Appendix A.1. List of SAW 59 Gulf of Maine Haddock SAW 59 Working Group participants

The following people participated in all or part of the Working Group meeting, June 2-6, 2014.

Name	Affiliation
Larry Alade	NEFSC Woods Hole
Terry Alexander	NEFMC member, Industry Advisor
Rich Bell	NEFSC Narragansett
Liz Brooks	NEFSC Woods Hole
Doug Butterworth	Univ. of Cape Town (Lead Industry Science Consultant)
Steve Correia	MA Div Marine Fisheries
Jamie Cournane	NEFMC staff
Jonathan Deroba	NEFSC Woods Hole
Dan Hennen	NEFSC Woods Hole
Fiona Hogan	NEFMC staff
Chris Legault	NEFSC Woods Hole, NEFMC SSC Member
Brian Linton	NEFSC Woods Hole
Tim Miller	NEFSC Woods Hole
Paul Nitschke	NEFSC Woods Hole
Loretta O'Brien	NEFSC Woods Hole
Jackie O'Dell	Northeast Seafood Coalition
Mike Palmer	NEFSC Woods Hole (Lead NEFSC Scientist)
Rebecca Rademeyer	Univ. of Cape Town
Paul Rago	NEFSC Woods Hole
Maggie Raymond	Associated Fisheries of Maine
David Richardson	NEFSC Narragansett
Fred Serchuk	NEFSC Woods Hole
Mark Terceiro	NEFSC Woods Hole (Meeting Chair)
Susan Wigley	NEFSC Woods Hole
Tony Wood	NEFSC Woods Hole
Chao Zou	Univ. of Rhode Island

Appendix A.2. Additional ASAP sensitivity runs

This appendix provides results from sensitivity runs that were conducted on the SAW/SARC 59 ASAP reference model (ASAP_BASE). The sensitivity runs fell into two categories: 1) determining whether an alternate model formulation offered improved fit to the data; and 2) evaluating the sensitivity of the model with respect to a range of assumptions.

A.2.1. Profiling across a range of natural mortality values

A sensitivity analysis explored the response of the ASAP base (ASAP_BASE) model to natural mortality (M) estimates ranging from 0.0 to 1.0. There was model preference for M around 0.1 (Fig. A.2.1), with a four point difference in the objective between the M=0.1 and M=0.2 runs. This does not indicate strong preference for a lower M, but is suggestive the M may be lower than the M=0.2 assumption. The occurrence of age-15 fish showing up in considerable numbers in recent years is indicative of an environment of low natural mortality, at least over the recent time period.

A.2.2. Evaluation of the impacts of using SHG or TOGA tow evaluation criteria

During the transition from the FSV Albatross IV survey vessel to the FSV Henry B. Bigelow there were several noted changes in survey protocols which are summarized in table A.51. One of these changes was a change in the protocol used to determine when survey tows could be considered 'representative' and of sufficient quality for inclusion in the calculation of stratified mean survey indices. The procedure from the Albatross survey years, known as the station-haul-gear (SHG) criteria, evaluates the station type (random vs. non-random, etc.), the haul type (good haul, bad haul due to being too short or too long, etc.) and gear condition (no gear damage, gear damage, etc.). The Bigelow survey protocol uses a revised tow-operations-gear-acquisition (TOGA) criteria. The primary difference between the SHG and TOGA criteria is that the TOGA criteria takes advantage of the extensive sensor information collected on the net performance (bottom contact, wing spread, door spread, head rope high, etc.) to determine when a survey tow should be considered 'representative' and included in survey indices. The differences in survey indices between the protocols is variable, though in general, reflect similar trends (Table A.53).

The ASAP_BASE model was constructed using the TOGA selection criteria for the Bigelow years (2009-2013), though the updated VPA model used the SHG indices for all years (1977-2013). The transition from the SHG to TOGA indices was not explicitly evaluated in a model bridge building step. To document the impacts on the results of the ASAP_BASE model resulting from the use of indices based on the TOGA criteria, a single sensitivity run was conducted using the SHG indices in the ASAP model (ASAP_SHG). All other data configurations were left identical to the ASAP_BASE model. The model results between the two runs are nearly identical (Fig. A.2.2). Interestingly, the only discernible differences between the two runs is at the beginning of the time series when survey data were identical.

A.2.3. Use of survey numbers vs. biomass indices

Analyses were undertaken to compare the use of either survey aggregate abundance (numbers/tow) or biomass (weight/tow) in the model fitting. The abundance indices at age are presented in Tables A.57 and A.63 for the NEFSC spring and NEFSC fall surveys respectively. Biomass indices at age are presented in Tables A.60 and A.66 for the NEFSC spring and NEFSC fall surveys respectively. To correctly convert indices-at-age to numbers (which are the units that the ASAP model is tuning to) the model requires input of survey weights-at-age (e.g., Fig. A.99). The survey weight-at-age matrices contained several holes for age/year combinations, particularly among the older ages. Rather than impute the various holes, this sensitivity run used the stock/January 1 weight matrix (Table A.48) as a surrogate for the spring survey and the catch weight-at-age matrix assuming 100% recreational discard mortality (Table A.47) for the fall survey. A sensitivity model, ASAP_BIOMASS was constructed using the survey biomass indices and weight-at-age matrices as described above.

Summary model diagnostics for the ASAP_BASE and ASAP_BIOMASS model are presented in Table A.2.2. The two indices provided similar results in terms of biomass and fishing mortality, though the ASAP_BASE model had a higher terminal (2013) biomass and lower fishing mortality compared to the biomass model. The CVs on the 2013 spawning stock biomass were 0.15 for both the abundance-based model and the biomass-based model indicating that the biomass model offered no improvements in the precision on the terminal estimates. Additionally, the retrospective error was worse for the biomass model.

A.2.4. Treatment of the Bigelow survey years as independent survey indices

A number of operational changes have been made to the NEFSC spring and fall surveys during over the assessment times series including a changes in vessel (Delaware/Albatross historically and introduction of the Bigelow in 2009), trawl doors (between 1984 and 85) and trawl net (Yankee 36/41 in spring survey). The changes are summarized in Table A.52. Trends in the calibrated and un-calibrated surveys indices were very similar, but vary in scale (Fig. A.95). The ASAP_BASE model is tuned to the combined Albatross/Bigelow-calibrated series. To evaluate the sensitivity of the base model to the Bigelow calibrations, two separate sensitivity runs were conducted. The first tuned the model to the Albatross/Bigelow-converted series and a separate un-calibrated Bigelow series (ASAP_BIGELOW_SPLIT). The second run tuned the model to separate non-overlapping Albatross (1977-2008) and Bigelow (2009-2013) survey series (ASAP_BIGELOW_NOOVERLAP).

Summary model diagnostics for the ASAP_BASE, ASAP_BIGELOW_SPLIT and ASAP_BIGELOW_NOOVERLAP model are presented in Table A.2.3. Survey catchabilities for the NEFSC spring and fall surveys were similar across all three model runs, but the Bigelow spring and fall catchabilities varied considerably between the ASAP_BIGELOW_SPLIT and ASAP_BIGELOW_NOOVERLAP runs, with an approximate doubling of catchability under the non-overlapping run. The retrospective error increased under the ASAP_BIGELOW_NOOVERLAP run. Estimated survey selectivity for the NEFSC spring and fall surveys was similar between the ASAP_BASE and ASAP_BIGELOW_SPLIT runs, though

the spring survey became more domed and the fall survey, less domed, under the ASAP_BIGELOW_NOOVERLAP run. The estimated Bigelow selectivity patterns were irregular and poorly estimated in both of the Bigelow runs. It could be that the presence of at least two moderate-to-large years classes within the Bigelow series are confounding the selectivity estimates for this short survey series.

The large increase in estimated Bigelow catchability lead to lowered estimates of spawning stock biomass and increased estimates of fishing mortality at the end of the time series of the ASAP_BIGELOW_NOOVERLAP run (Fig. A.2.3). The model fits to the survey indices were similar across runs (Fig. A.2.4), though the incorporation of the Bigelow series in addition to the single Albatross/Bigelow calibrated series does result in slightly tighter fits to the terminal spring and fall Albatross/Bigelow calibrated series observations. This translates in slightly higher estimates of the 2012 year class size, but has little impact on the spawning biomass and fishing mortality estimates. The results of this sensitivity show little utility in applying non-overlapping Albatross and Bigelow series owing to the poor diagnostics in the way of retrospective error and imprecisely estimated survey selectivity. The combined run applying both the calibrated and un-calibrated series suffers from the same issues with respect to estimation of survey selectivity, but it is helpful for gaining a better understanding the relative catchability differences between the Albatross and the Bigelow surveys. While the survey catchabilities are not directly translatable to the length-based calibration factors applied to the Bigelow series, the scale in the catchability differences between the spring (0.87/0.26=3.35) and fall (1.90/1.00=1.90) survey series from the ASAP_BIGELOW_SPLIT is of similar scale to the range of the length-based calibration factors (1.164-2.626; Table A.50).

A.2.5. Inclusion/exclusion of survey indices

To better understand how the model results are being influenced by each of the survey indices, the ASAP_BASE model was run using only one index at a time. The two sensitivity runs were ASAP_NEFSC_spring (spring survey only) and ASAP_NEFSC_fall (fall survey only). In both sensitivity runs all other model configurations were left unchanged relative to the ASAP_BASE model.

Both of the single-survey model runs exhibited lower biomass and higher fishing mortality at the start and end of the time series compared to the base run; however, the trajectories throughout the time series were variable (Table A.2.4, Fig. A.2.5). Retrospective error increased in both single-survey models. The precision in the spawning stock biomass over the time series was improved by using both survey indices in the model (Fig. A.2.6). Inclusion of only the NEFSC spring survey in the model leads to a large decrease in precision at the end of the time series. Overall, the model performance is improved through the inclusion of both the NEFSC spring and fall surveys in the base model.

A.2.6. Inclusion of state surveys

Previous Gulf of Maine haddock assessments have only included the NEFSC spring and fall

bottom trawl surveys as tuning indices. Both the Maine-New Hampshire (MENH) inshore bottom trawl survey and Massachusetts Department of Marine Fisheries (MADMF) bottom trawl survey encounter haddock in limited quantities. The MENH fall survey began in 2000 and the spring survey began in 2001. The MADMF survey began in 1978. Both surveys are characterized by high CVs (Tables A.69 and A.72) and catches are primarily comprised of smaller haddock (Figs. A.112 and A.123). Until recently, neither the MENH nor MADMF surveys had been aged. As of 2014, all of the otoliths collected from the MENH fall survey have been aged; however, otoliths collection did not begin until 2005 and was extremely limiting in some years (e.g., collected otoliths ranged from 2 to 117/year). The lack of age information, high imprecision and weak coherence with the NEFSC survey signal (Figs. A.128-129) precluded their use in previous assessments.

For this assessment, NEFSC age-length information has been applied to the MENH and MADMF indices-at-length to generate indices-at-age for the state surveys. Plots of indices-at-age show that both surveys primarily capture age-0 and 1 fish (Figs. A.113 and A.125), though there are sufficient number of some older fish captured such that some of the stronger Gulf of Maine haddock year classes track through the survey indices-at-age (e.g., 1998, 2003). The NEFSC spring age-1 index exhibits a moderate degree of correlation with both the MADMF and MENH age-1 indices (Fig. A.130), and the NEFSC fall age-1 index shows moderate degree of correlation with the MENH age-1 index (Fig. A.131).

Four different sensitivity runs of the base ASAP model were conducted which incorporated the state survey indices. The first two included the MADMF and MENH survey indices-at-age separately to evaluate the influence of each of the surveys on the base model and examine the model fits to both the aggregate survey indices and the indices-at-age (ASAP_MADMF and ASAP_MENH). The other two focused on fits to only the age-1 recruitment indices. The first of the models using state recruitment indices incorporated both the MADMF and MENH age-1 indices (ASAP_STATE_RECRUITMENT), the second used only the age-1 recruitment indices from the MENH survey (ASAP_MENH_RECRUITMENT).

A summary of model diagnostics from the four runs is presented in Table A.2.5. Model fits to the MADMF spring and fall survey are poor with large residuals in the fits to both spring and fall surveys (Fig. A.2.7). This is not unexpected given the large CVs on the MADMF indices (average 0.52 and 0.49 for spring and fall, respectively). The large number of zero survey observations in both spring and fall surveys are notable features of the MADMF survey. The model fit of the MENH spring survey is reasonable, though there are several large residuals in the fall survey, though no strong patterning in the fits to either survey (Fig. A.2.8). The fits to the indices-at-age show large residuals in the MADMF age-1 index, with several large positive and negative blocks throughout the survey time series (Fig. A.2.9).There are no strong residual patterns in the MENH spring survey, though the fall survey fits to the age-2 index are poor and the age-1 index contains several periods of large positive residuals. The trade-off between the age-1 and age-2 indices may be indicative of ageing issues complicated by the augmentation of the MENH fall survey with age-length information from the NEFSC survey. Index selectivity patterns for both surveys are characterized by low selectivity for older ages and high imprecision in estimates of selectivity-at-age (Table A.2.5). The combination of residual patterns and poorly estimated selectivity at older ages suggests that there is limited utility in incorporating the older

age classes from the state surveys in the tuning of the ASAP model.

The model fits to the state recruitment indices exhibit similar patterns to the fits to the aggregate surveys (Fig. A.2.10), which is expected given that the majority of the signal in the aggregate 1-9^+ indices is coming from the age-1 index. Among the recruitment indices, the MENH spring survey appears to have the best model fit. Incorporating all state recruitment indices into a single model resulted in some diagnostics problems, notably, large residual errors in the estimation of SSB and fishing mortality (Table A.2.5), overall problems with the estimation of the 2003 year class in the retrospective analysis (Fig. A.2.11) and an overall underestimation of the year class size which manifested itself in a large cohort effect on the 2003 year class in the fits to catch-at-age (Fig. A.2.12). The run with only the MENH recruitment indices does not have these diagnostics issues. Additionally, the addition of the recruitment indices does offer marginally improved CVs on the estimation of age-1 recruitment (Fig. A.2.13). However, the model results between the ASAP_BASE and ASAP_MENH_RECRUITMENT are similar with respect to biomass scale, terminal SSB and F and retrospective patterns, suggesting that the indicating that model results are relatively insensitive to the inclusion of the additional recruitment indices.

A.2.7. Inclusion of catch-per-unit-effort (CPUE) indices

While several concerns were noted in the main report regarding the use of catch/landings-per-unit-effort (LPUE) indices in the base assessment model, sensitivity runs were conducted incorporating the commercial (ASAP_LPUE_COM) and recreational (ASAP_LPUE_REC) LPUE indices separately within the base ASAP model.

A summary of model diagnostics for the three runs is presented in Table A.2.6. Model fits to both the commercial and recreation LPUE indices exhibit a poor fit the index with strong residual patterning (Fig. A.2.14). These fits suggest that the LPUE indices are not reflective of stock abundance and should not be used for model tuning.

A.2.8. Sensitivity to recreational discard mortality assumptions

Previous assessments of Gulf of Maine haddock have not included estimates of recreational discards. In this assessment, the base model has assumed that fish discarded in the recreational fishery suffer 50% mortality, though there is little empirical information to evaluate this assumption. To understand the sensitivity of the assessment results to this assumption, the base ASAP model was run using two alternate discard mortality assumptions: 0% (ASAP_REC_0_MORT) and 100% (ASAP_REC_100_MORT). Catch weights-at-age were adjusted accordingly in each of the sensitivity runs (e.g., Tables A.46-47).

A summary of model diagnostics for the three runs is presented in Table A.2.7. The model diagnostics are similar for all three models. Decreasing the discard mortality assumption lowers the selectivity for ages 2-4 in the third selectivity block (2005-2013; Fig. A.2.15). This corresponds to the period of increasing recreational discard. The selectivity patterns in the other two blocks are similar across mortality assumptions. With the exception of the estimate of 2013

fishing mortality, which increases with increasing discard mortality, the model results are largely insensitive to the recreational discard mortality assumption (Fig. A.2.16),

A.2.9. Explicit treatment of catch fleets

A sensitivity run of the base ASAP model treated the commercial and recreational fleets separately, as opposed the ASAP_BASE model where the fishery catch is modeled in aggregate. The model configuration of the two fleet run (ASAP_2FLEET) was identical to that of the base run. The recreational fleet was modeled with only two selectivity blocks: 1977-1988, and 1989-2013. The 1988/89 period corresponds to an increase in minimum retention size from 17 to 19 inches (Table A.4). The CV on the recreational catch was set at 0.2 for all years, owing to the overall higher uncertainty in the recreational catch estimates.

A comparison of the summary diagnostics between the base and two fleet models is presented in Table A.2.8. Overall, the two fleet model has generally good diagnostics, with reasonable fits to both the commercial and recreational catches (Fig. A.2.17) and fits to the catch-at-age. There was a period of large residuals in the recreational catch-at-age in the pre-1995 period (Fig. A.2.18) when length sampling was poor (Table A.35). The residual patterns present in the base model are also reflected in the fits to the commercial catch-at-age. The results of the two models are nearly identical, with terminal SSB estimated at 4,500 mt in the base model and 4,242 mt in the two fleet model. The partitioning of fishing mortality mirrors the catch patterns, with the recreational fishing mortality increasing over the last decade, with the recreational and commercial fully recruited fishing mortality nearly equal in 2013 (Fig. A.2.19). Retrospective error was low in both the base and two fleet models. Selectivity was generally well estimated for the recreational fleet (Table A.2.8). Interestingly, the commercial fishery exhibits only weak evidence of doming, though there is evidence that the recreational fleet may be driving the fleet doming evident in the third selectivity block of the ASAP_BASE model. Domed selectivity in the recreational fishery could be explained by the spatial distribution of the recreational fishery – it's plausible that the older haddock may be in the deeper waters to the east of where the recreational fleet is operating in the western Gulf of Maine.

A.2.10. Assessment starting points (e.g., 1956, 1963 vs. 1977)

The ASAP_BASE model run begins in 1977, the year for which catch-at-age information is first available. Two alternate start points were explored within the framework of the ASAP_BASE model: 1956 (ASAP_hist_1956), the year when catch information are first available, and 1963 (ASAP_hist_1963), the year when the NEFSC fall bottom trawl survey began and survey indices-at-age first start. The NEFSC spring bottom trawl survey did not begin until 1968. The catch CV was increased to 0.2 in years before 1977. The uncertainty of catch pre-1964 which predates the modern commercial data collection program, is probably higher than the catch from 1964-1977, though no explicit adjustment is made in these sensitivity models.

A summary of model diagnostics is presented in Table A.2.9. In both runs, the model-estimated fishery catch exceeds the observed catch until 1980, with a strong negative residual pattern in

these early years (Fig. A.2.20). The historical runs, ASAP_hist_1956 and ASAP_hist_1963, have nearly identical trends in spawning stock biomass, fishing mortality and age-1 recruitment during the overlapping years (Fig. A.2.21). With respect to evaluating the current condition of the stock, the choice in starting year has little impact, though both historical runs have slightly lower terminal SSB and higher fishing mortality. The 1956 run has a notable burn-in period from 1956 to 1960 – a large amount of fish are created in the 9^+ group at the start of the model and these fish leave the population before the availability of age information in 1963.

Extending the time series back in time establishes additional contrast in the spawner-recruit relationship, though given the large-burn in period in the 1956 run, the SR relationship of the pre-1964 year classes is questionable. The 1963 run shows evidence of small year classes spawned at high SSB, though the 1963 year class is the largest of the time series and was spawned during a year when SSB was near time series highs (Fig. A.2.22).

A.2.11. Placement of selectivity blocks

The base ASAP model included three fishery selectivity blocks: (1) 1977-1988, (2) 1989-2004, (3) 2005-2013. The model fits to the observed catch-at-age were generally good; however, there were some year class effects present, primarily associated with the 1998 and 2003 year classes. Several alternate model formulations explored different selectivity blocking to see if improvements could be made in the catch-at-age fits.

Two initial sensitivity runs exploring fits to a one- (ASAP_BASE_1BLOCK) and two-block (ASAP_BASE_2BLOCK) model did not yield appreciable gains in the catch-at-age fits. Summary diagnostics for these sensitivity runs are provided in Table A.83. The single block model exhibited strong residual runs in the fits to age-2 fish, did not mitigate the year class effects (Fig. A.2.23) and increased the retrospective error (Table A.83). The two-block model employed a split at 1993/1994. The choice of the split was informed by increases in the regulated mesh sizes (5.0 inches to 6.0 inches) and implementation of haddock trip limits (Table A.3). The post-1994 period also corresponds to a period of increasing recreational catch (Table A.8 and Fig. A.15). The two-block model exhibited nearly identical residual patterning to the three-block model and similar retrospective error. However, despite a decrease of eight parameters, the objective function increased by two points, primarily as results of a slight decrease in the fits to the catch-at-age. The two-block model is more parsimonious, but may not offer the flexibility to capture finer-scale dynamics of the fishery related to the increasing catch coming from the recreational fishery over time and changes in commercial minimum retention sizes from 2007 onward (Table A.4). The accurate estimation of selectivity in the most recent period has implications on reference point determination and setting catch advice.

Further refinement of the three-block model was explored by attempting different placements of the break between the second and third selectivity blocks. Several preliminary runs not described here were explored to find a year break point that offered improvements in the objective function and catch-at-age residual patterns. These runs resulted in an alternate three-block model with a split between the second and third blocks between 1999/2000 (ASAP_BASE_1989_2000). The first block timing remained unchanged.

Summary diagnostics for the three-block sensitivity runs are provided in Table A.84. The ASAP_BASE_1989_2000 model offered 35 point improvement in the objective function compared to the ASAP_BASE model with the improvements coming in the way of the fits to the catch-at-age and indices-at-age. The terminal spawning stock biomass and fishing mortality estimates were similar between the two models, though the 1999/2000 split model exhibited a minor increase in the retrospective error relative to the base model. Estimated selectivity was similar between the two runs for the first selectivity block, with both models estimating flat-topped selectivity in the 1977-1988 time period. There was severe doming in the second selectivity block, with the selectivity of the 9^+ group dropping to 0.11. The selectivity for ages 8 and 9^+ was poorly estimated, with CVs > 0.30. This doming effect is likely the result of the limited information on the older fish - the 1989-1999 period is characterized by a truncated population structure and very few old fish in the fishery catch. Compared to the ASAP_BASE model run, the selectivity in the third block of the ASAP_BASE_1989_2000 model was lower. The catch-at-age residual patterns were slightly improved in the ASAP_BASE_1989_2000 model, with reductions in the residuals on the 1998 and 2003 year classes (Fig. A.2.24). While the ASAP_BASE_1989_2000 model does exhibit some improved diagnostics, the severe doming in the second selectivity block is a concern. Additionally, some of the concerns with the two-block model (e.g., the increasing recreational fishery catch and changes in commercial minimum retention sizes in more recent period) also apply to the ASAP_BASE_1989_2000 model.

Given that the 1999/2000 run was suggestive of flat-topped selectivity in the first and third blocks, and poorly estimated selectivity on the older ages in the second block, an alternate formulation of the 1999/2000 run was explored where fishery selectivity was modeled using a single logistic function (ASAP_BASE_1989_2000_SL). The selectivity parameters were well estimated in the single logistic run. However, there was an overall degradation in model fit under this model, with 14 point increase in the objective function relative to the ASAP_BASE model and 49 point increase compared to the ASAP_BASE_1989_2000 model. The fits to the catch-at-age were the primary driver of the increase in the objective function (Table A.84). There is evidence for doming in the fishery, which is likely a function of the catchability of the recreational fishery. Use of a single logistic function to model fishery selectivity is probably not appropriate, particularly in the later part of the timer series when recreational catch increased.

Each of the three three-selectivity block models has advantages and disadvantages. However, the impacts on stock determination are minimal with the terminal spawning stock biomass and fishing mortality similar between all runs. While these investigations were useful, the decision was made to retain the ASAP_BASE formulation with three selectivity blocks and the 1988/1989 and 2004/2005 splits.

A.2.12. Catch precision assumptions

The CVs on the aggregate catch used in the base ASAP model varied from 0.15 early in the time series to 0.05 after 1989. The changes in assumed precision were reflective of the incorporation of direct commercial discard estimates in 1989 and imprecise recreational catch estimates early in the time period. Two different sensitivity runs were conducted to evaluate the impacts of

assuming increased catch imprecision on model performance and results. The first run increased CVs across the time series by 100% (range = 0.10 - 0.30; ASAP_CATCH_CV_100) and the second increased CVs across the time series by 200% (range = 0.15 - 0.45; ASAP_CATCH_CV_200).

The model runs and summary diagnostics are presented in Table A.2.12. Increasing catch CVs lead to slight improvements in the model fits to the survey indices, survey age composition and catch age composition. The primary effect of the higher CVs was reduced fit to the aggregate catch, primarily in the early part of the time series, with very little overall change in the residual patterns, only in the magnitude of the standardized residuals (Fig. A.2.25). The 2013 estimates of spawning stock biomass ranged from 4,500 mt in the base model to 4,951 mt under the 200% increase model with only a minor change in terminal fishing mortality. Overall, increasing CVs on the aggregate catch had negligible impacts on the assessment results. The catch CVs assumed in the base model are likely too low, whereas the 200% model assumed CVs probably capture the upper limit of believable precision levels. The final ASAP model should utilize CVs somewhere in the mid-range of these sensitivities, though the choice is likely to have minimal impacts on the assessment results.

A.2.13. Terminal recruitment assumptions

In both the VPA and preliminary ASAP models, the most notable feature of the assessment results is the presence of occasionally large year classes, which in turn lead to subsequent increases in spawning stock biomass. As has been seen from the results of various sensitivities examined, the overall biomass scale and time series trends in biomass and fishing mortality are insensitive to the model assumptions; however, the estimates of terminal recruitment are sensitive to model configurations.

The ASAP model allows the deviations to be constrained by applying a penalty on the deviations. For the base run the penalty function (lambda) was set at 0.2 and the CVs on the recruitment deviations were set at 0.5 for all years except the final three years, which were set at 0.1. This was an attempt to apply ‘shrinkage’ to the mean of the terminal year cohorts were there are limited observations available from which to accurately estimate year class size. This decision was based on past experience with Gulf of Maine haddock in a VPA model framework (Palmer et al. 2014b). However, within the context of the ASAP, statistical catch-at-age model, the application of shrinkage to the mean had not been evaluated. Within ASAP, there are several ways to model recruitment deviations. One method is to not apply any penalty function to the recruitment deviations (set lambda=0) and allow recruitment to be freely estimated. Another is set lambda at 1, but apply some constraint on the recruitment deviations through the adjustment of the CV values. When applying shrinkage to the mean, the shrinkage can be applied over several terminal years (e.g., those years not fully recruited to the surveys or fishery) or just on the terminal year.

A sensitivity was conducted evaluating the retrospective performance of the ASAP model under the four different configurations described above. The performance of the model was evaluated back to 2000 to understand how well the model estimated the size of the 1998 year class with

only three years of information, which is identical to the current scenario with respect to being able to estimate the size of the 2010 year class. For these sensitivities, a single-selectivity block variant of the ASAP_BASE model was created. Using a single selectivity block avoids complications that can occur when retrospective runs pass through selectivity blocks. For all runs, the recruitment deviation CV was set equal to 0.8, with the exception of the shrinkage runs. Where shrinkage was applied to the last four years, the CV was decreased by 30%/year (e.g., 2009=0.80, 2010=0.59, 2011=0.39, 2012=0.27, 2013=0.19). For the runs where shrinkage was only applied to the terminal year, the CV in the terminal year was set at 0.3.

The results of the retrospective analysis on a cohort basis are shown in Figure A.2.26. Results are expressed in terms of relative estimation error compared to the 2013 estimates of age-1 recruitment from the 'no shrinkage' model. Overall, the performance of the individual methods was variable. While the 'shrinkage on last four years' model performed poorly for some year classes (e.g., 2004, 2007), for some year classes it out-performed the other methods (e.g., 2000, 2001, 2009). For the three large year classes within the time series (1998, 2003, 2010), there were no clear 'preferred' method. Box plot distributions of the retrospective error by method were examined at yearly intervals in an attempt to summarize the performance of the methods when only one, two, three and four years of information were available with which to estimate the year class size. When only one year of information was available the 'no shrinkage' method had the lowest error distribution and exhibited the lowest degree of mean- and median-bias (Fig. A.2.27). For all other years, the 'no shrinkage', 'shrinkage in the terminal year' and 'lambda=0' methods appeared to perform similarly with only marginal differences between the methods. An interesting result from this analysis, is that at the three and four year horizons, all methods had a tendency to underestimate year class size. While not conclusive, this analysis does suggest that within a Gulf of Maine haddock ASAP model, the 'no shrinkage' method offers a lower degree of recruitment estimation error compared to the other methods evaluated.

The specification of the recruitment deviations CVs will affect the level of constraint the model places on recruitment estimates. The sensitivity of the model to recruitment deviation CVs was evaluated by profiling across CV values from 0.6 to 2.4. This sensitivity used the ASAP_BASE model, with the exception that the recruitment deviation lambda was set at 1.0 and the CV was held constant for all years. The results of the profiling exercise are shown in Figure A.2.28. Based on the profiles of the likelihoods, there is model preference for CVs on the order of 2.0; this is the point when the RMSE on the recruitment deviations approaches 1. Within this range, model results are relatively stable (e.g., 2013 SSB, 2010 and 2012 year class sizes and SSB and F retrospective patterns). One concern with the model runs at the high CVs are the fits to the survey indices - models with high recruitment deviation CVs tend to 'chase' the 2013 survey observation (Fig. A.2.29). Based on the model fits to large survey observations earlier in the time series, this degree of fit, seems unlikely.

Appendix A.2. Tables

Table A.2.1. Summary of model diagnostics from several ASAP runs exploring the sensitivity of the ASAP_BASE model to varying levels of natural mortality (M). For runs above M=0.4, only results from every other run are shown.

Model		ASAP_M_0	ASAP_M_1	ASAP_BASE	ASAP_M_3	ASAP_M_4	ASAP_M_6	ASAP_M_8	ASAP_M_10
Model description		M=0.0	M=0.1	M=0.2	M=0.3	M=0.4	M=0.6	M=0.8	M=1.0
Maximum gradient (*conv. criteria < 1e-4*)		1.62E-04	1.01E-03	1.10E-05	3.30E-05	4.28E-04	1.97E-04	1.26E-04	1.45E-03
Number of parameters		125	125	125	125	125	125	125	125
Objective function		2525	2520	2526	2542	2572	2671	2761	2840
Components of objective function	Recruit devs	105	107	110	114	119	129	144	160
	Suvey age comps	886	877	874	873	873	883	891	914
	Catch age comps	644	642	644	649	660	706	754	794
	Index fit	694	697	702	709	723	753	777	777
	Catch fit	197	196	196	197	198	199	194	194
RMSE	Fleet 1	0.37	0.34	0.34	0.38	0.44	0.52	0.07	0.03
	Index 1	2.03	2.06	2.10	2.16	2.26	2.47	2.65	2.65
	Index 2	1.96	1.98	2.00	2.04	2.12	2.26	2.34	2.34
	Index total	2.00	2.02	2.05	2.10	2.19	2.37	2.50	2.50
	Recruit devs	3.98	3.93	3.91	3.91	3.93	3.95	3.71	3.73
SSB_{1977} (mt)		6,057	7,491	9,470	16,907	24,006	62,059	1,013,640	2,196,730
SSB_{2013} (mt)		6,861	4,958	4,500	6,355	8,476	21,049	326,461	683,818
$F_{mult,\,2013}$		0.24	0.28	0.31	0.35	0.38	0.34	0.05	0.04
Mohn's rho (7 year peel)	SSB	0.25	0.10	-0.03	-0.15	-0.25	-0.34	-0.64	-0.52
	F_{mult}	-0.26	-0.13	0.05	0.24	0.47	0.82	4.85	4.08
	Age 1 N	0.32	0.24	0.18	0.11	0.05	-0.03	-0.65	-0.52
	Notes	M set to 0.0001 to get model to run							

Table A.2.2. Summary of model diagnostics from a sensitivity analysis of the Gulf of Maine haddock ASAP_BASE model to the use of survey abundance (numbers) or biomass (weight) indices.

Model		**ASAP_BASE**	**ASAP_BIOMASS**
Model description		Fit to NEFSC abundance indices	Fit to NEFSC biomass indices
Maximum gradient (*conv. criteria < 1e-4*)		1.10E-05	2.03E-04
Number of parameters		125	125
Objective function		2526	2670
Components of objective function	**Recruit devs**	110	100
	Suvey age comps	874	980
	Catch age comps	644	647
	Index fit	702	745
	Catch fit	196	197
RMSE	**Fleet 1**	0.34	0.40
	Index 1	2.10	2.59
	Index 2	2.00	1.90
	Index total	2.05	2.27
	Recruit devs	3.91	3.58
SSB_{1977} (mt)		9,470	10,586
SSB_{2013} (mt)		4,500	3,801
SSB_{2013} CV		0.15	0.15
$F_{mult,\ 2013}$		0.31	0.38
Mohn's rho (7 year peel)	**SSB**	-0.03	-0.14
	F_{mult}	0.05	0.32
	Age 1 N	0.18	0.16

Table A.2.3. Summary of model diagnostics for variants of the ASAP_BASE model fit to (1) a single Albatross/Bigelow-calibrated series (fall and spring; ASAP_BASE), (2) both the Albatross/Bigelow-converted series and a separate un-calibrated Bigelow series (ASAP_BIGELOW_SPLIT), and (3) separate Albatross (1977-2008) and Bigelow (2009-2013) non-overlapping series (ASAP_BIGELOW_NOOVERLAP).

Model		**ASAP_BASE**		**ASAP_BIGELOW_SPLIT**		**ASAP_BIGELOW_NOOVERLAP**	
Model description		Fit to NEFSC abundance indices		Treat Bigelow years as separate survey		Treat Bigelow years as separate survey	
Maximum gradient (*conv. criteria < 1e-4*)		1.10E-05		6.54E-04		9.10E-05	
Number of parameters		125		143		143	
Objective function		2526		2721		2470	
Components of objective function	**Recruit devs**	110		123		86	
	Suvey age comps	874		957		860	
	Catch age comps	644		643		640	
	Index fit	702		801		688	
	Catch fit	196		196		196	
RMSE	**Fleet 1**	0.34		0.34		0.34	
	Index 1	2.10		2.09		1.98	
	Index 2	2.00		1.98		1.75	
	Index 3			1.75		2.09	
	Index 4			1.84		2.41	
	Index total	2.05		2.01		1.92	
	Recruit devs	3.91		4.34		3.04	
Survey q	**NEFSC spring**	0.26	*(0.11)*	0.26	*(0.11)*	0.25	*(0.11)*
	NEFSC fall	0.99	*(0.11)*	1.00	*(0.11)*	1.10	*(0.11)*
	Bigelow spring			0.87	*(0.31)*	1.67	*(0.20)*
	Bigelow fall			1.90	*(0.23)*	4.04	*(0.21)*
SSB_{1977} (mt)		9,470		9,445		9,469	
SSB_{2013} (mt)		4,500		3,850		1,357	
$F_{mult,\ 2013}$		0.31		0.36		1.13	
Mohn's rho (7 year peel)	**SSB**	-0.03		0.04		0.36	
	F_{mult}	0.05		-0.02		-0.24	
	Age 1 N	0.18		0.31		1.36	
	Block/Index	**Selectivity**	**CV**	**Selectivity**	**CV**	**Selectivity**	**CV**
NEFSC spring	**1**	0.74	0.13	0.74	0.13	0.74	0.14
	2	0.62	0.14	0.62	0.14	0.61	0.15
	3	0.79	0.14	0.79	0.14	0.79	0.15
	4	1.00	0.00	1.00	0.00	1.00	0.00
	5	0.87	0.17	0.87	0.17	0.93	0.18
	6	1.00				1.00	
	7	0.82	0.25	0.82	0.25	0.57	0.31
	8	0.75	0.34	0.76	0.34	0.68	0.39
	9^+	0.76	0.30	0.76	0.30	0.51	0.38
NEFSC fall	**1**	0.28	0.14	0.29	0.14	0.23	0.15
	2	0.35	0.14	0.35	0.14	0.28	0.15
	3	0.60	0.13	0.60	0.13	0.50	0.14
	4	0.62	0.14	0.61	0.14	0.58	0.15
	5	0.76	0.15	0.75	0.14	0.65	0.15
	6	1.00				1.00	
	7	1.00	0.00	1.00	*0.00*	1.00	0.00
	8	1.00	0.00	1.00	0.00	1.00	0.00
	9^+	0.66	0.25	0.66	0.25	0.80	0.26
Bigelow spring	**1**			0.89	0.36	1.00	0.00
	2			0.96	0.42	1.00	0.00
	3			0.84	0.47	0.87	0.41
	4			0.49	0.61	0.43	0.58
	5			0.37	0.83	0.31	0.80
	6					1.00	
	7			1.00	0.00	1.00	0.00
	8			0.68	0.80	0.56	0.76
	9^+			0.71	0.50	0.49	0.45
Bigelow fall	**1**			0.61	0.27	0.74	0.26
	2			1.00	0.00	1.00	0.00
	3			0.97	0.32	1.00	0.00
	4			0.34	0.53	0.30	0.52
	5			1.00	0.00	1.00	0.00
	6					1.00	
	7			0.46	0.54	0.38	0.54
	8			0.99	0.58	0.89	0.59
	9^+			0.25	0.57	0.18	0.57

Table A.2.4. Summary model diagnostics from a sensitivity analysis of the Gulf of Maine haddock ASAP_BASE model to inclusion of only a single NEFSC survey index at one time.

Model		**ASAP_BASE**	**ASAP_NEFSC_spring**	**ASAP_NEFSC_fall**
Model description		Fit to NEFSC abundance indices	Run _BASE w/ spring only	Run _BASE w/ fall only
Maximum gradient (*conv. criteria < 1e-4*)		1.10E-05	6.97E-04	1.26E-04
Number of parameters		125	116	116
Objective function		2526	1652	1785
Components of objective function	**Recruit devs**	110	89	99
	Suvey age comps	874	381	489
	Catch age comps	644	629	634
	Index fit	702	381	368
	Catch fit	196	196	195
RMSE	**Fleet 1**	0.34	0.29	0.24
	Index 1	2.10		
	Index 2	2.00		
	Index total	2.05	2.25	2.14
	Recruit devs	3.91	3.13	3.52
SSB_{1977} (mt)		9,470	8,347	9,314
SSB_{2013} (mt)		4,500	2,828	3,825
$F_{mult, 2013}$		0.31	0.47	0.40
Mohn's rho (7 year peel)	**SSB**	-0.03	0.19	-0.05
	F_{mult}	0.05	-0.13	0.15
	Age 1 N	0.18	0.29	0.75
Survey q	**NEFSC spring**	0.26	0.27	
	NEFSC fall	0.99		0.96

Table A.2.5. Summary model diagnostics from a sensitivity analysis of the Gulf of Maine haddock base ASAP model to the incorporation of state survey indices.

Model		ASAP_BASE		ASAP_MADMF		ASAP_MENH		ASAP_STATE_RECRUITMENT	ASAP_MENH_RECRUITMENT
Model description		Fit to NEFSC abundance indices		Include MADMF inshore surveys		Include MADMF inshore surveys		Include state surveys as recruitment indices	Include MENH survey as recruitment indices
Maximum gradient (*conv. criteria < 1e-4*)		1.10E-05		9.70E-05		2.90E-05		8.00E-05	2.60E-05
Number of parameters		125		143		143		129	127
Objective function		2526		3111		2761		3132	2670
Components of objective function	**Recruit devs**	110		102		110		102	112
	Suvey age comps	874		1082		940		875	872
	Catch age comps	644		658		643		681	644
	Index fit	702		1070		871		1272	846
	Catch fit	196		198		196		202	196
RMSE	**Fleet 1**	0.34		0.48		0.34		0.64	0.38
	Index 1	2.10		2.05		2.12		2.09	2.11
	Index 2	2.00		2.03		2.03		2.07	2.01
	Index 3			2.83		0.88		4.37	1.19
	Index 4			2.50		1.88		2.60	1.63
	Index 5							0.88	
	Index 6							1.83	
	Index total	2.05		2.33		1.94		2.61	1.93
	Recruit devs	3.91		3.64		3.91		3.64	3.98
Survey q	**NEFSC spring**	0.26		0.27		0.26		0.28	0.26
	NEFSC fall	0.99		1.10		1.00		1.12	1.00
	MADMF spring			0.02				0.01	
	MADMF fall			0.01				0.01	
	MENH spring					0.17		0.19	0.17
	MENH fall					0.05		0.04	0.03
SSB_{1977} (mt)		9,470		9,224		9,441		9,320	9,452
SSB_{2013} (mt)		4,500		4,240		3,923		3,512	4,082
$F_{mult,2013}$		0.31		0.32		0.35		0.43	0.34
Mohn's rho (7 year peel)	**SSB**	-0.03		0.00		-0.04		-0.30	-0.04
	F_{mult}	0.05		0.00		0.04		0.51	0.05
	Age 1 N	0.18		0.19		0.08		-0.20	-0.07
	Block/Index	**Selectivity**	**CV**	**Selectivity**	**CV**	**Selectivity**	**CV**		
State spring	**1**			1.00		1.00			
	2			0.18	0.34	0.08	0.54		
	3			0.33	0.32	0.05	0.76		
	4			0.26	0.36	0.08	0.59		
	5			0.93	0.28	0.08	0.57		
	6			0.43	0.36	0.05	0.95		
	7			1.00	0.00	0.05	0.96		
	8			1.00	0.00	0.05	1.35		
	9^+			0.88	0.47	0.05	0.85		
State fall	**1**			1.00		1.00			
	2			0.05	0.50	0.29	0.35		
	3			0.02	0.65	0.09	0.50		
	4			0.04	0.68	0.02	1.14		
	5			0.28	0.37	0.12	0.60		
	6			0.22	0.58	0.04	0.98		
	7			0.17	0.69	0.16	0.84		
	8			0.15	0.85	0.04	1.61		
	9^+			0.46	0.53	0.01	2.01		

Table A.2.6. Summary model diagnostics from a sensitivity analysis of the Gulf of Maine haddock base ASAP model to the incorporation of commercial (COM_LPUE), recreational (REC_LPUE) landings-per-unit-effort indices.

Model		ASAP_BASE		ASAP_LPUE_COM		ASAP_LPUE_REC	
Model description		Fit to NEFSC abundance indices		Commercial LPUE		Recreational LPUE	
Maximum gradient (*conv. criteria < 1e-4*)		1.10E-05		2.96E-04		5.90E-05	
Number of parameters		125		126		126	
Objective function		2526		2535		2575	
Components of objective function	Recruit devs	110		109		112	
	Suvey age comps	874		871		874	
	Catch age comps	644		672		654	
	Index fit	702		684		739	
	Catch fit	196		198		196	
RMSE	Fleet 1	0.34		0.45		0.35	
	Index 1	2.10		2.12		2.07	
	Index 2	2.00		2.07		1.98	
	Index 3			1.59		1.67	
	Index total	2.05		1.94		1.96	
	Recruit devs	3.91		3.89		3.96	
SSB_{1977} (mt)		9,470		9,520		9,513	
SSB_{2013} (mt)		4,500		3,441		5,437	
$F_{mult,2013}$		0.31		0.53		0.21	
Mohn's rho (7 year peel)	SSB	-0.03		-0.15		-0.05	
	F_{mult}	0.05		0.34		0.07	
	Age 1 N	0.18		0.17		0.05	
	Notes					*Note that 0.2 were added to the CVs	
	Block/Index	Selectivity	CV	Selectivity	CV	Selectivity	CV
Fleet block 1 (1977-1988)	1	0.00	0.61	0.01	0.60	0.00	0.61
	2	0.22	0.12	0.32	0.09	0.22	0.12
	3	0.39	0.11	0.51	0.07	0.39	0.11
	4	0.64	0.10	0.87	0.07	0.64	0.10
	5	0.65	0.11	1.00	0.00	0.65	0.11
	6	0.77	0.12	1.00	0.00	0.78	0.12
	7	1.00					
	8	1.00	0.00	1.00	0.00	1.00	0.00
	9^+	1.00	0.00	1.00	0.00	1.00	0.00
Fleet block 2 (1989-2004)	1	0.01	0.27	0.00	0.26	0.01	0.25
	2	0.06	0.16	0.04	0.13	0.05	0.13
	3	0.34	0.14	0.20	0.11	0.27	0.10
	4	0.55	0.14	0.32	0.11	0.41	0.11
	5	0.72	0.14	0.42	0.11	0.53	0.11
	6	0.96	0.14	0.57	0.11	0.73	0.11
	7	1.00					
	8	0.94	0.21	0.63	0.19	0.70	0.19
	9^+	0.67	0.30	0.34	0.28	0.47	0.27
Fleet block 3 (2005-2013)	1	0.01	0.42	0.01	0.41	0.01	0.41
	2	0.06	0.21	0.04	0.20	0.08	0.20
	3	0.22	0.17	0.15	0.16	0.26	0.15
	4	0.31	0.17	0.24	0.16	0.35	0.16
	5	0.56	0.15	0.43	0.15	0.63	0.15
	6	0.77	0.15	0.60	0.14	0.91	0.14
	7	1.00					
	8	1.00	0.00	0.88	0.14	1.00	0.00
	9^+	0.74	0.19	0.80	0.18	1.00	0.00

Table A.2.7. Summary model diagnostics from a sensitivity analysis of the Gulf of Maine haddock base ASAP model to different assumptions on the mortality of fish discarded in the recreational fishery.

Model		**ASAP_REC_0_MORT**	**ASAP_BASE**	**ASAP_REC_100_MORT**
Model description		ASAP base run (0% rec disc mort)	ASAP base run (50% rec disc mort)	ASAP base run (100% rec disc mort)
Maximum gradient (*conv. criteria < 1e-4*)		1.31E-03	1.10E-05	3.00E-05
Number of parameters		125	125	125
Objective function		2534	2526	2523
Components of objective function	**Recruit devs**	108	110	111
	Suvey age comps	878	874	871
	Catch age comps	650	644	643
	Index fit	702	702	701
	Catch fit	195	196	197
RMSE	**Fleet 1**	0.34	0.34	0.34
	Index 1	2.10	2.10	2.09
	Index 2	2.01	2.00	2.00
	Index total	2.06	2.05	2.05
	Recruit devs	3.83	3.91	3.94
SSB_{1977} (mt)		9,507	9,470	9,461
SSB_{2013} (mt)		4,764	4,500	4,419
$F_{mult,2013}$		0.21	0.31	0.38
Mohn's rho (7 year peel)	**SSB**	-0.06	-0.03	-0.04
	F_{mult}	0.11	0.05	0.05
	Age 1 N	0.16	0.18	0.14

Table A.2.8. Summary model diagnostics from a sensitivity analysis of the Gulf of Maine haddock base ASAP model with explicit treatment of the commercial and recreational fleets.

Model		ASAP_BASE		ASAP_2_FLEETS	
Model description		Fit to NEFSC abundance indices		Commercial and recreational catch	
Maximum gradient (*conv. criteria < 1e-4*)		1.10E-05		1.60E-04	
Number of parameters		125		178	
Objective function		2526		2905	
Components of objective function	Recruit devs	110		111	
	Suvey age comps	874		878	
	Catch age comps	644		967	
	Index fit	702		702	
	Catch fit	196		247	
RMSE	Fleet 1	0.34		0.35	
	Fleet 2			0.12	
	Catch total			0.26	
	Index 1	2.10		2.11	
	Index 2	2.00		2.00	
	Index total	2.05		2.06	
	Recruit devs	3.91		3.96	
SSB_{1977} (mt)		9,470		9,167	
SSB_{2013} (mt)		4,500		4,242	
$F_{mult,\ 2013}$		0.31		0.45	
Mohn's rho (7 year peel)	SSB	-0.03		0.04	
	F_{mult}	0.05		-0.02	
	Age 1 N	0.18		0.30	
	Block/Index	Selectivity	CV	Selectivity	CV
Fleet block 1 (1977-1988)	1	0.00	0.61	0.00	0.64
	2	0.22	0.12	0.19	0.17
	3	0.39	0.11	0.33	0.16
	4	0.64	0.10	0.56	0.16
	5	0.65	0.11	0.57	0.16
	6	0.77	0.12	0.69	0.17
	7	1.00		0.81	0.20
	8	1.00	0.00	1.00	
	9^+	1.00	0.00	0.97	0.36
Fleet block 2 (1989-2004)	1	0.01	0.27	0.01	0.26
	2	0.06	0.16	0.06	0.15
	3	0.34	0.14	0.31	0.12
	4	0.55	0.14	0.51	0.12
	5	0.72	0.14	0.68	0.12
	6	0.96	0.14	0.94	0.12
	7	1.00		1.00	
	8	0.94	0.21	1.00	0.00
	9^+	0.67	0.30	0.87	0.29
Fleet block 3 (2005-2013)	1	0.01	0.42	0.01	0.36
	2	0.06	0.21	0.03	0.27
	3	0.22	0.17	0.11	0.21
	4	0.31	0.17	0.20	0.20
	5	0.56	0.15	0.46	0.18
	6	0.77	0.15	0.63	0.17
	7	1.00		0.81	0.16
	8	1.00	0.00	1.00	
	9^+	0.74	0.19	0.71	0.19
Recreational block 1 (1977-1999)	1			0.01	0.42
	2			0.10	0.21
	3			0.41	0.19
	4			0.37	0.20
	5			0.41	0.21
	6			0.35	0.25
	7			0.45	0.31
	8			1.00	
	9^+			0.36	0.55
Recreational block 2 (2000-2013)	1			0.01	0.86
	2			0.12	0.33
	3			0.33	0.29
	4			0.46	0.30
	5			0.72	0.29
	6			0.96	0.28
	7			0.91	0.30
	8			1.00	
	9^+			0.68	0.31

Table A.2.9. Summary model diagnostics from a sensitivity analysis of the Gulf of Maine haddock base ASAP model to the assessment starting year.

Model		**ASAP_BASE**	**ASAP_HIST_1956**	**ASAP_HIST_1963**
Model description		Starts in 1977 w/start of CAA	Starts in 1956 w/ start of catch series	Starts in 1963 w/ start of NEFSC survey
Maximum gradient (*conv. criteria < 1e-4*)		1.10E-05	4.90E-05	3.80E-05
Number of parameters		125	167	153
Objective function		2526	3153	3088
Components of objective function	**Recruit devs**	110	160	146
	Suvey age comps	874	1039	1039
	Catch age comps	644	662	663
	Index fit	702	936	938
	Catch fit	196	357	301
RMSE	**Fleet 1**	0.34	0.56	0.58
	Index 1	2.10	2.08	2.09
	Index 2	2.00	2.01	2.03
	Index total	2.05	2.04	2.06
	Recruit devs	3.91	3.58	3.77
SSB_{start} (mt)			58,610	19,131
SSB_{1977} (mt)		9,470	12,248	12,582
SSB_{2013} (mt)		4,500	3,595	3,493
$F_{mult, 2013}$		0.31	0.40	0.41
Mohn's rho (7 year peel)	**SSB**	-0.03	-0.16	-0.16
	F_{mult}	0.05	0.28	0.27
	Age 1 N	0.18	0.17	0.14
	Notes		Some retro iterations did not converge	

Table A.2.10. Summary model diagnostics from a sensitivity analysis of the Gulf of Maine haddock base ASAP model exploring one- and two-selectivity block model formulations.

Model		ASAP_BASE_1BLOCK		ASAP_BASE_2BLOCK		ASAP_BASE	
Model description		1 catch selectivity block		2 catch selectivity blocks (1994)		3 catch selectivity blocks (1989,2005)	
Maximum gradient (*conv. criteria < 1e-4*)		3.45E-04		2.20E-05		1.10E-05	
Number of parameters		109		117		125	
Objective function		2575		2528		2526	
Components of objective function	Recruit devs	109		113		110	
	Suvey age comps	880		869		874	
	Catch age comps	684		654		644	
	Index fit	706		697		702	
	Catch fit	197		196		196	
RMSE	Fleet 1	0.36		0.32		0.34	
	Index 1	2.12		2.07		2.10	
	Index 2	2.04		1.97		2.00	
	Index total	2.08		2.02		2.05	
	Recruit devs	3.86		4.01		3.91	
SSB_{1977} (mt)		8,708		9,027		9,470	
SSB_{2013} (mt)		4,309		3,821		4,500	
$F_{mult,2013}$		0.27		0.41		0.31	
Mohn's rho (7 year peel)	SSB	-0.13		-0.04		-0.03	
	F_{mult}	0.15		0.07		0.05	
	Age 1 N	0.19		0.25		0.18	
	Block/Index	Selectivity	CV	Selectivity	CV	Selectivity	CV
Fleet block 1	A50%						
	Slope						
Fleet block 2	A50%						
	Slope						
Fleet block 3	A50%						
	Slope						
Fleet block 1	1	0.01	0.21	0.00	0.61	0.00	0.61
	2	0.09	0.11	0.19	0.15	0.22	0.12
	3	0.30	0.10	0.33	0.13	0.39	0.11
	4	0.48	0.10	0.55	0.13	0.64	0.10
	5	0.57	0.10	0.56	0.14	0.65	0.11
	6	0.74	0.10	0.68	0.14	0.77	0.12
	7	0.84	0.10	0.76	0.17	1.00	
	8	1.00		1.00		1.00	0.00
	9^+	0.79	0.18	1.00	0.00	1.00	0.00
Fleet block 2	1			0.01	0.23	0.01	0.27
	2			0.05	0.14	0.06	0.16
	3			0.26	0.13	0.34	0.14
	4			0.41	0.13	0.55	0.14
	5			0.57	0.12	0.72	0.14
	6			0.78	0.12	0.96	0.14
	7			0.87	0.13	1.00	
	8			1.00		0.94	0.21
	9^+			0.76	0.19	0.67	0.30
Fleet block 3	1					0.01	0.42
	2					0.06	0.21
	3					0.22	0.17
	4					0.31	0.17
	5					0.56	0.15
	6					0.77	0.15
	7					1.00	
	8					1.00	0.00
	9^+					0.74	0.19
NEFSC spring	1	0.75	0.13	0.74	0.13	0.74	0.13
	2	0.63	0.14	0.62	0.14	0.62	0.14
	3	0.79	0.14	0.79	0.14	0.79	0.14
	4	1.00	0.00	1.00	0.00	1.00	0.00
	5	0.86	0.17	0.87	0.17	0.87	0.17
	6	1.00		1.00		1.00	
	7	0.84	0.25	0.82	0.25	0.82	0.25
	8	0.76	0.34	0.75	0.34	0.75	0.34
	9^+	0.78	0.30	0.81	0.31	0.76	0.30
NEFSC fall	1	0.29	0.13	0.28	0.14	0.28	0.14
	2	0.35	0.14	0.35	0.14	0.35	0.14
	3	0.60	0.13	0.60	0.13	0.60	0.13
	4	0.60	0.14	0.61	0.14	0.62	0.14
	5	0.74	0.14	0.75	0.15	0.76	0.15
	6	1.00		1.00		1.00	
	7	1.00	0.00	1.00	0.00	1.00	0.00
	8	1.00	0.00	1.00	0.00	1.00	0.00
	9^+	0.67	0.26	0.71	0.26	0.66	0.25

Table A.2.11. Summary model diagnostics from a sensitivity analysis of the Gulf of Maine haddock base ASAP model exploring alternate three-block models.

Model		ASAP_BASE		ASAP_BASE_1989_2000		ASAP_BASE_1989_2000_SL	
Model description		3 catch selectivity blocks (1989,2005)		3 catch selectivity blocks (1989,2000)		3 catch selectivity blocks (1989,2000), catch selectivity modelled as single logistic function	
Maximum gradient (*conv. criteria < 1e-4*)		1.10E-05		1.85E-04		2.35E-04	
Number of parameters		125		125		107	
Objective function		2526		2491		2540	
Components of objective function	Recruit devs	110		112		112	
	Suvey age comps	874		858		861	
	Catch age comps	644		623		672	
	Index fit	702		701		700	
	Catch fit	196		196		196	
RMSE	Fleet 1	0.34		0.29		0.31	
	Index 1	2.10		2.10		0.00	
	Index 2	2.00		1.99		2.08	
	Index total	2.05		2.05		1.99	
	Recruit devs	3.91		3.99		2.04	
SSB_{1977} (mt)		9,470		9,529		9,096	
SSB_{2013} (mt)		4,500		4,391		4,050	
$F_{mult,\ 2013}$		0.31		0.33		0.41	
Mohn's rho (7 year peel)	SSB	-0.03		0.11		0.10	
	F_{mult}	0.05		-0.09		-0.03	
	Age 1 N	0.18		0.29		0.30	
Block/Index		Selectivity	CV	Selectivity	CV	Selectivity	CV
Fleet block 1	A50%					2.90	0.05
	Slope					0.62	0.11
Fleet block 2	A50%					2.85	0.03
	Slope					0.40	0.06
Fleet block 3	A50%					4.62	0.04
	Slope					0.84	0.07
Fleet block 1	1	0.00	0.61	0.00	0.61		
	2	0.22	0.12	0.24	0.13		
	3	0.39	0.11	0.42	0.11		
	4	0.64	0.10	0.68	0.11		
	5	0.65	0.11	0.69	0.11		
	6	0.77	0.12	0.80	0.13		
	7	1.00		1.00			
	8	1.00	0.00	1.00	0.00		
	9^+	1.00	0.00	1.00	0.00		
Fleet block 2	1	0.01	0.27	0.01	0.31		
	2	0.06	0.16	0.09	0.22		
	3	0.34	0.14	0.51	0.19		
	4	0.55	0.14	0.77	0.19		
	5	0.72	0.14	0.85	0.19		
	6	0.96	0.14	0.91	0.20		
	7	1.00		1.00			
	8	0.94	0.21	0.57	0.33		
	9^+	0.67	0.30	0.11	0.43		
Fleet block 3	1	0.01	0.42	0.01	0.39		
	2	0.06	0.21	0.05	0.18		
	3	0.22	0.17	0.17	0.14		
	4	0.31	0.17	0.32	0.13		
	5	0.56	0.15	0.60	0.12		
	6	0.77	0.15	0.91	0.11		
	7	1.00		1.00			
	8	1.00	0.00	1.00	0.00		
	9^+	0.74	0.19	0.90	0.18		
NEFSC spring	1	0.74	0.13	0.75	0.13	0.72	0.14
	2	0.62	0.14	0.63	0.14	0.61	0.15
	3	0.79	0.14	0.79	0.14	0.76	0.16
	4	1.00	0.00	1.00	0.00	1.00	
	5	0.87	0.17	0.87	0.17	0.88	0.18
	6	1.00		1.00		0.99	0.21
	7	0.82	0.25	0.79	0.25	0.84	0.26
	8	0.75	0.34	0.70	0.34	0.75	0.34
	9^+	0.76	0.30	0.71	0.30	0.86	0.28
NEFSC fall	1	0.28	0.14	0.30	0.14	0.21	0.21
	2	0.35	0.14	0.37	0.14	0.26	0.22
	3	0.60	0.13	0.64	0.13	0.45	0.21
	4	0.62	0.14	0.65	0.14	0.47	0.22
	5	0.76	0.15	0.78	0.15	0.59	0.22
	6	1.00		1.00		0.68	0.23
	7	1.00	0.00	1.00	0.00	0.80	0.24
	8	1.00	0.00	1.00	0.00	1.00	
	9^+	0.66	0.25	0.63	0.25	0.61	0.27

Table A.2.12. Summary model diagnostics from a sensitivity analysis of the Gulf of Maine haddock base ASAP model exploring varying levels of assumed precision in fishery catches.

Model		**ASAP_BASE**	**ASAP_CATCH_CV_100**	**ASAP_CATCH_CV_200**
Model description		Fleet CVs ranged 0.05-0.15	Inflate CVs by 100%	Inflate CVs by 200%
Maximum gradient (*conv. criteria < 1e-4*)		1.10E-05	9.90E-05	8.20E-05
Number of parameters		125	125	125
Objective function		2526	2545	2552
Components of objective function	**Recruit devs**	110	110	111
	Suvey age comps	874	873	871
	Catch age comps	644	640	635
	Index fit	702	695	688
	Catch fit	196	227	247
RMSE	**Fleet 1**	0.34	0.63	0.84
	Index 1	2.10	2.07	2.03
	Index 2	2.00	1.95	1.89
	Index total	2.05	2.00	1.96
	Recruit devs	3.91	3.91	3.92
SSB_{1977} (mt)		9,470	9,927	10,854
SSB_{2013} (mt)		4,500	4,651	4,951
$F_{mult,2013}$		0.31	0.29	0.27
Mohn's rho (7 year peel)	**SSB**	-0.03	0.00	0.05
	F_{mult}	0.05	0.01	-0.05
	Age 1 N	0.18	0.19	0.22
Survey q	**NEFSC spring**	0.26	0.25	0.24
	NEFSC fall	0.99	0.97	0.93

Appendix A.2. Figures

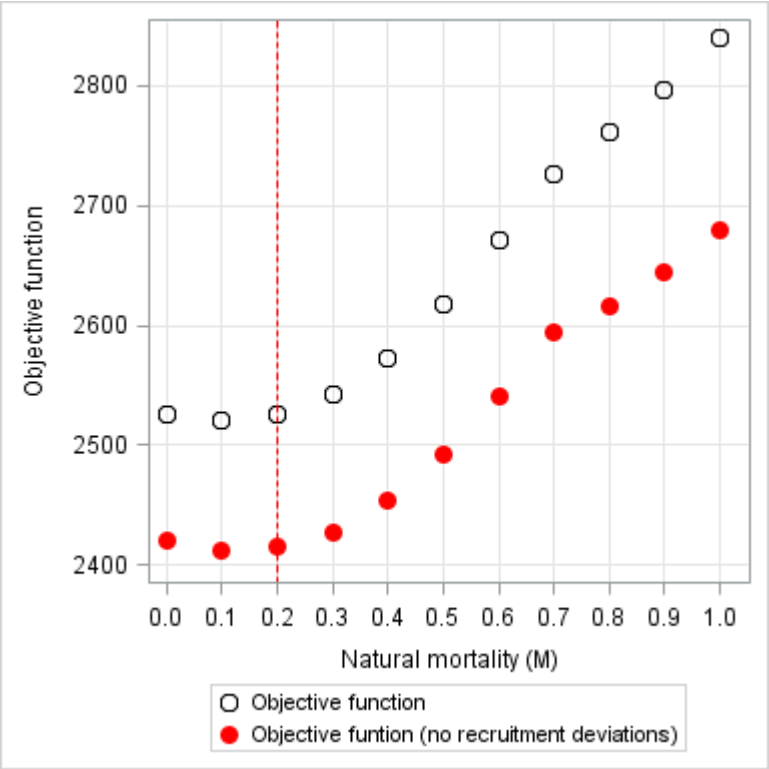

Figure A.2.1. Response of the model objective function to profiling over a range of Gulf of Maine haddock natural mortality values. The dashed red line indicates the M=0.2 assumption applied in the ASAP_BASE model.

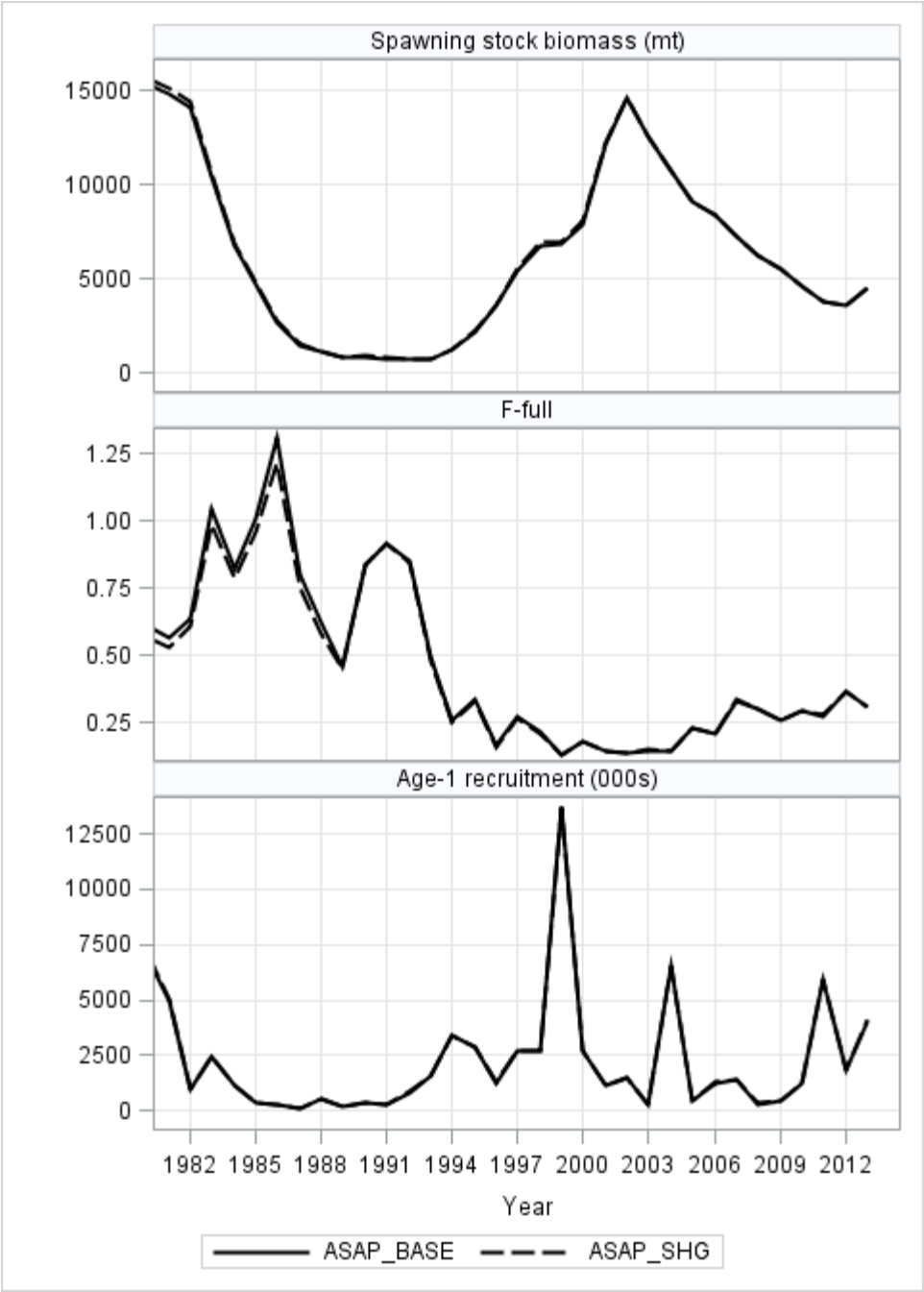

Figure A.2.2. Sensitivity of the Gulf of Maine haddock ASAP_BASE assessment model to use of either the SHG or TOGA tow evaluation criteria.

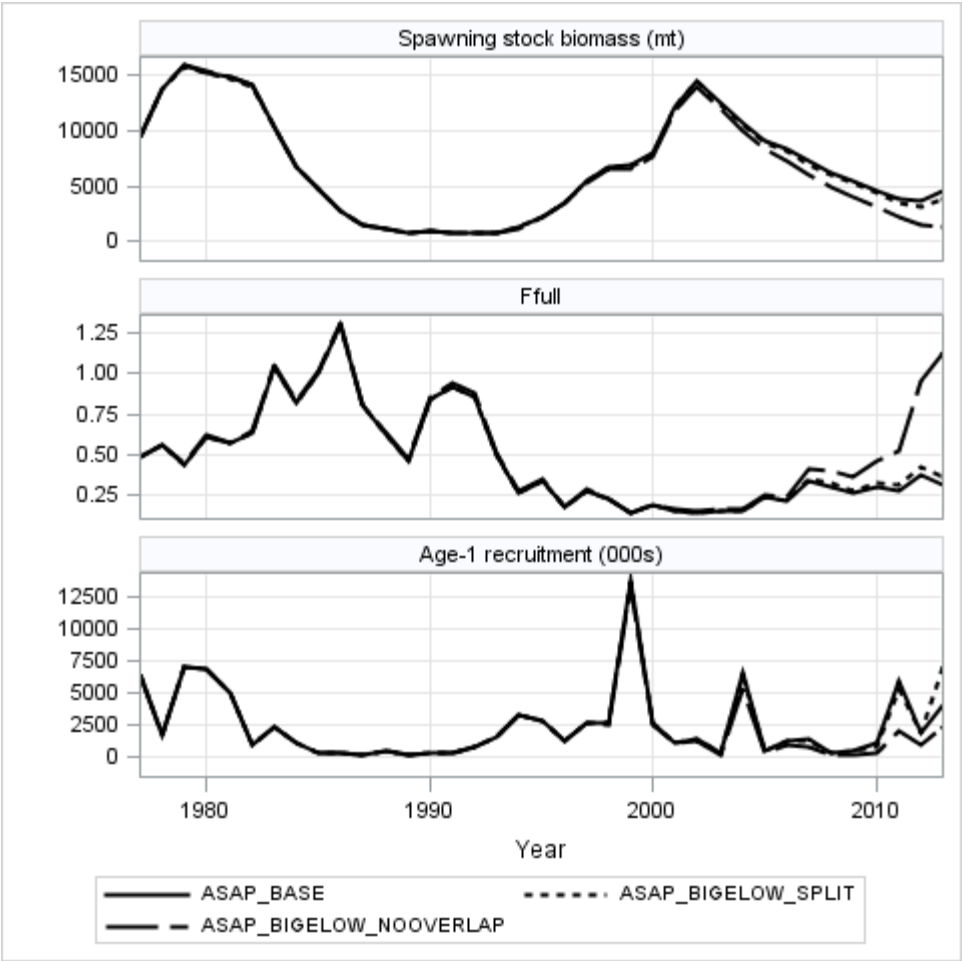

Figure A.2.3. Comparison of model results for two model variants of the Gulf of Maine haddock ASAP_BASE model. Sensitivity models were fit to both the Albatross/Bigelow-calibrated series and a separate un-calibrated Bigelow series (ASAP_BIGELOW_SPLIT), and separate Albatross (1977-2008) and Bigelow (2009-2013) non-overlapping series (ASAP_BIGELOW_NOOVERLAP).

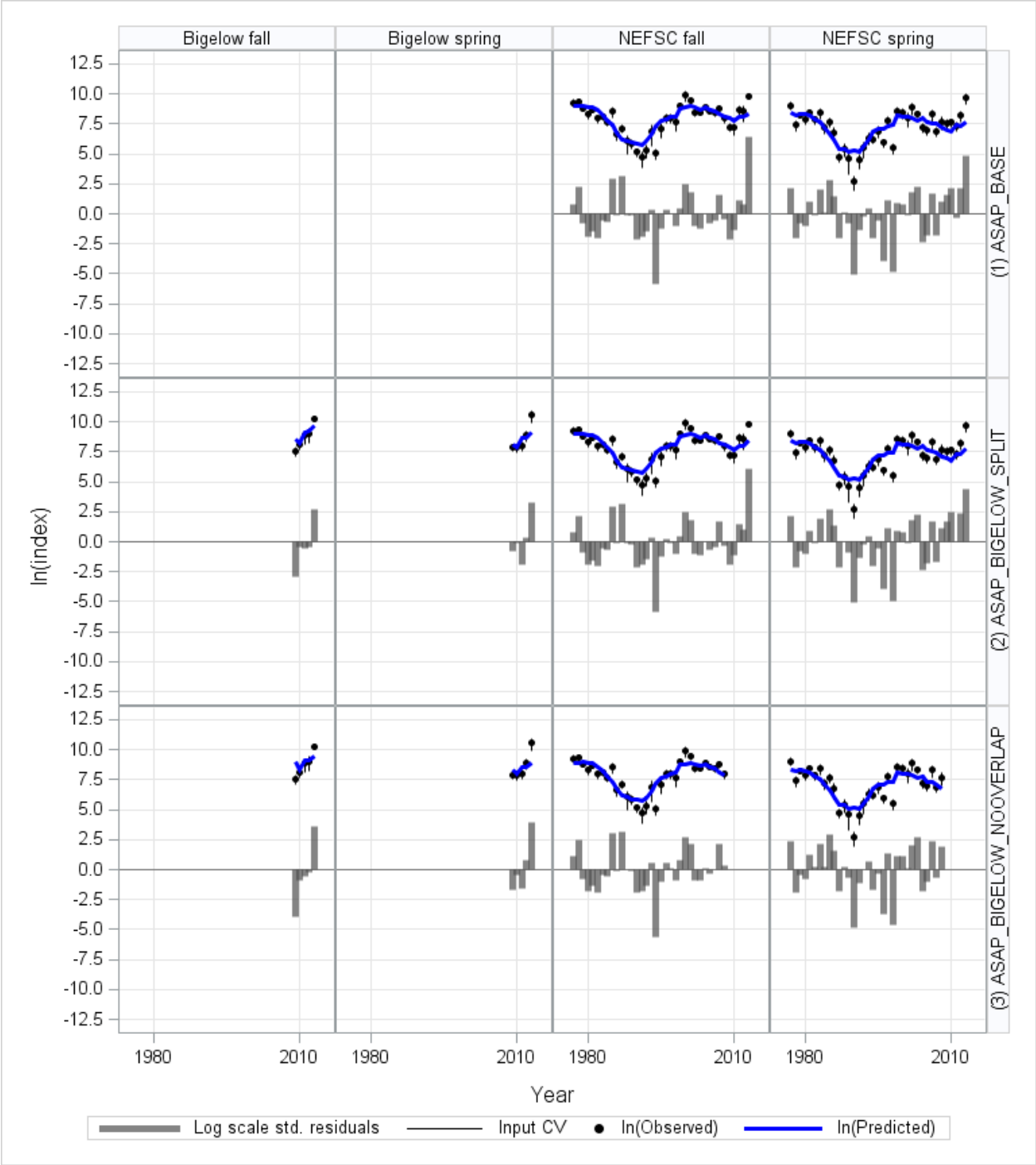

Figure A.2.4. Comparison of model fits to survey indices for variants of the ASAP_BASE model fit to (1) a single Albatross/Bigelow-calibrated series (fall and spring), (2) both the Albatross/Bigelow-converted series and a separate un-calibrated Bigelow series, and (3) separate Albatross (1977-2008) and Bigelow (2009-2013) non-overlapping series.

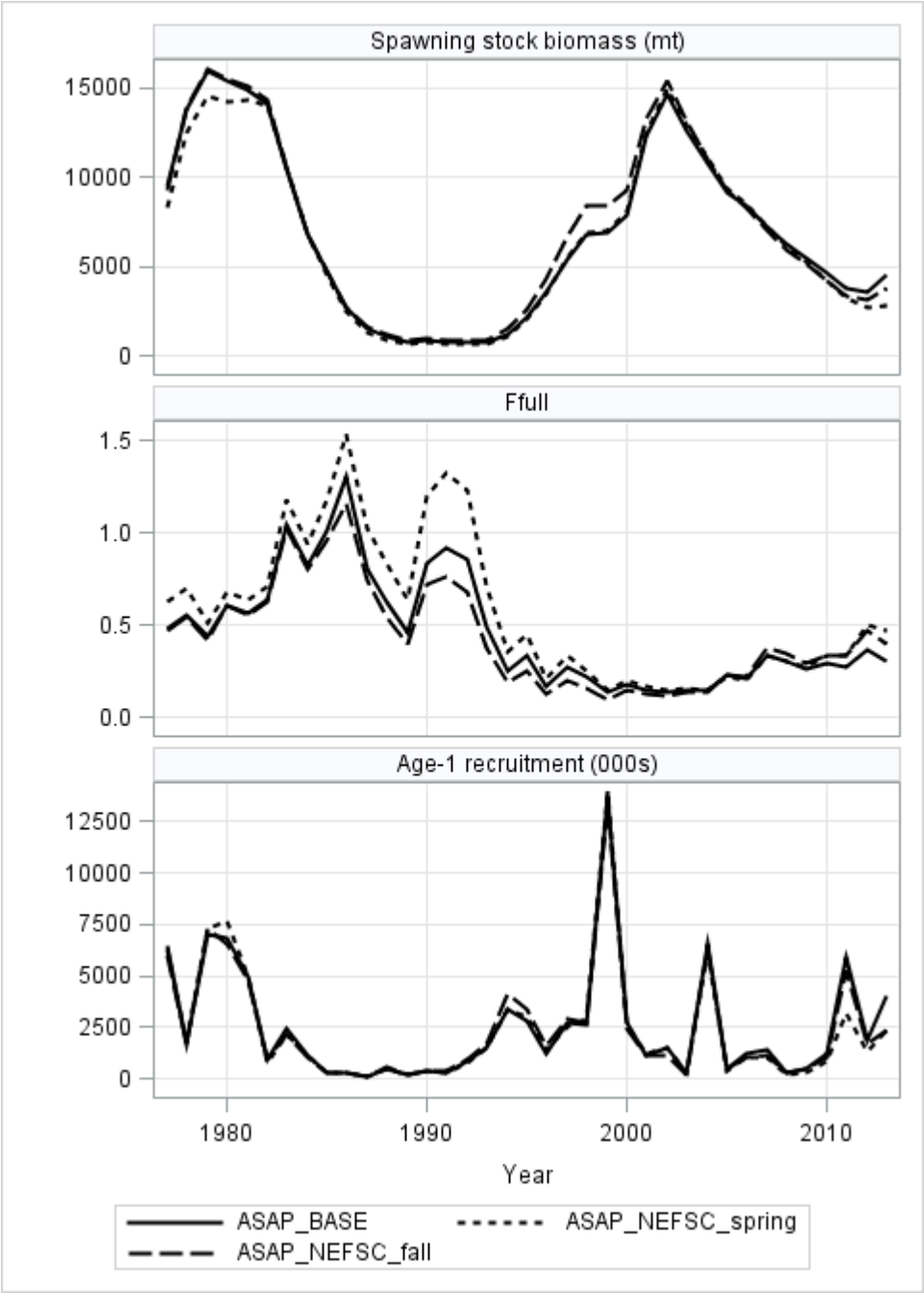

Figure A.2.5. Model results from the ASAP_BASE model compared to the results when run using only the NEFSC spring or NEFSC fall survey.

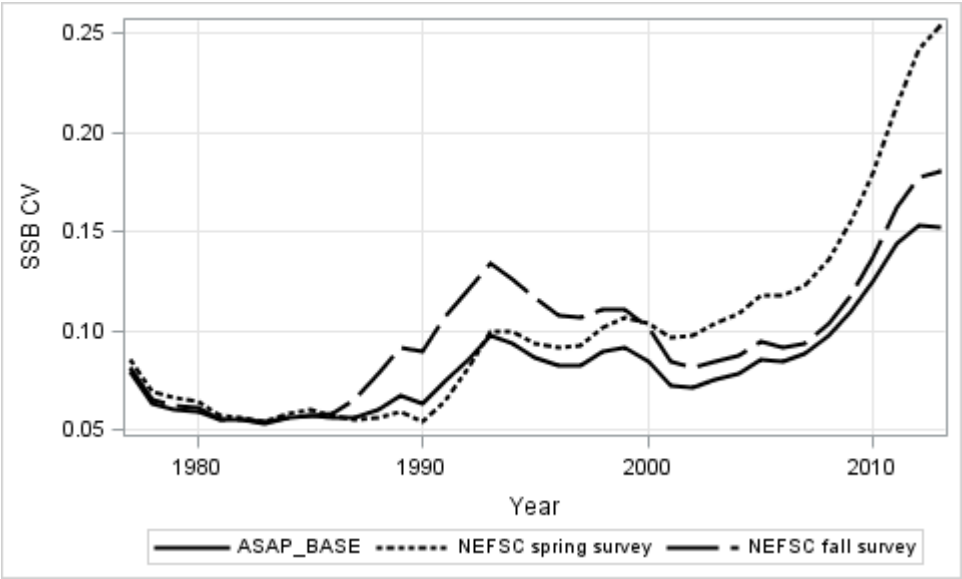

Figure A.2.6. Comparison of the coefficient of variation (CV) in spawning stock biomass (SSB) estimates between the ASAP_BASE model and the model run using only the NEFSC spring or NEFSC fall survey.

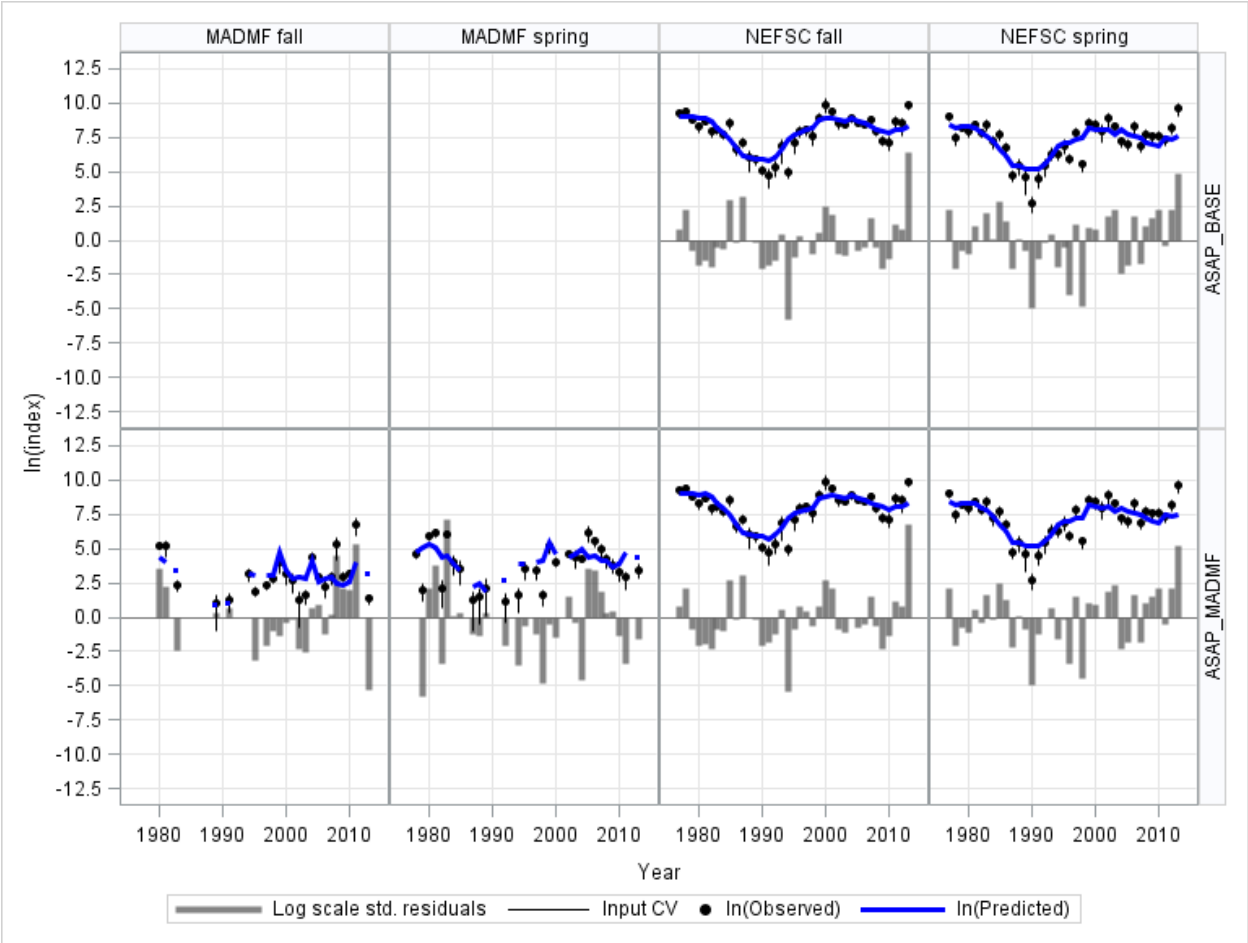

Figure A.2.7. Comparison of model fits to survey indices for both the base ASAP model (ASAP_BASE) model and the base ASAP model with Massachusetts Department of Marine Fisheries (MADMF) spring and fall survey indices.

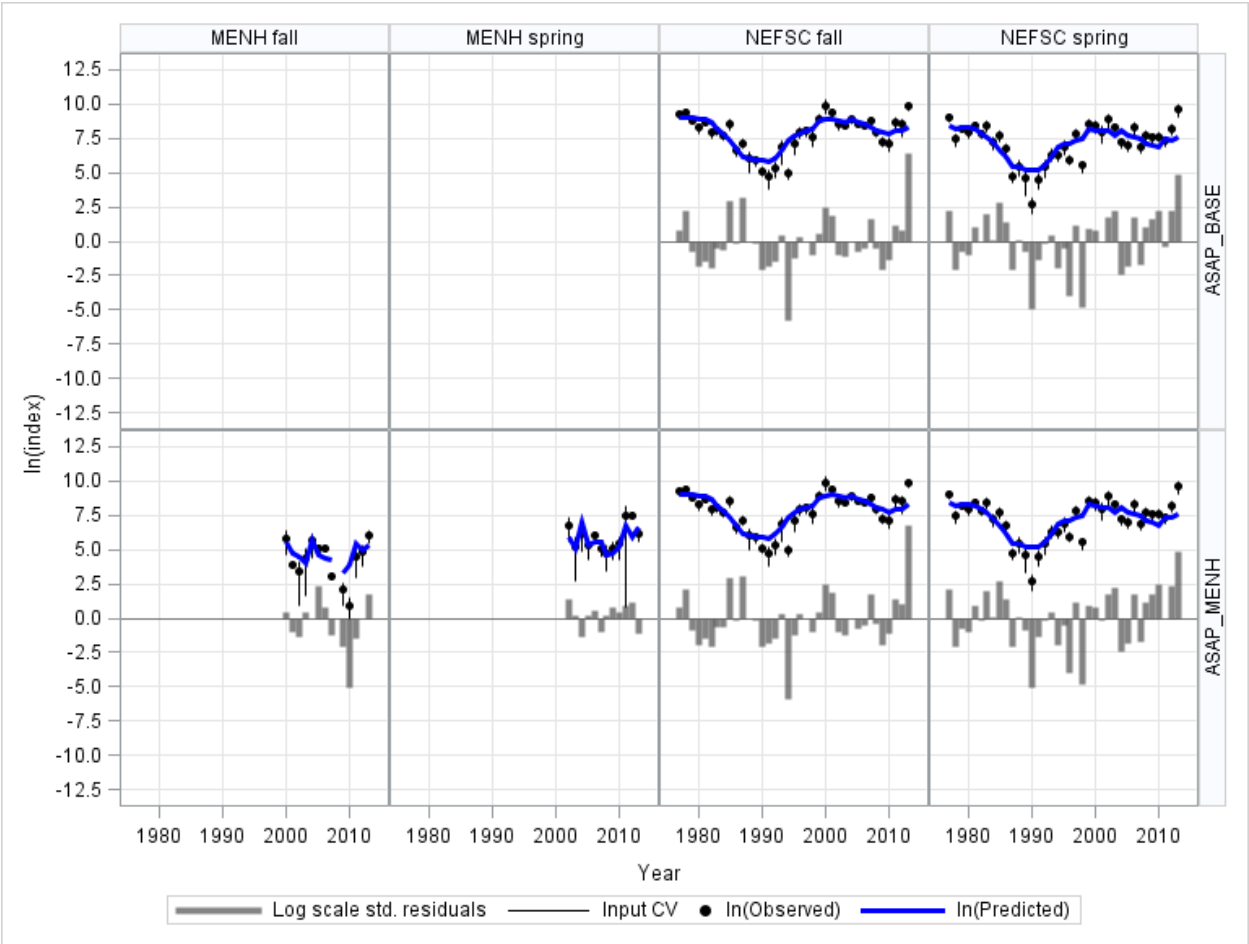

Figure A.2.8. Comparison of model fits to survey indices for both the base ASAP model (ASAP_BASE) model and the base ASAP model with Maine-New Hampshire (MENH) inshore spring and fall survey indices.

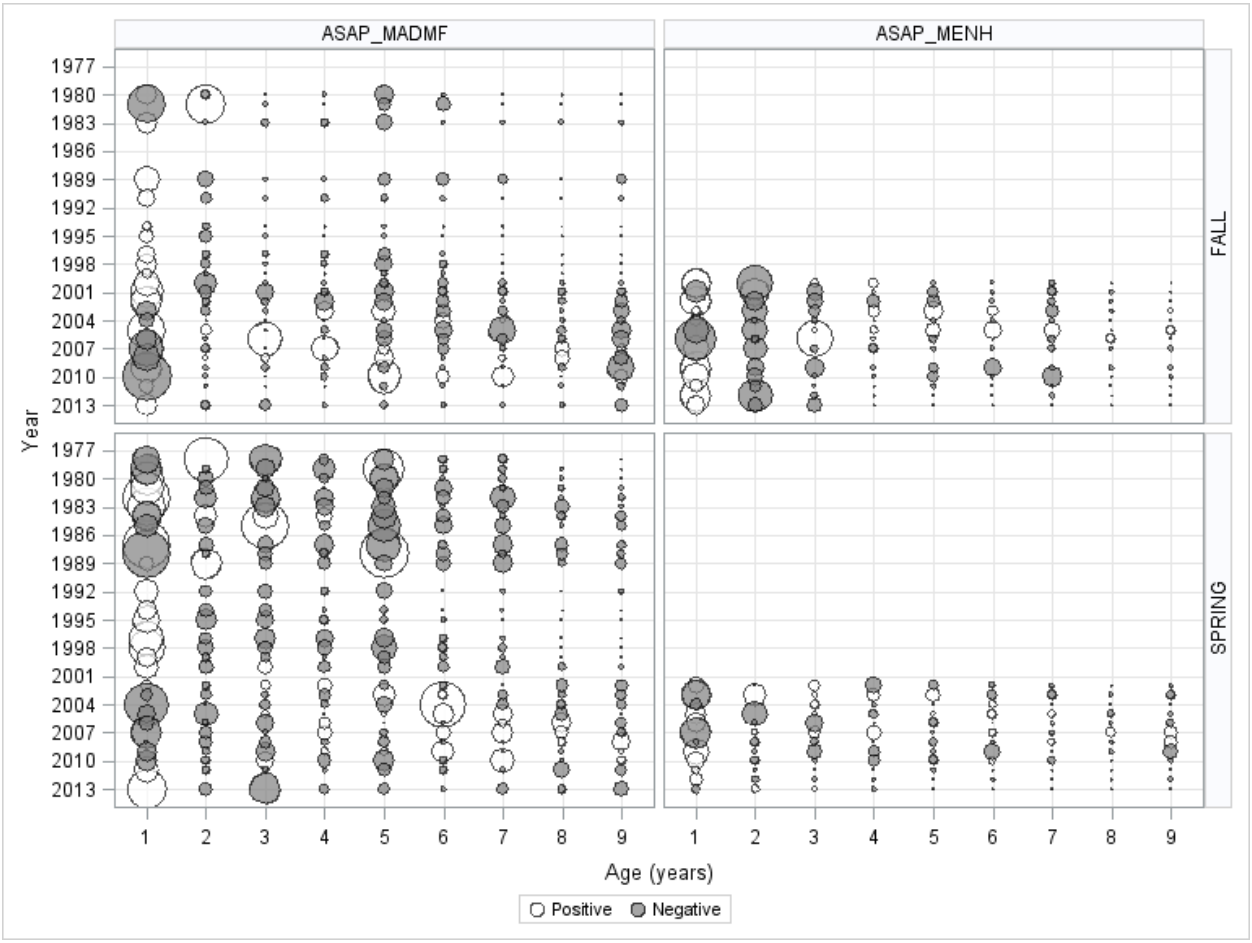

Figure A.2.9. Residual plots of the Gulf of Maine haddock ASAP model fits to the Massachusetts Department of Marine Fisheries (ASAP_MADMF) and Maine-New Hampshire inshore (ASAP_MENH) indices-at-age.

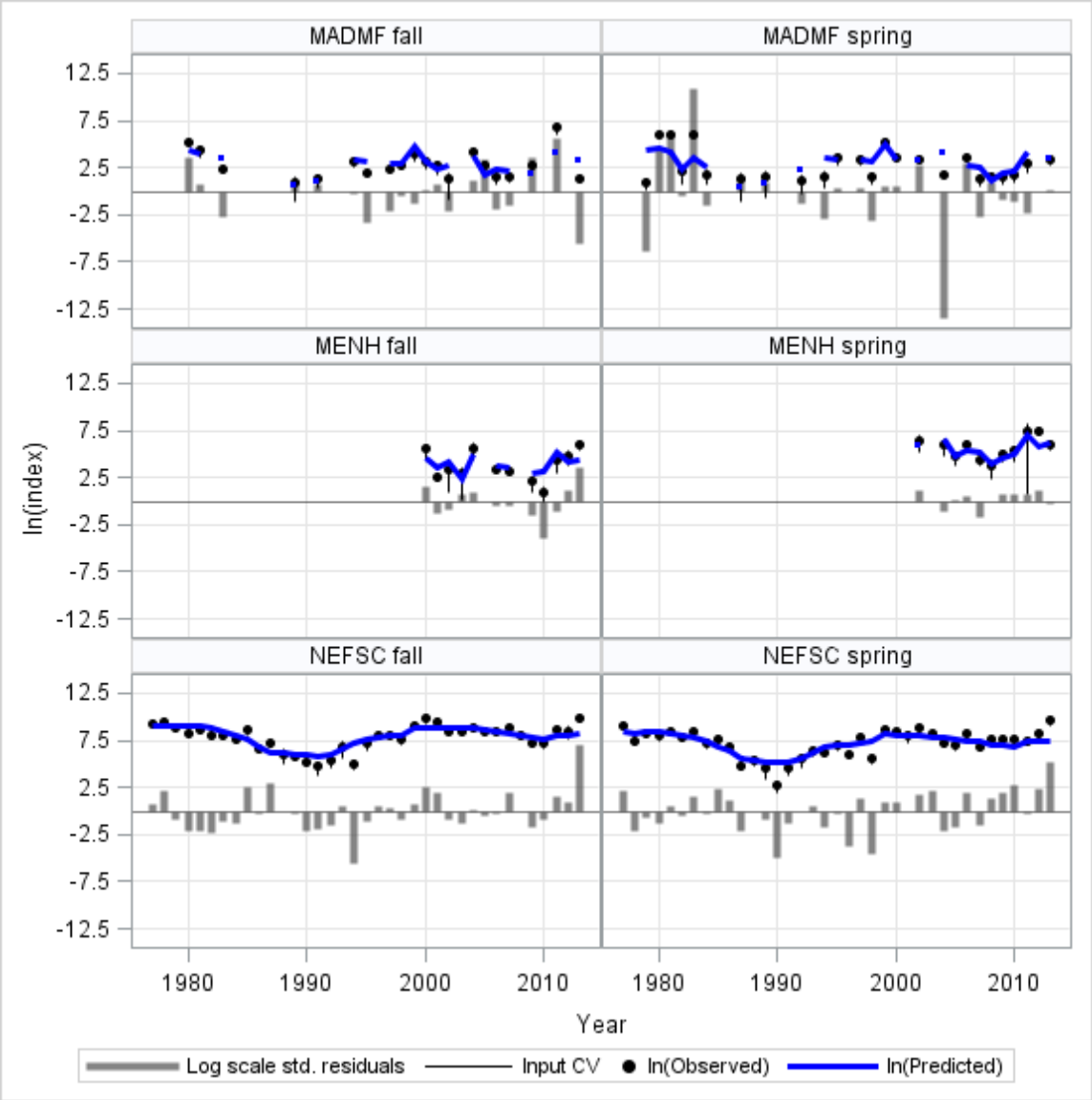

Figure A.2.10. Model fits to survey indices from a run of the base ASAP model which included both the Massachusetts Department of Marine Fisheries (MADMF) and Maine-New Hampshire (MENH) inshore spring and fall survey indices.

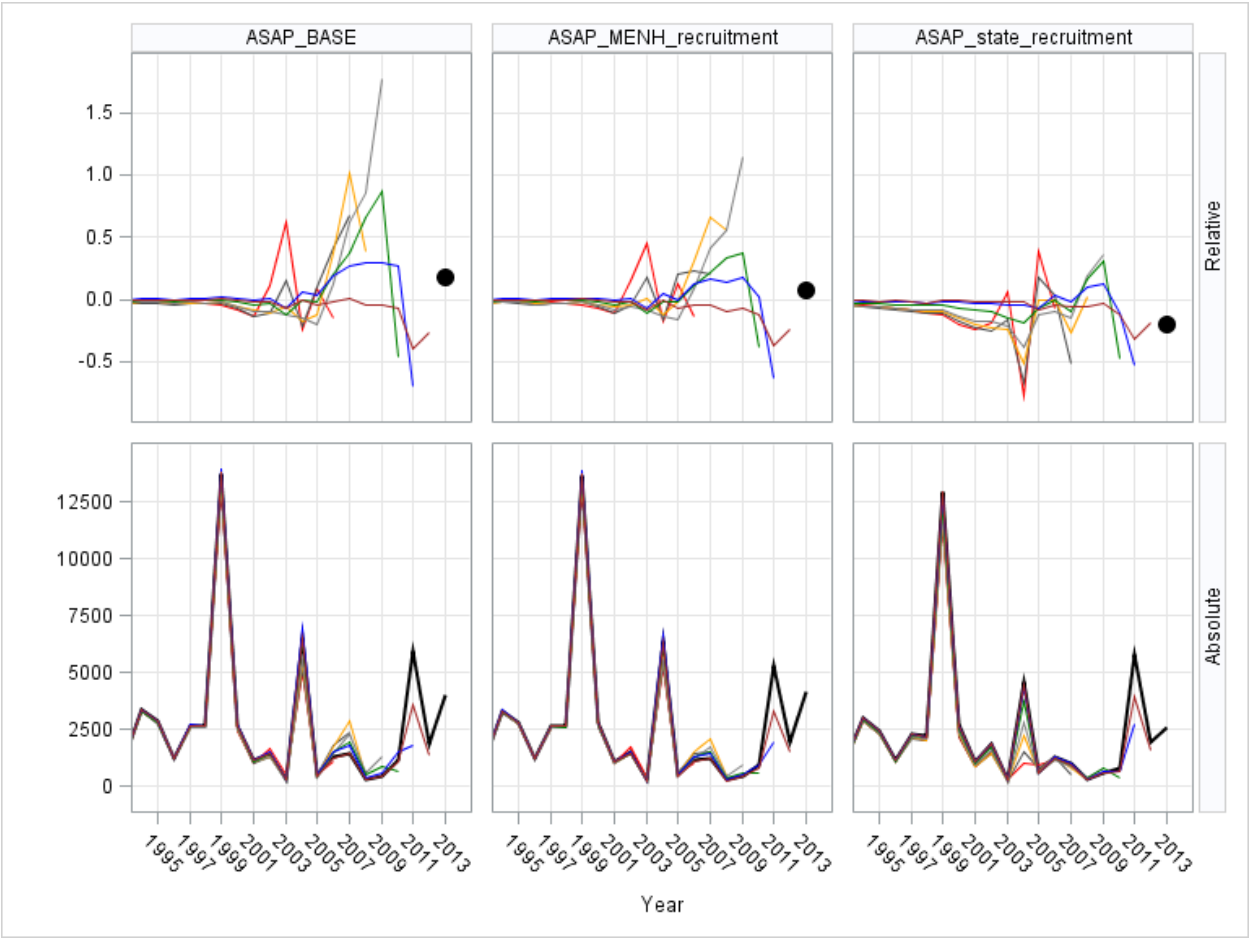

Figure A.2.11. Retrospective plots for age-1 recruitment from the ASAP_BASE, ASAP_MENH_recruitment and ASAP_state_recruitment models. Plots are shown on both the relative difference (top) and absolute (bottom) scales. The average relative difference over a 7-year peel (Mohn's rho) is indicated by the black circle in the top plot.

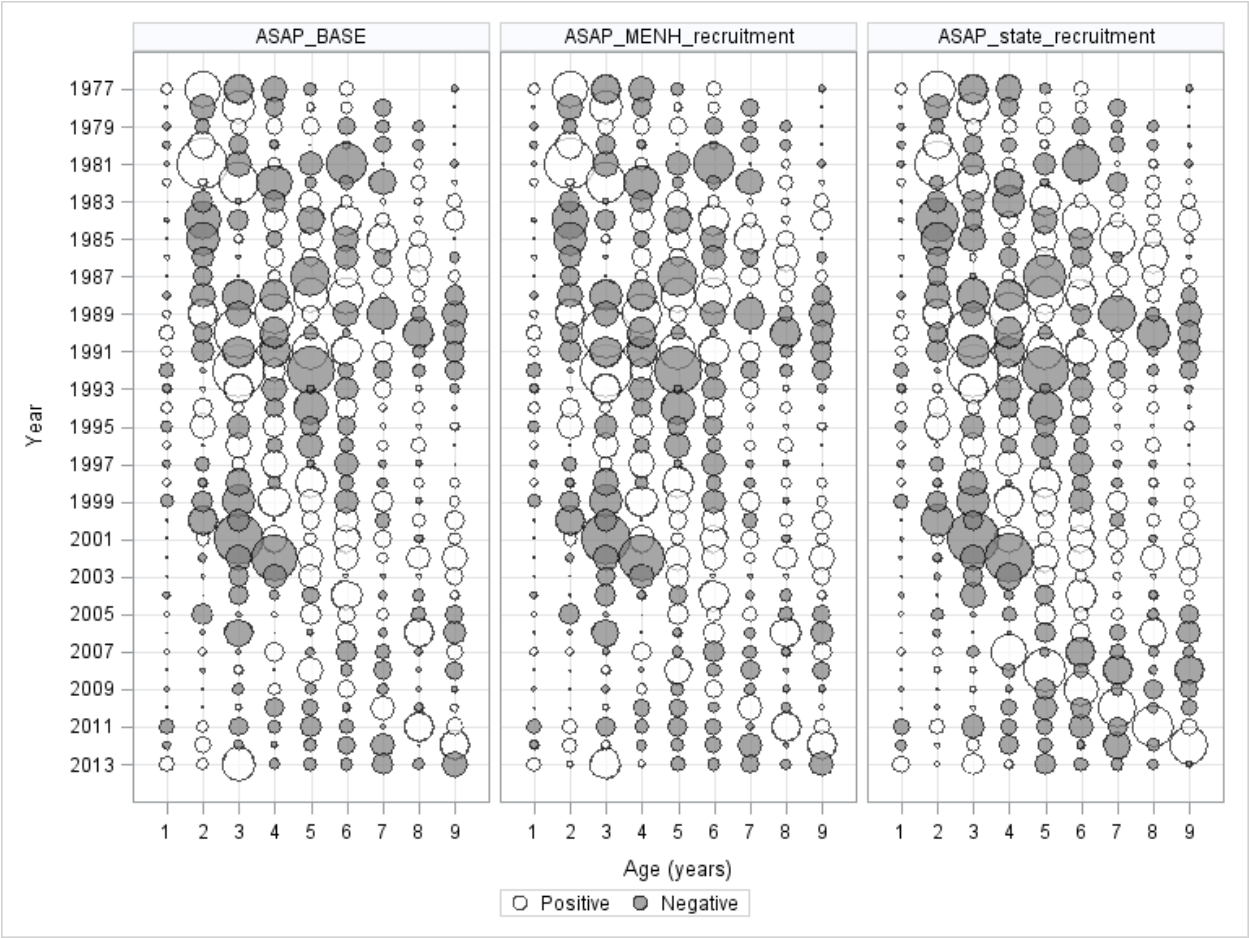

Figure A.2.12. Residual plots of the Gulf of Maine haddock catch-at-age fits compared between the ASAP_BASE model and the model tuned with age-1 spring and fall survey indices from the Maine-New Hampshire inshore survey (ASAP_MENH_recruitment) and both Maine-New Hampshire and Massachusetts Department of Marine Fisheries (ASAP_state_recruitment).

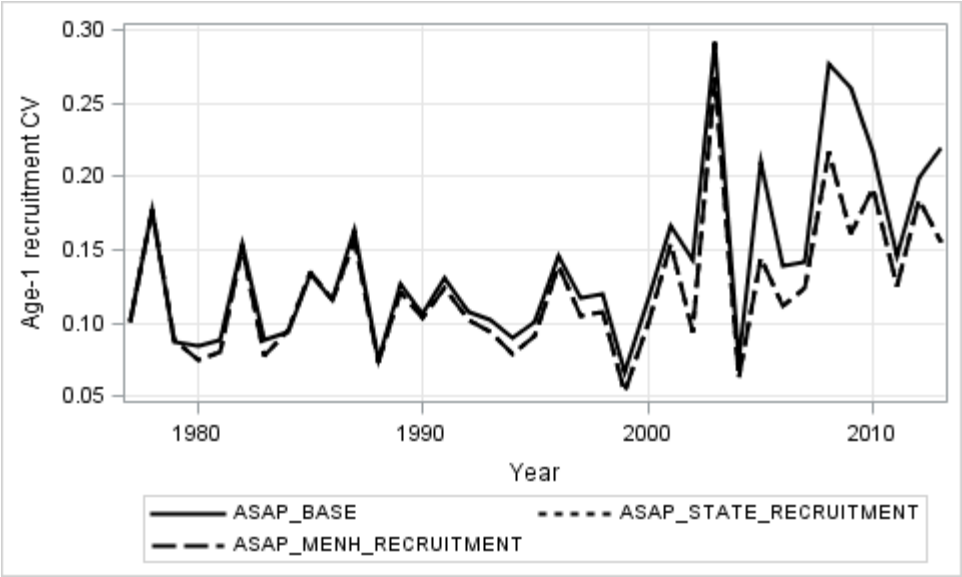

Figure A.2.13. Comparison of the coefficient of variation (CV) age-1 recruitment estimates between the ASAP_BASE model and the model runs incorporating age-1 spring and fall survey indices from the Maine-New Hampshire inshore survey (ASAP_MENH_recruitment) and both Maine-New Hampshire and Massachusetts Department of Marine Fisheries (ASAP_state_recruitment).

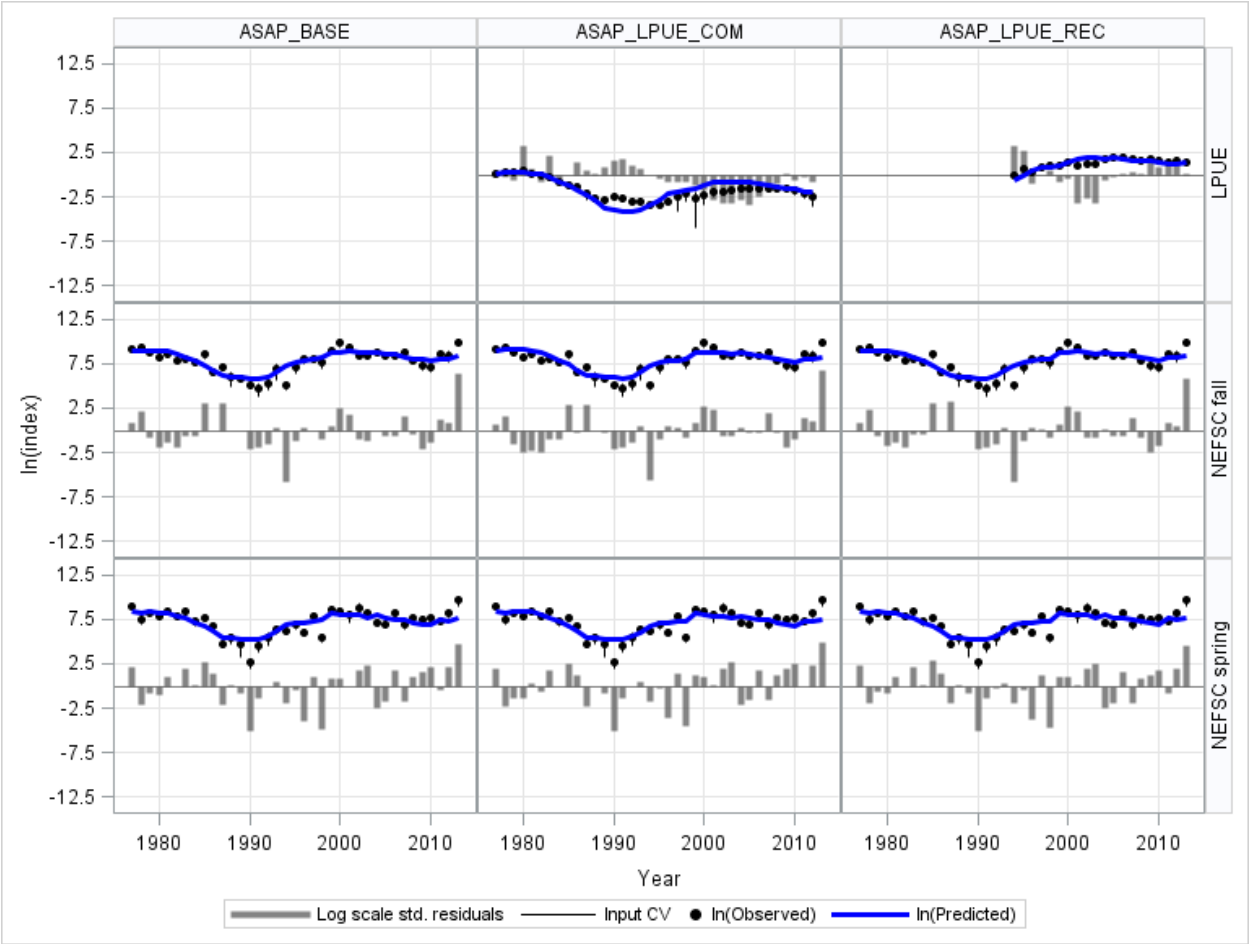

Figure A.2.14. Comparison of model fits to the NEFSC spring and fall survey indices and landings-per-unit-effort (LPUE) indices from both the commercial and recreational fishery. The ASAP_BASE model is compared to an equivalent model run incorporating either the commercial (ASAP_LPUE_COM) or recreational (ASAP_LPUE_REC) LPUE index.

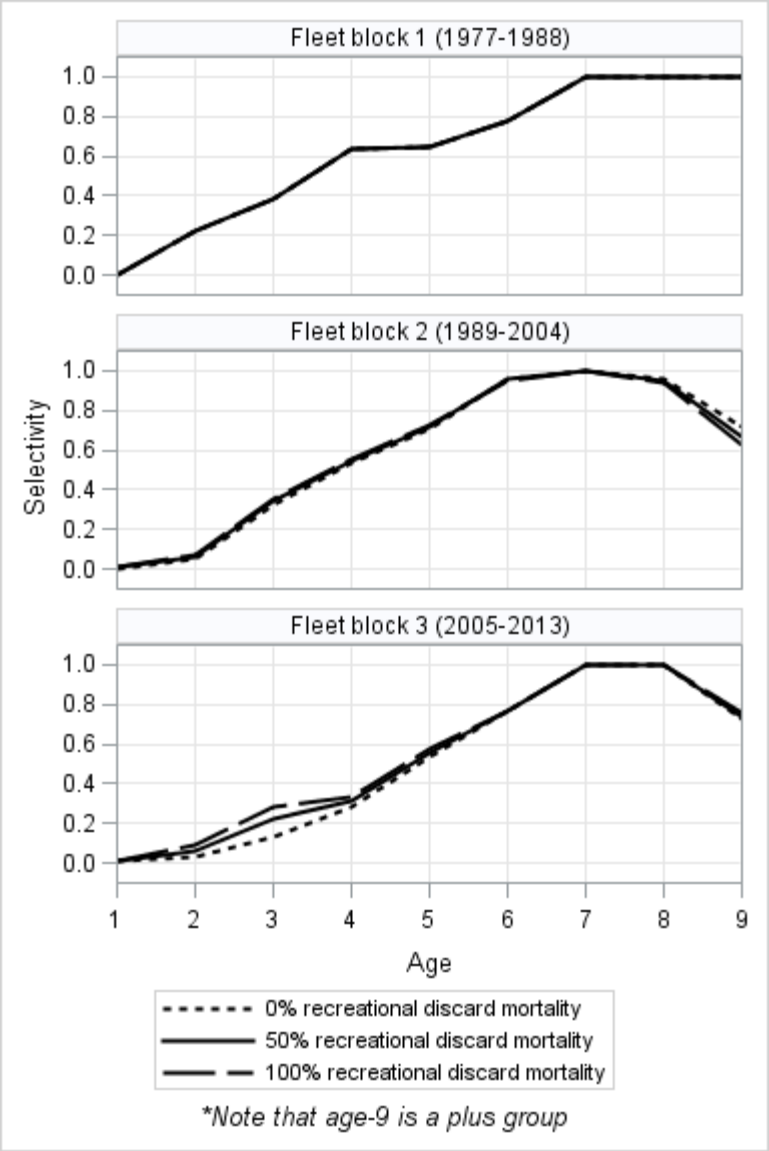

Figure A.2.15. Estimated fleet selectivities under a range of discard mortality sections for each of the fleet selectivity blocks.

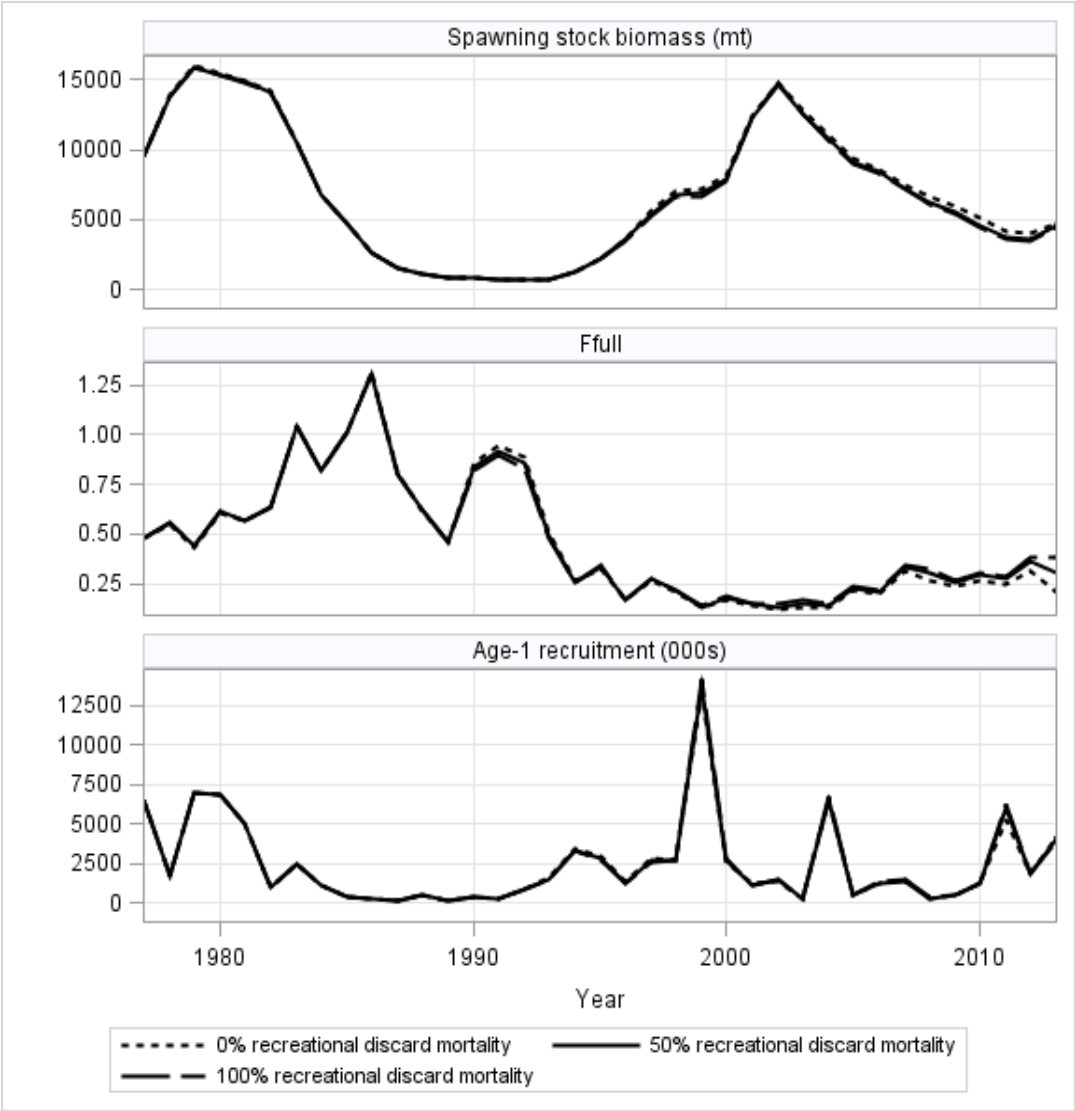

Figure A.2.16. Model results from the ASAP_BASE model under a range of discard mortality sections.

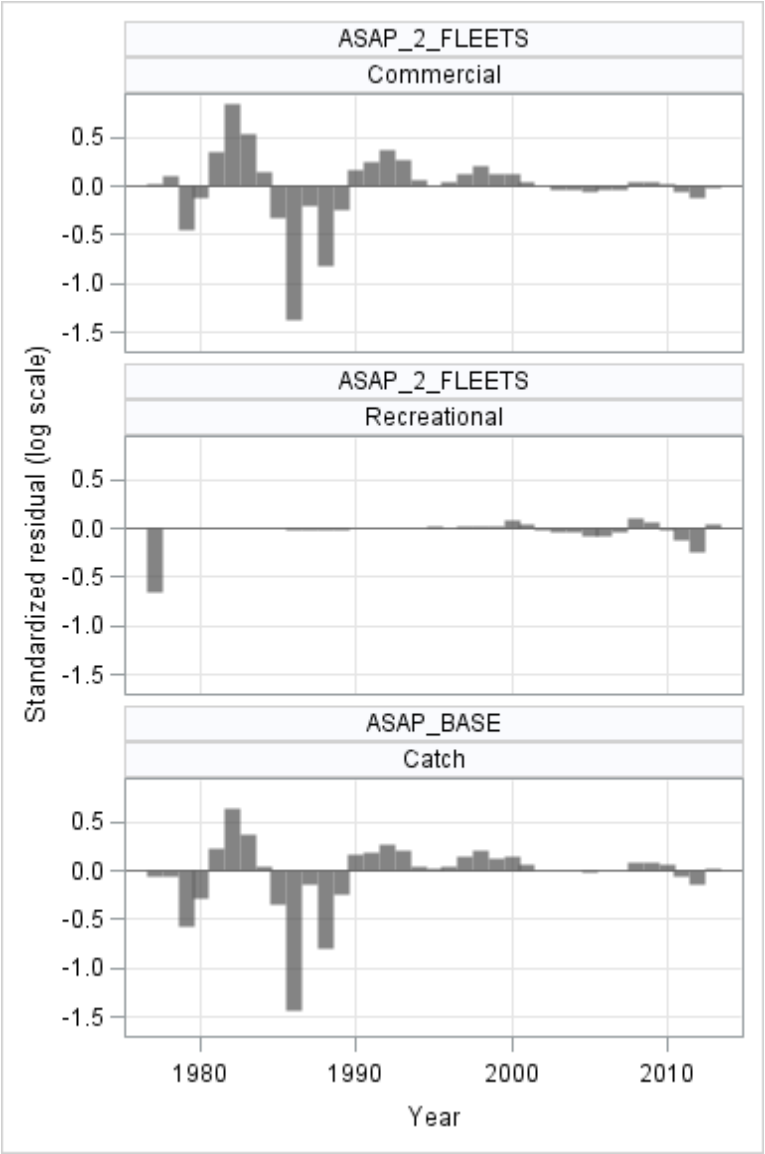

Figure A.2.17. Comparison of model fits to catch time series for both the ASAP_BASE model which includes an aggregated commercial and recreational catch and the ASAP_2_FLEET model which treats commercial and recreational catch separately.

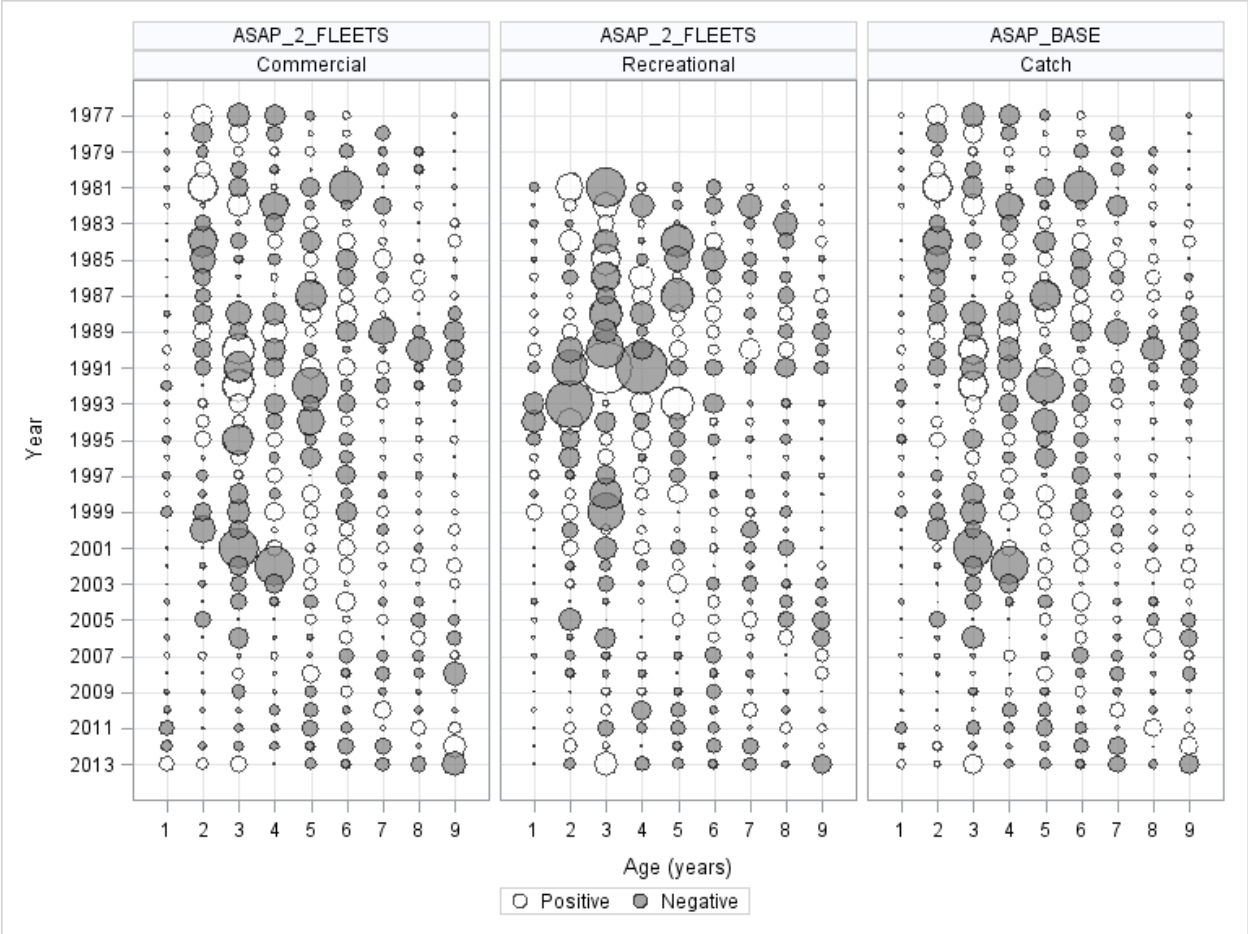

Figure A.2.18. Residual plots of the Gulf of Maine Atlantic cod catch-at-age fits compared between the ASAP_BASE model and the ASAP_2_FLEET model.

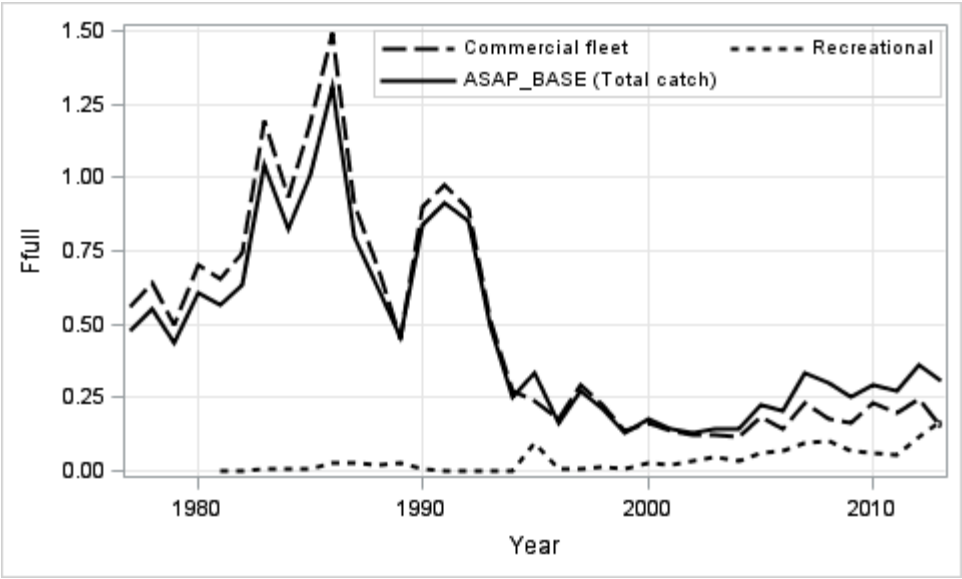

Figure A.2.19. Plot of the fully recruited fishing mortality from ASAP_BASE model and the disaggregated commercial and recreational fishing mortality from the ASAP_2_FLEET model.

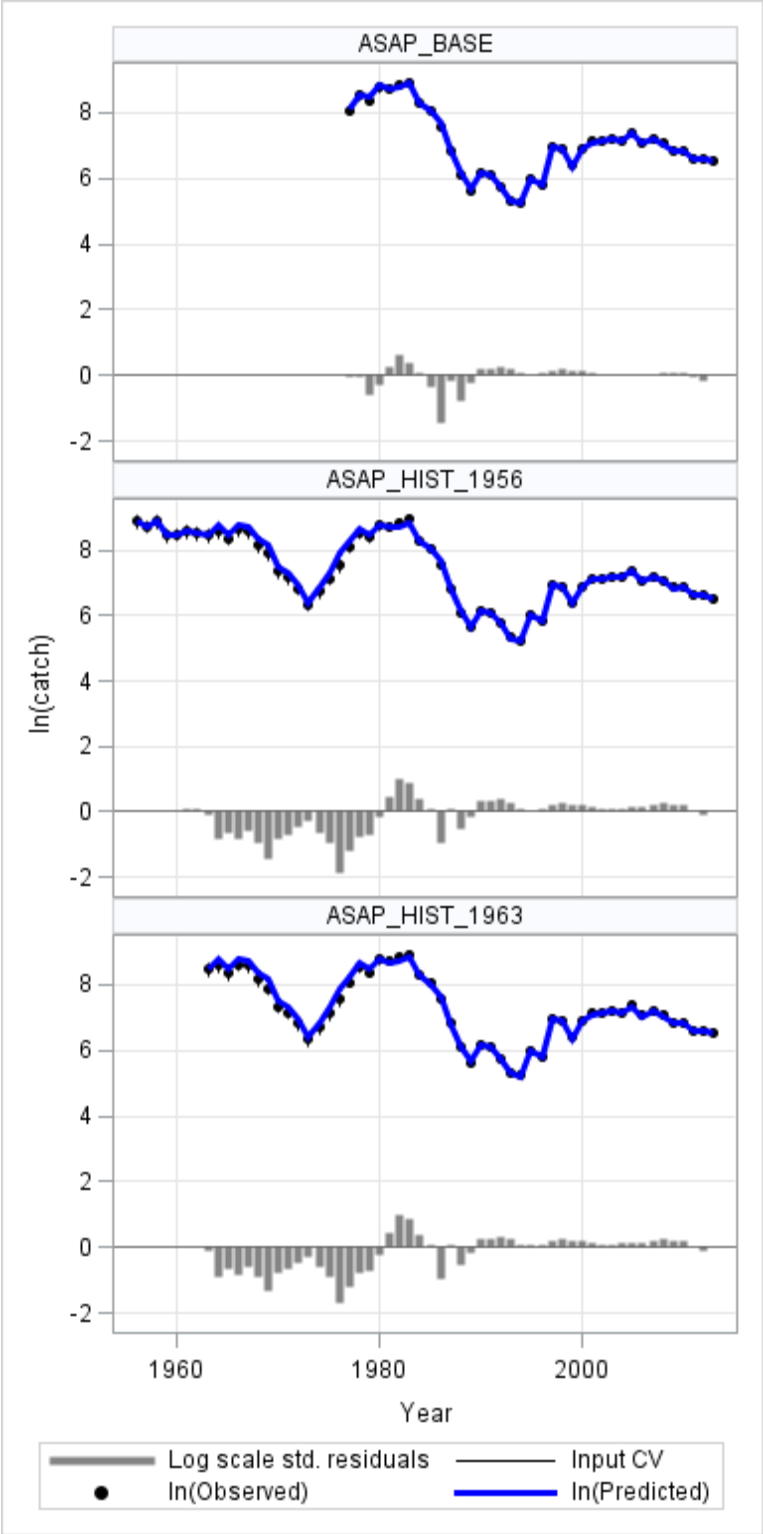

Figure A.2.20. Comparison of model fits to fishery catches from three variants of the base ASAP model with different starting years: ASAP_BASE (1977), ASAP_HIST_1956 and ASAP_HIST_1963.

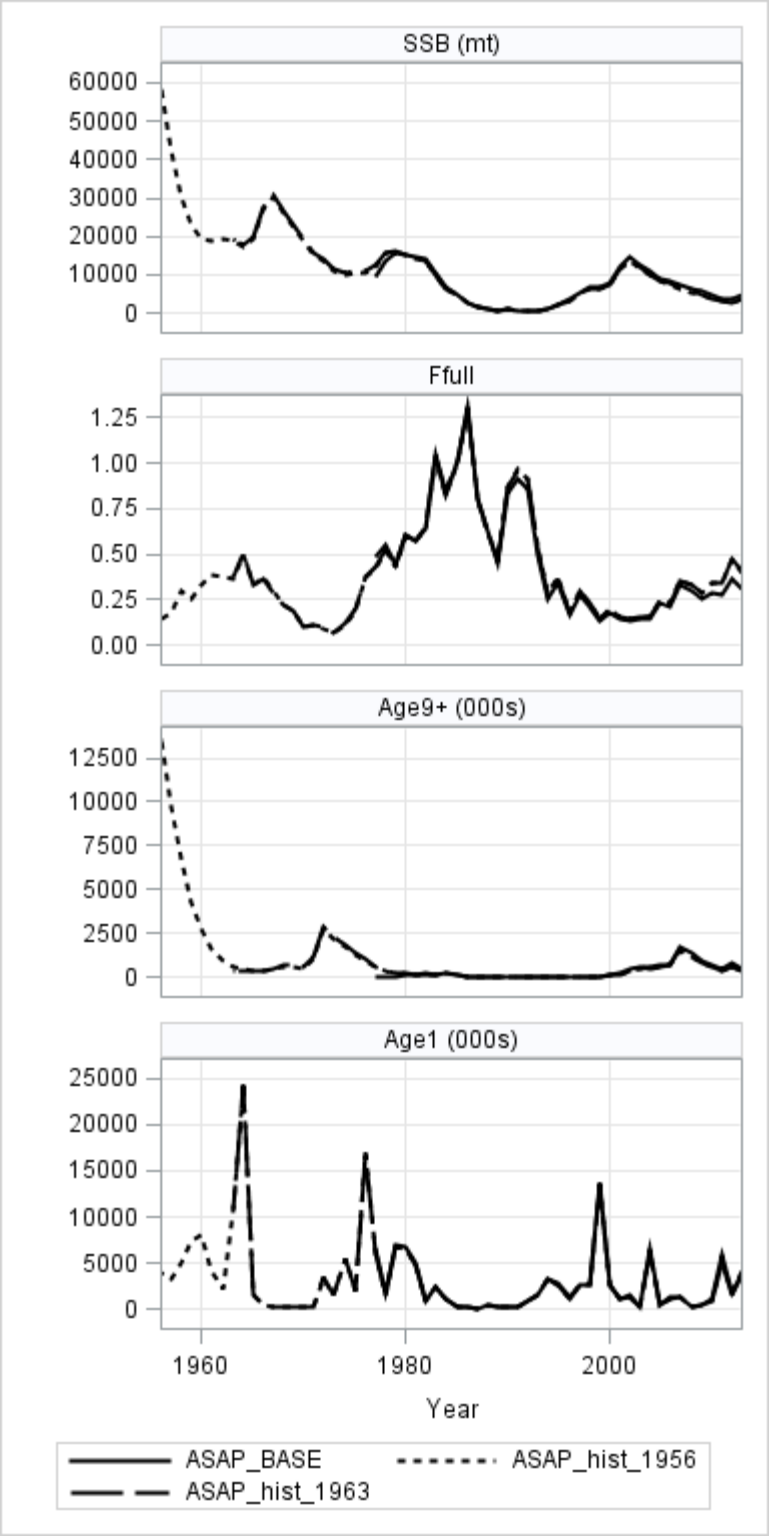

Figure A.2.21. Comparison of the Gulf of Maine haddock assessment results from models using different starting years. All models are based on the ASAP_BASE model which starts in 1977. The ASAP_HIST_1956 and ASAP_HIST_1963 models started in 1956 and 1963, respectively.

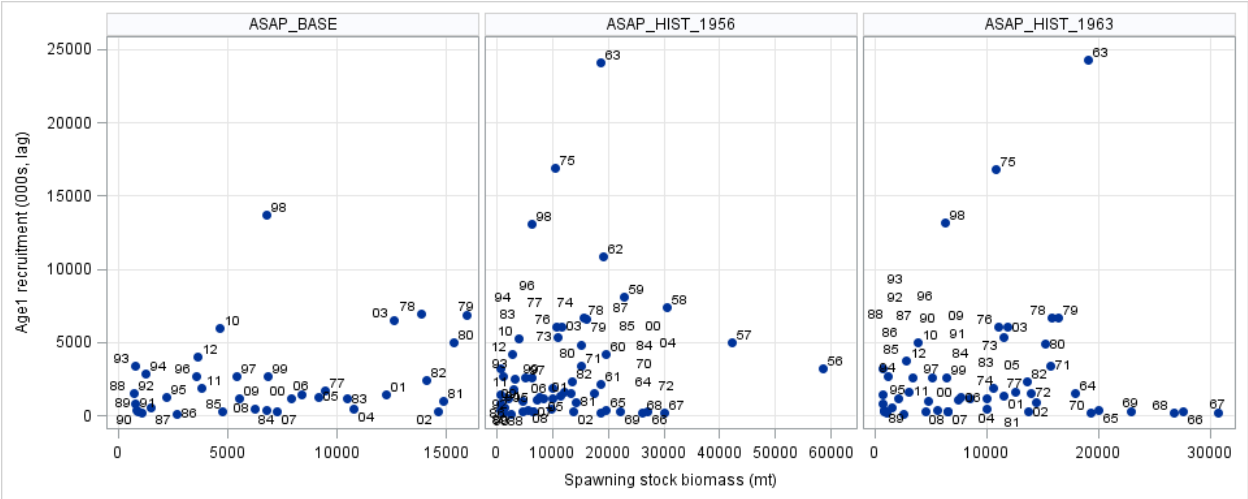

Figure A.2.22. Scatter plots of Gulf of Maine haddock age-1 recruits vs. spawning stock biomass from the ASAP_BASE, ASAP _HIST_1956, and ASAP _HIST_1963 ASAP models. The starting year for each of the models was 1977, 1956 and 1963 respectively. The data labels indicate the spawning year of the individual year classes.

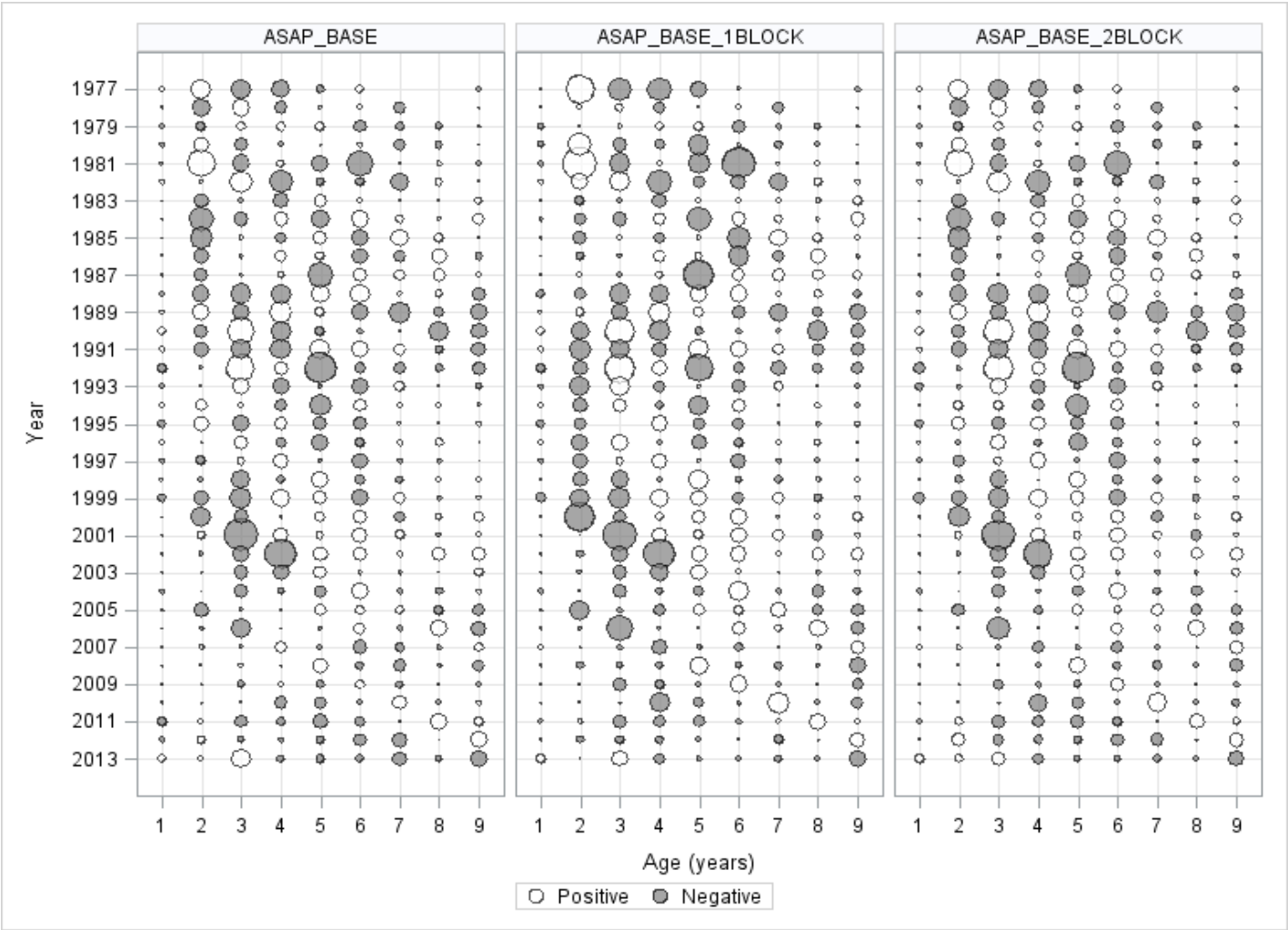

Figure A.2.23. Residual plots of the Gulf of Maine haddock catch-at-age fits compared between the ASAP_BASE model and one- and two-selectivity block sensitivity runs.

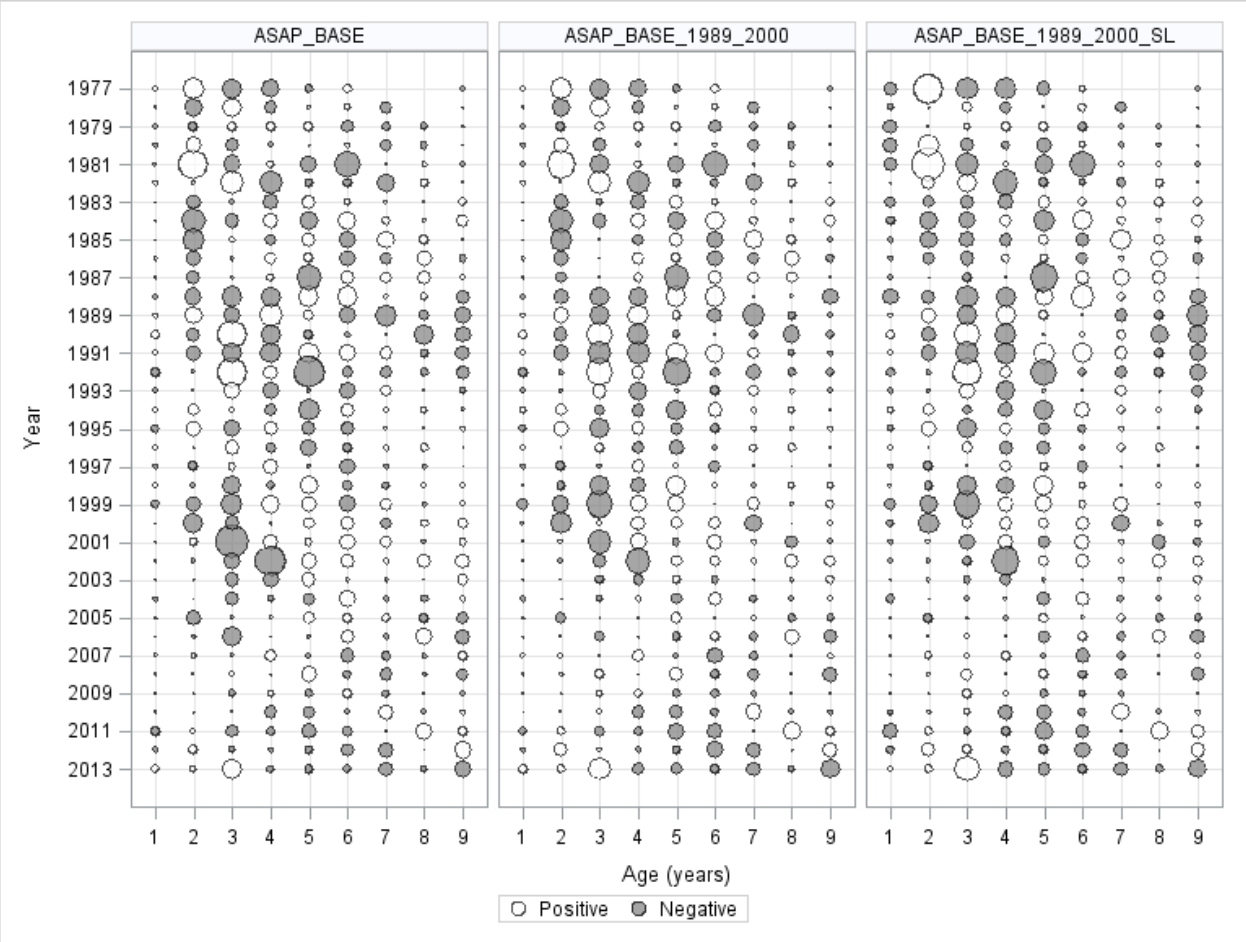

Figure A.2.24. Residual plots of the Gulf of Maine haddock catch-at-age fits compared between the ASAP_BASE model and variants of a similar three-block model exploring a 1999/2000 split between the second and third selectivity block (ASAP_BASE_1989_2000). The ASAP_BASE model employs a 2004/2005 split.

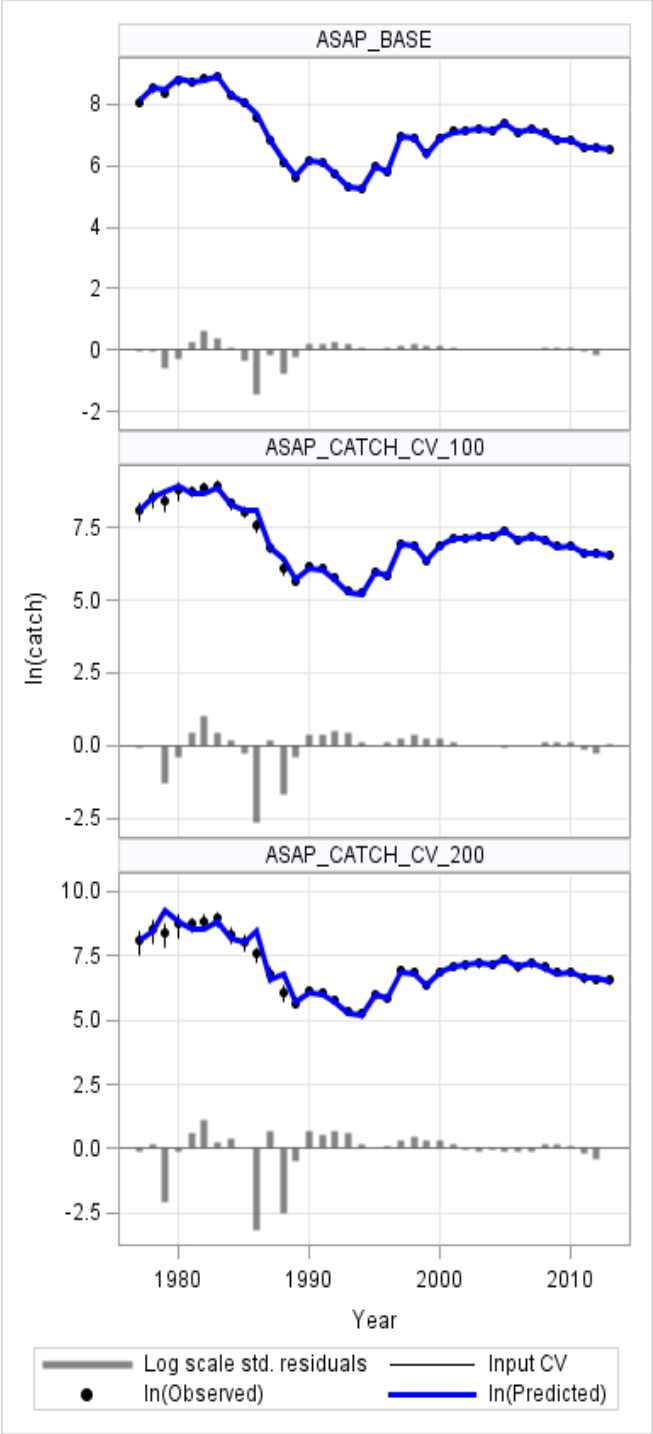

Figure A.2.25. Comparison of model fits to fishery catches from three variants of the base ASAP model with varying levels of assumed precision on fishery catches.

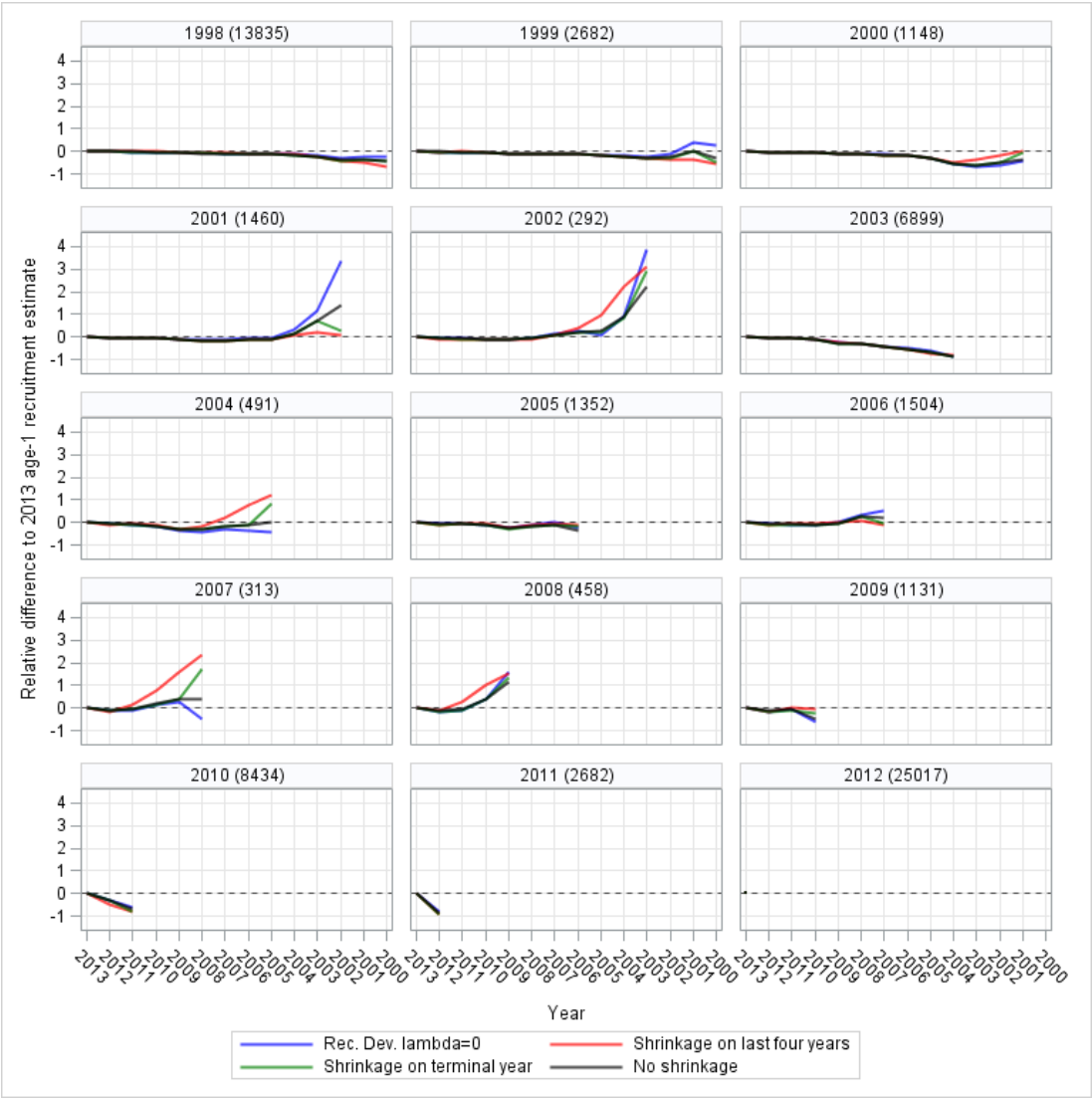

Figure A.2.26. Retrospective estimates of year class size using four different methods to model recruitment deviations. The 2013 estimate of year class size based on the 'No shrinkage' model are indicated in parentheses next to the year class identifier.

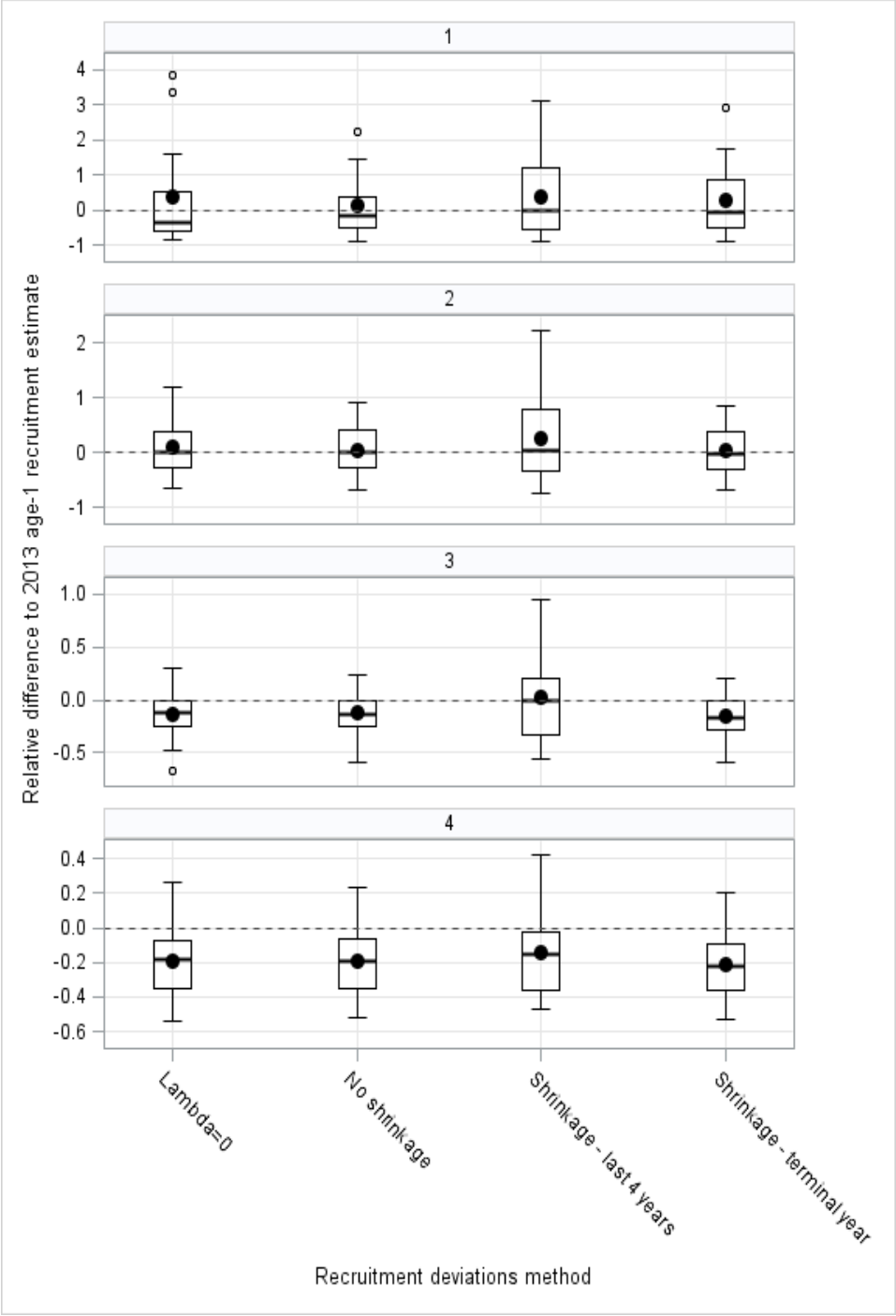

Figure A.2.27. Distribution of the retrospective errors from four different methods to model recruitment deviations. Panels represent the number of years from the initial spawning event (e.g., the '4' panel reflects the distribution of errors four years from the spawning event). Note that the scale varies between panels.

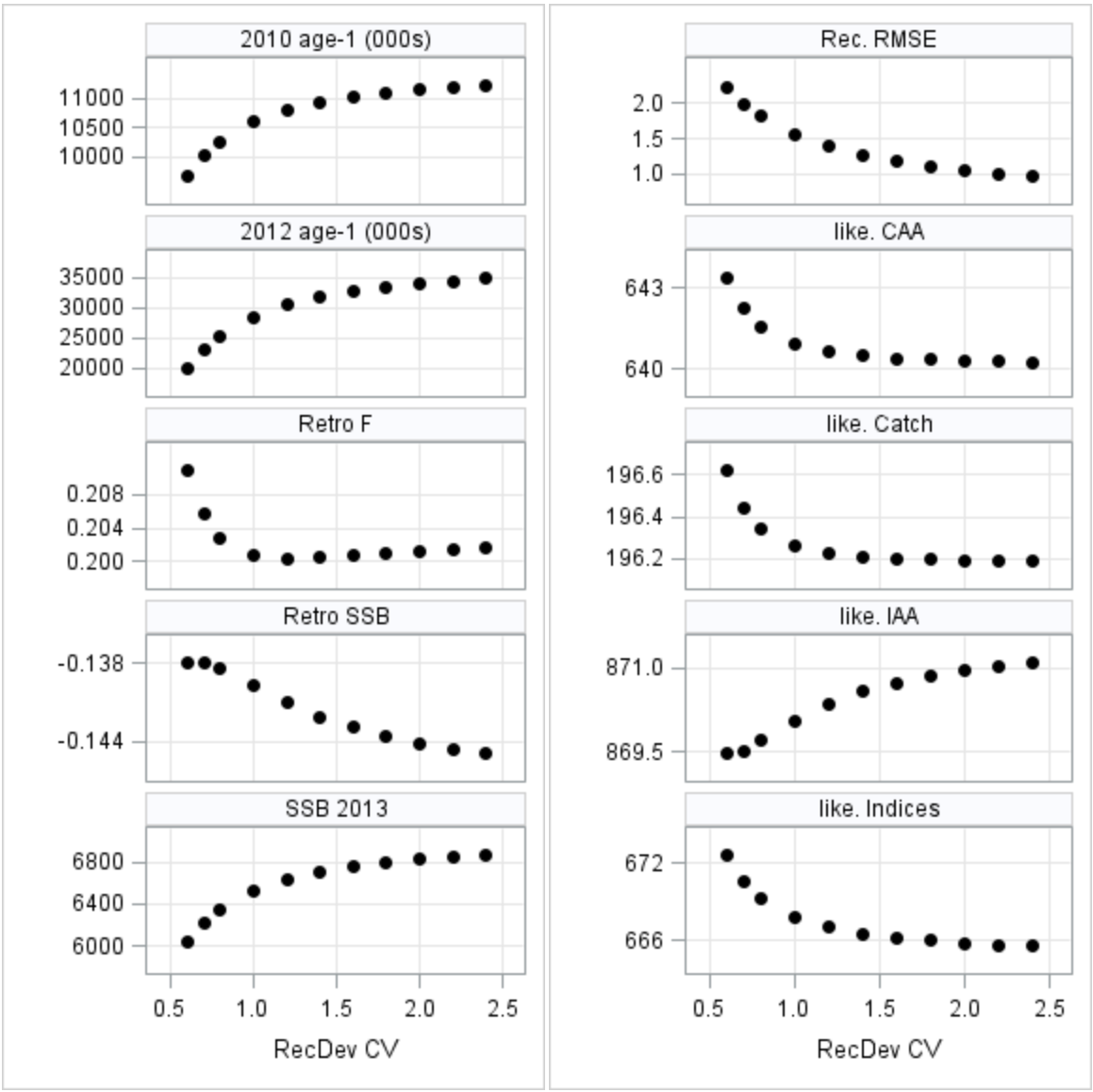

Figure A.2.28. Model response to profiling over a range of recruitment deviation coefficient of variation (CV) values.

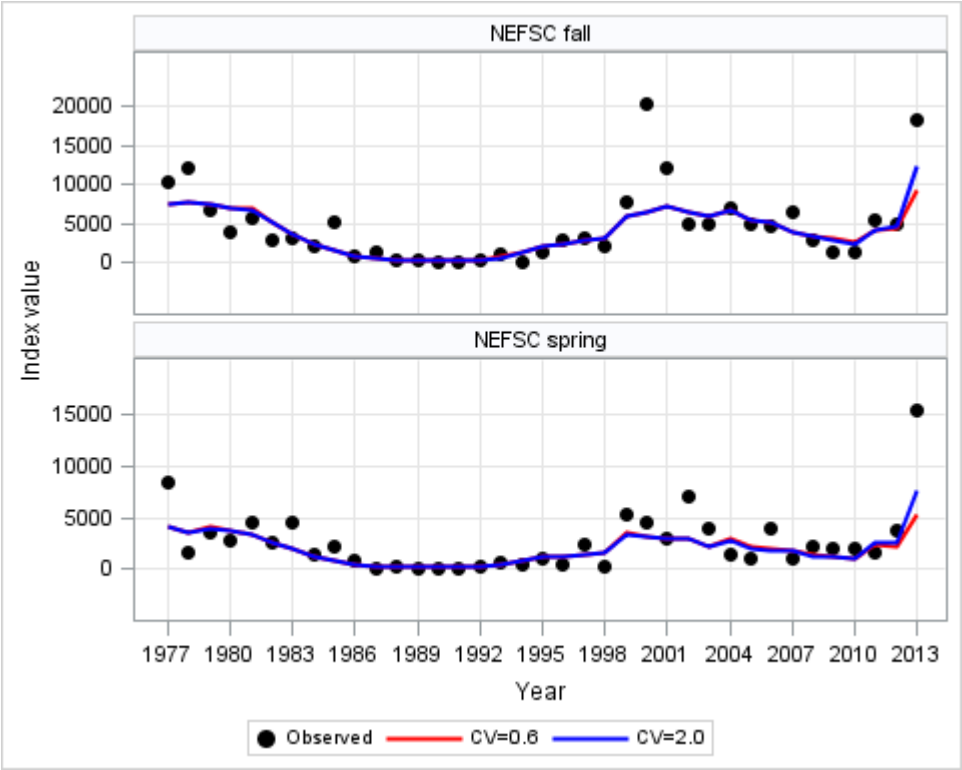

Figure A.2.29. Example of model fits to the NEFSC spring and fall bottom trawl surveys when the recruitment deviation coefficient of variation (CV) is set at 0.6 and 2.0.

Appendix A.3. Gulf of Maine haddock SCAA exploratory model runs

Assessments of the Gulf of Maine haddock[1]

Doug S. Butterworth and Rebecca A. Rademeyer

Marine Resource Assessment and Management Group (MARAM)
Department of Mathematics and Applied Mathematics

University of Cape Town

Rondebosch 7701, South Africa

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Summary

The Gulf of Maine haddock population is assessed in three ways. The first considers the haddock in this area to be an isolated stock. The other two incorporate movement into that area, either permanent or temporary, by haddock from Georges Bank. The evidence for such movement from these analyses alone is sufficient to point to scenarios involving limited movement being of similar plausibility to that of an isolated stock. Catch projections under constant fishing mortality are found to be sensitive, in particular, to this possibility of limited movement for the case where the movement is permanent. Assessment results for the most recent recruitment are sensitive to the procedure used to shrink this estimate to the mean.

Introduction

This paper presents results for three approaches to the assessment of the Gulf of Maine (GoM) haddock stock, all of which use SCAA methodology (see, e.g., Butterworth and Rademeyer, 2011). The first approach explores assessment options when the stock is treated as isolated. The second allows for interchanges in the form of permanent migration from (and to) the neighbouring Georges Bank (GB) haddock population. The third approach (known in the IWC Scientific Committee as the "sabbatical model") also allows for interchanges, but these are not of a permanent nature. Some GB haddock may visit the GoM area during a year, and perhaps be caught there; however if not suffering mortality of some form, they return later that same year to the GB area.

The paper first summarises the data used, and then details the methodologies applied for the isolated stock and interchange models, followed by the assumptions made for calculating four-year catch projections. The results of applying these methodologies, together with some sensitivity tests, are then discussed, followed by some concluding remarks.

1 This paper is a revision of an earlier version presented to the SAW meeting held at the NEFSC, Woods Hole over 2-5 June, 2014. Here Base Case run assumptions have been made to maximize comparability with the preferred ASAP model described in the main text of the report.

Data

The catch and survey based data together with some biological data for the GoM haddock population were kindly provided by Michael Palmer, and are listed in Tables in Annex A.

The second and third assessment approaches, which take interchange (movement) into account, utilise estimates of annual numbers-at-age from the most recent GB haddock assessment for the period from 1977 to 2011 (NEFSC, 2012). These values are listed in Table A8 of Annex A. This Table includes projections to 2017 kindly provided by Liz Brooks; the basis for the computation of these projections is detailed in Table A8's caption.

Methodology

The details of the basic SCAA assessment methodology are provided in Annex B.

Isolated stock

In the interests of maximal comparability with preferred ASAP model of the main text of the report, the following methodological options were chosen/implemented for this Base Case SCAA run (SCAA BC1).

- The stock recruitment curve was assumed to be constant with log-normally distributed residuals. The contribution to the negative log-likelihood from these residuals was calculated assuming a residual CV of 1 (this correspond to a $\sigma_{R,y}$ value of 0.833, which is roughly comparable, though slightly below, the level of variation shown in assessment outputs).
- Selectivities-at-age for the fishery and survey series were estimated separately for each age, though the survey selectivities were set flat above certain ages (see Annex B, section B.4.1, for further details). These decisions were AIC-justified.

Some other choices amongst the standard SCAA options that were made were as follows.

- The multinomial-mimicking "*sqrt(p)*" formulation of the proportions-at-age contribution to the overall negative log-likelihood (Butterworth and Rademeyer, 2012) was used, rather than the "adjusted log-normal", as the former deals more naturally with the relatively large numbers of zeros in the catch-at-age matrices for this stock.
- These proportion-at-age contributions to the negative log likelihood were fully weighted (W_{CAA}=1 – see equation B14), as is broadly comparable to the approach used to set effective sample sizes for the preferred ASAP model. The variance of the associated residuals was estimated assuming age-independence.

The authors' base case choices for implementing the SCAA, differ from those of the preferred ASAP model in one respect.

- The numbers at age vector for the starting year was estimated only to age 3, and thereafter the procedure of equations B9 and B10 of Annex B used (AIC justified).

In addition certain sensitivity runs were pursued:

- An alternative lower value of 0.5 for the recruitment CV for 2013, corresponding to setting $\sigma_{R,y}$ for 2013 to 0.472, was considered to stabilise this estimation to a greater extent. Note that the rightmost term in equation B18 of Annex B includes years to 2010 only, so that changing "weights" in this way on the last year's recruitment does not directly impact the estimate of the geometric mean recruitment R_{gm}.

- The standard deviation of the (transformed) proportion-at-age residuals (σ_{CAA} – see equation B16 of Annex B) for each series was estimated separately for each age rather than for all ages combined.
- The contribution of the proportion-at-age data to the negative log likelihood was down weighted (W_{CAA}=0.5 – see equation B14), to show the effect of possible non-independence of these data.
- The fishing "fleet" was disaggregated into commercial landings, commercial discards, and recreational landings together with recreational discards.

Migration model

There is evidence of interchange between the GoM and GB haddock stocks (e.g. Begg, 1998), but unfortunately the tagging exercises conducted to date have not been designed in a way that allows annual interchange proportions to be estimated reliably. However, since (for example) survey results would have included GB haddock which had moved into the GoM area, it is possible to extend the assessment to take this into account. Normally this would require assessing both stocks simultaneously, but an advantage in this case is that the GB stock is assessed to be so much larger than the GoM stock. This enables the results from the GB stock assessment (NEFSC, 2012) (kindly projected into the future by Liz Brooks, see Table A8 of Annex A) to be used directly, since unlike for the GoM haddock, those GB results would hardly change in such a joint assessment.

In the case of permanent interchange (i.e. migration) between the GoM and GB haddock stocks, equations B1 and B2 of Annex B are replaced by the following equations:

$$N_{y+1,a+1}^{GoM} = \left(N_{y,a}^{GoM} + \mu\rho_y N_{y,a}^{GB} - \lambda N_{y,a}^{GoM}\right)e^{-Z_{y,a}} \qquad \text{for } 1 \le a \le m-2 \qquad (1)$$

$$N_{y+1,m} = \left(N_{y,m-1}^{GoM} + \mu\rho_y N_{y,m-1}^{GB} - \lambda N_{y,m-1}^{GoM}\right)e^{-Z_{y,m-1}} + \left(N_{y,m}^{GoM} + \mu\rho_y N_{y,m}^{GB} - \lambda N_{y,m}^{GoM}\right)e^{-Z_{y,m}} \qquad (2)$$

where

μ is the proportion of the GB haddock (above a critical level) migrating annually and permanently to the Gulf of Maine, with a value estimated when fitting the model,

λ is the proportion of GoM haddock migrating annually and permanently to Georges Bank,

$$\rho_y = \frac{\sum_a N_{y,a}^{GB} - GB_{crit}}{\sum_a N_{y,a}^{GB}} \qquad (3)$$

and

GB_{crit} is the level of 2+ GB haddock numbers below which no GB haddock are assumed to immigrate into the GoM (i.e. the GB stock has to be "large" for any such migration to take place). For all the runs except one sensitivity, $GB_{crit} = 0$. For this sensitivity, $GB_{crit} = 47559$, which is half of the 1977-2013 average of the numbers of 2+ fish, so that movement occurs about 50% of the time over the this period.

The lower bound for age a in equation (1) is adjusted to correspond to the lowest age at which interchange takes place. This is taken to be a=2 for the Base Case implementation, based on indications to this effect provided in NEFC (1986).

Sabbatical model

Under the sabbatical model for movement, each year a proportion (θ) of the GB haddock "visit" the GoM area each year and mix with the GoM haddock (and hence are assumed to be available for capture in this area, and to be amongst the haddock monitored by the two NEFSC surveys each year). The GoM catches of haddock are taken from GoM and GB haddock in proportion to their relative abundances by age in the GoM area. Hence the fishing mortality F_y applies to both the GoM haddock stock and to the GB haddock "visitors". The total predicted catch C_y^* is computed as:

$$C_y^* = \sum_{a=1}^{m} w_{y,a}^{\text{mid}} N_{y,a}^* S_{y,a} F_y \left(1 - e^{-Z_{y,a}}\right) / Z_{y,a} \qquad (4)$$

where

$$N_{y,a}^* = \left(N_{y,a}^{GoM} + \theta N_{y,a}^{GB}\right) \qquad (5)$$

$$Z_{y,a} = F_y S_{y,a} + M_a \qquad (6)$$

and the θ term in equation (5) (where the value of θ is estimated when fitting the model) applies only to ages for which movement is assumed to occur (a = 2+ for the Base Case, as for the migration model).

Spawning biomass (equation B5) is computed using the GoM haddock numbers only ($N_{y,a}$), while predicted survey indices (equation B7) and catches-at-age (B17) are computed with the GoM + GB visitors numbers ($N_{y,a}^*$), i.e. equations B7 and B17 are replaced by:

$$N_y^{\text{surv}} = \sum_{a=1}^{m} S_a^{\text{surv}} N_{y,a}^* e^{-Z_{y,a} T^{surv}/12} \qquad (7)$$

$$\hat{p}_{y,a}^{surv} = S_a^{\text{surv}} N_{y,a}^* e^{-Z_{y,a} T^{surv}/12} \Big/ \sum_{a'=0}^{m} S_{a'}^{\text{surv}} N_{y,a}^* e^{-Z_{y,a} T^{surv}/12} \qquad (8)$$

<u>*Projections*</u>

Four-year projections have been run under constant fishing mortalities of F_{MSY}, where F_{MSY} is taken to be $F_{40\%}$, as estimated in this paper or as estimated for the preferred ASAP model (see Annex B, section B.4.3). For these projections, the following assumptions have been made:

- the weight-at-age and commercial selectivity vectors are taken as the 2009-2013 average, as assumed for the $F_{40\%}$ computations for the preferred ASAP model - see Annex B section B.4.3;
- future recruitments are taken to be constant at their arithmetic mean level over the period chosen for the preferred ASAP model, i.e. 1977 to 2011 (to avoid inclusion of the recruitments for 2012 and 2013 for which the estimates have high variance); and
- in the cases with interchange (permanent migration) between the GoM and GB haddock stocks, the future GB haddock stock and age-structure is projected over the 2012 to 2017 period on the basis detailed in the caption to Table A8 of Annex A.

Results and Discussion

Isolated stock

Comparisons of the results from the preferred ASAP model SCAA Base Case without movement (SCAA-BC1) are provided in Table 1 and Figure 1, and evidence little difference. This SCAA-Base Case exhibits a reasonable fit to the survey indices of abundance and proportion-at-age data for both the fishery and the surveys, and indicates a slightly higher current spawning biomass than the preferred ASAP model does.

Table 1 and Figure 2 show the consequences of reducing the value assumed for the variability ($\sigma_{R,y}$) of the recruitment for the most recent years (2013) to a CV of 0.5 compared to the SCAA-Base Case choice of 1.0. This has a major impact on the estimate of recruitment for the last year, which drops by more than 50%, but the estimate of spawning biomass for 2013 falls only slightly. Formally the choice of 1.0 (corresponding, roughly, to the variability shown by past recruitment) is the most appropriate statistically for the shrinkage to the mean of the estimates that would otherwise result. However this leads to a high variance associated with the 2013 recruitment estimate. A case could be made that a lower choice than 1.0 is appropriate in the interests of providing more robust estimates, but the difficulty is in choosing what value it would be best to set in any such down-weighting parameter. Results are also shown for downweighting the contribution of the proportions-at-age data to the negative log likelihood. This has little impact on estimates, though the confidence intervals shown in Table 1 widen slightly, and those for parameters such as selectivity-at-age somewhat more so.

Allowing for the variance parameter associated with the proportions-at-age residuals (σ_{CAA}) to be estimated separately by age improves the fit to the data, and to an extent which is AIC justified (Table 1 and Figure 3). However, as the impact of allowing for this effect on key results (such as those for spawning biomass) is minimal, this adjustment was not incorporated into the SCAA Base Case to maintain greater comparability with the preferred ASAP model. Similarly, initial attempts to disaggregate the fishing "fleet" into commercial landing, discards and recreational components also led to little difference in such results, and hence was not explored further.

Migration model

Results for the permanent migration model are shown in Table 4 for the best estimate of 0.2% (SCAA BC2) for the annual proportion μ moving from the GB to the GoM area. Results for a range of μ values are shown in Figure 4. These indicate that the estimate of μ = 0.2% is significantly different from zero at the 10% (and 5%) levels, while the diagnostics shown in Figure 5 evidence a satisfactory fit to the data. For μ = 0.2%, the recent spawning biomass estimates are not greatly affected; they do become appreciably larger for higher values of μ, but those results are not compatible with the data. If movement is allowed in the reverse direction as well (i.e. the λ parameter is set to be different from zero), results are hardly affected (see Figure 6), so that λ has been kept at zero for all subsequent results for this model.

Table 4 and Figures 7 to 9 provide results for some sensitivities to SCAA BC2. Changing the age at which fish can move from the GB to the GoM area from 2+ to either 1+ or 3+ impacts results, but only to small extents. The consequences of allowing random annual variation (with a CV = 1.0) about a mean proportional movement of 0.2%, and of precluding movement below an abundance threshold for GB haddock, are also relatively small.

Sabbatical model

Results for the sabbatical model (non-permanent interchange) are given in Table 3 and Figure 10, again indicating reasonable fits to the data. The best estimate of the proportion of GB haddock moving temporarily each year to the GoM area, θ, is 0.75% (SCAA BC3). This is shown to be statistically different from zero at the 10% (and 5%) levels in Figure 11.

Figure 11 also shows spawning biomass trajectories for various values of θ for the component of the haddock in the GoM area belonging to the true GoM stock. Unsurprisingly, this is less for larger values of θ, as those reflect greater proportions of the catch from the GoM area being comprised of GB haddock. In addition, the Figure shows how this proportion has changed over time for the different values of θ. Table 3 and Figure 12 show that changing the age at which fish can move from the GB to the GoM area from 2+ to either 1+ or 3+ has some though not a substantial impact on results.

Overall comparison and Retrospectives

Figure 13 compares the results for the Base Case for no movement model (SCAA BC1) with those for the two models which allow for movement (SCAA-BC2 for permanent and SCAA-BC3 for temporary migration). The first two sets of results are fairly similar, but the sabbatical model (SCAA-BC3) unsurprisingly shows lower spawning biomass and recruitment values as these plots do not include the haddock "visiting" the GoM area from the GB stock, even though those haddock contribute to catches made in the GoM area.

Figure 14 shows retrospective plots for all three models. None reflect serious systematic trends. The estimates of the movement parameters μ and θ are stable and consistently significantly different from zero. Examination of the negative log likelihood contributions in Tables 2 and 3 shows that it is the proportions at age data that provide the key information to allow the values of these parameters to be estimated. These negative log likelihoods also indicate a preference for the migration over the sabbatical model, but not to any substantial extent; indeed from a biological perspective, one might tend to consider the sabbatical model as the more plausible of the two.

Catch projections

Four year catch projections under F_{MSY} are shown in Table 4. For the sabbatical model scenarios, results given reflect the total catch allowed, and this will include a component of GB haddock. The figures in parentheses in Table 4 show the part of this that comes from the "true" GoM haddock stock only. The F_{MSY} values are provided by the $F_{40\%}$ proxy, though this is calculated in two ways: first for the SCAA model estimates (and specific to the model in question with or without movement), and then for the preferred ASAP model (see Annex B, section B.4.3 for details).

These projection results are quite similar for the no movement and sabbatical models, but give values some 20-40% higher for the permanent migration model.

Concluding Remarks

The results above for catch projections (in particular) from these assessment model variants for the GoM haddock stock point to two key factors to which model outputs are particularly sensitive. These are:

1) the extent to which the estimate of recruitment for the most recent year is shrunk to the mean; and

2) how the possibility of exchanges with GB haddock is best to be taken into account; the estimates of annual movement proportions, although small in percentage terms, are statistically significant at the 5% level so that the associated exchange hypotheses

are plausible; furthermore in the case of permanent exchange, catch projections under F_{MSY} proxies are increased by amounts in roughly the 20-40% range.

Acknowledgements

We thank Michael Palmer for provision of the data upon which the analyses reported in this paper are based, and Liz Brooks for the future projections for the Georges Bank numbers-at-age matrix.

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Table 1: Estimates of abundance and related quantities for the Gulf of Maine haddock for the preferred ASAP model and SCAA runs for isolated stock (with no movement) assessments. Values in parentheses are Hessian based 90% CIs. Biomass units in this and all following tables are mt unless otherwise indicated. The fishing mortality *F* applies to the commercially fully selected 7+ fish.

	No movement models								
	ASAP	SCAA BC1		CV_{SR}=0.5 in 2013		Age-specific σ_{CAA}		W_{CAA}=0.5	
'-lnL:overall		-1438.7		-1431.8		-1474.5		-692.8	
'-lnL:Index		11.0		14.8		12.5		10.7	
'-lnL:comCAA		-743.9		-743.4		-765.2		-369.1	
'-lnL:indexCAA		-749.8		-748.2		-763.6		-375.3	
'-lnL:catch		0.9		0.8		0.9		0.4	
-lnL:epsμ		0.0		0.0		0.0		0.0	
'-lnL:RecRes		43.1		44.1		41.0		40.5	
B^{sp}_{1977}	9438	7871	(6693; 9049)	7875	(6695; 9055)	7878	(6724; 9032)	8032	(6496; 9568)
B^{sp}_{2013}	4153	5206	(2889; 7522)	3943	(1999; 5887)	4861	(2611; 7111)	5523	(3039; 8008)
$B^{sp}_{2013}/B^{sp}_{1977}$	0.44	0.66	(0.35; 0.97)	0.50	(0.24; 0.76)	0.62	(0.32; 0.92)	0.69	(0.35; 1.02)
$N_{1,1977}$	5997	6441	(5198; 7683)	6428	(5186; 7670)	6821	(5472; 8170)	6359	(4682; 8036)
$N_{1,2011}$	6659	8667	(4771; 12563)	6578	(3422; 9735)	7704	(4135; 11273)	8998	(4637; 13359)
$N_{1,2013}$	16565	15824	(5309; 26339)	6280	(2462; 10098)	14889	(5036; 24742)	14030	(2758; 25302)
$F_{30\%}$		0.74	-	0.73	-	0.69	-	0.74	-
$B_{MSY}(F_{30\%})$		2652	(2299; 3005)	2553	(2211; 2895)	2667	(2324; 3010)	2724	(2262; 3186)
$MSY(F_{30\%})$		908	(828; 988)	873	(797; 948)	910	(826; 994)	932	(839; 1025)
$F_{40\%}$	0.46	0.43	-	0.42	-	0.41	-	0.43	-
$B_{MSY}(F_{40\%})$		3536	(3109; 3964)	3404	(2990; 3817)	3556	(3136; 3977)	3632	(3087; 4177)
$MSY(F_{40\%})$		825	(751; 899)	793	(722; 863)	825	(748; 903)	848	(760; 935)
Spring *q*	0.25	0.26	(0.22; 0.30)	0.27	(0.23; 0.31)	0.25	(0.22; 0.29)	0.27	(0.22; 0.32)
Fall *q*	0.92	0.94	(0.71; 1.16)	0.97	(0.74; 1.20)	0.98	(0.76; 1.21)	0.96	(0.65; 1.26)
Spring AddVar		0.10	(0.00*; 0.33)	0.12	(0.00*; 0.37)	0.10	(0.00*; 0.34)	0.10	(0.00*; 0.33)
Fall AddVar		0.00	(0.00; 0.00)	0.00	(0.00; 0.00)	0.00	(0.00; 0.00)	0.00	(0.00; 0.00)
σ_{Rout}		1.27	(1.21; 1.33)	1.22	(1.17; 1.27)	1.24	(1.18; 1.30)	1.23	(1.16; 1.30)

Table 2: Estimates of abundance and related quantities for the Gulf of Maine haddock for the SCAA migration model (i.e. with movement of 2+ year old haddock for the Base Case BC2). Values in parentheses are Hessian based 90% CIs. The value of μ is the proportion of (here 2+ year old for BC2) GB haddock which permanently migrate to the GoM each year, while λ specifies the proportion of such migration in the reverse direction. The text explains the role of the GBcrit constraint.

	No movement				Migration models									
	SCAA BC1		SCAA BC2		$\lambda=\mu$		1+ moving		3+ moving		GBcrit=50% of 1977-2013 average		Random effects on μ	
'-lnL:overall	-1438.7		-1447.7		-1447.6		-1446.5		-1447.1		-1444.8		-1452.4	
'-lnL:Index	11.0		9.9		9.9		10.2		9.5		10.7		9.7	
'-lnL:comCAA	-743.9		-750.9		-750.9		-750.1		-751.7		-746.0		-757.0	
'-lnL:indexCAA	-749.8		-753.7		-753.8		-753.4		-751.9		-752.6		-756.4	
'-lnL:catch	0.9		0.9		0.9		0.9		0.9		0.9		0.9	
-lnL:epsμ	0.0		0.0		0.0		0.0		0.0		0.0		3.7	
'-lnL:RecRes	43.1		46.1		46.2		45.9		46.1		42.3		46.8	
μ (%)	0		0.20	(0.13; 0.28)	0.20	(0.13; 0.28)	0.18	(0.11; 0.24)	0.22	(0.13; 0.31)	0.28	(0.15; 0.41)	0.20	(0.20; 0.20)
B^{sp}_{1977}	7871	(6693; 9049)	7742	(6570; 8913)	7779	(6602; 8955)	7755	(6584; 8926)	7718	(6549; 8888)	7842	(6663; 9022)	7710	(6541; 8879)
B^{sp}_{2013}	5206	(2889; 7522)	6061	(3690; 8431)	6079	(3703; 8454)	5690	(3428; 7952)	6394	(3873; 8915)	6705	(3819; 9591)	5376	(3050; 7702)
$B^{sp}_{2013}/B^{sp}_{1977}$	0.66	(0.35; 0.97)	0.78	(0.45; 1.11)	0.78	(0.45; 1.11)	0.73	(0.42; 1.05)	0.83	(0.48; 1.18)	0.85	(0.47; 1.24)	0.70	(0.38; 1.02)
$N_{1,1977}$	6441	(5198; 7683)	6259	(5046; 7472)	6309	(5087; 7531)	6274	(5059; 7490)	6286	(5073; 7499)	6406	(5172; 7641)	6206	(5009; 7402)
$N_{1,2011}$	8667	(4771; 12563)	7493	(3983; 11003)	7561	(4019; 11103)	7311	(3857; 10766)	8607	(4875; 12339)	8124	(4176; 12073)	6928	(3388; 10469)
$N_{1,2013}$	15824	(5309; 26339)	15270	(5533; 25007)	15405	(5579; 25231)	14594	(5151; 24037)	16544	(6036; 27052)	16960	(5964; 27956)	13776	(4745; 22807)
$F_{30\%}$	0.74	-	0.62	-	0.62	-	0.63	-	0.61	-	0.63	-	0.64	-
$B_{MSY}(F_{30\%})$	2652	(2299; 3005)	2226	(1841; 2611)	2249	(1864; 2634)	2275	(1898; 2651)	2322	(1936; 2709)	2467	(2072; 2863)	2085	(1741; 2429)
$MSY(F_{30\%})$	908	(828; 988)	755	(676; 835)	763	(683; 843)	773	(694; 851)	788	(711; 864)	837	(753; 921)	708	(623; 793)
$F_{40\%}$	0.43	-	0.37	-	0.37	-	0.38	-	0.37	-	0.38	-	0.38	-
$B_{MSY}(F_{40\%})$	3536	(3109; 3964)	2968	(2509; 3427)	2999	(2540; 3458)	3033	(2584; 3482)	3097	(2640; 3554)	3290	(2819; 3760)	2780	(2359; 3201)
$MSY(F_{40\%})$	825	(751; 899)	684	(612; 756)	691	(619; 764)	700	(629; 771)	713	(644; 783)	758	(681; 836)	642	(564; 720)
Spring q	0.26	(0.22; 0.30)	0.27	(0.23; 0.31)	0.27	(0.23; 0.31)	0.27	(0.23; 0.31)	0.27	(0.23; 0.31)	0.25	(0.21; 0.29)	0.28	(0.24; 0.32)
Fall q	0.94	(0.71; 1.16)	0.92	(0.69; 1.14)	0.91	(0.69; 1.14)	0.93	(0.71; 1.16)	0.91	(0.69; 1.14)	0.85	(0.63; 1.07)	0.98	(0.73; 1.22)
Spring AddVar	0.10	(0.00*; 0.33)	0.08	(0.00*; 0.30)	0.08	(0.00*; 0.30)	0.09	(0.00*; 0.31)	0.08	(0.00*; 0.30)	0.09	(0.00*; 0.31)	0.09	(0.00*; 0.30)
Fall AddVar	0.00	(0.00; 0.00)	0.00	(0.00; 0.00)	0.00	(0.00; 0.00)	0.00	(0.00; 0.00)	0.00	(0.00; 0.00)	0.00	(0.00; 0.00)	0.00	(0.00; 0.00)
σ_{Rout}	1.27	(1.21; 1.33)	1.31	(1.24; 1.39)	1.32	(1.24; 1.39)	1.31	(1.24; 1.38)	1.31	(1.25; 1.38)	1.26	(1.19; 1.32)	1.32	(1.25; 1.40)

Table 3: Estimates of abundance and related quantities for the Gulf of Maine haddock stock for the SCAA sabbatical model. The value of □ is the proportion of GB haddock (aged 2+ for the Base Case BC3) which move temporarily to the GoM area each year; the values shown in the Table do not include those GB fish, and refer to haddock from the GoM stock only). Values in parentheses are Hessian based 90% CIs.

	No movement		Sabbatical models					
	SCAA BC1		SCAA BC3		1+ moving		3+ moving	
'-lnL:overall	-1438.7		-1446.3		-1441.2		-1445.8	
'-lnL:Index	11.0		11.0		10.2		10.0	
'-lnL:comCAA	-743.9		-747.3		-747.6		-749.7	
'-lnL:indexCAA	-749.8		-757.4		-750.1		-753.5	
'-lnL:catch	0.9		0.9		0.9		0.9	
-lnL:epsμ	0.0		0.0		0.0		0.0	
'-lnL:RecRes	43.1		46.4		45.3		46.5	
θ (%)	0		0.75	(0.49; 1.02)	0.53	(0.20; 0.85)	0.64	(0.40; 0.89)
B^{sp}_{1977}	7871	(6693; 9049)	7602	(6419; 8786)	7632	(6453; 8811)	7698	(6514; 8881)
B^{sp}_{2013}	5206	(2889; 7522)	3131	(1580; 4682)	3707	(1671; 5744)	4185	(2427; 5944)
$B^{sp}_{2013}/B^{sp}_{1977}$	0.66	(0.35; 0.97)	0.41	(0.20; 0.63)	0.49	(0.21; 0.76)	0.54	(0.30; 0.79)
$N_{1,1977}$	6441	(5198; 7683)	6255	(5035; 7475)	6304	(5075; 7533)	6284	(5066; 7501)
$N_{1,2011}$	8667	(4771; 12563)	4813	(1933; 7693)	5895	(2177; 9613)	6929	(3792; 10066)
$N_{1,2013}$	15824	(5309; 26339)	12277	(4394; 20160)	12195	(2580; 21810)	14611	(5443; 23777)
$F_{30\%}$	0.74	-	0.69	-	0.71	-	0.69	-
$B_{MSY}(F_{30\%})$	2652	(2299; 3005)	2123	(1761; 2484)	2280	(1861; 2700)	2280	(1926; 2634)
$MSY(F_{30\%})$	908	(828; 988)	725	(640; 810)	780	(675; 885)	777	(697; 856)
$F_{40\%}$	0.43	-	0.41	-	0.41	-	0.41	-
$B_{MSY}(F_{40\%})$	3536	(3109; 3964)	2830	(2390; 3270)	3041	(2524; 3558)	3040	(2614; 3465)
$MSY(F_{40\%})$	825	(751; 899)	658	(580; 736)	708	(612; 804)	706	(633; 778)
Spring q	0.26	(0.22; 0.30)	0.28	(0.24; 0.32)	0.28	(0.24; 0.32)	0.27	(0.23; 0.31)
Fall q	0.94	(0.71; 1.16)	1.01	(0.77; 1.24)	1.02	(0.78; 1.26)	0.98	(0.75; 1.21)
Spring AddVar	0.10	(0.00*; 0.33)	0.09	(0.00*; 0.32)	0.10	(0.00*; 0.33)	0.09	(0.00*; 0.30)
Fall AddVar	0.00	(0.00; 0.00)	0.00	(0.00; 0.00)	0.00	(0.00; 0.00)	0.00	(0.00; 0.00)
σ_{Rout}	1.27	(1.21; 1.33)	1.32	(1.25; 1.39)	1.30	(1.23; 1.38)	1.32	(1.25; 1.39)

Table 4: Catch (mt) projections from 2014 for the three SCAA Base Cases under $F_{40\%}$ as estimated by the SCAA models, and F=0.46 (the value of estimated for $F_{40\%}$ for the preferred ASAP model - see Annex B, section B.4.3). The lowest section of the Table shows results for F=0.46 from 2015 with 500mt for the 2014 catch for these three Base Cases. For the sabbatical model, the values in parentheses refer to the catch arising from the GoM haddock stock only.

	1	2	3	
	SCAA BC1 "no movement"	SCAA BC2 "migration model"	SCAA BC3 "sabbatical model"	
$F_{40\%}$ (SCAA)	(0.43)	(0.37)	(0.41)	
C_{2014}	1318	1661	1226	(848)
C_{2015}	2018	2503	1918	(1373)
C_{2016}	2414	2909	2326	(1709)
C_{2017}	2793	3294	2711	(2021)
$F_{40\%}$ (ASAP)=0.46 (applied to all three cases)				
C_{2014}	1409	2011	1374	(951)
C_{2015}	2139	2942	2127	(1517)
C_{2016}	2531	3313	2545	(1857)
C_{2017}	2894	3627	2920	(2153)
500mt, $F_{40\%}$ (ASAP)=0.46 (applied to all three cases)				
C_{2014}	500	500	500	(345)
C_{2015}	2341	3315	2264	(1654)
C_{2016}	2702	3604	2661	(1973)
C_{2017}	3030	3842	3013	(2245)

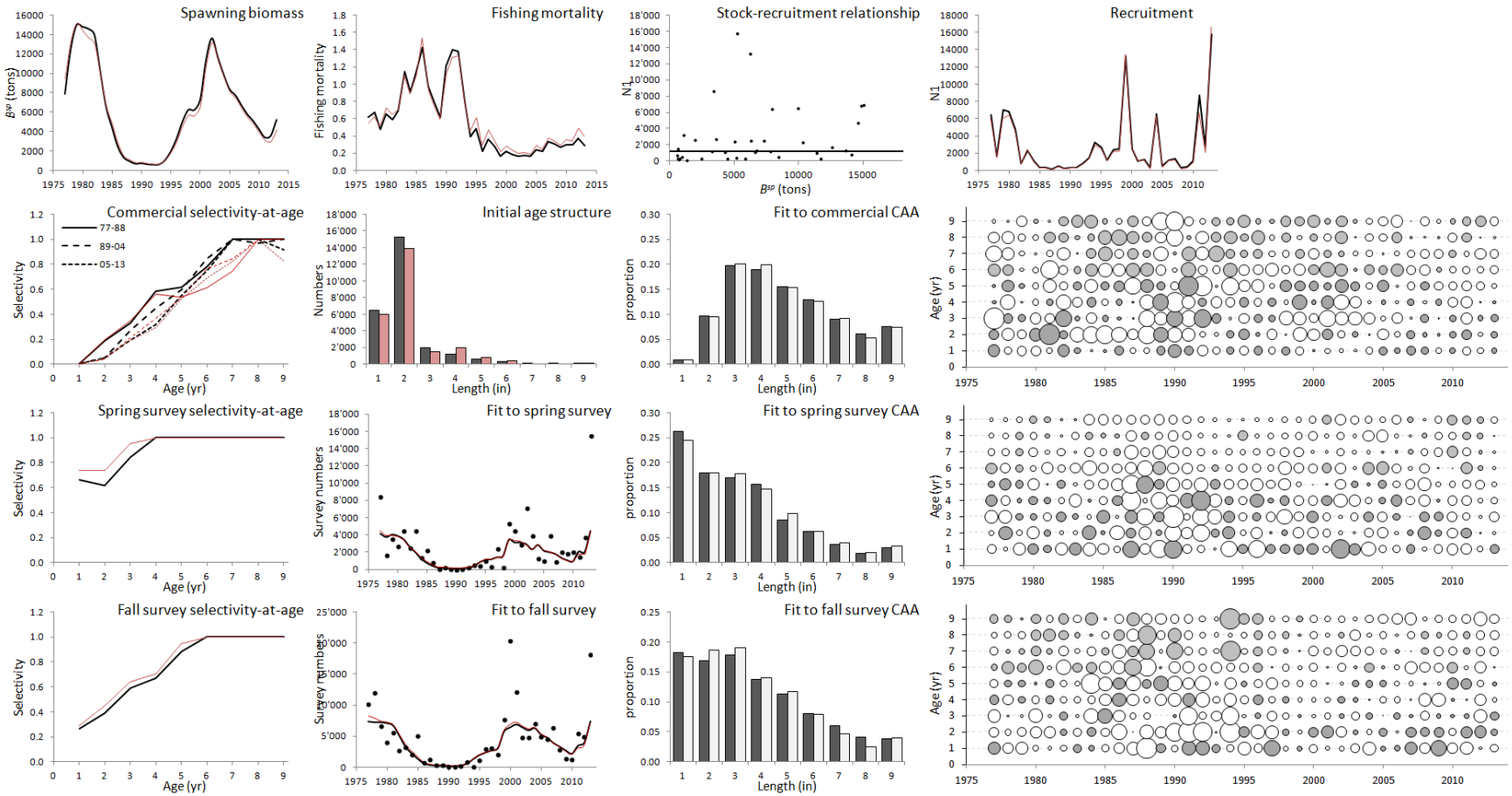

Figure 1: Comparison of the **SCAA-BC1 (isolated stock so no movement)** (in black) results with the **preferred ASAP-model** (in red).The fits to the CAA data are first shown as the averages over all years for each age, and then as bubble plots of standardised residuals. The area of the bubble is proportional to the magnitude of the corresponding residuals. For positive residuals the bubbles are grey, whereas for negative residuals the bubbles are white.

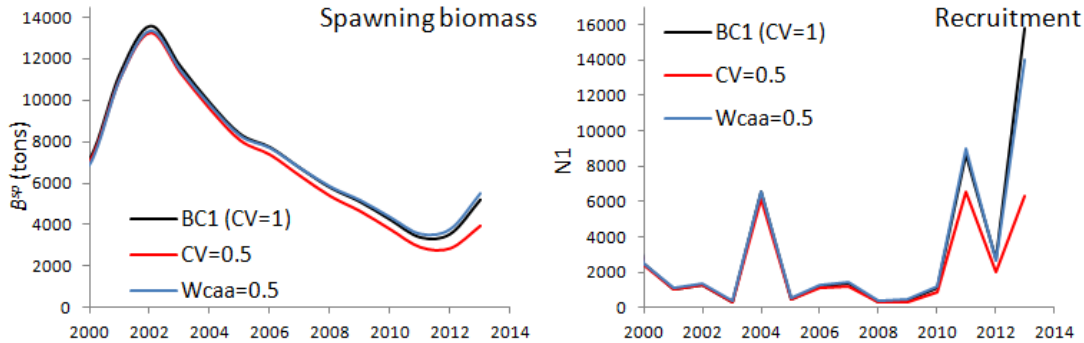

Figure 2: Comparison of spawning biomass and recruitment trajectories for the **SCAA-BC1 (isolated stock so no movement)** with a different stock-recruitment residual CV for 2013 (red lines), and for the proportions-at-age contributions to the negative log likelihood downweighted by a multiplicative factor of 0.5 (blue lines). The SCAA-Base Case assessment uses a CV of 1.0 for recruitment residuals for all years and is shown in black in the plots.

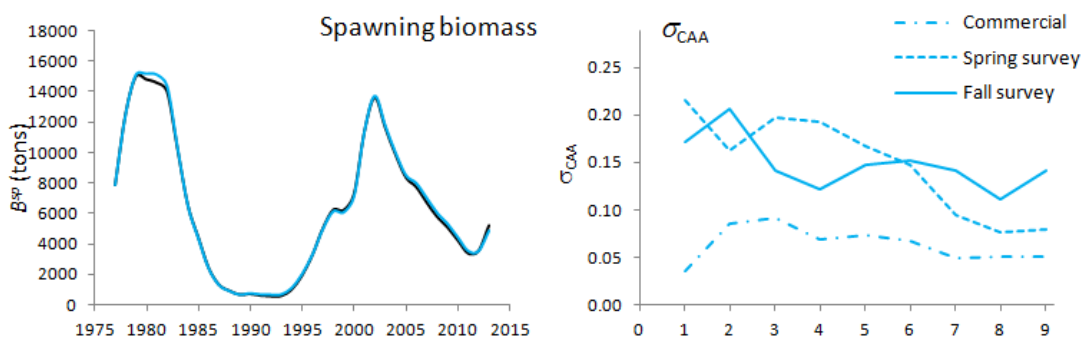

Figure 3: Comparison of spawning biomass trajectories for the **SCAA-Base Case (isolated stock so no movement)** (black line) and the sensitivity using age-specific σ_{CAA} values for the commercial and survey CAA data (blue line). The estimated σ_{CAA} values are also shown.

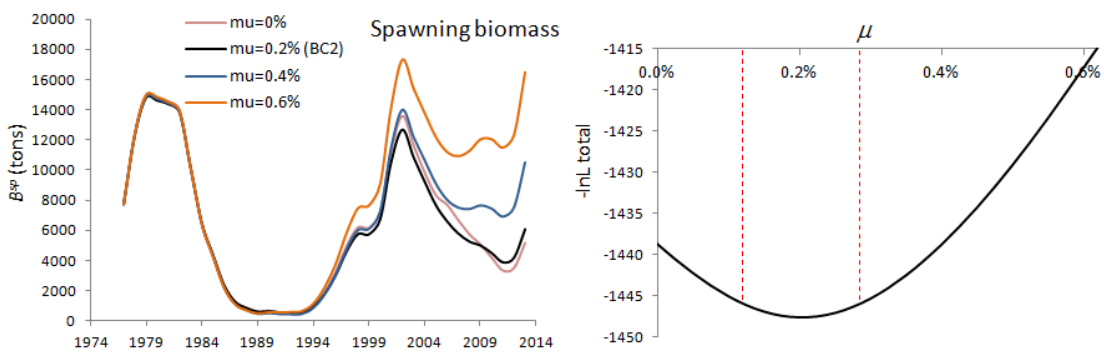

Figure 4: Comparison of spawning biomass trajectories for the **SCAA-BC2 (with movement)** with a series of fixed alternative movement proportions. Note that the μ=0% trajectory corresponds to **SCAA-BC1 (with no movement).** The right side plot shows the likelihood profile for the movement proportion μ (the vertical dashed lines correspond to the 90% confidence limits).

Figure 5: Comparison of the **SCAA-BC1 (isolated stock so no movement)** (in black) and **SCAA-BC2 (with movement)** (in blue) results. The fits to the CAA data are shown for SCAA-BC2 only, first as the averages over all years for each age, and then as bubble plots of standardised residuals. The area of the bubble is proportional to the magnitude of the corresponding residuals. For positive residuals the bubbles are light blue, whereas for negative residuals the bubbles are white.

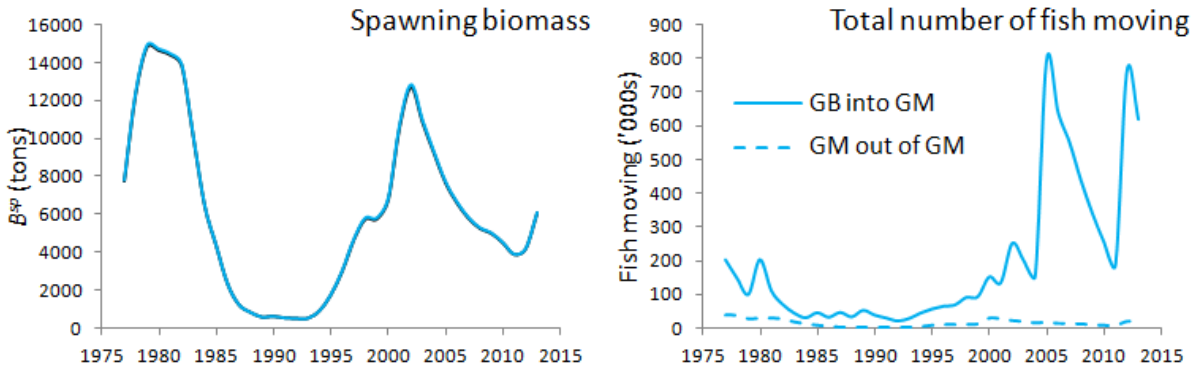

Figure 6: Comparison of spawning biomass trajectories for the **SCAA-BC2 (with movement)** (black line) and the sensitivity that also includes Gulf of Maine haddock emigrating out of the Gulf of Maine ($\lambda = \mu$) (blue line, which nearly always covers the black line). The right side-plot shows the total number of fish estimated to move in and out of the Gulf of Maine each year for this sensitivity.

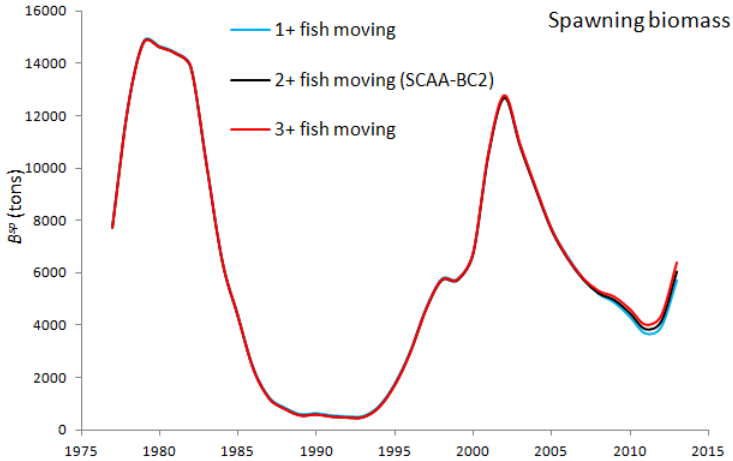

Figure 7: Comparison of spawning biomass trajectories for the **SCAA-BC2 (with movement)** with sensitivities to the choice of the age at which fish start to move (note that μ is estimated separately for each of these runs).

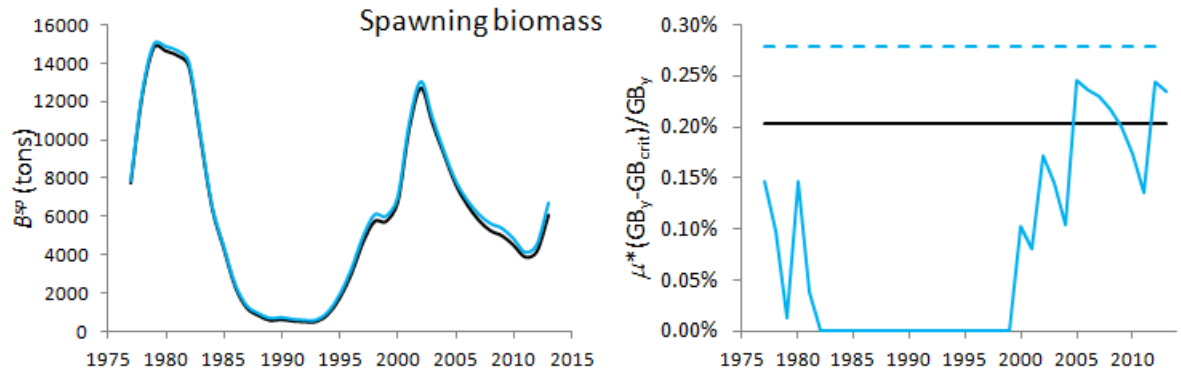

Figure 8: Comparison of spawning biomass trajectories for the **SCAA-BC2 (with movement)** (estimated $\mu = 0.20\%$, black line) and the sensitivity in which George's Bank fish move into Gulf of Maine only if the total number of fish of age 2+ is greater than GB_{crit} (see the text for details of how this threshold is defined). The horizontal dashed blue line is the maximum value which the proportion moving can attain in this sensitivity ($\mu = 0.28\%$).

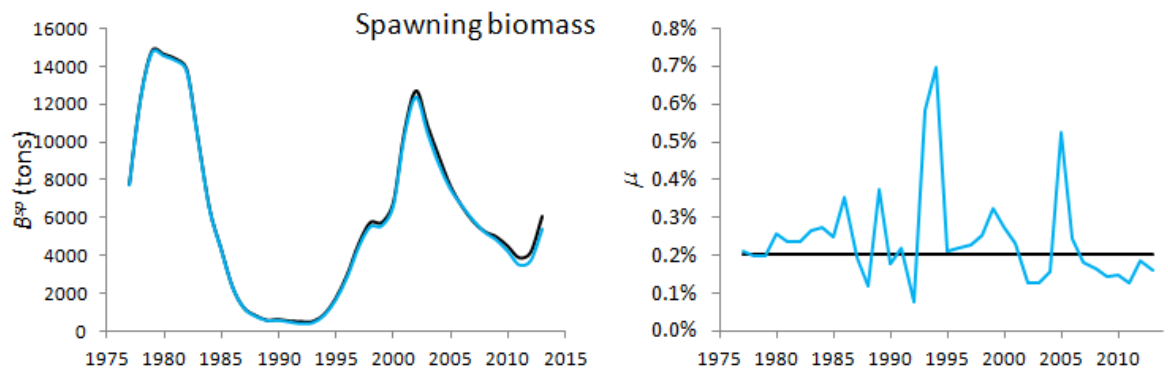

Figure 9: Comparison of spawning biomass trajectories for the **SCAA-BC2 (with movement)** (estimated $\mu = 0.20\%$, black line) and the sensitivity with random effects about μ = 0.20% (fixed) (blue line).The right side plot shows the fixed μ value together with the annual values estimated under the random effects approach.

Figure 10: Comparison of the **SCAA-BC1 (isolated stock so no movement)** (in black) and **SCAA-BC3 (sabbatical model)** (in blue) results. The fits to the CAA data are shown for SCAA-BC3 only, first as the averages over all years for each age, and then as bubble plots of standardised residuals. The area of the bubble is proportional to the magnitude of the corresponding residuals. For positive residuals the bubbles are light blue, whereas for negative residuals the bubbles are white.

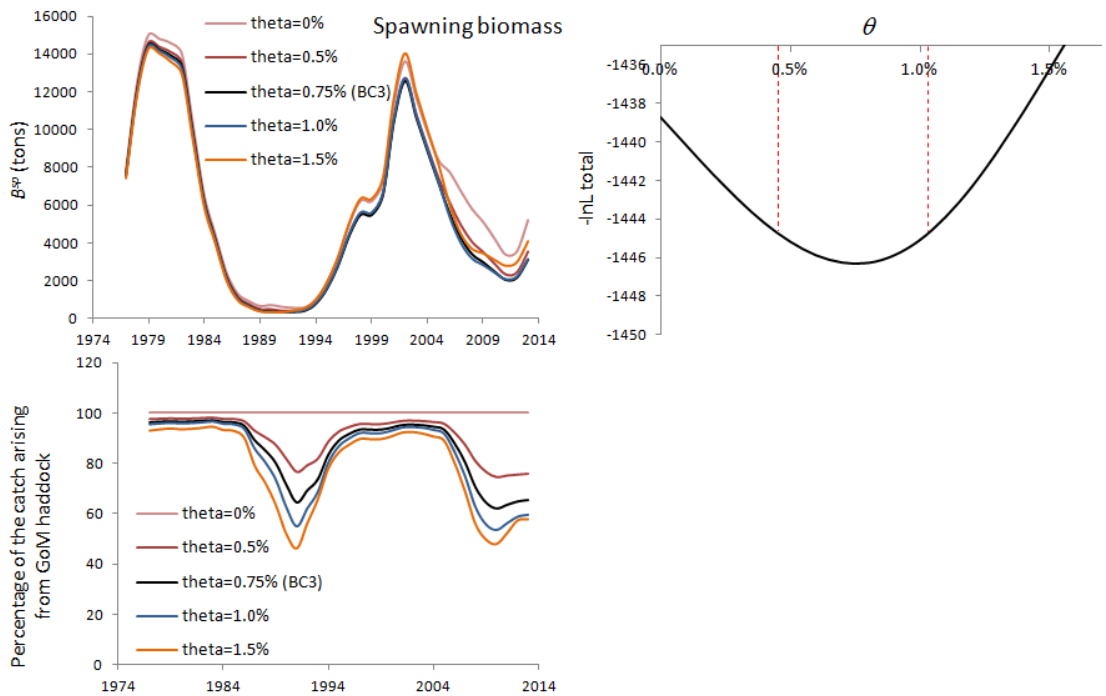

Figure 11: Comparison of spawning biomass trajectories for the **SCAA-BC3 (sabbatical model)** with a series of fixed alternative movement proportions (top left plot). Note that the θ=0% trajectory corresponds to the **SCAA-Base Case with no movement.** The top right side plot shows the likelihood profile for the movement proportion θ (the vertical dashed lines correspond to the 90% confidence limits). The bottom plot shows the percentage of the total haddock catch in the GoM area arising from the "true" GoM haddock stock for a series of θ values.

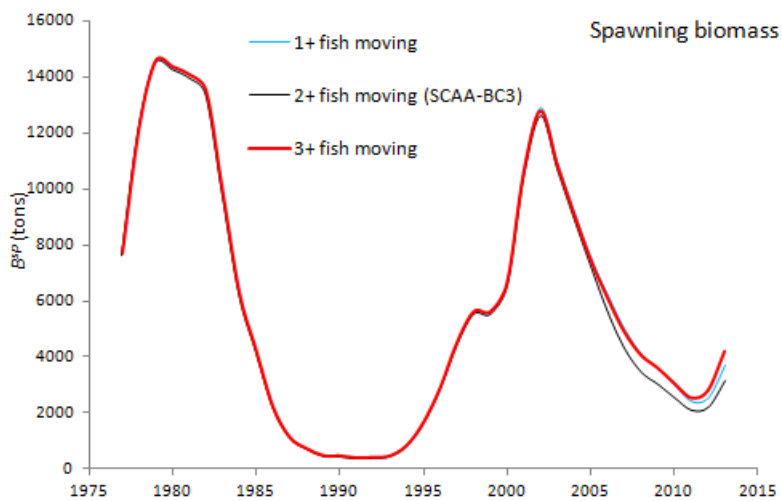

Figure 12: Comparison of spawning biomass trajectories for the **SCAA-BC3 (sabbatical model)** with sensitivities to the choice of the age at which fish start to move (note that θ is estimated separately for each of these runs).

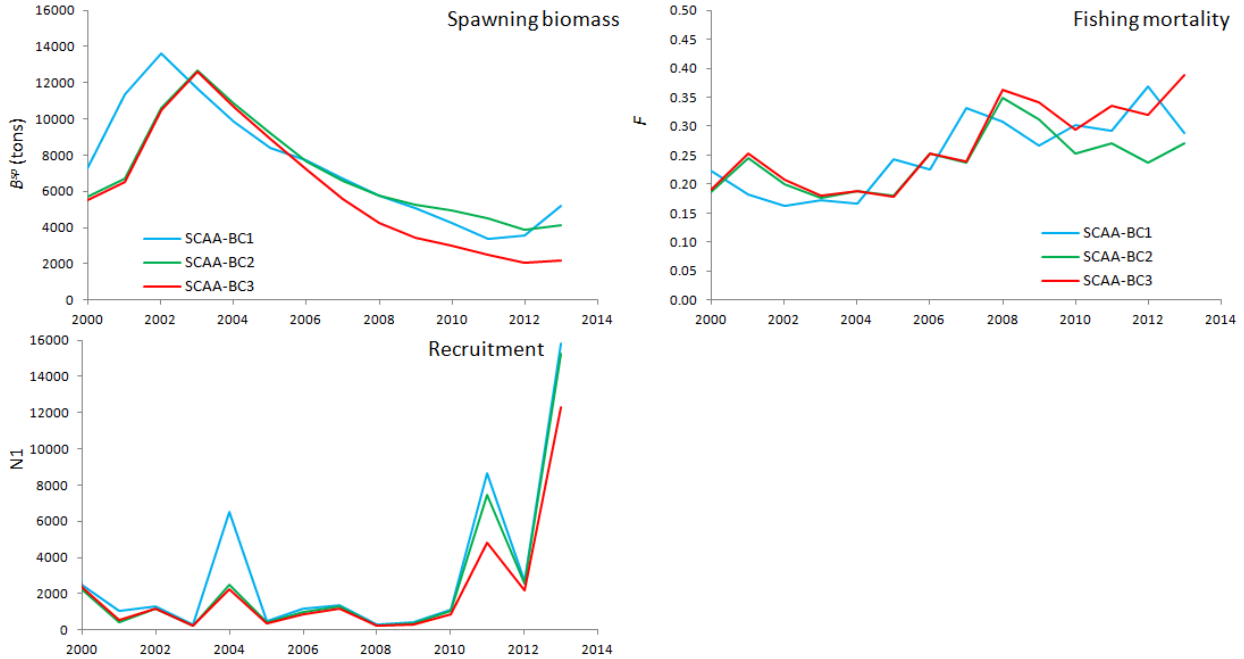

Figure 13: Comparison of spawning biomass, fishing mortality and recruitment trajectories for the **three SCAA Base Cases**. Note that the results shown for SCAA-BC3 (sabbatical model) exclude fish from the GB stock present in the GoM.

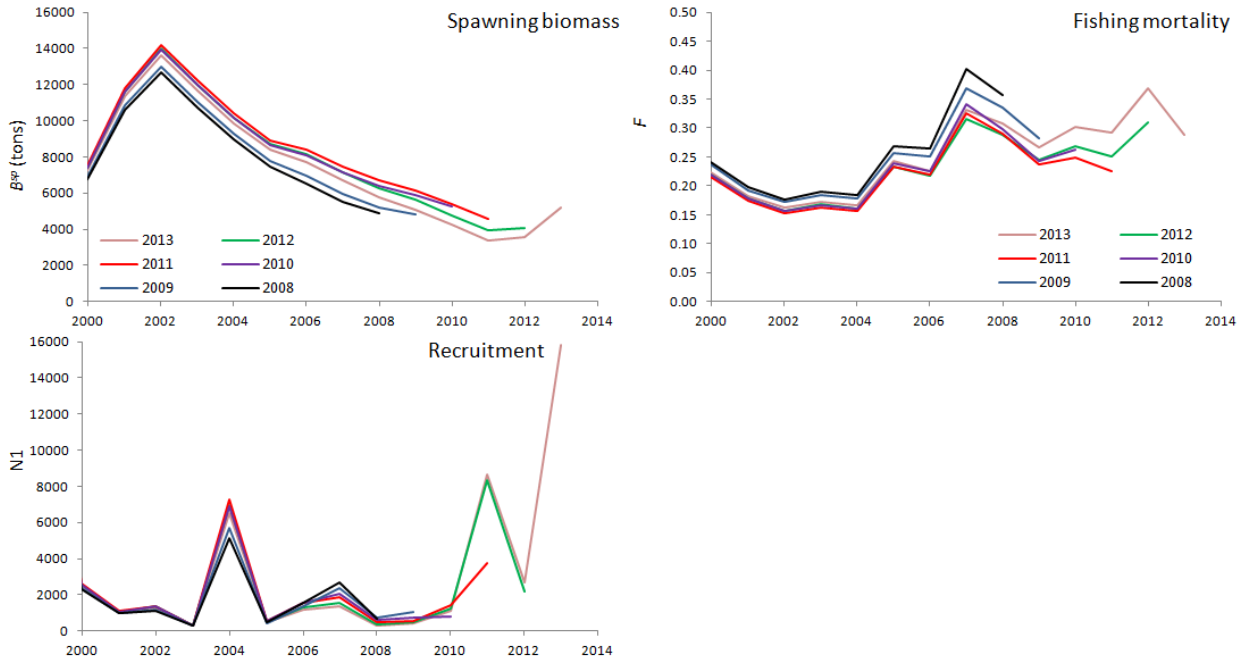

Figure 14a: Retrospective plots for **SCAA-BC1 (no movement).**

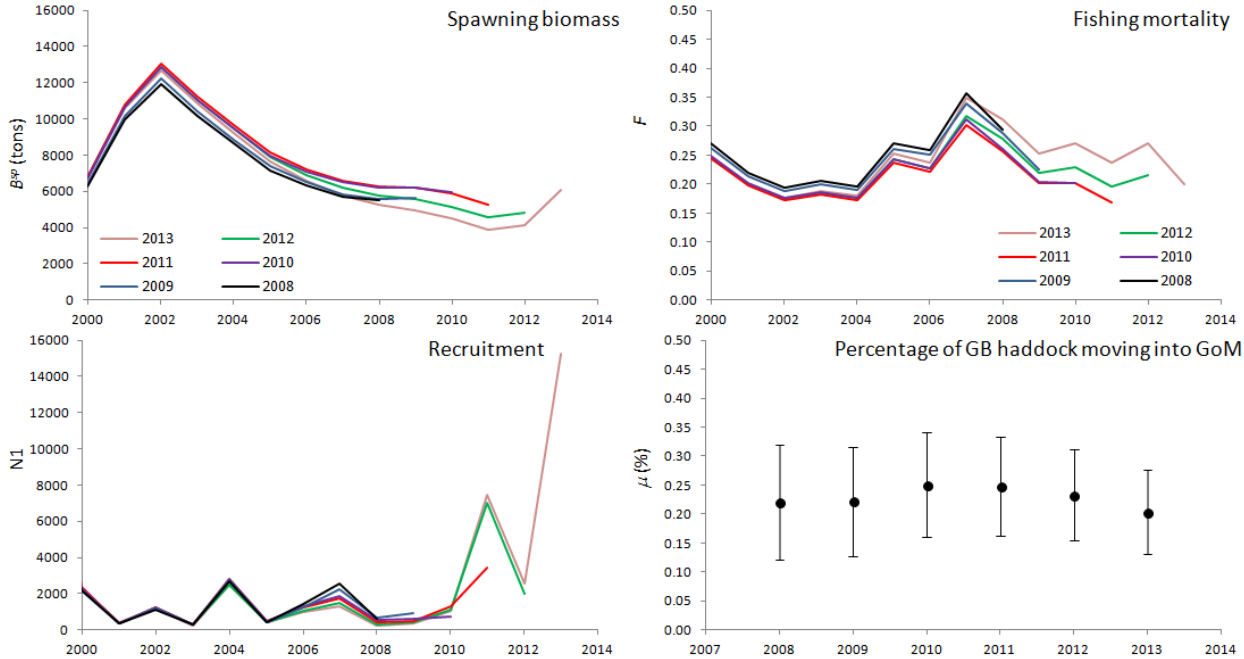

Figure 14b: Retrospective plots for **SCAA-BC2 migration model (permanent movement)**. The error bars for μ show the 90% Hessian-base CIs.

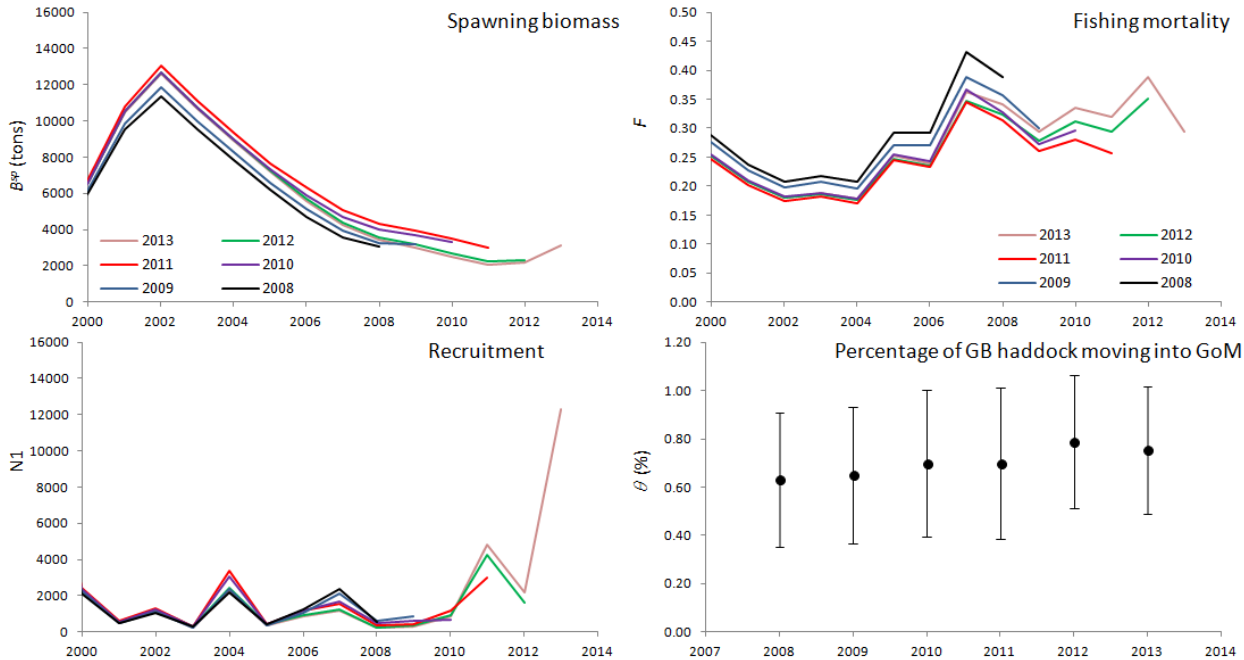

Figure 14c: Retrospective plots for **SCAA-BC3 sabbatical model (temporary movement)**. The error bars for θ show the 90% Hessian-base CIs.

ANNEX A – Data

Table A1: Total catch (metric tons) of haddock from the Gulf of Maine, 1977-2013 (Michael Palmer, pers. commn).

Year	Total catches (mt)	Year	Total catches (mt)	Year	Total catches (mt)
1977	3256.1	1990	472.4	2003	1346.7
1978	5023.5	1991	446.6	2004	1307.9
1979	4387.6	1992	321.4	2005	1576.7
1980	6520.6	1993	206.9	2006	1166.9
1981	6264.5	1994	186.7	2007	1343.2
1982	6941.7	1995	403.7	2008	1161.6
1983	7655.6	1996	341.0	2009	945.6
1984	4101.4	1997	1037.9	2010	958.1
1985	3088.2	1998	988.4	2011	744.2
1986	1922.2	1999	594.1	2012	739.1
1987	909.4	2000	985.5	2013	692.4
1988	438.8	2001	1232.4		
1989	284.6	2002	1251.8		

Table A2: Mean weight-at-age (kg) at the beginning of the year for the Gulf of Maine haddock stock (Michael Palmer, pers. commn).

Year	Age1	Age2	Age3	Age4	Age5	Age6	Age7	Age8	Age9+
1977	0.043	0.593	0.967	1.822	2.321	2.856	3.539	3.648	4.686
1978	0.083	0.296	0.967	1.400	2.213	2.820	3.948	3.888	6.088
1979	0.143	0.296	0.947	1.492	1.951	2.546	2.937	4.081	4.724
1980	0.169	0.506	0.951	1.463	2.077	2.754	3.095	3.558	4.204
1981	0.185	0.566	1.073	1.520	2.212	2.689	3.502	3.882	3.917
1982	0.151	0.589	0.826	1.800	2.267	2.864	3.322	3.886	4.293
1983	0.105	0.501	0.863	1.311	2.253	2.777	3.237	3.682	4.215
1984	0.123	0.384	0.907	1.471	2.003	2.743	3.413	3.897	4.073
1985	0.139	0.557	0.932	1.513	2.054	2.483	3.370	4.006	4.153
1986	0.174	0.400	1.081	1.247	2.052	2.416	2.850	3.612	4.592
1987	0.146	0.653	0.898	1.547	1.870	2.431	2.857	3.602	5.279
1988	0.142	0.380	0.958	1.607	2.268	2.490	3.178	3.902	5.180
1989	0.126	0.598	0.835	1.398	1.950	2.708	3.025	4.195	4.244
1990	0.135	0.464	1.292	2.375	2.113	2.669	3.275	3.651	4.189
1991	0.146	0.658	1.249	2.025	3.175	2.692	3.192	4.075	3.881
1992	0.165	0.643	1.604	1.926	2.656	3.047	2.480	3.548	3.450
1993	0.149	0.630	1.378	1.898	2.192	2.838	3.226	2.667	3.657
1994	0.148	0.533	1.186	1.866	2.500	2.606	3.315	3.402	3.721
1995	0.162	0.527	0.944	1.678	2.349	3.286	3.395	4.342	5.665
1996	0.076	0.439	0.906	1.436	1.974	2.819	2.953	3.141	3.164
1997	0.147	0.539	1.095	1.329	2.050	2.557	3.065	2.752	3.607
1998	0.124	0.579	1.108	1.800	1.914	2.574	3.170	3.067	2.988
1999	0.077	0.397	1.106	1.523	1.792	2.061	2.543	3.200	3.295
2000	0.137	0.411	0.778	1.402	1.685	1.882	2.143	2.477	3.101
2001	0.122	0.469	0.852	1.190	1.657	1.971	2.120	2.436	2.532
2002	0.086	0.346	0.908	1.252	1.532	1.955	2.385	2.258	2.624
2003	0.147	0.267	0.668	1.076	1.354	1.654	2.112	2.480	2.502
2004	0.107	0.428	0.681	1.109	1.249	1.528	1.761	2.060	2.202
2005	0.133	0.333	0.656	0.940	1.401	1.372	1.663	1.880	2.297
2006	0.121	0.375	0.690	0.722	1.215	1.537	1.461	1.668	2.006
2007	0.122	0.374	0.614	0.938	0.916	1.404	1.632	1.536	1.707
2008	0.096	0.362	0.743	0.954	1.190	1.213	1.565	1.681	1.744
2009	0.136	0.329	0.645	1.016	1.217	1.447	1.382	1.754	1.946
2010	0.150	0.421	0.741	0.928	1.238	1.399	1.674	1.825	2.067
2011	0.177	0.462	0.775	0.959	1.246	1.493	1.671	1.820	2.113
2012	0.125	0.441	0.724	1.041	1.292	1.414	1.670	1.807	1.975
2013	0.138	0.370	0.673	1.048	1.210	1.421	1.532	1.890	2.106

Table A3: Mean weight-at-age (kg) of landings for the Gulf of Maine haddock stock (Michael Palmer, pers. commn).

Year	Age1	Age2	Age3	Age4	Age5	Age6	Age7	Age8	Age9+
1977	0.113	0.757	1.163	2.008	2.558	3.358	3.709	3.587	4.686
1978	0.113	0.777	1.234	1.684	2.438	3.108	4.642	4.075	6.088
1979	0.337	0.774	1.155	1.805	2.261	2.659	2.775	3.587	4.724
1980	0.468	0.760	1.168	1.852	2.389	3.354	3.602	4.562	4.204
1981	0.560	0.685	1.516	1.978	2.641	3.026	3.657	4.184	3.917
1982	0.376	0.620	0.995	2.137	2.598	3.106	3.646	4.129	4.293
1983	0.181	0.667	1.200	1.727	2.376	2.969	3.373	3.719	4.215
1984	0.313	0.816	1.233	1.803	2.324	3.166	3.923	4.502	4.073
1985	0.315	0.980	1.068	1.859	2.339	2.652	3.588	4.090	4.153
1986	0.503	0.507	1.192	1.456	2.265	2.495	3.062	3.636	4.592
1987	0.350	0.856	1.592	2.008	2.402	2.609	3.272	4.236	5.279
1988	0.331	0.412	1.100	1.623	2.561	2.582	3.871	4.652	5.180
1989	0.251	1.126	1.779	1.824	2.343	2.864	3.543	4.545	4.244
1990	0.296	0.831	1.543	3.331	2.450	3.041	3.745	3.762	4.189
1991	0.347	1.459	1.880	2.657	3.027	2.958	3.350	4.433	3.881
1992	0.448	1.192	1.764	1.973	2.654	3.067	2.079	3.757	3.450
1993	0.364	0.885	1.592	2.041	2.436	3.035	3.393	3.422	3.657
1994	0.362	0.787	1.589	2.186	3.062	2.788	3.620	3.410	3.721
1995	0.275	0.802	1.156	1.774	2.525	3.526	4.133	5.209	5.665
1996	0.337	0.674	1.073	1.803	2.196	3.148	2.473	2.387	3.164
1997	0.354	0.891	1.802	1.662	2.330	2.977	2.985	3.063	3.607
1998	0.250	0.975	1.448	1.827	2.212	2.843	3.376	3.152	2.988
1999	0.266	0.611	1.309	1.608	1.765	1.926	2.281	3.033	3.295
2000	0.260	0.607	1.022	1.535	1.773	2.013	2.390	2.696	3.101
2001	0.242	0.889	1.260	1.490	1.811	2.210	2.243	2.483	2.532
2002	0.121	0.473	1.025	1.340	1.631	2.143	2.598	2.303	2.644
2003	0.318	0.583	0.887	1.230	1.468	1.770	2.134	2.425	2.513
2004	0.185	0.560	0.809	1.373	1.358	1.681	1.820	2.027	2.208
2005	0.286	0.583	0.815	1.139	1.464	1.443	1.684	1.954	2.297
2006	0.238	0.474	0.840	0.745	1.359	1.644	1.507	1.683	2.008
2007	0.243	0.560	0.777	1.121	1.203	1.510	1.625	1.578	1.714
2008	0.156	0.544	0.995	1.207	1.341	1.339	1.700	1.740	1.758
2009	0.304	0.699	0.809	1.135	1.282	1.625	1.563	1.877	1.947
2010	0.350	0.609	0.785	1.129	1.406	1.563	1.731	2.131	2.069
2011	0.341	0.588	1.029	1.191	1.401	1.602	1.801	1.915	2.113
2012	0.246	0.538	0.954	1.106	1.406	1.451	1.742	1.815	1.979
2013	0.283	0.550	0.870	1.267	1.498	1.486	1.658	2.051	2.104

Table A4: Maturity-at-age for Gulf of Maine haddock (Michael Palmer, pers. commn).

Age1	Age2	Age3	Age4	Age5	Age6	Age7	Age8	Age9+
0.036	0.284	0.809	0.978	0.998	1.000	1.000	1.000	1.000

Table A5: Total (commercial and recreational landings and discards) catches-at-age for the Gulf of Maine haddock stock (Michael Palmer, pers. commn).

Year	Age1	Age2	Age3	Age4	Age5	Age6	Age7	Age8	Age9+
1977	39'755	1'762'962	53'167	366'967	184'629	189'299	0	0	2'411
1978	0	374'650	2'291'417	172'388	363'003	208'654	10'580	0	5'290
1979	0	67'315	559'608	1'576'962	183'133	99'093	45'294	10'898	0
1980	0	884'750	104'084	755'832	1'366'770	143'816	95'570	27'794	25'756
1981	2'068	1'604'702	721'620	293'675	342'978	545'064	92'209	117'389	27'084
1982	30'427	620'596	1'519'414	620'677	100'582	300'972	477'524	107'352	75'881
1983	10'807	12'387	836'523	976'308	791'273	148'624	252'954	348'053	115'652
1984	1'202	88'981	49'873	597'996	256'658	364'974	62'198	64'813	147'568
1985	889	30'219	349'627	85'945	356'193	152'044	242'038	47'396	54'557
1986	4'278	10'819	183'531	358'782	81'336	114'028	86'352	102'482	14'690
1987	0	20'569	34'669	106'129	48'809	34'435	56'925	33'835	16'451
1988	305	471	12'442	12'340	54'752	55'564	7'635	15'049	4'149
1989	1'390	23'187	3'477	42'428	19'308	23'964	15'004	764	943
1990	7'007	2'033	143'062	1'686	28'820	17'607	27'466	4'050	0
1991	3'130	7'153	16'338	58'599	28'398	27'861	12'632	5'811	3'140
1992	1'819	13'092	94'371	36'543	19'112	2'246	1'134	0	1'895
1993	3'654	20'094	36'293	22'965	9'918	10'957	4'586	1'713	1'158
1994	6'455	23'681	44'531	13'600	3'419	9'230	5'675	1'711	705
1995	2'722	71'268	90'548	75'684	10'164	6'273	4'656	4'345	3'038
1996	2'789	23'528	129'505	56'458	16'363	4'055	7'112	5'599	1'162
1997	1'673	7'336	166'754	256'770	90'137	18'896	6'878	2'788	2'280
1998	5'833	23'752	25'097	132'738	192'766	52'737	17'433	8'611	7'557
1999	5'325	3'788	39'470	65'848	96'775	69'185	38'452	7'149	5'879
2000	2'355	68'641	66'083	106'777	65'090	128'456	72'058	31'811	25'699
2001	250	29'532	235'124	133'562	96'770	87'348	80'744	40'447	24'091
2002	420	2'372	27'821	275'333	117'143	110'413	32'129	70'430	68'048
2003	112	10'816	6'947	54'106	506'905	90'486	62'967	21'551	70'262
2004	1'834	1'903	14'147	32'957	71'982	512'704	59'670	34'048	51'126
2005	3'102	33'576	6'330	49'301	84'813	138'500	534'892	53'682	71'810
2006	2'461	2'174	123'574	8'459	52'663	71'713	83'463	366'977	61'040
2007	7'838	24'934	17'335	332'664	11'399	54'415	43'212	87'858	371'105
2008	1'779	18'476	55'817	19'091	407'625	5'033	42'176	29'576	225'281
2009	62	3'367	40'230	51'070	15'069	294'907	5'334	31'991	146'769
2010	2'412	6'725	13'762	39'606	52'249	19'113	294'288	3'477	134'175
2011	6'319	19'160	4'549	4'734	50'912	47'368	16'338	181'006	93'273
2012	2'642	110'559	48'841	19'988	12'290	67'218	37'764	13'802	204'436
2013	23'980	36'977	317'467	48'103	18'637	9'159	41'078	27'677	76'878

Table A6: Catch-at-age of haddock in the NEFSC offshore spring research vessel bottom trawl surveys in the Gulf of Maine, 1977-2013 (Michael Palmer, pers. commn).

Year	Age1	Age2	Age3	Age4	Age5	Age6	Age7	Age8	Age9+	Cumulative 1-9+	CV
1977	1306.1	4237.2	40.7	1731.1	499.9	700.8	0.0	0.0	0.0	8515.7	(0.31)
1978	107.0	854.5	444.4	37.7	255.0	0.0	0.0	0.0	0.0	1698.5	(0.40)
1979	365.2	121.2	879.4	1587.7	292.3	168.7	114.5	65.3	0.0	3594.3	(0.22)
1980	1319.1	191.3	223.4	684.5	274.2	31.6	0.0	0.0	46.0	2770.0	(0.38)
1981	1396.3	1370.0	688.0	299.7	437.0	208.9	31.7	42.2	50.9	4524.7	(0.25)
1982	0.0	505.5	1168.5	466.4	177.4	86.3	128.5	15.8	15.8	2564.1	(0.31)
1983	1746.6	167.1	1361.8	384.0	608.6	0.0	136.0	67.6	28.1	4499.9	(0.40)
1984	24.3	713.9	68.1	374.5	134.9	0.0	0.0	56.1	0.0	1371.9	(0.41)
1985	16.0	401.1	1349.6	68.3	194.3	103.8	62.4	24.8	0.0	2220.2	(0.38)
1986	63.9	0.0	203.0	453.3	0.0	45.5	91.2	28.7	0.0	885.5	(0.46)
1987	45.0	30.8	38.8	0.0	0.0	0.0	0.0	0.0	0.0	114.6	(0.36)
1988	54.4	0.0	0.0	18.2	149.2	0.0	0.0	13.0	0.0	234.7	(0.52)
1989	0.0	44.6	14.9	0.0	14.9	29.7	0.0	0.0	0.0	104.1	(0.75)
1990	14.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	14.9	(0.54)
1991	17.8	9.3	9.3	55.9	0.0	0.0	0.0	0.0	0.0	92.2	(0.53)
1992	106.0	0.0	0.0	136.3	0.0	0.0	0.0	0.0	0.0	242.2	(0.59)
1993	326.3	183.4	0.0	0.0	36.2	18.2	0.0	0.0	0.0	564.0	(0.45)
1994	92.2	227.7	145.8	37.2	0.0	0.0	0.0	0.0	0.0	502.9	(0.34)
1995	552.6	300.0	99.1	28.7	0.0	0.0	0.0	28.7	0.0	1009.0	(0.46)
1996	0.0	45.7	183.4	153.4	0.0	0.0	0.0	0.0	0.0	382.5	(0.31)
1997	970.2	262.6	322.1	753.1	87.5	27.9	0.0	0.0	0.0	2423.6	(0.40)
1998	100.6	57.7	0.0	77.4	11.3	0.0	0.0	0.0	0.0	247.0	(0.41)
1999	4663.8	108.8	199.9	36.2	280.9	55.0	0.0	0.0	0.0	5344.7	(0.39)
2000	1293.0	1465.8	1218.3	171.1	155.4	54.4	163.1	0.0	0.0	4521.0	(0.41)
2001	91.4	158.1	1369.4	616.0	218.3	241.1	90.6	53.4	122.5	2960.7	(0.56)
2002	4132.1	257.9	751.4	1772.7	122.7	34.2	27.9	45.5	0.0	7144.4	(0.51)
2003	449.8	260.6	113.6	134.6	2525.9	254.4	151.9	44.6	61.4	3996.9	(0.25)
2004	144.0	0.0	193.1	27.2	119.2	782.2	45.5	0.0	18.2	1329.4	(0.35)
2005	12.9	214.8	0.0	124.0	101.1	274.3	316.4	0.0	36.2	1079.7	(0.39)
2006	224.1	95.7	2068.1	397.9	130.4	24.0	251.9	682.5	72.4	3947.0	(0.45)
2007	194.8	106.2	34.9	303.5	0.0	35.3	36.2	35.3	218.8	965.1	(0.37)
2008	54.4	706.8	508.9	0.0	379.5	0.0	33.4	64.8	368.2	2116.0	(0.49)
2009	40.2	111.5	527.1	274.5	49.8	685.7	0.0	16.9	211.5	1917.3	(0.36)
2010	129.0	15.8	9.9	163.8	161.7	63.3	985.2	0.0	512.8	2041.4	(0.35)
2011	694.6	248.6	12.1	0.0	31.1	218.3	0.0	203.0	136.4	1544.2	(0.34)
2012	666.2	1991.0	241.2	61.4	0.0	203.4	105.6	54.4	406.3	3729.4	(0.41)
2013	11846.9	1011.1	2037.6	168.6	45.3	33.6	145.3	100.2	116.9	15505.4	(0.44)

Table A7: Catch-at-age of haddock in the NEFSC offshore autumn research vessel bottom trawl surveys in the Gulf of Maine, 1977-2013 (Michael Palmer, pers. commn).

Year	Age1	Age2	Age3	Age4	Age5	Age6	Age7	Age8	Age9+	Cumulative 1-9+	
1977	3863.8	4289.8	158.9	1309.2	149.9	360.0	0.0	0.0	128.6	10260.4	(0.32)
1978	86.2	1941.1	7098.5	184.7	954.8	1450.9	156.2	0.0	145.2	12017.6	(0.18)
1979	508.5	109.6	1389.5	3425.1	597.4	535.9	153.1	0.0	16.4	6735.6	(0.20)
1980	637.1	365.7	0.0	373.5	1330.3	796.2	226.8	161.1	116.1	4006.9	(0.33)
1981	749.0	588.0	1276.7	421.7	1002.1	1004.6	152.2	386.6	0.0	5581.0	(0.18)
1982	46.3	733.6	1134.3	470.1	61.9	0.0	120.2	120.2	120.2	2806.9	(0.35)
1983	667.8	63.3	845.3	629.9	502.6	222.2	85.5	205.5	0.0	3222.2	(0.28)
1984	263.3	668.2	0.0	365.9	0.0	517.2	0.0	42.7	267.7	2124.9	(0.26)
1985	111.5	495.9	3499.9	21.3	240.6	167.5	487.2	0.0	84.8	5108.6	(0.40)
1986	18.2	0.0	94.7	443.3	127.0	22.7	0.0	74.1	0.0	779.9	(0.41)
1987	0.0	190.5	127.3	118.2	76.2	377.3	222.3	0.0	148.2	1259.9	(0.32)
1988	0.0	0.0	51.9	28.7	114.7	0.0	80.5	143.4	0.0	419.2	(0.65)
1989	74.3	74.3	23.5	14.9	102.5	41.5	23.5	0.0	0.0	354.5	(0.38)
1990	29.7	0.0	70.5	0.0	0.0	0.0	47.1	23.5	0.0	170.8	(0.37)
1991	59.4	0.0	0.0	52.1	0.0	0.0	0.0	0.0	0.0	111.5	(0.60)
1992	181.1	0.0	28.7	0.0	0.0	0.0	0.0	0.0	0.0	209.8	(0.53)
1993	585.0	283.3	37.1	37.1	18.5	0.0	0.0	0.0	0.0	961.0	(0.72)
1994	59.1	0.0	0.0	0.0	0.0	0.0	45.5	0.0	45.5	150.0	(0.42)
1995	117.9	756.6	230.6	45.5	44.7	0.0	0.0	0.0	28.7	1223.9	(0.54)
1996	158.6	244.6	1330.7	774.4	85.0	142.3	88.9	45.5	90.9	2960.9	(0.37)
1997	1663.6	37.7	482.3	724.1	76.9	113.2	0.0	0.0	0.0	3097.8	(0.36)
1998	301.7	521.5	162.7	539.8	379.0	87.9	61.7	30.8	0.0	2085.3	(0.51)
1999	4043.7	744.5	1038.1	316.6	598.6	643.0	212.0	73.8	72.3	7742.6	(0.30)
2000	828.4	14160.3	2112.0	1632.1	531.8	726.5	276.6	92.6	0.0	20360.1	(0.45)
2001	301.1	2876.5	6089.8	899.9	1012.5	376.6	241.5	366.9	64.3	12229.0	(0.25)
2002	150.9	17.2	677.0	3074.0	428.1	180.7	0.0	269.4	95.7	4893.0	(0.35)
2003	0.0	334.7	89.9	630.8	3089.2	439.3	66.6	0.0	209.3	4859.7	(0.20)
2004	435.2	36.2	683.9	313.1	1037.4	4050.5	154.9	195.8	146.5	7053.6	(0.25)
2005	137.1	1995.2	83.9	184.5	375.2	509.4	1431.4	110.7	112.7	4940.2	(0.19)
2006	330.8	104.5	2230.7	33.3	257.3	134.8	363.5	1062.1	91.7	4608.6	(0.26)
2007	1333.5	1061.6	276.6	2665.4	75.9	17.7	204.3	143.0	657.8	6435.8	(0.30)
2008	0.0	505.4	138.7	0.0	1308.7	0.0	201.9	142.7	541.1	2838.4	(0.31)
2009	323.5	115.0	235.2	14.4	50.6	435.4	0.0	64.6	174.6	1413.3	(0.35)
2010	43.1	26.6	62.2	210.5	363.9	139.7	301.1	0.0	151.4	1298.5	(0.47)
2011	1491.4	1045.8	245.9	121.1	1064.0	276.4	169.7	936.0	148.4	5498.7	(0.46)
2012	658.7	4122.1	13.0	0.0	24.7	34.7	34.7	0.0	34.7	4922.6	(0.58)
2013	6333.5	2273.5	8469.4	519.5	325.5	112.6	34.7	0.0	100.5	18169.3	(0.23)

Table A8: Estimated numbers at age for Georges Bank haddock for ages 1-9+ for 1977 to 2011 from NEFSC (2012, Table B17). The projected numbers (in *italics*) for 2012 to 2017 were kindly provided by Liz Brooks, based on the following assumptions (Liz Brooks, pers. commn):

1. the fully selected *F* is 0.15 in 2011 to2016;
2. the recruitment in 2012 does not appear large based on surveys, and hence is possibly similar to recent recruitment (excluding 2010);
3. at first glimpse of 2013 recruitment seems VERY large; here it is arbitrarily assumed to be the same size as 2013 year-class; and
4. recruitment in years 2014-2017 is assumed to be time series median (from Table B17 in GB haddock report: NEFSC, 2012)

Year	Age1	Age2	Age3	Age4	Age5	Age6	Age7	Age8	Age9+
1977	13'983	86'117	4'726	4'473	2'540	1'132	73	196	558
1978	6'125	11'447	52'655	3'698	3'041	1'610	602	56	270
1979	83'888	5'014	8'680	30'082	2'751	1'975	851	367	176
1980	10'934	68'674	4'081	5'539	18'124	1'775	1'245	412	218
1981	7'364	8'945	28'384	3'027	3'653	9'382	918	529	315
1982	2'581	6'028	5'744	13'325	1'727	2'143	5'355	453	470
1983	3'284	2'112	3'879	3'226	7'533	1'060	1'240	3'370	320
1984	18'080	2'688	1'534	2'438	2'015	4'138	621	846	1'720
1985	2'518	14'801	2'116	986	1'335	1'288	2'044	296	577
1986	16'786	2'061	9'900	1'227	628	670	844	1'190	268
1987	2'614	13'738	1'638	5'549	801	381	391	555	706
1988	19'995	2'140	9'414	1'223	3'066	544	245	239	395
1989	1'364	16'366	1'704	5'517	877	1'656	308	150	230
1990	3'406	1'115	12'081	1'285	3'600	523	927	197	174
1991	2'716	2'732	902	8'362	810	1'939	290	563	213
1992	10'741	2'217	1'799	628	4'719	533	1'123	123	263
1993	15'568	8'718	1'576	1'107	337	2'110	274	538	261
1994	15'420	12'716	6'810	896	601	169	1'063	168	334
1995	12'687	12'601	9'926	4'503	517	364	72	589	156
1996	11'778	10'372	10'232	7'572	3'262	370	271	52	586
1997	23'451	9'637	8'441	7'866	5'372	2'265	244	202	537
1998	14'637	19'187	7'760	6'664	5'768	3'892	1'658	184	382
1999	49'156	11'979	15'501	5'929	4'953	4'032	2'673	1'205	352
2000	11'668	40'242	9'768	11'874	4'366	3'510	2'791	1'843	703
2001	90'866	9'551	32'580	7'433	8'306	3'045	2'398	1'946	1'422
2002	5'551	74'382	7'689	24'515	5'188	5'647	1'903	1'570	2'824
2003	2'870	4'542	60'540	5'983	17'209	3'414	3'629	1'197	2'192
2004	412'375	2'345	3'703	47'812	4'483	11'670	2'251	2'324	1'685
2005	7'985	337'041	1'890	2'922	34'534	3'014	6'917	1'227	1'336
2006	28'833	6'520	275'392	1'510	2'086	20'631	1'769	4'008	1'084
2007	7'123	23'458	5'322	222'615	1'172	1'371	12'024	1'154	2'296
2008	9'365	5'814	19'042	4'148	173'187	801	927	8'192	2'065
2009	4'773	7'660	4'723	15'197	3'122	130'269	552	661	4'480
2010	7'605	3'891	6'152	3'687	11'644	2'298	94'968	376	2'206
2011	374'008	6'195	3'132	4'658	2'672	8'234	1'481	65'649	300
2012	*8'000*	*305'513*	*5'022*	*2'477*	*3'603*	*1'967*	*5'802*	*1'061*	*47'393*
2013	*374'008*	*6'535*	*247'686*	*3'972*	*1'916*	*2'653*	*1'386*	*4'157*	*34'820*
2014	*11'301*	*305'513*	*5'298*	*195'868*	*3'072*	*1'411*	*1'869*	*993*	*28'010*
2015	*11'301*	*9'231*	*247'686*	*4'190*	*151'496*	*2'262*	*994*	*1'339*	*20'842*
2016	*11'301*	*9'231*	*7'484*	*195'868*	*3'240*	*111'547*	*1'594*	*712*	*15'940*
2017	*11'301*	*9'231*	*7'484*	*5'918*	*151'496*	*2'386*	*78'606*	*1'142*	*11'967*

ANNEX B - The Statistical Catch-at-Age Model

The text following sets out the equations and other general specifications of the SCAA followed by details of the contributions to the (penalised) log-likelihood function from the different sources of data available and assumptions concerning the stock-recruitment relationship. Quasi-Newton minimization is then applied to minimize the total negative log-likelihood function to estimate parameter values (the package AD Model Builder™, Otter Research, Ltd is used for this purpose).

B.1. Population dynamics

B.1.1 Numbers-at-age

The resource dynamics are modelled by the following set of population dynamics equations:

$N_1 = R_{y+1}$ (B1)

$N_{y+1,a+1} = N_{y,a} e^{-Z_{y,a}}$ for $1 \leq a \leq m-2$ (B2)

$N_{y+1,m} = N_{y,m-1} e^{-Z_{y,m-1}} + N_{y,m} e^{-Z_{y,m}}$ (B3)

where

$N_{y,a}$ is the number of fish of age *a* at the start of year *y*,

R_y is the recruitment (number of 1-year-old fish) at the start of year *y*,

m is the maximum age considered (taken to be a plus-group, and set here to be 9).

$Z_{y,a} = F_y S_{y,a} + M_a$ is the total mortality in year *y* on fish of age *a*, where

M_a denotes the natural mortality rate for fish of age *a*,

F_y is the fishing mortality of a fully selected age class in year *y*, and

$S_{y,a}$ is the commercial selectivity at age *a* for year *y*.

B.1.2. Recruitment

The number of recruits (i.e. new 1-year old) at the start of year *y* is taken as an average recruitment, allowing for annual fluctuation about the deterministic relationship.

$R_y = R_{gm} e^{\varsigma_y}$ (B4)

R_{gm} is the geometric mean (median under a log-normality assumption) recruitment over the period considered (see equation B18 below),

ς_y reflects fluctuation about the expected recruitment for year *y*, which is assumed to be normally distributed with standard deviation $\sigma_{R,y}$ (which is input in the applications considered here); these residuals are treated as estimable parameters in the model fitting process.

The spawning biomass at the start of year *y*, is computed as:

$$B_y^{\text{sp}} = \sum_{a=1}^{m} f_a w_{y,a}^{\text{strt}} N_{y,a} e^{-Z_{y,a}/4} \qquad \text{(B5)}$$

because spawning for the haddock stock under consideration is taken to occur three months after the start of the year and some mortality has therefore occurred,

where

$w_{y,a}^{\text{strt}}$ is the mass of fish of age *a* during spawning (Table A2), and

f_a is the proportion of fish of age *a* that are mature (Table A4).

B.1.3. Total catch and catches-at-age

The total catch by mass in year *y* is given by:

$$C_y = \sum_{a=1}^{m} w_{y,a}^{\text{mid}} C_{y,a} = \sum_{a=1}^{m} w_{y,a}^{\text{mid}} N_{y,a} \; S_{y,a} F_y \left(1 - e^{-Z_{y,a}}\right) / Z_{y,a} \qquad \text{(B6)}$$

where

$w_{y,a}^{\text{mid}}$ denotes the mass of fish of age *a* landed in year *y* (Table A3),

$C_{y,a}$ is the catch-at-age, i.e. the number of fish of age *a*, caught in year *y*,

The model estimate of survey index is computed as:

$$N_y^{\text{surv}} = \sum_{a=1}^{m} S_a^{\text{surv}} N_{y,a} e^{-Z_{y,a} T^{surv}/12} \qquad \text{(B7)}$$

where

S_a^{surv} is the survey selectivity for age *a*, which is taken to be year-independent, and

T^{surv} is the month in which the survey is taking place (T^{surv} =4 for spring surveys and T^{surv} =10 for fall surveys)

B.1.4. Initial conditions

For the first year (y_0) considered in the model, the numbers-at-age are estimated directly for ages 1 to a^{est}, with a parameter ϕ mimicking recent average fishing mortality for ages above a^{est}, i.e.

$$N_{y_0,a} = N_{\text{start},a} \qquad \text{for } 1 \le a \le a^{est} \qquad \text{(B8)}$$

and

$$N_{\text{start},a} = N_{\text{start},a-1} e^{-M_{a-1}} (1-\phi S_{a-1}) \qquad \text{for } a^{est} < a \le m-1 \qquad \text{(B9)}$$

$$N_{\text{start},m} = N_{\text{start},m-1} e^{-M_{m-1}} (1-\phi S_{m-1}) \big/ (1-e^{-M_m}(1-\phi S_m)) \qquad \text{(B10)}$$

B.2. The (penalised) likelihood function

The model can be fit to (a subset of) survey abundance indices, and commercial and survey catch-at-age data to estimate model parameters (which may include residuals about the stock-recruitment function, facilitated through the incorporation of a penalty function described below). Contributions by each of these to the negative of the (penalised) log-likelihood (- $\ell n L$) are as follows.

B2.1. Survey abundance data

The likelihood is calculated assuming that a survey index is lognormally distributed about its expected value:

$$I_y^{surv} = \hat{I}_y^{surv} \exp\left(\varepsilon_y^{surv}\right) \quad \text{or} \quad \varepsilon_y^{surv} = \ell n\left(I_y^{surv}\right) - \ell n\left(\hat{I}_y^{surv}\right) \qquad \text{(B11)}$$

where

I_y^{surv} is the survey biomass index for survey *surv* in year *y*,

$\hat{I}_y^{surv} = \hat{q}^{surv} \widehat{N}_y^{surv}$ is the corresponding model estimate, where

$\hat{q}^{surv}$ is the constant of proportionality (catchability) for the survey series *surv*, and

ε_y^{surv} from $N\left(0, \left(\sigma_y^{surv}\right)^2\right)$.

The contribution of the survey biomass data to the negative of the log-likelihood function (after removal of constants) is then given by:

$$-\ell n\, L^{\text{survey}} = \sum_{surv} \sum_{y} \left\{ \ell n\left(\sqrt{\left(\sigma_y^{surv}\right)^2 + \left(\sigma_{Add}^{surv}\right)^2} \right) + \left(\varepsilon_y^{surv}\right)^2 / \left[2\left(\left(\sigma_y^{surv}\right)^2 + \left(\sigma_{Add}^{surv}\right)^2 \right) \right] \right\} \qquad \text{(B12)}$$

where

σ_y^{surv} is the standard deviation of the residuals for the logarithm of index *i* in year *y* (which is input), and

σ_{Add}^{surv} is the square root of the additional variance for survey biomass series *surv*, which is estimated in the model fitting procedure, with an upper bound of 0.5.

The catchability coefficient q^{surv} for survey biomass index *surv* is estimated by its maximum likelihood value:

$$\ell n\, \hat{q}^{surv} = 1/n_{surv} \sum_{y} \left(\ln I_y^{surv} - \ln \widehat{N}_y^{surv} \right) \qquad \text{(B13)}$$

B.2.3. Commercial catches-at-age

The contribution of the catch-at-age data to the negative of the log-likelihood function is given by:

$$-\ell\mathrm{n}\, L^{\mathrm{CAA}} = W_{CAA} \sum_{y} \sum_{a} \left[\ell n\left(\sigma_a^{com}\right) + \left(\sqrt{p_{y,a}} - \sqrt{\hat{p}_{y,a}}\right)^2 / 2\left(\sigma_a^{\mathrm{com}}\right)^2 \right] \quad \text{(B14)}$$

where

$p_{y,a} = C_{y,a} / \sum_{a'} C_{y,a'}$ is the observed proportion of fish caught in year *y* that are of age *a*,

$\hat{p}_{y,a} = \hat{C}_{y,a} / \sum_{a'} \hat{C}_{y,a'}$ is the model-predicted proportion of fish caught in year *y* that are of age *a*,

where

$$\hat{C}_{y,a} = N_{y,a}\ S_{y,a} F_y \left(1 - e^{-Z_{y,a}}\right) \Big/ Z_{y,a} \quad \text{(B15)}$$

W_{CAA} is a relative weighting accorded to these data in the negative log-likelihood, which is set equal to 1 for the Base Case runs in these analyses,

and

σ_{CAA}^{com} is the standard deviation associated with the catch-at-age data, which is estimated in the fitting procedure by:

$$\hat{\sigma}_{CAA}^{com} = \sqrt{\sum_{y} \left(\sqrt{p_{y,a}} - \sqrt{\hat{p}_{y,a}}\right)^2 / \sum_{y} 1} \quad \text{(B16)}$$

This formulation mimics a multinomial form for the error distribution by forcing a near-equivalent variance-mean relationship for the error distributions.

Commercial catches-at-age are incorporated in the likelihood function using equation (B14), for which the summation over age *a* is taken from age a_{minus} (considered as a minus group) to a_{plus} (a plus group), taken here as 1 and 9 respectively.

B.2.4. Survey catches-at-age

The survey catches-at-age are incorporated into the negative of the log-likelihood in an analogous manner to the commercial catches-at-age (equation (B14)) where:

$p_{y,a}^{surv} = C_{y,a}^{surv} / \sum_{a'} C_{y,a'}^{surv}$ is the observed proportion of fish of age *a* in year *y* for survey *surv*,

$\hat{p}_{y,a}^{surv}$ is the expected proportion of fish of age *a* in year *y* in the survey *surv*, given by:

$$\hat{p}_{y,a}^{surv} = S_a^{\mathrm{surv}} N_{y,a} e^{-Z_{y,a} T^{surv}/12} \Bigg/ \sum_{a'=0}^{m} S_{a'}^{\mathrm{surv}} N_{y,a'} e^{-Z_{y,a'} T^{surv}/12} \quad \text{(B17)}$$

As for the commercial data, the minus and plus groups for both surveys are taken here as 1 and 9 respectively.

B.2.5. Stock-recruitment function residuals

The stock-recruitment residuals are assumed to be lognormally distributed and serially correlated. Thus, the contribution of the recruitment residuals to the negative of the (now penalised) log-likelihood function is given by:

$$-\ell nL^{\text{pen}} = W_{SRpen}\left[\sum_{y=1977}^{2013}\left[\varepsilon_y^2 / 2\sigma_{\text{R,y}}^2\right] + 10000\left(\sum_{y=1977}^{2010}\varepsilon_y\right)^2\right] \quad \text{(B18)}$$

where

ε_y from $N\left(0,\left(\sigma_{R,y}\right)^2\right)$,

$\sigma_{R,y} = \sqrt{\ln\left(CV_y^2 + 1\right)}$ is the standard deviation of the log-residuals, which is input. For the SCAA-Base assessment, $CV_y = 1$ for all years.

$W_{SRpen} = 1$.

Note that the purpose of the second term on the right hand side of equation B.18 is to ensure that R_{gm} corresponds to the geometric mean (likely to closely approximate the median) of the pre-2011 recruitments.

B.2.5. Catches

$$-\ell nL^{\text{Catch}} = \sum_u \sum_y \left[\frac{\ell n\, C_y - \ell n\, \hat{C}_y}{2\sigma_{\text{C,y}}^2}\right] \quad \text{(B19)}$$

where

C_y is the observed catch in year y,

$\hat{C}_y$ is the predicted catch in year y, and

$\sigma_{\text{C,y}}$ is the input CV in year y. It is taken to be 0.15 over 1977-1981, 0.1 over 1982-1988 and 0.05 thereafter, as for the preferred ASAP model..

B.3. Estimation of precision

Where quoted, CV's or 90% probability interval estimates are based on the Hessian.

B.4. Model parameters

B.4.1. Fishing selectivity-at-age:

The commercial and survey fishing selectivities are estimated separately for each age. For the NEFSC offshore surveys, the fishing selectivities are assumed to be flat from age 4 and 6 onwards for the spring and fall surveys respectively.

The commercial selectivity is taken to differ over three blocks, as for the preferred ASAP model: 1977-1988, 1989-2004 and 2005-2013. These selectivities are set to 1 for age 7, and may not increase for greater ages.

B.4.2. Natural mortality

This was set to 0.2, independent of year and age.

B.4.3. Biological reference points

In the computation of the biological reference points, the weight-at-age, maturity-at-age and commercial selectivity vectors are taken as the average over the 2009-2013 period.