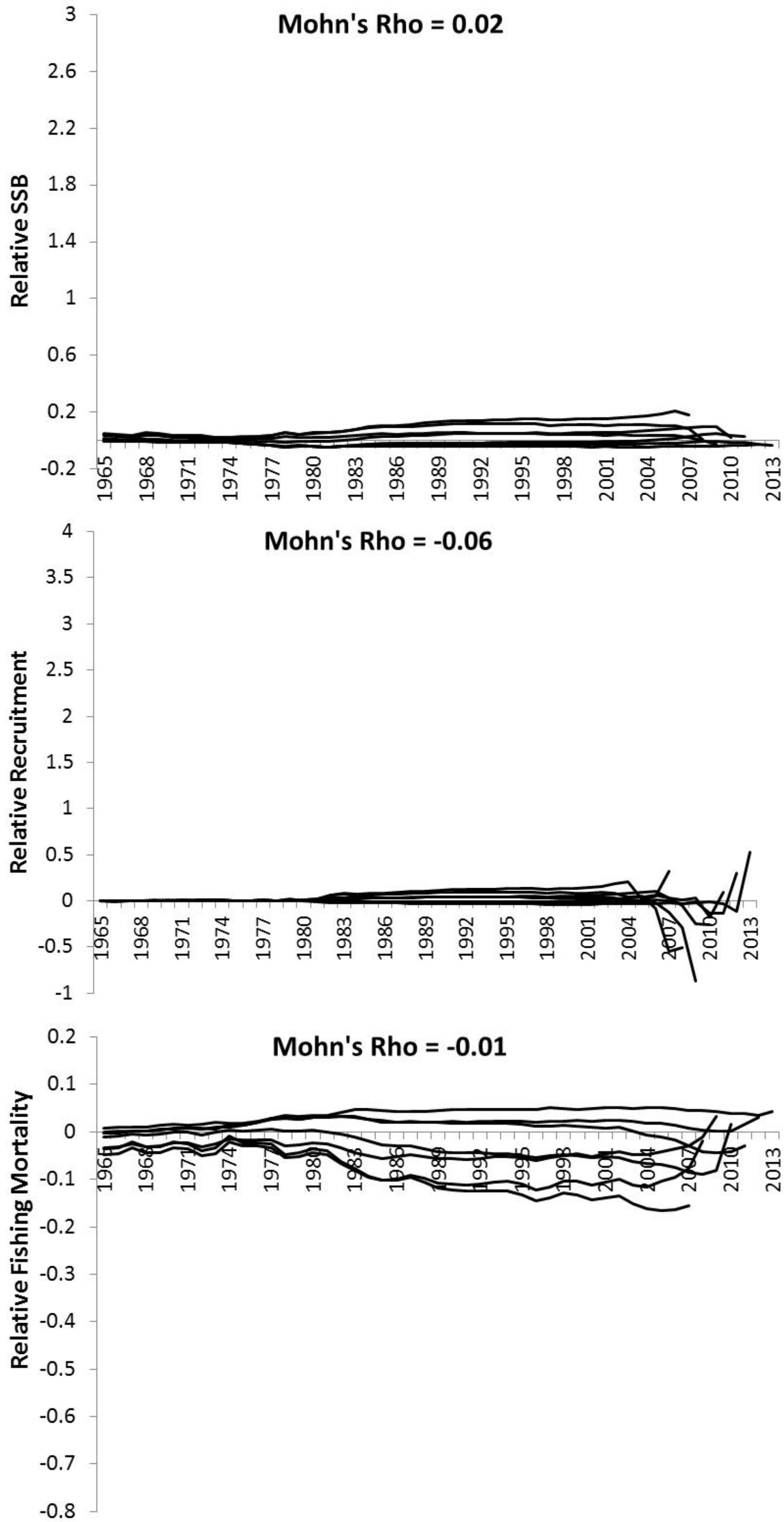


Figure 10. Retrospective patterns for the Atlantic herring update assessment, 1965-2014, with natural mortality rates increased during 1996-2014 to reduce the retrospective pattern.

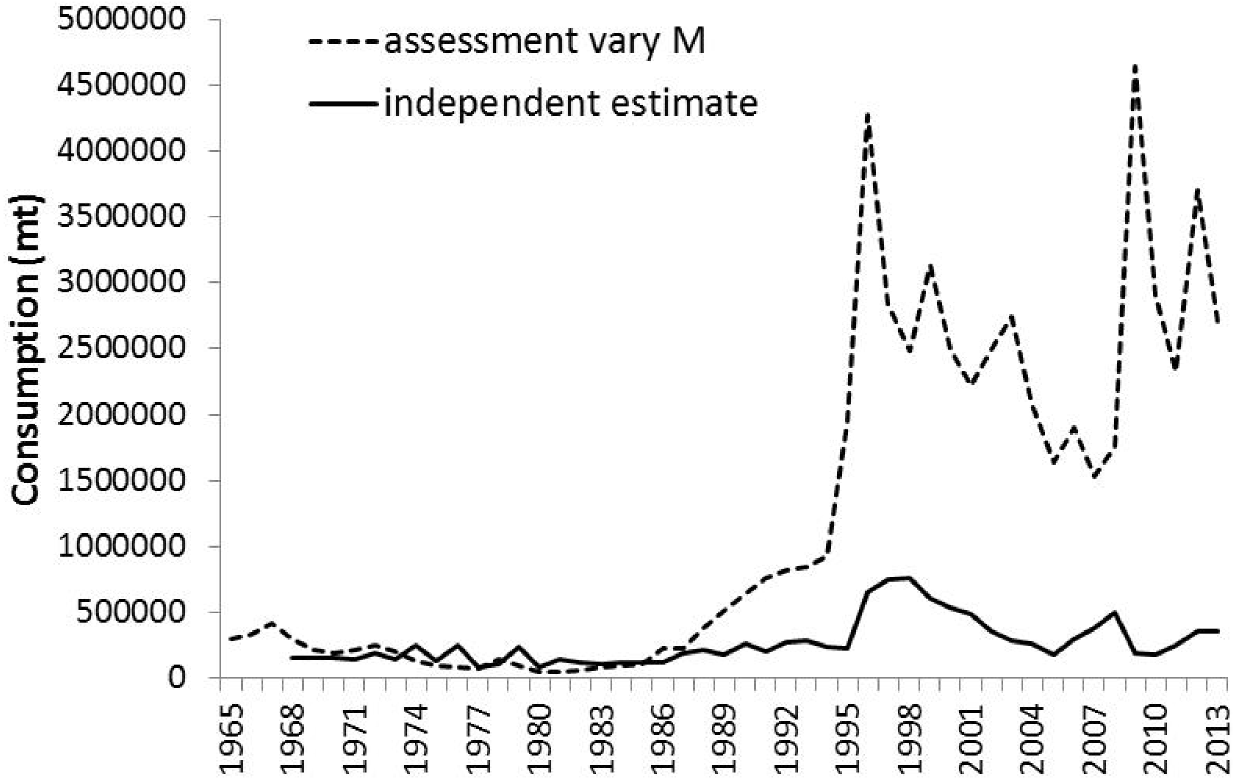


Figure 11. Total consumption of Atlantic herring by predators (solid black; "independent estimate"), 1965-2014, and the consumption of herring that would result with input natural mortality rates increased by 100% during 1996-2014 in the updated stock assessment (dashed black, "assessment vary M").

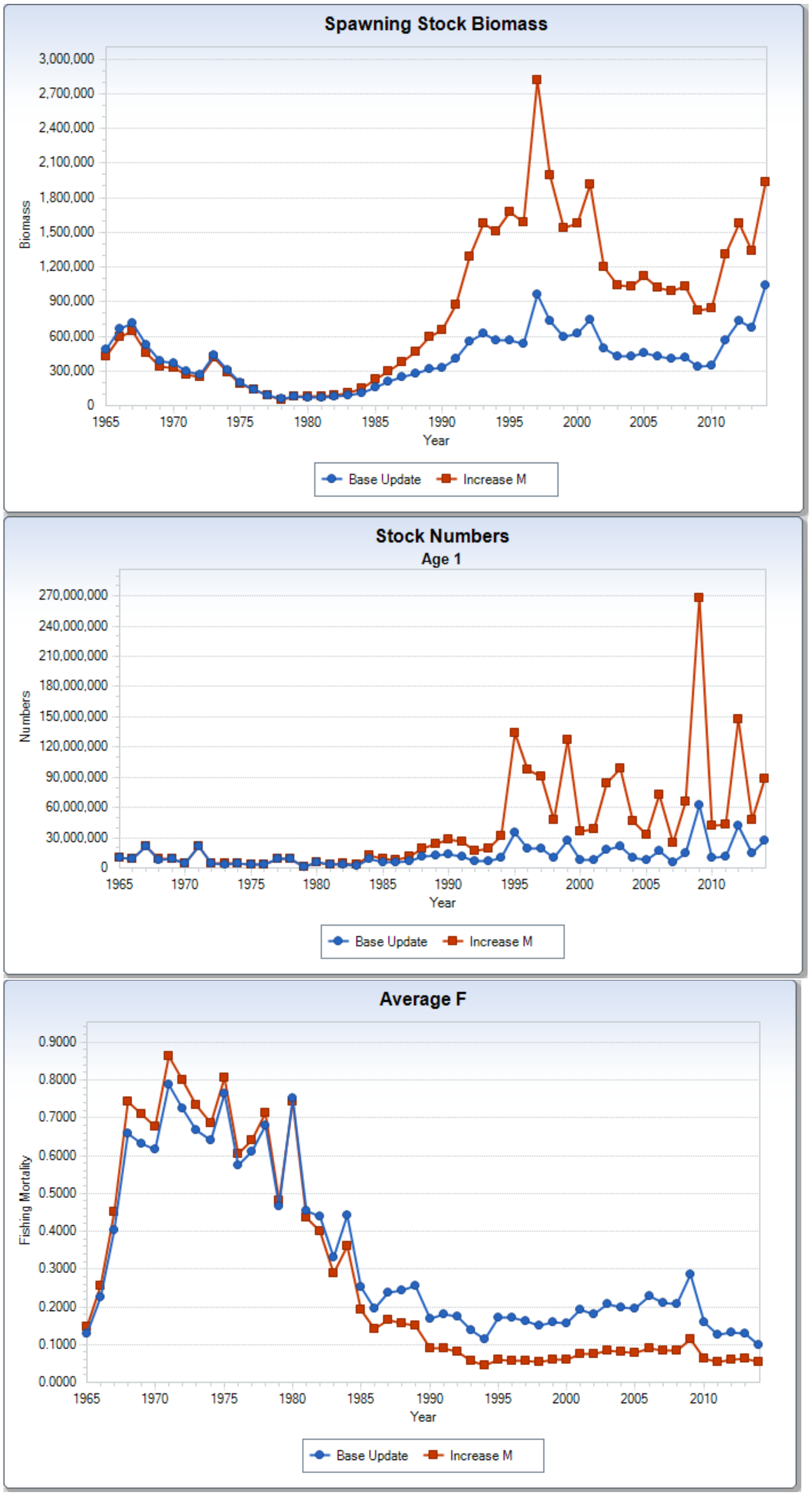


Figure 12. Comparison of SSB, age-1 recruitment, and fishing mortality from the base update Atlantic herring assessment (Base Update), 1965-2014, and a run with natural mortality increased during 1996-2014 to reduce the retrospective pattern (Increase M).

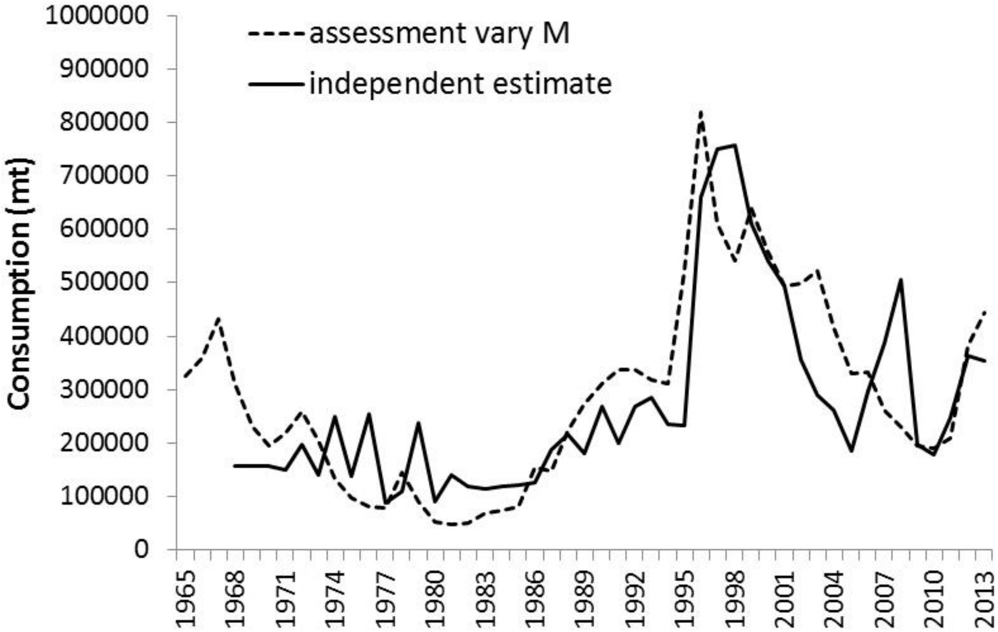


Figure 13. Total consumption of Atlantic herring by predators (solid black; "independent estimate"), 1965-2014, and the consumption of herring that would result with input natural mortality rates decreased by 30% during 2009-2014 in the updated stock assessment (dashed black, "assessment vary M").

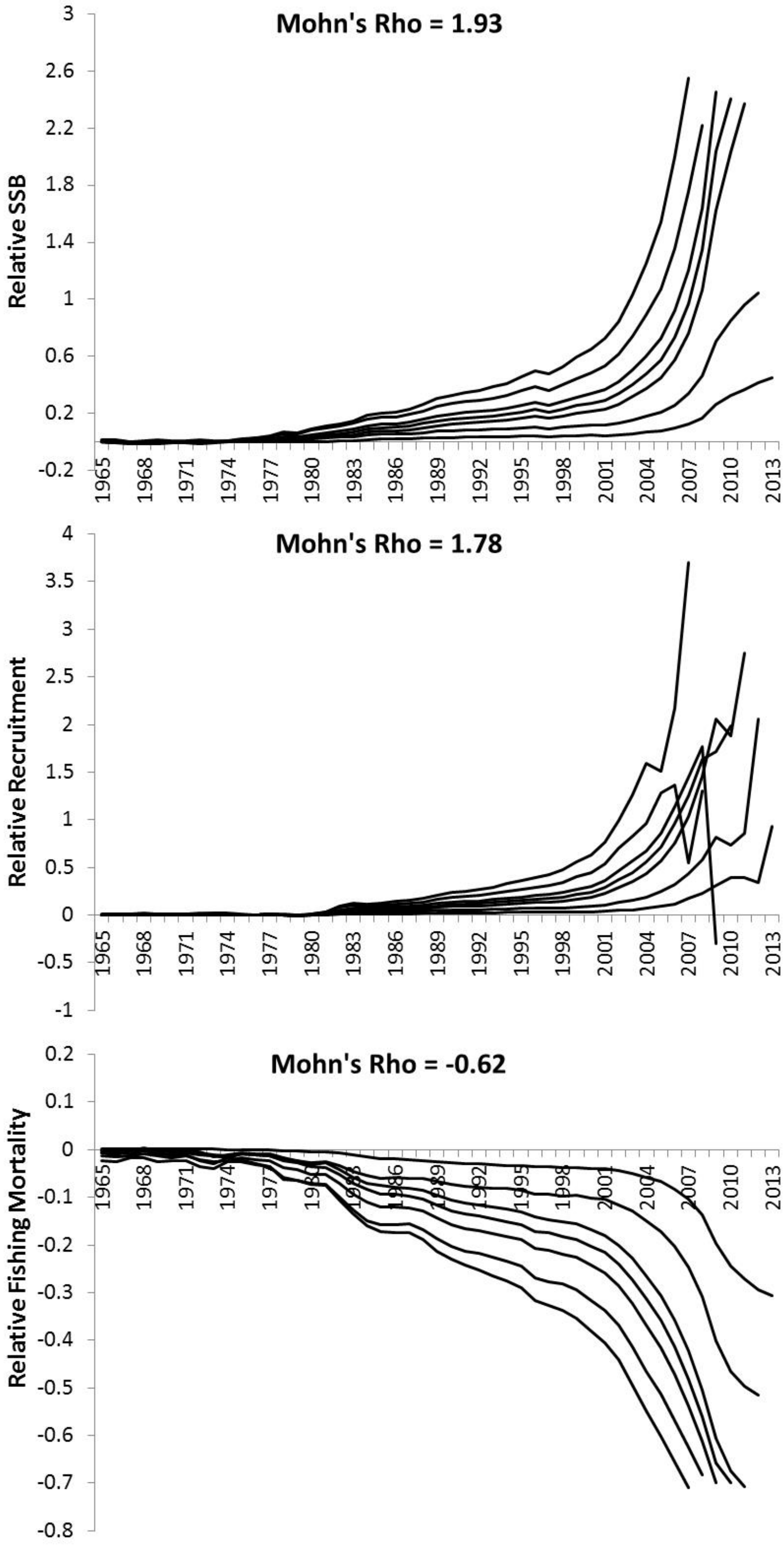


Figure 14. Retrospective patterns for the Atlantic herring update assessment, 1965-2014, with natural mortality rates decreased during 1999-2014 to improve the consistency between implied levels of consumption based on input rates and estimates of consumption from stomach contents data.

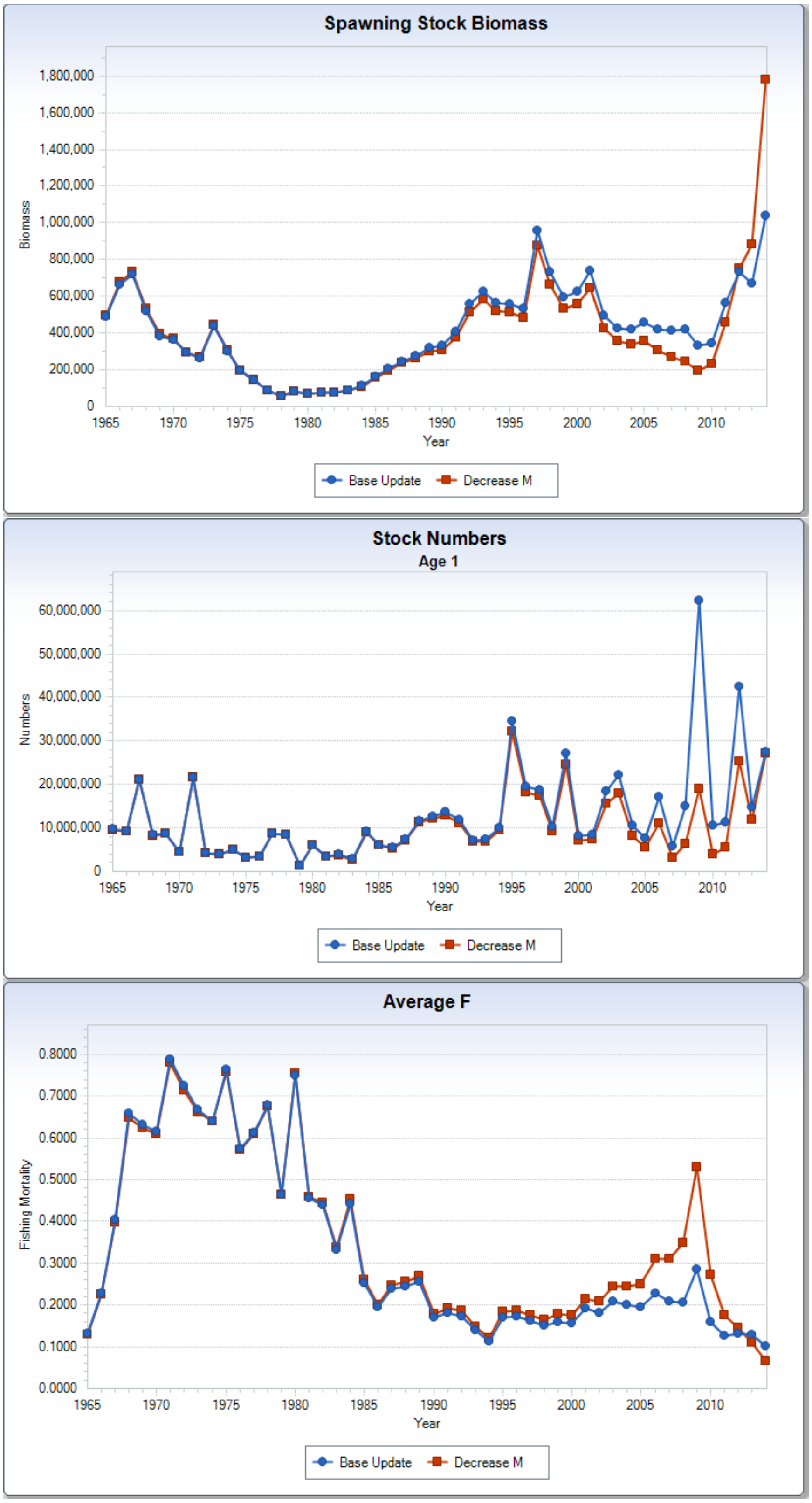


Figure 15. Comparison of SSB, age-1 recruitment, and fishing mortality from the base update Atlantic herring assessment (Base Update) , 1965-2014, and a run with natural mortality decreased during 2009-2014 to improve the consistency between implied levels of consumption based on input rates and estimates of consumption from stomach contents data (Decrease M).

Table 1. Atlantic herring catch (metric tons) in the mobile gear, US fixed gear, and New Brunswick weir fishery, 1965-2014.

Year	Mobile	US Fixed	NB Weir
1965	58161	36440	31682
1966	162022	23178	35602
1967	258306	17458	29928
1968	421091	24565	32111
1969	362148	9007	25643
1970	302107	4316	15070
1971	327980	5712	12136
1972	225726	22800	31893
1973	247025	7475	19053
1974	203462	7040	19020
1975	190689	11954	30816
1976	79732	35606	29207
1977	56665	26947	19973
1978	52423	20309	38842
1979	33756	47292	37828
1980	57120	42325	13526
1981	26883	58739	19080
1982	29334	15113	25963
1983	29369	3861	11383
1984	46189	471	8698
1985	27316	6036	27864
1986	38100	2120	27885
1987	47971	1986	27320
1988	51019	2598	33421
1989	54082	1761	44112
1990	54737	670	38778
1991	78032	2133	24574
1992	88910	3839	31968
1993	74593	2288	31572
1994	63161	539	22242
1995	106179	6	18248
1996	116788	631	15913
1997	123824	275	20551
1998	103734	4889	20092
1999	110200	654	18644
2000	109087	54	16830
2001	120548	27	20210
2002	93176	46	11874
2003	102320	152	9008
2004	94628	96	20685
2005	93670	68	13055
2006	102994	1007	12863
2007	81116	403	30944
2008	84650	31	6448
2009	103458	98	4031
2010	67191	1263	10958
2011	82022	421	3711
2012	87164	9	504
2013	95182	9	6431
2014	92651	518	2149

Table 2. Number of US trips sampled, 1965-2014.

	Number of Trips Sampled	
Year	**US Fixed Gear**	**US Mobile Gear**
1965	353	13
1966	221	29
1967	241	66
1968	308	14
1969	300	25
1970	117	40
1971	103	91
1972	120	103
1973	95	69
1974	144	146
1975	154	131
1976	238	150
1977	248	106
1978	232	276
1979	559	121
1980	192	268
1981	352	100
1982	127	105
1983	62	134
1984	10	161
1985	54	88
1986	18	56
1987	21	79
1988	24	77
1989	29	68
1990	37	107
1991	24	99
1992	38	126
1993	32	125
1994	15	75
1995		124
1996	6	137
1997		213
1998	10	173
1999	3	206
2000		195
2001	2	214
2002		200
2003		155
2004		141
2005		186
2006	1	211
2007	1	147
2008		125
2009		123
2010		119
2011		119
2012		120
2013		132
2014	1	142

Table 3. Time series estimates of spawning stock biomass (SSB), age-1 recruitment, and age-5 fishing mortality from the Atlantic herring operational update assessment, 1965-2014.

Year	SSB	Age-1 Recruitment (000s)	Age-5 Fishing Mortality
1965	487,791	9,673,290	0.13
1966	664,671	9,316,950	0.23
1967	718,733	21,239,500	0.40
1968	522,820	8,330,330	0.66
1969	384,600	8,636,760	0.63
1970	363,094	4,585,220	0.62
1971	292,821	21,664,900	0.79
1972	265,695	4,194,630	0.72
1973	439,370	3,923,930	0.67
1974	302,931	4,969,610	0.64
1975	193,876	3,124,010	0.76
1976	143,253	3,311,420	0.58
1977	89,992	8,680,250	0.61
1978	56,509	8,553,230	0.68
1979	80,081	1,269,840	0.46
1980	71,723	5,966,670	0.75
1981	72,968	3,550,190	0.46
1982	75,904	3,838,310	0.44
1983	89,223	2,802,820	0.33
1984	111,320	9,118,220	0.44
1985	161,943	6,187,970	0.25
1986	204,845	5,413,870	0.19
1987	245,771	7,348,750	0.24
1988	274,854	11,645,300	0.24
1989	320,960	12,768,900	0.26
1990	329,208	13,668,000	0.17
1991	406,173	11,761,500	0.18
1992	554,490	7,205,610	0.17
1993	628,688	7,281,060	0.14
1994	562,838	10,014,400	0.11
1995	560,655	34,648,500	0.17
1996	534,057	19,493,400	0.17
1997	959,694	18,842,900	0.16
1998	734,714	10,178,100	0.15
1999	592,598	27,222,400	0.16
2000	628,921	8,066,140	0.16
2001	739,698	8,487,150	0.19
2002	495,772	18,475,400	0.18
2003	426,021	22,083,700	0.21
2004	421,699	10,603,100	0.20
2005	460,035	7,593,670	0.20
2006	422,208	17,108,300	0.23
2007	411,626	5,739,830	0.21
2008	420,561	15,098,800	0.21
2009	332,461	62,377,200	0.29
2010	347,675	10,568,800	0.16
2011	564,969	11,473,600	0.13
2012	735,915	42,388,700	0.13
2013	671,555	14,731,100	0.13
2014	1,041,500	27,517,700	0.10

Table 4. Stock-recruit parameters estimated in the Atlantic herring update assessment and used for projections.

Parameter	Value
Alpha α	22505700
Variance σ^2	0.359
Bias-corrected Alpha $\tilde{\alpha}$	18810594
Beta β	394391

Table 5. Results of Atlantic herring operational assessment projections.

	Harvest Scenario		
	F_{MSY}		
Result	**2016**	**2017**	**2018**
F	0.24	0.24	0.24
80%CI	-	-	-
Median Catch mt	138,000	113,000	107,000
80%CI	95,000-208,000	81,000-166,000	74,000-162,000
Median SSB mt	536,000	440,000	412,000
80%CI	354,000-880,000	312,000-669,000	282,000-631,000
Prob SSB<(SSB_{MSY}/2)	0.00	0.00	0.00
Prob F>F_{MSY}	-	-	-
	0.75F_{MSY}		
F	0.18	0.18	0.18
80%CI	-	-	-
Median Catch mt	106,000	90,000	88,000
80%CI	73,000-159,000	65,000-132,000	61,000-132,000
Median SSB mt	560,000	477,000	456,000
80%CI	369,000-914,000	337,000-721,000	314,000-695,000
Prob SSB<(SSB_{MSY}/2)	0.00	0.00	0.00
Prob F>F_{MSY}	-	-	-
	Status Quo ABC (114,000mt)		
Median F	0.19	0.24	0.26
80%CI	0.13-0.30	0.15-0.37	0.15-0.44
Catch mt	114,000	114,000	114,000
80%CI	-	-	-
Median SSB mt	555,000	454,000	421,000
80%CI	341,000-940,000	279,000-756,000	232,000-732,000
Prob SSB<(SSB_{MSY}/2)	0.00	0.00	0.02
Prob F>F_{MSY}	0.27	0.47	0.54
	F_{MSY} with 2011 year class reduced to average		
F	0.24	0.24	0.24
80%CI	-	-	-
Median Catch mt	111,000	98,000	96,000
80%CI	74,000-176,000	70,000-149,000	65,000-149,000
Median SSB mt	446,000	392,000	370,000
80%CI	282,000-785,000	275,000-613,000	250,000-575,000
Prob SSB<(SSB_{MSY}/2)	0.00	0.00	0.00
Prob F>F_{MSY}	-	-	-

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