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Atlantic herring *Clupea harengus* Operational Assessment Update 2015
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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

US catch data were separated into two 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 US mobile gear fishery peaked in the late 1960s and early 70s, 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 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 five years ranged from 79,413 mt in 2010 to 101,622 mt in 2013 and averaged 90,040 mt.

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 weir.

The US 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 two 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 ten years (Figure 3). The indices from the NMFS summer shrimp survey have been near or below the time series average for about eight 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, 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 three (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 three 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 three (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 assessments 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., worsening retrospective patterns). The model structure and all other model specifications were the same as in the NEFSC (2012) base model.

The point estimate of spawning stock biomass (SSB) in 1965 equaled 487,791mt (Figure 5). SSB generally declined from 1965 to a time series low of 56,293mt in 1978. SSB generally increased from 1978 through the mid-90s. SSB declined from 1997 to 345,828mt in 2010, but then increased to the time series high of 1,056,160mt in 2014. The point estimate of unexploited SSB equaled 831,913mt

Mean recruitment from 1965 to 2014 equaled 12.6 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 62.1 billion fish (Figure 5). The 2012 age-1 recruitment was estimated to be the second largest in the time series and equaled 42.2 billion fish. The point estimate of unexploited recruitment equaled 15.0 billion fish, and steepness equaled 0.46.

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 5). 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 here were 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 0.66 (Figure 6). The relative retrospective pattern for recruitment had all positive peels, except for two years, and Mohn's Rho equaled 0.42 (Figure 6). The relative retrospective pattern for age-5 fishing mortality had all negative peels and Mohn's Rho equaled -0.37 (Figure 6). 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 7), 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 7).

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 = 80,151mt, F_{MSY} = 0.27, and SSB_{MSY} = 299,802mt. The values for these reference points during the previous benchmark assessment (NEFSC 2012) were: MSY = 53,000mt, F_{MSY} = 0.27, and SSB_{MSY} = 157,000mt.

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 worsened, 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 8).

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. 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 9). 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 10). 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 11). 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 12). Retrospective patterns for SSB, fishing mortality, and recruitment for this sensitivity run were the worst of any model considered (Figure 13).

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 14).

Figure 1. Herring catches by mobile gears, fixed gears, and total.

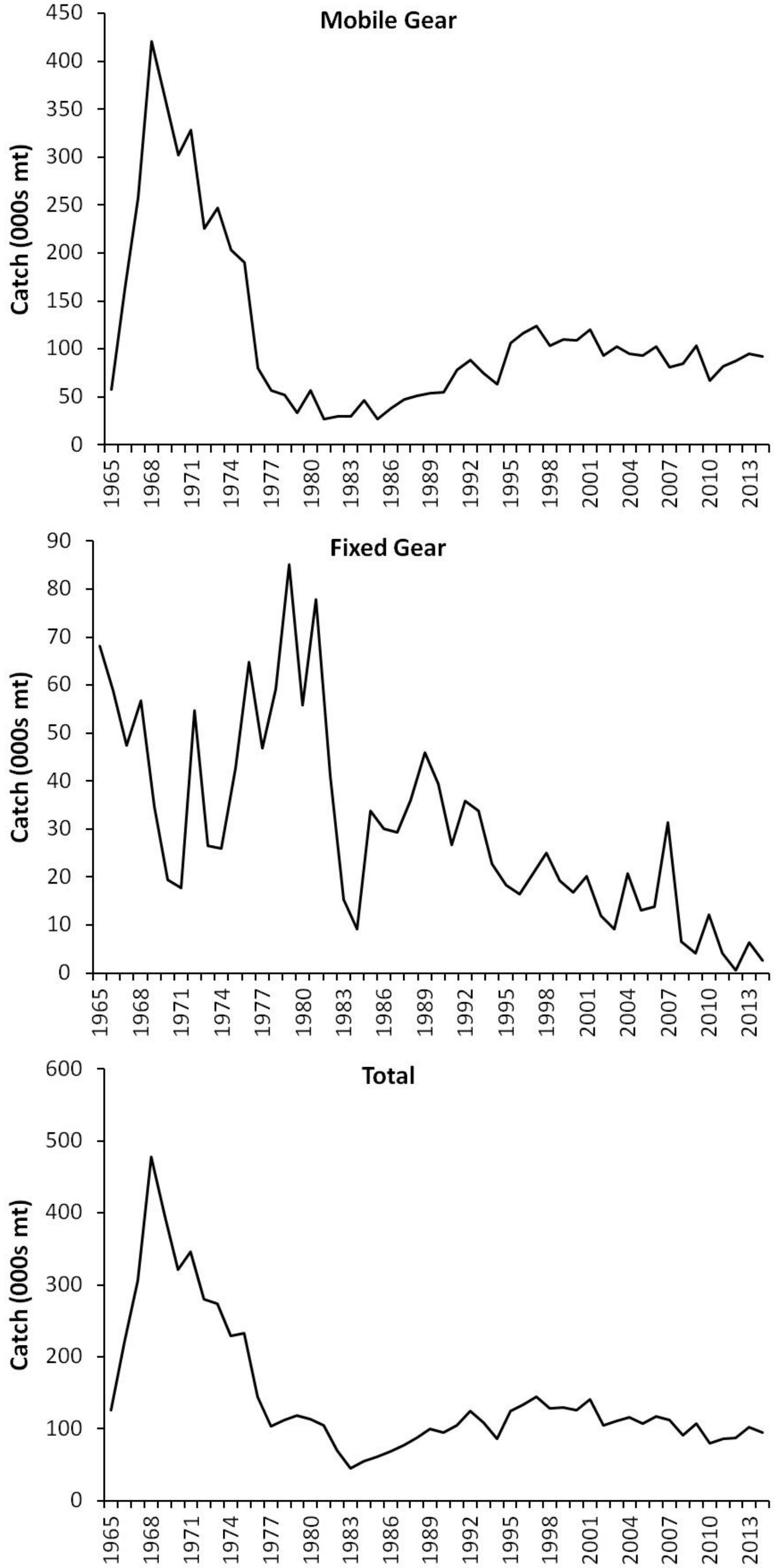
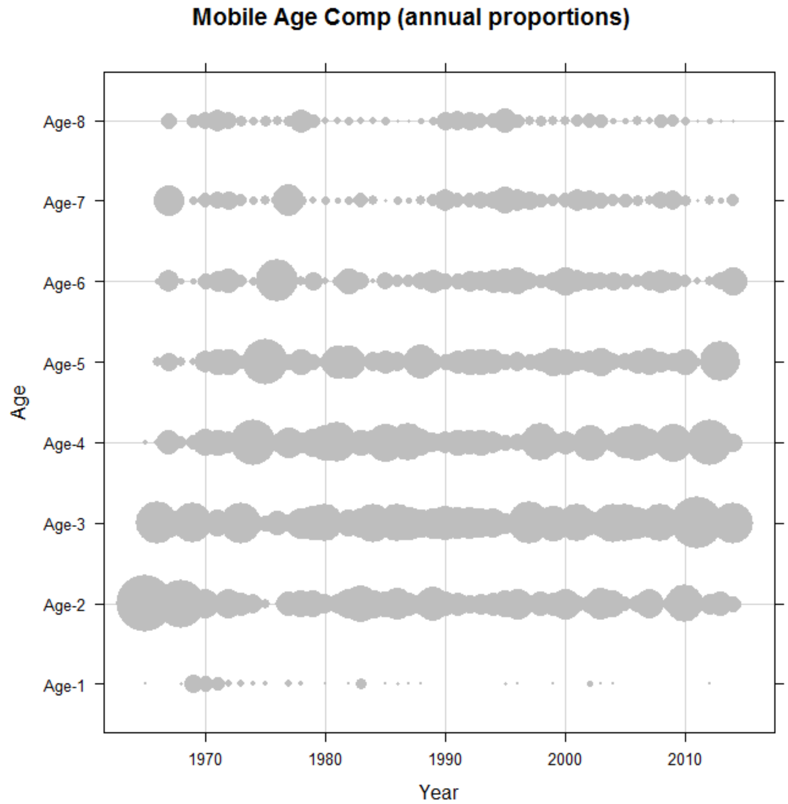


Figure 2. Mobile and fixed gear fishery age compositions for Atlantic herring (values-at-age for each year sum to 1.0).



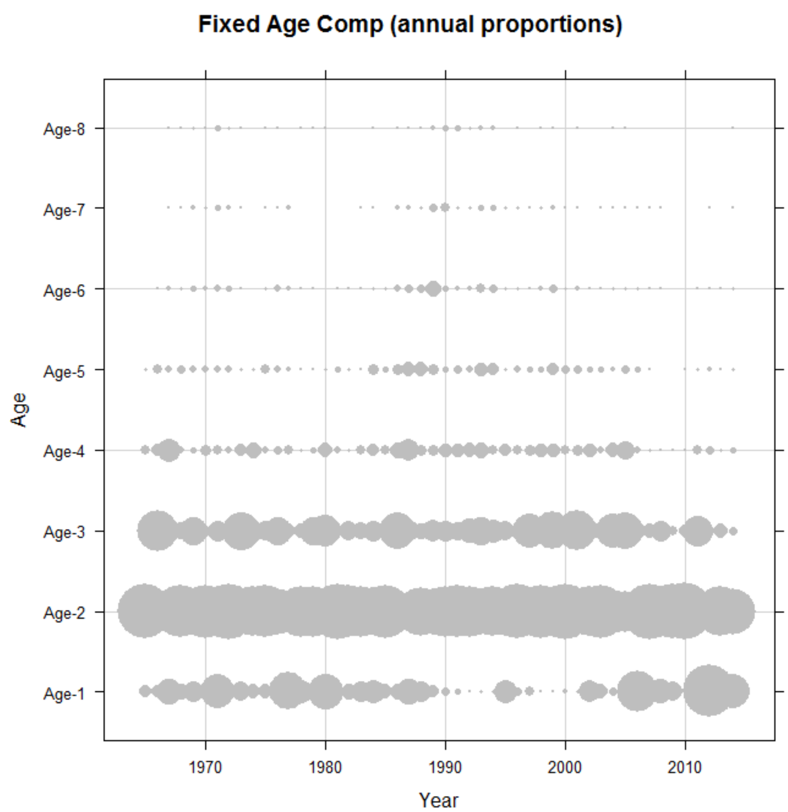


Figure 3. NMFS spring, fall, and summer shrimp bottom trawl survey indices for Atlantic herring (plus/minus 1 standard deviation). The horizontal dashed line is the average value from 1985-2014 for each survey.

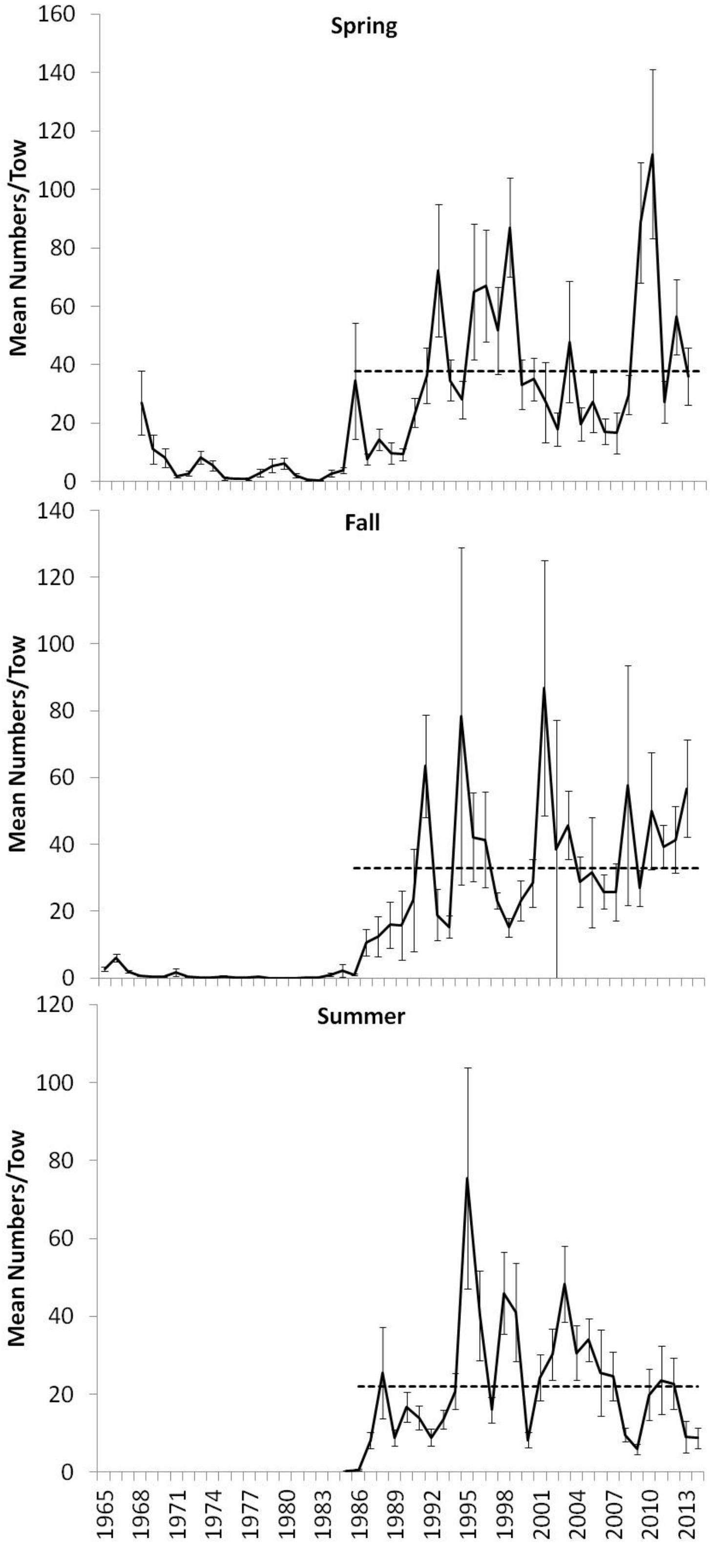
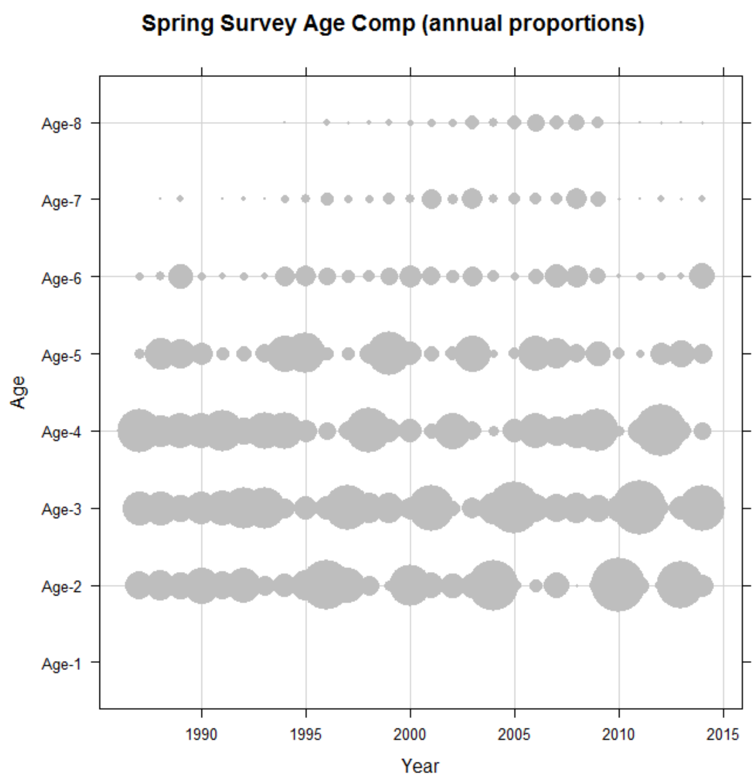


Figure 4. NMFS spring and fall bottom trawl survey age compositions for Atlantic herring (values-at-age for each year sum to 1.0).



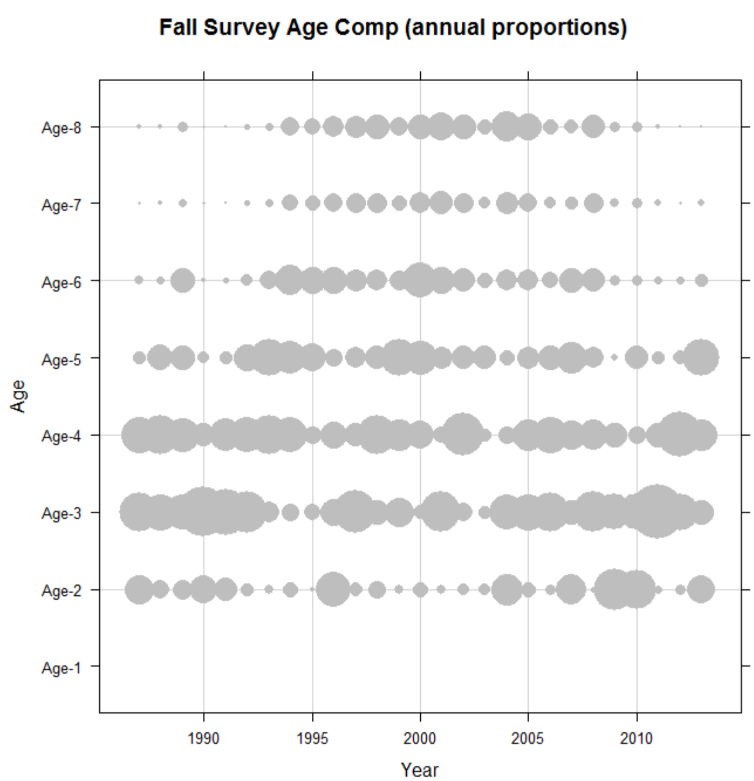


Figure 5. Estimates of SSB (mt), age-1 recruitment, and age-5 fishing mortality for the Atlantic herring update.

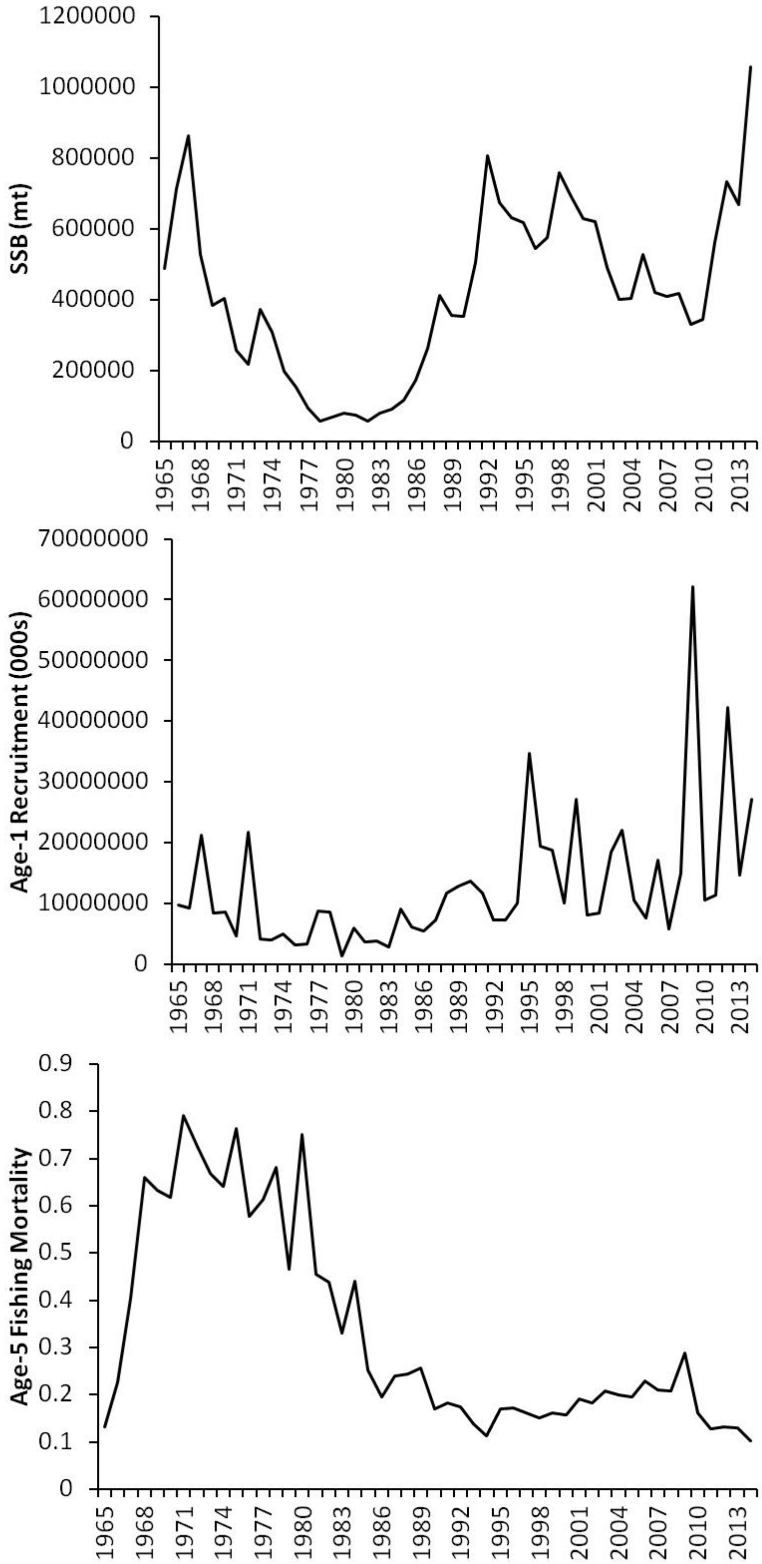


Figure 6. Retrospective patterns for the Atlantic herring update.

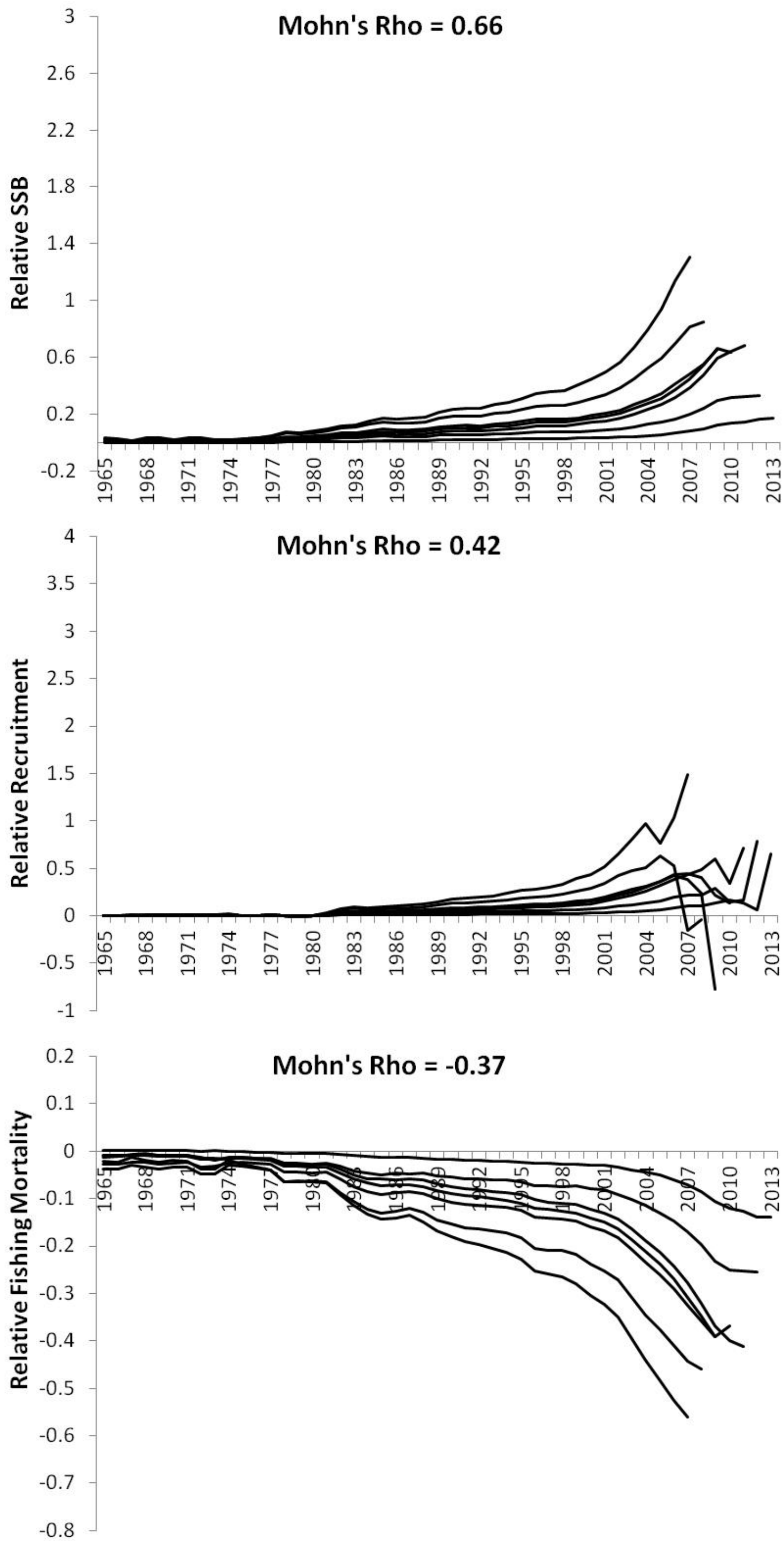


Figure 7. Total consumption of Atlantic herring by predators (solid black; "Estimated from Stomach Contents") and the consumption of herring that would result based on input natural mortality rates in the updated stock assessment (dashed black, "Implied from Input M").

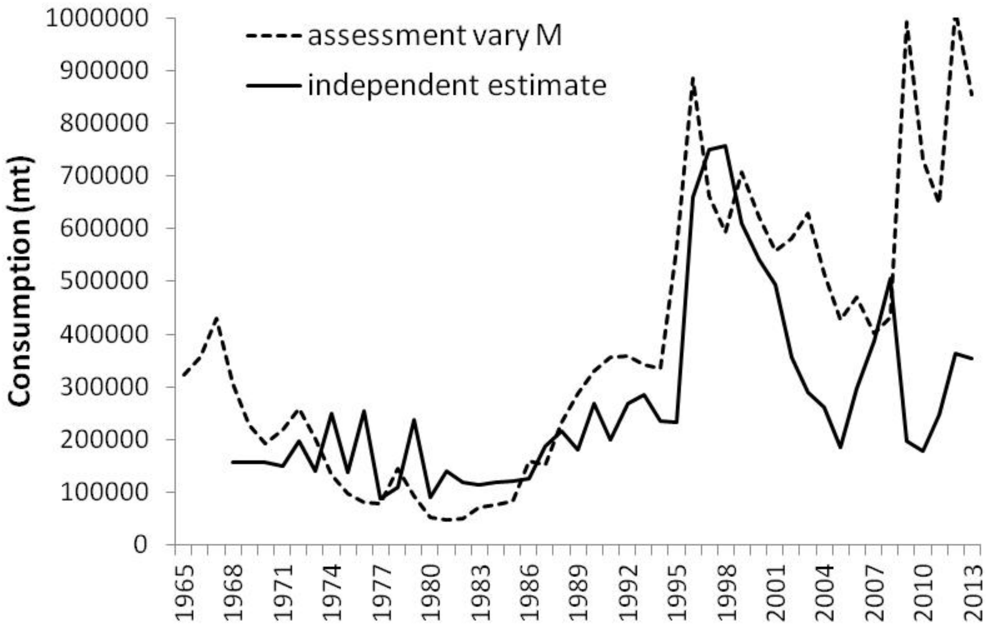


Figure 8. Fishing mortality in 2014 relative to F_{MSY} and SSB in 2014 relative to SSB_{MSY} (black circle; error bars are 10th and 90th percentiles based on MCMC of fishing mortality and SSB in 2013). The redline shows retrospective adjusted values.

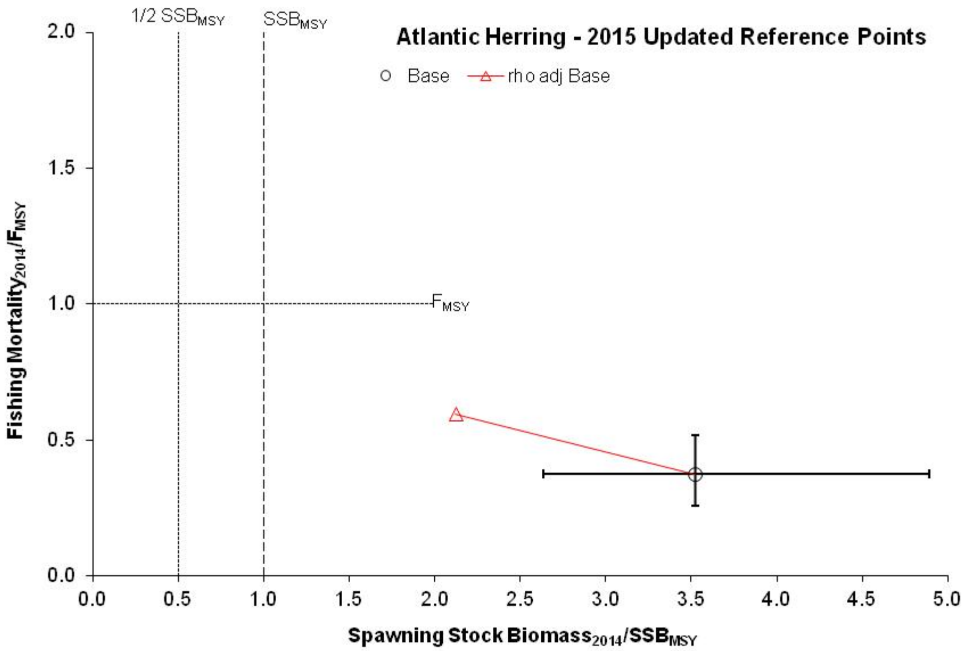


Figure 9. Retrospective patterns for the Atlantic herring update assessment with natural mortality rates increased during 1996-2013 to reduce the retrospective pattern.

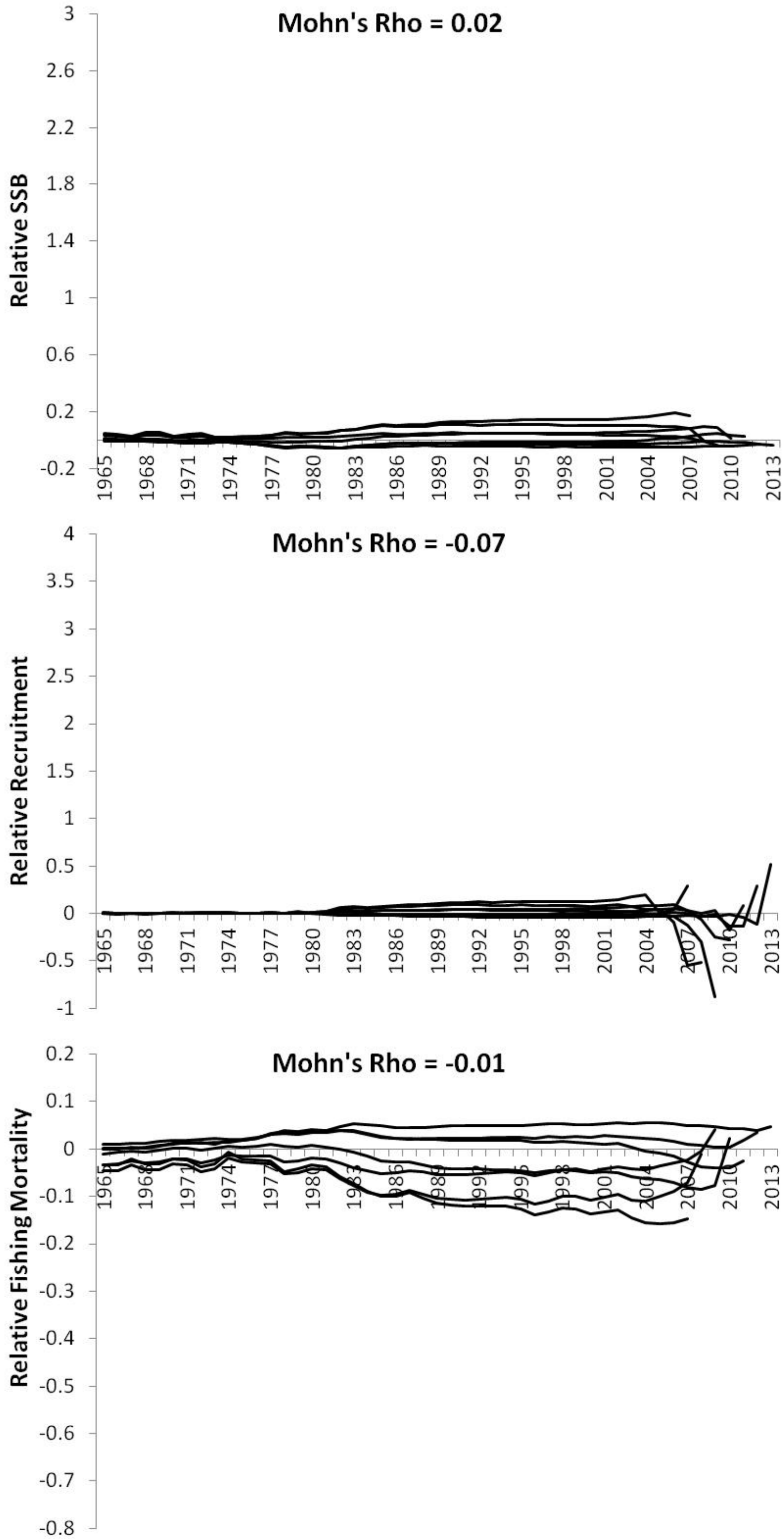


Figure 10. Total consumption of Atlantic herring by predators (solid black; “Estimated from Stomach Contents”) and the consumption of herring that would result with input natural mortality rates increased by 100% during 1996-2014 in the updated stock assessment (dashed black, “Implied from Input M”).

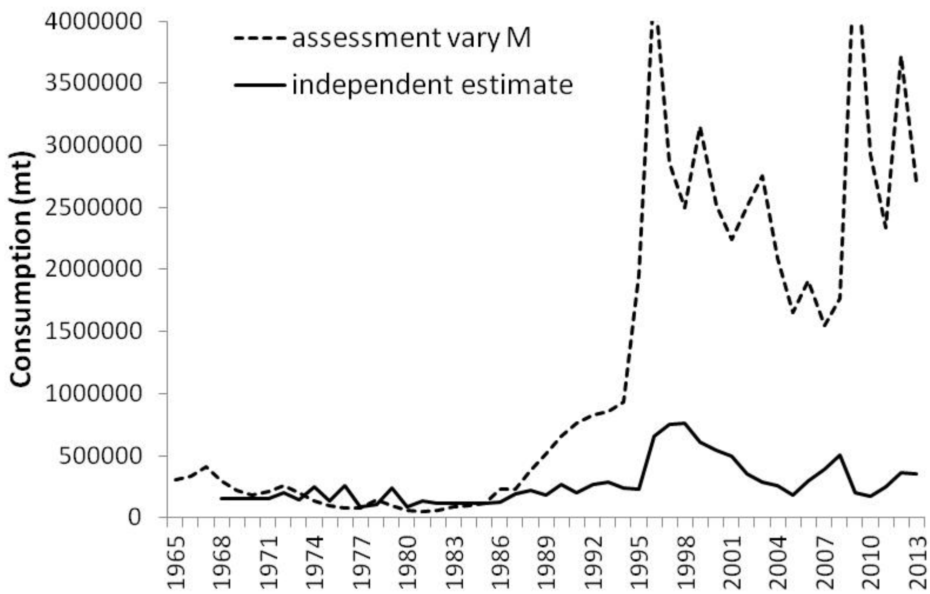


Figure 11. Comparison of SSB, age-1 recruitment, and fishing mortality from the base update Atlantic herring assessment (Base Update) and a run with natural mortality increased during 1996-2013 to reduce the retrospective pattern (Increase M).

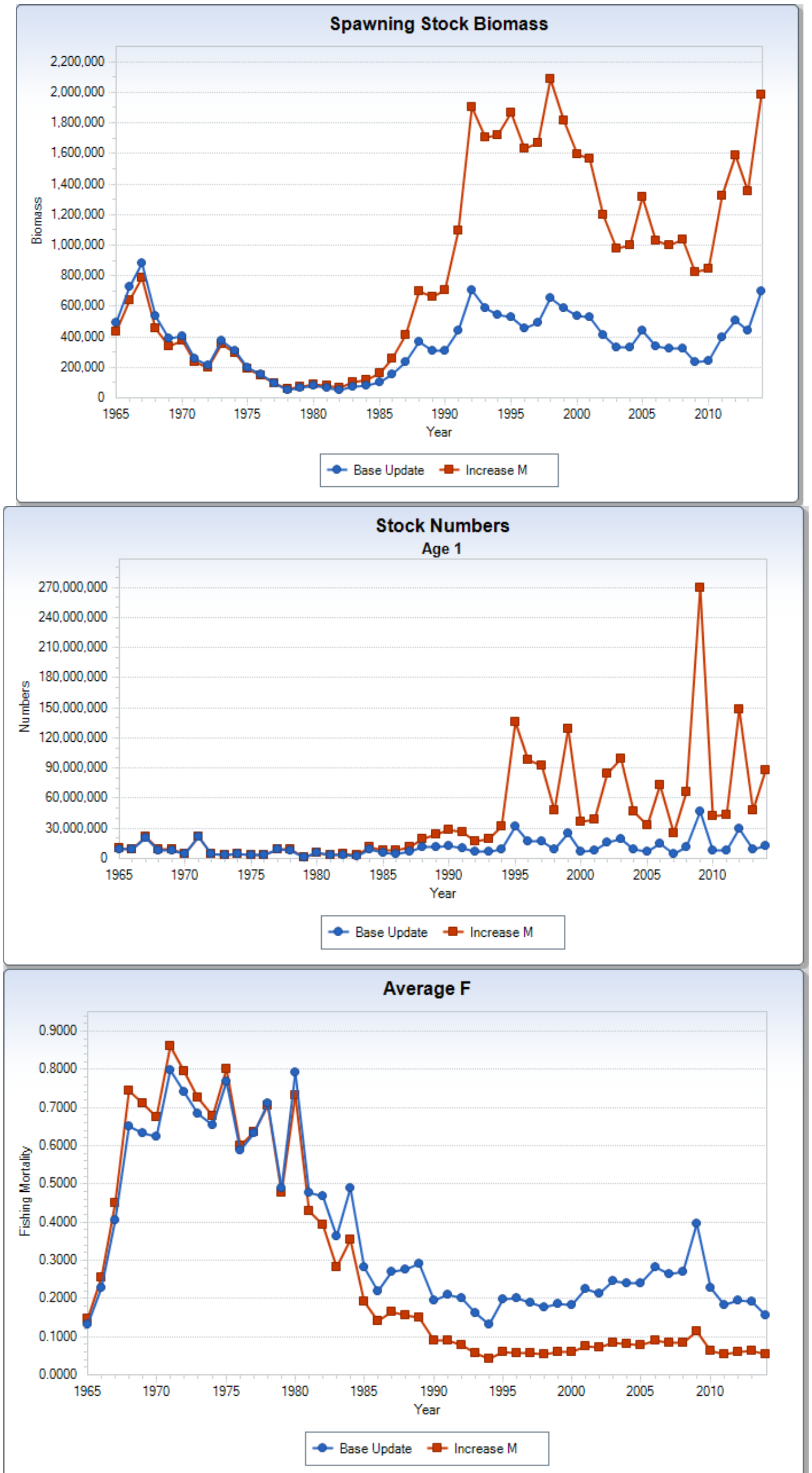


Figure 12. Total consumption of Atlantic herring by predators (solid black; "Estimated from Stomach Contents") and the consumption of herring that would result with input natural mortality rates decreased by 30% during 1999-2014 in the updated stock assessment (dashed black, "Implied from Input M").

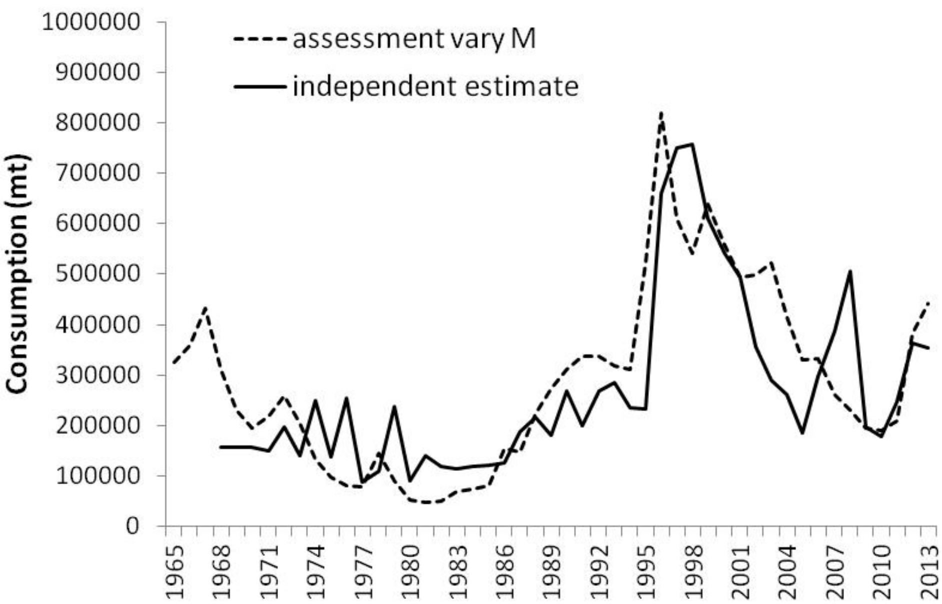


Figure 13. Retrospective patterns for the Atlantic herring update assessment with natural mortality rates decreased during 1999-2014 to improve the consistency between implied levels of consumption based on input rates and estimates of consumption from stomach contents data.

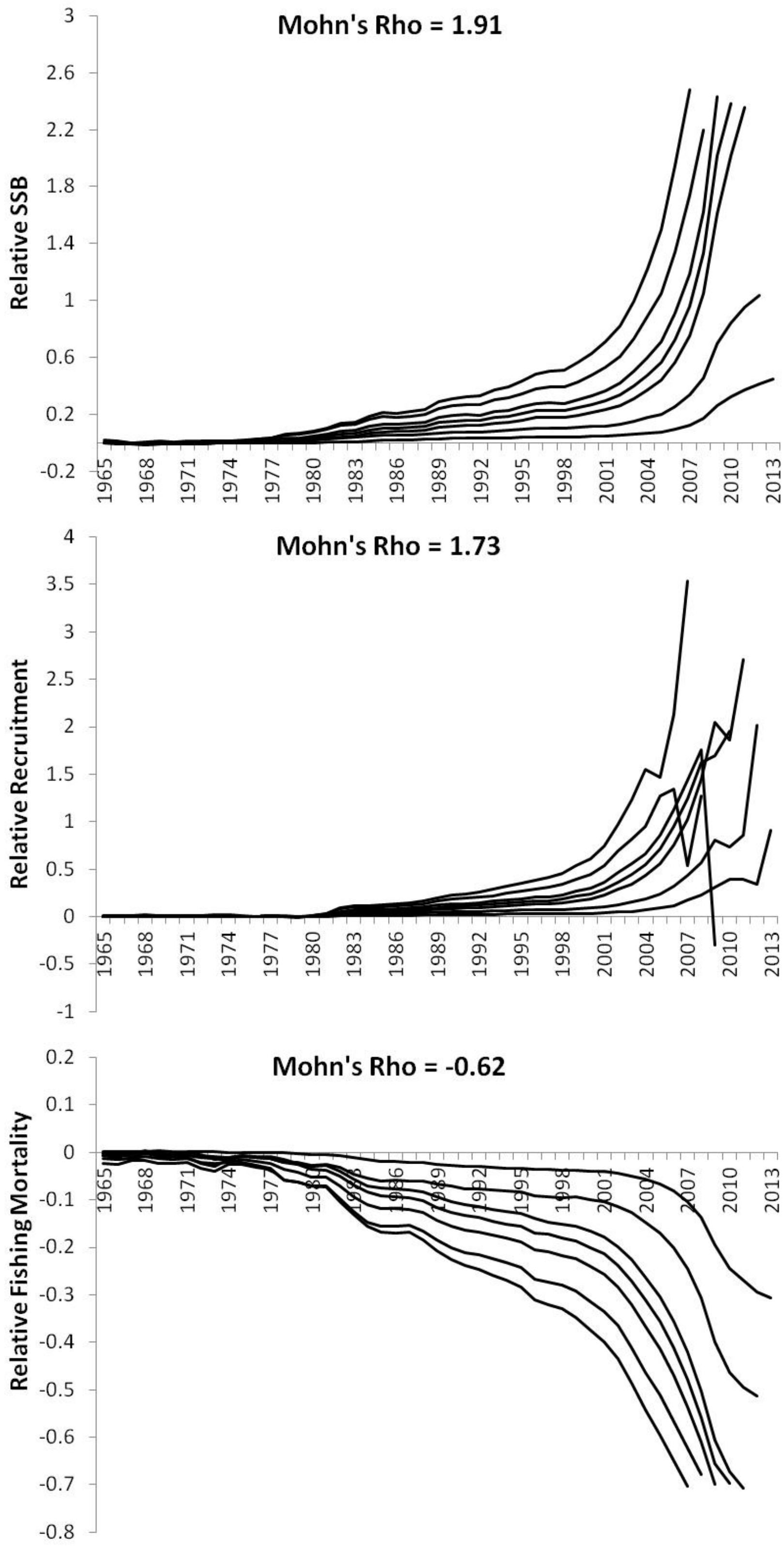


Figure 14. Comparison of SSB, age-1 recruitment, and fishing mortality from the base update Atlantic herring assessment (Base Update) and a run with natural mortality decreased during 1999-2014 to improve the consistency between implied levels of consumption based on input rates and estimates of consumption from stomach contents data (Decrease M).

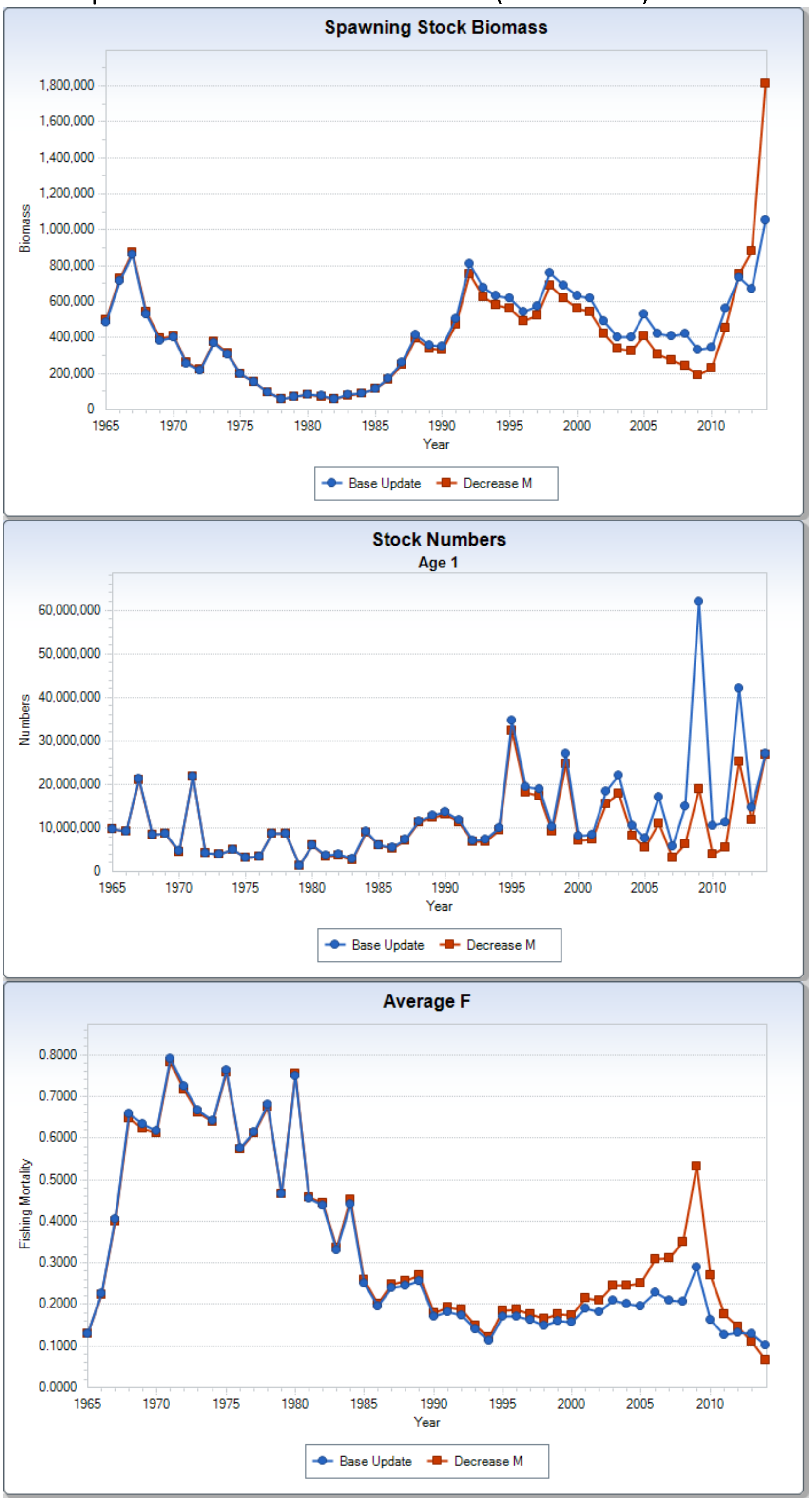


Table 1. Catch (metric tons) in the US mobile gear, US fixed gear, and New Brunswick weir fishery.

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.

	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