

APPENDIX A. 2014 Statistical Catch at Age (ASAP) Model Update for Eastern Georges Bank Atlantic

Introduction

This assessment presents an update of the statistical catch at age model ‘Age Structured Assessment Program’ (ASAP) reviewed at the 2012 April Eastern Georges Bank cod benchmark model meeting. The ASAP model was not chosen by the TRAC as a benchmark model for stock status or catch advice, however, the TRAC agreed to apply the ASAP model results in a consequence analysis (Appendix B) of projection results.

The ASAP model was chosen to explore as an alternative model to the virtual population model (VPA) during the EGB cod benchmark in part because ASAP had recently been accepted as the new benchmark model for the NEFSC GB cod assessment, replacing the VPA that had historically been applied since 1978 (NEFSC 2013). Prior to 2004, both the EGB and GB cod assessments had been conducted with VPA and had similar formulations. After the 2002 EGB cod benchmark review (O’Boyle and Overholtz 2002) the assessments started to diverge. While it is not mandatory that the two assessments be similarly formulated, given that EGB cod data is in both assessments, it would be appropriate to have the populations on the same scale. Also, given that part or all of the Georges Bank cod stock is managed by both the TMGC and the NEFMC, respectively, similarly scaled populations would allow for compatibility in management decisions.

ASAP was used to derive estimates of instantaneous fishing mortality in 2013 and stock size in 2013. A retrospective analysis was performed for terminal year fishing mortality, spawning stock biomass, and age1 recruitment. Stochastic projections from model results were performed to provide estimated landings and spawning stock biomass (SSB) in 2015-2016.

Assessment Model Formulation

Model description

ASAP, a forward projecting statistical catch at age model (Legault and Restrepo 1998) can be downloaded from the NOAA Fisheries Toolbox (NFT, <http://nft.nefsc.noaa.gov/>). As described on the NFT website, ASAP is an age-structured model that uses forward computations assuming separability of fishing mortality into year and age components to estimate population sizes given observed catches, catch-at-age, and indices of abundance. Discards can be treated explicitly. The separability assumption is partially relaxed by allowing for fleet-specific computations and by allowing the selectivity at age to change in blocks of years. Weights are input for different components of the objective function which allows for configurations ranging from relatively simple age-structured production models to fully parameterized statistical catch at age models.

The objective function is the sum of the negative log-likelihood of the fit to various model components. Catch at age composition is modeled assuming a multinomial distribution. Surveys can be treated as either “west coast style” in the same manner as the catch data with a total survey time series and survey catch at age composition modeled assuming a multinomial

distribution, or “east coast style” with the survey indices at age entered as separate series. Most other model components are assumed to have lognormal error. Specifically, lognormal error is assumed for: total catch in weight by fleet, survey indices, stock recruit relationship, and annual deviations in fishing mortality. Recruitment deviations are also assumed to follow a lognormal distribution, with annual deviations estimated as a bounded vector to force them to sum to zero (this centers the predictions on the expected stock recruit relationship). For further details, the reader is referred to the technical manual (Legault 2008).

Data input

Input to the ASAP model is the same as the VPA and includes the total catch (mt) for the combined landings and discards of USA and Canadian fleets (Table 1, Figure 2), and the catch-at-age (Table 5, Figure 12) and weight-at-age (Table 6, Figure 13) for ages 1-10+ during 1978-2013. Beginning year weight-at-age is back-calculated from the mid-year catch weight-at-age (Appendix A. Table 1) and also estimated from an average of the DFO and NEFSC spring research survey weight-at-age (Table 16). Swept-area population estimates derived from indices of abundance include the Canadian DFO 1986-2013 estimates for ages 1- 10+ (Table 9, Figure 19), the NEFSC 1978-2013 standardized spring estimates for ages 1- 10+ (Table 10, Figure 19), and the NEFSC 1978-2013 standardized autumn estimates for ages 1-6 (Table 11, Figure 19). The NEFSC spring survey was dis-aggregated into two series based on the use of the Yankee #41 otter trawl from 1978-1981 and the Yankee #36 otter trawl from 1982-2008. The NEFSC spring survey has been conducted by the NOAA Ship Henry B. Bigelow since 2009 and these indices have been calibrated to Albatross IV units ((Table 8). Maturity was age and time invariant and knife edge maturity was assumed at age 3 as in previous EGB cod assessments. Natural mortality was age and time invariant and was assumed to be 0.2 as in earlier assessments (Wang and O’Brien 2012).

Model formulation

The 2013 ASAP model formulation (base_rivard) presented and reviewed at the June 2013 TRAC (Wang and O’Brien 2014) was updated for the 2014 assessment. A multinomial distribution was assumed for both fishery catch at age and survey age compositions. The survey time series were not split between 1994/1995 as had been done in previous EGB cod VPA formulations (Wang and O’Brien 2012). The catch CV was set equal to 0.05 and the recruitment CV set equal to 0.5, however, the recruitment deviations were set with $\lambda = 0$, so the deviations did not contribute to the objective function.

Both the fishery and survey selectivity was modeled as ‘flat-topped’. For the fisheries, two selectivity blocks were modeled as single logistic from 1978-1993 and 1994-2013.

The effective samples size (ESS) of the catch and surveys were adjusted based on interpretation of ‘Ianelli’ plots (McAllister and Ianelli 1997). The input ESS is compared to the model predicted ESS; an appropriate ESS is considered to be that which intersects the input ESS.

The catch ESS was set at 75 for 1978-1995 and 125 for 1996-2013, and the ESS for each survey was set at 50.

At the 2012 benchmark (WP 2013/08) the CV for each survey was initially set at the value generated from the survey estimate of stratified mean number per tow (DFO STRANAL). For the DFO survey the CVs averaged 0.31, with a range of 0.15-0.66, for the NEFSC spring the CVs averaged 0.32, with a range of 0.13-0.83, and for the NEFSC autumn survey the CVs averaged 0.47, with a range of 0.24-0.88. Further examination of the model fits to the survey indices resulted in adding the following constant to each survey CV vector: 0.25 (DFO), 0.3 (NEFSC spring #36), and 0.2 (NEFSC autumn), except the NEFSC spring #4, which was not adjusted. These same values were added during this 2014 update.

Model Results

Model results, including the objective function (OF), components to the OF, the root mean square error (RMSE), computed from standardized residuals, SSB, fishing mortality (F), recruitment estimates at age 1, and the Mohn's rho retrospective bias adjustments are summarized in Appendix A. Table 2 for all model runs conducted.

A bridge ASAP run was conducted to include several corrections to the input data. A correction was made to the US catch at age (CAA) due to the misapplication of discard length frequencies. Last year, the January-June length frequency was erroneously applied to the July-December data. Also, an adjustment was made to the DFO and NEFSC spring survey CAA due to the incorrect summation of the 10+ age group. And the 2012 NEFSC spring and 2011 autumn survey indices were re-estimated due to missing station data when first estimated using preliminary data in 2013.

A comparison of the differences between the 2013 ASAP model results (2013 run2) and the bridge run (2014 run1) resulted in an increase in the objective function (OF), and minor changes in age composition and root mean square errors (RMSE). There was a decline in estimates of recruitment and SSB, and an increase in fishing mortality (F) and the retrospective Mohn's rho estimate for SSB and F increased, whereas the recruitment rho estimate declined (Appendix Table 2).

BASE 2014 ASAP

The bridge run was updated with 2013 catch estimates and survey data and the results are described below.

Catch

The model fit to the observed catch is almost exact with the CV of 0.05 assigned to the commercial catch (Appendix A. Figure 1). The catch age composition exhibits larger residuals yearly in the time period, with a pattern of negative residuals for age 3 (Appendix A. Figure 2). The magnitude of the input ESS appears appropriate given that the predicted ESS generally bisects the observed ESS (Appendix A. Figure 3).

Indices

The fit of the predicted indices through the observed DFO survey indices was better during the period 1995-2000 than before or after that period; in recent years the model fit does not bisect the survey confidence bounds for all years (Appendix A. Figure 4). A pattern of negative residuals in the older age groups during 1986-1995 and in the younger ages during 2000-2013 is apparent in the age composition (Appendix A. Figure 5). The final DFO survey ESS was set at 50 and appears appropriate given that the predicted ESS generally bisects the observed ESS (Appendix A. Figure 6).

The fit of the predicted indices through the NEFSC autumn survey indices did not show any strong patterning, although in recent years the model fit does not bisect the survey confidence bounds for all years (Appendix A. Figure 7). The maximum residual of the age composition is the largest of the 4 surveys at 0.36 (Appendix A. Figure 8). The age 1 residuals are large and have a positive values in the early years and a negative pattern in the later years, however the older ages do not exhibit this pattern (Appendix A. Figure 8). The final input ESS was set = 50 and appears appropriate given that the predicted ESS generally bisects the observed ESS (Appendix A. Figure 9).

The model fit diagnostics for the NEFSC spring (Yankee #41) are presented in Appendix A. Figures 10-12. With only 4 years of survey indices, no patterns are easily described or evaluated.

The fit of the predicted indices through the NEFSC spring (Yankee #36) survey indices indicated, similar to the DFO survey, a series of negative residuals in the late 1980s to 1994 and a series of positive residuals since the mid-2000s (Appendix A. Figure 13). The residuals of the age composition show a pattern of positive residuals in age 2 and negative in age 4 in the early years and the opposite in the later years (Appendix A. Figure 14). The input ESS was set =50 and appears appropriate given that the predicted ESS generally bisects the observed ESS (Appendix A. Figure 15).

Fishing mortality, SSB, and recruitment

Fully recruited F (unweighted, ages 5+) was estimated at 0.33 in 2013 (Appendix A. Table 3, Appendix A. Figure 16), a 59% decrease from 2012. SSB in 2013 was estimated at 2,142 mt, a 80% increase from 2012 (Appendix A. Table 3, Appendix A. Figure 16). Recruitment (millions of age 1 fish) of the 2003 year class (2.4 million) is now estimated to be smaller than the 1998 year class (3.4 million), the 2010 year class is estimated at 1.5 million, and the 2012 year class is the smallest year class estimated at 0.125 million (Appendix A. Table 3, Appendix A. Figures 16-17).

Retrospective analysis

A retrospective analysis was performed to evaluate how well the ASAP calibration would have estimated F, SSB, and recruits at age 1 for seven years (2006-2012) prior to the terminal year, 2013. The pattern of overestimating SSB and underestimating F relative to the terminal year, is stronger than last year in last years' ASAP run, and there is a pattern of underestimating recruitment relative to the terminal year estimate (Appendix A. Figure 18). The retrospective rho values, the average of the last 7 years of the relative retrospective peels, were 0.46 for SSB, -0.32

for F_{5+} , and -0.25 for recruitment. Applying a retrospective adjustment $((1/(1+\rho)) * \text{estimate})$ results in 2013 estimates of $F = 0.49$, $SSB=1,470$ mt, age 1 recruitment =0.17 million fish.

Model uncertainty - MCMC

A Monte Carlo Markov chain (MCMC) simulation was performed to estimate uncertainty in the model estimates. The MCMC provides posterior probability distributions of the SSB and average F_{5+} time series. Two MCMC chains of initial length of 5.0 million were simulated with every 2,500th value saved. The trace of each chain’s saved draws suggests good mixing for both SSB and F (Appendix A.Figure 19). The lagged autocorrelations showed variable correlation with increased lag, with correlations ≤ 0.1 beyond lag 0 for SSB and F (Appendix A.Figure 20). From the MCMC distributions, a 90% probability interval (PI) was calculated to provide a measure of uncertainty for the model point estimates for SSB and average F_{5+} . Time series plots of the 90% PIs as well as plots of the posterior probability distributions for SSB_{2012} and average F_{5+} are shown in Appendix A. Figures 21-22.

The 2013 SSB MCMC estimate of 2,134 mt has a 90% PI of 1,384 mt – 3,345 mt and the 2013 MCMC average $F_{5+} = 0.33$ has a 90% PI of 0.20- 0.56.

Sensitivity Runs

The base ASAP model was run using Jan.1 back-calculated mean weight at age based on the Rivard method (Rivard 1982). A sensitivity run was done using Jan.1 weight at age based on an average of the DFO and NMFS spring survey data as applied in the VPA. The results (Appendix A.Table 2) indicate minimal differences when applying these two weight-at-age matrices. The base run with rivard weights will be used in projections, as this follows the weight at age used for the GB cod assessment (NEFSC 2013b).

Various other sensitivity runs were conducted, but none showed substantial improvements in model diagnostics.

Biological Reference Points

Yield per Recruit Analysis

For the 2013 cod model benchmark, a yield per recruit (YPR) analysis was conducted using the methods of Thompson and Bell (1934). Input data for catch and stock weights (ages 1-10+) were derived from an average of the most recent five years (2007-2011). The partial recruitment (PR) was based on a normalized arithmetic mean of 2007-2011 total fishing mortality from the ASAP model run3f.1. The maturity ogive was knife-edge at age 3. Results of YPR analysis are presented below. The current negotiated EGB cod F reference point is $F_{ref} = 0.18$ (TMGC meeting December 2002). (The current GB cod F_{MSY} proxy= $F_{40\%} = 0.18$).

| | F |
|----------|------|
| F0.1 | 0.19 |
| fmax | 0.43 |
| F30% | 0.29 |
| F40% | 0.19 |
| Fcurrent | 0.45 |

EGB cod is not managed by biomass reference points, however, for background purposes, non-parametric estimates of MSY and SSB_{MSY} based on $F_{40\%}$ were estimated using the 34-year time series mean recruitment (5.484 million age 1 fish), Y/R (1.22) and SSB/R (7.18) as:

$$F_{40\%} = 0.19,$$

$$MSY = 6,677 \text{ mt},$$

$$SSB_{msy} = 39,353 \text{ mt}.$$

The yield per recruit analysis was not updated with the 2014 June ASAP results.

MSY Biological Reference Points

Long-term Stochastic Projection

For the 2013 cod model benchmark, long term (100 years) stochastic projections were run using the same input data as the YPR with $F_{ref} = 0.18$. Following the GB cod accepted assessment projection formulation (NEFSC 2013), recruitment was estimated from a 2 stage cumulative distribution function (CDF) based on either 19 low estimates or 14 high estimates of age 1 recruitment. Based on a visual examination of the stock recruit plot (Appendix A.Figure 17), when SSB is < 15,000 mt recruitment is drawn from the low recruitment CDF, and when SSB >15,000 mt then recruitment is drawn from the high recruitment CDF.

The long term projection provided the following non-parametric biomass reference points:

$$F_{REF} = 0.18,$$

$$MSY = 11,059 \text{ mt (80\% CI: 2,065 mt - 14,180 mt)},$$

$$SSB_{MSY} = 30,622 \text{ mt (80\% CI: 25,450 mt - 84,346 mt)}.$$

Projections

Short term stochastic projections under $F_{40\%}$ were performed from the updated 2014 ASAP model results to estimate landings and SSB during 2015-2016. The input values for mean catch and stock weights, partial recruitment (PR), and maturity were estimated as 3-year averages from 2011-2013. Recruitment was estimated using the 2-stage CDF described above and associated with a SSB breakpoint of 15,000 mt. Catch in 2014 was estimated based on assumption that the 2013 quota of 700 mt would be caught.

The results of the short term projections indicate under the $F_{ref} = 0.18$ catch is projected to decrease in 2015 then increase in 2016, and similarly, SSB is projected to decrease in 2015, then increase in 2016.

| Year | SSB | F | Catch |
|-------------|------------|----------|--------------|
| 2014 | 2914 | 0.32 | 700 |
| 2015 | 2820 | 0.18 | 489 |
| 2016 | 3283 | 0.18 | 525 |

Summary Discussion

Productivity of EGB has been low for the last two decades with poor recruitment and truncated age structure. An increase in natural mortality may have contributed to the recent low productivity, however, food habits data do not support this hypothesis (NEFSC 2013b). Analysis of tagging data indicates minimal increase in M from the 1980s to the 2000s, and thus does not appear sufficient to explain the long term low productivity (Miller WP 2). Lack of large numbers of older repeat spawners in the EGB cod population since the mid-1980s may contribute to the long-term low productivity. Cod have a low success rate of hatching for 1st and 2nd time spawners (13% and 62%) until the 3rd spawning (100%), suggesting that an expanded age structure of fish that have spawned 3 or more times would contribute to higher productivity (Trippel 1998). Long-term overfishing may have also had indirect effects. Fishing activity disrupts the spawning aggregation and thus behaviors and rituals of cod, reducing the potential of good recruitment (Dean 2012). Spawning of cod involves complex behaviors that have only recently been observed including arrival and departure of fish on the spawning ground at different times dependent upon sex, age, and stage of maturity (Lawson and Rose 2000) and the formation of spawning leks, where the males set up and defend territory (Windle and Rose 2007).

The updated model formulation exhibits an increase in the retrospective bias in F and SSB compared to the 2013 ASAP model results. In the is ASAP formulation additional variability is added to the survey abundance estimates, thus placing more emphasis on the reported catch data.

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Appendix A. Table 1. January 1 catch weight at age (kg) for ages 1-10+, for Eastern Georges Bank cod,1978-2013.

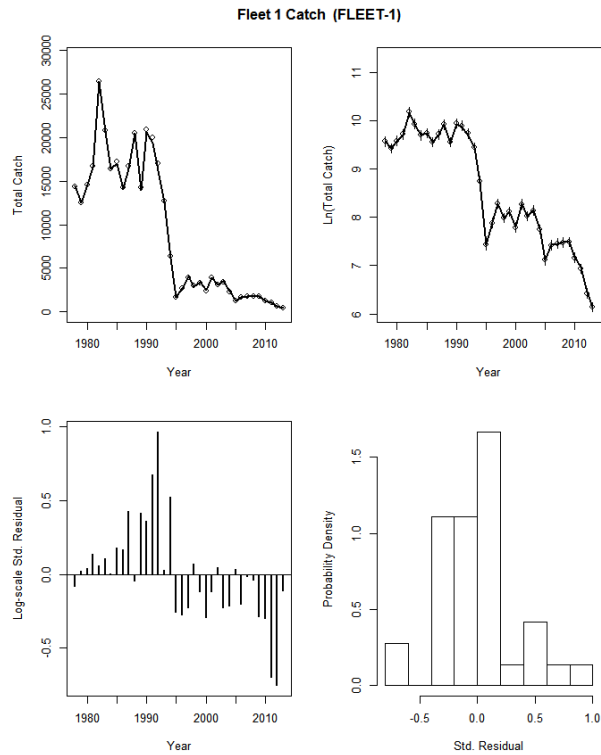
| Year | AGE | | | | | | | | | |
|------|-------|-------|-------|-------|-------|-------|-------|--------|--------|--------|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| 1978 | 0.245 | 1.149 | 1.639 | 2.121 | 2.799 | 4.103 | 4.285 | 7.587 | 7.881 | 13.216 |
| 1979 | 0.564 | 0.800 | 1.386 | 2.601 | 3.477 | 4.954 | 7.137 | 7.347 | 9.036 | 14.362 |
| 1980 | 0.207 | 0.955 | 1.789 | 2.161 | 4.030 | 5.289 | 6.898 | 10.385 | 10.008 | 13.455 |
| 1981 | 0.331 | 0.697 | 1.572 | 2.603 | 3.731 | 5.675 | 7.101 | 8.170 | 11.537 | 15.920 |
| 1982 | 0.340 | 0.825 | 1.651 | 2.681 | 3.919 | 5.537 | 7.438 | 8.895 | 10.471 | 16.018 |
| 1983 | 0.674 | 0.909 | 1.699 | 2.572 | 4.077 | 5.529 | 7.262 | 9.298 | 10.635 | 15.056 |
| 1984 | 0.486 | 1.202 | 1.853 | 2.753 | 3.843 | 5.290 | 7.116 | 8.545 | 10.646 | 13.731 |
| 1985 | 0.337 | 0.945 | 1.705 | 2.712 | 3.946 | 5.322 | 6.938 | 8.930 | 10.030 | 13.758 |
| 1986 | 0.326 | 0.853 | 1.787 | 2.446 | 3.922 | 5.522 | 6.933 | 8.529 | 10.454 | 12.262 |
| 1987 | 0.410 | 0.886 | 1.797 | 3.086 | 4.215 | 5.908 | 7.662 | 8.744 | 10.183 | 13.811 |
| 1988 | 0.435 | 0.826 | 1.787 | 2.705 | 4.393 | 5.725 | 7.730 | 9.308 | 10.266 | 13.719 |
| 1989 | 0.391 | 0.889 | 1.516 | 2.706 | 3.877 | 5.437 | 6.434 | 9.003 | 10.286 | 13.839 |
| 1990 | 0.469 | 0.981 | 1.738 | 2.513 | 3.921 | 5.435 | 6.849 | 8.163 | 10.475 | 13.417 |
| 1991 | 0.544 | 1.027 | 1.937 | 2.732 | 3.695 | 5.041 | 6.711 | 8.587 | 9.494 | 13.813 |
| 1992 | 0.675 | 1.026 | 1.861 | 2.831 | 3.650 | 4.898 | 6.130 | 8.033 | 10.299 | 15.042 |
| 1993 | 0.404 | 1.097 | 1.723 | 2.544 | 3.773 | 4.787 | 6.186 | 7.504 | 8.896 | 12.002 |
| 1994 | 0.410 | 0.895 | 1.731 | 2.691 | 3.532 | 5.249 | 6.232 | 7.421 | 8.125 | 12.629 |
| 1995 | 0.153 | 0.893 | 1.683 | 2.680 | 4.119 | 5.293 | 8.052 | 8.482 | 9.223 | 17.374 |
| 1996 | 0.306 | 0.677 | 1.690 | 2.543 | 3.970 | 5.365 | 6.399 | 9.510 | 10.178 | 10.964 |
| 1997 | 0.483 | 0.853 | 1.715 | 2.519 | 3.430 | 5.023 | 6.505 | 7.303 | 10.139 | 11.130 |
| 1998 | 0.524 | 0.956 | 1.749 | 2.480 | 3.409 | 4.536 | 5.945 | 7.536 | 9.220 | 13.567 |
| 1999 | 0.343 | 0.959 | 1.630 | 2.579 | 3.413 | 4.666 | 5.780 | 7.050 | 8.566 | 13.926 |
| 2000 | 0.487 | 0.844 | 1.597 | 2.392 | 3.527 | 4.288 | 5.599 | 6.517 | 7.936 | 13.056 |
| 2001 | 0.087 | 0.751 | 1.562 | 2.319 | 3.220 | 4.423 | 4.954 | 6.449 | 7.654 | 10.674 |
| 2002 | 0.169 | 0.501 | 1.351 | 2.289 | 3.316 | 4.180 | 5.589 | 6.554 | 7.617 | 11.169 |
| 2003 | 0.138 | 0.639 | 1.598 | 2.303 | 3.169 | 4.123 | 5.167 | 6.622 | 7.924 | 8.729 |
| 2004 | 0.135 | 0.595 | 1.512 | 2.425 | 3.063 | 4.013 | 4.709 | 6.293 | 7.643 | 10.017 |
| 2005 | 0.085 | 0.445 | 1.388 | 2.077 | 3.112 | 3.930 | 4.710 | 5.971 | 7.637 | 9.364 |
| 2006 | 0.123 | 0.328 | 1.192 | 1.904 | 2.779 | 3.871 | 5.217 | 5.308 | 6.850 | 7.384 |
| 2007 | 0.278 | 0.514 | 1.023 | 2.019 | 2.639 | 3.589 | 5.116 | 6.459 | 6.320 | 9.541 |
| 2008 | 0.148 | 0.763 | 1.530 | 2.124 | 2.911 | 3.885 | 4.771 | 6.949 | 7.382 | 9.086 |
| 2009 | 0.467 | 0.572 | 1.556 | 2.595 | 3.215 | 4.055 | 5.368 | 6.258 | 8.897 | 10.910 |
| 2010 | 0.326 | 0.936 | 1.521 | 2.203 | 3.201 | 3.565 | 4.795 | 5.898 | 7.693 | 11.265 |
| 2011 | 0.163 | 0.712 | 1.513 | 2.293 | 2.985 | 3.804 | 3.809 | 5.561 | 7.737 | 9.627 |
| 2012 | 0.162 | 0.523 | 1.326 | 2.133 | 3.072 | 3.799 | 4.458 | 4.909 | 5.685 | 5.230 |
| 2013 | 0.623 | 0.522 | 1.329 | 2.174 | 3.150 | 4.199 | 4.694 | 5.401 | 7.180 | 7.220 |

Appendix A. Table 2. ASAP model diagnostics and results for four model formulations: total objective function (OF) value, contribution to the OF by components, root mean square error (RMSE) of the standardized residuals, catch and survey coefficient of variation (CV) and effective sample size (ESS) and the spawning stock biomass and fishing mortality of unweighted ages 5+ for the terminal year (TY), and the Mohn's rho retrospective bias adjustments.

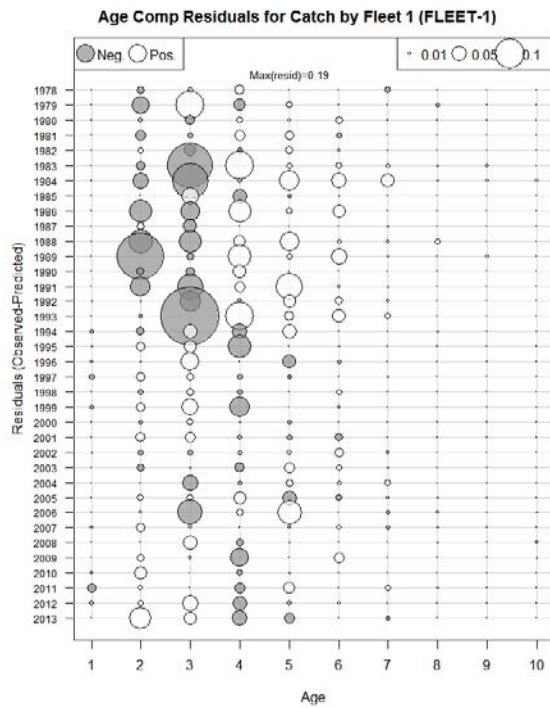
| | | 2013 run2 | 2014 run1 | run 2 | run2b |
|------------------------------------|------------------------------|--------------------|--------------------|--------------------|--------------------|
| | | TY=2012 | TY=2012 | TY=2013 | TY=2013 |
| Model | | base_rivard | bridge | base_rivard | base_sv_wts |
| objective function | | 3017.29 | 3057.51 | 3163.31 | 3163.31 |
| components of obj. function | catch total | 230.458 | 230.526 | 234.975 | 234.975 |
| | | | 0.00 | 0.00 | 0.00 |
| | index fit total | 873.41 | 875.14 | 914.99 | 914.99 |
| | catch age composition | 567.608 | 570.91 | 588.49 | 588.49 |
| | | | 0.00 | 0.00 | 0.00 |
| | Index age composition | 1345.81 | 1380.94 | 1424.86 | 1424.86 |
| | Recruit deviations | 0 | 0 | | |
| RMSE | Catch fleet | 0.29 | 0.30 | 0.33 | 0.33 |
| | total catch | 0.29 | 0.30 | 0.33 | 0.33 |
| | discards | 0.00 | 0.00 | 0.00 | 0.00 |
| | total discards | 0.00 | 0.00 | 0.00 | 0.00 |
| | DFO | 1.41 | 1.44 | 1.53 | 1.53 |
| | Autumn | 1.35 | 1.28 | 1.34 | 1.34 |
| | Spring 41 | 0.76 | 0.78 | 0.78 | 0.78 |
| | Spring 36 | 1.35 | 1.42 | 1.50 | 1.50 |
| | Index total | 1.35 | 1.35 | 1.43 | 1.43 |
| CV | catch | 0.05 | 0.05 | 0.05 | 0.05 |
| | dfo | 0.25+ | 0.25+ | 0.25+ | 0.25+ |
| | fall | 0.2+ | 0.2+ | 0.2+ | 0.2+ |
| | spring #41 | 1x | 1x | 1x | 1x |
| | spring #36 | 0.3+ | 0.3+ | 0.3+ | 0.3+ |
| ESS | catch | 75/125('96) | 75/125('96) | 75/125('96) | 75/125('96) |
| | dfo | 50 | 50 | 50 | 50 |
| | fall | 50 | 50 | 50 | 50 |
| | 41 | 50 | 50 | 50 | 50 |
| | 36 | 50 | 50 | 50 | 50 |
| Jan 1 biomass | | 2989 | 2546 | 2729 | 2581 |
| SSB TY mt | | 1922 | 1695 | 2142 | 1965 |
| SSB TY retro bias adj | | 1567 | 1330 | 1470 | 1345 |
| F TY (age 5+) | | 0.44 | 0.53 | 0.33 | 0.33 |
| F TY retro bias adj. | | 0.53 | 0.67 | 0.49 | 0.49 |
| TY age 1 (millions) | | 0.446 | 0.190 | 0.125 | 0.125 |
| TY age 1 retro bias adj. | | 0.689 | 0.276 | 0.166 | 0.166 |
| rho F | | -0.17 | -0.22 | -0.32 | -0.32 |
| rho SSB | | 0.23 | 0.27 | 0.46 | 0.46 |
| rho rct | | -0.35 | -0.31 | -0.25 | -0.25 |

Appendix A. Table 3. ASAP model results for January 1 biomass (mt), spawning stock biomass (SSB (mt), age 3+), fishing mortality (F) and recruitment (age 1, 000s fish), 1978-2013.

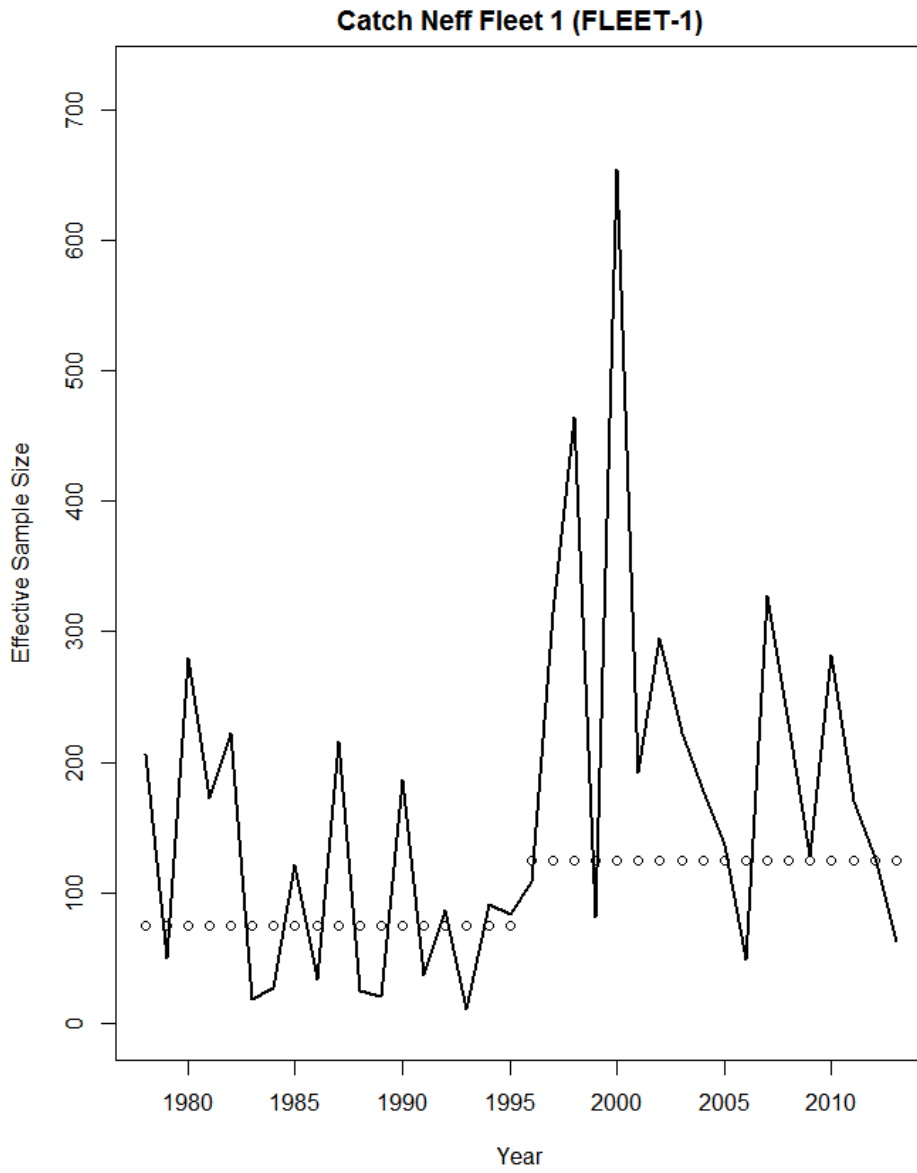
| Year | Jan. 1 Biomass | SSB | F | Recruitment |
|-------------|-----------------------|------------|----------|--------------------|
| 1978 | 38869 | 30710 | 0.44 | 10936 |
| 1979 | 43986 | 28098 | 0.37 | 10554 |
| 1980 | 47567 | 33947 | 0.39 | 9111 |
| 1981 | 50438 | 34824 | 0.46 | 19351 |
| 1982 | 52993 | 32109 | 0.72 | 7430 |
| 1983 | 45547 | 32853 | 0.61 | 3606 |
| 1984 | 41530 | 27444 | 0.59 | 13723 |
| 1985 | 35308 | 19278 | 0.83 | 5418 |
| 1986 | 35224 | 19869 | 0.65 | 26261 |
| 1987 | 42203 | 17998 | 0.60 | 6499 |
| 1988 | 48307 | 32932 | 0.64 | 13978 |
| 1989 | 41023 | 25640 | 0.46 | 5762 |
| 1990 | 42813 | 30396 | 0.65 | 6838 |
| 1991 | 39049 | 22523 | 0.91 | 11483 |
| 1992 | 29176 | 14592 | 1.02 | 2519 |
| 1993 | 19341 | 12673 | 1.15 | 3074 |
| 1994 | 10932 | 6332 | 1.55 | 1961 |
| 1995 | 8157 | 6075 | 0.42 | 1226 |
| 1996 | 9555 | 7348 | 0.52 | 2606 |
| 1997 | 11108 | 6567 | 0.85 | 3508 |
| 1998 | 10532 | 6418 | 0.68 | 1226 |
| 1999 | 10989 | 7964 | 0.69 | 3406 |
| 2000 | 10868 | 7113 | 0.44 | 1535 |
| 2001 | 10458 | 8347 | 0.75 | 1053 |
| 2002 | 8445 | 6983 | 0.56 | 1493 |
| 2003 | 7651 | 5885 | 0.83 | 391 |
| 2004 | 5720 | 4573 | 0.75 | 2434 |
| 2005 | 4408 | 3154 | 0.49 | 424 |
| 2006 | 4490 | 3832 | 0.66 | 867 |
| 2007 | 4400 | 3257 | 0.71 | 1179 |
| 2008 | 4171 | 2936 | 0.77 | 563 |
| 2009 | 3919 | 2970 | 1.00 | 433 |
| 2010 | 2964 | 2056 | 1.00 | 699 |
| 2011 | 2349 | 1414 | 1.18 | 1534 |
| 2012 | 2134 | 1192 | 0.81 | 866 |
| 2013 | 2729 | 2142 | 0.33 | 125 |



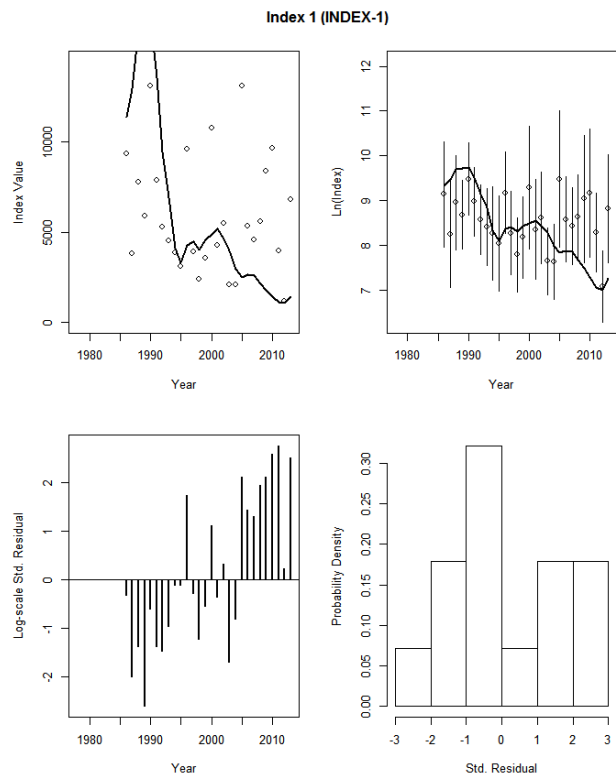
Appendix A. Figure 1. ASAP model fit to total catch of Eastern Georges Bank cod, 1978-2013.



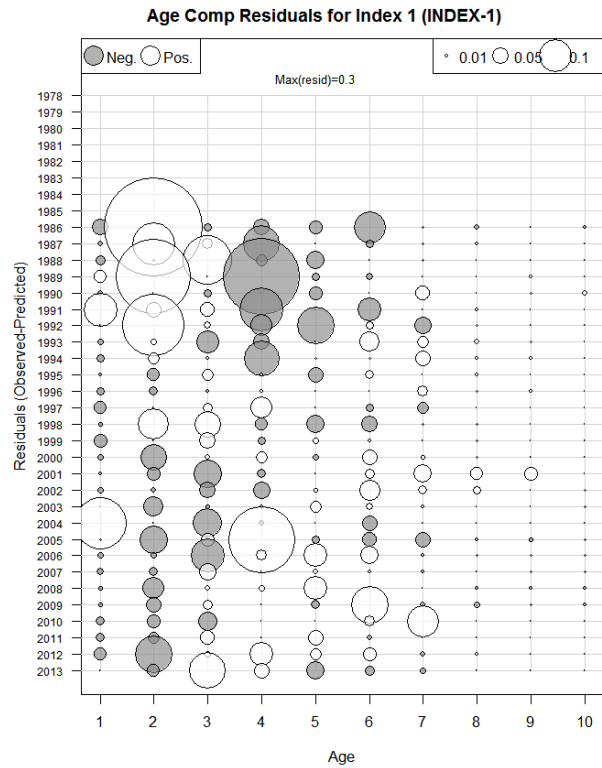
Appendix A. Figure 2. ASAP model residuals for the commercial catch age composition of Eastern Georges Bank cod, 1978-2013.



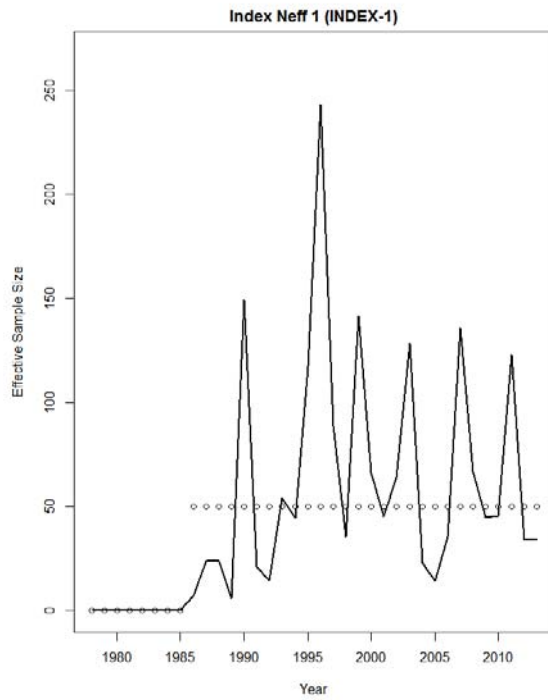
Appendix A. Figure 3. ASAP model observed (line) and predicted (circles) effective sample size of Eastern Georges Bank cod in the total catch, 1978-2013.



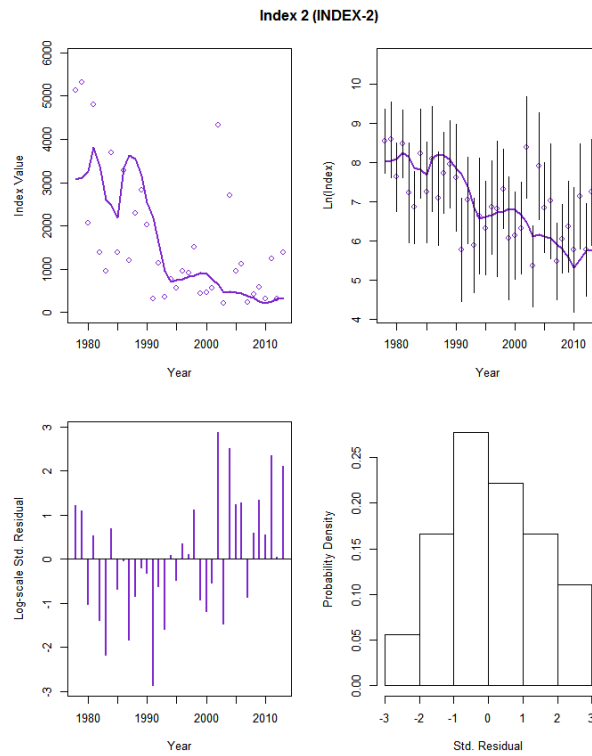
Appendix A. Figure 4. ASAP model fit to DFO survey indices of Eastern Georges Bank cod, 1978-2013.



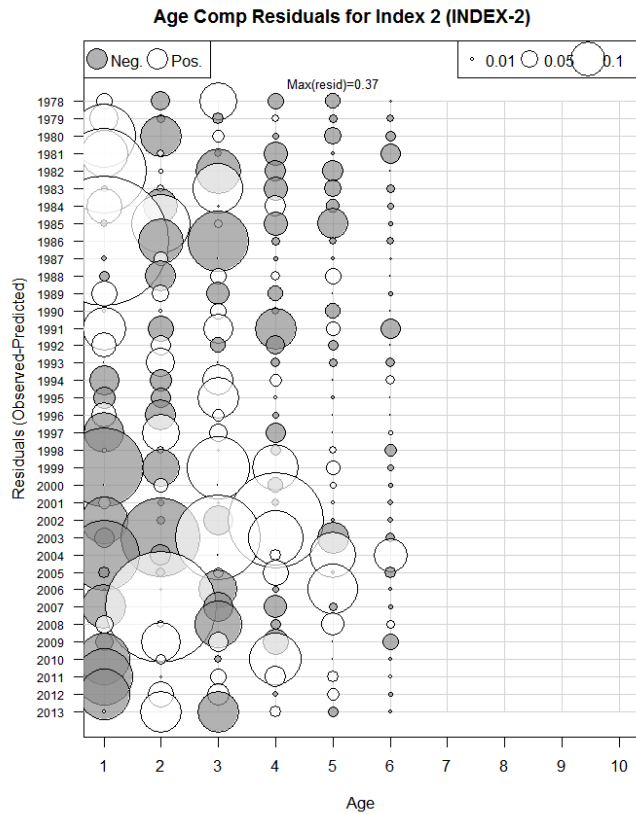
Appendix A. Figure 5. ASAP model run age composition residuals for DFO survey index of Eastern Georges Bank cod, 1978-2013.



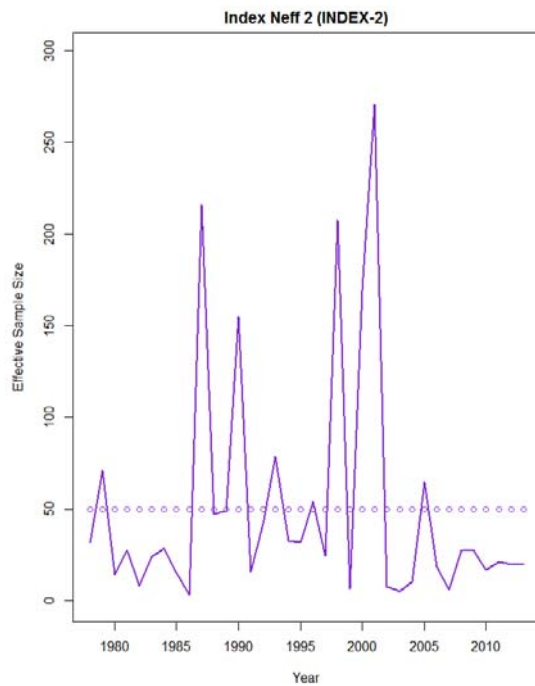
Appendix A, Figure 6. ASAP model observed (line) and predicted (circles) effective sample size of Eastern Georges Bank cod in the DFO survey, 1978-2013.



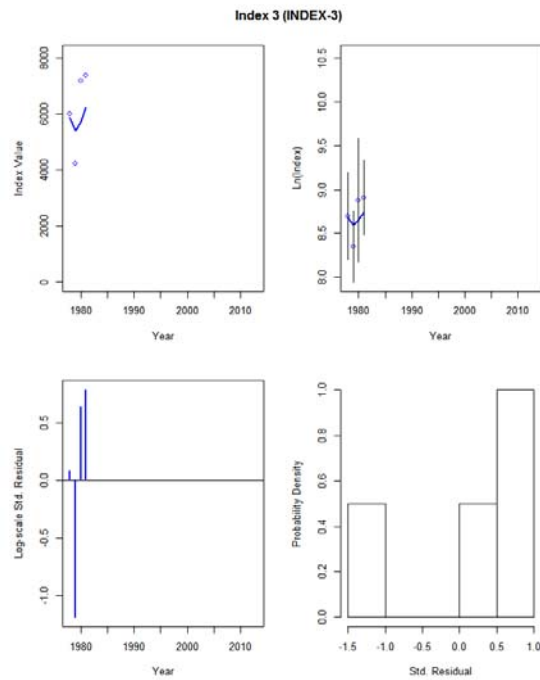
Appendix A, Figure 7. ASAP model fit to NEFSC autumn survey indices of Eastern Georges Bank cod, 1978-2013.



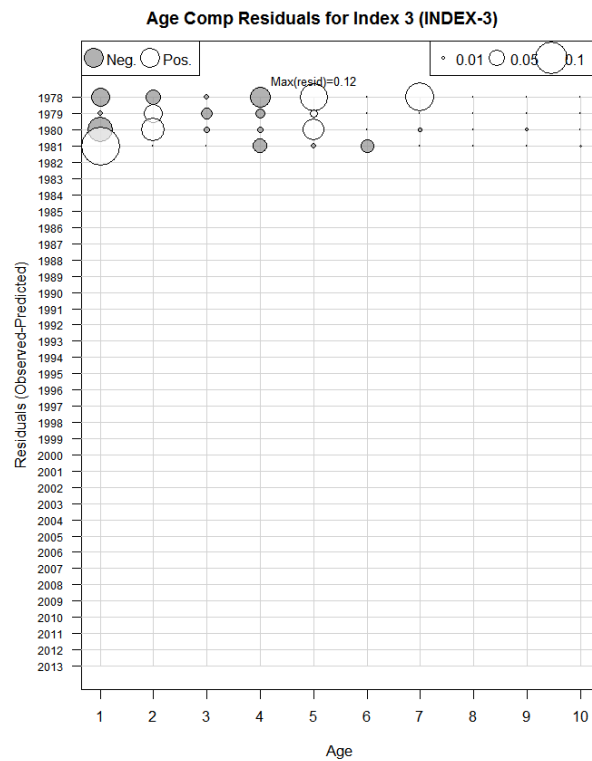
Appendix A. Figure 8. ASAP model age composition residuals for NEFSC autumn survey index of Eastern Georges Bank cod, 1978-2013.



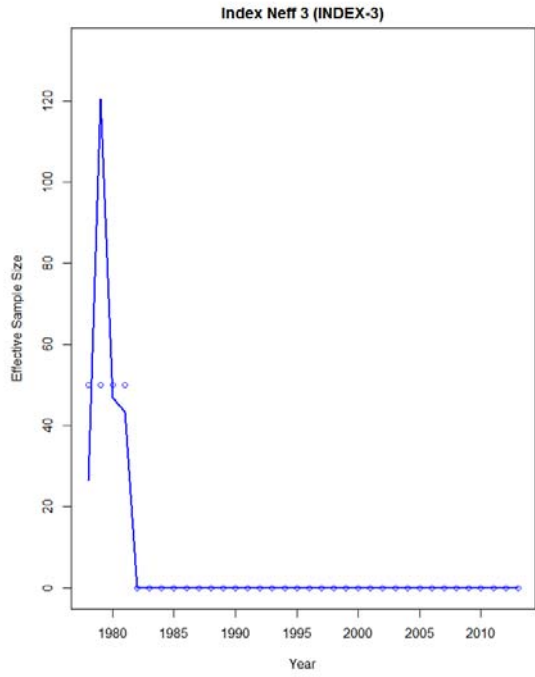
Appendix A. Figure 9. ASAP model observed (line) and predicted (circles) effective sample size of Eastern Georges Bank cod in the NEFSC autumn survey, 1978-2013.



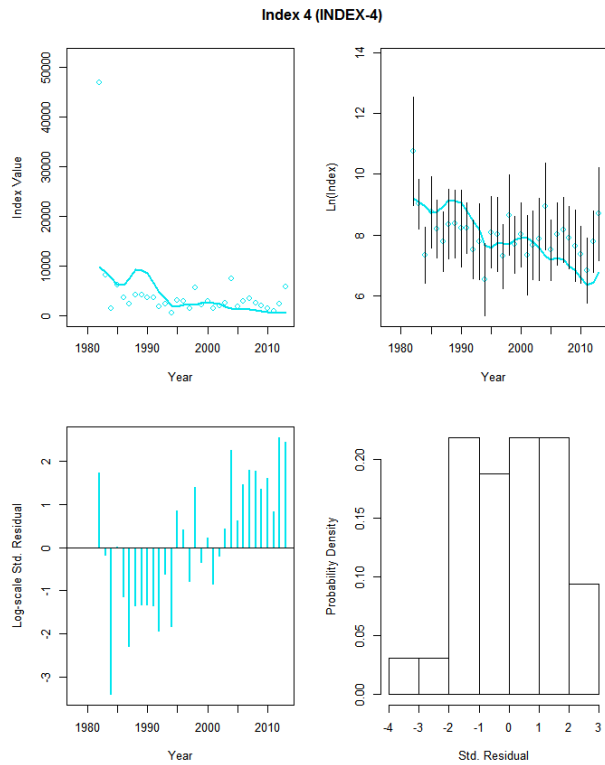
Appendix A. Figure 10. ASAP model fit to NEFSC spring Yankee #41 trawl survey indices of Eastern Georges Bank cod, 1978-1981.



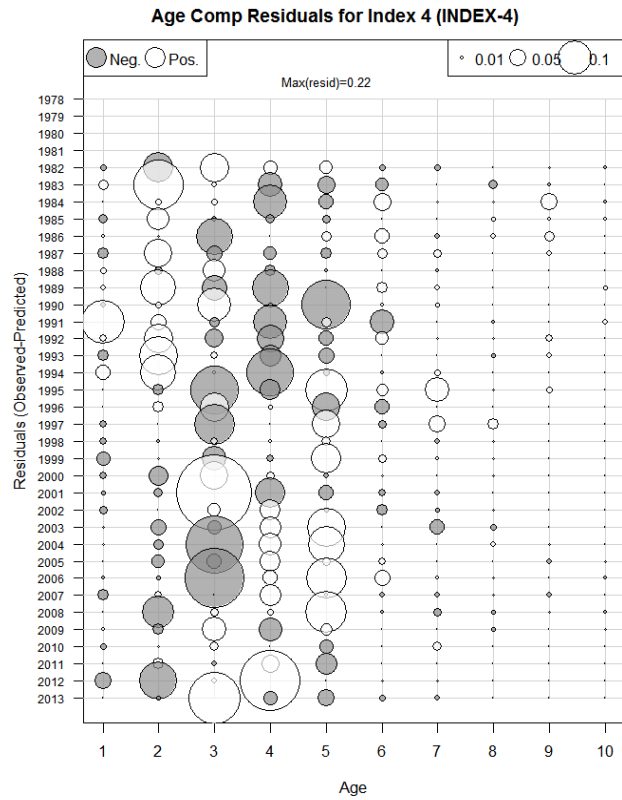
Appendix A. Figure 11. ASAP model age composition residuals for NEFSC spring Yankee #41 trawl survey index of Eastern Georges Bank cod, 1978-1981.



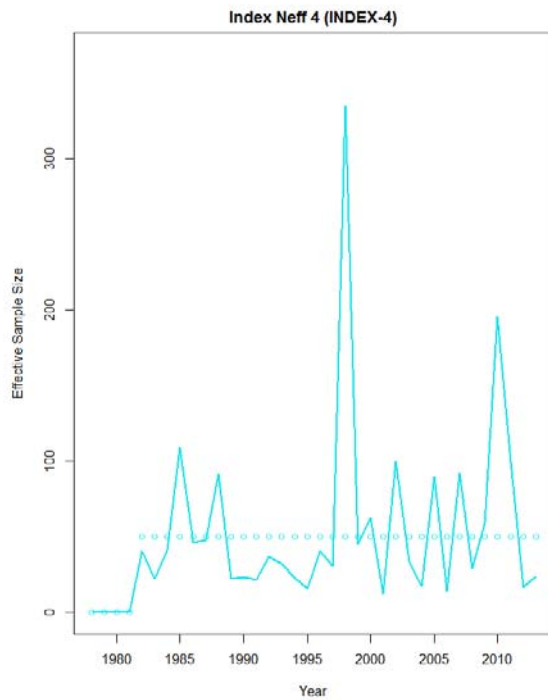
Appendix A. Figure 12. ASAP model observed (line) and predicted (circles) effective sample size of Eastern Georges Bank cod in the NEFSC spring Yankee #41 trawl survey, 1978-1981.



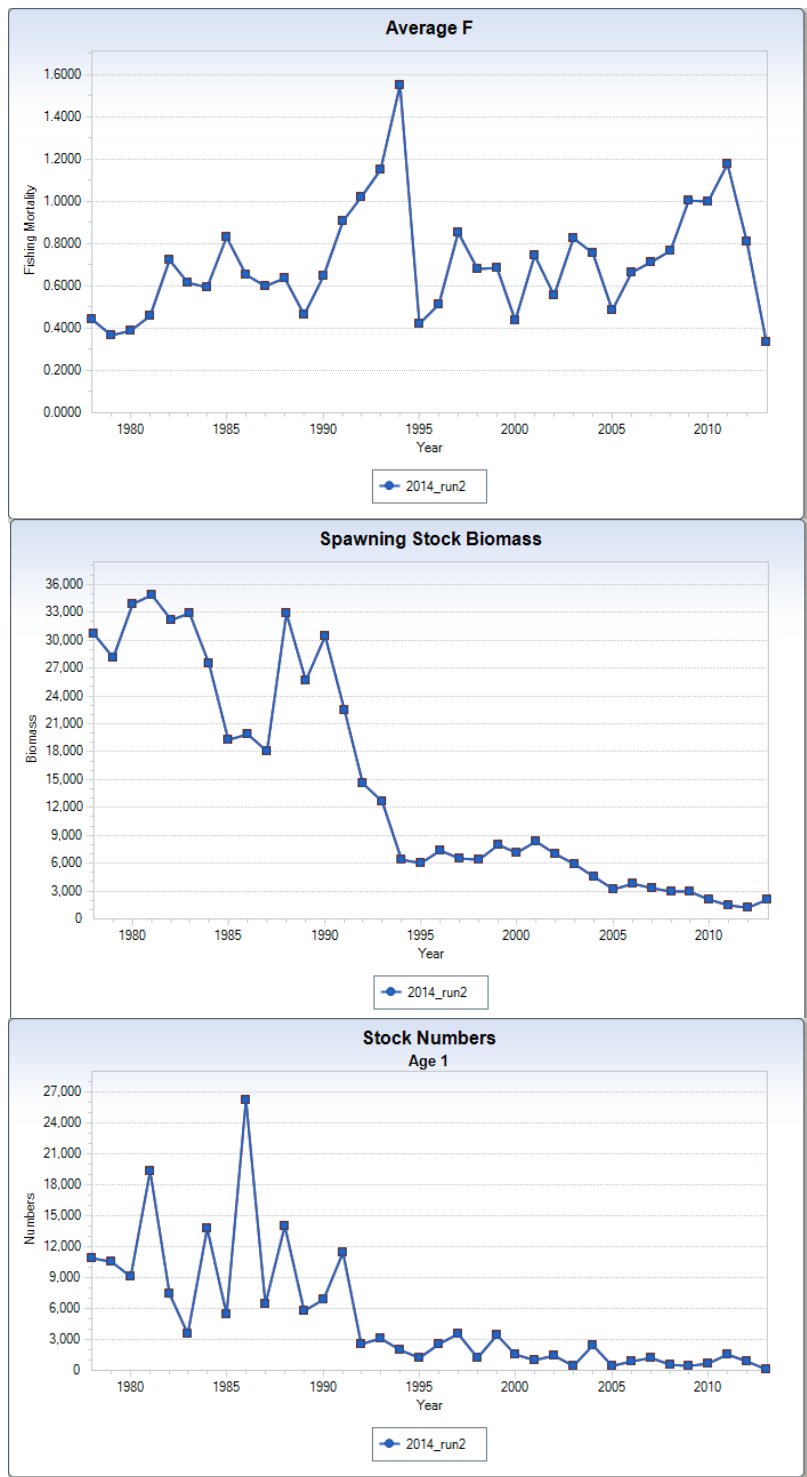
Appendix A. Figure 13. ASAP model fit to NEFSC spring Yankee #36 trawl survey indices of Eastern Georges Bank cod, 1982-2013.



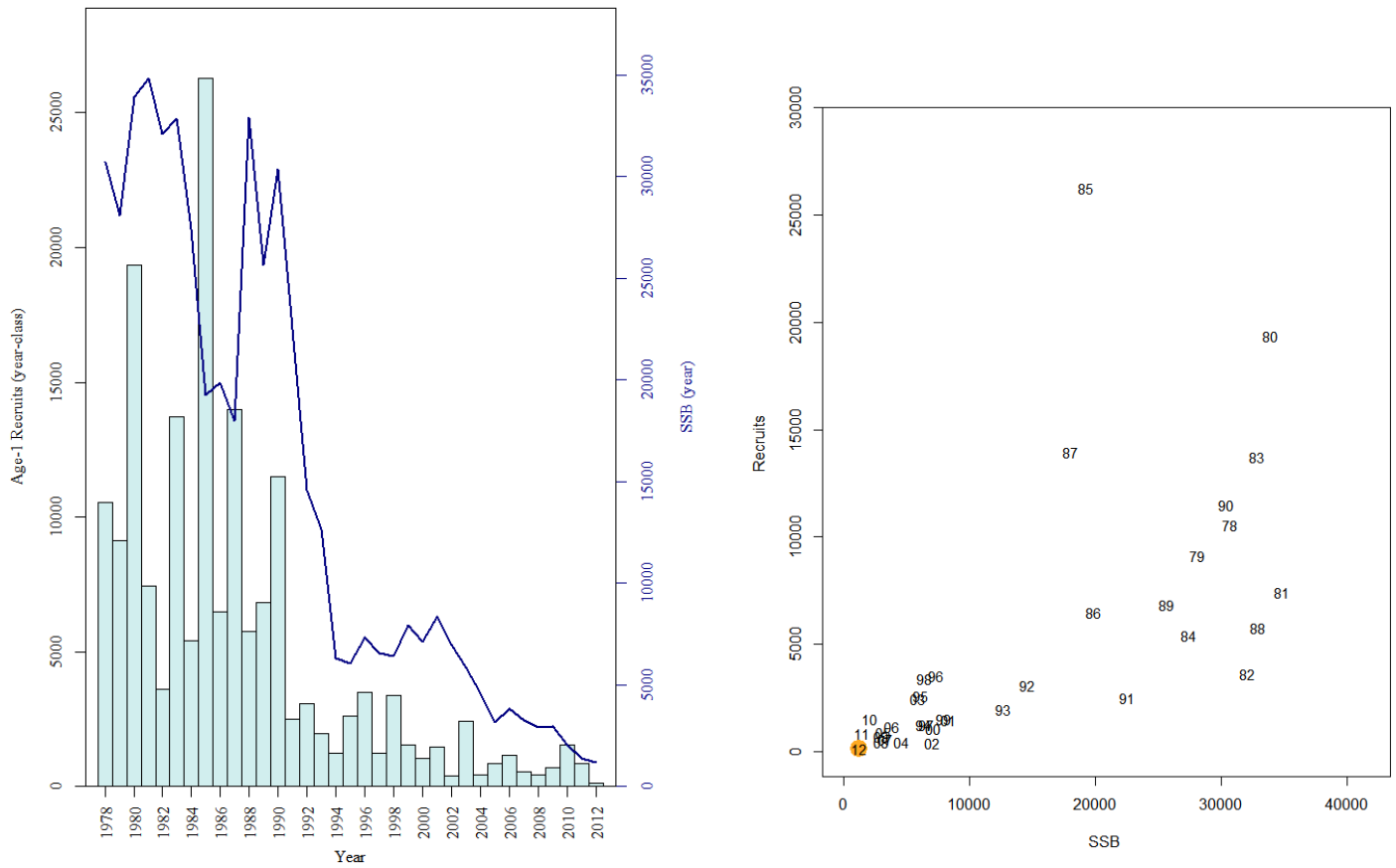
Appendix A. Figure 14. ASAP model age composition residuals for NEFSC spring Yankee #36 trawl survey index of Eastern Georges Bank cod, 1982-2013.



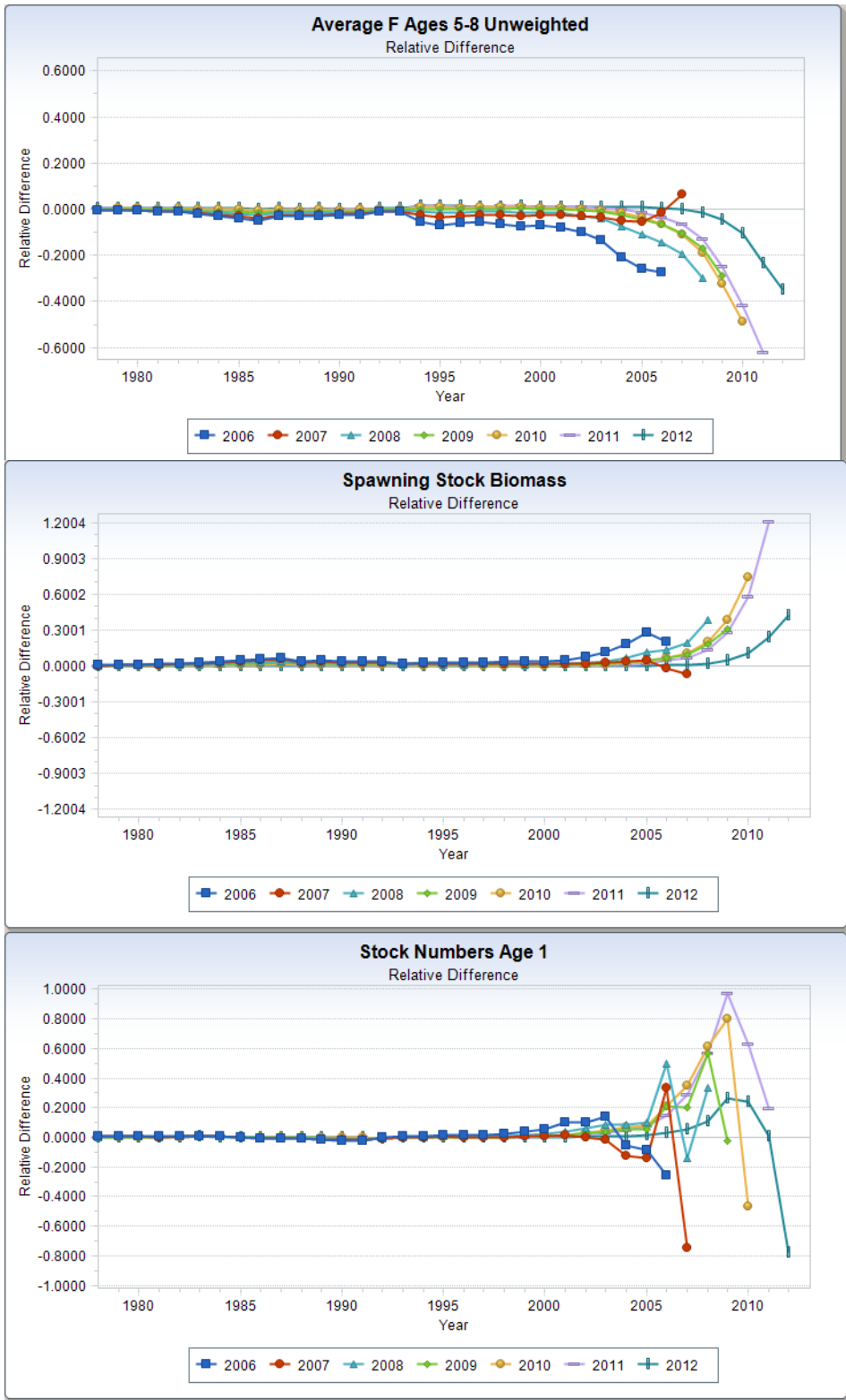
Appendix A. Figure 15. ASAP model observed (line) and predicted (circles) effective sample size of Eastern Georges Bank cod in the NEFSC spring Yankee #36 trawl survey, 1982-2013.



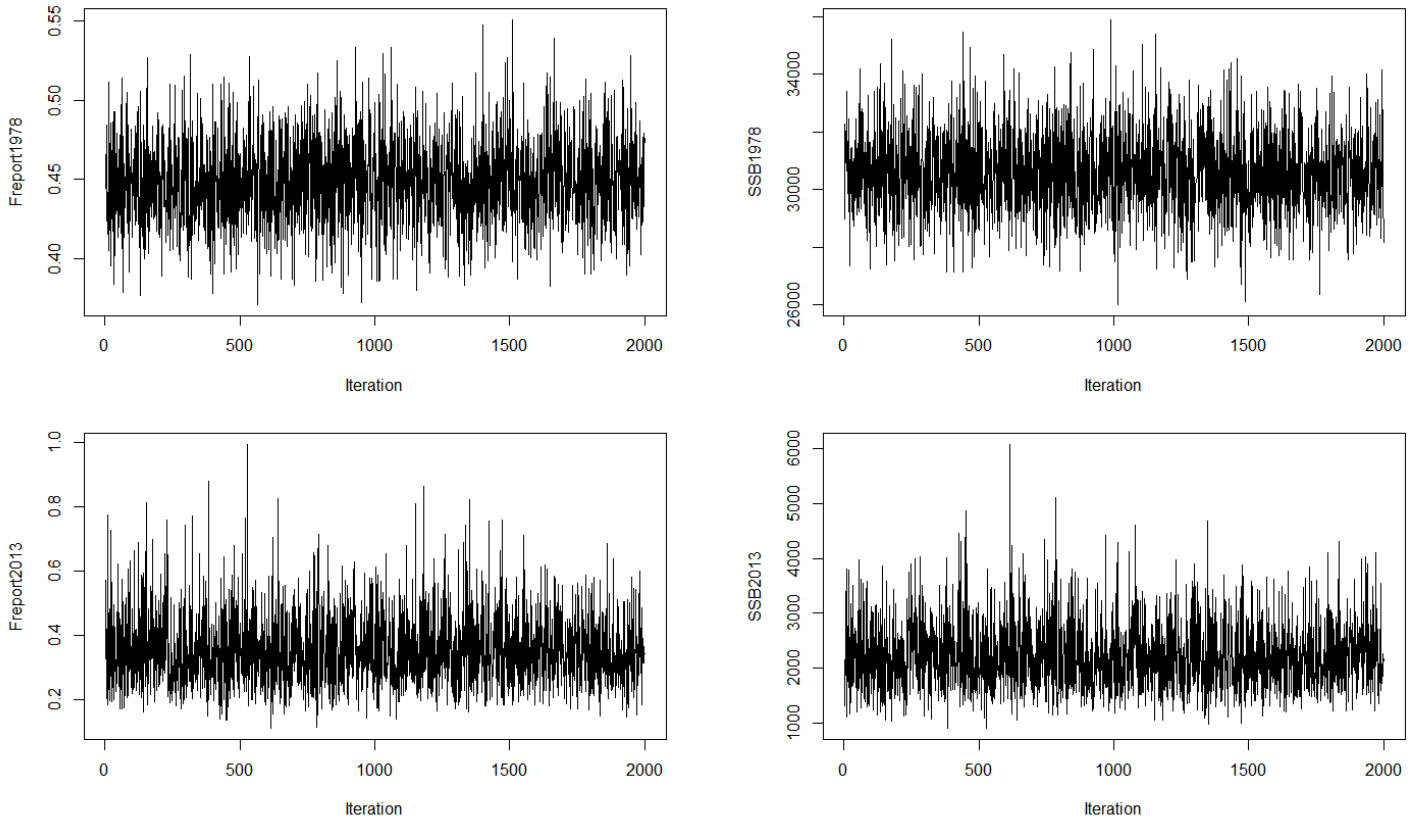
Appendix A. Figure 16. ASAP model results for fishing mortality (ages 5+), spawning stock biomass, and recruitment (age 1, 000s fish), 1978-2013.



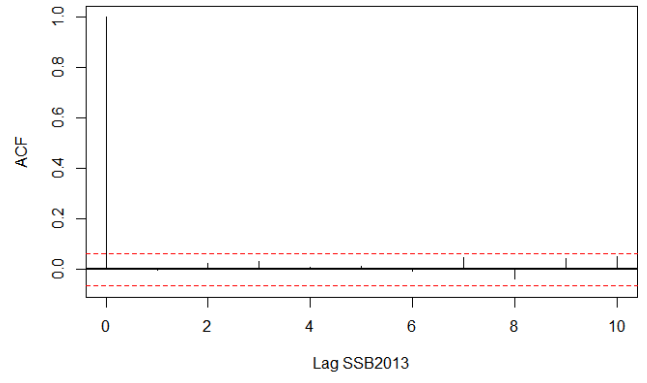
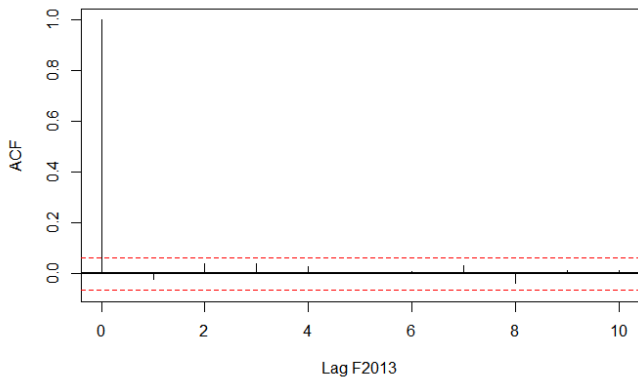
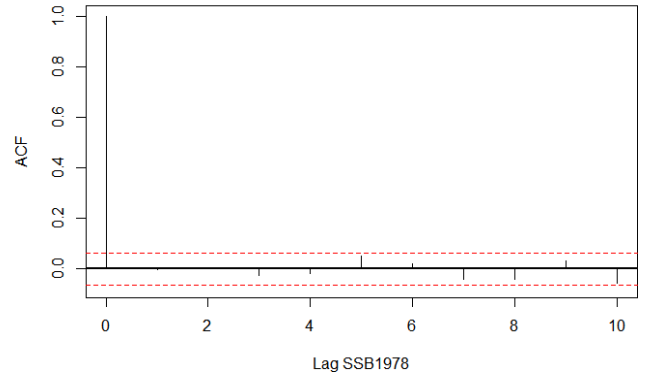
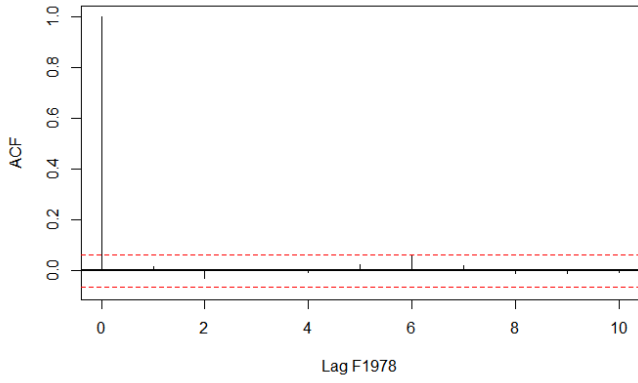
Appendix A. Figure 17. ASAP model results (left panel) for spawning stock biomass (mt, line) and recruitment (age1, 000s fish, bars) and the stock – recruitment plot (right panel) with year-class designation, 1978-2013.



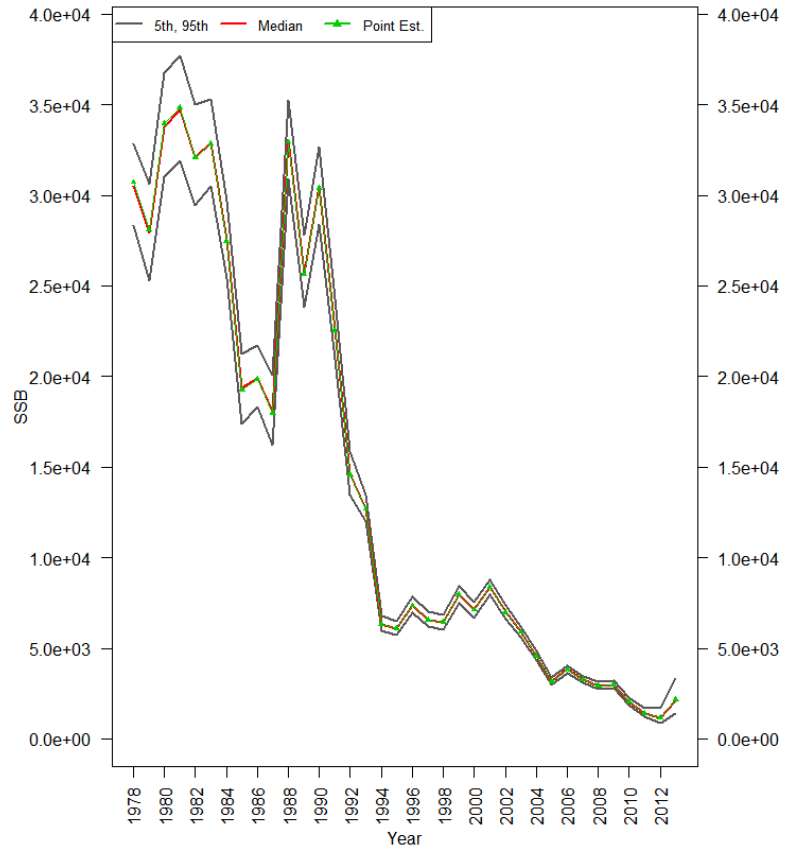
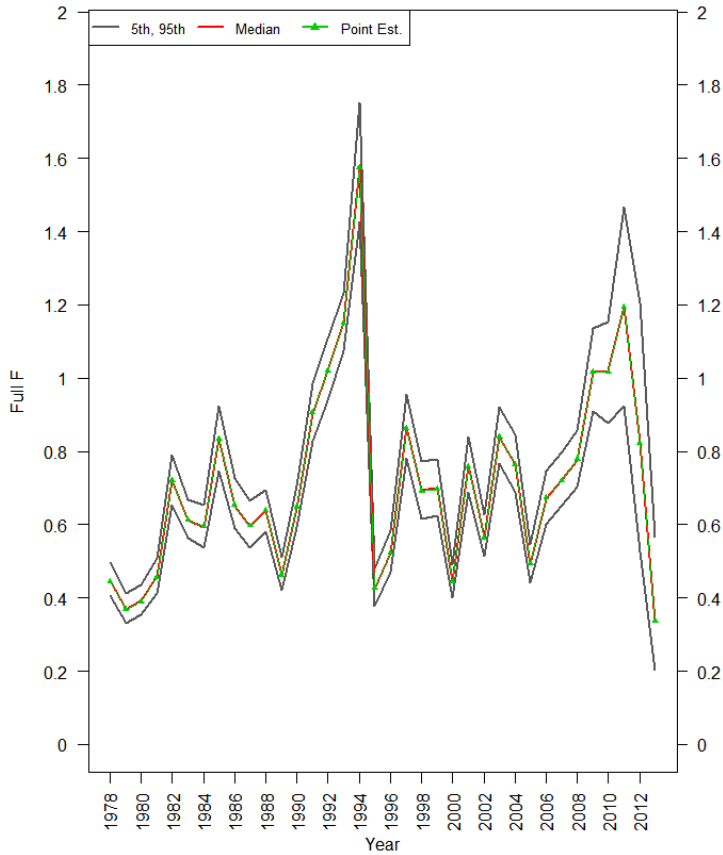
Appendix A. Figure 18. ASAP model results of retrospective bias of fishing mortality (F), spawning stock biomass (SSB), and age1 recruitment. Retrospective bias adjustment for $F = -0.32$, $SSB = 0.46$, and age 1 recruitment = -0.25 .



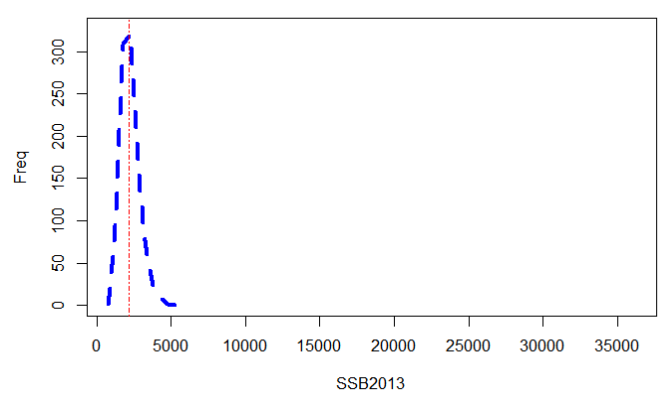
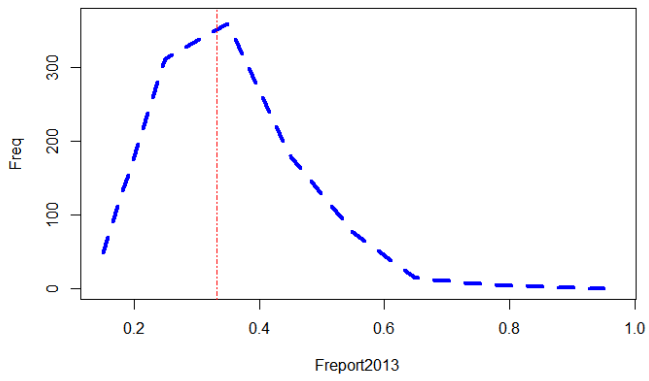
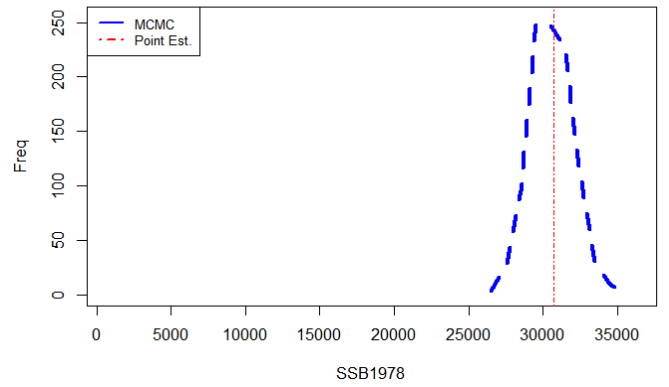
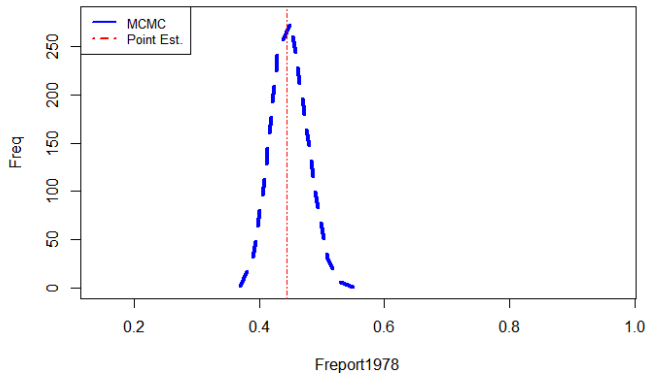
Appendix A. Figure 19. ASAP model results of trace of MCMC chains for Eastern Georges Bank cod fishing mortality (left) and spawning stock biomass (right) for 1978 and 2013. Each chain had an initial length of 5.0 million and was thinned at a rate of one out of every 2,500th resulting in a final chain length of 2000.



Appendix A. Figure 20. ASAP model autocorrelation within the 1978 and 2013 MCMC chains for fishing mortality (F, left panel) and spawning stock biomass (SSB, right panel) for Eastern Georges Bank cod.



Appendix A. Figure 21. ASAP model 90% probability interval for Eastern Georges Bank fishing mortality (left) and cod spawning stock biomass (SSB). The median value is in red, while the 5th and 95th percentiles are in dark grey. The point estimate from the model (joint posterior modes) is shown in the thin green line with filled triangles.



Appendix A. Figure 22. ASAP model MCMC distribution of Eastern Georges Bank and fishing mortality (F, left panel) and cod spawning stock biomass (SSB, right panel) in 1978 and 2013. The model point estimate is indicated by the dashed red line.