A Comparison Between ADAPT-VPA and ASPM-based Assessments of the Gulf of Maine Cod Stock

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ABSTRACT

ADAPT-VPA and ASPM assessment methods are applied to the same data set for the Gulf of Maine cod stock to attempt to ascertain the reasons for the rather different results provided by past applications of the two approaches. A number of sensitivity tests for the ASPM assessment are also conducted. Results indicate the primary reasons for the past differences to be the longer period of data which the ASPM approach is able to take into account, and the fact that this approach estimates selectivity to be decreasing at larger ages whereas the ADAPT-VPA method assumes the selectivity at such ages to be flat. Arguments are presented that an ASPM-based assessment of this resource would provide a better basis for management advice than the current ADAPT-VPA method. Since the former consistently indicates current status of the resource to be appreciably better relative to the B^{sp}_{MSY} reference point than does the latter, such a suggestion has important implications for current management measures for the Gulf of Maine cod fishery.

INTRODUCTION

This document presents further work on the evaluation of the status of the Gulf of Maine cod stock, comparing the ASPM and the ADAPT-VPA approaches. Importantly, calculations use identical (post-1981) data for both approaches, which both also utilise Pope’s form of the catch equation. First some data and methodological adjustments relative to those of the most recent earlier ASPM analyses of Butterworth (2003) are detailed and a consequently revised “ASPM New Reference Case” assessment is developed. Sensitivity tests for this assessment are also presented. A series of ADAPT-VPA variants are computed and compared to the results obtained using the ASPM approach, with the aim of identifying the reasons for differences between results of applications of the two approaches reported earlier.

DATA

The data used in previous ASPM analyses of the Gulf of Maine cod stock (Butterworth *et al.* 2003a,b,c) did not include all the information used to produce the ADAPT-VPA results of Mayo *et al.* (2002). The ADAPT-VPA analyses presented in this document now include exactly the same data (kindly provided by NEFSC staff) as used in the Mayo *et al.* (2002) analysis, while the ASPM analyses also include the data available pre-1982.

The data are detailed in Appendix 1.

METHODS

ASPM methodology

The basic ASPM methodology, with its associated penalised MLE approach, is set out in Appendix 2.

The "ASPM New Reference Case" of this document, as for previous Reference Cases, assumes a Beverton-Holt stock-recruitment function (γ=1) and that exploitation starts in 1893 with the resource at unexploited equilibrium (θ=1, ϕ=0). However, in a change from previous practice, it now estimates stock-recruitment function residuals for all the years from 1894 to 2001, i.e. covering the complete history of the fishery examined, with deterministic unexploited equilibrium age-structure assumed for the starting 1893 population. Note that the stock-recruitment penalty function (Appendix 2, equation A2.28) added to the negative log likelihood ensures that recruitment is set to its stock-recruitment function expectation in years for which the available catch-at-age or survey abundance information has no influence. Anomalous behaviour of recruitment residual MLEs, which sometimes occurs in such models, is avoided in this instance because for every year for which there are some abundance data, there are also catch-at-age data. Steepness h is now restricted so that it does not exceed 0.98; thus recruitment starts falling towards zero as spawning biomass B^{sp} is reduced, and *before* it reaches zero. For *MSY* and *MSYL* computations only, commercial selectivity is redefined as $S_a^*(F)$ where:

$$S_a^*(F) = \begin{cases} S_a & F < 0.95 \\ S_a + (1 - S_a)\left[\dfrac{(F - 0.95)^2}{0.05^2}\right] & 0.95 \le F \le 1 \end{cases} \qquad (1)$$

i.e. there is a proportionately greater focus on younger fish at very large *F*. The reason for the modification of equation (A2.29 of Appendix 2) is that for Pope's form of the catch equation, when the fishing proportion *F* attains its maximum value F = 1, age groups for which $S_a < 1$ do not tend to zero size even though the age-at-first-capture is less than the age-at-first-maturity. The modification of equation (1) "rectifies" this, ensuring that B^{sp} decreases as required in this limit.

ADAPT-VPA methodology

The methodology used for the ADAPT-VPA assessments is as described in Appendix 3 and replicates the methodology described in the reference manual of the VPA/ADAPT Model

Version 2.1.1 (Anon., 2003). The "VPA Reference Case" specifications follow those of the "final VPA formulation" in Mayo *et al.* (2002). Note that for this Reference Case:

- The partial recruitment vector (PR_a) is taken as: (0.000, 0.053, 0.421, 1.000, 1.000, 1.000) for ages *a* of 1 to 6 (as in Mayo *et al.* 2002), age 6 being the oldest true age (*m*-1, with *m* the age of the plus group, which is 7+ in this case).
- The fully-recruited fishing mortality in year *y* (F_y^{FULL}) is computed using the "classic method", i.e. F_y^{FULL} is taken as the average of the fishing mortalities in year *y* for fully recruited age classes, excluding the oldest true age (i.e. average over ages 4 and 5); thus the PR_a values input for ages 1-3 play no role in this application. The fishing mortality on the oldest true age in year *y* ($F_{m-1,y} = F_{6,y}$) is then computed as the product of F_y^{FULL} and the input $PR_{m-1}(= PR_6 = 1)$. In all years, the fishing mortality on the 7+ group ($F_{m,y}$) is computed as the product of $F_{m-1,y}$ and the input plus-group ratio (α). In the "VPA Reference Case" α is taken as 1 for all years. Spawning stock biomass is calculated at spawning time (March 1) by applying the period-specific maturity ogives (Table A1.1 of Appendix 1). Natural mortality is taken as independent of age and equal to 0.2 for the "VPA Reference Case".
- Pope's form of the catch equation is used to back-calculate numbers in each cohort.

RESULTS

ASPM

Results for the current ASPM New Reference Case are compared to those for the July 2003 (Butterworth *et al.* 2003c) and October 2003 (Butterworth, 2003) New Reference Cases in Table 1. Even with the addition now of the MA survey and CPUE data (Tables A1.8-10 of Appendix 1), the estimates of K^{sp}, *M*, *MSY* and $MSYL^{sp}$ are similar to the results from the October 2003 evaluations. The model estimate for the steepness parameter is still high (0.98). The addition of the extra data brings the estimate of natural mortality *M* down to 0.25 yr^{-1}. Figs 1 and 2 compare the time-series of spawning biomass and fishing proportion respectively, for these three cases. The current ASPM New Reference Case results do not modify the key feature of earlier results from this approach, which suggested a resource above *MSYL*, in contrast to the ADAPT-VPA based inference that the resource is currently well below its *MSYL*.

Figs 3 to 4 show the current ASPM New Reference Case fit to the abundance indices and catch-at-age data. The model shows broadly reasonable fits to all the indices. The bubble plots in Fig. 5 show the standardised catch-at-age residuals for the survey and commercial data. The patterns of residuals for Fig. 5 do not indicate any very obvious model-misspecification.

Four sensitivities for the current ASPM New Reference Case assessment have been conducted so that ASPM and ADAPT-VPA results can be more easily compared. Results for these sensitivities are shown in Table 2.

In Case IV, with *h* reduced to 0.8 and *M* to 0.2, current abundance is still estimated higher than by the ADAPT-VPA. Current spawning biomass drops below *MSYL*, to about 84% of *MSYL*, which still differs substantially from the 26% of the ADAPT-VPA based estimate ($B_{2001}^{sp} = 21843$ t - from VPA and $B_{MSY}^{sp} = 82830$ t - NEFSC, 2002).

The current ASPM New Reference Case assessment (as did that for October 2003) allows for the possibility of decreasing commercial selectivity at large age (by estimating the selectivities for ages 6 and 7+ directly). In Case V, the commercial selectivity is forced to 1 for ages 6 and 7+, a selectivity pattern which is more comparable to that of the ADAPT-VPA assessment. For comparison purposes, the natural mortality M is fixed at 0.25 (the estimate from the current ASPM New Reference Case assessment). In this case, current spawning biomass is estimated to be similar to that from the ADAPT-VPA assessment (see Table 6). However, the commercial catch-at-age residuals for this case that are shown in Fig. 6 display a clear systematic pattern, with virtually all the 6 and 7+ residuals negative.

The ASPM methodology allows for the use of data in all years, even if commercial catch-at-age data are not available for the whole period, and therefore pre-1982 survey data (biomass series and catches-at-age) have been included in the current ASPM New Reference Case assessment. These earlier data have not been included in Cases VI and VII. In Case VI, excluding the pre-1982 survey data results in an estimate of natural mortality M close to that used in the ADAPT-VPA assessment (0.2). The estimate of steepness h is also reduced to 0.81. Although, the current abundance is still estimated to be high, and well above the estimate from the ADAPT-VPA assessment, it is nevertheless estimated to be closer to *MSYL* than in the case of the current ASPM New Reference Case (see also Fig. 7). In Case VII, M is fixed at the value estimated in the current ASPM New Reference Case assessment (0.25) to further facilitate comparisons.

A number of further sensitivity tests to the current New ASPM Reference Case are reported in Table 3. These comprise:

- Use of a more general form for the stock-recruitment relationship to the Beverton-Holt form assumed for the current ASPM New Reference Case (Case VIII) – see equation A2.4,
- increasing the variability of the stock-recruitment fluctuations (σ_R=0.4 instead of 0.25 – Case IX),
- starting the assessment in a later year, first assuming unexploited equilibrium in the start year (Cases Xa-c for starting years 1950, 1970 and 1982 respectively), and then with the θ and ϕ “starting” parameters treated as estimable (Cases XIa-c) – see equations A2.15 to A2.19,
- changing the commercial selectivity function, first so that the selectivity pre-1982 is the same as that post-1991 (Case XIIa), and secondly to change in the reverse direction by increasing the selectivity of younger fish pre-1982 by inputting a selectivity of 0.3 for age 2, 0.85 for age 3 and 1.0 for age 4 (Case XIIb), and
- a retrospective analysis (Cases XIIIa-c).

Fig. 8 compares estimated spawning biomass trajectories for these sensitivity tests with that for the current ASPM New Reference Case. The retrospective results are illustrated in Fig. 9, and Fig. 10 compares stock-recruitment plots for the current ASPM New Reference Case (Beverton-Holt form), and a Ricker-like relationship obtained when a more general functional form is admitted.

A sensitivity in which an age-dependent natural mortality is estimated was also run, but as the results did not change from those of the current ASPM New Reference Case, they are not included here.

ADAPT-VPA

The "VPA Reference Case" described here corresponds to the assessment presented in *Mayo et al.* (2002). Table 4 gives the numbers-at-age matrix for this VPA Reference Case, while Fig. 11 shows a bubble plots of the residuals for the survey and CPUE series for this assessment. There is a suggestion of some banding in these plots, with groups of years with nearly all positive, or nearly all negative residuals.

Table 5 contrasts the objective function contribution from each abundance index used for the VPA Reference Case, a), and a series of five sensitivity tests to this assessment. These sensitivities are:

b) "PR(6)=0.8": the partial recruitment for age 6 is fixed at 0.8, instead of assuming that fish of age 6 are fully recruited, as is the case in the VPA Reference Case; this is equivalent to a decrease in selectivity of older fish;

c) "PR(6)=0.4": the partial recruitment for age 6 is fixed at 0.4;

d) "*M*=0.25": the natural mortality is fixed at 0.25 (the value estimated in the current ASPM New Reference Case assessment) instead of 0.2;

e) "α=0.5": the plus-group ratio (reflecting the relative selectivity of 7+ fish to those of age 6) is fixed at 0.5 for all years instead of 1.0; and

f) "*M*=0.25, PR(6)=0.4, α=0.5": a combination of cases c), d) and e).

Table 6 compares the 1982 and 2001 spawning biomass for the ASPM and VPA assessments.

Fig. 12 compares the time-series of spawning biomass for the current ASPM New Reference Case, the VPA Reference Case and the five VPA sensitivity tests, while Fig. 13 shows the commercial selectivities for these cases. Commercial selectivities for the VPA assessments have been computed as:

$$S_a^{com} = \sum_{y=1992}^{2001} F_{a,y} \Big/ 10 \qquad (2)$$

and then renormalised so that $\max(S_a^{com}) = 1$.

It is clear from Fig. 12 that the VPA results obtained when the selectivity on older ages is decreased (PR(6)=0.4 and α=0.5) and the natural mortality increased to 0.25 (i.e. sensitivity f)) show a similar behaviour to those of the ASPM assessment.

DISCUSSION

Now that the same data are being used in the ASPM and VPA assessments (from 1982 only in the VPA assessments and from the beginning of the series in the ASPM assessments), the results of the two methods are more readily and appropriately compared. It is clear that both methods can generate similar results under certain assumptions for their data inputs and parameter choices. By running a series of sensitivity tests for both the ASPM and ADAPT-VPA assessments, two primary reasons for the differences between earlier results from the two methods have been identified: a) the use (or otherwise) of pre-1982 data, and b) the assumption made concerning the fishing selectivity of older fish.

Pre-1982 data

Including the data available pre-1982 in the ASPM assessments has a considerable impact on the results and this points to a relative disadvantage for the VPA approach. Results from Case VI (Table 2) show that excluding these data brings the estimate of $B_{2001}^{sp}/B_{MSY}^{sp}$ down to about 1, compared to a ratio of nearly 2 in the current ASPM New Reference Case. Natural mortality and steepness estimates are also reduced, but the results for Case VII show that even with natural mortality fixed to 0.25 (the value estimated for the current ASPM New Reference Case) the estimate of $B_{2001}^{sp}/B_{MSY}^{sp}$ is substantially reduced when excluding the pre-1982 data. The current abundance, however, is still estimated to be much higher than in the VPA Reference Case (Table 6). Fig. 7 compares the spawning biomass trajectories for the current ASPM New Reference Case and Case VI.

The pre-1982 catch-at-age data from the NEFSC offshore spring and autumn surveys are the cause of this effect. This was determined by including each set of pre-1982 data one at a time in turn in the ASPM assessment. These data (Tables A1.6 and A1.7 in Appendix 1) show that more older fish (ages 6 and 7+ principally) were available at the beginning of the period (the 1960's and 1970's) than later. As the surveys have been consistent over time, selectivity must presumably have remained unchanged, so that the age data simply reflect different proportions in the true population over time. This observation accordingly is consistent with the results of the current ASPM New Reference Case assessment, which estimates the population to be nearly returned to its pre-exploitation level in the 1970's.

Fishing selectivity

The current ASPM New Reference Case has an estimated selectivity for the 7+ group that is much less than for age 6, for both the NEFSC offshore surveys and the commercial catches. This is in sharp contrast to the assumption of the VPA Reference Case which sets fishing mortality for the plus-group in the commercial catches to be equal to that on age 6. This plays an important role in explaining the difference between the ASPM and ADAPT-VPA results. By forcing a flat selectivity from age 5 in the ASPM analysis (Case V), the current estimate of spawning biomass is reduced to a value close to the VPA Reference Case (Table 6), which corresponds to approximately 80% of the estimated *MSYL*. However, this flat selectivity option causes a severe deterioration in the fit to the data, particularly the fit to the commercial catch-at-age data. In this case, the predicted catches of ages 6 and 7+ are consistently overestimated throughout the period (Fig. 6).

Similarly, if the selectivity is forced to decrease for ages 6 and 7+ in the VPA assessments (e.g. case f), Fig. 13), the estimate of current spawning biomass is greatly increased (Table 6) and the abundance trajectory is very similar to that of the ASPM New Reference Case assessment (Fig. 12).

Admittedly, a decrease in commercial selectivity for older ages is not supported in terms of the objective function used for the VPA assessments (Table 5). It should be noted, however, that information on the plus group is not taken into account in the fitting process used for the VPAs, unlike for the ASPM.

Other ASPM sensitivity tests

Tests involving a more general form of the stock-recruitment relationship (which is estimated to be Ricker-like, as $\hat{\gamma} > 1$, Case VIII), a larger input value for recruitment variability σ_R, and alternative pre-1982 commercial catch selectivity functions all lead to little change in spawning biomass estimates over the last 40 years, though there are some differences before then (Fig. 8). If the starting year for the analysis is changed from 1893, while nevertheless assuming pre-exploitation equilibrium at the revised start time, biomass estimates over the most recent 20 years are scarcely affected for commencement year choices as recent as 1970 (Fig. 8). The estimation of parameters reflecting non-equilibrium at the start time in such circumstances increases the variability in results, but nevertheless B_{2001}^{sp} generally remains estimated close to or in excess of B_{MSY}^{sp} (Fig. 8 and Table 3). The current ASPM New Reference Case assessment exhibits no marked retrospective pattern (Fig. 9).

The sensitivities do nevertheless point towards two likely desirable future modifications to this New Reference Case. First, comparisons of σ_R (input) with σ_R (output) (Table 3) suggest that the former should be increased from its presently chosen value of 0.25. The likely consequence of this would be some reduction in estimation precision. Perhaps more important is the indication from Case VIII (Table 3) of an estimate of the stock-recruitment function parameter γ whose entire 95% CI exceeds 1; in other words, there is a statistically significant indication of a dome-shaped stock-recruitment function. The associated indication of a tendency towards lower recruitment at higher spawning stock size explains the penchant for fits using the monotonically increasing Beverton-Holt form to tend towards flattish trends and hence values of steepness h close to their maximum limit of 1 (or here the bound of 0.98 imposed) in such circumstances. Allowance for the dome shape sees B_{MSY}^{sp} increase, and with it *MSYL*, so that Case VIII provides the one instance in this paper of estimates of $B_{2001}^{sp}/B_{MSY}^{sp}$ which are notably below 1 at values slightly above 0.5. These estimates nevertheless remain well above the 0.26 of NEFSC (2002), essentially because of the greater ASPM-based estimate of B_{2001}^{sp}.

In addition to further examination of this Ricker-like form, future work might desirably focus on an extension of the approach to a fully Bayesian form (Butterworth *et al.* 2003c reports some initial results for such an extension). Given the non-linearities of the problem with likely associated asymmetric confidence intervals, posterior medians might provide more appropriate statistics upon which to base management decisions than the posterior modes to which the penalised MLEs of this paper correspond. Clearly the ASPM approach also warrants application to other US Northeast groundfish stocks for which appropriate data are available. Furthermore, given the important role that appears to be played by dome-shaped selectivity, the population model might be improved by extending the age-structure beyond the plus-group age used for the data. This would allow for differential selectivity-at-age within the plus-group, before aggregating model predicted values for comparison with observations in the model fitting process.

CONCLUSIONS

The analyses of this paper would seem to have successfully addressed the February 2003 Durham independent Peer Review Panel advocation to seek reasons for the different results presented at that time for ADAPT-VPA and ASPM assessments of (at least) the Gulf of Maine cod stock. These differences result from the longer period of survey data that the ASPM approach is able to take into account, and from the ASPM's estimation of selectivity as decreasing at larger ages whereas the ADAPT-VPA method assumes selectivity at these ages to be flat.

The Review Panel also expressed concern that "the ASPM seems to be overly sensitive to the assumptions made" (paragraph 11 of their response regarding biological reference points in their Chair's report of the 3-8 February 2003 meeting). That comment retains some validity for the updated ASPM results reported here, but as evident from Table 6, it is equally true of ADAPT-VPA once sensitivity tests to the assumptions of that approach are similarly explored. Nevertheless, the greater sensitivity would seem to lie in the estimation of B^{sp}_{MSY}, rather than of the current spawning biomass B^{sp}_{2001}.

The issue of the extent to which selectivity might decline at larger ages is of particular importance in estimating the current status of the Gulf of Maine cod stock. In favour of the flat selectivity assumption underlying the Mayo *et al.* (2002) ADAPT-VPA assessment is that this is favoured in terms of the fitting criterion adopted for that application. However, that has to be weighed against internal mathematical inconsistencies in that particular application of ADAPT-VPA (see Appendix 4), together with the fitting criterion ignoring plus-group related information, particularly when attempts to force such flatness onto the ASPM approach (Case V) lead to clear evidence of model misspecification (Fig. 6).

The ASPM approach has the advantages of allowing more data to be taken into account, and not having to make the unrealistic assumption of error-free catch-at-age estimation. It appears able to estimate M with relatively narrow confidence intervals (see Table 1), though the appreciable decline it suggests in the selectivity for older cod merits further discussion. Furthermore, there are indications that the possibility of a dome-shaped stock-recruitment curve should be entertained, rather than limiting assessments to the Beverton-Holt form.

Viewed overall, these considerations indicate that it would be preferable to base management recommendations for the Gulf of Maine cod stock on an ASPM rather than the present ADAPT-VPA based assessment approach. Further consideration of this suggestion is of particular importance as the ASPM assessments explored all show the general feature of estimating the status of this stock to be appreciably better relative to the B^{sp}_{MSY} reference point than do the ADAPT-VPA based inferences of NEFSC (2002). Acceptance of this conclusion would in turn imply that the management restrictions currently applied to this resource would appropriately be made less stringent.

The comments of the preceding paragraph should not be misinterpreted as advocacy of a particular implementation of the ASPM approach (such as the current ASPM New Reference Case) as the specific basis for revised management of the Gulf of Maine cod resource. Clearly scope remains for further discussion to hopefully reach consensus on the best formulation of the approach to apply.

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Table 1: Estimates of management quantities for the Case I), Case II) and Case III) assessments, which constitute the preceding two and current "ASPM New Reference Cases". Biomass units are tons. The two sets of estimates given for quantities such as $B^{sp}(MSY)$ refer to the two different commercial selectivity functions: i) for 1893-1991 and ii) from 1992+. Values in parenthesis next to the MLE estimates of $B^{sp}(2001)/B^{sp}(MSY)$, h and M are 95% CIs derived from likelihood profiles. Values in bold are inputs to the model. For further details/definitions of the symbols used in this and following similar Tables, see Appendix 2 and particularly section A2.5.

	I) July 2003 "New Reference Case"				**II) October 2003 "Case 8" (New Reference Case)**				**III) Current ASPM New Reference Case**					
-lnL: overall	-126.2				-139.8				73.3					
-lnL: Survey	-19.6				-18.8				-21.3					
-lnL: CAA	-52.9				-57.8				-48.8					
-lnL: CAAsurv	-122.1				-132.0				76.1					
-lnL: RecRes	68.4				68.8				67.4					
K^{sp}	89822				126044				137964					
$B^{sp}(2001)$	41645				45664				41559					
$B^{sp}(MSY)$	14921	19522			19882	21357			22059	23545				
$B^{sp}(2001)/B^{sp}(MSY)$	2.79	2.13			2.30	2.14			1.88	1.77	(1.71; 1.78)			
$MSYL^{sp}$	0.17	0.22			0.16	0.17			0.16	0.17				
MSY	12286	11743			11297	11297			10754	10889				
F(MSY)	0.95	0.95			0.61	0.73			0.54	0.62				
F(MSY)*	3.00	3.01			0.95	1.32			0.78	0.98				
F(2001)	0.26				0.28				0.27					
F(2001)*	0.30				0.33				0.31					
h	0.98				0.98				0.98	(0.96; 0.98)				
M	0.42				0.31				0.25	(0.20; 0.28)				
Gamma	**1.00**				**1.00**				**1.00**					
Theta	**1.00**				**1.00**				**1.00**					
Phi	**0.00**				**0.00**				**0.00**					
σ_R (in,out)	**0.25**				**0.25**				**0.25**	0.47				
Selectivities	WHSpr	WHAut	Com1	Com2	WHSpr	WHAut	Com1	Com2	WHSpr	WHAut	MASpr	MAAut	Com1	Com2
	0.10	0.05	0.01	0.00	0.19	0.08	0.02	0.00	0.10	0.06	1.00	1.00	0.02	0.00
	0.25	0.13	0.15	0.04	0.38	0.23	0.17	0.05	0.30	0.22	0.63	0.56	0.17	0.05
	0.40	0.40	0.69	0.43	0.58	0.58	0.72	0.47	0.50	0.50	0.39	0.32	0.69	0.49
	0.55	0.55	0.97	0.93	0.77	0.77	0.97	0.94	0.70	0.70	0.25	0.18	0.96	0.95
	0.70	0.70	1.00	1.00	0.97	0.97	1.00	1.00	0.90	0.90	0.15	0.10	1.00	1.00
	0.85	0.85	1.00	1.00	1.00	1.00	0.97	0.69	1.00	1.00	0.10	0.06	1.00	0.64
	1.00	1.00	1.00	1.00	0.58	0.58	0.30	0.25	0.51	0.51	0.06	0.03	0.18	0.20

Table 2: Estimates of management quantities for Case III) (the current ASPM New Reference Case) together with Case IV), Case V), Case VI) and Case VII) assessments. These alternatives are shown primarily to assist in relating ASPM to ADAPT-VPA results Biomass units are tons. The two sets of estimates given for quantities such as $B^{sp}(MSY)$ refer to the two different commercial selectivity functions: i) for 1893-1991 and ii) from 1992+. Values in bold are inputs to the model.

	III) Current ASPM New Reference Case						**IV) With h fixed to 0.8 and M to 0.2**						**V) With flat commercial selectivity from age 5 and M fixed at 0.25**					
-lnL: overall	73.3						77.9						99.1					
-lnL: Survey	-21.3						-22.9						-22.2					
-lnL: CAA	-48.8						-48.6						-29.0					
-lnL: CAAsurv	76.1						80.9						74.6					
-lnL: RecRes	67.4						68.5						75.7					
K^{sp}	137964						200581						106367					
$B^{sp}(2001)$	41559						39551						28055					
$B^{sp}(MSY)$	22059	23545					45368	47299					27162	29082				
$B^{sp}(2001)/B^{sp}(MSY)$	1.88	1.77	(1.71; 1.78)				0.87	0.84					1.03	0.96				
$MSYL^{sp}$	0.16	0.17					0.23	0.24					0.26	0.27				
MSY	10754	10889					9276	9716					9324	9566				
$F(MSY)$	0.54	0.62					0.32	0.37					0.31	0.33				
$F^*(MSY)$	0.78	0.98					0.39	0.46					0.37	0.41				
$F(2001)$	0.27						0.30						0.29					
$F^*(2001)$	0.31						0.36						0.34					
h	0.98	(0.96; 0.98)					**0.80**						0.98					
M	0.25	(0.20; 0.28)					**0.20**						**0.25**					
Gamma	**1.00**						**1.00**						**1.00**					
Theta	**1.00**						**1.00**						**1.00**					
Phi	**0.00**						**0.00**						**0.00**					
σ_R (in,out)	**0.25**	0.47					**0.25**	0.47					**0.25**	0.50				
Selectivities	WHSpr	WHAut	MASpr	MAAut	Com1	Com2	WHSpr	WHAut	MASpr	MAAut	Com1	Com2	WHSpr	WHAut	MASpr	MAAut	Com1	Com2
	0.10	0.06	1.00	1.00	0.02	0.00	0.12	0.07	1.00	1.00	0.02	0.00	0.10	0.06	1.00	1.00	0.02	0.00
	0.30	0.22	0.63	0.56	0.17	0.05	0.33	0.26	0.60	0.54	0.18	0.06	0.31	0.23	0.63	0.56	0.19	0.06
	0.50	0.50	0.39	0.32	0.69	0.49	0.55	0.55	0.36	0.29	0.71	0.51	0.53	0.53	0.39	0.32	0.76	0.52
	0.70	0.70	0.25	0.18	0.96	0.95	0.76	0.76	0.21	0.15	0.96	0.95	0.74	0.74	0.25	0.18	0.98	0.95
	0.90	0.90	0.15	0.10	1.00	1.00	0.97	0.97	0.13	0.08	1.00	1.00	0.95	0.95	0.16	0.10	1.00	1.00
	1.00	1.00	0.10	0.06	1.00	0.64	1.00	1.00	0.08	0.04	1.00	0.60	1.00	1.00	0.10	0.06	1.00	1.00
	0.51	0.51	0.06	0.03	0.18	0.20	0.36	0.36	0.05	0.02	0.09	0.14	0.79	0.79	0.06	0.03	1.00	1.00

Table 2: continued

	III) Current ASPM New Reference Case						**VI) With data from 1982 only**						**VII) With data 1982 only and *M* fixed at 0.25**					
-lnL: overall	73.3						26.2						27.5					
-lnL: Survey	-21.3						-5.7						-5.5					
-lnL: CAA	-48.8						-49.3						-49.6					
-lnL: CAAsurv	76.1						47.3						49.2					
-lnL: RecRes	67.4						34.0						33.4					
K^{sp}	137964						227869						188491					
$B^{sp}(2001)$	41559						52399						50975					
$B^{sp}(MSY)$	22059	23545					49916	50585					46929	47603				
$B^{sp}(2001)/B^{sp}(MSY)$	1.88	1.77	(1.71; 1.78)				1.05	1.04					1.09	1.07				
$MSYL^{sp}$	0.16	0.17					0.22	0.22					0.25	0.25				
MSY	10754	10889					10233	10562					10405	10736				
F(MSY)	0.54	0.62					0.34	0.40					0.33	0.39				
F(MSY)*	0.78	0.98					0.42	0.51					0.41	0.49				
F(2001)	0.27						0.25						0.24					
F(2001)*	0.31						0.28						0.28					
h	0.98	(0.96; 0.98)					0.81						0.75					
M	0.25	(0.20; 0.28)					0.20						**0.25**					
Gamma	**1.00**						**1.00**						**1.00**					
Theta	**1.00**						**1.00**						**1.00**					
Phi	**0.00**						**0.00**						**0.00**					
σ_R (in,out)	**0.25**	0.47					**0.25**	0.33					**0.25**	0.33				
Selectivities	WHSpr	WHAut	MASpr	MAAut	Com1	Com2	WHSpr	WHAut	MASpr	MAAut	Com1	Com2	WHSpr	WHAut	MASpr	MAAut	Com1	Com2
	0.10	0.06	1.00	1.00	0.02	0.00	0.11	0.03	1.00	1.00	0.02	0.00	0.09	0.03	1.00	1.00	0.02	0.00
	0.30	0.22	0.63	0.56	0.17	0.05	0.33	0.23	0.62	0.54	0.19	0.06	0.32	0.22	0.65	0.56	0.18	0.05
	0.50	0.50	0.39	0.32	0.69	0.49	0.55	0.55	0.38	0.29	0.74	0.53	0.55	0.55	0.42	0.32	0.73	0.51
	0.70	0.70	0.25	0.18	0.96	0.95	0.78	0.78	0.24	0.15	0.97	0.96	0.77	0.77	0.27	0.18	0.97	0.95
	0.90	0.90	0.15	0.10	1.00	1.00	1.00	1.00	0.15	0.08	1.00	1.00	1.00	1.00	0.18	0.10	1.00	1.00
	1.00	1.00	0.10	0.06	1.00	0.64	0.95	0.95	0.09	0.04	0.77	0.49	0.98	0.98	0.11	0.06	0.71	0.52
	0.51	0.51	0.06	0.03	0.18	0.20	0.21	0.21	0.06	0.02	0.08	0.09	0.30	0.30	0.07	0.03	0.11	0.12

Table 3: Estimates of management quantities for Case III) (the “ASPM New Reference Case”) and a series of sensitivity assessments (Cases VIII to XIII). Biomass units are tons. The two sets of estimates given for quantities such as $B^{sp}(MSY)$ refer to the two different commercial selectivity functions: i) for 1893-1991 and ii) from 1992+. Values in bold are inputs to the model.

	III) Current ASPM New Reference Case						**VIII) With γ estimated (potential pseudo-Ricker SR relationship - see equation A2.4)**						**IX) σ_R =0.4**					
-lnL: overall	73.3						70.2						26.6					
-lnL: Survey	-21.3						-22.2						-22.0					
-lnL: CAA	-48.8						-49.1						-48.4					
-lnL: CAAsurv	76.1						77.2						62.5					
-lnL: RecRes	67.4						64.3						34.4					
K^{sp}	137964						119565						143248					
$B^{sp}(2001)$	41559						38161						37317					
$B^{sp}(MSY)$	22059	23545					69631	74917					23121	25234				
$B^{sp}(2001)/B^{sp}(MSY)$	1.88	1.77	(1.71; 1.78)				0.55	0.51					1.61	1.48				
$MSYL^{sp}$	0.16	0.17					0.58	0.63					0.16	0.18				
MSY	10754	10889					9536	9070					10566	10770				
$F(MSY)$	0.54	0.62					0.22	0.22					0.52	0.58				
$F^*(MSY)$	0.78	0.98					0.25	0.25					0.73	0.87				
$F(2001)$	0.27						0.29						0.30					
$F^*(2001)$	0.31						0.34						0.35					
h	0.98	(0.96; 0.98)					1.08						0.98					
M	0.25	(0.20; 0.28)					0.22						0.24					
Gamma	**1.00**						2.28	(1.68; 2.88)					**1.00**					
Theta	**1.00**						**1.00**						**1.00**					
Phi	**0.00**						**0.00**						**0.00**					
σ_R (in,out)	**0.25**	0.47					**0.25**	0.46					**0.40**	0.54				
Selectivities	WHSpr	WHAut	MASpr	MAAut	Com1	Com2	WHSpr	WHAut	MASpr	MAAut	Com1	Com2	WHSpr	WHAut	MASpr	MAAut	Com1	Com2
	0.10	0.06	1.00	1.00	0.02	0.00	0.10	0.06	1.00	1.00	0.02	0.00	0.10	0.06	1.00	1.00	0.02	0.00
	0.30	0.22	0.63	0.56	0.17	0.05	0.30	0.22	0.62	0.55	0.18	0.06	0.29	0.21	0.62	0.56	0.17	0.05
	0.50	0.50	0.39	0.32	0.69	0.49	0.50	0.50	0.38	0.31	0.69	0.50	0.49	0.49	0.39	0.31	0.69	0.48
	0.70	0.70	0.25	0.18	0.96	0.95	0.70	0.70	0.23	0.17	0.96	0.95	0.69	0.69	0.24	0.17	0.96	0.94
	0.90	0.90	0.15	0.10	1.00	1.00	0.90	0.90	0.14	0.09	1.00	1.00	0.89	0.89	0.15	0.09	1.00	1.00
	1.00	1.00	0.10	0.06	1.00	0.64	1.00	1.00	0.09	0.05	1.00	0.67	1.00	1.00	0.09	0.05	1.00	0.66
	0.51	0.51	0.06	0.03	0.18	0.20	0.45	0.45	0.05	0.03	0.15	0.20	0.49	0.49	0.06	0.03	0.18	0.22

Table 3: continued

	Xa) Start year 1950, ϕ and θ fixed						**Xb) Start year 1970, ϕ and θ fixed**						**Xc) Start year 1982, ϕ and θ fixed**					
-lnL: overall	73.0						104.7						48.7					
-lnL: Survey	-21.3						-16.5						-5.8					
-lnL: CAA	-48.9						-49.0						-36.6					
-lnL: CAAsurv	75.9						108.6						62.4					
-lnL: RecRes	67.4						61.5						28.6					
K^{sp}	138635						106791						130654					
$B^{sp}(2001)$	41603						42022						68963					
$B^{sp}(MSY)$	38310	45990					16767	18510					15488	21109				
$B^{sp}(2001)/B^{sp}(MSY)$	1.09	0.90					2.51	2.27					4.45	3.27				
$MSYL^{sp}$	0.28	0.33					0.16	0.17					0.12	0.16				
MSY	10090	9801					10394	10441					14942	14786				
F(MSY)	0.35	0.35					0.65	0.75					0.91	0.95				
F(MSY)*	0.43	0.43					1.06	1.37					2.44	3.00				
F(2001)	0.27						0.27						0.18					
F(2001)*	0.31						0.31						0.20					
h	0.98						0.98						0.97					
M	0.25						0.30						0.37					
Gamma	**1.00**						**1.00**						**1.00**					
Theta	**1.00**						**1.00**						**1.00**					
Phi	**0.00**						**0.00**						**0.00**					
σ_R (in,out)	**0.25**	0.47					**0.25**	0.50					**0.25**	0.43				
Selectivities	WHSpr	WHAut	MASpr	MAAut	Com1	Com2	WHSpr	WHAut	MASpr	MAAut	Com1	Com2	WHSpr	WHAut	MASpr	MAAut	Com1	Com2
	0.10	0.06	1.00	1.00	0.02	0.00	0.09	0.06	1.00	1.00	0.02	0.00	0.08	0.02	1.00	1.00	0.01	0.00
	0.30	0.22	0.63	0.56	0.17	0.05	0.30	0.22	0.65	0.59	0.16	0.05	0.31	0.20	0.70	0.61	0.18	0.05
	0.50	0.50	0.39	0.32	0.69	0.49	0.51	0.51	0.42	0.34	0.69	0.48	0.54	0.54	0.49	0.38	0.78	0.51
	0.70	0.70	0.25	0.18	0.96	0.95	0.72	0.72	0.27	0.20	0.96	0.94	0.77	0.77	0.34	0.23	0.98	0.96
	0.90	0.90	0.15	0.10	1.00	1.00	0.92	0.92	0.18	0.12	1.00	1.00	1.00	1.00	0.24	0.14	1.00	1.00
	1.00	1.00	0.10	0.06	0.99	0.63	1.00	1.00	0.11	0.07	0.91	0.63	0.79	0.79	0.17	0.09	0.46	0.45
	0.50	0.50	0.06	0.03	0.17	0.19	0.61	0.61	0.07	0.04	0.20	0.21	0.28	0.28	0.12	0.05	0.11	0.12

Table 3: continued

	XIa) Start year 1950, ϕ and θ estimated						**XIb) Start year 1970, ϕ and θ estimated**						**XIc) Start year 1982, ϕ and θ estimated**					
-lnL: overall	71.9						72.3						35.8					
-lnL: Survey	-21.2						-16.6						-5.0					
-lnL: CAA	-49.3						-48.4						-41.8					
-lnL: CAAsurv	76.0						80.4						48.9					
-lnL: RecRes	66.3						56.9						33.6					
K^{sp}	143412						198612						243073					
$B^{sp}(2001)$	44390						35935						53718					
$B^{sp}(MSY)$	24908	26208					43589	44535					31826	31399				
$B^{sp}(2001)/B^{sp}(MSY)$	1.78	1.69					0.82	0.81					1.69	1.71				
$MSYL^{sp}$	0.17	0.18					0.22	0.22					0.13	0.13				
MSY	10615	10825					11020	11269					10911	11154				
F(MSY)	0.50	0.58					0.34	0.39					0.47	0.56				
F(MSY)*	0.70	0.87					0.42	0.49					0.64	0.83				
F(2001)	0.26						0.29						0.24					
F(2001)*	0.30						0.35						0.27					
h	0.94						0.88						0.98					
M	0.25						0.20						0.17					
Gamma	**1.00**						**1.00**						**1.00**					
Theta	0.69						0.33						0.25					
Phi	0.73						0.00						0.37					
σ_R (in,out)	**0.25**	0.47					**0.25**	0.48					**0.25**	0.47				
Selectivities	WHSpr	WHAut	MASpr	MAAut	Com1	Com2	WHSpr	WHAut	MASpr	MAAut	Com1	Com2	WHSpr	WHAut	MASpr	MAAut	Com1	Com2
	0.10	0.06	1.00	1.00	0.02	0.00	0.09	0.06	1.00	1.00	0.02	0.00	0.11	0.03	1.00	1.00	0.02	0.00
	0.31	0.23	0.62	0.56	0.18	0.05	0.27	0.21	0.61	0.55	0.17	0.06	0.33	0.24	0.61	0.53	0.20	0.06
	0.52	0.52	0.39	0.32	0.71	0.50	0.45	0.45	0.37	0.30	0.66	0.49	0.56	0.56	0.37	0.28	0.74	0.53
	0.73	0.73	0.24	0.18	0.97	0.95	0.64	0.64	0.23	0.16	0.95	0.94	0.78	0.78	0.23	0.15	0.97	0.96
	0.93	0.93	0.15	0.10	1.00	1.00	0.82	0.82	0.14	0.09	0.99	1.00	1.00	1.00	0.14	0.08	1.00	1.00
	1.00	1.00	0.10	0.06	0.88	0.59	1.00	1.00	0.08	0.05	1.00	0.71	0.95	0.95	0.09	0.04	0.73	0.51
	0.43	0.43	0.06	0.03	0.14	0.16	0.50	0.50	0.05	0.03	0.24	0.24	0.25	0.25	0.05	0.02	0.11	0.10

Table 3: continued (Note here for the commercial selectivities, “Com1’ ” applies to the pre-1982 period, “Com1” to the 1982-1991 period and “Com2” to the post -1991 period.)

	XIIa) Alternative earlier commercial selectivity (pre-1982 as post-1991)							**XIIb) Alternative earlier commercial selectivity (higher values at younger ages pre-1982)**						
-lnL: overall	76.7							71.4						
-lnL: Survey	-21.5							-21.4						
-lnL: CAA	-47.9							-49.0						
-lnL: CAAsurv	79.3							74.4						
-lnL: RecRes	66.8							67.4						
K^{sp}	132535							141085						
$B^{sp}(2001)$	40514							42299						
$B^{sp}(MSY)$	23047	23047						20800	23909					
$B^{sp}(2001)/B^{sp}(MSY)$	1.76	1.76						2.03	1.77					
$MSYL^{sp}$	0.17	0.17						0.15	0.17					
MSY	10754	10754						10755	11046					
F(MSY)	0.62	0.62						0.50	0.62					
F(MSY)*	0.97	0.97						0.70	0.98					
F(2001)	0.27							0.27						
F(2001)*	0.32							0.31						
h	0.98							0.98						
M	0.25							0.25						
Gamma	**1.00**							**1.00**						
Theta	**1.00**							**1.00**						
Phi	**0.00**							**0.00**						
σ_R (in,out)	**0.25**	0.47						**0.25**	0.47					
Selectivities	WHSpr	WHAut	MASpr	MAAut	Com1'	Com1	Com2	WHSpr	WHAut	MASpr	MAAut	Com1'	Com1	Com2
	0.10	0.06	1.00	1.00	0.00	0.02	0.00	0.10	0.06	1.00	1.00	0.02	0.02	0.00
	0.29	0.21	0.63	0.57	0.05	0.17	0.05	0.30	0.22	0.63	0.56	**0.30**	0.17	0.05
	0.49	0.49	0.39	0.32	0.50	0.68	0.50	0.50	0.50	0.39	0.32	**0.85**	0.68	0.49
	0.68	0.68	0.25	0.18	0.95	0.96	0.95	0.70	0.70	0.25	0.18	**1.00**	0.96	0.95
	0.88	0.88	0.16	0.10	1.00	1.00	1.00	0.90	0.90	0.16	0.10	1.00	1.00	1.00
	1.00	1.00	0.10	0.06	0.66	1.00	0.66	1.00	1.00	0.10	0.06	1.00	1.00	0.63
	0.52	0.52	0.06	0.03	0.21	0.18	0.21	0.50	0.50	0.06	0.03	0.17	0.17	0.19

Table 3: continued (Note that year *y* here is the last year for which data are available.)

	XIIIa) Retrospective analysis: data up to 1999						**XIIIb) Retrospective analysis: data up to 1997**						**XIIIb) Retrospective analysis: data up to 1995**					
-lnL: overall	73.7						64.5						39.3					
-lnL: Survey	-18.2						-22.1						-30.9					
-lnL: CAA	-40.9						-34.6						-32.8					
-lnL: CAAsurv	69.8						60.4						45.2					
-lnL: RecRes	62.9						60.8						57.7					
K^{sp}	133669						134090						122666					
$B^{sp}(y)$	30659						26833						21388					
$B^{sp}(MSY)$	20699	21916					21919	22355					22104	21530				
$B^{sp}(y)/B^{sp}(MSY)$	1.48	1.40					1.22	1.20					0.97	0.99				
$MSYL^{sp}$	0.15	0.16					0.16	0.17					0.18	0.18				
MSY	10748	10854					10876	10931					10813	10816				
$F(MSY)$	0.55	0.63					0.56	0.68					0.56	0.66				
$F^*(MSY)$	0.79	1.01					0.81	1.15					0.81	1.06				
$F(y)$	0.28						0.33						0.63					
$F^*(y)$	0.33						0.39						0.99					
h	0.98						0.98						0.98					
M	0.25						0.26						0.27					
Gamma	**1.00**						**1.00**						**1.00**					
Theta	**1.00**						**1.00**						**1.00**					
Phi	**0.00**						**0.00**						**0.00**					
σ_R (in,out)	**0.25**	0.47					**0.25**	0.47					**0.25**	0.47				
Selectivities	WHSpr	WHAut	MASpr	MAAut	Com1	Com2	WHSpr	WHAut	MASpr	MAAut	Com1	Com2	WHSpr	WHAut	MASpr	MAAut	Com1	Com2
	0.08	0.06	1.00	1.00	0.02	0.00	0.09	0.06	1.00	1.00	0.02	0.00	0.08	0.06	1.00	1.00	0.02	0.00
	0.28	0.21	0.63	0.56	0.17	0.06	0.29	0.21	0.65	0.57	0.17	0.06	0.28	0.20	0.68	0.58	0.17	0.06
	0.49	0.49	0.39	0.31	0.69	0.49	0.49	0.49	0.42	0.32	0.69	0.47	0.47	0.47	0.46	0.34	0.67	0.53
	0.69	0.69	0.25	0.17	0.96	0.94	0.69	0.69	0.27	0.18	0.96	0.93	0.67	0.67	0.31	0.20	0.96	0.95
	0.89	0.89	0.15	0.10	1.00	1.00	0.90	0.90	0.18	0.10	1.00	1.00	0.86	0.86	0.21	0.11	1.00	1.00
	1.00	1.00	0.10	0.05	1.00	0.63	1.00	1.00	0.11	0.06	1.00	0.64	1.00	1.00	0.14	0.07	1.00	0.78
	0.53	0.53	0.06	0.03	0.19	0.20	0.54	0.54	0.07	0.03	0.19	0.15	0.61	0.61	0.09	0.04	0.24	0.18

Table 4: Begin-year numbers-at-age (in thousands) for the “VPA Reference Case assessment” for the Gulf of Maine cod.

Year	1	2	3	4	5	6	7+
1982	7748	10870	5359	2993	1772	170	550
1983	7513	6264	7094	2261	1196	802	303
1984	10466	6138	3919	3188	780	360	249
1985	6981	8547	4290	1786	1130	214	221
1986	10091	5672	6103	1602	447	323	312
1987	12564	8238	4455	2508	471	117	144
1988	25262	10249	5924	2365	674	87	58
1989	4276	20677	7921	2914	896	159	107
1990	4020	3497	16450	4418	849	295	185
1991	6963	3285	2597	9672	1470	254	143
1992	6425	5696	2285	905	3442	348	138
1993	9386	5260	4347	1328	265	842	68
1994	3374	7684	4169	1751	375	91	108
1995	3483	2762	6239	2165	322	22	54
1996	3357	2852	2009	4066	574	79	17
1997	5012	2748	2257	1022	1571	137	15
1998	5158	4104	2195	1401	415	477	25
1999	10052	4223	3260	1358	590	177	236
2000	4555	8229	3450	2160	600	241	63
2001	564	3729	6650	2386	923	300	251
2002	5898	462	3003	4540	1351	421	280

Table 5: Objective function contributions for each abundance index for various sensitivities on the VPA assessments contrasted to those of the “VPA Reference Case”.

	a) "VPA Reference Case"	b) PR(6)=0.8	c) PR(6)=0.4	d) M=0.25	e) α = 0.5	f) M=0.25, PR(6)=0.4, α=0.5
WHSpr2	9.33	9.54	10.68	9.54	9.33	11.05
WHSpr3	2.67	2.59	2.37	2.64	2.67	2.41
WHSpr4	2.44	2.36	2.31	2.40	2.44	2.39
WHSpr5	4.91	4.85	4.95	4.91	4.91	5.07
WHSpr6	15.93	15.64	15.02	15.88	15.93	15.22
Tot WHSpr	**35.28**	**34.98**	**35.33**	**35.38**	**35.28**	**36.14**
WHAut2	11.27	11.34	11.98	11.43	11.27	12.30
WHAut3	6.23	6.29	6.67	6.28	6.23	6.78
WHAut4	6.18	6.34	7.09	6.23	6.18	7.19
WHAut5	6.17	5.97	5.74	6.12	6.17	5.86
WHAut6	6.11	6.54	8.33	6.23	6.11	8.64
Tot WHAut	**35.96**	**36.48**	**39.81**	**36.29**	**35.96**	**40.76**
MASpr2	6.43	6.66	7.90	6.65	6.43	8.29
MASpr3	4.45	4.54	5.26	4.45	4.45	5.44
MASpr4	9.52	9.55	10.41	9.52	9.52	10.69
Tot MASpr	**20.40**	**20.74**	**23.58**	**20.61**	**20.40**	**24.43**
MAAut2	45.40	45.43	44.97	45.61	45.40	44.95
Tot MAAut	**45.40**	**45.43**	**44.97**	**45.61**	**45.40**	**44.95**
CM_CPE3	1.91	1.94	2.10	1.95	1.91	2.17
CM_CPE4	0.45	0.49	0.78	0.47	0.45	0.85
CM_CPE5	0.26	0.31	0.61	0.27	0.26	0.66
CM_CPE6	0.09	0.10	0.24	0.09	0.09	0.27
Tot CM_CPE	**2.71**	**2.84**	**3.73**	**2.79**	**2.71**	**3.95**
Total SS	139.75	140.48	147.42	140.68	139.75	150.22

Table 6: Comparison of the 1982 and 2001 spawning biomass estimates for the ASPM and the ADAPT-VPA assessments.

		B^{sp}(1982)	B^{sp}(2001)
ASPM	III) New ASPM Reference Case	58231	41559
	IV) h=0.8, M=0.2	77189	39551
	V) flat commercial selectivity, M=0.25	38428	28055
	VI) data from 1982 only	89510	52399
	VII) data from 1982 only, M=0.25	77036	50975
ADAPT-VPA	a) "VPA Reference Case"	23844	21843
	b) PR(6)=0.8	27062	23131
	c) PR(6)=0.4	54967	31477
	d) M=0.25	25498	23056
	e) α = 0.5	28306	23420
	f) M=0.25, PR(6)=0.4, α=0.5	86735	38939

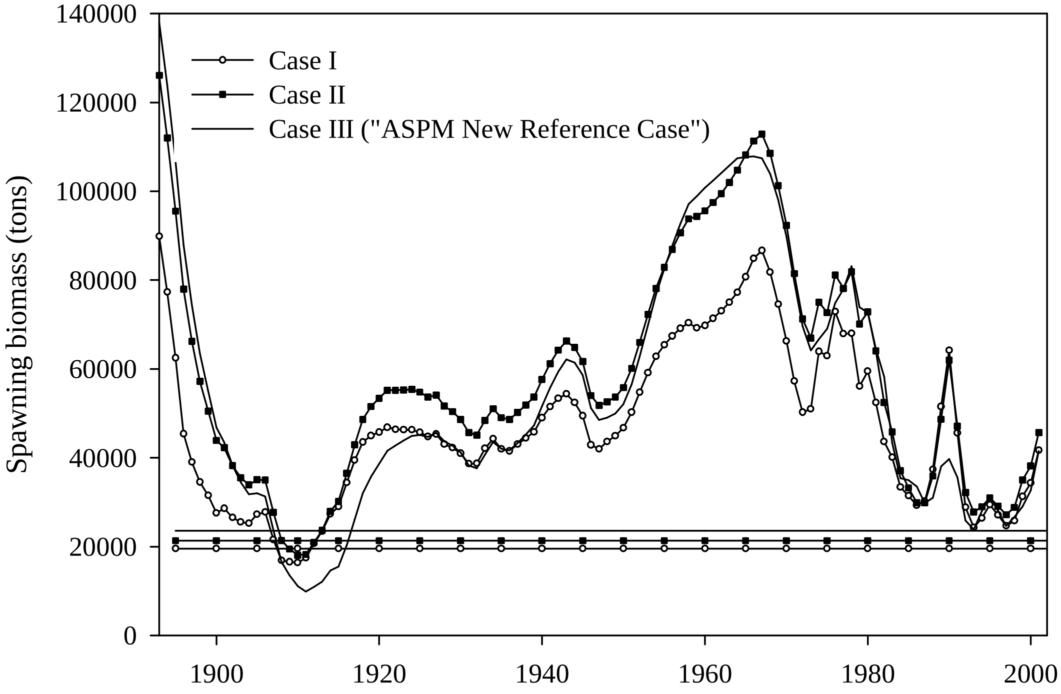


Fig. 1: Spawning biomass trajectories for the ASPM assessments for Case I, Case II and Case III (the two preceding and current “New Reference Cases” respectively). The corresponding *MSYL*s are also shown.

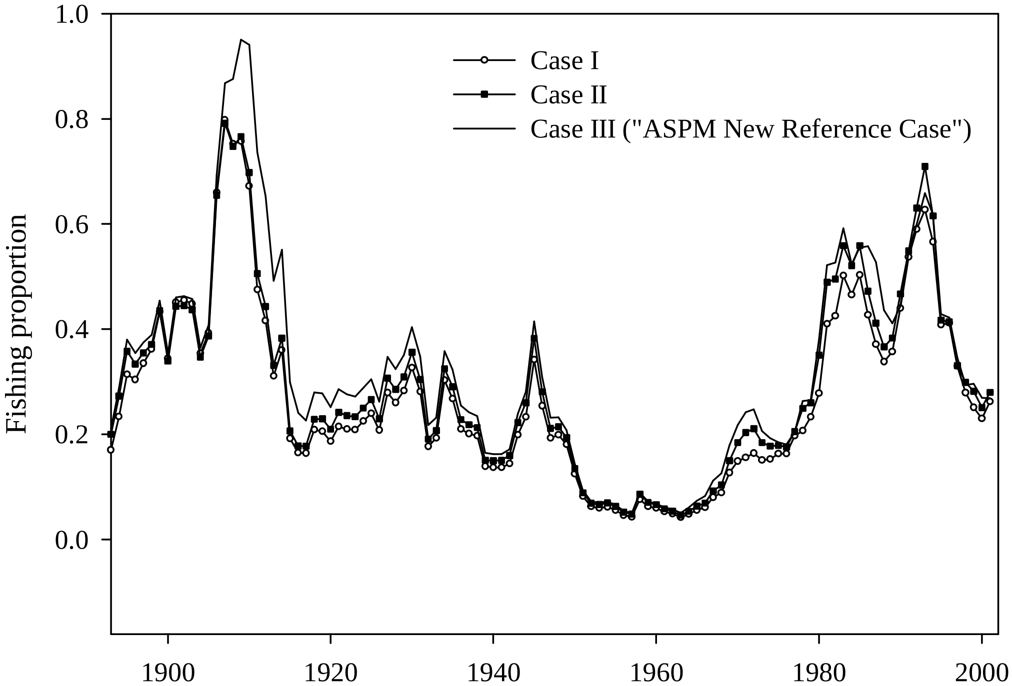


Fig. 2: Fishing proportion trajectories for the ASPM assessments for Case I, Case II and Case III.

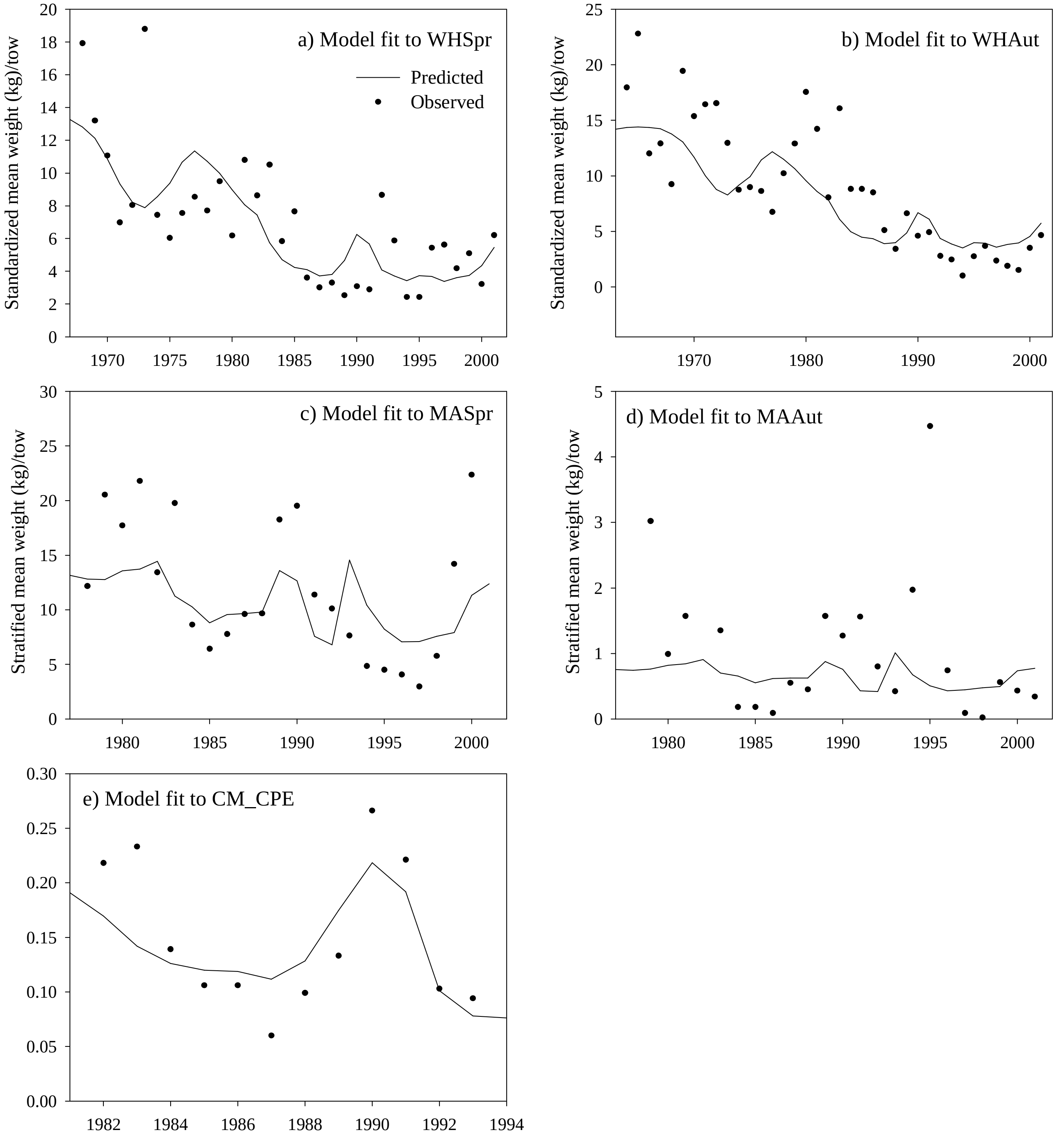


Fig. 3: Current ASPM New Reference Case (Case III) assessment model fits to the abundance indices (survey and CPUE) for the Gulf of Maine cod stock.

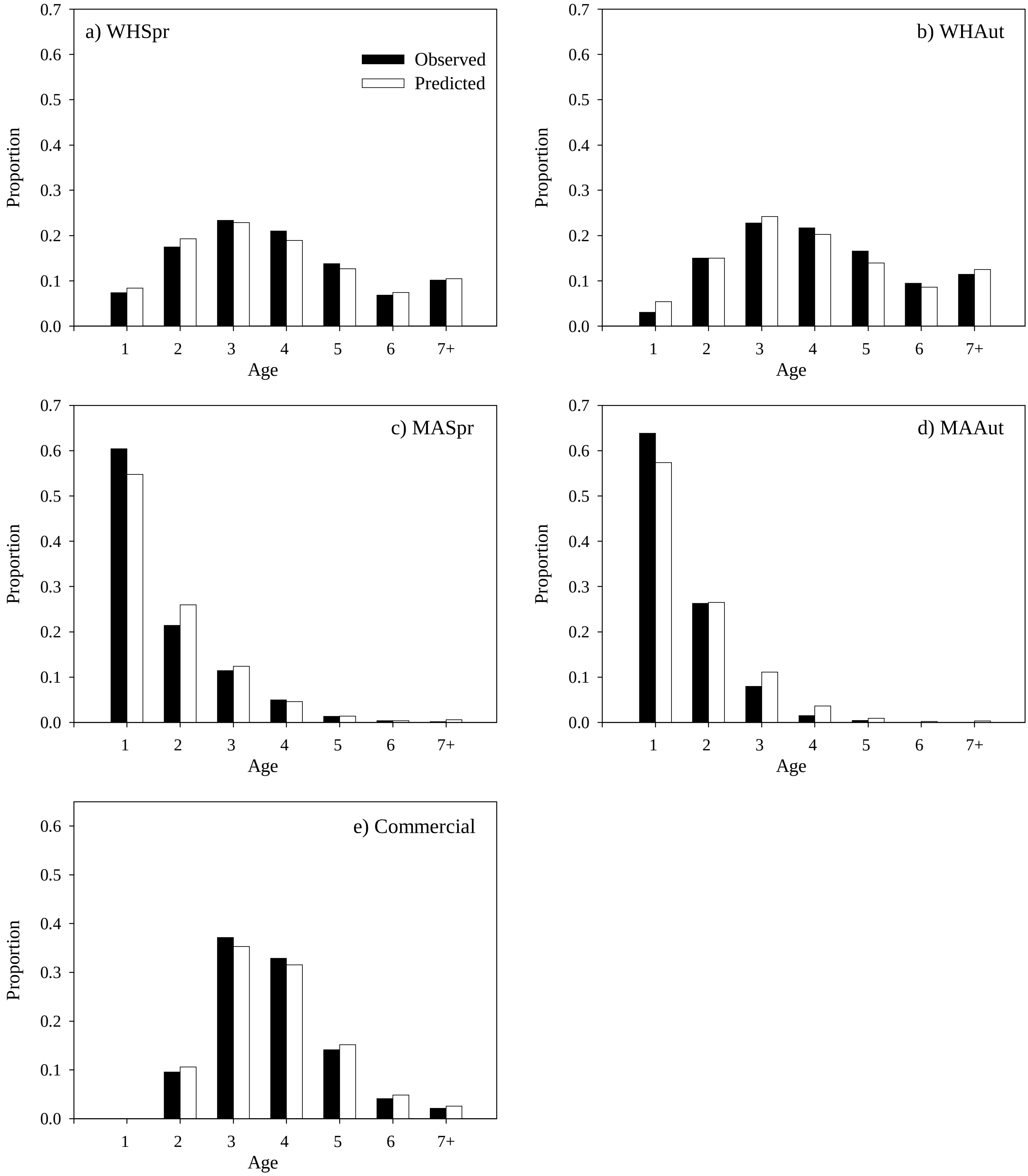
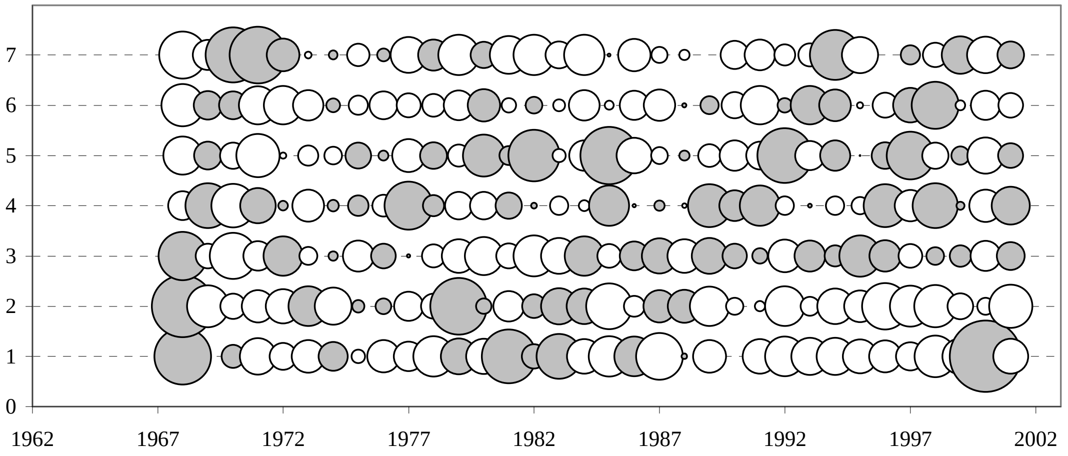
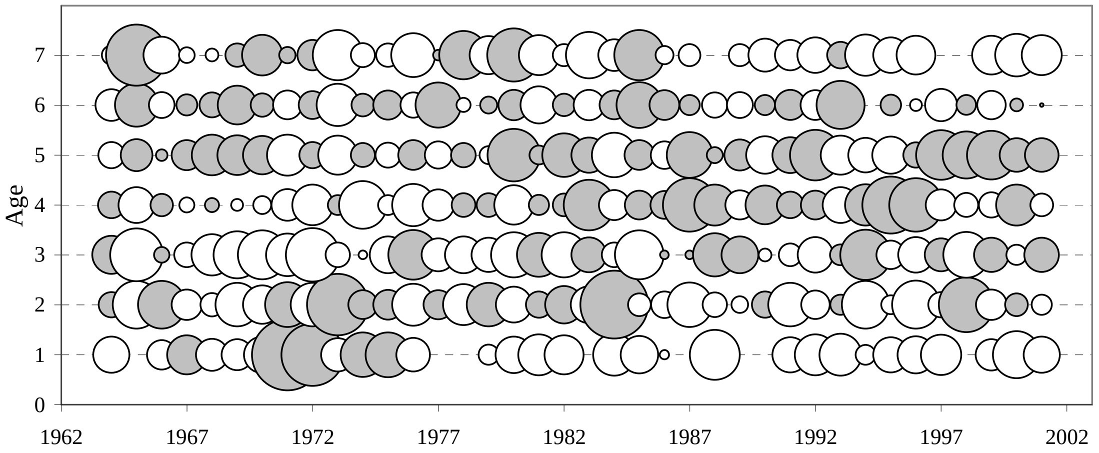


Fig. 4: Current ASPM New Reference Case (Case III) assessment model fits to the catch-at-age data (survey and commercial) for the Gulf of Maine cod stock, as averaged over all the years with data for each set.

a) WHSpr



b) WHAut



c) MASpr

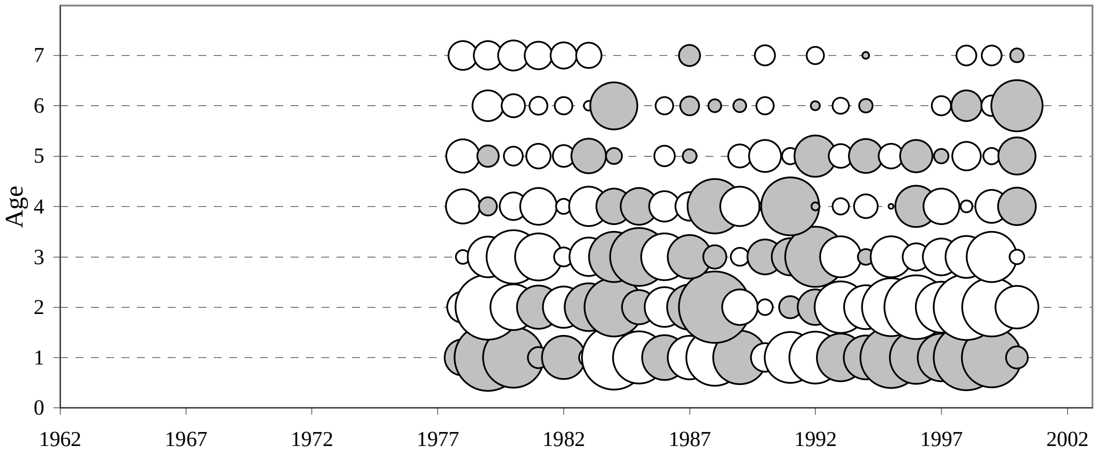
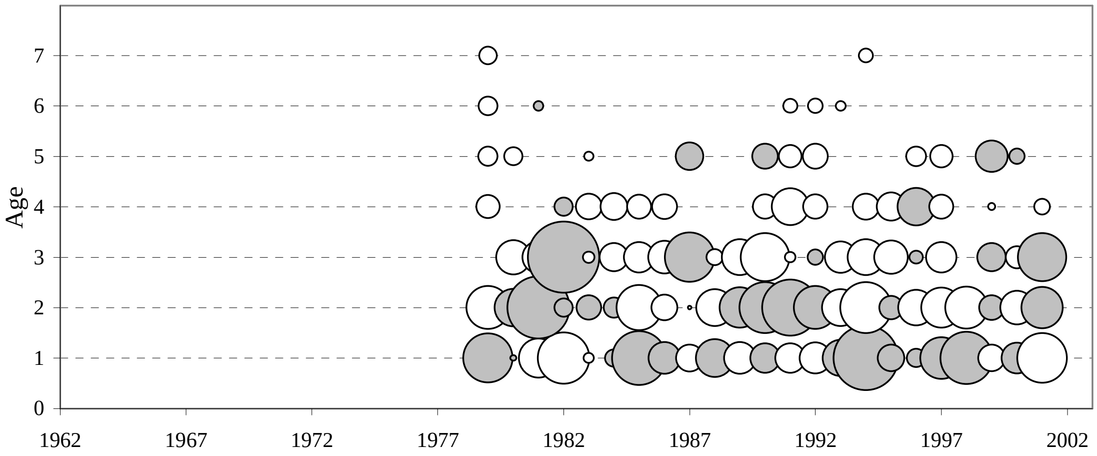


Fig. 5: Bubble plots of the standardised residuals for the catch-at-age data for the current ASPM New Reference Case (Case III) assessment. The size (area) of the bubbles represent the size of the residuals. Grey bubbles represent positive residuals and white bubbles represent negative residuals.

d) MAAut



e) Commercial

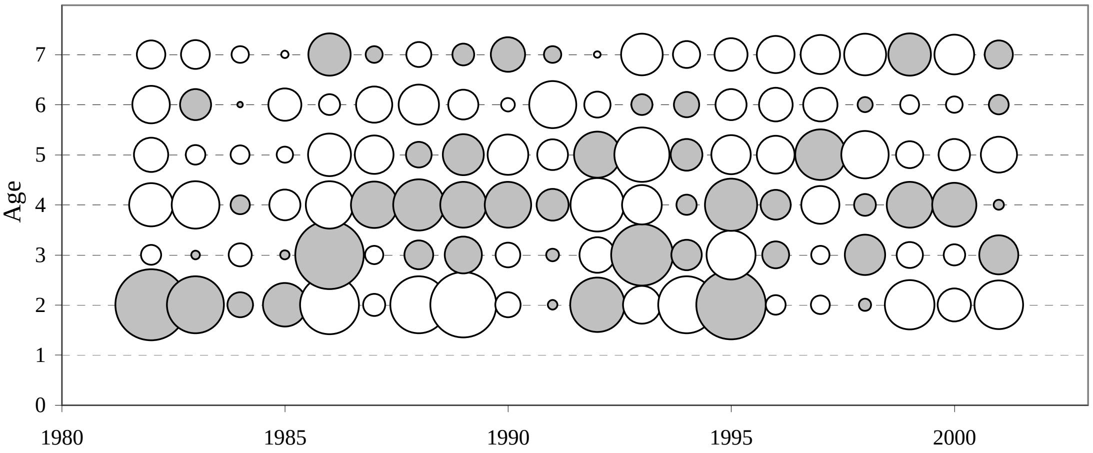


Fig. 5: continued.

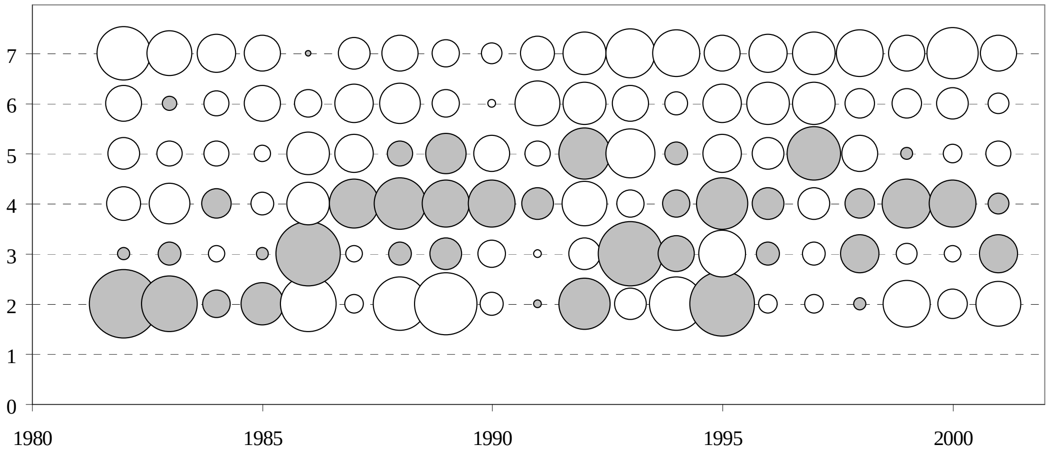


Fig. 6: Bubble plots of the residuals for the commercial catch-at-age data for the ASPM assessment with a flat commercial selectivity (Case V). The size (area) of the bubbles represent the size of the residuals. Grey bubbles represent positive residuals and white bubbles represent negative residuals.

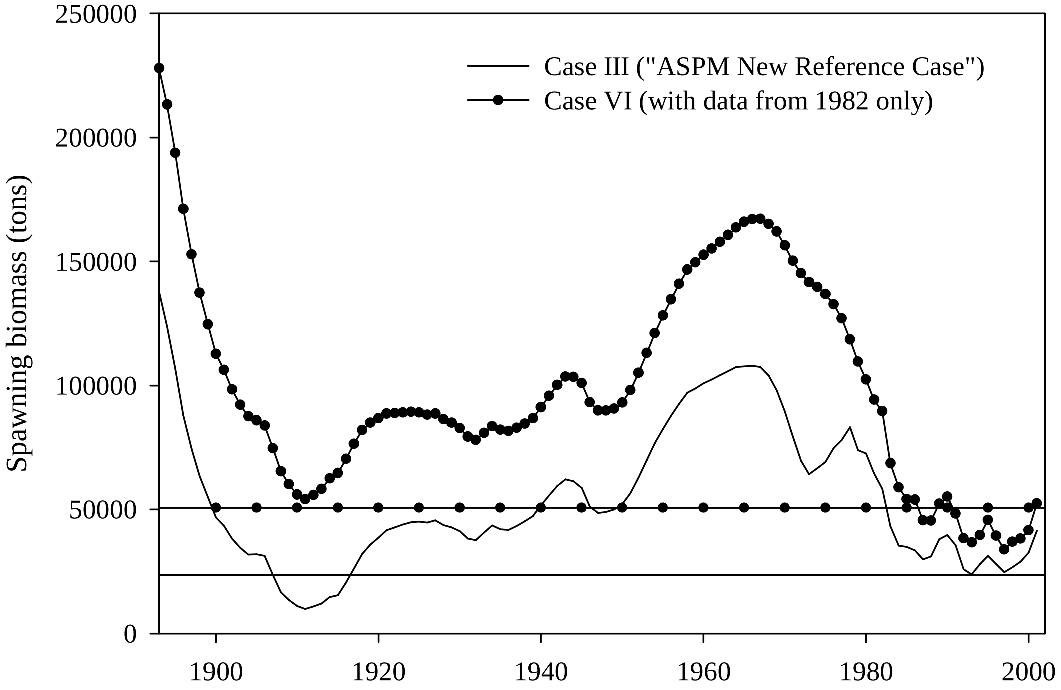


Fig. 7: Spawning biomass trajectories for the current ASPM New Reference Case (Case III) and Case VI in which only data from 1982 are included. The corresponding *MSYL*s are also shown.

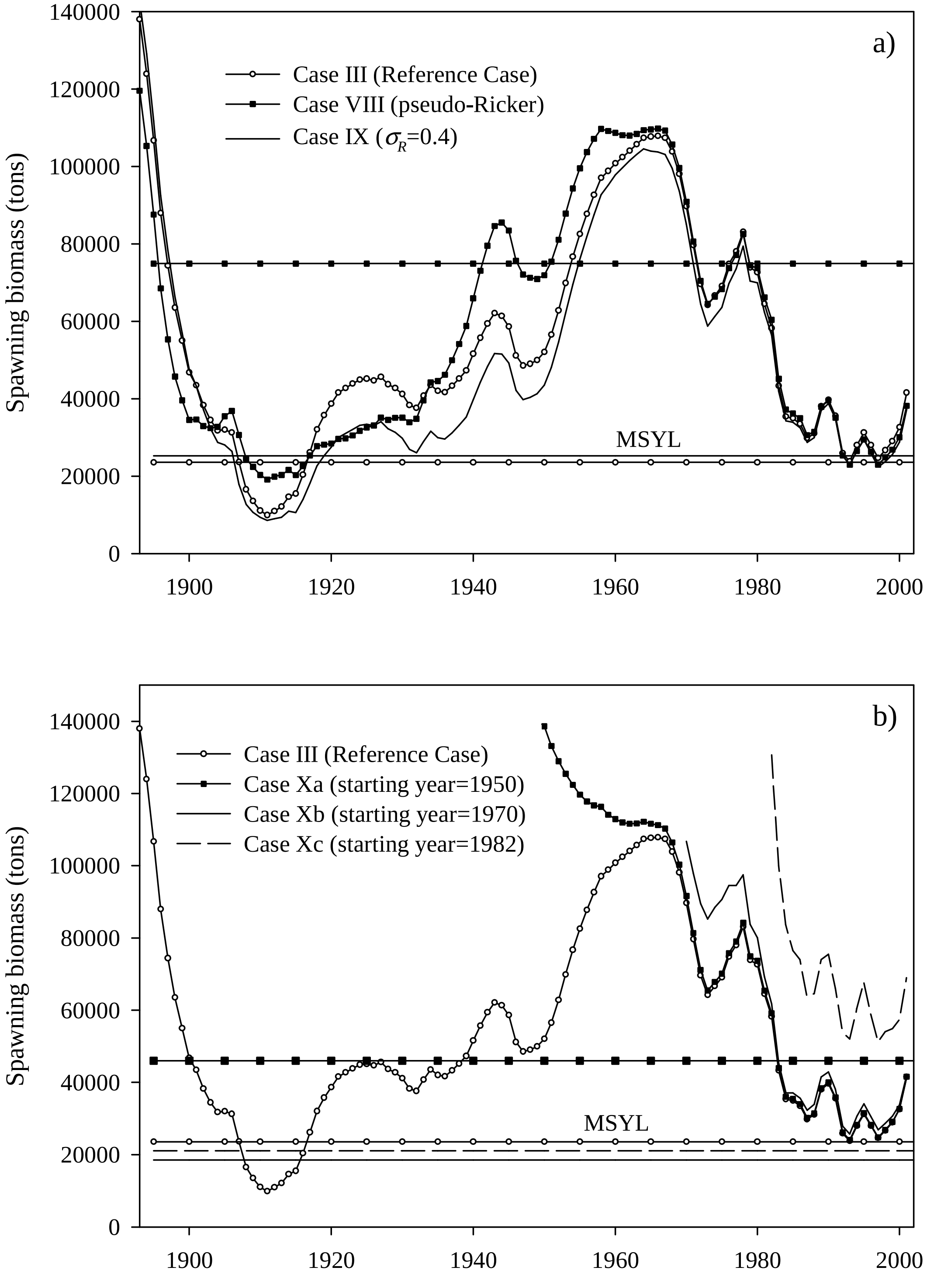


Fig. 8: Spawning biomass trajectories for the current ASPM New Reference Case (Case III) and various sensitivities whose features are summarised within the captions: a) Cases VIII and IX, b) Cases Xa-b, c) Cases XIa-c and d) Case XIIa. The corresponding *MSYL*s are also shown.

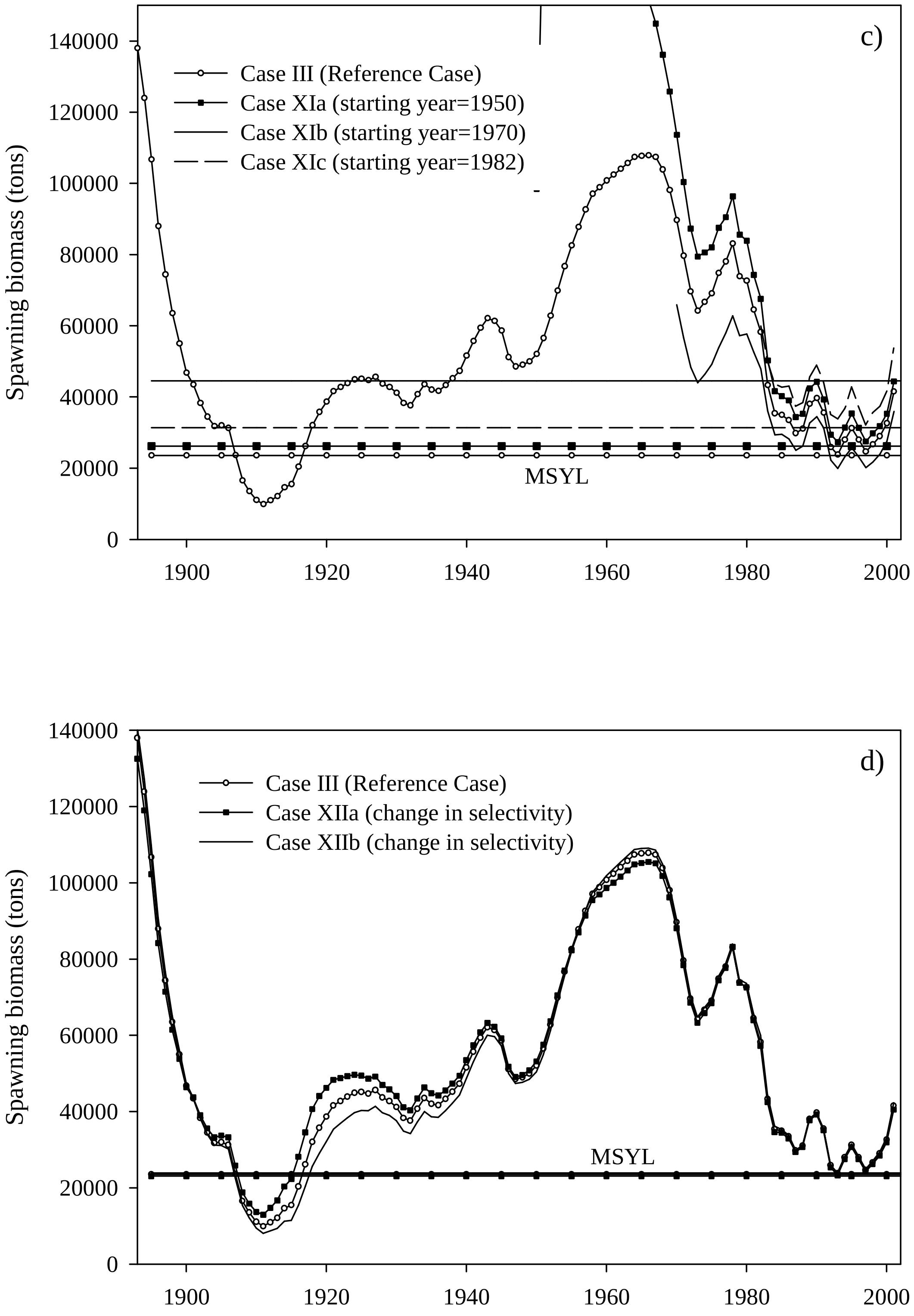


Fig. 8: continued

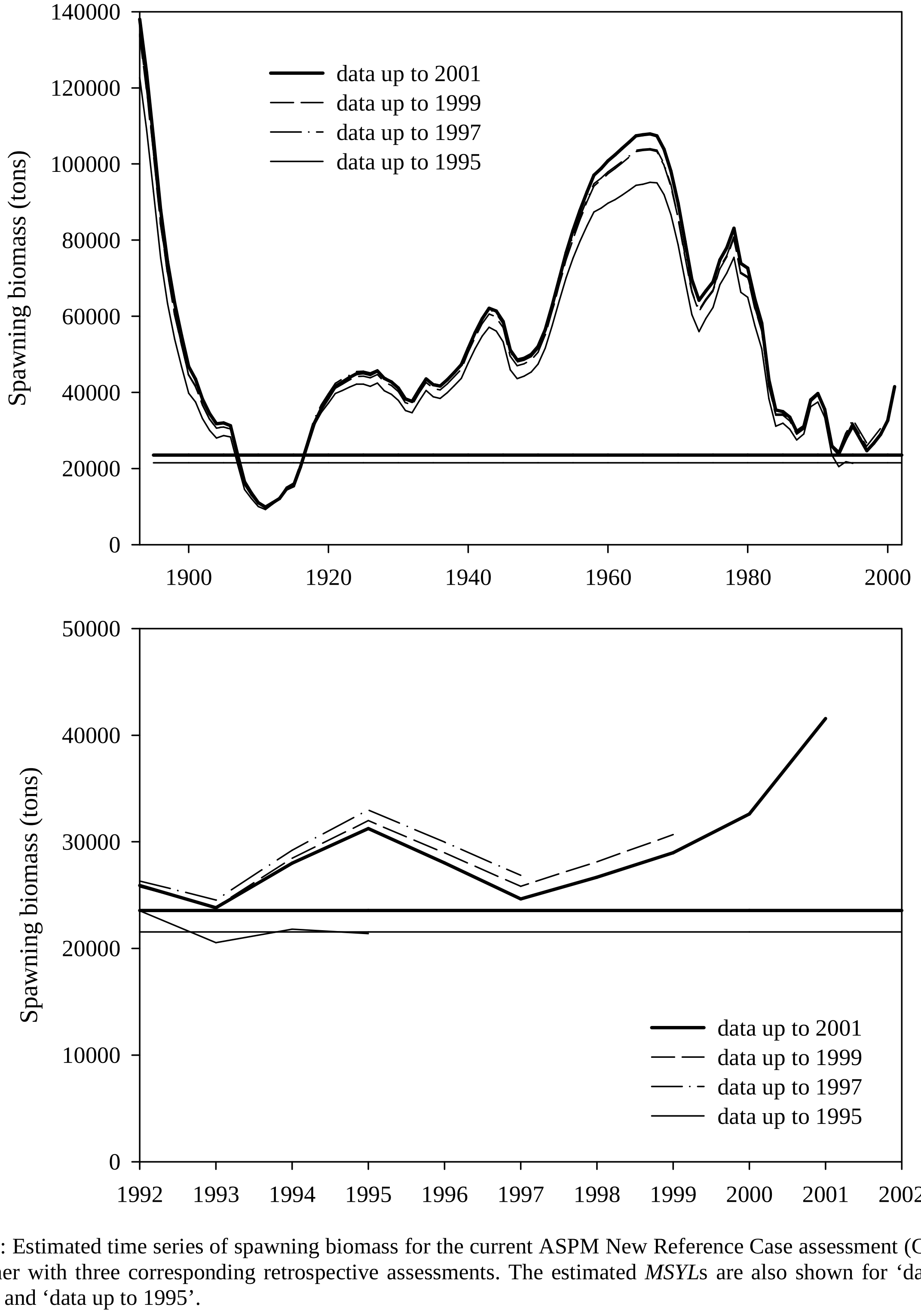


Fig. 9: Estimated time series of spawning biomass for the current ASPM New Reference Case assessment (Case III), together with three corresponding retrospective assessments. The estimated *MSYL*s are also shown for 'data up to 2001' and 'data up to 1995'.

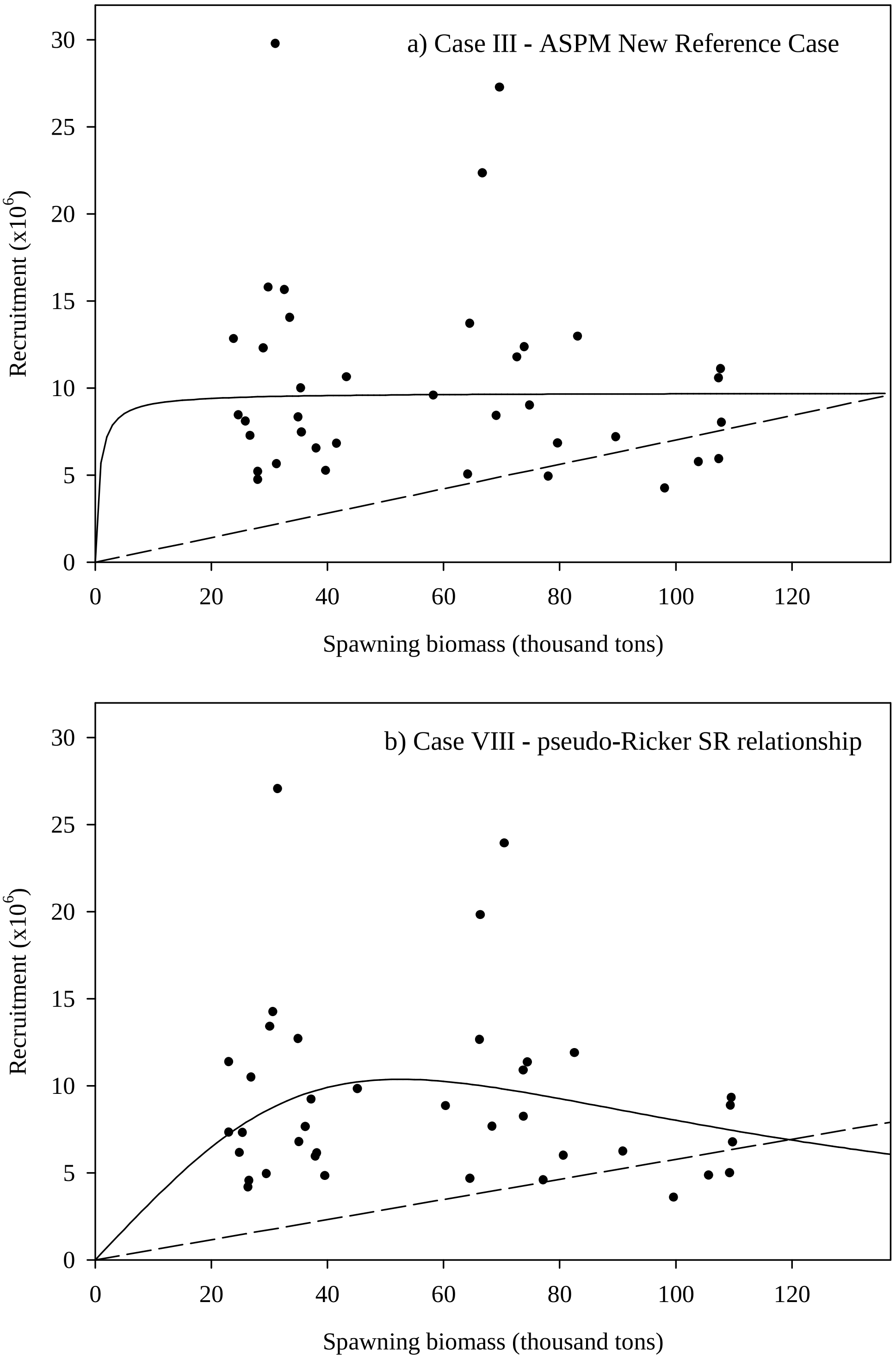
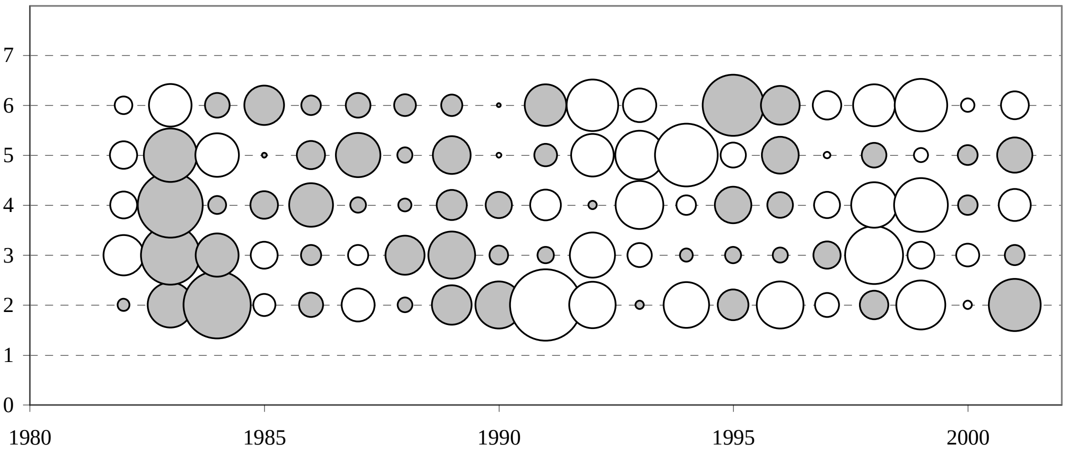


Fig. 10: Stock-recruit relationship for a) the current ASPM New Reference Case and b) Case VIII (which allows for a possible Ricker-like relationship – see equation A2.4 of Appendix 2). Estimated (spawning biomass, recruitment) points are shown for years 1964 to 2001. The straight dashed line through the origin is the replacement line which intersects the stock-recruit curve at a spawning biomass of K^{sp}. The data points shown are estimates from the first year for which catch-at-age data are available (1964), hence allowing recruitment estimates to deviate from the deterministic stock-recruit relationship.

a) WHSpr

b) WHAut



c) MASpr

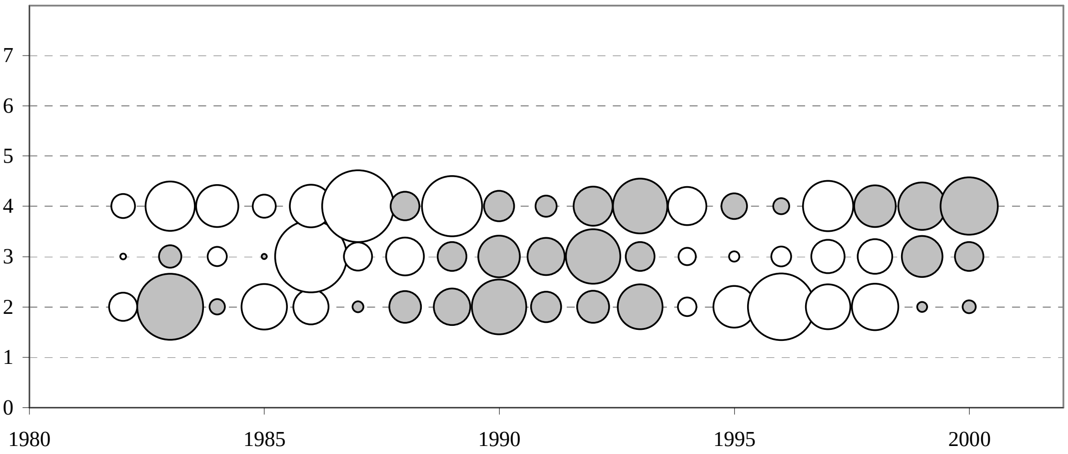


Fig. 11: Bubble plots of the residuals (see equation A3.7 of Appendix 3) for the survey and CPUE series for the "VPA Reference Case" assessment. The size (area) of the bubbles represent the size of the residuals. Grey bubbles represent positive residuals and white bubbles represent negative residuals.

d) MAAut

e) Commercial

Fig. 11: continued

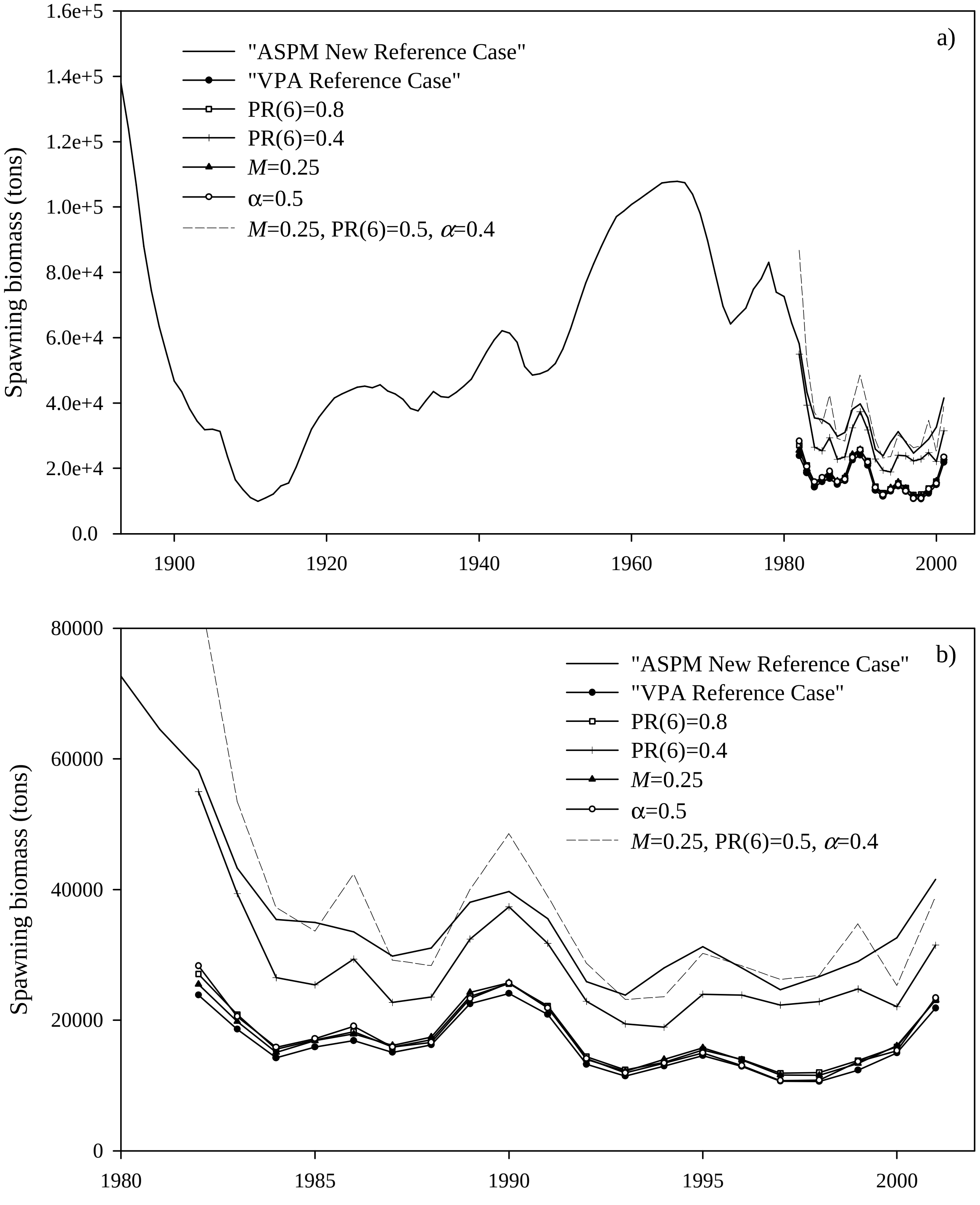


Fig. 12: Time-series of spawning biomass for the current ASPM and VPA Reference Cases and a series of VPA sensitivities.

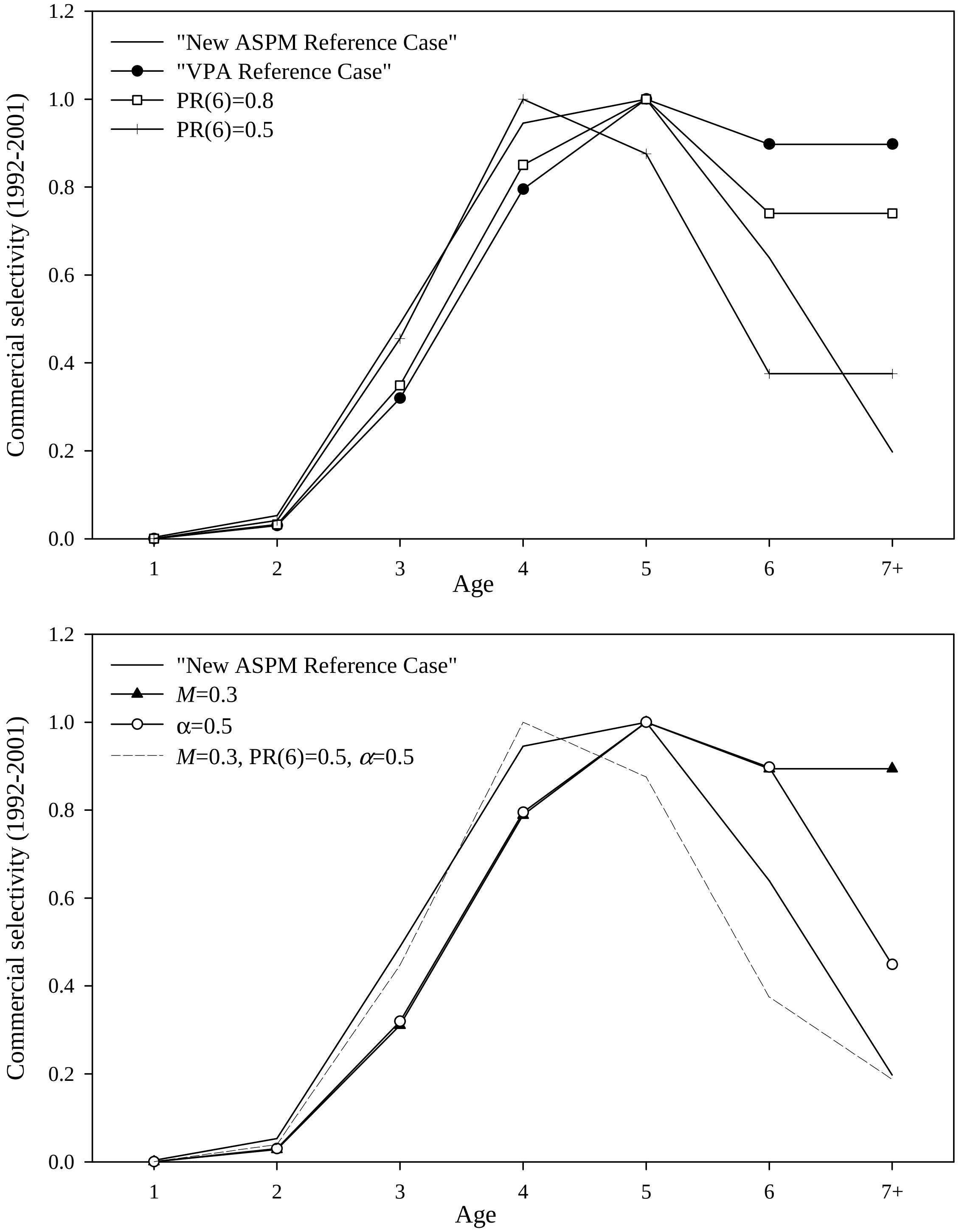


Fig. 13: Commercial selectivities-at-age (average over 1993-2001) for the current ASPM and VPA Reference Cases and a series of VPA sensitivities.

Appendix 1 - The Data Used

The data used for the ADAPT-VPA and the "ASPM New Reference Case" assessments, and their sensitivities, that are developed in this paper are as reported in Mayo *et al.* (2002).

Maturity-at-age is period-specific and is given in Table A1.1. In the ASPM assessment, for years prior to 1982, the maturity-at-age vector is taken as that in 1982.

Spawning (begin-year) and landed (mid-year) weights-at-age are given in Tables A1.2 and A1.3 respectively. In the ASPM assessment, for years prior to 1982, the begin-year and mid-year weights-at-age are taken as the average of the corresponding weights for each age over the full period available. Furthermore, for the *MSY* calculations, the mid-year weight-at-age vector used is as used in the projections in NEFSC (2002), viz. (0.418 1.582 2.064 2.726 3.982 5.804 10.767), while for the maturity and begin-year weight-at-age, the corresponding 2001 vectors are used.

Total (commercial and recreational) landings-at-age (in thousands of fish) for the period 1982-2001 are given in Table A1.4, while the total catch (in metric tons) is given in Table A1.5 for the period 1893-2001.

Data from the surveys, including catch-at-age and biomass indices, are shown in Tables A1.6 and A1.7 for the NEFSC offshore spring (WHSpr) and autumn (WHAut) research vessel bottom trawl surveys and in Tables A1.8 and A1.9 for the State of Massachusetts inshore spring (MASpr) and autumn (MAAut) bottom trawl surveys.

USA commercial LPUE indices through 1993 for ages 3 to 6 (CM_CPE) are shown in Table A1.10.

In the ADAPT-VPA assessments, the following indices of abundance are used for fitting the model: WHSpr for ages 2 to 6, WHAut for ages 2 to 6, MASpr for ages 2 to 4, MAAut for age 2 and CM_CPE for ages 3 to 6.

Table A1.1: Percentage of mature females for each age for the Gulf of Maine cod stock.

	1	2	3	4	5	6	7+
1982	0.07	0.26	0.61	0.88	0.97	1.00	1.00
1983	0.07	0.26	0.61	0.88	0.97	1.00	1.00
1984	0.07	0.26	0.61	0.88	0.97	1.00	1.00
1985	0.04	0.48	0.95	1.00	1.00	1.00	1.00
1986	0.04	0.48	0.95	1.00	1.00	1.00	1.00
1987	0.04	0.48	0.95	1.00	1.00	1.00	1.00
1988	0.04	0.48	0.95	1.00	1.00	1.00	1.00
1989	0.04	0.48	0.95	1.00	1.00	1.00	1.00
1990	0.11	0.28	0.56	0.81	0.93	0.98	1.00
1991	0.11	0.28	0.56	0.81	0.93	0.98	1.00
1992	0.11	0.28	0.56	0.81	0.93	0.98	1.00
1993	0.11	0.28	0.56	0.81	0.93	0.98	1.00
1994	0.04	0.38	0.89	0.99	1.00	1.00	1.00
1995	0.04	0.38	0.89	0.99	1.00	1.00	1.00
1996	0.04	0.38	0.89	0.99	1.00	1.00	1.00
1997	0.04	0.38	0.89	0.99	1.00	1.00	1.00
1998	0.04	0.38	0.89	0.99	1.00	1.00	1.00
1999	0.04	0.38	0.89	0.99	1.00	1.00	1.00
2000	0.04	0.38	0.89	0.99	1.00	1.00	1.00
2001	0.04	0.38	0.89	0.99	1.00	1.00	1.00

Table A1.2: Spawning (begin-year) weight-at-age (kg) for the Gulf of Maine cod stock.

	1	2	3	4	5	6	7+
1982	0.415	0.882	1.282	2.270	4.199	5.582	11.314
1983	0.280	0.777	1.317	1.970	3.172	5.331	9.941
1984	0.350	0.658	1.313	2.084	2.984	4.669	10.296
1985	0.220	0.713	1.279	2.125	3.447	4.458	9.686
1986	0.274	0.613	1.353	2.162	3.559	5.150	11.711
1987	0.180	0.654	1.256	2.368	3.697	5.615	10.289
1988	0.063	0.559	1.334	1.915	3.978	5.461	10.676
1989	0.461	0.445	1.302	2.271	3.023	4.641	11.902
1990	0.051	0.781	1.400	1.979	3.506	5.393	13.562
1991	0.057	0.403	1.242	2.020	3.030	5.509	11.106
1992	0.254	0.512	1.474	2.031	2.747	4.486	10.593
1993	0.855	0.688	1.672	2.152	3.398	4.315	10.974
1994	0.212	1.170	1.451	2.374	2.835	5.074	9.864
1995	0.210	0.823	1.591	2.228	3.953	4.873	13.382
1996	0.206	0.831	1.841	2.079	3.094	6.118	10.900
1997	0.234	0.848	1.907	2.492	2.708	4.044	8.875
1998	0.242	0.747	1.905	2.543	3.501	3.600	9.909
1999	0.151	0.723	1.568	2.420	3.470	4.869	7.702
2000	0.244	0.728	1.686	2.469	3.451	4.881	7.307
2001	0.244	0.717	1.689	2.475	3.679	5.087	8.103
2002	0.213	0.717	2.107	1.881	2.932	4.545	8.103

Table A1.3: Landed (mid-year) weight-at-age (kg) for the Gulf of Maine cod stock.

	1	2	3	4	5	6	7+
1982	0.568	1.078	1.589	2.683	4.731	6.587	11.314
1983	0.429	1.063	1.610	2.442	3.749	6.007	9.941
1984	0.500	1.009	1.623	2.697	3.646	5.815	10.296
1985	0.367	1.018	1.621	2.782	4.405	5.451	9.686
1986	0.423	1.024	1.799	2.884	4.553	6.020	11.711
1987	0.317	1.011	1.541	3.116	4.739	6.924	10.289
1988	0.167	0.987	1.759	2.381	5.078	6.294	10.676
1989	0.600	1.185	1.717	2.932	3.837	4.242	11.902
1990	0.143	1.017	1.655	2.282	4.193	7.581	13.562
1991	0.171	1.134	1.516	2.466	4.024	7.238	11.106
1992	0.418	1.531	1.915	2.722	3.060	5.000	10.593
1993	1.000	1.132	1.827	2.418	4.243	6.085	10.974
1994	0.418	1.368	1.861	3.086	3.324	6.068	9.864
1995	0.418	1.620	1.851	2.667	5.064	7.143	13.382
1996	0.418	1.651	2.093	2.335	3.590	7.391	10.900
1997	0.418	1.721	2.202	2.966	3.140	4.556	8.875
1998	0.418	1.336	2.109	2.937	4.133	4.128	9.909
1999	0.331	1.250	1.841	2.776	4.100	5.736	7.702
2000	0.418	1.600	2.274	3.310	4.291	5.811	7.307
2001	0.418	1.229	1.782	2.694	4.089	6.031	8.103

Table A1.4: Total (commercial and recreational) landings-at-age (thousands of fish) of Atlantic cod from the Gulf of Maine stock (NAFO Division 5Y), 1982-2001.

	1	2	3	4	5	6	7+
1982	88	1995	2350	1386	717	75	242
1983	14	1337	2896	1184	685	448	169
1984	24	813	1572	1636	469	205	142
1985	49	989	2111	1122	665	133	137
1986	26	208	2750	929	275	197	190
1987	41	907	1418	1525	330	79	97
1988	6	520	2140	1149	434	51	34
1989	5	530	2284	1698	485	91	61
1990	7	294	4195	2373	488	167	105
1991	5	447	1349	4948	946	151	85
1992	0	350	600	526	2184	218	86
1993	1	152	1998	787	140	481	39
1994	0	57	1380	1228	315	74	88
1995	0	279	1152	1324	204	14	34
1996	0	86	688	1943	368	46	10
1997	0	61	494	466	894	72	8
1998	0	110	485	616	180	211	11
1999	1	8	563	566	267	78	104
2000	0	97	485	934	211	96	25
2001	0	56	1000	666	370	104	87

Table A1.5: Total catch (incl. USA, DWF and recreational landings, and discards) (metric tons) of Atlantic cod from the Gulf of Maine (NAFO Division 5Y), 1893-2001.

Year	Total catch	Year	Total catch	Year	Total catch
1893	13.179	1930	11.489	1967	5.973
1894	15.539	1931	9.265	1968	6.421
1895	17.256	1932	5.858	1969	8.484
1896	13.339	1933	7.025	1970	8.684
1897	12.763	1934	11.619	1971	7.662
1898	12.269	1935	9.679	1972	6.917
1899	13.420	1936	7.442	1973	6.146
1900	9.448	1937	7.432	1974	7.764
1901	12.572	1938	7.547	1975	9.015
1902	11.660	1939	5.504	1976	10.188
1903	10.895	1940	5.836	1977	12.426
1904	8.447	1941	6.124	1978	12.426
1905	10.092	1942	6.679	1979	11.680
1906	17.137	1943	9.397	1980	13.528
1907	15.706	1944	10.516	1981	18.083
1908	11.226	1945	14.532	1982	16.278
1909	11.025	1946	9.248	1983	15.920
1910	9.670	1947	6.916	1984	12.160
1911	7.344	1948	7.462	1985	12.549
1912	7.770	1949	7.033	1986	12.514
1913	6.698	1950	5.062	1987	10.976
1914	9.120	1951	3.567	1988	9.902
1915	5.130	1952	3.011	1989	12.504
1916	5.221	1953	3.121	1990	17.394
1917	5.928	1954	3.411	1991	20.598
1918	8.281	1955	3.171	1992	11.791
1919	8.324	1956	2.693	1993	9.675
1920	7.599	1957	2.562	1994	8.800
1921	8.905	1958	4.670	1995	7.704
1922	8.572	1959	3.795	1996	7.889
1923	8.475	1960	3.577	1997	5.781
1924	9.070	1961	3.234	1998	4.703
1925	9.538	1962	3.072	1999	4.961
1926	8.047	1963	2.731	2000	5.996
1927	10.931	1964	3.251	2001	6.490
1928	9.655	1965	3.928		
1929	10.288	1966	4.392		

Table A1.6: 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, 1968-2001.

	Age group							Standardized mean wt/tow (kg)
	1	2	3	4	5	6	7+	
1968	0.613	1.234	1.407	0.846	0.538	0.207	0.464	17.92
1969	0.000	0.036	0.307	0.880	0.807	0.633	0.590	13.20
1970	0.159	0.123	0.055	0.094	0.273	0.466	1.036	11.06
1971	0.025	0.142	0.109	0.292	0.048	0.083	0.732	6.98
1972	0.353	0.153	0.519	0.197	0.200	0.036	0.600	8.04
1973	0.034	4.249	0.906	0.619	0.349	0.195	1.181	18.79
1974	0.476	0.056	1.359	0.329	0.222	0.114	0.348	7.44
1975	0.094	0.699	0.106	1.065	0.259	0.111	0.173	6.03
1976	0.042	0.304	1.048	0.153	0.897	0.086	0.247	7.55
1977	0.025	0.298	0.521	1.994	0.109	0.791	0.144	8.54
1978	0.034	0.105	0.285	0.348	0.766	0.075	0.442	7.70
1979	0.535	1.630	0.212	0.499	0.401	0.685	0.266	9.49
1980	0.070	0.440	0.343	0.123	0.418	0.239	0.446	6.18
1981	1.014	0.662	0.986	1.216	0.328	0.287	0.371	10.79
1982	0.336	1.019	0.516	0.694	0.864	0.117	0.189	8.62
1983	0.626	0.978	0.833	0.641	0.357	0.181	0.283	10.50
1984	0.151	1.033	1.147	0.741	0.190	0.053	0.088	5.83
1985	0.028	0.238	0.622	0.665	0.677	0.095	0.192	7.65
1986	0.417	0.330	0.647	0.387	0.074	0.046	0.056	3.60
1987	0.049	0.638	0.486	0.300	0.128	0.011	0.070	3.01
1988	0.663	1.053	0.633	0.355	0.217	0.087	0.090	3.30
1989	0.023	0.649	0.790	0.632	0.090	0.077	0.000	2.53
1990	0.000	0.190	1.327	0.627	0.167	0.032	0.018	3.08
1991	0.043	0.209	0.355	1.477	0.268	0.024	0.018	2.89
1992	0.050	0.230	0.240	0.280	1.310	0.220	0.080	8.66
1993	0.200	0.500	0.800	0.330	0.090	0.480	0.103	5.87
1994	0.016	0.316	0.387	0.213	0.095	0.047	0.192	2.43
1995	0.050	0.180	1.120	0.370	0.150	0.030	0.010	2.43
1996	0.060	0.020	0.590	1.330	0.400	0.060	0.000	5.43
1997	0.158	0.132	0.399	0.264	0.876	0.242	0.120	5.62
1998	0.018	0.224	0.330	0.517	0.142	0.421	0.059	4.18
1999	0.166	0.344	0.713	0.344	0.315	0.134	0.284	5.09
2000	1.184	0.725	0.438	0.457	0.107	0.101	0.046	3.21
2001	0.029	0.323	0.716	0.497	0.354	0.064	0.164	6.20

Table A1.7: 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, 1964-2001.

	Age group							Standardized mean wt/tow (kg)
	1	2	3	4	5	6	7+	
1964	0.050	0.649	1.349	1.253	0.849	0.579	1.190	17.95
1965	0.000	0.092	0.122	0.471	0.856	0.853	1.608	22.79
1966	0.002	0.850	0.880	0.824	0.750	0.496	0.693	12.00
1967	0.170	0.204	0.640	0.697	0.718	0.558	0.795	12.91
1968	0.012	0.129	0.215	0.574	0.671	0.384	0.575	9.23
1969	0.012	0.036	0.179	0.719	1.256	0.973	1.211	19.44
1970	0.016	0.059	0.123	0.354	0.630	0.552	1.022	15.37
1971	0.743	0.941	0.265	0.551	0.329	0.488	1.584	16.43
1972	1.346	0.178	0.239	0.211	0.597	0.460	1.334	16.52
1973	0.031	5.579	1.217	1.526	0.234	0.094	0.628	12.96
1974	0.636	0.328	2.173	0.139	0.507	0.212	0.461	8.73
1975	0.282	1.123	0.189	1.744	0.292	0.359	0.342	8.97
1976	0.047	0.147	3.067	0.134	2.356	0.254	0.144	8.62
1977	0.000	0.243	0.209	0.632	0.100	0.768	0.200	6.74
1978	0.000	0.022	0.359	0.550	1.155	0.152	0.846	10.22
1979	0.249	1.369	0.371	1.118	0.656	1.430	0.557	12.89
1980	0.005	0.368	0.594	0.162	0.836	0.392	1.131	17.54
1981	0.027	1.264	2.602	1.754	0.497	0.232	0.661	14.21
1982	0.012	0.619	0.382	0.549	0.474	0.089	0.292	8.05
1983	0.000	0.700	3.142	2.473	1.167	0.248	0.039	16.07
1984	0.045	1.660	0.977	0.852	0.139	0.264	0.287	8.81
1985	0.044	0.384	0.421	0.565	0.399	0.220	0.390	8.81
1986	0.266	0.378	0.910	0.763	0.209	0.218	0.178	8.49
1987	0.000	0.301	0.490	0.654	0.333	0.086	0.087	5.10
1988	0.138	0.599	1.324	0.600	0.257	0.061	0.000	3.41
1989	0.000	1.951	2.245	0.960	0.528	0.110	0.109	6.61
1990	0.000	0.416	2.391	1.356	0.294	0.174	0.023	4.58
1991	0.006	0.029	0.367	1.643	0.623	0.278	0.038	4.91
1992	0.008	0.142	0.142	0.221	0.632	0.079	0.024	2.78
1993	0.060	0.290	0.450	0.140	0.040	0.330	0.120	2.45
1994	0.040	0.198	0.569	0.363	0.032	0.000	0.032	1.00
1995	0.030	0.210	0.880	0.830	0.090	0.050	0.050	2.74
1996	0.010	0.070	0.280	1.230	0.330	0.080	0.010	3.67
1997	0.030	0.120	0.380	0.190	0.540	0.060	0.000	2.35
1998	0.000	0.297	0.086	0.160	0.182	0.149	0.000	1.87
1999	0.050	0.097	0.320	0.115	0.192	0.039	0.031	1.50
2000	0.025	0.431	0.363	0.590	0.243	0.132	0.023	3.50
2001	0.008	0.533	0.984	0.394	0.507	0.134	0.044	4.65

Table A1.8: 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), 1978-2001.

	Age group							Stratified mean wt/tow (kg)
	1	2	3	4	5	6	7+	
1978	34.749	4.162	4.572	0.872	1.028	0.000	0.023	12.16
1979	93.023	2.581	1.533	4.659	1.995	0.183	0.069	20.53
1980	58.467	12.679	0.971	0.745	0.737	0.080	0.239	17.71
1981	44.547	23.884	3.122	1.279	0.041	0.146	0.044	21.79
1982	17.724	7.060	3.418	1.147	0.232	0.011	0.102	13.42
1983	28.156	18.572	5.331	0.501	1.221	0.142	0.022	19.77
1984	3.102	5.408	2.271	0.865	0.138	0.162	0.000	8.63
1985	3.504	3.822	2.794	0.692	0.000	0.000	0.000	6.42
1986	20.917	3.222	0.887	0.426	0.090	0.019	0.000	7.77
1987	9.249	6.997	2.268	0.257	0.147	0.048	0.087	9.59
1988	13.436	11.356	2.511	1.370	0.000	0.039	0.000	9.66
1989	20.836	25.260	6.580	0.458	0.106	0.124	0.000	18.26
1990	10.430	6.890	17.770	2.640	0.180	0.050	0.020	19.51
1991	6.200	3.560	2.540	5.030	0.360	0.000	0.000	11.37
1992	7.780	6.350	3.580	0.650	1.370	0.120	0.040	10.10
1993	72.430	7.760	3.600	1.450	0.050	0.300	0.000	7.63
1994	8.350	5.670	2.460	0.520	0.230	0.030	0.090	4.83
1995	16.250	1.360	3.890	1.200	0.090	0.000	0.000	4.49
1996	7.760	0.650	1.150	2.000	0.380	0.000	0.000	4.06
1997	14.060	1.250	1.050	0.220	0.500	0.030	0.000	2.97
1998	23.870	1.800	0.990	1.060	0.080	0.460	0.040	5.76
1999	130.580	3.570	3.460	1.200	1.080	0.060	0.260	14.19
2000	29.820	7.120	2.850	2.600	0.780	0.770	0.190	22.36

Table A1.9: Stratified mean catch per tow in numbers and weight (kg) of Atlantic cod in State of Massachusetts inshore autumn bottom trawl surveys in territorial waters adjacent to the Gulf of Maine (Mass. Regions 4-5), 1978-2001.

	Age group							Stratified mean wt/tow (kg)
	1	2	3	4	5	6	7+	
1979	151.533	2.082	0.000	0.120	0.140	0.318	0.080	3.02
1980	4.933	3.430	0.042	0.000	0.026	0.000	0.000	0.99
1981	5.680	8.834	0.052	0.000	0.000	0.050	0.000	1.57
1982	2.018	5.652	7.290	0.729	0.000	0.000	0.000	6.65
1983	4.667	2.346	1.005	0.060	0.050	0.000	0.000	1.35
1984	1.308	0.651	0.100	0.013	0.000	0.000	0.000	0.18
1985	12.296	0.344	0.022	0.013	0.000	0.000	0.000	0.18
1986	2.832	0.419	0.018	0.010	0.000	0.000	0.000	0.09
1987	2.478	1.150	0.833	0.000	0.067	0.000	0.000	0.55
1988	389.584	2.386	0.020	0.000	0.000	0.000	0.000	0.45
1989	4.571	20.490	0.679	0.000	0.000	0.000	0.000	1.57
1990	2.971	2.700	0.350	0.210	0.185	0.000	0.000	1.27
1991	9.370	9.130	1.740	0.310	0.060	0.030	0.000	1.56
1992	4.650	4.200	0.810	0.030	0.050	0.010	0.000	0.80
1993	24.300	2.010	0.110	0.000	0.000	0.060	0.000	0.42
1994	49.920	3.320	0.610	0.330	0.000	0.000	0.010	1.97
1995	33.490	14.130	6.370	0.260	0.000	0.000	0.000	4.47
1996	2.560	0.640	0.540	0.790	0.020	0.000	0.000	0.74
1997	7.590	0.150	0.020	0.010	0.010	0.000	0.000	0.09
1998	2.020	0.020	0.000	0.000	0.000	0.000	0.000	0.02
1999	2.610	1.040	0.620	0.080	0.110	0.000	0.000	0.56
2000	6.340	0.980	0.280	0.000	0.060	0.000	0.000	0.43
2001	0.040	0.540	0.270	0.020	0.000	0.000	0.000	0.34

Table A1.10: USA commercial LPUE index through 1993 for ages 3-6.

	LPUE, ages 3-6
1982	0.218
1983	0.233
1984	0.139
1985	0.106
1986	0.106
1987	0.06
1988	0.099
1989	0.133
1990	0.266
1991	0.221
1992	0.103
1993	0.094

Appendix 2 - The Age-Structured Production Model

The model used for these assessments of the Gulf of Maine cod stock is an Age-Structured Production Model (ASPM) (e.g. Hilborn, 1990). Models of this type are sometimes termed Statistical Catch-at-Age Analyses. The approach used in an ASPM assessment involves constructing an age-structured model of the population dynamics and fitting it to the available abundance indices by maximising the likelihood function. The model equations and the general specifications of the model are described below, followed by details of the contributions to the log-likelihood function from the different sources of data available. Quasi-Newton minimization is used to minimize the total negative log-likelihood function (the package AD Model Builder^{TM}, Otter Research, Ltd is used for this purpose).

A2.1 Population dynamics

A2.1.1 Numbers-at-age

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

$$N_{y+1,1} = R_{y+1} \qquad \text{A2.1}$$

$$N_{y+1,a+1} = \left(N_{y,a}\, e^{-M_a/2} - C_{y,a}\right) e^{-M_a/2} \qquad \text{for } 1 \le a \le m-2 \qquad \text{A2.2}$$

$$N_{y+1,m} = \left(N_{y,m-1}\, e^{-M_{m-1}/2} - C_{y,m-1}\right) e^{-M_{m-1}/2} + \left(N_{y,m}\, e^{-M_m/2} - C_{y,m}\right) e^{-M_m/2} \qquad \text{A2.3}$$

where

$N_{y,a}$ is the number of fish of age *a* at the start of year *y* (which refers to a calendar year),

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

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

$C_{y,a}$ is the predicted number of fish of age *a* caught in year *y*, and

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

These equations simply state that for a closed population, with no immigration and emigration, the only sources of loss are natural mortality (predation, disease, etc.) and fishing mortality (catch). They reflect Pope's form of the catch equation (Pope, 1972) (the catches are assumed to be taken as a pulse in the middle of the year) rather than the more customary Baranov form (Baranov, 1918) (for which catches are incorporated under the assumption of steady continuous fishing mortality). Pope's form has been used in order to simplify computations (and because the authors' already had tested code available based upon this form). As long as mortality rates are not too high, the differences between the Baranov and Pope formulations will be minimal.

A2.1.2. Recruitment

Tomorrow's recruitment depends upon the reproductive output of today's fish. The number of recruits (i.e. new 1-year old fish – we work here with 1- rather than 0-year old fish as recruits to conform with customary practice for US northeast assessments) at the start of year *y* is assumed to be related to the spawning stock size (i.e. the biomass of mature fish) by a modified Beverton-Holt stock-recruitment relationship (Beverton and Holt, 1957), allowing for annual fluctuation about the deterministic relationship:

$$R_y = \frac{\alpha B^{sp}_{y-1}}{\beta + \left(B^{sp}_{y-1}\right)^{\gamma}}\, e^{(\varsigma_y - (\sigma_R)^2/2)} \qquad \text{A2.4}$$

where

α, β and γ are spawning biomass-recruitment relationship parameters (note that cases with $\gamma > 1$ lead to recruitment which reaches a maximum at a certain spawning biomass, and thereafter declines towards zero, and thus have the capability of mimicking a Ricker-type relationship),

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. Estimating the stock-recruitment residuals is made possible by the availability of catch-at-age data, which give some indication of the age-structure of the population.

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

$$B^{sp}_y = \sum_{a=1}^{m} f_{y,a} w^{strt}_{y,a} \left[N_{y,a} e^{-M_a/12} - C_{y,a} \big/ 6 \right] e^{-M_a/12} \qquad \text{A2.5}$$

because spawning for the cod stocks under consideration is taken to occur 2 months after the start of the year and some mortality (natural and fishing) has therefore occurred (note that the equation A2.4 above refers to B^{sp}_y in year *y*-1 to account for the fact that recruitment here refers to 1-year-old fish),

where

$w^{strt}_{y,a}$ is the mass of fish of age *a* during spawning, and

$f_{y,a}$ is the proportion of fish of age *a* that are mature.

In order to work with estimable parameters that are more meaningful biologically, the stock-recruitment relationship is re-parameterised in terms of the pre-exploitation equilibrium spawning biomass, K^{sp}, and the “steepness”, *h*, of the stock-recruitment relationship, which is the proportion of the virgin recruitment that is realized at a spawning biomass level of 20% of the virgin spawning biomass:

$$\beta = \frac{\left(K^{sp}\right)^{\gamma}\left(1 - 5h0.2^{\gamma}\right)}{5h - 1} \qquad \text{A2.6}$$

and

$$\alpha = \frac{\beta + \left(K^{sp}\right)^{\gamma}}{SPR_{virg}} \qquad \text{A2.7}$$

where

$$SPR_{virg} = \sum_{a=1}^{m} f_{y,a} w^{strt}_{y,a} N^{virg}_a e^{-M_a/6} \qquad \text{A2.8}$$

with

$$N^{virg}_1 = 1 \qquad \text{A2.9}$$

$$N^{virg}_a = N^{virg}_{a-1} e^{-M_{a-1}} \qquad \text{for } 2 < a < m\text{-}1 \qquad \text{A2.10}$$

$$N^{virg}_m = N^{virg}_{m-1}\, e^{-M_{m-1}} \big/ \left(1 - e^{-M_m}\right) \qquad \text{A2.11}$$

In the fitting procedure, both *h* and K^{sp} are estimated. Steepness is an important parameter, as the overall potential yield for an ASPM depends primarily on the steepness of the stock-recruitment curve and on the natural mortality rate.

In cases where γ is estimated (rather than setting γ=1 to correspond to a Beverton-Holt form), note that steepness *h* can exceed 1 (unlike for the Beverton-Holt form) for γ>1.

A2.1.3. Total catch and catches-at-age

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

$$C_y = \sum_{a=1}^{m} w_{y,a}^{mid}\ C_{y,a} = \sum_{a=1}^{m} w_{y,a}^{mid}\ N_{y,a}\ e^{-M_a/2}\ S_{y,a}\ F_y \qquad \text{A2.12}$$

where

$w_{y,a}^{mid}$ 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*,

$S_{y,a}$ is the commercial selectivity (i.e. vulnerability to fishing gear) at age *a* for year *y*; when $S_{y,a} = 1$, the age-class *a* is said to be fully selected, and

F_y is the fished proportion of a fully selected age class.

The model estimate of the mid-year exploitable ("available") component of biomass is calculated by converting the numbers-at-age into mid-year mass-at-age (using the individual weights of the landed fish) and applying natural and fishing mortality for half the year:

$$B_y^{ex} = \sum_{a=1}^{m} w_{y,a}^{mid} S_{y,a} N_{y,a} e^{-M_a/2} (1 - S_{y,a} F_y\ /2) \qquad \text{A2.13}$$

whereas for survey estimates of biomass in the beginning of the year (for simplicity spring and autumn surveys are both treated as begin-year surveys):

$$B_y^{surv} = \sum_{a=1}^{m} w_{y,a}^{strt} S_a^{surv} N_{y,a} \qquad \text{A2.14}$$

where

S_a^{surv} is the survey selectivity for age *a*

A2.1.4. Initial conditions

As the first year for which data (even annual catch data) are available for these cod stocks clearly does not correspond to the first year of (appreciable) exploitation, one cannot make the conventional assumption in the application of ASPM's that this initial year reflects a population (and its age-structure) at pre-exploitation equilibrium. For the first year (y_0) considered in the model therefore, the stock is assumed to be at a fraction (θ) of its pre-exploitation biomass, i.e.:

$$B_{y_0}^{sp} = \theta \cdot K^{sp} \qquad \text{A2.15}$$

with the starting age structure:

$$N_{y_0,a} = R_{start} N_{start,a} \qquad \text{for } 1 \le a \le m \qquad \text{A2.16}$$

where

$$N_{start,1} = 1 \qquad \text{A2.17}$$

$$N_{start,a} = N_{start,a-1} e^{-M_{a-1}} (1 - \phi S_{a-1}) \qquad \text{for } 2 \le a \le m-1 \qquad \text{A2.18}$$

$$N_{start,m} = N_{start,m-1} e^{-M_{m-1}} (1 - \phi S_{m-1}) \big/ (1 - e^{-M_m} (1 - \phi S_m)) \qquad \text{A2.19}$$

where ϕ characterises the average fishing proportion over the years immediately preceding y_0.

A2.2. The (penalised) likelihood function

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

A2.2.1 CPUE relative abundance data

The likelihood is calculated assuming that an observed CPUE abundance index for a particular fishing fleet is log-normally distributed about its expected value:

$$I_y^i = \hat{I}_y^i \exp\left(\varepsilon_y^i\right) \quad \text{or} \quad \varepsilon_y^i = \ell\text{n}\left(I_y^i\right) - \ell\text{n}\left(\hat{I}_y^i\right) \tag{A2.20}$$

where

I_y^i is the CPUE abundance index for year y and series i,

$\hat{I}_y^i = \hat{q}^i \hat{B}_y^{ex}$ is the corresponding model estimate, where $\hat{B}_y^{ex}$ is the model estimate of exploitable resource biomass, given by equation A2.13,

$\hat{q}^i$ is the constant of proportionality (catchability) for CPUE abundance series i, and

ε_y^i from $N\left(0, \left(\sigma_y^i\right)^2\right)$.

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

$$-\ell\text{n}\,L^{CPUE} = \sum_i \sum_y \left[\ell\text{n}\left(\sigma_y^i\right) + \left(\varepsilon_y^i\right)^2 / 2\left(\sigma_y^i\right)^2\right] \tag{A2.21}$$

where

σ_y^i is the standard deviation of the residuals for the logarithm of index i in year y.

Homoscedasticity of residuals is assumed, so that $\sigma_y^i = \sigma^i$ is estimated in the fitting procedure by its maximum likelihood value:

$$\hat{\sigma}^i = \sqrt{1/n_i \sum_y \left(\ell\text{n}(I_y^i) - \ell\text{n}(q^i \hat{B}_y^{ex})\right)^2} \tag{A2.22}$$

where

n_i is the number of data points for CPUE abundance index i.

The catchability coefficient q^i for CPUE abundance index i is estimated by its maximum likelihood value:

$$\ell n\,\hat{q}^i = 1/n_i \sum_y \left(\ln I_y^i - \ln \hat{B}_y^{ex}\right) \tag{A2.23}$$

A2.2.2. Survey abundance data

In general, data from the surveys are treated as relative abundance indices in exactly the same manner to the CPUE series above, with survey selectivity function S_a^{surv} replacing the commercial selectivity $S_{y,a}$. Account is also taken of the time of year when the survey is held. For these analyses, selectivities are estimated as detailed in section A2.4.2 below.

A2.2.3. 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:

$$-\ell\text{n}\, L^{CAA} = \sum_y \sum_a \left[\ell n\left(\sigma_{com} / \sqrt{p_{y,a}}\right) + p_{y,a}\left(\ell n\, p_{y,a} - \ell n\, \hat{p}_{y,a}\right)^2 / 2\left(\sigma_{com}\right)^2 \right] \qquad \text{A2.24}$$

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

$$\hat{C}_{y,a} = N_{y,a}\, e^{-M_a/2}\, S_{y,a}\, F_y \qquad \text{A2.25}$$

and

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

$$\hat{\sigma}_{com} = \sqrt{\sum_y \sum_a p_{y,a}\left(\ell n\, p_{y,a} - \ell n\, \hat{p}_{y,a}\right)^2 / \sum_y \sum_a 1} \qquad \text{A2.26}$$

The log-normal error distribution underlying equation A2.25 is chosen on the grounds that (assuming no ageing error) variability is likely dominated by a combination of interannual variation in the distribution of fishing effort, and fluctuations (partly as a consequence of such variations) in selectivity-at-age, which suggests that the assumption of a constant coefficient of variation is appropriate. However, for ages poorly represented in the sample, sampling variability considerations must at some stage start to dominate the variance. To take this into account in a simple manner, motivated by binomial distribution properties, Punt (pers. commn) advised weighting by the observed proportions (as in equation A2.25) so that undue importance is not attached to data based upon a few samples only.

Commercial catches-at-age are incorporated in the likelihood function using equation A2.25, for which the summation over age *a* is taken from age a_{minus} (considered as a minus group) to a_{plus} (a plus group). For these analyses, a_{minus} was taken to be 2 and a_{plus} to be 7.

A2.2.4. 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 log-normal error distribution (equation A2.25) where:

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

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

$$\hat{p}_{y,a} = S_a^{surv} N_{y,a} \Big/ \sum_{a'=0}^{m} S_a^{surv} N_{y,a} \qquad \text{for begin-year surveys.} \qquad \text{A2.27}$$

A2.2.5. Stock-recruitment function residuals

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

$$-\ell nL^{pen} = \sum_{y=y1+1}^{y2}\left[\left(\frac{\lambda_y - \rho\lambda_{y-1}}{\sqrt{1-\rho^2}}\right)^2 \Big/ 2\sigma_R^2\right] \qquad \text{A2.28}$$

where

$\lambda_y = \rho\lambda_{y-1} + \sqrt{1-\rho^2}\,\varepsilon_y$ is the recruitment residual for year *y*, which is estimated for year *y*1 to *y*2 (see equation A2.4),

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

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

ρ is the serial correlation coefficient, which is input.

In the interest of simplicity, equation A2.28 omits a term in λ_{y1} for the case when serial correlation is assumed ($\rho \neq 0$), which is generally of little quantitative consequence to values estimated.

The analyses conducted in this paper have however all assumed $\rho = 0$.

A2.3. Estimation of precision

Where quoted, 95% confidence interval estimates have been evaluated using the likelihood profile method as available in ADMB. Note that such ADMB output for quantities that are functions of parameters estimated in the model fit, though not for those parameters themselves, differs slightly from exact likelihood profile results, being rather approximations to a Bayesian posterior.

A2.4. Model parameters

A2.4.1 Natural mortality:

Natural mortality (M_a) is generally taken to be age independent and is estimated in the model fitting process.

In one sensitivity test where age-dependence is admitted, it is taken to have the form:

$$M_a = \mu_1 + \mu_2/a \qquad \text{A2.29}$$

A2.4.2 Fishing selectivity-at-age:

The commercial fishing selectivity, S_a, is estimated in terms of a logistic curve given by:

$$S_a = \left[1 + \exp\left(-\left(a - a_c\right)/\delta\right)\right]^{-1} \qquad \text{A2.30}$$

where

a_c years is the age-at-50% selectivity,

δ year^{-1} defines the steepness of the ascending limb of the selectivity curve.

The commercial selectivity is taken to differ over the 1893-1991 and 1992+ periods, with the parameters a_c and δ being estimated separately for each. 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. Quantities such as *MSY* and *MSYL* depend on S_a, so that estimates for the two periods are differentiated in Tables by the annotations (1) and (2) respectively. Equation A2.30 applies to age 5 only, with values renormalised so that $S_5=1$; selectivities for ages 6 and 7+ are estimated directly in the model fitting process for each period.

Regarding survey selectivity, S_a^{surv}, a linear increase over ages a = 1 to 5 is assumed for the NEFSC offshore spring and autumn research vessel bottom trawl surveys (WHSpr and WHAut) as suggested by NEFSC scientists:

$$S_a^{WH} = s(a-1) + c^{WH} \quad \text{where} \quad S_5^{WH} = 1 \qquad \text{A2.31}$$

Selectivity for ages 1 and 2 is taken to differ for the NEFSC offshore spring and autumn surveys:

$$S_a^{WHAut} = p_a \, S_a^{WHSpr} \quad \text{for} \quad a = 1, 2 \qquad \text{A2.32}$$

where the p_a are estimated in the fitting process. Furthermore, the selectivities for ages 6 and 7+ for these surveys are estimated directly in the model fitting process.

For the State of Massachusetts inshore spring and autumn bottom trawl surveys (MASpr and MAAut), an exponentially decrease over ages a = 1 to m is assumed:

$$S_a^{MA} = \exp\left(-\gamma^{MA}(a-1)\right) \qquad \text{A2.33}$$

A different selectivity function is estimated for the spring and autumn bottom trawl surveys, so that both γ^{MASpr} and γ^{MAAut} are estimated in the fitting process.

Note that introductions of additional parameters (the commercial selectivity change after 1991, the p_a's for the NEFSC surveys, and the seasonally-dependent γ^{MA}'s for the Massachusetts surveys) were checked to be justified in terms of AIC.

A2.4.3 Age-at-maturity:

The proportion of fish of age a that are mature in year y is input (see Table A1.1).

A2.4.4 Weight-at-age:

Spawning (w_a^{sp}) and landed ($w_{y,a}^{landed}$) weight-at-age are input (see Tables A1.2 and A1.3).

A2.5. Model outputs shown in tables

Most of the quantities reported in the standard tabular output used for the results of the fits of the ASPM are defined above ($-\ell nL$ contributions, and parameters/variables such as K^{sp}, B^{sp}, h, M, etc.). Note that σ_R (in) reflects the input value for σ_R in equation A2.4; σ_R out is the standard deviation of the residuals estimated in the model fit for the years for which information is available to allow estimation (1964 to 2001). Selectivities shown are for ages a=1, …,6,7+.

MSY is straightforwardly calculated for the dynamics indicated above (the value given corresponds to the deterministic $\sigma_R \rightarrow 0$ of equation A2.4), as is the corresponding value of spawning biomass $B^{sp}(MSY)$. The *MSY* level, $MSYL^{sp}$ is the ratio $B^{sp}(MSY)/K^{sp}$.

Values are given for an equivalent annual fishing mortality rate (F*) corresponding to the fully selected fishing proportion (F) of equation A2.12. The relationship between these two quantities is:

$$1 - F = e^{-F*} \qquad \text{A2.34}$$

Appendix 3 - The ADAPT-VPA Model

Note that the specifications set out below are not their most general form (see Anon. 2003), but rather as implemented for the Mayo *et al.* (2002) application to Gulf of Maine cod. To avoid confusion the notation of Anon. (2003) of F for fishing mortality has been maintained here and in Appendix 4, though note that earlier in this document F is used for fishing proportion and F^* for fishing mortality.

A3.1 Population Dynamics

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

$$N_{y,a} = N_{y+1,a+1} e^{M_a} + C_{y,a} e^{M_a/2} \qquad \text{for } 1 \le a \le m-2 \qquad \text{A3.1}$$

$$Z_{y,a} = \ell n\left(\frac{N_{y,a}}{N_{y+1,a+1}}\right) \qquad \text{A3.2}$$

$$F_{y,a} = Z_{y,a} - M_a \qquad \text{A3.3}$$

where

$N_{y,a}$ is the number of fish of age a at the start of year y (which refers to a calendar year),

M_a denotes the instantaneous rate of natural mortality on fish of age a,

$C_{y,a}$ is the number of fish of age a caught in year y,

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

$Z_{y,a}$ is the instantaneous rate of mortality during year y from all causes (total mortality) on fish of age a, and

$F_{y,a}$ is the instantaneous rate of fishing mortality on fish of age a.

The stock sizes of the oldest true age (m-1) and the plus-group (m) are computed as follows:

$$N_{y,a} = \frac{Z_{y,a} C_{y,a}}{F_{y,a}\left(1 - e^{-Z_{y,a}}\right)} \qquad \text{for } a = m\text{-}1 \text{ and } a = m \qquad \text{A3.4}$$

Fishing mortality on the oldest true age is defined as:

$$F_{y,m-1} = PR_{m-1} F_y^{full} \qquad \text{A3.5}$$

where

$F_y^{full} = \frac{1}{N_R} \sum_{a \in R} F_{y,a}$ is the fully-recruited fishing mortality in year y, R denoting the set of fully-recruited age classes, excluding the oldest true age m-1, and

PR_{m-1} is the partial recruitment for fish of age m-1, which is input. (Note the partial recruitment PR_a is essentially the selectivity S_a of the ASPM approach of Appendix 2.)

Fishing mortality on the plus-group is defined as:

$$F_{y,m} = \alpha F_{y,m-1} \qquad \text{A3.6}$$

where

α is the plus-group ratio, which is input.

A3.2. The objective function

The model is fitted to survey abundance and CPUE indices. Contributions by each of these to the objective function (maximised in the fit) are computed as follows.

The objective function is calculated assuming that the observed abundance indices are log-normally distributed about their expected values:

$$I^i_{y,a} = \hat{I}^i_{y,a} \exp\left(\varepsilon^i_{y,a}\right) \quad \text{or} \quad \varepsilon^i_{y,a} = \ell\text{n}\left(I^i_{y,a}\right) - \ell\text{n}\left(\hat{I}^i_{y,a}\right) \qquad \text{A3.7}$$

where

$I^i_{y,a}$ is the observed abundance index for year *y*, age *a* and series *i*,

$\hat{I}^i_{y,a}$ is the corresponding model estimate, where

$\hat{I}^i_{y,a} = q^i N_{y,a}$ for begin-year indices or

$\hat{I}^i_{y,a} = q^i N_{y,a} \dfrac{1-e^{-Z_{y,a}}}{Z_{y,a}}$ for mid-year indices, and

$\hat{q}^i$ is the constant of proportionality (catchability) for abundance series *i*.

The objective function is then given by:

$$SS = \sum_{i,y,a} \left[\ell n\left(I^i_{y,a}\right) - \ell n\left(\hat{I}^i_{y,a}\right)\right]^2 \qquad \text{A3.8}$$

The function is minimised by treating the abundances for ages 2 to *m*-1 in the final year+1 as estimable parameters.

Appendix 4 – Some Reservations concerning the ADAPT-VPA Model Implementation for Gulf of Maine Cod

[Note that as in Appendix 3, this Appendix uses F to indicate fishing mortality rather than fishing proportion.]

There are two inconsistencies in the ADAPT-VPA model as applied to Gulf of Maine cod (see Appendix 3).

The first concerns equation A3.4 which provides abundance estimates for ages m-1 and m given values for the corresponding fishing mortality and catch:

$$N_{y,a} = \frac{Z_{y,a} C_{y,a}}{F_{y,a}\left(1 - e^{-Z_{y,a}}\right)} \qquad \text{A3.4}$$

Since the abundances of younger age groups are estimated by use of Pope's form of the catch equation:

$$N_{y,a} = N_{y+1,a+1} e^{M_a} + C_{y,a} e^{M_a/2} \qquad \text{A3.1}$$

it seems strange to revert to equation A3.4, which is based on the Baranov equation (continuous rather than pulse fishing) for the oldest ages. This is as equation A3.1 can readily be cast into the form required to solve for $N_{y,a}$ given catch and fishing mortality values, *viz*.:

$$N_{y,a} = \frac{C_{y,a} e^{M_a/2}}{1 - e^{-F_{y,a}}} \qquad \text{A4.1}$$

A potentially more serious problem, however, is the overall approach used to compute plus-group abundances. Essentially this consists of fitting a model to the data up to age m-1 to estimate a numbers-at-age matrix $N_{y,a}$ for ages 2 to m-1, and then applying equation A3.4 for each year (or alternatively A4.1 could be applied) in conjunction with equation A3.6 to provide the plus-group abundance for that year. The difficulty with this is that plus-group abundance is governed by the equation:

$$N_{y+1,m} = \left(N_{y,m} e^{-M_m/2} - C_{y,m}\right) e^{-M_m/2} + \left(N_{y,m-1} e^{-M_{m-1}/2} - C_{y,m-1}\right) e^{-M_{m-1}/2} \qquad \text{A4.2}$$

and results obtained from the combined application of equations A3.4 (or even A4.1) to A3.6 will not necessarily satisfy equation A4.2, because of the specification of potentially contradictory conditions. In other words, the overspecification of the approach of Appendix 3 leads to incorrect estimates of plus-group abundance.

Now in circumstances of asymptotically flat selectivity (partial recruitment) at higher ages, together with heavy fishing mortality so that few fish survive to reach the plus-group, any errors to which these inconsistencies give rise are likely slight. It is not clear, however, whether this will continue to be the case in circumstances of lesser fishing mortality, and particularly selectivity that declines with age at larger ages, as may well be the situation in this application to Gulf of Maine cod.

ANNEXURE A:

RESPONSE TO COMMENTS RE ASPM METHODOLOGY BY REVIEW PANELIST McALLISTER

Pages 29 and 30 of this reviewer's report list the following reasons why the results[1] we reported to the Durham meeting allegedly "lack credibility". Our response to his allegations of our lack of scrutiny in each respect is given after each reason.

1) "the various inaccuracies in the time series of catch biomass data due to discarding and under-reporting" - the data used were as provided to us by NEFSC scientists, presumably considered by them to be the most appropriate and as used for their ADAPT-VPA analyses, so that such criticism is as pertinent to the one approach as the other; there is no immediately obvious reason to suspect that alternative assumptions regarding these data would affect results of the two forms of analyses in qualitatively different ways.

2) "modeling the vulnerability-at-age patterns in the trawl survey data" - different formulations were reported by us in Durham, with no qualitative impact on results of key concern for management; the paper attached[2] extends these investigations, and the fits to the data show no obvious indications of model mis-specification, as discussed in the paper; it is important to contrast this with the ADAPT-VPA approach which normally ignores this consideration through making the questionable assumption of error-free catch-at-age data; no information was, to our knowledge, presented to the Durham meeting showing the selectivity patterns and their temporal changes implied by the ADAPT-VPA assessments, and it would seem important that these are extracted and considered in respect of their plausibility.

3) "the potential inaccuracies of Pope's approximation" (to the catch equation) - the Baranov equation underlying the ADAPT-VPA is equally an approximation, given that fishing effort is not distributed uniformly through the year - however again there is no obvious reason, given circumstances where mortality rates are not enormous, to suspect that these two approximations will give qualitatively different answers for the key management quantities of concern here.[3]

4) "the appropriateness of the likelihood functions used" - these have been peer-reviewed and considered acceptable for other fisheries (see main text above); again the same could likely be said of the fitting criteria used for the ADAPT-VPA; but fundamentally the main purpose of getting such functions "right" is to achieve appropriate weighting of different data inputs to the assessment, and hence minimum variance estimates – the residual patterns reported in the paper attached offer no obvious indication that the approach we applied has used formulations sufficiently inappropriate to qualitatively change key results.

5) "identifying an appropriate set of estimable parameters" - this presumably means that estimable parameters should ideally be chosen to have low covariances, for faster and more reliable estimation; again, the same could be said of the ADAPT-VPA approach; however, this is not an absolute requirement, as convergence performance can be readily checked by commencing the parameter search from different initial guesses, as was done for a number of the fits we reported.

6) "identifying appropriate values for the magnitude of the variance in stock-recruit model deviates" - it is unclear what the most appropriate value for this variance should be; for this reason, results we reported in Durham were presented over a wide range of choices for this input, with the alternatives not leading to qualitative changes in key results when compared to those from ADAPT-VPA[4].

7) "the abundance of each age-class in the initial year of the model" - this applies equally to ADAPT-VPA, where such values depend heavily on assumptions made for relationships between fishing mortalities on the oldest ages; the ASPM results we reported in Durham did investigate this (see Tables 4b and 5 of Butterworth *et al.* (2003a)), showing sensitivity to be very slight, as is additionally confirmed by further results reported in the paper attached (see Table 4)[5].

8) "a suitable model for the survey constant of proportionality and fishery catchability" - the first aspect again applies equally to the ADAPT-VPA analyses; both approaches assume the survey to have provided a consistent index of abundance over time; indeed the Panel's summary report recommends that these survey data continue to be used unadjusted for stock assessment, so that this particular reservation by this Panelist is inconsistent with the overall Panel report; the comment about fishery catchability is irrelevant, as the ASPM analyses presented made no use of commercial CPUE data.[6]

9) "the potential inaccuracies of temporal changes in growth rate and fecundity at age over the long time series modeled" – our analyses made use of such data in this respect as NEFSC scientists provided, which are presumably the same as those they have used in their ADAPT-VPA analyses.

10) "the choice of an appropriate starting year for the stock assessment model" - see response 7) above; this was investigated and found hardly to affect key results[7].

X) "advisable to use a prior or fix a value for steepness" - agreed, but it is best for all scientists involved to pre-agree this, and in any case analyses we presented for alternative choices for this value showed no qualitative change to key results when compared to those from ADAPT-VPA[8].

Y) "Before any such (ASPM) approach could be considered a suitable candidate for stock assessment modeling of New England groundfish, it would need to be very thoroughly simulation tested using an operating model approach that the first author is infinitely well familiar with." - Simulation testing of this nature is a substantial exercise which experience has shown yields no satisfactory agreed outcome unless all the scientists involved first meet to agree to the specifications of the tests, which need to be conditioned across the range of results provided by the various approaches under consideration for the resources in question. This has not (yet) been done for the ADAPT-VPA approach any more than for the ASPM approach in this instance. Application of the ADAPT-VPA methodology to these resources in March 2002 predates that of our ASPM approach by only a few months. It is therefore unclear to us what justification might be offered by this Panelist for the different standards he implies that the two approaches are required to meet to be acceptable candidates for assessing New England groundfish: why should ADAPT be accorded uncontested default status in the absence of such testing, whereas ASPM be unacceptable until it undergoes such?

Annexure A – Appendix of Clarifications/Updates (corresponding to numbered footnotes in Annexure A)

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[1] The results referenced are those reported in Butterworth *et al.* 2003a (the February 2003 paper).

[2] Butterworth *et al.* 2003b (the March 2003 paper).

[3] At the time this was written, we had not realized that the original ADAPT-VPA results of Mayo *et al.* (2002) are also based on Pope's form of the catch equation – see Appendix 3 of the main text.

[4] A similar sensitivity test (Case IX) for the current ASPM New Reference Case is reported in the main text, and again does not lead to qualitative changes.

[5] Similar results (Cases X and XI) follow for the current ASPM New Reference Case. The "results reported in the paper attached" refer to Butterworth *et al.* 2003b.

[6] The current ASPM New Reference Case does now make limited use of CPUE data (see Table A1.10 of Appendix 1) for compatibility with the ADAPT-VPA analyses of Mayo *et al.* (2002).

[7] Response under footnote 5) applies.

[8] Sensitivity to the value for steepness h for the current ASPM New Reference Case is again addressed (Case IV in the main text); for a lower value of h, the value of $B^{sp}(2001)/B^{sp}(MSY)$ falls, but that and the value of $B^{sp}(2001)$ itself remain well above the ADAPT-VPA based estimates of NEFSC (2002) and Mayo *et al.* (2002) respectively.

ANNEXURE B

The references below to our papers forwarded to NEFSC and NEFMC since the peer review meeting in Durham in February are as follows:

"March 2003": Butterworth, Rademeyer and Plagányi: Further investigations of an ASPM-based assessment for the Gulf of Maine cod[1]

"July 2003": Butterworth, Rademeyer and Plagányi: ASPM-based assessment of the Gulf of Maine cod stock: a comparison with ADAPT-VPA and extension to a Bayesian form[2]

References of the form "Annex n" refer to earlier correspondence reproduced as annexures to this Appendix.[3]

(1) Time varying commercial selection at age data

A time change in 1992 was introduced in "March 2003" (pgs 3-4 give the rationale[4], and the Tables provide numerous associated results).

In Annex 1 (7 Feb), point 3), we asked for further information to pursue such work. In Annex 2 (12 Feb), para 3, NEFSC advised that they would be sending us a list in response, but we have yet to receive that. In Annex 3 (21 Mar), we sought comment from NEFSC on the change in 1992 we proposed to introduce (and eventually did so in "March 2003"), but received no response. In "July 2003" (pg 9) we again make suggestions for further work along these lines, and comment that this would be facilitated by input from NEFSC, which we have again requested in Annex 8 (14 July), para 2.

(2) Age dis-aggregated survey catch at age

These data have been incorporated in the analyses: "March 2003" (see pg 3, para 2), and to a further extent in "July 2003" through the modification elaborated there in the second last para on pg 3.[5]

(3) Age specific survey *q*'s

This is termed "survey selectivity" in the two papers submitted. The suggestion to take this into account, as earlier put forward by NEFSC scientists, was incorporated in "March 2003" (see equation 1 on pg 3).[6]

(4) Incorporate additional survey series -- Mass. & commercial CPUE

Such data have been requested by us - Annex 1 (7 Feb), point 7), but we have yet to receive a response.[7] Given this information we would be happy to rerun our analyses incorporating it.

(5) Estimate and provide profile of likelihood of management parameters

Information on such estimates of precision, though based on the Hessian, was provided in "March 2003" - see Table 2, New Reference Case column. The profile likelihood approach is a better method than that based on the Hessian, and in response to a specific NEFSC request in this regard (16 Jun), a profile likelihood for natural mortality *M* was attached to Annex 7 (17 Jun).[8] The Bayesian approach of "July 2003" provides a yet better way to develop this information, which may be found for various important management quantities in Table 5 and Fig 4b thereof.

(6) Starting age structure of the model and start date (1963?)

This specific request was addressed in "March 2003" (see pg 6, second last para, and Table 4, column headed "Start in 1963").[9]

(7) Retrospective analyses

These were reported in "March 2003" (see pg 7, first para, Table 6 and Figs 6 and 7).[10]

(8) More complete age-specific diagnostics and components of likelihoods

The contributions to the different components of the (negative log) likelihoods are routinely reported for each fit in the two papers - see, for example, Table 2 of "March 2003". The age-specific diagnostics have been extended beyond what were reported in the submissions to the February meeting in Durham - see particularly Fig 2 of "March 2003" and Fig 2 (apologies for the typo that mislabelled this as the apparent first of two Fig 3's!) of "July 2003", and the associated points of discussion in the text.[11]

(9) Share AD code, documents, and output

We had hoped to make this code available earlier, but for reasons of unfortunate personal circumstances outlined at the top of page 2 of Annex 5 (31 March), and referenced also in para 2 of Annex 4 (31 March) sent to NEFSC, an unavoidable delay occurred that slowed the process of adding the necessary explanatory text to our code. This information was nevertheless duly forwarded on 30 May (Annex 6), and receipt acknowledged by NEFSC on 16 June (Annex 7).[12]

(10) Investigate model estimability with age-specific selectivity versus estimability of *M* and/or age-varying *M*.

Both "March 2003" and "July 2003" consider models which estimate selectivity (both commercial and survey) as well as *M* - indeed the Reference Cases for each incorporate this. The simultaneous estimability of both within the model as configured is demonstrated, for example, by the relatively narrow posterior pdf for *M* shown in Fig 4b of "July 2003", which also advocates further lines of investigation in this regard (pg 10), to which the suggestion of an age-dependent *M* could readily be added.[13]

Annexure B

Annexure B – Appendix of Clarifications/Updates (corresponding to numbered footnotes in Annexure B)

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[1] Refers to Butterworth *et al.* 2003b.

[2] Refers to Butterworth *et al.* 2003c

[3] Refers to annexures which are not included here and which are not pertinent in the current context.

[4] This rationale is repeated in Section A2.4.2 of Appendix 2 of the main text.

[5] This is explained in Section A2.2.4 of Appendix 2.

[6] Section A2.4.2 of Appendix 2 reports subsequent developments.

[7] These data have now been received and are incorporated in the current ASPM New Reference Case (see Appendix 1, Tables A1.8 to A1.10).

[8] Likelihood profile–based estimates of confidence intervals for key quantities are reported in the Tables of the main text.

[9] See sensitivities Cases X and XI reported in Table 3 and Fig. 8 of the main text for updates in regard to the current ASPM New Reference Case.

[10] See sensitivities Cases XIII a-c reported in Table 3 and Fig. 9 of the main text for updates in regard to the current ASPM New Reference Case.

[11] These continue to be reported: log likelihood contributions from various sources are given in Tables 1 to 3 and fit residuals for the current ASPM New Reference Case are shown in Figs 3-5 of the main text.

[12] Updated ADMB code can be provided if requested.

[13] Evidence for the continued estimability of M for the current ASPM New Reference Case is provided by the reasonably narrow likelihood profile-based 95% CI of [0.20; 0.28] reported for Case III in Table 1 of the main text.

ANNEXURE C

10 October, 2003

Dr John Boreman
Acting Science and Research Director
Northeast Fisheries Science Center
Woods Hole, MA

Dear John,

Thank you for your communication of 12 September with its comments on our earlier submissions regarding the assessment of the Gulf of Maine cod stock and related issues. Forgive us for taking some time to reply, but it seemed worthwhile to us to first carry out some further computations which facilitate addressing and hopefully resolving some of the points you raise.

Below we respond on a paragraph by paragraph basis to the issues you raised, and include also the results of the further computations to which I have just referred. Probably the most important of these responses are those numbered 1) –4), which pertain to the summarized four "sources of major disagreement" to which the third last paragraph of your letter refers. We hope that these resolve these matters, and will be interested to receive your response on that point.

You will note that, in part in the light of your comments received, we have amended our Reference Case assessment, and now find ourselves in an area of parameter space in which we (and we hope you and your colleagues) feel somewhat more comfortable. Nevertheless, our earlier conclusion remains given these updated results: that all indications are of a current spawning biomass relative to the MSYL which is substantially greater than suggested by NMFS' ADAPT-VPA based computations – results which clearly have major implications for management actions currently under consideration.

A key question now is how this process be taken forward. Your communication requested that our interchange take the form of a review among (scientific) colleagues. This indeed was our initial preference, as the technical nature of many of the points at issue renders their discussion most appropriately confined initially to a scientific audience.

However, when we first suggested this mode of interchange (in February at the Peer Review meeting), we had the impression that we were at the start of a process which would move ahead quite rapidly. Indeed the Peer Review Group's report pointed to the need to address the model robustness of reference point estimates (Para 10 of their Summary), and this is what our work has sought to do. Yet the first response to our submissions received from yourself and your colleagues arrived as long as six months after the proceedings in Durham. This places us in a very difficult position with our principals, given that the management actions about which they are concerned, and in the light of which they are supporting our contributions, are now much closer at hand. For that reason they require our best scientific advice on the current state of play with assessment evaluations, and have limited time left to allow us for “private” scientific interactions before they may need to put certain wheels in motion (which will in due course require our input as their scientific advisers).

In these circumstances, I would appreciate your feedback on how you see the best way to proceed. My own feeling, from a purely scientific perspective, is that the sooner a meeting could be organized to discuss the model robustness of the reference point evaluations so as to inform the management process of the implications, the better. It would be very important that such a meeting include scientists from other areas who are familiar with what we term the “ASPM approach”. However, I offer this obviously ignorant of the constraints that govern the options open to you.

To more technical matters, in taking forward the suggestion (see response 39) below) that ASPM and ADAPT-VPA comparisons be based on exactly the same data, with which we quite agree, there are some clarification issues which need to be addressed (see also 26 below) upon which we trust your colleagues can assist. It would seem most sensible to base comparisons on the assessments used for the GARM report (NEFSC, 2002), as those formed the basis for the reference point evaluations. Our understanding is that the input data used in that report have been updated (not only in respect of one further year, but also some other changes made) from the values in Mayo *et al.* (2002). However, unlike in the Mayo *et al.* paper, all inputs are not listed in the GARM report; missing data include, for example, the mean SSB weights and maturity at age for the 1982-2001 period and the Massachusetts trawl survey data. A file including the direct inputs and outputs from the ADAPT-VPA model implemented for the GARM report would greatly assist the comparison exercise.[1]

In earlier correspondence, you also advised us that the methodology used for your ADAPT-VPA computations was specified in the NMFS tool-box. In asking Clay Porch and Maurico Ortiz of NMFS’ Miami Laboratory about the availability of this during a recent ICCAT meeting in Madrid, they advised that the tool-box is not yet publicly available, and that someone (they were not sure who) had to be written to for permission to acquire this. A key piece of information we require is an algebraic elaboration of the ADAPT objective function used for the estimation of current year numbers-at-age, as the details given on pg 106 of Appendix 4 of the Mayo *et al.* (2002) GoM cod assessment are not sufficient to determine that. Please advise how we should best proceed to acquire this information, at least.

Regards

Doug Butterworth

Annexure C

RESPONSES TO NMFS COMMENTS ON ASPM ASSESSMENTS OF GoM COD

Before responding to your comments specifically by means of inserts below, it is perhaps helpful to briefly summarise the results of further ASPM computations, attached below, which have been pursued to facilitate these responses.

Furthermore, for convenience, I will refer to the three primary submissions we have made on the application of our ASPM methodology to the GoM cod stock as:

> February paper: Butterworth, Rademeyer and Plaganyi - An age-structured production model assessment and reference point evaluation for the Gulf of Maine cod stock.[2]
>
> March paper: Butterworth, Rademeyer and Plaganyi – Further investigations of an ASPM-based assessment for the Gulf of Maine cod stock.[3]
>
> July paper: Butterworth, Rademeyer and Plaganyi – ASPM-based assessment of the Gulf of Maine cod stock: a comparison with ADAPT-VPA and extension to a Bayesian form.[4]

Table1:

Case 1: The Reference Case, which is the “New Reference Case” of the July paper; all other cases are described in terms of how they differ from this.

Case 2: Replacement of linear form of survey selectivity function – see March paper equation 1 – by a logistic form.

Case 3: Selectivities for ages greater than 5 are modified by a multiplicative factor exp[-slope*(a-5)] where slope is estimated separately for the two commercial and the survey selectivity functions. Note that the estimation of three extra parameters is AIC justified compared to the Reference Case. Fits where this potential decrease was introduced from the lower age of 4 provided much less improvement to the log likelihood.

Case 4: As for Case 3, but the selectivities for ages 6 and 7+ are estimated separately, rather than linked by a common slope parameter. Note that the estimation of a further three extra parameters is AIC justified.

Case 5: The abundance in 1893 when the model commences is set to half its unexploited equilibrium level, and the age-structure related parameter estimated – see equations A.16 to A.20 of the February paper.

Case 6: Reference Case with steepness h = 0.9 instead of estimated.

Case 7: Reference Case with steepness h = 0.76 instead of estimated.

Case 8: Case 4, but here also with survey selectivities for ages 1 and 2 allowed to differ by amounts that are different by age between the autumn and spring surveys, i.e. the parameter p of equation 2 of the March paper is estimated separately for ages 1 and 2. This further extra estimable parameter is AIC justified. Case 8 now serves as the New Reference Case.

Case 9: Case 8, but with steepness h = 0.8 rather than estimated.

Case 10: Case 9, but with $M = 0.2$ rather than estimated.
Case 11: Case 8, but with the total catch time series replaced by what we think is your preferred version (see below) and including alternative weights and maturity at age inputs (see "UCT sensitivity" in the Appendix of the July paper).

95% C.I.'s based upon the likelihood profile method are shown for some of these Cases. In the cases of estimable parameters *h* and *M*, these have been separately rechecked, as the automated likelihood profile routine in ADMB can misbehave when the minimization has convergence difficulties (see discussion concerning Fig. 2 below). This is the reason the C.I. quoted below for *M* for Case 1 differs marginally from the result given in our July paper. For functions of estimable parameters, the results shown are not for the true likelihood profile, but for a modification thereof computed by ADMB with the intent that it approximate the Bayes posterior distribution for the quantity in question.

Fig. 1: Plots of fishing proportion *vs* year for Cases 1, 8 and 9.

Fig. 2: Likelihood profiles for *M* for Cases 1, 3 and 8. Note that these have been shown in the form of plots of –*ln*L less its minimum value for the Case concerned, so that a common horizontal line can be drawn whose intercepts with the –*ln*L curves provide estimates of the 95%C.I.'s. For lower values of *M* the ADMB minimization sometimes has difficulty in converging to a minimum, so that the results output are less reliable. These sections of the curves have been differentiated (shown by dots instead of full lines) to show this distinction.

Fig. 3: a) Reference Case 1 and b) New Reference Case 8 comparisons of observed and predicted catch-at-age proportions averaged over years.

Fig. 4: As for Fig. 3, but showing comparisons by both year and age through the medium of bubble plots, as in earlier papers.

Fig. 5: Retrospective plot of spawning biomass as a proportion of its pre-exploitation level, and of fishing proportion, for the New Reference Case 8.

RESPONSES TO SPECIFIC COMMENTS:

12 September 2003

Dr. Douglas Butterworth
Marine Resource Assessment and Management Group
Department of Mathematics and Applied Mathematics
University of Capetown

Annexure C

Rondebosch, 7701, South Africa

Dear Doug,

I indicated in an earlier e-mail to you that assessment scientists at the Northeast Fisheries Science Center would conduct a collegial review of your recent Gulf of Maine cod documents (*ASPM-Based Assessment of the Gulf of Maine Cod Stock: A Comparison with ADAPT-VPA and Extension to a Bayesian Form*, July, 2003, by D.S. Butterworth, R.A. Rademeyer and E. Plaganyi, and *Further Investigations of an ASPM-Based Assessment for the Gulf of Maine Cod Stock, March, 2003,* by the same authors), and supply you with a formal critique. I am attaching a series of specific comments related to the technical details of the papers. We assume that the model results of the former paper supersede those provided in the latter, and thus our comments primarily reflect the more recent (July) document. That document specifically addresses the issue raised in the peer review that one should be able reconcile results from various approaches (e.g., ASPM, ADAPT-VPA), given similar inputs and structural equations.

It is clear that we continue to have major technical disagreements regarding the specifics of your analytical approach and the interpretation of results of your implementation, as they relate to the provision of consistent management advice. While the details in the attached review may seem arcane to most of the lay public, the significant points upon which we fundamentally disagree are straightforward and can be summarized thusly:

- The F_{MSY} value resulting from the "New Reference Case (5)" provided in the July document (F^*_{MSY} = 3.004) is not credible. An F of 3.0 implies an annual exploitation rate for fully-recruited ages in excess of 97% (with the calculated M > 0.4). The Gulf of Maine cod stock has never experienced a fishing mortality rate this high, and, in fact, declined to a time-series low with Fs about one-third of this value. The F_{MSY} value estimated by your ASPM model is 13 times the F_{MSY} value provided by the Reference Point Review Committee, and is far higher than any such value proposed as a management reference point for Atlantic cod anywhere in the world. I think you will agree that while this is an analytical result consistent with the way you

> have structured your model, it clearly would not pass muster in a formal peer review forum that includes people familiar with the biology and dynamics of cod. As you acknowledge (top of page 5), there are "…potential problems with F_{MSY} as a reference point….". We feel that these problematic values of reference points stem primarily from the extremely high steepness coefficient (h=0.98) at the origin of the S-R relationship used as a constraint into your ASPM code, to which the solution converges, basically rendering this stock impervious to recruitment overfishing. Further, we feel that this result is an artifact of modeling rather than a real-world phenomenon.

1) First it is important to clear what seems to be a misunderstanding, as it underlies much of your critique. Nowhere, we believe, do we advocate (nor did we intend) that our F_{MSY} estimate from the July paper (for example) was itself a *specific* proposed candidate for an alternative adoptable reference point for actual management. We share your obvious reservations about its usage in that context. We get similar results (with *h* essentially 1) when applying this methodology (with the incorporation of a B-H S/R curve) to certain South African fish stocks, but do not then advocate the associated *MSY*-related quantities estimated as targets. I suspect you might not have grasped the sense with which we use the term "Reference Case", which may not have been totally clear from our description thereof on pgs 2 and 4 of the February paper. This is as is conventional usage in a number of international fisheries scientific committees, where "Reference Case" refers to a convenient benchmark for comparison for a set of sensitivity runs. It has a deliberately different meaning to "Base Case", which implies one's "best assessment", taking account of all pertinent factors. I suspect you mistakenly think we intended our "Reference Cases" as "Base Cases". This is not so – our aim has been to explore the robustness of certain results related to the reference point estimates based on your original ADAPT-VPA assessment (such as the current status of the resource relative to *MSYL*) to alternative model formulations – this is the essential charge of the Payne *et al.* February Peer Review report (see their Summary, para 10). For example, all our past results have shown a consistent pattern that whatever model variation we investigate, we estimate the current resource status relative to *MSYL* to be much better than indicated by your ADAPT-based results – it is that *qualitative* result that is the nub of our conclusions, and what we sought to point to in the Abstracts of our papers.

Our July New Reference Case result corresponded to an MLE (or strictly MPLE – P=Penalised, corresponding to a Bayesian posterior mode), but the reservations you express about it have nothing to do with "the way you have structured **your** model". It is rather a possible outcome of the combination of a Y/R and monotonically increasing (e.g. B/H) S/R curve to estimate MSY-related parameters, which is the paradigm your scientists are using (and hence we have followed). You did not get the behaviour you question simply because you did not venture into the region of parameter space to which it corresponds – we did, in the context of taking the MPLE process to its consistent conclusion (not that we always consider that the best conclusion).

Your suspicion that our results are problematic because of our high estimated steepness values of $h = 0.98$ is incorrect. Note Cases 6 and 7 in Table 1 where we have fixed h at the two ends of the range you later suggest as probable based upon the Myers *et al.* evaluations. These indicate no qualitative change to our Reference Case result that the present spawning biomass is above *MSYL*.[5]

- You provide sensitivity analyses in the July document that elucidate the consequences of allowing your model to estimate the value of M (when estimated in your versions of ASPM, M ranges from 0.4-0.5), rather than using the previously estimated value of M=0.2. Apart from the issues of the simultaneous estimability of M and fishery selectivity at age (explored in the attached comments), we feel that it is important to have some biological justification supporting such a major increase in M over the earlier estimates. What would kill large mature cod at a rate more than twice that that would be consistent with the observed maximum life span (~18 years) and other life history parameters? One obvious place to look is at cannibalism and predation by other fishes. Food habits data collected during spring and autumn NEFSC surveys during 1973-1997 show that the observed incidence of cannibalism in cod is very low. Out of 12,305 Atlantic cod stomachs examined, only 16 contained cannibalized cod (<0.2%) and the average percent composition by weight of the cannibalized cod was less than 0.1%. Other sampled fish species eat cod no more frequently. Likewise, stomach content data and scat samples from seal haul-out sites indicate that cod are a minor prey item in the Gulf of Maine area. Given the population sizes of the seals, low frequency of occurrence of cod in their diets, and size-selection of cod prey for relatively small animals, it is implausible that this source of M could generate the millions of predation-related deaths at all ages that would be required to support M=0.4-0.5. Thus, there is no known biological mechanism that would be responsible for such a high M.

2) Let me say at the outset that we do not pretend to be experts on the ecology of Northeast Atlantic cod. Our results are based on the analytical principle of “letting the data speak for themselves”. We consider that apparent possible “conflicts” between

what the data do say, and ecological perceptions, merit more widespread discussion, in particular to facilitate better understanding, particularly as regards management implications.

Your comments go to essentially two separate issues: the reasonableness of our estimates of *M*, and the question of whether *M* is estimable within such assessments, which I will take in order.

You say that there is "no known biological mechanism that would be responsible for such a high *M*". In South Africa we have qualitatively exactly the same "problem" for our southern African hake assessments: "unrealistically" high *M* estimates (particularly for the older and larger fish). We do not pretend to fully understand why, but we think we do know what is one major contributor to this result. Though one tends to refer to *M* as "natural mortality", in reality of course, it represents the sum of natural mortality *and emigration*. In our hake case, the older animals go deeper than the fishery and surveys operate, and are also found preferentially on rocky ground, where recently introduced longlining has been able to operate though trawling and trawl surveys cannot. Is your comment intended to mean that there is certainty that such a mechanism plays *absolutely no appreciable* role in the Gulf of Maine cod case? Note that allowing for the possibility of decreasing selectivity at large age does not exactly mimic potential emigration – for the former, such fish all remain catchable if fishing effort is high enough, whereas for the latter they are essentially in a refuge. Naturally cod in such a refuge might still be contributing to spawning products for the GoM stock – however, given the low correlation of recruitment with spawning biomass in this case, the assessment would not be much affected were this taken into account – only the actual abundance of cod would be rather higher than we estimate, but management targets based upon the high *M* and non-emigrated component would remain perfectly sound.

You refer to earlier lower estimates (of $M = 0.2$ or thereabouts) for cod. Presumably these are the Canadian estimates referenced in Mayo *et al.* (2002) as the basis for setting $M = 0.2$ in the ADAPT-VPA runs (we have been unable to discover any direct estimate of *M* for the GoM cod stock itself). One of the three papers quoted (Paloheimo and Kohler, 1968) refers to the southern Gulf of St Lawrence stock – we note that a more recent analysis for this resource estimates recent $M = 0.4$ (Chouinard *et al.*, 2002). Without intending disrespect to the other two papers your scientists cite - Pinhorn (1975) and Minet (1977) – one has to recognize that the methodologies they use are now very dated. Though they would have been considered acceptable at the time given contemporary computing capabilities, the field has since moved on. Furthermore, these older analyses say little about the variance of their estimates. Consider, for example, the method linked to Fig. 2 of Pinhorn's paper: a rough computation of the 95% CI for the associated estimate of $M = 0.16$ yields a result as wide as [0 ; 0.3]. [6]

This leads on to the matter of the estimability of *M* within assessments. The Canadian papers you cite as the basis for your chosen value for *M* are based essentially on the analysis of catch-curves. It is now generally known that this method is flawed – certainly this is well appreciated by those involved in the IWC Scientific Committee from debates there in the late 1980's, to which I was one of the contributors (Butterworth and Punt, 1990). The problem is confounding from selectivity and recruitment effects (Minet happens to acknowledge the former). To properly offset the bias to which neglect of these factors can give rise, any estimation of *M* **has** to take place within the overall assessment process. In Butterworth and Punt (1990), we point out (pg. 303) that though reasonable assumptions regarding temporal invariance of certain parameters render *M* estimable in principle, in practice "for many of the data sets typical of fisheries ….. noise added to the dominant linear effects … swamps the interaction terms that would in principle allow … these effects [e.g. the value of *M*] to be distinguished." This quote would appear to support your contention that questions our estimating *M*, but note our use of the word "many" (and not "all"). In the case of our hake assessments, for example, initially to our surprise we found that the large *M* estimates forthcoming did not drop to more "sensible" values when allowing for the possibility that selectivity decreases at large age – the reason in that case was that such scenarios did not reconcile with large historic declines in abundance evident from the CPUE series.

What determines whether or not *M* is estimable in a particular case is the behaviour of the likelihood used for fitting. In the case of the GoM cod assessment, there seem to be some factors at work similar to our domestic hake. Were *M* not estimable (being confounded with *F*), as you argue, the likelihood profile would yield an enormous associated confidence interval, but that *isn't* the case here. The assessment methodology being applied in the CCSBT is also used to provide information on the value of *M*, so as to reduce the range of values considered in the scenarios to be used for management procedure testing – note that work in the scientific committee of this Commission takes place under the ongoing review of a high level international peer review group, which includes a senior NMFS assessment scientist.

The likelihood profile estimate of the 95% CI for our July paper estimate of *M* (see Case 1 in Table 1) is relatively tight: [0.40 ; 0.46], suggesting that *M* well estimated. However, we deliberately used the words "ASPM *as presently configured*" to describe this result in our July paper. The reason is that we had yet to pursue a fuller investigation of the possible impact of allowing for possible decreasing selectivity at larger ages. It turns out that the tightish interval we obtained earlier is primarily a consequence of our implementation of the suggestion made to us by your scientists in Durham in February (see March paper, pg 3) that we model survey selectivity as a linearly increasing trend. If we remove that constraint, allowing for dome-shaped survey selectivity (Case 3 in Table 1, and see also the associated likelihood profile plotted in Fig. 2), the point estimate of *M* decreases, and the 95% CI broadens to [0.32 ; 0.43]. If we further allow yet more flexibility in the selectivity functions, primarily at large age, to remove some systematic effects in the catch-at-age residuals to which you allude (see discussion under 23) and 40) below), we arrive at what we now consider as a more appropriate New Reference Case, Case 8 in Table 1, for which the estimated *M* is 0.31, with 95% CI [0.25 ; 0.37] – more realistic in your terms, and also a result with which we are ecologically more "comfortable", but **still** statistically excluding the estimate of *M* = 0.2 adopted for your ADAPT-VPA assessment.[7]

For Case 8, the current spawning biomass is still estimated to be substantially in excess of *MSYL*. Given your (and our) concerns about the MPLE of $h = 0.98$, in Case 9 we repeat this estimation fixing $h = 0.8$ (nearer the lower end of Myers' plausible range, and in likelihood profile terms within the 95% confidence interval for h); note that the current spawning biomass estimate for this Case *still* remains above *MSYL*. Only when we fix M to 0.2 (Case 10), does the estimate of current abundance drop below *MSYL*, though this low a value for M is not supported given the associated deterioration of the model fit (see the –lnL values in Table 1). But even if this statistical argument is overlooked, current spawning biomass is estimated at about 80% of *MSYL*, which still differs enormously from the some 17% of your ADAPT-VPA based estimate. Thus our analyses still question the robustness of that estimate, and consequentially still carry important implications concerning the justification for planned imminent management action.

- The primary conclusion of the July paper is that there is little probability that the biomass in 2001 is less than B_{MSY}. In fact, in examining results provided in Figure 5, there is only one brief period (around 1910) when the biomass ever declined below the maximum likelihood estimate of B_{MSY}, despite the nearly four-fold decline in calculated biomass from the 1960s to the 1990s (Figure 5). This result is clearly dictated by the very high resiliency of the stock implied by finding the maximum slope of the S-R curve at the origin at such a high value (to which the model solution converges). The value of B_{MSY} estimated in the "New Reference Case" is 14.9 thousand tons, with an MSY value of 12.3 thousand tons; the percentage of MSY to B_{MSY} is thus about 83%. In contrast, using ADAPT-VPA estimates and associated reference points, this ratio about 20%. Harvesting the equivalent of 80% of the SSB each year from a relatively long-lived, iteroparous gadoid is inconsistent with much of the growing body of current literature that is showing the importance of multiple spawning and maternal size as related to egg and larval survival and life history development (e.g. see Trippel *et al.* 1997).

3) Comments already under 1) and 2) above have addressed most of these points. In particular, results of Cases 6, 7, 9 and 10 in Table 1 show that your comment that our results (particularly regarding the current status of the resource relative to MSYL) "are clearly dictated by the very high resiliency of the stock implied by" our MPLE for h, is incorrect.[8]

Your last statement does not seem pertinent in the light of your misunderstanding which we have hopefully resolved under 1) above. Even so, if this is a concern, the way to deal with it is to model effective spawning biomass accordingly in the assessment – though in this case, given the weak correlation between recruitment and spawning biomass, the impact on the assessment outcome is unlikely to be substantial.

Your calculations go a considerable way in explaining why your implementations of ASPM result in such fundamentally different management parameters as compared to the ADAPT-VPA and working group conclusions. As you state, there remain some unresolved issues related to M, commercial selectivity, objective functions and other related themes. However, it is abundantly clear that the major sources of disagreement lie not in models but in fundamental assumptions regarding natural mortality, the ability to estimate this parameter internally in a stock assessment model, assumptions regarding S-R function resiliency, and the use of commercial catch time series data for which no independent relative abundance index or demographic data are available. If we cannot agree on how such issues should be handled, no amount of alternative assessment modeling or simulations will be able to close this gap.

4) Hopefully our responses 1) – 3) above have addressed the first three of the four "major sources of disagreement" which you list. Regarding the fourth, we find your statement surprising. This is routine practice in the scientific committees of many international fishery commissions, who do this in their assessments. For example, all the whale assessments conducted by the IWC do exactly this, and current CCSBT assessments do it. Furthermore the ICCAT albacore working group meeting I have just attended welcomed our method for albacore (a variant of our methodology applied to GoM cod), and quite independently ICCAT has been investigating the use of MULTIFAN-CL, an approach very similar to our ASPM; the very reason underlying their view is to gain insight into stock dynamics in periods when catch, but not abundance information, is available. The NMFS assessment scientists present at that meeting also welcomed this. Obviously estimates for such periods will not be as precise or reliable as those for periods with abundance information, as is well illustrated by Fig. 5 of our July paper[9]. Nevertheless the process is helpful if only to influence improved specification of an appropriate numbers-at-age vector for the year in which the abundance information series commence.

As always, our scientists remain open to a vigorous debate regarding the fundamental calculations supporting assessments of these stocks. Thank you for allowing us to comment on your documents. We welcome any thoughts you may have regarding our review, and are willing to meet with you to discuss our comments in more detail.

Consistent with your request for a review between colleagues, we are not providing copies of this document to the Fishery Management Council.

Sincerely,

John Boreman, Ph.D.
Acting Science and Research
Director

Annexure C

Detailed Comments:

Comments on: *ASPM-Based Assessment of the Gulf of Maine Cod Stock: A Comparison with ADAPT-VPA and Extension to a Bayesian Form*

This document provides an updated analysis of the Gulf of Maine cod stock by using an age structured production model. It attempts to respond to a number of comments provided by various agency and independent scientists at the Groundfish Peer Review held in New Hampshire during February 2003.

Major Comments:

- The authors fit an ASPM population dynamics model to the period 1893-2001 without a relative abundance index throughout most of this time series. In particular, there is no information on trends in relative abundance prior to 1963 (70 yrs). Thus, model-based estimates of abundance prior to 1963 are extrapolations (over 60% of the time horizon). The assumption that the Gulf of Maine cod population was in equilibrium in 1893 at an unexploited state is clearly unfounded, since large catches in 1893 through 1899 were documented. That the Gulf of Maine stock was not at virgin stock size in the late 1800s is consistent with the documented history of the fishery going back at least to the 1600s. In fact, there are indications of human removals that go back to pre-history. It is highly likely that the fishing mortality rates in the 1800s were very high, prompting these fishermen to explore grounds offshore as far as the Grand Banks. Clearly this assumption of a virgin age composition in the 1890s is not viable.

5) See 4) above – this scarcely affects estimates of the parameters that are of primary relevance for recommending current management action.[10]

- AD Model Builder code provided to NEFSC for the previous March document includes a likelihood penalty term for negative population sizes (negpen). This penalty term constrains the optimization algorithm to avoid regions of parameter space where exploitation rate (U) exceeds 0.95. It is problematic that the MLE point estimate of the exploitation rate that produces maximum sustained yield (U_{MSY}) is exactly U_{MSY}=0.95. The correspondence between the constraint and the MLE point estimate implies that the model solution depends on the constraint. This indicates that the estimation problem is not well defined which, in turn, means the numerical solutions are not well determined.

6) Essentially points made in 1) above cover this – see particularly the second paragraph.

- The authors assert that the MLE point estimate of natural mortality of 0.42 is appropriate for an Atlantic cod stock. This assertion ignores published research, peer-reviewed assessments, and general knowledge of the biology of Atlantic cod. Even if the assertion was based on a stable estimation model, it is myopic to ignore the multiple lines of evidence that indicate M=0.2. Further, the authors include no auxiliary information to identify estimates of F and M. The lack of separate sufficient statistics for M and F implies that these parameters are confounded. In most cases, M is not likely to be an estimable parameter (Schnute and Richards 1995). It is also important to note that overestimation of M causes larger percentage errors in stock abundance estimates than underestimation of M (Sims 1984).

7) See 2) above.

- The authors acknowledge (top of page 5), that there are "...potential problems with F_{MSY} as a reference point....". If the estimation of the reference point values (e.g., the stock recruitment relationship) within ASPM is so problematic, then the obvious solution is to export the estimated spawning biomass and resulting recruitment data, and fit these relationships outside the model. This would obviate the issues associated with how much weight to put on this solution in the overall objective function. Further, it would allow exploration of the assessment free of the highly problematic slope at the origin constraints in the code.

8) Our comment has been misinterpreted. The problem with F_{MSY} here has no specific link to our methodology – it is an inevitable consequence of the paradigm your scientists have adopted – see 1) above, second paragraph. Our

point here was that F_{MSY}, albeit consistently estimated within this paradigm, would not therefore necessarily provide a sensible target reference point.

We would not agree with the comment about separating the assessment and the S/R model parameter estimation. A high level international peer review panel which we import for annual reviews of our local assessments, severely criticised us for a similar estimation separation in one of our assessments. It that case we had the defense of needing to address the consequence of bias known to be present in one of the data sources which we had consequently analysed separately, but would fully agree with our reviewers in the context of your assessments and associated reference point evaluation. While such estimation separation may be useful during an exploratory investigation stage, it would seem statistically dubious to maintain it for the final result advocated unless compelling reasons to do otherwise can be offered. After all, if one believes that the stock-recruit curve fitted is appropriate for projection purposes, and estimates it from information for preceding years, then *ipso facto* it has relevance to estimation for those years and hence needs to be taken into account in the assessment itself. Furthermore, failing to do so likely introduces biases into computation of variances associated with projections.

- Table 1 in the July 2003 document contains catch information used to fit the model. This information is not consistent with the catch input to the Gulf of Maine cod VPA in Table F4a of the GARM report (NEFSC 2002a).

9) In Case 11, the total catch input has been replaced by the series you mention above. Alternative weights and maturity at age inputs have also been used (see “UCT sensitivity” in the Appendix of the July paper). Using these alternative input data does not affect the results greatly (see Table 1).[11]

- The MLE point estimate of F_{MSY} of F_{MSY} >3.00 is not consistent with a sustainable harvest rate on any cod stock. The new reference case presented in the paper estimates steepness at the subjectively-set limit of 0.98. This allows the fishing mortality rate at MSY value to exceed 3.0 because there is no decrease in recruitment at extremely high fishing rates. The MLE point estimate of steepness of h=0.98 is above the probable range of (0.76, 0.9) reported in Myers *et al.* (1999). These two observations are very serious and fundamentally call into question the viability of this approach for a cod stock.

10) See comments under 1) and 3) above, particularly the third paragraph under 1) and the reference therein to Cases 6 and 7 in Table 1.

- The use of an uninformative prior distribution for M is insufficient. This approach ignores published information on the likely range of natural mortality. An informative prior for M is needed.

11) See discussion under 2) above, and also the likelihood profiles for estimates of *M* shown in Fig. 2, together with associated 95% C.I.'s quoted in Table 1. As stated there, our approach is to let the data speak for themselves. Given that reasonably precise estimates result, there is no necessary reason to include a prior based on information from other stocks:

> i) because information from areas where the dynamics could be different could bias results; and
> ii) given that there are questions about the associated estimates, as discussed in 2) above.

- Changes in the MLE point estimates between this document and the March 2003 document are substantial. F_{MSY} changes from 0.54 to 3.00 (+460%). B_{MSY} changes from 29991 to 14921 (-50%). The lack of stability of these reference point estimates indicates that the authors= estimation model does not produce consistent estimates, given moderate changes in the input data. The authors need to explain why their results are not stable.

12) As stated in 1) and also 8) above, this is not a property of "the authors' estimation model", but rather of your scientists' basic paradigm for reference point evaluation. Fig. 1[12] of our July paper makes clear why this paradigm can be problematic in certain regions of parameter space.

- The use of the Pope approximation for the calculation of F in an assessment model is not recommended for M>0.3 and F>1.2 (Pope1972). Clearly these results violate this rule of thumb on both counts.

13) See Fig. 1 for times series of *F* (fishing proportion) estimates for three of the cases reported in Table 1, including Case 8), the New Reference Case with *M* estimated at 0.32 – marginally outside the limit above. A fishing mortality *F** of 1.2 corresponds to a fishing proportion of *F* = 0.7 – note from the plots that this limit is reached only in the early 1900's (of little relevance to key estimates – see 4) and 5) above) and barely once more recently.

But in any case it must be borne in mind that though reality does not correspond exactly to the Pope formulation (pulse fishing), it does not correspond exactly to the Baranov formulation (steady fishing effort throughout the year) either. Provided applied consistently throughout an analysis, either can often be argued as reasonable approximations of reality.

We doubt that the interchange of Pope and Baranov formulations will have any qualitative impact on key model outputs. Nevertheless, it might assist in identifying the reasons for differences in the ASPM and ADAPT-VPA results. Our original choice of the Pope form was dictated almost entirely by the fact that we already had tested code available for that. However, we do hope to be able, in due course, to convert our code to be able to implement the Baranov form as well, to facilitate this comparison.[13]

- The use of fishing proportion (therein defined as F), as opposed to the usual way of defining F, clouds the straightforward interpretation of some unusual results from the model. The fishing proportion is related to the standard fishing mortality rate (denoted F* by the authors) by the equation 1-F = exp(-F*). Thus, as the fishing proportion F approaches 1, the fishing mortality rate F* approaches infinity, as seen by rearranging the equation to F* = -ln(1-F). The graph of yield vs. fishing proportion (Fig 1) is thus highly misleading because the location of the sudden bend in the new RC line occurs at a fishing mortality rate above 3.0. Note that the use of Pope=s approximation in the catch equation (see point above) causes the relationship between fishing proportion and fishing mortality rate to break down at high fishing proportions, and thus the need for equation 4.

14) Probably the density of any clouds varies with the eye of the beholder! Certainly lay-persons sit much easier with the concept of fishing proportion than fishing mortality. The issue here is merely one of a non-linear transformation of an axis. The bend would occur for either parameterization.

- The use of equation 4 "…for MSY and MSYL computations only@ is also problematic because the estimates of current F are no longer directly comparable to F_{MSY} due to the change in selectivity pattern. This is an *ad hoc* procedure to deal with the Pope approximation that is non-standard and should probably be reviewed in detail as a separate issue.

15) This procedure is pretty much as has also been adopted by CCSBT. It is merely a device to deal in a mathematically consistent way with an area of parameter space which otherwise offers some definition problems for MSY. However, as stated in 1) above, we are not suggesting this area to be one of any real pertinence to the final selection of any reference point, so this does not seem to be a major issue.

- The assumption of only two selectivity patterns during the time period 1893 to 2001 also demonstrates a lack of knowledge regarding the many management regulations that have occurred in this fishery. Mesh sizes of two inches or less were common in the early 1900s and cannot be considered to have the same selectivity pattern as the catches during 1982 to 1991 (the time period of observed catch at age). There were at least four major changes in minimum regulated mesh size that occurred since the 1950s. This fitting of a selectivity pattern to recent catch at age data but applying it to time periods with significantly different mesh sizes is not appropriate.

16) We do not claim expertise in the history of this fishery, and for that reason have on more than one occasion asked your scientists for their specific suggestions for what magnitude of changes (and when) we need include in our model, but without any response to date. The change we did include after 1991 was motivated by inspection of the residuals for the fit to the commercial catch-at-age data (see pg 4 of our March paper). These data (as made available to us) extend back only until 1982, and there is not other obvious evidence of lack of fit in Fig. 4 for that period, so such further changes to regulations as there may have been in this period would seem unlikely to be introducing any substantial bias into the results of our fits.

Otherwise the effect of mesh changes generally impacts selectivity for the youngest ages. But from the point of view of estimating broad stock dynamics, such variations customarily have little impact on key estimates.

We remain happy to check sensitivity here, given the requested response from your scientists.[14]

- There is no auxiliary information included in the model with which to determine M as a separate parameter from fishing mortality F. This leads to an estimate of M of about 0.4 for Gulf of Maine cod since F and M are confounded parameters. At present, it is not clear that the code can produce a reliable estimate of M without auxiliary information.

17) See 2) above.

Minor Comments:

- The author's lack of familiarity with the VPA program used by NEFSC leads to some incorrect statements regarding differences between the VPA and ASPM results. The authors have spent considerable time in the ICCAT arena where linkages for the fishing mortality rate on the plus group are made directly with the previous age. This contrasts with the use of an estimate for the fishing mortality rate on the oldest true age derived from previous ages and later calculation of the fishing mortality rate on the plus group, as done in the NEFSC assessments. This may be important for such a heavily fished stock.

18) We are perplexed by this statement. The opening section of Appendix 4 of Mayo *et al.* (2002) states that: "F for age 7+ is then calculated from the following ratios of F(age 7+) to F(age 6)", and then indicates all these ratios set to 1. That is what we had assumed from the equality of the F_6 and F_{7+} estimates for each year in the results given in this paper. Yet the comment above states that we are wrong in this assumption???[15]

- The assertion that ASPM is superior to ADAPT-VPA (e.g., abstract, page 6, page 7, page 9) is not supported based on the results provided. To the contrary, Table 3 shows that the VPA start ASPM (column 2) has a lower negative log-likelihood (-47.7) than that of the ASPM data from 1982 (column 3, -37.5). The authors claim that the recruitment residuals must be excluded from the ASPM data from 1982 fit to be "comparable". This is not true. Adding parameters to the model fitting, in this case due to estimating recruitment, but not accounting for these additional parameters when reporting the fit of the model is an inconsistent use of the results and the evaluation criterion. Note also in the ASPM data from 1982 case there is a much larger change in biomass from 1982 to 2000 (most likely due to assuming equilibrium in 1982; it is unclear whether this equilibrium accounted for fishing mortality) and that the steepness estimate is again at the bound of 0.98. It is extremely difficult to see how a claim could be made that ASPM is Abetter@ than ADAPT-VPA given these results.

19) There appears to be a misunderstanding regarding what we have done here on a number of counts. In the case where you state we are "adding parameters", we are in fact effectively "subtracting" them. When the ASPM estimates recruitment residuals for only some years, it uses the deterministic form of the S/R relationship for others, thus leaving it with **fewer**, rather than more degrees of freedom (compared to VPA). – this is why only 1987+ contributions to –*ln*L were included for a fairer comparison. The misunderstanding here may be linked to incorrectly presuming that we are "assuming equilibrium in 1982". We are not – for Case 3) of Table 3 of our July paper, for example, the ASPM model is run commencing in 1893 as usual; it is only the **data** considered in the likelihood for the fitting process that are restricted to 1982+ for comparability.

While these results therefore do give some indication that the ASPM approach is to be preferred, we are happy to acknowledge that there is room for more to be done in this area for improved clarification of the reason for differences. Some suggestions are made in 13) above and 23) below.[16]

- The large discrepancy between the MLE and posterior median for the steepness parameter calls into question both results and points to an instability in the model, most likely due to attempting to estimate the natural mortality rate without additional ancillary information.

20) We do not agree. The MPLE is (also) the posterior mode. In non-linear models, such as this, the shape of the likelihood (aside from the fact that penalties/priors could also so contribute) can readily be such that the marginal posterior distribution for a quantity is skew, and with mode and median possibly quite different, as in this case for *h*. Estimation or otherwise of *M* is hardly of relevance here – the wideish variance associated with the estimation of *h* for your ADAPT-VPA assessment (which fixes *M*) is obvious from the associated S/R plot in Fig 3.1.7 of the Report of your March 2002 Working Group on the Re-Evaluation of Biological Reference Points.

- The new reference case presented by the authors has some unusual properties beyond, but related to, the fishing mortality at MSY estimate of greater than 3.0. The MSY of 12,286 mt is 82.3% of the spawning biomass expected to be present in equilibrium (B_{MSY} = 14,921 mt). In contrast, the B_{MSY} is 16.8% of the unexploited spawning biomass (K = 89,822). Given the extremely high fishing mortality rate at MSY (above 3.0), one would expect the spawners-per-recruit to be much less than 16.8% of the unexploited population spawners-per-recruit. Perhaps this is a symptom of the problems encountered when using Pope=s approximation to the catch equation in high fishing mortality situations. In any regard, at an F of 3.0 and M=0.42, virtually all the spawning biomass would be produced by age 2-3 animals (mostly first time spawners), since the PR on age 2 is only 0.15. However, such a strategy is in direct conflict with the growing body of research (e.g. Trippel *et al.* 1999; Murawski *et al.* 2001) indicating that spawning in cod should be supported by a diversity of age groups and multiple-time spawners. These studies call into serious question the veracity of results indicating F_{MSY} = 3.0 and M=0.42.

21) See 1) and 3) above.

- The standardized residuals presented in figure 3 are computed in an usual manner (ln(obs) - ln(pred) / (sigma/sqrt(obs)) that should be reviewed in more detail.

22) Is “usual” a typo for “unusual”? This form for standardized residuals is appropriate given the formulation of the associated likelihood – the reasons for this are discussed on pg 37 of our February paper.[17]

- Figure 3 shows that the model consistently predicts higher catches in the plus group and age 6 than observed, a cause for concern in the overall fit of the model.

23) Indeed. Our intention with earlier results presented was to obtain comments before proceeding with further refinements of the model. As discussed above, we now know that this feature arose primarily from adopting your scientists’ earlier suggestion that we model survey selectivity as a linearly increasing function of age. For our New Reference Case – Case 8) of Table 1 – we have dropped that assumption to allow more flexibility in the selectivity functions fitted. This removes the bias evident earlier (see Figs 3 and 4).

Note that Case 8) (see Table 1) has an estimated selectivity for the 7+ group that is much less than for age 6, for both surveys and commercial catches. This is in sharp contrast to the assumption of the ADAPT-VPA which sets selectivity to be equal for these ages (see 19) above), and merits further investigation as it may play an important role in explaining the difference between the ASPM and ADAPT-VPA results.[18]

- Based on NEFSC (2002) there is a very legitimate reason why data A3 in Table A.1 has a plus group weight at age that does not correspond to the 4-year average. This value was computed assuming equilibrium conditions at an appropriate fishing mortality rate for use in the projections and reference point calculations.

24) This vector was used as the SSB mean weights at age throughout the period in the Reference Case. The mean weights at age from the Mayo *et al.* (2002) report have been used in Case 11 as a sensitivity test - the results are not qualitatively different (see Table 1). [19]

- The authors argue that predation mortality on cod is likely higher than M=0.2 assumed for ages 2+ for the Gulf of Maine. In fact, published literature shows that gadids make up a relatively minor component (~2-3%) of the diet of Atlantic cod off the USA (Link and Garrison. 2002). Further information on the potential for cod cannibalism as contributing to increased natural mortality was available to the authors in NEFSC (2002b, p. 204), e.g.,

AOne possible mechanism for strong density-dependent intraspecific interactions is cannibalism. Cannibalism in the primary New England groundfish stocks examined in this report appears to be relatively minor. Food habits data collected during spring and autumn NEFSC surveys during 1973-1997 (Dr. J. Link, Northeast Fisheries Science Center, Pers. comm.) show that the observed incidence of cannibalism in cod and haddock is very low. Out of 12,305 Atlantic cod stomachs examined, only 16 contained cannibalized cod (<0.2%) and the average percent composition by weight of the cannibalized cod was less than 0.1%. Thus, the observed data on groundfish food habits do not support the hypothesis that cannibalism is a viable mechanism for overcompensatory stock-recruitment dynamics in primary New England groundfish stocks.@

Furthermore, the results of a preliminary multispecies VPA constructed for the adjacent Georges Bank cod stock (Tsou and Collie 2001) showed that for ages one and older the predation mortality rates on groundfish species examined (cod, haddock, yellowtail flounder) were 0.2 or smaller (declining significantly with age). In fact, Georges Bank predation mortality at age was calculated to very much lower than for the North Sea. Tsou and Collie (2001) noted specifically for Georges Bank cod:

"*...predation mortality at age of cod ranged from 0.3 at age 0 to 0.003 at age 3 (Fig. 4)*" (page 914).

Note that age 0 is not evaluated in any stock assessment models (the models evaluate the populations and reference points beginning at age 1 or older for cod).

- Stomach content data and scat samples from seal haul-out sites indicate that cod are a minor prey item in the Gulf of Maine area. Given the population sizes of the seals, low frequency of occurrence of cod in their diets, and size-selection of cod prey for relatively small animals, it is implausible that this source of M could generate the millions of predation-related deaths at all ages that would be required to support M=0.4-0.5. Thus, there is no known biological mechanism that would be responsible for such a high M.

25) See 2) above.

Comment applicable to both documents:

- Neither versions of the models incorporate the Massachusetts state survey data, which are used in the ADAPT runs. These data are particularly helpful in estimating recruitment since they catch primarily young fish that are distributed nearshore. The lack of inclusion of these data is, therefore, one potential source of discrepancy between the ASPM and ADAPT results.

26) We are happy to incorporate such further data in our ASPM evaluations, but until recently have been unclear where to obtain them. We note that Mayo *et al.* (2002), Appendix 3, includes information on both Massachusetts DMF spring surveys and USA commercial LCPUE indices. Should we be including one or both of these to be comparable to the ADAPT-VPA?

Before we might do that, however, we note that data for these series is reported on a per-age per-year basis. Could you kindly clarify whether the values for different ages are comparable - in the sense, can they be summed as they stand to provide an age-aggregated index? – or if not, can you please provide these data to us as an age-aggregated time series (as far as we can determine, Mayo *et al.* provide this only for the Massachusetts time series), with proportions at age for each year. The reason for this is that it is generally not desirable to use such data in the form of separate at-age time series in fitting models, because catchability fluctuations between ages for the same year are customarily highly correlated, so that only the age-aggregated series should be included in the likelihood function.[20]

Annexure C

Comments Applicable to the March Document:

General Considerations:

- Use of an 1893-2001 time horizon is inappropriate. There is no information on trends in relative abundance prior to 1963. Model results prior to 1963 appear to be very sensitive to estimates of current spawning biomass – see Figure 5 Panel c, p. 20. The authors need to explain why their model estimates an increasing trend in SSB from the late-1940s to the 1960s. What data support this trend? This is important because the model prediction that the stock is above B_{MSY} is contingent upon it being well above B_{MSY} and near the estimated unfished biomass in the 1960s. In contrast, the lack of sensitivity of spawning biomass estimates from 1963 onwards (Fig 5) indicates that the substantial downward trend is robust. It is ironic that the estimated SSB in the 1960s is roughly equal to the current estimate of BMSY=82.8 kt for Gulf of Maine cod from NEFSC (2002).

27) See 4) above. The information (rather than “data” *per se*) which support the trend from the 40s to the 60s is the combination of catch levels relative to and the same S/R relationship as for the subsequent years.

- The authors need to explain their rationale for including M as an estimable parameter. This is not a standard procedure. Estimates of M and F are highly confounded (Schnute and Richards. 1995). The fact that the model-based estimate of M is consistently greater than 0.4 is a severe problem. An M=0.4 is not consistent with the biology of Atlantic cod. It also is inconsistent with the observed NEFSC survey age data. These data show that there are far too many cod over age-7 than could be expected if M=0.4, even with the stock under intensive exploitation.

28) See 2) above - (“standard” procedures clearly vary around the world!). If a model, estimating a particular value of *M*, provides a satisfactory fit to a set of catch-at-age data in terms of standard goodness-of-fit criteria, surely it cannot be said to be inconsistent with those data?

Specific Comments:

1. Linear selectivity for the surveys implies a fixed increase in selectivity with age. It is difficult to see why there should be a linear increase over the age range of 1 to 7+. It would be more

realistic to use a logistic curve, as was done for the commercial selectivity.

29) Use of the linear form was at your scientists' suggestion (March paper, pg 3). We have attempted use of the logistic form suggested, but this leads to a much inferior fit – see Case 2 in Table 1.

2. Estimating two periods of commercial selectivity is an improvement over the previous model. It is questionable, however, to use 1992 as the break point for a selectivity change (see the point above regarding multiple mesh changes since 1950). There have been numerous changes in mesh size regulations over the years, as well as long-term changes in fishing gears and fishing vessels. The authors should use information on regulation changes to guide their choice of time periods for selectivity. In particular, the use of a constant selectivity for 1893-1991 is inappropriate. There have been too many changes for this to be a reasonable assumption.

30) See 16) above.

3. There needs to be more diagnostic information presented. Standard errors are approximated using the observed information matrix (or Hessian). This is a satisfactory approximation for linear models but may be a poor approximation for nonlinear ones, such as an ASPM. The authors appear to be aware of this fact but use the estimated standard errors anyway. It would be preferable to use a bootstrapping approach to estimate standard errors.

31) Indeed. The Hessian estimates were presented as they are much quicker to produce. We consider likelihood profile estimates still better (though they take longer to compute), and have generally referenced them in this document. Ultimately we'd in principle prefer to go the Bayesian posterior rather than the bootstrapping route for estimates of precision (though then requiring yet further computing time!).

4. The authors present no information on correlations among parameters. We suggest correlations between M and F be shown given the potential for confounding of these parameters.

32) As discussed in 2), we don't think potential confounding here is a major problem *vis-à-vis* the estimability of M. Correlations as requested could be produced the next time we get to running an MCMC to get Bayesian posteriors – but with what year's F is the correlation of M of most interest to your scientists?

5. The authors appear satisfied that the MLE point estimate of $F_{MSY}=0.60$ is credible. This value is more than 2-fold greater than $F_{MAX}=0.27$. The authors need to explain their rationale as to why F_{MSY} is so much greater than F_{MAX}. In particular, they need to identify biological mechanisms that would support $F_{MSY} >> F_{MAX}$.

33) Comments in 1) above and further results in Table 1 likely render this question dated. We do not, however, understand the source of the numbers quoted. We understand F_{MAX} to refer to the fishing mortality that maximizes Y/R. For a monotonically increasing S/R relationship (such as B-H) then, how can F_{MSY} be other than less than F_{MAX} for the same assessment?

6. The model shows a clear retrospective pattern (Fig. 6) of underestimating F and overestimating SSB. This pattern warrants further examination.

34) Fig. 5 shows the retrospective results for the estimated time series of spawning biomass and fishing proportion for the New Reference Case. Differences are both less, and no longer in a consistent directional pattern, compared to the earlier results quoted, so that retrospective patterns would no longer seem to be an issue.[21]

7. It would be helpful if the authors provided some more details of their methods so that they could be evaluated. In particular, they need to explain how the survey age composition data were fit. The remark that "*This was taken into account in the model fitting process*" is not clear.

35) The method used to fit the survey age composition data is fully explained on pg 38 of our February paper.[22]

8. The authors assert that the new reference case is "*statistically justified*" in comparison to the previous one based on comparison of likelihood values. This is not a logical comparison because the two models use different data sets (i.e., survey age compositions are not included in the previous model). Thus, the total log likelihood is not, in fact, directly comparable (see comment above).

36) Apologies – the text on pg 4 of our March paper was ambiguous. The reference to statistical justification related to the changes to the **model** that were reported in Table 2, i.e. case 9d *vs* 9c *vs* 9b; it was not intended to cover case 8, which reflects the old Reference Case **before** additional data were added. The data for 9b, 9c and 9d are the same, so that these three variants are comparable in *ln*L terms.

9. The authors attempt to compare ASPM and ADAPT-based results by not using survey data prior to 1982 in the ASPM model. This is, again, not a particularly helpful comparison because the ASPM model is still using catch data from 1893 onwards. A more useful comparison would be to run the ASPM model using only data from 1982 onwards. This would be a direct comparison of the two models.

37) Yes, this could be done using the formulation on pg 34 of our February paper to estimate the starting numbers at age vector. But it makes this a somewhat obtuse comparison, as a major reason for applying the ASPM approach is that it is able to take specific account of these data, and further, the suggested means of comparison runs into yet more problems of "fairness", as discussed in 19) above.

10. The fact that "*the model has difficulty converging for values lower than this [M=0.3]*" indicates that the model is not stable at biologically realistic values of M. Given this lack of stability, it is not clear why the authors attempt to estimate both M and F.

38) See 2) above. It now seems evident that the convergence problem was more a consequence of following your scientists' suggestion to model survey selectivity as linearly increasing with age.

11. The use of a penalty term on current spawning biomass is not particularly informative as the basis for a comparison with ADAPT results. In particular, if the authors want to make a direct comparison with ADAPT, they need to use exactly the same input time series.

39) We agree regarding use of exactly the same data, but there are ambiguities as regards exactly what your NEFSC (2002) analyses have used, which we trust your responses to this will resolve.

12. The residual patterns on p. 17 indicate a consistent overestimation of fishery age composition at ages 6 and 7+ (Fig. 2). This non-random pattern suggests that the selectivity is not well-estimated for these age groups. The same pattern shows up in the NEFSC fall survey age composition residuals since the mid-1980s. There are also blocks of overestimates and underestimates in the late-1960s and early-1970s for both surveys. The fact that this pattern is consistent across the surveys suggests that the model cannot fit the data in this period. Last, the NEFSC spring survey has a consistent pattern of underestimation of age-1 fish. This non-random pattern is likely related to the choice of selectivity pattern

40) See 23) above, which addresses the first point. The last point has also been addressed in the formulation of the New Reference Case – Case 8) of Table 1. The earlier problems with systematic patterns in the residuals in question now seem reasonably addressed (see Figs 3 and 4). To us, it seems that the only remaining potential "problem" is with the survey residuals at large age (6 and 7+), where the autumn survey shows a pattern, but the spring survey does not. Since we are using the same selectivity function (at large ages) to represent both, clearly we cannot match both. We could allow these patterns to differ by survey in the estimation, but would rather first wait on some biological input from your scientists on their understanding of the reason for this difference in the data before deciding exactly how best to modify the present model structure.

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Table 1: Estimates of management quantities for 1) the July paper New Reference Case assessment and ten sensitivities to this assessment, including the current New Reference Case (Case 8). Biomass units are tons. The two sets of estimates given for quantities such as $B^{sp}(MSY)$ refer to the two different commercial selectivity functions: i) for 1893-1991 and ii) from 1992+. Values in parenthesis next to the MLE estimates of $B^{sp}(2001)/B^{sp}(MSY)$, h and M for Cases 1), 3) and 8) are 95% CI derived from likelihood profiles.

	1) Reference Case				**2) Logistic survey selectivity**				**3) Estimated selectivity slope**				**4) S6 and S7 estimated directly**				**5) θ = 0.5, phi estimated**			
-lnL: overall	-126.2				-105.6				-132.9				-137.2				-126.2			
-lnL: Survey	-19.6				-20.0				-18.0				-18.8				-19.6			
-lnL: CAA	-52.9				-55.4				-56.7				-57.9				-52.9			
-lnL: CAAsurv	-122.1				-96.3				-126.3				-129.0				-122.1			
-lnL: RecRes	68.4				66.2				68.1				68.5				68.4			
K^{sp}	89822				87525				102638				120910				89822			
$B^{sp}(2001)$	41645				42575				45027				45597				41645			
$B^{sp}(MSY)$	14921	19522			15796	20516			13963	18756			18834	20686			14921	19522		
$B^{sp}(2001)/B^{sp}(MSY)$	2.79	2.13	(2.10; 2.43)		2.70	2.08			3.22	2.40	(2.07; 2.72)		2.42	2.20			2.79	2.13		
$MSYL^{sp}$	0.17	0.22			0.18	0.23			0.14	0.18			0.16	0.17			0.17	0.22		
MSY	12286	11743			12729	12034			11990	11703			11430	11400			12286	11743		
$F(MSY)$	0.95	0.95			0.95	0.95			0.95	0.95			0.65	0.77			0.95	0.95		
$F^*(MSY)$	3.00	3.01			3.01	3.05			3.00	3.00			1.05	1.46			3.00	3.01		
$F(2001)$	0.26	0.30			0.26				0.27				0.28				0.26			
$F^*(2001)$	0.30				0.30				0.32				0.32				0.30			
h	0.98	(0.73; 0.98)			0.98				0.98	(0.79; 0.98)			0.98				0.98			
M	0.42	(0.40; 0.46)			0.44				0.37	(0.32; 0.44)			0.32				0.42			
Gamma	1.00				1.00				1.00				1.00				1.00			
Theta	1.00				1.00				1.00				1.00				0.50			
Phi	0.00				0.00				0.00				0.00				0.44			
σ_R(in,out)	0.25	0.28			0.25	0.28			0.25	0.28			0.25	0.28			0.25	0.28		
	survS1	survS2	comS1	comS2	survS1	survS2	comS1	comS2	survS1	survS2	comS1	comS2	survS1	survS2	comS1	comS2	survS1	survS2	comS1	comS2
	0.10	0.05	0.01	0.00	0.08	0.08	0.01	0.00	0.15	0.08	0.01	0.00	0.17	0.09	0.01	0.00	0.10	0.05	0.01	0.00
	0.25	0.13	0.15	0.04	0.17	0.17	0.14	0.04	0.36	0.20	0.15	0.04	0.36	0.20	0.16	0.05	0.25	0.13	0.15	0.04
	0.40	0.40	0.69	0.43	0.34	0.34	0.69	0.42	0.58	0.58	0.71	0.44	0.56	0.56	0.72	0.46	0.40	0.40	0.69	0.43
	0.55	0.55	0.97	0.93	0.57	0.57	0.97	0.93	0.79	0.79	0.97	0.93	0.76	0.76	0.97	0.94	0.55	0.55	0.97	0.93
	0.70	0.70	1.00	1.00	0.79	0.79	1.00	1.00	1.00	1.00	1.00	1.00	0.95	0.95	1.00	1.00	0.70	0.70	1.00	1.00
	0.85	0.85	1.00	1.00	0.93	0.93	1.00	1.00	0.99	0.99	0.83	0.67	1.00	1.00	0.96	0.71	0.85	0.85	1.00	1.00
	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.96	0.96	0.69	0.45	0.62	0.62	0.33	0.27	1.00	1.00	1.00	1.00

Table 1 cont.

	6) h = 0.9				7) h = 0.76				8) S6 and S7 est directly, survS2 different				9) as 8 but with h=0.8				10) as 8 but with h=0.8, M=0.2				11) as 8 but different data			
-lnL: overall	-125.8				-124.6				-139.8				-137.9				-131.0				-148.3			
-lnL: Survey	-19.9				-20.3				-18.8				-20.2				-20.5				-24.7			
-lnL: CAA	-53.0				-53.1				-57.8				-58.0				-57.2				-58.1			
-lnL: CAAsurv	-121.7				-120.7				-132.0				-129.7				-124.5				-133.6			
-lnL: RecRes	68.7				69.4				68.8				69.9				71.1				68.1			
K^{sp}	91604				95812				126044				133451				221580				121408			
$B^{sp}(2001)$	40803				39079				45664				43146				43729				43650			
$B^{sp}(MSY)$	18467	18477			27491	29329			19882	21357			33311	33963			53710	55418			20664	22141		
$B^{sp}(2001)/B^{sp}(MSY)$	2.21	2.21			1.42	1.33			2.30	2.14	(1.91; 2.16)		1.30	1.27			0.81	0.79			2.11	1.97		
$MSYL^{sp}$	0.20	0.20			0.29	0.31			0.16	0.17			0.25	0.25			0.24	0.25			0.17	0.18		
MSY	11254	11073			10236	10206			11297	11297			10051	10166			9291	9714			11027	11087		
$F(MSY)$	0.68	0.95			0.41	0.47			0.61	0.73			0.38	0.46			0.32	0.37			0.59	0.69		
$F^*(MSY)$	1.15	3.00			0.53	0.63			0.95	1.32			0.48	0.62			0.39	0.46			0.89	1.18		
$F(2001)$	0.27				0.28				0.28				0.30				0.33				0.25			
$F^*(2001)$	0.31				0.33				0.33				0.35				0.40				0.29			
h	0.90				0.76				0.98	(0.80; 0.98)			0.80				0.80				0.98			
M	0.42				0.43				0.31	(0.25; 0.37)			0.32				0.20				0.28			
Gamma	1.00				1.00				1.00				1.00				1.00				1.00			
Theta	1.00				1.00				1.00				1.00				1.00				1.00			
Phi	0.00				0.00				0.00				0.00				0.00				0.00			
σ_R(in,out)	0.25	0.28			0.25	0.28			0.25	0.28			0.25	0.28			0.25	0.29			0.25	0.28		
	survS1	survS2	comS1	comS2	survS1	survS2	comS1	comS2	survS1	survS2	comS1	comS2	survS1	survS2	comS1	comS2	survS1	survS2	comS1	comS2	survS1	survS2	comS1	comS2
	0.10	0.05	0.01	0.00	0.09	0.05	0.01	0.00	0.19	0.08	0.02	0.00	0.18	0.08	0.01	0.00	0.26	0.11	0.02	0.00	0.20	0.09	0.02	0.00
	0.25	0.13	0.15	0.04	0.25	0.13	0.15	0.04	0.38	0.23	0.17	0.05	0.38	0.23	0.17	0.05	0.44	0.28	0.19	0.06	0.40	0.24	0.17	0.05
	0.40	0.40	0.69	0.43	0.40	0.40	0.69	0.43	0.58	0.58	0.72	0.47	0.57	0.57	0.72	0.46	0.63	0.63	0.75	0.52	0.60	0.60	0.72	0.48
	0.55	0.55	0.97	0.93	0.55	0.55	0.97	0.93	0.77	0.77	0.97	0.94	0.77	0.77	0.97	0.94	0.81	0.81	0.98	0.95	0.79	0.79	0.97	0.94
	0.70	0.70	1.00	1.00	0.70	0.70	1.00	1.00	0.97	0.97	1.00	1.00	0.96	0.96	1.00	1.00	1.00	1.00	1.00	1.00	0.99	0.99	1.00	1.00
	0.85	0.85	1.00	1.00	0.85	0.85	1.00	1.00	1.00	1.00	0.97	0.69	1.00	1.00	0.93	0.70	0.89	0.89	0.93	0.61	1.00	1.00	0.94	0.67
	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.58	0.58	0.30	0.25	0.59	0.59	0.28	0.26	0.27	0.27	0.09	0.13	0.52	0.52	0.24	0.22

Annexure C

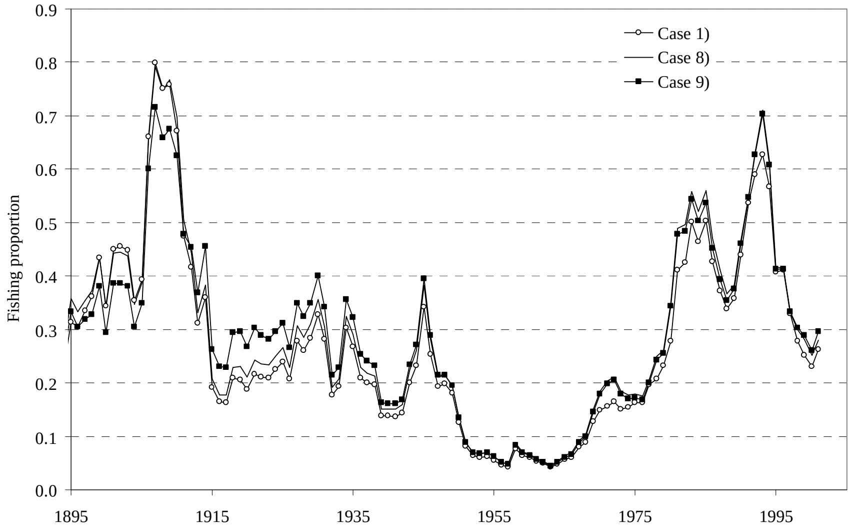

Fig. 1: Time series of fishing proportion for Cases 1, 8 and 9.

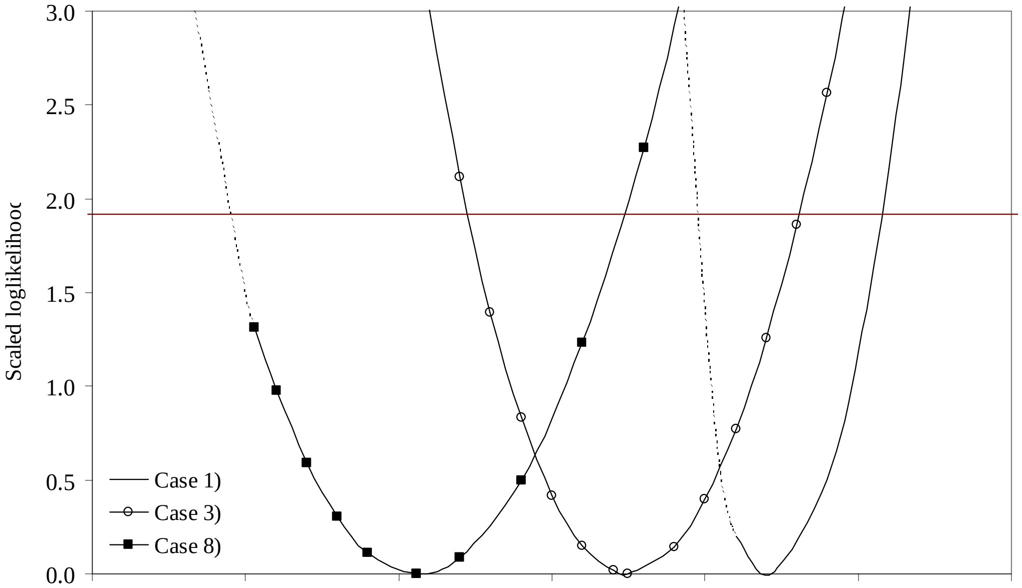

Fig. 2: Likelihood profiles for *M* for Cases 1, 3 and 8, shown as scaled loglikelihoods (see text). The horizontal full line intersects at the 95% confidence intervals. The dotted lines show regions with minimisation convergence problems.

Annexure C

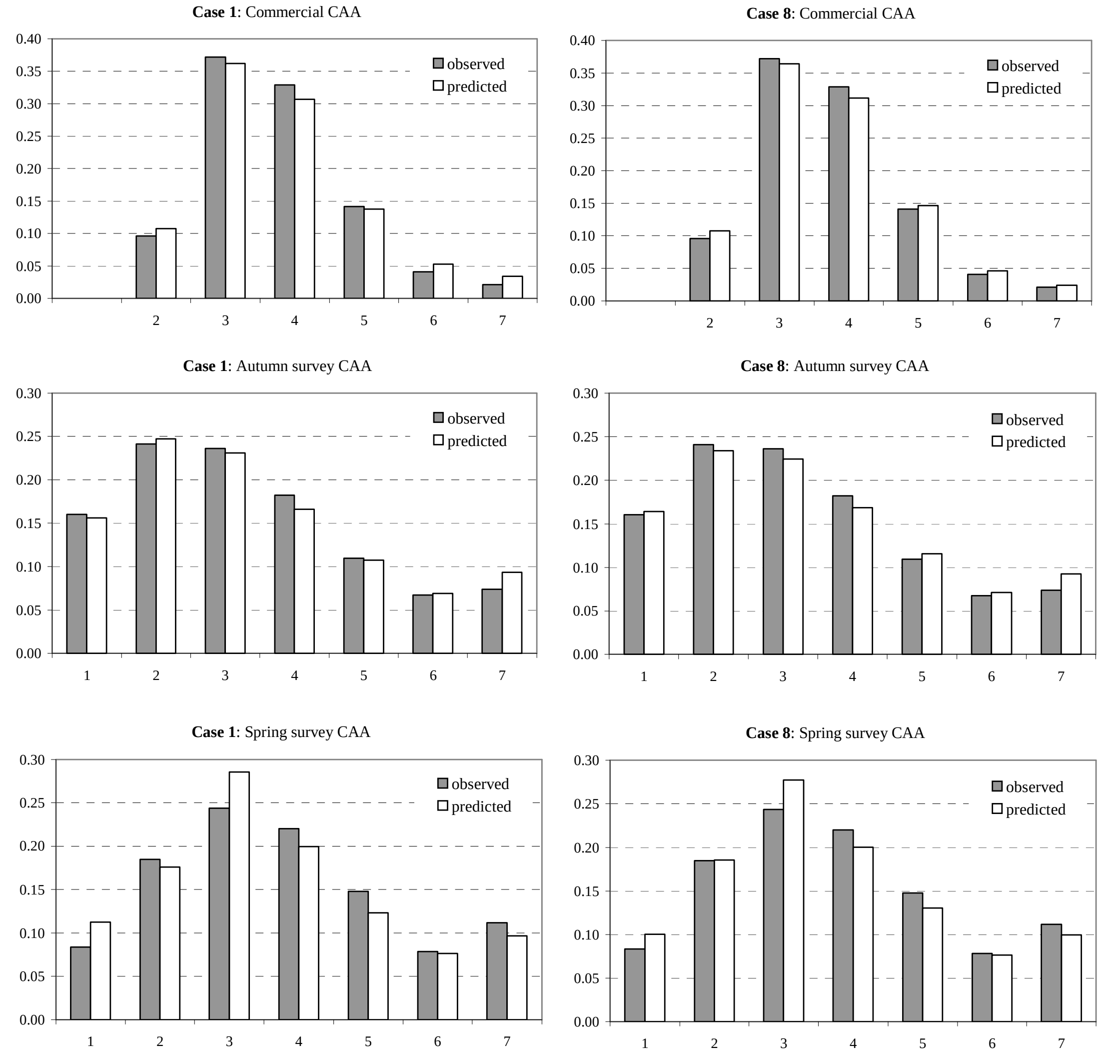

Fig. 3: Model fit to commercial and survey catch-at-age proportions as averaged over all the years with data, for Cases 1 and 8.

Fig. 4: Bubble plots of the standardised residuals for the commercial and survey catch-at-age proportions for Cases 1 and 8. The size (radius) of the bubbles represent the size of the residuals. Grey bubbles represent positive residuals and white bubbles represent negative residuals.

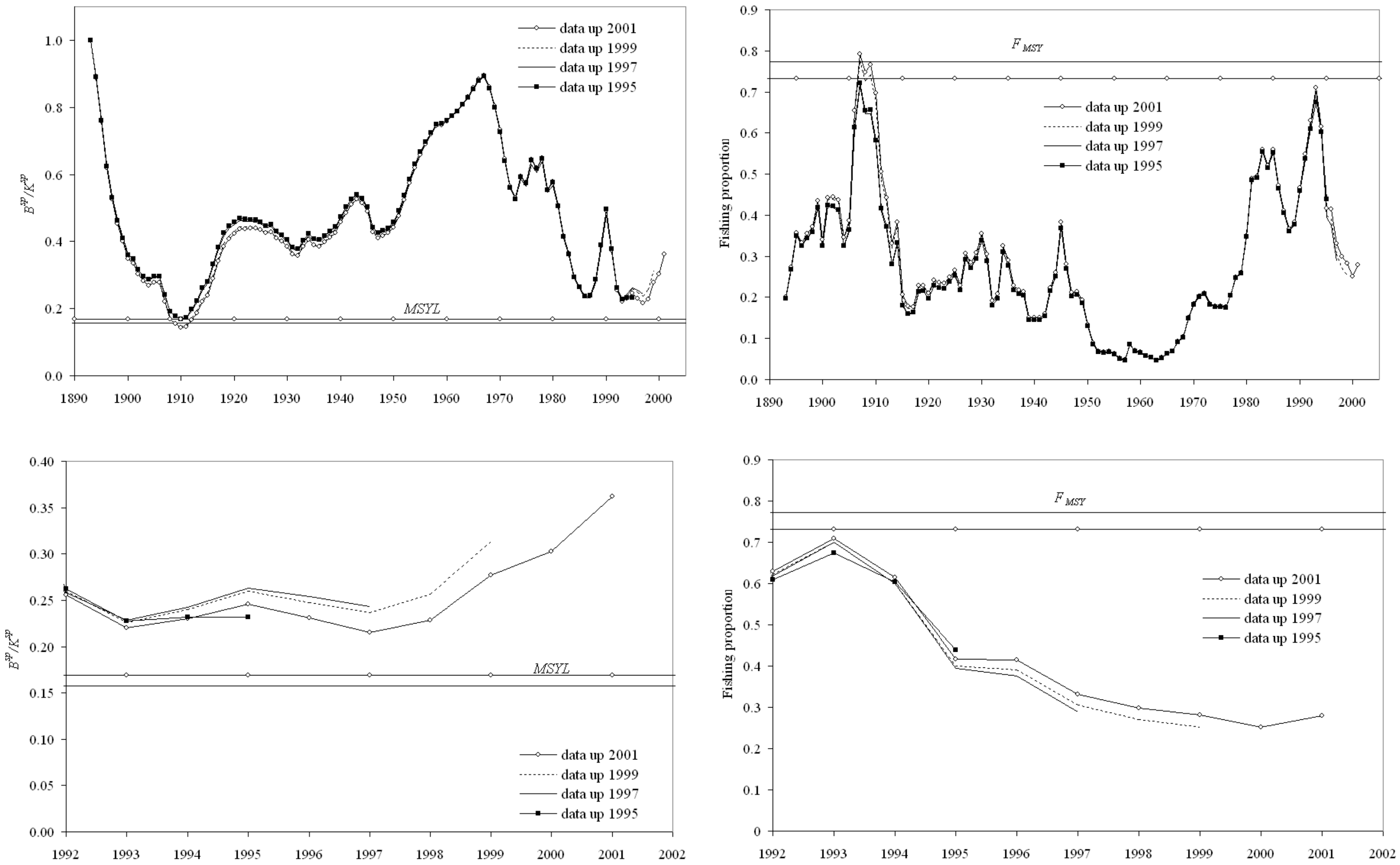

Fig. 5: Estimated time series of spawning biomass and fishing proportion for the New Reference Case assessment (Case 8), together with three retrospective assessments. The estimated *MSYL*s and F_{MSY} are also shown for ‘data up to 2001’ and ‘data up to 1997’.

Annexure C – Appendix of Clarifications/Updates (corresponding to numbered footnotes in Annexure C)

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[1] These issues have since been addressed, and the methodological comparisons of the main text are based on identical data.

[2] Butterworth *et al.* 2003a

[3] Butterworth *et al.* 2003b

[4] Butterworth *et al.* 2003c

[5] The sensitivity test for the current ASPM New Reference Case of a fixed lower value for h (Case IV) leads to a reduction in the $B^{sp}(2001)/B^{sp}(MSY)$ estimate, but this remains at a much higher level than estimated from the ADAPT-VPA based analyses of NEFSC (2002).

[6] Note that the current ASPM New Reference Case estimate of $M = 0.25$ differs less from the input choice of $M = 0.2$ for the ADAPT-VPA of Mayo *et al.* (2002), so matters debated here may now be less of an issue (though the estimate of $B^{sp}(2001)/B^{sp}(MSY)$ remains much higher than that based on ADAPT-VPA).

[7] The likelihood profile-based 95% CI for M for the current ASPM New Reference Case is [0.20;0.28], so that the value of 0.2 adopted for the Mayo *et al.* assessment is now compatible with the estimate from the ASPM.

[8] The comment under footnote 5) above refers also here.

[9] The Fig. 5 of Butterworth *et al.* (2003c) referenced is attached hereunder to aid interpretation of these comments.

[10] Updated sensitivities for the current ASPM New Reference Case (Cases X and XI of the main text) yield similar results.

[11] This is no longer an issue, as the comparative analyses of the main text use identical data.

[12] The Fig. 1 of Butterworth *et al.* (2003c) referenced is attached hereunder to aid interpretation of these comments.

[13] Note that the ADAPT-VPA application of Mayo *et al.* (2002) also uses Pope's form of the catch equation, so that matters raised here would now seem less of an issue.

[14] Note that sensitivity of the current ASPM New Reference Case results to alternative assumptions for historic commercial selectivity have been checked and found to be only slight (see Case XII in Table 3 and Fig. 8 of the main text).

[15] Note further the internal inconsistencies in the ADAPT-VPA approach as implemented in Mayo *et al.* (2002) that are described in Appendix 4 of the main text.

[16] The methodological comparisons pursued in Butterworth *et al.* (2003c) and here are now effectively superseded by the more straightforward comparison approach reported in the main text, so further debate on the issues raised here is now likely moot.

[17] This is also explained in Section A2.2.3 of Appendix 2.

[18] See Fig. 4 of the main text for this comparison for the current ASPM New Reference Case, which would seem here to indicate a reasonable fit. As discussed in the main text, it does indeed now appear that the issue of plus group selectivity is key in explaining the differences between past ASPM and ADAPT-VPA results.

[19] This is no longer an issue, as the comparative analyses of the main text use identical data.

[20] These data have since been received and clarified, and are incorporated in the current ASPM New Reference Case (see Appendix 1, Table A1.8 to A1.10).

[21] An updated retrospective analysis for the current ASPM New Reference Case is pursued in Case XIII a-c of the main text (see Table 3 and Fig. 9), and similarly indicates no marked retrospective patterns.

[22] This method is explained in Sections A2.2.1 and A2.2.2 of Appendix 2 of the main text.

Annexure C –Figures extracted from Butterworth *et al.* (2003c)

Figure referenced under footnote 8 above (from Butterworth et al. 2003c):

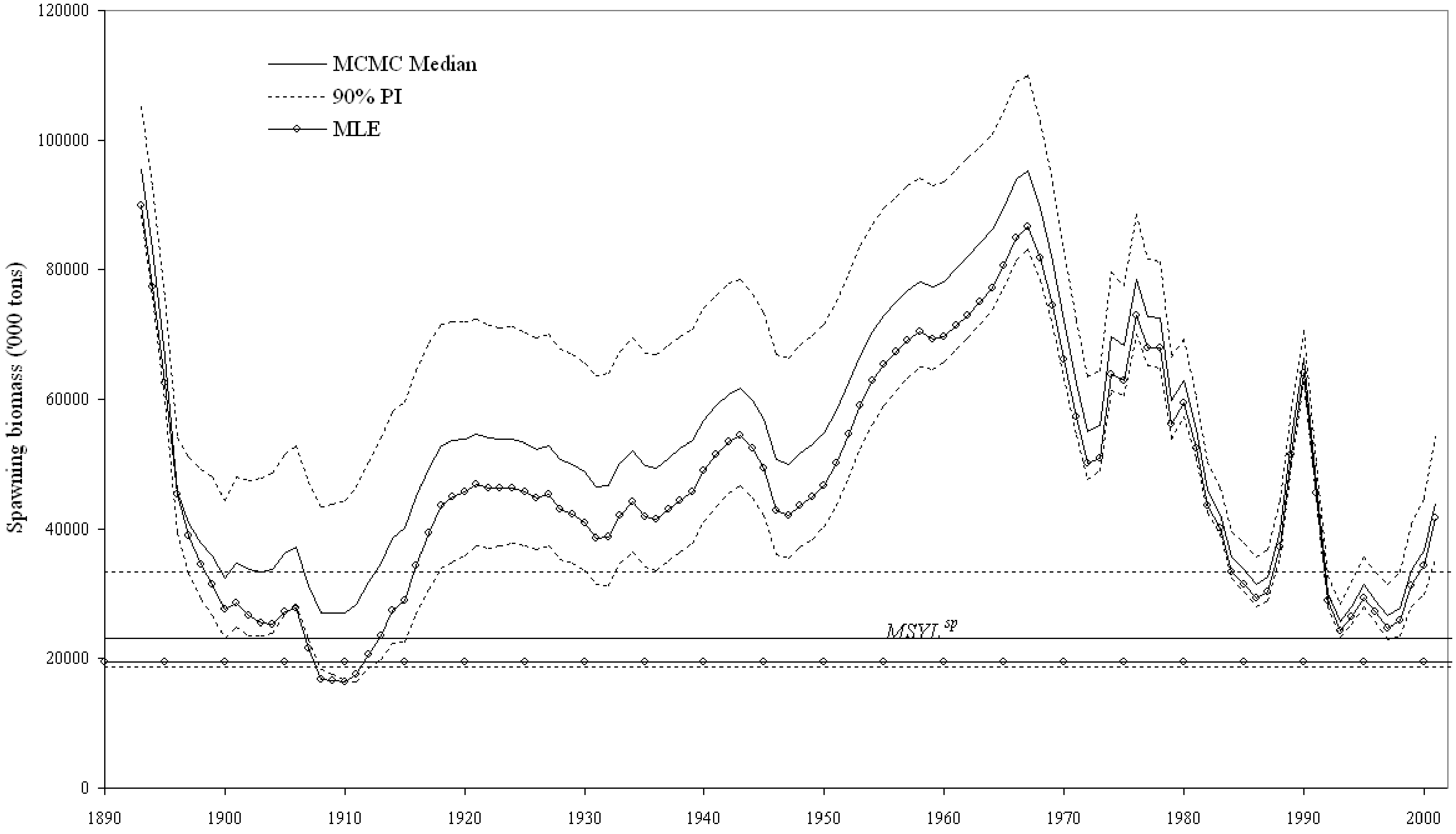

Fig. 5: New Reference Case Bayesian assessment posterior distribution results for the spawning biomass (B^{sp}) time series and gpt $MSYL^{sp}$. The corresponding MLE's are also shown.

Annexure C –Figures extracted from Butterworth *et al.* (2003c)

Figure referenced under footnote 11 above (from Butterworth et al. 2003c):

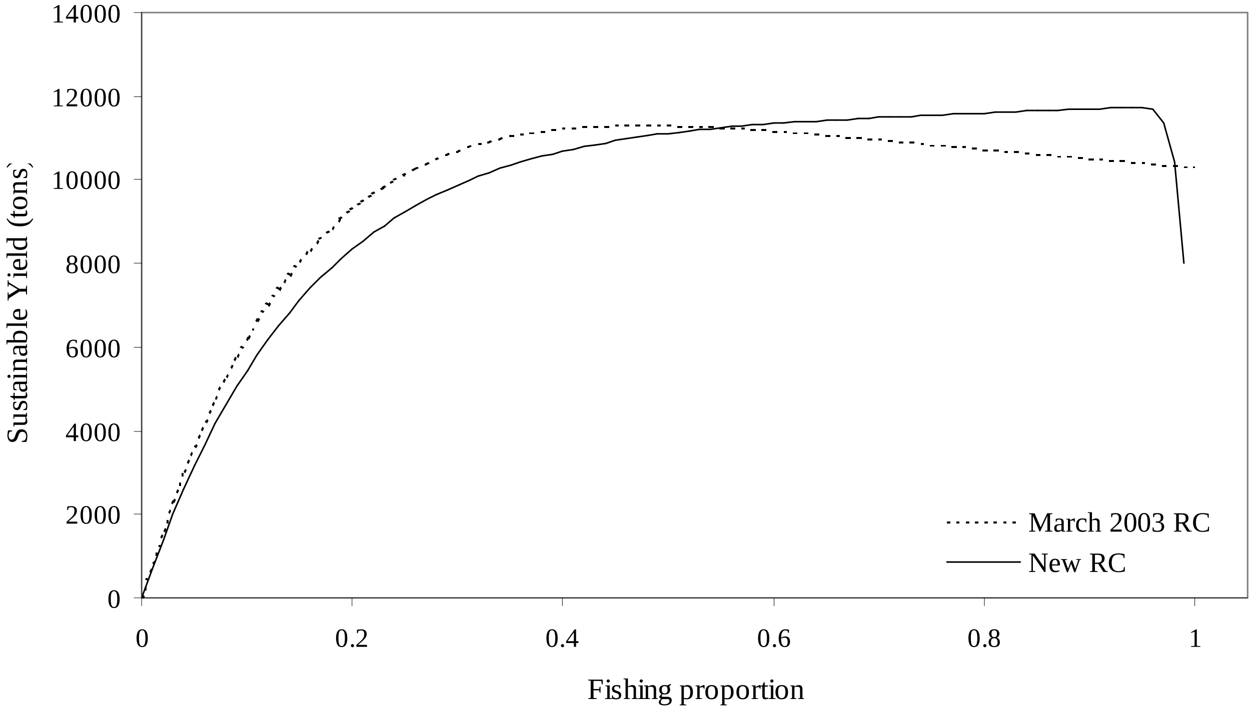

Fig. 1: Sustainable yield *vs* fishing proportion (*F*) plots for the March 2003 Reference Case assessment of Butterworth *et al.* (2003b), and of the New Reference Case of these analyses, i.e. Cases 1) and 2) respectively of Table 2 (of Butterworth *et al.* 2003b).