APPENDICES

Appendix A.1. List of 55th Stock Assessment Workshop (SAW 55) Working Group (WG) participants

Note: participants of at least one day of a working group meeting are listed

Participant Last Name	Participant First Name	Affiliation	SAW 55 WG - Data Meeting	SAW 55 WG - Modeling Meeting	SAW 55 WG - BRP and Modeling Meeting	SAW 55 WG - Follow up BRP and Reports Organization
Alade	Larry	NEFSC				
Blaylock	Jessica	NEFSC				
Brazer	Eric	CCCHFA				
Brooks	Liz	NEFSC				
Butterworth	Doug	UCT				
Cadrin	Steve	SMAST				
Clark	Don	DFO				
Col	Laurel	NEFSC				
Correia	Steve	MA DMF				
Crawford	Jud	Pew Charitable Trusts				
Curti	Kiersten	NEFSC				
Dean	Micah	MA DMF				
Deroba	Jon	NEFSC				
Dority	Aaron	Penobscot East				
Fairbrother	Alison	Public Trust Project				
Giacalone	Vito	Northeast Seafood Coalition				
Hart	Dvora	NEFSC				
Hendrickson	Lisa	NEFSC				
Hogan	Fiona	NEFMC				
King	Jeremy	MA DMF				
Legault	Chris	NEFSC				
Link	Jason	NEFSC				
Miller	Tim	NEFSC				
Nieland	Julie	NEFSC				
Nies	Tom	NEFMC				
Nitschke	Paul	NEFSC				
O'Boyle	Robert	Beta Scientific Consulting (WG Chair)				
O'Brien	Loretta	NEFSC (GBK cod assessment lead)				
Odell	Jackie	Northeast Seafood Coalition				
Palmer	Michael	NEFSC (GOM cod assessment lead)				
Pol	Mike	MA DMF				
Rago	Paul	NEFSC				
Raymond	Maggie	AFM				
Richardson	David	NEFSC - Naragansett				
Serchuk	Fred	NEFSC				
Shepherd	Gary	NEFSC				
Sherman	Sally	ME DMR				
Sosebee	Kathy	NEFSC				
Terceiro	Mark	NEFSC				
Traver	Michelle	NEFSC				
Vecchio	Victor	NERO				
Wang	Yanjun	Fisheries and Oceans Canada				
Waring	Gordon	NEFSC				
Weinberg	James	NEFSC				
Wigley	Susan	NEFSC				
Wood	Tony	NEFSC				
Zemeckis	Doug	SMAST				

[SAW55 Editor's Note: The SARC-55 review panel <u>did not recommend</u> adopting the GOM cod Statistical Catch-at-Age (SCAA) assessment results that are in Appendices A.2 – A.5. These appendices are included in this report to document and demonstrate the work that was done by the SAW Working Group for the December 2012 peer review.]

Appendix A.2. Preferred Statistical Catch-at-Age Assessments of Gulf of Maine Cod, November 2012.

Introduction

This Appendix summarizes the development of the Statistical Catch-at-Age (SCAA) methodology applied to Gulf of Maine cod as presented to the NEFMC SSC in March 2012 (Butterworth and Rademeyer 2012) and further refined during deliberations at SAW/SARC 55 Working Group meetings held at Woods Hole over 15-19 October and 30 October-2 November 2012. It also summarises the process leading to the authors' choice of their "preferred" variant of the approach at this time. The primary reason for adopting the SCAA methodology is that it allows age-based assessments to be extended to cover a longer period without, for example, requiring catch-at-age data to be available for every year, and thus tends to provide the enhanced contrast desirable for more precise estimates of Biological Reference Points (BRPs) related to MSY.

The text first outlines the methodology used, and then provides estimates for current stock status and BRPs for a set of four final assessments which cross two factors to which results are particularly sensitive:

- Natural mortality: $M = 0.2$ and time invariant, or ramping linearly from a constant 0.2 to a constant 0.4 yr^{-1} over the period from 1988 to 2003 (*M* ramp).
- Stock-recruitment functional form: Ricker or Beverton-Holt (BH).

It concludes with a summary of the results as they relate to the SAW/SARC55 TORs.

Methodology

The algebraic details of the methods used for the SCAA assessments, BRP estimation and future projections are set out in Appendix A3.

For the SCAA assessments, there are a number of factors for which choices amongst different options (as detailed in Appendix A3) may be made. The options chosen for the assessments reported here are specified (where this is relevant) in **bold** at the end of each section of Appendix A3. In broad terms, the primary reasons underlying these choices

were AIC-based selection or lower variance of estimates. However in cases where these criteria did not lead to clear-cut guidance (e.g. domes in selectivity) and/or the impact on results was small (e.g. refining of the *Bigelow-Albatross* calibration function within the assessment) relative to factors such as natural mortality or stock-recruitment function choice, the choices made reflect a consensus agreed for practical purposes during the recent Working Group meetings referenced above, rather than necessarily the options the authors' consider to be the most appropriate.

These choices have also been informed by extensive sensitivity tests reported in papers presented to those Working Group meetings, and reproduced here as Appendices A4 and A5[1]. These showed, for example, that the assumptions that have to be made about commercial selectivity for the period prior to 1982 for which commercial catch-at-age data are not available, have very little impact on estimates of past spawning biomass and recruitment trajectories, as well as on BRP estimates. Those tests included a comparison of internal (within assessment) compared to external estimation of stock-recruitment relationships and hence of BRPs, revealing that this made little difference to results. The former was preferred for the results that follow because it take full account of the variance-covariance structure of the estimates of recruitment and spawning biomass used to obtain these relationships (rather than only of the variance of recruitment estimates treated as independent in external estimation), and hence provides more reliable estimates of their precision.

The choice of an early starting year for these assessments is to be consistent with the intent of using as long a time-series of data as possible to potentially better inform BRP estimates. The specific choice of 1932 is not critical, as the information content of available abundance index and size/age data extends back only to year-classes from about 1960. However commencing calculations earlier is convenient in allowing transient effects associated with uncertainties linked to the estimation of the components of the initial numbers-at-age vector to damp out before the abundance index and size/age information start having an influence on the results.

Results

App. A2, Table A2.1 lists estimates of primary parameters and management-related quantities for Gulf of Maine cod for the four final assessments listed above, together with estimates for BRPs and projected future catches under a $0.75F_{MSY}$ strategy evaluated on the basis set out in the final section of Appendix A3. BRP and current stock status estimates are summarized in App. A2, Table A2.2.

As the Ricker is preferred over the BH form of the stock-recruitment relationship for reasons given below, a number of the plots that follow show results for only the two Ricker assessments, rather than for all four variants. App. A2, Fig. A2.1 shows point estimate trajectories for spawning biomass, recruitment (0-year class strength) and fully

1 An error was subsequently found in the code used to estimate the stock-recruitment function parameters in this paper. This does not change results qualitatively. The error has been corrected for the results reported in this paper.

selected fishing mortality for the four assessments, while App. A2, Fig. A2.2 repeats some of these plots for the two Ricker assessments with the addition of Hessian based estimates of precision, together with a similar plot for the input time-series of annual catches. Note that moving backwards in time, recruitment estimates are generally reasonably precise up to and including the low estimates of the mid- to late 1960s, but are poorly estimated prior to that, whereas the precision of the spawning biomass estimates reduces in the 1970s and reduces further before that in a manner that depends on the natural mortality assumptions made.

App. A2, Fig. A2.3 shows survey and commercial selectivity-at-age estimates for the two Ricker assessments, and App. A2, Fig. A2.4 the (mean-unbiased) stock-recruitment curves fitted internally, together with the associated "data" for all four assessments. For $M = 0.2$ assessments, higher recruitments tend to occur only for intermediate spawning biomass levels, whereas for M ramp assessments these are absent at the higher spawning biomass levels only, leading to the BH curve estimated hitting an upper bound for the steepness parameter h. These features have an impact on the estimates of the spawning biomass at MSY, which are indicated on each plot as well as reported in App. A2, Tables A2.1 and A2.2.

Diagnostics for the fits of the two Ricker assessments to the abundance indices and catch-at-age and –at-length proportions for commercial catches and surveys (as relevant) are shown in App. A2, Figs A2.5 and A2.6, and Fig. A2.7 shows the retrospective analyses for these two cases.

Preference amongst four final assessments

Some WG members prefer the Ricker to the BH based assessments based on the former's better fits to the "data". This is a reflection of the six or seven points at the highest spawning biomasses in App. A2, Fig. A2.4 which all correspond to the rather low but still reasonably precisely determined recruitments in the 1960s (see App. A2, Fig. A2.2). More quantitatively, Ricker is preferred over BH by 3 log-likelihood points for $M = 0.2$, and by a more substantial 8 points for M ramp (see App. A2, Table A2.1). Of course a continuum is possible across the BH to Ricker shapes and beyond. If the shape parameter γ of the modified Ricker (equation A3.6 of Appendix A3) is estimated, the result is greater than 1 in both cases, suggesting stronger doming than for the classical Ricker form, and increasing the log-likelihood points difference for BH to 5 for $M = 0.2$.

Of the two Ricker assessments, the authors prefer the M ramp case for three reasons:

- the indications from tagging data (see Working Group reports) that M is distinctly larger than 0.2, at least in the 2000s;
- an 11 point improvement in the log-likelihood (see App. A2, Table A2.1), reflecting mainly improved fits to the survey indices of abundance and to the stock-recruitment function; and
- a lesser retrospective pattern (see App. A2, Fig. A2.7).

Relationships to ToR

ToR 5 (relating to assessment results)

The assessment results required are to be found in App. A2, Table A2.1 and Figs A2.1-3 and A2.5-7. No survey catchability q estimate exceeds 1. Model details are provided in Appendix A3.

Historical retrospective results are shown in App. A2, Fig. A2.8. They are referenced by the time at which they were developed, as they don't always correspond to the times of advice given in GARM/SAW exercises, and did not always correspond to the authors' preference at the time. For example the Ricker G option of August 2008 was the final documented "preference" in GARM III, but invoked increasing natural mortality at age rather than domed selectivity in response to the preference of the penultimate GARM panel that year – a preference with which the final GARM panel disagreed. The 2007 and March 2012 assessments estimate domed survey selectivity, but the other two shown force this to be asymptotically flat. There is a notable difference in post-1990 estimated trends between the two earlier and two later assessments in this set of four. The reason relates primarily to a revision of the catch (and discard) inputs with their associated age structure information in the intervening period. The earlier data were statistically incompatible with the joint assumptions of $M = 0.2$ and asymptotically flat survey selectivity. After revision of these data, the evidence against this option became much less clear-cut, and the size of any possible effect on assessment results also much less.

ToRs 6 and 7 (relating to stock status and BRP estimates)

The requisite information here is provided in App. A2, Table A2.2. In terms of the authors' preferred assessment (Ricker and *M* ramp), at present the stock is not overfished and overfishing is not taking place. Estimates of the precision of BRP estimates may be found in App. A2, Table A2.1.

ToR 8 (relating to projections)

Projected catches under a $0.75F_{MSY}$ harvesting strategy are given in App. A2, Table A2.1. These and their implications are discussed further in the main text.

References

Butterworth DS and Rademeyer RA. 2008a. Statistical catch-at-age analysis vs. ADAPT-VPA: the case of Gulf of Maine cod. ICES Journal of Marine Science, 65. pp 1717-1732.

Butterworth DS and Rademeyer RA. 2008b. Further SCAA/ASPM Assessments of Gulf of Maine Cod Including Data for 2007 and Exploring the Impact of Age-Dependence in Natural Mortality. GARM WP 1.Fb. 19pp.

Butterworth DS and Rademeyer RA. 2012. An investigation of differences amongst SCAA and ASAP assessment (including Reference Point) estimates for Gulf of Maine Cod. Document submitted to the March 2012 meeting of the New England Fisheries Management Council SSC . 34pp.

Appendix A.2 Tables

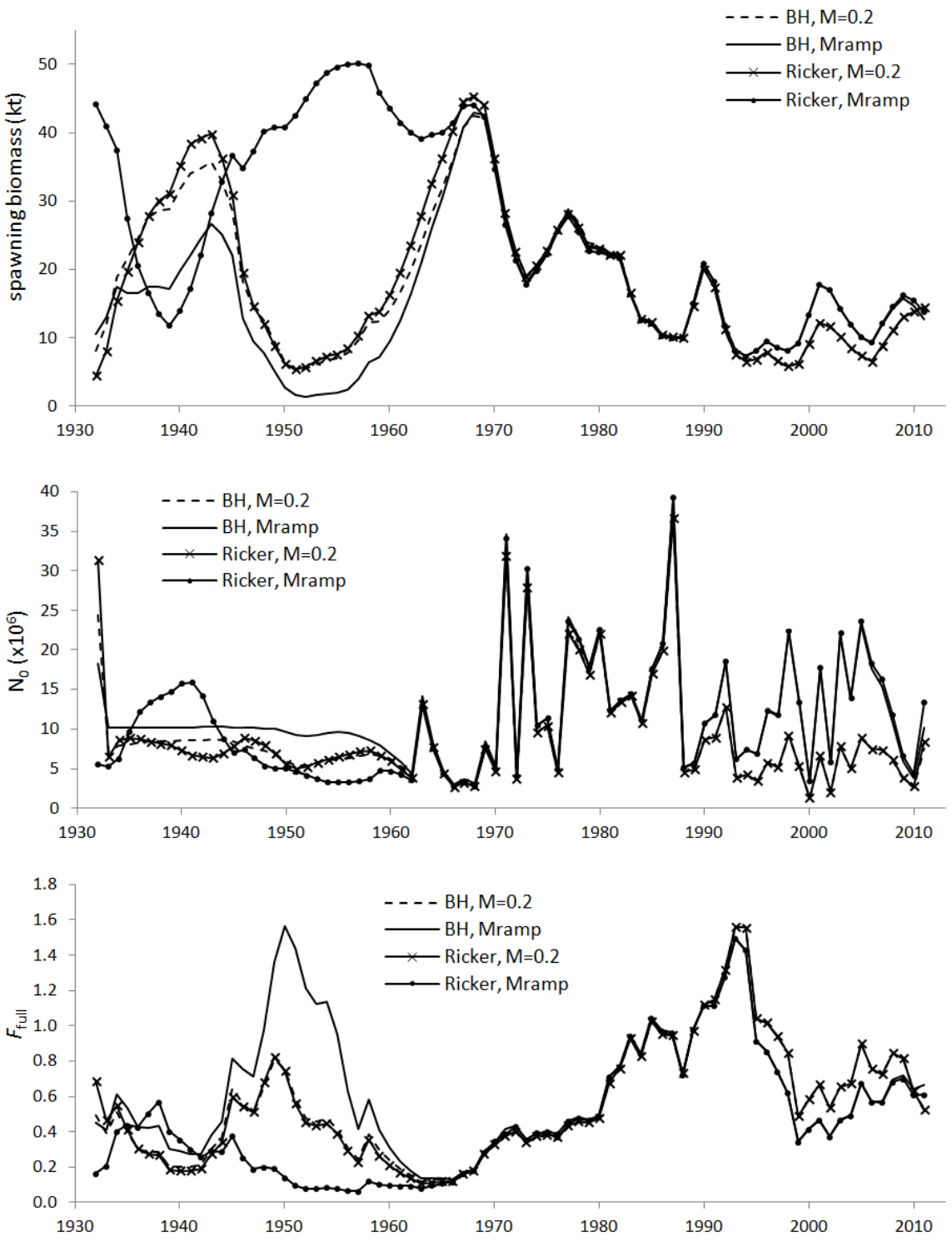
App. A2, Table A2.1: Estimates of abundance, MSY-related biological reference points (BRPs), and related quantities for the Gulf of Maine cod SCAA assessments for all combinations of two assessment factors: the form of the stock-recruitment relationship, and the time dependence of natural mortality *M* (see text for further details). Values in round parentheses are Hessian based CV's, while maximum gradient refers to the quantity reported with the ADMB estimation results. Mass units are '000 tons. *y*1 refers to the start year for the assessment. Recruitment $N_{y1,0}$ is in millions. Refer to Appendix A3 for definitions of some of the symbols used.

	Start year 1932 *M* =0.2				Start year 1932 *M* ramp			
	Ricker		BH		Ricker		BH	
-lnL: overall	-2748		-2745		-2759		-2751	
-lnL: survey	-24.2		-24.1		-29.8		-31.8	
-lnL: comCAA	-786.7		-786.6		-783.4		-783.3	
-lnL: survCAA	-1812.6		-1813		-1812.6		-1812	
-lnL: survCAL	-160.7		-160.2		-161.6		-160.2	
-lnL: RecRes	32.8		35.6		25.0		31.8	
-lnL: Catch	3.4		3.0		3.2		4.0	
Maximum gradient	0.620*		0.172*		0.000		1.544+	
$N_{y1,0}$	31.40	(0.66)	24.42	(341.15)	5.51	(1.39)	18.28	(497.47)
ϕ	0.96	(0.75)	0.72	(383.39)	0.12	(4.13)	0.58	(520.66)
B^{sp}_{2011}	14.51	(0.05)	14.38	(0.05)	13.73	(0.05)	12.74	(0.05)
B^{sp}_{1982}	22.12	(0.17)	22.16	(0.16)	21.55	(0.15)	21.64	(0.14)
B^{sp}_{y1}	4.45	(1.61)	8.12	(740.87)	44.16	(2.32)	10.49	(870.98)
	q	σ_{Add}	q	σ_{Add}	q	σ_{Add}	q	σ_{Add}
NEFSC spring	0.84	0.16	0.84	0.16	0.79	0.11	0.79	0.11
NEFSC fall	0.67	0.10	0.68	0.10	0.64	0.12	0.64	0.11
MADMF spring	0.22	0.30	0.22	0.30	0.15	0.24	0.15	0.24
K	62.32	(0.12)	193.02	(0.22)	29.54	(0.08)	33.97	(0.09)
h	2.62	(0.14)	0.92	(0.06)	1.15	(0.17)	0.98++	(0.00)
MSY	12.84	(0.08)	13.29	(0.18)	7.17	(0.14)	5.51	(0.09)
F_{MSY}	0.75		0.31		0.95		0.95	
B^{sp}_{MSY}	20.91	(0.08)	46.31	(0.18)	11.18	(0.14)	8.57	(0.09)
B^{sp}_{MSY}/K^{sp}	0.34	(0.11)	0.24	(0.05)	0.38	(0.17)	0.25	(0.02)
$B^{sp}_{2011}/B^{sp}_{MSY}$	0.69	(0.08)	0.31	(0.18)	1.23	(0.14)	1.49	(0.09)
Projected catch:								
2013	8.423		3.870		5.803		5.066	
2014	7.621		4.336		4.507		3.847	
2015	8.424		5.229		5.020		4.041	

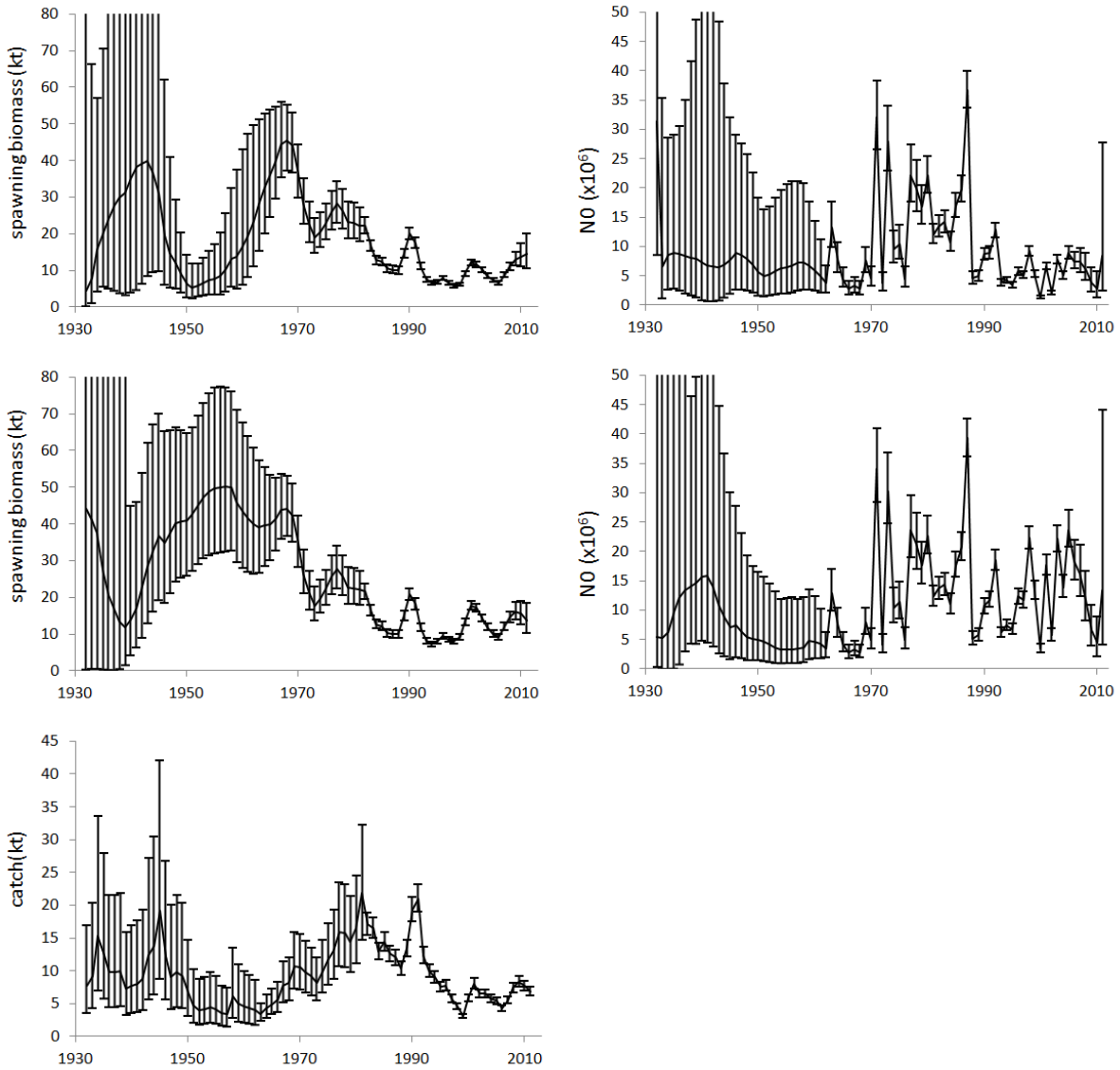
* This occurs for the selectivity parameters for ages 3 and 4 in the Massachusetts survey. The selectivity is constrained not to increase with age, and the estimation in these cases hits this bound. + This occurs for a single selectivity parameter (age 4) for the period 1982-1988 of the commercial selectivity. ++ This steepness estimate is at its upper bound.

App. A2, Table A2.2: Biological Reference Points and current status for four SCAA assessments of Gulf of Maine cod.

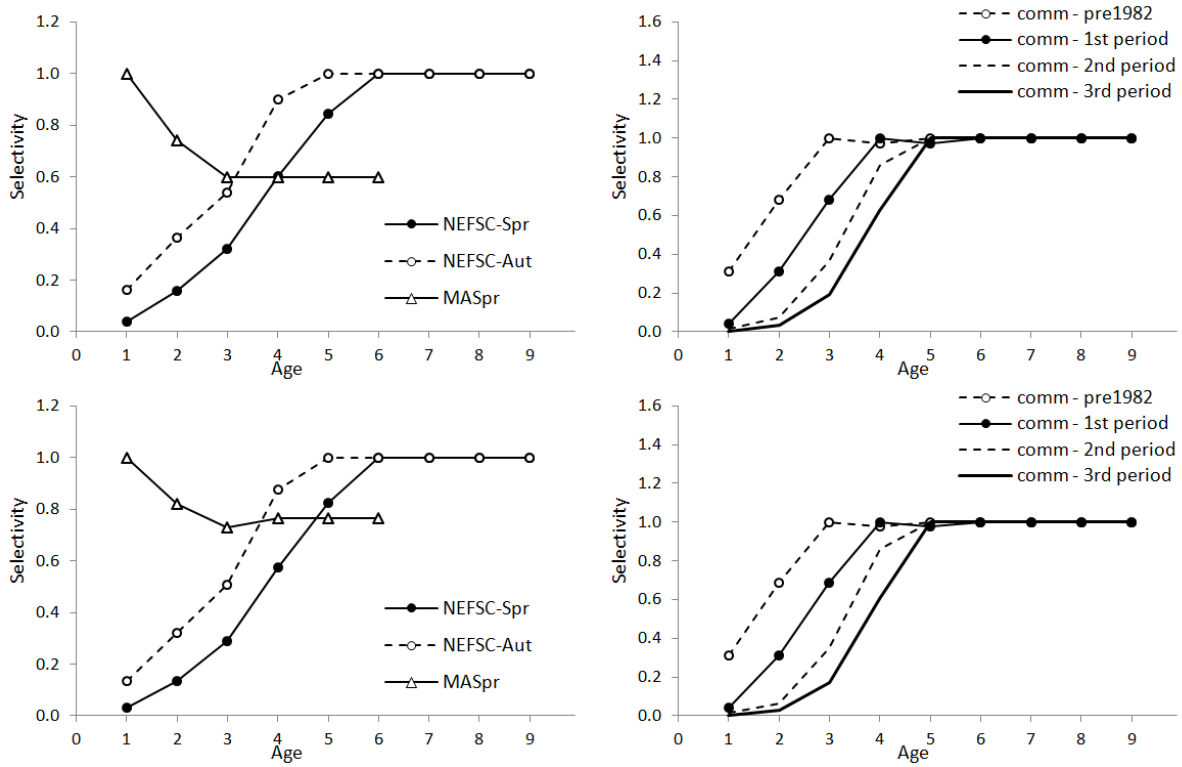
	Start year 1932 M =0.2		Start year 1932 M ramp	
	Ricker	BH	Ricker	BH
B^{sp}_{MSY}	20.91	46.31	11.18	8.57
$1/2\ B^{sp}_{MSY}$	10.45	23.15	5.59	4.29
MSY	12.84	13.29	7.17	5.51
F_{MSY}	0.75	0.31	0.95	0.95
$0.75\ F_{MSY}$	0.56	0.23	0.71	0.71
B^{sp}_{2011}	14.51	14.38	13.73	12.74
F_{2011}	0.52	0.53	0.61	0.66
$B^{sp}_{2011}/(1/2\ B^{sp}_{MSY})$	1.39	0.62	2.46	2.97
F_{2011}/F_{MSY}	0.70	1.73	0.64	0.70
Status	Not overfished No overfishing	Overfished Overfishing	Not overfished No overfishing	Not overfished No overfishing



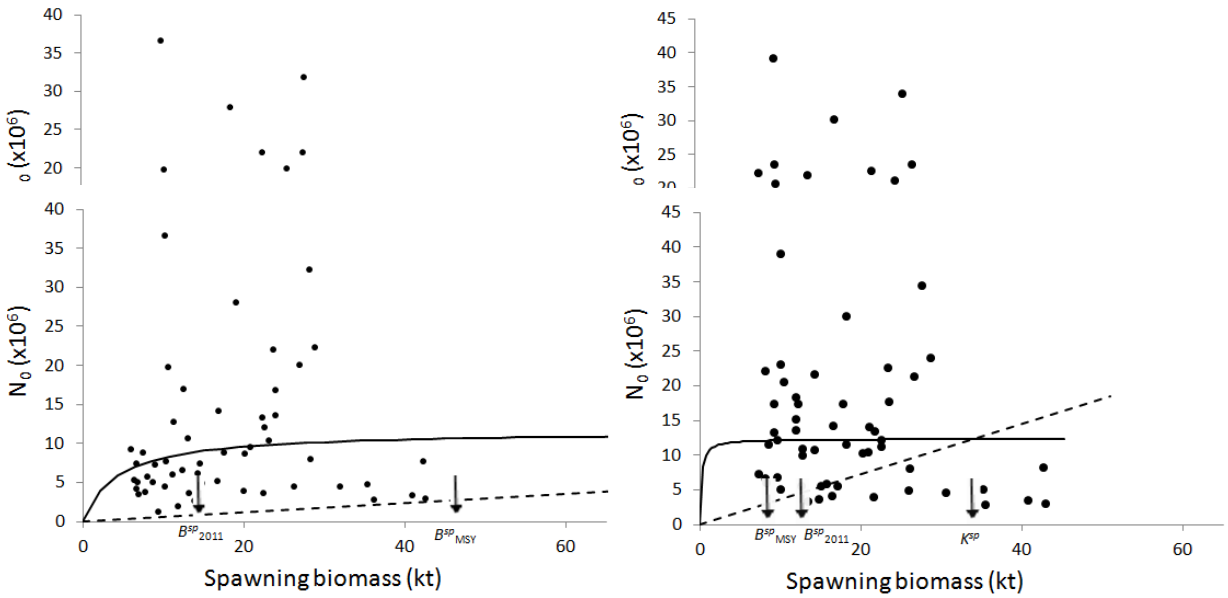
App. A2, Fig. A2.1: Spawning biomass, recruitment (0-year-class strength) and fully selected fishing mortality trajectories for the two Ricker and two Beverton-Holt SCAA assessments.



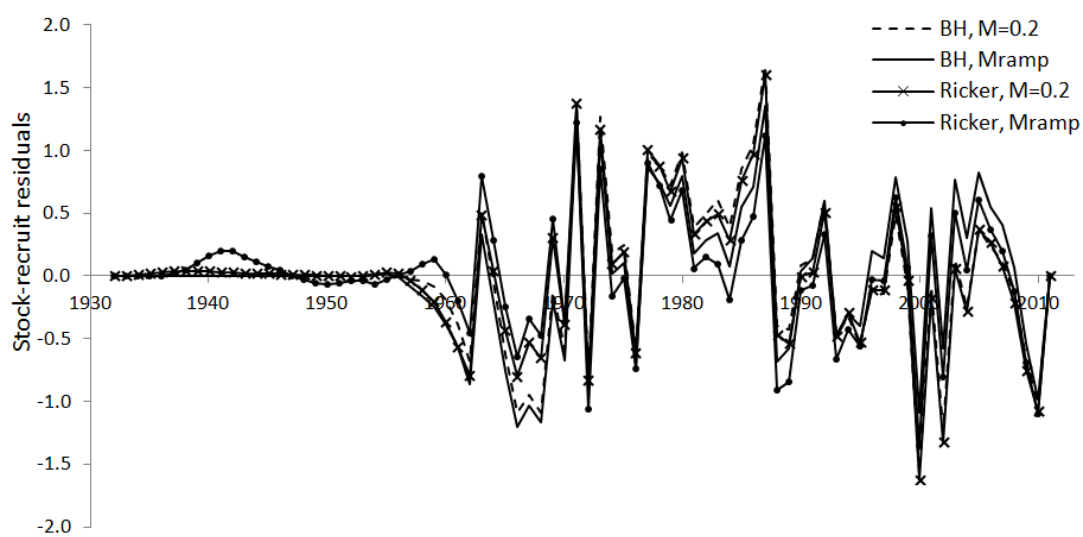
App. A2, Fig. A2.2: Spawning biomass, recruitment and catch trajectories for the Ricker internal assessment, with the start in 1932, and with *M = 0.2* (top row) and *M* ramp (bottom row) with CIs based on Hessian CVs and the assumption of distribution lognormality.



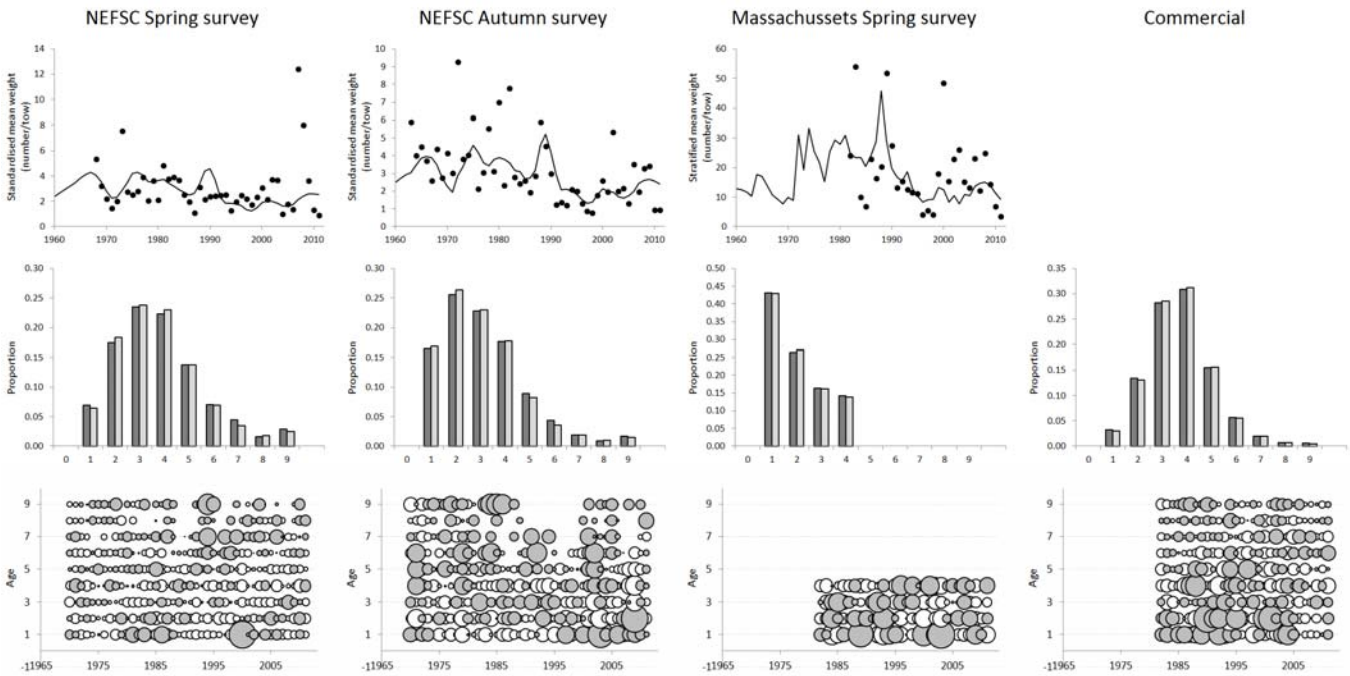
App. A2, Fig. A2.3: Pre-1982 commercial selectivities and the NEFSC survey selectivities for the Ricker internal assessment, with the start in 1932, and with *M = 0.2* (top row) and *M* ramp (bottom row).



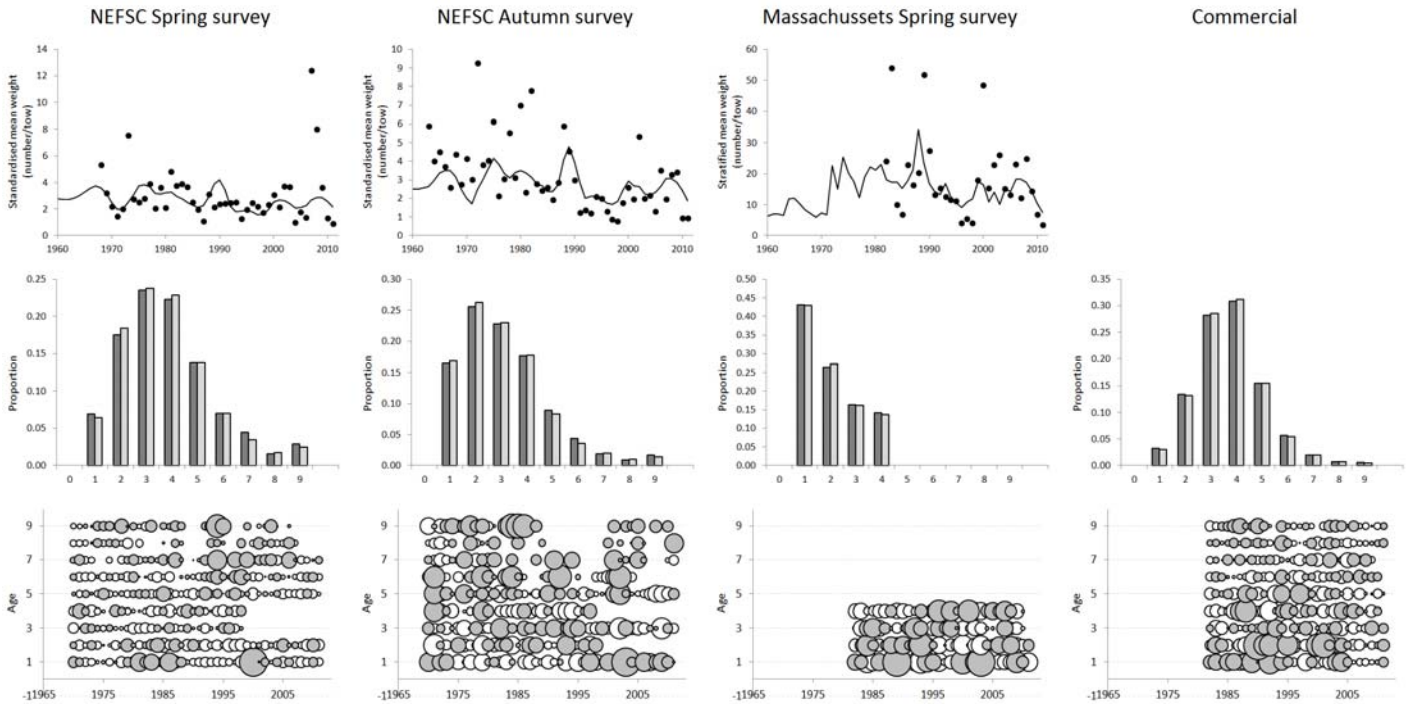
App. A2, Fig. A2.4a: Stock-recruitment curve and estimated recruitment for assessments starting in 1932 for the Ricker internal cases (top row), with *M = 0.2* (left) and *M* ramp (right), and for the Beverton-Holt cases (bottom row), with *M = 0.2* (left) and *M* ramp (right). Only values reasonably informed by the data (from 1960 onwards) are shown. Replacement lines are shown dashed; for the *M* ramp cases these correspond to the current *M* value of 0.4.



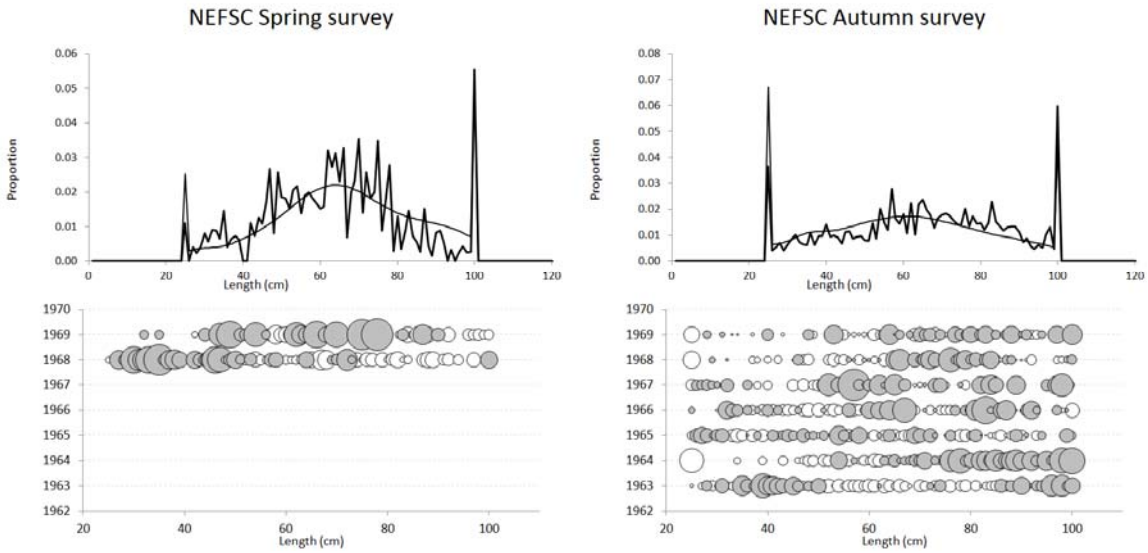
App. A2, Fig. A2.4b: Time series of stock-recruit residuals ς_y (see equation A3.5 of Appendix A3) for the two Ricker and two Beverton-Holt assessments.



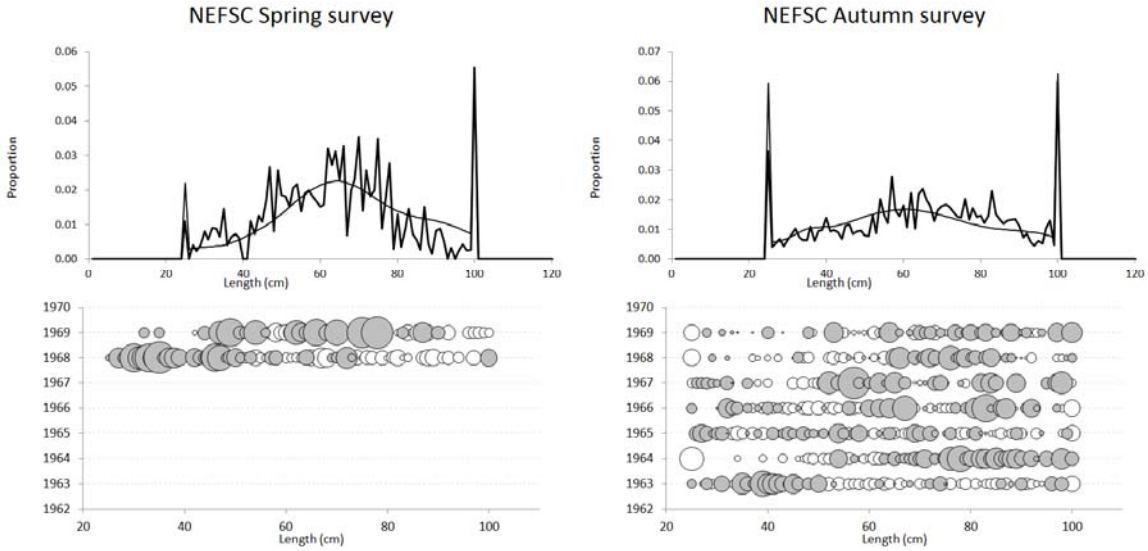
App. A2, Fig. A2.5a: Fits to the abundance indices (top row) and to the survey and commercial catch-at-age data for the Ricker internal assessment, with the start in 1932, and with *M = 0.2*. The second row plots compare the observed and predicted CAA as averaged over all years for which data are available, while the third row plots show the standardised residuals, with the size (area) of the bubbles being proportional to the magnitude of the corresponding standardised residuals. For positive residuals, the bubbles are grey, whereas for negative residuals, the bubbles are white.



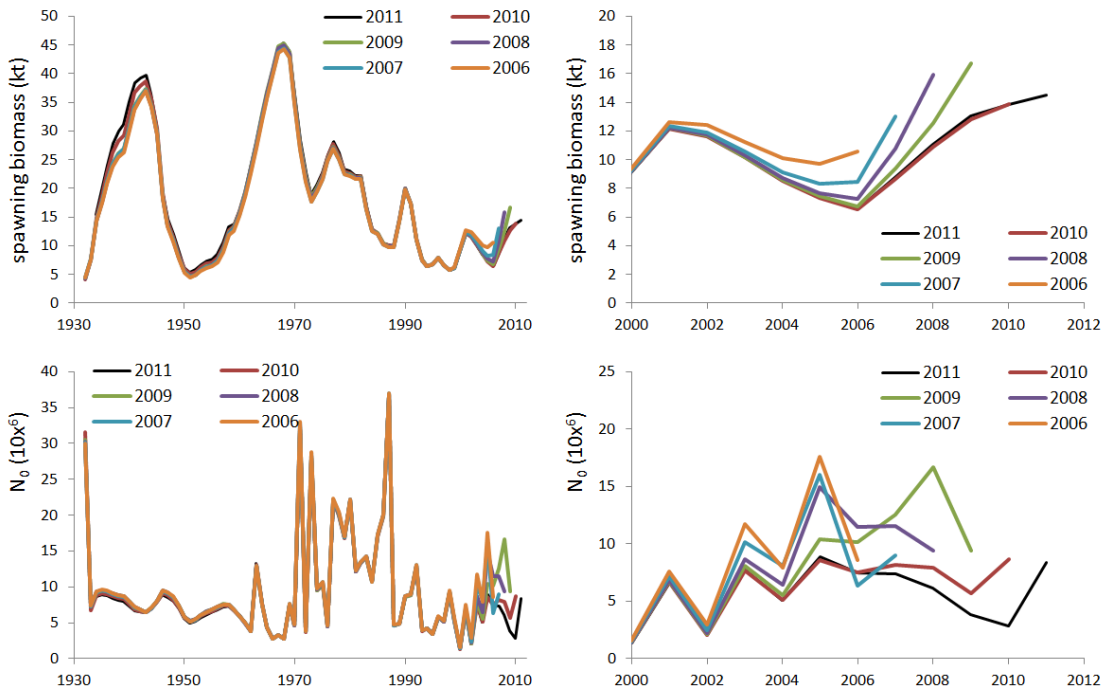
App. A2, Fig. A2.5b: Fits to the abundance indices (top row) and to the survey and commercial catch-at-age data for the Ricker internal assessment, with the start in 1932, and with *M* ramp. The second row plots compare the observed and predicted CAA as averaged over all years for which data are available, while the third row plots show the standardised residuals, with the size (area) of the bubbles being proportional to the magnitude of the corresponding standardised residuals. For positive residuals, the bubbles are grey, whereas for negative residuals, the bubbles are white.



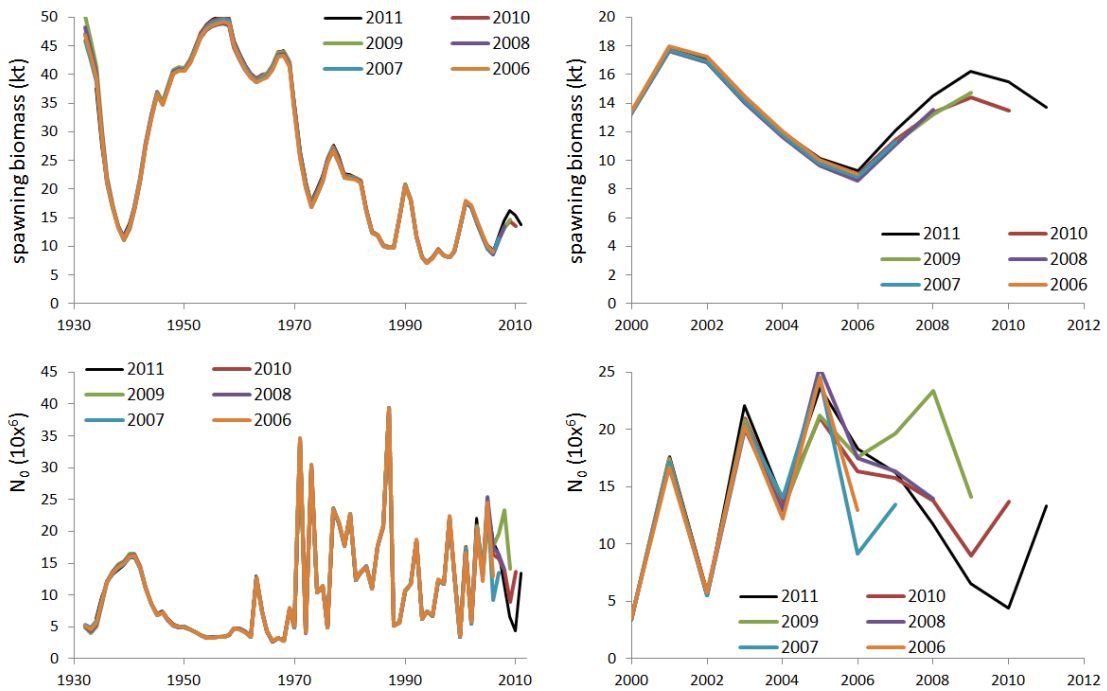
App. A2, Fig. A2.6a: Fits to the survey catch-at-length data for the Ricker internal assessment, with the start in 1932, and with *M* =0.2. The first row plots compare the observed and predicted CAL as averaged over all years for which data are available (the spikes correspond to minus and plus groups), while the third row plots show the standardised residuals, with the size (area) of the bubbles being proportional to the magnitude of the corresponding standardised residuals. For positive residuals, the bubbles are grey, whereas for negative residuals, the bubbles are white.



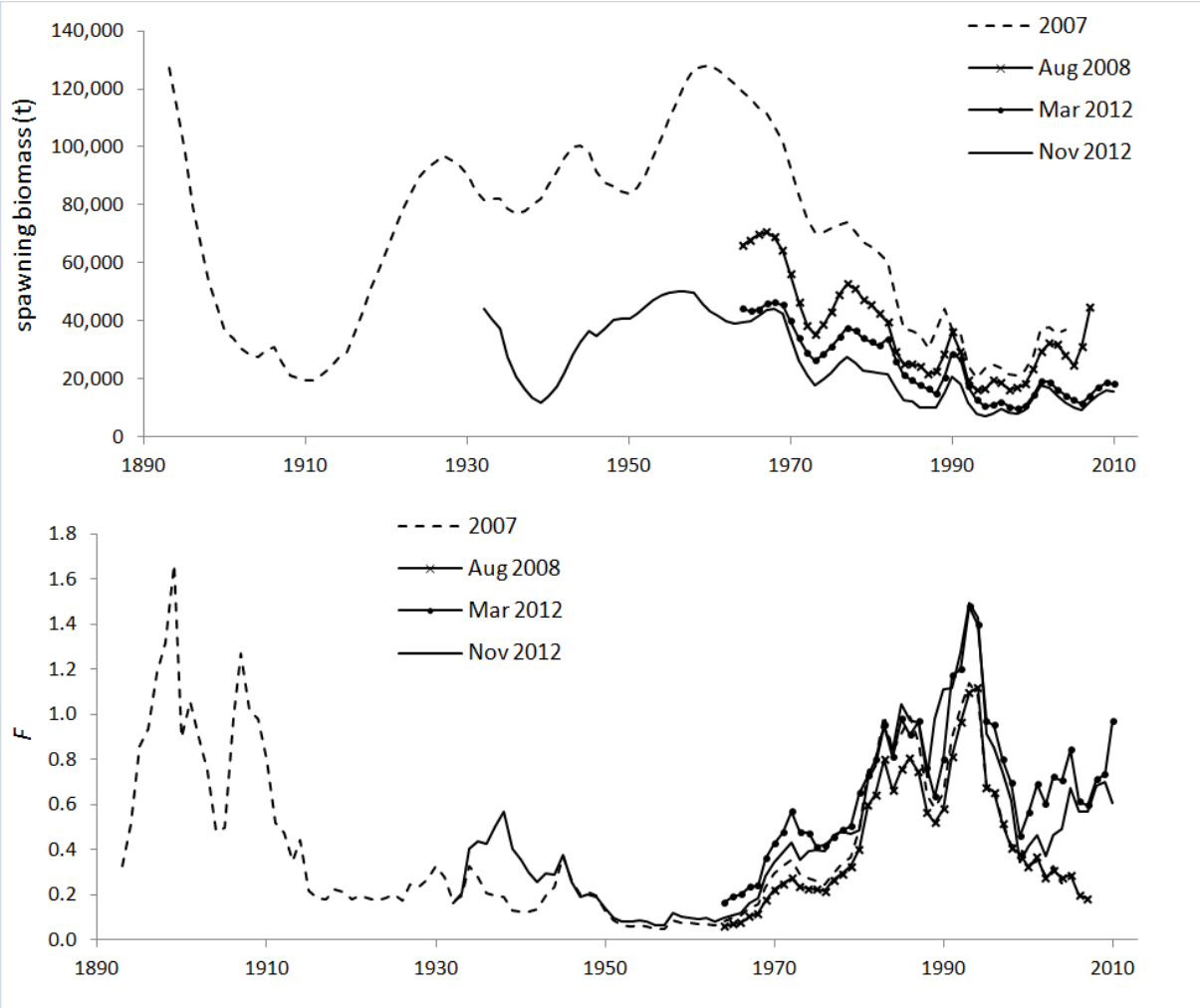
App. A2, Fig. A2.6b: Fits to the survey catch-at-length data for the Ricker internal assessment, with the start in 1932, and with *M* ramp. The first row plots compare the observed and predicted CAL as averaged over all years for which data are available (the spikes correspond to minus and plus groups), while the third row plots show the standardised residuals, with the size (area) of the bubbles being proportional to the magnitude of the corresponding standardised residuals. For positive residuals, the bubbles are grey, whereas for negative residuals, the bubbles are white.



App. A2, Fig. A2.7a: Retrospective analysis for the Ricker internal assessment, with the start in 1932 and *M = 0.2*.



App. A2, Fig. A2.7b: Retrospective analysis for the Ricker internal assessment, with the start 1932 and *M* ramp.



App. A2, Fig. A2.8: Comparison of spawning biomass and fishing mortality trajectories from previous SCAA assessment of Gulf of Maine cod, including "2007" (Reference Case of Butterworth and Rademeyer, 2008a), "Aug 2008" (Ricker G of Butterworth and Rademeyer, 2008b), "Mar 2012" (NBC2 of Butterworth and Rademeyer, 2012) and "Nov 2012" (Ricker, *M* ramp, this analysis). The fishing mortality shown is the fully selected fishing mortality, but this corresponds to different ages for the different assessments: ages 5 for "2007", 5 for "Aug 2008", 4 (pre 1991) or 5 (post 1990) for "Mar 2012" and 6+ for "Nov 2012". The fishing mortality plot for "2007" after 1995 is virtually identical to that for "Aug 2008", and hence is not readily evident over that period in the plot.

[SAW55 Editor's Note: The SARC-55 review panel <u>did not recommend</u> adopting the GOM cod Statistical Catch-at-Age (SCAA) assessment results that are in Appendices A.2 – A.5. These appendices are included in this report to document and demonstrate the work that was done by the SAW cod Working Group for the December 2012 peer review.]

Appendix A.3. Algebraic details of the Statistical Catch-at-Age Model.

The text following sets out the equations and other general specifications of the Statistical Catch-at-Age (SCAA) assessment model applied to Gulf of Maine cod, 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 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).

Where options are provided under a particular section, the section concludes with a statement in **bold** as to which option was selected for the final assessment run selected.

A3.1. Population dynamics

A3.1.1 Numbers-at-age

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

$$N_{y+1,0} = R_{y+1} \tag{A3.1}$$

$$N_{y+1,a+1} = N_{y,a} e^{-Z_{y,a}} \qquad \text{for } 0 \le a \le M-2 \tag{A3.2}$$

$$N_{y+1,m} = N_{y,m-1} e^{-Z_{y,m-1}} + N_{y,m} e^{-Z_{y,m}} \tag{A3.3}$$

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 0-year-old fish) at the start of year y,

m is the maximum age considered (taken to be a plus-group).

$Z_{y,a} = F_y S_{y,a} + M_a$ 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.

Note that for the "M ramp" scenario for which M increases linearly from 0.2 to 0.4 over

the period from 1988 to 2003, M is year dependent but this complication is omitted from the equations above to avoid clutter.

A3.1.2. Recruitment

The number of recruits (i.e. new 0-year old) at the start of year y is assumed to be related to the spawning stock size (i.e. the biomass of mature fish) by either a modified Ricker or a standard or adjusted Beverton-Holt stock-recruitment relationship, allowing for annual fluctuation about the deterministic relationship.

For the modified Ricker:

$$R_y = \alpha B_y^{\mathrm{sp}} \exp\left[-\beta\left(B_y^{\mathrm{sp}}\right)^{\gamma}\right] e^{(\varsigma_y - (\sigma_{\mathrm{R}})^2/2)} \tag{A3.4}$$

for the (standard) Beverton-Holt:

$$R_y = \frac{\alpha B_y^{sp}}{\beta + B_y^{sp}} e^{(\varsigma_y - (\sigma_{\mathrm{R}})^2/2)} \tag{A3.5}$$

and for the adjusted Beverton-Holt:

$$R_y = \begin{cases} \dfrac{\alpha B_y^{sp}}{\beta + B_y^{sp}} & \text{if } B_y^{sp} \le B^* \\ \dfrac{\alpha B^*}{\beta + B^*} \exp\left(-\left(\dfrac{B_y^{sp} - B^*}{\sigma_N}\right)^2\right) & \text{if } B_y^{sp} > B^* \end{cases} \tag{A3.6}$$

where

α, β, γ, $B^*$and σ_N are spawning biomass-recruitment relationship parameters,

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

B_y^{sp} is the spawning biomass at the start of year y, computed as:

$$B_y^{\mathrm{sp}} = \sum_{a=1}^{m} f_a w_{y,a}^{\mathrm{strt}} N_{y,a} e^{-Z_{y,a}/4} \tag{A3.7}$$

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

where

$w_{y,a}^{\mathrm{strt}}$ is the mass of fish of age a during spawning, and

f_a is the proportion of fish of age a that are mature.

Section *A3.2.6* details the procedure adopted when recruitment is not assumed to be related to spawning biomass , at least internal to the assessment.

For the final run, the modified Ricker, with γ fixed to 1, has been used, i.e. the classical Ricker function.

A3.1.3. Total catch and catches-at-age

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

$$C_y = \sum_{a=1}^{m} w_{y,a}^{\text{mid}}\, C_{y,a} = \sum_{a=1}^{m} w_{y,a}^{\text{mid}}\, N_{y,a}\;\; S_{y,a}\, F_y \left(1 - e^{-Z_{y,a}}\right) \Big/ Z_{y,a} \qquad \text{(A3.8)}$$

where

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

$C_{y,a}$ 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:

$$B_y^{\text{surv}} = \sum_{a=1}^{m} w_{y,a}^{\text{surv}} S_a^{\text{surv}} N_{y,a} e^{-Z_{y,a} T^{surv}/12} \qquad \text{(A3.9)}$$

for biomass indices and

$$N_y^{\text{surv}} = \sum_{a=1}^{m} S_a^{\text{surv}} N_{y,a} e^{-Z_{y,a} T^{surv}/12} \qquad \text{(A3.10)}$$

for numbers indices

where

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

T^{surv} is the season in which the survey is taking place (T^{surv}=1 for spring surveys and T^{surv}=3 for fall surveys), and

$w_{y,a}^{surv}$ denotes the mass of fish of age a from survey *surv* year y.

For the Massachusetts spring survey, the summation is taken from age 1 to age 6.

The final run is fitted to numbers indices.

A3.1.4. Initial conditions

For the first year (y_0) considered in the model, the numbers-at-age are estimated directly for ages 0 to a^{est}, with a parameter ϕ mimicking recent average fishing mortality for ages above a^{est}, i.e.

$$N_{y_0,a} = N_{\text{start},a} \qquad \text{for } 0 \le a \le a^{est} \qquad \text{(A3.11)}$$

and

$$N_{\text{start},a} = N_{\text{start},a-1} e^{-M_{a-1}} (1 - \phi S_{a-1}) \qquad \text{for } a^{est} < a \le m-1 \qquad \text{(A3.12)}$$

$$N_{\text{start},m} = N_{\text{start},m-1} e^{-M_{m-1}} (1 - \phi S_{m-1}) \Big/ (1 - e^{-M_m} (1 - \phi S_m)) \qquad \text{(A3.13)}$$

For the final run which starts in 1932 only the number for age 0 is estimated, with equation A3.12 applying from age 1.

A3 B.2. The (penalised) likelihood function

The model can be fit to (a subset of) CPUE and survey abundance indices, and commercial and survey catch-at-age and catch-at-length 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 ($-\ell nL$) are as follows. Details related to fitting to CPUE series are not included below, as such series are not considered in the analyses of this paper.

A3.2.1. Survey abundance data

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

$$I_y^{surv} = \hat{I}_y^{surv} \exp\left(\varepsilon_y^{surv}\right) \quad \text{or} \quad \varepsilon_y^{surv} = \ell n\left(I_y^{surv}\right) - \ell n\left(\hat{I}_y^{surv}\right) \tag{A3.14}$$

where

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

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

$\hat{q}^{surv}$ is the constant of proportionality (catchability) for the survey biomass 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:

$$-\ell n\, L^{\text{survey}} = \sum_{surv}\sum_{y}\left\{\ell n\left(\sqrt{\left(\sigma_y^{surv}\right)^2 + \left(\sigma_{Add}^{surv}\right)^2}\right) + \left(\varepsilon_y^{surv}\right)^2 / \left[2\left(\left(\sigma_y^{surv}\right)^2 + \left(\sigma_{Add}^{surv}\right)^2\right)\right]\right\} \tag{A3.15}$$

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:

$$\ell n\, \hat{q}^{surv} = 1/n_{surv} \sum_{y}\left(\ln I_y^{surv} - \ln \hat{B}_y^{surv}\right) \tag{A3.16}$$

A3.2.3. Commercial catches-at-age

The contribution of the catch-at-age data to the negative of the log-likelihood function under the assumption of an "adjusted" lognormal error distribution is given by:

$$-\ell n\, L^{\text{CAA}} = \sum_{y}\sum_{a}\left[\ell n\left(\sigma_a^{com} / \sqrt{p_{y,a}}\right) + p_{y,a}\left(\ell n\, p_{y,a} - \ell n\, \hat{p}_{y,a}\right)^2 / 2\left(\sigma_a^{com}\right)^2\right] \tag{A3.17}$$

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

$$\hat{C}_{y,a} = N_{y,a} \; S_{y,a} F_y \left(1 - e^{-Z_{y,a}}\right) / Z_{y,a} \qquad \text{(A3.18)}$$

and

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

$$\hat{\sigma}_a^{com} = \sqrt{\sum_y p_{y,a} \left(\ell n \, p_{y,a} - \ell n \, \hat{p}_{y,a}\right)^2 / \sum_y 1} \qquad \text{(A3.19)}$$

Evaluations in Butterworth and Rademeyer (2012) demonstrated the need for allowing for age dependence in σ_a^{com}.

Commercial catches-at-age are incorporated in the likelihood function using equation (A3.17), for which the summation over age a is taken from age a_{minus} (considered as a minus group) to a_{plus} (a plus group).

In application of this approach ages are often aggregated to avoid values of $p_{y,a}$ or $\hat{p}_{y,a}$ that are too small in the interests of estimation robustness. In this paper individual ages have been maintained between the selected minus and plus-groups to provide potential discrimination of different shapes for the selectivity functions at older ages in particular. This however does mean that there are certain cells for which $p_{y,a}$ values are zero. That does not cause any problems because the limit of $p_{y,a}\left(\ln p_{y,a}\right)^2$ as $p_{y,a} \to 0$ is 0, so these terms can be omitted from the summation in equation B17. One could argue that they should nevertheless be included in the summations in equation B18, but exclusion seems more appropriate as the structural zero contributions then included would seem likely to bias the estimates of $\hat{\sigma}_a^{com}$ downwards.

In addition to this "adjusted" lognormal error distribution, some computations use an alternative "sqrt(p)" formulation, for which equation A3.20 is modified to:

$$-\ell \text{n} \, L^{\text{CAA}} = \sum_y \sum_a \left[\ell n\left(\sigma_a^{com}\right) + \left(\sqrt{p_{y,a}} - \sqrt{\hat{p}_{y,a}}\right)^2 / 2\left(\sigma_a^{\text{com}}\right)^2 \right] \qquad \text{(A3.21)}$$

and equation B21 is adjusted similarly:

$$\hat{\sigma}_a^{com} = \sqrt{\sum_y \left(\sqrt{p_{y,a}} - \sqrt{\hat{p}_{y,a}}\right)^2 / \sum_y 1} \qquad \text{(A3.22)}$$

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

The final run uses "sqrt(p)" formulation for the error distribution of the commercial catches-at-age, survey catches-at-age and survey catches-at-length.

A3.2.4. 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, assuming an "adjusted" lognormal error distribution (equation (A19)) 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:

$$\hat{p}_{y,a}^{surv} = S_a^{\text{surv}} N_{y,a} e^{-Z_{y,a} T^{surv}/12} \Big/ \sum_{a'=1}^{m} S_{a'}^{\text{surv}} N_{y,a'} e^{-Z_{y,a'} T^{surv}/12} \quad . \tag{A3.23}$$

For the Massachusetts spring survey, the summation is taken from age 1 to age 6.

A3.2.5. Survey catches-at-length

In some runs, catches-at-length are also incorporated in the likelihood function. These data are incorporated in the similar manner as the catches-at-age. When the model is fit to catches-at-length, the predicted catches-at-age are converted to catches-at-length:

$$\hat{p}_{y,l}^{surv} = \sum_a \hat{p}_{y,a}^{surv} A_{a,l}^{strt} \tag{A3.24}$$

for the spring survey, and

$$\hat{p}_{y,l}^{surv} = \sum_a \hat{p}_{y,a}^{surv} A_{a,l}^{mid} \tag{A3.25}$$

for the fall survey,

where $A_{a,l}^{strt}$ and $A_{a,l}^{mid}$ are the proportions of fish of age *a* that fall in the length group *l* (i.e., $\sum_l A_{a,l}^{strt} = 1$ and $\sum_l A_{a,l}^{mid} = 1$ for all ages) at the beginning of the year and at the middle of the year respectively.

The matrices $A_{a,l}^{strt}$ and $A_{a,l}^{mid}$ are calculated under the assumption that length-at-age is normally distributed about a mean given by the von Bertalanffy equation, i.e.:

$$L_a^{strt} \sim N\left[L_\infty\left(1 - e^{-\kappa(a-t_o)}\right), \left(\theta_a^{strt}\right)^2\right] \tag{A3.26}$$

for the spring survey and

$$L_a^{mid} \sim N\left[L_\infty\left(1 - e^{-\kappa(a+0.5-t_o)}\right), \left(\theta_a^{mid}\right)^2\right] \tag{A3.27}$$

for the fall survey,

where

θ_a^{strt} and θ_a^{mid} are the standard deviation of begin and mid-year length-at-age *a* respectively, which are modelled to be proportional to the expected length-at-age *a*, i.e.:

$$\theta_a^{strt} = \beta\left[L_\infty\left(1 - e^{-\kappa(a-t_o)}\right)\right]^\gamma \tag{A3.28}$$

and

$$\theta_a^{mid} = \beta\left[L_\infty\left(1 - e^{-\kappa(a+0.5-t_o)}\right)\right]^\gamma \tag{A3.29}$$

with β an estimable parameter and $\gamma = 0.5$ (a value which was found to lead to reasonable fits to the data).

$L_\infty = 150.93\,cm$,
$\kappa = 0.11\,yr^{-1}$,
$t_o = 0.13\,yr$,

The following term is then added to the negative log-likelihood:

$$-\ell n\, L^{\mathrm{CAL}} = w_{len} \sum_{surv} \sum_{y} \sum_{l} \left[\ell n \left(\sigma_{\mathrm{len}}^{surv} / \sqrt{p_{y,l}^{surv}} \right) + p_{y,l}^{surv} \left(\ell n\, p_{y,l}^{surv} - \ell n\, \hat{p}_{y,l}^{surv} \right)^2 / 2 \left(\sigma_{\mathrm{len}}^{surv} \right)^2 \right] \quad \text{(A3.30)}$$

The w_{len} weighting factor may be set to a value less than 1 to downweight the contribution of the catch-at-length data (which tend to be positively correlated between adjacent length groups because the length distributions for adjacent ages overlap) to the overall negative log-likelihood compared to that of the CPUE data. The value used for w_{len} is 0.1, being roughly equivalent to the ratio of the number to length groups to the number of age groups considered. Instances of observed proportions of zero are dealt with in the same manner as for catches-at-age, as is the alternative "sqrt(p)" error distribution formulation.

The final run incorporates these catch-at-length data and uses the "sqrt(p)" formulation.

A3.2.6. 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:

$$-\ell n L^{\mathrm{pen}} = \sum_{y=y_1+1}^{y_2} \left[\varepsilon_y^2 / 2\sigma_{\mathrm{R}}^2 \right] \quad \text{(A31)}$$

where

ε_y from $N\left(0, (\sigma_R)^2\right)$,

σ_{R} is the standard deviation of the log-residuals, which is input.

Equation A3.31 is used when the stock-recruitment curve is estimated internally. In some analyses reported in this paper where BRP estimates are based on stock-recruitment curves estimated "externally" using the assessment outputs,, this "stock-recruitment" term is included for the last two years only, simply to stabilise these estimates which are not well determined by the other data. In these cases, the ε_y are calculated as the deviations from the mean log recruitment for the ten preceding years, i.e. recruitment estimates for 2010 and 2011 are shrunk towards the geometric mean recruitment over the preceding decade.

A3.2.7. Catches

$$-\ell n L^{\mathrm{Catch}} = \sum_{y} \left[\frac{\ell n\, C_y - \ell n\, \hat{C}_y}{2\sigma_{\mathrm{C}}^2} \right] \quad \text{(A3.32)}$$

where

C_y is the observed catch in year *y*,

$\hat{C}_y$ is the predicted catch in year *y* (equation A3.8), and

σ_C is the CV input: 0.4 for pre-1964 catches, 0.2 for catches between 1964 and 1981 and 0.05 for catches from 1982 onwards.

A3.2.8 Incorporation of Bigelow vs Albatross survey calibration

The survey data provided are adjusted for the years 2009 to 2012 which were obtained from *Bigelow* surveys have been adjusted to "*Albatross* equivalents" through use of calibration factors estimated independently from paired tow experiments (Miller *et al*., 2010). However the survey data before and after the switch of vessels also provide information on the calibration factors because they sample the same cohorts. Incorporation of this information in assessments in this paper has been effected by treating the estimates, with their variance-covariance matrix, as a form of "joint-prior" which is effectively updated in the penalised likelihood estimation when fitting the model. The process is as follows.
First *Bigelow* length frequency distributions are converted to *Albatross* equivalent length frequency distributions:

$$C_{y,l}^{surv,A} = C_{y,l}^{surv,B} \big/ F_l \qquad \text{(A3.33)}$$

where

$C_{y,l}^{surv,B}$ is the measured catch-at-length for the *Bigelow* in year *y* for survey *surv,*

$C_{y,l}^{surv,A}$ is the inferred catch-at-length for the *Albatross* equivalent in year *y* for survey *surv,*

F_l is the length-based calibration factor (*Bigelow/Albatross*),

The *Albatross* equivalent length distributions are then converted to age distributions:

$$C_{y,a}^{surv,A} = \sum_l C_{y,l}^{surv,A} ALK_{y,a,l}^{surv} \qquad \text{(A3.34)}$$

where

$ALK_{y,a,l}^{surv}$ is the age-length key (proportion of fish of length *l* that have age *a*) in year *y* for survey *surv.*

Indices are then obtained from the *Albatross* equivalent age distributions as follows:

$$I_y^{surv,A} = \sum_a C_{y,a}^{surv,A} w_{y,a}^{surv} \qquad \text{(A3.35)}$$

for biomass indices and

$$I_y^{surv,A} = \sum_a C_{y,a}^{surv,A} \qquad \text{(A3.36)}$$

for numbers indices,
where

$w_{y,a}^{surv}$ is the weight-at-age in year *y* for survey *surv*.

The calibration factor has four parameters, three of which are estimable and the other input: X_1=20cm, X_2, F_1 and F_2

$$F_l = \begin{cases} F_1 & \text{if } l \le X_1 \\ \dfrac{(F_2 - F_1)}{(X_2 - X_1)} l + \dfrac{(F_1 X_2 - F_2 X_1)}{(X_2 - X_1)} & \text{if } X1 < l < X_2 \\ F_2 & \text{if } l \ge X_2 \end{cases} \qquad \text{(A3.37)}$$

The following contribution is therefore added to the negative log-likelihood in the assessment:

$$-\ln L^{calib} = \frac{1}{2}\ln|\mathbf{\Sigma}| + \frac{1}{2}(\mathbf{x} - \boldsymbol{\mu})^{\mathrm{T}} \mathbf{\Sigma}^{-1}(\mathbf{x} - \boldsymbol{\mu}) \qquad \text{(A3.38)}$$

where the parameters X_2, F_1 and F_2 are components of the vector $\boldsymbol{x}$,
$\mathbf{\Sigma}$ is the variance covariance matrix as estimated by Miller *et al.* (2010), and
$\boldsymbol{\mu}$ is a vector which contains the Miller *et al.* (2010) estimates of the parameters.
These estimates and the variance-covariance matrix are given in table A3.1 below:

In the final run, the calibration parameters are fixed to those estimated by Miller *et al.* (2010).

App. A3, Table A3.1: Estimates and variance-covariance matrix for the calibration parameters (Miller, pers. commn).

μ	$ln(F_2)$	$ln(F_1-F_2)$	$ln(X_2-X_1)$
	0.4713	1.4163	3.5086
Σ	$ln(F_2)$	$ln(F_1-F_2)$	$ln(X_2-X_1)$
$ln(F_2)$	0.006674	-0.002515	-0.002559
$ln(F_1-F_2)$	-0.002515	0.051592	-0.007601
$ln(X_2-X_1)$	-0.002559	-0.007601	0.006757

A3.3. Estimation of precision

Where quoted, CV's or 95% probability interval estimates are based on the Hessian.

A3.4. Model parameters

A3.4.1. Fishing selectivity-at-age:

For the NEFSC offshore surveys, the fishing selectivities are estimated separately for ages 1 to age 6 and are flat thereafter. For the Massachusetts inshore spring survey, the selectivities are estimated separately for ages 1 to 4. The estimated proportional decrease from ages 3 to 4 is assumed to continue multiplicatively to age 6; this decrease parameter is bounded by 0, i.e. no increase is permitted. For all three surveys, age 0 is not considered.

The commercial fishing selectivity, S_a, is estimated separately for ages a_{minus} to a_{plus} (1 to 9) It is taken to differ over four periods: a) pre-1982, b) 1982-1988, c)1989-2004, and d) 2005-present. The selectivities are estimated directly for the last three periods. For the pre-1982 period, the selectivity is taken as that for the 1989-1988 block, but shifted one year to the left. For the implementations in this paper, given that there were difficulties with imprecise estimates at larger ages for period d) given its shortness, a common selectivity at age was estimated across all periods for ages 7 and above.

In the final run, the commercial fishing selectivities are taken to be flat from age 5 onwards.

A3.4.2. Other parameters

Model plus group			
m	9		
Commercial CAA			
a_{minus}*	1		
a_{plus}	9		
Survey CAA	NEFSC spr	NEFSC fall	MASS spr
a_{minus}*	1	1	1
a_{plus}	9	9	4
Natural mortality:			
M	Age independent: i) 0.2 for all years ii) 0.2 until 1988, thereafter a linear increase to 0.4 in 2003 and constant at 0.4 thereafter		
Proportion mature-at-age:			
f_a	Input, see main text		
Weight-at-age:			
$w_{y,a}^{strt}$	input, see main text		
$w_{y,a}^{mid}$	input, see main text		
$w_{y,a}^{surv}$	input, see main text		
Stock recruit residuals std dev:			
σ_R	0.6		
Initial conditions :			
$N_{y0,a}$	estimated directly for ages 0 to xx depending on AIC criterion		
ϕ	estimated		

* Strictly not a minus group anymore since the catches at age zero are ignored.

A3.5.Biological Reference Points (BRPs)

It is possible to estimate BRPs internally within the assessment by fitting the stock-recruitment relationship directly within the assessment itself. The F_{MSY} estimate is obtained by using a bisection routine to find where the derivative of the equilibrium catch vs F relationship has a zero derivative. This has to be based on point estimates, so that the estimate of other BRPs are conditional on this point estimate of F_{MSY}, with no Hessian based CV available for this quantity.

For some results reported here, however, the stock-recruitment relationships are fitted to the estimates of recruitment and spawning biomass provided by the various assessments to provide a basis to estimate BRPs. The rationale for estimation external to the assessment itself is to avoid assumptions about the form of the relationship influencing the assessment results. These fits are achieved by minimising the following negative log-likelihood, where the $e^{-\frac{\sigma_R^2}{2}}$ term is added for consistency with equation A3.4, i.e. the stock-recruitment curves estimated are mean-unbiased rather than median unbiased:

$$-\ln L = \sum_{y=y1}^{2009} \left[\frac{\left(\ln(N_{y,0}) - \ln\left(\hat{N}_{y,0} e^{-\frac{\sigma_R^2}{2}} \right) \right)^2}{2\left((\sigma_R)^2 + (CV_y)^2 \right)} \right] \qquad \text{(A3.39)}$$

where

$N_{y,0}$ is the "observed" (assessment estimated) recruitment in year *y*,

$\hat{N}_{y,0}$ is the stock-recruitment model predicted recruitment in year *y*,

σ_R is the standard deviation of the log-residuals which is input (and set here to 0.6), and

CV_y is the Hessian-based CV for the "observed" recruitment in year *y*.

Note that the differential precision of the assessment estimates of recruitment is taken into account, and that the summation ends at 2009 because little by way of direct observation is as yet available to inform estimates of recruitment for 2010 and 2011.

For the final run, the stock-recruitment relationship and hence also the BRP's are estimated internally in the model fitting minimisation process.

A3.6. Projections

The first step in the projections process is generating a future catch vector corresponding to a harvesting strategy, with $0.75F_{MSY}$ being the strategy chosen for this purpose, where this corresponds to a fishing mortality vector with a maximum *F* of $0.75F_{MSY}$ and a selectivity-at-age equal to that estimated for the most recent commercial block (2005-2011).

The starting numbers at age vector for ages 0 to 9+ is the best estimate obtained from the assessment for the start of the year 2012. Error is included for ages 0 to 3 because these are poorly estimated in the assessment given limited information on these year-classes; thus: $N_{2012,a} \rightarrow N_{2012,a} e^{\varepsilon_a}$ with ε_a from $N\left(0,(\sigma_R)^2\right)$. For subsequent years, age-0 recruitment is determined by the stock-recruitment relationship of equation (A3.4), i.e. incorporating a stochastic component with σ_R set to the same value as used in the assessment, i.e. 0.6. For 2012, for which a fixed catch estimate of 3767 t is provided, the catch equation is solved to provide a value for *F*. For subsequent years, the harvest strategy chosen determines the *F* vector, and the catch taken is calculated from that together with the projected numbers-at-age vector.

A total of 1000 forward simulations are run incorporating recruitment variability. This provides a distribution of catches for each future year. For the selected catch vector, the value for each year is then set equal to the median of the distribution calculated for that year.

For "consequences" plots, the process set out above provides the results reported in the main text for the case where the catches are implemented for a real situation corresponding to the assessment from which those catches were derived. However, when the catches implemented were derived from a different assessment, the process is then repeated, though now with fixed input catches for each year to which the catch equation is applied to find the corresponding full-selectivity F value, and hence project the numbers-at-age vector forwards. This then yields 1000 values each year for quantities such as spawning biomass and fully selected fishing mortality. The medians of these distributions for each year then provide the trajectories for the quantities shown in the consequences plots.

Weights-at-age for the projections are taken as the average of the 2009-2011 values (tables in main text) to compute spawning biomass and catches.

References

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[SAW55 Editor's Note: The SARC-55 review panel <u>did not recommend</u> adopting the GOM cod Statistical Catch-at-Age (SCAA) assessment results that are in Appendices A.2 – A.5. These appendices are included in this report to document and demonstrate the work that was done by the SAW cod Working Group for the December 2012 peer review.]

Appendix A.4. Applications of Statistical Catch-at-Age Assessment Methodology to Gulf of Maine cod, October 2012.

Summary

The Statistical Catch-at-Age assessment conducted by the authors earlier in 2012 is updated to take account of more recent data, and refined by introducing two new features: fitting to length distribution data for the NEFSC surveys in the 1960s for which age information is not available, and adjusting the externally provided estimates of the *Bigelow-Albatross* calibration function through adding the calibration information contained in cohorts present both before and after the survey vessel change to the model fitting process. The options selected for the Base Case assessment are those motivated in the assessment conducted earlier in the year. The resultant estimate of the 2011 spawning biomass is 12.0 thousand tons with a CV of 13%. The survey calibration function is slightly modified, resulting in an increase of about 3% in the 2011 spawning biomass. The survey catch-at-length data are consistent with previous estimates of poor recruitments from relatively large spawning biomasses in the 1960s. This last result is robust under a range of sensitivity tests, and is suggestive of a Ricker-like stock-recruitment relationship for the stock. These sensitivity tests also suggest that the 2011 spawning biomass estimate of 12.0 thousand tons is robustly determined. The range of this estimate across these sensitivities is 9.9 to 16.6 thousand tons, with lower values arising from the sqrt(p) weighting approach for proportions data and from forcing selectivities above age 6 to be flat, and the higher values coming from inclusion of the stock-recruitment function in the assessment and increasing the value of *M*. The evidence for commercial selectivities to be domed relative to the NEFSC surveys appears reasonably strong, but less so that for the selectivities for these surveys themselves to be domed.

Introduction

This paper is an extension of the Statistical Catch-at-Age (SCAA) assessment advocated in Butterworth and Rademeyer (2012) which was presented to a meeting of the NEFMC SSC in March earlier this year (2012). The NBC2 variant selected there is extended here to incorporate one further year's data, and refined to also take account of length distribution data available for the un-aged pre-1970 NEFSC surveys, and to use the population model fit to improve estimates of the *Bigelow-Albatross* survey calibration relationship.

The paper also checks the sensitivity of results for its Base Case assessment to some of the factors on which discussions at the SSC indicated an absence of unanimity. For the most part, only single factor changes to the Base Case have been run. Further runs combining more than one change to such factors could be specified by the coming October assessment meeting, and run during its duration, if required.

This paper focuses on assessment aspects, with a further paper on the estimation of reference points to follow shortly.

Data and Methodology

The catch and survey based data (including catch-at-length information) and some biological data used for the analyses are listed in Tables in App. A4, Appendix A.

The details of the SCAA assessment methodology are provided in App. A4, Appendix B of this appendix.

Results

Results are given for a Base Case (Run 1) and various sensitivities. As indicated in the Introduction, this Base Case makes choices for various options in the assessment in line with those motivated in Butterworth and Rademeyer (2012), specifically:

- Start in 1964
- Estimate the first three numbers-at-age for 1964, and then the parameter ϕ (see equation B11) to provide estimates for the numbers at older ages – note that unlike in Butterworth and Rademeyer (2012), the value of ϕ is not restricted by bounds in this estimation process
- Set $M = 0.2$ for all ages
- Use the "adjusted" lognormal formulation of equation B.16 to describe the distribution of proportions-at-age (in relation to numbers of fish)
- Admit the possible estimation of domed selectivity for the NEFSC surveys and for the commercial fishery
- Do not fit the stock-recruitment function is within the population model fitting procedure
- Make allowance for additional variance when fitting to time series of abundance indices

- Fit to the aggregated abundance indices as expressed in terms of biomass rather than numbers.

In addition, this Base Case incorporates what are considered to be improvements to the model:

- Allow the assessment data to update the independent estimate of the *Bigelow-Albatross* calibration function parameters that have been determined from experimental paired trawls (see section B.2.7)
- Incorporate data on NEFSC survey length compositions from the 1960s when catches from these surveys were not aged.

App. A4, Tables 1-4 list results for Base Case and various sensitivities, focusing on the contributions to the assessment period considered, as well values for the survey catchabilities q.

App. A4, Figs 1-4 provide estimates and diagnostic plots for the Base Case fit, while App. A4, Fig. 5 shows how the *Bigelow-Albatross* survey calibration function has been updated. App. A4, Figs 6-12 and 14-15 show results for various sensitivities to the Base Case, while App. A4, Fig. 13 shows results for a retrospective analysis of the Base Case.

Discussion

The Base Case results in App. A4, Table 1 and Fig. 1 show a spawning biomass that has been decreasing somewhat over the last two years, essentially as a consequence of a decline in recruitment since 2005. As to be expected, the precision of spawning biomass estimates is less in the 1960s and 70s when less age information is available, and also drops for the most recent few years. In contrast the annual recruitment estimates are all fairly precise except for the final year (2011). Survey catchability (q) estimates are all below 1, and non-trivial levels of additional variance are estimated for all three abundance indices. The 2011 spawning biomass is estimated at 12.0 thousand tons with an associated CV of 13%.

For this Base Case, both commercial and NEFSC survey selectivities are estimated to be appreciably domed (Fig. 2). Standard fit diagnostics for both abundance indices and proportion-at-age data in Fig. 3 show broadly reasonable fits, though there is some evidence of systematic trends in the proportion-at-age residuals for the Massachusetts Spring survey and for the commercial catch. The last might be ameliorated by allowing for a change in the recent commercial selectivity pattern (for whose values the model often struggles to obtain convergence) to occur in the mid-2000s. The fits to the survey proportions-at-length data over the 1960s (App. A4, Fig. 4) is fair, but does evidence some data conflict with proportions at the smaller lengths underestimated for the spring surveys and overestimated for the autumn surveys, with the reverse effect at larger lengths.

Updating the *Bigelow-Albatross* calibration function in the model suggests that the results from the paired trawls experiment slightly overestimated the factor at larger lengths, but

similarly underestimated it at smaller lengths (App. A4, Fig. 5). Using the existing *Bigelow-Albatross* calibration function without this model-fitting refinement would result in a slightly lower 2011 spawning biomass of 11.7 thousand tons

Moving on to sensitivity tests, alternative starting years for the assessment have a negligible impact on estimates of the current spawning biomass, but there is some sensitivity shown by the estimates of spawning biomass in the 1960s, though these still remain high relative to estimates for the last two decades (App. A4, Table 1, Runs 2a-d and App. A4, Fig. 6). For a 1982 start, the catchability coefficient (q) estimate for the NEFSC Spring survey increases above 1 to 1.09.

The parameter ϕ related to the starting numbers-at-age vector for 1964 is estimable, but with quite a high CV of 47%, so that it is not surprising that the starting spawning biomass is not that well determined (App. A4, Table 1, Runs 3a-e and App. A4, Figs 1 and 6). The selection of how many ages to estimate starting numbers-at-ages to estimate in this starting vector is clearly suggested to be three (ages 0-2) for the Base Case by the process of considering successive improvements in –lnL as this number is increased (App. A4, Table 2, Runs 4a-h). Alternative selections for both these factors have minimal impact on estimates of the 2011 spawning biomass.

Increasing the weight given to the survey catch-at-length data from the 1960s suggests a slight decrease in recruitment in the 1960s (App. A4, Table 3, Runs 5a-b and Fig. 8, so that these data do not contradict earlier inferences of poor recruitment over this period (when spawning biomass was relatively high) which were made in the absence of this information (Butterworth and Rademeyer, 2011 and 2012). If less weight is placed on the input information for the *Bigelow-Albatross* calibration function, the calibration factor moves still lower at higher lengths, and still higher at lower lengths (App. A4, Table 3, Run 6 and Fig.9). This indicates that the information on calibration provided by the presence of common cohorts in both the pre- and post-vessel-change periods points somewhat differently from the independent experiment in regard to the values of the calibration function, so that estimates of this may change further as more data from these cohorts accumulates over the next few years.

Including estimation of a Ricker stock recruitment function in the assessment leads to a higher estimate of the 2011 spawning biomass of about 14 thousand tons as a result of increased estimates of recruitment over recent years (App. A4, Table 3, Run 7 and Fig. 10). In contrast using the sqrt(p) option of weighting proportion-at-age data in the log likelihood in place of the "adjusted" lognormal see this estimate drop to some 11 thousand tons (App. A4, Table 3, Run 8). App. A4, Fig. 3 also shows the fit residuals for age and length distribution data under this alternative; there is no obvious improvement or deterioration in the pattern of these residuals for the sqrt(p) compared to the "adjusted" lognormal run, and so no clear reason from these plots to prefer one distributional form over the other.

Sensitivities which modify the commercial selectivity-at-age for the pre-1982 period to reflect a relatively greater catch of smaller fish (Palmer, pers. commn, advises that nets in that period tended to have smaller mesh sizes) have scarcely any impact on spawning biomass trends, and are somewhat less preferred in likelihood terms (App. A4, Table 3,

Runs 9a-b, and Fig. 11). Increasing natural mortality *M* from 0.2 to 0.3 increases spawning biomass estimates as would be expected, and is slightly preferred in likelihood terms (App. A4, Table 3, Run 10 and Fig. 12).

App. A4, Fig. 13 shows the results from a retrospective analysis for the Base Case assessment. There is a large difference evident for assessments carried out in 2007 and 2008 (possibly linked to the high NEFSC Spring survey estimates at that time), but thereafter any retrospective effect is fairly small.

Runs 11 and 12 in Table 4 show the consequences of forcing either the survey selectivity or both the survey and commercial selectivities to be flat at older ages above 6. These correspond to estimating 3 or 9 fewer parameter values, with associate deterioration in –lnL by some 7 or 24 points respectively. Assuming domes is thus AIC justified in both cases. Forcing this flatness results in lower spawning biomass (App. A4, Fig. 14), though most of this effect comes from forcing flatness in the commercial selectivity function, e.g. with the survey selectivities only forced to be flat, the 2011 spawning biomass estimate drops only from 12.0 to 11.6 thousand tons (a 4% effect).

App. A4, Table 4 and Fig. 15 show results from repeating the flat selectivity sensitivities of Runs 11 and 12, but here under the sqrt(p) weighting approach for proportions data in place of the "adjusted" lognormal distribution assumption. Again the assumption of a dome in the commercial selectivity is AIC justified, but the extension of that to the NEFSC survey data is marginal in that respect. Butterworth and Rademeyer (2012) found that the Massachusetts Spring survey showed a selectivity pattern which was flat for the sqrt(p) case rather than decreasing at ages above 3 as in the case of the "adjusted" lognormal, which they considered of questionable realism given the more near-shore area which this survey covers. However this argument for preferring the "adjusted" lognormal is less clear for these updated computations. These results may be compromised by failure to achieved convergence in some of these runs (see App. A4, Tables 3 and 4 captions), though as this arises only from sensitivity of the process to estimation of the commercial selectivity parameters for the more recent period, this seems unlikely to have a great influence on abundance estimates and trends. Overall the case for a dome in the commercial relative to the NEFSC survey catches seems reasonably strong, but that for a dome in these survey selectivities themselves less so.

Conclusions

Key features of these results are:

a) Although there is some uncertainty about spawning biomass estimates in the 1960s, nevertheless these are robustly estimated to be towards the higher end of the range of spawning biomasses through the 1964-2011 period considered. Further the recruitments at that time are precisely and robustly estimated to have been towards the low end of the range of recruitment levels throughout this period. This is suggestive of a Ricker-type stock-recruitment relationship, something that is not *a priori* surprising for a cod stock given the species' cannibalistic behaviour.

b) The spawning biomass in 2011 is relatively robustly estimated at 12.0 thousand tons. The range of this estimate across the sensitivities examined is 9.9 to 16.6 thousand tons, with lower values arising from the sqrt(p) weighting for proportions data and from forcing selectivities above age 6 to be flat, and the higher values coming from including the stock-recruitment function in the assessment and increasing the value of *M*.

Some Working Group members prefer including a stock recruitment relationship in fitting assessment models. This was not included in the Base Case here so that other sensitivities could be examined without the inclusion of the relationship perhaps confounding interpretation of the results.

Acknowledgements

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References

Butterworth DS and Rademeyer RA. 2011. Applications of statistical catch-at-age assessment methodology to Gulf of Maine cod. Document submitted to the 17-21 October, 2011 workshop on the assessment of Gulf of Maine cod, Falmouth. 31pp.

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Miller TJ, Das, C, Politis PJ, Miller AS, Lucey SM, Legault CM, Brown RW and Rago PJ. 2010. Estimation of *Albatross IV* to *Henry B. Bigelow* Calibration Factors. U.S. Depart. of Commerce, Northeast Fisheries Science Center Ref. Doc. 10-05; 233 pp.

Appendix A4. Tables

App. A4, Table 1: Estimates of abundance and related quantities for the Gulf of Maine cod for a series of assessment sensitivities. Values in parentheses are Hessian based CV's. Mass units are '000 tons. *y*1 refers to the start year for the assessment. $N_{y1,0}$ is in millions. Refer to Appendix for definition of some of the symbols used. Note that Runs 2a) to 2d) were conducted with the same number of ages in the starting numbers-at-age vector as for the Base Case (*viz*. ages 0-2); later starting years, it is probable that extending this estimation to further ages is statistically justifiable.

	1) Base Case		2) Alternative start year								3) Alternative fixed values of ϕ									
			2a)		2b)		2c)		2d)		3a) ϕ=0.0		3b) ϕ=0.05		3c) ϕ=0.1		3d) ϕ=0.2		3e) ϕ=0.3	
Start year	1964		1965		1967		1970		1982		1964		1964		1964		1964			
-lnL: overall	-162.8		-158.9		-148.5		-147.9		-95.0		-160.2		-161.7		-162.3		-162.2		-159.4	
-lnL: survey	-37.5		-37.4		-35.5		-32.4		-17.3		-37.5		-37.5		-37.5		-37.3		-36.8	
-lnL: comCAA	-129.6		-129.6		-129.5		-129.5		-120.8		-129.6		-129.6		-129.3		-129.7		-129.5	
-lnL: survCAA	-13.9		-6.4		6.8		17.7		47.6		-13.2		-13.7		-13.9		-13.5		-12.6	
-lnL: survCAL	22.1		18.1		13.3		0.0		0.0		24.0		23.1		22.3		22.1		23.5	
-lnL: RecRes	1.3		1.3		1.3		1.3		1.2		1.3		1.3		1.3		1.3		1.3	
-lnL: calibration	-5.2		-5.0		-5.0		-5.1		-5.6		-5.2		-5.2		-5.3		-5.2		-5.2	
$N_{y1,0}$	7.49	(0.13)	4.15	(0.17)	3.63	(0.17)	4.21	(0.16)	12.94	(0.07)	7.55	(0.13)	7.53	(0.13)	7.42	(0.13)	7.45	(0.13)	7.43	(0.13)
ϕ	0.14	(0.47)	0.45	(0.14)	0.29	(0.15)	0.10	(0.70)	0.52	(0.07)	0.00	-	0.05	-	0.10	-	0.20	-	0.30	-
B^{sp}_{2011}	12.02	(0.13)	12.01	(0.13)	11.97	(0.14)	11.98	(0.16)	12.03	(0.17)	12.03	(0.14)	12.03	(0.13)	12.04	(0.13)	12.03	(0.13)	12.00	(0.13)
B^{sp}_{1982}	32.25	(0.06)	32.24	(0.07)	32.25	(0.06)	32.25	(0.12)	32.31	(0.10)	32.25	(0.06)	32.25	(0.06)	32.40	(0.06)	32.21	(0.06)	32.25	(0.06)
B^{sp}_{y1}	42.40	(0.24)	25.32	(0.20)	42.52	(0.16)	45.17	(0.32)	32.31	(0.10)	56.88	(0.15)	51.58	(0.14)	46.82	(0.14)	36.68	(0.14)	28.46	(0.14)
	q	σ_{Add}	q	σ_{Add}	q	σ_{Add}	q	σ_{Add}	q	σ_{Add}	q	σ_{Add}	q	σ_{Add}	q	σ_{Add}	q	σ_{Add}	q	σ_{Add}
NEFSC spring	0.91	0.19	0.91	0.19	0.91	0.19	0.91	0.19	1.09	0.24	0.91	0.19	0.91	0.19	0.90	0.19	0.91	0.19	0.91	0.19
NEFSC fall	0.83	0.07	0.84	0.07	0.84	0.07	0.84	0.07	0.73	0.10	0.82	0.07	0.83	0.07	0.83	0.07	0.84	0.07	0.85	0.07
MADMF spring	0.20	0.13	0.20	0.13	0.20	0.13	0.20	0.13	0.20	0.16	0.20	0.13	0.20	0.13	0.20	0.13	0.20	0.13	0.20	0.13

App. A4, Table 2: Estimates of abundance and related quantities for the Gulf of Maine cod for a series of assessment sensitivities relating to the initial numbers-at-age vector. Values in parentheses are Hessian based CV's. Mass units are '000 tons. $y1$ refers to the start year for the assessment. $N_{y1,0}$ is in millions. Refer to Appendix B for definition of some of the symbols used.

	4) Fewer or more $N_{y1,a}$ values estimated															
	4a) age 0		4b) ages 0-1		4c) ages 0-2 (BC)		4d) ages 0-3		4e) ages 0-4		4f) ages 0-5		4g) ages 0-6		4h) ages 0-7	
Start year	1964		1964		1964		1964		1964		1964		1964		1964	
-lnL: overall	-146.7		-147.4		-162.8		-163.1		-163.7		-163.8		-164.9		-164.9	
-lnL: survey	-36.8		-36.7		-37.5		-37.3		-37.4		-37.3		-37.6		-37.6	
-lnL: comCAA	-129.7		-129.8		-129.6		-129.8		-129.6		-130.0		-129.6		-129.5	
-lnL: survCAA	-1.1		-2.2		-13.9		-13.7		-13.9		-13.5		-14.0		-14.0	
-lnL: survCAL	24.6		25.0		22.1		21.7		21.1		20.9		20.2		20.2	
-lnL: RecRes	1.3		1.3		1.3		1.3		1.3		1.3		1.3		1.3	
-lnL: calibration	-5.0		-5.0		-5.2		-5.2		-5.2		-5.2		-5.2		-5.2	
$N_{y1,0}$	7.93	(0.08)	7.17	(0.14)	7.49	(0.13)	7.48	(0.13)	7.57	(0.13)	7.71	(0.13)	7.56	(0.13)	7.57	(0.13)
ϕ	0.38	(0.15)	0.40	(0.16)	0.14	(0.47)	0.19	(0.45)	0.29	(0.44)	0.43	(0.44)	0.68	(0.39)	0.87	(1.19)
B^{sp}_{2011}	12.01	(0.13)	12.02	(0.13)	12.02	(0.13)	12.01	(0.13)	12.01	(0.18)	11.97	(0.14)	12.03	(0.13)	12.03	(0.13)
B^{sp}_{1982}	32.29	(0.07)	32.34	(0.08)	32.25	(0.06)	32.39	(0.06)	32.29	(0.06)	32.58	(0.06)	32.31	(0.06)	32.31	(0.06)
B^{sp}_{y1}	26.88	(0.24)	26.20	(0.24)	42.40	(0.24)	39.90	(0.25)	38.50	(0.24)	36.46	(0.24)	34.55	(0.22)	33.95	(0.23)
	q	σ_{Add}	q	σ_{Add}	q	σ_{Add}	q	σ_{Add}	q	σ_{Add}	q	σ_{Add}	q	σ_{Add}	q	σ_{Add}
NEFSC spring	0.91	0.19	0.92	0.19	0.91	0.19	0.91	0.19	0.91	0.19	0.90	0.19	0.91	0.19	0.91	0.19
NEFSC fall	0.84	0.07	0.84	0.07	0.83	0.07	0.83	0.07	0.83	0.07	0.82	0.07	0.83	0.07	0.83	0.07
MADMF spring	0.20	0.13	0.20	0.13	0.20	0.13	0.20	0.13	0.20	0.13	0.20	0.13	0.20	0.13	0.20	0.13

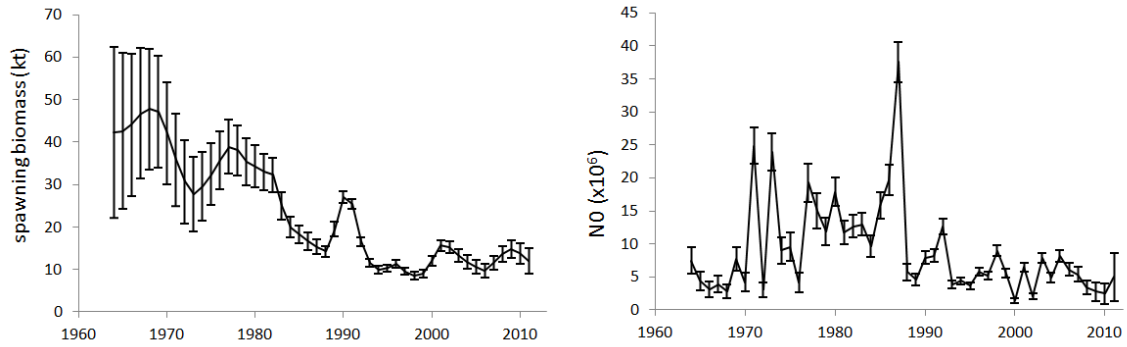
App. A4, Table 3: Estimates of abundance and related quantities for the Gulf of Maine cod for a series of assessment sensitivities. Values in parentheses are Hessian based CV's. Mass units are '000 tons. $y1$ refers to the start year for the assessment. $N_{y1,0}$ is in millions. Refer to Appendix B for definition of some of the symbols used. Runs marked * did not converge fully. The associated sensitivity of the fitting process arises in estimating the selectivity vector for the second commercial period. In all such cases, a rerun was conducted with this vector fixed at the best estimates that had been achieved thus far, and convergence was readily achieved.

	1) Base Case		5) Higher weight for CAL				6) Less weight input calibration		7) Ricker internal		8) sqrt(p) option for CAA and CAL weighting		9) Alternative pre-1982 commercial selectivity				10) Higher M	
			5a) W_{CAL}=1		5b) W_{CAL}=5								9a) option 1		9b) option 2		10a) M =0.3	
Start year	1964		1964		1964	*	1964	*	1964		1964	*	1964		1964		1964	*
-lnL: overall	-162.8		15.1		660.2		-160.2		-125.5		-2503.7		-161.2		-158.4		-164.6	
-lnL: survey	-37.5		-37.6		-39.1		-38.0		-35.4		-36.7		-37.8		-37.8		-37.9	
-lnL: comCAA	-129.6		-129.3		-131.0		-129.7		-129.5		-737.6		-128.8		-128.0		-131.3	
-lnL: survCAA	-13.9		2.1		89.6		-16.1		-12.6		-1611.9		-13.0		-10.8		-12.9	
-lnL: survCAL	22.1		183.9		744.8		22.1		22.0		-113.4		22.2		22.3		21.8	
-lnL: RecRes	1.3		1.2		1.3		1.3		35.3		1.4		1.2		1.2		0.7	
-lnL: calibration	-5.2		-5.2		-5.3		1.8		-5.3		-5.5		-5.2		-5.2		-5.0	
$N_{y1,0}$	7.49	(0.13)	6.89	(0.12)	7.45	(0.11)	7.52	(0.13)	7.26	(0.13)	7.23	(0.14)	8.19	(0.13)	8.65	(0.13)	16.30	(0.13)
ϕ	0.14	(0.47)	0.11	(1.21)	0.18	(0.23)	0.14	(0.46)	0.08	(0.99)	0.17	(0.37)	0.12	(0.48)	0.12	(0.45)	0.01	(0.03)
B^{sp}_{2011}	12.02	(0.13)	12.89	(0.48)	11.38	(0.14)	12.04	(0.19)	14.03	(0.17)	10.83	(0.10)	11.94	(0.13)	11.88	(0.11)	16.61	(0.11)
B^{sp}_{1982}	32.25	(0.06)	33.72	(0.25)	29.91	(0.07)	32.24	(0.06)	33.30	(0.07)	28.91	(0.03)	33.29	(0.07)	33.96	(0.04)	39.23	(0.06)
B^{sp}_{y1}	42.40	(0.24)	58.53	(0.86)	34.60	(0.26)	42.15	(0.25)	53.65	(0.29)	33.69	(0.19)	42.54	(0.24)	42.54	(0.18)	74.73	(0.11)
	q	σ_{Add}	q	σ_{Add}	q	σ_{Add}	q	σ_{Add}	q	σ_{Add}	q	σ_{Add}	q	σ_{Add}	q	σ_{Add}	q	σ_{Add}
NEFSC spring	0.91	0.19	0.86	0.18	0.89	0.17	0.91	0.19	0.89	0.20	0.95	0.19	0.92	0.18	0.93	0.17	0.63	0.19
NEFSC fall	0.83	0.07	1.03	0.08	1.57	0.07	0.84	0.07	0.82	0.07	0.85	0.07	0.86	0.08	0.87	0.08	0.58	0.07
MADMF spring	0.20	0.13	0.19	0.13	0.20	0.13	0.20	0.13	0.19	0.14	0.32	0.13	0.20	0.13	0.20	0.13	0.13	0.12

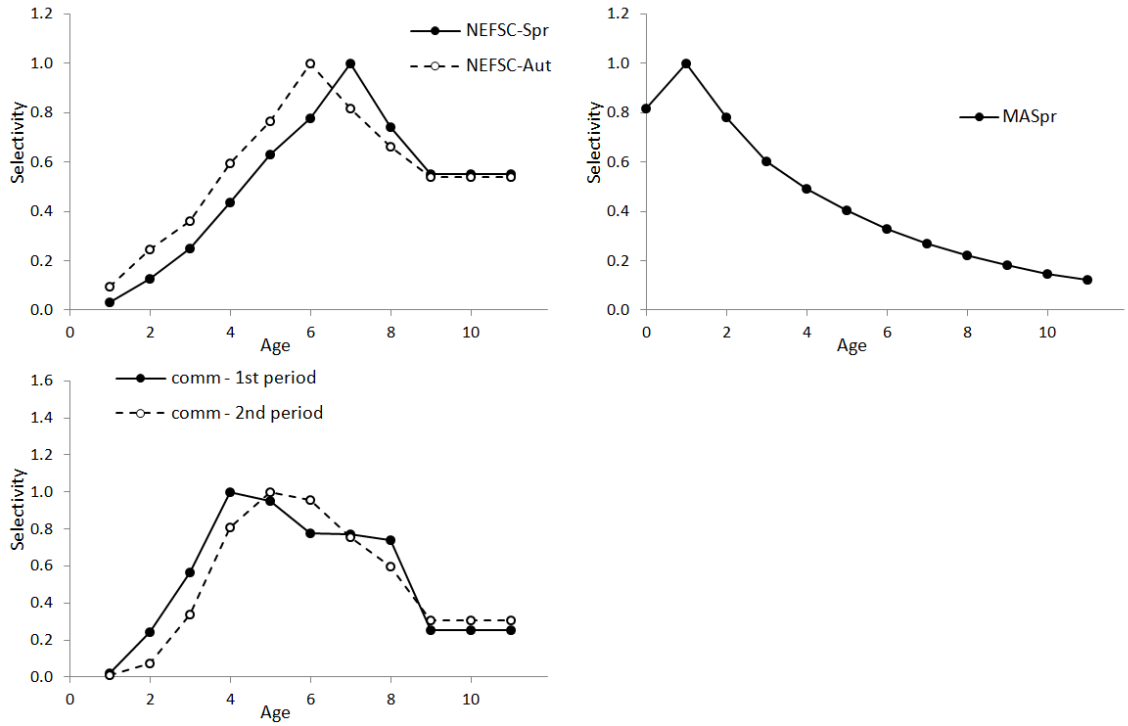
App. A4, Table 4: Estimates of abundance and related quantities for the Gulf of Maine cod for a series of assessment sensitivities. Values in parentheses are Hessian based CV's. Mass units are '000 tons. $y1$ refers to the start year for the assessment. $N_{y1,0}$ is in millions. Refer to Appendix B for definition of some of the symbols used. Runs marked * did not converge fully. The associated sensitivity of the fitting process arises in estimating the selectivity vector for the second commercial period. In all such cases, a rerun was conducted with this vector fixed at the best estimates that had been achieved thus far, and convergence was readily achieved.

	1) Base Case		11) Flat NEFSC survey selectivities		12) Flat NEFSC survey and commercial selectivities		8) sqrt(p) option for CAA and CAL weighting		13) sqrt(p) option and flat NEFSC surv sel		14) sqrt(p) option and flat NEFSC surv and com sel	
Start year	1964		1964 *		1964 *		1964 *		1964 *		1964 *	
-lnL: overall	-162.8		-155.6		-138.5		-2503.7		-2501.0		-2491.6	
-lnL: survey	-37.5		-39.3		-36.8		-36.7		-37.8		-37.1	
-lnL: comCAA	-129.6		-129.2		-120.5		-737.6		-737.3		-735.0	
-lnL: survCAA	-13.9		-6.8		1.3		-1611.9		-1609.3		-1601.5	
-lnL: survCAL	22.1		23.3		21.6		-113.4		-112.4		-113.8	
-lnL: RecRes	1.3		1.4		1.4		1.4		1.4		1.5	
-lnL: calibration	-5.2		-5.0		-5.4		-5.5		-5.5		-5.7	
$N_{y1,0}$	7.49	(0.13)	7.39	(0.13)	6.89	(0.13)	7.23	(0.14)	7.56	(0.13)	6.70	(0.14)
ϕ	0.14	(0.47)	0.17	(0.35)	0.17	(0.36)	0.17	(0.37)	0.20	(0.31)	0.17	(0.37)
B^{sp}_{2011}	12.02	(0.13)	11.63	(0.11)	9.94	(0.10)	10.83	(0.10)	10.78	(0.10)	10.03	(0.09)
B^{sp}_{1982}	32.25	(0.06)	29.80	(0.03)	28.09	(0.03)	28.91	(0.03)	28.56	(0.03)	27.03	(0.03)
B^{sp}_{y1}	42.40	(0.24)	31.88	(0.15)	29.72	(0.16)	33.69	(0.19)	28.61	(0.16)	30.19	(0.16)
	q	σ_{Add}	q	σ_{Add}	q	σ_{Add}	q	σ_{Add}	q	σ_{Add}	q	σ_{Add}
NEFSC spring	0.91	0.19	0.75	0.18	0.90	0.19	0.95	0.19	0.84	0.19	0.92	0.19
NEFSC fall	0.83	0.07	0.73	0.07	0.87	0.07	0.85	0.07	0.79	0.07	0.84	0.07
MADMF spring	0.20	0.13	0.20	0.13	0.20	0.14	0.32	0.13	0.32	0.13	0.32	0.13

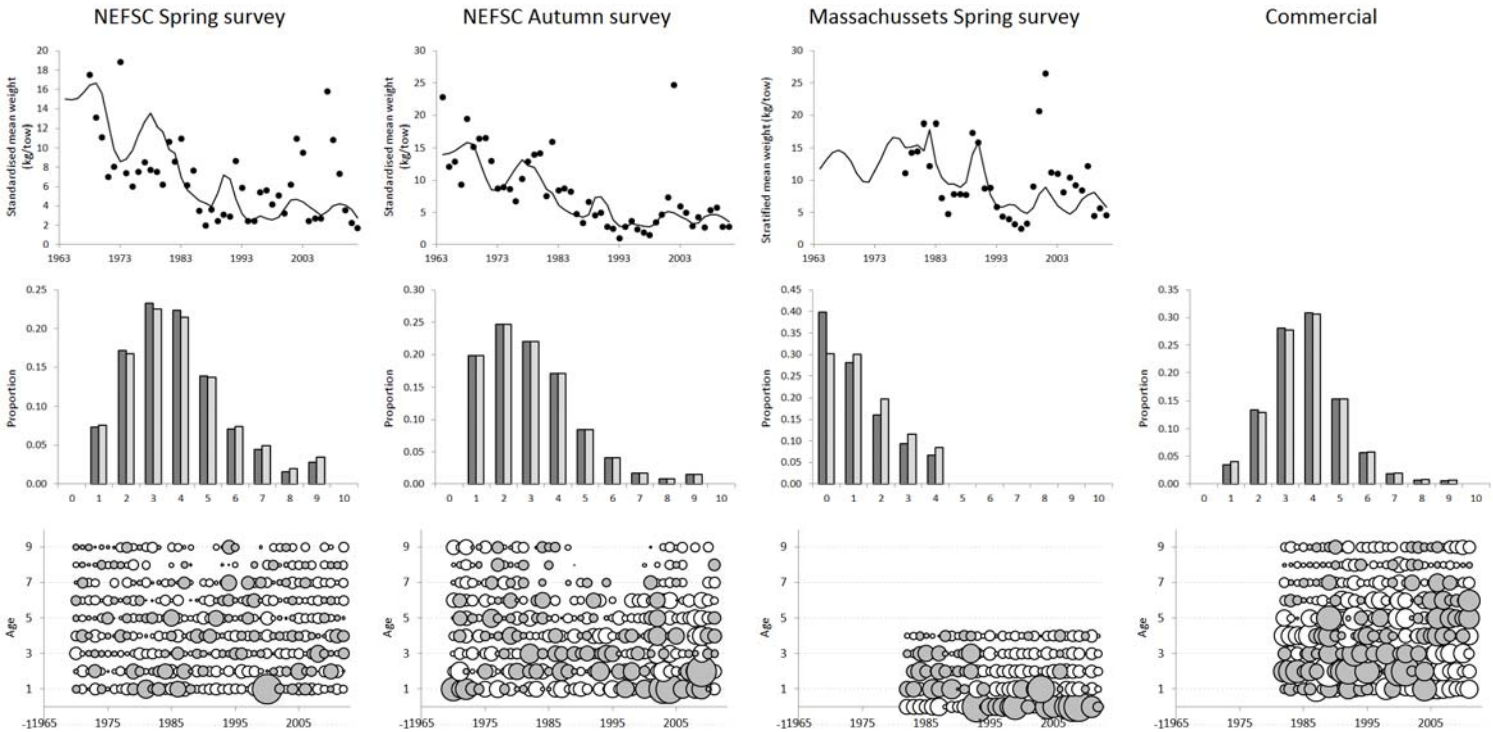
Appendix A4. Figures.



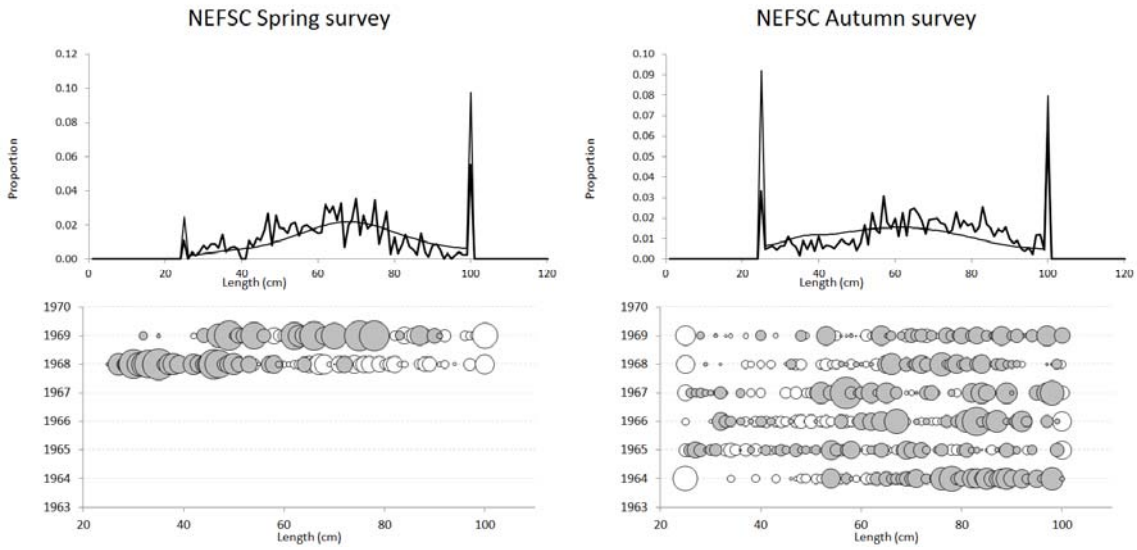
App. A4, Fig. 1: Spawning biomass and recruitment trajectories for the Base Case with ±2 s.e.



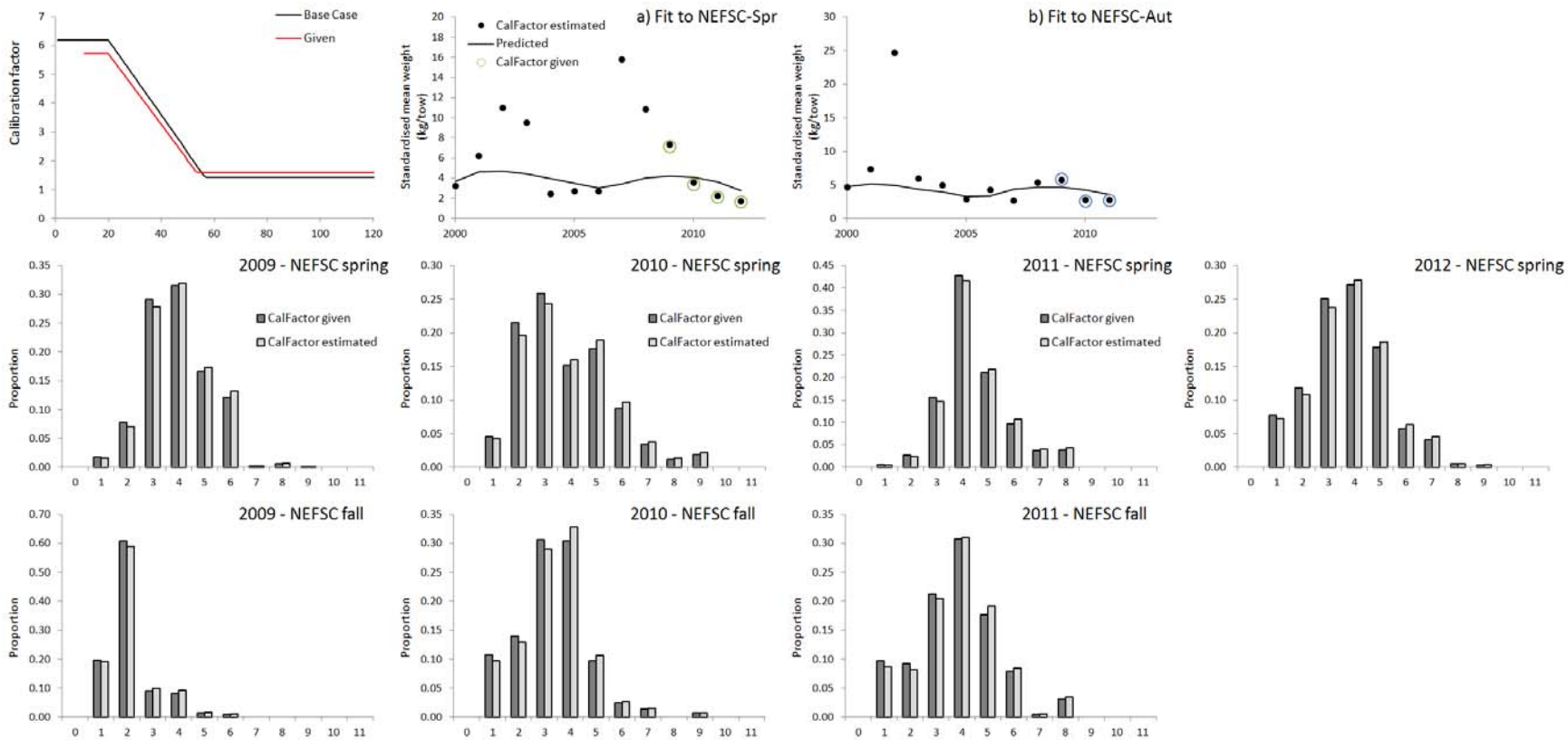
App. A4, Fig. 2: Survey and commercial selectivities-at-age estimated for the Base Case.



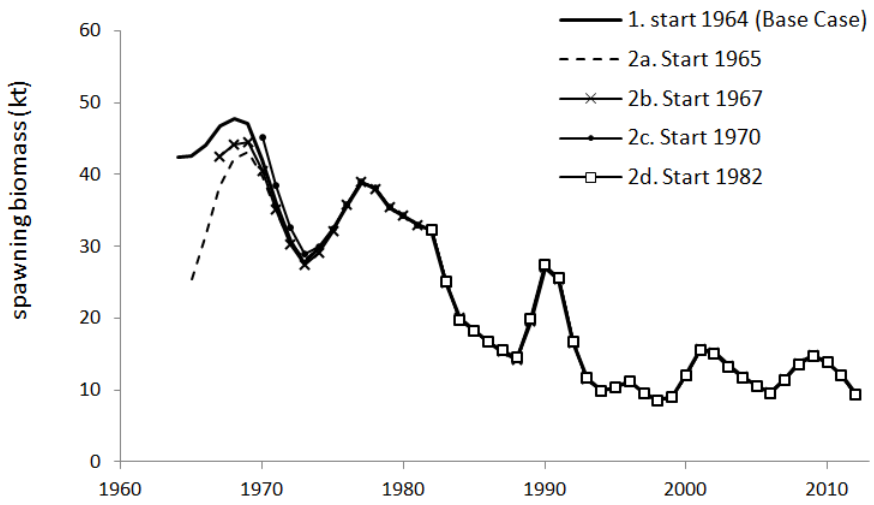
App. A4, Fig. 3: Fits to the abundance indices (top row) and to the survey and commercial catch-at-age data for the Base Case. The second row plots compare the observed and predicted CAA as averaged over all years for which data are available, while the third row plots show the standardised residuals, with the size (area) of the bubbles being proportional to the magnitude of the corresponding standardised residuals. For positive residuals, the bubbles are grey, whereas for negative residuals, the bubbles are white. The last row plots show the comparable standardised residuals for Case 8 (sqrt(p)).



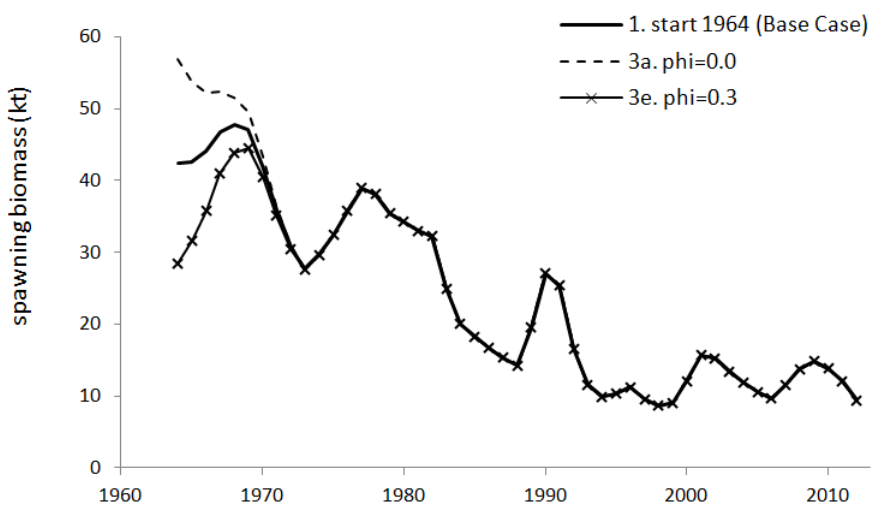
App. A4, Fig. 4: Fits to the survey catch-at-length data for the Base Case. The first row plots compare the observed and predicted CAL as averaged over all years for which data are available, while the third row plots show the standardised residuals, with the size (area) of the bubbles being proportional to the magnitude of the corresponding standardised residuals. For positive residuals, the bubbles are grey, whereas for negative residuals, the bubbles are white.



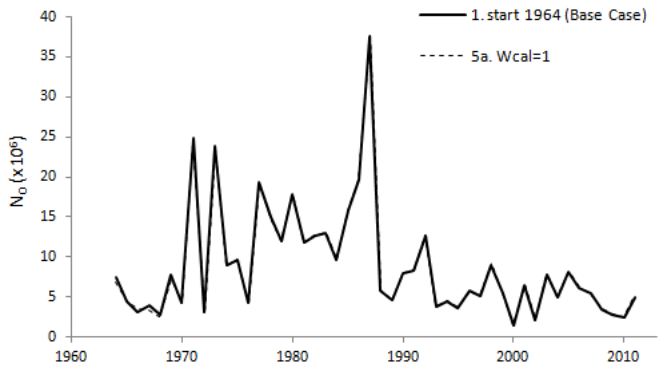
App. A4, Fig. 5: Comparison of calibration results for the calibration factor estimated within the assessment (Base Case) and calibration factor given.



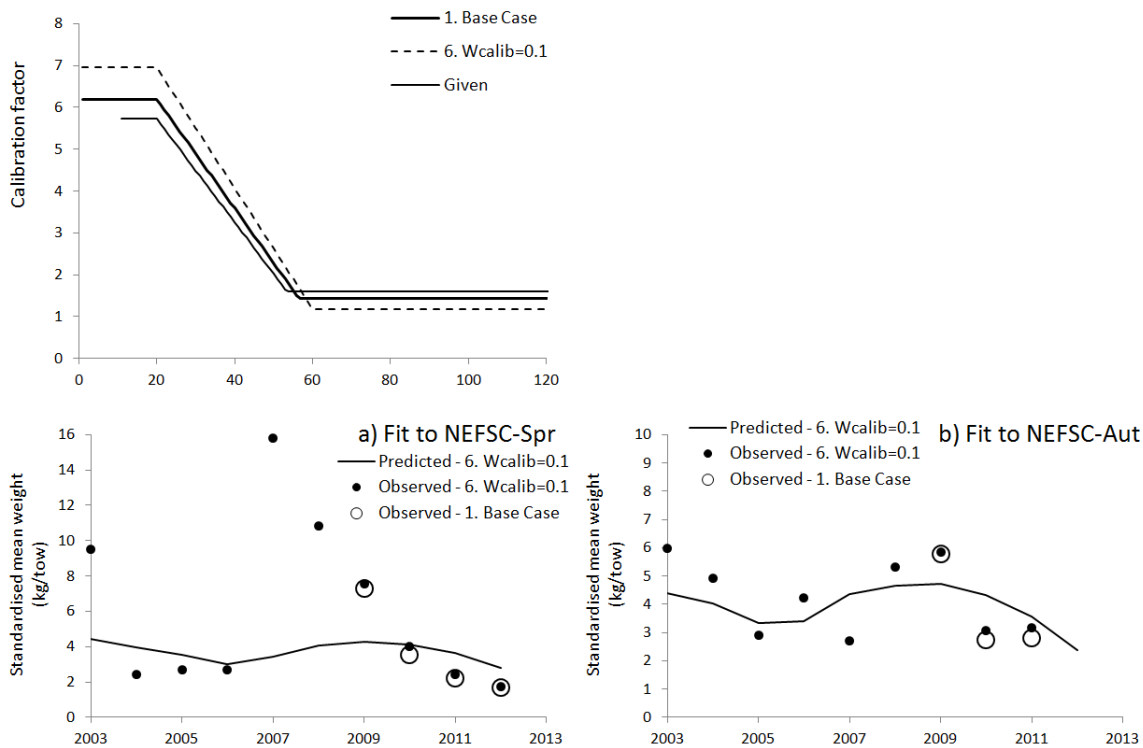
App. A4, Fig. 6: Spawning biomass trajectories for the Base Case and four sensitivities with different starting year.



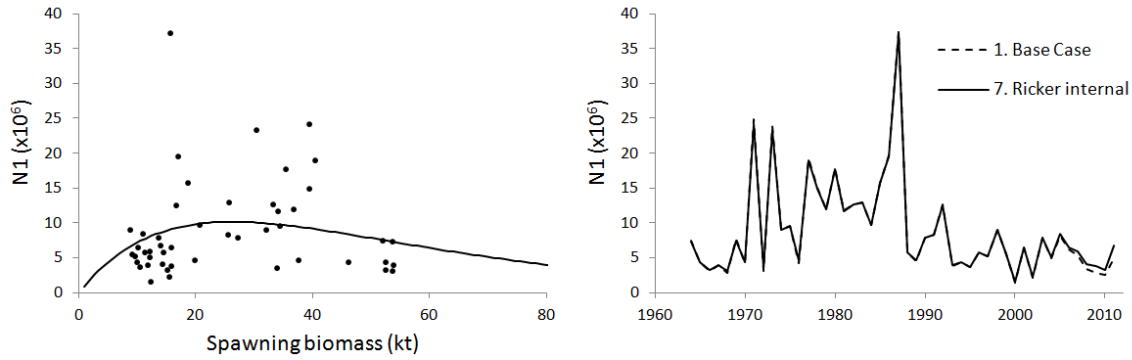
App. A4, Fig. 7: Spawning biomass trajectories for the Base Case and two sensitivities with different fixed ϕ values. For the Base Case, ϕ is estimated (ϕ=0.14).



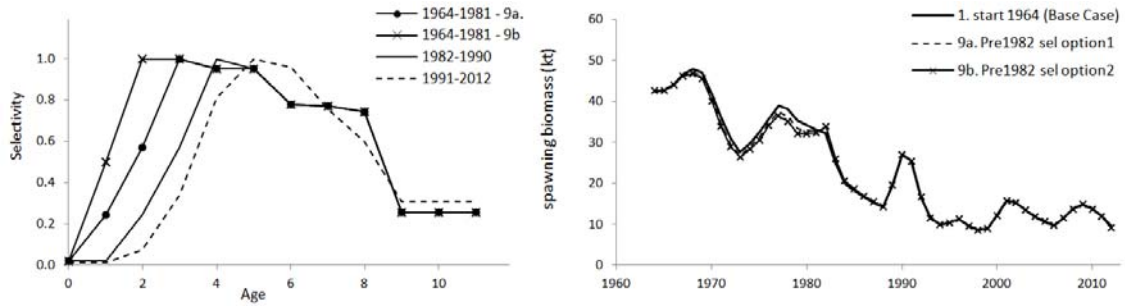
App. A4, Fig. 8: Recruitment trajectories for the Base Case and Case 5a for which more weight is given to the CAL data.



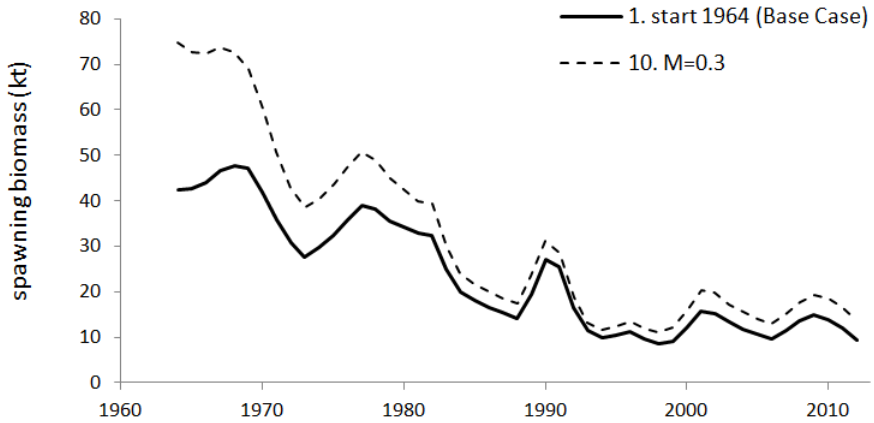
App. A4, Fig. 9: Calibration factor.



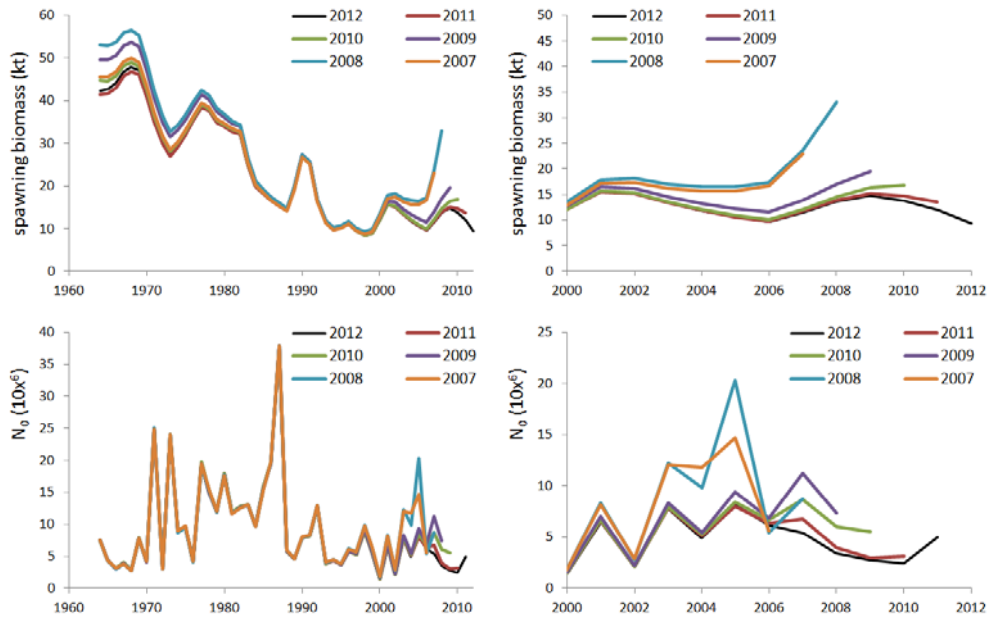
App. A4, Fig. 10: Fits to the stock-recruitment data for the case with an internal Ricker stock-recruitment curve estimated (Case 7) (left-hand plot) and trajectories of recruitment for the Base Case and Case 7.



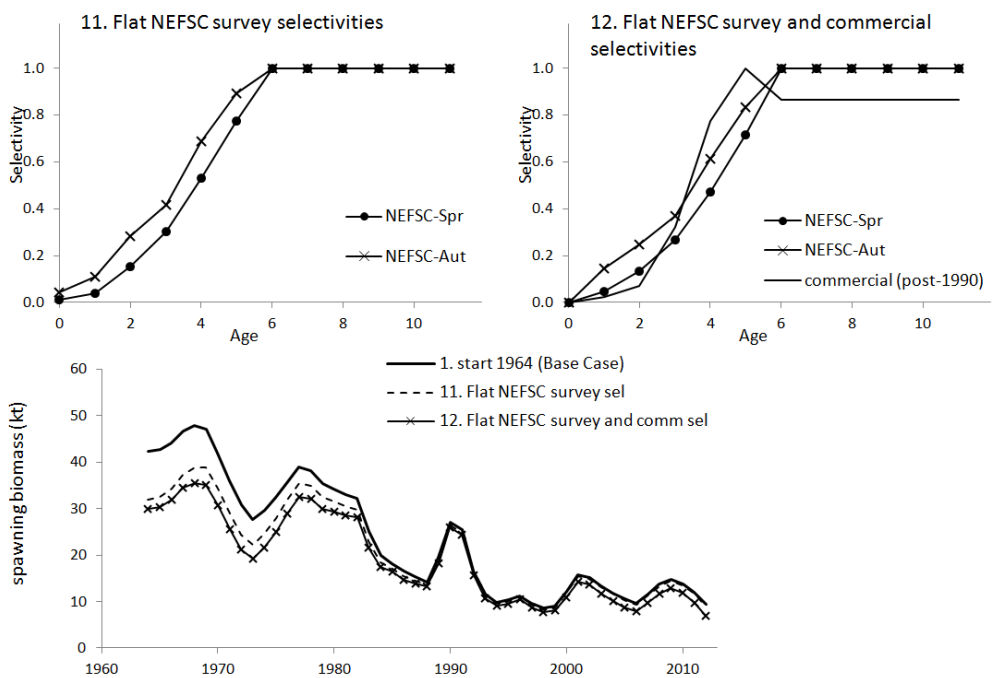
App. A4, Fig. 11: Commercial selectivities (left-hand plot) for cases 9a-b with alternative pre-1982 commercial selectivities and spawning biomass trajectories.



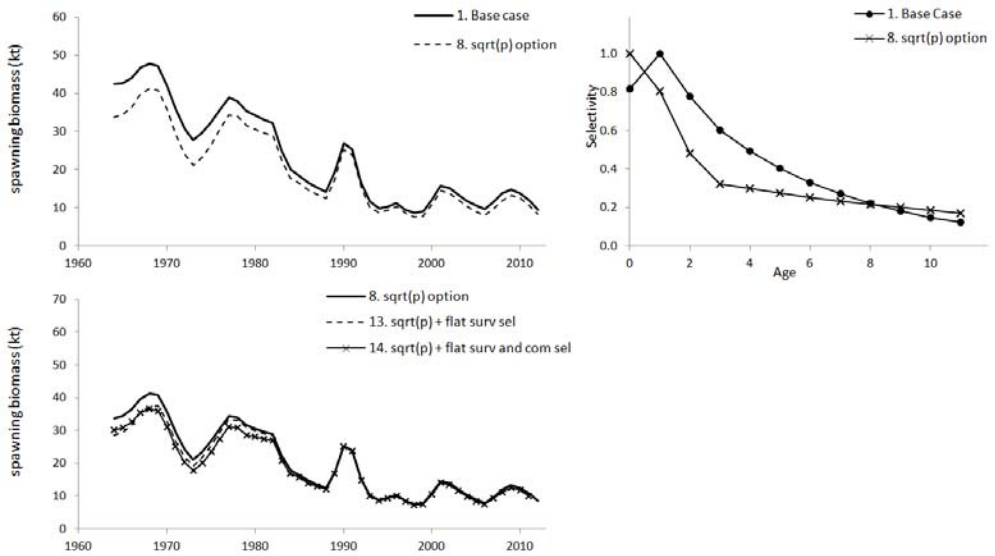
App. A4, Fig. 12: Spawning biomass trajectories for the Base Case and Case 10 with *M*=0.3.



App. A4, Fig. 13 Retrospective analysis for the **Base Case A** for spawning biomass and recruitment.



App. A4, Fig. 14: Selectivities and spawning biomass trajectories for the Base Case and Cases 11 and 12 for which the selectivity functions indicated are forced to be flat above age 6.



App. A4, Fig. 15: Selectivities and spawning biomass trajectories for the Base Case and the sqrt(p) cases (Cases 8, 13 and 14).

Appendix A4 (Appendices A and B within App. A4)

APPENDIX A – Data

App. A4 (Append. A), Table A1: Total catch (incl. USA, DWF and recreational landings, and discards) (thousand metric tons) of Atlantic cod from the Gulf of Maine (NAFO Division 5Y), 1964-2012 (Michael Palmer, pers. commn). The revised discard mortality assumptions have been applied. Note that pre-1982 catches have been increased by 25% in the Base Case to allow for levels of discards suggested by recent analyses by the NEFSC. The 2012 catch is assumed to be 6.830 thousand metric tons, as in 2011; some assumption is needed to be able to take account of the Spring 2012 NEFSC survey given that this occurs though equation B.9 which requires this input.

Year	Total catch	Year	Total catch	Year	Total catch
1964	3.242	1980	12.515	1996	7.757
1965	3.759	1981	16.512	1997	5.814
1966	4.225	1982	17.096	1998	4.578
1967	5.824	1983	16.487	1999	3.078
1968	6.137	1984	12.868	2000	5.823
1969	8.155	1985	14.391	2001	8.055
1970	7.961	1986	12.572	2002	6.509
1971	7.475	1987	12.005	2003	6.497
1972	6.927	1988	10.333	2004	5.766
1973	6.138	1989	13.371	2005	5.441
1974	7.550	1990	19.314	2006	4.268
1975	8.788	1991	20.978	2007	5.527
1976	9.894	1992	12.347	2008	7.375
1977	11.993	1993	9.960	2009	8.355
1978	11.890	1994	9.060	2010	7.670
1979	10.972	1995	7.566	2011	6.830

App. A4 (Append. A), Table A2: Mean weight-at-age (kg) at the beginning of the year for the Gulf of Maine cod stock. Values derived from aggregated commercial landings and discard mean weight-at-age data (mid-year) using procedures described by Rivard (1980) (Michael Palmer, pers. commn) and applying the revised mortality assumptions. Pre-1982, the 1982-1991 average mean weight-at-age is assumed; for 2012, the 2002-2011 average mean weight-at-age is used.

	0	1	2	3	4	5	6	7	8	9	10	11+
1982	0.0024	0.241	0.594	1.165	2.127	4.635	7.622	9.289	9.037	13.235	15.592	18.240
1983	0.0077	0.050	0.501	1.114	1.894	3.136	5.539	6.549	9.962	10.565	12.076	18.713
1984	0.0001	0.075	0.372	1.019	2.021	2.952	4.593	7.118	7.845	11.843	12.834	16.087
1985	0.0146	0.014	0.403	0.910	2.013	3.532	4.608	6.863	9.700	11.147	13.591	14.610
1986	0.0009	0.104	0.316	1.077	1.917	3.670	5.504	6.908	9.315	12.169	13.018	18.102
1987	0.0007	0.028	0.406	0.777	2.273	3.574	5.889	8.079	9.487	11.842	14.008	16.407
1988	0.0003	0.022	0.293	0.980	1.709	4.010	4.927	6.705	10.069	10.761	15.633	12.054
1989	0.0223	0.027	0.292	0.887	2.179	3.172	5.578	6.945	8.799	13.032	14.593	24.532
1990	0.0063	0.095	0.431	0.937	1.742	3.627	5.750	8.043	10.440	13.894	16.575	22.637
1991	0.0069	0.071	0.450	1.083	1.689	2.846	5.654	8.972	11.518	13.416	9.721	24.937
1992	0.0116	0.028	0.476	1.215	2.026	2.564	4.629	8.832	10.453	12.827	17.092	23.406
1993	0.0116	0.046	0.191	1.254	1.702	3.449	4.083	7.388	12.219	12.332	15.361	23.790
1994	0.0095	0.038	0.236	1.003	2.244	2.571	5.294	6.601	11.095	11.435	17.872	22.643
1995	0.0122	0.051	0.275	0.946	2.021	3.934	4.722	8.526	10.045	15.741	14.877	22.643
1996	0.0223	0.060	0.356	1.462	1.784	2.971	6.185	8.967	12.844	14.654	19.623	22.643
1997	0.0049	0.049	0.391	1.466	2.407	2.571	3.973	8.245	11.940	14.994	17.039	17.655
1998	0.0015	0.059	0.256	1.445	2.245	3.423	3.558	5.739	10.442	14.585	15.340	17.655
1999	0.0224	0.044	0.343	1.196	2.237	3.139	4.752	5.301	8.351	12.198	17.158	17.655
2000	0.0092	0.120	0.461	1.063	2.257	3.422	4.773	5.508	7.882	11.040	13.348	18.741
2001	0.0229	0.097	0.456	1.305	2.420	3.851	5.091	6.513	6.912	9.042	14.823	16.934
2002	0.0115	0.089	0.465	1.050	2.249	3.247	5.296	6.514	7.924	10.032	9.746	18.741
2003	0.0217	0.089	0.346	1.053	1.742	2.977	4.118	6.837	8.011	9.693	11.538	15.128
2004	0.0105	0.066	0.351	0.971	2.110	2.620	4.199	5.908	8.627	10.747	12.280	15.612
2005	0.0082	0.060	0.248	0.821	1.654	3.338	3.841	5.758	7.593	10.204	13.212	15.649
2006	0.0428	0.089	0.295	0.808	1.890	2.467	4.076	4.912	6.744	8.837	11.620	16.704
2007	0.0086	0.124	0.450	0.925	1.771	3.005	3.723	5.020	6.329	8.703	10.979	15.470
2008	0.0464	0.085	0.420	1.117	1.888	2.892	3.630	5.147	6.803	8.308	12.351	16.157
2009	0.0137	0.171	0.480	1.248	2.283	2.908	3.658	4.735	6.735	9.047	9.942	15.516
2010	0.0061	0.100	0.589	1.168	2.328	3.198	3.685	4.778	7.153	8.815	10.755	14.649
2011	0.0836	0.087	0.492	1.353	1.972	3.262	4.114	4.788	5.751	10.189	11.448	18.157
2012	0.0253	0.096	0.414	1.052	1.989	2.991	4.034	5.440	7.167	9.457	11.387	16.178

App. A4 (Append. A), Table A3: Mean weight-at-age (kg) of landings for the Gulf of Maine cod stock applying the revised mortality assumptions (Michael Palmer, pers. commn). Pre-1982, the 1982-1991 average mean weight-at-age is assumed.

	0	1	2	3	4	5	6	7	8	9	10	11+
1982	0.013	0.356	0.858	1.514	2.606	5.067	7.065	9.620	9.772	12.642	19.230	18.240
1983	0.024	0.224	0.768	1.542	2.418	3.808	6.055	6.071	10.317	11.424	11.535	18.713
1984	0.001	0.234	0.653	1.478	2.678	3.609	5.540	8.368	10.138	13.595	14.419	16.087
1985	0.039	0.206	0.733	1.404	2.819	4.658	5.884	8.502	11.244	12.256	13.587	14.610
1986	0.005	0.277	0.501	1.699	2.774	4.778	6.504	8.109	10.207	13.170	13.827	18.102
1987	0.004	0.154	0.642	1.323	3.090	4.668	7.259	10.036	11.099	13.739	14.899	16.407
1988	0.003	0.122	0.577	1.667	2.360	5.206	5.200	6.193	10.103	10.434	17.787	12.054
1989	0.046	0.237	0.752	1.518	2.959	4.282	5.980	9.276	12.519	16.810	20.410	24.532
1990	0.021	0.193	0.811	1.349	2.141	4.474	7.721	10.820	11.750	15.440	16.344	22.637
1991	0.014	0.236	1.113	1.601	2.281	3.894	7.144	10.429	12.261	15.276	6.122	24.937
1992	0.023	0.055	1.033	1.530	2.747	2.976	5.588	10.921	10.483	13.418	19.072	23.406
1993	0.021	0.081	0.690	1.748	2.150	4.420	5.670	9.817	13.673	12.332	17.586	23.790
1994	0.022	0.058	0.730	1.712	3.085	3.251	6.335	7.684	12.542	9.563	22.008	22.643
1995	0.027	0.103	1.288	1.591	2.649	5.090	6.865	11.466	13.128	19.756	23.143	22.643
1996	0.033	0.100	1.293	2.096	2.260	3.462	7.558	11.728	14.455	16.269	19.490	22.643
1997	0.017	0.064	1.351	2.128	3.022	3.074	4.699	9.000	12.156	15.625	17.749	17.655
1998	0.008	0.202	1.071	1.931	2.633	3.972	4.255	7.122	12.118	17.500	15.060	17.655
1999	0.052	0.222	0.635	1.723	2.777	3.892	5.670	6.704	9.811	12.279	16.823	17.655
2000	0.030	0.282	1.081	2.150	3.316	4.325	5.898	5.352	9.331	12.401	14.506	19.056
2001	0.045	0.316	0.890	2.176	3.144	4.666	6.140	7.273	9.072	8.788	17.660	15.417
2002	0.032	0.185	0.795	1.797	2.906	3.792	6.132	6.969	8.809	11.036	10.796	19.056
2003	0.038	0.202	0.809	1.843	2.378	3.654	5.112	7.649	9.191	10.871	11.890	15.176
2004	0.025	0.111	0.483	1.606	2.965	3.547	5.350	7.220	9.764	12.557	13.931	15.657
2005	0.027	0.126	0.558	1.625	2.401	4.233	4.502	6.350	8.002	10.698	13.899	15.627
2006	0.071	0.289	0.648	1.493	2.932	3.357	4.463	5.562	7.430	9.779	12.646	16.704
2007	0.025	0.220	0.744	1.731	2.922	3.735	4.771	6.167	7.302	10.554	12.338	15.470
2008	0.085	0.247	0.862	2.179	2.818	3.530	3.988	5.819	7.528	9.464	14.461	16.174
2009	0.032	0.337	0.911	2.153	3.126	3.575	4.368	5.959	8.000	10.894	10.454	15.523
2010	0.023	0.264	1.200	1.995	3.203	3.914	4.447	5.708	8.730	9.967	10.628	14.650
2011	0.0856	0.3289	0.9331	2.0561	2.874	3.8696	4.839	5.7166	5.9528	11.876	13.15	18.157

App. A4 (Append. A), Table A4: Mean weight-at-age (kg) in the NEFSC spring and fall surveys, used to compute Albatross converted survey biomass indices.

	0	1	2	3	4	5	6	7	8	9	10	11+
NEFSC spring survey												
2009	0.000	0.031	0.523	1.441	2.067	2.601	2.876	8.067	9.930	0.000	12.919	-
2010	0.000	0.076	0.356	1.203	2.805	3.849	4.602	7.314	10.712	10.247	22.407	17.019
2011	0.000	0.064	0.453	1.177	1.717	2.706	3.509	5.906	8.521	-	-	-
2012	0.000	0.082	0.517	1.299	2.060	2.462	3.235	5.047	11.576	6.323	-	-
NEFSC fall survey												
2009	0.035	0.555	1.174	3.366	4.503	10.575	6.618	-	-	-	-	-
2010	0.019	0.335	1.170	1.774	3.904	4.784	4.548	3.461	-	-	-	25.000
2011	0.022	0.286	0.942	1.775	2.323	4.581	4.931	10.775	7.135	-	-	-

App. A4 (Append. A), Table A5: Total (commercial and recreational landings and discards) catches-at-age for the Gulf of Maine cod stock, applying the revised mortality assumptions (Michael Palmer, pers. commn).

	0	1	2	3	4	5	6	7	8	9+
1982	1346	448849	2926542	2287192	1430682	748755	65880	94051	72553	90055
1983	13645	597496	2462037	2913215	1201593	704010	452680	50022	62542	56198
1984	18275	370324	2129556	1675931	1643588	437453	219625	105649	9495	53395
1985	67101	505660	1944327	2405137	1151815	738096	161362	107192	48359	33213
1986	17767	760701	1747046	2747811	991982	279282	202725	48016	38188	47527
1987	100702	281794	2018317	1568334	1574499	345353	89415	81032	14459	37549
1988	3446	415081	1542790	2086633	1156925	447729	67430	25560	26247	9267
1989	43	166436	1247203	2385088	1651856	521108	87147	70289	9369	19564
1990	0	65527	812544	5547767	2717623	541353	189069	29703	36417	43315
1991	3251	121627	499588	942731	5561272	1037852	150670	55540	25983	15805
1992	23803	370302	830147	867564	502084	2189957	226167	80181	6044	5530
1993	26570	105929	512307	2149041	944709	103328	497117	41561	11264	0
1994	11734	123996	201923	1525603	1294203	266291	66224	74158	28714	7870
1995	11572	78932	319462	1321833	1260435	221653	29931	6521	18184	2808
1996	22067	37536	111569	627693	2003886	405881	36651	4039	491	1623
1997	1472	69144	137484	519557	467768	869161	72472	5523	2272	1029
1998	917	5941	171062	492301	628941	152820	205873	28696	5168	2257
1999	63	73948	90853	347840	336596	172344	53699	59469	12388	1067
2000	0	24758	485043	556537	813684	176640	85157	12485	10521	0
2001	0	584	393951	1163770	684449	385530	106600	57232	8262	11577
2002	0	16831	41591	374949	912638	323797	163476	66392	28087	20263
2003	22873	44899	125587	167812	582079	706098	186022	75694	29224	26844
2004	187	149420	105917	609344	259720	407447	251632	68378	33017	27442
2005	1487	23545	180064	159581	945815	89223	246596	109148	28457	31674
2006	231	19249	59082	426566	290132	461742	30341	79655	39016	27343
2007	430	12171	108471	299416	976424	137404	230163	7947	19244	21999
2008	415	12156	130508	598424	707392	780450	86355	110576	4041	16558
2009	99	10651	101492	622453	1093273	477852	304754	20896	30506	9646
2010	213	8159	83580	394486	888549	668256	164291	71683	11213	7611
2011	653	8683	60526	322164	589583	573856	339910	34926	38408	9433

App. A4 (Append. A), Table A6: Standardized stratified mean numbers per tow at age and standardized mean weight (kg) per tow of Atlantic cod in NEFSC offshore spring research vessel bottom trawl surveys in the Gulf of Maine, 1968-2012 (Michael Palmer, pers. commn).

	0	1	2	3	4	5	6	7	8	9	10	11+	Stratified mean wt/tow	CV
1968													17.480	(0.153)
1969													13.100	(0.329)
1970	0.000	0.159	0.124	0.053	0.098	0.290	0.475	0.589	0.073	0.045	0.076	0.210	11.089	(0.237)
1971	0.000	0.069	0.109	0.099	0.280	0.086	0.096	0.280	0.207	0.142	0.050	0.013	7.004	(0.211)
1972	0.053	0.300	0.153	0.499	0.208	0.205	0.052	0.083	0.119	0.300	0.027	0.059	8.031	(0.233)
1973	0.000	0.053	4.273	0.917	0.614	0.384	0.144	0.106	0.186	0.276	0.186	0.386	18.807	(0.415)
1974	0.164	0.311	0.081	1.534	0.177	0.231	0.082	0.000	0.064	0.038	0.089	0.131	7.419	(0.199)
1975	0.012	0.094	0.707	0.095	1.139	0.246	0.073	0.000	0.006	0.025	0.028	0.088	6.039	(0.249)
1976	0.000	0.052	0.253	1.114	0.150	0.870	0.131	0.056	0.038	0.000	0.036	0.081	7.556	(0.166)
1977	0.000	0.068	0.264	0.460	2.015	0.139	0.775	0.000	0.114	0.000	0.000	0.038	8.541	(0.208)
1978	0.000	0.070	0.083	0.297	0.383	0.764	0.084	0.226	0.013	0.108	0.000	0.022	7.697	(0.207)
1979	0.044	0.426	1.407	0.186	0.470	0.301	0.549	0.094	0.104	0.013	0.031	0.020	7.555	(0.176)
1980	0.070	0.037	0.500	0.436	0.123	0.294	0.226	0.337	0.000	0.105	0.026	0.000	6.232	(0.182)
1981	0.000	1.091	0.619	0.850	1.335	0.318	0.304	0.080	0.144	0.091	0.000	0.000	10.650	(0.205)
1982	0.014	0.357	1.040	0.498	0.737	0.848	0.083	0.135	0.000	0.040	0.010	0.000	8.616	(0.223)
1983	0.013	0.610	0.968	1.042	0.453	0.336	0.250	0.060	0.000	0.071	0.033	0.077	10.962	(0.225)
1984	0.000	0.151	1.309	0.987	0.853	0.229	0.047	0.090	0.000	0.000	0.000	0.000	6.143	(0.324)
1985	0.000	0.029	0.238	0.676	0.612	0.707	0.094	0.109	0.026	0.026	0.000	0.000	7.645	(0.223)
1986	0.000	0.537	0.259	0.767	0.218	0.075	0.046	0.038	0.000	0.000	0.000	0.018	3.476	(0.197)
1987	0.000	0.030	0.471	0.191	0.222	0.075	0.000	0.068	0.011	0.000	0.000	0.015	1.976	(0.314)
1988	0.029	0.719	0.926	0.791	0.283	0.205	0.099	0.036	0.020	0.020	0.000	0.000	3.603	(0.281)
1989	0.000	0.025	0.609	0.712	0.630	0.069	0.068	0.000	0.000	0.000	0.000	0.000	2.424	(0.207)
1990	0.000	0.009	0.233	1.325	0.669	0.076	0.032	0.018	0.000	0.000	0.000	0.000	3.077	(0.280)
1991	0.000	0.028	0.077	0.233	1.750	0.247	0.041	0.018	0.000	0.000	0.000	0.000	2.891	(0.240)
1992	0.000	0.050	0.247	0.223	0.248	1.368	0.213	0.073	0.000	0.012	0.000	0.000	8.627	(0.374)
1993	0.000	0.201	0.507	0.804	0.364	0.084	0.446	0.055	0.023	0.000	0.023	0.000	5.875	(0.347)
1994	0.000	0.015	0.316	0.407	0.201	0.083	0.053	0.142	0.009	0.027	0.018	0.000	2.428	(0.216)
1995	0.000	0.037	0.187	1.165	0.321	0.147	0.034	0.000	0.011	0.000	0.028	0.000	2.432	(0.257)
1996	0.000	0.057	0.022	0.586	1.355	0.385	0.060	0.000	0.000	0.000	0.000	0.000	5.427	(0.275)
1997	0.000	0.159	0.139	0.390	0.271	0.874	0.244	0.115	0.000	0.000	0.000	0.000	5.616	(0.192)
1998	0.000	0.018	0.228	0.359	0.513	0.143	0.408	0.021	0.020	0.000	0.000	0.000	4.180	(0.324)
1999	0.000	0.166	0.342	0.726	0.351	0.305	0.134	0.266	0.000	0.000	0.000	0.011	5.090	(0.320)
2000	0.026	1.173	0.737	0.438	0.485	0.099	0.092	0.011	0.022	0.000	0.000	0.000	3.211	(0.155)
2001	0.000	0.029	0.355	0.683	0.510	0.342	0.065	0.097	0.055	0.000	0.011	0.000	6.215	(0.327)
2002	0.000	0.340	0.045	0.548	1.584	0.606	0.342	0.185	0.057	0.017	0.000	0.000	10.934	(0.215)
2003	0.000	0.075	0.825	0.059	0.718	1.072	0.387	0.340	0.081	0.082	0.030	0.011	9.495	(0.368)
2004	0.000	0.136	0.045	0.230	0.116	0.208	0.213	0.011	0.011	0.010	0.000	0.000	2.412	(0.293)
2005	0.000	0.029	0.739	0.081	0.623	0.011	0.138	0.128	0.015	0.000	0.000	0.000	2.701	(0.248)
2006	0.028	0.184	0.237	0.434	0.049	0.197	0.023	0.126	0.069	0.000	0.015	0.000	2.702	(0.249)
2007	0.000	0.100	3.422	3.077	4.446	0.437	0.796	0.075	0.041	0.000	0.000	0.000	15.811	(0.540)
2008	0.000	0.079	1.165	3.930	1.582	1.099	0.053	0.082	0.000	0.000	0.000	0.000	10.823	(0.609)
2009	0.000	0.063	0.279	1.050	1.135	0.600	0.438	0.008	0.022	0.000	0.004	0.000	7.161	(0.491)
2010	0.000	0.059	0.279	0.335	0.197	0.229	0.113	0.043	0.016	0.010	0.005	0.010	3.336	(0.264)
2011	0.000	0.005	0.024	0.140	0.383	0.189	0.086	0.033	0.035	0.000	0.000	0.000	2.133	(0.201)
2012	0.000	0.069	0.105	0.224	0.243	0.159	0.051	0.036	0.004	0.003	0.000	0.000	1.645	(0.209)

App. A4 (Append. A), Table A7: Standardized stratified mean numbers per tow at age and standardized mean weight (kg) per tow of Atlantic cod in NEFSC offshore autumn research vessel bottom trawl surveys in the Gulf of Maine, 1964-2011 (Michael Palmer, pers. commn).

	0	1	2	3	4	5	6	7	8	9	10	11+	Stratified mean wt/tow	CV
1964	-	-	-	-	-	-	-	-	-	-	-	-	22.799	(0.496)
1965	-	-	-	-	-	-	-	-	-	-	-	-	12.089	(0.273)
1966	-	-	-	-	-	-	-	-	-	-	-	-	12.838	(0.227)
1967	-	-	-	-	-	-	-	-	-	-	-	-	9.313	(0.219)
1968	-	-	-	-	-	-	-	-	-	-	-	-	19.437	(0.198)
1969	-	-	-	-	-	-	-	-	-	-	-	-	15.154	(0.217)
1970	0.743	0.938	0.254	0.520	0.336	0.487	0.424	0.836	0.130	0.090	0.037	0.110	16.442	(0.248)
1971	1.334	0.207	0.224	0.190	0.607	0.444	0.509	0.222	0.280	0.193	0.031	0.121	16.529	(0.307)
1972	0.031	5.663	1.118	1.595	0.181	0.072	0.122	0.031	0.121	0.351	0.000	0.016	12.988	(0.199)
1973	0.638	0.327	2.146	0.179	0.540	0.191	0.055	0.018	0.039	0.182	0.122	0.016	8.764	(0.267)
1974	0.265	1.131	0.267	1.922	0.125	0.276	0.000	0.052	0.036	0.066	0.000	0.189	8.959	(0.201)
1975	0.006	0.223	3.028	0.139	2.354	0.250	0.105	0.020	0.000	0.000	0.000	0.018	8.619	(0.153)
1976	0.000	0.209	0.216	0.578	0.104	0.835	0.044	0.099	0.000	0.000	0.063	0.000	6.740	(0.214)
1977	0.000	0.046	0.446	0.456	1.151	0.133	0.604	0.024	0.083	0.021	0.061	0.048	10.199	(0.126)
1978	0.241	1.411	0.359	1.141	0.661	1.450	0.101	0.269	0.012	0.082	0.000	0.047	12.899	(0.151)
1979	0.000	0.364	0.617	0.131	0.696	0.319	0.754	0.056	0.135	0.000	0.053	0.018	13.927	(0.128)
1980	0.027	1.319	2.558	1.664	0.518	0.236	0.402	0.192	0.022	0.012	0.000	0.085	14.202	(0.153)
1981	0.010	0.581	0.399	0.469	0.509	0.092	0.081	0.081	0.099	0.000	0.028	0.000	7.533	(0.233)
1982	0.000	0.835	3.264	2.476	0.971	0.222	0.000	0.000	0.000	0.000	0.000	0.000	15.919	(0.670)
1983	0.000	0.305	0.905	0.757	0.267	0.250	0.219	0.000	0.000	0.000	0.018	0.065	8.416	(0.188)
1984	0.000	0.513	0.418	0.586	0.384	0.196	0.194	0.062	0.000	0.016	0.000	0.080	8.735	(0.334)
1985	0.218	0.445	0.917	0.627	0.201	0.246	0.064	0.000	0.034	0.070	0.000	0.000	8.264	(0.354)
1986	0.000	0.394	0.404	0.626	0.368	0.073	0.041	0.000	0.000	0.045	0.000	0.000	4.715	(0.228)
1987	0.128	0.570	1.388	0.586	0.198	0.125	0.000	0.000	0.000	0.000	0.000	0.000	3.394	(0.234)
1988	0.000	1.889	2.366	1.069	0.367	0.146	0.000	0.044	0.000	0.011	0.011	0.000	6.616	(0.232)
1989	0.000	0.145	2.468	1.458	0.283	0.138	0.053	0.000	0.009	0.000	0.000	0.000	4.535	(0.181)
1990	0.000	0.057	0.218	1.788	0.611	0.255	0.048	0.010	0.000	0.000	0.000	0.000	4.912	(0.204)
1991	0.009	0.144	0.151	0.230	0.621	0.075	0.000	0.023	0.000	0.000	0.000	0.000	2.782	(0.246)
1992	0.059	0.289	0.448	0.144	0.041	0.327	0.126	0.000	0.000	0.000	0.000	0.000	2.448	(0.243)
1993	0.031	0.210	0.575	0.361	0.017	0.000	0.038	0.000	0.000	0.000	0.000	0.000	1.003	(0.263)
1994	0.032	0.184	0.909	0.816	0.093	0.051	0.000	0.045	0.000	0.000	0.000	0.000	2.737	(0.292)
1995	0.008	0.068	0.308	1.226	0.304	0.082	0.011	0.000	0.000	0.000	0.000	0.000	3.665	(0.325)
1996	0.029	0.122	0.379	0.231	0.516	0.050	0.000	0.000	0.000	0.000	0.000	0.000	2.352	(0.249)
1997	0.000	0.297	0.091	0.165	0.168	0.151	0.000	0.000	0.000	0.000	0.000	0.000	1.872	(0.307)
1998	0.050	0.085	0.342	0.110	0.185	0.041	0.031	0.000	0.000	0.000	0.000	0.000	1.501	(0.287)
1999	0.025	0.432	0.375	0.590	0.244	0.122	0.019	0.000	0.000	0.000	0.000	0.000	3.505	(0.193)
2000	0.008	0.540	0.981	0.399	0.492	0.140	0.010	0.000	0.034	0.000	0.000	0.000	4.652	(0.332)
2001	0.018	0.000	0.171	0.720	0.478	0.356	0.124	0.092	0.000	0.023	0.000	0.000	7.324	(0.279)
2002	0.000	0.269	0.104	0.333	2.683	1.070	0.750	0.077	0.043	0.000	0.000	0.000	24.659	(0.686)
2003	0.542	0.461	0.186	0.216	0.518	0.451	0.071	0.062	0.000	0.011	0.000	0.011	5.988	(0.251)
2004	1.369	0.661	0.172	0.577	0.254	0.250	0.149	0.057	0.023	0.010	0.011	0.000	4.906	(0.214)
2005	0.034	0.153	0.378	0.078	0.456	0.023	0.090	0.082	0.023	0.021	0.000	0.000	2.897	(0.228)
2006	0.064	1.241	0.599	1.007	0.252	0.293	0.037	0.053	0.036	0.000	0.000	0.014	4.229	(0.188)
2007	0.011	0.136	0.863	0.395	0.496	0.023	0.067	0.000	0.000	0.000	0.000	0.000	2.714	(0.277)
2008	0.165	0.650	1.227	1.060	0.189	0.139	0.000	0.000	0.000	0.010	0.021	0.000	5.307	(0.285)
2009	0.020	0.660	2.096	0.314	0.277	0.045	0.035	0.000	0.000	0.000	0.000	0.000	5.845	(0.429)
2010	0.008	0.094	0.132	0.290	0.288	0.092	0.023	0.013	0.000	0.000	0.000	0.006	2.572	(0.304)
2011	0.036	0.060	0.091	0.210	0.304	0.175	0.078	0.005	0.031	0.000	0.000	0.000	2.647	(0.336)

App. A4 (Append. A), Table A8: Stratified mean catch per tow in numbers and weight (kg) of Atlantic cod in State of Massachusetts inshore spring bottom trawl surveys in territorial waters adjacent to the Gulf of Maine (Mass. Regions 4-5), 1978-2012 (Michael Palmer, pers. commn).

	0	1	2	3	4	5	6	7	8	9	10	11+	Stratified mean wt/tow	CV
1978													11.058	(0.138)
1979													14.276	(0.219)
1980													14.509	(0.128)
1981													18.689	(0.265)
1982	1.668	13.218	6.649	2.921	1.024	0.216	0.049	0.046	0.050	0.000	0.000	0.000	12.161	(0.175)
1983	0.718	30.253	17.570	4.710	0.347	1.121	0.075	0.023	0.033	0.000	0.000	0.000	18.746	(0.153)
1984	0.257	1.898	5.090	2.101	0.751	0.147	0.086	0.000	0.000	0.000	0.000	0.000	7.240	(0.259)
1985	1.569	1.670	2.695	2.024	0.498	0.000	0.000	0.000	0.000	0.000	0.000	0.000	4.765	(0.194)
1986	1.075	18.031	3.376	0.903	0.582	0.100	0.023	0.000	0.000	0.000	0.000	0.000	7.841	(0.354)
1987	0.725	8.622	5.376	2.045	0.168	0.147	0.053	0.000	0.000	0.070	0.000	0.000	7.865	(0.271)
1988	1.895	10.409	6.750	1.927	1.211	0.016	0.033	0.000	0.000	0.000	0.000	0.000	7.703	(0.237)
1989	0.298	21.463	22.947	6.868	0.513	0.108	0.048	0.000	0.000	0.000	0.000	0.000	17.346	(0.342)
1990	4.930	4.972	5.938	14.182	2.149	0.155	0.083	0.000	0.000	0.000	0.000	0.000	15.879	(0.341)
1991	0.355	5.331	2.295	1.801	3.669	0.249	0.000	0.000	0.000	0.000	0.000	0.000	8.730	(0.122)
1992	1.506	4.379	5.699	3.444	0.484	1.301	0.066	0.044	0.000	0.000	0.000	0.000	8.766	(0.321)
1993	80.090	2.842	6.100	2.509	0.879	0.166	0.074	0.000	0.000	0.000	0.000	0.000	5.861	(0.270)
1994	4.627	5.406	3.883	1.703	0.608	0.131	0.000	0.000	0.000	0.000	0.000	0.000	4.334	(0.241)
1995	11.998	5.985	2.420	2.408	0.525	0.028	0.000	0.000	0.000	0.000	0.000	0.000	3.993	(0.225)
1996	8.843	0.777	0.497	0.955	1.590	0.299	0.000	0.000	0.000	0.000	0.000	0.000	3.152	(0.305)
1997	12.431	2.910	1.035	0.920	0.190	0.383	0.018	0.000	0.000	0.000	0.000	0.000	2.500	(0.250)
1998	23.481	1.487	0.924	0.779	0.637	0.034	0.211	0.017	0.000	0.000	0.000	0.000	3.250	(0.468)
1999	143.000	11.832	2.407	2.275	0.735	0.630	0.036	0.127	0.017	0.000	0.000	0.000	8.997	(0.261)
2000	2.151	35.360	6.995	2.371	2.316	0.784	0.663	0.059	0.073	0.000	0.000	0.000	20.604	(0.459)
2001	25.987	0.084	4.998	4.710	3.448	1.961	0.323	0.227	0.106	0.000	0.000	0.000	26.445	(0.536)
2002	0.924	19.340	0.220	1.379	1.145	0.561	0.318	0.111	0.253	0.025	0.049	0.012	11.158	(0.390)
2003	0.000	17.109	5.496	0.439	1.938	0.937	0.221	0.074	0.014	0.025	0.000	0.014	10.984	(0.219)
2004	116.135	8.927	1.882	2.627	0.361	1.083	0.455	0.076	0.029	0.000	0.014	0.000	8.147	(0.278)
2005	179.479	5.524	4.141	0.795	1.955	0.263	0.663	0.243	0.094	0.105	0.000	0.000	10.402	(0.197)
2006	0.000	9.992	7.139	3.930	0.525	1.532	0.109	0.057	0.000	0.017	0.028	0.000	9.177	(0.181)
2007	49.323	3.776	3.078	2.303	2.163	0.343	0.519	0.025	0.046	0.000	0.000	0.000	8.430	(0.251)
2008	456.954	7.275	10.336	3.242	2.287	1.695	0.155	0.155	0.000	0.000	0.000	0.000	12.229	(0.215)
2009	466.098	8.907	2.350	1.654	1.045	0.348	0.112	0.000	0.000	0.000	0.000	0.000	4.489	(0.187)
2010	1.165	2.415	1.393	1.423	0.819	0.678	0.129	0.000	0.000	0.000	0.052	0.000	5.645	(0.456)
2011	55.378	0.326	1.001	0.621	0.933	0.558	0.139	0.086	0.021	0.000	0.000	0.000	4.519	(0.424)
2012	6.239	3.368	0.671	0.446	0.304	0.415	0.021	0.000	0.000	0.000	0.000	0.000	2.276	(0.401)

App. A4 (Append. A), Table A9: Percentage of mature females for each age for the Gulf of Maine cod stock (Michael Palmer, pers. commn).

0	1	2	3	4	5	6	7	8	9	10	11+
0.025	0.092	0.287	0.613	0.862	0.961	0.990	0.997	0.999	1.000	1.000	1.000

App. A4 (Append. A), Table A10: Length frequency distributions for NEFSC offshore spring and autumn research vessel bottom trawl surveys in the Gulf of Maine conducted by the *Bigelow* (Michael Palmer, pers. commn).

	NEFSC spring survey				NEFSC call survey		
Year	2009	2010	2011	2012	2009	2010	2011
-25cm	0.5634	0.4138	0.0286	0.4159	0.3967	0.0605	0.2489
26cm	0.0496	0.0189	0.0000	0.0113	0.1330	0.0283	0.0850
27cm	0.0425	0.0756	0.0000	0.0057	0.1731	0.0142	0.0283
28cm	0.0638	0.1501	0.0000	0.0170	0.1251	0.0000	0.0142
29cm	0.0553	0.0945	0.0000	0.0057	0.1330	0.0283	0.0000
30cm	0.0283	0.1134	0.0000	0.0113	0.2330	0.0567	0.0142
31cm	0.0544	0.1397	0.0486	0.0057	0.2834	0.0283	0.0136
32cm	0.0142	0.0945	0.0113	0.0337	0.4412	0.1134	0.0377
33cm	0.0213	0.0935	0.0113	0.0113	0.5951	0.0425	0.0142
34cm	0.0958	0.1572	0.0000	0.0404	0.9068	0.0567	0.0506
35cm	0.0743	0.1407	0.0227	0.0170	0.7147	0.0142	0.0283
36cm	0.0887	0.1029	0.0000	0.0582	0.6659	0.0394	0.0142
37cm	0.0695	0.0853	0.0340	0.0283	0.5014	0.0278	0.0000
38cm	0.1204	0.0945	0.0113	0.0207	0.6155	0.0425	0.0000
39cm	0.1748	0.0567	0.0000	0.0659	0.3400	0.0142	0.0543
40cm	0.1559	0.0283	0.0431	0.0548	0.2516	0.0242	0.0283
41cm	0.1629	0.0283	0.0227	0.0453	0.2888	0.0425	0.0364
42cm	0.1771	0.0276	0.0599	0.0639	0.3103	0.0850	0.0380
43cm	0.1565	0.0378	0.0793	0.0564	0.2834	0.0425	0.0401
44cm	0.2125	0.0378	0.0907	0.0860	0.3400	0.0283	0.0222
45cm	0.2287	0.0378	0.0340	0.0746	0.3280	0.0384	0.0640
46cm	0.2196	0.0283	0.0214	0.0380	0.2776	0.0283	0.0567
47cm	0.1913	0.0189	0.0340	0.0434	0.1901	0.0242	0.0000
48cm	0.2371	0.0095	0.0340	0.0283	0.2692	0.0425	0.0364
49cm	0.2017	0.0283	0.0214	0.0394	0.2125	0.0343	0.0623
50cm	0.2240	0.0647	0.0793	0.0510	0.1700	0.0283	0.0647
51cm	0.1845	0.0095	0.0441	0.0264	0.0951	0.0394	0.0364
52cm	0.3077	0.0953	0.0768	0.0944	0.1199	0.0778	0.0383
53cm	0.2122	0.0000	0.0680	0.0394	0.0992	0.0142	0.0425
54cm	0.2517	0.1236	0.0826	0.0567	0.0809	0.0425	0.0506
55cm	0.3245	0.0322	0.0340	0.0453	0.0708	0.0384	0.0330
56cm	0.1946	0.0646	0.0700	0.0491	0.0000	0.0425	0.0599
57cm	0.2046	0.0276	0.0441	0.0377	0.0492	0.0567	0.0000
58cm	0.2358	0.0370	0.0582	0.0644	0.0384	0.0242	0.0000
59cm	0.2347	0.0455	0.0000	0.0519	0.0686	0.0257	0.0161
60cm	0.2537	0.0444	0.0227	0.0349	0.0425	0.0142	0.0383
61cm	0.2547	0.0000	0.0803	0.0511	0.0447	0.0242	0.0588
62cm	0.1164	0.0081	0.0214	0.0227	0.0307	0.0401	0.0383
63cm	0.2003	0.0180	0.0113	0.0154	0.0142	0.0236	0.0222
64cm	0.1725	0.0227	0.0214	0.0406	0.0874	0.0142	0.1130
65cm	0.0341	0.0000	0.0302	0.0227	0.0142	0.0336	0.0222
66cm	0.0611	0.0189	0.0467	0.0170	0.0667	0.0401	0.0303
67cm	0.0850	0.0544	0.0101	0.0321	0.0201	0.0242	0.0303
68cm	0.0414	0.0276	0.0227	0.0154	0.0196	0.0848	0.0401
69cm	0.0370	0.0000	0.0372	0.0154	0.0142	0.0000	0.0481
70cm	0.0923	0.0632	0.0259	0.0170	0.0283	0.0201	0.0581
71cm	0.0387	0.0161	0.0101	0.0097	0.0142	0.0353	0.0283
72cm	0.0287	0.0719	0.0322	0.0057	0.0696	0.0236	0.0259
73cm	0.0259	0.0322	0.0349	0.0000	0.0350	0.0310	0.0420
74cm	0.0128	0.0423	0.0113	0.0097	0.0108	0.0142	0.0081
75cm	0.0199	0.0000	0.0101	0.0000	0.0101	0.0360	0.0081
76cm	0.0704	0.0081	0.0000	0.0000	0.0283	0.0840	0.0222
77cm	0.0058	0.0161	0.0000	0.0196	0.0142	0.0000	0.0222
78cm	0.0115	0.0181	0.0101	0.0057	0.0000	0.0201	0.0000
79cm	0.0058	0.0563	0.0227	0.0057	0.0283	0.0283	0.0108
80cm	0.0270	0.0181	0.0101	0.0040	0.0000	0.0101	0.0000
81cm	0.0270	0.0343	0.0000	0.0054	0.0000	0.0000	0.0540
82cm	0.0000	0.0000	0.0101	0.0000	0.0101	0.0000	0.0222
83cm	0.0283	0.0000	0.0000	0.0000	0.0000	0.0000	0.0161
84cm	0.0115	0.0489	0.0000	0.0000	0.0000	0.0454	0.0000
85cm	0.0115	0.0081	0.0259	0.0000	0.0000	0.0236	0.0081
86cm	0.0071	0.0262	0.0101	0.0000	0.0000	0.0101	0.0000
87cm	0.0186	0.0081	0.0000	0.0000	0.0000	0.0000	0.0000
88cm	0.0058	0.0000	0.0000	0.0057	0.0142	0.0101	0.0142
89cm	0.0058	0.0161	0.0000	0.0000	0.0000	0.0000	0.0000
90cm	0.0071	0.0081	0.0113	0.0000	0.0101	0.0000	0.0000
91cm	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
92cm	0.0058	0.0000	0.0000	0.0057	0.0000	0.0000	0.0142
93cm	0.0000	0.0000	0.0000	0.0000	0.0101	0.0000	0.0081
94cm	0.0058	0.0081	0.0340	0.0000	0.0000	0.0000	0.0000
95cm	0.0058	0.0000	0.0000	0.0000	0.0000	0.0000	0.0081
96cm	0.0128	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
97cm	0.0000	0.0000	0.0000	0.0000	0.0142	0.0000	0.0000
98cm	0.0000	0.0081	0.0000	0.0057	0.0000	0.0000	0.0081
99cm	0.0000	0.0175	0.0000	0.0000	0.0000	0.0000	0.0000
100cm+	0.0115	0.0403	0.0214	0.0000	0.0000	0.0101	0.0081

App. A4 (Append. A), Table A11a: Age-length keys for NEFSC offshore spring research vessel bottom trawl surveys in the Gulf of Maine conducted by the *Bigelow* (Michael Palmer, pers. commn).

	NEFSC Spring, 2009							Age					NEFSC Spring, 2010							Age				
Length	0	1	2	3	4	5	6	7	8	9	10	11+	0	1	2	3	4	5	6	7	8	9	10	11+
≤25	0	39	24	0	0	0	0	0	0	0	0	0	0	28	11	0	0	0	0	0	0	0	0	0
26	0	0	5	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
27	0	0	4	1	0	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0
28	0	0	3	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0
29	0	0	7	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0
30	0	0	2	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0
31	0	0	6	0	0	0	0	0	0	0	0	0	0	0	6	1	0	0	0	0	0	0	0	0
32	0	0	0	1	0	0	0	0	0	0	0	0	0	0	5	0	0	0	0	0	0	0	0	0
33	0	0	3	0	0	0	0	0	0	0	0	0	0	0	3	1	0	0	0	0	0	0	0	0
34	0	0	1	5	0	0	0	0	0	0	0	0	0	0	2	4	0	0	0	0	0	0	0	0
35	0	0	4	3	0	0	0	0	0	0	0	0	0	0	2	4	0	0	0	0	0	0	0	0
36	0	0	4	1	0	0	0	0	0	0	0	0	0	0	3	1	0	0	0	0	0	0	0	0
37	0	0	2	4	0	0	0	0	0	0	0	0	0	0	1	4	0	0	0	0	0	0	0	0
38	0	0	2	4	0	0	0	0	0	0	0	0	0	0	2	2	0	0	0	0	0	0	0	0
39	0	0	1	2	1	0	0	0	0	0	0	0	0	0	3	4	0	0	0	0	0	0	0	0
40	0	0	2	6	0	0	0	0	0	0	0	0	0	0	2	1	0	1	0	0	0	0	0	0
41	0	0	2	2	1	1	0	0	0	0	0	0	0	0	1	3	0	0	0	0	0	0	0	0
42	0	0	1	1	0	0	0	0	0	0	0	0	0	0	1	2	0	0	0	0	0	0	0	0
43	0	0	2	5	0	0	0	0	0	0	0	0	0	0	2	1	0	1	0	0	0	0	0	0
44	0	0	1	5	0	0	0	0	0	0	0	0	0	0	2	3	1	0	0	0	0	0	0	0
45	0	0	1	6	4	1	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0
46	0	0	0	3	2	2	1	0	0	0	0	0	0	0	0	2	1	0	1	0	0	0	0	0
47	0	0	0	2	2	0	0	0	0	0	0	0	0	0	0	2	2	0	0	0	0	0	0	0
48	0	0	0	2	4	1	0	0	0	0	0	0	0	0	0	1	3	0	0	0	0	0	0	0
49	0	0	0	3	4	1	2	0	0	0	0	0	0	0	0	2	0	1	1	0	0	0	0	0
50	0	0	0	2	5	1	0	0	0	0	0	0	0	0	0	2	3	2	0	0	0	0	0	0
51	0	0	1	2	2	0	1	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0
52	0	0	0	4	4	0	0	0	0	0	0	0	0	0	0	4	2	1	0	0	0	0	0	0
53	0	0	0	3	4	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
54	0	0	0	2	2	2	0	0	0	0	0	0	0	0	0	7	1	2	0	0	0	0	0	0
55	0	0	0	5	1	2	1	0	0	0	0	0	0	0	0	2	1	0	0	0	0	0	0	0
56	0	0	0	1	2	0	1	0	0	0	0	0	0	0	0	2	2	2	0	0	0	0	0	0
57	0	0	0	2	3	2	1	0	0	0	0	0	0	0	0	1	2	0	1	0	0	0	0	0
58	0	0	0	0	5	3	1	0	0	0	0	0	0	0	0	3	0	1	1	0	0	0	0	0
59	0	0	0	1	3	1	5	0	0	0	0	0	0	0	0	2	0	1	0	0	0	0	0	0
60	0	0	0	1	3	1	2	0	0	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0
61	0	0	0	4	2	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
62	0	0	0	1	1	3	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
63	0	0	0	0	3	3	4	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0
64	0	0	0	1	5	1	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
65	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
66	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0
67	0	0	0	1	2	0	0	0	0	0	0	0	0	0	0	0	2	1	0	0	0	0	0	0
68	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0
69	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
70	0	0	0	0	3	1	2	0	0	0	0	0	0	0	0	0	1	2	1	1	0	0	0	0
71	0	0	0	0	0	2	2	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0
72	0	0	0	0	2	2	1	0	0	0	0	0	0	0	0	0	2	1	1	0	0	0	0	0
73	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0
74	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0
75	0	0	0	0	2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
76	0	0	0	0	2	3	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
77	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0
78	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0
79	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	2	1	0	0	0	0	0
80	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
81	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0
82	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
83	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
84	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	2	0	1	0	0	0	0
85	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
86	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0
87	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
88	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
89	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0
90	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
91	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
92	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
93	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
94	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
95	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
96	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
97	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
98	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
99	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
>100	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	1	0	1	1	2

App. A4 (Append. A), Table A11b: Age-length keys for NEFSC offshore spring research vessel bottom trawl surveys in the Gulf of Maine conducted by the *Bigelow* (Michael Palmer, pers. commn).

	NEFSC Spring, 2011							Age					NEFSC Spring, 2012							Age				
Length	0	1	2	3	4	5	6	7	8	9	10	11+	0	1	2	3	4	5	6	7	8	9	10	11+
≤25	0	2	0	0	0	0	0	0	0	0	0	0	1	38	3	0	0	0	0	0	0	0	0	0
26	0	0	0	0	0	0	0	0	0	0	0	0	0	1	2	0	0	0	0	0	0	0	0	0
27	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0
28	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0
29	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0
31	0	0	2	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
32	0	0	0	1	0	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0
33	0	0	1	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0
34	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0
35	0	0	1	1	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0
36	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	2	0	0	0	0	0	0	0	0
37	0	0	0	2	1	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0
38	0	0	0	1	0	0	0	0	0	0	0	0	0	0	2	1	0	0	0	0	0	0	0	0
39	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	3	0	0	0	0	0	0	0	0
40	0	0	1	2	0	0	0	0	0	0	0	0	0	0	5	6	0	0	0	0	0	0	0	0
41	0	0	0	1	0	0	0	0	0	0	0	0	0	0	3	5	0	0	0	0	0	0	0	0
42	0	0	1	1	1	0	0	0	0	0	0	0	0	0	3	7	1	0	0	0	0	0	0	0
43	0	0	0	2	2	0	0	0	0	0	0	0	0	0	2	7	2	1	0	0	0	0	0	0
44	0	0	0	0	2	0	0	0	0	0	0	0	0	0	2	9	1	0	0	0	0	0	0	0
45	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	5	2	2	0	0	0	0	0	0
46	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	3	2	1	0	0	0	0	0	0
47	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	3	4	1	0	0	0	0	0	0
48	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	5	2	0	0	0	0	0	0	0
49	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	5	4	0	0	0	0	0	0	0
50	0	0	0	1	3	0	0	0	0	0	0	0	0	0	0	4	1	3	0	0	0	0	0	0
51	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	2	3	1	0	0	0	0	0	0
52	0	0	0	0	3	1	0	0	0	0	0	0	0	0	0	3	7	4	1	0	0	0	0	0
53	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	2	5	1	0	0	0	0	0	0
54	0	0	0	2	1	0	0	0	0	0	0	0	0	0	0	3	2	3	0	0	0	0	0	0
55	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	6	1	0	0	0	0	0	0
56	0	0	0	1	2	1	0	0	0	0	0	0	0	0	0	5	4	5	2	0	0	0	0	0
57	0	0	0	0	3	1	0	0	0	0	0	0	0	0	0	2	3	1	1	0	0	0	0	0
58	0	0	0	2	1	0	0	0	0	0	0	0	0	0	0	1	6	3	1	0	0	0	0	0
59	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	4	0	1	2	0	0	0	0
60	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	2	2	2	1	0	0	0	0	0
61	0	0	0	0	3	1	1	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0
62	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	6	1	0	0	0	0	0	0
63	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	2	3	1	1	0	0	0	0
64	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	3	2	1	0	0	0	0	0
65	0	0	0	0	0	2	1	0	0	0	0	0	0	0	0	0	2	2	2	0	0	0	0	0
66	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	1	2	0	0	0	0	0
67	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	3	4	0	0	0	0	0	0
68	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0
69	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	2	1	0	0	0	0	0	0
70	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	1	0	1	0	0	0	0
71	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
72	0	0	0	0	0	2	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
73	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
74	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
75	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
76	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
77	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
78	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
79	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
80	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
81	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
82	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
83	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
84	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
85	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
86	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
87	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
88	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
89	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
90	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
91	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
92	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
93	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
94	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
95	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
96	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
97	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
98	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
99	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
>100	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

App. A4 (Append. A), Table A12: Age-length keys for NEFSC offshore autumn research vessel bottom trawl surveys in the Gulf of Maine conducted by the *Bigelow* (Michael Palmer, pers. commn).

	NEFSC Autumn, 2009						Age						NEFSC Autumn, 2010						Age						NEFSC Autumn, 2011						Age					
Length	0	1	2	3	4	5	6	7	8	9	10	11+	0	1	2	3	4	5	6	7	8	9	10	11+	0	1	2	3	4	5	6	7	8	9	10	11+
≤25	9	11	2	0	0	0	0	0	0	0	0	0	2	1	0	0	0	0	0	0	0	0	0	0	15	4	0	0	0	0	0	0	0	0	0	0
26	0	4	1	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0
27	0	4	2	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
28	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
29	0	4	2	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
30	0	3	1	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
31	0	1	0	0	0	0	0	0	0	0	0	0	0	5	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
32	0	4	1	0	0	0	0	0	0	0	0	0	0	5	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0
33	0	2	4	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
34	0	1	2	0	0	0	0	0	0	0	0	0	0	2	2	0	0	0	0	0	0	0	0	0	0	1	2	0	0	0	0	0	0	0	0	0
35	0	2	4	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0
36	0	0	1	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
37	0	0	2	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
38	0	2	5	0	0	0	0	0	0	0	0	0	0	0	2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
39	0	1	2	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	2	1	0	0	0	0	0	0	0	0
40	0	1	3	0	0	0	0	0	0	0	0	0	0	0	2	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
41	0	1	1	0	0	0	0	0	0	0	0	0	0	0	1	2	0	0	0	0	0	0	0	0	0	0	2	1	0	0	0	0	0	0	0	0
42	0	0	5	0	0	0	0	0	0	0	0	0	0	0	1	2	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0
43	0	0	4	0	0	0	0	0	0	0	0	0	0	0	2	1	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0
44	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0
45	0	0	3	0	0	0	0	0	0	0	0	0	0	0	1	2	0	0	0	0	0	0	0	0	0	0	2	3	0	0	0	0	0	0	0	0
46	0	0	7	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	1	3	0	0	0	0	0	0	0
47	0	0	3	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
48	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	1	2	1	0	0	0	0	0	0	0
49	0	0	1	1	0	0	0	0	0	0	0	0	0	0	1	2	0	0	0	0	0	0	0	0	0	0	0	1	3	0	0	0	0	0	0	0
50	0	0	2	1	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	1	3	0	1	0	0	0	0	0	0
51	0	0	3	0	1	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0
52	0	0	3	0	0	0	0	0	0	0	0	0	0	0	1	3	0	0	0	0	0	0	0	0	0	0	1	1	3	0	0	0	0	0	0	0
53	0	0	0	1	1	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	1	2	0	0	0	0	0	0	0
54	0	0	2	1	0	0	0	0	0	0	0	0	0	0	0	2	1	0	0	0	0	0	0	0	0	0	0	1	2	0	1	0	0	0	0	0
55	0	0	2	1	2	0	0	0	0	0	0	0	0	0	0	2	1	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0
56	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	2	1	0	0	0	0	0	0	0
57	0	0	1	1	2	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
58	0	0	1	0	2	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0
59	0	0	0	4	2	0	0	0	0	0	0	0	0	0	1	1	2	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0
60	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	3	0	1	0	0	0	0	0
61	0	0	0	2	1	0	0	0	0	0	0	0	0	0	0	1	1	0	1	0	0	0	0	0	0	0	1	2	2	0	0	0	0	0	0	0
62	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	2	2	0	0	0	0	0	0	0
63	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
64	0	0	1	1	3	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	4	6	1	0	0	0	0	0	0
65	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	2	0	1	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0
66	0	0	0	2	2	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	2	0	1	0	0	0	0	0
67	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	1	3	0	0	0	0	0	0	0	0	0	0	1	1	0	1	0	0	0	0	0
68	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	3	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0
69	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	2	0	0	0	0	0	0
70	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	3	2	0	0	0	0	0	0
71	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0
72	0	0	0	2	2	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
73	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	2	1	0	0	0	0	0	0	0	0	0	0	0	2	1	0	0	0	0	0
74	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
75	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	2	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
76	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0
77	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0
78	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
79	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
80	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
81	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0
82	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0
83	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0
84	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
85	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
86	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
87	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
88	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
89	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
90	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
91	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
92	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
93	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
94	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
95	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
96	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
97	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
98	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
99	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
>100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0

Appendix B (within App. A4) - 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).

For the convenience of readers, details which are changed or newly added relative to the specifications used for the analyses reported in Butterworth and Rademeyer (2012) are shown highlighted.

B.1. Population dynamics

B.1.1 Numbers-at-age

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

$$N_{y+1,0} = R_{y+1} \tag{B1}$$

$$N_{y+1,a+1} = N_{y,a} e^{-Z_{y,a}} \qquad \text{for } 0 \le a \le M-2 \tag{B2}$$

$$N_{y+1,m} = N_{y,m-1} e^{-Z_{y,m-1}} + N_{y,m} e^{-Z_{y,m}} \tag{B3}$$

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 0-year-old fish) at the start of year y,

m is the maximum age considered (taken to be a plus-group).

$Z_{y,a} = F_y S_{y,a} + M_a$ 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 0-year old) at the start of year y is assumed to be related to the spawning stock size (i.e. the biomass of mature fish) by either a modified Ricker or a standard or adjusted Beverton-Holt stock-recruitment relationship, allowing for annual fluctuation about the deterministic relationship.

For the modified Ricker:

$$R_y = \alpha B_y^{\text{sp}} \exp\left[-\beta\left(B_y^{\text{sp}}\right)^{\gamma}\right] e^{(\varsigma_y - (\sigma_{\text{R}})^2/2)} \tag{B4}$$

for the (standard) Beverton-Holt:

$$R_y = \frac{\alpha B_y^{sp}}{\beta + B_y^{sp}} e^{(\varsigma_y - (\sigma_{\text{R}})^2/2)} \tag{B5}$$

and for the adjusted Beverton-Holt:

$$R_y = \begin{cases} \dfrac{\alpha B_y^{sp}}{\beta + B_y^{sp}} & \text{if } B_y^{sp} \le B^* \\ \dfrac{\alpha B^*}{\beta + B^*} \exp\left(-\left(\dfrac{B_y^{sp} - B^*}{\sigma_N}\right)^2\right) & \text{if } B_y^{sp} > B^* \end{cases} \tag{B6}$$

where

α, β, γ, $B^*$and σ_N are spawning biomass-recruitment relationship parameters,

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

B_y^{sp} is the spawning biomass at the start of year y, computed as:

$$B_y^{\text{sp}} = \sum_{a=0}^{m} f_a w_{y,a}^{\text{strt}} N_{y,a} e^{-M_a/4} \tag{B7}$$

because spawning for the cod 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, and

f_a is the proportion of fish of age a that are mature.

Section *B.2.6* details the procedure adopted when recruitment is not assumed to be related to spawning biomass , at least internal to the assessment.

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

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

$$C_y = \sum_{a=0}^{m} w_{y,a}^{\text{mid}} C_{y,a} = \sum_{a=0}^{m} w_{y,a}^{\text{mid}} N_{y,a} \; S_{y,a} F_y \left(1 - e^{-Z_{y,a}}\right) \Big/ Z_{y,a} \tag{B8}$$

where

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

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

The model estimate of survey biomass is computed as:

$$B_y^{\text{surv}} = \sum_{a=0}^{m} w_{y,a}^{\text{surv}} S_a^{\text{surv}} N_{y,a} e^{-Z_{y,a} T^{surv}/12} \tag{B9}$$

where

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

T^{surv} is the season in which the survey is taking place (T^{surv}=1 for spring surveys and T^{surv}=3 for fall surveys), and

$w_{y,a}^{surv} = w_{y,a}^{strt}$ for spring surveys and $w_{y,a}^{surv} = w_{y,a}^{mid}$ 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 0 to a^{est}, with a parameter ϕ mimicking recent average fishing mortality for ages above a^{est}, i.e.

$$N_{y_0,a} = N_{\text{start},a} \qquad \text{for } 0 \le a \le a^{est} \tag{B10}$$

and

$$N_{\text{start},a} = N_{\text{start},a-1} e^{-M_{a-1}} (1 - \phi S_{a-1}) \qquad \text{for } a^{est} < a \le m-1 \tag{B11}$$

$$N_{\text{start},m} = N_{\text{start},m-1} e^{-M_{m-1}} (1 - \phi S_{m-1}) \big/ (1 - e^{-M_m} (1 - \phi S_m)) \tag{B12}$$

B.2. The (penalised) likelihood function

The model can be fit to (a subset of) CPUE and survey abundance indices, and commercial and survey catch-at-age and catch-at-length 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 ($-\ell nL$) are as follows. Details related to fitting to CPUE series are not included below, as such series are not considered in the analyses of this paper.

B2.1. Survey abundance data

The likelihood is calculated assuming that a survey biomass index is lognormally

distributed about its expected value:

$$I_y^{surv} = \hat{I}_y^{surv} \exp\left(\varepsilon_y^{surv}\right) \quad \text{or} \quad \varepsilon_y^{surv} = \ell\text{n}\left(I_y^{surv}\right) - \ell\text{n}\left(\hat{I}_y^{surv}\right) \tag{B13}$$

where

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

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

$\hat{q}^{surv}$ is the constant of proportionality (catchability) for the survey biomass 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:

$$-\ell\text{n}\, L^{\text{survey}} = \sum_{surv} \sum_{y} \left\{ \ell\text{n}\left(\sqrt{\left(\sigma_y^{surv}\right)^2 + \left(\sigma_{Add}^{surv}\right)^2} \right) + \left(\varepsilon_y^{surv}\right)^2 / \left[2\left(\left(\sigma_y^{surv}\right)^2 + \left(\sigma_{Add}^{surv}\right)^2\right)\right] \right\} \tag{B14}$$

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:

$$\ell n\, \hat{q}^{surv} = 1/n_{surv} \sum_{y} \left(\ln I_y^{surv} - \ln \hat{B}_y^{surv}\right) \tag{B15}$$

B.2.3. Commercial catches-at-age

The contribution of the catch-at-age data to the negative of the log-likelihood function under the assumption of an "adjusted" lognormal error distribution is given by:

$$-\ell\text{n}\, L^{\text{CAA}} = \sum_{y} \sum_{a} \left[\ell n\left(\sigma_a^{com} / \sqrt{p_{y,a}}\right) + p_{y,a}\left(\ell n\, p_{y,a} - \ell n\, \hat{p}_{y,a}\right)^2 / 2\left(\sigma_a^{com}\right)^2 \right] \tag{B16}$$

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

$$\hat{C}_{y,a} = N_{y,a}\ S_{y,a} F_y \left(1 - e^{-Z_{y,a}}\right) / Z_{y,a} \tag{B17}$$

and

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

$$\hat{\sigma}_a^{com} = \sqrt{\sum_y p_{y,a}\left(\ell n\, p_{y,a} - \ell n\, \hat{p}_{y,a}\right)^2 / \sum_y 1} \tag{B18}$$

Commercial catches-at-age are incorporated in the likelihood function using equation (B16), for which the summation over age a is taken from age a_{minus} (considered as a minus group) to a_{plus} (a plus group).

In application of this approach ages are often aggregated to avoid values of $p_{y,a}$ or $\hat{p}_{y,a}$ that are too small in the interests of estimation robustness. In this paper individual ages have been maintained between the selected minus and plus-groups to provide potential discrimination of different shapes for the selectivity functions at older ages in particular. This however does mean that there are certain cells for which $p_{y,a}$ values are zero. That does not cause any problems because the limit of $p_{y,a}\left(\ln p_{y,a}\right)^2$ as $p_{y,a} \to 0$ is 0, so these terms can be omitted from the summation in equation B16. One could argue that they should nevertheless be included in the summations in equation B18, but exclusion seems more appropriate as the structural zero contributions then included would seem likely to bias the estimates of $\hat{\sigma}_a^{com}$ downwards.

In addition to this "adjusted" lognormal error distribution, some computations use an alternative "sqrt(p)" formulation, for which equation B19 is modified to:

$$-\ell \mathrm{n}\, L^{\mathrm{CAA}} = \sum_y \sum_a \left[\ell n\left(\sigma_a^{com}\right) + \left(\sqrt{p_{y,a}} - \sqrt{\hat{p}_{y,a}}\right)^2 / 2\left(\sigma_a^{\mathrm{com}}\right)^2 \right] \tag{B19}$$

and equation B21 is adjusted similarly:

$$\hat{\sigma}_a^{com} = \sqrt{\sum_y \left(\sqrt{p_{y,a}} - \sqrt{\hat{p}_{y,a}}\right)^2 / \sum_y 1} \tag{B20}$$

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

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, assuming an "adjusted" lognormal

error distribution (equation (B19)) 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:

$$\hat{p}_{y,a}^{surv} = S_a^{\text{surv}} N_{y,a} e^{-Z_{y,a} T^{surv}/12} \Big/ \sum_{a'=0}^{m} S_{a'}^{\text{surv}} N_{y,a'} e^{-Z_{y,a'} T^{surv}/12} \quad . \tag{B21}$$

B.2.5. Survey catches-at-length

In some runs, catches-at-length are also incorporated in the likelihood function. These data are incorporated in the similar manner as the catches-at-age. When the model is fit to catches-at-length, the predicted catches-at-age are converted to catches-at-length:

$$\hat{p}_{y,l}^{surv} = \sum_a \hat{p}_{y,a}^{surv} A_{a,l} \tag{B22}$$

where $A_{a,l}$ is the proportion of fish of age *a* that fall in the length group *l* (i.e., $\sum_l A_{a,l} = 1$ for all ages).

The matrix $A_{a,l}$ is calculated under the assumption that length-at-age is normally distributed about a mean given by the von Bertalanffy equation, i.e.:

$$L_a \sim N\left[L_\infty \left(1 - e^{-\kappa(a-t_o)}\right), \theta_a^2\right] \tag{B23}$$

where

θ_a is the standard deviation of mid-year length-at-age a, which is modelled to be proportional to the expected length-at-age *a*, i.e.:

$$\theta_a = \beta\left[L_\infty \left(1 - e^{-\kappa(a+0.5-t_o)}\right)\right]^\gamma \tag{B24}$$

with β an estimable parameter and $\gamma = 0.5$ (a value which was found to lead to reasonable fits to the data).

$L_\infty = 150.93\,cm$,

$\kappa = 0.11\,yr^{-1}$,

$t_o = 0.13\,yr$,

The following term is then added to the negative log-likelihood:

$$-\ell n\, L^{\text{CAL}} = w_{len} \sum_{surv} \sum_y \sum_l \left[\ell n\left(\sigma_{\text{len}}^{surv} / \sqrt{p_{y,l}^{surv}}\right) + p_{y,l}^{surv}\left(\ell n\, p_{y,l}^{surv} - \ell n\, \hat{p}_{y,l}^{surv}\right)^2 / 2\left(\sigma_{\text{len}}^{surv}\right)^2\right] \tag{B25}$$

The w_{len} weighting factor may be set to a value less than 1 to downweight the

contribution of the catch-at-length data (which tend to be positively correlated between adjacent length groups because the length distributions for adjacent ages overlap) to the overall negative log-likelihood compared to that of the CPUE data. The value used for w_{len} is 0.1, being roughly equivalent to the ratio of the number to length groups to the number of age groups considered. Instances of observed proportions of zero are dealt with in the same manner as for catches-at-age, as is the alternative "sqrt(p)" error distribution formulation.

B.2.6. 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:

$$-\ell nL^{\text{pen}} = \sum_{y=y_1+1}^{y_2} \left[\varepsilon_y^2 / 2\sigma_{\text{R}}^2 \right] \qquad \text{(B26)}$$

where

ε_y from $N\left(0,(\sigma_R)^2\right)$,

σ_{R} is the standard deviation of the log-residuals, which is input.

In the analyses reported in this paper, unless otherwise stated, this "stock-recruitment" term is included for the last two years only, simply to stabilise these estimates which are not well determined by the other data. The ε_y are calculated as the deviations from the mean log recruitment for the ten preceding years, i.e. recruitment estimates for 2010 and 2011 are shrunk towards the geometric mean recruitment over the preceding decade.

B.2.7 Incorporation of Bigelow vs Albatross survey calibration

The survey data provided are adjusted for the years 2009 to 2012 which were obtained from *Bigelow* surveys have been adjusted to "*Albatross* equivalents" through use of calibration factors estimated independently from paired tow experiments (Miller *et al*., 2010). However the survey data before and after the switch of vessels also provide information on the calibration factors because they sample the same cohorts. Incorporation of this information in assessments in this paper has been effected by treating the estimates, with their variance-covariance matrix, as a form of "joint-prior" which is effectively updated in the penalised likelihood estimation when fitting the model. The process is as follows.

First *Bigelow* length frequency distributions are converted to *Albatross* equivalent length frequency distributions:

$$C_{y,l}^{surv,A} = C_{y,l}^{surv,B} / F_l \qquad \text{(B27)}$$

where

$C_{y,l}^{surv,B}$ is the measured catch-at-length for the *Bigelow* in year *y* for survey *surv,*

$C_{y,l}^{surv,A}$ is the inferred catch-at-length for the *Albatross* equivalent in year *y* for survey

surv,

F_l is the length-based calibration factor (*Bigelow/Albatross*),

The Albatross equivalent length distributions are then converted to age distributions:

$$C_{y,a}^{surv,A} = \sum_l C_{y,l}^{surv,A} ALK_{y,a,l}^{surv} \qquad \text{(B28)}$$

where

$ALK_{y,a,l}^{surv}$ is the age-length key (proportion of fish of length l that have age a) in year y for survey *surv.*

Biomass indices are then obtained from the *Albatross* equivalent age distributions as follows:

$$I_y^{surv,A} = \sum_a C_{y,a}^{surv,A} w_{y,a}^{surv} \qquad \text{(B29)}$$

where

$w_{y,a}^{surv}$ is the weight-at-age in year y for survey *surv*.

The calibration factor has four parameters, three of which are estimable and the other input: X_1=20cm, X_2, F_1 and F_2

$$F_l = \begin{cases} F_1 & \text{if } l \le X_1 \\ \dfrac{(F_2 - F_1)}{(X_2 - X_1)} l + \dfrac{(F_1 X_2 - F_2 X_1)}{(X_2 - X_1)} & \text{if } X1 < l < X_2 \\ F_2 & \text{if } l \ge X_2 \end{cases} \qquad \text{(B30)}$$

The following contribution is therefore added to the negative log-likelihood in the assessment:

$$-\ln L^{calib} = \frac{1}{2}\ln|\mathbf{\Sigma}| + \frac{1}{2}(\mathbf{x} - \boldsymbol{\mu})^{\mathrm{T}} \mathbf{\Sigma}^{-1} (\mathbf{x} - \boldsymbol{\mu})$$

where the parameters X_2, F_1 and F_2 are components of the vector $\boldsymbol{x}$,

$\mathbf{\Sigma}$ is the variance covariance matrix as estimated by Miller *et al.* (2010), and

$\boldsymbol{\mu}$ is a vector which contains the Miller *et al.* (2010) estimates of the parameters.

These estimates and the variance-covariance matrix are given in table B1 below:

Table B1: Estimates and variance-covariance matrix for the calibration parameters (Miller, pers. commn).

$\boldsymbol{\mu}$	$ln(F_2)$	$ln(F_1-F_2)$	$ln(X_2-X_1)$
	0.4713	1.4163	3.5086
$\boldsymbol{\Sigma}$	$ln(F_2)$	$ln(F_1-F_2)$	$ln(X_2-X_1)$
$ln(F_2)$	0.006674	-0.002515	-0.002559
$ln(F_1-F_2)$	-0.002515	0.051592	-0.007601
$ln(X_2-X_1)$	-0.002559	-0.007601	0.006757

B.3. Estimation of precision

Where quoted, CV's or 95% probability interval estimates are based on the Hessian.

B.4. Model parameters

B.4.1. Fishing selectivity-at-age:

The commercial fishing selectivity, S_a, as well as the fishing selectivities for the Massachusetts inshore spring survey, are estimated separately for ages a_{minus} to a_{plus}. The estimated proportional decrease from ages a_{plus}-1 to a_{plus} is assumed to continue multiplicatively to age 9+ for the commercial selectivity and to age 11+ (the model plus group) for the Massachusetts spring survey (if not otherwise specified) (see Table below for a_{minus} to a_{plus}). For the NEFSC offshore surveys, the fishing selectivities are estimated separately for ages a_{minus} to age 7 for the spring survey, and to age 6 for the fall survey, and thereafter an exponential decline to age 9+ is estimated separately for each survey.

The commercial selectivity is taken to differ over the 1893-1991 and 1992+ periods. The decision to incorporate a change after 1991 was made to remove non-random residual patterns in the fit to the commercial catch-at-age data if time-independence in selectivity was assumed.

B.4.2. Other parameters

Model plus group			
m	11		
Commercial CAA			
a_{minus}	1		
a_{plus}	9		
Survey CAA	NEFSC spr	NEFSC fall	MASS spr
a_{minus}	1	1	0
a_{plus}	9	9	4
Natural mortality:			
M	0.2 and age independent		
Proportion mature-at-age:			
f_a	input, see Table A8		
Weight-at-age:			
$w_{y,a}^{strt}$	input, see Table A2		
$w_{y,a}^{mid}$	input, see Table A3		
Initial conditions for a 1964 starting year:			
$N_{y0,a}$	estimated directly for ages 0 to 2		
ϕ	estimated, eqns B9-B10 for ages 3+		

B.5.Reference points

It is possible to estimate reference points internally within the assessment by fitting the stock-recruitment relationship directly within the assessment itself.

For most results reported here, however, the stock-recruitment relationships are fitted to the estimates of recruitment and spawning biomass provided by the various assessments to provide a basis to estimate reference points. The rationale for estimation external to the assessment itself is to avoid assumptions about the form of the relationship influencing the assessment results. These fits are achieved by minimising the following negative log-likelihood:

$$-\ln L = \sum_{y=y1}^{2009}\left[\frac{\left(\ln(N_{y,0}) - \ln\left(\hat{N}_{y,0}\right)\right)^2}{2\left((\sigma_R)^2 + (CV_y)^2\right)} + \ln\left(\sqrt{(\sigma_R)^2 + (CV_y)^2}\right)\right] \qquad \text{(B31)}$$

where

$N_{y,0}$ is the "observed" (assessment estimated) recruitment in year y,

$\hat{N}_{y,0}$ is the stock-recruitment model predicted recruitment in year y,

σ_R is the standard deviation of the log-residuals, and

CV_y is the Hessian-based CV for the "observed" recruitment in year y.

Note that the differential precision of the assessment estimates of recruitment is taken into account, and that the summation ends at 2009 because little by way of direct observation is as yet available to inform estimates of recruitment for 2010 and 2011.

[SAW55 Editor's Note: The SARC-55 review panel did not recommend adopting the GOM cod Statistical Catch-at-Age (SCAA) assessment results that are in Appendices A.2 – A.5. These appendices are included in this report to document and demonstrate the work that was done by the SAW cod Working Group for the December 2012 peer review.]

Appendix A.5. Further Statistical Catch-at-Age Assessment Results together with Biological Reference Point estimates for Gulf of Maine cod, October 2012

Summary

The Statistical Catch-at-Age assessments of the Gulf of Maine cod stock by Butterworth and Rademeyer (2012) are extended, with a particular focus on the estimation of Biological Reference Points (BRPs). The analysis supports starting these assessments from an early year to provide precise estimates of these BRPs, and the estimation n of the Ricker form of the stock –recruitment relationship within the assessment is found to be preferred. Across a wide range of sensitivity tests the 2011 spawning biomass is robustly estimated at about 14 thousand tons with specific estimates ranging from about 12.5 to 16 thousand tons. When starting the assessments in the 1960s or earlier with a Ricker stock-recruitment function, most estimates of the spawning biomass which provides MSY are around 25 thousand tons for the M = 0.2 scenario, and around 13 thousand tons for the M increasing scenario; the corresponding estimates of MSY itself are about 13 and 6 thousand tons respectively. The AIC selection criterion and a reduced retrospective pattern suggest that greater weight should be accorded to results for the M increasing compared to the M = 0.2 scenario.

Introduction

This paper continues from that (Butterworth and Rademeyer, 2012) submitted to the earlier SAW/SARC 55 Modeling Meeting. Taking account of advances made and some agreements reached at that meeting, it extends SCAA assessment analyses for Gulf of Maine cod, now particularly focusing also on the estimation of MSY-related biological reference points. (BRPs)

Data and Methodology

The catch and survey based data (including catch-at-length information) and some biological data used for the analyses are listed in Tables in Appendix A (within Appendix

A5). These have been updated in a few respects in the light of discussions at the earlier Modeling Meeting; the consequent changes are indicates through highlighting.

The details of the SCAA assessment methodology are provided in Appendix B (within Appendix A5). As in Appendix A, there are some recent changes which are highlighted.

Results

Results are first given for variants on an assessment run which incorporates the following choices, based primarily on those made for a comparison exercise with ASAP outputs run during the Modeling Meeting. These include:

- Use the sqrt(p) formulation of equation B.21 to describe the distribution of proportions-at-age (in relation to numbers of fish).
- No refinement of the *Bigelow-Albatross* calibration function within the assessment.
- Force flat selectivity at ages of 5/6 and above for the NEFSC autumn/spring surveys (though estimation of a common doming trend in the commercial selectivities is allowed – see Section B.4.1).
- Make allowance for additional variance when fitting to time series of abundance indices
- Fit to the aggregated abundance indices as expressed in terms of numbers (equation B10) rather than biomass.
- Where pertinent given the starting year, incorporate data on NEFSC survey length compositions from the 1960s when catches from these surveys were not aged.

The first sensitivity exercise conducted is run conduct assessments comprising a full cross of the following factors:

a) Start in 1963 (estimating the first three numbers-at-age in the starting vector and then the parameter ϕ) *vs* start in 1982 (estimating all elements of the starting numbers at age vector).
b) $M = 0.2$ *v*s M increasing linearly from 0.2 prior to 1989 to 0.4 from 2003
c) Internal (equation B31) *vs* external (equation B39) estimation of the stock-recruitment relationship; note that with external estimation, the assessment shrinks only the last two recruitment estimates as detailed in section B.2.6
d) Use of a Ricker (equation B4 with $\gamma = 1$) *vs* a Beverton Holt (equation B5) stock-recruitment relationship.

App. A5, Tables 1 and 2 list the results of this examination, showing log likelihood contributions and model parameter estimates, and also now estimates of BRPs.

For the purpose of further evaluation, a Reference Case (RC) is selected from the cases considered above, with the same specifications for each of the $M = 0.2$ and M increasing scenarios. This RC starts the assessment in 1963, and estimates a Ricker stock-recruitment curve internally.

App. A5, Table 3 shows results for sensitivities to the RC for $M = 0.2$. First sensitivities to different starting years are shown, and then some other factors investigated. For the different starting years, the numbers of ages which are estimated individually in the

starting vector are (1, 3, 3, 4, 5, all, all) for the years (1934, 1963, 1964, 1965, 1967, 1970 and 1982) respectively. These choices were made on an AIC basis. App. A5, Table 4 is similar to Table 3, but for the RC with *M* increasing and with somewhat fewer sensitivities.

App. A5, Table 5 gives results for the authors' "preferred" runs for the two different *M* scenarios. These "preferred" runs differ from the RC only in starting in 1934 rather than 1963, and in incorporating refinement of the *Bigelow-Albatross* calibration function within the assessment. The reasons for the various choices made for these "preferred" runs are given in the Discussion section following.

App. A5, Figs 1-7 are constructed to illustrate some of the sensitivities associated with different choices for a number of the factors requiring specification in the assessment. App. A5, Figs 1-3 show various trajectory plots for spawning biomass and recruitment, some of which also show approximate Hessian-based 95% CIs, and Fig. 1 also shows the total catch trajectory. Fig. 4 plots some of the selectivity functions that differ across the sensitivities investigated, while Fig. 5 compares spawning biomass trajectories for the two different *M* scenarios for the RC. App. A5, Figs 6-7 compare different estimated stock recruitment functions.

App. A5, Figs 8-13 show diagnostic plots for the "preferred" case with $M = 0.2$. These include spawning biomass and recruitment trajectories showing approximate 95% CIs, selectivity-at-age plots, fits/residuals to abundance indices and proportions-at-age and -at-length data, refined *Bigelow-Albatross* calibration functions, and retrospective analyses. App. A5, Figs 14-19 repeat these same plots for the other "preferred" case with *M* increasing. App. A5, Fig. 20 shows the fitted stock-recruiment relationships for each case.

Discussion

Several features are evident from the exploratory results in App. A5, Tables 1 and 2:

- Starting the assessment in 1982 provides no basis to discriminate alternative stock-recruitment relations, and the estimates of spawning biomass at MSY are hopelessly imprecise for the $M = 0.2$ case.
- For a 1963 start to the assessment, the Ricker form is preferred over the Beverton-Holt form in terms of AIC, particularly for the *M* increasing scenario. For $M = 0.2$, the Beverton-Holt estimate of spawning biomass at MSY is appreciably larger than its Ricker counterpart.
- Internal estimates of the spawning biomass at MSY for a 1963 start to the assessment are both somewhat higher and less precise than their external estimation counterparts, but this last result is not unexpected since the internal estimates take account of errors in estimates of spawning biomass and correlations amongst estimates over time, unlike the external estimates.
- Estimates of current (2011) spawning biomass are typically 1000 tons lower without internal estimation of the stock-recruitment function.

With BRP estimation in mind, and given the results summarised in the first three bullets above, preference is indicated for internal estimation using a Ricker form for the stock-

recruitment relationship, and for starting the assessment in an early year. Hence the Reference Case (RC) was selected to include these specifications, and with a 1963 start because that corresponded to the beginning of the NEFSC survey time series.

Further results shown in App. A5, Table 3 and plotted in App. A5, Figs 1-7 suggest little sensitivity of recruitment estimates to most of the assessment options examined, and also of the spawning biomass trajectory except for some variability in the early years depending on the 1960s starting year chosen (App. A5, Figs 1-3). However when the starting year is taken back to 1934, this results in a clear and relatively precise trend in spawning biomass of an increase over the 1950s and early 1960s co-incident with the low catches over that period (App. A5, Fig. 2). The survey CAL data from the 1960s also support this trend (lowest left plot in Fig. 3). Another feature of the results for BRPs is that once the contrast provided by the assessment estimates from the 1960s is lost, the ability for precise estimation of the stock-recruitment relationship, and hence of BRPs such as the spawning biomass at MSY, is lost with it (App. A5, Table 3 and Fig. 7). Comparison of relationships found by internal and external stock-recruit function estimation shows little difference (App. A5, Fig. 6).

The above points towards preferring an earlier start to the assessment than the 1963 of the RC, as the combination of the data and the stock-recruit relationship assumption inform the overall BRP estimation process further through providing meaningful information on stock dynamics back into the 1950s at least.

Regarding the other sensitivity tests for M = 0.2, alternative assumptions about selectivity-at-age pre-1982 make little difference to results (App. A5, Table 3 and Fig.3, third row). Fitting to abundance indices in terms of biomass rather than numbers decreases the current spawning biomass estimate slightly, but makes little difference otherwise (App. A5, Table 3, and Fig. 3, second row). Use of the adjusted log-normal form for the proportions data appreciably increases the variance of the BRP estimates (App. A5, Table 3). A domed survey selectivity is preferred under AIC, but trends into the 1960s (App. A5, Fig. 3, second row) seem at variance with the pattern suggested by Fig. 1 when earlier years are included in the assessment. Inclusion of the *Bigelow* calibration refinement has little impact on results (App. A5, Table 3).

Where examined, these same features seem broadly present for the increasing M case, though to lesser extents. Unsurprisingly once M becomes higher, both spawning biomass and recruitment estimates increase (App. A5, Fig. 5).

Based on these results, the authors' preference is to leave the RC specifications unchanged except to move to a 1934 starting year to make maximal use of data contrast in estimating BRPs, and to include the *Bigelow* calibration refinement because of its in principle desirability.

In broad terms the diagnostics for both the consequent "preferred" cases in App. A5, Figs 8-19 are satisfactory. The M increasing scenario shows an appreciably reduced retrospective pattern compared to the M = 0.2 case (App. A5, Fig. 19 compared to Fig. 13), and further is preferred in AIC terms (App. A5, Table 5). Accordingly it would seem that more weight should be placed on the results provided by the M increasing scenario.

Conclusions

Key conclusions from these results are:

- Assessments should start from as early a year as possible to maximise the contrast in data required to provide BRP estimates with better precision.
- Internal over external estimation of stock-recruitment functions is preferred to best take the variance-covariance of spawning biomass and recruitment estimates into account. The Ricker form for this relationship is AIC preferred to the Beverton-Holt form.
- Across a wide range of sensitivity tests (including treatment of the stock-recruitment relationship), the 2011 spawning biomass is robustly estimated at about 14 thousand tons with specific estimates ranging from about 12.5 to 16 thousand tons.
- Given a start to the assessments in the 1960s or earlier, with internal estimation of a Ricker stock-recruitment function, most estimates of the spawning biomass which provides MSY are around 25 thousand tons for the $M = 0.2$ scenario, and around 13 thousand tons for the M increasing scenario; the corresponding estimates of MSY itself are about 13 and 6 thousand tons respectively.
- The AIC selection criterion and a reduced retrospective pattern suggest that greater weight should be accorded to results for the M increasing compared to the $M = 0.2$ scenario.

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References

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Appendix A5. Tables

App. A5, Table 1: Estimates of abundance, MSY-related biological reference points (BRPs), and related quantities for the Gulf of Maine cod for a comparative exercise across four assessments factors: start date, internal or external estimation of the stock-recruitment relationship, the form of the stock-recruitment relationship, and the time dependence of natural mortality *M* (see text for further details). Values in round parentheses are Hessian based CV's, while maximum gradient refers to the quantity reported with the ADMB estimation results. Negative log-likelihood values shown in square parentheses denote non-comparability with values given in adjacent columns. Mass units are '000 tons. *y*1 refers to the start year for the assessment. Recruitment $N_{y1,0}$ is in millions. Refer to Appendix B for definitions of some of the symbols used.

	Start in y1=1963												Start in y1=1982											
	M=0.2						*M* increasing						*M*=0.2						*M* increasing					
	Ricker internal		BH internal		No SR		Ricker internal		BH internal		No SR		Ricker internal		BH internal		No SR		Ricker internal		BH internal		No SR	
-lnL: overall	-2765		-2763		-[2797]		-2774		-2769		-[2801]		-2128		-2128		-[2145]		-2137		-2137		-[2151]	
-lnL: survey	-24.2		-24.0		-25.4		-30.2		-30.6		-31.4		-15.5		-15.5		-17.0		-24.1		-24.3		-25.5	
-lnL: comCAA	-787.0		-786.9		-785.6		-783.9		-785.6		-782.4		-793.8		-793.8		-792.3		-791.1		-791.2		-790.1	
-lnL: survCAA	-1819		-1819		-1821		-1819		-1818		-1821		-1329		-1329		-1330		-1329		-1329		-1330	
-lnL: survCAL	-160.5		-160.4		-161.0		-161.0		-160.8		-161.5		-		-		0.0		-		-		0.0	
-lnL: RecRes	29.3		31.9		[0.0]		24.4		28.6		[0.0]		15.2		15.2		[0.0]		13.1		13.1		[0.0]	
-lnL: Catch	3.1		3.0		2.1		3.2		3.8		2.5		1.4		1.4		1.2		1.1		1.1		1.1	
-lnL: calibration	-6.7		-6.7		-6.7		-6.7		-6.7		-6.7		-6.7		-6.7		-6.7		-6.7		-6.7		-6.7	
Maximum gradient	0.000		0.000		0.000		0.000		0.000		0.000		2.600*		2.589*		1.073*		0.000		0.000		0.000	
$N_{y1,0}$	15.10	(0.14)	15.88	(0.14)	15.18	(0.14)	15.10	(0.14)	15.91	(0.14)	15.51	(0.14)	13.30	(0.07)	13.30	(0.07)	13.27	(0.07)	13.52	(0.07)	13.52	(0.07)	13.50	(0.07)
ϕ	0.09	(1.06)	0.19	(0.58)	0.16	(0.64)	0.08	(0.86)	0.16	(0.62)	0.16	(0.63)	-		-		-		-		-		-	
B^{sp}_{2011}	14.51	(0.16)	14.26	(0.16)	13.13	(0.17)	13.57	(0.14)	13.18	(0.14)	12.57	(0.15)	13.51	(0.16)	13.52	(0.16)	12.59	(0.17)	13.54	(0.14)	13.40	(0.14)	12.67	(0.15)
B^{sp}_{1982}	22.83	(0.05)	22.93	(0.05)	22.53	(0.05)	22.27	(0.05)	22.51	(0.05)	22.15	(0.05)	26.37	(0.04)	26.36	(0.04)	26.27	(0.04)	26.08	(0.04)	26.10	(0.04)	26.09	(0.04)
B^{sp}_{y1}	43.41	(0.28)	29.78	(0.34)	33.38	(0.31)	42.90	(0.22)	32.49	(0.31)	32.76	(0.31)	26.37	(0.04)	26.36	(0.04)	26.27	(0.04)	26.08	(0.04)	26.10	(0.04)	26.09	(0.04)
	q	σ_{Add}	q	σ_{Add}	q	σ_{Add}	q	σ_{Add}	q	σ_{Add}	q	σ_{Add}	q	σ_{Add}	q	σ_{Add}	q	σ_{Add}	q	σ_{Add}	q	σ_{Add}	q	σ_{Add}
NEFSC spring	0.84	0.16	0.84	0.16	0.84	0.16	0.79	0.11	0.79	0.11	0.78	0.11	0.96	0.18	0.96	0.18	0.96	0.18	0.83	0.12	0.83	0.12	0.83	0.11
NEFSC fall	0.67	0.10	0.68	0.10	0.68	0.10	0.64	0.12	0.64	0.12	0.64	0.12	0.54	0.06	0.54	0.06	0.54	0.05	0.47	0.06	0.47	0.06	0.47	0.05
MADMF spring	0.22	0.30	0.22	0.30	0.22	0.30	0.15	0.24	0.15	0.24	0.15	0.24	0.22	0.30	0.22	0.30	0.23	0.30	0.15	0.24	0.15	0.24	0.15	0.24
K	70.79	(0.13)	245.16	(0.26)			31.22	(0.08)	36.39	(0.09)			157.95	(1.35)	625.38	(1.47)			31.26	(0.26)	43.49	(0.35)		
h	2.44	(0.14)	0.88	(0.05)			1.00	(0.16)	0.98+	(0.00)			1.79	(0.25)	0.80	(0.08)			0.94	(0.29)	0.82	(0.39)		
MSY	13.48	(0.10)	15.27	(0.22)			6.31	(0.16)	5.83	(0.09)			23.77	(1.17)	36.66	(1.40)			5.88	(0.17)	5.76	(0.23)		
F_{MSY}	0.59		0.27				0.67		0.95				0.42		0.22				0.60		0.86			
B^{sp}_{MSY}	23.88	(0.10)	57.05	(0.23)			11.54	(0.16)	8.27	(0.10)			58.07	(1.17)	168.72	(1.40)			11.80	(0.17)	8.79	(0.23)		
B^{sp}_{MSY}/K^{sp}	0.34	(0.11)	0.23	(0.06)			0.37	(0.17)	0.23	(0.03)			0.37	(0.20)	0.27	(0.08)			0.38	(0.32)	0.20	(0.50)		
$B^{sp}_{2011}/B^{sp}_{MSY}$	0.61	(0.10)	0.25	(0.23)			1.18	(0.16)	1.59	(0.10)			0.23	(1.17)	0.08	(1.40)			1.15	(0.17)	1.53	(0.23)		

* This applies to the gradient for the age 4 parameter for selectivity in the first 1982-1988 block. All other estimated parameters have gradient $<10^{-3}$.
\+ Estimate on bound of *h*=0.98 imposed on Beverton-Holt stock-recruitment curve fits.

App. A5, Table 2: An extension of Table 1 which provides BRP values for external estimation of the stock-recruitment functions.

	Start in 1963								Start in 1982							
	M =0.2				*M* increasing				*M* =0.2				*M* increasing			
	Ricker		Beverton-Holt		Ricker		Beverton-Holt		Ricker		Beverton-Holt		Ricker		Beverton-Holt	
-lnL	8.7		11.4		1.5		6.1		2.8		2.7		-1.9		-1.8	
h	2.65	(0.14)	0.91	(0.05)	1.14	(0.16)	1.00	(0.00)	2.16	(0.24)	0.86	(0.08)	1.18	(0.29)	1.00	(0.00)
K^{sp}	66.41	(0.13)	220.04	(0.22)	29.83	(0.06)	36.86	(0.09)	89.51	(0.65)	324.35	(0.76)	27.22	(0.17)	39.44	(0.11)
F_{MSY}	0.87		0.38		1.11		5.00*		0.67		0.31		1.20		5.00*	
$MSYL^{sp}$	0.33	(0.11)	0.22	(0.05)	0.36	(0.16)	0.11	(0.00)	0.35	(0.18)	0.26	(0.07)	0.36	(0.29)	0.11	(0.00)
B^{sp}_{MSY}	21.94	(0.09)	49.41	(0.18)	10.88	(0.15)	3.87	(0.09)	31.57	(0.50)	83.96	(0.69)	9.86	(0.18)	4.15	(0.11)
MSY	13.55	(0.09)	14.32	(0.18)	7.01	(0.15)	6.59	(0.09)	15.62	(0.50)	20.36	(0.69)	6.65	(0.18)	7.05	(0.11)
B^{sp}_{2011}	13.11	(0.17)	13.11	(0.17)	12.57	(0.15)	12.57	(0.15)	12.59	(0.17)	12.59	(0.17)	12.67	(0.17)	12.67	(0.15)
$B^{sp}_{2011}/B^{sp}_{MSY}$	0.60	(0.09)	0.27	(0.18)	1.16	(0.15)	3.25	(0.09)	0.40	(0.50)	0.15	(0.69)	1.29	(0.18)	3.05	(0.11)
B^{sp}_{2011}/K^{sp}	0.20	(0.13)	0.06	(0.22)	0.42	(0.06)	0.34	(0.09)	0.14	(0.65)	0.04	(0.76)	0.47	(0.17)	0.32	(0.11)

* Estimate on upper bound of F=5.00 imposed on the search for F_{MSY}, which may occur in the limit of h=1 for the Beverton-Holt form. (Note that unlike for the internal estimation where a bound of h=0.98 is imposed, the bound imposed here is h=1.)

App. A5, Table 3: Estimates of abundance, MSY-related BRPs, and related quantities for the Gulf of Maine cod for different sensitivities about the Reference Case (start in 1963 with a Ricker stock-recruitment curve estimated internally) with $M = 0.2$, which is shown in **bold**. Values in round parentheses are Hessian based CV's, while maximum gradient refers to the quantity reported with the ADMB estimation results. Negative log-likelihood overall values shown in square parentheses denote non-comparability with values of all likelihood components given in adjacent columns. Mass units are '000 tons. $y1$ refers to the start year for the assessment. Recruitment $N_{y1,0}$ is in millions. Refer to Appendix B for definitions of some of the symbols used.

	Different start year														Adjusted log-normal CAA error		Fit to biomass instead of numbers		Domed NEFSC survey selectivity		Alternative pre-1982 commercial selectivities				Bigelow internal calibration		No CAL data	
			Reference Case																		Same as 82-88		Shifted 2yrs left					
Start year y1=	1934		1963		1964		1965		1967		1970		1982		1963		1963		1963		1963		1963		1963		1963	
-lnL: overall	-[2762]		**-2765**		-[2748]		-[2732]		-[2697]		-[2610]		-[2128]		-[298]		-[2777]		-2781		-2768		-2761		-2766		-[2605]	
-lnL: survey	-24.5		**-24.2**		-25.4		-25.1		-23.2		-19.4		-15.5		-24.2		-37.5		-25.3		-24.7		-23.8		-25.3		-24.1	
-lnL: comCAA	-787.0		**-787.0**		-787.0		-786.8		-786.6		-787.2		-793.8		-177.8		-786.3		-786.7		-790.6		-788.6		-787.0		-787.2	
-lnL: survCAA	-1819		**-1819**		-1819		-1820		-1820		-1820		-1329		-134		-1818		-1828		-1817		-1815		-1821		-1819	
-lnL: survCAL	-160.0		**-160.5**		-141.6		-126.1		-89.3		-		-		16.6		-160.3		-162.1		-160.6		-160.2		-160.6		0.0	
-lnL: RecRes	[31.9]		**29.3**		[29.1]		[29.7]		[26.4]		[21.3]		[15.2]		[25.0]		[29.9]		26.0		27.9		30.1		29.6		[28.7]	
-lnL: Catch	3.2		**3.1**		3.0		2.9		2.4		1.9		1.4		2.9		2.5		2.5		3.1		3.3		3.2		3.1	
-lnL: calibration	-6.7		**-6.7**		-6.7		-6.7		-6.7		-6.7		-6.7		-6.7		-6.7		-6.7		-6.7		-6.7		-5.4		-6.7	
Maximum gradient	0.000		**0.000**		0.000		0.000		0.000		0.000		2.600*		0.000		0.000		0.000		0.000		30.774		18.6[&]		0.000	
$N_{y1,0}$	9.52	(76.22)	**15.10**	**(0.14)**	8.56	(0.17)	4.65	(0.20)	3.25	(0.21)	4.84	(0.19)	13.30	(0.07)	16.02	(0.11)	15.41	(0.14)	16.29	(0.14)	14.08	(0.14)	15.41	(0.15)	15.09	(0.14)	15.17	(0.16)
ϕ	0.25	(152.54)	**0.09**	**(1.06)**	0.04	(2.05)	0.14	(0.78)	0.16	(0.73)	-		-		0.21	(0.35)	0.09	(0.91)	0.01	(0.08)	0.09	(0.97)	0.08	(1.08)	0.09	(1.05)	0.01	(0.02)
B^{sp}_{2011}	14.25	(0.16)	**14.51**	**(0.16)**	14.42	(0.16)	14.33	(0.16)	14.35	(0.16)	14.22	(0.16)	13.51	(0.16)	16.04	(0.17)	13.59	(0.15)	15.30	(0.17)	14.30	(0.16)	14.39	(0.16)	14.67	(0.16)	14.50	(0.16)
B^{sp}_{1982}	22.92	(0.05)	**22.83**	**(0.05)**	22.84	(0.05)	22.96	(0.05)	22.99	(0.05)	22.94	(0.05)	26.37	(0.04)	26.19	(0.05)	22.94	(0.05)	28.63	(0.09)	22.37	(0.05)	23.29	(0.05)	22.81	(0.05)	22.94	(0.05)
B^{sp}_{y1}	41.17	(140.75)	**43.41**	**(0.28)**	46.74	(0.24)	34.80	(0.27)	38.66	(0.13)	34.58	(0.10)	26.37	(0.04)	28.24	(0.23)	39.48	(0.23)	102.12	(0.17)	44.22	(0.26)	41.24	(0.32)	43.30	(0.28)	51.87	(0.13)
	q	σ_{Add}	q	σ_{Add}	q	σ_{Add}	q	σ_{Add}	q	σ_{Add}	q	σ_{Add}	q	σ_{Add}	q	σ_{Add}	q	σ_{Add}	q	σ_{Add}	q	σ_{Add}	q	σ_{Add}	q	σ_{Add}	q	σ_{Add}
NEFSC spring	0.84	0.16	**0.84**	**0.16**	0.84	0.16	0.84	0.16	0.84	0.16	0.84	0.17	0.96	0.18	0.89	0.16	0.83	0.15	0.86	0.16	0.84	0.16	0.85	0.16	0.84	0.16	0.84	0.16
NEFSC fall	0.67	0.10	**0.67**	**0.10**	0.66	0.09	0.65	0.09	0.64	0.10	0.64	0.11	0.54	0.06	0.79	0.11	0.66	0.07	0.69	0.09	0.66	0.10	0.68	0.10	0.67	0.10	0.66	0.10
MADMF spring	0.22	0.30	**0.22**	**0.30**	0.22	0.30	0.22	0.30	0.22	0.30	0.22	0.30	0.22	0.30	0.20	0.29	0.19	0.18	0.21	0.30	0.22	0.30	0.22	0.30	0.22	0.30	0.22	0.30
K	74.78	(0.19)	**70.79**	**(0.13)**	70.11	(0.14)	75.18	(0.19)	94.80	(0.27)	383.89	(1.81)	157.95	(1.35)	95.45	(0.29)	71.39	(0.15)	97.48	(0.12)	66.28	(0.12)	75.81	(0.16)	70.73	(0.14)	73.03	(0.13)
h	2.24	(0.15)	**2.44**	**(0.14)**	2.46	(0.14)	2.32	(0.16)	2.11	(0.16)	1.65	(0.18)	1.79	(0.25)	1.99	(0.18)	2.39	(0.15)	2.03	(0.12)	2.45	(0.14)	2.41	(0.14)	2.43	(0.14)	2.40	(0.13)
MSY	13.34	(0.12)	**13.48**	**(0.10)**	13.44	(0.10)	13.75	(0.12)	16.09	(0.19)	53.41	(1.69)	23.77	(1.17)	15.26	(0.18)	13.39	(0.10)	15.69	(0.10)	12.69	(0.09)	14.35	(0.10)	13.46	(0.10)	13.76	(0.10)
F_{MSY}	0.53		**0.59**		0.59		0.56		0.50		0.38		0.42		0.48		0.58		0.53		0.60		0.57		0.59		0.58	
B^{sp}_{MSY}	25.73	(0.12)	**23.88**	**(0.10)**	23.59	(0.10)	25.61	(0.12)	32.96	(0.19)	140.96	(1.69)	58.07	(1.17)	32.92	(0.19)	24.14	(0.10)	32.85	(0.12)	22.41	(0.10)	25.88	(0.11)	23.87	(0.10)	24.70	(0.10)
B^{sp}_{MSY}/K^{sp}	0.34	(0.12)	**0.34**	**(0.11)**	0.34	(0.11)	0.34	(0.13)	0.35	(0.13)	0.37	(0.15)	0.37	(0.20)	0.34	(0.15)	0.34	(0.12)	0.34	(0.11)	0.34	(0.11)	0.34	(0.12)	0.34	(0.11)	0.34	(0.11)
$B^{sp}_{2011}/B^{sp}_{MSY}$	0.55	(0.12)	**0.61**	**(0.10)**	0.61	(0.10)	0.56	(0.12)	0.44	(0.19)	0.10	(1.69)	0.23	(1.17)	0.49	(0.19)	0.56	(0.10)	0.47	(0.12)	0.64	(0.10)	0.56	(0.11)	0.61	(0.10)	0.59	(0.10)

App. A5, Table 4: Estimates of abundance, MSY-related BRPs, and related quantities for the Gulf of Maine cod for different sensitivities about the Reference Case (start in 1963 with a Ricker stock-recruitment curve estimated internally) with *M* increasing from 0.2 until 1988 to 0.4 in 2003 and constant at 0.4 thereafter. This case is shown in **bold.** Values in round parentheses are Hessian based CV's, while maximum gradient refers to the quantity reported with the ADMB estimation results. Negative log-likelihood overall values shown in square parentheses denote non-comparability with values given for all likelihood components in adjacent columns. Mass units are '000 tons. *y*1 refers to the start year for the assessment. Recruitment $N_{y1,0}$ is in millions. Refer to Appendix B for definition of some of the symbols used.

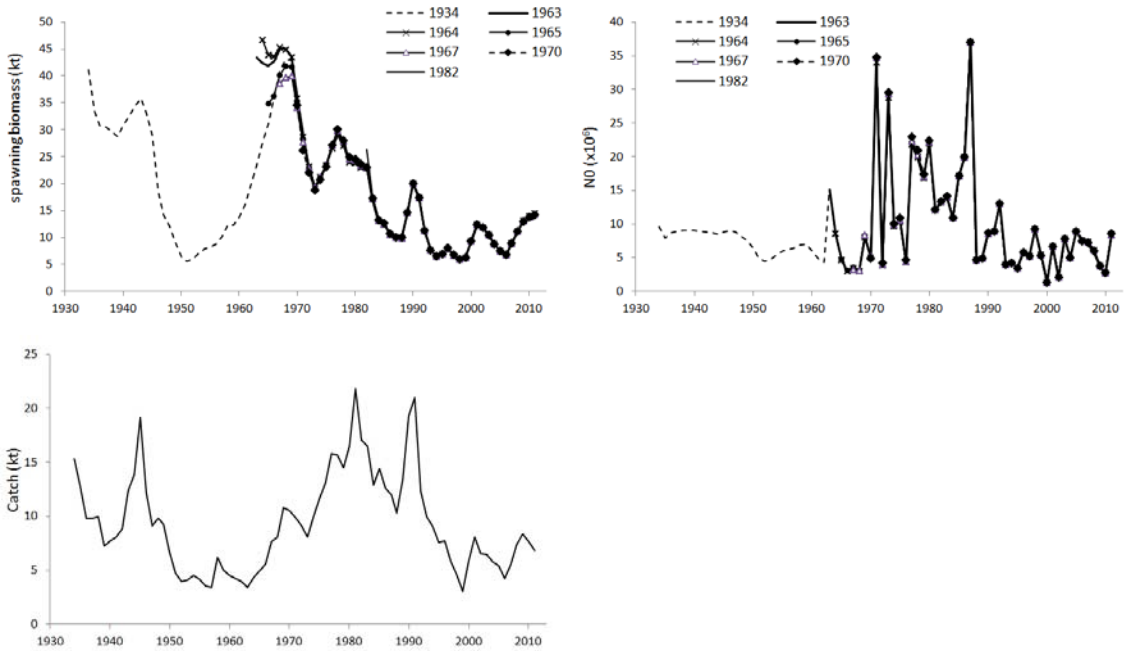
	Different start year														Adjusted log-normal CAA error	
Start year y1=	1934		1963		1964		1965		1967		1970		1982		1963	
-lnL: overall	-[2772]		**-[2774]**		-[2757]		-[2740]		-[2705]		-[2615]		-[2137]		-[311]	
-lnL: survey	-30.1		**-30.2**		-31.4		-31.1		-29.9		-26.4		-24.1		-29.3	
-lnL: comCAA	-785.1		**-783.9**		-785.9		-785.8		-784.5		-785.8		-791.1		-176.2	
-lnL: survCAA	-1818		**-1819**		-1818		-1818		-1820		-1819		-1329		-139	
-lnL: survCAL	-160.9		**-161.0**		-142.1		-126.1		-89.3		0.0		0.0		16.0	
-lnL: RecRes	[25.8]		**[24.4]**		[23.8]		[24.4]		[22.7]		[20.1]		[13.1]		[21.0]	
-lnL: Catch	3.4		**3.2**		3.1		3.1		2.7		2.0		1.1		3.5	
-lnL: calibration	-6.7		**-6.7**		-6.7		-6.7		-6.7		-6.7		-6.7		-6.7	
Maximum gradient	0.000		**0.000**		0.000		0.000		0.000		0.000		0.000		0.000	
$N_{y1,0}$	10.74	(1.98)	**15.10**	**(0.14)**	8.70	(0.17)	4.79	(0.20)	3.56	(0.21)	5.23	(0.19)	13.52	(0.07)	15.93	(0.11)
ϕ	0.33	(2.15)	**0.08**	**(0.86)**	0.03	(2.09)	0.08	(1.02)	0.13	(0.84)	-		-		0.18	(0.40)
B^{sp}_{2011}	13.64	(0.15)	**13.57**	**(0.14)**	13.54	(0.14)	13.55	(0.14)	13.57	(0.14)	13.58	(0.15)	13.54	(0.14)	15.07	(0.15)
B^{sp}_{1982}	22.17	(0.05)	**22.27**	**(0.05)**	22.38	(0.05)	22.46	(0.05)	22.33	(0.05)	22.54	(0.05)	26.08	(0.04)	25.71	(0.05)
B^{sp}_{y1}	25.81	(2.11)	**42.90**	**(0.22)**	46.72	(0.19)	38.85	(0.21)	38.64	(0.13)	33.05	(0.10)	26.08	(0.04)	32.43	(0.20)
	q	σ_{Add}	q	σ_{Add}	q	σ_{Add}	q	σ_{Add}	q	σ_{Add}	q	σ_{Add}	q	σ_{Add}	q	σ_{Add}
NEFSC spring	0.80	0.11	**0.79**	**0.11**	0.79	0.11	0.79	0.11	0.79	0.11	0.78	0.11	0.83	0.12	0.78	0.11
NEFSC fall	0.64	0.12	**0.64**	**0.12**	0.63	0.11	0.62	0.11	0.61	0.11	0.59	0.12	0.47	0.06	0.70	0.13
MADMF spring	0.15	0.24	**0.15**	**0.24**	0.15	0.24	0.15	0.24	0.15	0.24	0.15	0.24	0.15	0.24	0.13	0.24
K	31.64	(0.08)	**31.22**	**(0.08)**	31.26	(0.08)	31.03	(0.08)	33.59	(0.11)	44.77	(0.27)	31.26	(0.26)	32.72	(0.09)
h	1.02	(0.16)	**1.00**	**(0.16)**	1.01	(0.16)	1.01	(0.17)	0.91	(0.18)	0.72	(0.21)	0.94	(0.29)	0.95	(0.20)
MSY	6.50	(0.15)	**6.31**	**(0.16)**	6.37	(0.15)	6.32	(0.16)	6.16	(0.15)	6.27	(0.16)	5.88	(0.17)	6.24	(0.18)
F_{MSY}	0.69		**0.67**		0.68		0.68		0.58		0.39		0.60		0.57	
B^{sp}_{MSY}	11.66	(0.15)	**11.54**	**(0.16)**	11.54	(0.16)	11.46	(0.16)	12.72	(0.16)	17.95	(0.16)	11.80	(0.17)	12.22	(0.18)
B^{sp}_{MSY}/K^{sp}	0.37	(0.18)	**0.37**	**(0.17)**	0.37	(0.17)	0.37	(0.18)	0.38	(0.20)	0.40	(0.25)	0.38	(0.32)	0.37	(0.22)
$B^{sp}_{2011}/B^{sp}_{MSY}$	1.17	(0.15)	**1.18**	**(0.16)**	1.17	(0.16)	1.18	(0.16)	1.07	(0.16)	0.76	(0.16)	1.15	(0.17)	1.23	(0.18)

App. A5, Table 5: Estimates of abundance, MSY-related BRPs, and related quantities for the Gulf of Maine cod for the preferred cases for the two different *M* scenarios. Values in round parentheses are Hessian based CV's, while maximum gradient refers to the quantity reported with the ADMB estimation results. Mass units are '000 tons. *y*1 refers to the start year for the assessment. Recruitment $N_{y1,0}$ is in millions. Refer to Appendix B for definitions of some of the symbols used.

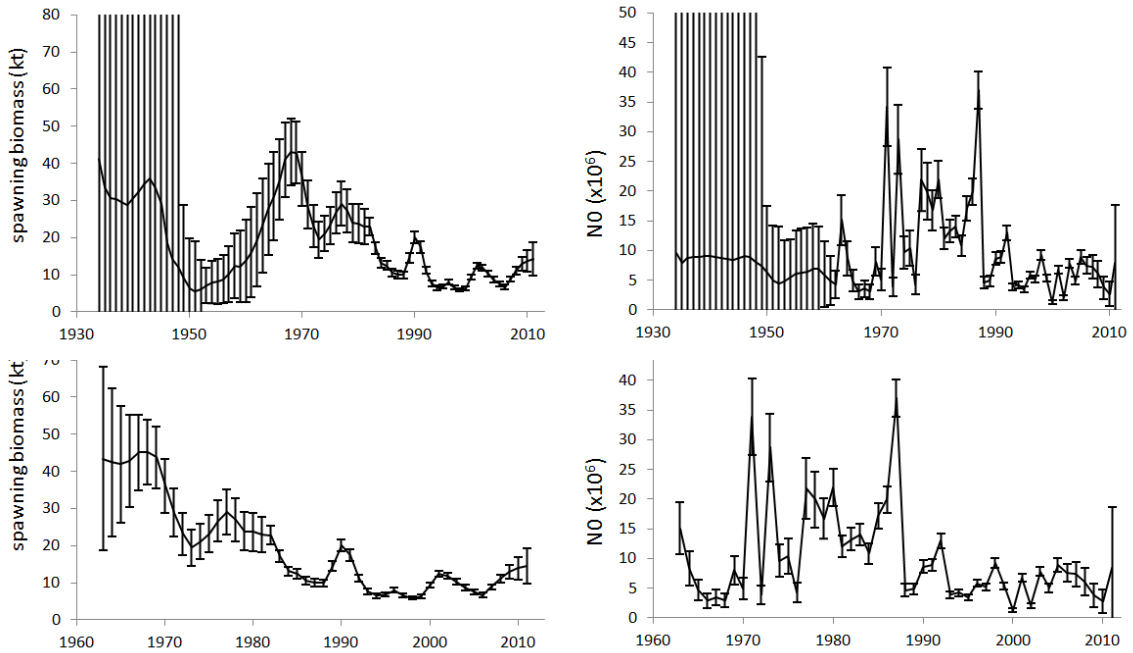
	M =0.2		*M* increasing	
Start year y1=	1934		1934	
-lnL: overall	-2764		-2773	
-lnL: survey	-25.4		-30.8	
-lnL: comCAA	-787.0		-785.2	
-lnL: survCAA	-1821		-1820	
-lnL: survCAL	-160.1		-161.0	
-lnL: RecRes	32.1		26.0	
-lnL: Catch	3.2		3.4	
-lnL: calibration	-5.4		-5.6	
Maximum gradient	18.5*		15.5	
$N_{y1,0}$	11.21	(175.51)	10.78	(1.97)
ϕ	0.32	(231.12)	0.33	(2.14)
B^{sp}_{2011}	14.49	(0.05)	13.79	(0.05)
B^{sp}_{1982}	22.90	(0.16)	22.15	(0.15)
B^{sp}_{y1}	32.69	(222.39)	25.73	(2.10)
	q	σ_{Add}	q	σ_{Add}
NEFSC spring	0.84	0.16	0.80	0.11
NEFSC fall	0.67	0.10	0.65	0.12
MADMF spring	0.22	0.30	0.15	0.24
K	74.70	(0.19)	31.58	(0.08)
h	2.24	(0.15)	1.02	(0.16)
MSY	13.33	(0.12)	6.49	(0.15)
F_{MSY}	0.53		0.69	
B^{sp}_{MSY}	25.70	(0.12)	11.64	(0.15)
B^{sp}_{MSY}/K^{sp}	0.34	(0.12)	0.37	(0.18)
$B^{sp}_{2011}/B^{sp}_{MSY}$	0.56	(0.12)	1.18	(0.15)

* This applies to the gradient for the third calibration parameter F2. All other estimated parameters have gradient $<10^{-5}$.

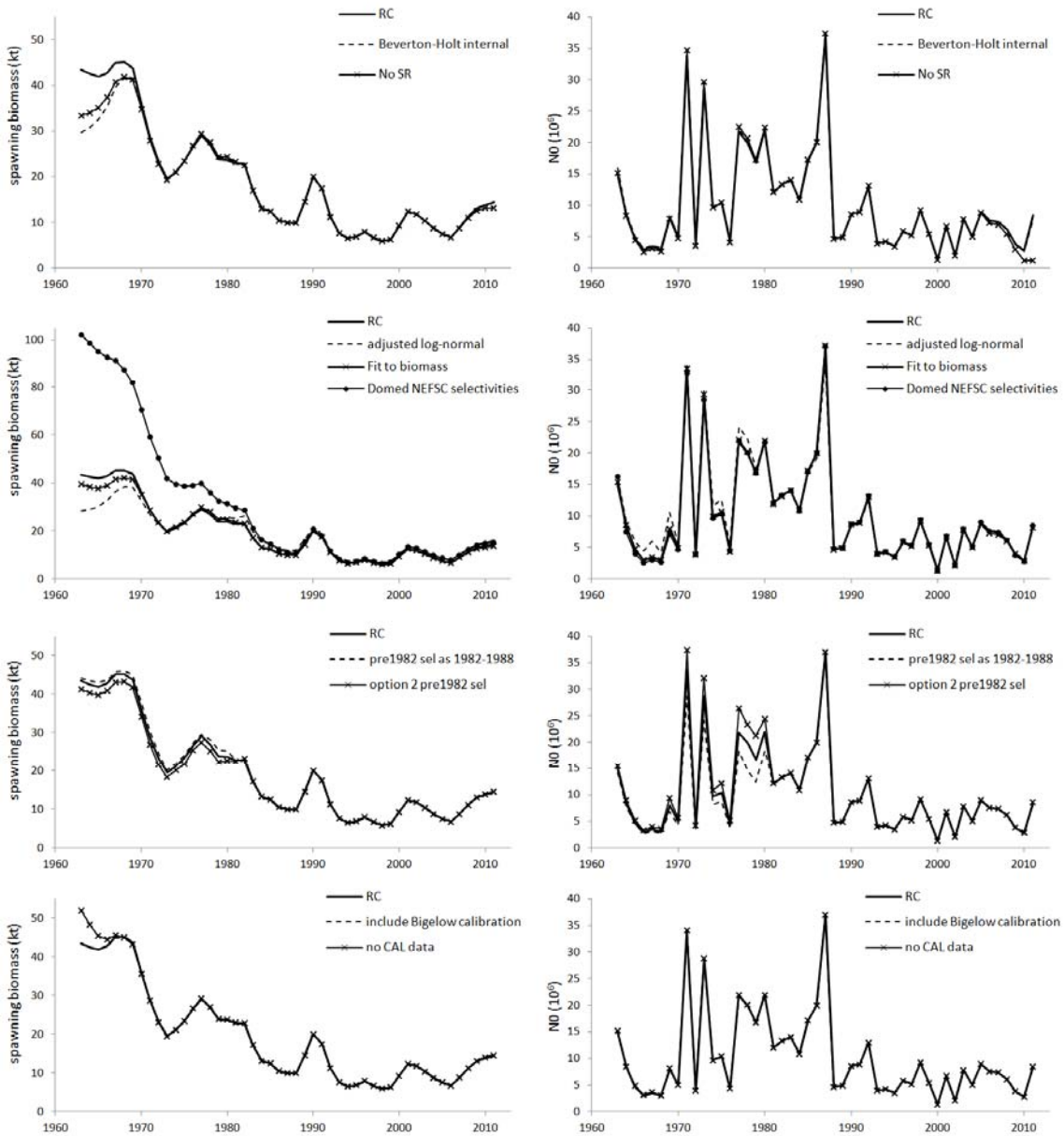
Appendix A5. Figures



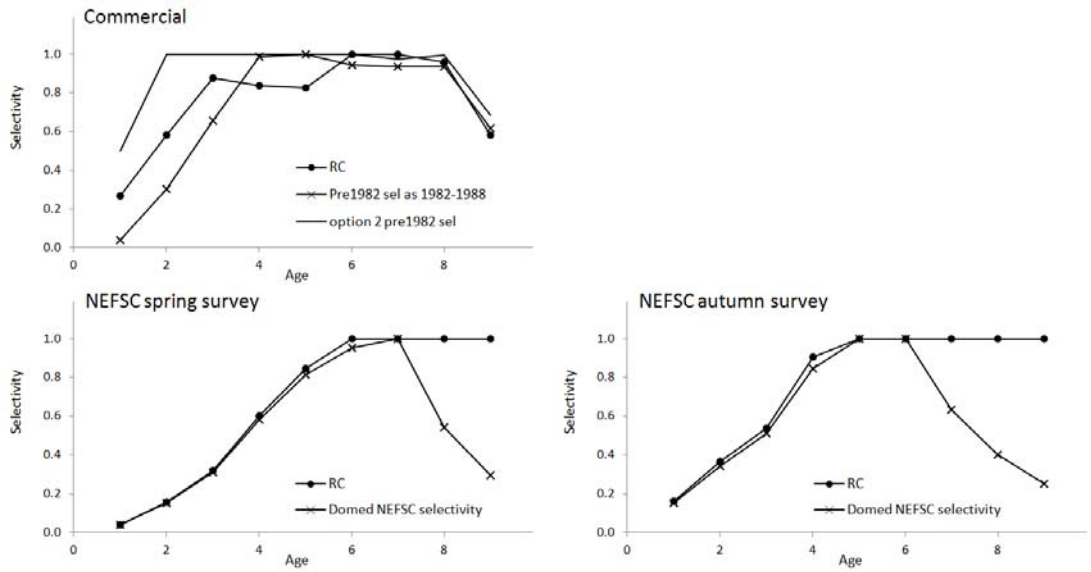
App. A5, Fig. 1: Spawning biomass and recruitment trajectories for the Ricker internal case with *M = 0.2* and different starting years. The time series of catches is also shown (including the 32% increase pre-1982 to take account of discards).



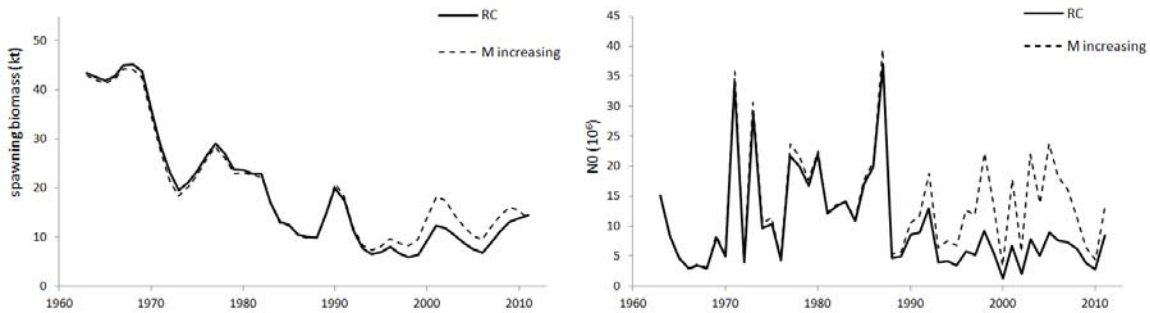
App. A5, Fig. 2: Spawning biomass and recruitment trajectories for the Ricker internal case with *M = 0.2*, start in 1934 (top row) and start in 1963 (bottom row) with ±2 se's shown to reflect approximate 95% CIs.



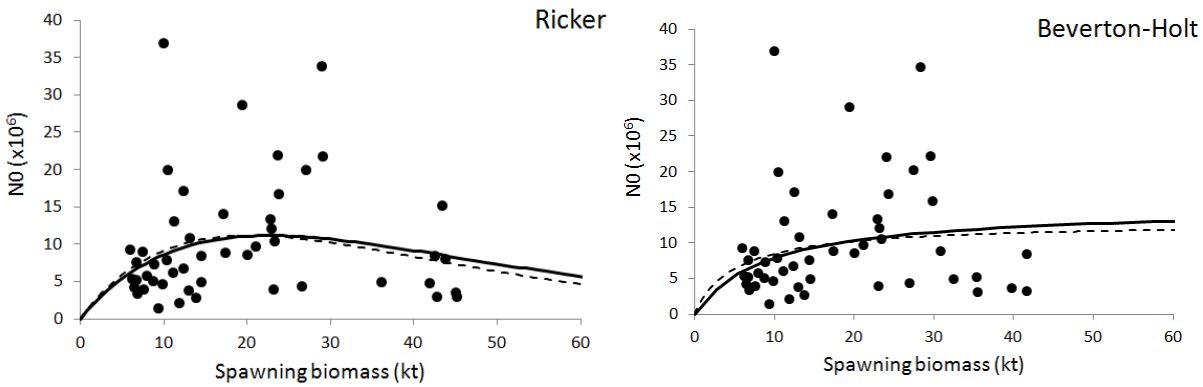
App. A5, Fig. 3: Spawning biomass and recruitment trajectories for various sensitivities about the Reference Case (RC - Ricker internal start in 1963) for $M = 0.2$.



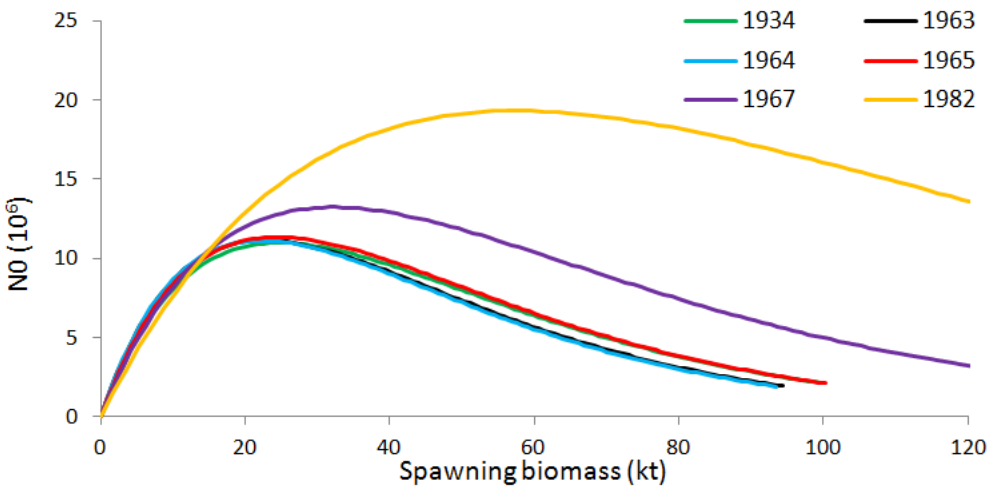
App. A5, Fig. 4: Pre-1982 commercial selectivities for the RC for M = 0.2and the two sensitivities relating to the pre-1982 commercial selectivity, and then for the NEFSC survey selectivities for the RC (flat) and the domed selectivity sensitivity.



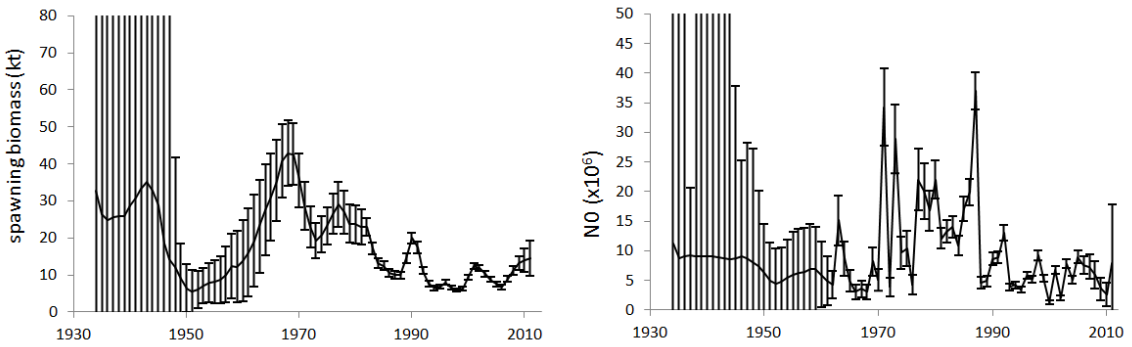
App. A5, Fig. 5: Spawning biomass and recruitment trajectories for the Reference Case with M = 0.2 and the corresponding case with M increasing.



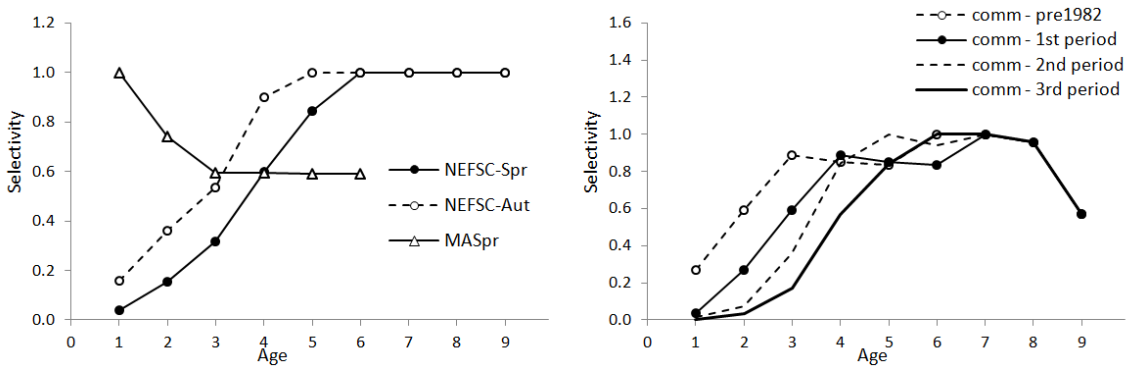
App. A5, Fig. 6: Stock-recruitment curve and "observed" recruitment for the Ricker and Beverton-Holt relationships estimated internally for the RC choice of a 1963 start year. The dashed lines show the corresponding estimated curves for external estimation.



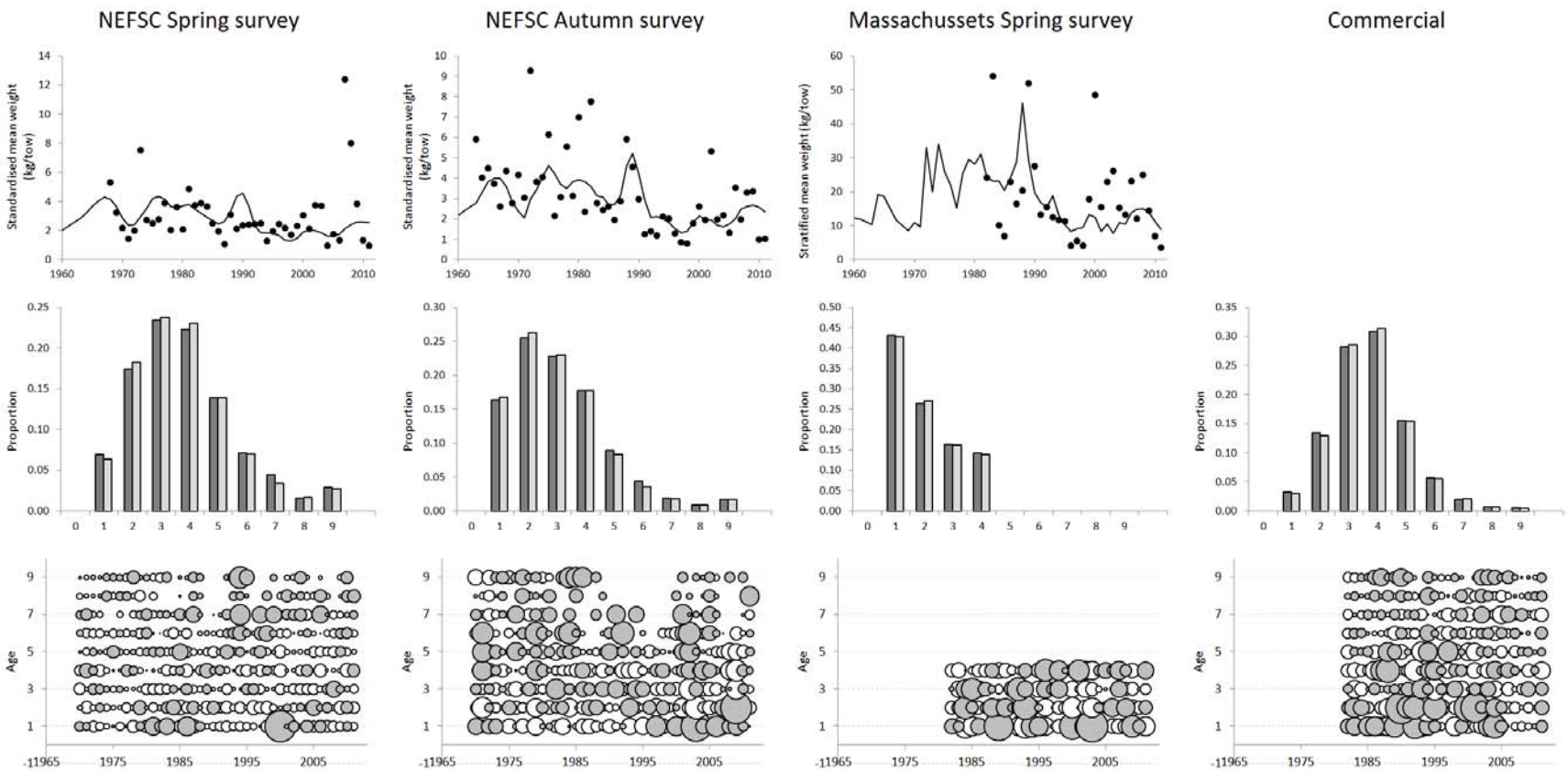
App. A5, Fig. 7: Stock-recruit relationship for the Reference Case with M = 0.2 and the cases with different start year. To improve discrimination, the very imprecisely estimated 1970 curve which goes to much higher levels than these others is omitted.



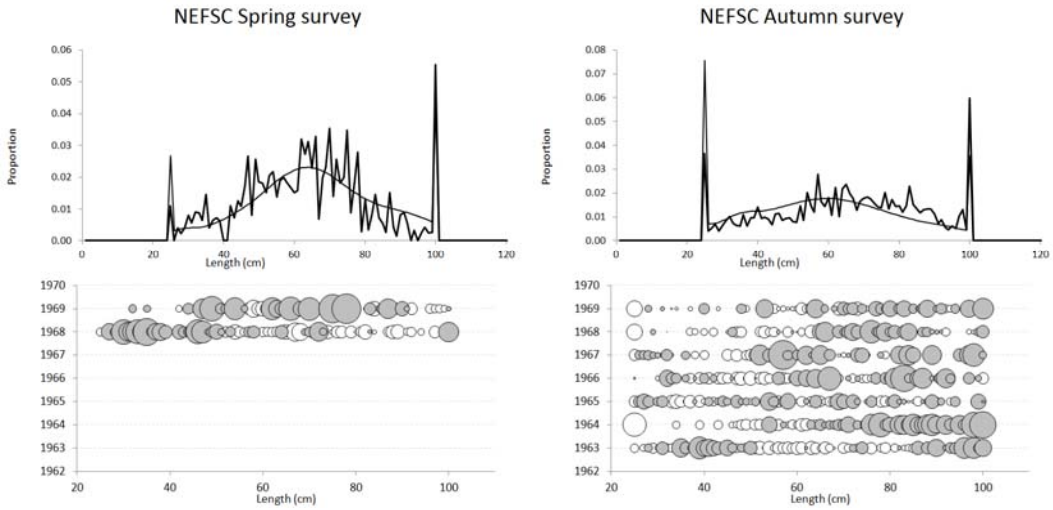
App. A5, Fig. 8. Spawning biomass and recruitment trajectories (with ±2 se's to reflect approximate 95% CIs) for the "preferred" run, *M = 0.2*.



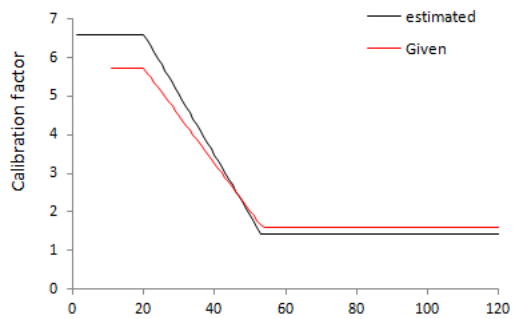
App. A5, Fig. 9. Survey and commercial selectivities estimated for the "preferred" run, *M = 0.2*.



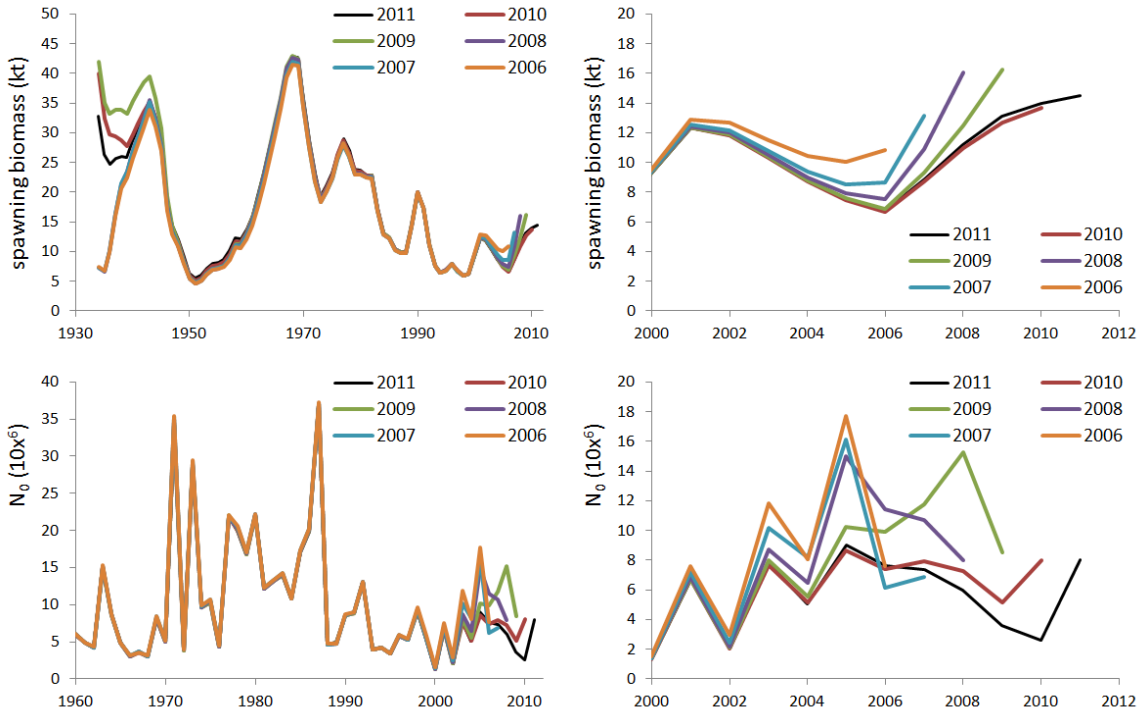
App. A5, Fig. 10: Fits to the abundance indices (top row) and to the survey and commercial catch-at-age data for the "preferred" run, *M = 0.2*. The second row plots compare the observed and predicted CAA as averaged over all years for which data are available, while the third row plots show the standardised residuals, with the size (area) of the bubbles being proportional to the magnitude of the corresponding standardised residuals. For positive residuals, the bubbles are grey, whereas for negative residuals, the bubbles are white.



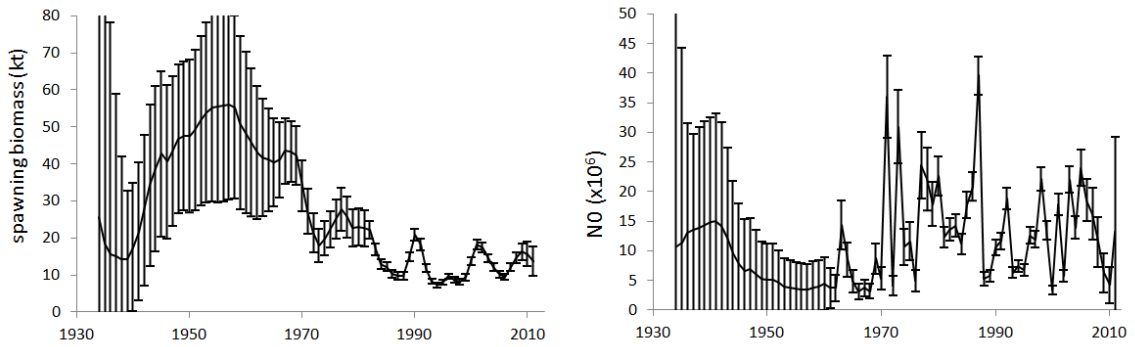
App. A5, Fig. 11: Fits to the survey catch-at-length data for the "preferred" run, *M = 0.2*. The first row plots compare the observed and predicted CAL as averaged over all years for which data are available, while the third row plots show the standardised residuals, with the size (area) of the bubbles being proportional to the magnitude of the corresponding standardised residuals. For positive residuals, the bubbles are grey, whereas for negative residuals, the bubbles are white.



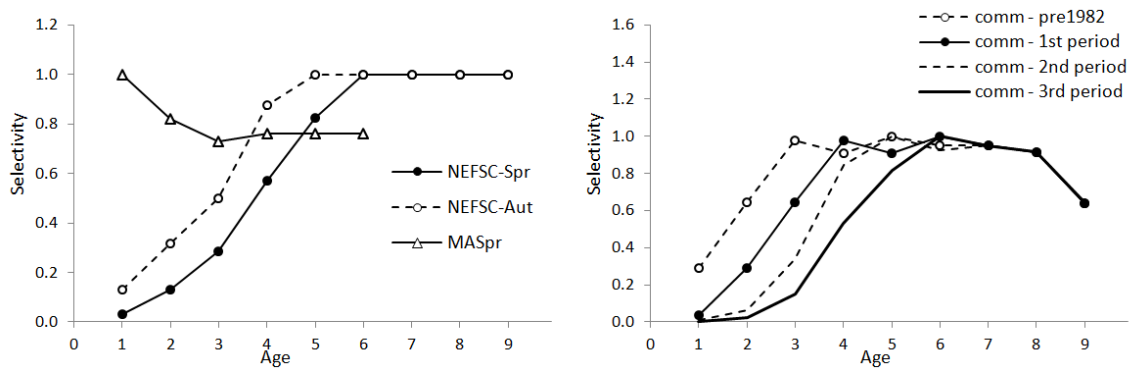
App. A5, Fig. 12: Comparison of *Bigelow-Albatross* calibration function estimated within the assessment ("preferred" run, *M = 0.2*) and calibration function given.



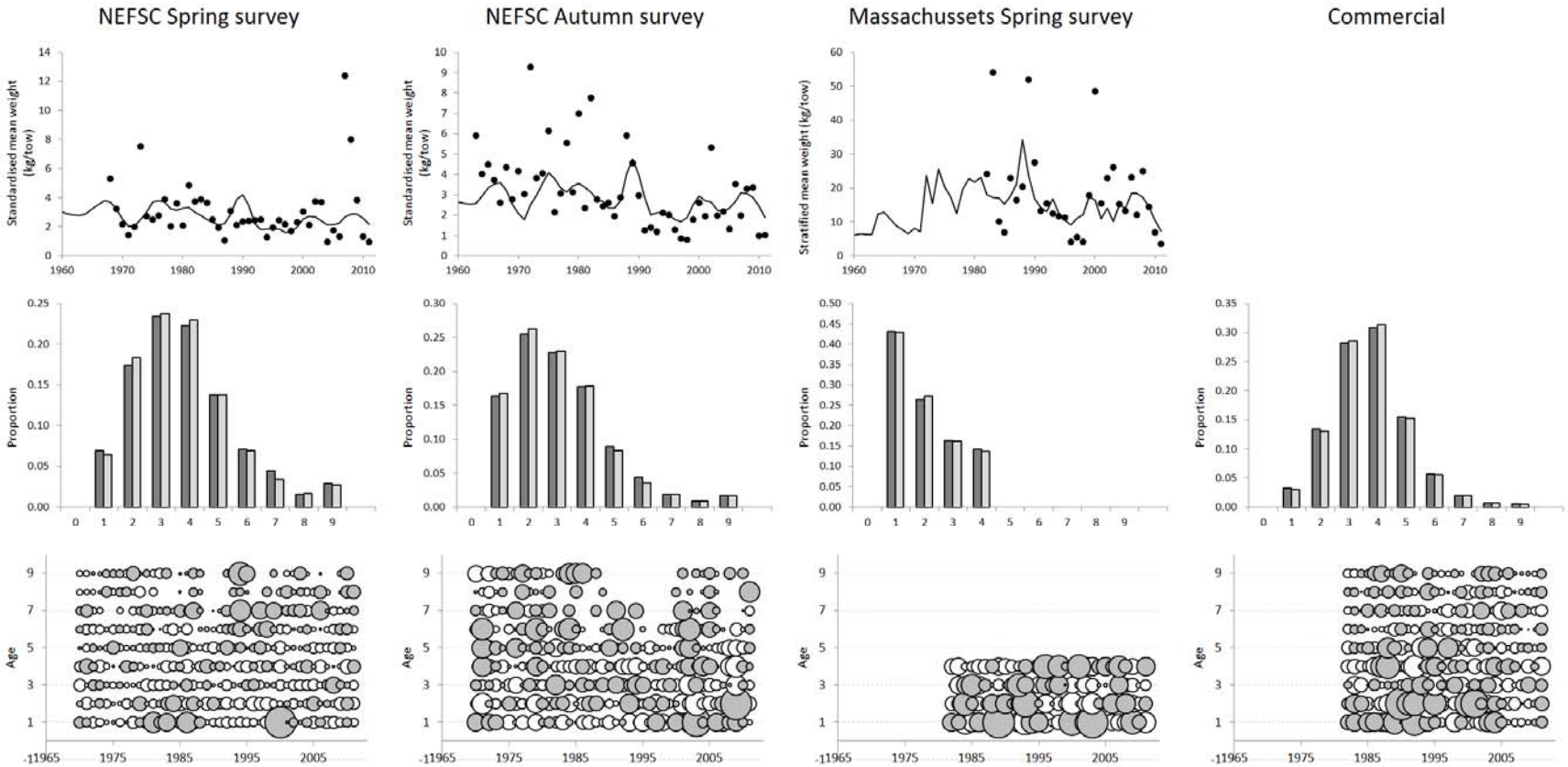
App. A5, Fig. 13: Retrospective analysis for the "preferred" run, *M = 0.2*.



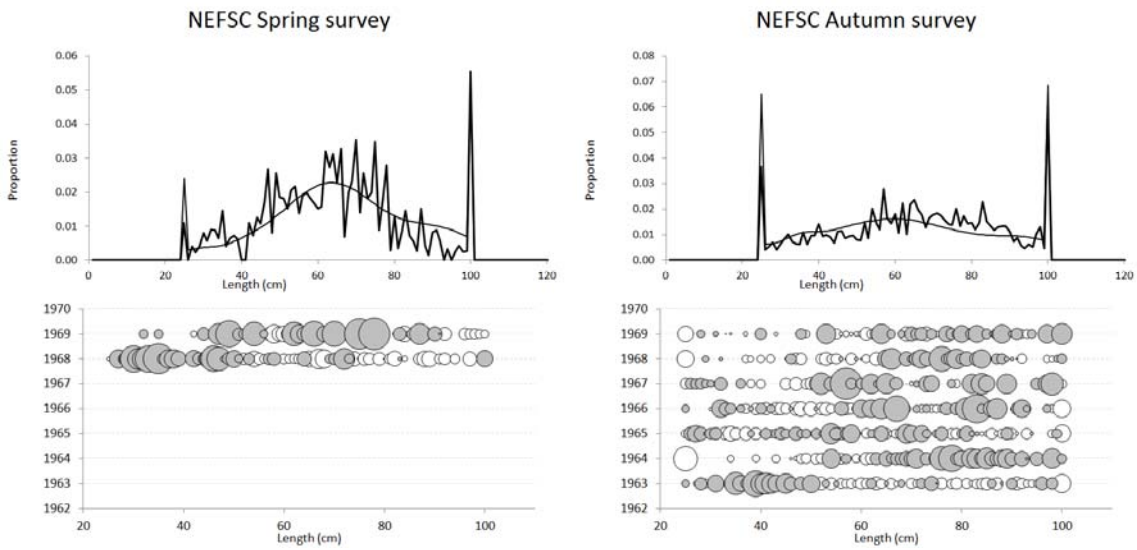
App. A5, Fig. 14. Spawning biomass and recruitment trajectories (with ±2 se's to reflect approximate 95% CIs) for the "preferred" run, *M* increasing.



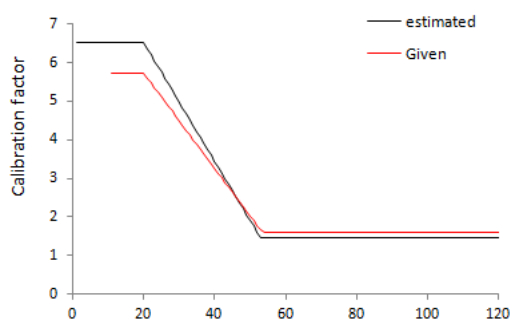
App. A5, Fig. 15. Survey and commercial selectivities estimated for the "preferred" run, *M* increasing. Note that for the Massachusetts survey as the age 4 selectivity is estimated to be greater than that for age 3, the selectivities for ages 5 and 6 are set equal to those for age 4 rather than continuing the trend from age 3 to age 4.



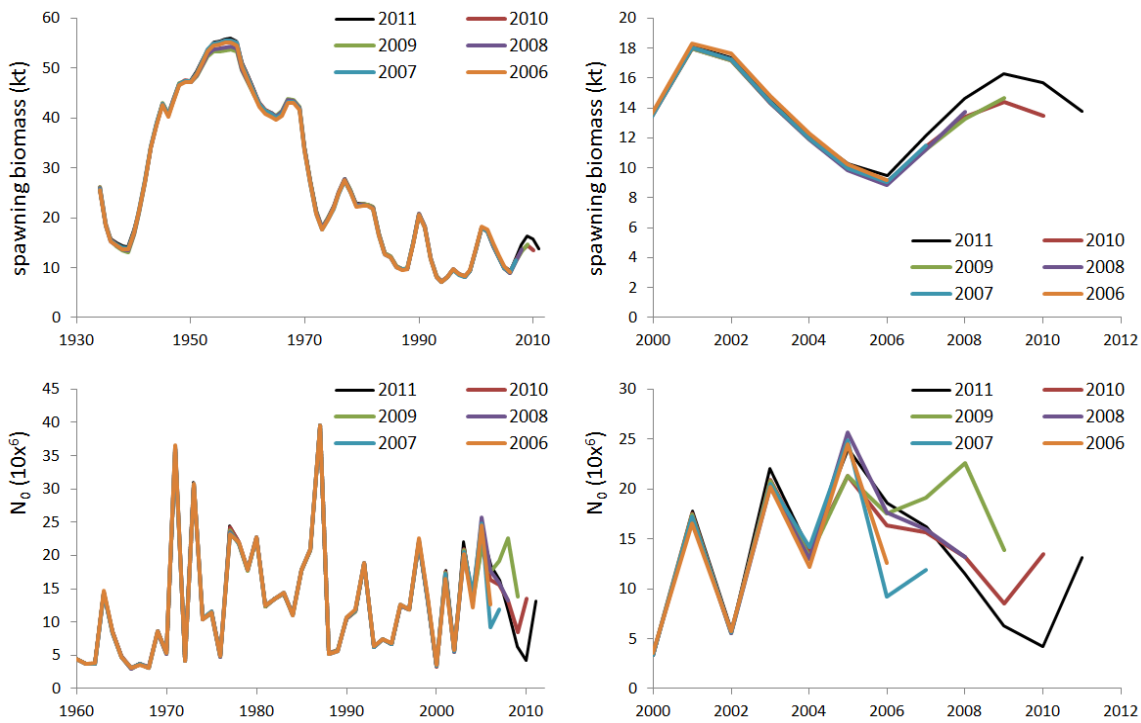
App. A5, Fig. 16: Fits to the abundance indices (top row) and to the survey and commercial catch-at-age data for the "preferred" run, *M* increasing. The second row plots compare the observed and predicted CAA as averaged over all years for which data are available, while the third row plots show the standardised residuals, with the size (area) of the bubbles being proportional to the magnitude of the corresponding standardised residuals. For positive residuals, the bubbles are grey, whereas for negative residuals, the bubbles are white.



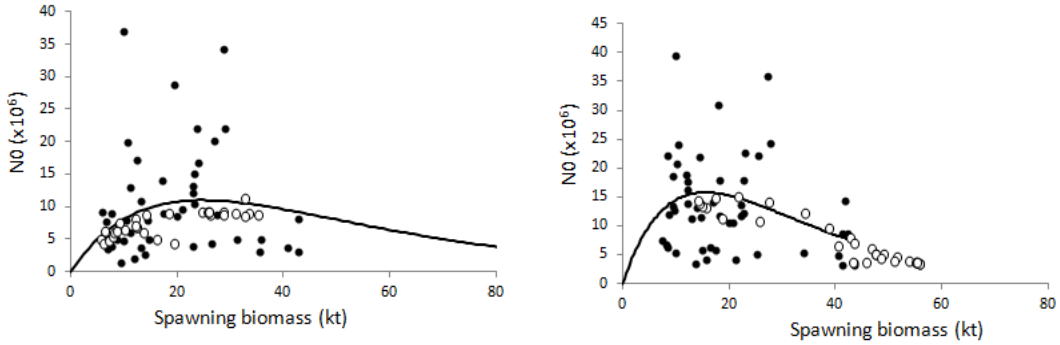
App. A5, Fig. 17: Fits to the survey catch-at-length data for the "preferred" run, *M* increasing. The first row plots compare the observed and predicted CAL as averaged over all years for which data are available, while the third row plots show the standardised residuals, with the size (area) of the bubbles being proportional to the magnitude of the corresponding standardised residuals. For positive residuals, the bubbles are grey, whereas for negative residuals, the bubbles are white.



App. A5, Fig. 18: Comparison of *Bigelow-Albatross* calibration function estimated within the assessment ("preferred" run, *M* increasing) and calibration function given.



App. A5, Fig. 19: Retrospective analysis for "preferred" run, *M* increasing.



App. A5, Fig. 20: Stock-recruitment curves and "observed" recruitment (pre-1963 data are shown as open circles) for the "preferred" runs *M = 0.2* (left-hand plot) and *M* increasing (right-hand plot).

Appendix A5 (Apendices A and B within App. A5)

APPENDIX A – Data

Note that the tables following, and the analyses reported in the main text, now exclude any 2012 data.

App. A5 (Append. A), Table A1: Total catch (incl. USA, DWF and recreational landings, and discards) (thousand metric tons) of Atlantic cod from the Gulf of Maine (NAFO Division 5Y), 1964-2012 (Michael Palmer, pers. commn). The revised discard mortality assumptions have been applied. Note that pre-1982 catches have been increased by 32% in the Base Case to allow for levels of discards suggested by recent analyses by the NEFSC.

Year	Total catch	Year	Total catch	Year	Total catch	Year	Total catch
1934	11.619	1954	3.411	1974	7.550	1994	9.060
1935	9.679	1955	3.171	1975	8.788	1995	7.566
1936	7.442	1956	2.693	1976	9.894	1996	7.757
1937	7.432	1957	2.562	1977	11.993	1997	5.814
1938	7.547	1958	4.670	1978	11.890	1998	4.578
1939	5.504	1959	3.795	1979	10.972	1999	3.078
1940	5.836	1960	3.448	1980	12.515	2000	5.823
1941	6.124	1961	3.216	1981	16.512	2001	8.055
1942	6.679	1962	2.989	1982	17.096	2002	6.509
1943	9.397	1963	2.595	1983	16.487	2003	6.497
1944	10.516	1964	3.242	1984	12.868	2004	5.766
1945	14.532	1965	3.759	1985	14.391	2005	5.441
1946	9.248	1966	4.225	1986	12.572	2006	4.268
1947	6.916	1967	5.824	1987	12.005	2007	5.527
1948	7.462	1968	6.137	1988	10.333	2008	7.375
1949	7.033	1969	8.155	1989	13.371	2009	8.355
1950	5.062	1970	7.961	1990	19.314	2010	7.670
1951	3.567	1971	7.475	1991	20.978	2011	6.830
1952	3.011	1972	6.927	1992	12.347		
1953	3.121	1973	6.138	1993	9.960		

App. A5 (Append. A), Table A2: Mean weight-at-age (kg) at the beginning of the year for the Gulf of Maine cod stock. Values derived from aggregated commercial landings and discard mean weight-at-age data (mid-year) using procedures described by Rivard (1980) (Michael Palmer, pers. commn) and applying the revised mortality assumptions. Pre-1982, the 1982-1991 average mean weight-at-age is assumed.

	0	1	2	3	4	5	6	7	8	9+
1982	0.0024	0.241	0.594	1.165	2.127	4.635	7.622	9.289	9.695	15.664
1983	0.0077	0.050	0.501	1.114	1.894	3.136	5.539	6.549	9.962	13.325
1984	0.0001	0.075	0.372	1.019	2.021	2.952	4.593	7.118	7.845	14.828
1985	0.0146	0.014	0.403	0.910	2.013	3.532	4.608	6.863	9.700	13.676
1986	0.0009	0.104	0.316	1.077	1.917	3.670	5.504	6.908	9.315	14.646
1987	0.0007	0.028	0.406	0.777	2.273	3.574	5.889	8.079	9.487	14.582
1988	0.0003	0.022	0.293	0.980	1.709	4.010	4.927	6.705	10.069	12.993
1989	0.0223	0.027	0.292	0.887	2.179	3.172	5.578	6.945	8.799	20.913
1990	0.0063	0.095	0.431	0.937	1.742	3.627	5.750	8.043	10.440	18.718
1991	0.0069	0.071	0.450	1.083	1.689	2.846	5.654	8.972	11.518	14.060
1992	0.0116	0.028	0.476	1.215	2.026	2.564	4.629	8.832	10.453	14.483
1993	0.0116	0.046	0.191	1.254	1.702	3.449	4.083	7.388	12.219	15.708
1994	0.0095	0.038	0.236	1.003	2.244	2.571	5.294	6.601	11.095	11.846
1995	0.0122	0.051	0.275	0.946	2.021	3.934	4.722	8.526	10.045	22.443
1996	0.0223	0.060	0.356	1.462	1.784	2.971	6.185	8.967	12.844	16.357
1997	0.0049	0.049	0.391	1.466	2.407	2.571	3.973	8.245	11.940	16.938
1998	0.0015	0.059	0.256	1.445	2.245	3.423	3.558	5.739	10.442	16.676
1999	0.0224	0.044	0.343	1.196	2.237	3.139	4.752	5.301	8.351	12.279
2000	0.0092	0.120	0.461	1.063	2.257	3.422	4.773	5.508	7.882	12.661
2001	0.0229	0.097	0.456	1.305	2.420	3.851	5.091	6.513	6.912	9.538
2002	0.0115	0.089	0.465	1.050	2.249	3.247	5.296	6.514	7.924	12.152
2003	0.0217	0.089	0.346	1.053	1.742	2.977	4.118	6.837	8.011	12.023
2004	0.0105	0.066	0.351	0.971	2.110	2.620	4.199	5.908	8.627	13.288
2005	0.0082	0.060	0.248	0.821	1.654	3.338	3.841	5.758	7.593	12.546
2006	0.0428	0.089	0.295	0.808	1.890	2.467	4.076	4.912	6.744	12.137
2007	0.0086	0.124	0.450	0.925	1.771	3.005	3.723	5.020	6.329	12.394
2008	0.0464	0.085	0.420	1.117	1.888	2.892	3.630	5.147	6.803	12.040
2009	0.0137	0.171	0.480	1.248	2.283	2.908	3.658	4.735	6.735	12.878
2010	0.0061	0.100	0.589	1.168	2.328	3.198	3.685	4.778	7.153	11.612
2011	0.0836	0.087	0.492	1.353	1.972	3.262	4.114	4.788	5.751	12.995

App. A5 (Append. A), Table A3: Mean weight-at-age (kg) of landings for the Gulf of Maine cod stock applying the revised mortality assumptions (Michael Palmer, pers. commn). Pre-1982, the 1982-1991 average mean weight-at-age is assumed.

	0	1	2	3	4	5	6	7	8	9+
1982	0.012	0.356	0.858	1.514	2.606	5.067	7.065	9.620	9.771	15.664
1983	0.024	0.224	0.768	1.542	2.418	3.808	6.055	6.071	10.317	13.325
1984	0.001	0.234	0.653	1.478	2.678	3.609	5.540	8.368	10.138	14.828
1985	0.039	0.206	0.733	1.404	2.819	4.658	5.884	8.502	11.244	13.676
1986	0.005	0.277	0.501	1.698	2.774	4.778	6.504	8.109	10.206	14.646
1987	0.004	0.154	0.642	1.323	3.090	4.668	7.259	10.036	11.099	14.582
1988	0.003	0.122	0.577	1.666	2.360	5.205	5.200	6.193	10.103	12.993
1989	0.046	0.236	0.752	1.518	2.959	4.282	5.980	9.276	12.519	20.913
1990	0.021	0.193	0.811	1.349	2.141	4.474	7.721	10.820	11.750	18.718
1991	0.014	0.236	1.113	1.601	2.281	3.894	7.144	10.429	12.261	14.031
1992	0.023	0.055	1.033	1.530	2.747	2.976	5.587	10.921	10.483	14.483
1993	0.021	0.081	0.690	1.748	2.150	4.420	5.670	9.817	13.673	15.701
1994	0.022	0.058	0.730	1.712	3.085	3.251	6.335	7.684	12.542	11.846
1995	0.027	0.103	1.288	1.591	2.649	5.090	6.865	11.466	13.128	22.443
1996	0.033	0.100	1.293	2.096	2.260	3.462	7.558	11.728	14.455	16.269
1997	0.017	0.064	1.351	2.128	3.022	3.074	4.699	9.000	12.156	16.938
1998	0.008	0.202	1.071	1.931	2.633	3.972	4.255	7.122	12.118	16.676
1999	0.052	0.222	0.635	1.723	2.777	3.892	5.670	6.704	9.811	12.279
2000	0.030	0.282	1.081	2.150	3.316	4.325	5.898	5.352	9.331	12.680
2001	0.045	0.316	0.890	2.176	3.144	4.666	6.140	7.273	9.072	9.559
2002	0.032	0.185	0.795	1.797	2.906	3.792	6.132	6.969	8.808	12.205
2003	0.038	0.202	0.809	1.843	2.378	3.654	5.112	7.649	9.191	12.058
2004	0.025	0.111	0.483	1.606	2.965	3.547	5.350	7.220	9.764	13.303
2005	0.027	0.126	0.558	1.625	2.401	4.233	4.502	6.349	8.002	12.549
2006	0.071	0.289	0.648	1.493	2.932	3.357	4.463	5.562	7.430	12.146
2007	0.025	0.220	0.744	1.731	2.922	3.735	4.771	6.167	7.302	12.394
2008	0.085	0.247	0.862	2.179	2.818	3.530	3.988	5.819	7.528	12.044
2009	0.032	0.337	0.911	2.153	3.126	3.575	4.368	5.959	8.000	12.887
2010	0.023	0.264	1.200	1.995	3.203	3.914	4.447	5.708	8.730	11.612
2011	0.0856	0.3289	0.9331	2.0561	2.874	3.8696	4.839	5.7166	5.9528	12.984

App. A5 (Append. A), Table A4: Total (commercial and recreational landings and discards) catches-at-age for the Gulf of Maine cod stock, applying the revised mortality assumptions (Michael Palmer, pers. commn).

	1	2	3	4	5	6	7	8	9+
1982	448849	2926542	2287192	1430682	748755	65880	94051	72553	90055
1983	597496	2462037	2913215	1201593	704010	452680	50022	62542	56198
1984	370324	2129556	1675931	1643588	437453	219625	105649	9495	53395
1985	505660	1944327	2405137	1151815	738096	161362	107192	48359	33213
1986	760701	1747046	2747811	991982	279282	202725	48016	38188	47527
1987	281794	2018317	1568334	1574499	345353	89415	81032	14459	37549
1988	415081	1542790	2086633	1156925	447729	67430	25560	26247	9267
1989	166436	1247203	2385088	1651856	521108	87147	70289	9369	19564
1990	65527	812544	5547767	2717623	541353	189069	29703	36417	43315
1991	121627	499588	942731	5561272	1037852	150670	55540	25983	15805
1992	370302	830147	867564	502084	2189957	226167	80181	6044	5530
1993	105929	512307	2149041	944709	103328	497117	41561	11264	0
1994	123996	201923	1525603	1294203	266291	66224	74158	28714	7870
1995	78932	319462	1321833	1260435	221653	29931	6521	18184	2808
1996	37536	111569	627693	2003886	405881	36651	4039	491	1623
1997	69144	137484	519557	467768	869161	72472	5523	2272	1029
1998	5941	171062	492301	628941	152820	205873	28696	5168	2257
1999	73948	90853	347840	336596	172344	53699	59469	12388	1067
2000	24758	485043	556537	813684	176640	85157	12485	10521	0
2001	584	393951	1163770	684449	385530	106600	57232	8262	11577
2002	16831	41591	374949	912638	323797	163476	66392	28087	20263
2003	44899	125587	167812	582079	706098	186022	75694	29224	26844
2004	149420	105917	609344	259720	407447	251632	68378	33017	27442
2005	23545	180064	159581	945815	89223	246596	109148	28457	31674
2006	19249	59082	426566	290132	461742	30341	79655	39016	27343
2007	12171	108471	299416	976424	137404	230163	7947	19244	21999
2008	12156	130508	598424	707392	780450	86355	110576	4041	16558
2009	10651	101492	622453	1093273	477852	304754	20896	30506	9646
2010	8159	83580	394486	888549	668256	164291	71683	11213	7611
2011	8683	60526	322164	589583	573856	339910	34926	38408	9433

App. A5 (Append. A), Table A5: Standardized stratified mean numbers per tow at age and standardized mean numbers and mean weight (kg) per tow for ages 1+ of Atlantic cod in NEFSC offshore spring research vessel bottom trawl surveys in the Gulf of Maine, 1968-2011 (Michael Palmer, pers. commn).

	1	2	3	4	5	6	7	8	9+	Stratified mean numbers/ tow	CV	Stratified mean wt/tow (kg)	CV
1968										5.329*	(0.127)	17.480*	(0.153)
1969										3.215*	(0.328)	13.100*	(0.329)
1970	0.159	0.124	0.053	0.098	0.290	0.475	0.589	0.073	0.330	2.191	(0.214)	11.089	(0.237)
1971	0.069	0.109	0.099	0.280	0.086	0.096	0.280	0.207	0.204	1.429	(0.190)	7.004	(0.211)
1972	0.300	0.153	0.499	0.208	0.205	0.052	0.083	0.119	0.386	2.004	(0.208)	8.031	(0.233)
1973	0.053	4.273	0.917	0.614	0.384	0.144	0.106	0.186	0.848	7.525	(0.328)	18.807	(0.415)
1974	0.311	0.081	1.534	0.177	0.231	0.082	0.000	0.064	0.258	2.738	(0.188)	7.417	(0.199)
1975	0.094	0.707	0.095	1.139	0.246	0.073	0.000	0.006	0.140	2.500	(0.222)	6.039	(0.249)
1976	0.052	0.253	1.114	0.150	0.870	0.131	0.056	0.038	0.117	2.782	(0.181)	7.555	(0.166)
1977	0.068	0.264	0.460	2.015	0.139	0.775	0.000	0.114	0.038	3.872	(0.269)	8.541	(0.208)
1978	0.070	0.083	0.297	0.383	0.764	0.084	0.226	0.013	0.131	2.050	(0.191)	7.697	(0.207)
1979	0.426	1.407	0.186	0.470	0.301	0.549	0.094	0.104	0.064	3.599	(0.234)	7.555	(0.176)
1980	0.037	0.500	0.436	0.123	0.294	0.226	0.337	0.000	0.132	2.084	(0.171)	6.231	(0.182)
1981	1.091	0.619	0.850	1.335	0.318	0.304	0.080	0.144	0.091	4.832	(0.194)	10.651	(0.205)
1982	0.357	1.040	0.498	0.737	0.848	0.083	0.135	0.000	0.050	3.749	(0.219)	8.616	(0.223)
1983	0.610	0.968	1.042	0.453	0.336	0.250	0.060	0.000	0.181	3.900	(0.263)	10.962	(0.225)
1984	0.151	1.309	0.987	0.853	0.229	0.047	0.090	0.000	0.000	3.667	(0.443)	6.143	(0.324)
1985	0.029	0.238	0.676	0.612	0.707	0.094	0.109	0.026	0.026	2.517	(0.202)	7.645	(0.223)
1986	0.537	0.259	0.767	0.218	0.075	0.046	0.038	0.000	0.018	1.957	(0.314)	3.476	(0.197)
1987	0.030	0.471	0.191	0.222	0.075	0.000	0.068	0.011	0.015	1.082	(0.257)	1.976	(0.314)
1988	0.719	0.926	0.791	0.283	0.205	0.099	0.036	0.020	0.020	3.099	(0.211)	3.603	(0.281)
1989	0.025	0.609	0.712	0.630	0.069	0.068	0.000	0.000	0.000	2.112	(0.184)	2.424	(0.207)
1990	0.009	0.233	1.325	0.669	0.076	0.032	0.018	0.000	0.000	2.362	(0.249)	3.077	(0.280)
1991	0.028	0.077	0.233	1.750	0.247	0.041	0.018	0.000	0.000	2.393	(0.251)	2.891	(0.240)
1992	0.050	0.247	0.223	0.248	1.368	0.213	0.073	0.000	0.012	2.435	(0.317)	8.627	(0.374)
1993	0.201	0.507	0.804	0.364	0.084	0.446	0.055	0.023	0.023	2.507	(0.223)	5.875	(0.347)
1994	0.015	0.316	0.407	0.201	0.083	0.053	0.142	0.009	0.045	1.271	(0.223)	2.428	(0.216)
1995	0.037	0.187	1.165	0.321	0.147	0.034	0.000	0.011	0.028	1.930	(0.273)	2.432	(0.257)
1996	0.057	0.022	0.586	1.355	0.385	0.060	0.000	0.000	0.000	2.465	(0.240)	5.427	(0.275)
1997	0.159	0.139	0.390	0.271	0.874	0.244	0.115	0.000	0.000	2.192	(0.168)	5.615	(0.192)
1998	0.018	0.228	0.359	0.513	0.143	0.408	0.021	0.020	0.000	1.711	(0.344)	4.180	(0.324)
1999	0.166	0.342	0.726	0.351	0.305	0.134	0.266	0.000	0.011	2.301	(0.242)	5.090	(0.320)
2000	1.173	0.737	0.438	0.485	0.099	0.092	0.011	0.022	0.000	3.057	(0.221)	3.211	(0.155)
2001	0.029	0.355	0.683	0.510	0.342	0.065	0.097	0.055	0.011	2.147	(0.311)	6.215	(0.327)
2002	0.340	0.045	0.548	1.584	0.606	0.342	0.185	0.057	0.017	3.724	(0.203)	10.934	(0.215)
2003	0.075	0.825	0.059	0.718	1.072	0.387	0.340	0.081	0.122	3.677	(0.223)	9.494	(0.368)
2004	0.136	0.045	0.230	0.116	0.208	0.213	0.011	0.011	0.010	0.981	(0.256)	2.412	(0.293)
2005	0.029	0.739	0.081	0.623	0.011	0.138	0.128	0.015	0.000	1.764	(0.241)	2.701	(0.248)
2006	0.184	0.237	0.434	0.049	0.197	0.023	0.126	0.069	0.015	1.334	(0.203)	2.702	(0.249)
2007	0.100	3.422	3.077	4.446	0.437	0.796	0.075	0.041	0.000	12.393	(0.665)	15.811	(0.540)
2008	0.079	1.165	3.930	1.582	1.099	0.053	0.082	0.000	0.000	7.990	(0.716)	10.824	(0.609)
2009	0.063	0.279	1.050	1.135	0.600	0.438	0.008	0.022	0.004	3.599	(0.531)	7.161	(0.491)
2010	0.059	0.279	0.335	0.197	0.229	0.113	0.043	0.016	0.025	1.296	(0.243)	3.336	(0.264)
2011	0.005	0.024	0.140	0.383	0.189	0.086	0.033	0.035	0.000	0.894	(0.279)	2.133	(0.201)

* Aggregate index for ages 0+ as numbers-at-age and biomasses-at-age are not available pre-1970.

App. A5 (Append. A), Table A6: Standardized stratified mean numbers per tow at age and standardized mean numbers and mean weight (kg) per tow for ages 1+ of Atlantic cod in NEFSC offshore autumn research vessel bottom trawl surveys in the Gulf of Maine, 1963-2011 (Michael Palmer, pers. commn).

	1	2	3	4	5	6	7	8	9+	Stratified mean numbers/ tow	CV	Stratified mean wt/tow (kg)	CV
1963										5.914*	(0.250)	17.950*	(0.391)
1964										4.015*	(0.412)	22.799*	(0.496)
1965										4.500*	(0.274)	12.089*	(0.273)
1966										3.720*	(0.217)	12.838*	(0.227)
1967										2.602*	(0.223)	9.313*	(0.219)
1968										4.374*	(0.181)	19.437*	(0.198)
1969										2.758*	(0.152)	15.154*	(0.217)
1970	0.938	0.254	0.520	0.336	0.487	0.424	0.836	0.130	0.237	4.162	(0.318)	16.437	(0.248)
1971	0.207	0.224	0.190	0.607	0.444	0.509	0.222	0.280	0.345	3.027	(0.205)	16.196	(0.307)
1972	5.663	1.118	1.595	0.181	0.072	0.122	0.031	0.121	0.367	9.269	(0.535)	12.988	(0.199)
1973	0.327	2.146	0.179	0.540	0.191	0.055	0.018	0.039	0.320	3.814	(0.151)	8.758	(0.267)
1974	1.131	0.267	1.922	0.125	0.276	0.000	0.052	0.036	0.255	4.063	(0.260)	8.959	(0.201)
1975	0.223	3.028	0.139	2.354	0.250	0.105	0.020	0.000	0.018	6.137	(0.226)	8.619	(0.153)
1976	0.209	0.216	0.578	0.104	0.835	0.044	0.099	0.000	0.063	2.148	(0.197)	6.740	(0.214)
1977	0.046	0.446	0.456	1.151	0.133	0.604	0.024	0.083	0.130	3.073	(0.124)	10.199	(0.126)
1978	1.411	0.359	1.141	0.661	1.450	0.101	0.269	0.012	0.129	5.531	(0.188)	12.895	(0.151)
1979	0.364	0.617	0.131	0.696	0.319	0.754	0.056	0.135	0.071	3.142	(0.112)	13.927	(0.128)
1980	1.319	2.558	1.664	0.518	0.236	0.402	0.192	0.022	0.097	7.007	(0.261)	14.202	(0.153)
1981	0.581	0.399	0.469	0.509	0.092	0.081	0.081	0.099	0.028	2.339	(0.224)	7.533	(0.233)
1982	0.835	3.264	2.476	0.971	0.222	0.000	0.000	0.000	0.000	7.769	(0.636)	15.919	(0.670)
1983	0.305	0.905	0.757	0.267	0.250	0.219	0.000	0.000	0.083	2.786	(0.170)	8.416	(0.188)
1984	0.513	0.418	0.586	0.384	0.196	0.194	0.062	0.000	0.096	2.449	(0.220)	8.735	(0.334)
1985	0.445	0.917	0.627	0.201	0.246	0.064	0.000	0.034	0.070	2.604	(0.176)	8.261	(0.354)
1986	0.394	0.404	0.626	0.368	0.073	0.041	0.000	0.000	0.045	1.950	(0.230)	4.715	(0.228)
1987	0.570	1.388	0.586	0.198	0.125	0.000	0.000	0.000	0.000	2.868	(0.308)	3.393	(0.234)
1988	1.889	2.366	1.069	0.367	0.146	0.000	0.044	0.000	0.022	5.903	(0.349)	6.616	(0.232)
1989	0.145	2.468	1.458	0.283	0.138	0.053	0.000	0.009	0.000	4.553	(0.223)	4.535	(0.181)
1990	0.057	0.218	1.788	0.611	0.255	0.048	0.010	0.000	0.000	2.986	(0.190)	4.912	(0.204)
1991	0.144	0.151	0.230	0.621	0.075	0.000	0.023	0.000	0.000	1.243	(0.267)	2.782	(0.246)
1992	0.289	0.448	0.144	0.041	0.327	0.126	0.000	0.000	0.000	1.375	(0.213)	2.447	(0.243)
1993	0.210	0.575	0.361	0.017	0.000	0.038	0.000	0.000	0.000	1.201	(0.259)	1.002	(0.263)
1994	0.184	0.909	0.816	0.093	0.051	0.000	0.045	0.000	0.000	2.098	(0.309)	2.736	(0.292)
1995	0.068	0.308	1.226	0.304	0.082	0.011	0.000	0.000	0.000	2.000	(0.301)	3.664	(0.325)
1996	0.122	0.379	0.231	0.516	0.050	0.000	0.000	0.000	0.000	1.299	(0.254)	2.351	(0.249)
1997	0.297	0.091	0.165	0.168	0.151	0.000	0.000	0.000	0.000	0.872	(0.299)	1.872	(0.307)
1998	0.085	0.342	0.110	0.185	0.041	0.031	0.000	0.000	0.000	0.793	(0.346)	1.499	(0.287)
1999	0.432	0.375	0.590	0.244	0.122	0.019	0.000	0.000	0.000	1.782	(0.181)	3.504	(0.193)
2000	0.540	0.981	0.399	0.492	0.140	0.010	0.000	0.034	0.000	2.596	(0.306)	4.652	(0.332)
2001	0.000	0.171	0.720	0.478	0.356	0.124	0.092	0.000	0.023	1.963	(0.271)	7.323	(0.279)
2002	0.269	0.104	0.333	2.683	1.070	0.750	0.077	0.043	0.000	5.328	(0.578)	24.659	(0.686)
2003	0.461	0.186	0.216	0.518	0.451	0.071	0.062	0.000	0.022	1.988	(0.307)	5.974	(0.251)
2004	0.661	0.172	0.577	0.254	0.250	0.149	0.057	0.023	0.021	2.165	(0.327)	4.903	(0.214)
2005	0.153	0.378	0.078	0.456	0.023	0.090	0.082	0.023	0.021	1.304	(0.065)	2.896	(0.228)
2006	1.241	0.599	1.007	0.252	0.293	0.037	0.053	0.036	0.014	3.531	(0.301)	4.229	(0.188)
2007	0.136	0.863	0.395	0.496	0.023	0.067	0.000	0.000	0.000	1.981	(0.368)	2.714	(0.277)
2008	0.650	1.227	1.060	0.189	0.139	0.000	0.000	0.000	0.031	3.295	(0.389)	5.292	(0.285)
2009	0.660	2.096	0.314	0.277	0.045	0.035	0.000	0.000	0.000	3.427	(0.535)	5.844	(0.429)
2010	0.094	0.132	0.290	0.288	0.092	0.023	0.013	0.000	0.006	0.940	(0.233)	2.571	(0.304)
2011	0.060	0.091	0.210	0.304	0.175	0.078	0.005	0.031	0.000	0.954	(0.304)	2.647	(0.336)

* Aggregate index for ages 0+ as numbers-at-age and biomasses-at-age are not available pre-1970.

App. A5 (Append. A), Table A7: Stratified mean numbers at age per tow and mean number and mean weight (kg) for ages 1 to 6 of Atlantic cod in State of Massachusetts inshore spring bottom trawl surveys in territorial waters adjacent to the Gulf of Maine (Mass. Regions 4-5), 1982-2011 (Michael Palmer, pers. commn).

	1	2	3	4	5	6	Stratified mean numbers /tow	CV	Stratified mean wt/tow (kg)	CV
1982	13.218	6.649	2.921	1.024	0.216	0.049	24.078	(0.221)	9.783	(0.175)
1983	30.253	17.570	4.710	0.347	1.121	0.075	54.076	(0.166)	15.639	(0.153)
1984	1.898	5.090	2.101	0.751	0.147	0.086	10.073	(0.289)	7.042	(0.259)
1985	1.670	2.695	2.024	0.498	0.000	0.000	6.886	(0.206)	4.535	(0.194)
1986	18.031	3.376	0.903	0.582	0.100	0.023	23.014	(0.552)	4.778	(0.354)
1987	8.622	5.376	2.045	0.168	0.147	0.053	16.411	(0.221)	6.305	(0.271)
1988	10.409	6.750	1.927	1.211	0.016	0.033	20.347	(0.206)	7.389	(0.237)
1989	21.463	22.947	6.868	0.513	0.108	0.048	51.946	(0.268)	15.801	(0.342)
1990	4.972	5.938	14.182	2.149	0.155	0.083	27.479	(0.288)	15.612	(0.341)
1991	5.331	2.295	1.801	3.669	0.249	0.000	13.344	(0.219)	8.123	(0.122)
1992	4.379	5.699	3.444	0.484	1.301	0.066	15.374	(0.287)	8.417	(0.321)
1993	2.842	6.100	2.509	0.879	0.166	0.074	12.569	(0.340)	5.666	(0.270)
1994	5.406	3.883	1.703	0.608	0.131	0.000	11.731	(0.227)	3.908	(0.241)
1995	5.985	2.420	2.408	0.525	0.028	0.000	11.366	(0.262)	3.695	(0.225)
1996	0.777	0.497	0.955	1.590	0.299	0.000	4.119	(0.218)	3.086	(0.305)
1997	2.910	1.035	0.920	0.190	0.383	0.018	5.456	(0.240)	2.281	(0.250)
1998	1.487	0.924	0.779	0.637	0.034	0.211	4.072	(0.261)	3.098	(0.468)
1999	11.832	2.407	2.275	0.735	0.630	0.036	17.914	(0.369)	7.219	(0.261)
2000	35.360	6.995	2.371	2.316	0.784	0.663	48.488	(0.391)	16.294	(0.459)
2001	0.084	4.998	4.710	3.448	1.961	0.323	15.524	(0.435)	24.860	(0.536)
2002	19.340	0.220	1.379	1.145	0.561	0.318	22.964	(0.096)	6.924	(0.390)
2003	17.109	5.496	0.439	1.938	0.937	0.221	26.139	(0.507)	8.674	(0.219)
2004	8.927	1.882	2.627	0.361	1.083	0.455	15.335	(0.459)	7.044	(0.278)
2005	5.524	4.141	0.795	1.955	0.263	0.663	13.342	(0.223)	7.798	(0.197)
2006	9.992	7.139	3.930	0.525	1.532	0.109	23.227	(0.337)	7.001	(0.181)
2007	3.776	3.078	2.303	2.163	0.343	0.519	12.181	(0.274)	7.937	(0.251)
2008	7.275	10.336	3.242	2.287	1.695	0.155	24.991	(0.204)	10.673	(0.215)
2009	8.907	2.350	1.654	1.045	0.348	0.112	14.417	(0.352)	3.839	(0.187)
2010	2.415	1.393	1.423	0.819	0.678	0.129	6.858	(0.234)	4.953	(0.456)
2011	0.326	1.001	0.621	0.933	0.558	0.139	3.579	(0.534)	4.027	(0.424)

App. A5 (Append. A), Table A8: Percentage of mature females for each age for the Gulf of Maine cod stock (Michael Palmer, pers. commn).

1	2	3	4	5	6	7	8	9+
0.092	0.287	0.613	0.862	0.961	0.990	0.997	0.999	1.000

App. A5 (Append. A), Table A9: Length frequency distributions for NEFSC offshore spring and autumn research vessel bottom trawl surveys in the Gulf of Maine conducted by the *Bigelow* (Michael Palmer, pers. commn).

	NEFSC spring survey			NEFSC call survey		
Year	2009	2010	2011	2009	2010	2011
-25cm	0.5634	0.4138	0.0286	0.3967	0.0605	0.2489
26cm	0.0496	0.0189	0.0000	0.1330	0.0283	0.0850
27cm	0.0425	0.0756	0.0000	0.1731	0.0142	0.0283
28cm	0.0638	0.1501	0.0000	0.1251	0.0000	0.0142
29cm	0.0553	0.0945	0.0000	0.1330	0.0283	0.0000
30cm	0.0283	0.1134	0.0000	0.2330	0.0567	0.0142
31cm	0.0544	0.1397	0.0486	0.2834	0.0283	0.0136
32cm	0.0142	0.0945	0.0113	0.4412	0.1134	0.0377
33cm	0.0213	0.0935	0.0113	0.5951	0.0425	0.0142
34cm	0.0958	0.1572	0.0000	0.9068	0.0567	0.0506
35cm	0.0743	0.1407	0.0227	0.7147	0.0142	0.0283
36cm	0.0887	0.1029	0.0000	0.6659	0.0394	0.0142
37cm	0.0695	0.0853	0.0340	0.5014	0.0278	0.0000
38cm	0.1204	0.0945	0.0113	0.6155	0.0425	0.0000
39cm	0.1748	0.0567	0.0000	0.3400	0.0142	0.0543
40cm	0.1559	0.0283	0.0431	0.2516	0.0242	0.0283
41cm	0.1629	0.0283	0.0227	0.2888	0.0425	0.0364
42cm	0.1771	0.0276	0.0599	0.3103	0.0850	0.0380
43cm	0.1565	0.0378	0.0793	0.2834	0.0425	0.0401
44cm	0.2125	0.0378	0.0907	0.3400	0.0283	0.0222
45cm	0.2287	0.0378	0.0340	0.3280	0.0384	0.0640
46cm	0.2196	0.0283	0.0214	0.2776	0.0283	0.0567
47cm	0.1913	0.0189	0.0340	0.1901	0.0242	0.0000
48cm	0.2371	0.0095	0.0340	0.2692	0.0425	0.0364
49cm	0.2017	0.0283	0.0214	0.2125	0.0343	0.0623
50cm	0.2240	0.0647	0.0793	0.1700	0.0283	0.0647
51cm	0.1845	0.0095	0.0441	0.0951	0.0394	0.0364
52cm	0.3077	0.0953	0.0768	0.1199	0.0778	0.0383
53cm	0.2122	0.0000	0.0680	0.0992	0.0142	0.0425
54cm	0.2517	0.1236	0.0826	0.0809	0.0425	0.0506
55cm	0.3245	0.0322	0.0340	0.0708	0.0384	0.0330
56cm	0.1946	0.0646	0.0700	0.0000	0.0425	0.0599
57cm	0.2046	0.0276	0.0441	0.0492	0.0567	0.0000
58cm	0.2358	0.0370	0.0582	0.0384	0.0242	0.0000
59cm	0.2347	0.0455	0.0000	0.0686	0.0257	0.0161
60cm	0.2537	0.0444	0.0227	0.0425	0.0142	0.0383
61cm	0.2547	0.0000	0.0803	0.0447	0.0242	0.0588
62cm	0.1164	0.0081	0.0214	0.0307	0.0401	0.0383
63cm	0.2003	0.0180	0.0113	0.0142	0.0236	0.0222
64cm	0.1725	0.0227	0.0214	0.0874	0.0142	0.1130
65cm	0.0341	0.0000	0.0302	0.0142	0.0336	0.0222
66cm	0.0611	0.0189	0.0467	0.0667	0.0401	0.0303
67cm	0.0850	0.0544	0.0101	0.0201	0.0242	0.0303
68cm	0.0414	0.0276	0.0227	0.0196	0.0848	0.0401
69cm	0.0370	0.0000	0.0372	0.0142	0.0000	0.0481
70cm	0.0923	0.0632	0.0259	0.0283	0.0201	0.0581
71cm	0.0387	0.0161	0.0101	0.0142	0.0353	0.0283
72cm	0.0287	0.0719	0.0322	0.0696	0.0236	0.0259
73cm	0.0259	0.0322	0.0349	0.0350	0.0310	0.0420
74cm	0.0128	0.0423	0.0113	0.0108	0.0142	0.0081
75cm	0.0199	0.0000	0.0101	0.0101	0.0360	0.0081
76cm	0.0704	0.0081	0.0000	0.0283	0.0840	0.0222
77cm	0.0058	0.0161	0.0000	0.0142	0.0000	0.0222
78cm	0.0115	0.0181	0.0101	0.0000	0.0201	0.0000
79cm	0.0058	0.0563	0.0227	0.0283	0.0283	0.0108
80cm	0.0270	0.0181	0.0101	0.0000	0.0101	0.0000
81cm	0.0270	0.0343	0.0000	0.0000	0.0000	0.0540
82cm	0.0000	0.0000	0.0101	0.0101	0.0000	0.0222
83cm	0.0283	0.0000	0.0000	0.0000	0.0000	0.0161
84cm	0.0115	0.0489	0.0000	0.0000	0.0454	0.0000
85cm	0.0115	0.0081	0.0259	0.0000	0.0236	0.0081
86cm	0.0071	0.0262	0.0101	0.0000	0.0101	0.0000
87cm	0.0186	0.0081	0.0000	0.0000	0.0000	0.0000
88cm	0.0058	0.0000	0.0000	0.0142	0.0101	0.0142
89cm	0.0058	0.0161	0.0000	0.0000	0.0000	0.0000
90cm	0.0071	0.0081	0.0113	0.0101	0.0000	0.0000
91cm	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
92cm	0.0058	0.0000	0.0000	0.0000	0.0000	0.0142
93cm	0.0000	0.0000	0.0000	0.0101	0.0000	0.0081
94cm	0.0058	0.0081	0.0340	0.0000	0.0000	0.0000
95cm	0.0058	0.0000	0.0000	0.0000	0.0000	0.0081
96cm	0.0128	0.0000	0.0000	0.0000	0.0000	0.0000
97cm	0.0000	0.0000	0.0000	0.0142	0.0000	0.0000
98cm	0.0000	0.0081	0.0000	0.0000	0.0000	0.0081
99cm	0.0000	0.0175	0.0000	0.0000	0.0000	0.0000
100cm+	0.0115	0.0403	0.0214	0.0000	0.0101	0.0081

App. A5 (Append. A), Table A10a: Age-length keys for NEFSC offshore spring research vessel bottom trawl surveys in the Gulf of Maine conducted by the *Bigelow* (Michael Palmer, pers. commn).

	NEFSC Spring, 2009						Age						NEFSC Spring, 2010						Age					
Length	0	1	2	3	4	5	6	7	8	9	10	11+	0	1	2	3	4	5	6	7	8	9	10	11+
≤25	0	39	24	0	0	0	0	0	0	0	0	0	0	28	11	0	0	0	0	0	0	0	0	0
26	0	0	5	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
27	0	0	4	1	0	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0
28	0	0	3	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0
29	0	0	7	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0
30	0	0	2	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0
31	0	0	6	0	0	0	0	0	0	0	0	0	0	0	6	1	0	0	0	0	0	0	0	0
32	0	0	0	1	0	0	0	0	0	0	0	0	0	0	5	0	0	0	0	0	0	0	0	0
33	0	0	3	0	0	0	0	0	0	0	0	0	0	0	3	1	0	0	0	0	0	0	0	0
34	0	0	1	5	0	0	0	0	0	0	0	0	0	0	2	4	0	0	0	0	0	0	0	0
35	0	0	4	3	0	0	0	0	0	0	0	0	0	0	2	4	0	0	0	0	0	0	0	0
36	0	0	4	1	0	0	0	0	0	0	0	0	0	0	3	1	0	0	0	0	0	0	0	0
37	0	0	2	4	0	0	0	0	0	0	0	0	0	0	1	4	0	0	0	0	0	0	0	0
38	0	0	2	4	0	0	0	0	0	0	0	0	0	0	2	2	0	0	0	0	0	0	0	0
39	0	0	1	2	1	0	0	0	0	0	0	0	0	0	3	4	0	0	0	0	0	0	0	0
40	0	0	2	6	0	0	0	0	0	0	0	0	0	0	2	1	0	1	0	0	0	0	0	0
41	0	0	2	2	1	1	0	0	0	0	0	0	0	0	1	3	0	0	0	0	0	0	0	0
42	0	0	1	1	0	0	0	0	0	0	0	0	0	0	1	2	0	0	0	0	0	0	0	0
43	0	0	2	5	0	0	0	0	0	0	0	0	0	0	2	1	0	1	0	0	0	0	0	0
44	0	0	1	5	0	0	0	0	0	0	0	0	0	0	2	3	1	0	0	0	0	0	0	0
45	0	0	1	6	4	1	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0
46	0	0	0	3	2	2	1	0	0	0	0	0	0	0	0	2	1	0	1	0	0	0	0	0
47	0	0	0	2	2	0	0	0	0	0	0	0	0	0	0	2	2	0	0	0	0	0	0	0
48	0	0	0	2	4	1	0	0	0	0	0	0	0	0	0	1	3	0	0	0	0	0	0	0
49	0	0	0	3	4	1	2	0	0	0	0	0	0	0	0	2	0	1	1	0	0	0	0	0
50	0	0	0	2	5	1	0	0	0	0	0	0	0	0	0	2	3	2	0	0	0	0	0	0
51	0	0	1	2	2	0	1	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0
52	0	0	0	4	4	0	0	0	0	0	0	0	0	0	0	4	2	1	0	0	0	0	0	0
53	0	0	0	3	4	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
54	0	0	0	2	2	2	0	0	0	0	0	0	0	0	0	7	1	2	0	0	0	0	0	0
55	0	0	0	5	1	2	1	0	0	0	0	0	0	0	0	2	1	0	0	0	0	0	0	0
56	0	0	0	1	2	0	1	0	0	0	0	0	0	0	0	2	2	2	0	0	0	0	0	0
57	0	0	0	2	3	2	1	0	0	0	0	0	0	0	0	1	2	0	1	0	0	0	0	0
58	0	0	0	0	5	3	1	0	0	0	0	0	0	0	0	3	0	1	1	0	0	0	0	0
59	0	0	0	1	3	1	5	0	0	0	0	0	0	0	0	2	0	1	0	0	0	0	0	0
60	0	0	0	1	3	1	2	0	0	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0
61	0	0	0	4	2	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
62	0	0	0	1	1	3	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
63	0	0	0	0	3	3	4	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0
64	0	0	0	1	5	1	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
65	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
66	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0
67	0	0	0	1	2	0	0	0	0	0	0	0	0	0	0	0	2	1	0	0	0	0	0	0
68	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0
69	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
70	0	0	0	0	3	1	2	0	0	0	0	0	0	0	0	0	1	2	1	1	0	0	0	0
71	0	0	0	0	0	2	2	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0
72	0	0	0	0	2	2	1	0	0	0	0	0	0	0	0	0	2	1	1	0	0	0	0	0
73	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0
74	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0
75	0	0	0	0	2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
76	0	0	0	0	2	3	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
77	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0
78	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0
79	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	2	1	0	0	0	0	0
80	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
81	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0
82	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
83	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
84	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	2	0	1	0	0	0	0
85	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
86	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0
87	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
88	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
89	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0
90	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
91	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
92	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
93	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
94	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
95	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
96	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
97	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
98	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
99	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
>100	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	1	0	1	1	2

App. A5 (Append. A), Table A10b: Age-length keys for NEFSC offshore spring research vessel bottom trawl surveys in the Gulf of Maine conducted by the *Bigelow* (Michael Palmer, pers. commn).

	NEFSC Spring, 2011						Age						NEFSC Spring, 2012						Age					
Length	0	1	2	3	4	5	6	7	8	9	10	11+	0	1	2	3	4	5	6	7	8	9	10	11+
≤25	0	2	0	0	0	0	0	0	0	0	0	0	1	38	3	0	0	0	0	0	0	0	0	0
26	0	0	0	0	0	0	0	0	0	0	0	0	0	1	2	0	0	0	0	0	0	0	0	0
27	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0
28	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0
29	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0
31	0	0	2	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
32	0	0	0	1	0	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0
33	0	0	1	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0
34	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0
35	0	0	1	1	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0
36	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	2	0	0	0	0	0	0	0	0
37	0	0	0	2	1	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0
38	0	0	0	1	0	0	0	0	0	0	0	0	0	0	2	1	0	0	0	0	0	0	0	0
39	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	3	0	0	0	0	0	0	0	0
40	0	0	1	2	0	0	0	0	0	0	0	0	0	0	5	6	0	0	0	0	0	0	0	0
41	0	0	0	1	0	0	0	0	0	0	0	0	0	0	3	5	0	0	0	0	0	0	0	0
42	0	0	1	1	1	0	0	0	0	0	0	0	0	0	3	7	1	0	0	0	0	0	0	0
43	0	0	0	2	2	0	0	0	0	0	0	0	0	0	2	7	2	1	0	0	0	0	0	0
44	0	0	0	0	2	0	0	0	0	0	0	0	0	0	2	9	1	0	0	0	0	0	0	0
45	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	5	2	2	0	0	0	0	0	0
46	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	3	2	1	0	0	0	0	0	0
47	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	3	4	1	0	0	0	0	0	0
48	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	5	2	0	0	0	0	0	0	0
49	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	5	4	0	0	0	0	0	0	0
50	0	0	0	1	3	0	0	0	0	0	0	0	0	0	0	4	1	3	0	0	0	0	0	0
51	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	2	3	1	0	0	0	0	0	0
52	0	0	0	0	3	1	0	0	0	0	0	0	0	0	0	3	7	4	1	0	0	0	0	0
53	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	2	5	1	0	0	0	0	0	0
54	0	0	0	2	1	0	0	0	0	0	0	0	0	0	0	3	2	3	0	0	0	0	0	0
55	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	6	1	0	0	0	0	0	0
56	0	0	0	1	2	1	0	0	0	0	0	0	0	0	0	5	4	5	2	0	0	0	0	0
57	0	0	0	0	3	1	0	0	0	0	0	0	0	0	0	2	3	1	1	0	0	0	0	0
58	0	0	0	2	1	0	0	0	0	0	0	0	0	0	0	1	6	3	1	0	0	0	0	0
59	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	4	0	1	2	0	0	0	0
60	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	2	2	2	1	0	0	0	0	0
61	0	0	0	0	3	1	1	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0
62	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	6	1	0	0	0	0	0	0
63	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	2	3	1	1	0	0	0	0
64	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	3	2	1	0	0	0	0	0
65	0	0	0	0	0	2	1	0	0	0	0	0	0	0	0	0	2	2	2	0	0	0	0	0
66	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	1	2	0	0	0	0	0
67	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	3	4	0	0	0	0	0	0
68	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0
69	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	2	1	0	0	0	0	0	0
70	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	1	0	1	0	0	0	0
71	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
72	0	0	0	0	0	2	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
73	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
74	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
75	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
76	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
77	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
78	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
79	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
80	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
81	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
82	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
83	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
84	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
85	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
86	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
87	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
88	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
89	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
90	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
91	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
92	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
93	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
94	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
95	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
96	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
97	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
98	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
99	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
>100	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

App. A5 (Append. A), Table A11: Age-length keys for NEFSC offshore autumn research vessel bottom trawl surveys in the Gulf of Maine conducted by the *Bigelow* (Michael Palmer, pers. commn).

	NEFSC Autumn, 2009												NEFSC Autumn, 2010												NEFSC Autumn, 2011											
	Age												Age												Age											
Length	0	1	2	3	4	5	6	7	8	9	10	11+	0	1	2	3	4	5	6	7	8	9	10	11+	0	1	2	3	4	5	6	7	8	9	10	11+
≤25	9	11	2	0	0	0	0	0	0	0	0	0	2	1	0	0	0	0	0	0	0	0	0	0	15	4	0	0	0	0	0	0	0	0	0	0
26	0	4	1	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0
27	0	4	2	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
28	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
29	0	4	2	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
30	0	3	1	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
31	0	1	0	0	0	0	0	0	0	0	0	0	0	5	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
32	0	4	1	0	0	0	0	0	0	0	0	0	0	5	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0
33	0	2	4	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
34	0	1	2	0	0	0	0	0	0	0	0	0	0	2	2	0	0	0	0	0	0	0	0	0	0	1	2	0	0	0	0	0	0	0	0	0
35	0	2	4	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0
36	0	0	1	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
37	0	0	2	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
38	0	2	5	0	0	0	0	0	0	0	0	0	0	0	2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
39	0	1	2	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	2	1	0	0	0	0	0	0	0	0
40	0	1	3	0	0	0	0	0	0	0	0	0	0	0	2	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
41	0	1	1	0	0	0	0	0	0	0	0	0	0	0	1	2	0	0	0	0	0	0	0	0	0	0	2	1	0	0	0	0	0	0	0	0
42	0	0	5	0	0	0	0	0	0	0	0	0	0	0	1	2	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0
43	0	0	4	0	0	0	0	0	0	0	0	0	0	0	2	1	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0
44	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0
45	0	0	3	0	0	0	0	0	0	0	0	0	0	0	1	2	0	0	0	0	0	0	0	0	0	0	2	3	0	0	0	0	0	0	0	0
46	0	0	7	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	1	3	0	0	0	0	0	0	0
47	0	0	3	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
48	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	1	2	1	0	0	0	0	0	0	0
49	0	0	1	1	0	0	0	0	0	0	0	0	0	0	1	2	0	0	0	0	0	0	0	0	0	0	0	1	3	0	0	0	0	0	0	0
50	0	0	2	1	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	1	3	0	1	0	0	0	0	0	0
51	0	0	3	0	1	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0
52	0	0	3	0	0	0	0	0	0	0	0	0	0	0	1	3	0	0	0	0	0	0	0	0	0	0	1	1	3	0	0	0	0	0	0	0
53	0	0	0	1	1	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	1	2	0	0	0	0	0	0	0
54	0	0	2	1	0	0	0	0	0	0	0	0	0	0	0	2	1	0	0	0	0	0	0	0	0	0	0	1	2	0	1	0	0	0	0	0
55	0	0	2	1	2	0	0	0	0	0	0	0	0	0	0	2	1	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0
56	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	2	1	0	0	0	0	0	0	0
57	0	0	1	1	2	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
58	0	0	1	0	2	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0
59	0	0	0	4	2	0	0	0	0	0	0	0	0	0	1	1	2	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0
60	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	3	0	1	0	0	0	0	0
61	0	0	0	2	1	0	0	0	0	0	0	0	0	0	0	1	1	0	1	0	0	0	0	0	0	0	1	2	2	0	0	0	0	0	0	0
62	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	2	2	0	0	0	0	0	0	0
63	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
64	0	0	1	1	3	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	4	6	1	0	0	0	0	0	0
65	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	2	0	1	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0
66	0	0	0	2	2	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	2	0	1	0	0	0	0	0
67	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	1	3	0	0	0	0	0	0	0	0	0	0	1	1	0	1	0	0	0	0	0
68	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	3	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0
69	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	2	0	0	0	0	0	0
70	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	3	2	0	0	0	0	0	0
71	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0
72	0	0	0	2	2	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
73	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	2	1	0	0	0	0	0	0	0	0	0	0	0	2	1	0	0	0	0	0
74	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
75	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	2	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
76	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0
77	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0
78	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
79	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
80	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
81	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0
82	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0
83	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0
84	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
85	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
86	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
87	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
88	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
89	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
90	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
91	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
92	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
93	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
94	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
95	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
96	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
97	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
98	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
99	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
>100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0

App. A5 (Append. A), Table A12a: Mean weight-at-age (kg) from NEFSC offshore spring surveys. Pre-1970, the 1970-1979 average mean weight-at-age is assumed (Michael Palmer, pers. commn). Note that for some years certain values at older ages have been determined by interpolation techniques as there were no data available.

	1	2	3	4	5	6	7	8	9+
1970	0.043	0.297	0.641	1.562	2.468	4.789	5.327	8.547	12.439
1971	0.201	0.507	1.340	2.225	4.484	3.570	6.379	8.557	9.301
1972	0.046	0.355	1.659	2.512	3.596	5.453	6.227	7.706	10.783
1973	0.043	0.180	0.972	2.898	3.730	4.518	7.229	6.216	13.401
1974	0.035	0.188	0.688	2.706	5.668	8.000	6.874	7.300	13.269
1975	0.030	0.255	1.027	1.898	3.883	7.050	6.874	8.413	14.817
1976	0.101	0.239	0.713	1.692	3.136	5.546	10.777	11.463	16.635
1977	0.112	0.328	0.780	1.058	2.315	4.787	6.874	9.953	21.006
1978	0.131	0.469	1.139	1.813	3.137	5.737	7.694	10.633	14.303
1979	0.078	0.404	1.367	1.972	3.056	4.093	7.685	7.159	17.912
1980	0.047	0.351	1.291	2.143	3.461	3.881	5.574	8.513	11.037
1981	0.125	0.460	1.103	2.477	4.056	6.138	7.568	8.456	11.041
1982	0.106	0.438	1.350	2.579	4.139	4.072	8.031	8.513	12.301
1983	0.094	0.463	1.475	2.513	5.110	6.693	11.352	8.513	20.470
1984	0.071	0.574	1.431	2.551	4.940	4.324	5.035	8.513	14.596
1985	0.045	0.426	1.329	2.707	4.293	5.492	6.065	13.198	16.558
1986	0.086	0.485	1.564	2.955	3.554	7.734	12.633	8.513	20.134
1987	0.065	0.348	0.729	2.585	3.058	5.084	6.378	5.420	25.016
1988	0.049	0.175	1.039	1.724	5.060	5.545	4.947	9.493	7.202
1989	0.043	0.182	0.728	1.828	2.631	6.784	6.874	8.513	14.596
1990	0.076	0.243	0.786	2.029	3.447	6.554	8.200	8.513	14.596
1991	0.078	0.197	0.875	1.190	1.524	2.557	6.008	8.513	14.596
1992	0.061	0.453	1.012	2.871	4.178	5.644	6.721	8.513	13.953
1993	0.057	0.323	1.368	1.963	3.809	5.255	10.622	11.372	16.642
1994	0.033	0.192	0.856	2.318	2.519	2.861	5.654	6.582	7.255
1995	0.111	0.240	0.681	1.277	2.825	3.956	6.874	2.828	20.994
1996	0.076	0.318	1.799	2.068	3.296	4.847	6.874	8.513	14.596
1997	0.064	0.445	1.416	2.658	2.954	3.745	6.749	8.513	14.596
1998	0.057	0.448	1.188	2.033	3.216	4.537	6.502	8.004	14.596
1999	0.088	0.335	0.994	1.949	3.123	5.723	5.574	8.513	31.105
2000	0.079	0.436	1.037	2.482	4.127	5.327	4.540	8.612	14.596
2001	0.119	0.474	1.107	2.738	4.242	8.950	9.035	14.481	16.784
2002	0.069	0.318	1.170	2.718	3.240	6.032	6.014	13.284	3.580
2003	0.123	0.198	0.820	1.588	2.661	3.991	5.783	6.627	10.133
2004	0.044	0.349	0.849	2.536	3.662	4.388	3.764	3.764	11.576
2005	0.031	0.211	1.031	1.739	2.628	3.979	5.597	5.494	14.596
2006	0.070	0.262	0.790	1.862	3.102	6.050	5.442	8.729	9.927
2007	0.092	0.388	0.876	1.649	3.059	3.244	4.130	5.428	14.596
2008	0.049	0.400	1.053	1.655	2.489	5.609	6.928	8.513	14.596
2009	0.031	0.523	1.441	2.067	2.601	2.876	8.067	9.930	12.919
2010	0.076	0.356	1.203	2.805	3.849	4.602	7.314	10.712	15.374
2011	0.064	0.453	1.177	1.717	2.706	3.509	5.906	8.521	14.596

App. A5 (Append. A), Table A12b: Mean weight-at-age (kg) from NEFSC offshore autumn surveys. Pre-1970, the 1970-1979 average mean weight-at-age is assumed (Michael Palmer, pers. commn). Note that for some years certain values at older ages have been determined by interpolation techniques as there were no data available.

	1	2	3	4	5	6	7	8	9+
1970	0.199	0.598	1.407	3.840	3.016	6.197	6.925	8.647	12.980
1971	0.241	1.201	1.688	2.916	4.818	5.392	6.853	9.008	14.100
1972	0.136	0.744	2.240	3.570	3.680	6.655	6.631	12.278	12.002
1973	0.111	0.458	2.093	4.229	4.814	5.814	9.916	6.042	10.734
1974	0.076	0.497	1.308	2.759	6.452	6.293	8.010	12.857	12.664
1975	0.249	0.439	1.041	2.290	2.775	5.598	8.472	12.044	14.086
1976	0.348	0.843	1.173	1.481	3.869	7.508	9.737	12.044	17.898
1977	0.201	0.531	1.238	1.843	3.809	5.940	7.696	11.211	15.843
1978	0.202	0.734	1.367	2.270	3.099	4.060	7.607	12.247	17.003
1979	0.385	0.878	2.644	3.347	5.462	6.791	10.187	11.930	21.717
1980	0.324	0.718	1.899	3.071	6.694	5.996	6.408	15.249	16.793
1981	0.232	1.102	2.116	4.419	5.583	8.130	8.390	12.349	22.998
1982	0.493	1.408	2.488	3.320	6.889	6.293	8.131	12.044	16.731
1983	0.236	1.082	1.732	3.583	4.878	9.825	8.131	12.044	20.891
1984	0.287	1.008	2.295	3.699	6.565	7.550	11.342	12.044	20.333
1985	0.208	1.054	2.503	3.879	7.494	10.403	8.131	20.320	23.705
1986	0.347	0.703	2.497	3.339	7.927	8.012	8.131	12.044	13.192
1987	0.151	0.648	1.502	3.596	6.505	6.293	8.131	12.044	16.731
1988	0.175	0.670	1.854	3.195	6.010	6.293	8.841	12.044	12.403
1989	0.276	0.410	1.176	2.727	4.911	3.877	8.131	13.292	16.731
1990	0.225	0.430	0.961	2.562	4.837	4.926	5.448	12.044	16.731
1991	0.172	0.715	1.703	2.566	5.374	6.293	11.513	12.044	16.731
1992	0.213	0.892	1.236	2.689	3.365	4.757	8.131	12.044	16.731
1993	0.122	0.512	1.529	3.547	5.284	1.778	8.131	12.044	16.731
1994	0.289	0.530	1.503	3.483	6.476	6.293	7.058	12.044	16.731
1995	0.125	0.876	1.597	2.612	7.143	4.318	8.131	12.044	16.731
1996	0.283	0.723	2.194	2.414	5.779	6.293	8.131	12.044	16.731
1997	0.151	0.903	1.761	4.593	4.518	6.293	8.131	12.044	16.731
1998	0.192	0.754	1.869	3.286	4.530	7.387	8.131	12.044	16.731
1999	0.302	1.013	2.100	3.862	5.499	7.563	8.131	12.044	16.731
2000	0.220	0.866	1.941	3.699	3.558	9.768	8.131	14.548	16.731
2001	0.239	0.755	1.819	2.721	6.266	9.096	10.713	12.044	11.023
2002	0.140	0.975	2.192	4.091	5.288	7.722	8.395	16.787	16.731
2003	0.373	0.654	2.304	2.708	5.232	6.267	8.633	12.044	19.375
2004	0.125	0.627	1.694	3.452	4.499	4.471	8.560	8.478	18.167
2005	0.109	0.453	1.599	2.162	5.916	3.464	6.592	10.172	17.780
2006	0.207	0.480	1.024	1.715	3.489	5.965	5.126	14.241	14.759
2007	0.166	0.528	1.018	2.639	4.276	6.346	8.131	12.044	16.731
2008	0.317	1.015	1.986	2.486	5.421	6.293	8.131	12.044	16.613
2009	0.555	1.174	3.366	4.503	10.575	6.618	8.131	12.044	16.731
2010	0.335	1.170	1.774	3.904	4.784	4.548	3.461	12.044	24.490
2011	0.286	0.942	1.775	2.323	4.581	4.931	10.775	7.135	16.731

App. A5 (Append. A), Table A12c: Mean weight-at-age (kg) from State of Massachusetts inshore spring surveys(Michael Palmer, pers. commn). Note that for some years certain values at older ages have been determined by interpolation techniques as there were no data available.

	1	2	3	4	5	6	7	8	9+
1982	0.116	0.453	1.106	2.031	5.606	5.073	6.778	10.426	10.361
1983	0.083	0.388	1.020	1.634	2.381	10.539	4.511	15.422	10.361
1984	0.104	0.415	1.295	1.884	3.717	2.893	4.519	7.652	10.361
1985	0.128	0.517	0.999	2.252	2.829	4.556	4.519	7.652	10.361
1986	0.170	0.453	1.592	2.271	3.638	5.563	4.519	7.652	10.361
1987	0.057	0.564	0.791	3.213	3.963	10.103	4.519	7.652	15.241
1988	0.030	0.335	1.216	2.041	6.171	6.392	4.519	7.652	10.361
1989	0.072	0.340	0.946	1.660	3.709	5.363	4.519	7.652	10.361
1990	0.053	0.409	0.654	1.317	3.311	6.779	4.519	7.652	10.361
1991	0.114	0.331	1.118	1.282	2.609	4.556	4.519	7.652	10.361
1992	0.049	0.447	0.753	1.410	1.716	5.513	3.018	7.652	10.361
1993	0.037	0.355	0.764	1.033	2.839	2.829	4.519	7.652	10.361
1994	0.079	0.279	0.842	1.685	2.791	4.556	4.519	7.652	10.361
1995	0.048	0.395	0.809	1.374	2.555	4.556	4.519	7.652	10.361
1996	0.081	0.426	0.806	1.010	1.664	4.556	4.519	7.652	10.361
1997	0.073	0.555	0.925	1.702	1.328	1.252	4.519	7.652	10.361
1998	0.063	0.390	1.085	1.756	2.496	3.266	2.431	7.652	10.361
1999	0.094	0.484	1.134	2.070	2.904	3.383	4.140	3.869	10.361
2000	0.094	0.466	1.366	2.031	2.802	4.363	5.546	9.013	10.361
2001	0.042	0.470	1.571	2.346	2.738	5.127	3.672	6.875	10.361
2002	0.039	0.230	0.945	1.947	3.012	5.184	5.928	7.440	11.027
2003	0.067	0.216	0.486	1.883	3.100	3.253	5.414	6.562	8.618
2004	0.039	0.383	0.810	1.760	2.143	2.730	3.770	8.342	12.697
2005	0.035	0.177	1.011	1.659	3.125	3.309	5.233	5.913	4.846
2006	0.048	0.116	0.568	1.136	2.048	1.930	4.783	7.652	9.447
2007	0.056	0.172	0.675	1.414	2.317	3.860	3.768	3.446	10.361
2008	0.064	0.277	0.747	1.375	1.013	3.419	5.194	7.652	10.361
2009	0.048	0.199	0.872	1.044	1.357	3.248	4.519	7.652	10.361
2010	0.060	0.230	0.647	1.634	2.482	5.356	4.519	7.652	10.652
2011	0.046	0.291	0.869	1.459	2.494	3.178	3.605	6.869	10.361

(Appendix B within Appendix A5)

Appendix 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).

For the convenience of readers, details which are changed or newly added relative to the specifications used for the analyses reported in Butterworth and Rademeyer (2012) are shown highlighted. Note that summations over ages now all exclude age a=0.

B.1. Population dynamics

B.1.1 Numbers-at-age

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

$$N_{y+1,0} = R_{y+1} \tag{B1}$$

$$N_{y+1,a+1} = N_{y,a} e^{-Z_{y,a}} \qquad \text{for } 0 \le a \le M-2 \tag{B2}$$

$$N_{y+1,m} = N_{y,m-1} e^{-Z_{y,m-1}} + N_{y,m} e^{-Z_{y,m}} \tag{B3}$$

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 0-year-old fish) at the start of year y,

m is the maximum age considered (taken to be a plus-group).

$Z_{y,a} = F_y S_{y,a} + M_a$ 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 0-year old) at the start of year y is assumed to be related to the spawning stock size (i.e. the biomass of mature fish) by either a modified Ricker or a standard or adjusted Beverton-Holt stock-recruitment relationship, allowing for annual fluctuation about the deterministic relationship.

For the modified Ricker:

$$R_y = \alpha B_y^{\text{sp}} \exp\left[-\beta\left(B_y^{\text{sp}}\right)^{\gamma}\right] e^{(\varsigma_y - (\sigma_{\text{R}})^2/2)} \tag{B4}$$

for the (standard) Beverton-Holt:

$$R_y = \frac{\alpha B_y^{sp}}{\beta + B_y^{sp}} e^{(\varsigma_y - (\sigma_{\text{R}})^2/2)} \tag{B5}$$

and for the adjusted Beverton-Holt:

$$R_y = \begin{cases} \dfrac{\alpha B_y^{sp}}{\beta + B_y^{sp}} & \text{if } B_y^{sp} \le B^* \\ \dfrac{\alpha B^*}{\beta + B^*} \exp\left(-\left(\dfrac{B_y^{sp} - B^*}{\sigma_N}\right)^2\right) & \text{if } B_y^{sp} > B^* \end{cases} \tag{B6}$$

where

α, β, γ, $B^*$and σ_N are spawning biomass-recruitment relationship parameters,

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

B_y^{sp} is the spawning biomass at the start of year y, computed as:

$$B_y^{\text{sp}} = \sum_{a=1}^{m} f_a w_{y,a}^{\text{strt}} N_{y,a} e^{-Z_{y,a}/4} \tag{B7}$$

because spawning for the cod 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, and

f_a is the proportion of fish of age a that are mature.

Section *B.2.6* details the procedure adopted when recruitment is not assumed to be related to spawning biomass , at least internal to the assessment.

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

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

$$C_y = \sum_{a=1}^{m} w_{y,a}^{\text{mid}} C_{y,a} = \sum_{a=1}^{m} w_{y,a}^{\text{mid}} N_{y,a} \; S_{y,a} F_y \left(1 - e^{-Z_{y,a}}\right) / Z_{y,a} \tag{B8}$$

where

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

$C_{y,a}$ 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:

$$B_y^{\text{surv}} = \sum_{a=1}^{m} w_{y,a}^{\text{surv}} S_a^{\text{surv}} N_{y,a} e^{-Z_{y,a} T^{surv}/12} \tag{B9}$$

for biomass indices and

$$N_y^{\text{surv}} = \sum_{a=1}^{m} S_a^{\text{surv}} N_{y,a} e^{-Z_{y,a} T^{surv}/12} \tag{B10}$$

for numbers indices

where

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

T^{surv} is the season in which the survey is taking place (T^{surv}=1 for spring surveys and T^{surv}=3 for fall surveys), and

$w_{y,a}^{surv}$ denotes the mass of fish of age a from survey *surv* year y (Table A12).

For the Massachusetts spring survey, the summation is taken from age 1 to age 6.

B.1.4. Initial conditions

For the first year (y_0) considered in the model, the numbers-at-age are estimated directly for ages 0 to a^{est}, with a parameter ϕ mimicking recent average fishing mortality for ages above a^{est}, i.e.

$$N_{y_0,a} = N_{\text{start},a} \qquad \text{for } 0 \le a \le a^{est} \tag{B11}$$

and

$$N_{\text{start},a} = N_{\text{start},a-1} e^{-M_{a-1}} (1 - \phi S_{a-1}) \qquad \text{for } a^{est} < a \le m-1 \tag{B12}$$

$$N_{\text{start},m} = N_{\text{start},m-1} e^{-M_{m-1}} (1 - \phi S_{m-1}) \big/ (1 - e^{-M_m} (1 - \phi S_m)) \tag{B13}$$

B.2. The (penalised) likelihood function

The model can be fit to (a subset of) CPUE and survey abundance indices, and commercial and survey catch-at-age and catch-at-length 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 ($-\ell nL$) are as follows. Details related to fitting to CPUE series are not included below,

as such series are not considered in the analyses of this paper.

B2.1. Survey abundance data

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

$$I_y^{surv} = \hat{I}_y^{surv} \exp\left(\varepsilon_y^{surv}\right) \quad \text{or} \quad \varepsilon_y^{surv} = \ell\text{n}\left(I_y^{surv}\right) - \ell\text{n}\left(\hat{I}_y^{surv}\right) \tag{B14}$$

where

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

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

$\hat{q}^{surv}$ is the constant of proportionality (catchability) for the survey biomass 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:

$$-\ell\text{n}\, L^{\text{survey}} = \sum_{surv}\sum_{y}\left\{\ell\text{n}\left(\sqrt{\left(\sigma_y^{surv}\right)^2 + \left(\sigma_{Add}^{surv}\right)^2}\right) + \left(\varepsilon_y^{surv}\right)^2 / \left[2\left(\left(\sigma_y^{surv}\right)^2 + \left(\sigma_{Add}^{surv}\right)^2\right)\right]\right\} \tag{B15}$$

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:

$$\ell n\, \hat{q}^{surv} = 1/n_{surv} \sum_{y}\left(\ln I_y^{surv} - \ln \hat{B}_y^{surv}\right) \tag{B16}$$

B.2.3. Commercial catches-at-age

The contribution of the catch-at-age data to the negative of the log-likelihood function under the assumption of an "adjusted" lognormal error distribution is given by:

$$-\ell\text{n}\, L^{\text{CAA}} = \sum_{y}\sum_{a}\left[\ell n\left(\sigma_a^{com} / \sqrt{p_{y,a}}\right) + p_{y,a}\left(\ell n\, p_{y,a} - \ell n\, \hat{p}_{y,a}\right)^2 / 2\left(\sigma_a^{com}\right)^2\right] \tag{B17}$$

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

$$\hat{C}_{y,a} = N_{y,a} \; S_{y,a} F_y \left(1 - e^{-Z_{y,a}}\right) / Z_{y,a} \qquad \text{(B18)}$$

and

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

$$\hat{\sigma}_a^{com} = \sqrt{\sum_y p_{y,a} \left(\ell n \, p_{y,a} - \ell n \, \hat{p}_{y,a}\right)^2 / \sum_y 1} \qquad \text{(B19)}$$

Commercial catches-at-age are incorporated in the likelihood function using equation (B17), for which the summation over age *a* is taken from age a_{minus} (considered as a minus group) to a_{plus} (a plus group).

In application of this approach ages are often aggregated to avoid values of $p_{y,a}$ or $\hat{p}_{y,a}$ that are too small in the interests of estimation robustness. In this paper individual ages have been maintained between the selected minus and plus-groups to provide potential discrimination of different shapes for the selectivity functions at older ages in particular. This however does mean that there are certain cells for which $p_{y,a}$ values are zero. That does not cause any problems because the limit of $p_{y,a}\left(\ln p_{y,a}\right)^2$ as $p_{y,a} \to 0$ is 0, so these terms can be omitted from the summation in equation B17. One could argue that they should nevertheless be included in the summations in equation B18, but exclusion seems more appropriate as the structural zero contributions then included would seem likely to bias the estimates of $\hat{\sigma}_a^{com}$ downwards.

In addition to this "adjusted" lognormal error distribution, some computations use an alternative "sqrt(p)" formulation, for which equation B20 is modified to:

$$-\ell \text{n} \, L^{\text{CAA}} = \sum_y \sum_a \left[\ell n\left(\sigma_a^{com}\right) + \left(\sqrt{p_{y,a}} - \sqrt{\hat{p}_{y,a}}\right)^2 / 2\left(\sigma_a^{\text{com}}\right)^2 \right] \qquad \text{(B21)}$$

and equation B21 is adjusted similarly:

$$\hat{\sigma}_a^{com} = \sqrt{\sum_y \left(\sqrt{p_{y,a}} - \sqrt{\hat{p}_{y,a}}\right)^2 / \sum_y 1} \qquad \text{(B22)}$$

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

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, assuming an "adjusted" lognormal error distribution (equation (B19)) 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:

$$\hat{p}_{y,a}^{surv} = S_a^{\text{surv}} N_{y,a} e^{-Z_{y,a} T^{surv}/12} \Big/ \sum_{a'=1}^{m} S_{a'}^{\text{surv}} N_{y,a'} e^{-Z_{y,a'} T^{surv}/12} \quad . \qquad \text{(B23)}$$

For the Massachusetts spring survey, the summation is taken from age 1 to age 6.

B.2.5. Survey catches-at-length

In some runs, catches-at-length are also incorporated in the likelihood function. These data are incorporated in the similar manner as the catches-at-age. When the model is fit to catches-at-length, the predicted catches-at-age are converted to catches-at-length:

$$\hat{p}_{y,l}^{surv} = \sum_a \hat{p}_{y,a}^{surv} A_{a,l}^{strt} \qquad \text{(B24)}$$

for the spring survey, and

$$\hat{p}_{y,l}^{surv} = \sum_a \hat{p}_{y,a}^{surv} A_{a,l}^{mid} \qquad \text{(B25)}$$

for the fall survey,

where $A_{a,l}^{strt}$ and $A_{a,l}^{mid}$ are the proportions of fish of age *a* that fall in the length group *l* (i.e., $\sum_l A_{a,l}^{strt} = 1$ and $\sum_l A_{a,l}^{mid} = 1$ for all ages) at the beginning of the year and at the middle of the year respectively.

The matrices $A_{a,l}^{strt}$ and $A_{a,l}^{mid}$ are calculated under the assumption that length-at-age is normally distributed about a mean given by the von Bertalanffy equation, i.e.:

$$L_a^{strt} \sim N\left[L_\infty\left(1 - e^{-\kappa(a-t_o)}\right), \left(\theta_a^{strt}\right)^2\right] \qquad \text{(B26)}$$

for the spring survey and

$$L_a^{mid} \sim N\left[L_\infty\left(1 - e^{-\kappa(a+0.5-t_o)}\right), \left(\theta_a^{mid}\right)^2\right] \qquad \text{(B27)}$$

for the fall survey,

where

θ_a^{strt} and θ_a^{mid} are the standard deviation of begin and mid-year length-at-age *a* respectively, which are modelled to be proportional to the expected length-at-age *a*, i.e.:

$$\theta_a^{strt} = \beta\left[L_\infty\left(1 - e^{-\kappa(a-t_o)}\right)\right]^\gamma \quad \text{(B28)}$$

and

$$\theta_a^{mid} = \beta\left[L_\infty\left(1 - e^{-\kappa(a+0.5-t_o)}\right)\right]^\gamma \quad \text{(B29)}$$

with β an estimable parameter and $\gamma = 0.5$ (a value which was found to lead to reasonable fits to the data).

$L_\infty = 150.93\,cm$,

$\kappa = 0.11\,yr^{-1}$,

$t_o = 0.13\,yr$,

The following term is then added to the negative log-likelihood:

$$-\ell\text{n}\,L^{\text{CAL}} = w_{len}\sum_{surv}\sum_{y}\sum_{l}\left[\ell n\left(\sigma_{\text{len}}^{surv} / \sqrt{p_{y,l}^{surv}}\right) + p_{y,l}^{surv}\left(\ell n\, p_{y,l}^{surv} - \ell n\, \hat{p}_{y,l}^{surv}\right)^2 / 2\left(\sigma_{\text{len}}^{surv}\right)^2\right] \quad \text{(B30)}$$

The w_{len} weighting factor may be set to a value less than 1 to downweight the contribution of the catch-at-length data (which tend to be positively correlated between adjacent length groups because the length distributions for adjacent ages overlap) to the overall negative log-likelihood compared to that of the CPUE data. The value used for w_{len} is 0.1, being roughly equivalent to the ratio of the number to length groups to the number of age groups considered. Instances of observed proportions of zero are dealt with in the same manner as for catches-at-age, as is the alternative "sqrt(p)" error distribution formulation.

B.2.6. 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:

$$-\ell n L^{\text{pen}} = \sum_{y=y_1+1}^{y_2}\left[\varepsilon_y^2 / 2\sigma_{\text{R}}^2\right] \quad \text{(B31)}$$

where

ε_y from $N\left(0,(\sigma_R)^2\right)$,

σ_{R} is the standard deviation of the log-residuals, which is input.

Equation B31 is used when the stock-recruitment curve is estimated internally. In some analyses reported in this paper where BRP estimates are based on stock-recruitment curves estimated "externally" using the assessment outputs,, this "stock-recruitment" term is included for the last two years only, simply to stabilise these estimates which are not well determined by the other

data. In these cases, the ε_y are calculated as the deviations from the mean log recruitment for the ten preceding years, i.e. recruitment estimates for 2010 and 2011 are shrunk towards the geometric mean recruitment over the preceding decade.

B.2.7. Catches

$$-\ell n L^{\text{Catch}} = \sum_y \left[\frac{\ell n C_y - \ell n \hat{C}_y}{2\sigma_{\text{C}}^2} \right] \qquad \text{(B32)}$$

where

C_y is the observed catch in year *y*,

$\hat{C}_y$ is the predicted catch in year *y* (eqn B8), and

σ_{C} is the CV input: 0.4 for pre-1964 catches, 0.2 for catches between 1964 and 1981 and 0.05 for catches from 1982 onwards.

B.2.8Incorporation of Bigelow vs Albatross survey calibration

The survey data provided are adjusted for the years 2009 to 2012 which were obtained from *Bigelow* surveys have been adjusted to "*Albatross* equivalents" through use of calibration factors estimated independently from paired tow experiments (Miller *et al*., 2010). However the survey data before and after the switch of vessels also provide information on the calibration factors because they sample the same cohorts. Incorporation of this information in assessments in this paper has been effected by treating the estimates, with their variance-covariance matrix, as a form of "joint-prior" which is effectively updated in the penalised likelihood estimation when fitting the model. The process is as follows.

First *Bigelow* length frequency distributions are converted to *Albatross* equivalent length frequency distributions:

$$C_{y,l}^{surv,A} = C_{y,l}^{surv,B} \big/ F_l \qquad \text{(B33)}$$

where

$C_{y,l}^{surv,B}$ is the measured catch-at-length for the *Bigelow* in year *y* for survey *surv,*

$C_{y,l}^{surv,A}$ is the inferred catch-at-length for the *Albatross* equivalent in year *y* for survey *surv,*

F_l is the length-based calibration factor (*Bigelow/Albatross*),

The Albatross equivalent length distributions are then converted to age distributions:

$$C_{y,a}^{surv,A} = \sum_l C_{y,l}^{surv,A} ALK_{y,a,l}^{surv} \qquad \text{(B34)}$$

where

$ALK_{y,a,l}^{surv}$ is the age-length key (proportion of fish of length *l* that have age *a*) in year *y* for survey *surv.*

Indices are then obtained from the *Albatross* equivalent age distributions as follows:

$$I_y^{surv,A} = \sum_a C_{y,a}^{surv,A} w_{y,a}^{surv} \qquad \text{(B35)}$$

for biomass indices and

$$I_y^{surv,A} = \sum_a C_{y,a}^{surv,A} \qquad \text{(B36)}$$

for numbers indices,

where

$w_{y,a}^{surv}$ is the weight-at-age in year y for survey *surv*.

The calibration factor has four parameters, three of which are estimable and the other input: X_1=20cm, X_2, F_1 and F_2

$$F_l = \begin{cases} F_1 & \text{if } l \le X_1 \\ \dfrac{(F_2 - F_1)}{(X_2 - X_1)} l + \dfrac{(F_1 X_2 - F_2 X_1)}{(X_2 - X_1)} & \text{if } X1 < l < X_2 \\ F_2 & \text{if } l \ge X_2 \end{cases} \qquad \text{(B37)}$$

The following contribution is therefore added to the negative log-likelihood in the assessment:

$$-\ln L^{calib} = \frac{1}{2}\ln|\boldsymbol{\Sigma}| + \frac{1}{2}(\mathbf{x} - \boldsymbol{\mu})^{\mathrm{T}} \boldsymbol{\Sigma}^{-1} (\mathbf{x} - \boldsymbol{\mu}) \qquad \text{(B38)}$$

where the parameters X_2, F_1 and F_2 are components of the vector $\boldsymbol{x}$,
$\boldsymbol{\Sigma}$ is the variance covariance matrix as estimated by Miller *et al.* (2010), and
$\boldsymbol{\mu}$ is a vector which contains the Miller *et al.* (2010) estimates of the parameters.

These estimates and the variance-covariance matrix are given in table B1 below:

Table B1: Estimates and variance-covariance matrix for the calibration parameters (Miller, pers. commn).

$\boldsymbol{\mu}$	$ln(F_2)$	$ln(F_1-F_2)$	$ln(X_2-X_1)$
	0.4713	1.4163	3.5086
$\boldsymbol{\Sigma}$	$ln(F_2)$	$ln(F_1-F_2)$	$ln(X_2-X_1)$
$ln(F_2)$	0.006674	-0.002515	-0.002559
$ln(F_1-F_2)$	-0.002515	0.051592	-0.007601
$ln(X_2-X_1)$	-0.002559	-0.007601	0.006757

B.3. Estimation of precision

Where quoted, CV's or 95% probability interval estimates are based on the Hessian.

B.4. Model parameters

B.4.1. Fishing selectivity-at-age:

For the NEFSC offshore surveys, the fishing selectivities are estimated separately for ages 1 to age 6 and are flat thereafter. For the Massachusetts inshore spring survey, the selectivities are estimated separately for ages 1 to 4. The estimated proportional decrease from ages 3 to 4 is assumed to continue multiplicatively to age 6; this decrease parameter is bounded by 0, i.e. no increase is permitted. For all three surveys, age 0 is not considered.

The commercial fishing selectivity, S_a, is estimated separately for ages a_{minus} to a_{plus} (1 to 9) It is taken to differ over four periods: a) pre-1982, b) 1982-1988, c)1989-2004, and d) 2005-present. The selectivities are estimated directly for the last three periods. For the pre-1982 period, the selectivity is taken as that for the 1989-1988 block, but shifted one year to the left. For the implementations in this paper, given that there were difficulties with imprecise estimates at larger ages for period d) given its shortness, a common selectivity at age was estimated across all periods for ages 7 and above.

B.4.2. Other parameters

Model plus group			
m	9		
Commercial CAA			
a_{minus}*	1		
a_{plus}	9		
Survey CAA	NEFSC spr	NEFSC fall	MASS spr
a_{minus}*	1	1	1
a_{plus}	9	9	4
Natural mortality:			
M	Age independent: i) 0.2 for all years ii) 0.2 until 1988, threafter a linear increase to 0.4 in 2003 and constant at 0.4 thereafter		
Proportion mature-at-age:			
f_a	input, see Table A8		
Weight-at-age:			
$w_{y,a}^{strt}$	input, see Table A2		
$w_{y,a}^{mid}$	input, see Table A3		
$w_{y,a}^{surv}$	input, see Table A12		
Stock recruit residuals std dev: σ_R	0.6		
Initial conditions :			
$N_{y0,a}$	estimated directly for ages 0 to xx depending on AIC criterion		
ϕ	estimated		

* Strictly not a minus group anymore since the catches at age zero are ignored.

B.5.Biological Reference Points (BRPs)

It is possible to estimate BRPs internally within the assessment by fitting the stock-recruitment relationship directly within the assessment itself.

For some results reported here, however, the stock-recruitment relationships are fitted to the estimates of recruitment and spawning biomass provided by the various assessments to provide a basis to estimate BRPs. The rationale for estimation external to the assessment itself is to avoid assumptions about the form of the relationship influencing the assessment results. These fits are achieved by minimising the following negative log-likelihood, where the $e^{-\frac{\sigma_R^2}{2}}$ term is added for consistency with equation B4, i.e. the stock-recruitment curves estimated are mean-unbiased rather than median unbiased:

$$-\ln L = \sum_{y=y1}^{2009} \left[\frac{\left(\ln(N_{y,0}) - \ln\left(\hat{N}_{y,0} e^{-\frac{\sigma_R^2}{2}} \right) \right)^2}{2\left((\sigma_R)^2 + (CV_y)^2 \right)} \right] \tag{B39}$$

where

$N_{y,0}$ is the "observed" (assessment estimated) recruitment in year *y*,

$\hat{N}_{y,0}$ is the stock-recruitment model predicted recruitment in year *y*,

σ_R is the standard deviation of the log-residuals which is input (and set here to 0.6), and

CV_y is the Hessian-based CV for the "observed" recruitment in year *y*.

Note that the differential precision of the assessment estimates of recruitment is taken into account, and that the summation ends at 2009 because little by way of direct observation is as yet available to inform estimates of recruitment for 2010 and 2011.

Appendix A.6. Additional ASAP sensitivity runs

This appendix (tables and figures in next section) provides results from sensitivity runs that were conducted on the SAW 55 ASAP reference model (SAW55_BASE) except where noted. These 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.6.1. Survey calibration coefficients

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 (during 1984-85) and trawl net (Yankee 36/41 in spring survey). The changes are summarized in Table A.52. Trends in the calibrated and uncalibrated surveys indices were very similar and with the exception of the fall 2009 abundance index (Fig. A.95). Overall, the effects of the Bigelow calibration were less than the historical door/vessel calibration effects. The SAW 55 WG recommended that the adjusted series of each NEFSC survey time series be used during SAW 55; however, the WG recommended that sensitivity analyses be undertaken during the modeling to explore the impact of uncertainty in the calibration coefficients.

Results of the sensitivity of the SAW55_BASE model to the upper and lower 95% confidence intervals of the calibration factors are provided in Table A.6.1 and Figure A.6.1. The main effect of the calibration coefficients was an increase in the uncertainty in recent biomass rather than adding bias. The 2011 spawning stock estimate ranged from 9,804 mt (upper 95% CI) to 15,098 mt (lower 95% CI) with the calibrated estimate of 11,974 mt (SAW55_BASE). Over the majority of the time series the effects of the calibration coefficients were minimal.

A.6.2. 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, A.59, and A.63 for the NEFSC spring, NEFSC fall, and MADMF spring survey respectively. Biomass indices at age are presented in Tables A.58, A.60, and A.64 for the NEFSC spring, NEFSC fall, and MADMF spring survey 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.11 and A.12). The survey weight-at-age matrices contained several holes for age/year combinations, particularly among the older ages. The missing values were imputed using a time series average weight-at-age. The ASAP sensitivity was conducted on the ASAP preferred model SAW55_3BLOCK_BASE which was tuned to the survey abundance (numbers) indices. A comparable model was constructed using the biomass indices as described above. To provide an equal comparison across models, the biomass model, SAW55_3BLOCK_BASE_BIOMASS was run initially and then the second stage Francis (2011) ESS multipliers were applied. The final biomass-based model is

SAW55_3BLOCK_BASE_BIOMASS_ADJ. The adjusted biomass model had improved model diagnostics relative to the unadjusted model (Table A.6.2).

The working group discussed the preferred metric to evaluate model preference and agreed that the coefficient of variation (CV) on the terminal (2011) estimate of spawning stock biomass should be used. The two indices provided similar results in terms of biomass trends (Fig. A.6.2) with the terminal (2011) estimates differing by 1,662 mt. The CVs on the 2011 spawning stock biomass were 0.176 for the abundance-based model and 0.181 for the biomass-based model. While the differences were small, the WG concluded to use abundance (numbers) indices for the final ASAP preferred model.

A.6.3. Survey catchability and an evaluation of biomass scale

The scale of model estimates of biomass can be affected by assumptions of the estimated efficiency of the surveys. Further work on the ASAP model was conducted to 1) evaluate the sensitivity of the SAW55_BASE model results to alternate assumptions of survey catchability (q), and 2) generate model-independent estimates of total biomass and compare to the model estimates to determine whether the model results are reasonable. The second analyses were originally conducted for the SAW 53 assessment (NEFSC 2012a), however given the nearly identical biomass scales between the SAW 53 and SAW 55 assessment results (Fig. A.138), the analyses remain relevant.

Model profiling across a range of NEFSC spring survey q values

The sensitivity of the SAW55_BASE model to alternate assumptions of survey catchability was evaluated by profiling across a range of q values from 0.1 to 1.3 in 0.1 increments. Priors were specified for catchability values by setting the input CV on catchability to 0.1 and setting lambda values at 1 (i.e., the initial q values were given little latitude to deviate from the initial conditions and a penalty was imposed for any deviations).

Results of the sensitivity runs are summarized in Fig. A.6.3. On the basis of the objective function, the model preferred q values in the range of 0.6 to 1.2. There was a general tendency for the model to estimate higher [lower] q values than inputted when the inputted q was below [above] the model preferred value of 0.89. Within the 0.6 to 1.2 range there was little impact in terms of SSB scaling (<8% difference from SAW55_BASE run). Even when forcing q to a minimum believable range (≈0.4) the SSB scaling differences only amount to <18% difference from the base run q preference of 0.89. The tradeoff in lower q reduces the overall fit in the NEFSC spring survey and by necessity, reduces q on the NEFSC fall survey. Additionally, a lower q requires an approximate 22% decrease in the selectivity on the oldest age in the second fishery selectivity block (i.e., a considerable increase in the doming assumption). The profiling across a range of q values shows strong model preference for the BASE model results, with little impact in terms of SSB within the range of believable alternatives.

Sensitivity of BASE results and estimates of survey q to area expansion factors

The Gulf of Maine cod stock boundary (Fig. A.1) encompasses a surface area of approximately 54.5 thousand km^2. The survey strata used in the Gulf of Maine cod stock assessment (Fig. A.85) encompasses 61.4 thousand km^2; approximately 17.1% larger than the stock area. Included in the survey strata set are three strata (29, 30 and 36) that extend beyond the United States Exclusive Economic Zone (EEZ) into Canadian waters. A sensitivity analyses was conducted to evaluate whether using a survey strata set that included only survey strata contained entirely within the US EEZ would affect model results and estimates of survey *q*.

NEFSC spring and fall survey indices, including indices at age, were recalculated using only strata 26-28 and 37-40 (excluded 29, 30 and 36). The revised survey area has a surface area of 34.2 thousand km^2 (37.2% smaller than the stock area).The recalculated aggregate abundance indices were nearly identical in terms of trends, but tended to be slightly higher (Fig. A.6.4). The rescaling of the survey indices is a product of dropping survey strata that have historically not contained high abundances of cod, thus increasing the stratified mean number/tow without impacting overall survey trends. When converted to area swept indices by accounting for the survey trawl area and revised surface area, the indices tended to be lower than those that included in the full strata set. The raising factor used to convert the mean number per tow to their area-swept equivalents was disproportionately smaller than the increases in the stratified mean number per tow. The revised survey indices were inputted into a revised ASAP model (SAW55_REV_SURV_STRATA).

The SAW55_REV_SURV_STRATA model is nearly identical to the BASE model with respect to the SSB, F and the age 1 recruitment time series (Fig. A.6.5). The slight deviations in the two runs are likely due to the small differences in the survey indices when calculated using the reduced strata set. While there were no major differences in estimates of SSB and F, using the reduced strata sets resulted in *q* estimates that were much lower relative to the BASE model. The NEFSC spring q went from 0.89 to 0.56, NEFSC fall from 0.53 to 0.41 and the MADMF spring survey went from 0.21 to 0.20 (Fig. A.6.6). Model estimates of *q* are highly sensitive to the estimated survey area used to expand mean number per tow survey indices to their area-swept equivalents. In addition to the assumptions about total survey area considered here, estimates of *q* are also likely to be sensitive to assumptions about the total trawl area, effective trawl sweep and the extent of cod herding that occurs in the survey net.

Model independent estimates of total biomass

All previous analyses have examined the sensitivity of the biomass estimates to different assumptions on model parameters. While these analyses show that the model-based biomass estimates are robust to alternate model configurations, they do not provide a sense for whether the model-based estimates are realistic relative to model-independent estimates of total stock biomass. Several different model-independent approaches are taken below to evaluate whether the ASAP estimates of biomass are realistic.

Model independent estimates of total biomass from the Bigelow survey years (2009-2011)

The conversion of Bigelow survey catches to Albatross equivalents is an uncertain, but necessary step in order to maintain a consistent time series and fully utilize the short Bigelow time series. To avoid any confounding effects of the Bigelow conversion in deriving model-independent estimates of biomass, an attempt was made to use raw (i.e., unconverted) Bigelow time series data (2009 – 2011) to estimate total biomass. Total survey area-swept biomass can be estimated using Appendix 6 Equation 1.

(1) $B_{AW} = I/1000 \bullet A/f \bullet 1/q$

where:

B_{AW} = Area swept biomass
I = survey index
A = survey area
f = trawl area
q = survey catchability

The survey area depends on the strata set included. For the purposes of these analyses, the inshore survey strata were included to better characterize total catch across all age classes (strata 57-69) in addition to the offshore survey strata (strata 26-30, 36-40). The nearshore area that makes up the inshore survey strata has higher abundance of juveniles relative to the offshore areas. During the Bigelow survey years, these strata have been consistently sampled. The differences in availability of young age classes between the inshore and offshore regions is evident when comparing the selectivity of NEFSC offshore surveys to the MADMF survey in the SAW55_3BLOCK_BASE model (Fig. A.177). The total surface area of strata 26-30, 36-40 and 57-69 is 63.8 thousand km^2 and 36.5 thousand km^2 when strata 29,30 and 36 are excluded. The total trawl area of the Bigelow is 0.024 km^2 when using wing spread to define the effective trawl area and 0.061 km^2 when using door spread. Comparatively, the Albatross tow area in terms of wing spread is 0.038 km^2.

Assumptions on the effective trawl area and q can have large impacts on survey-based estimates of total biomass. Moving from a q of 1.0 to 0.2 will result in a fivefold increase in terms of biomass (Fig. A.6.7). Assuming that the door spread best characterizes the effective trawl area results in biomass estimates less than half that compared to calculations made using wing spread. If there is herding between the doors and an assumption of wing spread is used to determine area swept biomass, biomass estimates may be inflated (or in the case of the model, q estimates, may be higher than reality). The true effective trawl area and survey catchability is not known, but an assumption that a wing spread-based estimate of effective trawl area and 80% efficiency (q=0.8) appears reasonable. Using these assumptions to estimate a survey-based estimate of total biomass yielded results similar to the SAW 53 BASE model estimates of total biomass at the time of the survey (i.e., total January 1 biomass decremented by total mortality, Z, occurring before the survey; Fig. A.6.8). In 2009 and 2010 the BASE biomass estimates are all within the 80% bootstrap CI of the Bigelow-based biomass estimates. Excluding the offshore survey strata does not impact the overall perception of Bigelow-based total biomass.

Given an assumption that the Bigelow survey q=0.8, it's reasonable to conclude that a comparative q for the Albatross survey is approximately 0.5 if the Bigelow to Albatross conversion coefficient of 1.602 on fish ≥ 54 cm is used as a rough estimate of differences in catchability (i.e., the Bigelow survey is 60% more efficient at catching cod compared to the Albatross survey). By performing a similar analysis on the Albatross survey series, but using a q assumption of 0.5, a time series of survey-estimated total biomass can be constructed. The survey-based time series is not inconsistent with the BASE model estimates of total biomass at the time of the survey (Z-decremented to the time of the survey). The BASE biomass estimates generally fall within the 80% CI of both the NEFSC spring and fall survey-based biomass estimates (Fig. A.6.9). While the estimates are not exact, they are all of the same relative scale, suggesting that the scale of the biomass estimated by the ASAP model is realistic.

Thinking of q in terms of the catchability of 'survey-able' biomass

The BASE model estimate of NEFSC spring survey q (0.92) seems unreasonably high when thought of in terms of total survey efficiency. However, when interpreting the model q values, the impact of survey selectivity on the q estimates needs to be considered. Effectively, the ASAP model q estimates represent the q in terms of fully selected fish (i.e., after accounting for survey selectivity). To examine whether the SAW 53 BASE q estimates were reasonable, the model estimates have been used to estimate survey-based total biomass as was done above. Unlike the previous analysis that incorporated the inshore survey strata, only the offshore survey strata are included here, as this is consistent with the NEFSC survey indices used in the SAW 53 BASE model. This maintains consistency between the survey index and model-based estimates of q and selectivity at age. Survey-based biomass indices were generated using both the full offshore strata set (26-30, 36-40) and with strata 29,30 and 36 excluded. The model estimates of q applied to estimate total biomass were: NEFSC spring = 0.92 (full strata set), 0.57 (exclude 29, 30 and 36) and NEFSC fall = 0.53 (full strata set), 0.42 (exclude 29, 30 and 36).

Total survey-based estimates of biomass were compared to the 'survey-able' biomass estimated from the SAW 53 BASE model. 'Survey-able' biomass was estimated by decrementing the January 1 biomass (NEFSC 2012a, Table A.63) by total Z between January 1 and the time of the survey (spring vs. fall) and filtering the Z-decremented biomass through the survey selectivity ogive. The SAW 53 BASE-estimated 'surveyable' biomass generally fell within the 80% survey CI on total biomass for both the spring (Fig. A.6.10) and fall (A.6.11) surveys. How q is defined, whether in terms of absolute efficiency or in terms of the fully selected ages, does impact the q value. However, when the q is properly applied in a model-independent exercise, the calculations yield biomass estimates that are comparable with those estimated by the BASE model.

A.6.4. Multiple fleet definitions

Preliminary ASAP runs attempted to break the fishery catch into separate fleets (commercial and recreational). Selectivity was fit non-parametrically (selectivity-at-age) with two selectivity blocks per fleet. The timing of the selectivity block varied slightly by fleet, but generally the split between blocks occurred during the 1990s. The SAW55_BASE model treats commercial and

recreational catch (landings and discards) as a single fleet. Three different alternate fleet formulations were explored: 1) for each fleet (commercial and recreational), catch was divided into retained and discarded catch, with each disposition constituting its own fleet such that there were 4 fleets total (SAW55_4FLEET); 2) catch was divided into commercial and recreational catch with each catch input treated as a separate fleet (SAW55_2FLEET); 3) catch was divided into landed and discarded catch with each catch input treated as a separate fleet (SAW55_SPLIT_LAND_DISC).

All of the split fleet models suffered from severe diagnostic issues. Most notably there was strong residual patterning in the fits to catch at age (Figs. A.6.12-A.6.14). Compared to the SAW55_BASE models, the split fleet models had lower estimates of 2011 spawning stock biomass and equal or higher estimates of age 5 fishing mortality (Table A.6.3). Given the problems experienced with these complex ASAP formulations and robustness of the assessment results, the SAW 55 WG supported the decision to use a simplified, single fleet, model formulation.

A.6.5. Inclusion of catch-per-unit-effort indices

During the SAW 55 Data Working Group (SAW 55 WG 2012a) commercial and recreational landings-per-unit-effort (LPUE) indices were presented. The WG expressed several concerns with the use of these indices which are summarized in detail in the assessment report. Because of these concerns, the WG recommended that the LPUE indices not be included in the GOM cod assessment model.

Sensitivity runs were however conducted to evaluate the impacts of including these LPUE indices in the SAW55_BASE model. The LPUE indices were inputted into the model both separately (SAW55_COM_LPUE and SAW55_REC_LPUE) and combined (SAW55_LPUE). Summary diagnostics of all runs are presented in Table A.6.4.

Initial attempts to fit the commercial LPUE indices revealed a poor fit the index with strong residual patterning (Fig. A.6.15). At the Data WG meeting there was considerable discussion about the contraction of the commercial fishery and intense aggregation of the fishery that occurred between 2006 and 2010. In the fits the commercial LPUE index there was a strong residual pattern that indicated differences in fleet catchability pre- and post-2006. Based on the similarities of the residual patterning to observed behavior of the fleet, a second commercial LPUE model was constructed that split the commercial LPUE index into two separate series (SAW55_COM_LPUE_SPLIT): one series included years 1982-2005 and the second included the years 2006-2011. The split model fits to the LPUE series were considerably better than those of the single series (Fig. A.6.15). There was three-fold increase in catchability (q) between the pre- and post-2006 periods. Interestingly, the model estimates of spawning stock biomass, fishing mortality and age 1 recruitment were nearly identical to that of the SAW55_BASE model (Fig. A.6.16).

Similar to the commercial LPUE index, the model fit to the recreational index was poor. There was a string of positive residuals early in the time series (pre-2002) and negative residuals in the

second half of the time series (Fig. A.6.17). Attempts to fit both LPUE indices (commercial and recreational) within a single model suffered from the same problems observed in the individual runs (Fig. A.6.18).

Because the LPUE indices do not have catch-at-age components, rather they are linked to the selectivity of the fishery, there was concern that the poor fits to the survey indices were due to attempting to link commercial or recreational LPUE indices to selectivities that included combined commercial and recreational catch patterns. Attempts were made to run LPUE models on the SAW55_2FLEET model described previously to address these concerns; however, these model runs did not converge.

A.6.6. Inclusion/exclusion of survey indices

To better understand how the model results are being influenced by each of the survey indices the SAW55_BASE model was run using only one index at a time. The three sensitivity runs were SAW55_NEFSC_SPRING (NEFSC spring survey), SAW55_NEFSC_FALL (NEFSC fall survey) and SAW55_MADMF_SPRING (MADMF spring survey). In all three sensitivity runs all other model configurations were left unchanged.

All three models had similar starting biomass values in 1982 ranging from 21,628 to 25,513 mt (Table S.6.7) however the MADMF spring survey model exhibited a large increase in spawning stock biomass over time such that by 2011, the spawning stock biomass was estimated at 34,137 mt compared to the 11,874 mt of the SAW55_BASE model. The survey fits from each of the models relative to the SAW55_BASE model was similar (Fig. A.6.19), however the large difference between models was due to a large buildup of age 9^+ fish in the MADMF spring survey (Fig. A.6.20). The increase in older age fish is a product of the declining selectivity with age in the MADMF spring survey (Fig. A.176). The MADMF survey contains very little information on older fish in the population; with only this survey in the model there is nothing to constrain build-up of biomass in the 9^+ group.

A.6.7. Survey selectivity assumptions (dome vs. flat topped) and plus group assumption (age 9^+ vs. 11^+)

Explorations were conducted to evaluate the impacts of: a) extending the age matrices out to age 11^+ (SAW55_11PLUS) compared to the 9^+ formulation used in the SAW55_BASE model; and b) allowing the NEFSC survey selectivities to be domed (SAW55_DOME) relative to the flat-topped assumed in the SAW55_BASE model. Additionally a combined model was run that allowed doming of the NEFSC survey selectivity and included extended age structure out to age 11^+ (SAW55_DOME11).

The SAW55_BASE model was insensitive to the plus group specification; the BASE and BASE_11 models achieved nearly identical results (67 mt difference) with respect to estimates of 2011 spawning stock biomass (Table A.6.6). The survey selectivities of ages 10 and 11 were poorly estimated as evidenced on the large CVs on these ages in both fishery blocks 1 and 2

(Table A.6.7). Selectivity of age 10 in block 1 hit a boundary at 1. Given the insensitivity of model results to the choice of the plus group and the poorly estimated selectivities on older ages, the base model configuration using an age 9^+ group is supported.

Relative to the SAW55_BASE model, the influence of allowing survey selectivities to be domed resulted in a positive rescaling of spawning stock biomass (e.g., 46% increase in 2011 SSB) and a decrease in age 5 fishing mortality from 0.59 to 0.50. Based on the evidence presented earlier, there is little biological or scientific evidence to support such strong doming, additionally, there was little model support for this with an increase of 6 parameters and an improvement of only 4 objective points. The improvement in the objective function was identical between the SAW55_11PLUS and SAW55_DOME11 runs. Given the lack of external evidence for domed-shaped survey selectivities, the lack of model preference for domed selectivity and the cautions highlighted in Legault (2012), the WG supported the assumption of flat-topped survey selectivity.

A.6.8. Assessment starting points (e.g., 1964, 1970 vs. 1982)

The SAW55_BASE assessment begins in 1982. The rationale for this approach is described in detail the main report. Two alternate start points were explored within the framework of the SAW55_BASE model: 1964 (SAW55_HIST_1964) and 1970 (SAW55_HIST_1970). Extending the time series back in time results in a loss of information content as described in the main report. For all historical runs the same adjustments described for the 1932 Beverton-Holt ASAP runs were applied to the SAW55_BASE historical runs. A summary of model diagnostics is presented in Table A.6.8. The historical runs, BASE_1970 and BASE_1964, did not alter the perception of the stock. Nearly identical trends were observed in spawning stock biomass, fishing mortality and age 1 recruitment (Fig. A.6.21). With respect to evaluating the current condition of the stock, the choice in starting year has little impact. Where the starting year does make a difference is in establishing reference points. Extending the time series back in time established additional contrast in the spawner-recuit relationship, however there remains no clear functional form to the relationship even when the assessment time series is extended back to 1964 (Fig. A.6.22). Given the experience of the GARM III, caution should be taken in placing too much weight on recruitment estimates driven entirely off of survey information (as are the recruitment estimates pre-1982) that cannot be corroborated with catch-at-age information.

A.6.9. Catch precision assumptions

At SARC 53, the Panel expressed concern that the CVs on the aggregate catch used in the base model (CV=0.05) assumed higher precision than was warranted given the CV estimates of 0.11 – 0.38 for commercial discards (Table A.25) and recreational catch percent standard errors (PSE) around 20% (Table A.43). Given that the same assumption has been made in SAW 55, explorations have been conducted evaluating the sensitivity of the model to both higher and lower CVs. In these sensitivity runs only the CVs on the aggregate catch were adjusted; all model inputs and parameters were held constant. Four different CVs were assumed in the model: 0.01, 0.10, 0.20, and 0.30. The model runs and summary diagnostics are presented in Table

A.6.9. Increasing catch CVs lead to slight improvements in the model fits to the survey indices, but only marginally (Appendix Fig. A1.11). The root mean square error on the total index fit went from 1.08 under the SAW55_BASE model to 1.00 in the 0.30 CV model. The primary effect of the higher CVs was reduced fit to the aggregate catch with very little overall change in the residual patterns, only in the magnitude of the residuals (Fig. A.6.23). The 2011 estimates of spawning stock biomass ranged from 11,990 mt to 10,535 mt with biomass decreasing with an increasing CV. Overall, increasing CVs on the aggregate catch had negligible impacts on the assessment results.

A.6.10. Stock structure considerations

Most of the discussion related to stock structure occurred during the SAW 55 Data WG. However, there were questions raised following the completion of the SAW 53 assessment that alternative definitions of stock structure could potentially change the perception of the cod resource(s). Here two different explorations have been conducted: 1) evaluate the likely outcome of considering only a western Gulf of Maine cod assessment; and 2) evaluate the likely outcome if the Georges Bank and Gulf of Maine cod resources were assessed as a single unit stock.

A western Gulf of Maine (wGOM) assessment model was constructed by first developing western Gulf of Maine survey indices. The western Gulf of Maine was defined at strata 26, 27 and 40 (Fig. A.6.24). These strata coincide with the region of highest cod density in the Gulf of Maine over the past five years (Fig. A.6.25). A comparison of the wGOM survey indices to those of the entire Gulf of Maine show that the survey trends from the wGOM are nearly identical to those of the Gulf of Maine as a whole (Fig. A.6.26). Conversely, the eastern Gulf of Maine have exhibited sharper declines in survey abundance relative to the Gulf of Maine as a whole. The declines seen in the eastern Gulf of Maine have only minimal effects on the full Gulf of Maine indices due to the dominance of the western Gulf signal. This effect can be better understood by examining the scale of the eastern Gulf of Maine survey indices relative to the Gulf of Maine as a whole (Fig. A.6.27). The abundance indices in the eastern component are approximately two to five times lower than those of the Gulf of Maine as a whole. The survey indices at age from the wGOM compared to the full GOM strata are nearly identical for both the spring (Fig. A.6.28) and (Fig. A.6.29).

Estimates of western Gulf of Maine catch were obtained by calculating the annual fraction of total Gulf of Maine commercial landings coming from statistical areas 513 and 514. Between 1982 and 2011, these two statistical areas have accounted for > 60% of the total Gulf of Maine cod landings and > 90% over the last five years (Fig. A.6.30). The annual fractions where then applied to the aggregate landings and discards (Table A.8) as well as the catch-at-age matrices (Tables A.17 and A.29). No changes were made to the recreational fishery catches since this fishery operates primarily in the western Gulf of Maine. A combined catch-at-age matrix was constructed using the revised catch inputs and the weight-at-age matrix was updated based on a numbers-weighted approach that incorporated the revised catches.

The SAW55_BASE model inputs were then modified by updating the NEFSC survey indices (aggregate, at-age and input CVs) and the catch inputs (aggregate catch, catch-at-age, weights-at-

age). All other model inputs and configurations were left the same. A comparison of the summary diagnostics of the SAW55_BASE and the SAW55_WESTERN models is provided in Table A.6.10. The trends in spawning stock biomass in the western Gulf of Maine have varied, but don't exhibit as large of long-term decline as seen over the entire Gulf of Maine region (Fig. A.6.31). While this could imply large declines in the eastern Gulf of Maine biomass, given non-linearities in the models the eastern Gulf of Maine biomass does not necessarily equal the total minus that of the wGOM. It's important to note that the 2011 estimates of spawning stock biomass and fishing mortality are nearly identical between the two models. This suggests that the current perception of the resource is not dramatically different if only the western Gulf of Maine is considered. Given that spawner-per-recruit (SPR) reference points are likely to be similar between the wGOM-only and GOM regions given the dominance of the wGOM signal in the SPR inputs, consideration of a wGOM only assessment would likely not alter the current stock status.

To construct a combined Georges Bank-Gulf of Maine assessment (SAW55_COMBINED_GOM_GBK) the following steps were taken:

- Started the model in 1982 and used age9^+ formulation.
    - Gulf of Maine assessment starts in 1982 with age 9^+ group.
    - Georges Bank assessment starts in 1978 with age 10^+ group.
- Treated Gulf of Maine and Georges Bank catches as separate fleets.
    - Used fleet-specific catch weights.
- Re-calculated Georges Bank catch weights to age9^+ formulation using numbers weighted approach.
- Re-calculated aggregate catch weights-at-age using numbers-weighted approach.
- Re-estimated stock/SSB weights-at-age using Rivard approach back to January 1.
- Assumed a mean spawning period at end of February (0.167), which is the mean spawning period used in the Georges Bank assessment.
    - It should be noted that this will have only marginal impacts on the assessment model since it is not directly used in the assessment solution, only in the calculation of spawning stock biomass.
- Used Gulf of Maine maturity ogive.
    - Similar to the spawning period assumption, this will have marginal impacts on the results because it is not directly used in the assessment solution.
- Indices inputted as stock-specific indices.
    - Both MADMF spring and DFO survey indices were included.

The combined GOM/GBK run was compared to the individual Gulf of Maine (SAW55_BASE) and Georges Bank (GBCOD_BASE_ASAP) model results as well as the sum of the individual assessments. The sum of the individual stock spawning stock biomasses and age1 recruitment are similar to the combined model results (Fig. A.6.32). The aggregate fishing mortality is an approximate average of the stock-specific fishing mortalities. Given these similarities, it is not likely that alternate stock structure assumptions will results in considerably different perceptions of resource status. Regardless of the assumptions on stock structure spawning stock biomasses are severely depleted from the highs observed in the early 1980s. Currently the Gulf of Maine assessment has a minor retrospective pattern relative to that observed for the Georges Bank

assessment. Combining the two stocks in to a single unit stock assessment does not resolve the retrospective pattern (Fig. A.6.33). Given the retrospective patterns observed in the combined assessment it's likely that a combined unit-stock approach would effectively degrade the quality of management information with respect to the Gulf of Maine resource.

It should be noted that the exploratory analyses conducted here, both with respect to the western Gulf of Maine and unit stock assessment are preliminary. A number of critical issues with respect to data inputs would need to be addressed before undertaking future such analyses in a more formal manner.

Appendix A.6. Tables

Table A.6.1. Summary of model diagnostics from a sensitivity analysis of the Gulf of Maine Atlantic cod SAW55_BASE assessment model to the upper and lower 95% confidence intervals of the survey calibration factors used throughout the history of the assessment time series.

Model		SAW55_BASE	SAW55_SURV_CONV_LOWER	SAW55_SURV_CONV_UPPER
Parameters		101	101	101
Objective function		2554	2563	2559
Components of objective function	Suvey age comps	860	866	858
	Catch age comps	395	396	398
	Index fit	794	798	799
	Catch fit	211	211	211
	Recruit devs	293	293	294
RMSE	Catch	0.29	0.30	0.28
	Index1	1.14	1.19	1.13
	Index2	0.97	1.04	1.09
	Index3	1.13	1.14	1.14
	Index total	1.08	1.12	1.12
	Recruit devs	1.42	1.38	1.45
Mean age RMSE	Fleet1	1.34	1.34	1.38
	Index1	1.50	1.61	1.63
	Index2	1.74	1.67	1.77
	Index3	1.37	1.36	1.37
Survey catchability (q)	NEFSC spring	0.89	0.87	0.95
	NEFSC fall	0.53	0.50	0.54
	MADMF spring	0.21	0.20	0.21
SSB_{1982} (mt)		23320	23086	23299
SSB_{2011} (mt)		11874	15098	9804
$F_{age5,\ 2011}$		0.59	0.52	0.73

Table A.6.2. Summary of model diagnostics from a sensitivity analysis of the Gulf of Maine Atlantic cod SAW55_3BLOCK_BASE assessment to the use of survey biomass indices relative to abundance (numbers) indices.

Model		SAW55_3BLOCK_BASE	SAW55_3BLOCK_BASE_BIOMASS	SAW55_3BLOCK_BASE_BIOMASS_ADJ
Selectivity blocks		3	3	3
Year splits		1989, 2005	1989, 2005	1989, 2005
Parameters		93	93	93
Objective function		2055	2192	1997
Maximum gradient		9.2E-05	3.7E-05	3.4E-05
Components of objective function	Suvey age comps	602	685	573
	Catch age comps	390	396	350
	Index fit	794	838	806
	Catch fit	210	213	210
	Recruit devs	59	59	59
RMSE	Catch	0.21	0.50	0.20
	Index1	1.13	1.75	1.09
	Index2	0.97	1.27	0.97
	Index3	1.14	1.87	0.91
	Index total	1.08	1.65	0.99
	Recruit devs	1.51	1.49	1.47
Mean age RMSE	Fleet1	0.96	1.13	0.94
	Index1	1.02	1.49	0.99
	Index2	1.18	1.63	1.21
	Index3	1.06	0.87	1.00
SSB_{1982} (mt)		22036	23610	22795
SSB_{2011} (mt)		9903	7607	8281
$F_{age5,2011}$		0.78	1.04	0.94

Table A.6.3. Summary of model diagnostics from a sensitivity analysis of the of Maine Atlantic cod SAW55_BASE assessment to the incorporation of multiple fleet definitions.

Model		SAW55_BASE	SAW55_4FLEET	SAW55_2FLEET	SAW55_SPLIT_LAND_DISC
Model description		Base model from SAW55	Commerical landings, discards and recreational landings/discards treated as separate fleets	Commercial and recreational fleets modelled separately	Modelled landings and discards separately
Number of parameters		101	239	147	147
Objective function		2554	3716	2970	2981
Components of objective function	Suvey age comps	860	888	859	861
	Catch age comps	395	1199	632	672
	Index fit	794	794	794	794
	Catch fit	211	546	392	361
	Recruit devs	293	289	293	293
RMSE	Fleet 1	0.29	0.21	0.23	0.27
	Fleet 2		0.05	0.20	0.12
	Fleet 3		0.05		
	Fleet 4		0.01		
	Total catch	0.29	0.11	0.21	0.21
	Index1	1.14	1.13	1.14	1.13
	Index2	0.97	0.96	0.97	0.96
	Index3	1.13	1.13	1.13	1.13
	Recruit devs	1.14	1.30	1.42	1.08
Mean age RMSE	Fleet1	1.34	1.31	1.24	1.50
	Fleet2		1.37	0.89	1.70
	Fleet3		1.48		
	Fleet4		1.65		
	Index1	1.50	1.49	1.43	1.45
	Index2	1.74	1.83	1.74	1.76
	Index3	1.37	1.36	1.38	1.38
SSB_{1982} (mt)		23,320	24,396	23,359	24,331
SSB_{2011} (mt)		11,874	10,657	11,635	10,755
$F_{age5,2011}$		0.59	0.70	0.59	0.61
Survey catchability (q)	Index 1	0.89	0.90	0.91	0.91
	Index 2	0.53	0.53	0.54	0.54
	Index 3	0.21	0.21	0.21	0.21

Table A.6.4. Summary of model diagnostics from a sensitivity analysis of the Gulf of Maine Atlantic cod SAW55_BASE assessment to the incorporation of commercial (COM_LPUE), recreational (REC_LPUE) and combined (_LPUE) landings-per-unit-effort indices.

Model		SAW55_BASE	SAW55_COM_LPUE	SAW55_COM_LPUE_SPLIT	SAW55_COM_LPUE_SPLIT_V2	SAW55_REC_LPUE	SAW55_LPUE	SAW55_LPUE_V2
Parameters		101	102	103		102	102	
Objective function		2554	2572	2568		2565	2582	
Components of objective function	Suvey age comps	860	860	860		860	860	
	Catch age comps	395	395	395	Did not converge	395	395	Did not converge
	Index fit	794	813	808		804	823	
	Catch fit	211	211	211		211	211	
	Recruit devs	293	293	293		293	293	
RMSE	Catch	0.29	0.29	0.29		0.28	0.29	
	Index1	1.14	1.15	1.14		1.14	1.15	
	Index2	0.97	0.99	0.97		0.97	0.98	
	Index3	1.13	1.13	1.13		1.13	1.13	
	Index5		0.55	0.24			0.56	
	Index6			0.27				
	Index7					0.37	0.38	
	Index total	1.08	0.99	0.95		1.00	0.93	
	Recruit devs	1.42	1.41	1.42		1.43	1.41	
Mean age RMSE	Fleet1	1.34	1.32	1.34		1.34	1.33	
	Index1	1.50	1.50	1.50		1.50	1.50	
	Index2	1.74	1.74	1.73		1.73	1.74	
	Index3	1.37	1.37	1.37		1.37	1.37	
SSB_{1982} (mt)		23320	23310	23383		23315	23301	
SSB_{2011} (mt)		11874	13853	11985		11635	13018	
$F_{age5,2011}$		0.59	0.52	0.59		0.60	0.53	

Table A.6.5. Summary of model diagnostics from a sensitivity analysis of the Gulf of Maine Atlantic cod SAW55_BASE assessment to inclusion of only a single survey index at one time.

Model		SAW55_BASE	SAW55_NEFSC_SPRING	SAW55_NEFSC_FALL	SAW55_MADMF_SPRING
Parameters		101	91	91	89
Objective function		2554	1508	1459	1348
Components of objective function	Suvey age comps	860	345	312	197
	Catch age comps	395	390	391	386
	Index fit	794	271	256	266
	Catch fit	211	210	210	210
	Recruit devs	293	292	291	290
RMSE	Catch	0.29	0.21	0.17	0.14
	Index1	1.14	1.14		
	Index2	0.97		0.97	
	Index3	1.13			1.08
	Index total	1.08	1.14	0.97	1.08
	Recruit devs	1.42	1.39	1.34	1.20
Mean age RMSE	Fleet1	1.34	1.27	1.26	1.04
	Index1	1.50	1.51		
	Index2	1.74		1.74	
	Index3	1.37			1.34
SSB_{1982} (mt)		23320	22217	25513	21628
SSB_{2011} (mt)		11874	11254	12345	34137
$F_{age5,2011}$		0.59	0.64	0.56	0.28

Table A.6.6. Summary of model diagnostics from a sensitivity analysis of the Gulf of Maine Atlantic cod SAW55_BASE assessment to the implementation of domed selectivity in the NEFSC survey indices and extension of the age structure out to an 11^+ group.

Model		SAW55_BASE	SAW55_DOME	SAW55_11PLUS	SAW55_DOME11
Parameters		101	107	107	117
Objective function		2554	2550	2582	2578
Components of objective function	Suvey age comps	860	859	875	874
	Catch age comps	395	395	408	409
	Index fit	794	793	794	792
	Catch fit	211	210	211	210
	Recruit devs	293	293	293	293
RMSE	Fleet 1	0.29	0.24	0.29	0.24
	Index 1	1.14	1.11	1.14	1.11
	Index 2	0.97	0.96	0.97	0.95
	Index 3	1.13	1.11	1.13	1.11
	Recruit devs	1.42	1.38	1.42	1.38
Mean age RMSE	Fleet1	1.34	1.34	1.33	1.34
	Index1	1.50	1.47	1.49	1.48
	Index2	1.74	1.75	1.73	1.74
	Index3	1.37	1.37	1.37	1.36
Survey catchability (q)	Index 1	0.89	0.52	0.89	0.71
	Index 2	0.53	0.34	0.53	0.44
	Index 3	0.21	0.25	0.21	0.21
SSB_{1982} (mt)		23320	37315	22640	39066
SSB_{2011} (mt)		11874	17279	11807	18670
$F_{age5,\ 2011}$		0.59	0.50	0.59	0.49

Table A.6.7. Summary of selectivity parameter estimates and corresponding coefficients of variation (*italics*) from a sensitivity analysis of the Gulf of Maine Atlantic cod SAW55_BASE assessment to the implementation of domed selectivity in the NEFSC survey indices and extension of the age structure out to an 11^+ group.

Model		SAW55_BASE		SAW55_DOME		SAW55_11PLUS		SAW55_DOME11	
Block 1	Age1	0.04	*0.18*	0.04	*0.18*	0.04	*0.18*	0.04	*0.18*
	Age2	0.25	*0.10*	0.26	*0.10*	0.25	*0.10*	0.26	*0.11*
	Age3	0.57	*0.09*	0.58	*0.10*	0.57	*0.09*	0.59	*0.10*
	Age4	1.00	*0.00*	1.00	*0.00*	1.00	*0.00*	1.00	*0.00*
	Age5	1.00		1.00		1.00		1.00	
	Age6	0.78	*0.25*	0.74	*0.26*	0.75	*0.25*	0.69	*0.26*
	Age7	1.00	*0.07*	0.88	*0.41*	0.84	*0.36*	0.64	*0.40*
	Age8	1.00	*0.00*	1.00	*0.00*	0.69	*0.53*	0.50	*0.59*
	Age9/+	0.33	*0.45*	0.10	*0.67*	0.55	*0.76*	0.42	*0.86*
	Age10					1.00	*0.01*	0.85	*1.51*
	Age11+					0.27	*0.81*	0.04	*1.35*
Block 2	Age1	0.02	*0.18*	0.02	*0.19*	0.02	*0.18*	0.02	*0.19*
	Age2	0.07	*0.11*	0.08	*0.12*	0.07	*0.11*	0.08	*0.13*
	Age3	0.32	*0.08*	0.36	*0.10*	0.32	*0.08*	0.37	*0.10*
	Age4	0.79	*0.07*	0.87	*0.08*	0.79	*0.07*	0.88	*0.09*
	Age5	1.00	*0.00*	1.00	*0.00*	1.00	*0.00*	1.00	*0.00*
	Age6	1.00		1.00		1.00		1.00	
	Age7	0.92	*0.17*	0.64	*0.22*	0.92	*0.17*	0.62	*0.23*
	Age8	0.88	*0.27*	0.44	*0.37*	0.87	*0.27*	0.42	*0.38*
	Age9/+	0.77	*0.50*	0.13	*0.60*	0.70	*0.44*	0.25	*0.58*
	Age10					0.86	*0.63*	0.16	*0.79*
	Age11+					1.00	*0.01*	0.04	*1.03*
Index 1	Age1	0.04	*0.19*	0.05	*0.21*	0.05	*0.18*	0.05	*0.22*
	Age2	0.14	*0.16*	0.17	*0.19*	0.14	*0.15*	0.17	*0.19*
	Age3	0.30	*0.15*	0.35	*0.18*	0.30	*0.15*	0.37	*0.19*
	Age4	0.51	*0.15*	0.61	*0.17*	0.53	*0.14*	0.63	*0.18*
	Age5	0.75	*0.15*	0.83	*0.16*	0.76	*0.15*	0.85	*0.16*
	Age6	1.00		1.00		1.00		1.00	
	Age7	1.00		1.00	*0.00*	1.00		1.00	*0.00*
	Age8	1.00		0.56	*0.40*	1.00		0.51	*0.40*
	Age9/+	1.00		0.16	*0.55*	1.00		0.38	*0.60*
	Age10					1.00		0.37	*0.75*
	Age11+					1.00		0.05	*1.02*
Index 2	Age1	0.17	*0.15*	0.20	*0.17*	0.17	*0.14*	0.20	*0.17*
	Age2	0.40	*0.14*	0.46	*0.16*	0.40	*0.13*	0.47	*0.16*
	Age3	0.59	*0.14*	0.66	*0.15*	0.58	*0.13*	0.68	*0.16*
	Age4	0.89	*0.14*	0.97	*0.15*	0.89	*0.13*	0.99	*0.15*
	Age5	1.00	*0.00*	1.00	*0.00*	1.00	*0.00*	1.00	*0.00*
	Age6	1.00		1.00		1.00		1.00	
	Age7	1.00		0.62	*0.38*	1.00		0.58	*0.38*
	Age8	1.00		0.42	*0.61*	1.00		0.38	*0.61*
	Age9/+	1.00		0.20	*0.61*	1.00		0.54	*0.67*
	Age10					1.00		0.16	*1.37*
	Age11+					1.00		0.10	*0.97*
Index 3	A50 ascend	0.00	*3000.30*	0.00	*3000.05*	0.00	*3316.67*	0.00	*3316.88*
	Slope ascend	10.00		10.00		1.00		10.00	
	A50 descend	0.00	*2994.57*	0.00	*3000.00*	0.00	*3316.65*	0.00	*3316.48*
	Slope descend	3.50	*0.18*	3.16	*0.15*	3.64	*0.18*	3.15	*0.15*

Table A.6.8. Summary of model diagnostics from a sensitivity analysis of the Gulf of Maine Atlantic cod SAW55_BASE assessment to the assessment starting year.

Model		SAW55_BASE	SAW55_HIST_1970	SAW55_HIST_1964
Starting year		1982	1970	1964
Parameters		101	133	145
Objective function		2554	3267	3439
Maximum gradient		0.0016	0.0005	0.0000
Components of objective function	Suvey age comps	860	1130	1131
	Catch age comps	395	396	396
	Index fit	794	1019	1089
	Catch fit	211	307	352
	Recruit devs	293	415	472
RMSE	Catch	0.29	0.28	0.27
	Index1	1.14	1.15	1.13
	Index2	0.97	1.14	1.08
	Index3	1.13	1.13	1.13
	Index total	1.08	1.14	1.11
	Recruit devs	1.42	1.43	1.43
Mean age RMSE	Fleet1	1.34	1.34	1.34
	Index1	1.50	1.35	1.35
	Index2	1.74	1.66	1.67
	Index3	1.37	1.37	1.37
Survey catchability (q)	NEFSC spring	0.89	0.74	0.76
	NEFSC fall	0.53	0.59	0.61
	MADMF spring	0.21	0.21	0.21
SSB_{1964} (mt)				14330
SSB_{1970} (mt)			33836	34381
SSB_{1982} (mt)		23320	23349	23228
SSB_{2011} (mt)		11874	12198	11776
$F_{age5,2011}$		0.59	0.58	0.60

Table A.6.9. Summary of model diagnostics from a sensitivity analysis of the Gulf of Maine Atlantic cod SAW55_BASE assessment to the assumed precision of the aggregate catch input. Precision is expressed in terms of the coefficient of variation (CV).

Model		SAW55_CATCH_CV01	SAW55_BASE	SAW55_CATCH_CV10	SAW55_CATCH_CV20	SAW55_CATCH_CV30
Catch CV		0.01	0.05	0.10	0.20	0.30
Parameters		101	101	101	101	101
Objective function		2507	2554	2572	2584	2588
Components of objective function	Suvey age comps	861	860	859	856	852
	Catch age comps	396	395	394	392	389
	Index fit	795	794	792	788	787
	Catch fit	161	211	234	259	273
	Recruit devs	294	293	292	289	287
RMSE	Catch	0.06	0.29	0.51	0.75	0.83
	Index1	1.15	1.14	1.11	1.03	0.99
	Index2	0.98	0.97	0.95	0.95	0.97
	Index3	1.14	1.13	1.11	1.06	1.04
	Index total	1.09	1.08	1.06	1.02	1.00
	Recruit devs	1.43	1.42	1.40	1.35	1.32
Mean age RMSE	Fleet1	1.34	1.34	1.33	1.31	1.29
	Index1	1.50	1.50	1.49	1.46	1.43
	Index2	1.74	1.74	1.72	1.69	1.67
	Index3	1.37	1.37	1.37	1.36	1.36
SSB_{1982} (mt)		23460	23320	22924	21702	20249
SSB_{2011} (mt)		11990	11874	11597	11026	10535
$F_{age5,2011}$		0.59	0.59	0.60	0.60	0.59

Table A.6.10. Summary of model diagnostics from a sensitivity analysis of the Gulf of Maine Atlantic cod SAW55_BASE assessment to considering only data from the western Gulf of Maine (NEFSC offshore survey strata 26, 27, 40).

Model		**SAW55_BASE**	**SAW55_WESTERN**
Model description		Base model from SAW55	Western Gulf of Maine only (513-514, strata 26-27, 40)
Number of parameters		101	101
Objective function		2554	2550
Components of objective function	**Suvey age**	860	885
	Catch age comps	395	398
	Index fit	794	778
	Catch fit	211	204
	Recruit devs	293	285
RMSE	**Fleet 1**	0.29	0.25
	Index 1	1.14	1.21
	Index 2	0.97	1.14
	Index 3	1.13	1.07
	Recruit devs	1.42	1.33
SSB_{1982} (mt)		23,320	16,526
SSB_{2011} (mt)		11,874	12,690
$F_{age5, 2011}$		0.59	0.53
Survey catchability (q)	**Index 1**	0.89	0.51
	Index 2	0.53	0.37
	Index 3	0.21	0.25

Appendix A.6. Figures

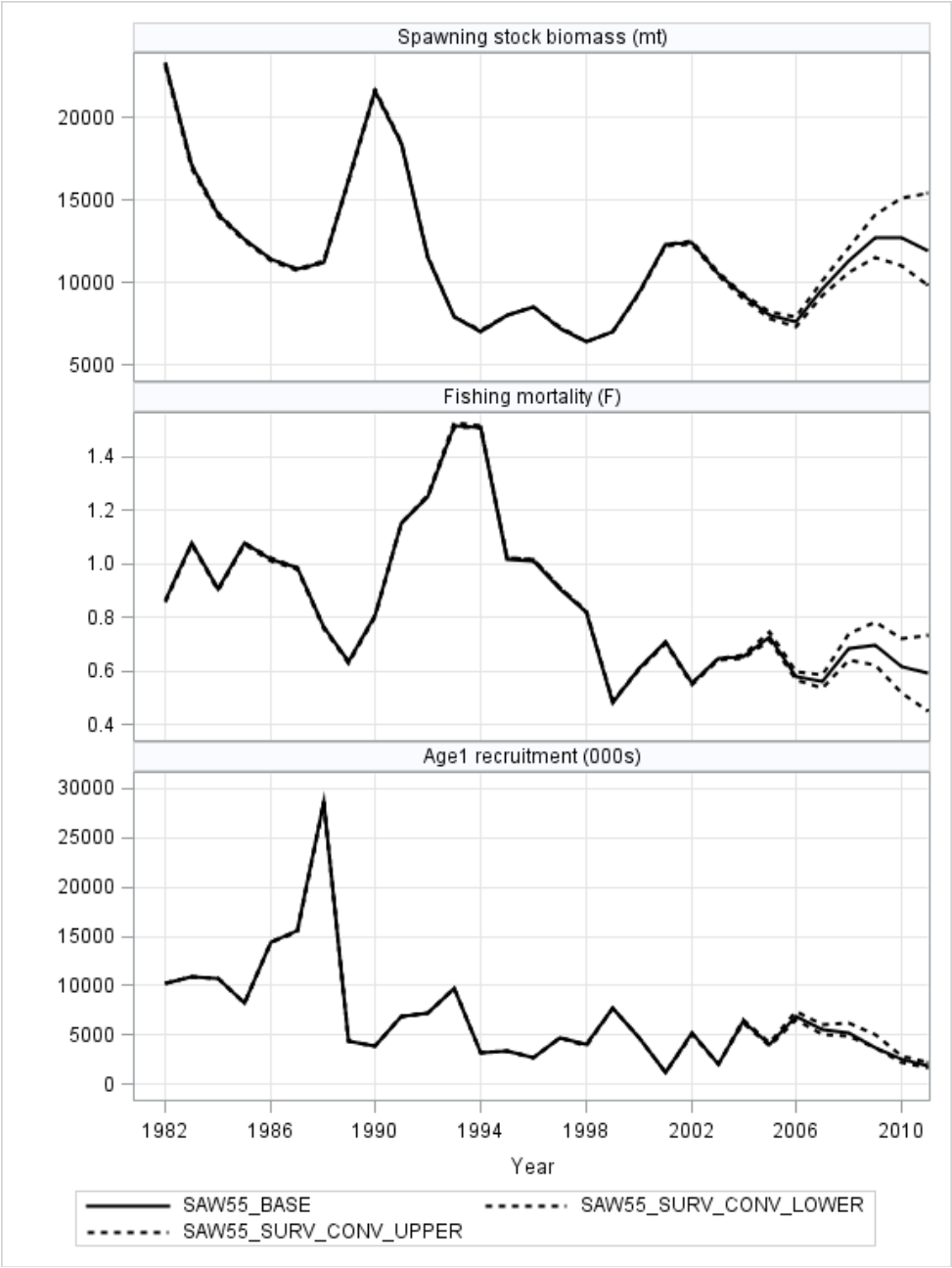


Figure A.6.1. Sensitivity of the Gulf of Maine Atlantic cod SAW55_BASE assessment model to the upper and lower 95% confidence intervals of the survey calibration factors used throughout the history of the assessment time series.

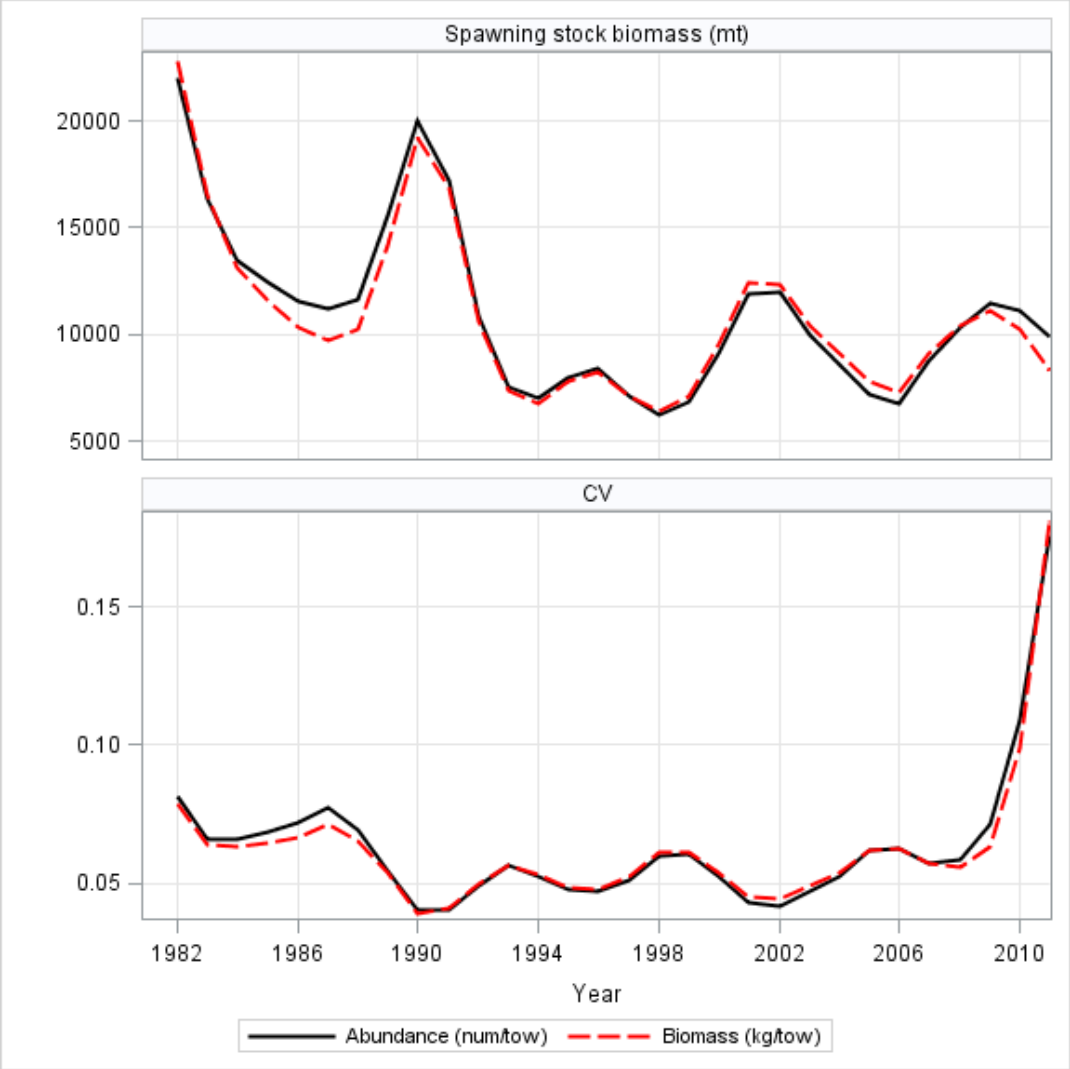


Figure A.6.2. Sensitivity of the Gulf of Maine Atlantic cod SAW55_3BLOCK_BASE assessment to the use of survey biomass indices relative to abundance (numbers) indices.

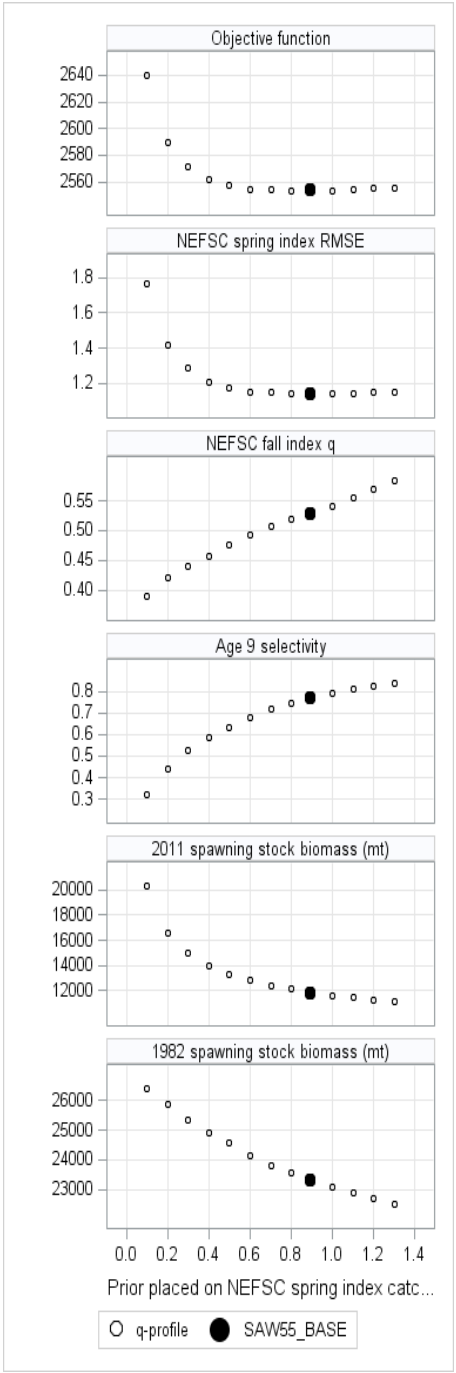


Figure A.6.3. Sensitivity analysis showing the response of the Gulf of Maine Atlantic cod ASAP SAW55_BASE model to different assumptions of survey catchability (*q*) of the Northeast Fisheries Science Center spring survey.

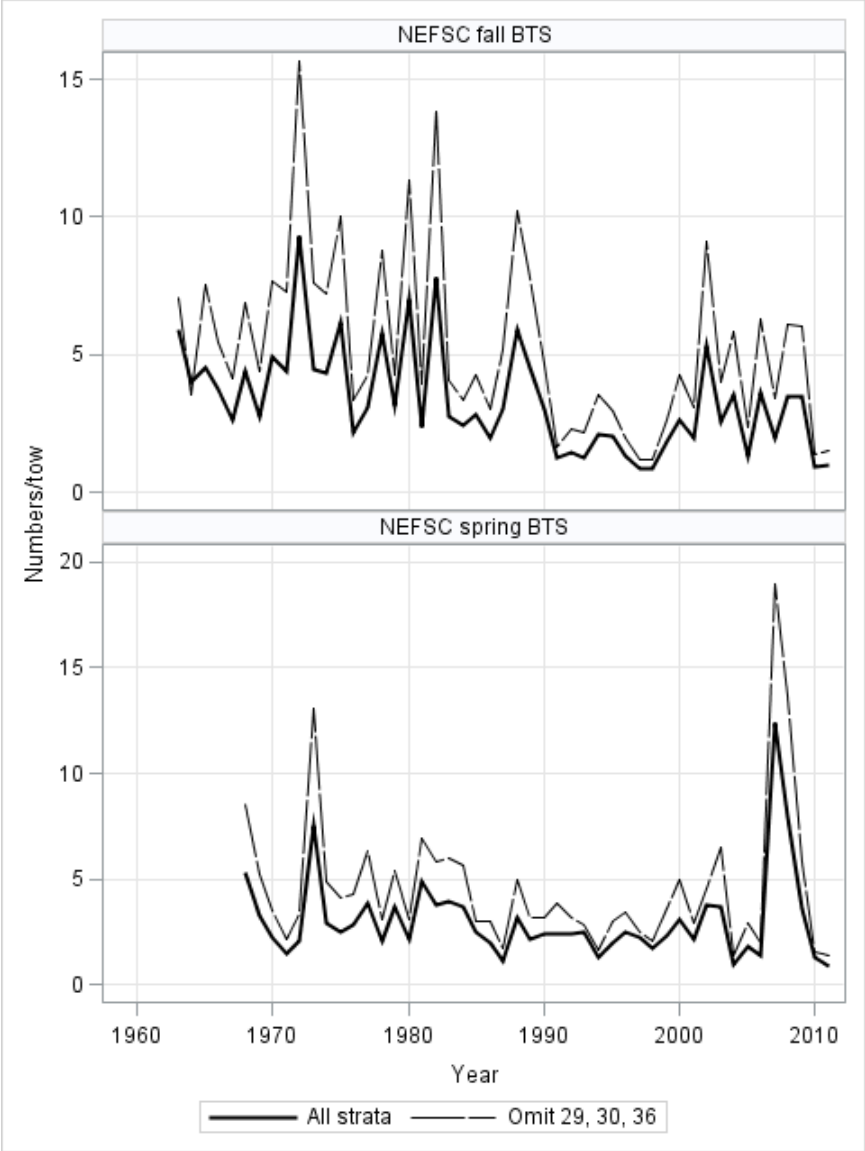


Figure A.6.4. Gulf of Maine Atlantic cod NEFSC spring (bottom) and fall (top) survey indices of abundance (numbers per tow) when estimated from all NEFSC offshore strata (26, 27, 28, 29, 30, 36, 37, 38, 39, 40; black line) and when strata 29, 30, and 36 are excluded (red line).

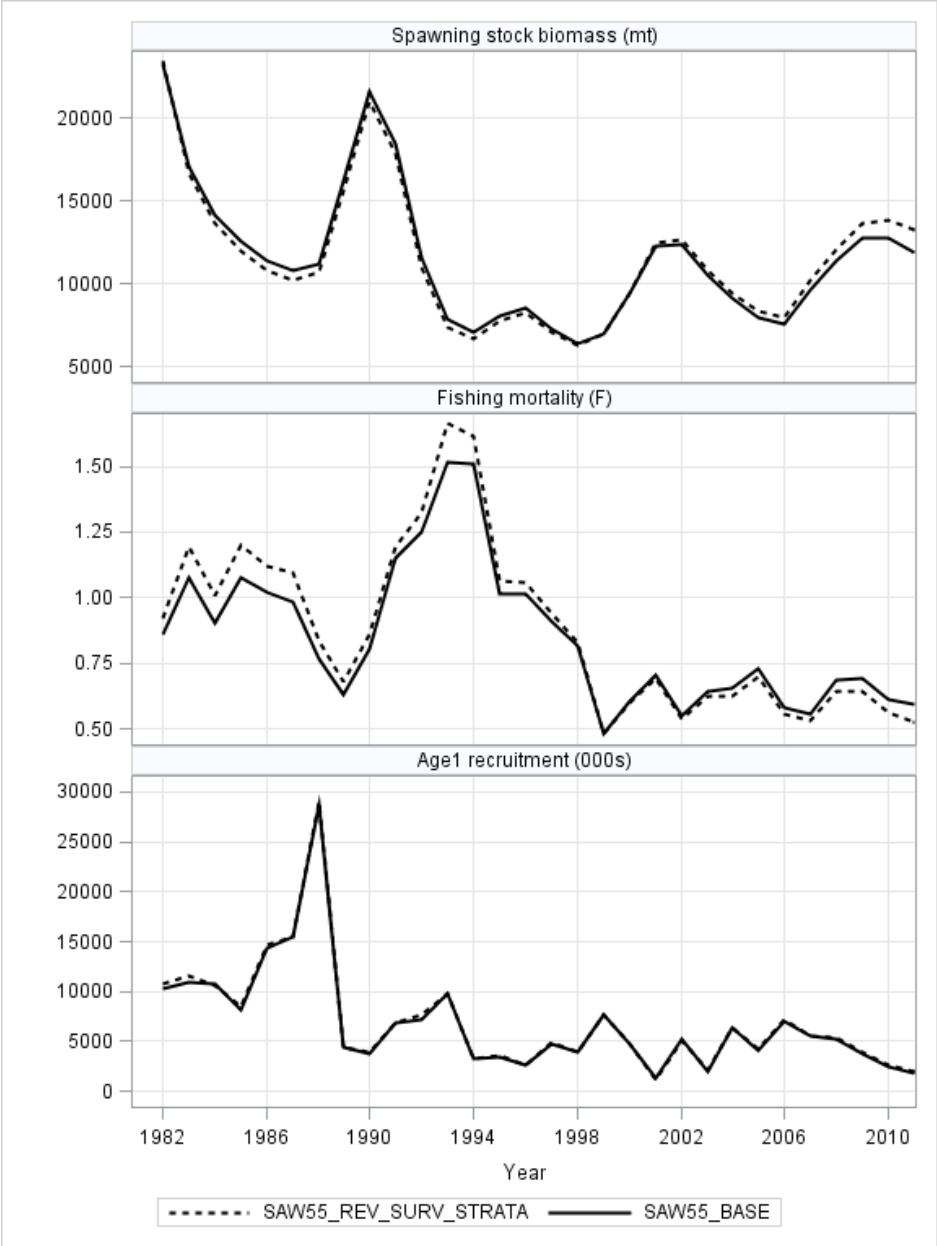


Figure A.6.5. Comparison of Gulf of Maine cod spawning stock biomass (top), age 5 fishing mortality (F) (middle) and age-1 recruitment (thousands of fish; bottom) between the SAW55_BASE model (all survey strata) and the SAW55_REV_SURV_STRATA (excludes offshore survey strata 29, 30 and 36).

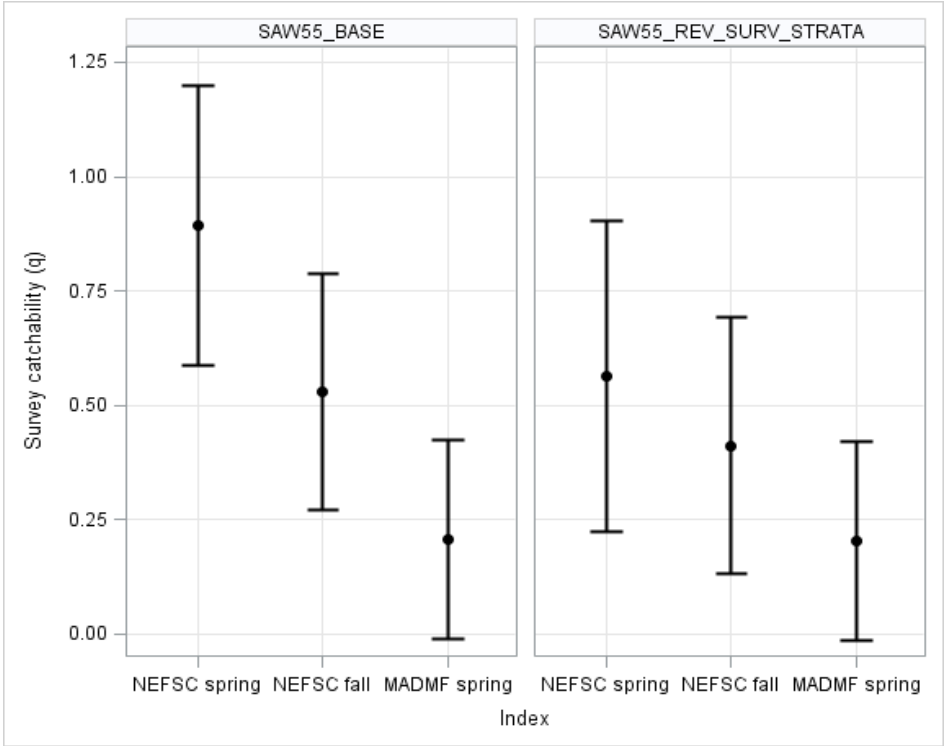
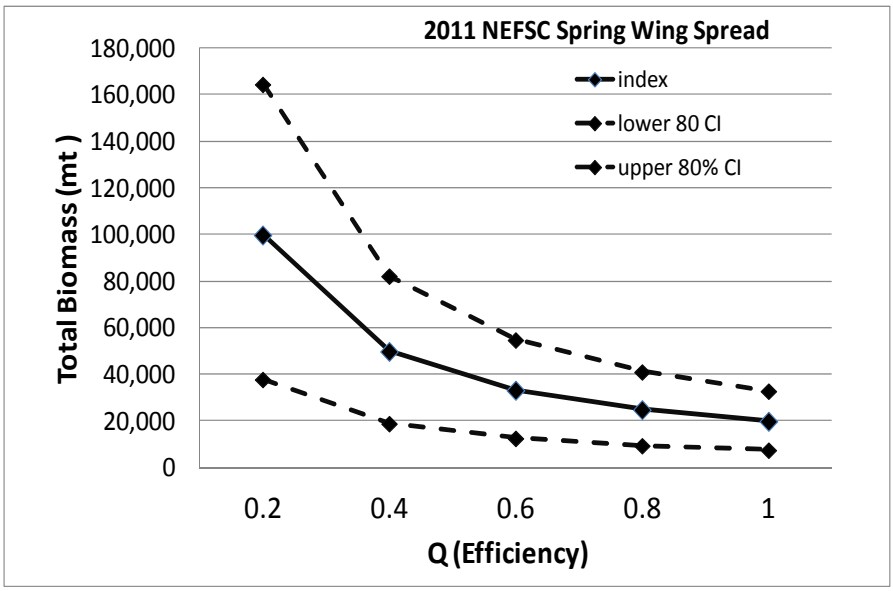


Figure A.6.6. ASAP model estimates of NEFSC survey catchability (*q*) for Gulf of Maine Atlantic cod when estimated by the SAW55_BASE model which includes swept area estimates from all survey strata and when estimated by the SAW55_REV_SURV_STRATA model which excludes offshore survey strata 29, 30, and 36.



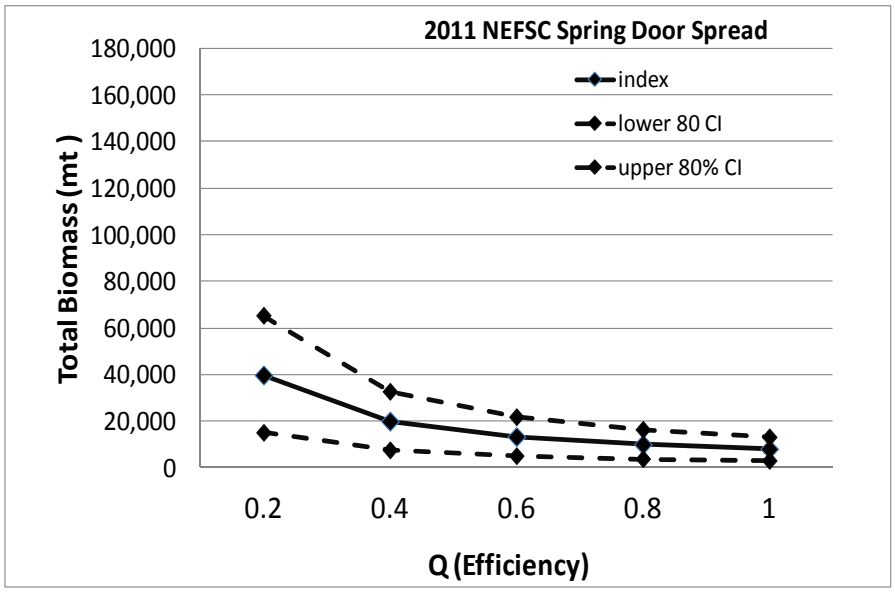


Figure A.6.7. Area swept estimates of total Gulf of Maine Atlantic cod biomass under different assumptions of NEFSC spring Bigelow survey catchability (*q*) and effective trawl area (wing spread vs. door spread). The 80% bootstrap confidence interval (CI) is shown by the dashed lines.

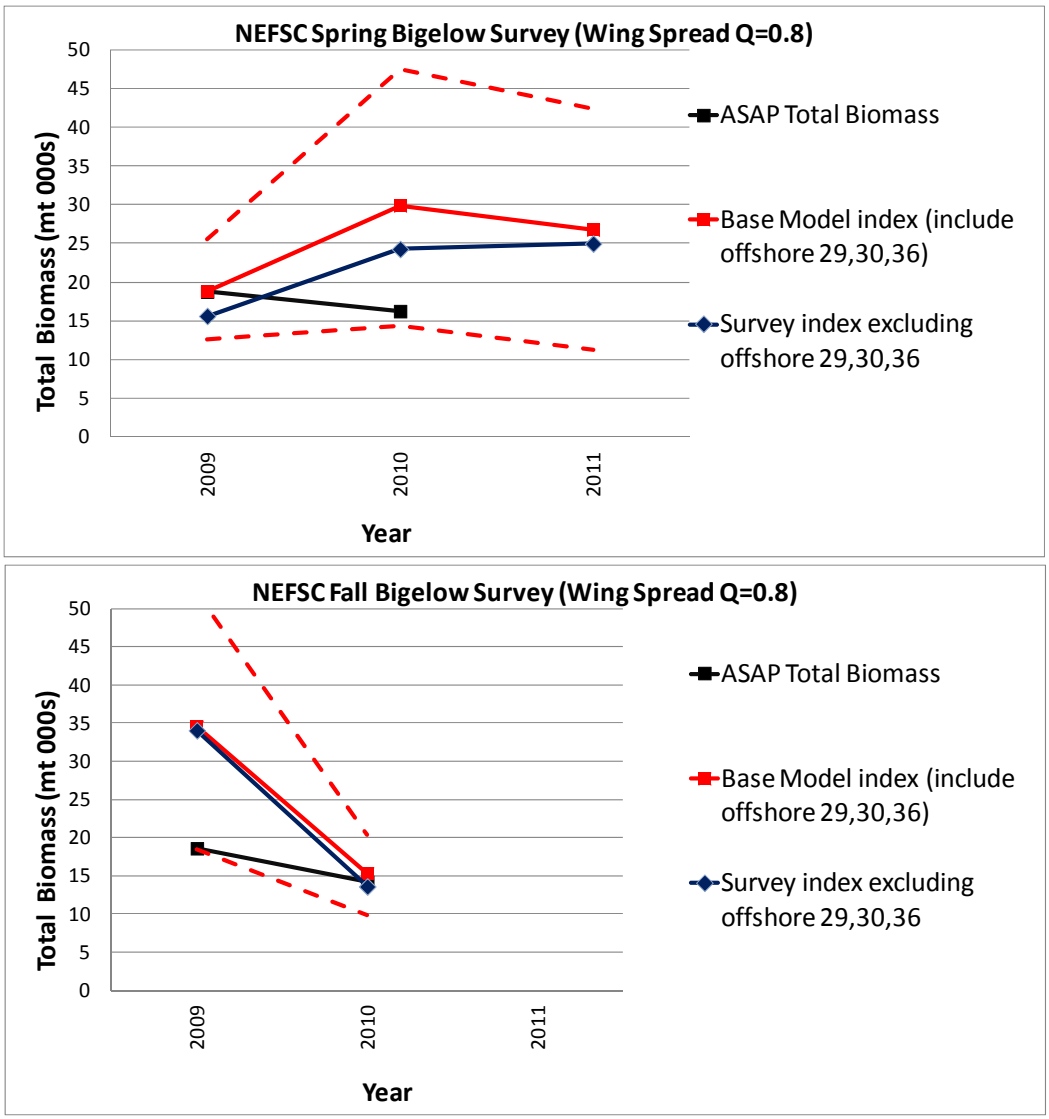


Figure A.6.8. Area swept estimates of total Gulf of Maine Atlantic cod biomass from 2009 to 2011 based on the NEFSC spring (top) and fall (bottom) Bigelow survey when the effective area is set equal to the wing spread and the survey is assumed to be 80% efficient (q=0.8). Biomass has been estimated using the full strata set (red line, with 80% bootstrap confidence intervals) and using a strata set that excludes strata 29,30 and 36 (blue line). In these analyses, the full strata set also includes inshore survey strata 57-69. Biomass estimates are compared to the annual total biomass estimated from the ASAP base model (black line) after accounting for total mortality between January 1 and the survey seasons. **NEFSC fall 2011 survey information were not available at the time of this report.*

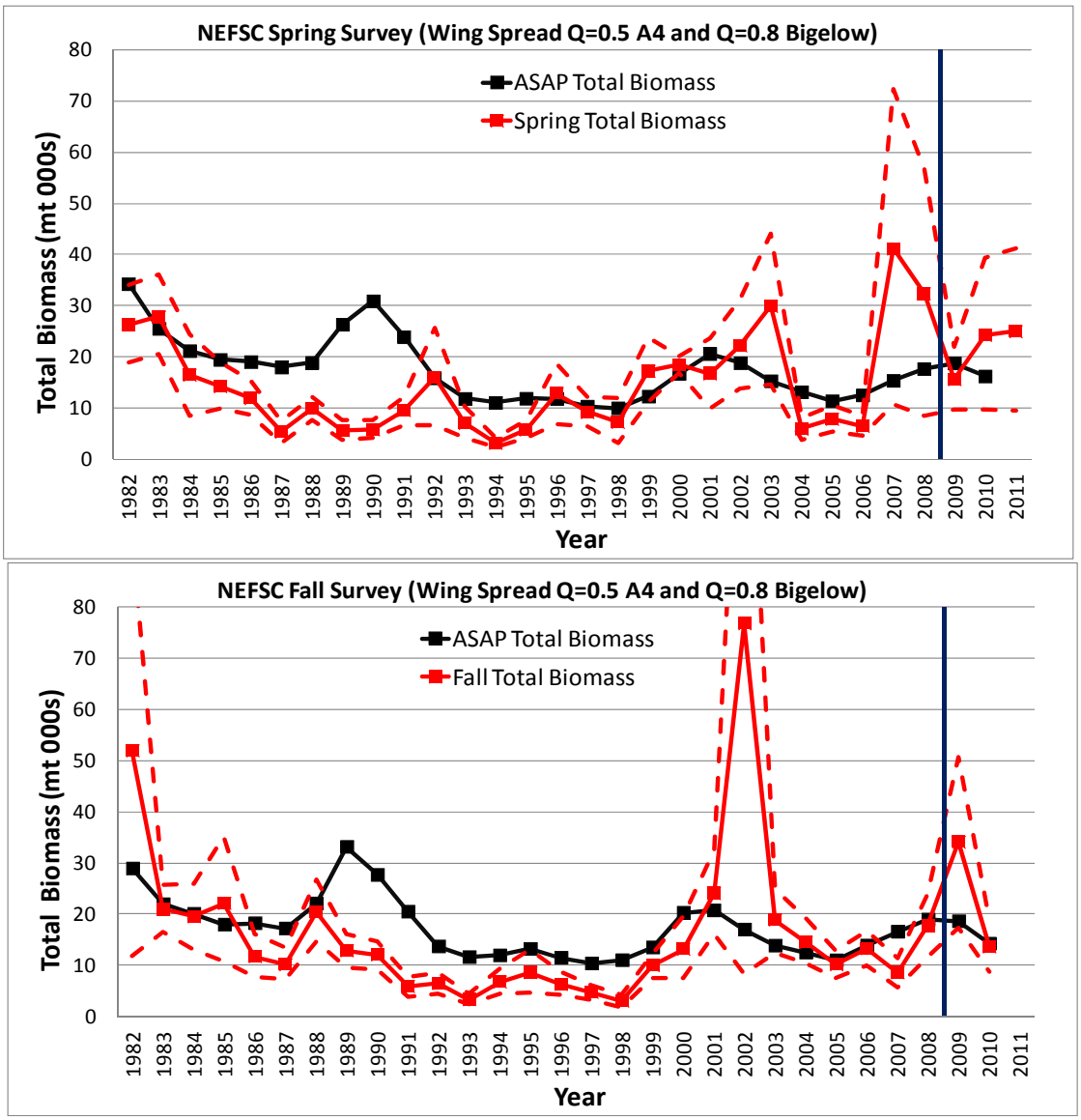


Figure A.6.9. Area swept estimates of total Gulf of Maine Atlantic cod biomass from 1982 to 2011 based on the NEFSC spring (top) and fall (bottom) survey when a the effective trawl area is set equal to the wing spread and strata set 29, 30 and 36 are excluded from the indices calculation. In these analyses, the full strata set also includes inshore survey strata 57-69. Survey efficiencies of 50% (q=0.5) and 80% (q=0.8) were assumed for the Albatross IV (1982-2008) and Bigelow (2009-2011) survey time series respectively (the vertical blue line delineates the split in survey time series). The 80% bootstrap confidence intervals of area swept estimates of biomass area shown by the dashed red lines. Biomass estimates are compared to the annual total biomass estimated from the ASAP base model (black line) after accounting for total mortality between January 1 and the survey seasons. **NEFSC fall 2011 survey information were not available at the time of this report.*

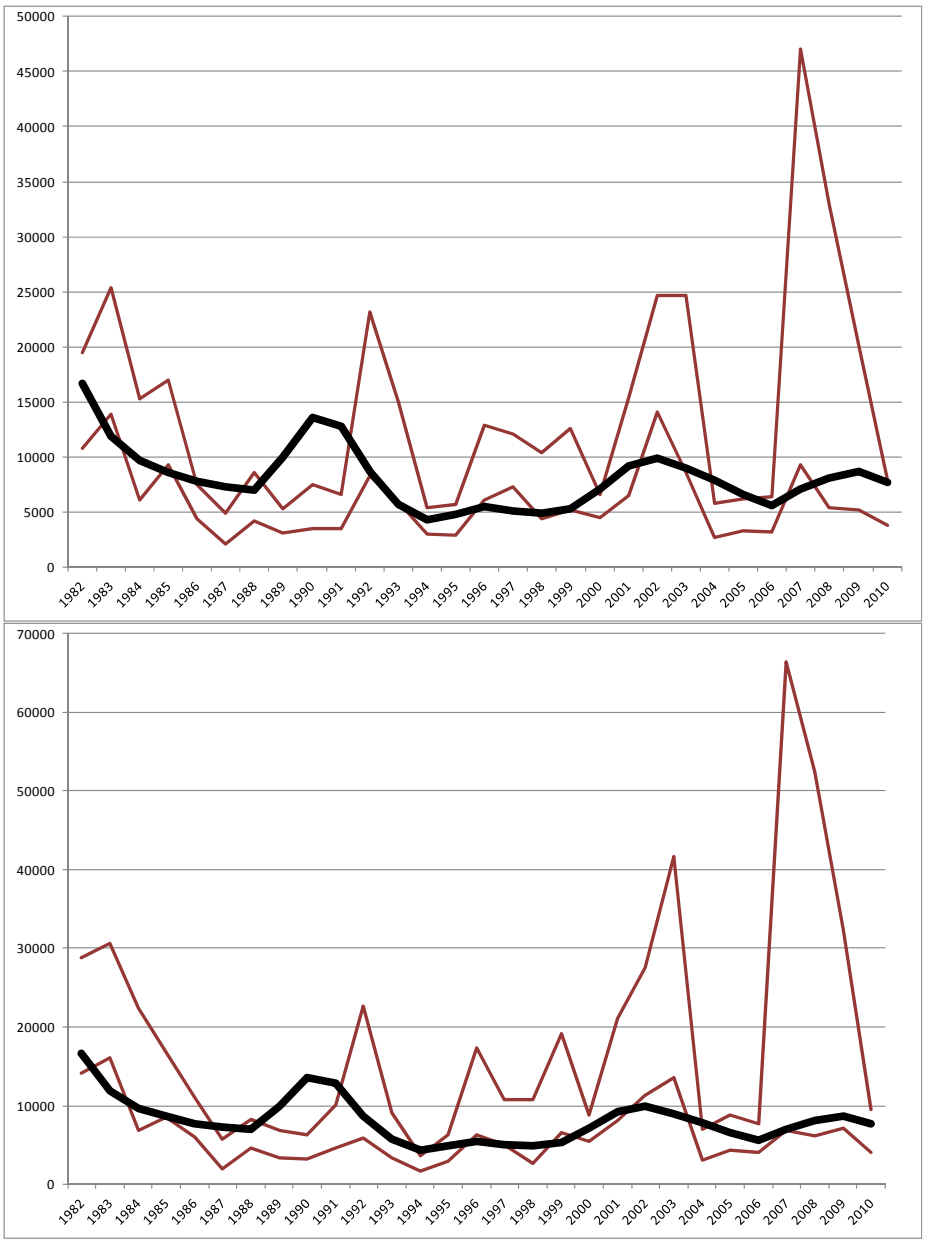


Figure A.6.10. Comparison of the SAW 53 ASAP estimated total 'survey-able' biomass (metric tons; black line) and the 80% confidence intervals (red lines) of area swept estimates of total Gulf of Maine cod biomass from 1982 to 2011 based on the NEFSC spring survey. Area swept biomass indices have been calculated using all strata (strata 26- 30 and 36- 40; top) and excluding strata 29, 30 and 36 (bottom). Survey efficiency was set at ASAP model estimates of q=0.92 when using all strata and q=0.53 when excluding strata 29, 30 and 36. ASAP 'survey-able' biomass was derived from total biomass by accounting for both total mortality since January 1 and survey selectivity at age.

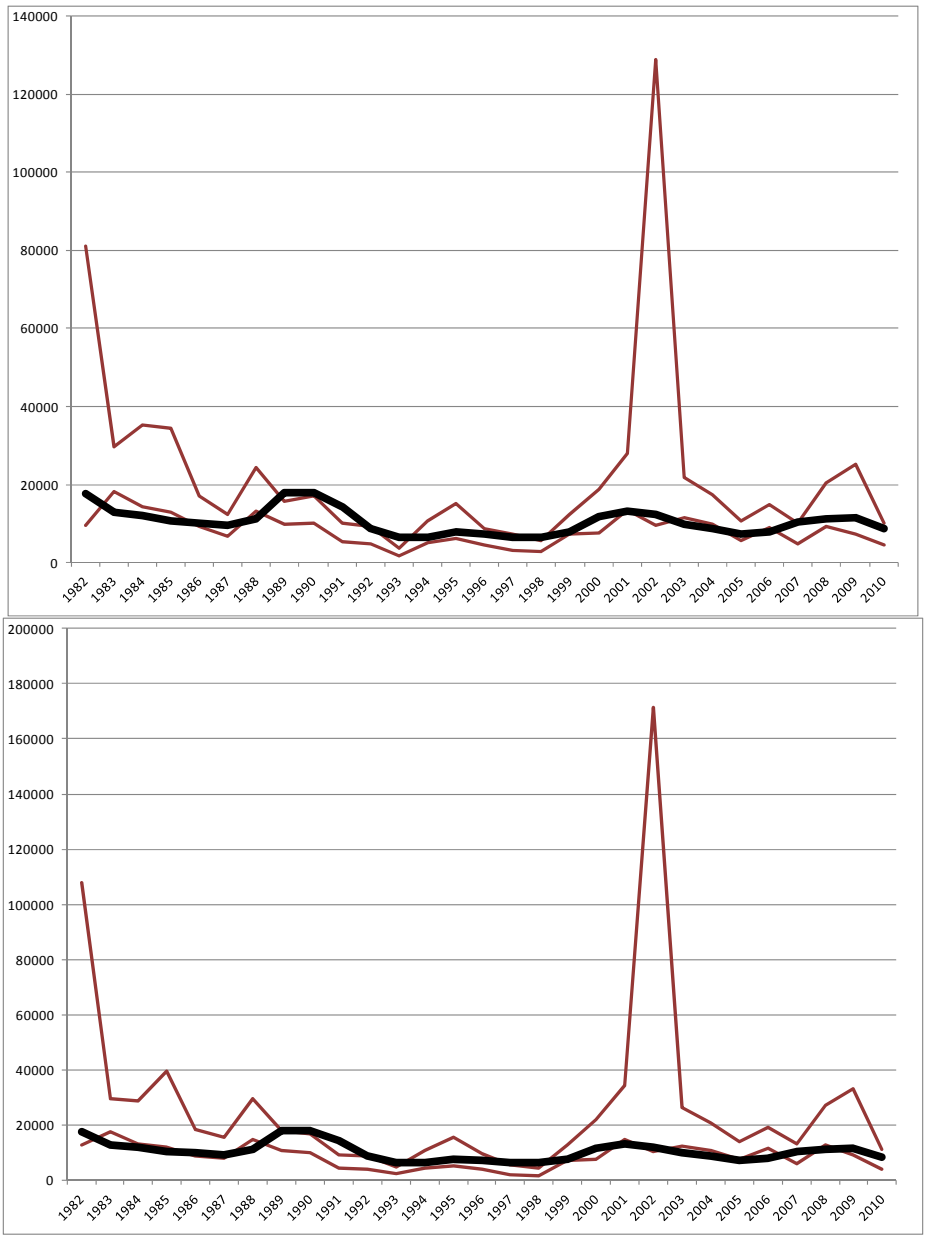


Figure A.6.11. Comparison of the SAW 53 ASAP estimated total 'survey-able' biomass (metric tons; black line) and the 80% confidence intervals (red lines) of area swept estimates of total Gulf of Maine cod biomass from 1982 to 2011 based on the NEFSC fall survey. Area swept biomass indices have been calculated using all strata (strata 26- 30 and 36- 40; top) and excluding strata 29, 30 and 36 (bottom). Survey efficiency was set at ASAP model estimates of q=0.57 when using all strata and q=0.42 when excluding strata 29, 30 and 36. ASAP 'survey-able' biomass was derived from total biomass by accounting for both total mortality since January 1 and survey selectivity at age.

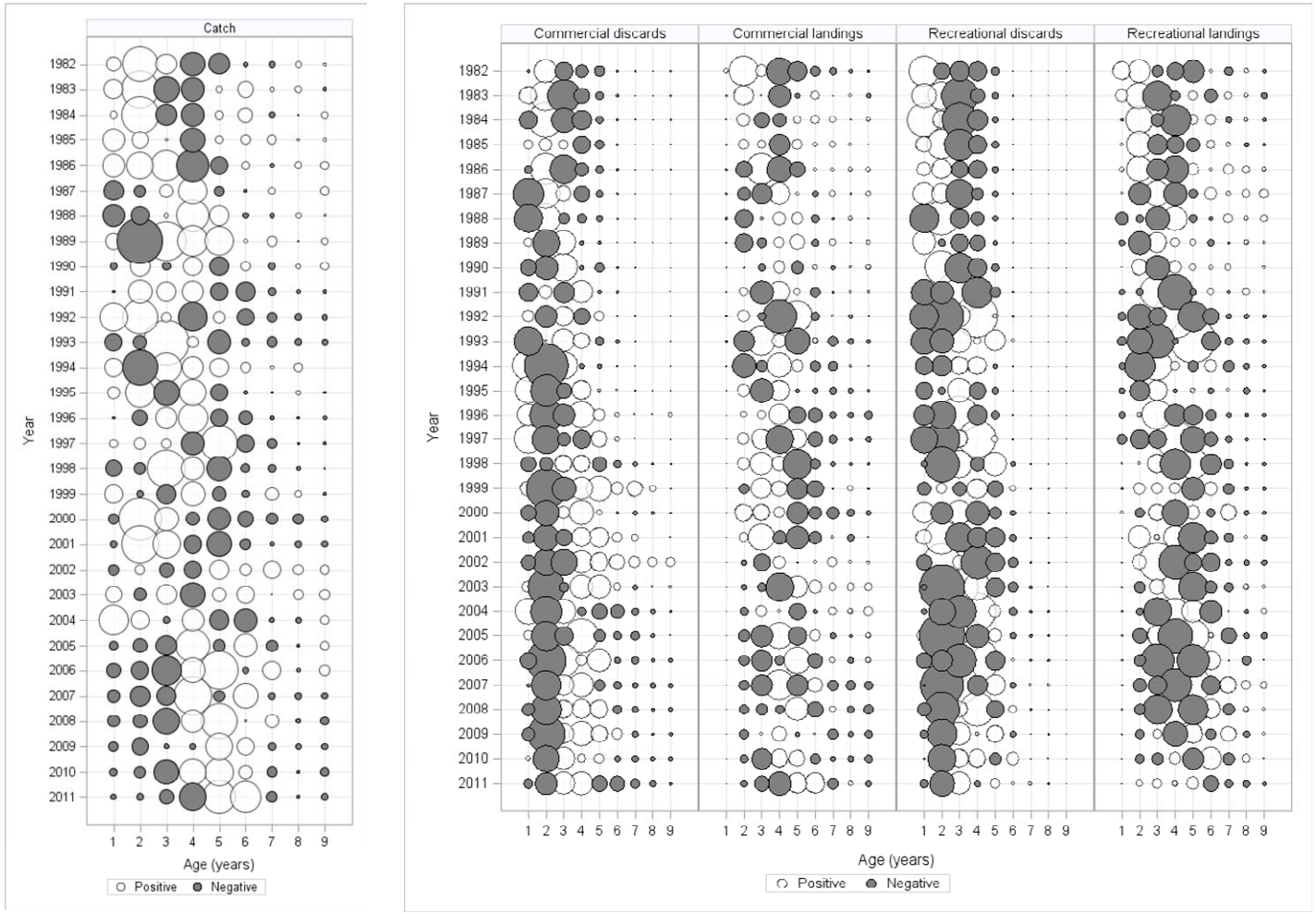


Figure A.6.12. Residual plots of the Gulf of Maine Atlantic cod catch-at-age fits compared between the SAW55_BASE model (left) and the SAW55_4FLEET (right).

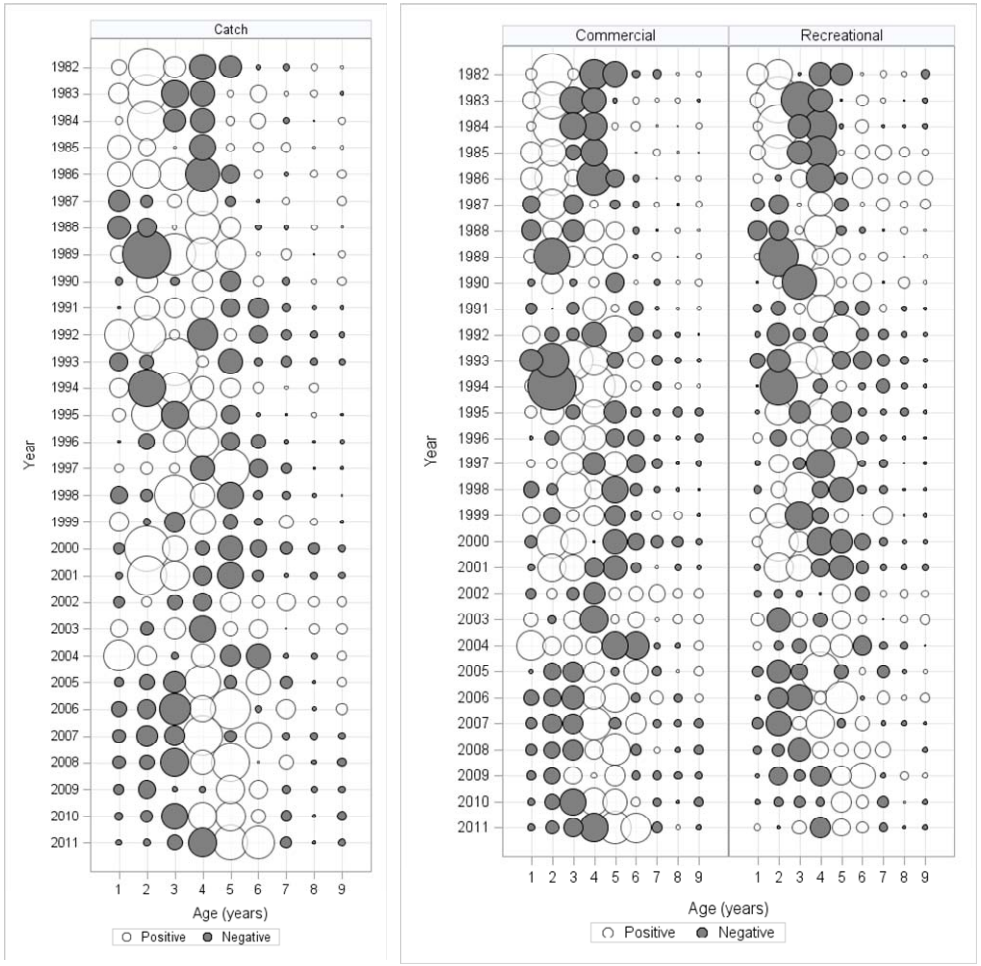


Figure A.6.13. Residual plots of the Gulf of Maine Atlantic cod catch-at-age fits compared between the SAW55_BASE model (left) and the SAW55_2FLEET (right).

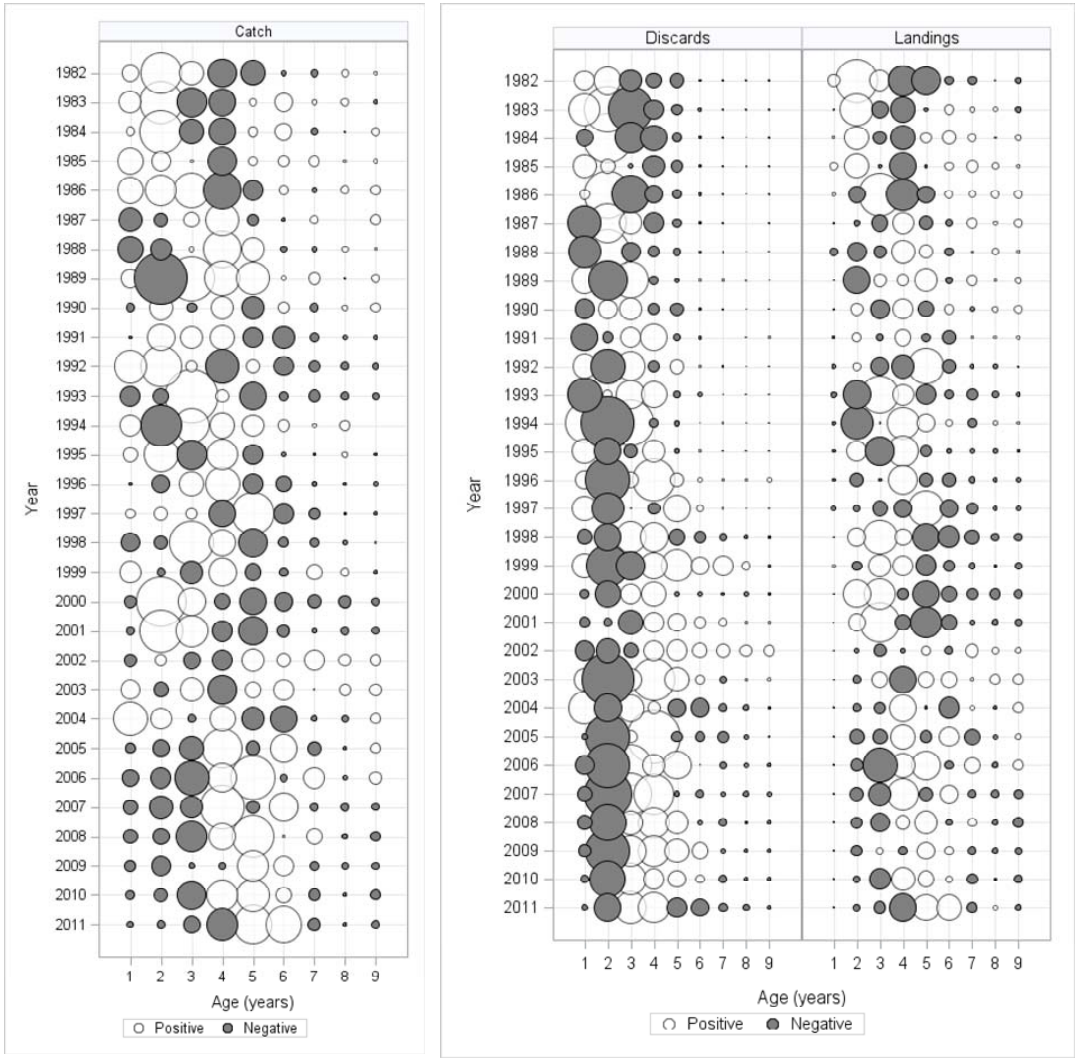


Figure A.6.14. Residual plots of the Gulf of Maine Atlantic cod catch-at-age fits compared between the SAW55_BASE model (left) and the SAW55_SPLIT_LAND_DISC (right).

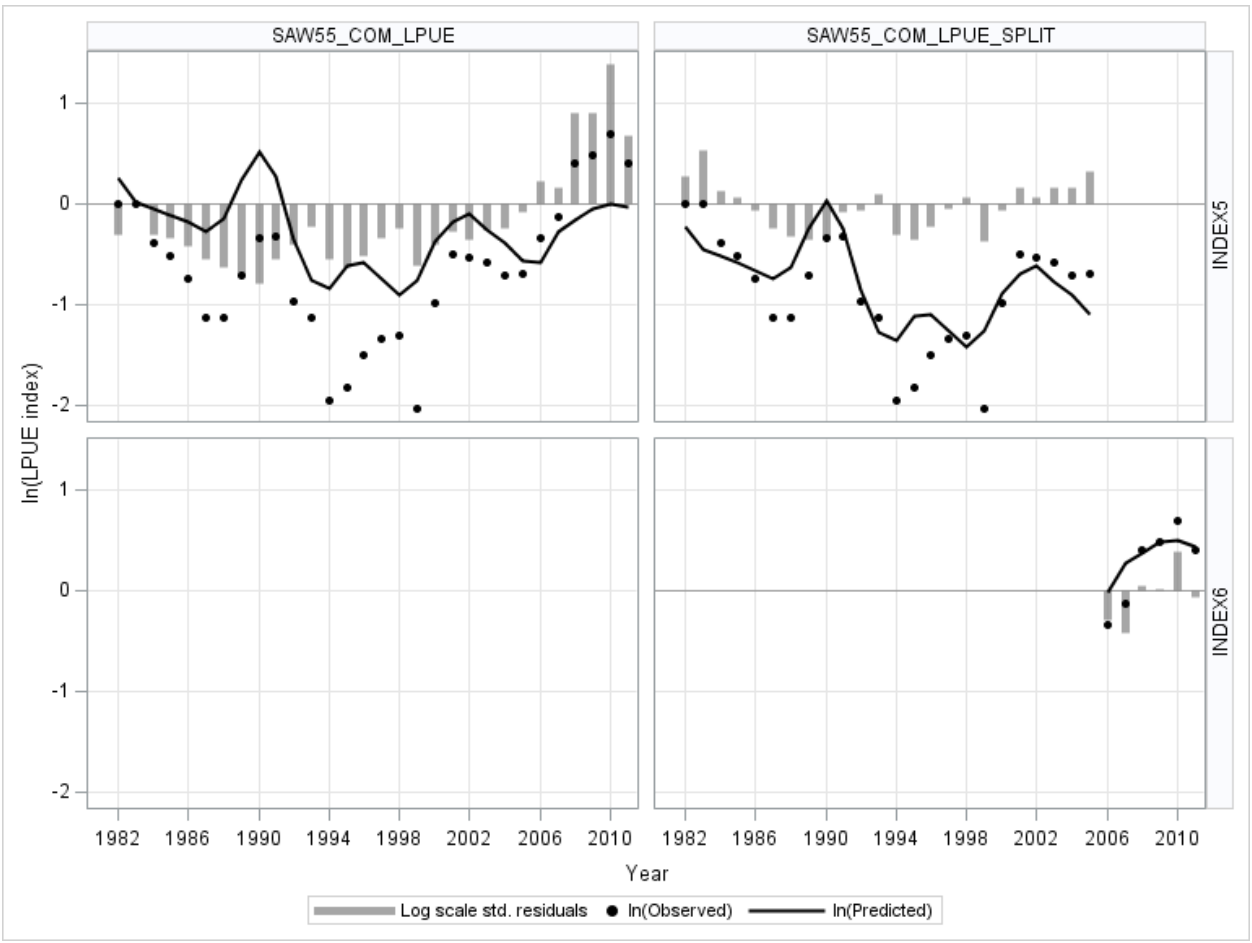


Figure A.6.15. Model fits of variants of the Gulf of Maine Atlantic cod ASAP SAW55_BASE model to the commercial landings-per-unit-effort (LPUE) index. The SAW55_COM_LPUE uses the commercial LPUE index as a single series. The SAW55_COM_LPUE_SPLIT model splits the commercial LPUE series between 2005 and 2006.

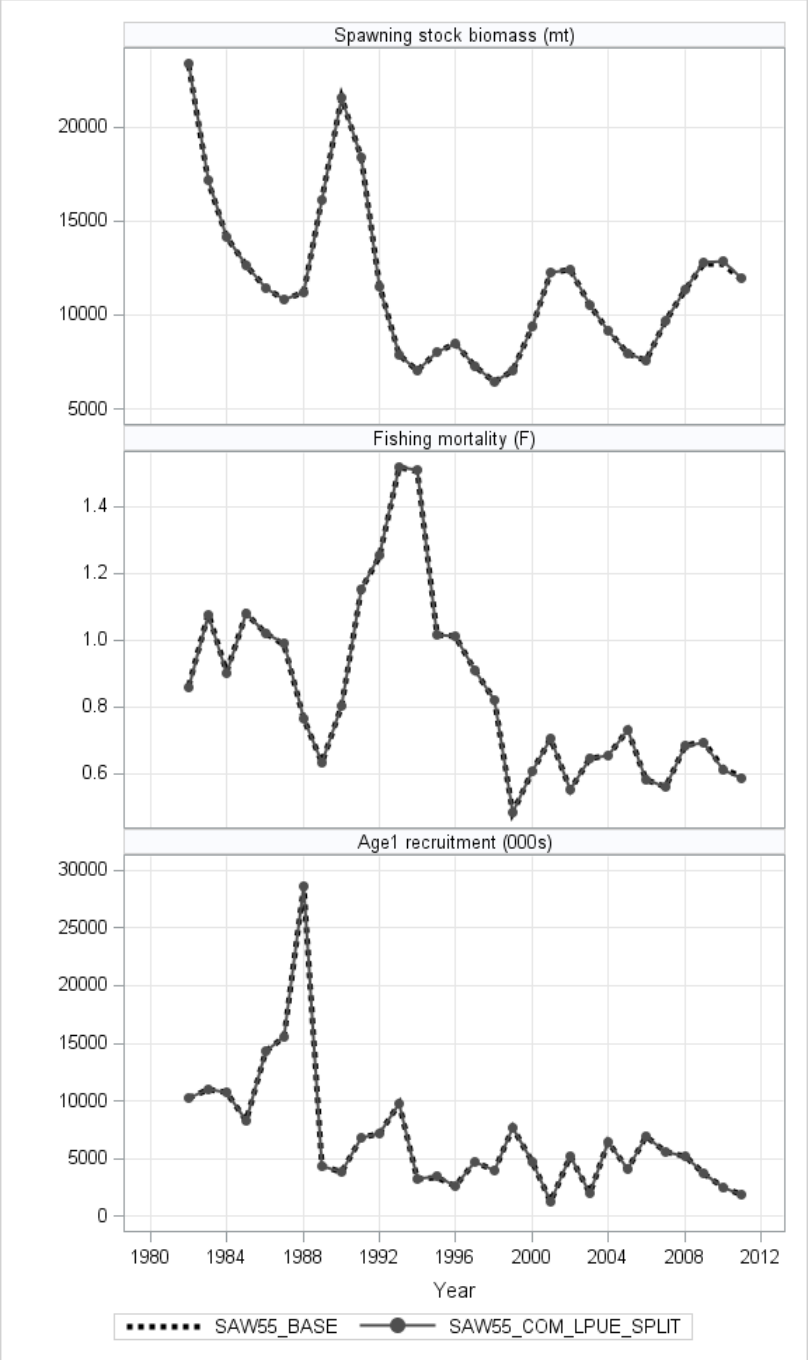


Figure A.6.16. Comparison of the Gulf of Maine Atlantic cod assessment results between the ASAP SAW55_BASE model and the SAW55_COM_LPUE_SPLIT model.

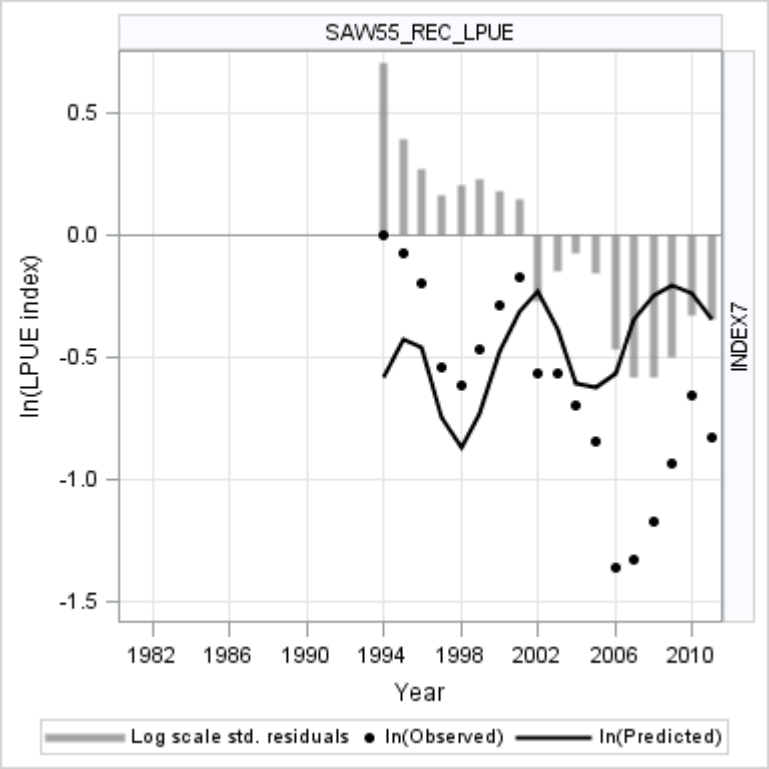


Figure A.6.17. Model fit of a variant of the Gulf of Maine Atlantic cod ASAP SAW55_BASE model, SAW55_REC_LPUE, to the recreational landings-per-unit-effort (LPUE) index.

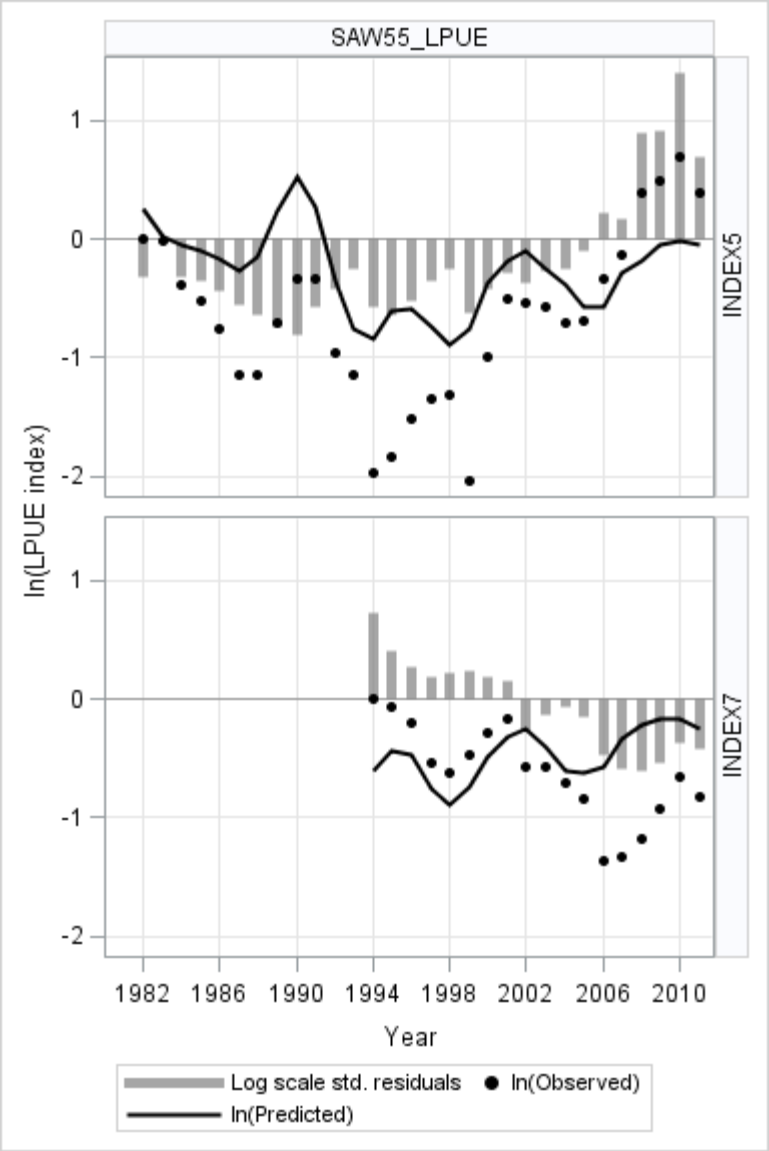


Figure A.6.18. Model fits of a variant of the Gulf of Maine Atlantic cod ASAP SAW55_BASE model, SAW55_LPUE, to the commercial (Index 5) and recreational landings-per-unit-effort (Index7) indices.

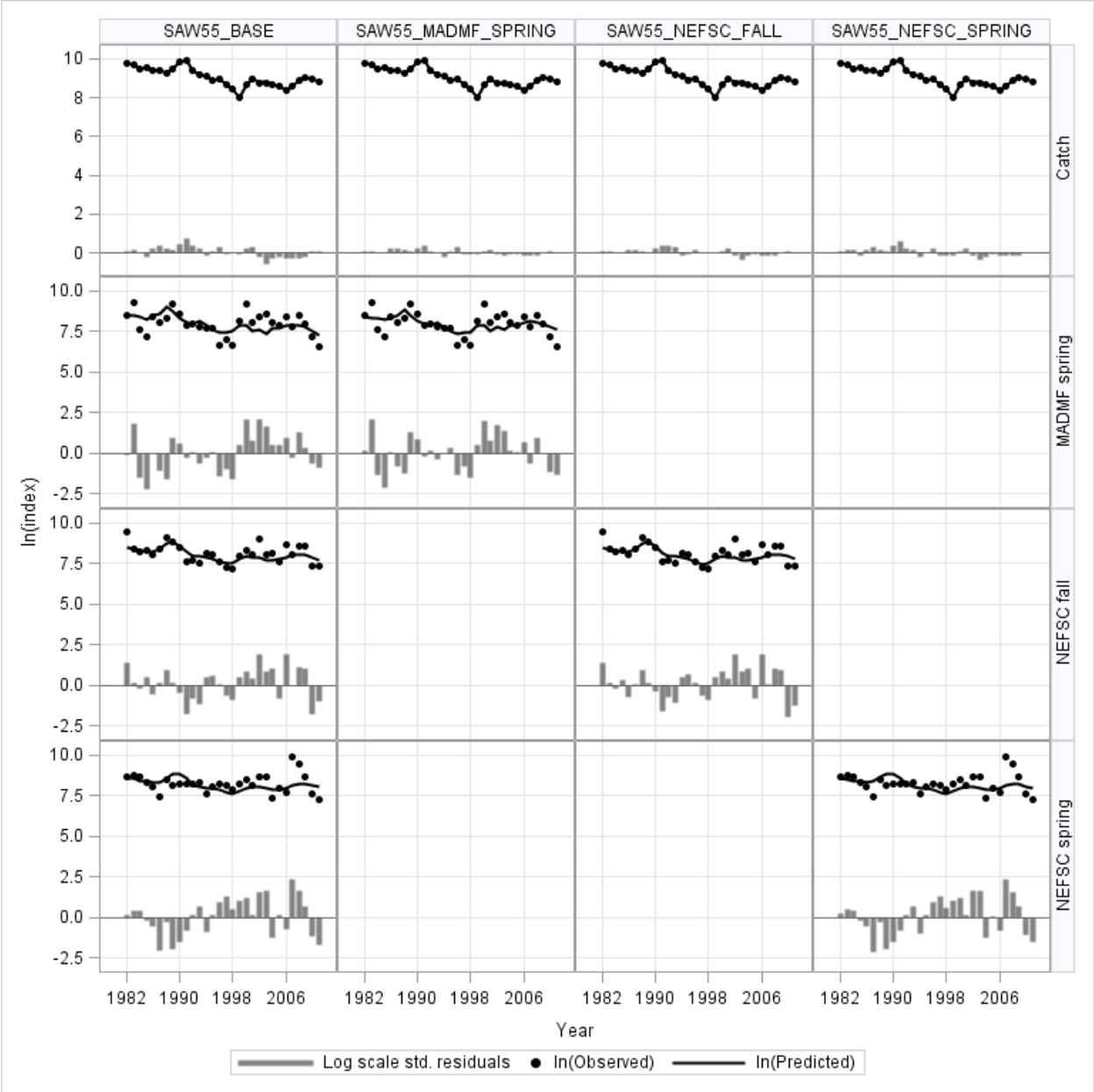


Figure A.6.19. Model fits of variants of the Gulf of Maine Atlantic cod ASAP SAW55_BASE model to the aggregate catch, NEFSC spring, NEFSC fall and MADMF spring survey indices. Each of the alternate models only included a single survey index.

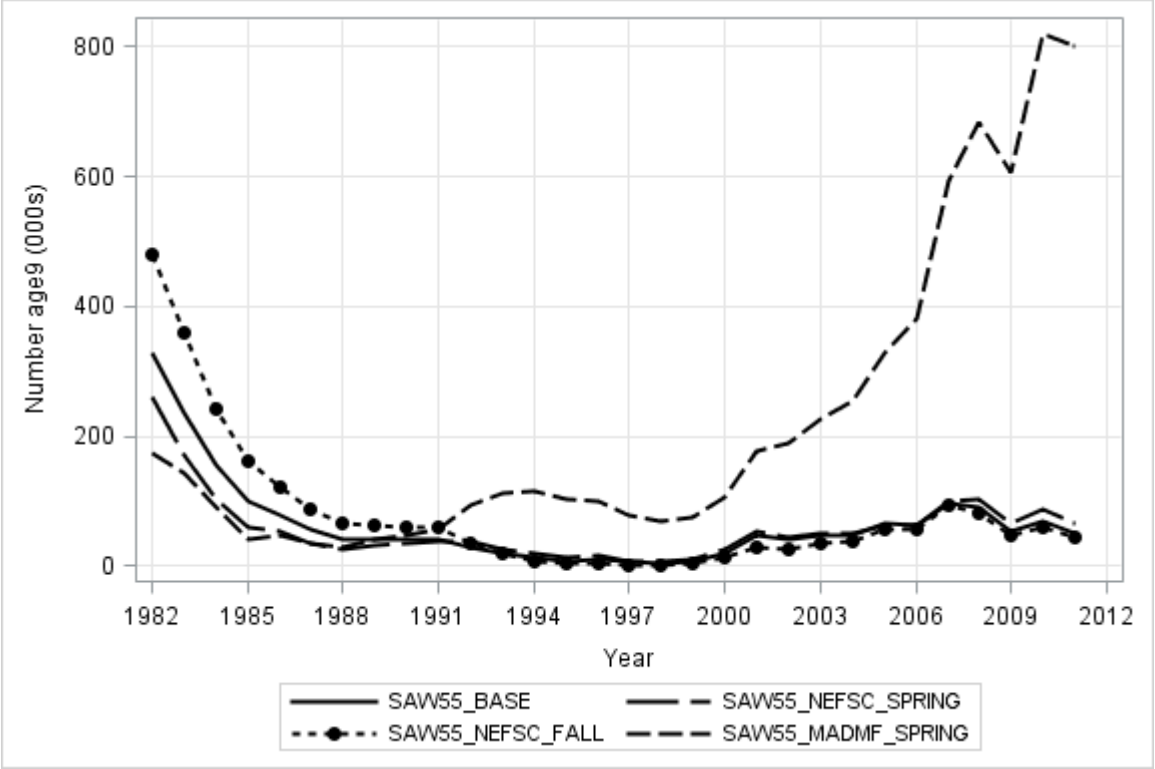


Figure A.6.20. Comparison of the Gulf of Maine Atlantic cod ASAP model estimates of numbers of age 9^+ fish over time between models exploring the sensitivity of the SAW55_BASE model to individual survey indices.

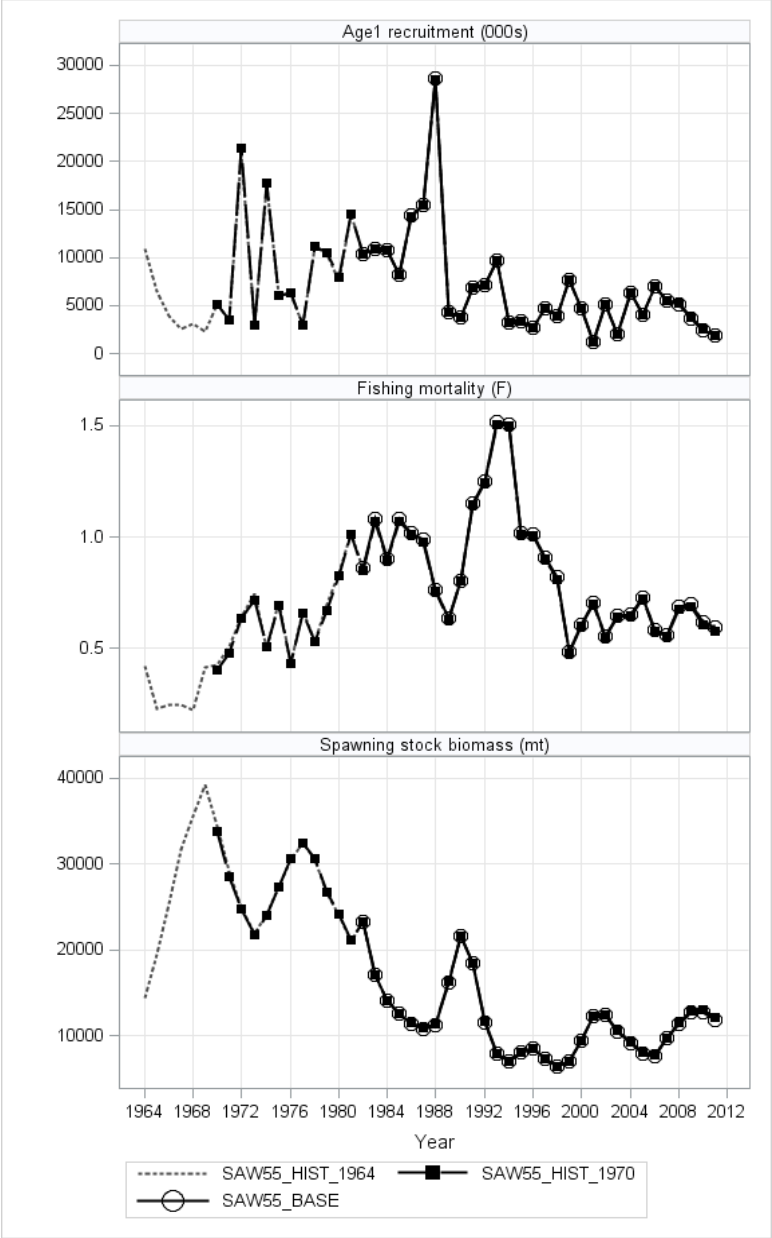


Figure A.6.21. Comparison of the Gulf of Maine Atlantic cod assessment results from models using different starting years. All models are based on the SAW55_BASE model which starts in 1982. The SAW55_HIST_1964 and SAW55_HIST_1970 models started in 1964 and 1970 respectively.

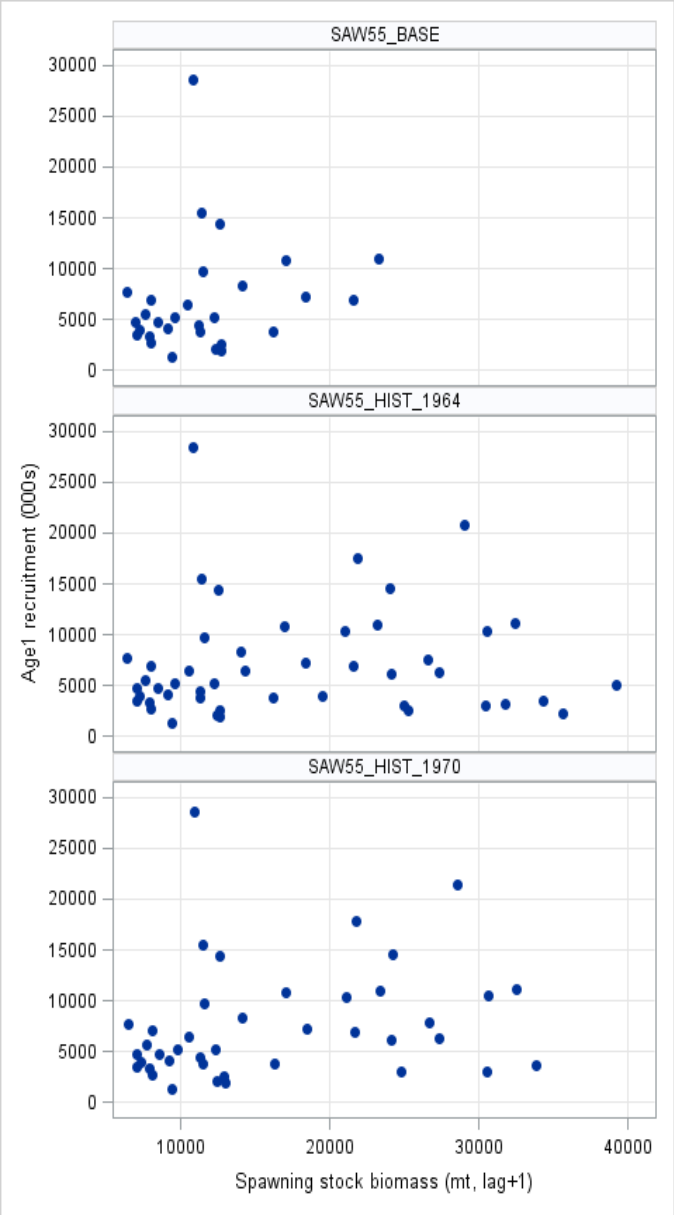


Figure A.6.22. Scatter plots of Gulf of Maine Atlantic cod age 1 recruits vs. spawning stock biomass from the SAW55_BASE, SAW55_HIST_1970, and SAW_HIST_1964 ASAP models. The starting year for each of the models was 1982, 1970 and 1964 respectively.

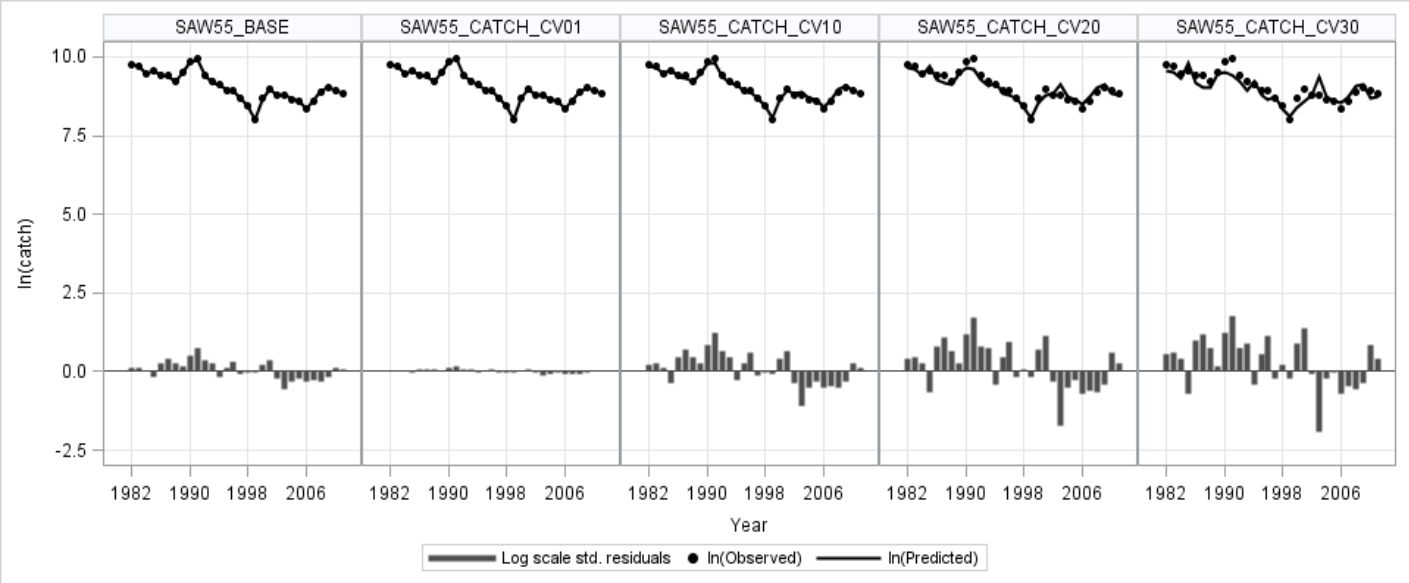


Figure A.6.23. Model fits of variants of the Gulf of Maine Atlantic cod ASAP SAW55_BASE model to the aggregate catch. The level of precision assumed for the aggregate catch was varied between models. The SAW55_BASE model assumed 0.05 coefficient of variation (CV) on the catch. The SAW55_CATCH_CV01, _CV10, _CV20, _CV30 assumed 0.01, 0.10, 0.20 and 0.30 respectively.

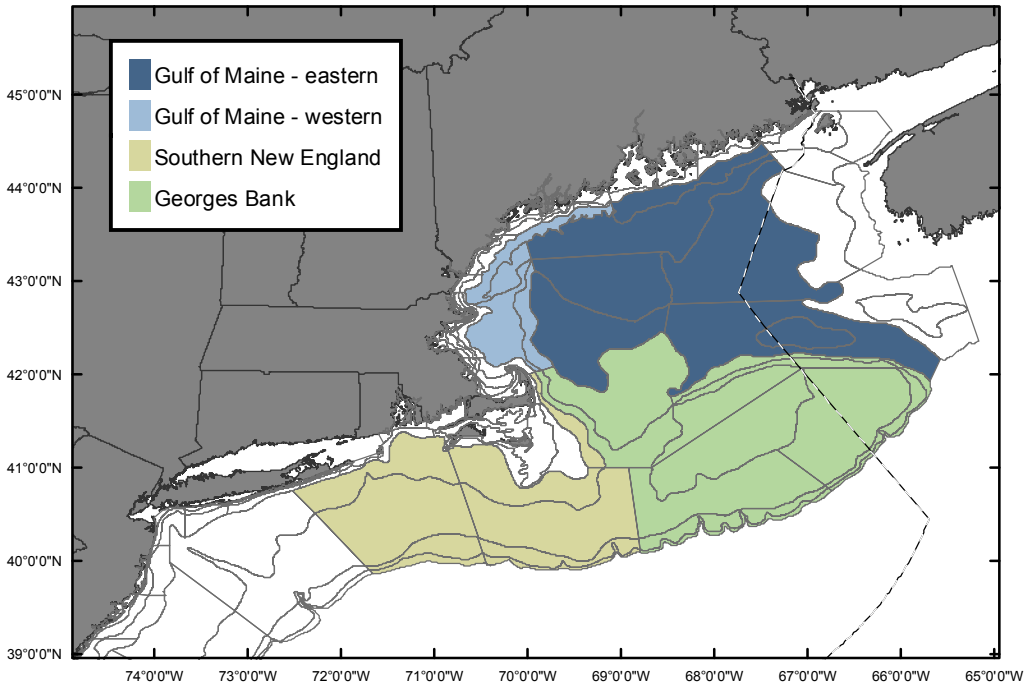


Figure A.6.24. Map of the northeast United States continental shelf showing sub-regions used to characterize NEFSC survey trends of Atlantic cod.

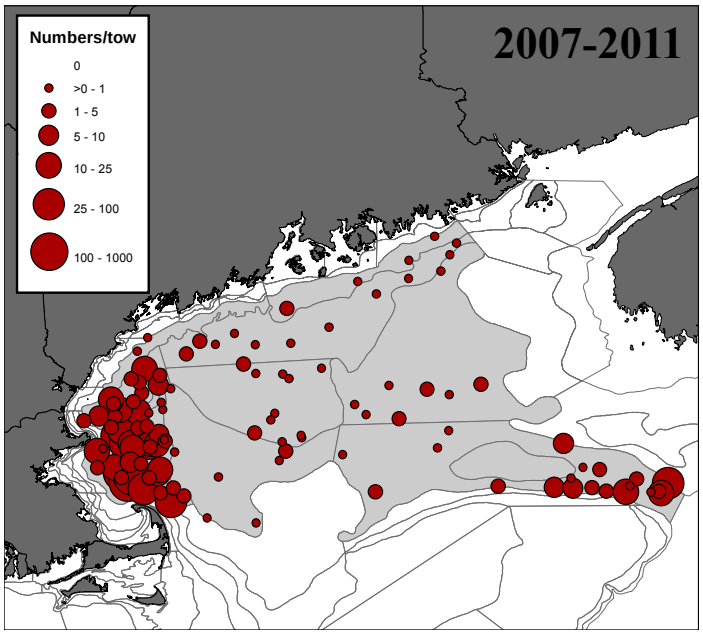


Figure A.6.25. Distribution of Gulf of Maine Atlantic cod between 2007 and 2011 from the NEFSC bottom trawl surveys (fall and spring combined).

Figure A.6.26. Northeast Fisheries Science Center (NEFSC) spring (left) and fall (right) bottom trawl survey abundance (numbers/tow) indices for Gulf of Maine Atlantic cod from 1963 to 2012 expressed as z-scores ($[x-\mu]/\sigma$). Plots on the top compare the indices for the entire Gulf of Maine region (red) to those from only the western Gulf of Maine (blue). Plots on the bottom compare the indices for the entire Gulf of Maine region (red) to those from only the eastern Gulf of Maine (blue).

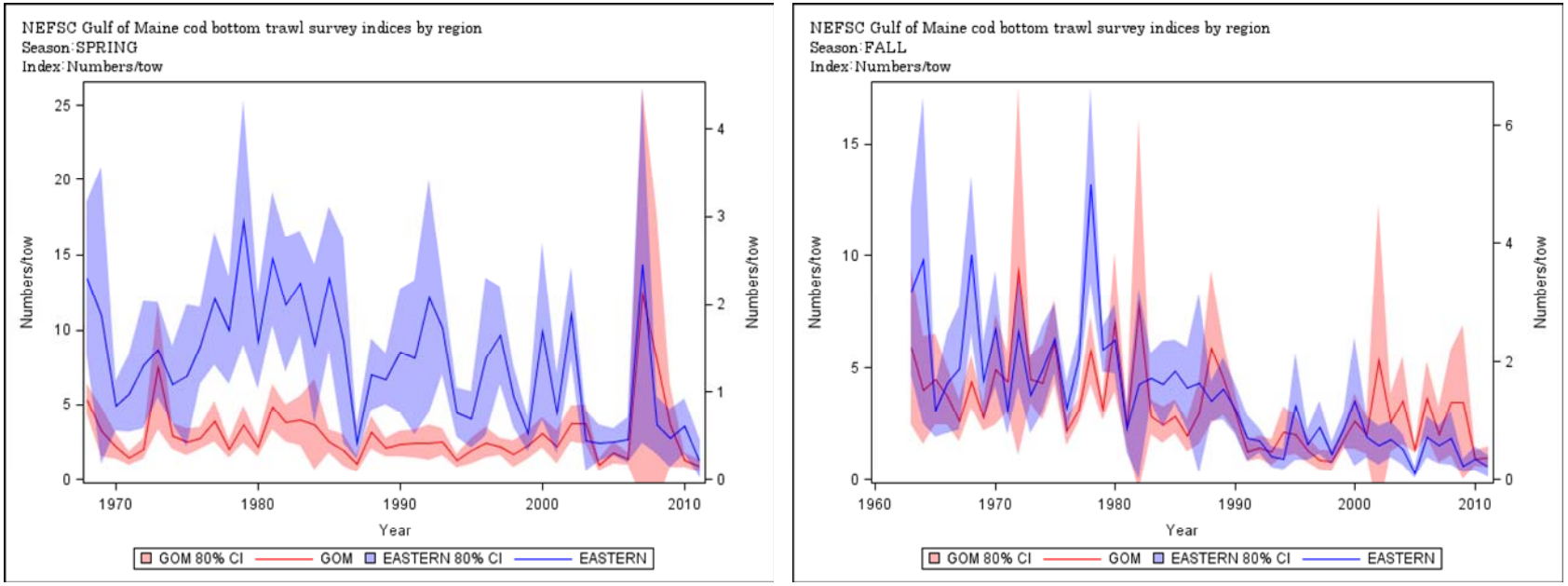


Figure A.6.27. Gulf of Maine Atlantic cod Northeast Fisheries Science Center (NEFSC) bottom trawl survey abundance indices (numbers/tow) from the spring (left) and fall (right) surveys showing the differences in scale between indices from the entire Gulf of Maine region (red) and those from only the eastern Gulf of Maine (blue).

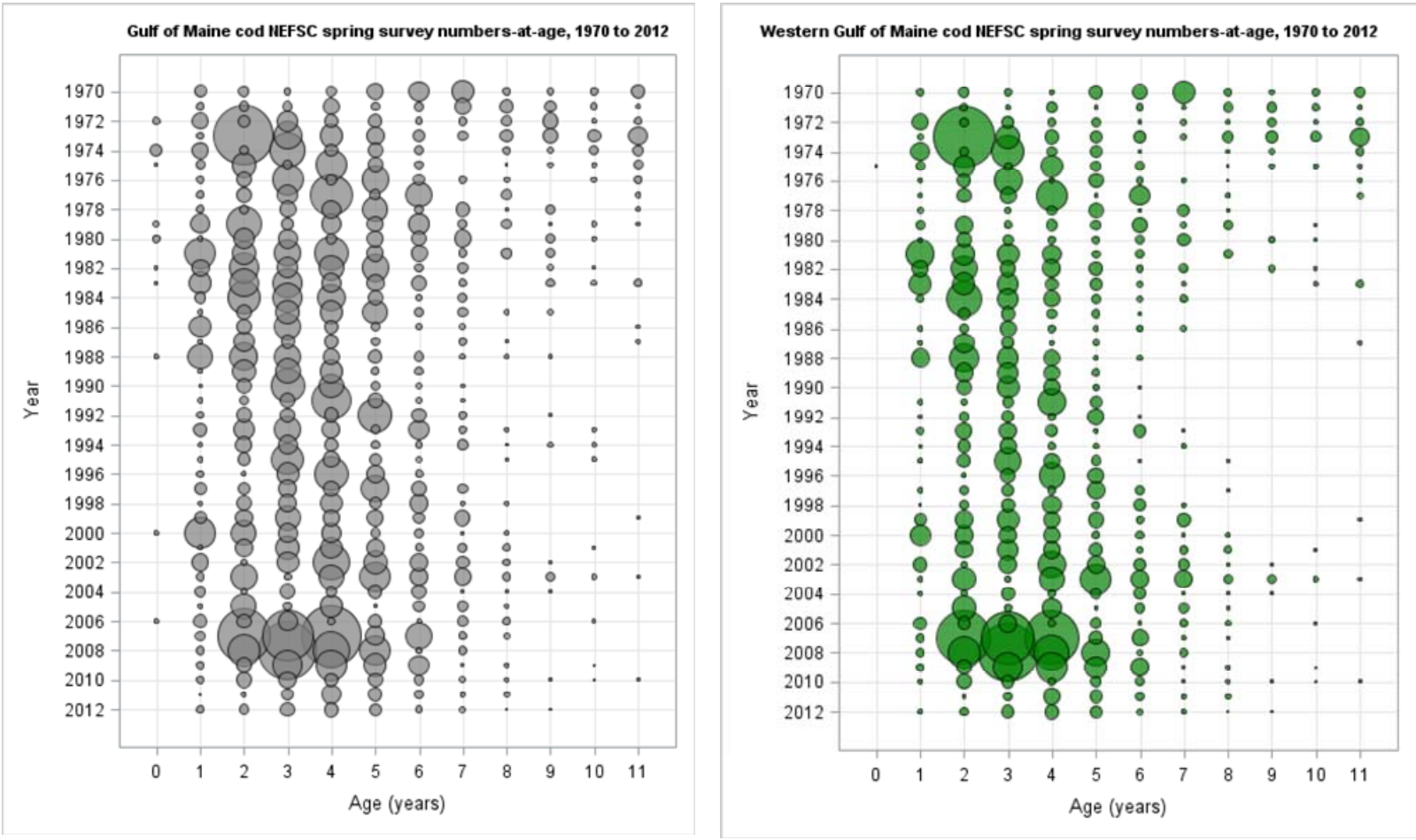


Figure A.6.28. Comparison of Notheast Fisheries Science Center (NEFSC) spring bottom trawl survey numbers at age indices for Gulf of Maine Atlantic cod calculated using all offshore strata (grey) and only those strata in the western Gulf of Maine (26, 27, 40; green).

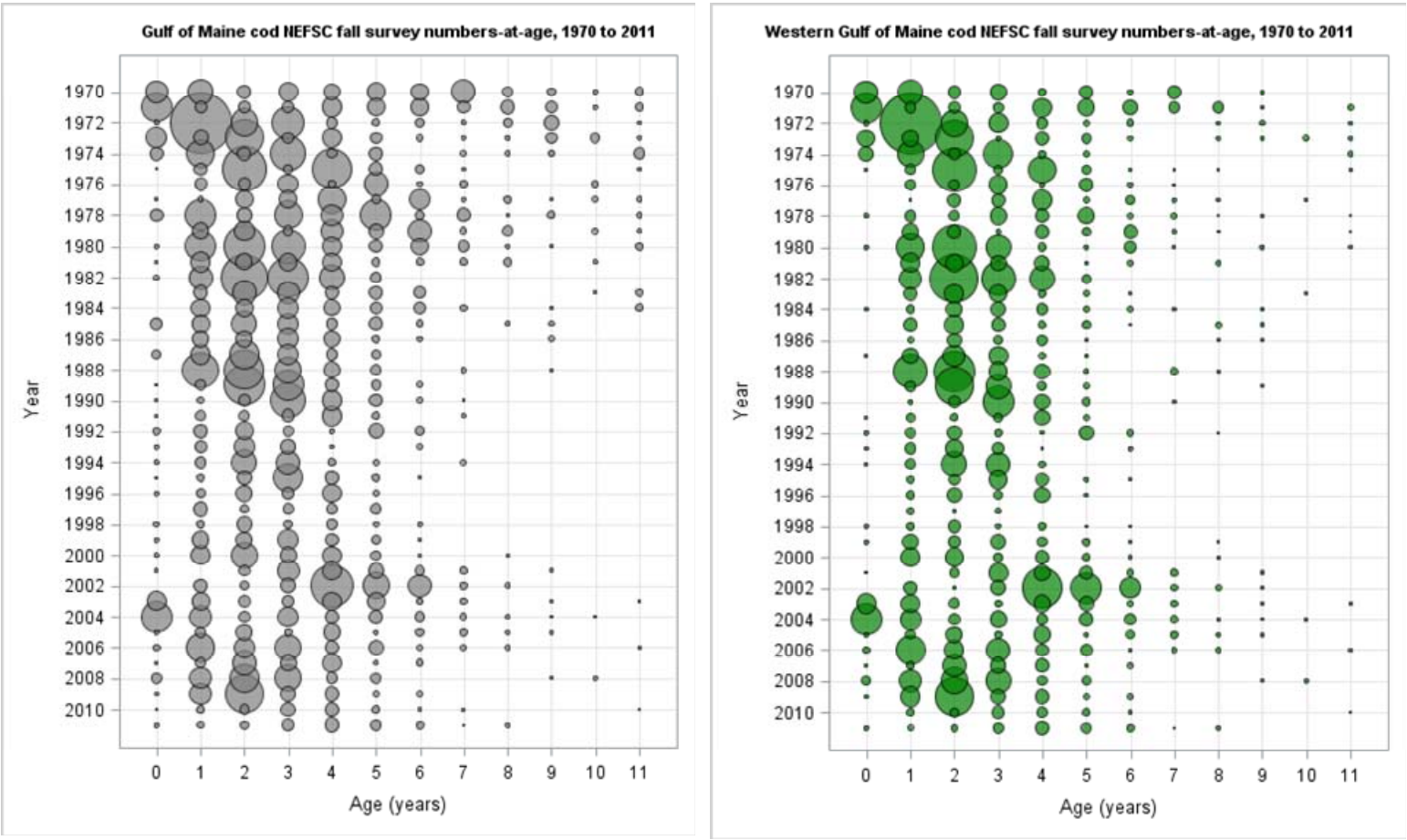


Figure A.6.29. Comparison of Notheast Fisheries Science Center (NEFSC) fall bottom trawl survey numbers at age indices for Gulf of Maine Atlantic cod calculated using all offshore strata (grey) and only those strata in the western Gulf of Maine (26, 27, 40; green).

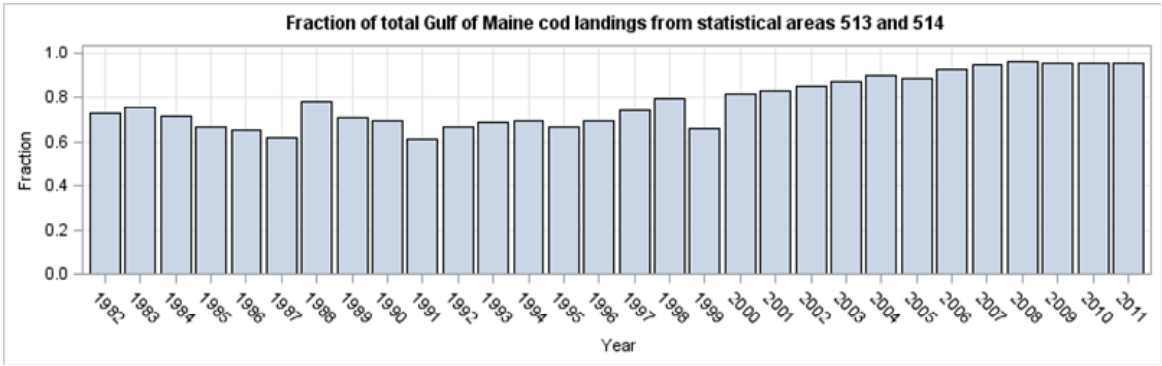


Figure A.6.30. Fraction of Gulf of Maine Atlantic cod commercial landings from statistical areas 513 and 514 between 1982 and 2011.

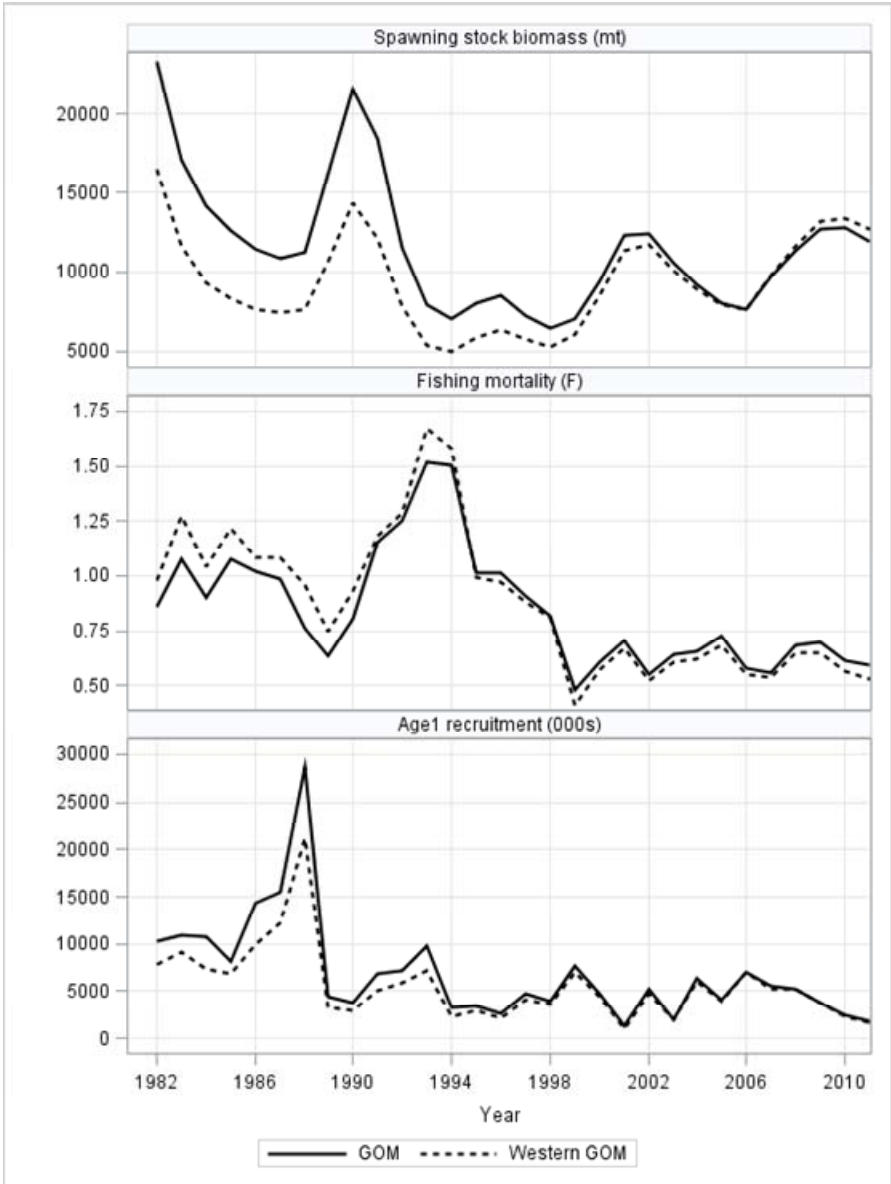


Figure A.6.31. Comparison of time series plots of spawning stock biomass, age 5 fishing mortality and age 1 recruitment from a western Gulf of Maine Atlantic cod stock assessment model to the SAW55_BASE assessment model which includes the entire western Gulf of Maine.

b

Figure A.6.32. Time series plots of spawning stock biomass, age 5 fishing mortality and age 1 recruitment from a combined Gulf of Maine-Georges Bank Atlantic cod stock assessment model. The model results from individual stock assessment models and the cumulative results are also shown.

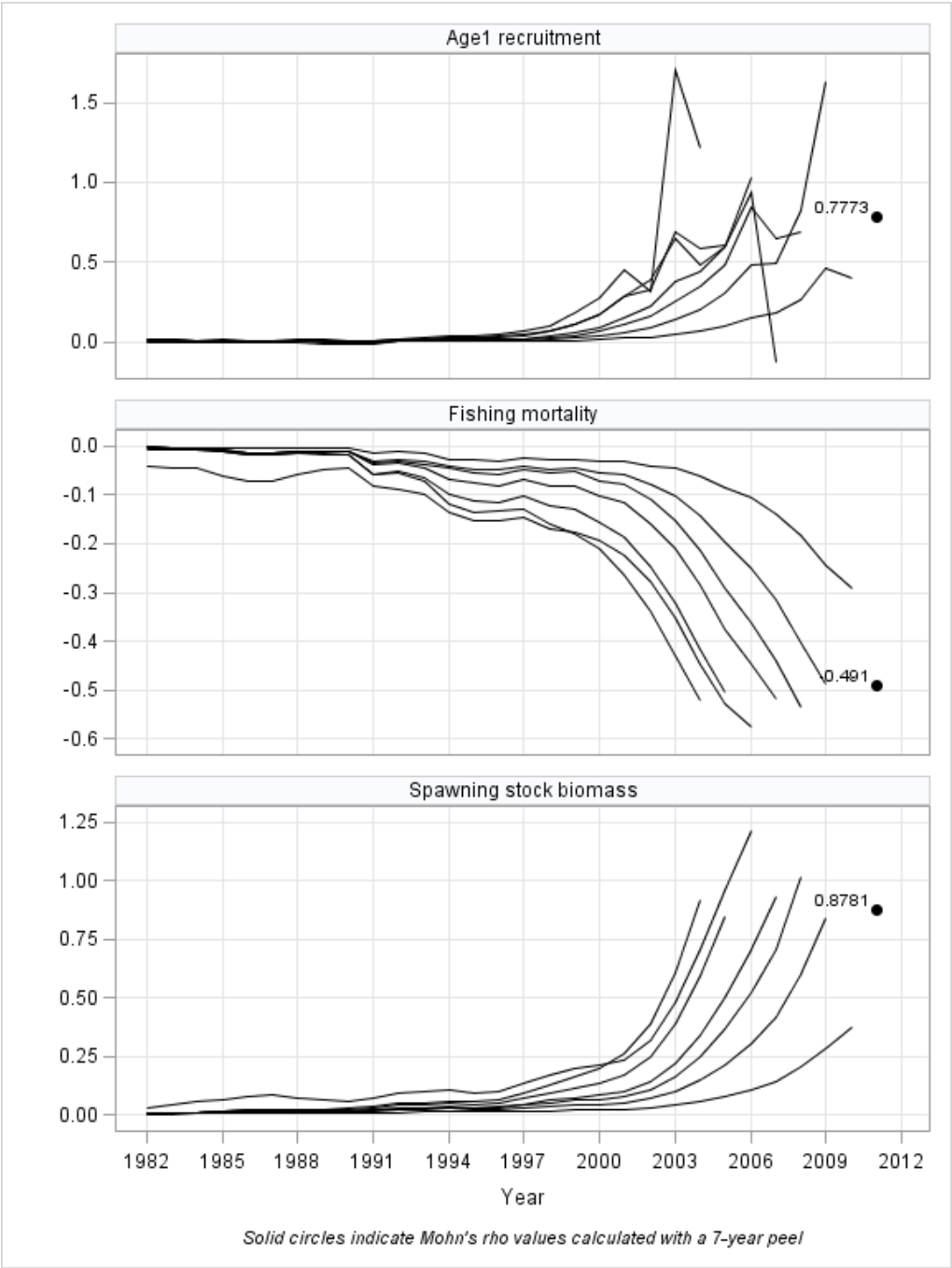


Figure A.6.33. Retrospective plots for spawning stock biomass, age 5 fishing mortality and age 1 recruitment from a combined Gulf of Maine-Georges Bank Atlantic cod stock assessment model.

[SAW55 Editor's Note: The SARC-55 review panel <u>did not recommend</u> adopting the GOM cod Statistical Catch-at-Age (SCAA) assessment results that are in Appendices A.2 – A.5 and referred to in Appendix A.7. Those results are included in this report to document and demonstrate the work that was done by the SAW cod Working Group]

Appendix A.7. Comparison of the four assessment models recommended by the SAW 55 Working Group and subsequent consequence analysis.

This appendix summarizes the comparison of the four assessments models and the corresponding reference points and short-term projections that were developed by the 55th Stock Assessment Workshop Working Group (SAW 55 WG) for consideration by the 55th Stock Assessment Review Committee (SARC 55) Panel. The four models for the Gulf of Maine Atlantic cod stock differed both in use of pre-1982 information and natural mortality (*M*) assumptions. Two main assessment model variants were configured as follows:

- Stock-recruit dynamics based on spawner per recruit analysis (SPR) of short-term (1982 – present) dataset with either natural mortality constant ($M = 0.2$) for the entire time series or *M* ramping up (linearly) from 0.2 during 1982 – 1988 period to 0.4 during 2003 – 2011 (*M*-ramp). These models were constructed using the statistical catch-at-age model ASAP (Age Structured Assessment Program) and are described in the main assessment report. ***It is important to note that there are differences in the estimation of the M-ramp reference points and short-term projections advanced by the SAW 55 WG compared to those ultimately accepted by the SARC 55 Panel. The details of the final M-ramp reference points and short-term projections accepted by the SARC 55 Panel are described in the main assessment report while the details of those forwarded by the SAW 55 WG are provided below.***

- Stock-recruit dynamics based on a stock recruitment model (SR) using long-term (1932 – present) dataset with either *M* constant (0.2) for the entire time series or *M* ramping up (linearly) from 0.2 during 1932 – 1988 to 0.4 during 2003 – 2011. These models were constructed using the Statistical Catch-at-Age (SCAA) formulation and are described in Appendix A.2 and A.3.

While the SAW 55 WG could not reach consensus on which model should serve as the basis of current stock status determination and management advice, it agreed that the 'newly proposed model' should be that of each lead scientist. Thus, for the ASAP formulation, the model which uses the 1982 – present dataset with *M* constant (0.2) for the entire time was preferred, while for the SCAA formulation, the model which uses the 1932 – present dataset with *M* ramping up from 0.2 to 0.4 was preferred. Notwithstanding this, the WG concurred that lack of consensus should not be interpreted as implying equal support for the models and developed pros and cons of the main features of each model to indicate their relative level of support.

M = 0.2

The features that lend support to the assumption that *M* has remained constant throughout the time series are those features which do not support the *M* ramp assumption, which is discussed below. The main feature against the assumption of constant *M* is the presence of a retrospective pattern. However, there is some evidence to suggest that this may be transitory and becoming less of an issue (SAW 55 WG, 2012c). It was for this reason that no adjustment for the retrospective pattern was made to any of the models.

M-ramp

One of the main features supporting the assumption of a recent change in natural mortality is that it employs an $M = 0.4$ which is generally consistent with the results of the 2003 – 2006 GMRI tagging data and associated analyses (if one assumes a 50% reporting rate of high reward tags). The tagging analysis indicated that *M* could be as high as 0.6. Tag reporting rates would have to be very low in order to be consistent with an *M* of 0.2.

Another line of support for this assumption is the model fits. The value of the objective function for the *M* ramp model was lower (by 8-10 log-likelihood points depending on the specific formulation) than that of the constant *M* model. Further, compared to the constant *M* model, assuming that *M* had changed more recently reduces the retrospective pattern.

The final observation supporting a recently elevated *M* in Gulf of Maine cod is evidence of increasing *M* in the adjacent NAFO Div. 4X cod stock based on both tagging analyses and assessment model fits.

A number of features don't lend support to a recently increasing *M*. There is no evidence for increased predation, either by fish or pinnipeds, in the diet compositional data collected by the NEFSC. Regarding the GMRI tagging analyses, if reporting rates of high reward tags were less than 50%, natural mortality would be less than 0.4. It is unfortunate that there are little or no historical tagging studies to which the results of the GMRI study could be compared. Besides using different assumptions, these earlier studies did not formally incorporate parameters to estimate movement. For these reasons, the tagging studies which suggested higher *M* (> 0.2) in 4X may not apply to Gulf of Maine Cod (SAW 55 WG 2012a).

Regarding model fits, the likelihood profile of *M* for the 2003 – 2011 period was relatively flat, with estimates between 0.1 and 0.6 potentially possible. Exploratory runs indicated that *M* profiling was sensitive to which years to include in the recent period of high *M*. A change of two years would result in a more informative profile (favoring higher *M*).

The final lines of evidence against a recently elevated *M* relate to the life history information. Compared to adjacent stocks, there have been little or no long-term changes in maturity at age, fish condition and growth. Meta-analyses of life history parameters suggest an *M* of 0.2 with no trend over time.

Long-term (1932 – present): recruitment productivity based on SR model

One of the features in support of using the longer term time series is the NEFSC survey dataset which contains information on Gulf of Maine cod year-class strengths during the 1960s (size frequency information during 1963 – 69 and indices of abundance at age during 1970 – 81). Sensitivity analyses (e.g. on catch CVs) did not indicate qualitative differences in the estimated reference points and alternative assumptions about fishery selectivities during the pre-1982 period also made minimal differences in the estimated reference points. Overall, the estimation process has explicitly taken into account the agreed levels of uncertainty in the catch and sampling during the historical period.

Use of the longer-term time series allows analytical estimation of MSY based reference points, due to the presence of more contrast in population dynamics, which thus avoids resorting to the use of proxies. Model fits indicate that there is a preference for Ricker stock-recruit over BH relationships, with even stronger domes in the former suggested, though as highlighted below, the model preference for a Ricker SR was small. Ricker-based estimates of B_{MSY} are reasonably precise (CVs of approx. 15%) although the 2011 spawning stock biomass is more precisely estimated when a BH relationship is assumed. Use of a Ricker relationship is consistent with evidence for cannibalism observed in other Cod stocks (Puvanendran et al., 2008) although there has been no evidence of post-larval cannibalism in either Gulf of Maine or Georges Bank Cod.

A number of features don't lend support to use of the long-term dataset. Models run with either the Ricker or BH relationship starting in 1970 provide relatively the same estimates of spawning biomass and recruitment, indicating that it is primarily the information in the 1960s which is providing the basis for differing stock-recruit relationships. This is a time period during which there is no age compositional data and fisheries statistics are most uncertain. Issues with the historical data quality are discussed in SAW 55 WG (2012a). Further, the survey aggregate numbers indices for the 1960s contains data on age 0 cod which cannot be removed from the analysis, although when aggregate biomass indices are used (in which age 0 cod would play a less prominent role), the assessment results are qualitatively similar.

Regarding model fits, there is little difference in the value of the objective function when using either a Ricker or BH relationship in a model starting in 1932 (about 3 points for $M = 0.2$ or 8 points for the M-ramp). For both M scenarios, the difference in log likelihoods between Ricker and BH was due to stock - recruit residuals during 1963 – 1969, the period with no age composition data. A pattern of positive residuals exists for both relationships during 1977 – 87, a period with high catches.

Simulation studies have indicated a propensity to fit domed stock -recruit relationships (i.e. Ricker), even when a BH is true (De Valpine and Hastings, 2002). However, the results of these studies depend heavily on the scenario being simulated (e.g. length of time series) and may not apply to the current situation. F_{MSY} (0.53) estimated using a Ricker model is generally larger than F_{MAX}, although this is to be expected when the stock-recruitment relationships are domed. On the other hand, spawning biomass did decline after the 1970s when the resource experienced fishing mortalities consistent with the Ricker-based F_{MSY}.

There is an overall concern that if there have been long-term stock productivity changes, analytically-derived estimates of B_{MSY} and F_{MSY} based on 1932 – present stock dynamics, which can be considered a weighted average over the entire time series, may not reflect current conditions.

Short-term (1982 – present): recruitment productivity based on SPR

The main feature supporting use of the shorter-term time series is that this is the period which has the highest data density. Data are available on the quantity and size composition of the landings and discards, both commercial and recreational. A number of survey indices are available, each with aggregate indices of abundance and biomass, along with data on age/size composition. Biological information such as growth, maturity and length / weight relationships are also available.

Regarding model fits, the estimates of biomass and fishing mortality, as well as the reference points are robust to a wide range of model assumptions and uncertainties.

The main issue against using the short-term time series is that it does not provide sufficient contrast to estimate stock-recruit relationships, and thus requires the use of B_{MSY} and F_{MSY} proxies which in turn has associated uncertainties (i.e. selection of percentage spawner per recruit).

Differences in the estimation of the M-ramp reference points and short-term projections advanced by the SAW 55 WG compared to those accepted by the SARC 55 Panel

There was consensus among the SAW 55 WG that a proxy reference point approach was the preferred approach for the ASAP 1982 models. A yield per recruit (YPR) analysis was performed using a 3-year average of weights-at-age which was consistent with the approach used in SAW/SARC 53 and supported by recent observed trends. The remaining YPR inputs were time invariant (maturity-at-age) or were constant in the most recent time block of the assessment model (selectivity, natural mortality). For the *M*-ramp model the SAW 55 WG assumed that *M* would remain at 0.4 and carried forward this assumption when setting reference points. **Contrary to the decisions made by the SAW 55 WG, the SARC 55 Panel concluded that "*…for long-term projections that [the] Review Panel decided that M should be 0.2, because the longer-term historical evidence seems to indicate that M = 0.2 is more plausible*" (SARC 55 2012). This had implications for the determination of appropriate F_{MSY} proxy as well as the estimation of SSB_{MSY} and MSY.** Unlike the *M*-ramp F_{MSY} proxy accepted by the SARC 55 Panel which were based on an $F_{40\%}$ SPR assuming $M = 0.2$, the SAW 55 WG *M*-Ramp F_{MSY} proxy was based on $F_{50\%}$ assuming $M = 0.4$. The basis for the existing (SAW 53; NEFSC 2012a) overfishing reference points was derived at GARM III (NEFSC 2008), and is based on $F_{40\%}$; however this decision was based on an assumed natural mortality of $M = 0.2$. Additional analyses by the SAW 55 WG evaluated various proxies for F_{MSY} by comparing estimated SSB and recruitment ratios (SSB/R) with expected spawning biomass per recruit (SPR) over a range of fishing mortalities (F=20% to F80% in 5% increments) to investigate the potential for replacement under equilibrium assumptions (i.e. constant harvest rate and biology over the

lifespan). An analysis of replacement lines under recent productivity (approximately last 10 years) indicated that for the *M* = 0.2 option, $F_{40\%}$ (0.18) was still appropriate. When the *M* was increased to 0.4 (*M*-ramp), the replacement lines became steeper with $F_{40\%}$ rising to 0.44 (Fig. A.7.1). It was noted that the F_{MSY} proxy for Georges Bank cod for the *M*-ramp model was set by the SAW 55 WG at $F_{50\%}$ based upon F_{med} considerations. Recognizing that it is a judgment call, the WG decided that the F_{MSY} proxy for the GOM cod M-ramp model should be based on $F_{50\%}$ (0.29), consistent with the $F_{MSYproxy}$ used for Georges Bank cod. It should be noted that subsequent to the SAW/SARC 55 work was presented at SAW 56 WG that invalidates the replacement line approach for determining an appropriate spawning potential ratio (Legault and Brooks 2013).

To arrive at estimates for SSB_{MSY} and a corresponding MSY, long term projections were run sampling from the empirical distribution of recruitment estimates from the preferred ASAP model (recruitment estimates from 1982-2009, final two years excluded). Based on suggestions made by the SARC 53 Panel, the modeling approach was modified to better account for uncertainty in projections at low stock sizes. The revised projection model samples from a cumulative density function derived from estimated age-1 recruitment. However, the revised model adjusts projected recruitment when SSB falls below some specified spawning biomass threshold based on a linear function that declines to zero at zero spawning stock biomass. Consistent with the SAW 53 assessment, the 'hinge' was set at the lowest observed SSB in the time series. For the *M* = 0.2 scenario, this was 6,300 mt and 7,900 mt for the *M*-ramp scenario. To approximate the distribution of the SSB and MSY distributions, the long term projections were made from 1000 estimates of numbers at age in 2011, which were estimated by performing MCMC simulation of the ASAP base model (described above under TOR 5). **Note that the 2011 age 1 estimates were based on sampling from the empirical distribution of recruitment estimates from only the ten year period 2000-2009.* All projections were conducted with the AGEPRO software (Age Structured Projection Model v4.1). The ASAP, 1982 start year reference points forwarded to the SARC 53 Panel for review are summarized in Table A.7.1.

Similar to the assumptions made for estimating reference points, the SAW 55 WG conducted short-term projections for each of the ASAP, 1982 start year scenarios assuming natural mortality to remain equal to the M in the terminal year of the assessment model. Short-term projections (3 years; 2013-2015) were conducted using 3-year averages of weights-at-age which was consistent with the approach used in SAW 53 and supported by recent observed trends. The remaining YPR inputs were time invariant (maturity-at-age) or were constant in the most recent time block of the assessment model (selectivity, natural mortality). The short term projections were conducted based on the current assessment results without accounting for retrospective bias. Numbers-at-age in 2012 were derived from 1000 different vectors of numbers-at-age produced from the MCMC chain with 2011 age 1 estimates based on sampling from the empirical distribution of recruitment estimates from only the ten year period 2000-2009. Short term projections have used an assumed catch in 2012 of 3,767 mt. This estimate is based on the current commercial and recreational catches as well as the expected catch over the remainder of the year which has been extrapolated using the harvest trajectories from the past two years (NEFMC PDT, T. Nies pers. comm.).

Recruitment was sampled from a cumulative density function (CDF) of estimated age 1 recruitment from 1982 to 2010. The same AGEPRO model used for reference point determination was used to conduct short-term projections (i.e., model adjusts projected recruitment based on a linear function that declines to zero at zero SSB when SSB falls below some 'hinge' SSB-level corresponding to the lowest SSB observed in the time series). For the *M*=0.2 scenario, the 'hinge' SSB value was set at 6,300 mt and 7,900 mt for the *M*-ramp scenario. All projections were run under the assumption of 75% F_{MSY} (*M* = 0.2 scenario = 0.14, *M*-ramp scenario = 0.22). **It is important to note that the 75% F_{MSY} assumption for the SAW 55 WG *M*-ramp projections differs from the 75% F_{MSY} proxy accepted by the SARC 55 Panel (75% of 0.18 = 0.14).**

Projection results for both the *M* = 0.2 and *M*-ramp models are summarized in terms of median SSB and fishery catch (yield) in Table A.7.2. Under 75% F_{MSY} exploitation, the stock is projected to rebuild under the *M* = 0.2 and *M*-ramp scenarios by 2022 and 2019 respectively.

Consequence Analysis

Biological reference points associated with each of the four models are presented in Table A.7.3. The risks associated with management actions taken during 2013 – 2015 were examined by undertaking short-term stock projections under the competing assumptions for the state of nature. For instance, if the true state of nature is that natural mortality has remained unchanged at 0.2 and that stock productivity is best reflected by the 1982 – present dataset (SPR, *M* = 0.2 model), then the consequences of management actions by setting projected catch according to 75% F_{MSY} based on the three alternative states of nature were examined (short-term (SPR) with *M*-ramp, long-term (SR) with *M* = 0.2 and long-term (SR) with *M*-ramp). In all cases, the 2012 catch was provided by the NEFMC Groundfish Plan Development Team. Projections were only conducted until 2015. There may be longer term consequences which might be revealed through a more extensive analysis. This is beyond the current terms of reference.

In these explorations, the assessments using the long-term dataset assumed a Ricker stock-recruitment relationship. Use of a BH relationship produced results for future catches under 50% F_{MSY} within the range of the other alternate states of nature, indicating that the analyses presented below bracket the risks to the stock of assuming one state of nature while another might be true. It should be pointed out that while these runs are not presented in detail here, the results of these BH runs are also plausible.

The column headers in Table A.7.4 and Figure A.7.2 represent the 'true' states of nature considered, these being:

- ASAP, 1982 start, *M = 0.2*: stock dynamics and assessment based on 1982 – present dataset with *M = 0.2* for the time series
- ASAP, 1982, *M*-ramp: stock dynamics and assessment based on 1982 – present dataset with *M* ramped from 0.2 to 0.4 during 1989 – 2002
- SCAA, 1932 start, Ricker, *M = 0.2*: stock dynamics and assessment based on 1932 – present dataset with *M = 0.2* for the time series

- SCAA, 1932, Ricker, *M*-ramp: stock dynamics and assessment based on 1932 – present dataset with *M* ramped from 0.2 to 0.4 during 1989 – 2002

The row headers in Table A.7.4 indicate the basis of the management action during the projection period (2013 – 2015). Thus, the row header 'SCAA, 1932, Ricker, *M*-ramp' indicates that catch was projected assuming that the stock conditions and reference points were as per these dynamics. All projections were conducted at 75% F_{MSY}, based on the assumed state of nature and thus which establishes the catch in each cell. This is the 'planned' catch. The cells of the table indicate the SSB and fully recruited fishing mortality (F_{full}) which are a consequence of applying the catch based on the assumed state of nature to the SSB of the 'true' state of nature. The diagonal rows represent the situation in which the management actions based upon the assumed state of nature are in fact correct. In these stochastic projections (see TOR 8a), there were cases in which the projection attempted to harvest more fish than exist in the population's exploitable biomass. The fraction of feasible projections for the eight combinations of states of nature and basis of management action are provided in Table A.7.5.

The consequence analysis is summarized in Figure A.7.2. As with Table A.7.3, the column headers indicate one of the 'true' states of nature. The row headers indicate whether or not catch, SSB or F_{full} is being displayed along the row. The content of each cell summarizes the consequences (reflected by the medians of the distributions in question) of assuming one state of nature when another is true. The black line in each cell indicates the catch, SSB and F_{full} for the 'true' state of nature. The coloured lines (for the projected period only) indicate the catch, SSB and F_{full} which result when the 75% F_{MSY} estimated catch is incorrectly based upon an alternate state of nature. The dashed lines in each figure are the B_{MSY}, F_{MSY} and MSY for the 'true' states of nature.

When management actions are correctly based upon a particular state of nature (the diagonals of Table A.97), a modest increase in SSB is projected until 2015 for the two ASAP and one of the SCAA (*M* = 0.2) options. Only in the case of the SCAA, 1932, Ricker, *M*-ramp option is SSB projected to decline, though this is a consequence, at least in part, of the harvest strategy being applied where the resource is estimated to be above SSB_{MSY}. The 2011 SSB estimates range 9,903 - 10,221 t and 13,735 - 14,509 t for the two ASAP and SCAA options respectively. Fully recruited fishing mortality declines for the two ASAP options (from 0.86 – 0.9 to 0.14 – 0.22), increases slightly (from 0.52 to 0.56) for the SCAA, 1932, Ricker, *M* = 0.2 option, and increases (from 0.61 to 0.71) for the SCAA, 1932, Ricker, *M*-ramp option. Catch for the two ASAP options declines from 6830 t in 2011 to 1,929 – 2,030 t in 2015. For the SCAA, 1932, Ricker, *M* = 0.2 option, catch increases from 6830 t in 2011 to 8,424 t in 2015 while it declines to 5,020 t over the same period for the SCAA, 1932, Ricker, *M*-ramp option. If the management actions are correctly based upon the 'true' state of nature, the two ASAP models indicate that, in 2013, the stock is in an overfished state (Table A.7.6). In contrast, the two SCAA models indicate that the stock would not be in an overfished state in 2013. In all cases, overfishing is not occurring in 2013.

It is useful to consider the consequences of mis-specifying natural mortality separately from stock – recruit dynamics (based on either the ASAP or SCAA models). For the two ASAP models which base stock-recruit dynamics on spawner per recruit considerations, mis-specifying

the natural mortality is inconsequential, with catch, SSB and F_{full} being very similar. Consequently, the 2013 stock status would remain as overfished but that overfishing is not occurring. The natural mortality assumption is slightly more of an issue when stock dynamics are based on the long-term derived stock-recruitment relationship (SCAA models). Assuming an *M*-ramp when *M* is actually equal to 0.2 results in a lower than 'planned' fishing mortality and catch and higher than 'planned' SSB. Status in 2013 would still be not overfished and overfishing not occurring. When *M* is assumed to be 0.2 but an *M*-ramp is correct, fishing mortality and thus catch would be considerably higher than 'planned' with the result that in 2013 the stock would be experiencing overfishing although it would not be overfished (Table A.7.6).

The consequences of mis-specifying the stock-recruit dynamics are overall more severe than mis-specifying natural mortality. If management actions during 2012 – 2015 are based on stock-recruit dynamics assuming SPR dynamics (the ASAP models) when those based on SR dynamics should have been used (the SCAA models), fishing mortality and thus catch would be lower than 'planned' while SSB would be higher than 'planned'. There would, nevertheless, be no change in the 2013 status.

If management actions during 2012 – 2015 were based on stock-recruit dynamics assuming an SR function (the SCAA models), when those based on SPR should have been used (the ASAP models), fishing mortality and thus catch would be much higher than 'planned' while SSB would decline more than 'planned', particularly if *M* had also been assumed to be 0.2. This would result in the stock being determined as overfished as well as overfishing occurring in 2013 regardless of the natural mortality.

To summarize, mis-specification of stock-recruit dynamics has greater implications for management actions during 2012 – 2015 than mis-specification of natural mortality. Mis-specification of natural mortality is inconsequential if stock-recruit dynamics conform to SPR considerations but are more of an issue when recruitment is based on an SR function (in this case a Ricker relationship).

Appendix A.7 Tables

Table A.7.1. Yield per recruit proxy reference points for Gulf of Maine Atlantic cod under both the ASAP SAW55_3BLOCK_BASE and ASAP_3BLOCK_BASE_M_SPLIT models.

Model	F_{MSY} (proxy)	Fmsy	SSB_{MSY} (mt)	MSY (mt)	Median age1 recruitment	SSB hinge (mt)	Hinge year
SAW55_3BLOCK_BASE	F40%	0.18	54,743 (40,207 - 73,354)	9,399 (6,806 - 13,153)	5,254	6,300	1998
SAW55_3BLOCK_BASE_M_SPLIT	F50%	0.29	19,605 (14,746 - 25,782)	4,840 (3,586 - 6,435)	9,446	7,900	1994

Table A.7.2. Short-term projections (3 years) for Gulf of Maine Atlantic cod under an assumed harvest of 75% F_{MSY} based on the ASAP SAW55_3BLOCK_BASE and SAW55_3BLOCK_BASE_M_SPLIT (*M*-ramp) models. **Note, the projections have not been adjusted for retrospective bias.*

Year	Input	SAW55_3BLOCK_BASE			SAW55_3BLOCK_BASE_M_SPLIT		
		Rebuild year at 75% Fmsy = 2022			Rebuild year at 75% Fmsy = 2019		
		Catch (mt)	Spawning stock biomass (mt)	F_{full}	Catch (mt)	Spawning stock biomass (mt)	F_{full}
2000	Result	5,823	9,070	0.62	5,823	12,976	0.45
2001	Result	8,055	11,885	0.72	8,055	17,222	0.51
2002	Result	6,509	11,951	0.57	6,509	17,208	0.40
2003	Result	6,497	10,005	0.67	6,497	13,966	0.48
2004	Result	5,766	8,594	0.68	5,766	11,878	0.50
2005	Result	5,441	7,213	0.92	5,441	9,831	0.70
2006	Result	4,268	6,752	0.78	4,268	9,311	0.60
2007	Result	5,527	8,725	0.75	5,527	11,693	0.60
2008	Result	7,375	10,282	0.94	7,375	13,297	0.77
2009	Result	8,355	11,457	0.98	8,355	14,332	0.83
2010	Result	7,670	11,141	0.87	7,670	12,979	0.79
2011	Result	6,830	9,903	0.86	6,830	10,221	0.90
2012	Assumed catch	3,767	8,995	0.46	3,767	7,711	0.58
2013	Projection	1,249	9,406	0.14	1,289	6,825	0.22
2014	Projection	1,503	12,143	0.14	1,396	8,426	0.22
2015	Projection	2,030	16,802	0.14	1,929	11,456	0.22

Table A.7.3. Reference points associated with states of nature of Gulf of Maine cod.

Reference Point	ASAP, 1982 start		SCAA, 1932 start, Ricker	
	M=0.2	M-ramp	M=0.2	M-ramp
SSB_{MSY} (B_{target})	54,743	19,605	20,910	11,180
1/2 SSB_{MSY} ($B_{threshold}$)	27,372	9,803	10,455	5,590
MSY	9,399	4,840	12,840	7,170
F_{MSY}	0.18	0.29	0.75	0.95
75% F_{MSY}	0.14	0.22	0.56	0.71

Table A.7.4. Results of consequence analysis of Gulf of Maine cod; column and row headers indicate 'true' state of nature and basis of management action (75% F_{MSY} for 2013 – 2015) under assumed states of nature; cells provide projections of SSB and fully recruited fishing mortality for 'true' states of nature for catch set according to assumed state of nature; diagonals (shaded) indicate that management actions were correctly specified for the state of nature.

			States of Nature											
Management actions - catches in 2013-2015	Year	Input	ASAP, 1982 start, M=0.2			ASAP, 1982 start, M-ramp			SCAA, 1932 start, Ricker, M=0.2			SCAA, 1932 start, Ricker, M-ramp		
			SSBmsy = 54,743 mt	MSY = 9,399 mt	F_{msy} = 0.18	SSBmsy = 19,605 mt	MSY = 4,840 mt	F_{msy} = 0.29	SSBmsy = 20,910 mt	MSY = 12,840 mt	F_{msy} = 0.75	SSBmsy = 11,180 mt	MSY = 7,170 mt	F_{msy} = 0.95
			Catch (mt)	SSB (mt)	F_{full}	Catch (mt)	SSB (mt)	F_{full}	Catch (mt)	SSB (mt)	F_{full}	Catch (mt)	SSB (mt)	F_{full}
ASAP, 1982 start, M=0.2	2011	Result	6,830	9,903	0.86	6,830	10,221	0.90	6,830	14,509	0.52	6,830	13,735	0.61
	2012	Assumed catch	3,767	8,995	0.46	3,767	7,711	0.58	3,771	16,427	0.25	3,771	12,582	0.37
	2013	Projection	1,249	9,406	0.14	1,249	6,833	0.21	1,249	17,661	0.07	1,249	10,921	0.12
	2014	Projection	1,503	12,143	0.14	1,503	8,436	0.24	1,503	24,375	0.06	1,503	13,527	0.13
	2015	Projection	2,030	16,802	0.14	2,030	11,432	0.23	2,030	33,073	0.06	2,030	16,709	0.15
ASAP, 1982 start, M-ramp	2011	Result	6,830	9,903	0.86	6,830	10,221	0.90	6,830	14,509	0.52	6,830	13,735	0.61
	2012	Assumed catch	3,767	8,995	0.46	3,767	7,711	0.58	3,771	16,427	0.25	3,771	12,582	0.37
	2013	Projection	1,289	9,389	0.14	1,289	6,825	0.22	1,289	17,661	0.07	1,289	10,921	0.13
	2014	Projection	1,396	12,145	0.13	1,396	8,426	0.22	1,396	24,328	0.06	1,396	13,488	0.12
	2015	Projection	1,929	16,937	0.13	1,929	11,456	0.22	1,929	33,161	0.06	1,929	16,791	0.14
SCAA, 1932 start, Ricker, M=0.2	2011	Result	6,830	9,903	0.86	6,830	10,221	0.90	6,830	14,509	0.52	6,830	13,735	0.61
	2012	Assumed catch	3,767	8,995	0.46	3,767	7,711	0.58	3,771	16,427	0.25	3,771	12,582	0.37
	2013	Projection	8,423	7,215	1.41	8,423	4,942	2.63	8,423	17,661	0.56	8,423	10,921	1.10
	2014	Projection	7,621	4,719	2.77	7,621	3,231	5.00	7,621	16,266	0.56	7,621	7,706	1.91
	2015	Projection	8,424	5,134	3.09	8,424	4,043	4.89	8,424	18,367	0.56	8,424	7,032	2.42
SCAA, 1932 start, Ricker, M-ramp	2011	Result	6,830	9,903	0.86	6,830	10,221	0.90	6,830	14,509	0.52	6,830	13,735	0.61
	2012	Assumed catch	3,767	8,995	0.46	3,767	7,711	0.58	3,771	16,427	0.25	3,771	12,582	0.37
	2013	Projection	5,803	8,214	0.81	5,803	7,711	1.46	5,803	17,661	0.34	5,803	10,921	0.71
	2014	Projection	4,507	7,354	0.81	4,507	5,450	1.84	4,507	19,447	0.25	4,507	9,252	0.71
	2015	Projection	5,020	9,159	0.76	5,020	4,636	1.46	5,020	25,272	0.22	5,020	10,385	0.71

Table A.7.5. Fraction of feasible projection runs from the Gulf of Maine Atlantic cod consequence analysis. Infeasible runs occur when the projection is attempting to harvest more fish than exist in the population's exploitable biomass will allow; Column headers indicate state of nature and row headings indicate basis of management action

Model	ASAP, 1982 start, M=0.2	ASAP, 1982 start, M-ramp	SCAA, 1932 start, Ricker, M=0.2	SCAA, 1932 start, Ricker, M-ramp
SAW55_3BLOCK_BASE	1.00	1.00	1.00	1.00
SAW55_3BLOCK_BASE_M_SPLIT	1.00	1.00	1.00	1.00
SCAA_1932_RICKER	0.44	0.13	1.00	0.69
SCAA_1932_RICKER_M_RAMP	0.97	0.93	1.00	1.00

Note:
SAW55_3BLOCK_BASE = ASAP, 1982 start, *M* = 0.2
SAW55_3BLOCK_BASE_M_SPLIT = ASAP, 1982 start, *M*-ramp
SCAA 1932 RICKER = SCAA, 1932 start, Ricker, *M* = 0.2
SCAA 1932 RICKER *M* RAMP = SCAA, 1932 start, Ricker, *M*-ramp

Table A.7.6. Status of 2013 spawning stock biomass and fishing mortality of Gulf of Maine cod; column and row headings indicate 'true' state of nature and basis of management action respectively; cells indicate 2013 stock status resulting from application of management actions under assumed state of nature (rows) to 'true' state of nature.

			True state of nature			
			ASAP, 1982 start		**SCAA, 1932 start, Ricker**	
			M=0.2	**M-ramp**	**M=0.2**	**M-ramp**
Management action basis	**ASAP, 1982 start, YPR**	**M=0.2**	Overfished, overfishing is not occuring	Overfished, overfishing is not occuring	Not overfished, overfishing is not occuring	Not overfished, overfishing is not occuring
		M-ramp	Overfished, overfishing is not occuring	Overfished, overfishing is not occuring	Not overfished, overfishing is not occuring	Not overfished, overfishing is not occuring
	SCAA, 1932 start, Ricker	**M=0.2**	Overfished, overfishing is occuring	Overfished, overfishing is occuring	Not overfished, overfishing is not occuring	Not overfished, overfishing is occuring
		M-ramp	Overfished, overfishing is occuring	Overfished, overfishing is occuring	Not overfished, overfishing is not occuring	Not overfished, overfishing is not occuring

Appendix A.7 Figures

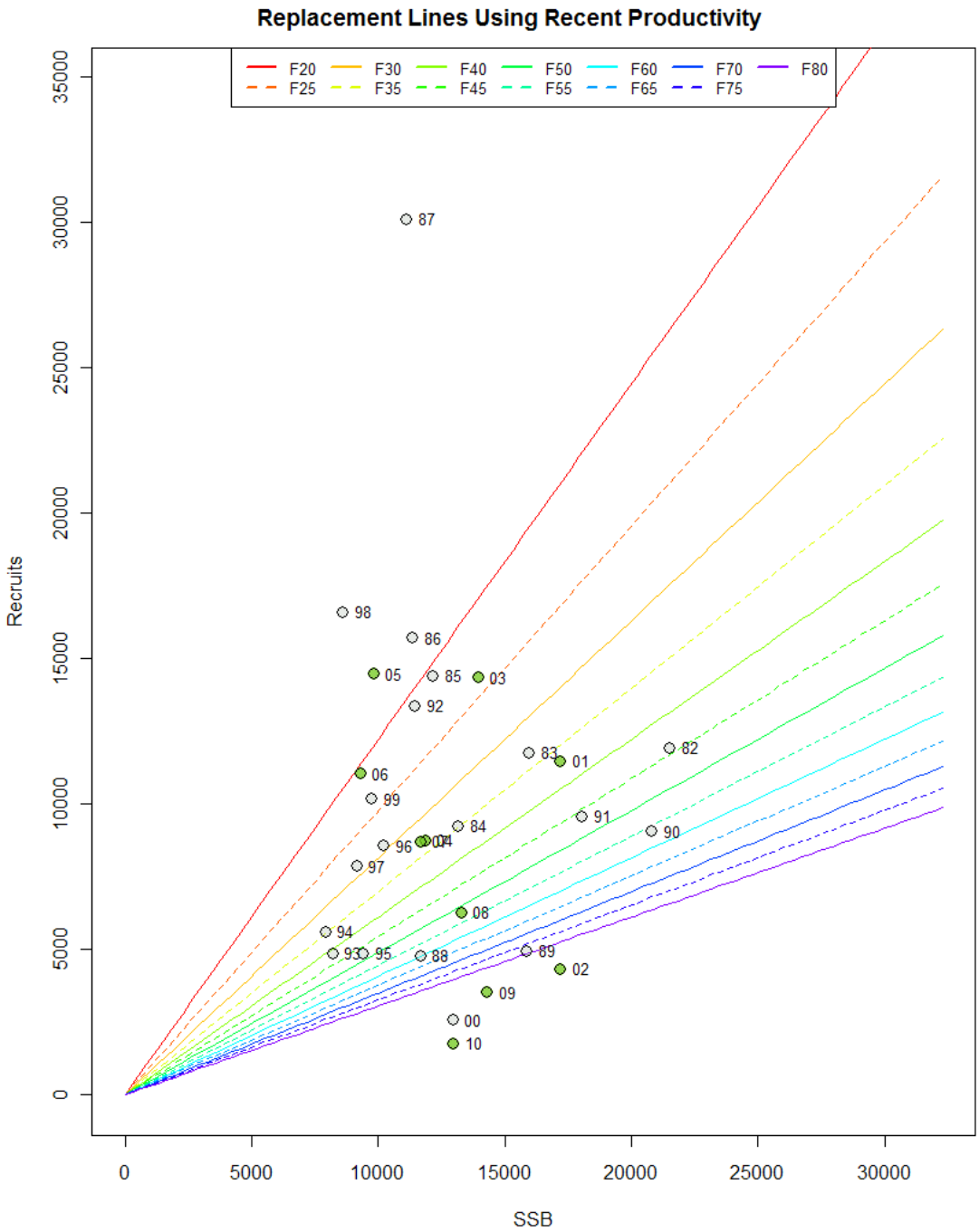


Figure A.7.1. Comparison Gulf of Maine Atlantic cod replacement lines under a range of percent spawner per recruit values based on an *M*-ramp (0.2→0.4) assumption (based on SAW55_3BLOCK_BASE_M_SPLIT model). The most recent ten years of recruitment observations (2001-2010) are highlighted green.

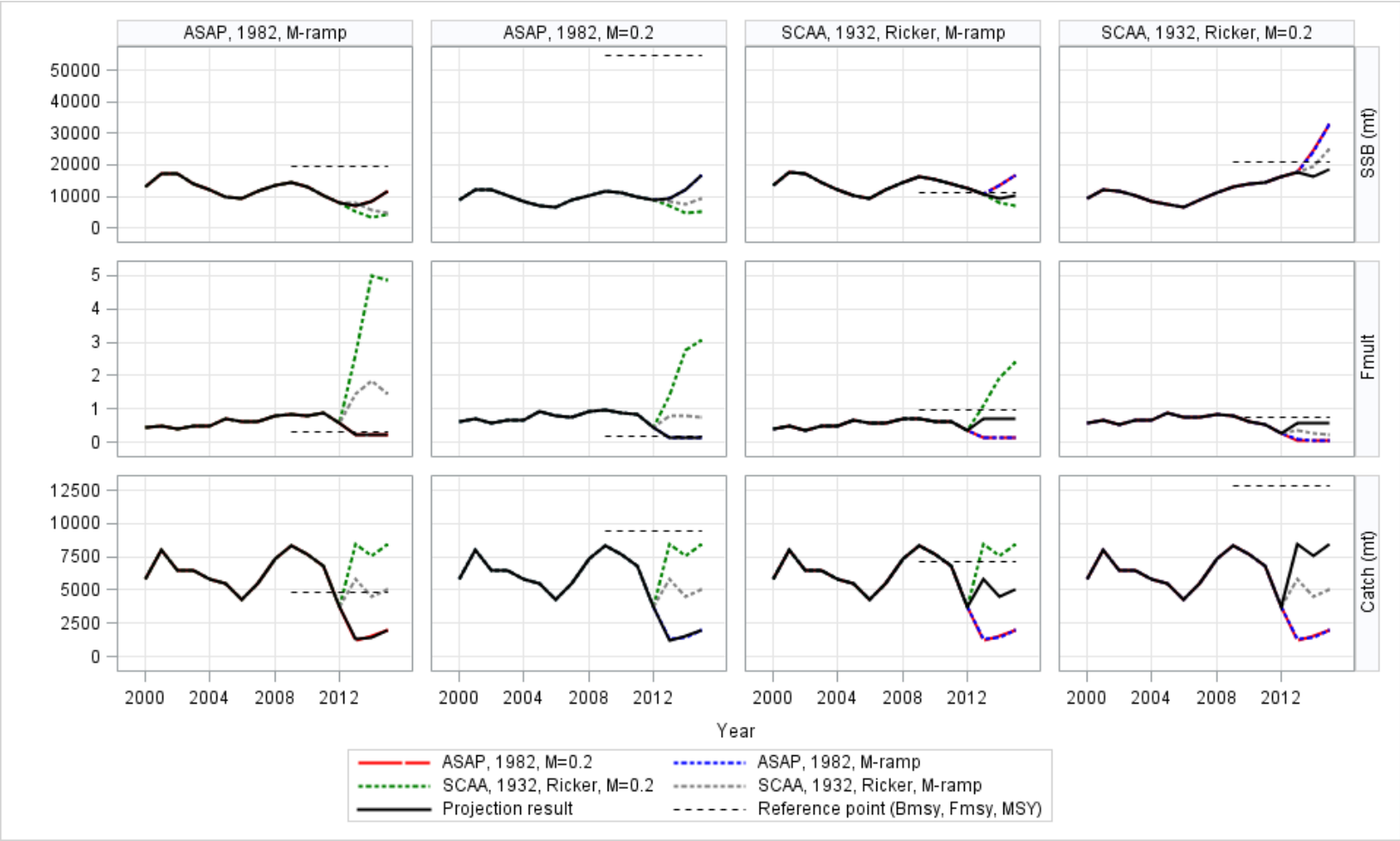


Figure A.7.2. Trends in Gulf of Maine cod SSB (top row), fully recruited fishing mortality (middle row) and catch (bottom row) during 2000 – 2015; column headers indicate 'true' state of nature; cells provide trend in indicator under 'true' state of nature when catch during projection period (based on 75% F_{MSY} is correctly specified (black) and mis-specified (red: ASAP, 1982, $M = 0.2$; blue: ASAP, 1982, M-ramp; green: SCAA, 1932, Ricker, $M = 0.2$; grey: SCAA, 1932, Ricker, M-ramp; MSY – based reference points indicated in dashed line on each pl