S. Atlantic halibut
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Additional details and supporting information can be found in the Appendix of the GARM-III Report (NEFSC 2008).

1.0 Background

Atlantic halibut (*Hippoglossus hippoglossus*) is the largest species of flatfish in the northwest Atlantic Ocean. It is a long-lived, late-maturing species distributed from Labrador to southern New England (Bigelow and Schroeder 1953). Atlantic halibut within the Gulf of Maine-Georges Bank region (NAFO Divisions 5Y and 5Z, Figure S1) have been exploited since the early 1800s, with major abundance declines noted as early as the 1870s (Goode 1886, Grasso 2008).

In previous index-based assessments (Brodziak and Col 2005, Brodziak 2002), Northeast Fisheries Science Center (NEFSC) autumn weight per tow survey indices were expanded to swept-area biomass estimates (assuming a catchability coefficient of one), and the 5-year average biomass index was compared to B_{MSY} proxy reference points for status determination (Table S3, Figure S2). Reference points for Atlantic halibut were originally determined by the New England Fisheries Management Council (NEFMC 1998) using Canadian Atlantic halibut length-weight equations (McCracken 1958) and von Bertalanffy growth curves (Nielson and Bowering 1989) to perform yield-per-recruit (YPR) and biomass-per-recruit analyses. M was assumed to be 0.1 and an MSY proxy was chosen to be 300 mt, yielding a B_{MSY} proxy = 5400 mt, a ½ B_{MSY} proxy = 2700 mt, and an F_{MSY} proxy (threshold) = $F_{0.1}$ = 0.06. Based on the Groundfish Assessment Review Meeting (GARM) 2005 assessment of Gulf of Maine-Georges Bank Atlantic halibut, the stock was overfished (B_{2004} was 5% of B_{MSY} proxy) and it was unknown whether overfishing was occurring (Brodziak and Col 2005).

In the Atlantic halibut assessment presented here, NEFSC survey and commercial fishery data were updated through 2007 and estimates of discards from the United States (US) commercial fishery were included in total catch estimates to reflect the GARM Data Meeting recommendations (GARM 2007). Reference points were re-evaluated by updating YPR analyses using recent estimates of growth (Sigourney 2002) and maturity parameters (Sigourney et al. 2006). The resulting F_{MSY} proxy was used to define the intrinsic rate of growth in a Replacement Yield Model as recommended by the GARM Biological Reference Points meeting panel (GARM 2008b). The Replacement Yield Model incorporates the entire time series of catch data, tunes to the autumn survey swept-area biomass index, and results in B_{MSY} and MSY proxy reference points, and annual estimates of biomass and relative fishing mortality.

2.0 Fishery

Commercial landings

Records of Atlantic halibut landings from the Gulf of Maine-Georges Bank region (Statistical Areas 511-515, 521-522, 525-526, 561-562) began in 1893 (ICNAF 1952, Table S1, Figure S3). However, substantial landings occurred prior to this, since the halibut fishery experienced sharp declines during the late 1870s (Hennemuth and Rockwell 1987, Goode 1887).

Current US landings were extracted from the NEFSC commercial fisheries database (CFDBS) AA tables, and Canadian landings (Division 5Zc) were extracted from the NAFO 21A database[8].

Landings have continued to decrease since the 1890s as components of the resource have been sequentially depleted. Annual landings averaged 663 mt between 1893 and 1940, declined to an average of 144 mt per year during 1941-1976, and declined further to an average of 91 mt per year during 1977-2000 (Table S1, Figure S3). Total reported commercial landings of halibut increased somewhat from record lows of 17-20 mt during 1998-2000 to 52 mt in 2007. Of the 2007 landings, 22 mt (42%) were landed by US fishermen and 30 mt (58%) were landed by Canadian fishermen.

Commercial discards

Discards from the Northeast Fisheries Observer Program database were estimated for the period 1989 to 2007 based on the Standardized Bycatch Reporting Methodology combined ratio estimation (Wigley et al. 2007). The 1999 implementation of a one halibut per trip limit as well as a 91 cm minimum retention size increased the discard to kept ratio from 17% during 1989-1998 to 147% during 1999-2007 (Table S2, Figure S4). Due to the low occurrence of Atlantic halibut in the observer database, the 1989-1998 average discards were applied to the landings from 1893 to 1998 and the 1999-2007 average discards were applied to landings in those years. Including US discards, total catch increased from 18 mt in 1998 to 84 mt in 2007 (Table S1, Figure S4).

3.0 Research Surveys

The NEFSC spring and autumn bottom trawl surveys provide measures of relative abundance of Atlantic halibut within the Gulf of Maine-Georges Bank region (offshore survey strata 13-30 and 36-40, Table S3). Both indices have high interannual variability since the surveys capture low numbers of halibut, and in some years there are no halibut caught (Figure S5), indicating that halibut abundance is close to being below the detectability levels of the surveys. The autumn survey biomass and abundance indices are relatively flat (Figures S6a and b), whereas the spring survey biomass and abundance indices (Figures S6a and b) suggest a relative increase during the late 1970s to early 1980s, a decline during the 1990s, and an increase since the late 1990s. However, it is unknown whether survey trends in the Gulf of Maine-Georges Bank region have been influenced by changes in the seasonal distribution and availability of Atlantic halibut. Due to the lack of alternative population estimates, the autumn survey has been used in previous assessments to estimate biomass. The autumn survey was chosen over the spring survey because of the longer time series as well as possible environmental forcing in the spring survey indicated by a negative correlation with spring bottom water temperature anomalies. There are no conversion factors available for Atlantic halibut catchability differences due to vessel, net or door changes that have occurred throughout the NEFSC survey time series. In previous assessments a survey catchability coefficient of one was assumed for swept-area biomass estimates.

[8] http://www.nafo.int/science/frames/research.html

4.0 Assessment

Input data and model formulation

YPR: The Gulf of Maine-Georges Bank region of the Atlantic halibut stock is severely data limited. Relatively few fish are encountered in either the commercial fishery or NEFSC bottom trawl surveys, and currently the NEFSC does not age samples from either source. Recent experimental halibut lonline data (Kanwit 2007), growth analyses (Sigourney 2002), and maturity analyses (Sigourney et al. 2006) have been used along with NEFSC length and weight data to update YPR analyses for Atlantic halibut.

Combined years (1992-2007) of NEFSC spring and autumn length and weight data over all strata were used to estimate length-weight parameters:

$W = \alpha L^{\beta}$

Where:

α was estimated to be 0.00415 and

β was estimated to be 3.23040.

Atlantic halibut from NEFSC spring and autumn surveys and the halibut experimental longline fishery were aged through 2001 and a von Bertalanffy growth equation was used to estimate length at age by sex (Sigourney 2002). The length-weight equation was then applied to the female lengths at age to determine weight-at-age inputs for YPR analyses (Table S4).

Maturity percentiles at age from Sigourney et al. (2006) were used to calculate a maturity ogive for female halibut:

$S(a) = (1+e^{(-\alpha - \beta a)})^{-1}$

Where:

a is age,

β is a parameter assumed to be equal to $(2\ln 3)/(L_{75}-L_{25})$, estimated to be 0.518, and

α is a parameter assumed to be equal to $-\beta L_{50}$, estimated to be -3.778.

The resulting weight at age and maturity at age were used in YPR analyses with a plus group for ages 41 to 50 (Table S4). Sigourney et al. (2006) recorded halibut from the recent NEFSC survey time series up to age 40, and it is likely that larger halibut landed in the earlier part of the fishery time series were at least 50 years of age. No estimates of natural mortality rates for Atlantic halibut or Greenland halibut are included in previous assessments (Brodziak and Col 2005, DFO 2006, DFO 2007, DFO 2008). Pacific halibut has similar growth patterns and maximum age, and in recent reports, M was estimated to be 0.15 for Pacific halibut based on catch curve analysis and energetic models of growth and reproduction (Clark and Hare 2006). Therefore M was assumed to be 0.15 for the Gulf of Maine-Georges Bank Atlantic halibut, however it should be cautioned that this estimate is somewhat higher than using maximum age as a proxy to estimate M (using $-\ln(0.05)/(\text{max age of } 50)$, $M \sim 0.06$).

As in the previous reference point determination (NEFMC 1998) a knife-edge selectivity at age 4 (~60cm and 2.4kg) was used for YPR analyses. Since Amendment 9 was implemented in 1999, regulations have prohibited landing halibut less than 91cm. However there is evidence from Northeast Fisheries Observer Program data that smaller halibut are continuing to be landed (Table S5). Kept halibut from observer data indicate that even after implementation, mean lengths of kept halibut generally ranged from 80-90cm (~ages 5.5-6.5), with minimum sizes of kept halibut generally ranging from 40-50cm (~ages 2.5-3.5, Table S5). Discarded halibut mean lengths have ranged from 27-70cm (~ages 2-5), with minimum discard lengths generally ranging from 20-40cm (~ages 1-3, Table S5). Survival of Atlantic halibut discarded from longline gear is estimated to be 77% whereas survival of discards from otter trawl gear was estimated to be substantially lower at 35% (Neilson et al. 1989). Thus, selectivity of Atlantic halibut likely starts around age 2 (30cm) for bottom trawl gear, which corresponds to the selectivity of other flatfish. Whereas selectivity from longline gear likely occurs at older ages around 6-7 years. This disparity in gear selectivity should be researched further, however with limited data to compare survey gear to commercial fishing gear, age 4 was chosen as a reasonable midpoint for knife-edged selectivity.

Replacement Yield Model

The resulting F_{MSY} proxy ($F_{0.1}$) from the YPR analysis was used to inform the intrinsic rate of growth (defined as $2*F_{0.1}$) for the Replacement Yield Model. Since Atlantic halibut catch predates reliable landings statistics beginning in 1893 (ICNAF 1953, Grasso 2008), a linear increase in catch was assumed from 1800-1893 following the advice of the GARM Biological Reference Points review panel (GARM 2008b, Table S7). Although this estimate is crude, it was considered to be better than assuming that 1893 biomass was representative of an unfished population and thus equal to carrying capacity.

A replacement yield model similar to that described in Brandao and Butterworth (2008a) was used to provide annual estimates of biomass, replacement yield and fishing mortality. In this model, estimated biomass is defined as:

$$B_y = B_{y-1} + R_{y-1} - C_{y-1}$$

Where:
B_y is the biomass at the start of year y,
B_{y-1} is the biomass at the start of the previous year,
C_{y-1} is the total catch in the previous year, and
R_{y-1} is the replacement yield in the previous year.

Replacement yield is defined as:

$$R_y = rB_y (1- B_y /K)$$

Where:
r is the intrinsic rate of growth, and
K is the carrying capacity (assumed to be equal to the model estimated biomass in 1800).

The model was fitted to the NEFSC autumn survey swept-area biomass index, and the following negative log-likelihood (-ln*L*) was used to determine the model with the best estimates of carrying capacity and predicted survey catchability coefficient parameters:

$-\ln L = \log(\delta) + 0.5\sum(\ln(I_y)-\ln(B_y q))^2/\delta^2 + p_1 + p_2$

Where:
δ is a constant,
I_y is the swept-area biomass index in year y,
q is the catchability of the NEFSC fall survey defined as the exponent of the average of $\ln(I_y)-\ln(B_y)$,
p_1 is the sum of the penalties for biomass going to the defined minimum boundary in a given year, and
p_2 is a penalty for the difference between the model-estimated q and the assumption that the NEFSC autumn survey q is roughly 0.5

Model selection process

Available models are limited for data poor species such as Atlantic halibut. An age-structured production model as described in Brandao and Butterworth (2008b) was not considered to be a reasonable approach given the lack of available data. A simplistic LOSS model without constraining the intrinsic rate of growth to YPR output or tuning to survey q yields a wide range of results with little information on which to inform model selection. By using $F_{0.1}$ to inform the intrinsic rate of growth in a Replacement Yield Model, and penalizing results that differ greatly from NEFSC autumn survey q, model results were considered to be more reliably estimated. This approach also incorporates the most data available for Atlantic halibut and was recommended by the GARM Biological Reference Points review panel (GARM 2008b).

Previous index-based assessments (Brodziak and Col 2005, Brodziak 2002) relied entirely on the expansion of NEFSC autumn survey indices to swept-area biomass estimates. This is particularly problematic with Atlantic halibut since the survey started roughly 100 years after the fishery collapsed, and encounter rates of halibut in consistently sampled survey strata are very low (Figure S5). Assuming a survey q of 1 for swept-area biomass estimates is likely high, and great uncertainty in previous MSY estimation leads to uncertainty in determining biomass reference points. Additionally, there have been changes in doors, nets and vessels throughout the time series which may affect catchability of Atlantic halibut over the time series. Since the surveys encounter so few halibut, conversion factors have not been estimable. The inability to calculate conversion factors for halibut will become a much larger problem in 2009 when the survey will change to the RV Henry Bigelow, which is likely to have vastly different catchabilities than the RV Albatross IV for most species. Therefore, relying entirely on the autumn survey index for the Atlantic halibut assessment is not recommended and the Replacement Yield Model is considered to be the preferred assessment method until further research can be performed.

An implicit assumption being made is that the current and historical productivity are similar. Given the long period of time being considered, this assumption is difficult to confirm.

Assessment results

NFT YPR version 2.7.2[9] was used to perform the YPR analysis, which resulted in an $F_{0.1}$ of 0.073. This is slightly higher than the previous $F_{threshold}$ of 0.06, using M = 0.1. The intrinsic

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[9] http://nft.nefsc.noaa.gov/YPR.html NOAA Fisheries Toolbox Version 3.0, 2008. Age Based Yield per Recruit Version 2.7.2

growth rate for the Replacement Yield Model was assumed to be $2*F_{0.1}$ (0.146), and the model was tuned to the NEFSC autumn survey swept-area biomass. The model estimated biomass indicated a sharp decline from around 4,000-5,000 mt during the early 1900s to around 1,000 mt during the mid-1900s. Atlantic halibut hit a record low biomass level of around 400 mt in the mid-1990s and has since increased to 1,300 mt in 2007 (Table S7, Figure S7). Relative F (catch/biomass) has been highly variable with spikes of fishing mortality close to 0.7 in the late 1800s, and around 0.4 in 1940 and 1967. However fishing mortality has been relatively low since the mid-1990s, with a slight increase to 0.065 in 2007 (Table S7, Figure S8). Replacement yield decreased sharply in the 1870s to a low of 500 mt in 1900, increased slightly to 700 mt around 1920, gradually decreased to 60 mt in the early 1990s, and is currently close to 190 mt (Table S7, Figure S9).

Diagnostics

No diagnostics are available for the previous index-based assessment. For the Replacement Yield Model, only the most recent 45 years can be included for residual pattern analyses, where survey swept-area biomass estimates are available. Figure S10 (Table S6) indicates that there is minor patterning in the residuals, with the Replacement Yield Model slightly overestimating biomass during the mid-1960s and greatly underestimating biomass in other years due to the high variability in the autumn survey index. However there are no periods of consistently strong residual patterns.

Sensitivity analyses

Two sensitivity analyses were run for the Replacement Yield Model based on panel recommendations from the GARM Biological Reference Points meeting (GARM 2008b). The first was to test using a parabolic increase of catch instead of a linear increase to represent 1800-1892 catch in the Replacement Yield Model. The resulting biomass estimates were essentially identical using either method, indicating that the Replacement Yield Model is not sensitive to the method of estimating historic catch.

The second sensitivity recommended by the review panel (GARM 2008b) was to test various natural mortality rates for Atlantic halibut in the Replacement Yield Model based on published values from halibut assessments in other regions. No alternative natural mortality rates were available from published assessments, however three natural mortality rates were tested in the YPR analyses to generate three $F_{0.1}$ estimates used to determine the intrinsic growth rates in Replacement Yield Models. The natural mortality estimate of 0.15 was the preferred M based on Pacific halibut estimates, resulting in $F_{0.1} = 0.073$. A natural mortality estimate of 0.08 was tested based on a maximum age of 40 years, resulting in $F_{0.1} = 0.046$. Finally, a natural mortality estimate of 0.10 was tested since this was used in the previous YPR analysis for Atlantic halibut (NEFSC 1998), resulting in $F_{0.1} = 0.053$. However, it should be noted that the M of 0.10 that was used for the previous YPR analysis was based on Pacific halibut assessments at that time (NEFSC 1998).

The reference point tables below indicate that biomass reference points from Replacement Yield Models increased with decreasing natural mortality rates. Although initially counter-intuitive, this is due to the intrinsic rate of growth in the Replacement Yield Model being defined as $2*F_{MSY}$ proxy from the YPR analysis. As the intrinsic growth rate decreases with M, carrying capacity and thus biomass reference points have to be increased in the Replacement Yield Model in order to keep biomass from decreasing to zero over the time series of the catch.

Since biomass reference points increased proportionally with biomass, all sensitivity runs for natural mortality rates resulted in current biomass levels of 5-6% of ½ B_{MSY} proxies.

5.0 Biological Reference Points

The fishing mortality reference point was estimated to be F_{MSY} proxy ($F_{0.1}$) = 0.073 from updated YPR analyses described above, using M = 0.15 based on Pacific halibut estimates (Clark and Hare 2006). Since the Pacific halibut assessment is the only halibut assessment that assumes a natural mortality rate based on empirical research, this is the preferred M. Biomass reference points were based on Replacement Yield Model estimated carrying capacity (97,000 mt = estimated biomass in 1800), which was informed by the F_{MSY} proxy from the YPR analysis. Target biomass (B_{MSY} proxy) was defined as half of K (49,000mt) and threshold biomass (1/2 B_{MSY} proxy) was equal to 24,000 mt. A maximum sustainable yield of 3,500 mt was calculated as the F_{MSY} proxy multiplied by the B_{MSY} proxy from the Replacement Yield Model. F_{MSY} proxies based on YPR analyses with alternative estimates of M are presented below with the resulting biomass reference points, MSY, current relative F and current biomass estimates from the Replacement Yield Model.

Replacement Yield Model Reference Points (M=0.15 based on Pacific halibut; Final BRPs):

	Threshold	**Target**	**Current Estimate**	**% Threshold**	**MSY**
Fishing mortality	**0.073**		**0.065**	**89%**	**3,500 mt**
Stock biomass	**24,000 mt**	**49,000 mt**	**1,300 mt**	**5%**	

Replacement Yield Model Reference Points (M=0.10 based on 1998 YPR):

	Threshold	Target	Current Estimate	% Threshold	MSY
Fishing mortality	0.053		0.038	72%	3,200 mt
Stock biomass	30,000 mt	60,000 mt	1,800 mt	6%	

Replacement Yield Model Reference Points (M=0.08 based on maximum age of 40):

	Threshold	Target	Current Estimate	% Threshold	MSY
Fishing mortality	0.046		0.043	93%	3,000 mt
Stock biomass	32,000 mt	65,000 mt	2,000 mt	6%	

In comparison to previous index-based assessments, B_{MSY}, MSY and current biomass from all of the Replacement Yield Model scenarios are substantially higher since they include the implied higher biomass levels that enabled large amounts of catch in the late 1800s. However current biomass as a percent of the threshold is similar for the two methods. Below are the biological reference points and 2007 estimates using the GARM 2005 index-based method.

Previous Index-Based Reference Points (M=0.10):

	Threshold	Target	Current Estimate	% Threshold	MSY
Fishing mortality	0.06	0.04	none	n/a	300 mt
Stock biomass	2,700 mt	5,400 mt	252 mt	9%	

6.0 Projection

$F_{REBUILD}$

Based on panel recommendations from the GARM III final meeting (August 4-8, 2008), projections were run for Atlantic halibut using the Replacement Yield Model, assuming M = 0.15 and a linear increase in catch from 1800-1893. In 2004 Amendment 13 was adopted, and although a trajectory for halibut could not be calculated at that time, a rebuilding program was commenced in that year. Therefore, the rebuilding time period for Atlantic halibut was determined to be from 2004 to the estimated year in which halibut would rebuild to B_{MSY} at F = 0, plus one mean generation time from the updated YPR analyses. The resulting rebuilding time frame for Atlantic halibut was 2056, and currently the $F_{REBUILD} = 0.044$.

There are a number of reasons to suggest that both the rebuilding time frame and the $F_{REBUILD}$ are highly optimistic, the first being that the Replacement Yield Model assumes maximum growth rate of the population at low abundance. There are currently no indications that Atlantic halibut are either reproducing or growing at their maximum potential in the currently depleted state. The second is that the Replacement Yield Model does not incorporate age structure. This is of particular concern for Atlantic halibut since the mean age of maturity for females is 7.3 years (Sigourney 2006), creating both a lag time of initial response to management measures and a slower rebuilding trajectory which are not realized in the current projections. The final source of concern for calculating rebuilding trajectories is that the currently assessed Gulf of Maine-Georges Bank region is likely a small portion of a larger US-Canadian Atlantic halibut stock (Kanwit 2007, see sources of uncertainty below). This substantially increases uncertainty in the current projections since the Replacement Yield Model does not incorporate the entire dynamics of the stock.

The $F_{REBUILD}$ for the current Replacement Yield Model is only slightly lower than the average model-estimated relative fishing mortality for the 1995-2007 period (0.052). Under this $F_{REBUILD}$ the projected biomass is estimated to roughly double over the next seven years and to continue with a roughly exponential growth throughout the rebuilding time period. This rate of increase has not been shown in the 200+ years of model estimated biomass and is thus unlikely to be biologically feasible. Further, there are no indications in the NEFSC survey indices that significant recent increases in population abundance or biomass are occurring. Therefore, both the rebuilding time frame and the $F_{REBUILD}$ from the Replacement Yield Model are highly optimistic.

2009 Catch Estimates

Three scenarios of relative F in 2009 were calculated for $F_{STATUS\ QUO}$, F_{MSY} and $F_{REBUILD}$. In each case the observed total catch for years 2004-2007 were used and catch in 2008 was set to equal the catch in 2007. The results for 2009 catch estimates based on the three scenarios were as follows: $F_{STATUS\ QUO}$: 100 mt, F_{MSY}: 112 mt, and $F_{REBUILD}$: 68 mt (Table S8).

7.0 Summary

Stock status

Using M = 0.15 in the YPR analysis resulted in a F_{MSY} proxy of 0.073. Current relative F from the Replacement Yield Model is 0.065 in 2007, indicating that overfishing is not occurring for Atlantic halibut, although relative F is 89% of the proxy F threshold. The 2007 estimated biomass from the Replacement Yield Model is 1,300 mt, or 5% of the biomass threshold, indicating that Atlantic halibut continues to be in an overfished condition (Figure S11).

Sources of uncertainty

Limited biological data lead to uncertainty in growth and maturity at age estimates for the YPR analysis, although recent research and the experimental halibut fishery have allowed for updated estimates to be based on Atlantic halibut in the Gulf of Maine-Georges Bank region. A lack of reported landings prior to 1893 lead to rough estimates of catch during 1800-1892, however the Replacement Yield Model does not appear to be highly sensitive to these estimates. A lack of available natural mortality estimates for Atlantic halibut necessitates the use of Pacific halibut estimates, and this leads to uncertainty in MSY and biomass reference point estimation in the Replacement Yield Model. However, the resulting status of Atlantic halibut being near overfishing levels and far below B_{MSY} levels remains regardless of M. Arguably the most problematic aspect of the Replacement Yield Model is providing informative tuning indices. Although the NEFSC autumn survey swept-area biomass index has been considered to be the best available estimate of commercially independent biomass in previous assessments, there is a great deal of uncertainty as to whether this index is reliable for detecting population biomass trends due to the low encounter rates of Atlantic halibut.

Another source of uncertainty is the stock boundary determination of Atlantic halibut. For management purposes the Gulf of Maine-Georges Bank region is considered to be a separate stock from Canadian Scotian Shelf-Southern Grand Banks and Gulf of St. Lawrence stocks. However, recent tagging information indicates that 28% of Atlantic halibut tagged off of the coast of Maine crossed into Canadian waters, and that some individuals traveled over 1,500 km north to Newfoundland (Kanwit 2007, Figure S12). This clearly indicates trans-boundary movement, and future assessments should consider combining the Gulf of Maine-Georges Bank region with Canadian stocks.

8.0 Panel Discussion/Comments

Conclusions

Consistent with the recommendations fo the GARM III ‘BRP’ review, the Panel accepted the replacement yield model and considered it sufficient for management purposes. This is a significant improvement from the previous assessment which was based on a relative index approach.

As recommended by the GARM III ‘BRP’ review, the Panel noted the further consideration of the estimate of M and agreed with the choice of 0.15 based upon estimates from Pacific Halibut. It also noted that the model results were relatively insensitive to assumptions on the trajectory of catches prior to 1893, an analysis suggested by the GARM III ‘BRP’ review.

Regarding uncertainties, it was noted that the research surveys do not provide a good estimate of abundance due to very low catch rates. The assessment suggests that, based upon this information, there has been an increase in abundance in recent years. However, the evidence for recovery is weak.

Another source of uncertainty is the stock definition with the tagging results presented at the meeting showing migration to the east into Canadian waters.

The Panel requested that a deterministic rebuilding projection be included in the assessment. $F_{REBUILD}$ was estimated to be 0.044.

Research Recommendations

There are a number of avenues that could be pursued to enhance the assessment. Further work on natural mortality is encouraged as is stock interactions with Atlantic Halibut in Canadian waters. In relation to the latter, joint work with Canadian halibut scientists is encouraged.

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Table S1. Reported catch (mt) of Atlantic halibut from the Gulf of Maine and Georges Bank (NAFO divisions 5Y and 5Z), 1893-2007.

Year	USA	US Discards	Canada	Other	Total Landings	Total Catch
1893	684	114	0	0	684	798
1894	843	140	0	0	843	983
1895	4200	699	0	0	4200	4899
1896	4908	817	0	0	4908	5725
1897	733	122	0	0	733	855
1898	564	94	0	0	564	658
1899	407	68	0	0	407	475
1900	331	55	0	0	331	386
1901	287	48	0	0	287	335
1902	367	61	0	0	367	428
1903	502	84	0	0	502	586
1904	332	55	0	0	332	387
1905	580	97	0	0	580	677
1906	542	90	0	0	542	632
1907	447	74	0	0	447	521
1908	891	148	0	0	891	1039
1909	193	32	0	0	193	225
1910	329	55	0	0	329	384
1911	389	65	0	0	389	454
1912	460	77	0	0	460	537
1913	402	67	0	0	402	469
1914	329	55	0	0	329	384
1915	336	56	0	0	336	392
1916	478	80	0	0	478	558
1917	293	49	0	0	293	342
1918	375	62	0	0	375	437
1919	498	83	0	0	498	581
1920	896	149	0	0	896	1045
1921	689	115	0	0	689	804
1922	694	115	0	0	694	809
1923	508	85	0	0	508	593
1924	616	103	0	0	616	719
1925	843	140	0	0	843	983
1926	944	157	0	0	944	1101
1927	831	138	0	0	831	969
1928	781	130	0	0	781	911
1929	570	95	0	0	570	665
1930	716	119	0	0	716	835
1931	511	85	0	0	511	596
1932	443	74	0	0	443	517
1933	279	46	0	0	279	325
1934	192	32	0	0	192	224
1935	292	49	0	0	292	341
1936	374	62	0	0	374	436
1937	187	31	0	0	187	218
1938	146	24	0	0	146	170
1939	124	21	0	0	124	145
1940	499	83	0	0	499	582
1941	145	24	0	0	145	169
1942	250	42	0	0	250	292
1943	76	13	0	0	76	89
1944	77	13	0	0	77	90
1945	55	9	0	0	55	64
1946	124	21	0	0	124	145
1947	198	33	0	0	198	231
1948	156	26	0	0	156	182
1949	157	26	0	0	157	183
1950	116	19	0	0	116	135
1951	154	26	0	0	154	180
1952	123	20	0	0	123	143
1953	104	17	0	0	104	121
1954	125	21	0	0	125	146
1955	74	12	0	0	74	86
1956	62	10	0	0	62	72
1957	80	13	0	0	80	93
1958	73	12	0	0	73	85
1959	59	10	0	0	59	69
1960	63	10	0	0	63	73
1961	79	13	5	0	84	97
1962	86	14	35	25	146	160
1963	94	16	88	1	183	199
1964	115	19	120	1	236	255
1965	128	21	153	18	299	320
1966	110	18	110	62	282	300
1967	102	17	386	26	514	531
1968	74	12	193	3	270	282
1969	63	10	96	9	168	178
1970	52	9	67	19	138	147
1971	81	13	38	0	119	132
1972	63	10	37	8	108	118
1973	51	8	38	0	89	97
1974	46	8	29	1	76	84
1975	70	12	36	0	106	118
1976	58	10	33	0	91	101
1977	50	8	31	0	81	89
1978	84	14	50	0	134	148
1979	125	21	29	0	154	175
1980	80	13	88	0	168	181
1981	80	13	118	0	198	211
1982	85	14	116	0	201	215
1983	72	12	131	0	203	215
1984	75	12	62	0	137	149
1985	61	10	57	0	118	128
1986	44	7	32	0	76	83
1987	27	4	23	0	50	54
1988	47	8	81	0	128	136
1989	13	2	65	0	78	80
1990	16	3	58	0	74	77
1991	30	5	58	0	88	93
1992	22	4	47	0	69	73
1993	15	2	50	0	65	67
1994	22	4	24	0	46	50
1995	11	2	8	0	19	21
1996	13	2	12	0	25	27
1997	14	2	14	0	28	30
1998	8	1	9	0	17	18
1999	12	18	8	0	20	40
2000	11	16	6	0	17	36
2001	11	16	11	0	22	41
2002	10	15	10	0	20	37
2003	17	25	14	0	31	60
2004	11	16	12	0	23	42
2005	17	25	9	0	26	55
2006	14	21	10	0	24	48
2007	22	32	30	0	52	84

Table S2. Atlantic halibut United States discards (mt) based on Standardized Bycatch Reduction Methodology combined ratio estimation (1989-2007).

Year	US Discards (mt)	cv	# Hauls with Observed Halibut Discards	US Landings (mt)		Average Discards (mt)	Total US Catch (mt)
1989	3.4	0.525	25	13		2	15
1990	10.2	0.578	22	16		3	19
1991	5.2	0.348	48	30		5	35
1992	1.6	0.394	17	22		4	26
1993	1.3	0.444	11	15		2	17
1994	1.4	0.474	8	22		4	26
1995	2.8	1.319	12	11		2	13
1996	0.6	0.491	4	13	1989-1998 Average	2	15
1997	0.6	0.788	11	14	Discards/Landings=	2	16
1998	0.2	1.014	1	8	0.166	1	9
1999	76.1	0.702	4	12		18	30
2000	9.3	0.352	30	11		16	27
2001	9.4	0.271	22	11		16	27
2002	16.8	0.410	44	10		15	25
2003	15.7	0.212	123	17		25	42
2004	18.2	0.207	182	11		16	27
2005	14.0	0.114	533	17	1999-2007 Average	25	42
2006	14.3	0.171	243	14	Discards/Landings=	21	35
2007	9.5	0.123	192	22	1.465	32	54

Table S3. Atlantic halibut stratified mean weight (kg) and numbers per tow from NEFSC spring and autumn surveys (offshore strata 13-30, 36-40) and 5-year average swept-area biomass estimates.

Year	Spring Survey Weight (kg) per Tow	5-Year Average Spring Swept-Area Biomass (mt)	Spring Survey Numbers per Tow	Autumn Survey Weight (kg) per Tow	5-Year Average Autumn Swept-Area Biomass (mt)	Autumn Survey Numbers per Tow
1963				0.085	282	0.039
1964				0.067	252	0.022
1965				0.032	204	0.015
1966				0.004	156	0.003
1967				0.009	131	0.003
1968	0.129	428	0.046	0.233	229	0.013
1969	0.236	606	0.028	0.494	512	0.025
1970	0.105	520	0.015	0.000	491	0.000
1971	0.033	417	0.013	0.091	549	0.011
1972	0.005	337	0.006	0.018	555	0.013
1973	0.113	327	0.015	0.131	487	0.015
1974	0.112	244	0.052	0.014	169	0.004
1975	0.000	175	0.000	0.095	232	0.017
1976	0.644	580	0.031	0.378	422	0.038
1977	0.142	671	0.052	0.059	449	0.012
1978	0.163	704	0.025	0.294	558	0.028
1979	0.357	867	0.048	0.040	575	0.015
1980	0.563	1241	0.056	0.010	518	0.007
1981	0.066	857	0.027	0.321	481	0.024
1982	0.082	817	0.011	0.115	518	0.015
1983	0.611	1115	0.035	0.000	323	0.000
1984	0.022	892	0.009	0.124	378	0.005
1985	0.063	560	0.024	0.106	442	0.015
1986	0.000	516	0.000	0.313	437	0.029
1987	0.287	653	0.009	0.033	382	0.029
1988	0.023	262	0.039	0.004	385	0.006
1989	0.000	248	0.000	0.066	347	0.046
1990	0.064	248	0.026	0.060	316	0.045
1991	0.062	289	0.034	0.243	270	0.034
1992	0.037	123	0.031	0.201	381	0.018
1993	0.006	112	0.003	0.046	409	0.013
1994	0.017	123	0.008	0.000	365	0.000
1995	0.005	84	0.008	0.066	369	0.011
1996	0.013	52	0.009	0.053	243	0.004
1997	0.063	69	0.025	0.174	225	0.046
1998	0.017	76	0.016	0.103	263	0.060
1999	0.239	224	0.012	0.015	273	0.006
2000	0.000	220	0.000	0.021	243	0.006
2001	0.163	320	0.046	0.247	372	0.030
2002	0.128	363	0.013	0.004	259	0.003
2003	0.052	386	0.037	0.049	223	0.040
2004	0.168	339	0.025	0.112	287	0.047
2005	0.025	356	0.034	0.111	347	0.030
2006	0.383	502	0.113	0.031	204	0.021
2007	0.195	546	0.109	0.077	252	0.033
2008	0.100	578	0.062			

Table S4. Input data for Atlantic halibut yield-per-recruit analysis.

Age	Selectivity on Fishing Mortality	Natural Mortality Rate	Fraction Mature	Mean Weight (kg)
0	0	0.15	0.01	0.00
1	0	0.15	0.04	0.02
2	0	0.15	0.06	0.25
3	0	0.15	0.10	0.96
4	1	0.15	0.15	2.36
5	1	0.15	0.23	4.57
6	1	0.15	0.34	7.64
7	1	0.15	0.46	11.57
8	1	0.15	0.59	16.32
9	1	0.15	0.71	21.83
10	1	0.15	0.80	28.01
11	1	0.15	0.87	34.78
12	1	0.15	0.92	42.03
13	1	0.15	0.95	49.68
14	1	0.15	0.97	57.63
15	1	0.15	0.98	65.79
16	1	0.15	0.99	74.09
17	1	0.15	0.99	82.46
18	1	0.15	1.00	90.83
19	1	0.15	1.00	99.15
20	1	0.15	1.00	107.36
21	1	0.15	1.00	115.43
22	1	0.15	1.00	123.33
23	1	0.15	1.00	131.02
24	1	0.15	1.00	138.48
25	1	0.15	1.00	145.70
26	1	0.15	1.00	152.65
27	1	0.15	1.00	159.35
28	1	0.15	1.00	165.77
29	1	0.15	1.00	171.91
30	1	0.15	1.00	177.78
31	1	0.15	1.00	183.38
32	1	0.15	1.00	188.70
33	1	0.15	1.00	193.76
34	1	0.15	1.00	198.57
35	1	0.15	1.00	203.12
36	1	0.15	1.00	207.43
37	1	0.15	1.00	211.50
38	1	0.15	1.00	215.35
39	1	0.15	1.00	218.98
40	1	0.15	1.00	222.40
41-50	1	0.15	1.00	222.40

Table S5. Mean and minimum sizes of Atlantic halibut discarded and landed from Northeast Fisheries Observer Program data.

Discarded Atlantic Halibut

Year	Mean Length (cm)	Std Err	N	Minimum Length (cm)
1992	33.0	.	1	33
1993	31.3	13.3458	3	17
1994	42.4	5.1049	5	24
1995	27.2	5.4858	6	18
1997	36.3	2.1858	3	32
1999	62.0	.	1	62
2000	57.0	4.0778	13	18
2001	67.5	2.9518	13	48
2002	70.2	4.7648	13	38
2003	64.0	1.6363	91	31
2004	57.1	1.3502	87	26
2005	60.4	1.3042	160	33
2006	63.0	1.495	107	38
2007	64.3	1.9969	75	24

Landed Atlantic Halibut

Year	Mean Length (cm)	Std Err	N	Minimum Length (cm)
1990	46.6	2.0012	6	42
1991	92.0	.	1	92
1992	67.1	5.2457	11	29
1993	62.8	5.5333	10	42
1994	73.3	5.0781	16	46
1995	79.6	4.6356	29	42
1996	69.2	10.027	5	50
1997	67.5	11.3893	6	44
2001	118.0	6	2	112
2002	88.0	9.0738	6	52
2003	81.0	5.349	29	41
2004	83.9	3.9709	33	43
2005	76.4	2.5691	80	40
2006	84.9	3.5611	37	50
2007	90.5	4.225	33	49

Note: 1999-2007 average observed landed minimum size = 55cm
Minimum size regulation for 1999-present = 91cm

Table S6. Residuals of NEFSC survey swept-area biomass indices to estimated swept-area biomass indices from the Replacement Yield Model.

Year	Z-Score Residuals
1963	-0.324
1964	-0.492
1965	-0.768
1966	-0.940
1967	-0.838
1968	1.264
1969	3.544
1970	-0.574
1971	0.204
1972	-0.402
1973	0.545
1974	-0.453
1975	0.200
1976	2.569
1977	-0.131
1978	1.811
1979	-0.319
1980	-0.550
1981	2.091
1982	0.413
1983	-0.490
1984	0.623
1985	0.511
1986	2.279
1987	-0.068
1988	-0.325
1989	0.233
1990	0.190
1991	1.732
1992	1.396
1993	0.100
1994	-0.283
1995	0.263
1996	0.125
1997	1.113
1998	0.486
1999	-0.296
2000	-0.281
2001	1.575
2002	-0.512
2003	-0.188
2004	0.294
2005	0.219
2006	-0.520
2007	-0.214

Table S7. Atlantic halibut catch and resulting biomass, replacement yield, and relative F from Replacement Yield model (M=0.15). Note that reported landings begin in 1893 and 1800-1892 catch is assumed to be a linear increase.

Year	Total Catch (mt)	Biomass (mt)	Replacement Yield (mt)	Relative F	Year	Total Catch (mt)	Biomass (mt)	Replacement Yield (mt)	Relative F
1800	10	97018	0	0.000	1852	3320	73579	2599	0.045
1801	20	97008	1	0.000	1853	3387	72858	2653	0.046
1802	30	96990	4	0.000	1854	3454	72123	2706	0.048
1803	37	96964	8	0.000	1855	3521	71375	2758	0.049
1804	104	96935	12	0.001	1856	3588	70612	2810	0.051
1805	171	96843	26	0.002	1857	3655	69834	2861	0.052
1806	238	96698	47	0.002	1858	3722	69040	2911	0.054
1807	305	96507	74	0.003	1859	3789	68229	2960	0.056
1808	372	96276	108	0.004	1860	3856	67400	3008	0.057
1809	439	96012	146	0.005	1861	3923	66552	3055	0.059
1810	506	95718	188	0.005	1862	3990	65684	3101	0.061
1811	573	95400	233	0.006	1863	4057	64796	3146	0.063
1812	640	95060	281	0.007	1864	4124	63885	3190	0.065
1813	707	94700	331	0.007	1865	4191	62951	3232	0.067
1814	774	94324	383	0.008	1866	4258	61992	3272	0.069
1815	841	93933	437	0.009	1867	4325	61006	3311	0.071
1816	908	93529	492	0.010	1868	4392	59992	3347	0.073
1817	975	93113	548	0.010	1869	4459	58947	3382	0.076
1818	1042	92686	605	0.011	1870	4526	57870	3414	0.078
1819	1109	92249	663	0.012	1871	4593	56758	3443	0.081
1820	1176	91803	722	0.013	1872	4660	55608	3470	0.084
1821	1243	91348	781	0.014	1873	4727	54418	3493	0.087
1822	1310	90886	840	0.014	1874	4794	53185	3513	0.090
1823	1377	90416	900	0.015	1875	4861	51904	3529	0.094
1824	1444	89938	960	0.016	1876	4928	50571	3540	0.097
1825	1511	89454	1020	0.017	1877	4995	49183	3545	0.102
1826	1578	88963	1080	0.018	1878	5062	47733	3545	0.106
1827	1645	88465	1140	0.019	1879	5129	46217	3538	0.111
1828	1712	87960	1201	0.019	1880	5196	44626	3523	0.116
1829	1779	87449	1261	0.020	1881	5263	42953	3500	0.123
1830	1846	86931	1321	0.021	1882	5330	41189	3465	0.129
1831	1913	86406	1382	0.022	1883	5397	39325	3419	0.137
1832	1980	85875	1442	0.023	1884	5464	37347	3358	0.146
1833	2047	85337	1502	0.024	1885	5531	35241	3281	0.157
1834	2114	84792	1562	0.025	1886	5598	32991	3183	0.170
1835	2181	84240	1622	0.026	1887	5665	30576	3061	0.185
1836	2248	83682	1682	0.027	1888	5732	27972	2910	0.205
1837	2315	83115	1741	0.028	1889	5799	25151	2724	0.231
1838	2382	82542	1801	0.029	1890	5866	22075	2493	0.266
1839	2449	81960	1860	0.030	1891	5933	18702	2207	0.317
1840	2516	81371	1919	0.031	1892	6000	14977	1852	0.401
1841	2583	80774	1977	0.032	1893	798	10828	1406	0.074
1842	2650	80168	2036	0.033	1894	983	11437	1475	0.086
1843	2717	79554	2094	0.034	1895	4899	11929	1530	0.411
1844	2784	78931	2151	0.035	1896	5725	8559	1141	0.669
1845	2851	78298	2209	0.036	1897	855	3975	557	0.215
1846	2918	77656	2266	0.038	1898	658	3678	517	0.179
1847	2985	77004	2323	0.039	1899	475	3537	498	0.134
1848	3052	76341	2379	0.040	1900	386	3561	502	0.108
1849	3119	75668	2435	0.041	1901	335	3677	517	0.091
1850	3186	74983	2490	0.042	1902	428	3859	542	0.111
1851	3253	74287	2545	0.044	1903	586	3973	557	0.147

Table S7 (cont.). Atlantic halibut catch and NEFSC autumn survey swept-area biomass index input and resulting biomass, replacement yield, and relative F from Replacement Yield model (M=0.15).

Year	Total Catch (mt)	Biomass (mt)	Replacement Yield (mt)	Relative F	Year	Total Catch (mt)	Swept-Area Biomass (mt)	Biomass (mt)	Replacement Yield (mt)	Relative F
1904	387	3944	553	0.098	1956	72		982	142	0.0737
1905	677	4110	575	0.165	1957	93		1052	152	0.0887
1906	632	4009	562	0.158	1958	85		1110	160	0.0767
1907	521	3939	553	0.132	1959	69		1186	171	0.0580
1908	1039	3970	557	0.262	1960	73		1288	186	0.0570
1909	225	3488	492	0.065	1961	97		1400	202	0.0694
1910	384	3754	528	0.102	1962	160		1505	217	0.1065
1911	454	3898	547	0.116	1963	199	282	1561	225	0.1272
1912	537	3991	559	0.134	1964	255	222	1587	228	0.1607
1913	469	4014	563	0.117	1965	320	106	1561	224	0.2052
1914	384	4108	575	0.093	1966	300	13	1465	211	0.2050
1915	392	4299	601	0.091	1967	531	30	1375	198	0.3861
1916	558	4508	628	0.124	1968	282	773	1043	151	0.2708
1917	342	4579	638	0.075	1969	178	1640	911	132	0.1959
1918	437	4875	677	0.090	1970	147	0	865	125	0.1696
1919	581	5114	708	0.114	1971	132	302	843	122	0.1571
1920	1045	5242	725	0.199	1972	118	60	833	121	0.1422
1921	804	4922	683	0.163	1973	97	435	835	121	0.1167
1922	809	4801	667	0.169	1974	84	46	859	124	0.0974
1923	593	4659	648	0.127	1975	118	315	900	130	0.1308
1924	719	4714	656	0.152	1976	101	1255	912	132	0.1103
1925	983	4652	647	0.211	1977	89	196	944	137	0.0947
1926	1101	4316	603	0.255	1978	148	976	991	143	0.1493
1927	969	3818	536	0.254	1979	175	133	986	143	0.1772
1928	911	3385	478	0.269	1980	181	33	954	138	0.1900
1929	665	2951	418	0.225	1981	211	1065	911	132	0.2319
1930	835	2705	384	0.309	1982	215	382	832	121	0.2586
1931	596	2254	322	0.264	1983	215	0	737	107	0.2916
1932	517	1980	284	0.261	1984	149	412	629	91	0.2375
1933	325	1747	251	0.186	1985	128	352	571	83	0.2244
1934	224	1672	240	0.134	1986	83	1039	526	76	0.1584
1935	341	1688	243	0.202	1987	54	110	519	76	0.1049
1936	436	1590	229	0.274	1988	136	13	540	79	0.2514
1937	218	1383	199	0.158	1989	80	219	483	70	0.1660
1938	170	1364	197	0.125	1990	77	199	473	69	0.1620
1939	145	1390	200	0.104	1991	93	807	465	68	0.1999
1940	582	1446	208	0.403	1992	73	667	440	64	0.1652
1941	169	1072	155	0.158	1993	67	153	431	63	0.1565
1942	292	1058	153	0.276	1994	50	0	427	62	0.1164
1943	89	919	133	0.096	1995	21	219	439	64	0.0474
1944	90	964	140	0.093	1996	27	176	482	70	0.0563
1945	64	1014	147	0.063	1997	30	578	525	76	0.0578
1946	145	1096	158	0.132	1998	18	342	571	83	0.0321
1947	231	1110	160	0.208	1999	40	50	636	92	0.0633
1948	182	1039	150	0.175	2000	36	70	688	100	0.0517
1949	183	1008	146	0.182	2001	41	820	752	109	0.0539
1950	135	970	140	0.139	2002	37	13	821	119	0.0449
1951	180	975	141	0.184	2003	60	163	903	131	0.0661
1952	143	937	136	0.153	2004	42	372	974	141	0.0427
1953	121	929	135	0.131	2005	55	368	1073	155	0.0509
1954	146	942	136	0.155	2006	48	103	1174	170	0.0405
1955	86	933	135	0.093	2007	84	256	1296	187	0.0650

Table S8. Projected catch and Biomass in 2009 for Atlantic halibut under three relative F scenarios in 2009 (Fsq, F_{MSY} and $F_{REBUILD}$), assuming catch in 2008 equals catch in 2007.

F2009 = Fstatus quo = F2007 = 0.065

	2007	2008	2009
Relative F	0.065	0.060	0.065
Biomass (mt)	1,296	1,399	1,539
Catch (mt)	84	84	100

F2009 = Frebuild = 0.044

	2007	2008	2009
Relative F	0.065	0.060	0.044
Biomass (mt)	1,296	1,399	1,539
Catch (mt)	84	84	68

F2009 = Fmsy = 0.073

	2007	2008	2009
Relative F	0.065	0.060	0.073
Biomass (mt)	1,296	1,399	1,539
Catch (mt)	84	84	112

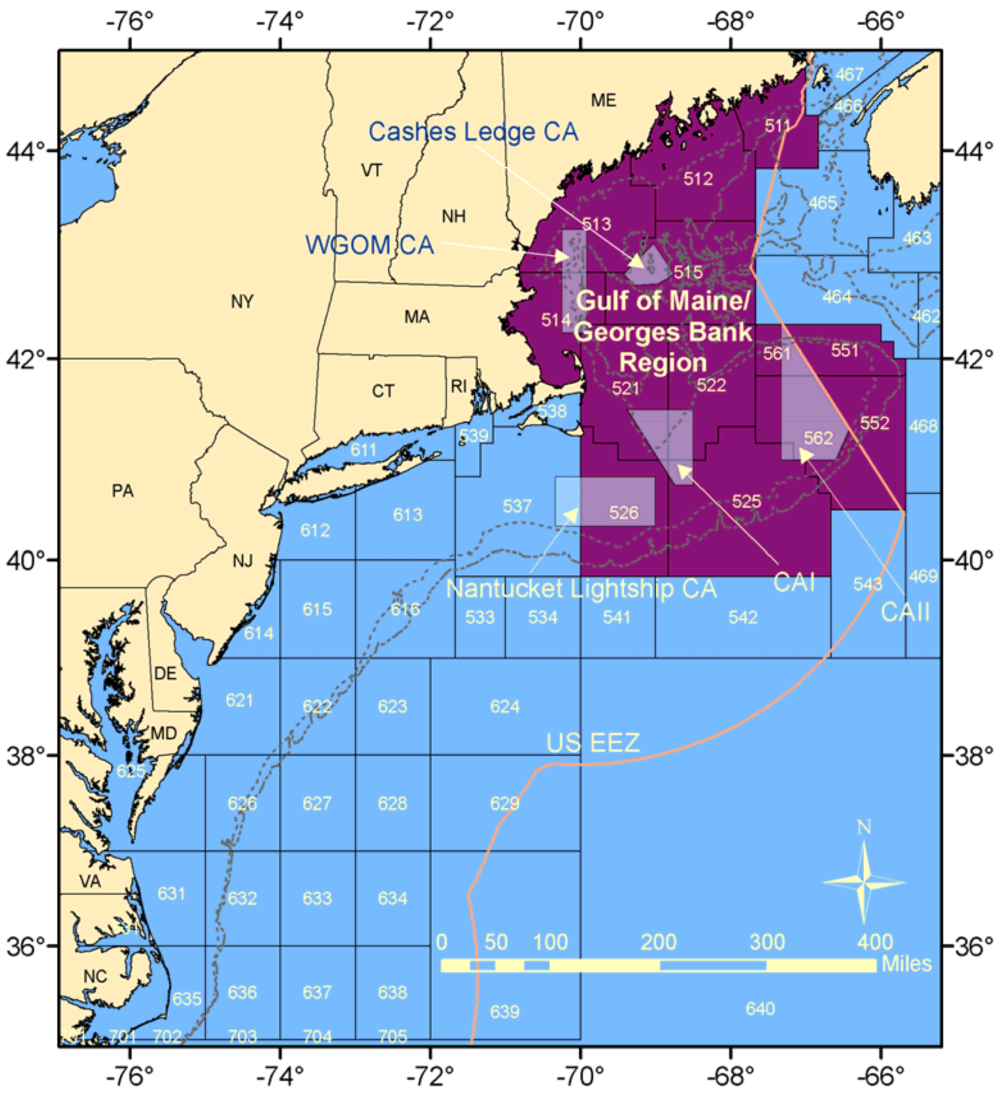

Figure S1. Statistical areas used to define United States commercial fishing catch for the Gulf of Maine-Georges Bank region of the Atlantic halibut stock.

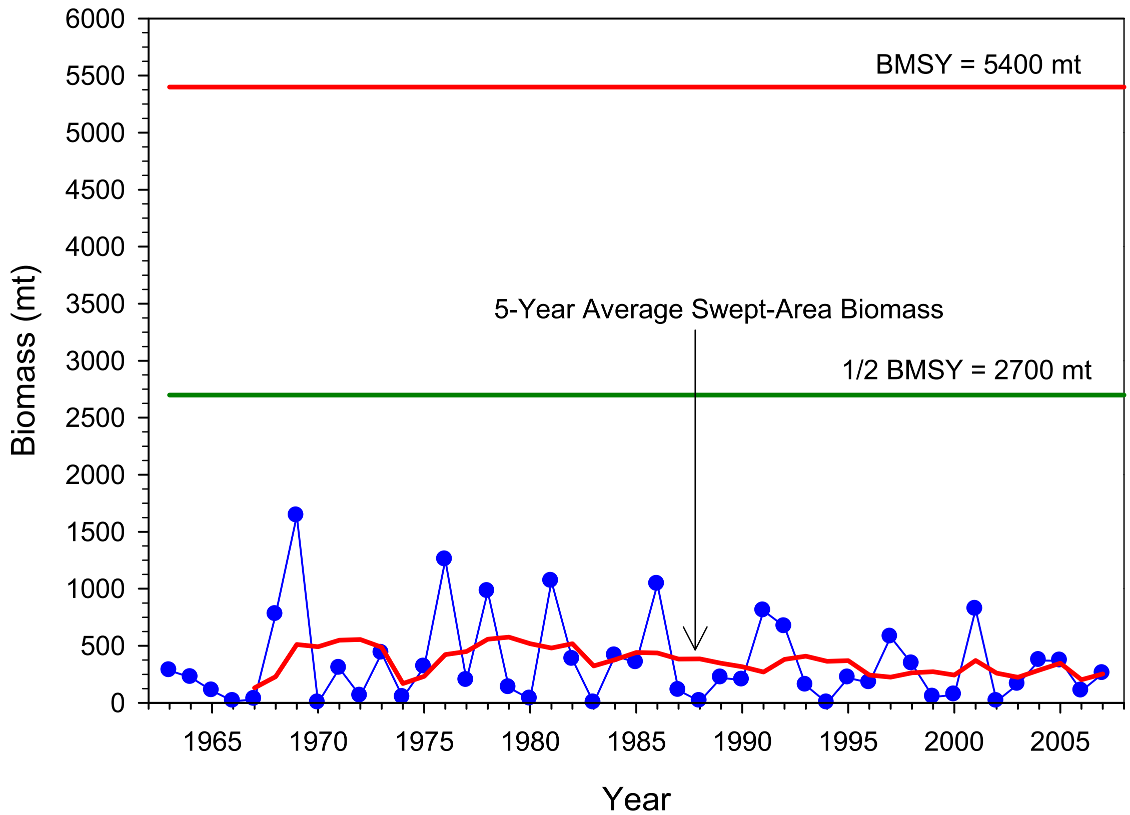

Figure S2. Trends in Atlantic halibut swept-area biomass indices from Northeast Fisheries Science Center autumn bottom trawl surveys and previous index-based assessment reference points.

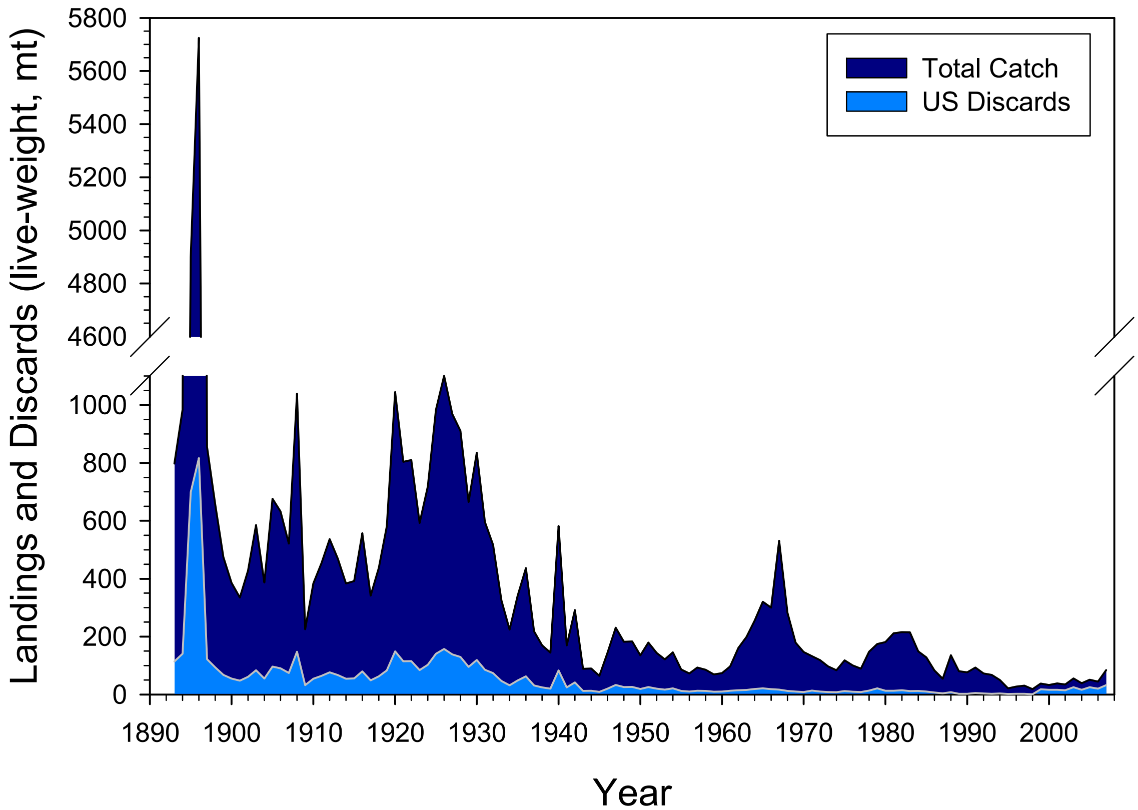

Figure S3. Atlantic halibut total catch (mt) from the Gulf of Maine-Georges Bank region (NAFO divisions 5Y and 5Z), 1893-2007.

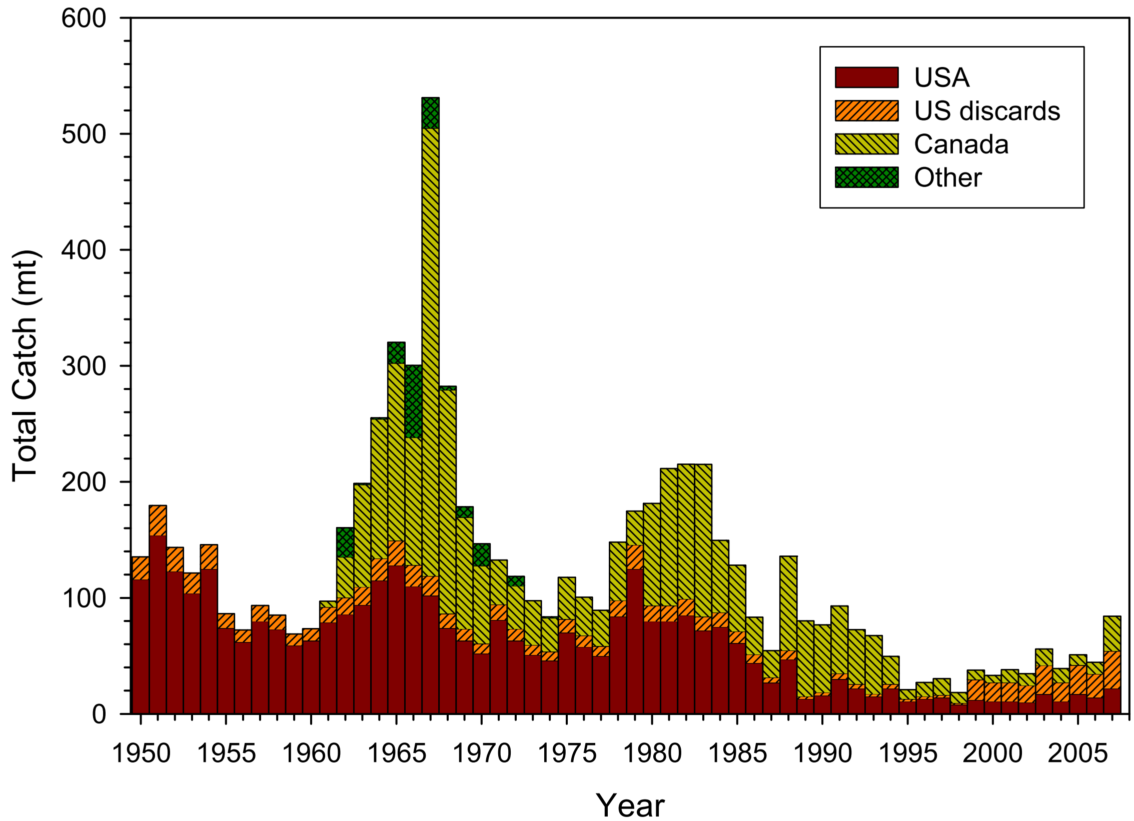

Figure S4. Atlantic halibut total catch (mt) by country, 1950-2007.

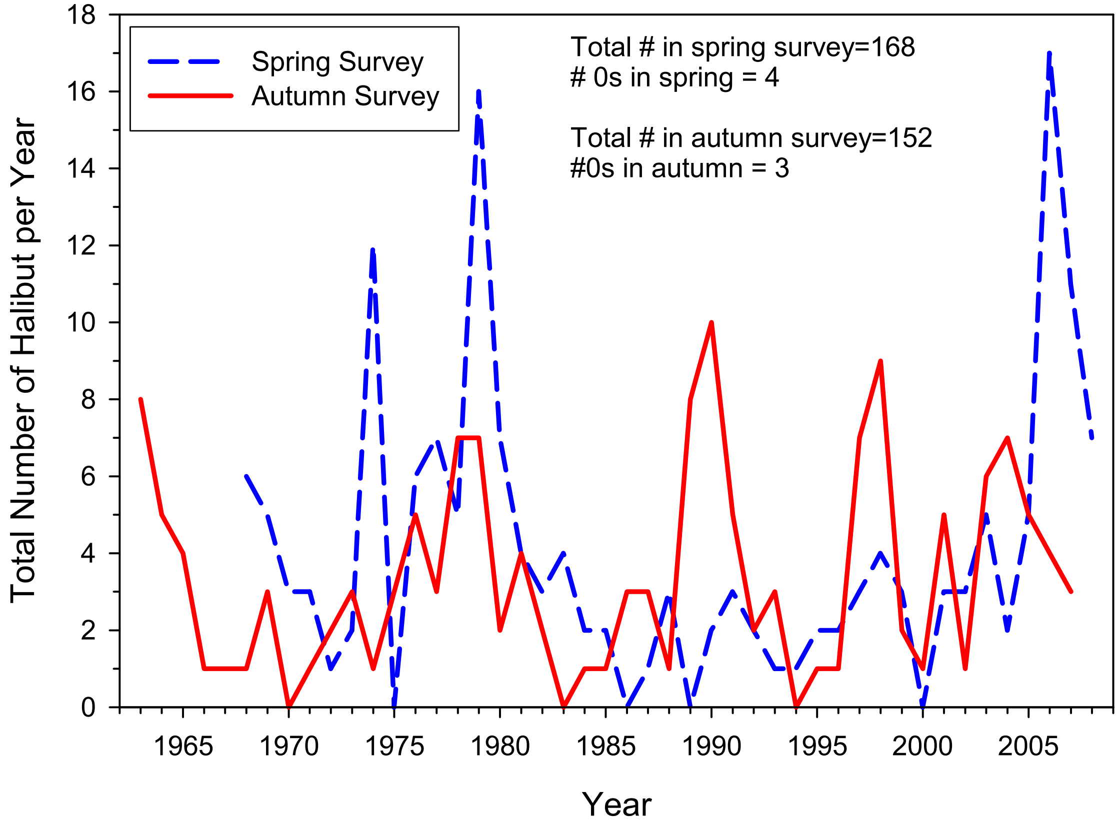

Figure S5. Total numbers of Atlantic halibut caught annually in Northeast Fisheries Science Center spring and autumn surveys.

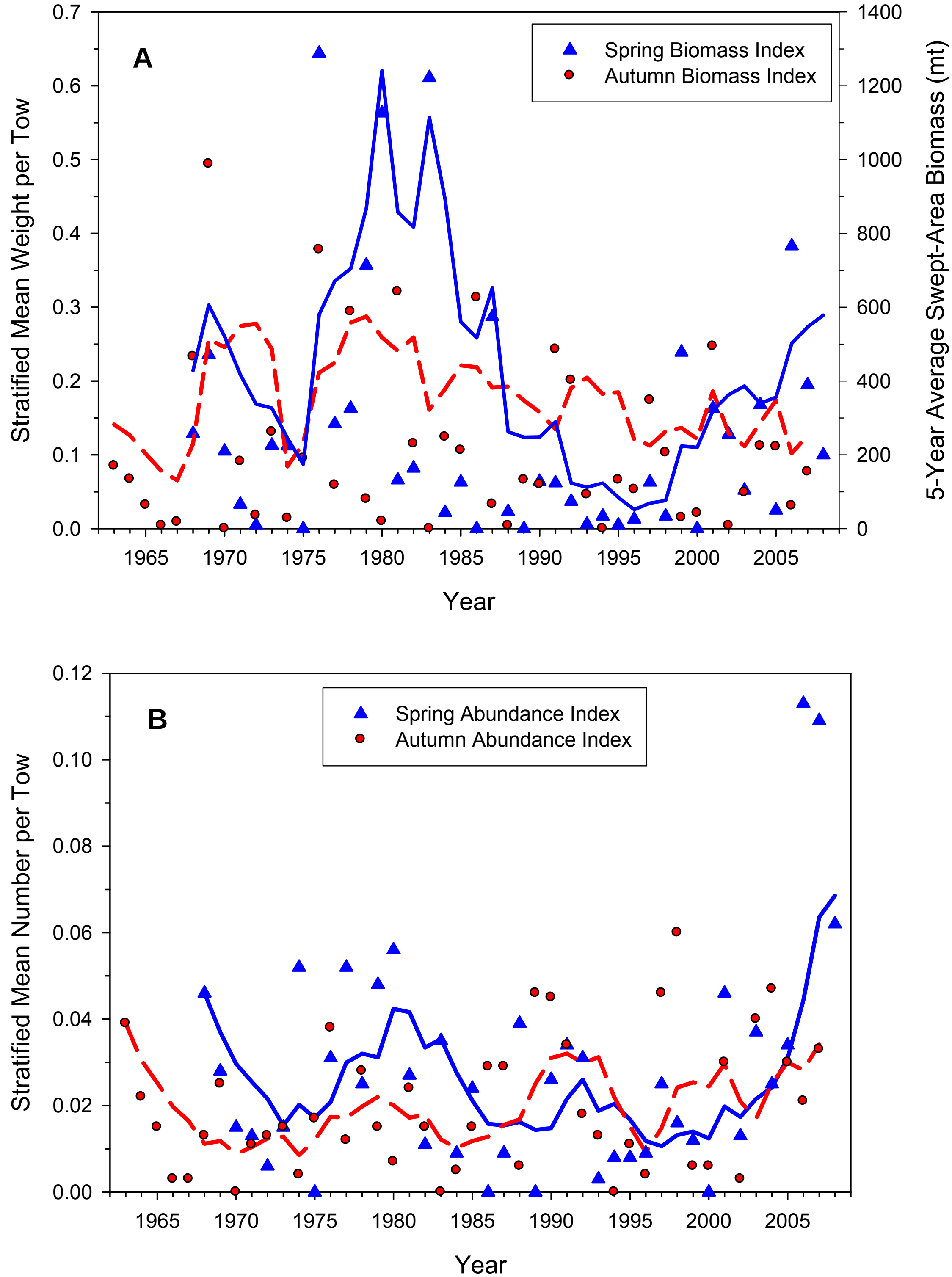

Figure S6. Northeast Fisheries Science Center spring and autumn survey trends for Atlantic halibut A) weight per tow indices and 5-year average swept-area biomass and B) number per tow indices and 5-year average number per tow from the Gulf of Maine-Georges Bank region, 1963-2008.

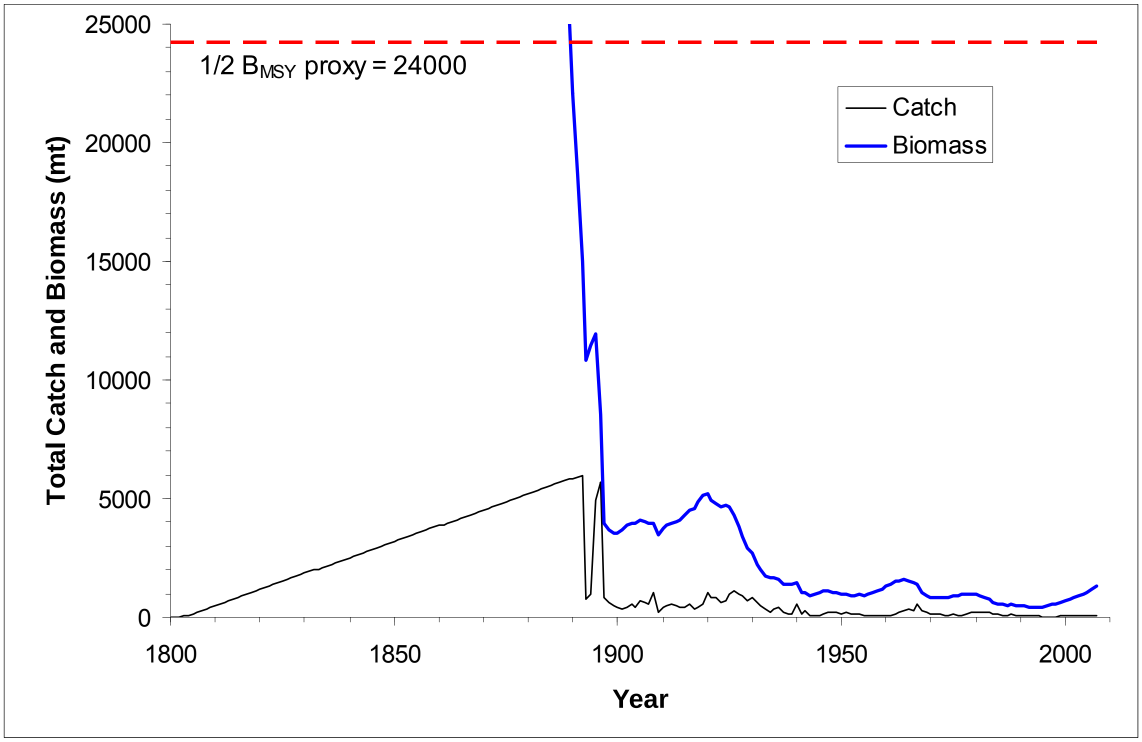

Figure S7. Atlantic halibut biomass and ½ B_{MSY} proxy from the Replacement Yield Model (M = 0.15).

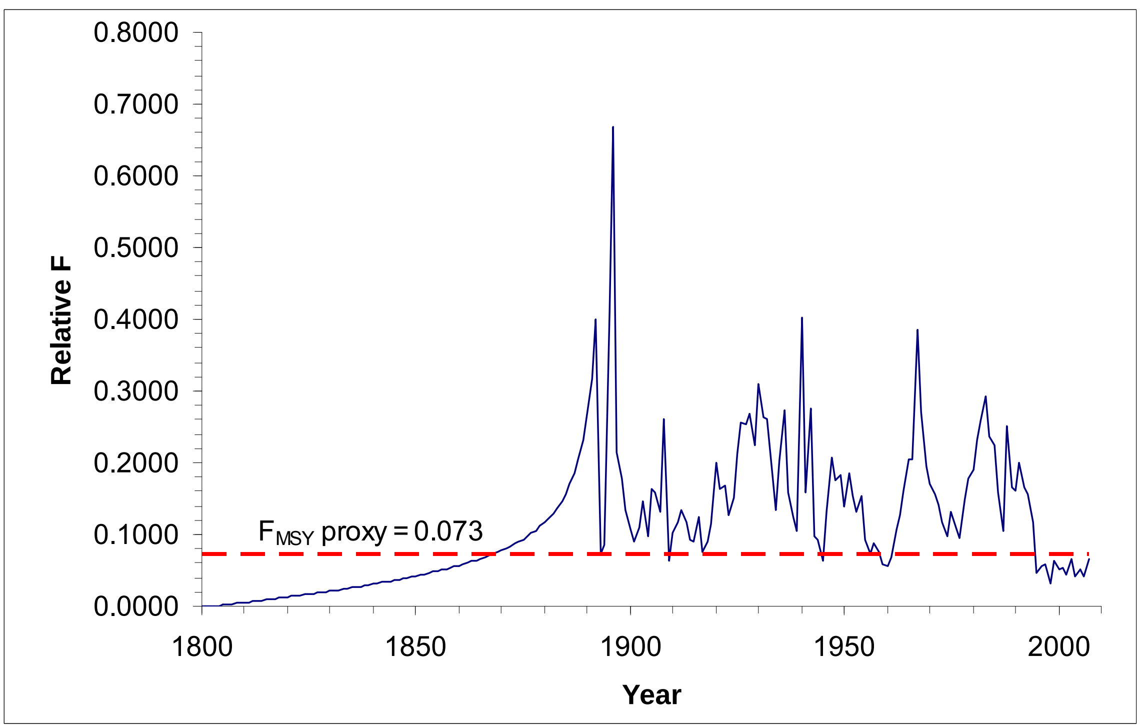

Figure S8. Atlantic halibut relative fishing mortality from the Replacement Yield Model (M = 0.15).

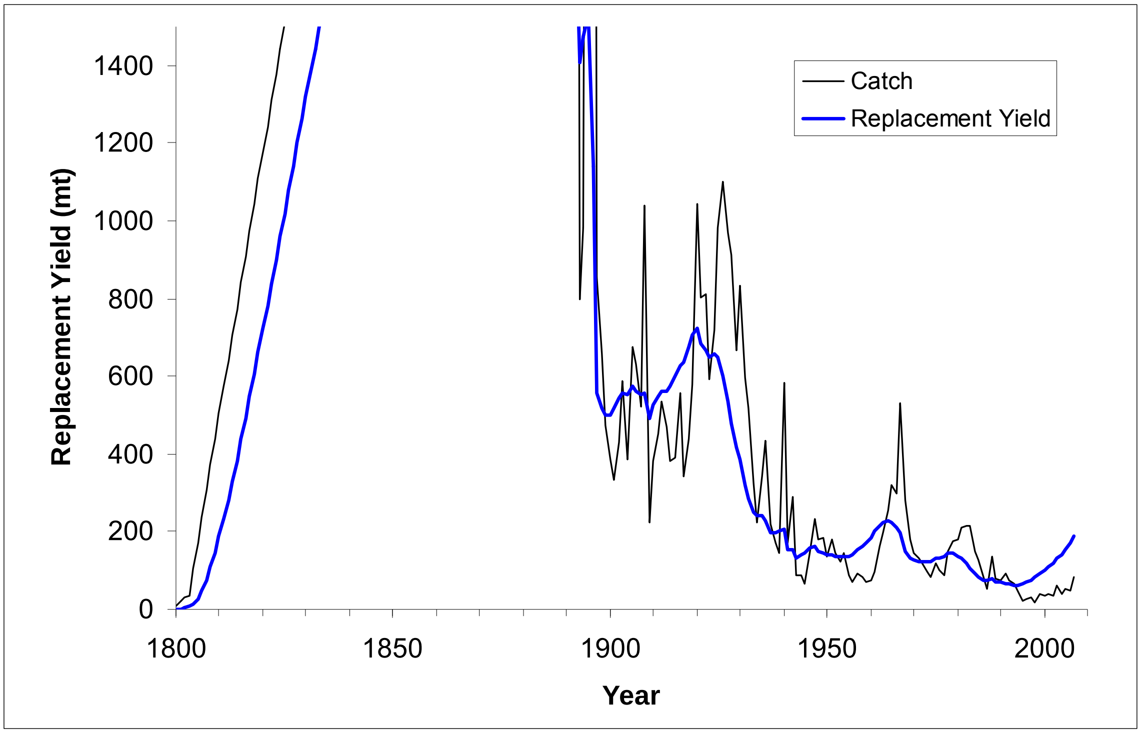

Figure S9. Atlantic halibut replacement yield from the Replacement Yield Model (M = 0.15).

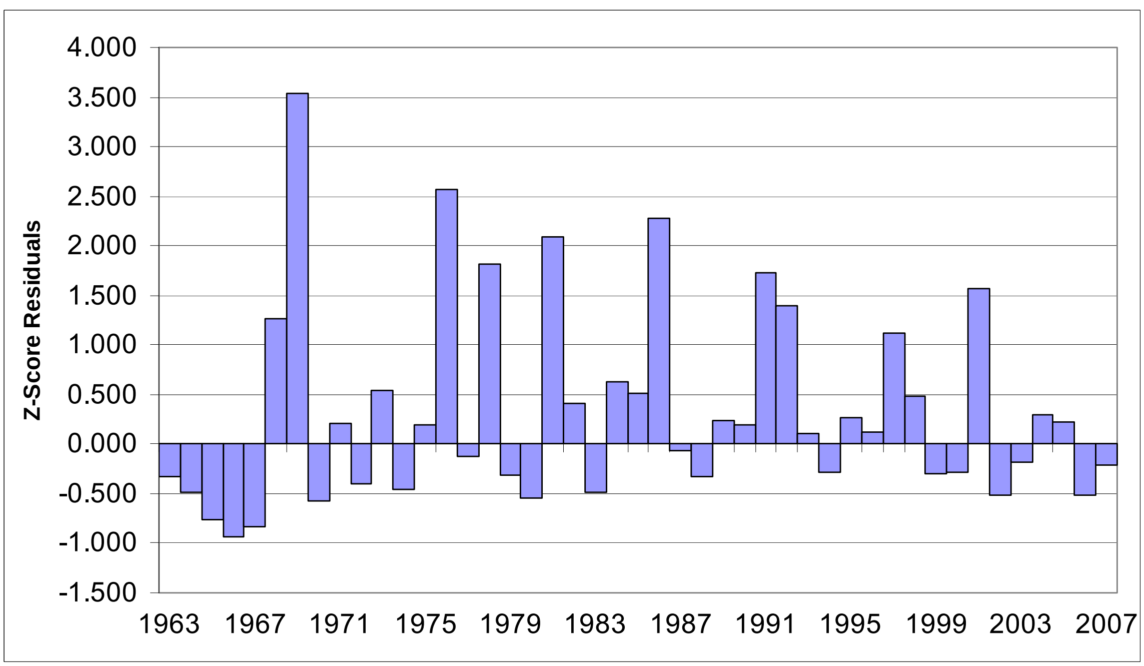

Figure S10. Z-score residuals of Atlantic halibut swept-area biomass estimates from the NEFSC autumn survey and predicted survey indices from the Replacement Yield Model.

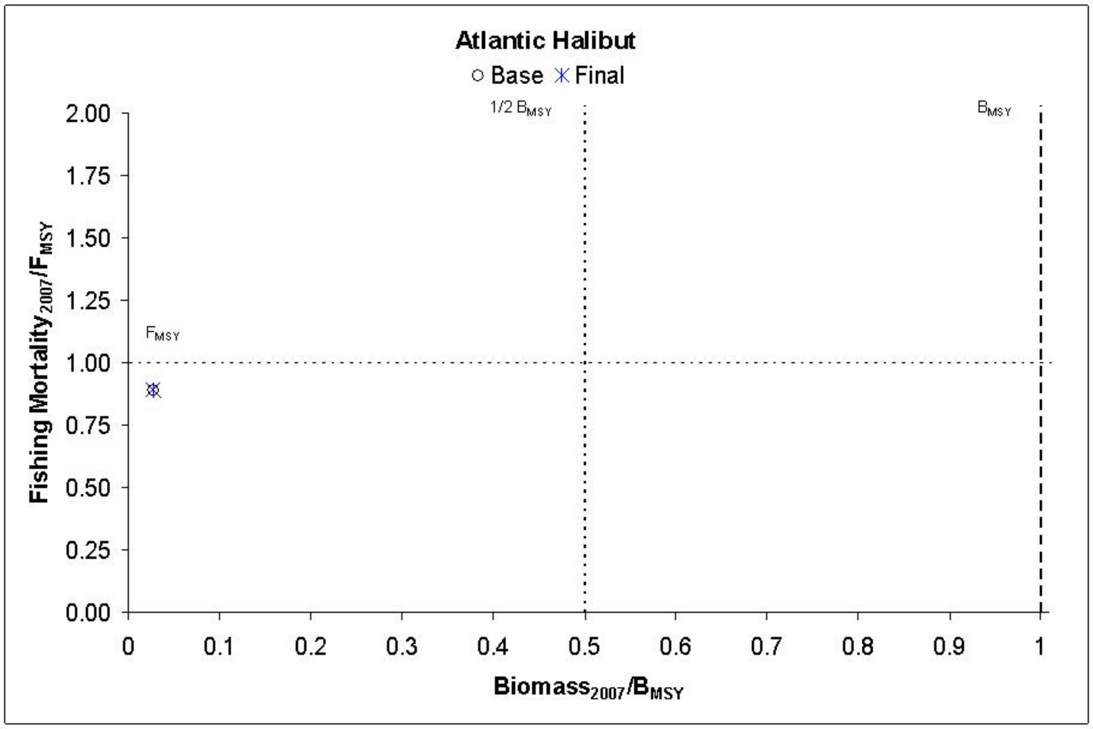

Figure S11. Status plot for Gulf of Maine-Georges Bank Atlantic halibut.

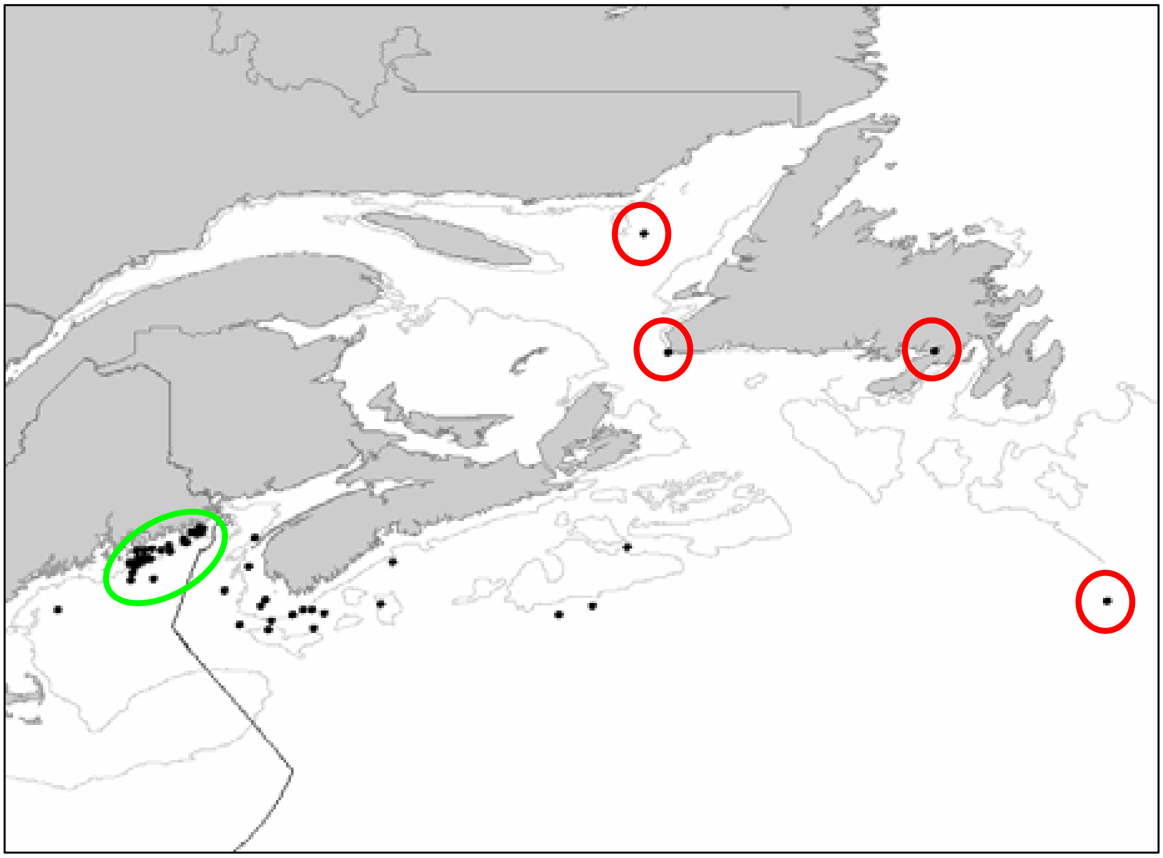

Figure S12. 2000-2004 Experimental Halibut Fishery tagging release location (green oval) and recapture locations (black dots). Red circles represent recapture locations where Atlantic halibut traveled more that 1,000 km.