A Statistical Catch at Age Stock Assessment Model of Eastern Georges Bank Atlantic Cod (*Gadus morhua*)

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ABSTRACT

Several model configurations of the statistical catch at age model 'Age Structured Assessment Program' (ASAP) were applied to data for Eastern Georges Bank Atlantic Cod, assessed by the Transboundary Resources Assessment Committee (TRAC). The ASAP model was chosen to explore as an alternative to the TRAC virtual population model (VPA) and also because ASAP was recently accepted as the new benchmark model for the USA Georges Bank cod assessment, replacing the VPA model that had historically been applied, since about 1978 (NEFSC 2013a).

The ASAP results for Eastern Georges Bank cod provided estimates of instantaneous fishing mortality (F) in 2011 and stock biomass in 2011. The preferred ASAP model estimated a fully recruited (unweighted, ages 5+) at 0.45 in 2011, a 48% decrease from 2010. Spawning stock biomass (SSB) in 2011 was estimated at 3002 mt, a 9% decrease from 2010 and recruitment (millions of age 1 fish) of the 2003 year class (2.7 million) was estimated to be smaller than the 1998 year class (3.4 million) and the 2010 year class was estimated at 2.4 million.

A retrospective analysis was performed for terminal year F, SSB, and age 1 recruitment. The retrospective rho values, estimated from the average of the last 7 years of the relative retrospective peels, were 0.025 for SSB, -0.054 for F_{5+}, and -0.529 for age 1 recruitment. Applying a retrospective adjustment ((1/(1+rho)) * estimate) results in 2011 estimates of F=0.48, SSB=2,930 mt, age 1 recruitment=5.1 million fish.

Results of short term projections indicate under an $F_{40\%}$= 0.19, that catch is projected to increase each year through 2015, and SSB is also projected to increase in each year through 2015.

Based on model diagnostics and the lack of strong retrospective bias, run3f.1 is put forth as the preferred model. This model formulation exhibits minimal retrospective bias in F and SSB that had been prevalent in previous assessments; however, additional variability was added to the survey abundance estimates, thus placing more emphasis on the catch data.

Modèle statistique d'évaluation des prises selon l'âge
de la morue franche (*Gadus morhua*) de l'est du banc de Georges

RÉSUMÉ

Plusieurs configurations du modèle statistique des prises selon l'âge du Programme d'évaluation selon la structure d'âge (PESA) ont été appliquées aux données concernant la morue franche de l'est du banc de Georges, évaluées par le Comité d'évaluation des ressources transfrontalières (CERT). On a choisi le modèle du PESA pour l'étudier comme solution de rechange au modèle d'analyse population virtuelle (APV) du CERT, et ce, parce que le modèle du PESA a récemment été reconnu comme le nouveau modèle de référence pour l'évaluation de la morue du banc de Georges aux États-Unis, remplaçant ainsi le modèle d'APV qui était appliqué depuis environ 1978 (NEFSC 2013a).

Les résultats du PESA en ce qui a trait à la morue de l'est du banc Georges ont fourni des estimations de la mortalité par pêche instantanée (F), ainsi que de la biomasse du stock reproducteur, en 2011. Le modèle privilégié du PESA a estimé la biomasse de morues pleinement recrutées (non pondérée, âge 5+) à 0,45 en 2011, soit une baisse de 48 % par rapport à 2010. En 2011, la biomasse du stock reproducteur (BSR) a été estimée à 3 002 tm, à savoir une baisse de 9 % par rapport à 2010. En outre, le recrutement (millions de poissons d'âge 1) de la classe d'âge 2003 (2,7 millions) a été estimé comme étant inférieur à celui de la classe d'âge 1998 (3,4 millions), tandis que le recrutement de la classe d'âge 2010 était estimé à 2,4 millions.

Une analyse rétrospective a été réalisée pour la mortalité par pêche (F) de l'année terminale, la BSR et le recrutement à l'âge 1. Les valeurs rétrospectives avec correction rho, estimées à partir de la moyenne des analyses rétrospectives relatives des sept dernières années, s'élevaient à 0,025 pour la BSR, à -0,054 pour la mortalité par pêche des morues âgées de 5 ans et plus (F_{5+}) et à -0,529 pour le recrutement à l'âge 1. L'application d'une correction rétrospective (estimation de [1/(1 + rho])*) a mené aux estimations suivantes en 2011 : F = 0,48, BSR = 2 930 tm et recrutement à l'âge 1 = 5,1 millions de poissons.

Compte tenu d'une $F_{40\%}$ de 0,19, les résultats de projections à court terme révèlent que les prises devraient augmenter chaque année jusqu'en 2015. Il en est de même pour la BSR.

D'après les diagnostics du modèle et le manque d'un important biais rétrospectif, on propose le modèle run3f.1 comme modèle privilégié. Cette formule de modèle révèle qu'il existe un biais rétrospectif minime de F et de la BSR, qui était répandu dans les évaluations précédentes. Toutefois, une variabilité supplémentaire a été ajoutée aux estimations de l'abondance du relevé pour mettre davantage l'accent sur les données sur les prises.

INTRODUCTION

The Transboundary Resources Assessment Committee (TRAC) was established in 1998 to peer review assessments of transboundary resources in the Gulf of Maine-Georges Bank region to support management decisions of both the USA and Canada. Three species on Georges Bank (GB) were of interest at that time: Atlantic Cod, Haddock, and Yellowtail Flounder. Prior to 1998 each country conducted assessments for these species; however, beyond exchanging the catch data required for each assessment, there was limited participation in the assessment preparation or subsequent peer review. For cod on Georges Bank, the USA conducted an assessment based on the unit stock of 'Georges Bank cod ' defined as cod from the Northwest Atlantic Fisheries Organization (NAFO) Division 5Z and south (Figure 1), which includes USA statistical areas (SA) 521-522, 561-562, 551-552, 525- 526, and SA areas southward. In Canada, the assessment of cod was based on the management unit of 'Eastern Georges Bank (EGB) cod' defined as cod from the eastern part of NAFO Division 5Ze that includes USA SAs 561-562 and 551-552, and Canadian SA 5j and m (Figure 2).

In 2000, the Transboundary Management Guidance Committee (TMGC) was established for the management of transboundary stocks in the Gulf of Maine-Georges Bank. In December 2001, the TMGC reached an agreement to recommend 5Zjm as the management unit for eastern Georges Bank (EGB) cod and EGB Haddock and 5Zhjmn for GB Yellowtail Flounder, with percentage catch share to each country based on contemporary resource distribution and historical landings (TMGC 2002). The USA; however, continued to assess and manage GB cod as a unit stock (NAFO Div. 5Z and Subarea 6, Figure 1).

Since the establishment of TRAC and TMGC, the EGB cod assessment is reviewed within TRAC and quota allocation recommended by the TMGC. The GB cod assessment, conducted by the USA, is reviewed in the Stock Assessment Workshop/Stock Assessment Review Committee (SAW/SARC) process at the Northeast Fisheries Science Center (NEFSC) and managed by the New England Fisheries Management Council. The NEFSC GB cod assessment was reviewed for a brief time (1998, 2000, and 2001) within the TRAC but has subsequently been reviewed in the SAW/SARC process.

This paper presents several model configurations of the statistical catch at age model 'Age Structured Assessment Program' (ASAP) as applied to the EGB cod data. The ASAP model was chosen to explore as an alternative to the virtual population model (VPA). In addition, ASAP was recently accepted as the new benchmark model for the USA GB cod assessment, replacing the VPA that had historically been applied, since about 1978 (NEFSC 2013a). 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 seem 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 Canada and the USA, respectively, similarly scaled populations would allow for compatibility in management decisions.

METHODS AND RESULTS

ASSESSMENT MODEL FORMULATION

ASAP

The ASAP was used to derive estimates of instantaneous fishing mortality (F) in 2011 and stock biomass in 2011. A retrospective analysis was performed for terminal year F, spawning stock biomass (SSB), and age 1 recruitment.

Model Description

ASAP, a forward projecting statistical catch at age model (Legault and Restrepo 1998) can be downloaded from the National Oceanic and Atmospheric Administration (NOAA) Fisheries Toolbox (NFT, http://nft.nefsc.noaa.gov/). As described at the NFT software 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, as in a VPA. 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 more technical details, the reader is referred to the technical manual (Legault 2008).

Data Input

Input to the ASAP model includes the total catch (mt) for the combined landings and discards of USA and Canadian fleets (Tables 1a-1b, Figure 3), and the catch-at-age (Table 2, Figure 4) and weight-at-age (Table 3, Figure 5) for ages 1-10+ during 1978-2011. Beginning year weight-at-age is back-calculated from the mid-year catch weight-at-age (Table 4, Figure 6) and also estimated from an average of the Fisheries & Oceans Canada (DFO) and NEFSC spring research survey weight-at-age (Table 5, Figure 7). Swept-area population estimates derived from indices of abundance include the 1986-2011 DFO estimates for ages 1-10+ (Table 6, Figure 8), the 1978-2011 NEFSC standardized spring estimates for ages 1- 10+ (Table 7, Figure 9a-9b), and the 1978-2011 NEFSC standardized autumn estimates for ages 1-6 (Table 8, Figure 10). 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 after that time. Maturity was age and time invariant and knife edge maturity was assumed at age 3 as in previous EGB cod assessments. Natural mortality (M) was age and time invariant and was assumed to be 0.2 as in assessments through 2008 (Clark *et al.* 2008) and in one of two models since that time (Wang and O'Brien 2012).

Model Formulations

Run1_o3.1

The first ASAP model run (run1_o3.1) was based closely on the formulation of the recent peer-reviewed benchmark model of GB cod (NEFSC 2013b). 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 coefficient variable (CV) was initially set equal to 0.05 and the recruitment CV set equal to 0.5, however, the recruitment deviations were set with lambda=0, so that the deviations did not contribute to the objective function. The CV for each survey was initially set at the value generated from the DFO Stratified Analysis (STRANAL) software package.

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 1994-2011, although initially four blocks had been considered. The determination for these choices is described below, which is excerpted from the GB cod assessment report (NEFSC 2013b):

> *"Model estimates of selectivity at age were initially freely estimated for the surveys and the fisheries with no restriction for flat-topped or dome-shaped results. Starting with the survey selectivity, the catchability (q) for each age was initially set based on values estimated by the VPA-like ASAP. Age 7 was fixed at 1 in the DFO survey, age 6 was fixed at age 1 in the NEFSC autumn, and age 8 was fixed at 1 in the NEFSC spring survey. The results of the fit indicated that the survey catchability was essentially 'flat-topped'. The CVs associated with each estimate at age were high for ages 9 and 10+ in both the DFO and NEFSC spring survey, indicating a poor fit. The CVs for all other ages were .25 or less for all three surveys. In each survey, selectivity was estimated at 1 for other ages in addition to the age that had been fixed at 1, i.e. ages 5 and 6 in DFO, age 4 in NEFSC autumn, and age 5 and 6 in the NEFSC spring. Given these results the NEFSC spring and DFO survey selectivities were fit using a single logistic. For the autumn survey, further comparison of selectivity at age vs. logistic fit indicated better diagnostics with selectivity for age 3 fixed at 1* (see Figure 11 - this document).
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> *For the fishery selectivity, when selectivity was freely estimated for both the survey and the fishery, each of the four fishery blocks appeared to have a moderate dome. Selectivity was fixed at 1 for age 3, age 4, age 5, and age 5 in blocks 1978-1982, 1983-1993, 1994-1999, and 2000-2011, respectively. Examination of the fit statistics for the older ages indicated high CVs for ages 9 and 10+ (0.78-2.92) in all blocks and for age 8 (CV=0.79) in the 1978-1982 block. These results indicated that a flat-topped selectivity was more appropriate. When the survey selectivities were fit with a logistic and the fishery selectivity blocks were freely estimated, the fishery indicated flat-topped selectivity in the 3rd block (1994-1999) and a weak dome in the other 3 blocks, again with high CVs for the older ages. In each of the blocks selectivity was estimated at 1 for at least one age. Given these results, a logistic was fit to all 4 fishery blocks. Examination of the logistic fit of the four blocks clearly indicates only 2 blocks are appropriate given the similarities between blocks 1 and 2 (1978-1982, 1983-1993) and blocks 3 and 4 (1994-1999, and 2000-2011)* (see Figure 12 - this document). *A model with two fishery blocks (objective function (OF)=2713, 91 parameters) is more parsimonious than a 4 block model (OF=2712, 95 parameters) with only 1 point increase in the OF with 4 less parameters."*

The diagnostics of the logistic fit of the EGB fishery selectivity blocks in run1_o3.1 (Figure 13) indicated low CVs for both blocks for all four parameters:

Index	Name	Value	Std Dev	CV
1978-1993	a50	2.11	0.04	0.02
	slope	0.21	0.03	0.15
1994-2001	a50	3.36	0.12	0.03
	slope	0.50	0.04	0.08

The effective samples size (ESS) of the catch and surveys were adjusted based on interpretation of the 'Francis' plots that compare the observed mean age with the model predicted estimates (Francis 2011). The ESS estimated for the catch-at-age data (treated as multinomial) was compared to the input ESS and was adjusted iteratively until the ESS specified generally matched the mean model estimated value. The final catch-at-age ESS was set at 32 based on the stage 2 multiplier as described by Francis (2011). The CV for total catch was initially set at 0.05 but preliminary runs indicated retrospective diagnostics with two years that had a divergent solution. Increasing the catch CV=0.1 resulted in a stable solution.

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. The input ESS for the survey catch-at-age was manually adjusted until the model estimate was close to the input value. The final ESS was based on the stage 2 multiplier as described by Francis (2011) and was set for each of the surveys as: DFO=15, NEFSC autumn=10, NEFSC spring 41=15 and NEFSC spring 36=22.

Run1_o3.1_sv

This run has the same input and formulation as run1_o3.1, except that the beginning year catch weight-at-age matrix is replaced with the survey averaged (DFO, NEFSC spring) weight-at-age matrix.

Run3d

This run has the same input and formulation as run1_o3.1, with two exceptions. The catch CV was set at 0.05 instead of 0.1, and instead of adjusting the ESS of catch and survey based on the Francis (2011) method, the ESS were adjusted based on the so-called 'Ianelli' plots (McAllister and Ianelli 1997). In this method, the input ESS is compared to the model predicted ESS and an appropriate ESS is considered to be that which more or less intersects the input ESS. This formulation was in response to the low ESS for the surveys in run1o_3.1. The relatively small ESS for the autumn and DFO surveys gives these surveys minimal influence in the model results.

The catch ESS was initially set at 100 and the ESS for each survey set at 50.

Run3f

This run has the same formulation as run3d, except that the catch ESS is split and set at 75 for 1978-1995 and 125 for 1996-2011, and the survey ESS remains at 50.

Model Results

Model results, including the objective function (OF), number of parameters, components to the OF, the root mean square error (RMSE), computed from standardized residuals, and the 2011 SSB and F estimates are summarized for all runs in Table 9. Specific results of several runs are described below.

Run1_o3.1 Results

Catch

As a result of the slight increase in CV from 0.05 to 0.1 assigned to the commercial catch the model fit to the observed catch is not fit as closely in the late 1980s and early 1990s as in the other years (Figure 14). The catch age composition exhibits higher residuals in the early time period, with a pattern of negative residuals for age 3 (Figure 15). The magnitude of the input ESS are appropriate given that the predicted mean age of the catch is generally within the 95% confidence interval (CI) of the observed mean ages (Figure 16) and the RMSE (0.92) is close to 1.0 (Francis 2011).

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 (Figure 17). A pattern of negative residuals in the older age groups during 1986-1995 and in the younger ages during 2000-2011 is apparent in the age composition (Figure 18). The final DFO survey ESS was set at 15, with a RMSE=0.98 and the predicted mean age fitting well in the middle of the time series but above the observed mean age earlier in the time series (Figure 19).

The fit of the predicted indices through the NEFSC autumn survey indices did not show any strong patterning (Figure 20). The maximum residual of the age composition is the largest of the 4 surveys (Figure 21). 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 (Figure 21). The final input ESS was set at 10, with a RMSE 1.37 (Figure 22). This is the lowest ESS of all the surveys and the predicted mean age does not fit the observed mean age as closely at the beginning of the time series compared to the later years (Figure 22).

The model fit diagnostics for the NEFSC spring (Yankee #41) are presented in Figures 23-25. 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 in the mid-2000s (Figure 26). 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 (Figure 27). The input ESS was set at 22, with an RMSE of 0.98. The predicted mean age fit through almost all the observed mean age confidence intervals (Figure 28).

Fishing Mortality, SSB, and Recruitment

Fully recruited F (unweighted, ages 5+) was estimated at 0.19 in 2011 (Table 10, Figure 29), a 36% decrease from 2010. SSB in 2011 was estimated at 6,293 mt, a 7% increase from 2010 (Table 10, Figures 29-30). Recruitment (millions of age 1 fish) of the 2003 year class (3 million) is now estimated to be smaller than the 1998 year class (3.5 million), and the 2010 year class is estimated to be 5.2 million, the largest since the 1990 year class (Table 10, Figures 29-30).

Retrospective Analysis

A retrospective analysis was performed to evaluate how well ASAP calibration would have estimated F, SSB, and recruits at age 1 for seven years (2004-2010) prior to the terminal year, 2011. The pattern of overestimating SSB and underestimating F relative to the terminal year as observed in the VPA (Wang and O'Brien 2012) continues in this model (Figure 31). The retrospective rho values, the average of the last 7 years of the relative retrospective peels, were 0.723 for SSB, -0.488 for F5+, and -0.265 for recruitment. Applying a retrospective adjustment ((1/1+rho) * estimate) results in 2011 estimates of F=0.37, SSB=3,633 mt, age 1 recruitment=7.1 million fish.

Run1_o3.1_sv Results

Model diagnostics and results are the same as run1_o3 (Table 9), except for results related to biomass, given that the beginning year weight-at-age is based on survey data rather than catch data.

Beginning year biomass in 2011 was 15% lower than that in run1_o3.1, and SSB was 9% lower than that in run1_o3.1.

Run3d.1 Results

Model results are presented in Table 9. Examination of the diagnostic plots of observed versus model predicted ESS for catch indicated that the value of 100 was perhaps not sufficient to characterize the difference before and after the mid-1990s (Figure 32). The ESS appears too high from 1978-1995 and too low from 1996-2011. The ESS was modified and detailed results are described for run3f.1.

SSB is lower than in run1 and F is higher (Table 9); however, the retrospective bias is reduced in this run and ranges between -0.25-0.25 and there is little retrospective pattern.

Run3f.1 Results

Catch

The model fit to the observed catch is almost exact with the CV of 0.05 assigned to the commercial catch (Figure 33). The catch age composition exhibits larger residuals in the early time period, with a pattern of negative residuals for age 3 (Figure 34). The magnitude of the input ESS appears appropriate given that the predicted ESS generally bisects the observed ESS (Figure 35).

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 (Figure 36). A pattern of negative residuals in the older age groups during 1986-1995 and in the younger ages during 2000-2011 is apparent in the age composition (Figure 37). The final DFO survey ESS was set at 50 and appears appropriate given that the predicted ESS generally bisects the observed ESS (Figure 38).

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 3 years (Figure 39). The maximum residual of the age composition is the largest of the 4 surveys at 0.36. 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 (Figure 40). The final input ESS was set=50 and appears appropriate given that the predicted ESS generally bisects the observed ESS (Figure 41).

The model fit diagnostics for the NEFSC spring (Yankee #41) are presented in Figures 42-44. 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 (Figure 45). 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 (Figure 46). The input ESS was set=50 and appears appropriate given that the predicted ESS generally bisects the observed ESS (Figure 47).

Fishing Mortality, SSB, and Recruitment

Fully recruited F (unweighted, ages 5+) was estimated at 0.45 in 2011 (Table 11, Figure 48), a 48% decrease from 2010. SSB in 2011 was estimated at 3002 mt, a 9% decrease from 2010 (Table 11, Figures 48-49). Recruitment (millions of age 1 fish) of the 2003 year class (2.7 million) is now estimated to be smaller than the 1998 year class (3.4 million) and the 2010 year class is estimated at 2.4 million (Table 11, Figures 48-49).

Retrospective Analysis

A retrospective analysis was performed to evaluate how well ASAP calibration would have estimated F, SSB, and recruits at age 1 for seven years (2004-2010) prior to the terminal year, 2011. The pattern of overestimating SSB and underestimating F relative to the terminal year as observed in the VPA (Wang and O'Brien 2012) is not very strong in this model for F and SSB, but there is a pattern of underestimating recruitment relative to the terminal year estimate (Figure 50). The retrospective rho values, the average of the last 7 years of the relative retrospective peels, were 0.025 for SSB, -0.054 for F_{5+}, and -0.529 for age 1 recruitment. Applying a retrospective adjustment ((1/(1+rho)) * estimate) results in 2011 estimates of F=0.48, SSB=2,930 mt, age 1 recruitment=5.1 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 2,500[th] value saved. The trace of each chain's saved draws suggests good mixing for both SSB (Figure 51) and F (Figure 52). Autocorrelation plots were provided to ensure that the burn-in phase has been passed. The lagged autocorrelations showed decreased correlation with increased lag with correlations ≤0.1 beyond lag 1 for SSB and F (Figure 53), so no further burn-in was required.

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_{2011} and average F_{5+} are shown in Figures 54-56.

The 2011 SSB estimate of 3,002 mt has a 90% PI of 2,093 mt – 4,307 mt and the 2011 average F_{5+}=0.45 has a 90% PI of 0.30-0.69.

Envelope Analysis

An 'envelope analysis' is presented as a simple method to bound reasonable abundance estimates. Based on Baranov's catch equation, with swept area estimates of biomass from the NEFSC spring, NEFSC autumn, and DFO surveys, plausible assumptions are made on upper and lower bounds of catchability (q) and F to estimate population biomass for each survey. Specific details can be found in Appendix A. The upper and lower bounds of biomass from each of the surveys and the catch from the analysis indicate that the ASAP model run3f.1

results are within the bounds (at lower end of upper bounds and higher end of lower bounds) and thus is not an unreasonable estimate of biomass (Figure 57).

Biological Reference Points

Yield per Recruit Analysis

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 F from the ASAP model run3f.1. The maturity ogive is knife-edge at age 3. Results of YPR analysis are presented below, in Table 12 and Figures 58-59. 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
$F_{0.1}$	0.19
F_{max}	0.43
$F_{30\%}$	0.29
$F_{40\%}$	0.19
$F_{current}$	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 mt, SSB_{MSY}=39,353 mt (Table 13).

MSY Biological Reference Points Long-term Stochastic Projection

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 2013b), 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 (Figure 49), 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 mt (80% CI: 2,065 mt - 14,180 mt),
- SSB_{MSY} = 30,622 mt (80% CI: 25,450 mt - 84,346 mt).

Projections

Short term stochastic projections under $F_{40\%}$ were performed from the run 3f.1 model results to estimate landings and SSB during 2013-2015. The input values for mean catch and stock weights, PR, and maturity are the same as described above for the YPR analysis. Recruitment

was estimated from the 2-stage CDF described above and associated with a SSB breakpoint of 15,000 mt. Catch in 2012 was estimated based on assumption that the 2012 quota would be caught.

The results of the short term projections (Table 14) indicate under an $F_{40\%}$=0.19 catch is projected to increase each year through 2015, and SSB is also projected to increase in each year through 2015 (Table 14).

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, this meeting). 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 first and second time spawners (13% and 62%) until the third spawning (100%), suggesting that an expanded age structure of fish that have spawned three 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 *et al.* 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).

Based on model diagnostics and the lack of strong retrospective bias, run3f.1 is put forth as the preferred model. This model formulation exhibits minimal retrospective bias in F and SSB that had been prevalent in previous assessments; however, additional variability was added to the survey abundance estimates, thus placing more emphasis on the catch data.

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TABLES

Table 1a. Total catch (landings and discards) of Eastern Georges Bank cod by Canada and USA, 1978-2011.

Year	Canada Landings	Discards Scallop	Discards Groundfish	Total	USA Landings	Discards	Total	Total
1978	8,777	98		8,875	5,502		5,502	14,377
1979	5,979	103		6,082	6,408		6,408	12,490
1980	8,066	83		8,149	6,418		6,418	14,567
1981	8,508	98		8,606	8,092		8,092	16,698
1982	17,827	71		17,898	8,565		8,565	26,463
1983	12,131	65		12,196	8,572		8,572	20,769
1984	5,761	68		5,829	10,550		10,550	16,379
1985	10,442	103		10,545	6,641		6,641	17,186
1986	8,504	51		8,555	5,696		5,696	14,251
1987	11,844	76		11,920	4,793		4,793	16,713
1988	12,741	83		12,824	7,645		7,645	20,470
1989	7,895	76		7,971	6,182	100	6,282	14,253
1990	14,364	70		14,434	6,414	92	6,506	20,940
1991	13,467	65		13,532	6,353	149	6,501	20,034
1992	11,667	71		11,738	5,080	235	5,315	17,053
1993	8,526	63		8,589	4,019	69	4,088	12,677
1994	5,277	63		5,340	998	6	1,005	6,344
1995	1,102	38		1,140	543	0.3	544	1,683
1996	1,924	56		1,980	676	1	677	2,658
1997	2,919	58	428	3,405	549	6	555	3,960
1998	1,907	92	273	2,272	679	7	686	2,959
1999	1,818	85	253	2,156	1,195	13	1,207	3,364
2000	1,572	69		1,641	772	22	793	2,434
2001	2,143	143		2,286	1,488	195	1,682	3,968
2002	1,278	94		1,372	1,688	12	1,700	3,072
2003	1,317	200		1,528	1,851	105	1,955	3,483
2004	1,112	145		1,257	1,006	69	1,075	2,332
2005	630	84	144	859	171	253	424	1,282
2006	1,096	112	237	1,445	131	126	257	1,702
2007	1,108	114		1,222	234	355	589	1,811
2008	1,390	36	103	1,529	224	27	251	1,780
2009	1,003	69	137	1,209	433	194	628	1,837
2010	748	44	48	840	357	129	486	1,326
2011	702	29	13	743	267	27	294	1,037
Minimum	630	29	13	743	131	1	251	1,037
Maximum	17,827	200	428	17,898	10,550	355	10,550	26,463
Average	5,751	82	182	5,881	3,535	91	3,600	9,481

Table 1b. Catch of Eastern Georges Bank cod used in ASAP model, 1978-2011.

Year	Catch
1978	14,377
1979	12,489
1980	14,568
1981	16,700
1982	26,463
1983	20,768
1984	16,387
1985	17,188
1986	14,250
1987	16,713
1988	20,470
1989	14,237
1990	20,918
1991	19,996
1992	16,996
1993	12,663
1994	6,341
1995	1,683
1996	2,656
1997	3,958
1998	2,956
1999	3,360
2000	2,428
2001	3,919
2002	3,069
2003	3,452
2004	2,321
2005	1,229
2006	1,671
2007	1,734
2008	1,773
2009	1,789
2010	1,294
2011	1,030

Table 2. Catch-at-age (000s fish) of Eastern Georges Bank cod for ages 0-10+, 1978-2011.

Year						AGE					
	0	1	2	3	4	5	6	7	8	9	10+
1978	1.35	8.40	108.34	3643.45	1167.11	393.70	162.87	127.41	22.08	22.90	9.75
1979	1.07	15.07	889.73	734.48	1519.86	543.29	182.28	73.81	60.55	10.73	6.28
1980	2.23	6.22	972.65	1649.98	301.19	968.32	353.95	97.14	26.01	46.42	20.67
1981	3.40	35.01	860.09	1865.55	1337.20	278.68	474.58	181.01	96.29	58.63	25.39
1982	0.01	14.95	3515.80	1970.79	1269.29	1087.40	195.49	399.37	155.22	49.03	49.71
1983	10.10	22.06	783.09	2510.36	1297.08	562.35	398.06	117.87	181.92	102.47	69.53
1984	0.13	16.77	230.64	805.44	1353.79	546.23	376.65	278.87	38.73	90.25	68.53
1985	32.70	9.09	2860.82	1409.12	660.98	987.29	270.55	110.24	110.28	21.10	36.39
1986	1.24	41.49	450.71	2265.89	588.24	343.24	455.62	67.97	47.75	28.62	12.45
1987	2.28	22.15	4116.17	845.54	1148.19	163.42	132.17	174.18	40.51	23.53	11.98
1988	0.90	22.70	288.58	4189.77	680.28	855.31	129.96	116.48	182.10	52.45	37.60
1989	1.43	7.85	689.45	811.75	1983.72	227.99	373.45	56.36	39.90	58.61	27.02
1990	1.13	11.22	728.47	3111.31	1038.72	1373.70	145.36	152.81	12.29	12.33	29.90
1991	0.44	54.83	996.69	1008.42	1929.55	903.84	746.13	104.96	69.18	20.80	27.20
1992	0.00	49.04	2596.44	1378.78	462.42	888.89	313.95	314.93	45.15	34.34	11.26
1993	0.00	8.11	497.17	1898.68	909.04	298.95	359.17	132.79	96.90	25.18	19.33
1994	0.77	4.51	183.01	483.28	788.27	270.04	44.58	61.21	29.75	20.56	2.67
1995	3.23	1.15	57.27	236.66	93.94	105.13	18.41	7.03	4.02	3.62	0.28
1996	0.11	5.29	40.03	234.17	397.63	79.14	60.44	13.44	3.62	2.86	0.44
1997	0.95	7.87	146.34	206.07	358.40	358.19	83.49	37.39	13.22	3.61	1.68
1998	0.10	3.66	101.59	313.91	161.30	158.11	134.23	22.52	13.31	4.06	2.00
1999	0.13	6.42	80.00	483.91	336.90	109.18	60.57	56.73	14.11	2.45	0.79
2000	1.17	1.95	63.66	111.04	381.07	150.63	37.25	22.38	12.31	2.74	0.60
2001	1.06	3.19	94.96	524.38	210.39	398.46	104.83	31.89	17.33	6.93	1.06
2002	0.66	0.41	9.76	125.70	446.97	108.35	155.66	30.03	8.78	5.52	3.23
2003	13.12	0.00	25.08	154.02	246.11	406.06	81.87	88.96	18.87	3.98	1.72
2004	0.00	20.46	10.41	141.59	151.88	147.77	138.80	35.22	30.15	6.64	2.18
2005	0.00	0.88	67.44	44.14	204.57	52.32	31.86	38.93	10.81	5.21	1.55
2006	0.00	1.96	19.74	223.47	79.45	194.26	48.78	17.92	16.98	2.41	1.79
2007	0.01	0.83	44.04	61.50	429.79	35.31	85.73	11.72	7.23	6.52	0.59
2008	0.00	0.88	40.64	144.95	61.17	249.44	14.93	33.38	4.17	2.12	0.95
2009	0.82	0.62	50.99	205.93	138.12	41.85	136.30	9.42	10.62	1.32	0.66
2010	0.01	1.25	25.12	107.29	214.84	74.17	14.65	34.74	2.78	1.58	0.35
2011	0.00	4.50	43.71	76.82	93.27	114.74	26.22	12.14	7.26	0.23	0.24

Table 3. Mid-year catch weight at age (kg) of Eastern Georges Bank cod for ages 1-10+, 1978-2011.

Year	AGE									
	1	2	3	4	5	6	7	8	9	10+
1978	0.443	1.262	2.065	2.716	3.724	5.411	5.611	8.281	7.503	12.923
1979	0.734	1.447	1.522	3.277	4.451	6.591	9.413	9.620	9.861	14.388
1980	0.380	1.243	2.211	3.068	4.956	6.285	7.219	11.457	10.411	13.455
1981	0.523	1.277	1.989	3.064	4.537	6.499	8.024	9.245	11.618	15.930
1982	0.556	1.303	2.134	3.614	5.012	6.756	8.513	9.861	11.859	16.025
1983	0.900	1.488	2.215	3.100	4.599	6.098	7.805	10.155	11.471	15.038
1984	0.678	1.605	2.308	3.422	4.765	6.086	8.304	9.354	11.161	13.623
1985	0.536	1.317	1.810	3.185	4.550	5.945	7.909	9.603	10.755	13.771
1986	0.538	1.357	2.425	3.304	4.829	6.701	8.084	9.196	11.378	12.261
1987	0.581	1.459	2.379	3.928	5.376	7.229	8.760	9.458	11.274	13.801
1988	0.622	1.172	2.188	3.075	4.913	6.096	8.267	9.890	11.144	13.714
1989	0.383	1.263	1.959	3.345	4.888	6.017	6.790	9.804	10.697	13.842
1990	0.670	1.550	2.376	3.222	4.595	6.044	7.797	9.811	11.193	13.413
1991	0.729	1.515	2.415	3.138	4.235	5.530	7.452	9.457	9.182	13.808
1992	0.894	1.405	2.279	3.306	4.242	5.665	6.795	8.660	11.215	15.044
1993	0.644	1.398	2.105	2.840	4.291	5.403	6.755	8.286	9.140	11.983
1994	0.589	1.330	2.142	3.436	4.392	6.420	7.188	8.152	7.963	12.460
1995	0.322	1.318	2.123	3.350	4.938	6.380	10.095	10.008	10.434	17.709
1996	0.505	1.419	2.168	3.046	4.705	5.829	6.419	8.957	10.352	10.850
1997	0.648	1.426	2.057	2.923	3.862	5.363	7.260	8.306	11.486	11.091
1998	0.690	1.334	2.146	2.979	3.971	5.327	6.590	7.820	10.233	13.602
1999	0.568	1.285	1.973	3.098	3.910	5.483	6.271	7.540	9.376	13.987
2000	0.585	1.320	1.959	2.895	4.016	4.702	5.717	6.775	8.376	13.254
2001	0.208	0.907	1.823	2.742	3.577	4.871	5.220	7.276	8.650	10.681
2002	0.343	1.197	1.956	2.843	4.013	4.885	6.411	8.229	7.977	11.142
2003	*0.285*	1.155	2.089	2.693	3.527	4.217	5.467	6.839	7.630	8.731
2004	0.227	1.225	1.822	2.769	3.459	4.559	5.234	7.245	8.541	9.871
2005	0.181	0.840	1.395	2.296	3.496	4.426	4.817	6.807	7.982	9.140
2006	0.086	0.591	1.750	2.315	3.291	4.226	6.124	5.807	6.846	7.502
2007	0.297	0.960	1.569	2.293	2.993	3.888	6.053	6.837	6.895	9.431
2008	0.130	1.231	2.198	2.776	3.638	5.004	5.824	7.916	7.971	9.085
2009	0.172	1.250	1.909	3.052	3.630	4.500	5.726	6.695	10.000	10.910
2010	0.419	1.152	1.974	2.512	3.383	3.432	5.100	6.075	8.805	11.265
2011	0.249	1.017	1.715	2.551	3.513	4.279	4.227	6.063	9.853	9.627

Table 4. Beginning year catch weight-at-age (kg) of Eastern Georges Bank cod estimated from mid-year weight-at-age for ages 1-10+, 1978-2011.

Year	AGE									
	1	2	3	4	5	6	7	8	9	10+
1978	0.245	1.149	1.639	2.122	2.799	4.103	4.285	7.589	7.882	12.923
1979	0.564	0.801	1.386	2.601	3.477	4.954	7.137	7.347	9.037	14.388
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	7.102	8.169	11.537	15.930
1982	0.340	0.826	1.651	2.681	3.919	5.536	7.438	8.895	10.471	16.025
1983	0.674	0.910	1.699	2.572	4.077	5.528	7.262	9.298	10.636	15.038
1984	0.487	1.202	1.853	2.753	3.843	5.291	7.116	8.545	10.646	13.623
1985	0.337	0.945	1.704	2.711	3.946	5.322	6.938	8.930	10.030	13.771
1986	0.327	0.853	1.787	2.446	3.922	5.522	6.933	8.528	10.453	12.261
1987	0.409	0.886	1.797	3.086	4.215	5.908	7.662	8.744	10.182	13.801
1988	0.437	0.825	1.787	2.705	4.393	5.725	7.731	9.308	10.266	13.714
1989	0.190	0.886	1.515	2.705	3.877	5.437	6.434	9.003	10.286	13.842
1990	0.446	0.771	1.732	2.512	3.921	5.435	6.849	8.162	10.476	13.413
1991	0.525	1.008	1.935	2.731	3.694	5.041	6.711	8.587	9.491	13.808
1992	0.715	1.012	1.858	2.826	3.649	4.898	6.130	8.033	10.299	15.044
1993	0.448	1.118	1.720	2.544	3.766	4.787	6.186	7.504	8.897	11.983
1994	0.394	0.926	1.731	2.689	3.532	5.249	6.232	7.421	8.123	12.460
1995	0.153	0.881	1.680	2.679	4.119	5.294	8.051	8.482	9.223	17.709
1996	0.301	0.676	1.690	2.543	3.970	5.365	6.400	9.509	10.179	10.850
1997	0.452	0.849	1.709	2.517	3.430	5.023	6.505	7.302	10.143	11.091
1998	0.506	0.930	1.749	2.475	3.407	4.536	5.945	7.535	9.219	13.602
1999	0.373	0.942	1.622	2.578	3.413	4.666	5.780	7.049	8.563	13.987
2000	0.470	0.866	1.587	2.390	3.527	4.288	5.599	6.518	7.947	13.254
2001	0.087	0.728	1.551	2.318	3.218	4.423	4.954	6.450	7.655	10.681
2002	0.187	0.499	1.332	2.277	3.317	4.180	5.588	6.554	7.618	11.142
2003	0.138	0.629	1.581	2.295	3.167	4.114	5.168	6.622	7.924	8.731
2004	0.118	0.591	1.451	2.405	3.052	4.010	4.698	6.294	7.643	9.871
2005	0.100	0.437	1.307	2.045	3.111	3.913	4.686	5.969	7.605	9.140
2006	0.026	0.327	1.212	1.797	2.749	3.844	5.206	5.289	6.827	7.502
2007	0.146	0.287	0.963	2.003	2.632	3.577	5.058	6.471	6.328	9.431
2008	0.042	0.605	1.453	2.087	2.888	3.870	4.759	6.922	7.382	9.085
2009	0.067	0.403	1.533	2.590	3.174	4.046	5.353	6.244	8.897	10.910
2010	0.269	0.445	1.571	2.190	3.213	3.530	4.791	5.898	7.678	11.265
2011	0.095	0.653	1.406	2.244	2.971	3.805	3.809	5.561	7.737	9.627

Table 5. Beginning year weight-at-age (kg) of Eastern Georges Bank cod estimated from the average of the DFO and NEFSC spring research survey weight-at-age for ages 1-10+, 1970-2011. The age 10+ values are derived as an average from the catch number weighted fishery weight at age. The 2012 weight at age 9 is based on regression, because only one fish sample was available.

Year	Age 1	Age 2	Age 3	Age 4	Age 5	Age 6	Age 7	Age 8	Age 9	Age 10+
1978	0.112	0.886	1.624	3.564	5.414	6.247	8.626	8.973	10.226	14.635
1979	0.112	0.868	1.740	2.995	4.565	5.188	9.629	10.885	10.976	14.635
1980	0.276	0.706	1.892	2.786	5.244	6.281	5.919	8.973	11.762	14.635
1981	0.095	0.852	1.826	3.342	4.971	6.862	8.184	12.712	11.262	14.635
1982	0.092	0.869	2.219	3.050	4.114	6.427	8.061	8.828	10.776	14.635
1983	0.224	1.131	1.871	2.263	3.132	6.011	8.153	8.653	10.525	14.635
1984	0.050	0.582	1.954	2.443	2.699	4.121	5.890	8.973	10.279	14.635
1985	0.087	0.646	1.926	3.205	3.781	5.834	8.771	9.866	14.114	14.635
1986	0.131	0.770	1.742	3.217	4.920	5.698	7.439	8.988	10.684	14.635
1987	0.150	0.845	1.701	2.686	5.672	7.487	7.480	6.659	10.100	14.635
1988	0.152	0.931	1.785	3.020	4.169	6.268	8.438	8.724	12.330	14.635
1989	0.142	0.832	1.705	2.759	4.306	6.432	7.615	7.813	11.320	14.635
1990	0.215	0.787	1.843	2.899	4.362	6.003	8.589	9.518	13.493	14.635
1991	0.088	0.897	1.952	3.167	4.243	4.895	7.544	10.059	9.973	14.635
1992	0.127	0.846	2.045	2.793	4.163	6.127	6.979	8.555	9.906	14.635
1993	0.070	0.955	1.845	2.907	4.513	5.889	6.999	7.383	9.279	14.635
1994	0.143	0.657	1.433	2.629	3.954	7.458	7.330	8.661	8.871	14.635
1995	0.183	0.794	1.587	2.245	3.474	4.697	6.692	7.920	11.886	14.635
1996	0.088	0.838	1.553	2.597	3.908	6.112	5.458	12.028	11.920	14.635
1997	0.190	0.717	1.694	2.176	3.218	6.200	6.204	9.796	10.174	14.635
1998	0.078	0.650	1.382	2.258	3.034	4.516	5.831	7.787	8.211	14.635
1999	0.111	1.001	1.350	2.237	2.973	4.635	6.513	8.250	8.448	14.635
2000	0.060	0.896	1.587	2.326	3.234	4.461	6.501	8.211	11.523	14.635
2001	0.010	0.771	1.418	2.584	3.602	5.089	6.909	7.552	10.254	11.653
2002	0.016	0.495	1.214	2.269	3.538	4.385	5.856	8.436	10.001	11.653
2003	0.016	0.441	1.141	1.882	3.046	3.361	5.120	6.702	7.661	11.653
2004	0.022	0.288	1.454	2.447	3.449	4.086	4.312	6.320	10.535	11.653
2005	0.058	0.589	1.167	1.770	2.972	3.297	3.936	7.655	6.448	11.653
2006	0.031	0.307	1.151	1.574	2.621	3.182	4.615	4.684	5.729	11.653
2007	0.054	0.625	1.073	1.764	2.622	4.098	5.789	6.810	7.981	11.653
2008	0.046	0.577	1.450	2.041	2.504	3.465	4.165	7.931	10.050	11.653
2009	0.114	0.724	1.470	2.482	2.701	3.527	4.479	5.594	8.667	11.653
2010	0.079	0.657	1.575	2.214	3.194	3.501	3.963	5.380	7.284	11.653
2011	0.038	0.482	1.193	2.036	2.709	3.581	3.670	4.484	5.080	11.653
2012	0.027	0.512	1.181	2.130	2.889	3.771	5.106	6.329	5.302	11.653

Table 6. Swept area abundance estimates of Eastern Georges Bank cod in the Canadian Department of Fisheries and Oceans (DFO) Georges Bank research bottom trawl survey, 1986-2012.

Year	AGE													
	0	1	2	3	4	5	6	7	8	9	10	11	12	13
1986	0.0	770.5	3538.5	3204.4	331.3	691.6	445.1	219.2	35.0	65.6	0.0	10.2	0.0	0.0
1987	0.0	48.2	1790.7	642.0	753.4	162.3	89.3	181.2	88.9	13.4	13.4	0.0	13.4	15.6
1988	0.0	147.9	449.9	5336.8	564.6	838.2	95.1	78.5	179.3	18.0	12.0	3.9	0.0	16.4
1989	0.0	350.1	2168.7	764.2	1705.5	258.3	332.0	41.7	84.7	111.7	5.3	32.2	8.0	5.2
1990	20.1	105.7	794.8	3471.2	1953.0	4402.1	535.2	1094.1	144.3	156.8	288.8	65.0	52.0	36.8
1991	0.0	1197.6	1019.4	1407.7	1639.5	881.6	1194.8	147.6	249.5	38.2	45.4	30.2	12.3	4.6
1992	0.0	47.5	2049.1	1220.8	409.1	643.4	451.2	300.3	92.6	38.0	0.0	3.2	3.3	17.8
1993	0.0	31.0	354.9	1722.9	621.5	370.3	754.0	274.4	267.6	50.9	31.4	0.0	19.6	5.6
1994	0.0	12.5	629.2	691.3	1288.8	476.7	181.9	363.4	84.0	118.9	11.9	0.0	0.0	0.0
1995	0.0	32.1	187.3	1240.1	756.6	520.0	186.3	43.8	66.9	28.5	17.7	7.5	5.9	0.0
1996	0.0	90.1	202.9	1744.3	4336.8	1432.0	1033.9	445.1	107.1	149.4	38.6	4.1	0.0	0.0
1997	0.0	29.8	375.9	568.0	1324.8	1261.6	216.4	50.4	34.6	23.1	17.0	0.0	3.3	0.0
1998	0.0	6.0	582.0	830.6	322.4	316.9	237.6	56.0	28.6	6.7	8.4	2.8	4.2	0.0
1999	0.0	3.4	156.2	1297.8	1090.5	449.2	317.4	190.5	9.9	28.2	5.2	8.9	0.0	3.5
2000	0.0	0.0	423.0	1294.3	4967.1	2156.6	1031.3	509.8	317.0	19.9	22.7	12.2	0.0	0.0
2001	0.0	3.3	36.5	802.5	519.3	1390.6	644.8	334.0	224.4	224.8	36.4	23.7	7.4	0.0
2002	0.0	0.0	118.3	476.5	2097.5	694.2	1282.6	458.1	188.4	63.4	76.4	7.0	0.0	0.0
2003	0.0	0.0	8.0	199.5	509.5	867.1	193.9	219.3	68.9	11.9	0.0	0.0	0.0	0.0
2004	0.0	427.0	39.8	246.4	380.5	422.0	353.2	59.1	108.0	24.7	5.1	0.0	3.2	0.0
2005	0.0	25.1	1024.7	1398.4	7149.1	1766.5	816.2	742.6	60.3	87.3	8.1	3.8	0.0	0.0
2006	0.0	0.0	41.4	1500.2	672.8	1779.2	757.1	217.4	216.1	82.6	34.0	9.5	14.5	0.0
2007	0.0	18.1	130.1	548.5	2605.6	378.9	652.9	119.0	81.4	52.8	0.0	3.7	0.0	0.0
2008	0.0	12.3	147.1	1026.6	754.6	2977.5	193.7	392.0	41.2	4.4	19.6	0.0	0.0	0.0
2009	0.0	10.9	51.0	2486.9	2261.1	519.2	2955.5	0.0	81.6	0.0	0.0	0.0	17.6	0.0
2010	0.0	4.6	91.9	955.8	4105.4	1781.2	702.8	1827.7	64.6	83.8	4.9	0.0	0.0	0.0
2011	0.0	192.5	271.4	766.2	951.9	1323.8	255.8	67.2	112.1	14.4	7.9	1.6	0.0	0.0
2012	0.0	0.0	149.4	326.7	315.0	195.0	158.2	6.8	18.2	4.1	0.0	0.0	0.0	0.0

Table 7. Swept area aboundance estimates of Eastern Georges Bank cod in the Northeast Fisheries Science Center (NEFSC) spring research bottom trawl survey, 1978-2012.

Year						AGE						
	0	1	2	3	4	5	6	7	8	9	10	11
1978	372.6	187.1	0.0	2825.0	614.5	916.3	153.2	787.0	62.2	43.4	39.6	0.0
1979	71.3	338.9	1332.1	121.7	1429.9	542.5	176.3	90.6	130.4	0.0	0.0	0.0
1980	0.0	11.5	2251.1	2168.4	168.8	1983.5	409.8	78.4	47.5	31.4	0.0	46.7
1981	282.8	1955.5	1311.2	2005.9	1093.0	42.5	452.6	196.7	58.9	0.0	0.0	0.0
1982	44.5	454.9	6642.0	13613.7	12666.6	9405.8	0.0	3087.7	991.6	119.6	0.0	0.0
1983	0.0	388.7	2016.8	3780.7	779.2	608.1	315.0	105.6	97.9	0.0	70.4	0.0
1984	0.0	103.4	116.8	343.8	482.8	91.7	182.3	74.0	18.4	104.8	0.0	0.0
1985	57.5	36.3	2032.2	633.5	1061.2	1517.9	327.5	217.4	213.1	82.7	116.1	33.9
1986	97.0	619.3	339.2	1131.9	298.3	426.5	536.4	20.3	108.8	141.7	0.0	0.0
1987	0.0	0.0	1194.1	246.8	567.7	0.0	152.3	148.3	30.5	54.1	0.0	0.0
1988	137.6	319.8	242.8	2794.7	274.0	461.5	51.3	4.9	67.3	0.0	0.0	9.8
1989	0.0	173.8	1237.9	338.3	1684.6	234.3	395.7	99.4	12.0	36.1	48.1	24.1
1990	24.1	45.4	360.3	1686.7	586.4	633.8	152.5	164.5	18.6	0.0	0.0	24.1
1991	216.5	725.0	620.0	514.1	902.6	459.7	381.6	44.1	17.1	0.0	24.1	52.6
1992	0.0	80.5	665.5	349.3	102.9	261.1	152.0	158.9	27.4	52.1	0.0	0.0
1993	0.0	0.0	462.1	1283.7	262.2	45.7	182.2	45.6	43.1	45.9	12.0	0.0
1994	38.3	53.8	193.7	151.9	185.3	44.3	11.4	33.3	0.0	7.7	0.0	0.0
1995	383.9	69.8	293.6	927.1	495.3	932.4	191.3	253.1	0.0	67.7	0.0	0.0
1996	0.0	139.3	300.3	990.4	1342.7	121.4	93.6	28.3	0.0	0.0	0.0	0.0
1997	270.5	54.1	218.1	47.8	401.8	518.6	53.1	126.0	57.1	0.0	0.0	0.0
1998	54.1	0.0	1039.6	1985.2	995.1	983.4	609.5	30.5	31.4	0.0	0.0	0.0
1999	21.6	22.1	144.6	673.4	623.5	369.6	172.5	106.6	33.8	7.9	0.0	0.0
2000	36.1	0.0	304.0	642.7	1348.5	491.6	137.8	52.1	19.6	0.0	0.0	0.0
2001	0.0	0.0	64.2	889.4	95.8	349.6	108.9	0.0	11.8	9.8	0.0	0.0
2002	36.1	0.0	120.6	470.3	1081.0	175.0	214.5	60.9	0.0	0.0	0.0	0.0
2003	0.0	0.0	124.6	286.7	812.5	1154.0	134.7	77.7	9.2	0.0	0.0	0.0
2004	0.0	549.1	9.8	838.4	2091.1	2105.1	1350.9	238.8	382.4	29.0	0.0	0.0
2005	36.1	14.7	345.4	69.8	747.4	286.8	190.3	130.8	33.8	0.0	0.0	0.0
2006	0.0	36.8	73.2	951.6	411.4	1007.4	340.4	150.6	79.0	0.0	0.0	0.0
2007	0.0	0.0	369.2	308.0	2258.5	239.0	291.2	46.8	27.8	0.0	0.0	0.0
2008	43.3	36.9	112.2	675.1	372.0	1385.2	50.9	65.6	0.0	0.0	0.0	0.0
2009	0.0	60.7	85.8	874.9	408.1	219.4	377.1	24.0	12.0	15.5	0.0	0.0
2010	0.0	25.2	126.5	366.7	667.3	167.8	44.0	146.8	0.0	11.6	0.0	0.0
2011	0.0	87.6	163.7	163.7	265.9	144.3	55.9	9.3	23.9	0.0	0.0	0.0
2012	0.0	0.0	279.6	413.2	545.3	188.1	122.9	14.2	0.0	0.0	0.0	0.0

Table 8. Swept area abundance estimates of Eastern Georges Bank cod in the Northeast Fisheries Science Center (NEFSC) fall research bottom trawl survey, 1978-2011.

Year	AGE										
	0	1	2	3	4	5	6	7	8	9	10+
1978	112.6	1518.9	57.7	3026.6	417.4	57.5	62.9	76.8	0.0	0.0	0.0
1979	182.2	1704.0	1694.7	115.6	1521.8	242.6	47.9	19.8	10.5	17.8	0.0
1980	315.1	781.7	409.2	648.9	21.7	184.5	14.0	17.1	20.2	0.0	0.0
1981	360.3	2351.7	1208.4	933.4	269.2	14.9	28.8	0.0	0.0	0.0	53.3
1982	0.0	548.6	718.0	53.7	59.0	0.0	0.0	26.7	0.0	0.0	0.0
1983	948.1	72.7	266.9	566.6	24.0	7.7	7.7	0.0	23.0	0.0	0.0
1984	28.7	1804.6	120.3	690.4	1024.8	23.3	32.5	0.0	0.0	9.1	0.0
1985	1245.2	209.1	993.2	161.5	18.2	4.6	9.2	0.0	0.0	0.0	4.4
1986	118.9	3017.7	55.7	197.6	0.0	0.0	5.9	0.0	0.0	0.0	0.0
1987	155.5	129.2	844.8	120.8	99.5	0.0	0.0	0.0	0.0	0.0	0.0
1988	94.8	560.7	177.2	1181.8	162.7	206.5	0.0	29.5	40.6	10.2	0.0
1989	317.9	570.1	1334.6	221.9	606.9	78.5	24.1	0.0	0.0	0.0	0.0
1990	197.6	402.7	441.8	830.8	119.9	204.0	20.5	0.0	15.0	0.0	0.0
1991	0.0	157.9	60.5	70.6	9.7	23.7	0.0	0.0	0.0	0.0	0.0
1992	0.0	205.2	726.0	153.9	0.0	36.8	12.3	0.0	0.0	0.0	0.0
1993	0.0	80.7	104.3	158.2	19.0	0.0	0.0	0.0	0.0	0.0	0.0
1994	9.8	78.5	281.9	219.7	142.9	12.9	25.8	0.0	0.0	0.0	0.0
1995	222.8	27.7	122.4	303.8	65.8	29.4	7.4	0.0	0.0	0.0	0.0
1996	9.8	290.6	75.6	292.8	210.9	53.3	28.3	0.0	0.0	0.0	0.0
1997	0.0	160.6	394.2	181.1	58.1	83.9	29.4	0.0	0.0	0.0	0.0
1998	0.0	170.9	683.6	480.3	65.3	108.6	0.0	0.0	29.4	0.0	0.0
1999	0.0	14.7	14.3	249.5	123.7	31.9	0.0	0.0	0.0	0.0	0.0
2000	30.5	55.0	204.4	68.2	89.2	45.8	0.0	0.0	0.0	0.0	0.0
2001	24.5	73.6	105.6	256.7	37.8	75.0	12.3	12.3	0.0	0.0	0.0
2002	121.8	110.3	634.5	712.3	2498.5	170.3	211.3	16.7	0.0	0.0	0.0
2003	75.6	0.0	23.9	100.3	70.1	17.4	0.0	5.8	0.0	0.0	0.0
2004	108.5	422.0	68.0	840.1	385.5	544.9	436.1	102.9	30.5	0.0	30.5
2005	21.2	29.4	507.5	114.4	251.0	42.6	0.0	9.8	0.0	0.0	0.0
2006	0.0	145.7	123.0	529.7	37.0	262.9	16.0	16.0	16.0	16.0	0.0
2007	60.4	22.1	135.9	7.4	68.7	0.0	7.4	0.0	0.0	0.0	0.0
2008	0.0	73.6	169.6	55.3	15.2	97.6	15.1	15.2	0.0	0.0	0.0
2009	53.9	36.8	194.4	280.1	39.2	17.7	11.0	0.0	0.0	0.0	0.0
2010	433.6	27.1	79.3	73.9	121.3	20.1	0.0	0.0	0.0	0.0	0.0
2011	126.1	599.5	472.0	260.0	176.6	110.3	31.7	0.0	0.0	0.0	0.0

Table 9. ASAP model diagnostics and results for four model formulations: number of parameters, 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), effective sample size (ESS), and the spawning stock biomass (SSB 2011) and unweighted fishing mortality of ages 5+ (F2011 for terminal year 2011).

Model		1o_3.1	1o_3_sv	3d	3f.1
number of parameters		94	94	94	94
objective function		2120.49	2120.49	2997.61	2967.13
components of					
obj. function	catch total	250.115	250.115	225.98	225.948
	index fit total	829.993	829.993	842.94	842.41
	catch age composition	334.555	334.555	572.93	551.534
		0	0	0.00	0
	Index age composition	705.828	705.828	1355.75	1347.24
	Recruit deviations	0	0	0	0
RMSE	Catch fleet	0.34	0.34	0.28	0.28
	total catch	0.34	0.34	0.28	0.28
	discards	0.00	0.00	0.00	0.00
	total discards	0.00	0.00	0.00	0.00
	DFO	1.14	1.14	1.35	1.34
	Autumn	1.20	1.20	1.27	1.27
	Spring 41	0.77	0.77	0.77	0.76
	Spring 36	1.23	1.23	1.32	1.32
	Index total	1.18	1.18	1.29	1.29
CV	catch	0.01	0.01	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 #26	0.3+	0.3+	0.3+	0.3+
ESS	catch	32	32	100	75/125('96)
	dfo	15	15	50	50
	fall	10	10	50	50
	41	15	15	50	50
	36	22	22	50	50
Jan 1 biomass		8425	7139		4140
SSB 2011 (mt)		6292	5668	3124	3002
SSB 2001 retro bias adj		3633			2930
F 2011 (age 5+)		0.19	0.19	0.43	0.45
F 2011 retro bias adj.		0.37			0.48
2011 age 1 (millions,2010 yc)		5.21			2.41
2011 age 1 retro bias adj.		7.1			5.12

*Table 10. ASAP model **run1_o3.1** results for January 1 biomass, spawning stock biomass (SSB), fishing mortality (ages 5+), and recruitment (age1, 000s fish), 1978-2011.*

Year	Jan1 Biomass	SSB	F	Recruitment
1978	40,015	31,306	0.43	11,422
1979	45,785	29,304	0.35	10,957
1980	50,043	36,043	0.37	9,116
1981	52,910	37,618	0.43	18,048
1982	55,271	35,165	0.68	6,909
1983	47,069	34,539	0.60	3,724
1984	42,260	28,311	0.57	13,207
1985	35,911	20,333	0.79	5,138
1986	35,323	20,540	0.64	24,938
1987	41,690	18,413	0.59	6,462
1988	47,337	32,208	0.64	13,675
1989	38,918	25,106	0.46	5,300
1990	40,561	29,802	0.64	6,597
1991	37,505	21,924	0.90	10,969
1992	28,236	14,312	0.99	2,423
1993	19,205	12,508	1.13	3,120
1994	10,998	6,327	1.47	2,047
1995	8,371	6,231	0.40	1,254
1996	9,838	7,617	0.49	2,598
1997	11,296	6,839	0.83	3,513
1998	10,673	6,619	0.66	1,249
1999	11,334	8,141	0.67	3,525
2000	11,197	7,272	0.43	1,605
2001	10,728	8,576	0.73	1,125
2002	8,791	7,233	0.53	1,651
2003	8,086	6,226	0.78	452
2004	6,192	4,986	0.67	2,995
2005	5,108	3,632	0.42	562
2006	5,425	4,774	0.53	1,252
2007	5,464	4,369	0.52	2,145
2008	6,078	4,501	0.47	1,465
2009	6,918	5,805	0.45	1,445
2010	7,490	5,897	0.30	2,345
2011	8,425	6,293	0.19	5,209

*Table 11. ASAP model **run3f.1** results for January 1 biomass, spawning stock biomass (SSB), fishing mortality (ages 5+), and recruitment (age1, 000s fish), 1978-2011.*

Year	Jan1 Biomass	SSB	F	Recruitment
1978	38,611	30,442	0.45	10,974
1979	43,743	27,797	0.37	10,604
1980	47,327	33,661	0.39	9,160
1981	50,234	34,567	0.46	19,425
1982	52,866	31,890	0.73	7,460
1983	45,468	32,716	0.62	3,638
1984	41,529	27,345	0.60	13,814
1985	35,308	19,181	0.84	5,436
1986	35,282	19,861	0.66	26,309
1987	42,263	17,998	0.60	6,512
1988	48,457	32,994	0.64	14,064
1989	39,958	25,684	0.46	5,782
1990	41,795	30,486	0.65	6,862
1991	38,904	22,640	0.91	11,500
1992	29,250	14,665	1.03	2,492
1993	19,563	12,729	1.15	3,056
1994	10,990	6,341	1.55	1,963
1995	8,140	6,070	0.42	1,231
1996	9,554	7,355	0.51	2,610
1997	11,007	6,568	0.85	3,514
1998	10,455	6,420	0.69	1,233
1999	11,099	7,964	0.69	3,446
2000	10,956	7,128	0.44	1,544
2001	10,483	8,387	0.75	1,079
2002	8,525	7,019	0.55	1,524
2003	7,745	5,965	0.82	405
2004	5,748	4,622	0.74	2,565
2005	4,528	3,229	0.47	454
2006	4,635	4,046	0.63	993
2007	4,400	3,488	0.65	1,520
2008	4,498	3,289	0.66	903
2009	4,622	3,788	0.74	791
2010	4,257	3,291	0.58	1,166
2011	4,140	3,002	0.45	2,412

*Table 12. ASAP model **run3f.1** Yield per recruit (YPR) and fishing mortality (F) at percent spawning potential ratio (%SPR) targets.*

SPR Target Refeence Points (Years Avg = 5)

% SPR	F(%SPR)	YPR
0.2	0.4909	1.3331
0.25	0.3703	1.3318
0.3	0.292	1.3097
0.35	0.2362	1.2706
0.4	0.1941	1.2175
0.45	0.1608	1.1526
0.5	0.1336	1.0778
0.55	0.1109	0.9945
0.6	0.0917	0.904
0.65	0.075	0.807
0.7	0.0604	0.7044
0.75	0.0475	0.5968
0.8	0.036	0.4847

*Table 13. ASAP model **run3f.1** biomass reference points based on yield per recruit (YPR) and spawner per recruit estimates at $F_{40\%}$.*

Model	YPR
$F_{40\%}$	0.19
Y/R	1.22
SSB / R	7.18
Recruitment (000s)	5,484
SSB_{MSY} (mt)	39,353
MSY (mt)	6,677

*Table 14. ASAP model **run3f.1** projection of spawning stock biomass (SSB), fishing mortality(F), and catch (mt) during 2013-2015 assuming quota taken in 2012 and fishing under $F_{40\%}$.*

Year	SSB	F	Catch
2012	3,413	0.21	675
2013	5,270	0.19	840
2014	5,209	0.19	993
2015	6,092	0.19	1,077

FIGURES
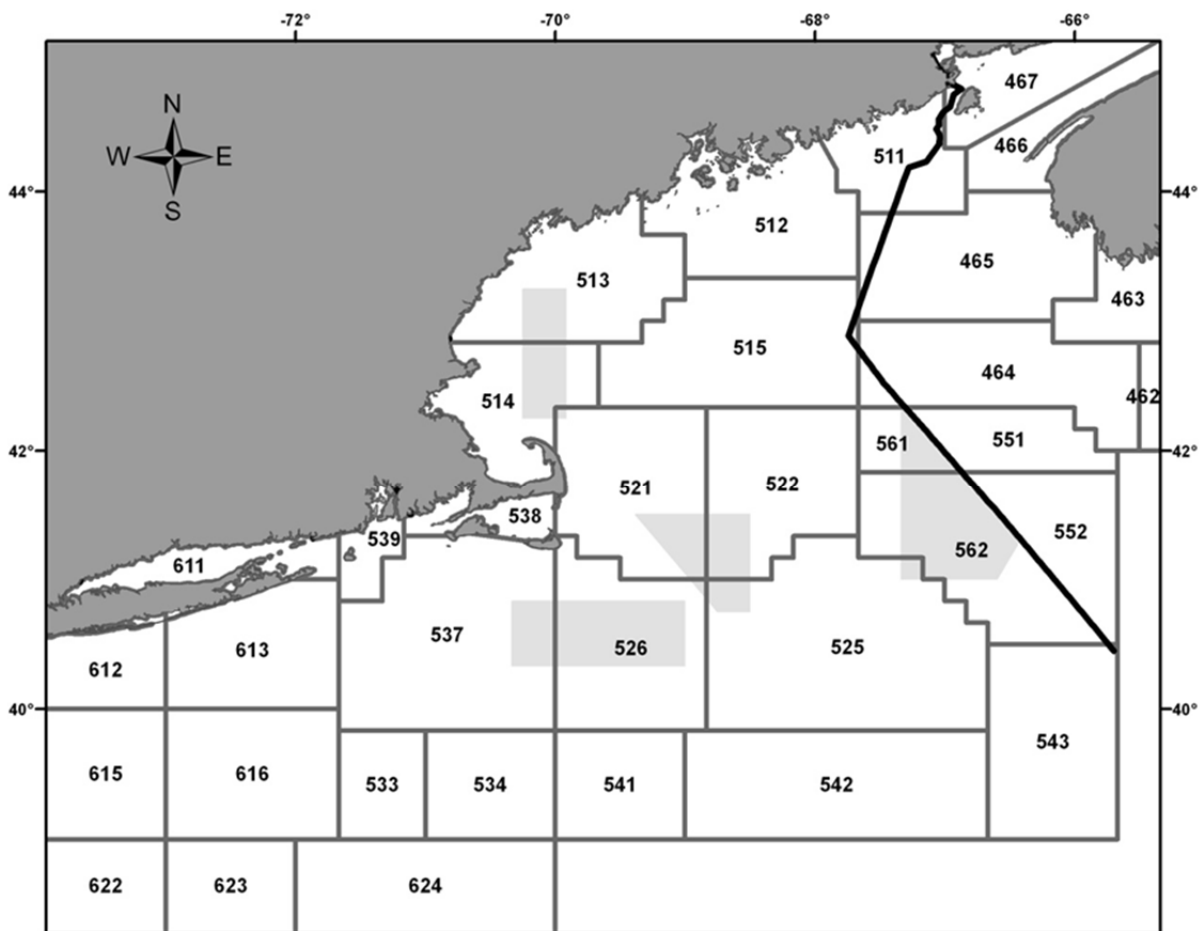
Figure 1. USA statistical areas (SA) for the Gulf of Maine (NAFO Division 5Y; SA 511-515) and Georges Bank (NAFO Division 5Z; SA 521-525, 551-552,561-562) and south (NAFO Subarea 6).
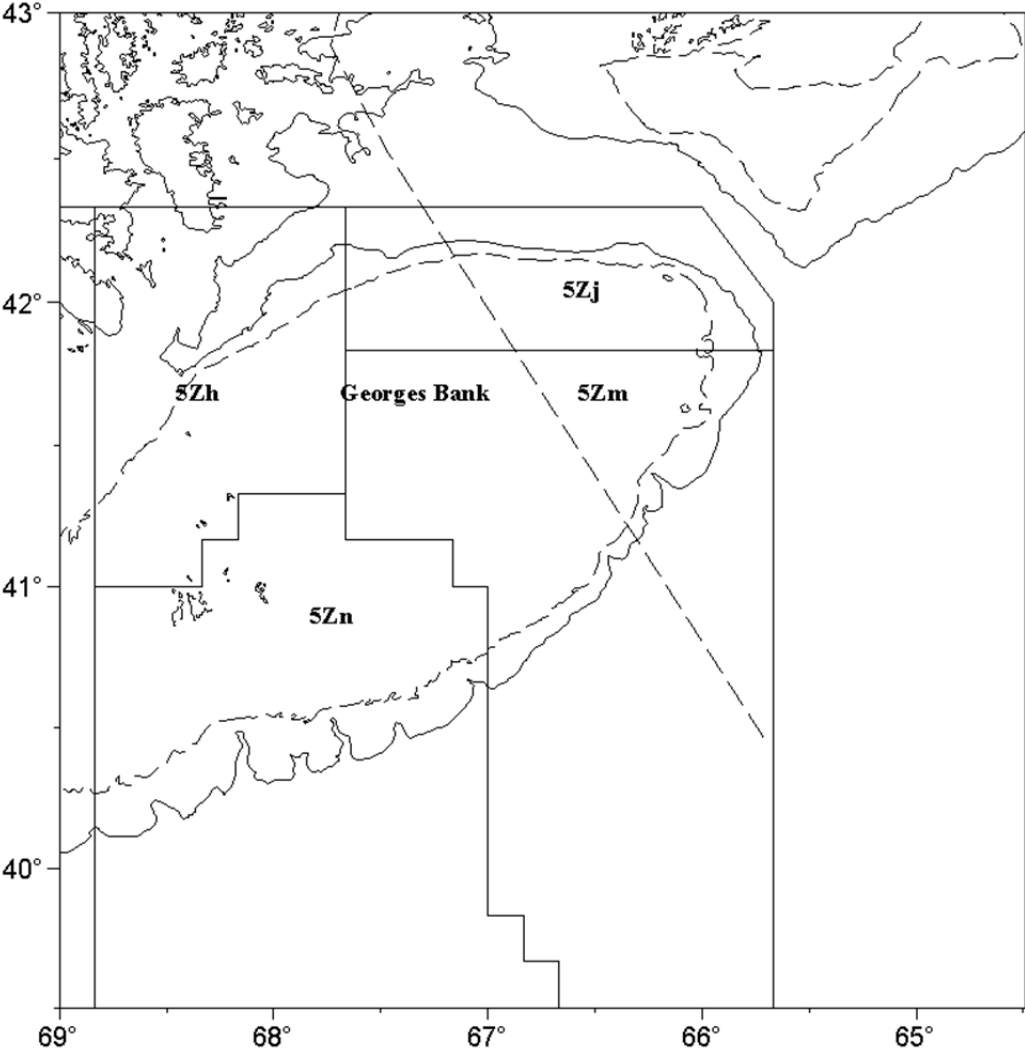
Figure 2. Canadian Department of Fisheries and Oceans statistical areas (SA) for Georges Bank (NAFO Subdivision 5Ze; SA 5Zj, 5Zm, 5Zn, 5Zh).
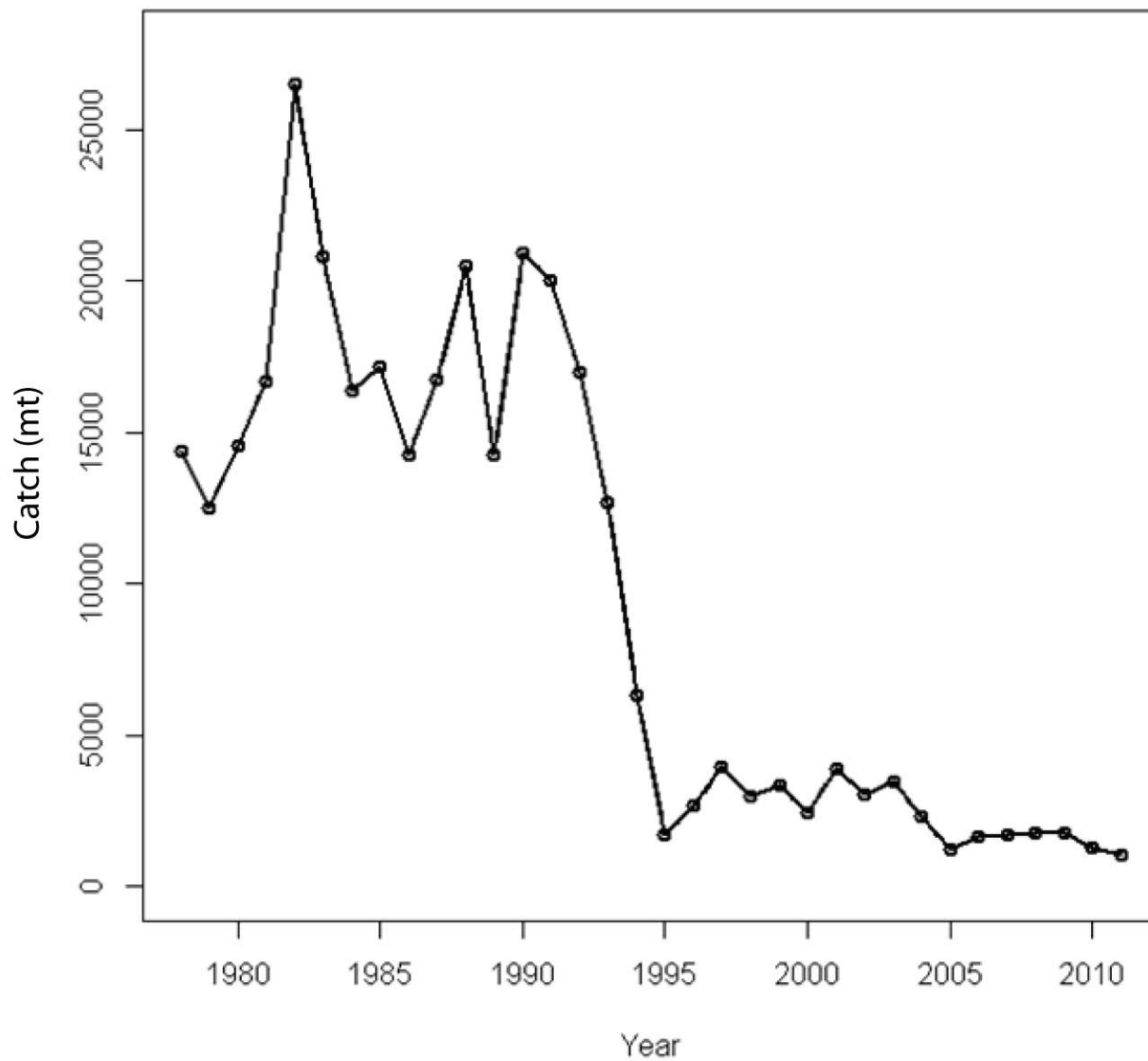
Figure 3. Catch of Eastern Georges Bank cod used in ASAP model, 1978-2011.
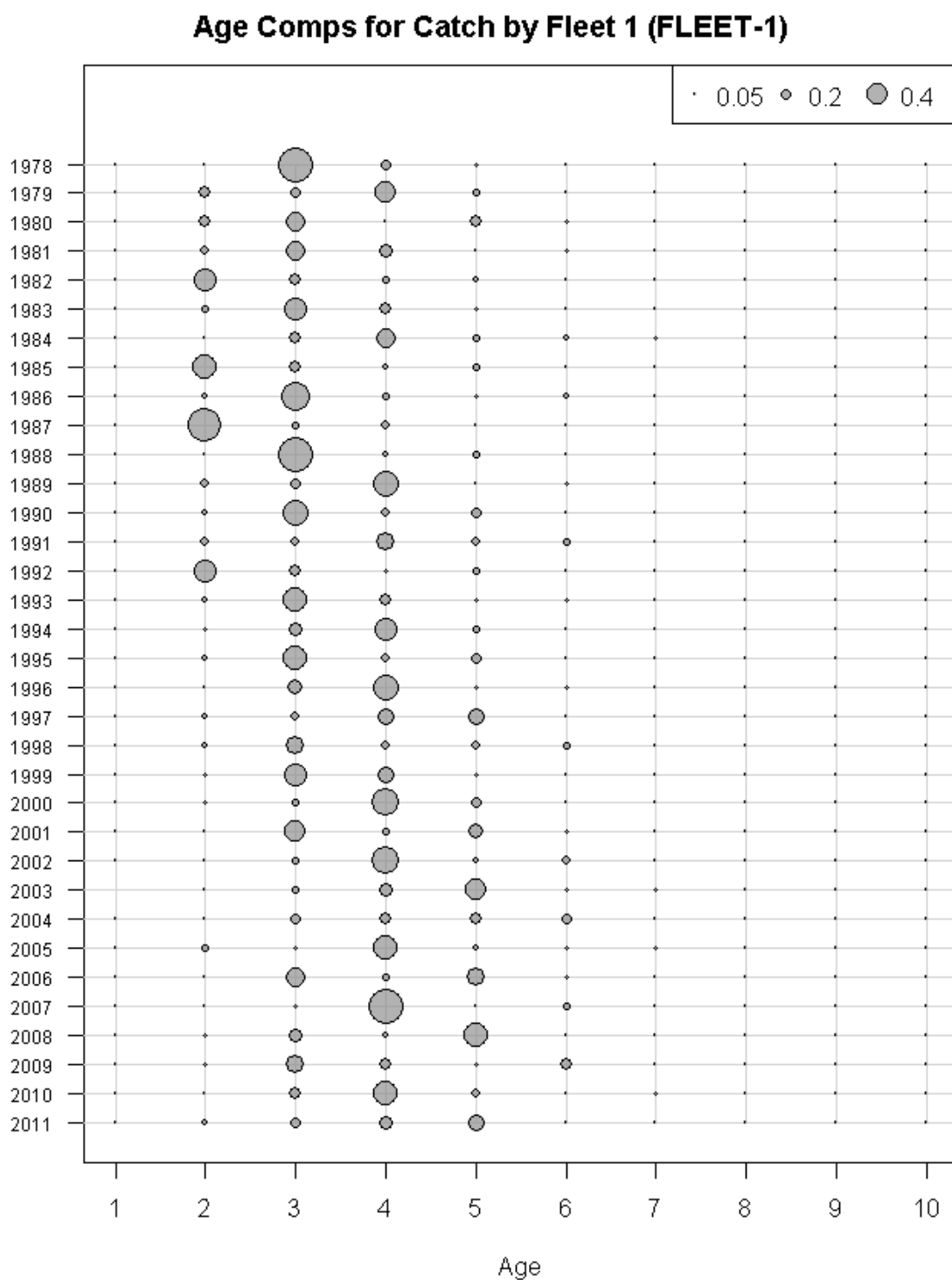
Figure 4. Catch-at-age of Eastern Georges Bank cod, 1978-2011. Bubble size denotes magnitude of catch.
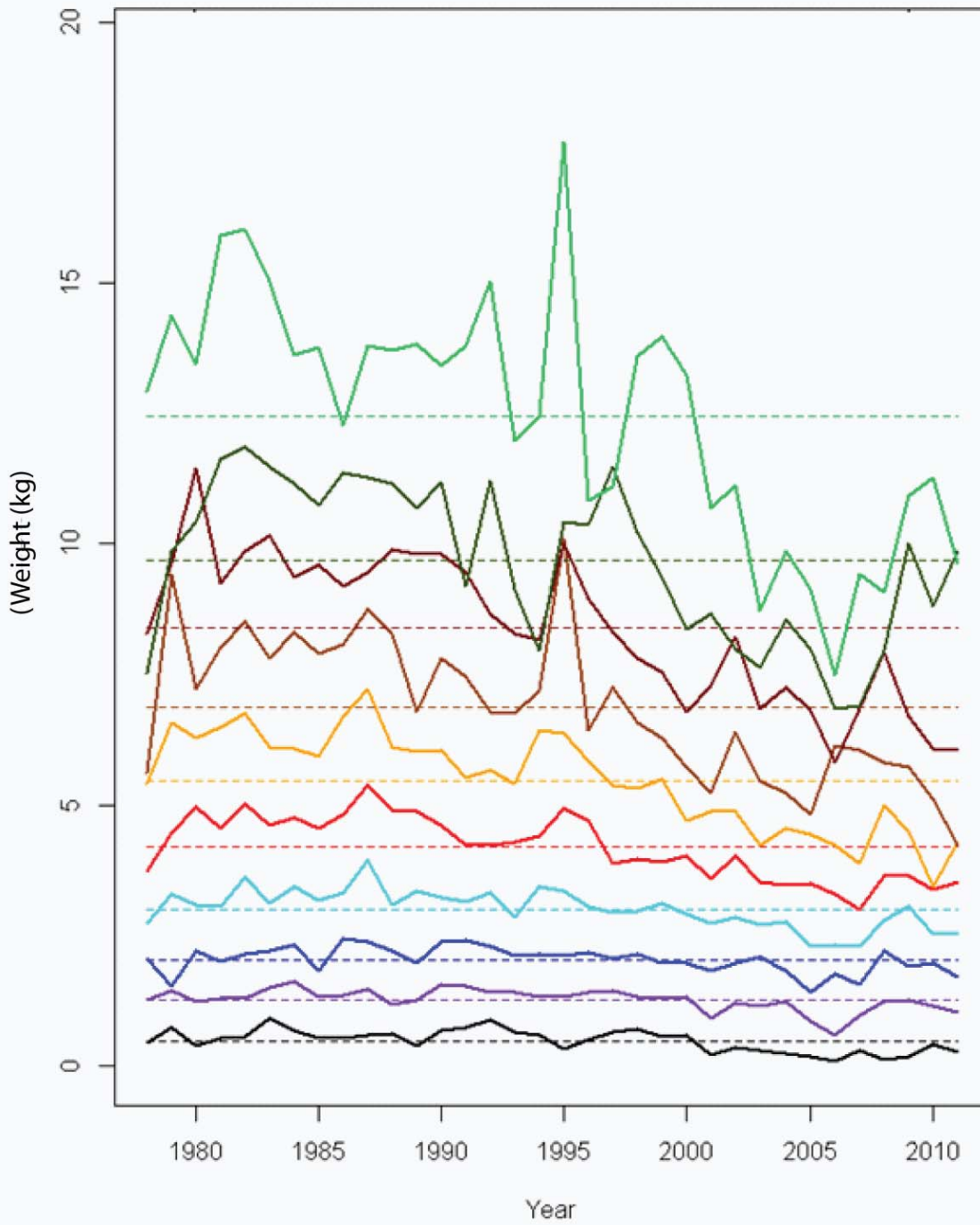
Figure 5. Catch weight-at-age (kg) of Eastern Georges Bank cod, 1978-2011. The lines are ages 1-10+, where age 1 is at the bottom of the plot (black) and age 10+ is at the top (green).
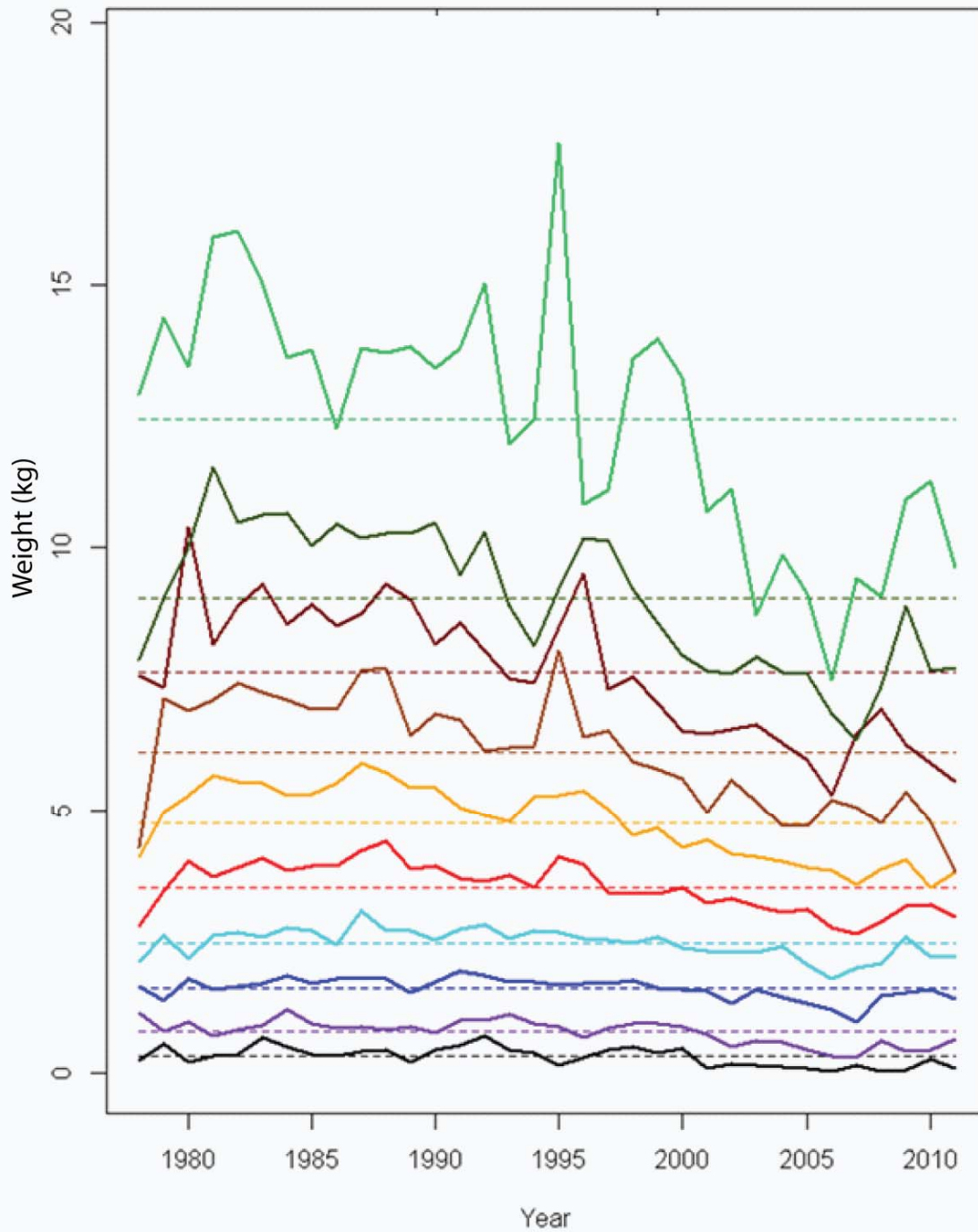
Figure 6. Beginning year catch weight-at-age (kg) of Eastern Georges Bank cod, 1978-2011.The lines are ages 1-10+, where age 1 is at the bottom of the plot (black) and age 10+ is at the top (green).
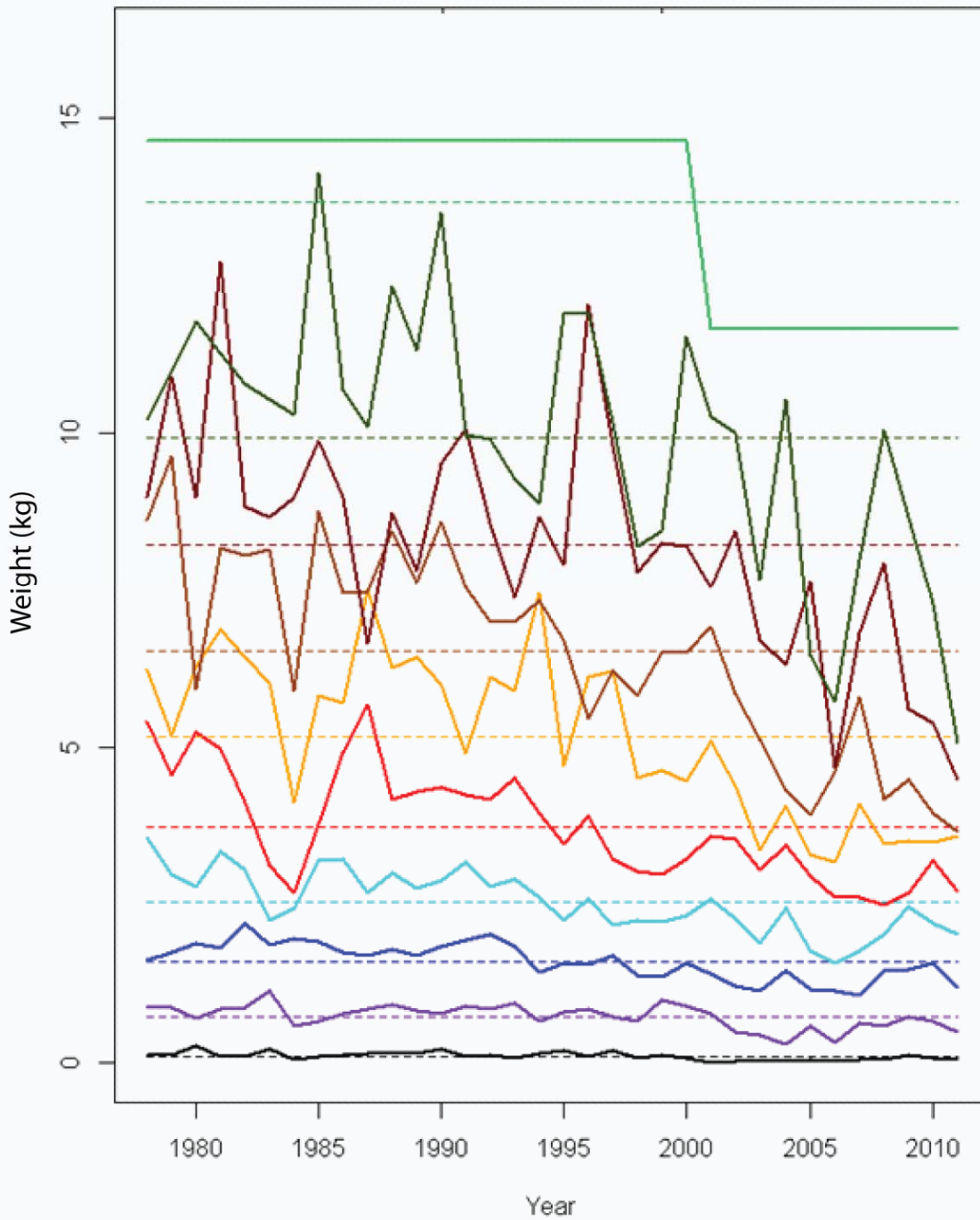
Figure 7. Beginning year weight-at-age (kg) of Eastern Georges Bank cod estimated from the DFO and NEFSC spring survey weight-at-age, 1978-2011. The lines are ages 1-10+, where age 1 is at the bottom of the plot (black) and age 10+ is at the top (green).
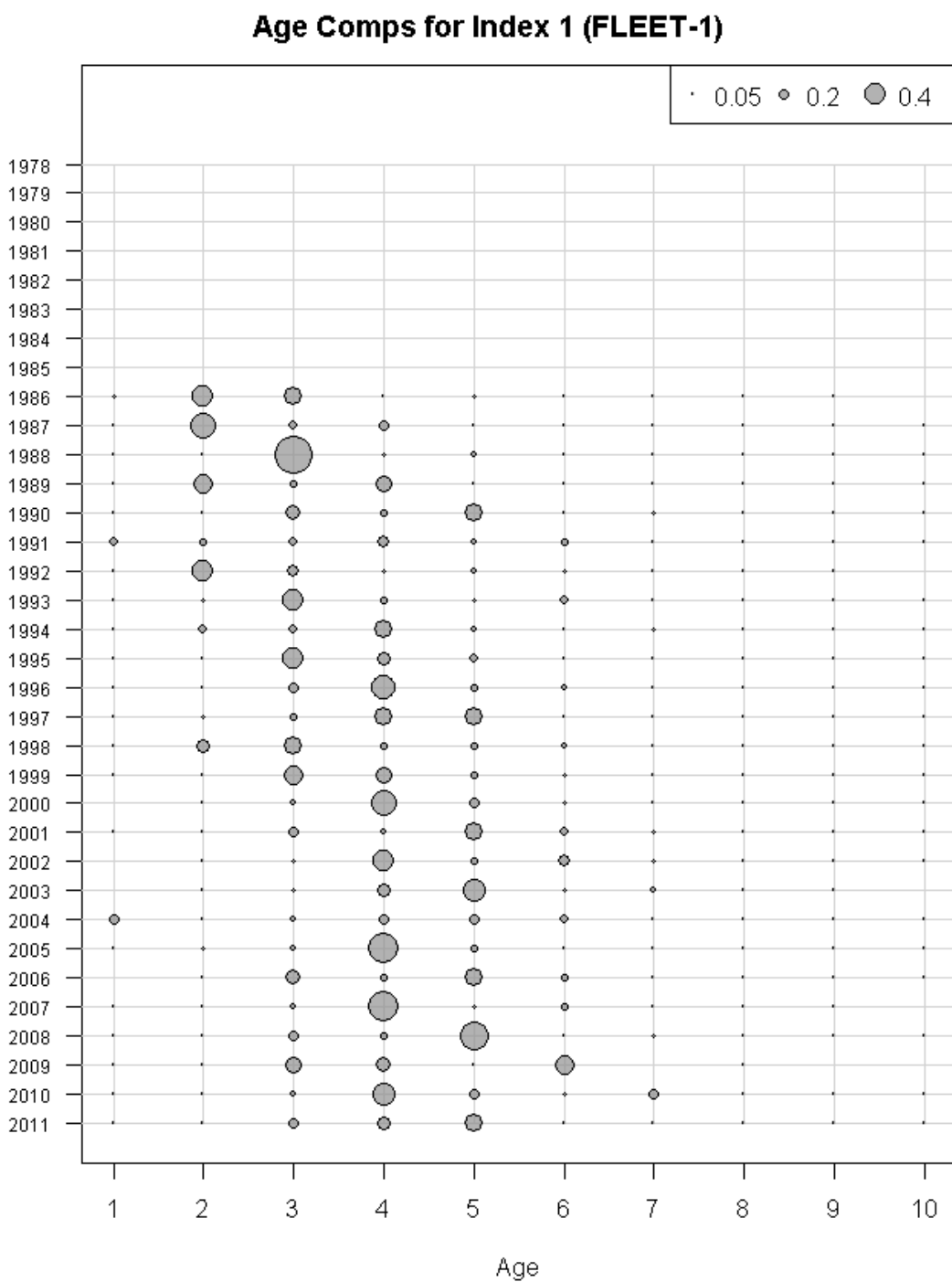
Figure 8. Age composition of stratified mean number catch (numbers) per tow at age of Eastern Georges Bank cod in the DFO research bottom trawl survey (strata 5Z1-5Z4), 1986-2011. Bubble size denotes magnitude.
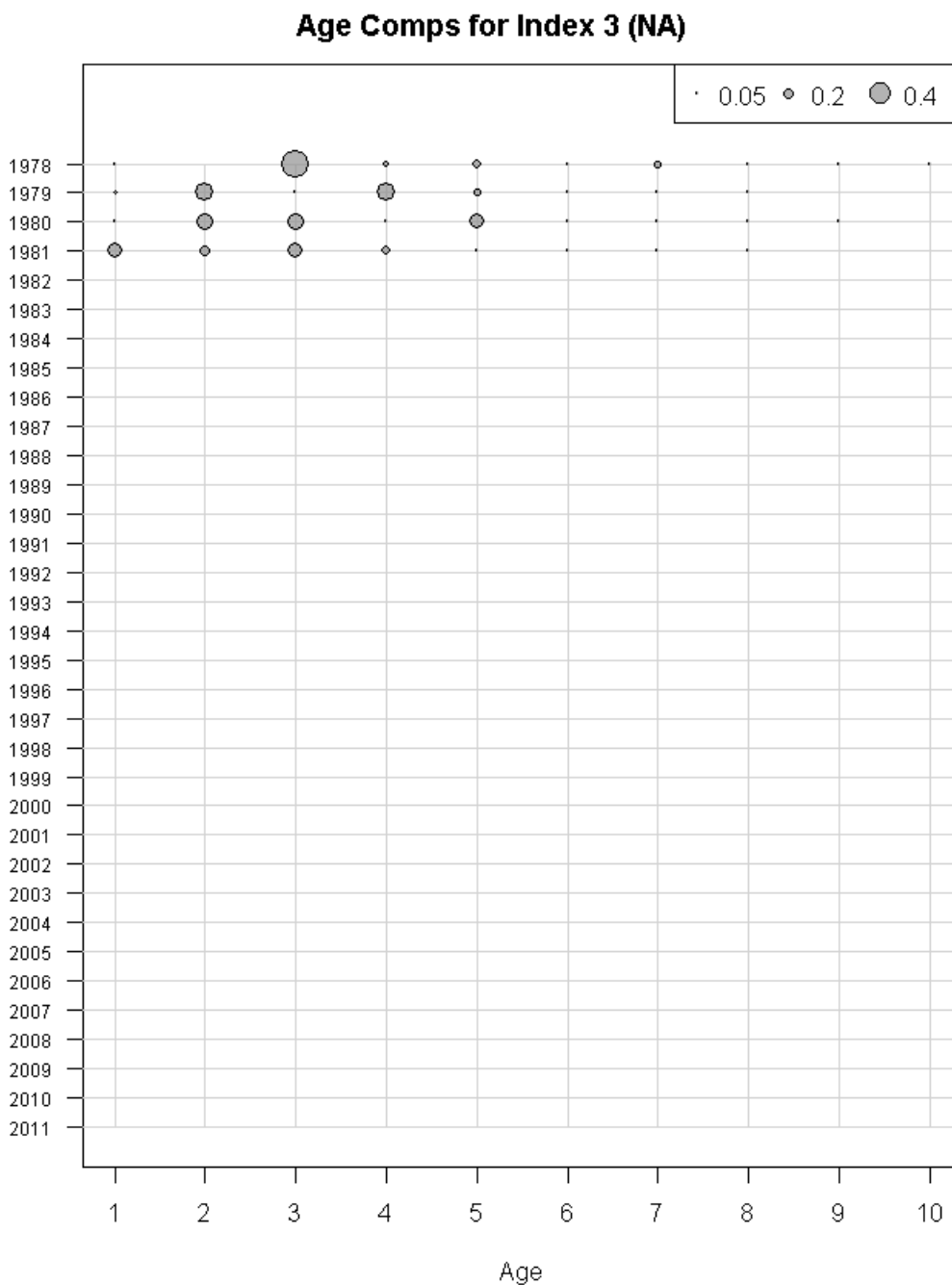
Figure 9a. Age composition of stratified mean number catch (numbers) per tow at age of Eastern Georges Bank cod in the NEFSC spring research bottom trawl survey (Yankee #41 otter trawl), 1978-1981. Bubble size denotes magnitude.
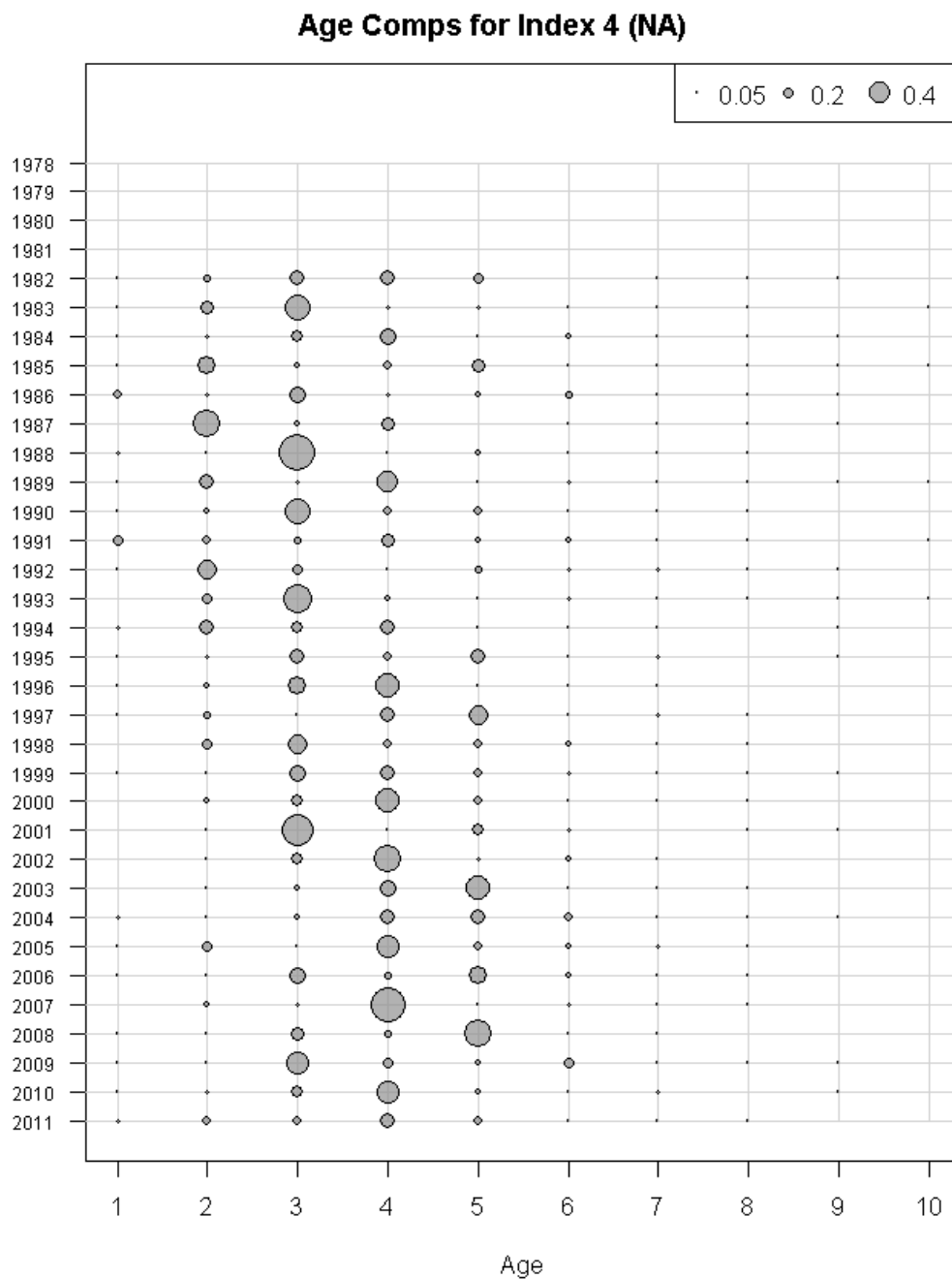
Figure 9b. Age composition of stratified mean number catch (numbers) per tow at age of Eastern Georges Bank cod in the NEFSC spring research bottom trawl survey (Yankee #36 otter trawl), 1982-2011. Bubble size denotes magnitude.
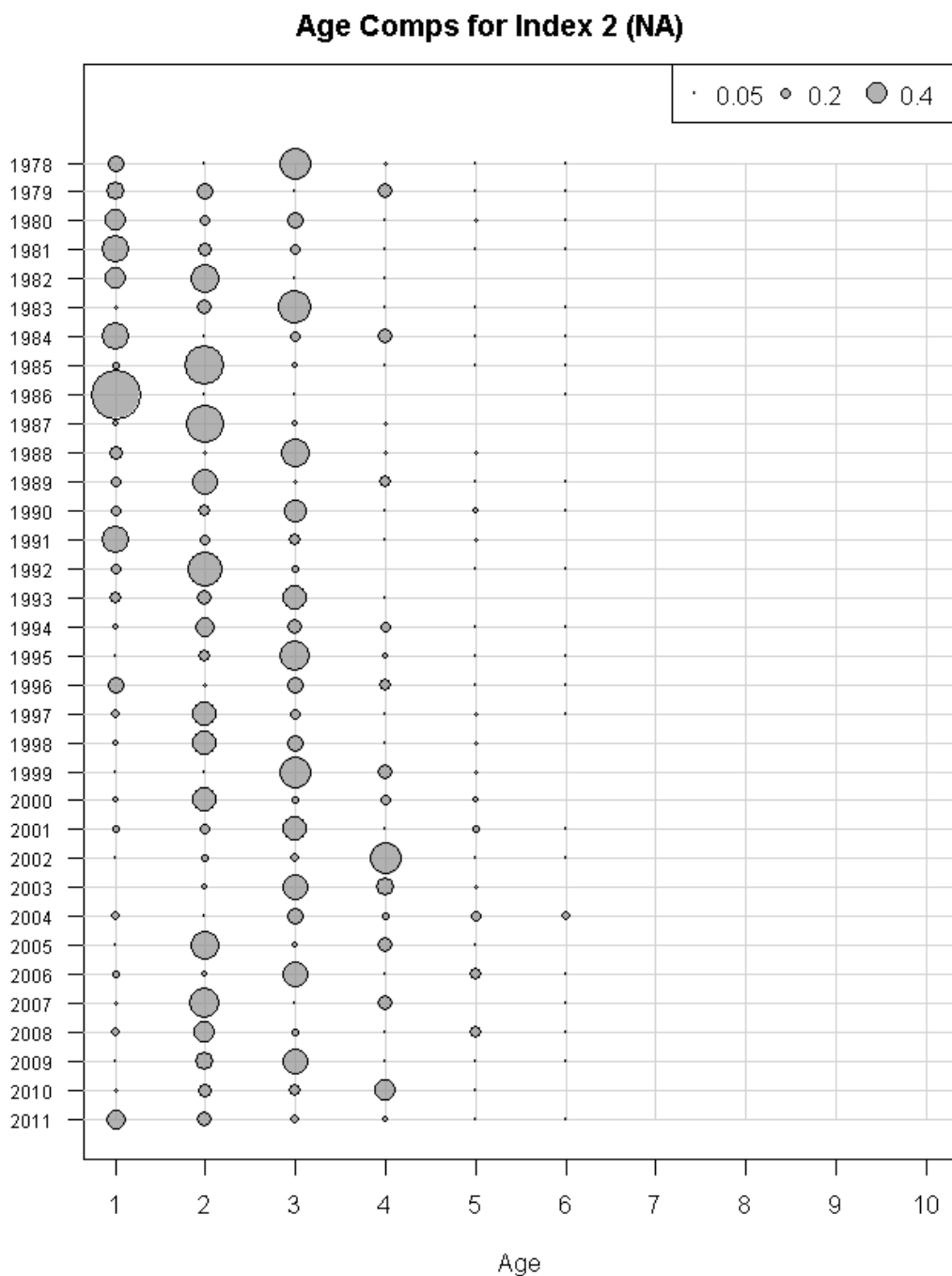
Figure 10. Age composition of stratified mean number catch (numbers) per tow at age of Eastern Georges Bank cod in the NEFSC autumn research bottom trawl survey (Yankee #36 otter trawl), 1978-2011. Bubble size denotes magnitude.
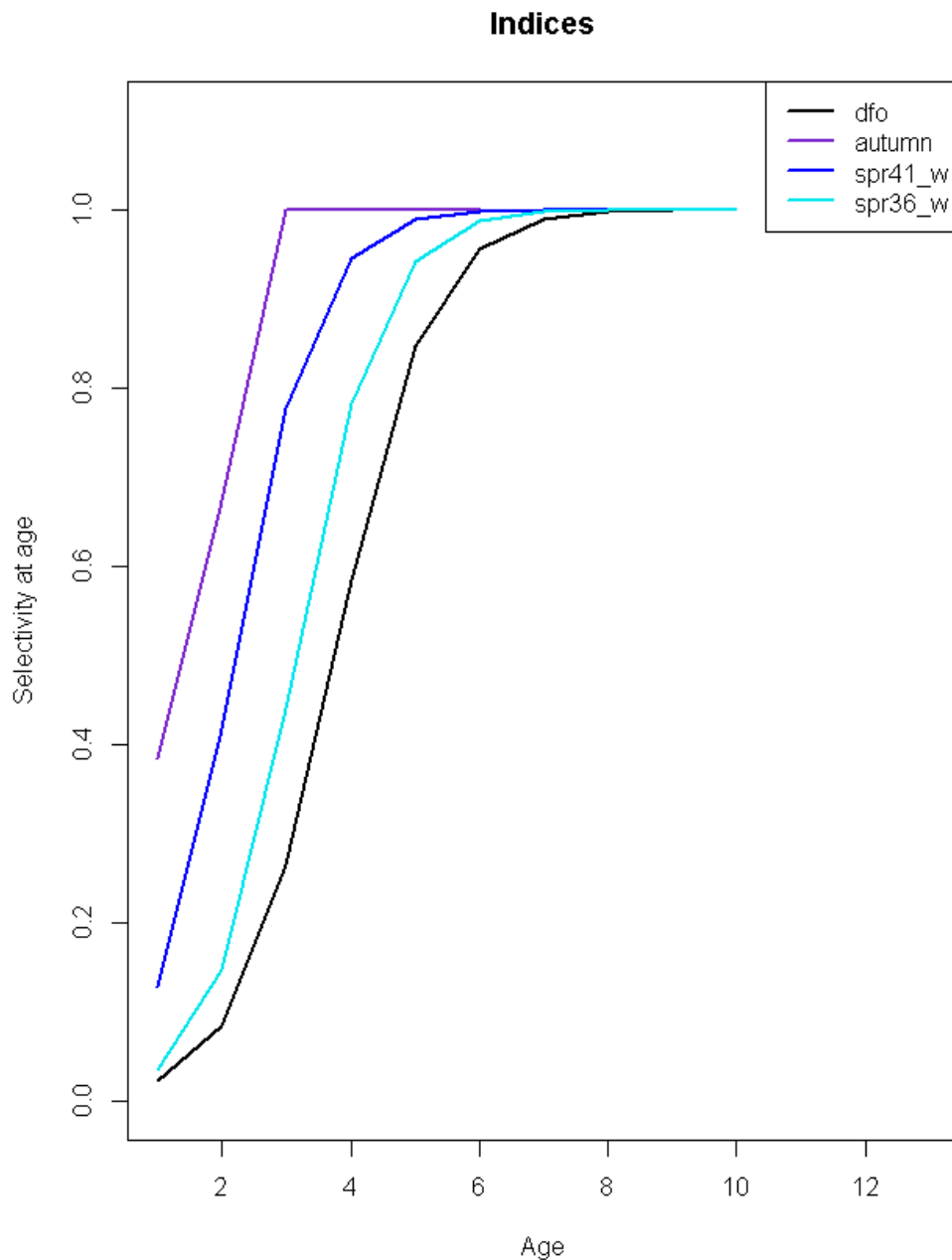
Figure 11. Survey selectivity at age for DFO (logistic), NEFSC autumn (fixed, age 3=1), and NEFSC spring (logistic) in run1_o3.1.
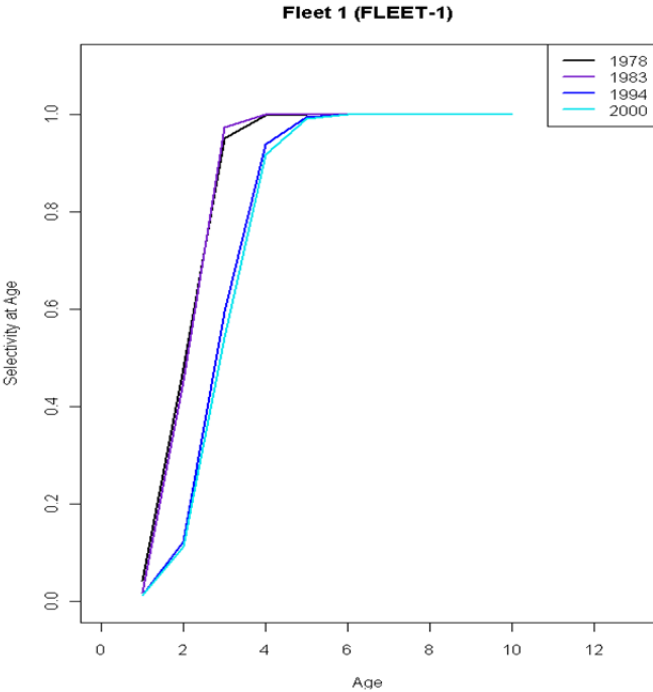
Figure 12. Fishery selectivity for four blocks from GB cod assessment (NEFSC 2013b).
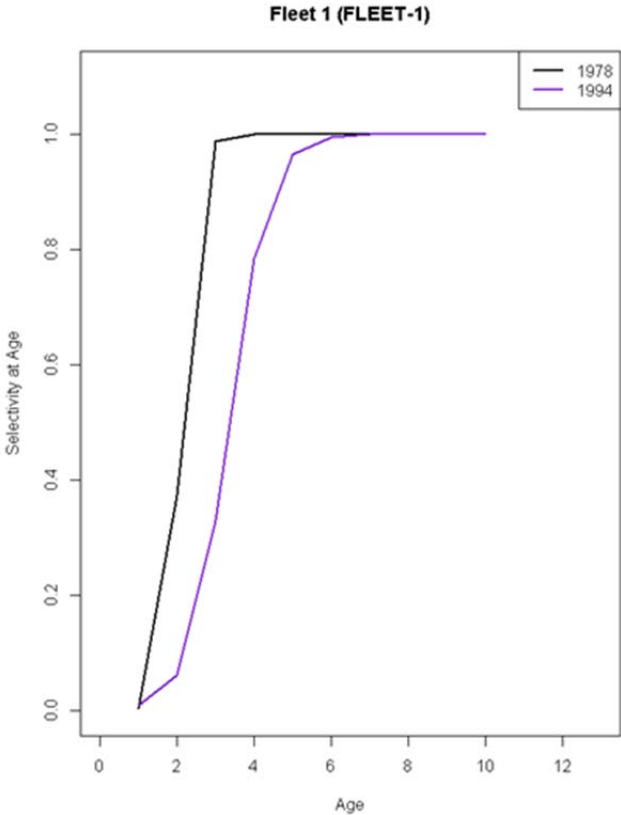
Figure 13. Fishery selectivity for two blocks for EGB cod fishery for run1_o3.1.

Fleet 1 Catch (FLEET-1)
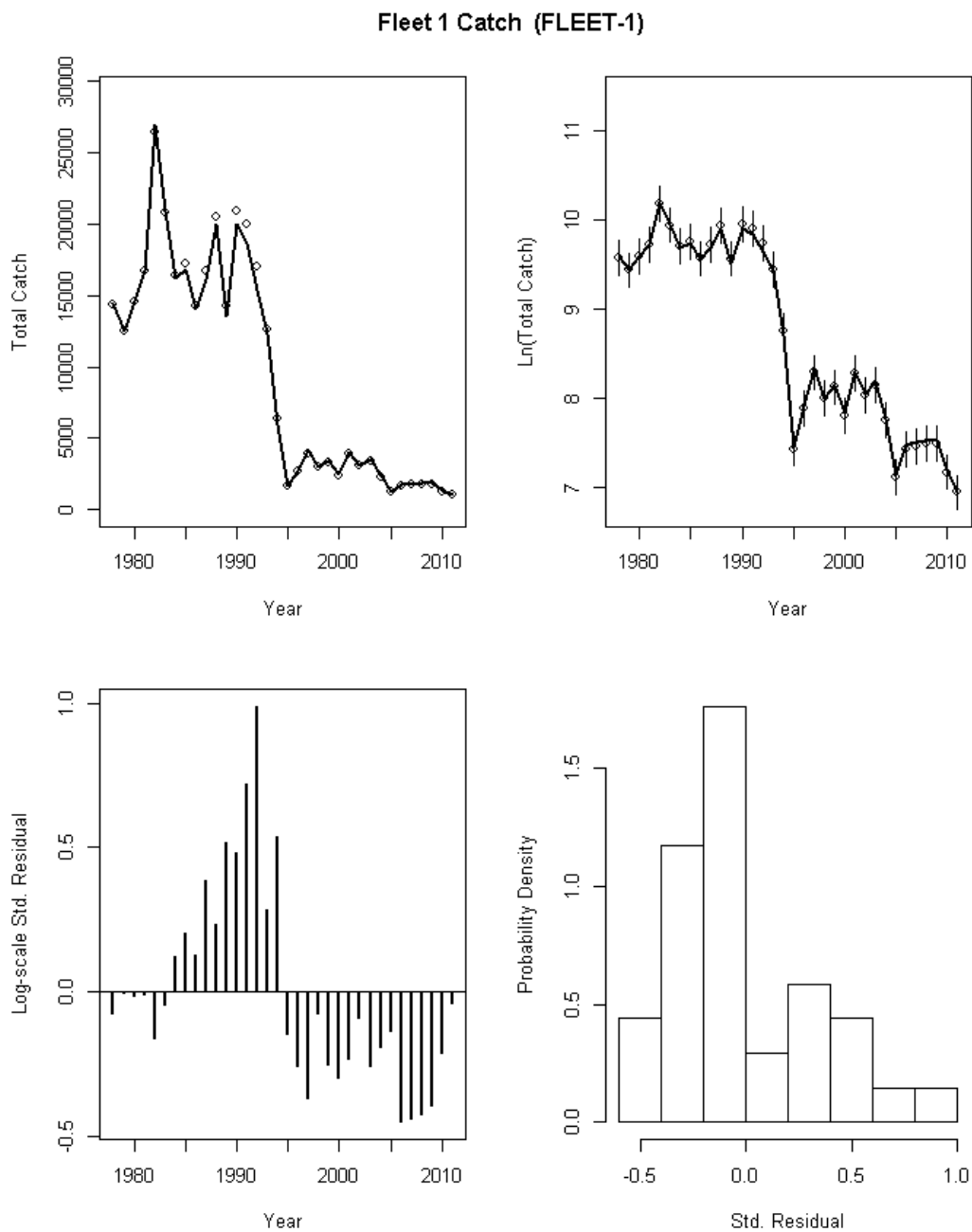
Figure 14. ASAP model run1_o3.1 fit to total catch of Eastern Georges Bank cod, 1978-2011.
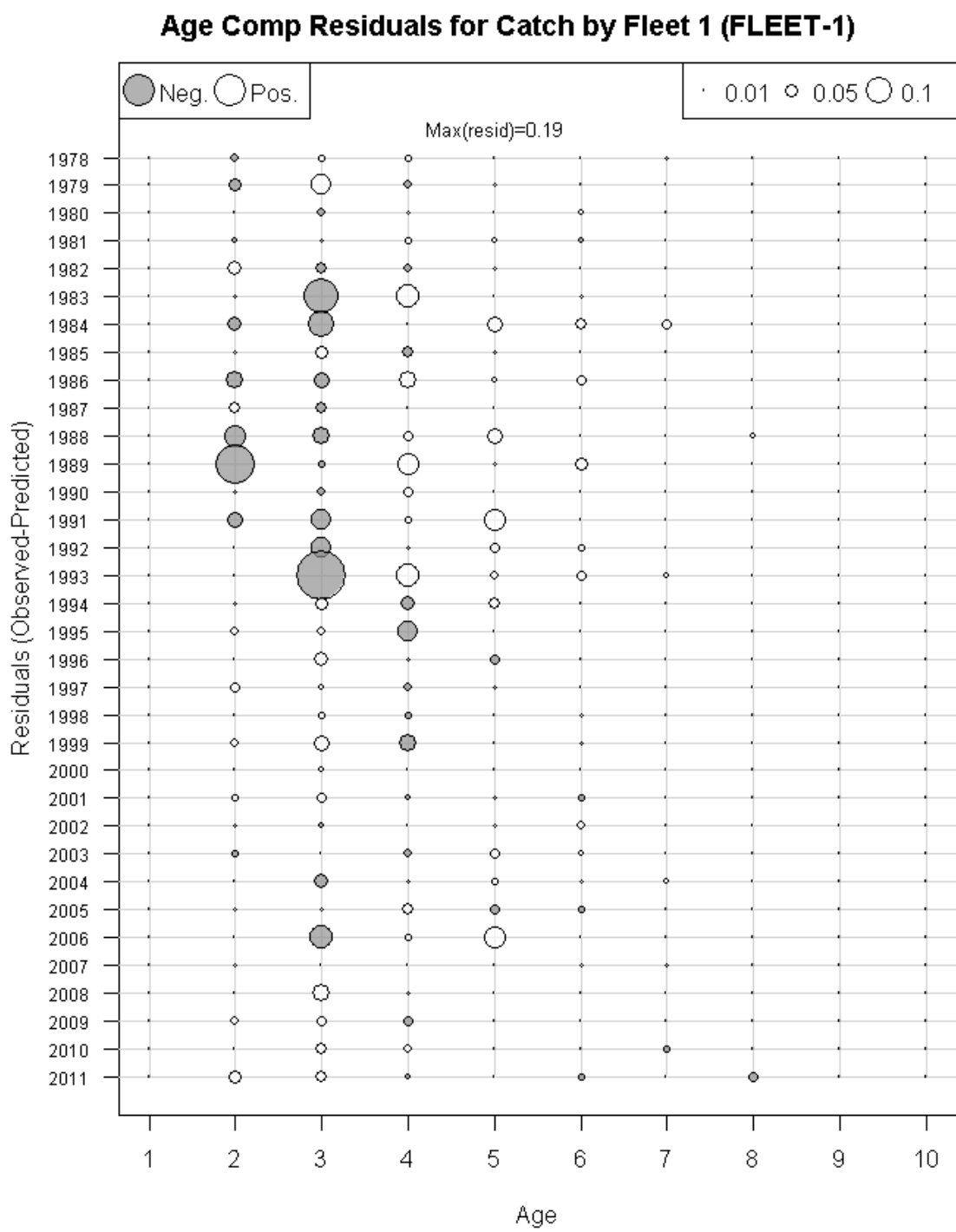
Figure 15. ASAP model run1_o3.1 residuals for the commercial catch age composition of Eastern Georges Bank cod, 1978-2011.
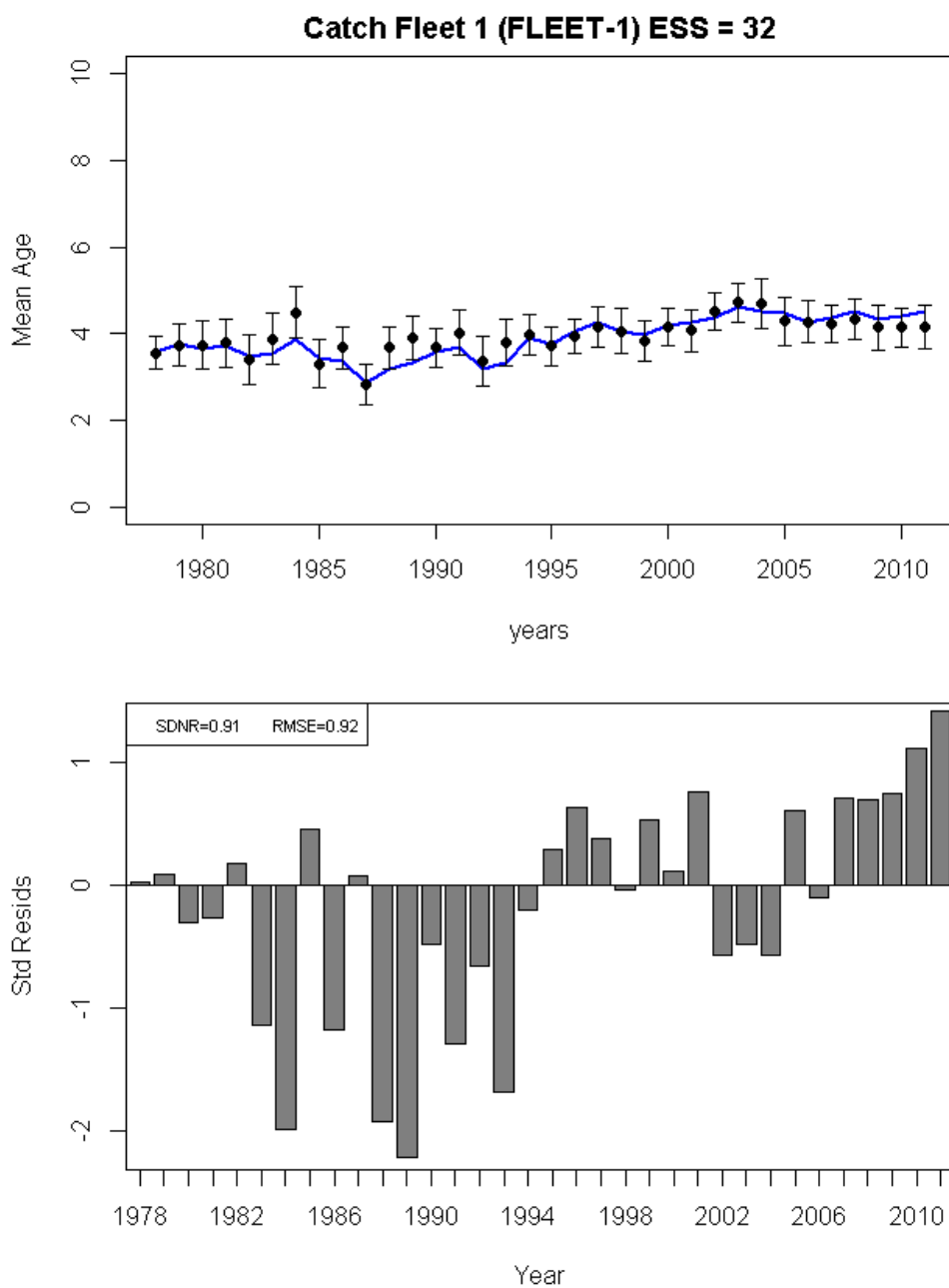
Figure 16. ASAP model run1_o3.1 predicted mean age of Eastern Georges Bank cod in the total catch (blue line) compared to the observed mean age (top plot) and the residuals about the mean (bottom plot), 1978-2011.

Index 1 (dfo)
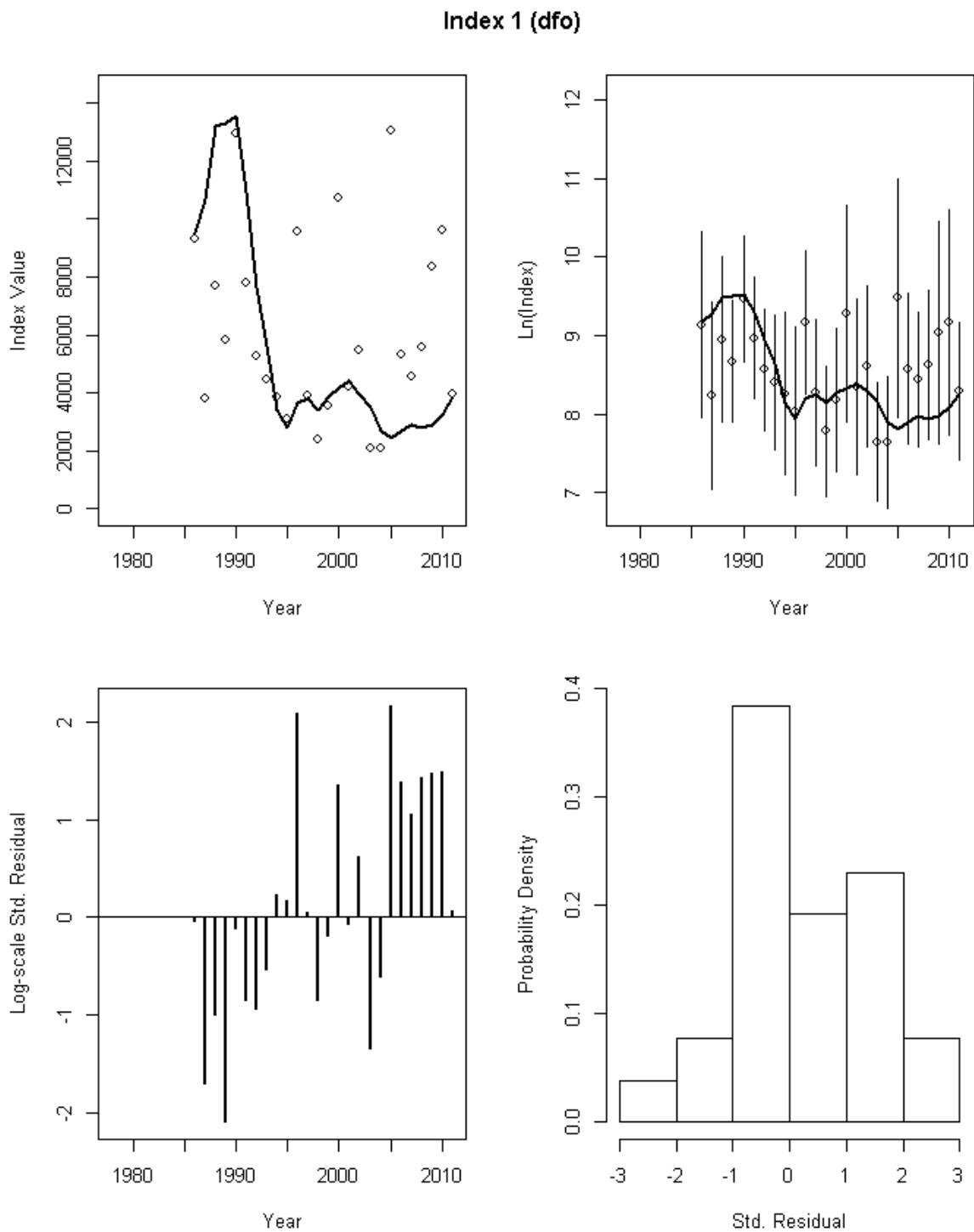
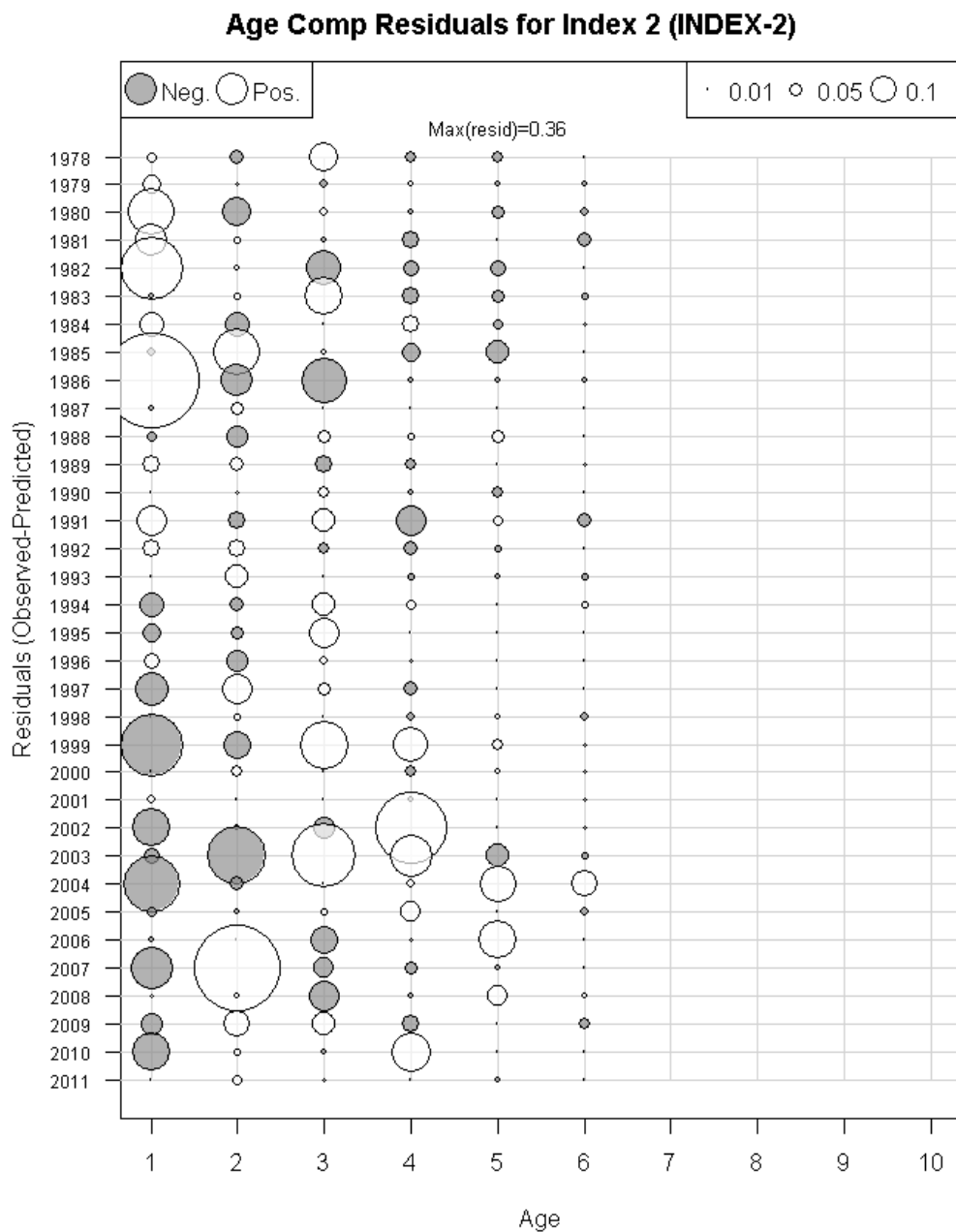*Figure 17. ASAP model run1_o3.1 fit to DFO survey indices of Eastern Georges Bank cod, 1978-2011.*
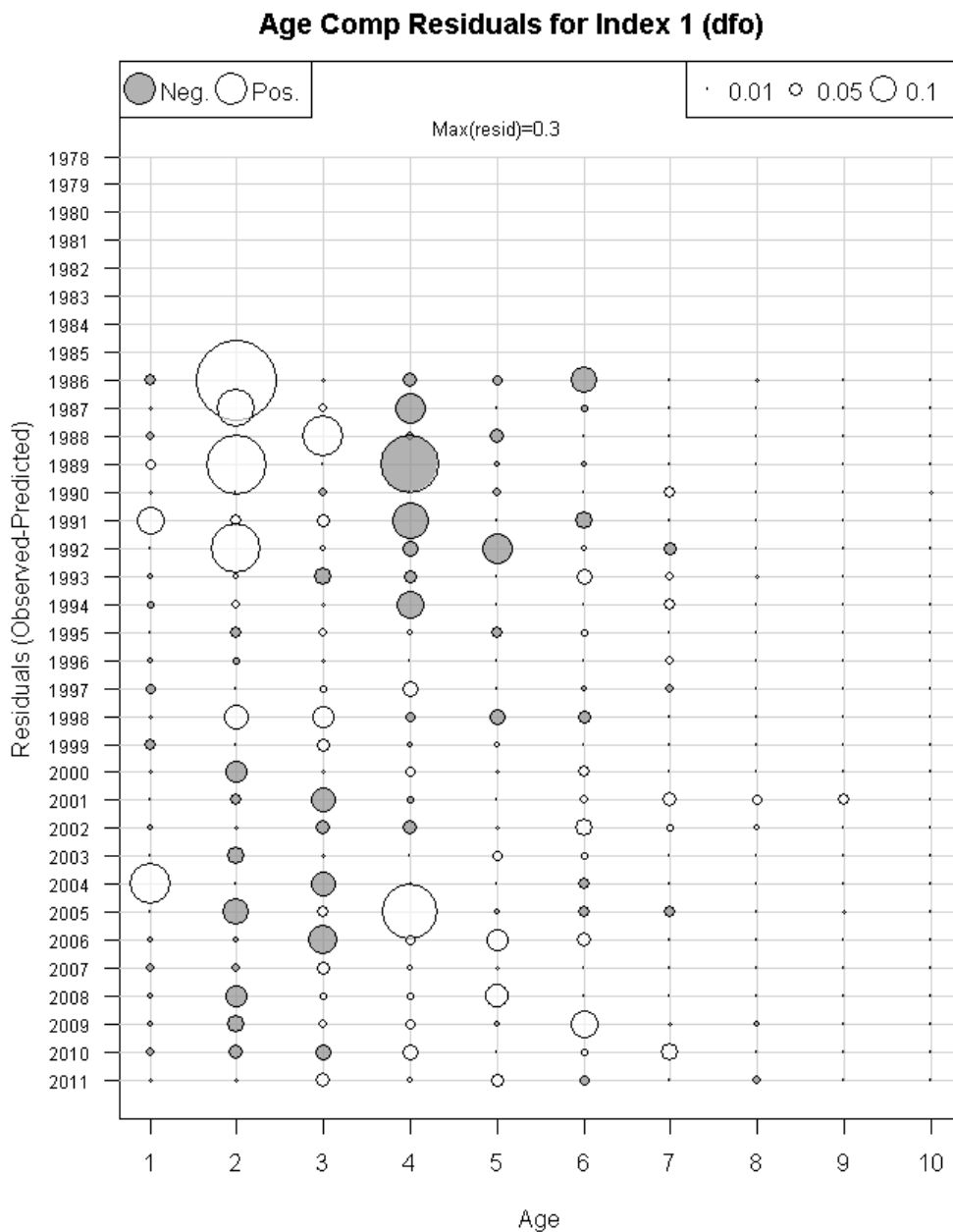
Figure 18. ASAP model run1_o3.1 age composition residuals for DFO survey index of Eastern Georges Bank cod, 1978-2011.
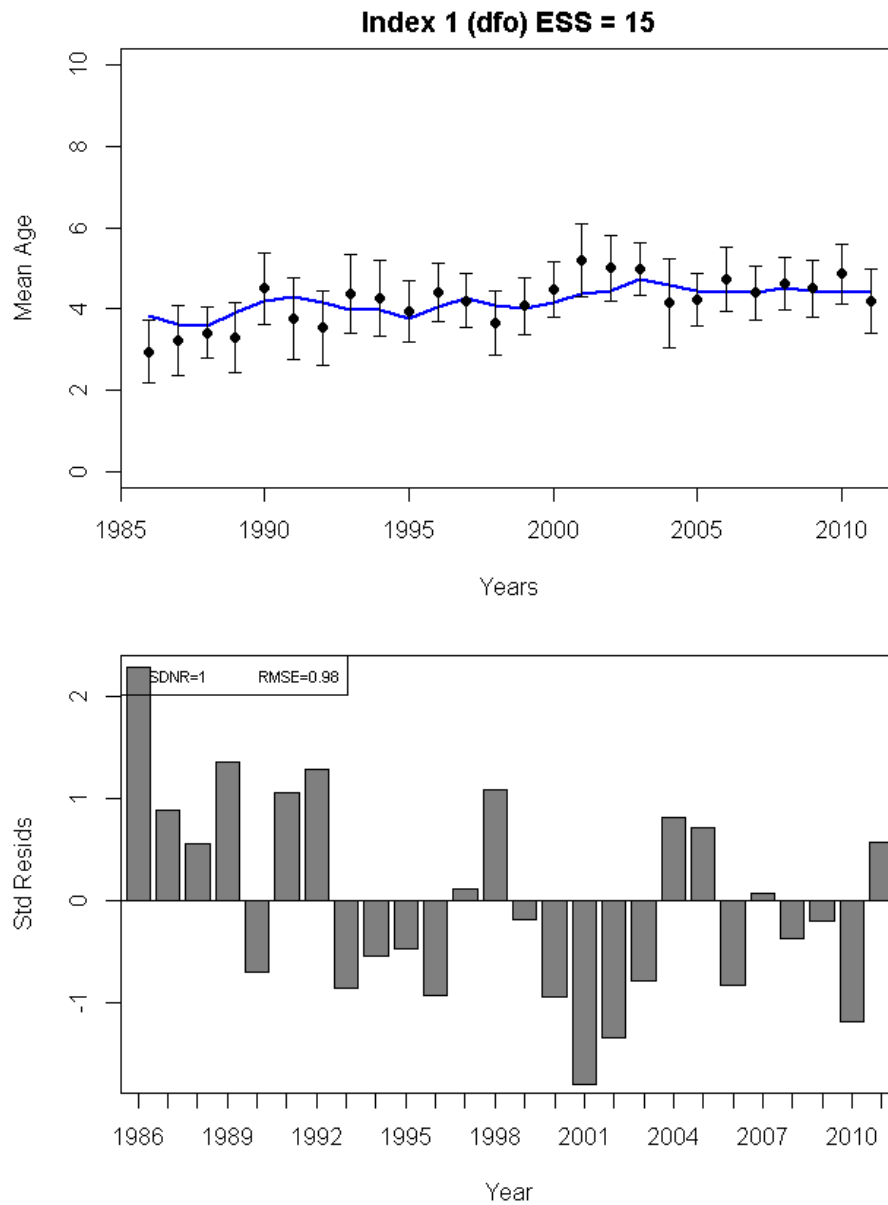
Figure 19. ASAP model run1_o3.1 predicted mean age of Eastern Georges Bank cod in the DFO survey (blue line) compared to the observed mean age (top plot) and the residuals about the mean (bottom plot), 1978-2011.
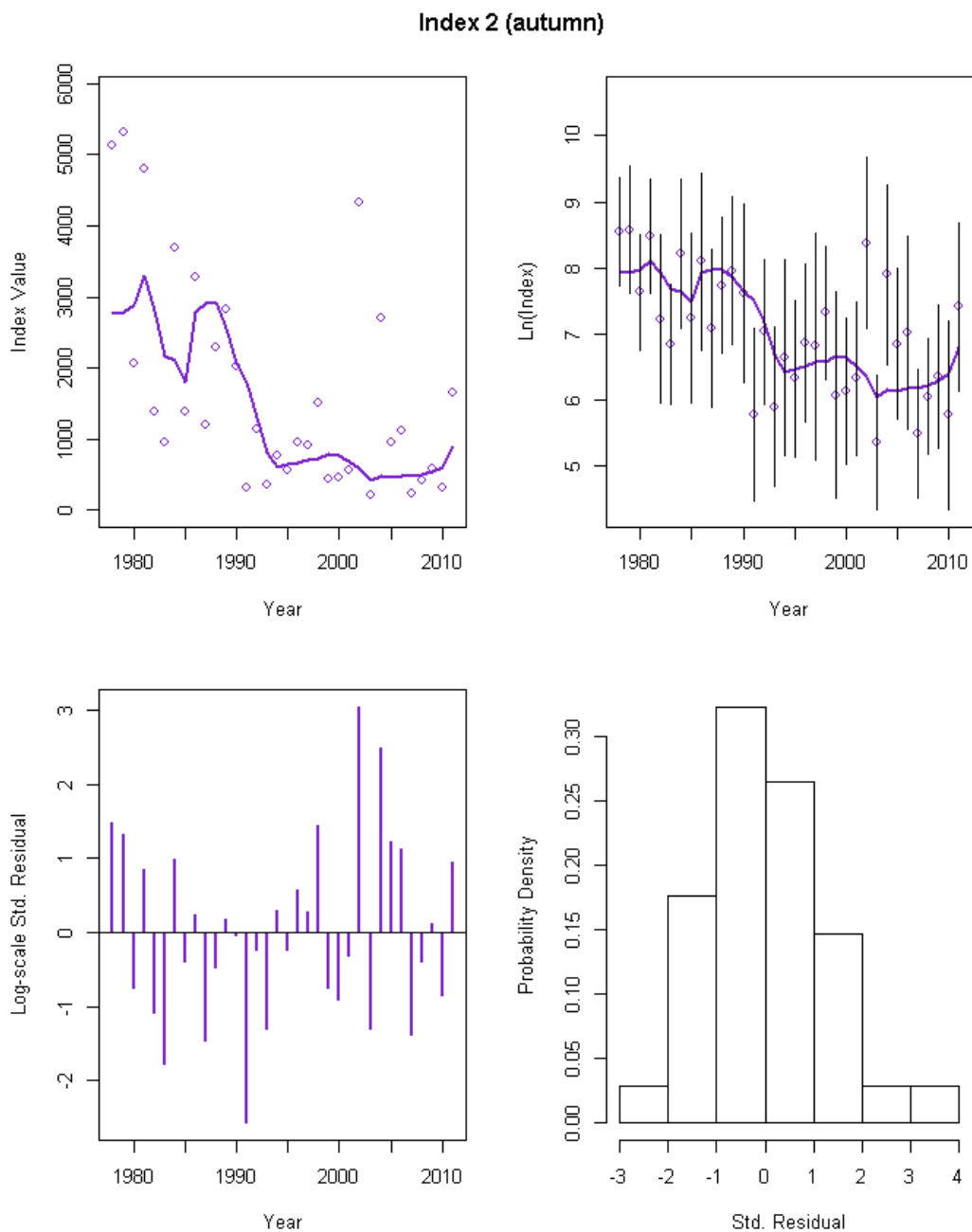
Figure 20. ASAP model run1_o3.1 fit to NEFSC autumn survey indices of Eastern Georges Bank cod, 1978-2011.
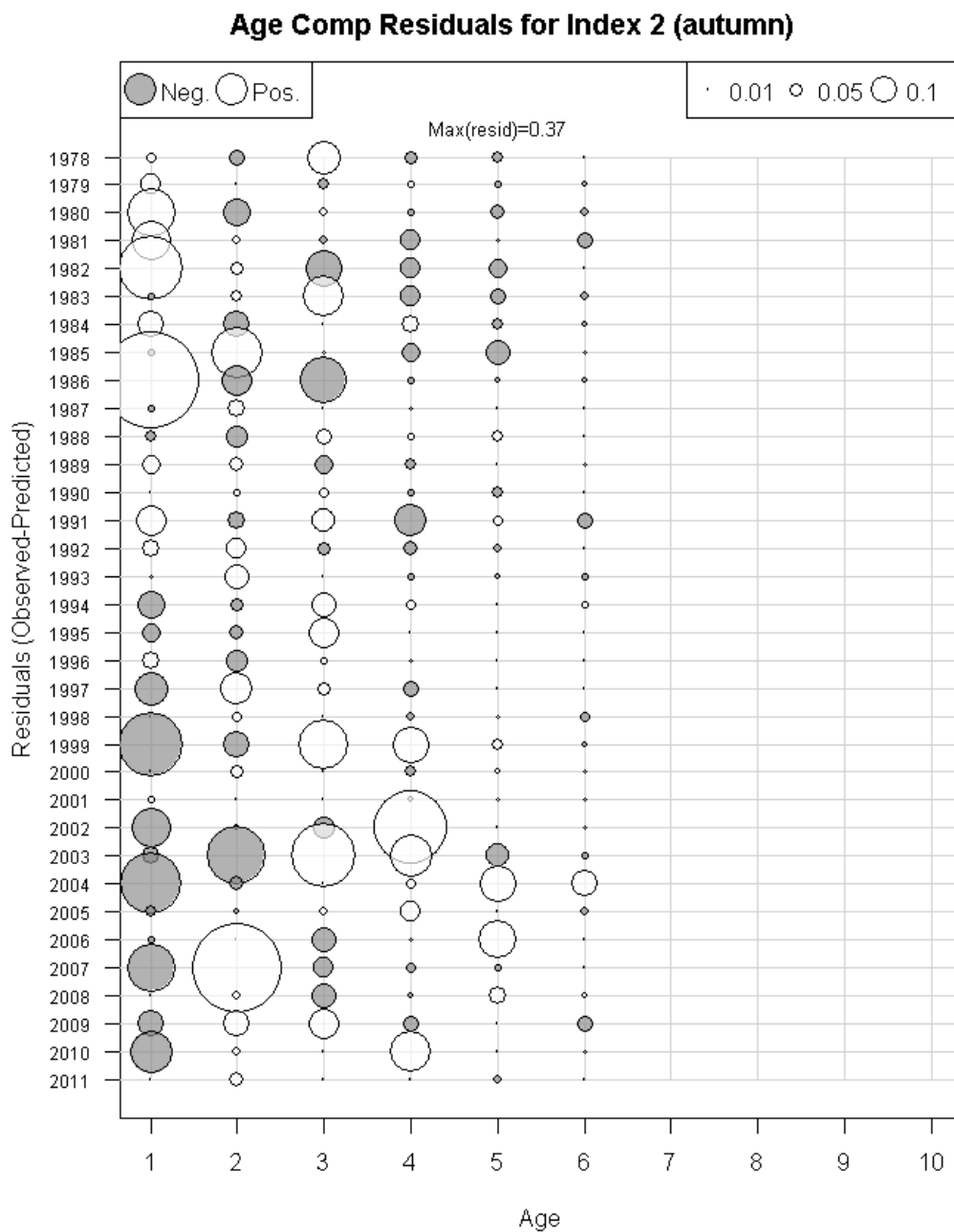
Figure 21. ASAP model run1_o3.1 age composition residuals for NEFSC autumn survey index of Eastern Georges Bank cod, 1978-2011.
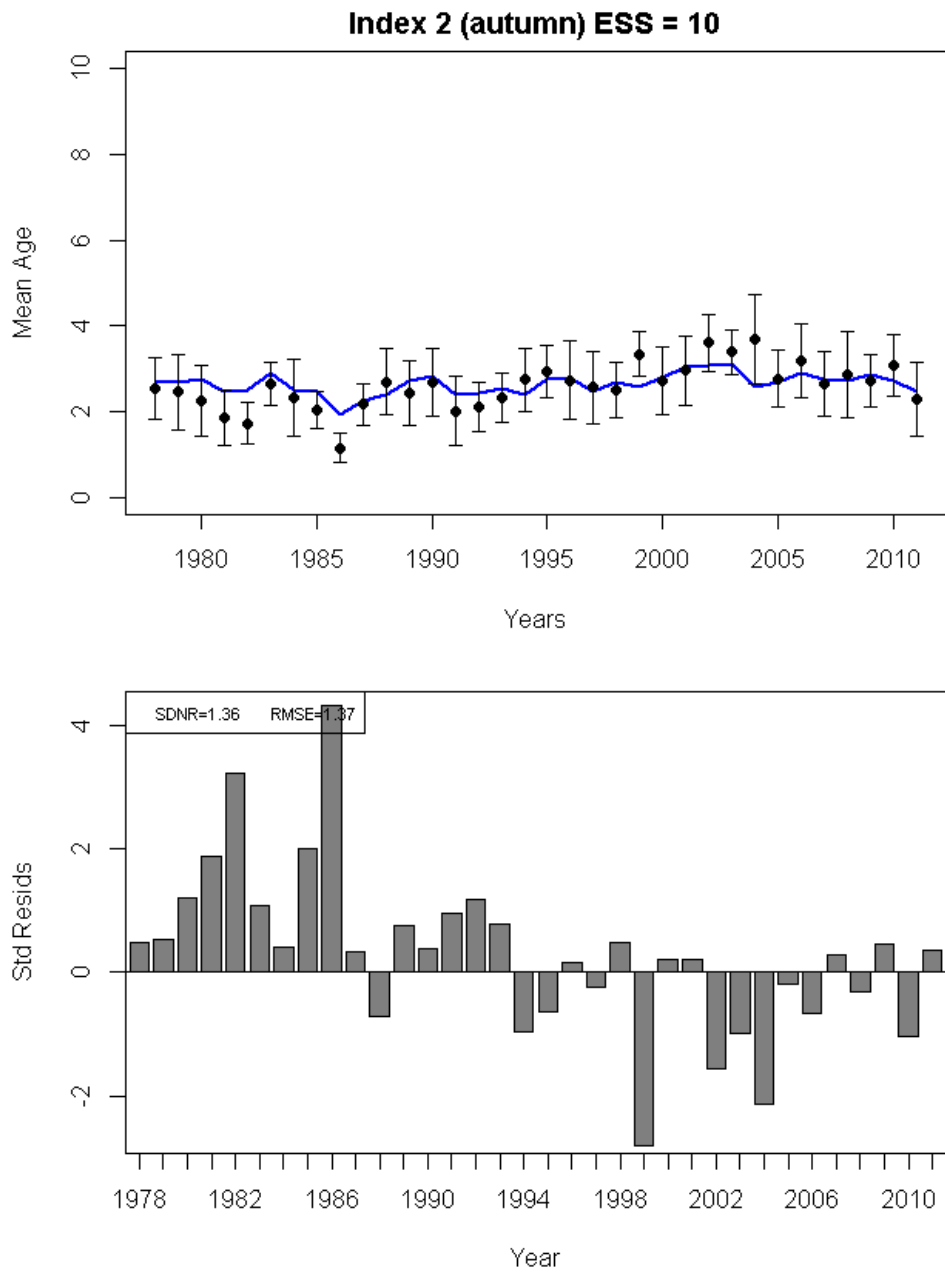
*Figure 22. ASAP model run1_o3.1 predicted mean age of Eastern Georges Bank cod in the NEFSC autumn survey (blue line) compared to the observed mean age (top plot) and the residuals about the mean (bottom plot), 1978-2011.*
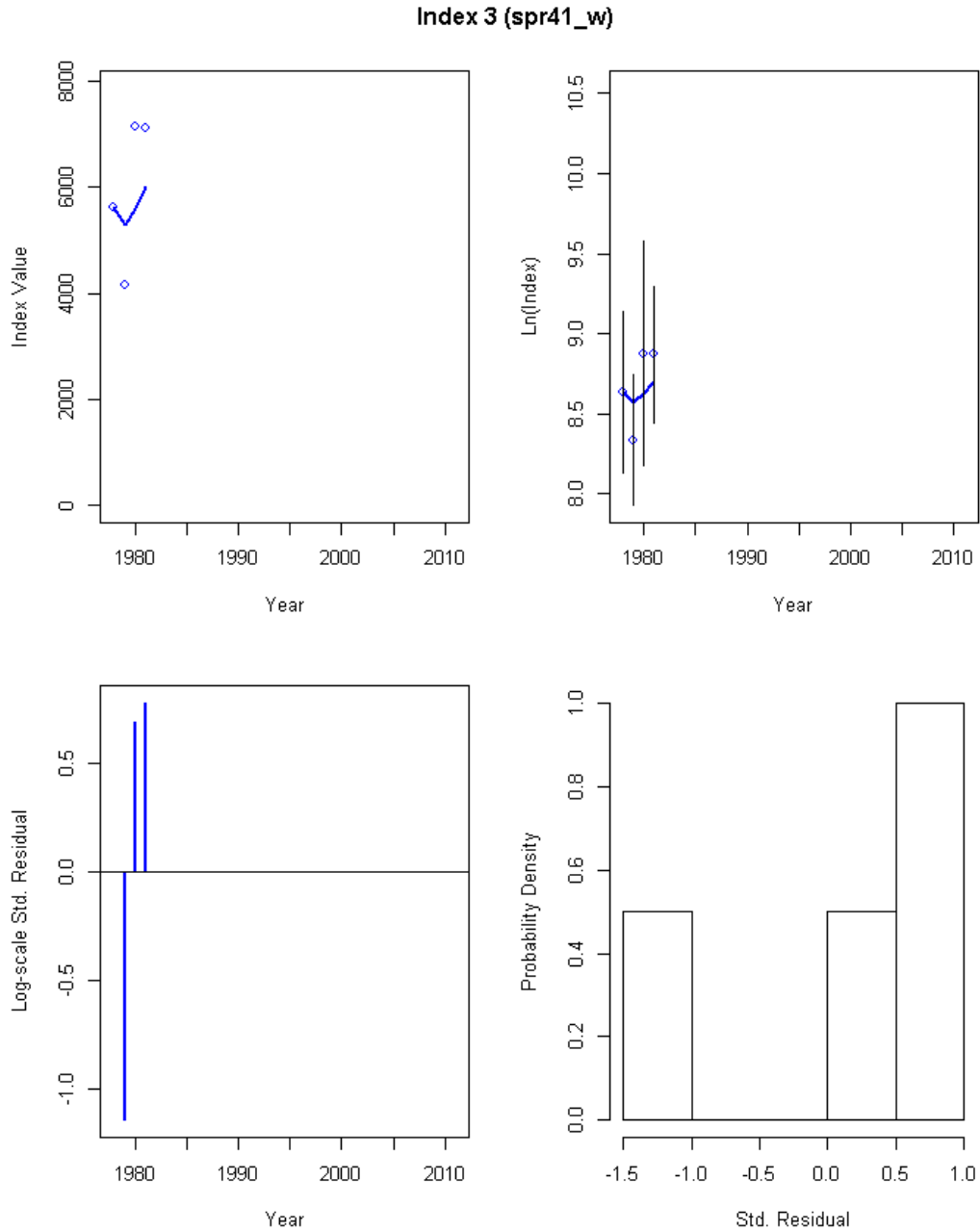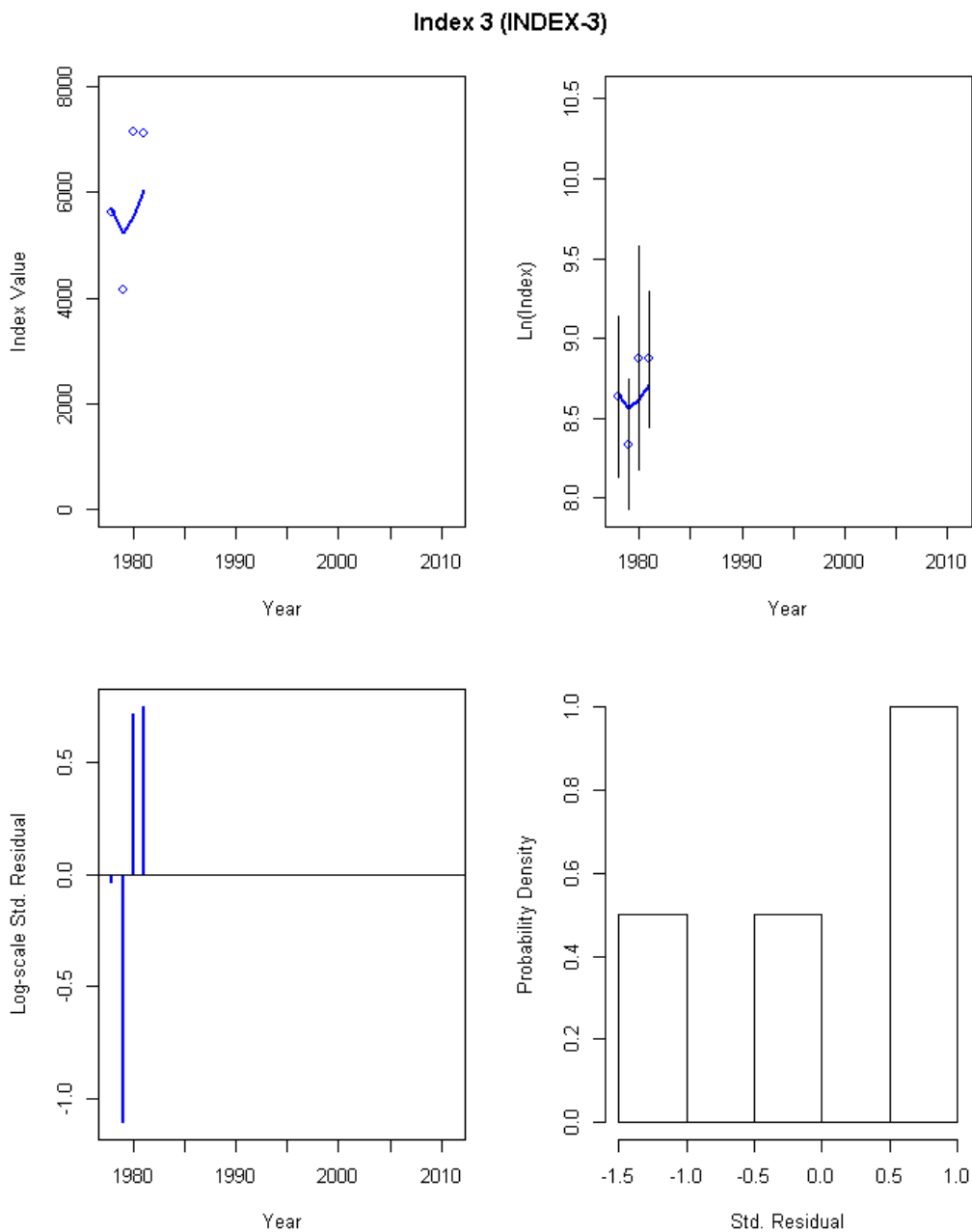
Figure 23. ASAP model run1_o3.1 fit to NEFSC spring Yankee #41 trawl survey indices of Eastern Georges Bank cod, 1978-2011.
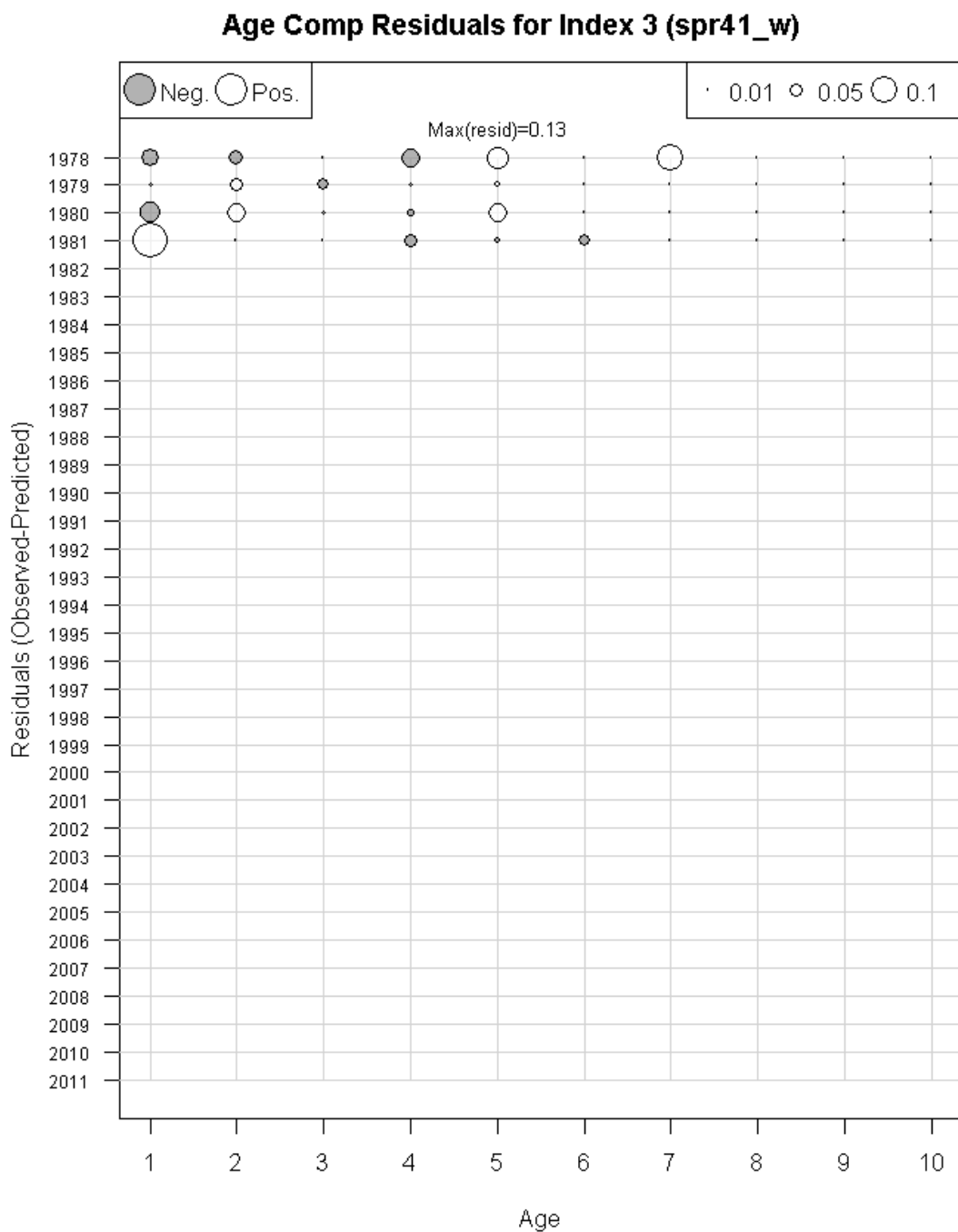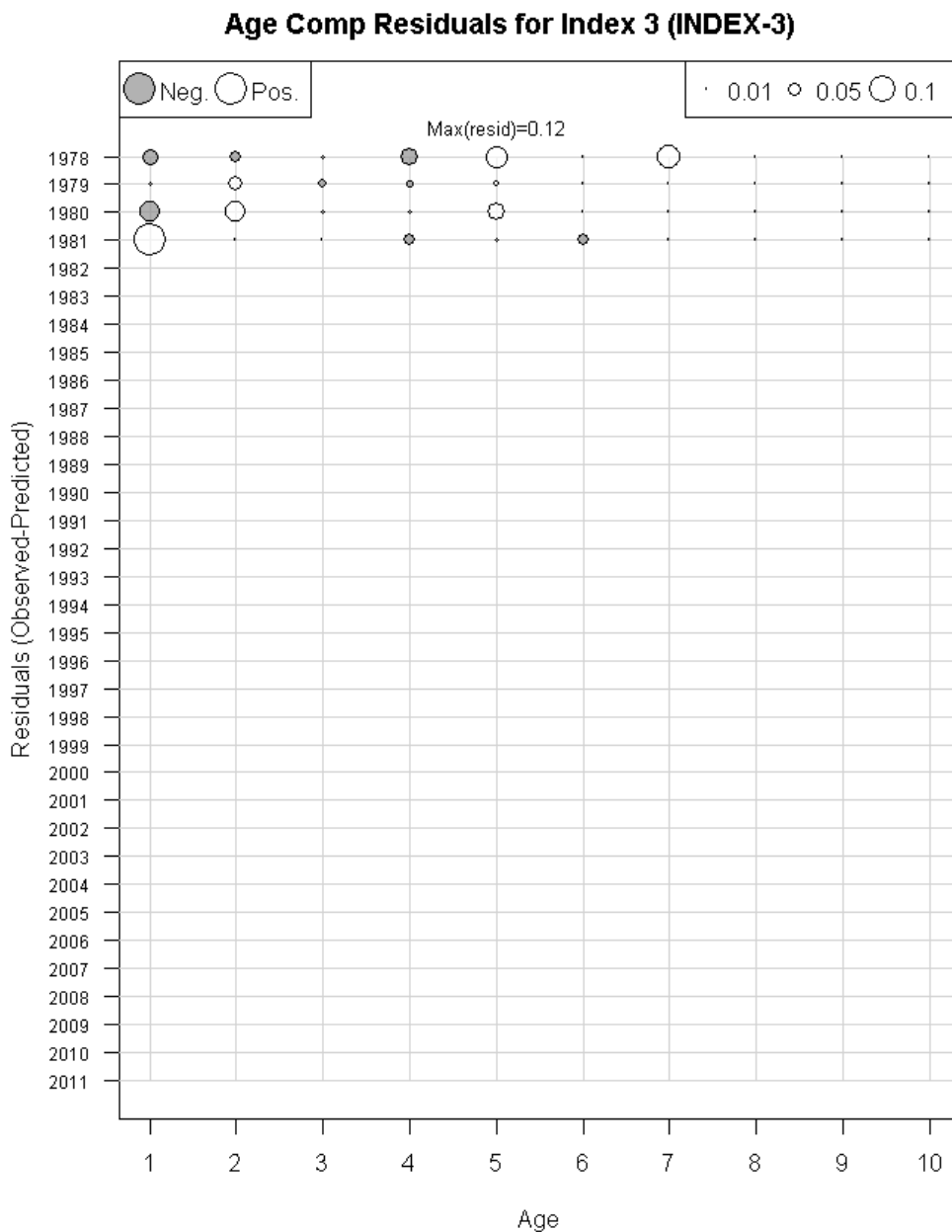
Figure 24. ASAP model run1_o3.1 age composition residuals for NEFSC spring Yankee #41 trawl survey index of Eastern Georges Bank cod, 1978-1981.
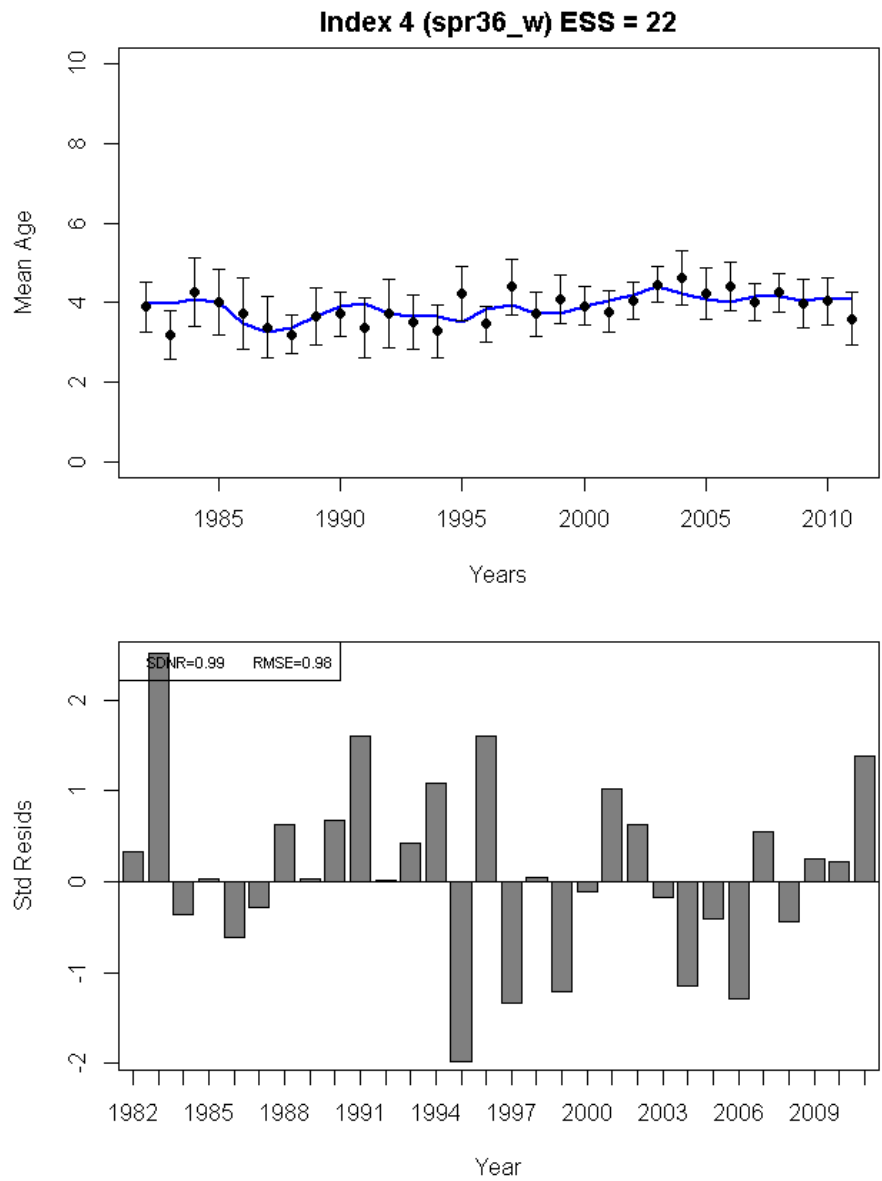
Figure 25. ASAP model run1_o3.1 predicted mean age of Eastern Georges Bank cod in the NEFSC spring Yankee #41 trawl survey (blue line) compared to the observed mean age (top plot) and the residuals about the mean (bottom plot), 1978-1981.
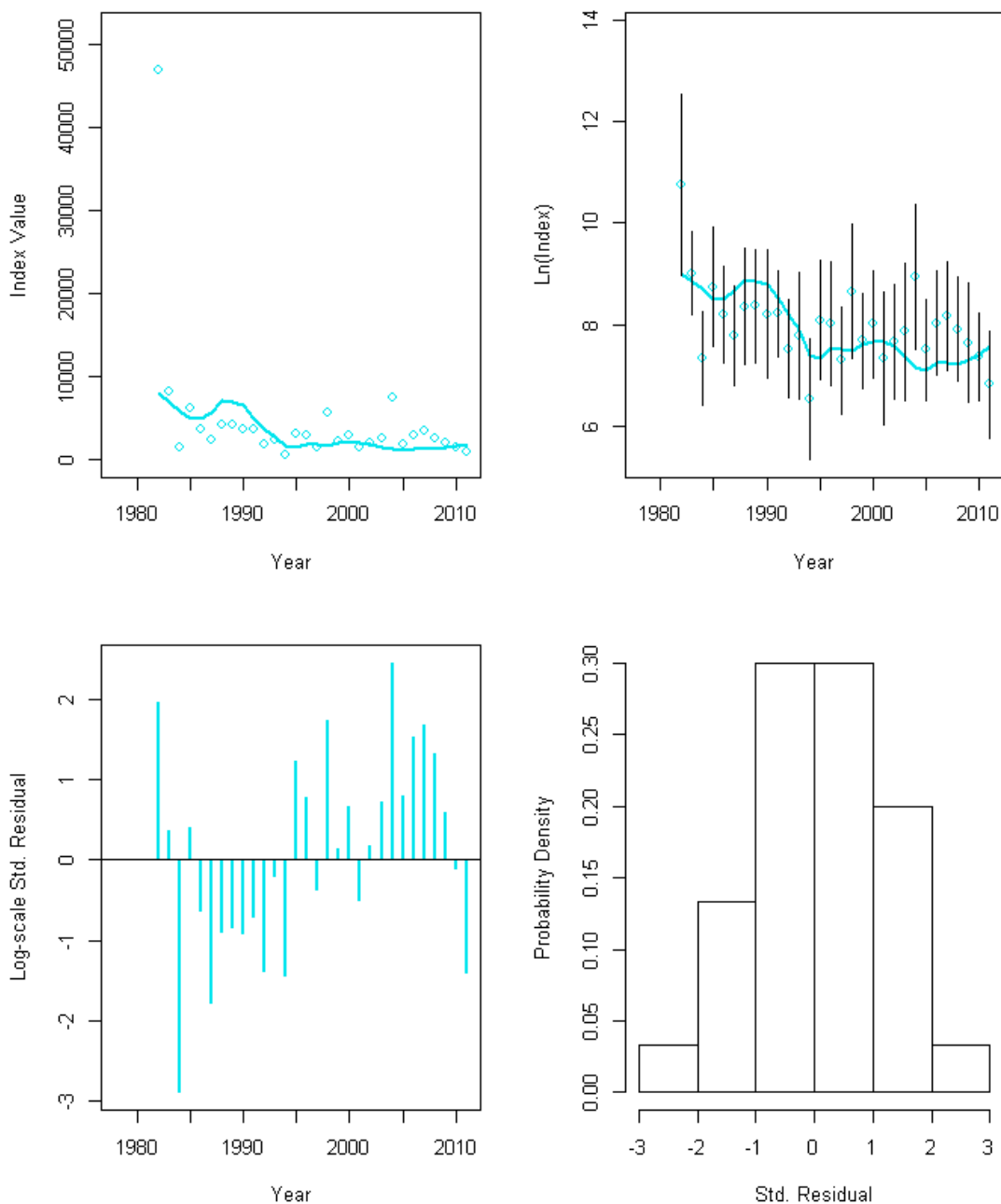
Figure 26. ASAP model run1_o3.1 fit to NEFSC spring Yankee #36 trawl survey indices of Eastern Georges Bank cod, 1982-2011.
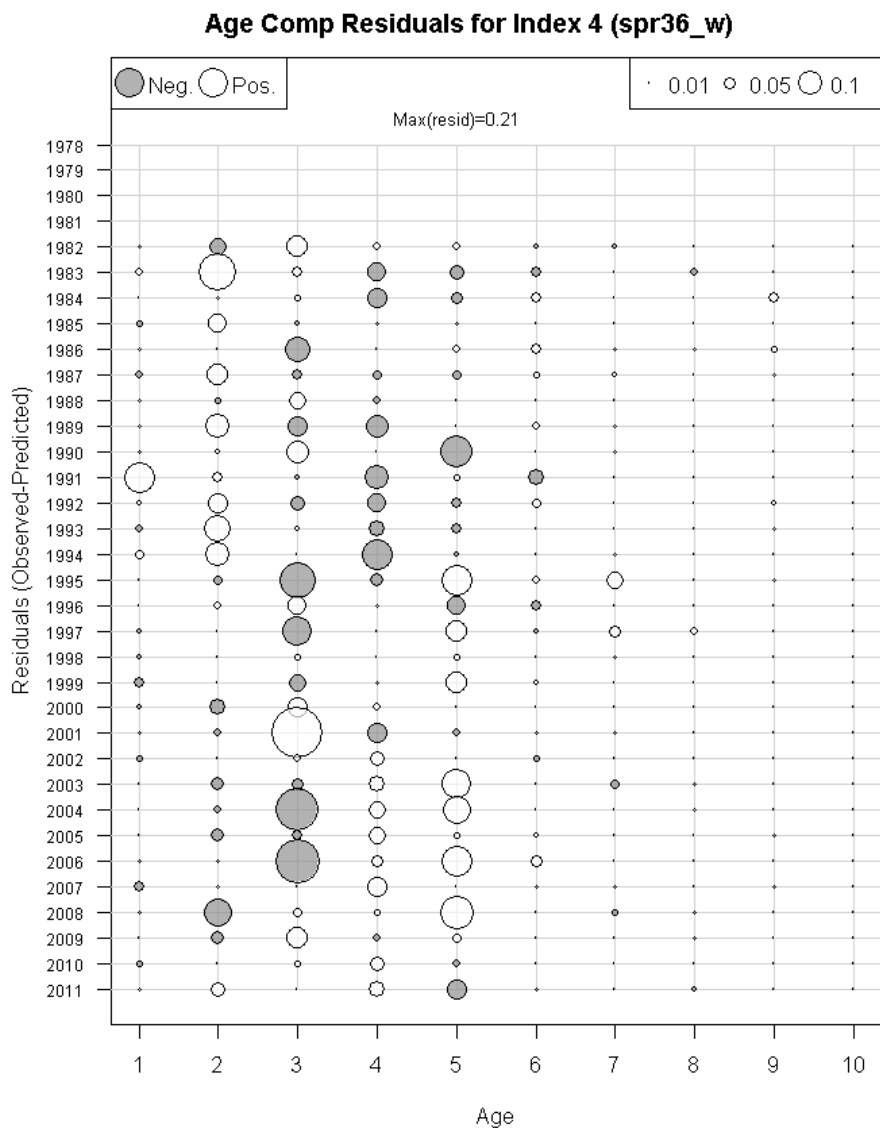
Figure 27. ASAP model run1_o3.1 age composition residuals for NEFSC spring Yankee #36 trawl survey index of Eastern Georges Bank cod, 1982-2011.
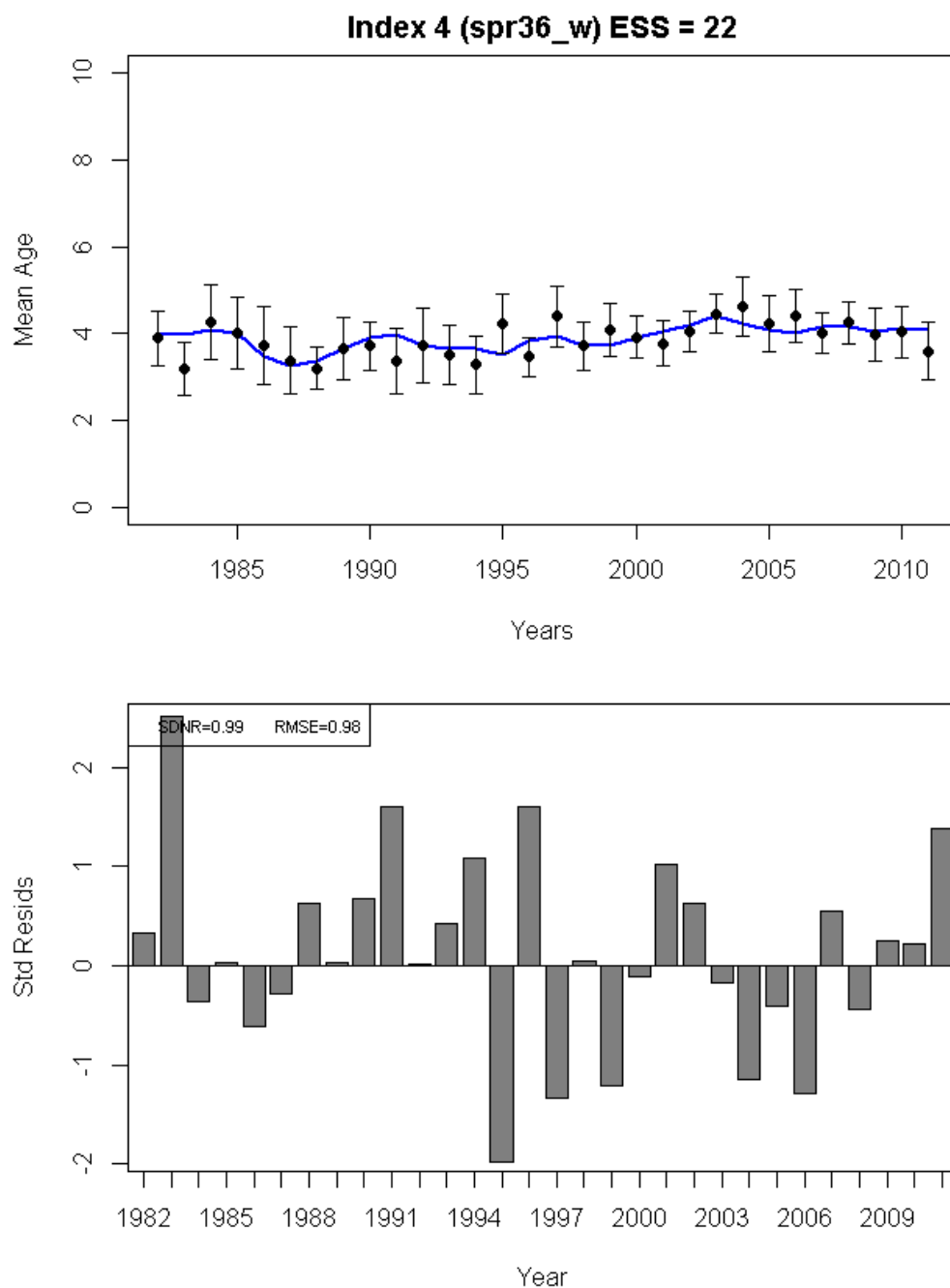
Figure 28. ASAP model run1_o3.1 predicted mean age of Eastern Georges Bank cod in the NEFSC spring Yankee #36 trawl survey (blue line) compared to the observed mean age (top plot) and the residuals about the mean (bottom plot), 1982-2011.
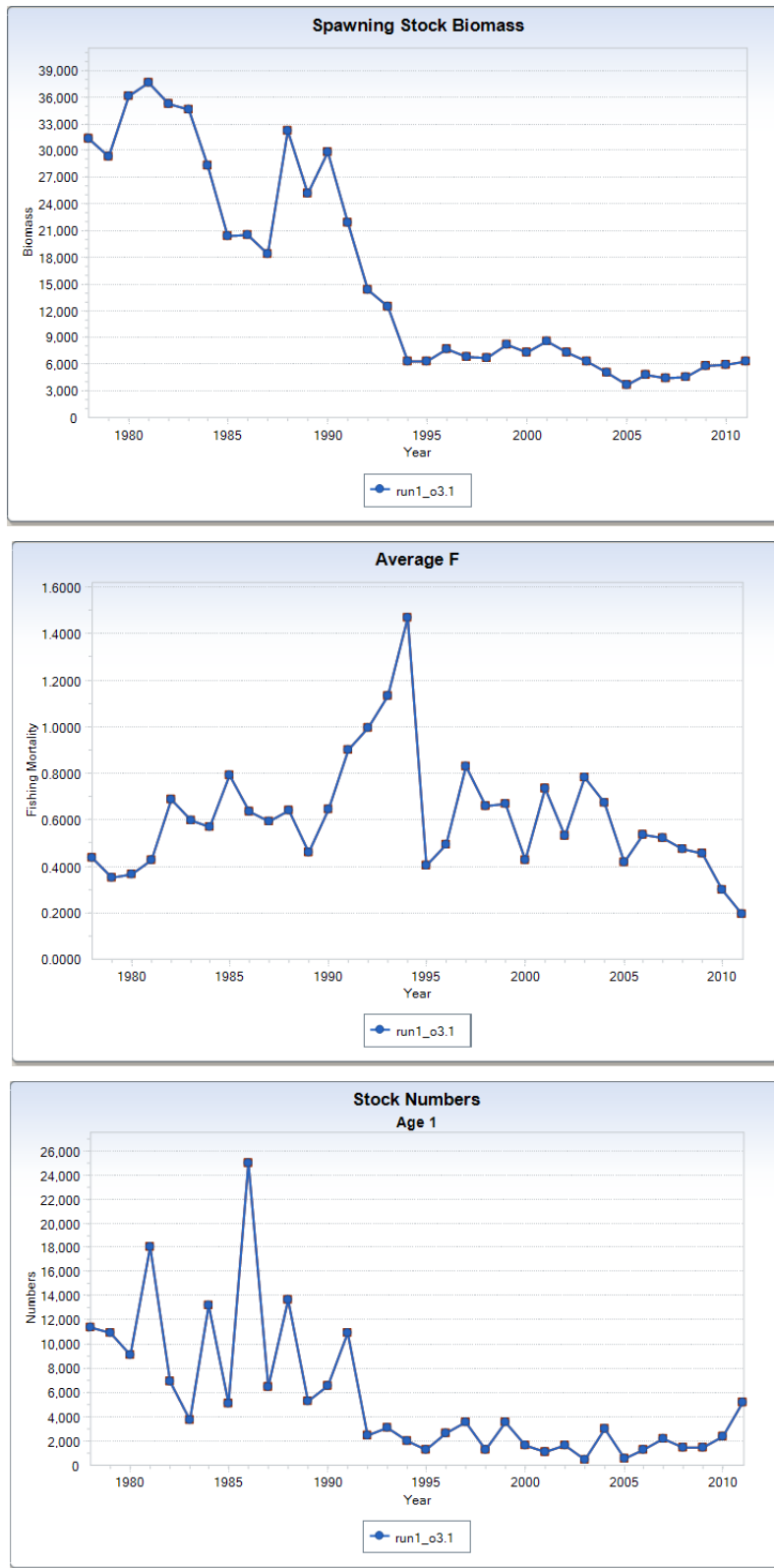
Figure 29. ASAP model run1_o3.1 results for fishing mortality (ages 5+), spawning stock biomass, and recruitment (age1, 000s fish), 1978-2011.
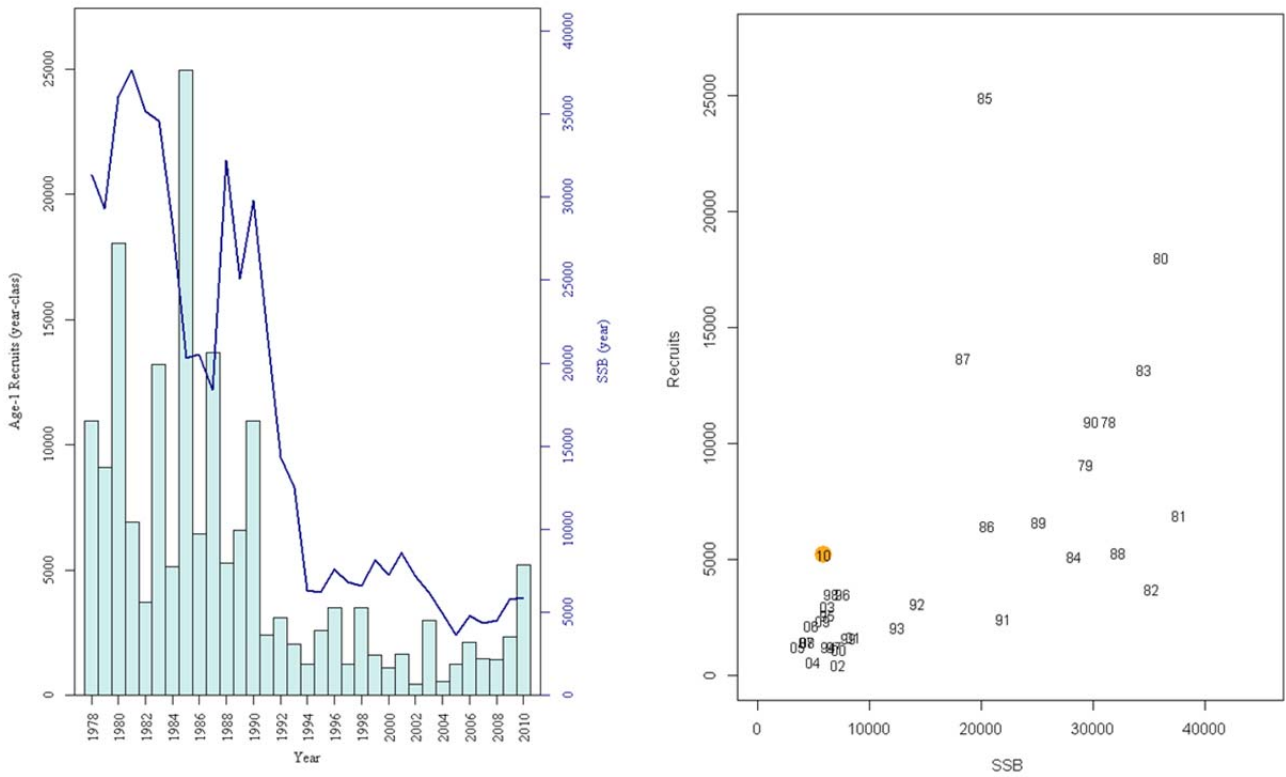
Figure 30. ASAP model run1_o3.1 results for spawning stock biomass (mt) and recruitment (age1, 000s fish), 1978-2011.
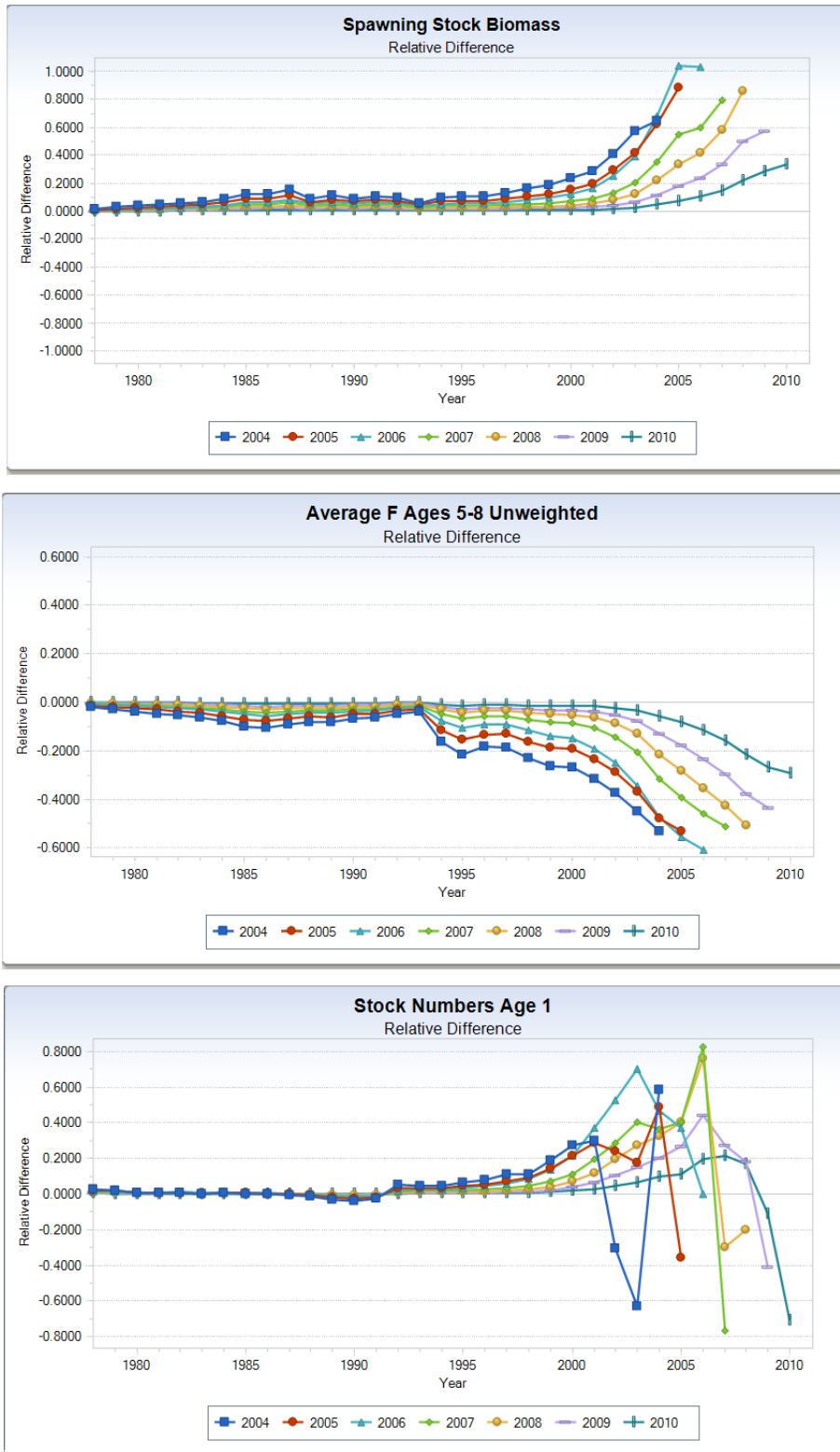
Figure 31. ASAP model run1_o3.1 results of retrospective bias of spawning stock biomass (SSB), fishing mortality (F), and age 1 recruitment. Retrospective bias adjustment for SSB=0.723, F=-0.488, age 1 recruitment=-0.265.
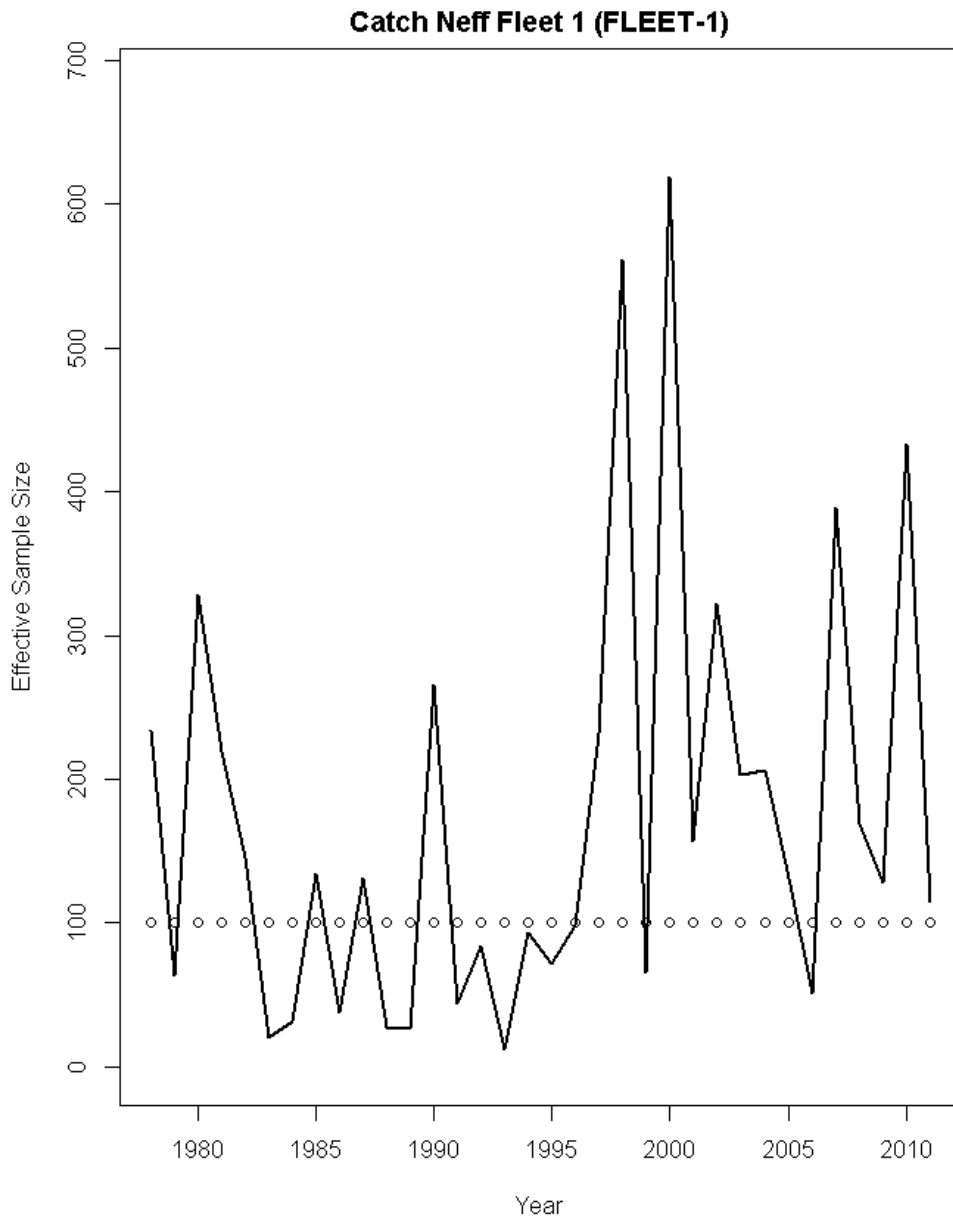
Figure 32. ASAP model run3d.1 observed effective sample size (line) and model predicted effective sample size (circles) for catch.
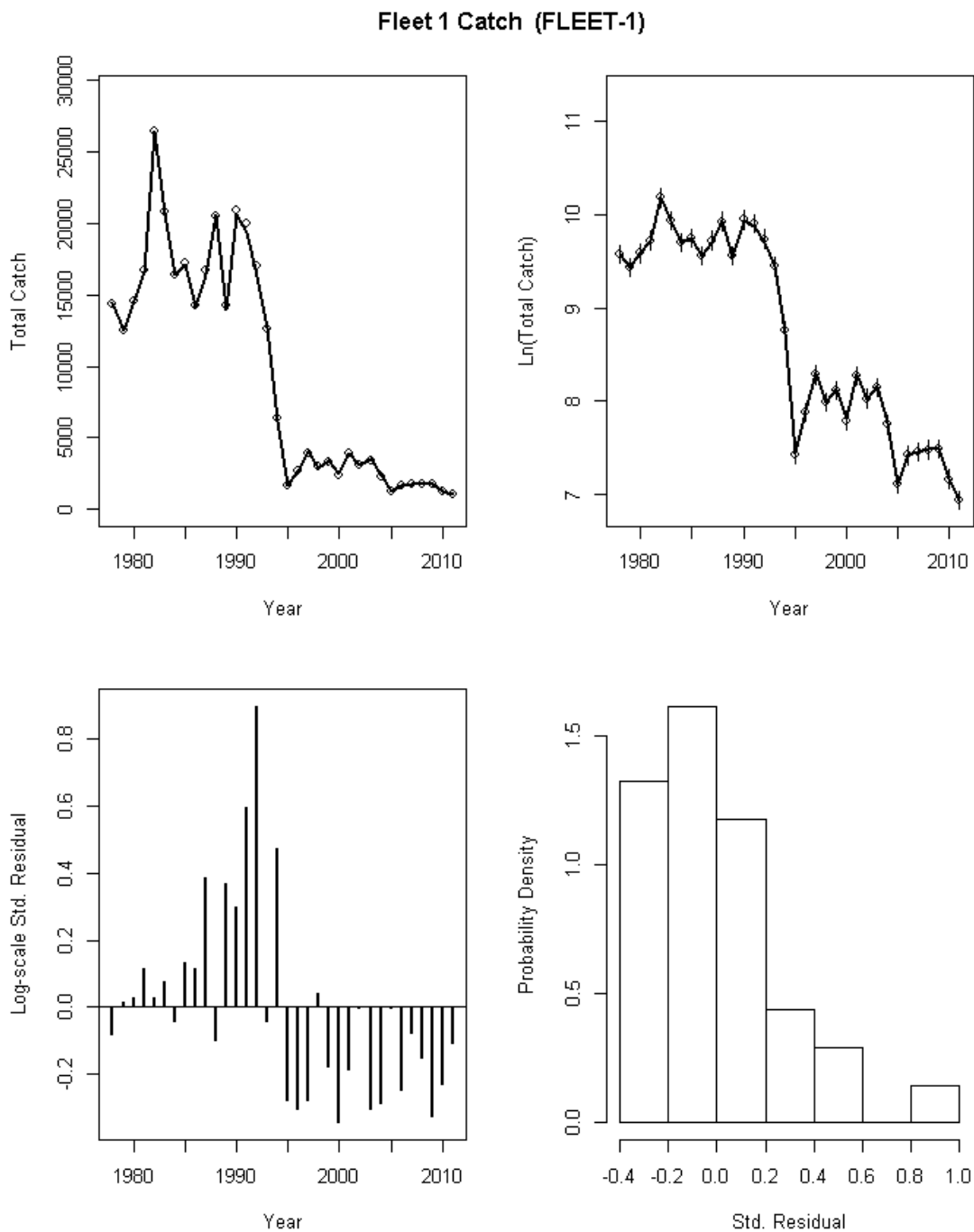
*Figure 33. ASAP model **run3f.1** fit to total catch of Eastern Georges Bank cod, 1978-2011.*
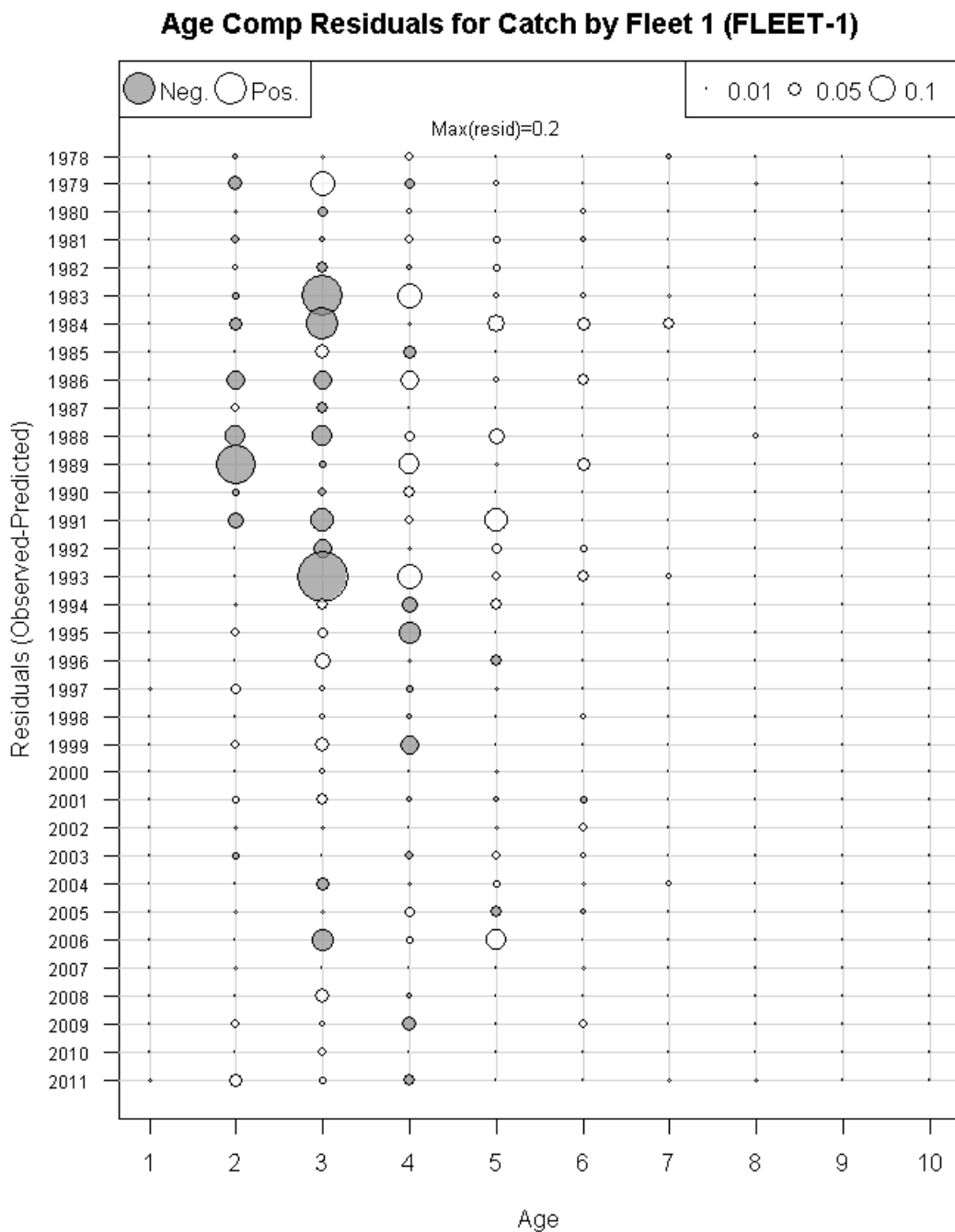
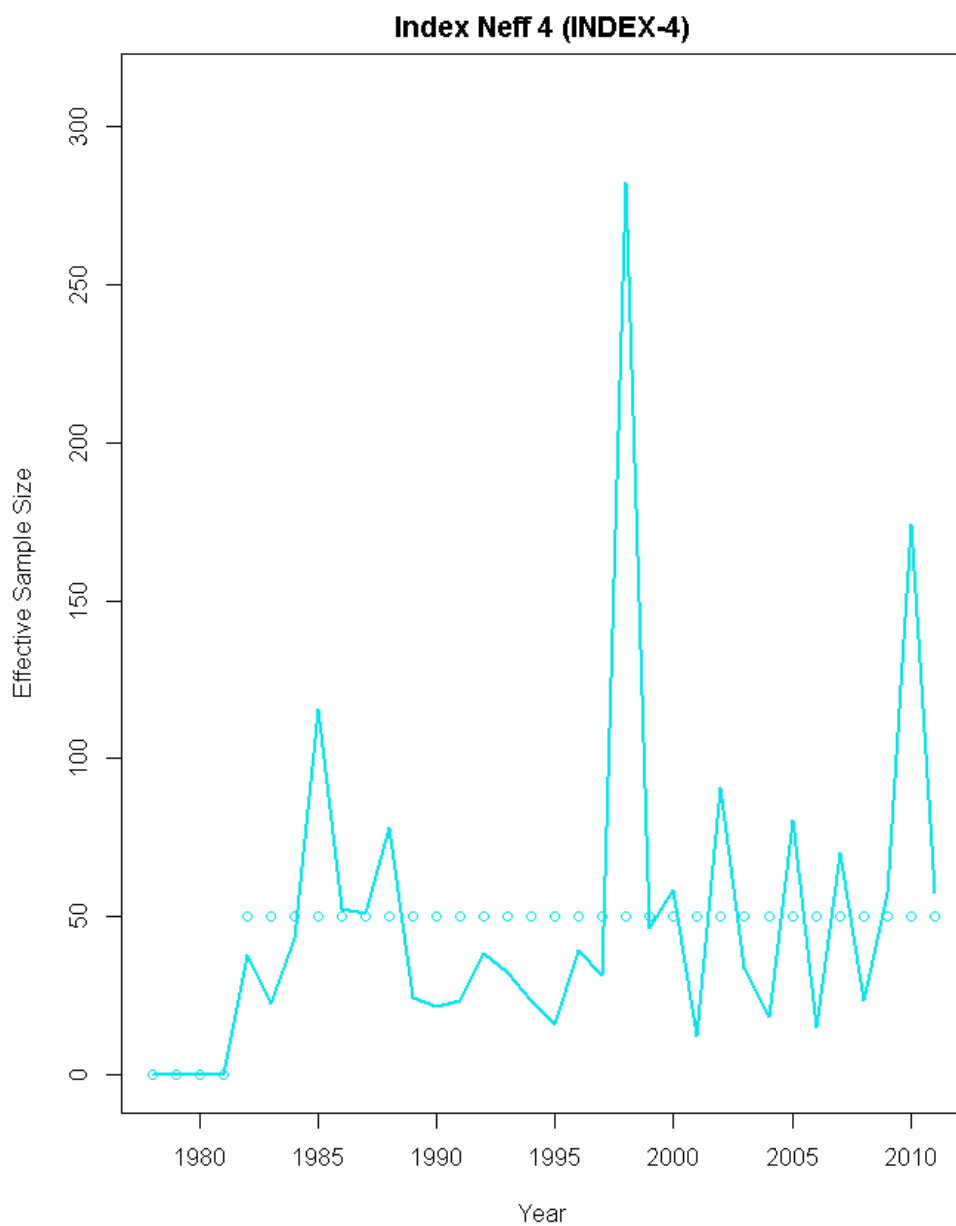*Figure 34. ASAP model **run3f.1** residuals for the commercial catch age composition of Eastern Georges Bank cod, 1978-2011.*
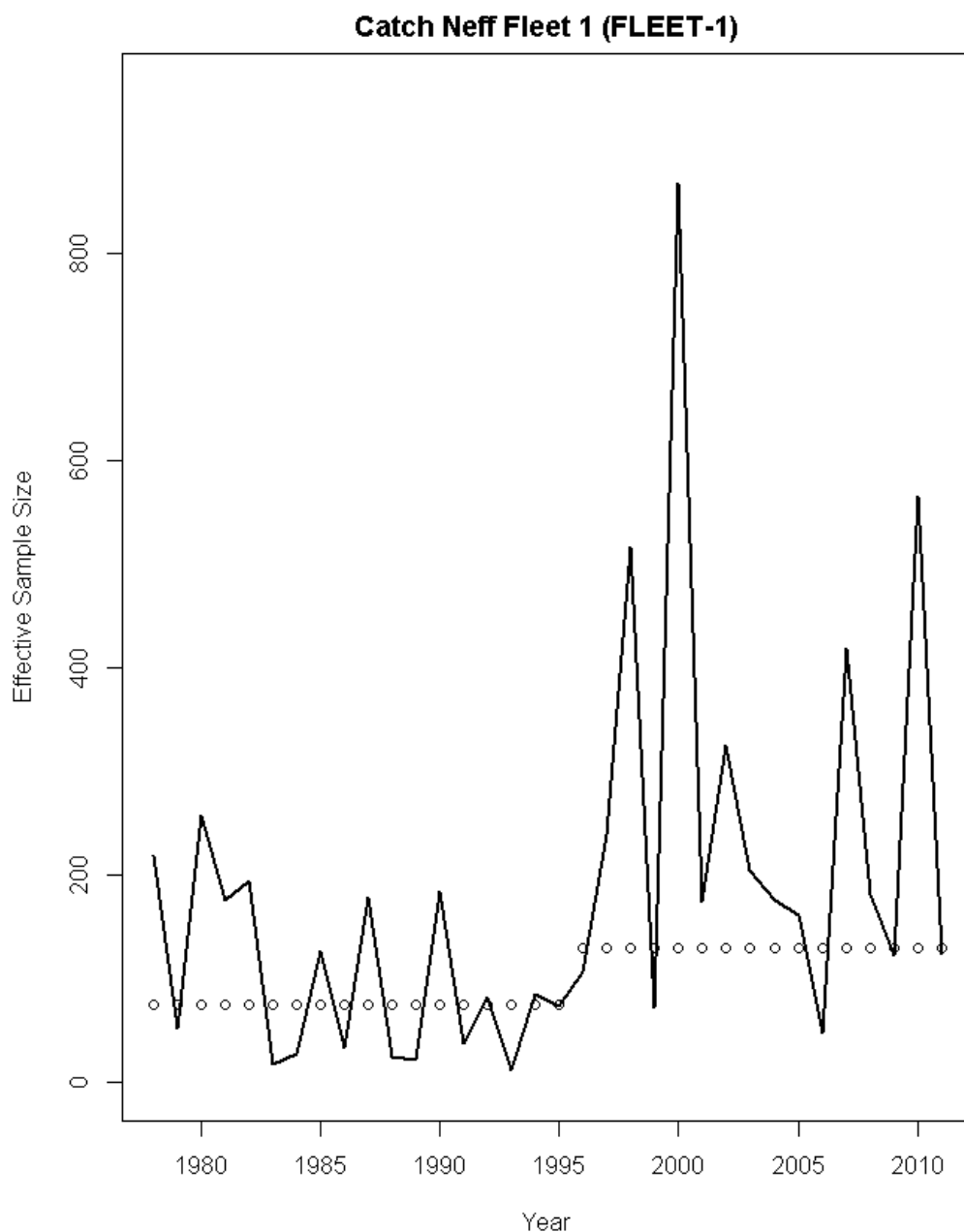
*Figure 35. ASAP model **run3f.1** observed (line) and predicted (circles) effective sample size of Eastern Georges Bank cod in the total catch, 1978-2011.*

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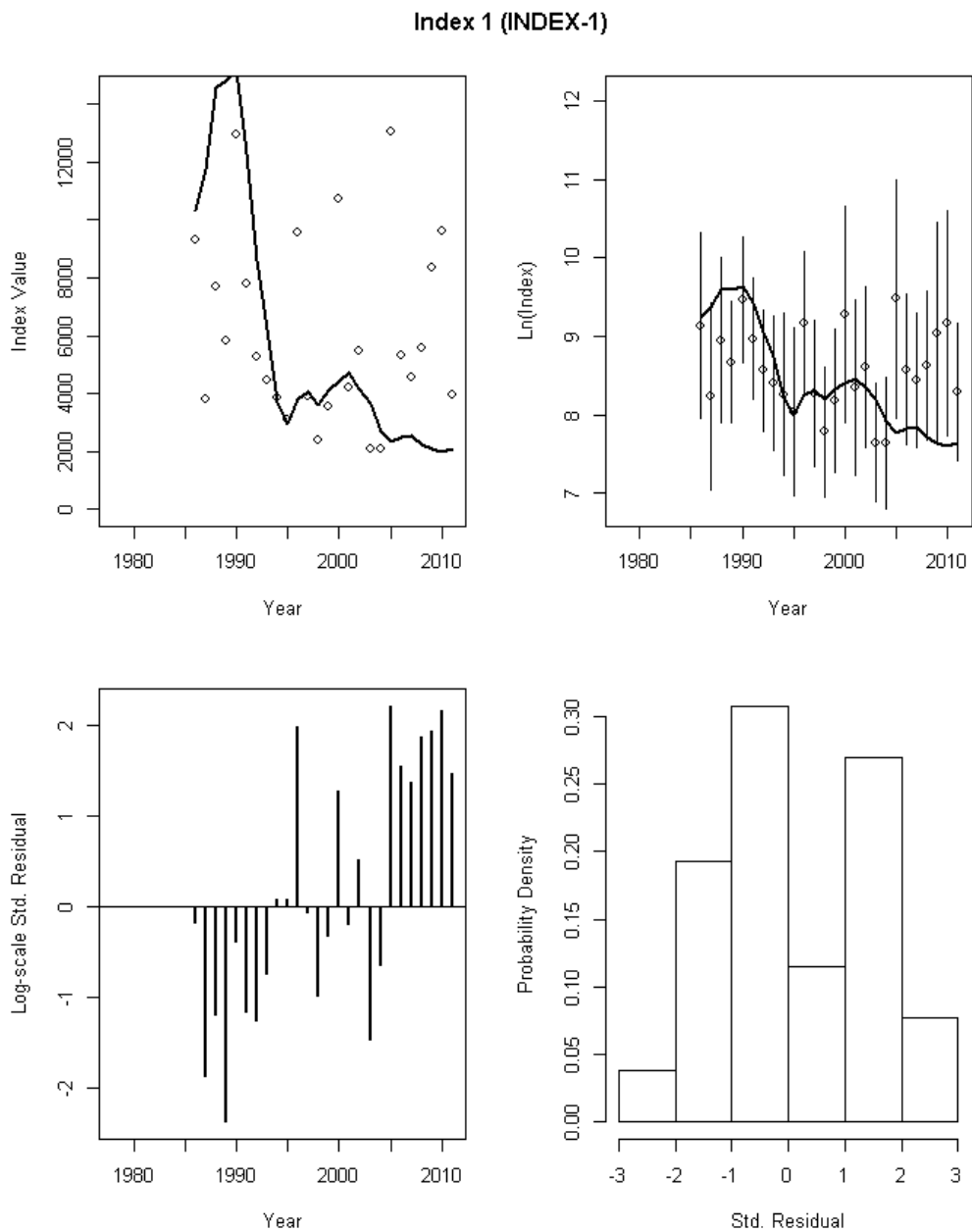
*Figure 36. ASAP model **run3f.1** fit to DFO survey indices of Eastern Georges Bank cod, 1978-2011.*
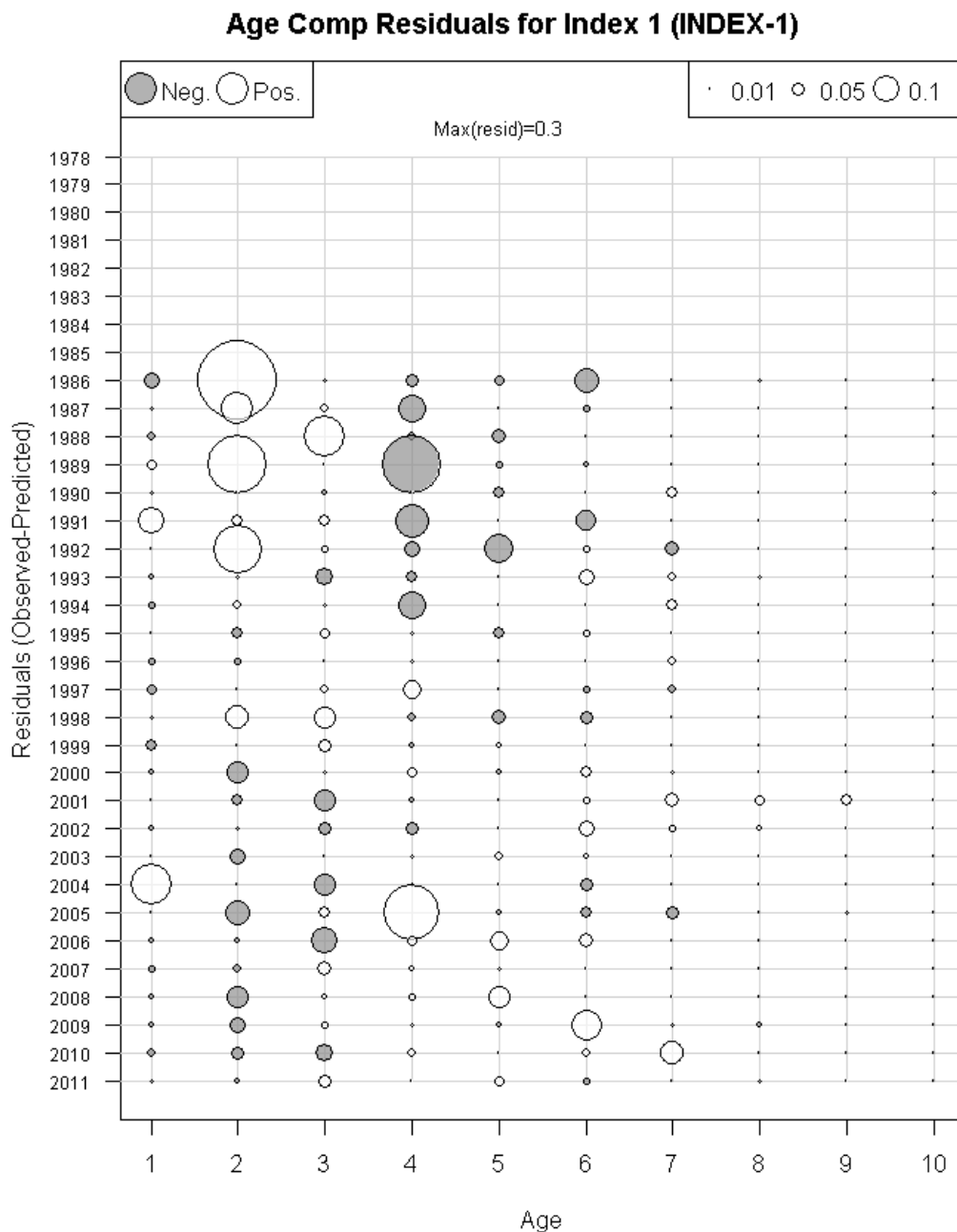
*Figure 37. ASAP model **run3f.1** age composition residuals for DFO survey index of Eastern Georges Bank cod, 1978-2011.*
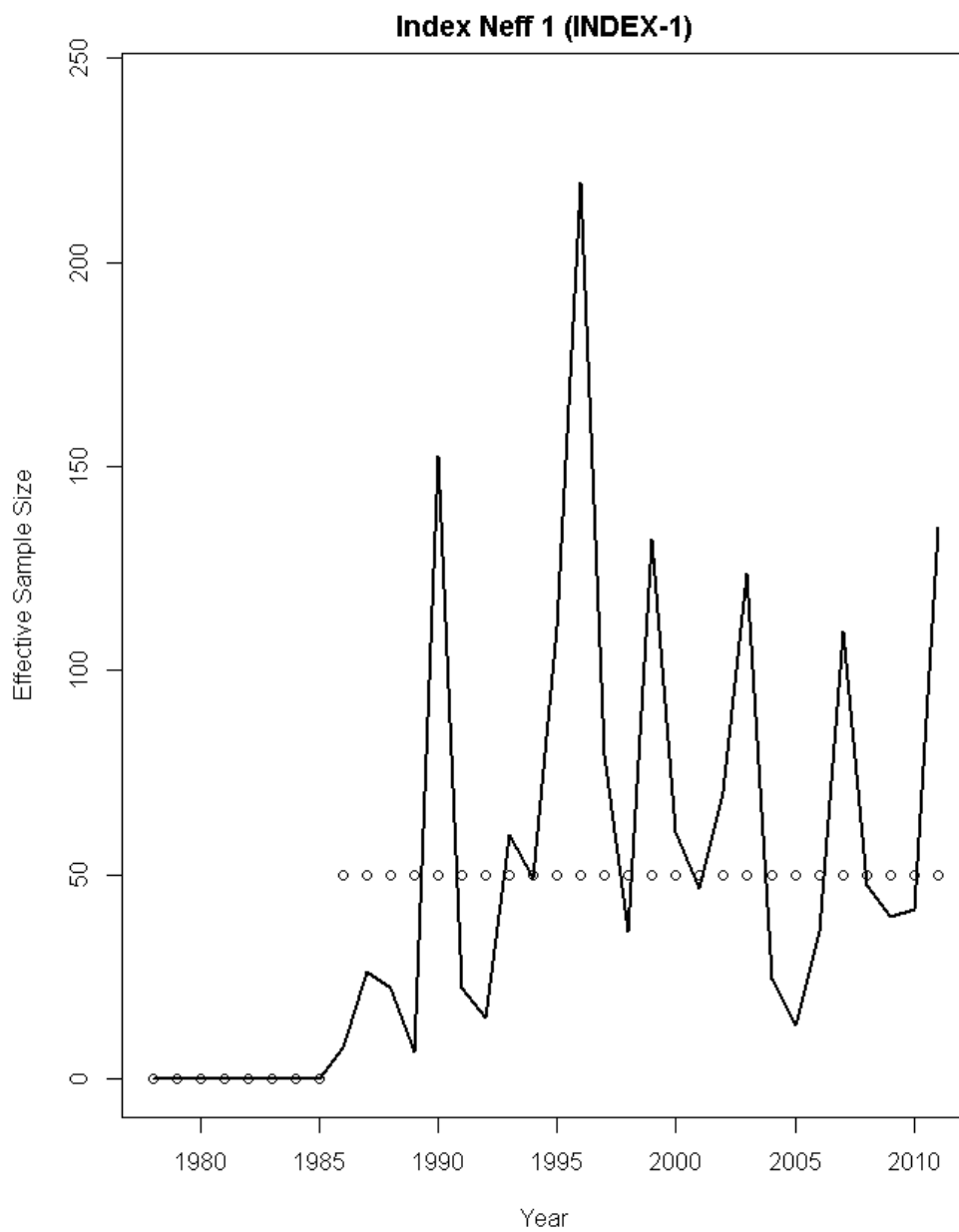
*Figure 38. ASAP model **run3f.1** observed (line) and predicted (circles) effective sample size of Eastern Georges Bank cod in the DFO survey, 1978-2011.*
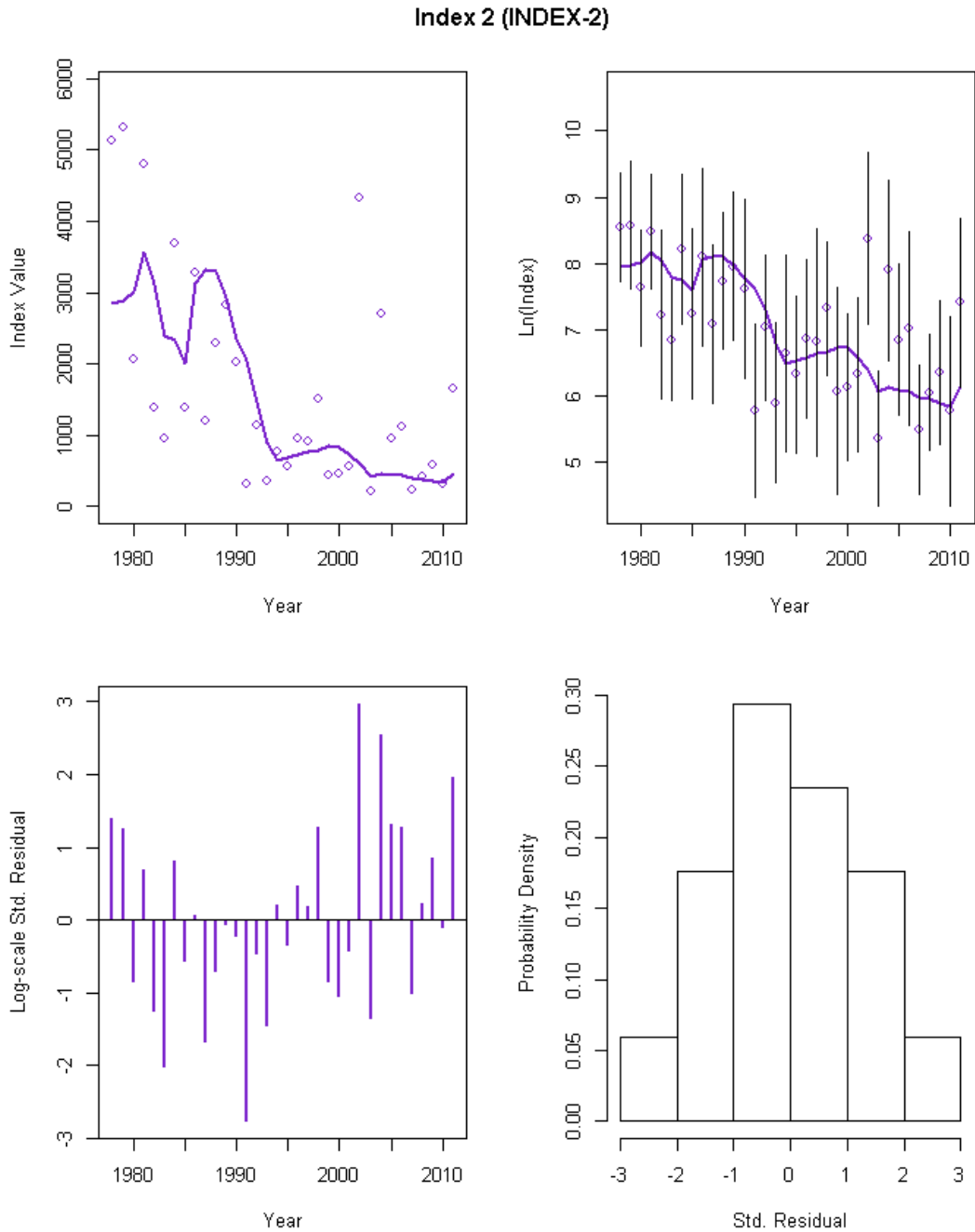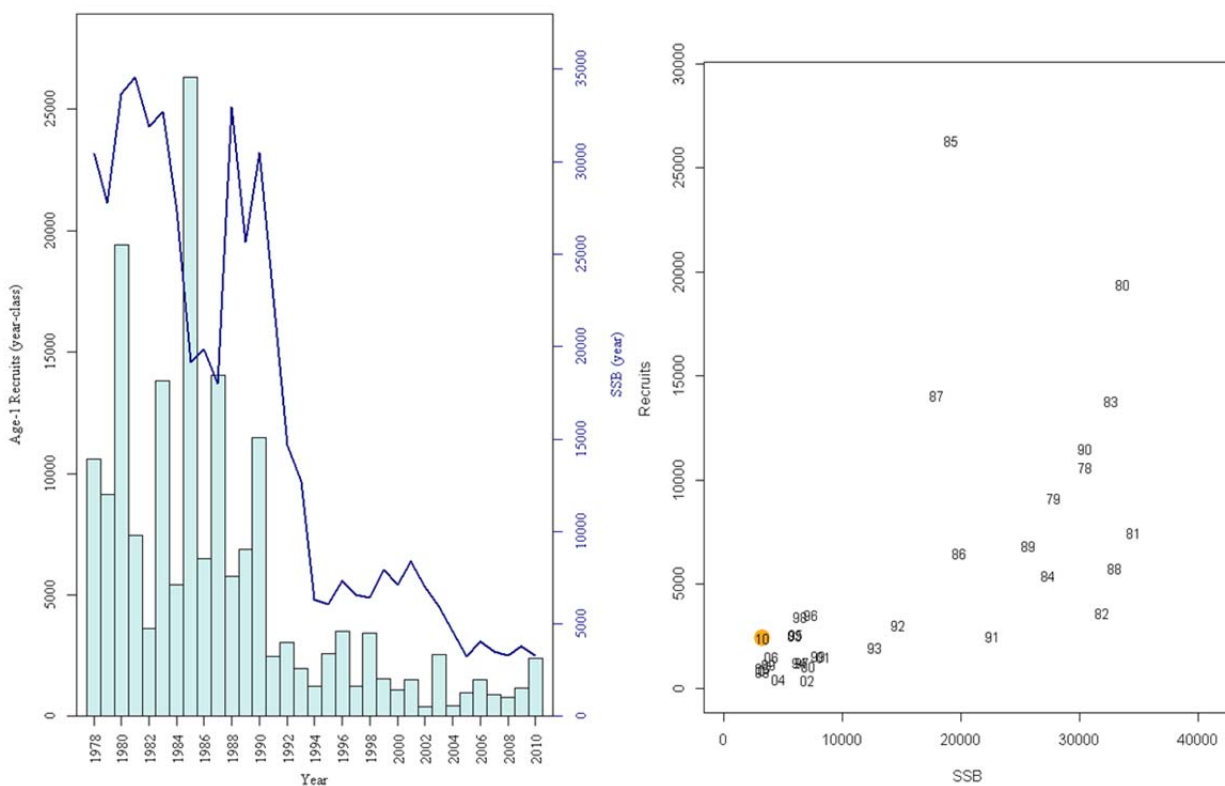
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Figure 30. ASAP model run1_o3.1 results for spawning stock biomass (mt) and recruitment (age1, 000s fish), 1978-2011. The most recent year class, 2010, is circled in orange (right panel).

*Figure 40. ASAP model **run3f.1** age composition residuals for NEFSC autumn survey index of Eastern Georges Bank cod, 1978-2011.*
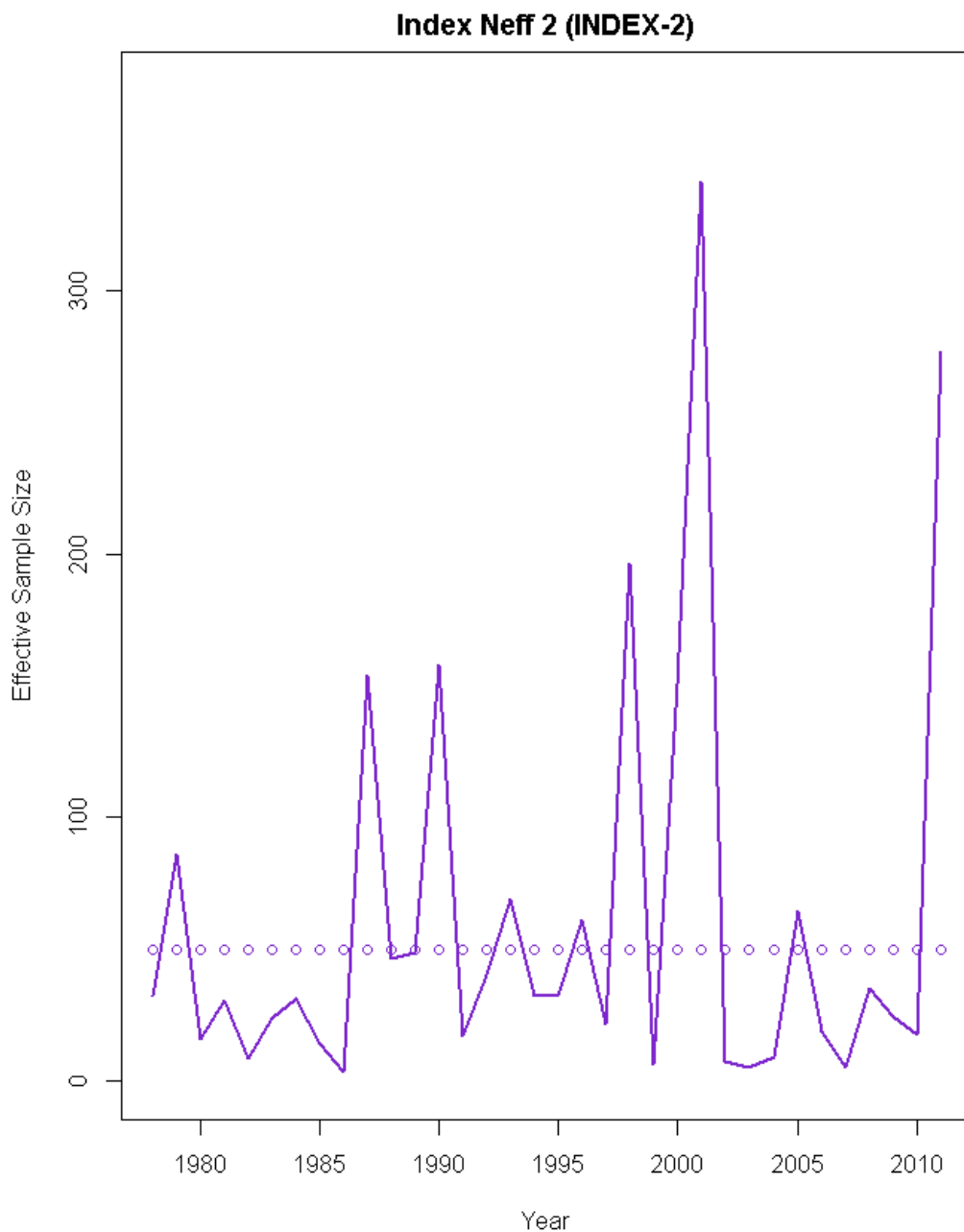
*Figure 41. ASAP model **run3f.1** observed (line) and predicted (circles) effective sample size of Eastern Georges Bank cod in the NEFSC autumn survey, 1978-2011.*

Figure 42. ASAP model **run3f.1** fit to NEFSC spring Yankee #41 trawl survey indices of Eastern Georges Bank cod, 1978-2011.

*Figure 43. ASAP model **run3f.1** age composition residuals for NEFSC spring Yankee #41 trawl survey index of Eastern Georges Bank cod, 1978-1981.*
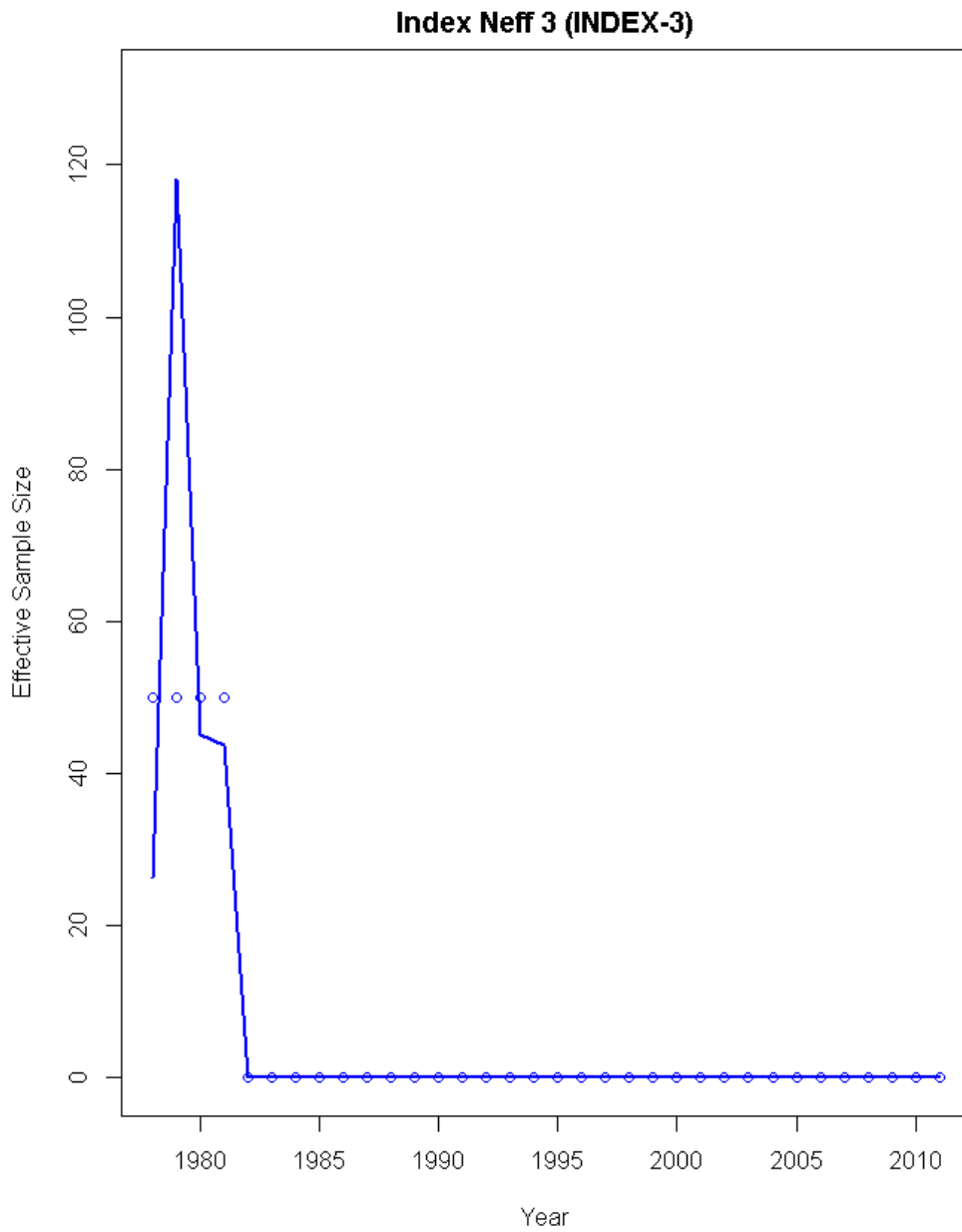
*Figure 44. ASAP model **run3f.1** observed (line) and predicted (circles) effective sample size of Eastern Georges Bank cod in the NEFSC spring Yankee #41 trawl survey, 1978-2011.*
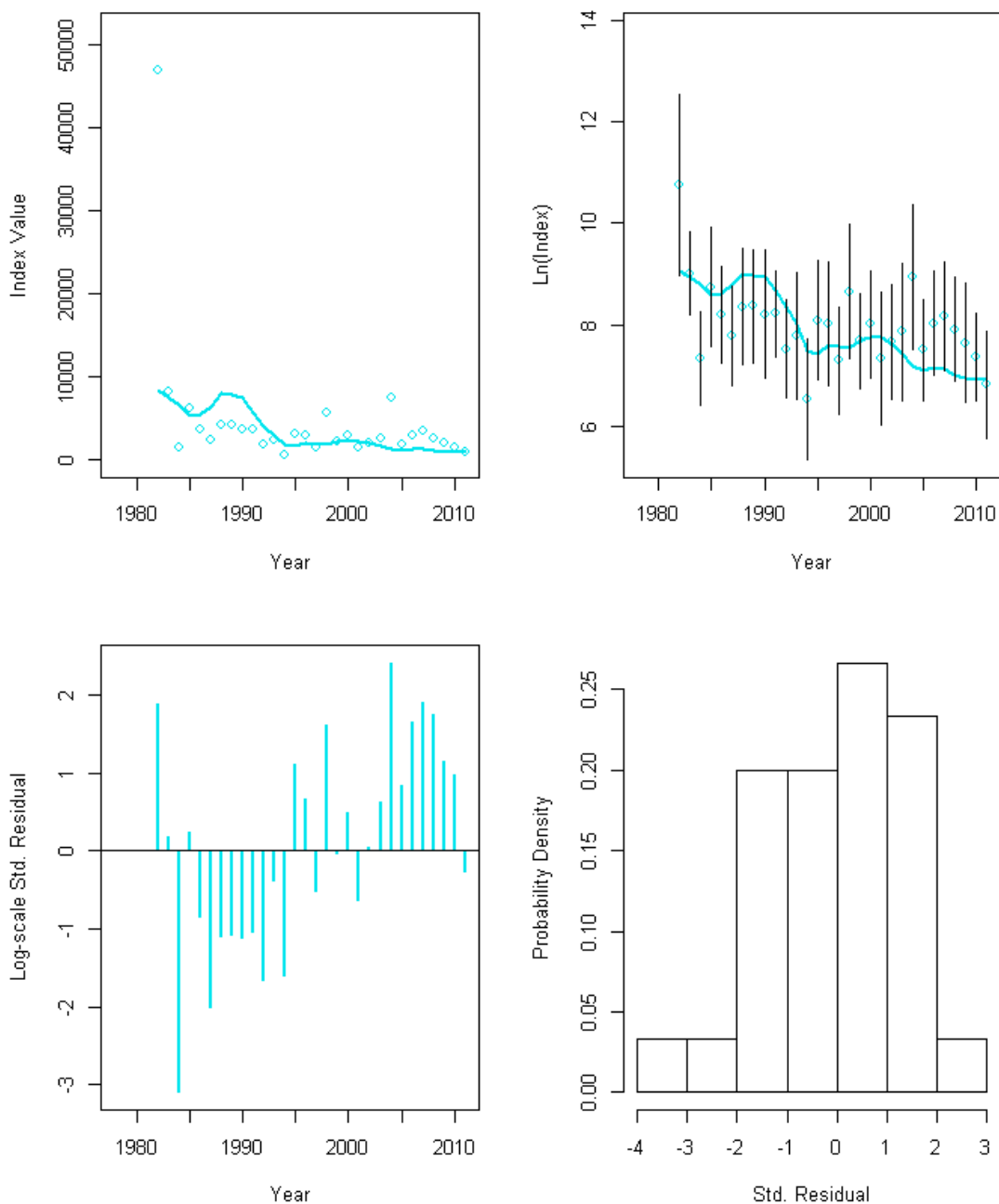
*Figure 45. ASAP model **run3f.1** fit to NEFSC spring Yankee #36 trawl survey indices of Eastern Georges Bank cod, 1982-2011.*
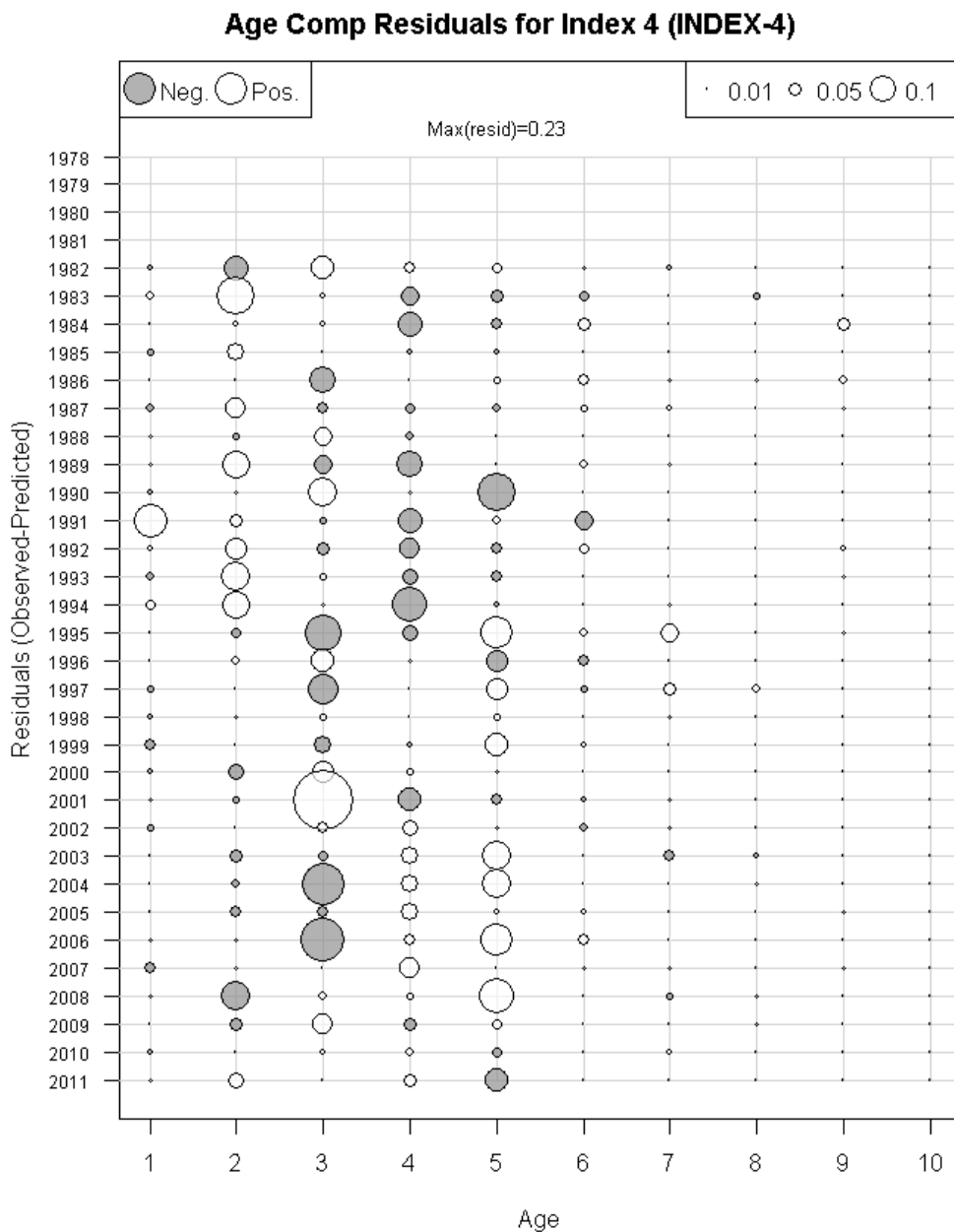
*Figure 46. ASAP model **run3f.1** age composition residuals for NEFSC spring Yankee #36 trawl survey index of Eastern Georges Bank cod, 1982-2011.*

*Figure 47. ASAP model **run3f.1** observed (line) and predicted (circles) effective sample size of Eastern Georges Bank cod in the NEFSC spring Yankee #36 trawl survey, 1982-2011.*
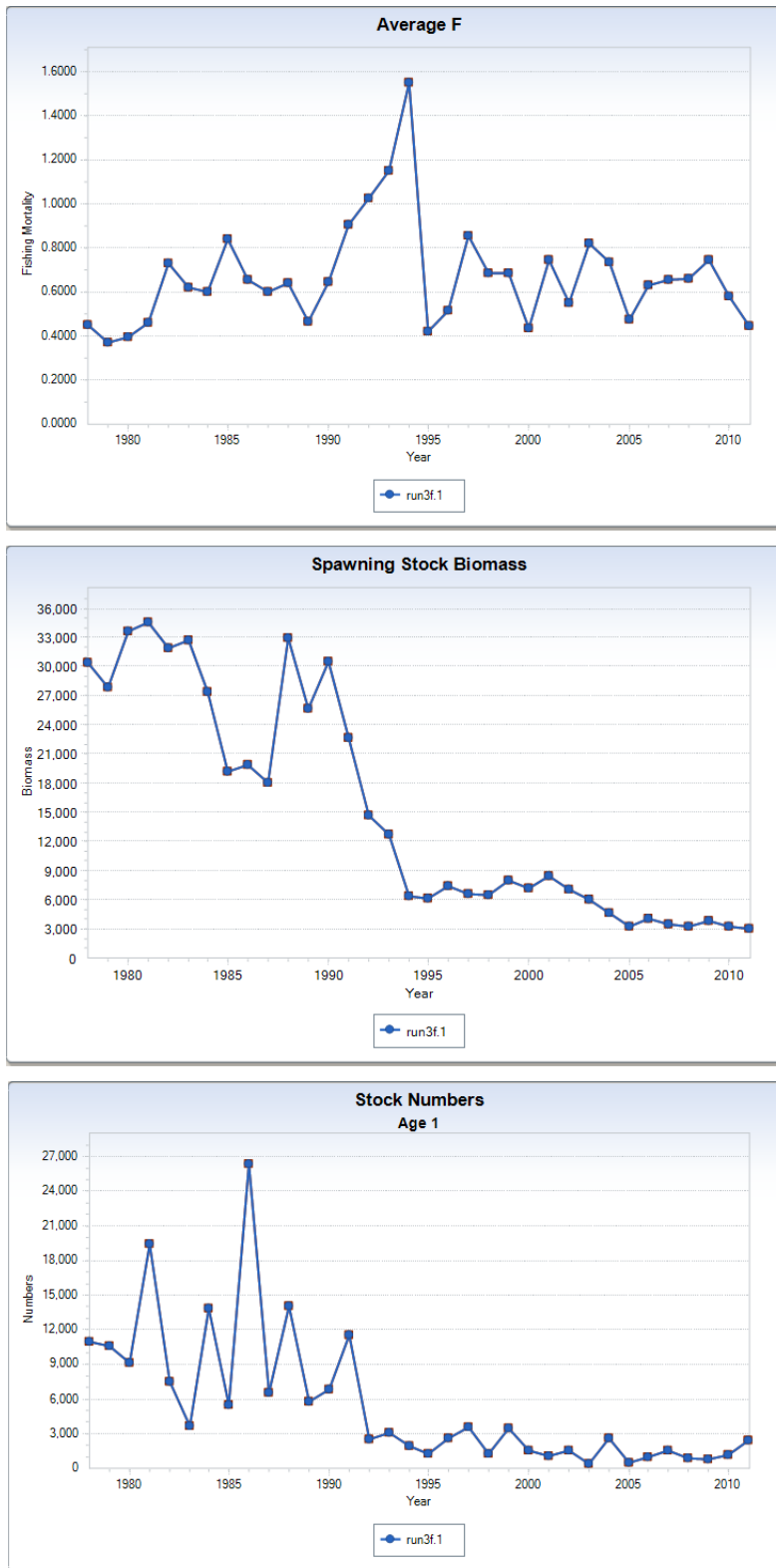
Figure 48. ASAP model **run3f.1** results for fishing mortality (ages 5+), spawning stock biomass, and recruitment (age1, 000s fish), 1978-2011.

*Figure 49. ASAP model **run3f.1** results for spawning stock biomass (SSB, mt) and recruitment (age1, 000s fish), 1978-2011. The most recent year class, 2010, is circled in orange (right panel).*
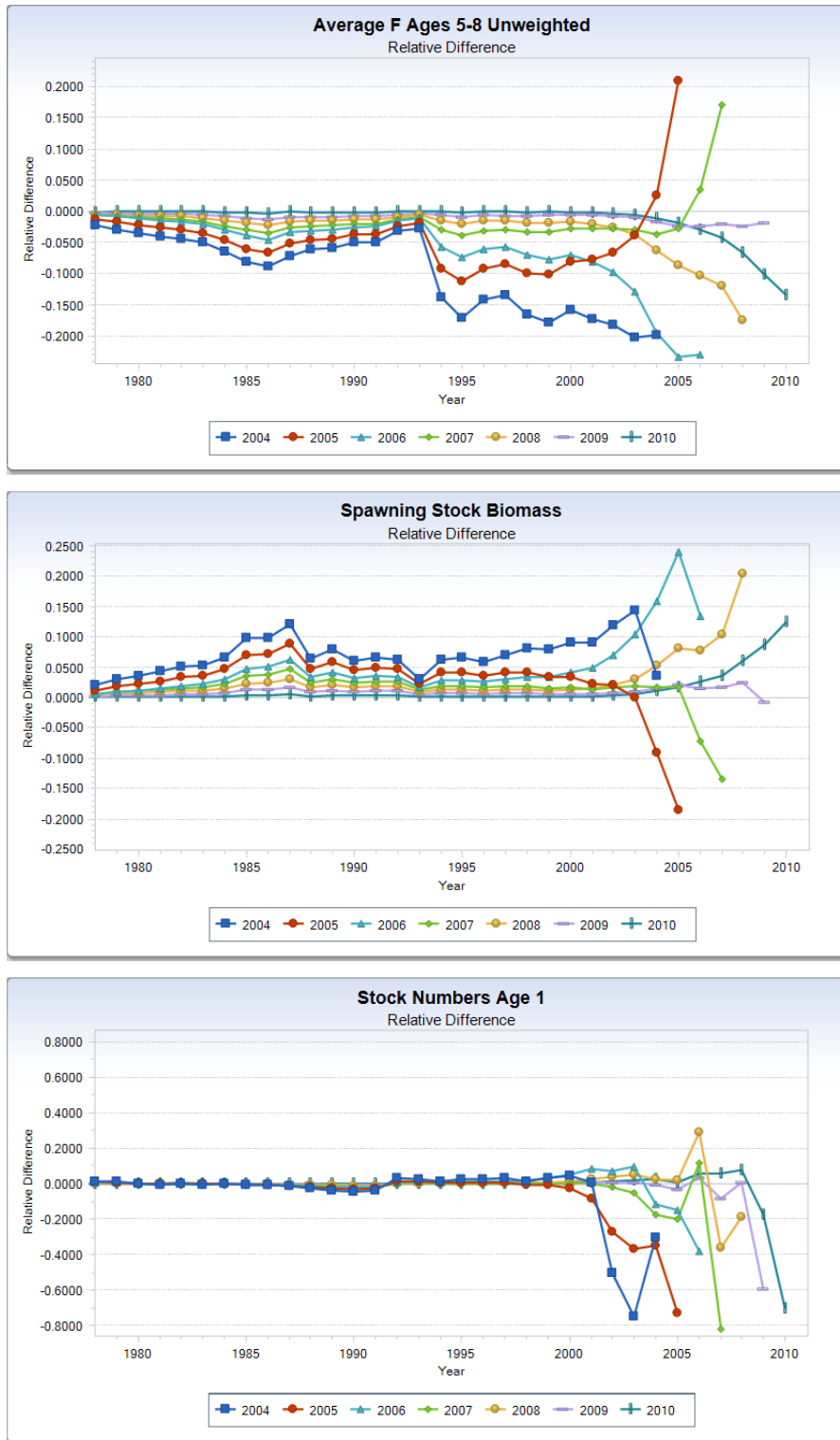
Figure 50. ASAP model **run3f.1** results of retrospective bias of fishing mortality (F), spawning stock biomass (SSB), and age1 recruitment. Retrospective bias adjustment for F=-0.054, SSB=0.025, and age 1 recruitment=-0.529.
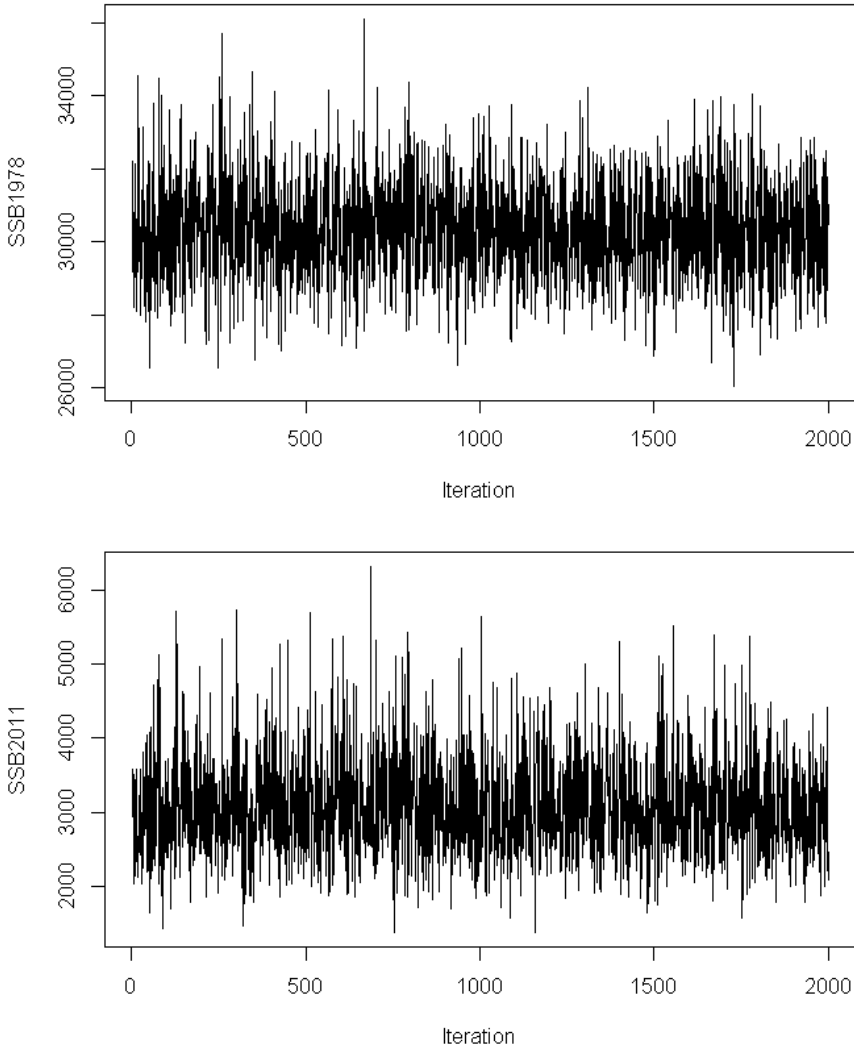
*Figure 51. ASAP model **run3f.1** results of trace of MCMC chains for Eastern Georges Bank cod spawning stock biomass for 1978 and 201. Each chain had an initial length of 5.0 million and was thinned at a rate of one out of every 2,500th resulting in a final chain length of 2000.*
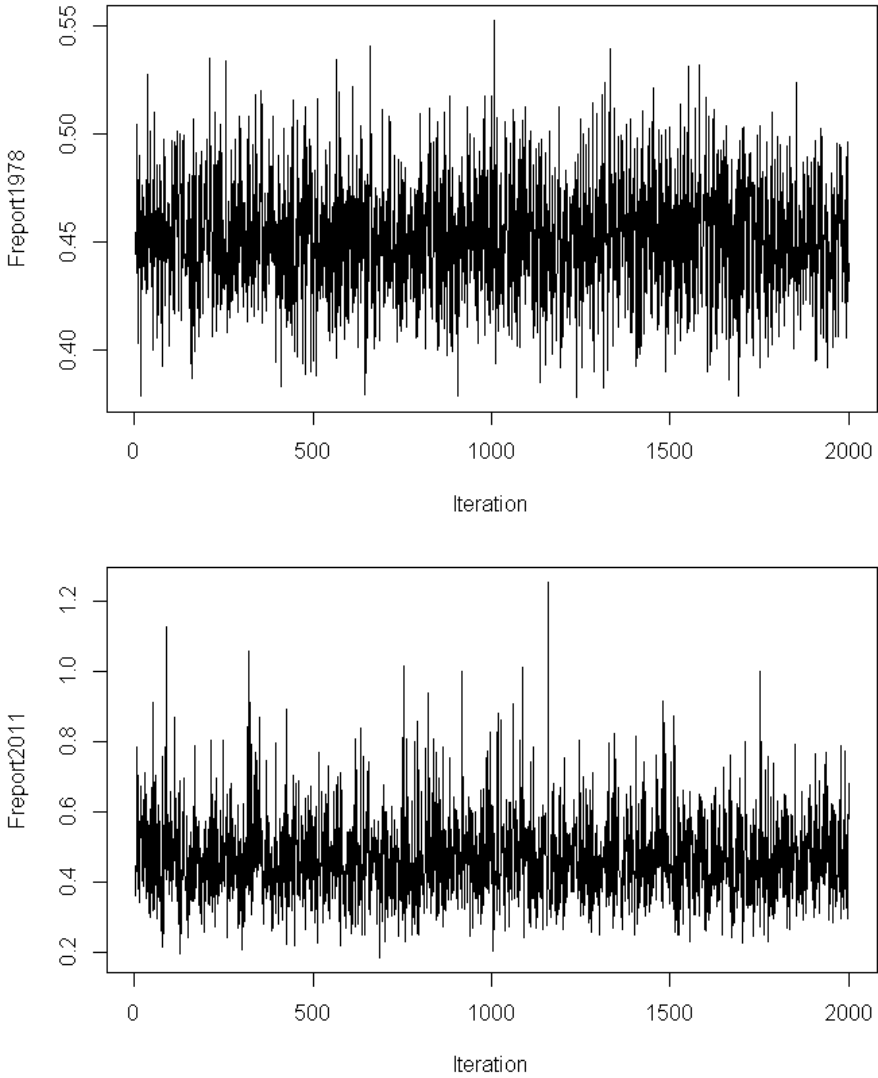
*Figure 52. ASAP model **run3f.1** results of trace of MCMC chains for Eastern Georges Bank cod fishing mortality for 1978 and 2011. Each chain had an initial length of 5.0 million and was thinned at a rate of one out of every 2,500[th] resulting in a final chain length of 2000.*
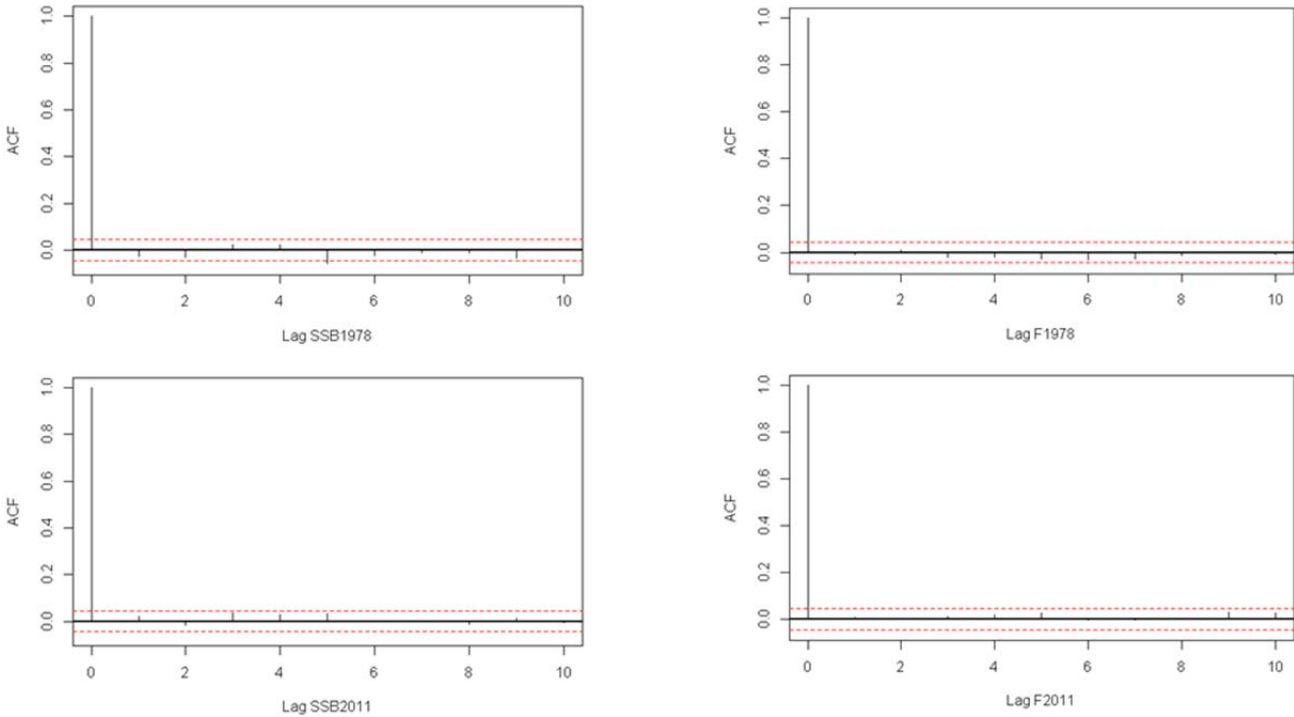
*Figure 53. ASAP model **run3f.1** auto correction within the 1978 and 2011 MCMC chains for spawning stock biomass (SSB, left panel) and fishing mortality (F, right panel) for Eastern Georges Bank cod.*
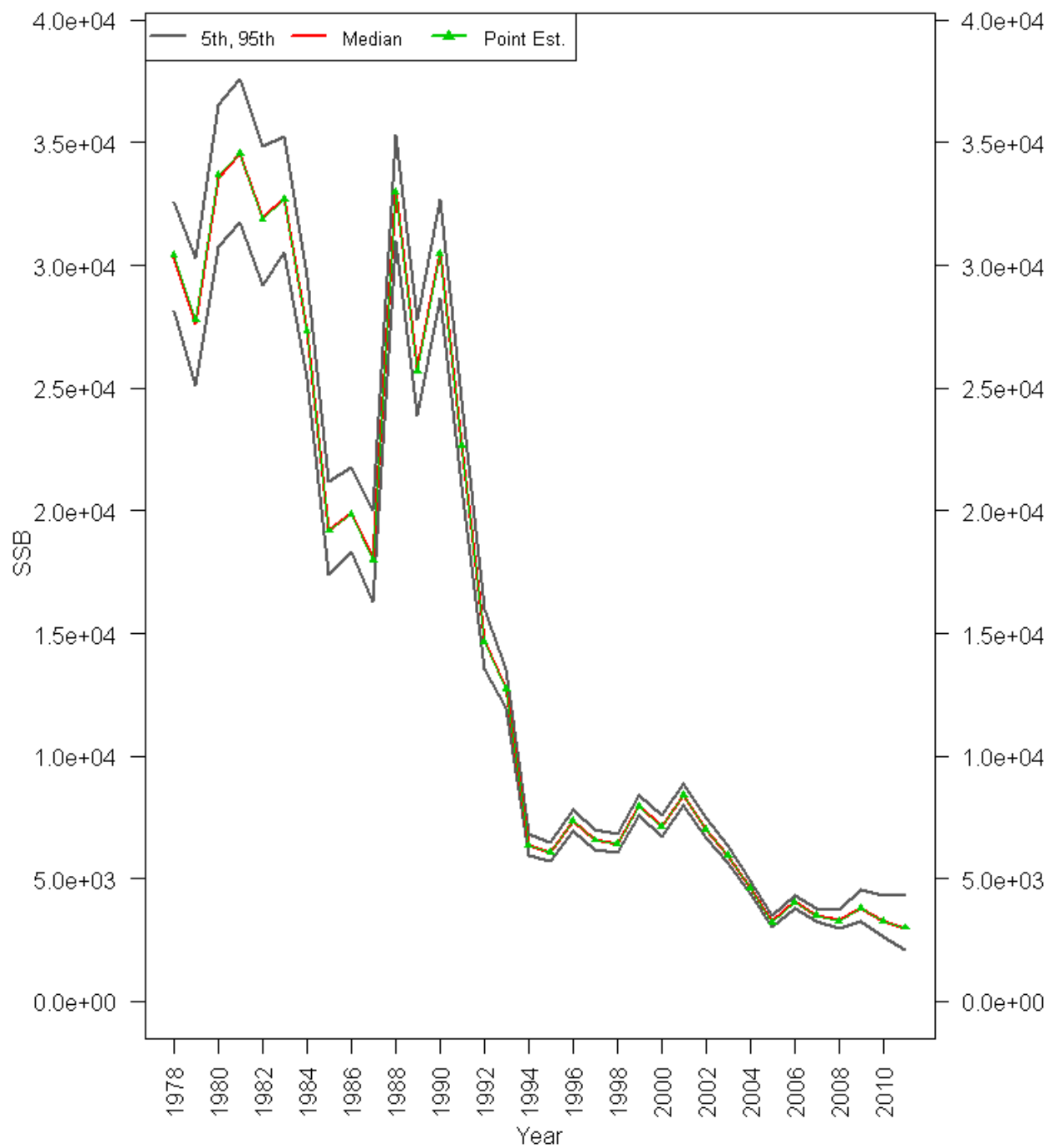
*Figure 54. ASAP model **run3f.1** 90% probability interval for Eastern Georges Bank cod spawning stock biomass (SSB). The median value is in red, while the 5th and 95th percentiles are in dark gray. The point estimate from the model (joint posterior modes) is shown in the thin green line with filled triangles.*
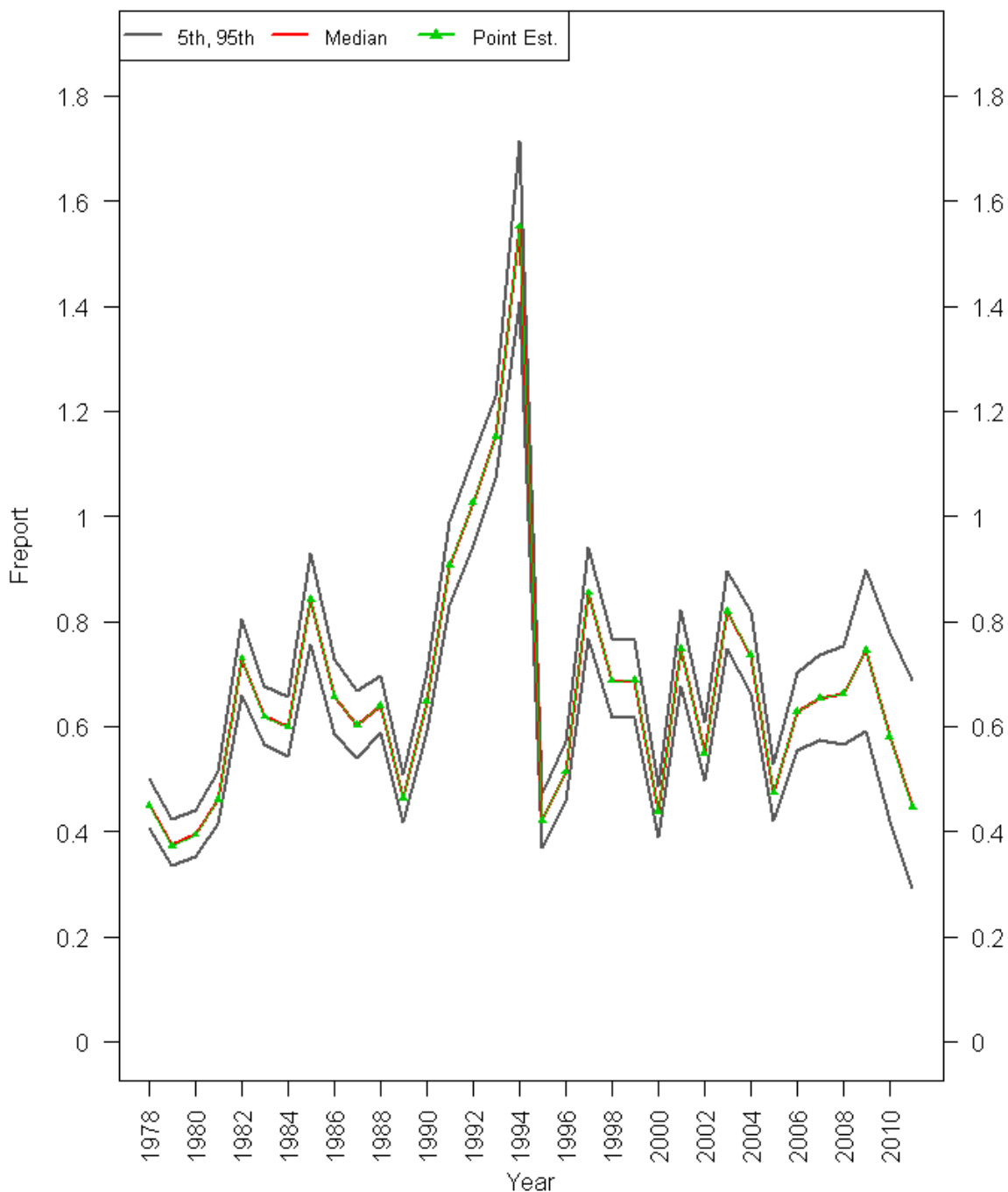
*Figure 55. ASAP model **run3f.1** 90% probability interval for Eastern Georges Bank cod fishing mortality (F). The median value is in red, while the 5th and 95th percentiles are in dark gray. The point estimate from the model (joint posterior modes) is shown in the thin green line with filled triangles.*
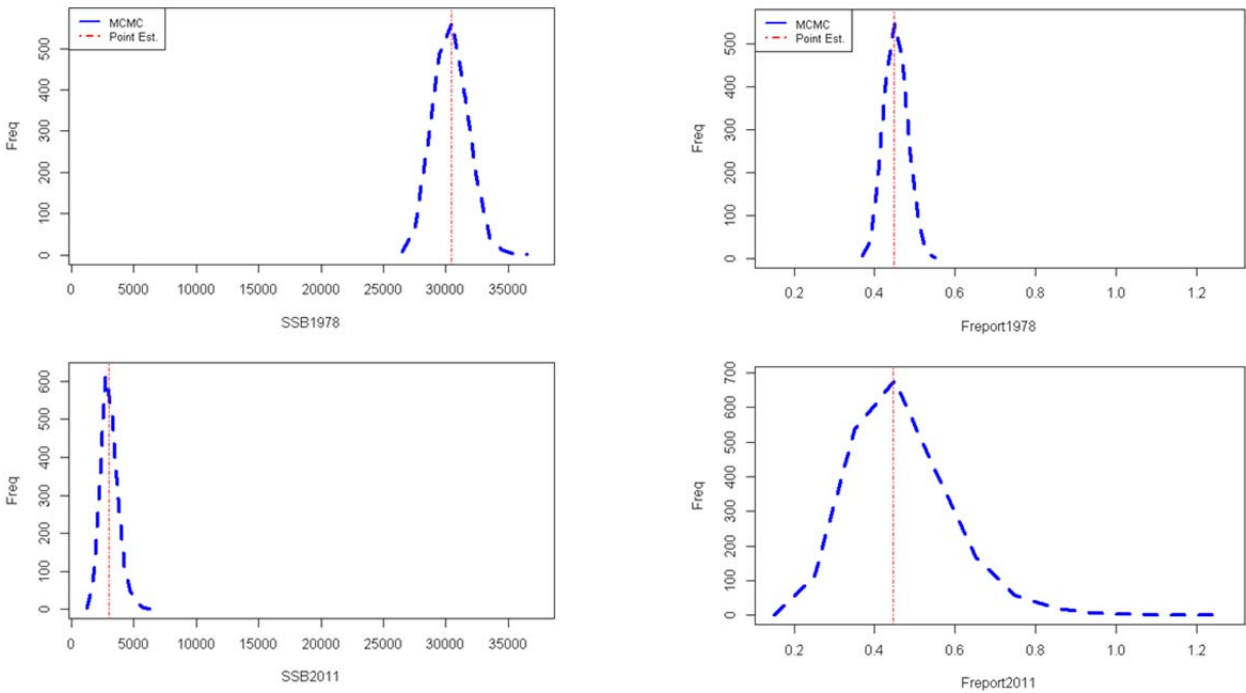
*Figure 56. ASAP model **run3f.1** MCMC distribution of Eastern Georges Bank cod spawning stock biomass (SSB, left panel) and fishing mortality (F, right panel) in 1978 and 2011. The model point estimate is indicated by the dashed red line.*
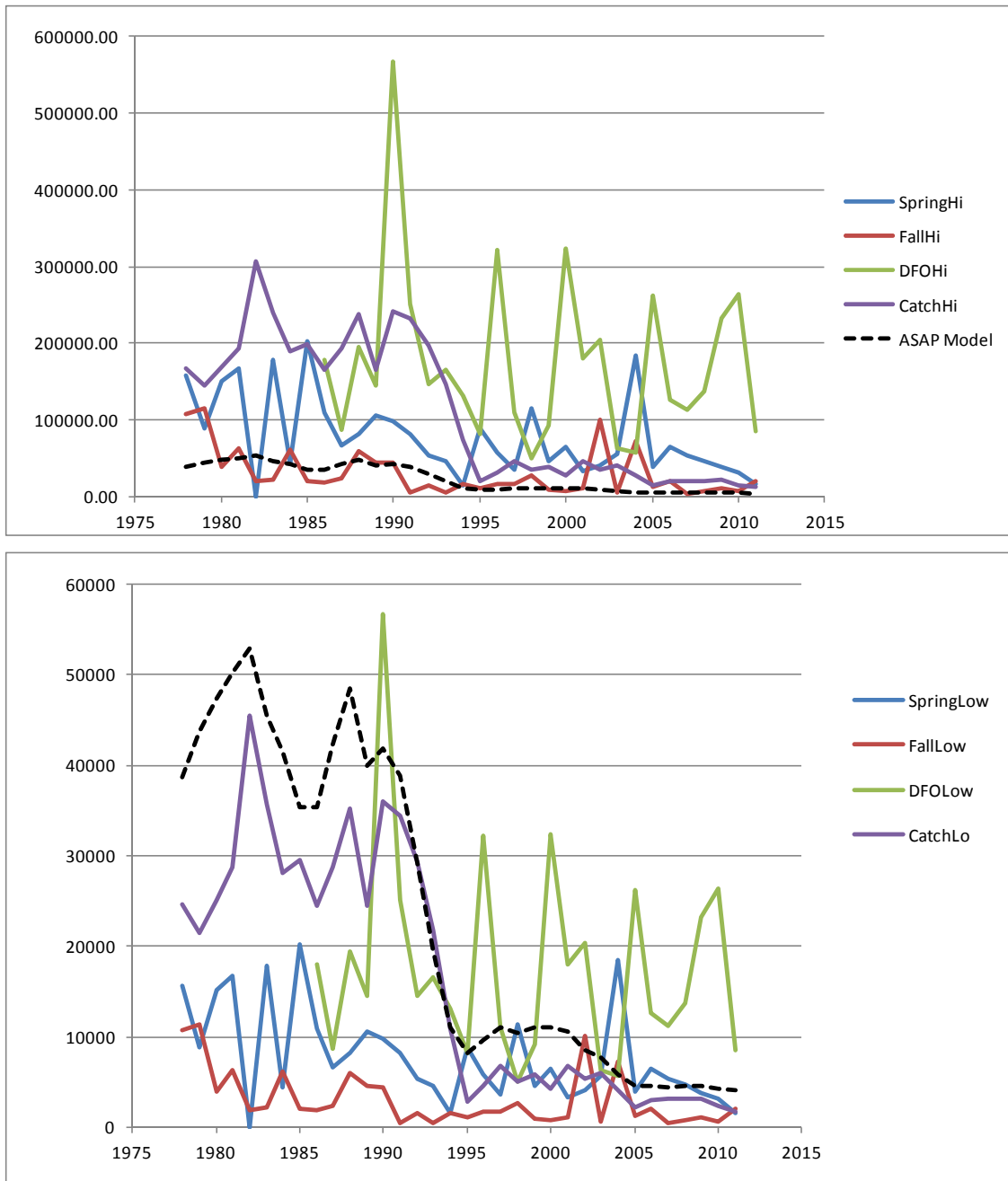
*Figure 57. Upper and lower bound estimate of total biomass for each survey from the 'envelope analysis' (see Appendix A) with ASAP Jan1 biomass estimated from model **run3f.1**. Black dashed line in lower panel = ASAP Model results.*
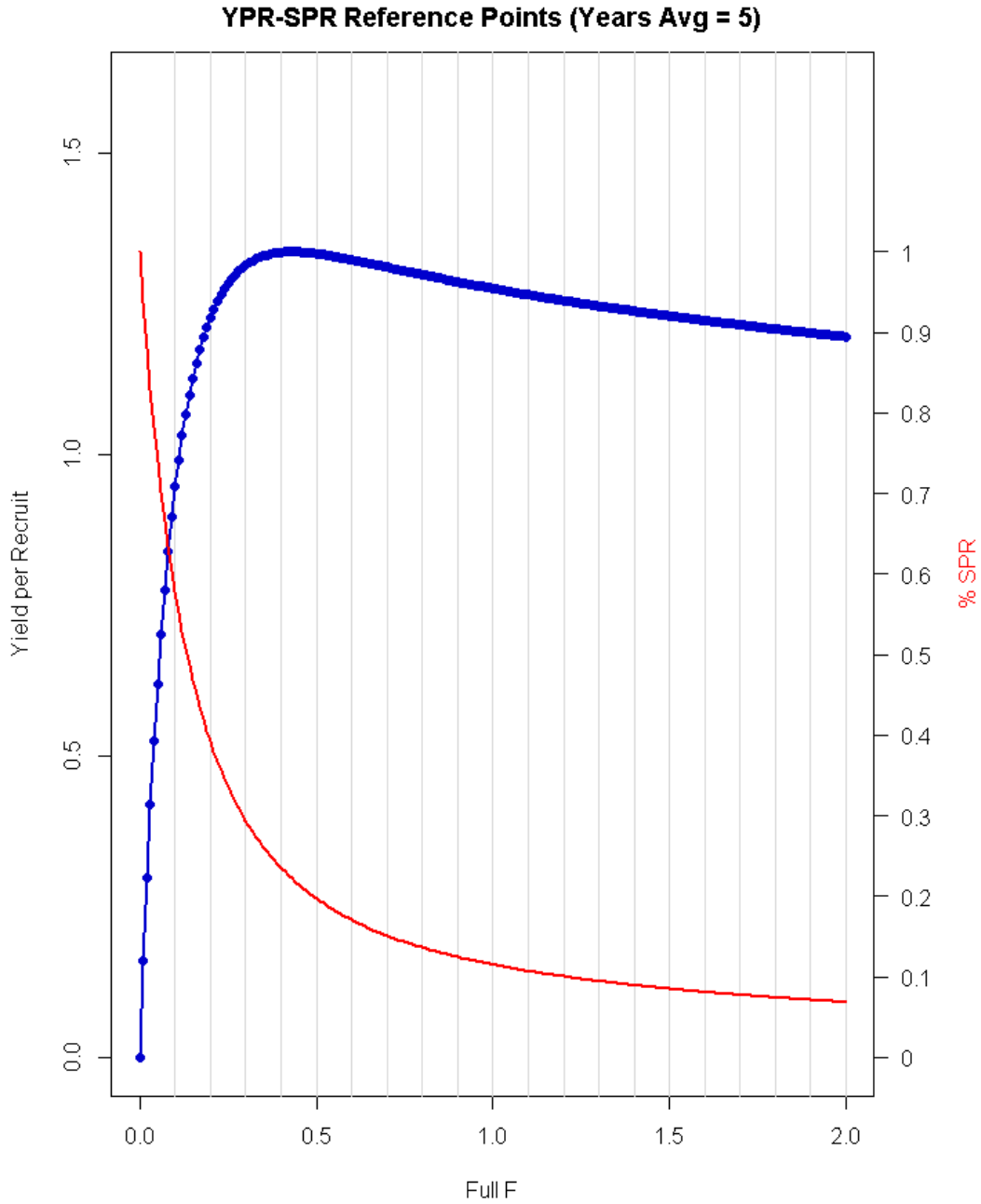
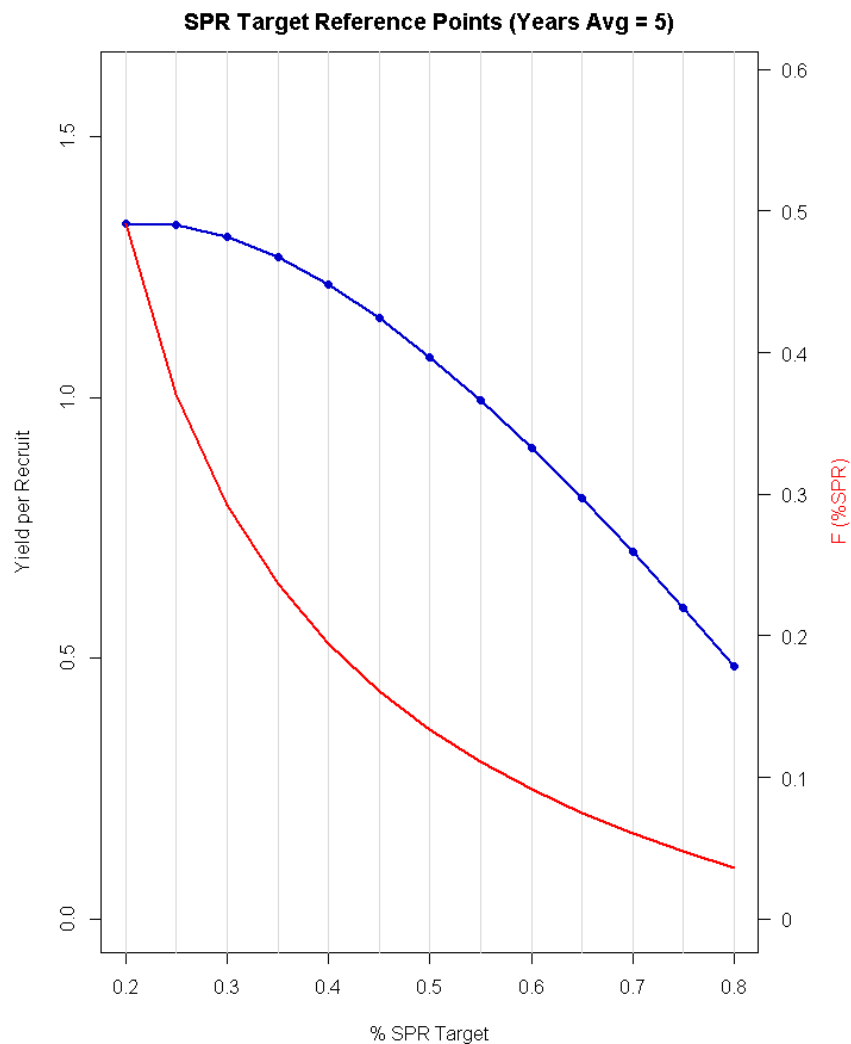*Figure 58. ASAP model **run3f.1** yield per recruit (YPR) analysis and percent spawning potential ratio (%SPR).*

*Figure 59. ASAP model **run3f.1** yield per recruit (YPR) and fishing mortality (F) at percent spawning potential ratio (%SPR) targets.*

APPENDIX 1

Envelope Analysis for Eastern Georges Bank Cod
Paul Rago and Loretta O'Brien

INTRODUCTION

The 'envelope method' is a heuristic method to find a feasible range of biomass and fishing mortality rates (F) consistent with a plausible range of assumptions. The data used in this method are the research survey 'swept area' population estimates of stock biomass combined with the Baranov catch equation. Although not an assessment, the results can be useful in guiding assessment and management decisions.

METHODS

Swept Area Estimates

Let I_t represent both the observed index of biomass at time t and the catch at time t. The estimated swept area total biomass, B_t , consistent with the index is:

$$B_t = \frac{I_t}{q} \frac{A}{a}$$

1)

where the catchability or efficiency q , is an assumed value. The average area swept per tow is a and the total area of the survey is A.

The biomass consistent with observed catch can be obtained from the Baranov catch equation as:

$$B_O = \frac{C_t}{\frac{F}{F+M}(1-e^{-(F+M)})}$$

2)

$$B_f = B_O\, e^{-(F+M)f}$$

where fishing mortality (F) is unknown and natural mortality (M) is derived from life history theory. The second equation in Eq. 2 adjusts the biomass to the time of year when the survey occurs, thus keeping Eq. 1 and 2 consistent. Thus biomass can be written as a function of arbitrary scalars q and F in equations 1 and 2 respectively.

Neither q nor F are known but feasible ranges can be obtained from expert judgment. We also know that biomass estimates derived from some feasible range must be consistent with each other:

$B'_{1,t} = B\,(\,I_t,\,q_{low})$

$B'_{2,t} = B\,(\,I_t,\,q_{high})$

$B'_{3,t} = B\,(\,C_t,\,F_{low},\,M\,)$

$B'_{4,t} = B\,(\,C_t,\,F_{high},\,M\,)$

By inspection it is evident that q_{low} and F_{low} constitute an upper range, and q_{high} and F_{high} constitute a lower range. Upper and lower bounds consistent with these estimates are:

$B'_{upper, t}$ = min ($B_{1,t}$, $B_{3,t}$)

$B'_{lower, t}$ = max ($B_{2,t}$, $B_{4,t}$)

Values of biomass that exceed $B'_{upper, t}$ implies catchabilities smaller than q_{low} or fishing mortalities less than F_{low}. Conversely, values of biomass less than $B'_{lower, t}$ implies catchabilities greater than q_{high} or fishing mortalities greater than F_{high}. These bounds describe a set of feasible options that are consistent with the assumed ranges of q and F. In theory, a more sophisticated population model should lie within this feasible range.