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Further SCAA/ASPM Assessments of Gulf of Maine Cod Including Data for 2007 and Exploring the Impact of Age-Dependence in Natural Mortality

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ABSTRACT

The ASPM (SCAA) Gulf of Maine cod assessments presented at previous GARM meetings are extended to take account of data for 2007. In response to concerns about the reliability of earlier annual catch data, the assessments commence in 1964 rather than 1893; this necessitates careful consideration of the parameters that determine the starting numbers-at-age vector. Further, in response to recommendations from the Panel, scenarios are investigated which maintain asymptotically flat survey selectivity but increase the value of an age-independent M or admit an estimable increase in M with age for older ages. Either of these mechanisms is able to achieve model fits that do reflect the relative paucity of older cod in particularly the proportions-at-age data for the NEFSC surveys. From 16 assessments presented, a selection is made based on AIC, but factoring in concerns about the lack of direct evidence for the cryptic older fish implied by domed survey selectivity, and the biological realism of the higher values of age-independent natural mortality required to account for the relative paucity of older cod in the surveys. Specifically assessment "Ricker G", which has asymptotically flat NEFSC survey selectivity and M increasing above 0.2 for ages above 4, is put forward as the basis for providing management advice. This option has an AIC-weight of some 10^{10} relative to the current default of flat selectivity and an age-independent M of 0.2, which is unable to fit the proportion-at-age data for older ages adequately. The analysis also provides strong statistical evidence that selectivity for the commercial fishery is domed even if that for the NEFSC surveys is asymptotically flat. A number of reasons for preferring ASPM to VPA as the basis for providing management advice for the stock are put forward.[1]

REFERENCE POINT SUMMARY

B^{sp}_{2007}	45
B^{*sp}_{MSY}	32
$B^{sp}_{2007}/B^{*sp}_{MSY}$	1.41
F_{2007}	0.18
F_{MSY}	0.43

Note: Biomass units are '000 tons; F refers to age 5 where the commercial selectivity peaks; the * indicates that the deterministic estimate of B^{sp}_{MSY} has been adjusted for the bias associated with the lognormal variability of recruitment about the Ricker stock-recruitment curve to which these results correspond.

[1] $F_{rebuild}$ -related statistics indicated in Table 3 have yet to be computed; this paper will be updated later to include these.

INTRODUCTION

This paper extends the SCAA/ASPM assessments of Gulf of Maine cod reported to previous GARM meetings (Butterworth and Rademeyer 2008a, b, c) by taking data for 2007 (provided by Ralph Mayo, NEFSC) into account.

Further it pursues some of the recommendations of the Panel at the last GARM meeting that assessments of this resource examine higher values for natural mortality (*M*), and explore higher rates for this mortality at older ages. The last is an alternative possibility to domed selectivity to account for the greater than expected paucity of older cod in the catches and surveys (without the need to infer cryptic fish at these ages which is associated with domed selectivity). For example, each of these two possibilities is considered as a mechanism to account for similar features in the data available to assess the New Zealand hoki (*Macruronus novaezelandiae*) resource (e.g. Francis 2008).

Following concerns expressed at previous GARM meetings about the reliability of annual catch data prior to about 1960, the assessments reported here no longer commence in 1893, but instead in 1964. For assessments commencing appreciably earlier than this, transient effects dependent upon initial numbers-at-age in the population have died out and so have little effect on estimates of quantities pertinent to present management (Butterworth and Rademeyer 2008a, b). However more care has to be taken about this aspect for a 1964 starting year, so that some attention is given to the specification/estimation of the parameters of the model that specify the starting numbers-at-age, namely θ which is the ratio of the starting spawning biomass B^{sp} to that for the pristine resource K^{sp}, and ϕ which effectively specifies the extent to which the mean Z reflected by the starting age-structure of the population exceeds M (for full details, see Butterworth and Rademeyer (2008a), equations A.2.13 and 14) (see Table 1 for a full list of the symbols used in this paper, together with their definitions).

DATA AND METHODOLOGY

The data used for the assessments reported in this paper are essentially those considered in Butterworth and Rademeyer (2008a), as updated first for Butterworth and Rademeyer (2008b – see Appendix A), and now extended further to include data for 2007 (R, Mayo, NEFSC, pers. commn).

The methodology is as detailed in Butterworth and Rademeyer (2008a – Appendix 2, with minor adjustments as specified in Appendix A of 2008b). The only additional feature considered here is the possibility of natural mortality at age *a*, after having a constant value up to age *a'*, thereafter increasing exponentially with age, i.e.:

$$M_a = \begin{cases} M & a \le a' \\ Me^{\eta(a-a')} & a \ge a' \end{cases}$$

where η is a parameter estimated when fitting the model to the data.

Introduction of starting numbers-at-age parameters θ and ϕ is not entirely straightforward, as sometimes the data typical of those available here contain insufficient information content to estimate one or both of these. Table 2 shows results for the Reference Case adopted by Butterworth and Rademeyer (2008b), whose specifications included a Ricker stock-recruitment function, M = 0.2, and estimable survey selectivity at large ages (which resulted in a dome shape), and which corresponds (aside from the starting year) to what is referred to in this document as "assessment Ricker A". These results are for three fixed values of each of θ and ϕ, as well at the best estimate of θ for each of these ϕ values – the range chosen was informed by results in Butterworth and Rademeyer (2008b) which suggest a relatively high θ and low ϕ (as might be expected since the available data suggest that the 1950s were a period of relatively low catches of cod). These results suggest that it is reasonable to estimate θ; however ϕ is less well determined, though the highest value considered did show some deterioration in fits to the data. The decision was made to fix ϕ = 0.1, noting that for higher values results tended towards a current spawning biomass in excess of the MSY level, so that any bias introduced by the 0.1 choice would err on the conservative side. The parameter θ, though treated as estimable, was constrained to be no greater than 0.95 to allow for the fact that there were catches immediately before 1964, which suggests a higher spawning biomass (relative to pristine) at that time to be unlikely.

The results presented focus on the factors found in Butterworth and Rademeyer (2008a, b, c) to be the most influential on key results:

a) the shape of the stock-recruitment relationship (specifically here Ricker *vs* Beverton-Holt), and
b) alternative explanations for the relative paucity of older cod: domed selectivity, a higher M, or M increasing at larger ages.

Unless domed selectivity is specified and hence estimated, selectivity at larger ages for the NEFSC surveys is taken to be flat. The slope of selectivity at these ages for the commercial fishery remains estimable however, given evidence in Butterworth and Rademeyer (2008b) that estimating the difference in slope between the commercial and survey selectivities was statistically justified in AIC terms.

RESULTS

Table 3a lists the results obtained for a Ricker form for the stock-recruitment relationship, and Table 3b for a Beverton-Holt form. In each case eight combinations of options for domed survey selectivity, different age-independent values of M, and M increasing from age 4 are considered. Assessments A-C allow for domed survey selectivity to be estimated for different age-independent values of M, while assessments D-F give corresponding results when survey selectivity if forced to be flat at large ages; finally assessments G-H allow different constant values of M to increase above age 4 with survey selectivity forced to be flat. For only one of these 16 assessment options is B^{sp}_{2007} estimated to be below B^{sp}_{MSY} (for assessment Beverton-Holt D).

Because plots of such results will be very familiar from previous presentations (Butterworth and Rademeyer 2008a, b and c), only a limited number are shown here in the interests of brevity. In most cases, for reasons explained in the following section, these are for assessment Ricker G, though for selectivity-at-age and stock-recruitment plots results for some alternative assessments are also shown to illustrate contrast. Fig. 1 shows the estimated spawning biomass trajectory, Fig. 2 the fits to the abundance indices, Figs 3 and 4 the fits to the annual catch-at-age proportions for the surveys and the commercial fishery, Fig. 5 estimated selectivities-at-age, Fig. 6 fitted stock-recruitment curves and recruitment residual time-series, and Fig. 7 gives results for a retrospective analysis.

The plots shown for assessment Ricker G in Figs 2-4 do not indicate any serious model mis-specification. Over the last four years there is little retrospective pattern (Fig. 7). For either stock-recruitment relationship, estimates of B^{*sp}_{MSY} are less when increasing M at age rather than domed selectivity is the mechanism which explains the relative paucity of older cod. Essentially this is because the former reflects that cod are less likely to reach higher ages; therefore such age groups do not make as large a contribution to spawning biomass as they do under the dome mechanism which indicates such fish to be present but not available to the survey.

DISCUSSION

Factors not considered in this paper

This paper does not present results for sensitivity to a number of factors fixed for these assessments, as such sensitivities have been considered and reported upon in detail in previous papers (Butterworth and Rademeyer 2008a, b), and found to have impacts that are quantitatively quite small, and generally any associated introduction of further estimable parameters is not justified in AIC terms. These factors have included:

- Use of the Baranov equation rather than the approximate Pope form for the dynamics.
- A gear change over 1973-1981 for the NEFSC spring surveys.
- Age dependence of M at younger ages.
- Changed commercial selectivity-at-age in the past.
- Different values for the slopes of selectivity-at-age for the NEFSC spring and autumn surveys.
- Different input values for σ_R , the extent of variability about the stock-recruitment relationship.
- Estimation of the shape parameter γ of the generalised Ricker stock-recruitment function (see equation A2.4 of Butterworth and Rademeyer, 2008a). For assessment Ricker G, estimation of this parameter yields a value of $\gamma > 1$, and hence increases the estimated value of $B^{sp}_{2007}/ B^{*sp}_{MSY}$.
- Starting the assessment in years earlier than 1964.

Note further that all results given in this paper are for a choice of 8+ for the plus-group for the age data fitted by the assessment model, for reasons that are detailed in Appendix A of Butterworth and Rademeyer (2008b), though within the model itself the age structure is taken to age 11+.

A choice amongst the assessments presented

The authors' choice amongst the 16 assessments presented in Tables 3a and b (under the assumption that a single selection needs to be put forward) is primarily likelihood/AIC based – models which fit the data better (subject to over-parametrisation considerations which are addressed by AIC) should be preferred unless there are compelling reasons which suggest otherwise.

The Ricker form of the stock-recruitment relationship consistently outperforms the Beverton-Holt form on this basis. Furthermore for the latter form, steepness h often hits the constraint boundary of 0.98 imposed, because the data favour some decrease in expected recruitment at larger spawning biomass which this form cannot admit; in turn this leads to estimates of B^{sp}_{MSY} that are low compared to K^{sp} as well as below most of the spawning biomasses which occurred over the period assessed, with neither of these features being very "satisfactory". Accordingly the Ricker form, which also avoids both of these last two problems, is preferred.

The current default for the Gulf of Maine cod assessment is an age-independent value of 0.2 for M and flat selectivity at large ages, corresponding to assessments D in Table 3 which show –lnL values ranging from 26 to 39 units higher than all the other options reported. In AIC-weighting terms (Burnham and Anderson 1998), this default thus merits to a relative weight of less than some 10^{-10} compared to these other options; even though the AIC difference may be positively biased to some extent as a result of some of the input data not being completely independent of each other, this still indicates that the weight accorded to the default when considering the alternative assumptions should be very low. The primary reason for this low relative weight is the poor fit to the survey age proportions at older ages, where the results in this paper are similar to those presented in Butterworth and Rademeyer (2008a and b) in showing an inability of the default to reflect the relative paucity of cod at older ages in the surveys (and commercial catches). (Note that this relative paucity cannot be attributed to the effects of past fishing; what is shown here is an effect remaining ***after*** the assessment has already taken those effects into account.) The default is therefore statistically incompatible with the data, and must be rejected in favour of alternative models which ***do*** fit these data unless there are compelling reasons to question the reasonableness of those alternatives.

Though the domed survey selectivity option provides the best fit to the data (assessment Ricker B with M = 0.3 is marginally better than assessment Ricker A with M = 0.2), in deference to the Panel's concerns about making recommendations which rest on indirect inferences about presence of older cod not directly observed, our choice is restricted to the options for which the -lnL is not very much greater than that for options A or B. This also excludes option E, leaving F, G and H. (The relatively poor result here for option E compared to B may seen surprising, as in Butterworth and Rademeyer (2008c), setting M = 0.3 saw a flat survey selectivity option virtually compatible statistically with fitting a dome; the reason is that those results were based on fixing θ at 0.5, whereas here it has been shown in this paper (see Table 2) that the data indicate a strong preference for a higher θ value.)

The results in Table 3 show that an age-independent M value as high as about 0.4 is needed before the statistical preference for domed-selectivity falls away. An M this high is however pushing the biological limits of conventional assumptions for cod. For this reason the mechanism of increasing M at larger ages is preferred, with option G chosen over option H because maintaining the default M = 0.2 at lower ages loses relatively little in terms of goodness of fit.

Note that for the chosen assessment Ricker G, forcing commercial as well as survey selectivity to be flat at older ages increases –lnL by over 10 units. There is thus strong statistical evidence for concluding that commercial selectivity-at-age is domed, given also that the alternative of an increasing survey selectivity-at-age at older ages hardly seems likely. The associated estimate of B^{*sp}_{MSY} is dependent on the Ricker stock-recruitment function assumed; however, if the $F_{40\%}$ proxy basis for estimating this reference point is used instead, the estimate increases by only about 7%, and remains well below the estimate for B^{sp}_{2007} (see Table 3a).
The choice of an option with M increasing with age is also consistent with estimates of M from tagging analyses (Hart and Miller 2008), which suggest an M value both higher than 0.2, and higher still for older cod, though their results could also be explained as a reflection of domed shaped selectivity, and initial tagging mortality may also be playing a role. In the authors' view, the explanation for the relative paucity of older cod in the surveys and commercial catches is likely a combination of lesser extents of all of the three mechanisms considered here (domed selectivity, a higher value for age-averaged M, and M increasing at older ages) than indicated in Table 3, where each of these mechanisms is considered in isolation. The data considered cannot alone distinguish these effects or their proportional impacts. However it is clear from the results in Table 3 that whether in isolation or combination, the effect on assessments of incorporating these to resolve the inability of the M = 0.2/flat selectivity default to account for the relative paucity of older cod in the surveys and commercial catches, is to indicate that the stock at present is certainly above its MSY level.

Advantages of an SCAA/ASPM approach over VPA

The current default assessment approach to providing scientific management advice for the Gulf of Maine cod stock is VPA with an age-independent M = 0.2 and assumed asymptotically flat commercial selectivity. There are several reasons why the authors consider that an SCAA/ASPM approach is to be scientifically preferred, in particular compared to the manner in which VPA has been implemented for this stock in the past.

- VPA is restricted to a period of years for which age data for the commercial fishery is available throughout (from 1982 in this case). This restricts such analyses to a period where spawning biomass is relatively low, and thus the contrast required to better estimate the MSY level is limited compared to the much greater range of years (from 1964) which ASPM assessments can incorporate. Butterworth and Rademeyer (2008a) show that this approximately doubles the precision with which this quantity, which plays a key role in management under the terms of the Magnusson-Stevens Act, can be estimated.

- Past VPA's for this stock have assumed asymptotically flat selectivity for the commercial fishery. However the ASPM assessments provide statistically significant evidence that this selectivity must be domed, even if the survey selectivity is taken to be flat at large ages so that the issue of cryptic fish does not arise.
- As pointed out in Butterworth and Rademeyer (2008a, see Appendix 1), there is a mathematical inconsistency in the manner in which plus-group numbers have been calculated in previous implementations of VPA for this stock. Given heavy fishing mortality and asymptotically flat selectivity-at-age, this inconsistency makes little difference to results, essentially because of the backwards convergence property of VPA as an estimator in these circumstances. However, this property does not necessarily hold when selectivity is dome shaped, or natural mortality increases at older ages (at least one of which seems likely for Gulf of Maine cod), and self-consistent equations are used for the plus-group dynamics. Because of the small numbers caught at large ages (a problem exacerbated if the age-structure is extended to yet higher ages so as to try not through aggregation to subsume information pertinent to dependencies on age at these larger ages), treating the plus-group in a mathematically consistent way requires the addition of a smoothing penalty to the VPA objective function to stabilise estimates. However, we have recently found that this can lead to multi-modality in the objective function in the case of Gulf of Maine cod, with the results consequently not particularly robust to the weight given to this penalty.
- The SCAA/ASPM approach has a statistical basis which *inter alia* allows the application of model selection criteria based on likelihoods whose usage in the biological modelling field is now widespread. In contrast, past implementations of VPA have not been developed in this manner, which introduces difficulties in selecting amongst alternative variants.

IN SUMMARY

There are a number of sound scientific reasons to prefer SCAA/ASPM to VPA as the basis to develop scientific recommendations for the Gulf of Maine cod stock. Advised by AIC in considering the fits of SCAA/ASPM models to the data, but factoring in concerns about the lack of direct evidence for the cryptic older fish implied by domed survey selectivity, and the biological realism of the higher values of age-independent natural mortality required to account for the relative paucity of older cod in the survey data in particular, assessment Ricker G, which has M increasing above 0.2 for ages above 4, is put forward as the basis for providing management advice. The associated BRP values are summarise immediately below the Abstract on page 1.

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Table 1: Definitions of symbols used in presenting results (the order follows that used for Table 3). Unless otherwise indicated biomasses are "deterministic", i.e. as estimated in the model fit, prior to any bias adjustment for recruitment variability.

'-lnL:overall	Total negative log-likelihood
-lnL:Survey/CAL CAAsurv/CAA/RecRes	Contributed to -lnL from survey indices/survey catch-at-age proportions/survey catch-at-length proportions/commercial catch-at-age proportions/ recruitment residuals
h	Stock recruitment curve steepness
γ	Parameter of generalised Ricker S/R function (γ=1 for Ricker)
θ	B^{sp}/K^{sp} for starting year
ϕ	$Z_a \approx M_a + \phi$ for starting year
K^{sp}	Pristine spawning biomass
$B^{sp}{}_{2007}$	Spawning biomass in 2007
MSYL^{sp}	$B^{sp}{}_{\text{MSY}}/K^{sp}$
$B^{sp}{}_{\text{MSY}}$	Spawning biomass at MSY
$B^{*sp}{}_{\text{MSY}}$	Spawning biomass at MSY adjusted for recruitment variability by multiplying by exp($-\sigma_R$out^2/2)
MSY	Maximum sustainable yield
MSY*	MSY adjusted for recruitment variability as above
F_{MSY}	Fishing mortality rate (F) at MSY (corresponds to F at the age at which commercial selectivity = 1)
$F_{rebuild}$	F to achieve 50% probability that B^{sp} recovers to $B^{*sp}{}_{\text{MSY}}$ by 2014
F_{2007}	F for year 2007
F_{2007} (av ages 4-5)	Average of F on ages 4 and 5 in 2007
$F_{40\%}$	F at which B^{sp}/R (R = recruitment) equals 40% of its value when F=0
$B^{*sp}{}_{\text{MSY}}$_40%	Spawning biomass corresponding to $F_{40\%}$; evaluated as (B^{sp}/R for $F_{40\%}$)$\overline{R}$ where $\overline{R}$ is average of recruitment estimates
MSY*_40%	MSY corresponding to $F_{40\%}$; evaluated as (Y/R for $F_{40\%}$)$\overline{R}$; shown with * as based on average over fluctuations
C_{2008}	Catch in 2008, assumed equal to 2007 catch
C_{2009} (F_{MSY})	Projected 2009 catch under F_{MSY}
C_{2009} ($F_{\text{status quo}}$)	Projected 2009 catch under F_{2009}=F_{2008}
C_{2009} (F_{rebuild})	Projected 2009 catch under $F_{rebuild}$
q spring/autumn	Multiplicative bias for spring/autumn NEFSC survey swept-area-based biomass estimate relative to actual survey selectivity-at-age weighted biomass
Slope_com/surv 7/8	Selectivity slope given by$S_8 = e^{-Slope}\, S_7$
$\sigma_R$out	Standard deviation of distribution of logs of multiplicative recruitment residuals about estimated S/R relationship
$M$1/$M$11+	Natural mortality rate for age 1/11+

Table 2: Overall negative log-likelihood and current spawning biomass relative to B^{*sp}_{MSY} for a series of θ and ϕ values for assessment Ricker A. For the final column, θ is estimated rather than fixed.

ϕ = 0.05	θ	0.95	0.75	0.55	1.00
	'-lnL:overall	20.4	27.0	37.1	19.7
	$B^{sp}_{2007}/B^{sp}_{MSY}$	0.90	0.72	0.50	0.93
ϕ = 0.1	θ	0.95	0.75	0.55	0.93
	'-lnL:overall	19.5	22.6	31.3	19.5
	$B^{sp}_{2007}/B^{sp}_{MSY}$	1.04	0.88	0.63	1.04
ϕ = 0.2	θ	0.95	0.75	0.55	0.69
	'-lnL:overall	31.2	23.6	25.3	23.1
	$B^{sp}_{2007}/B^{sp}_{MSY}$	1.18	1.21	0.98	1.17

Table 3a: Estimates of management quantities for the Gulf of Maine cod with a Ricker stock-recruitment curve. The symbols are defined in the Results section of the text. Values in bold are inputs, and those in parentheses are Hessian based CV's. Mass units are '000 tons.

	Domed survey selectivity						Flat survey selectivity						M incr with age			
	M=0.2		M=0.3		M=0.4		M=0.2		M=0.3		M=0.4		M(4)=0.2		M(4)=0.3	
	A		*B*		*C*		*D*		*E*		*F*		*G*		*H*	
'-lnL:overall	19.5		19.0		22.9		58.1		32.4		23.6		23.8		22.7	
'-lnL:Survey	-11.3		-12.0		-12.2		-8.4		-11.5		-12.3		-12.1		-12.4	
'-lnL:CAA	-39.4		-39.4		-38.5		-36.0		-38.1		-38.4		-39.5		-39.1	
'-lnL:CAAsurv	31.2		31.6		34.8		55.2		40.3		35.5		35.9		35.1	
'-lnL:RecRes	39.0		38.8		38.8		47.4		41.7		38.9		39.5		39.1	
h	1.39	(0.15)	1.09	(0.14)	0.86	(0.15)	2.59	(0.15)	1.47	(0.15)	0.93	(0.14)	0.99	(0.16)	0.95	(0.16)
γ	**1.00**	-	**1.00**	-	**1.00**	-	**1.00**	-	**1.00**	-	**1.00**	-	**1.00**	-	**1.00**	-
θ	0.93	(0.08)	0.95*	-	0.95*	-	0.66	(0.10)	0.83	(0.09)	0.95*	-	0.95*	-	0.95*	-
ϕ	**0.10**	-	**0.10**	-	**0.10**	-	**0.10**	-	**0.10**	-	**0.10**	-	**0.10**	-	**0.10**	-
K^{sp}	129.9	(0.13)	90.7	(0.12)	75.7	(0.11)	63.5	(0.09)	65.1	(0.08)	70.1	(0.08)	69.3	(0.09)	69.8	(0.09)
B^{sp}_{2007}	52.8	(0.15)	50.5	(0.14)	51.6	(0.13)	33.4	(0.13)	42.0	(0.13)	50.3	(0.13)	44.5	(0.13)	47.1	(0.13)
B^{sp}_{2007}/K^{sp}	0.41	(0.15)	0.56	(0.15)	0.68	(0.15)	0.53	(0.16)	0.65	(0.14)	0.72	(0.14)	0.64	(0.14)	0.68	(0.14)
MSYL^{sp}	0.34	(0.14)	0.36	(0.15)	0.38	(0.17)	0.33	(0.12)	0.35	(0.15)	0.37	(0.16)	0.39	(0.13)	0.39	(0.14)
B^{sp}_{MSY}	44.2	(0.11)	32.6	(0.11)	28.5	(0.12)	20.9	(0.08)	22.6	(0.10)	26.0	(0.12)	27.3	(0.10)	26.9	(0.11)
B^{*sp}_{MSY}	51.0	(0.11)	37.5	(0.11)	32.8	(0.12)	24.8	(0.08)	26.3	(0.10)	30.0	(0.12)	31.5	(0.10)	31.0	(0.11)
$B^{sp}_{2007}/B^{*sp}_{MSY}$	1.04	(0.15)	1.35	(0.14)	1.57	(0.15)	1.35	(0.13)	1.60	(0.14)	1.68	(0.15)	1.41	(0.14)	1.52	(0.14)
MSY	11.7	(0.09)	11.5	(0.10)	11.6	(0.12)	10.7	(0.07)	11.2	(0.10)	11.8	(0.12)	11.7	(0.10)	11.6	(0.11)
*MSY**	13.4	(0.09)	13.2	(0.10)	13.4	(0.12)	12.7	(0.07)	13.1	(0.10)	13.5	(0.12)	13.5	(0.10)	13.4	(0.11)
F_{MSY}	0.37	(0.00)	0.41	(0.00)	0.49	(0.00)	0.49	(0.00)	0.54	(0.00)	0.56	(0.00)	0.43	(0.00)	0.47	(0.00)
$F_{rebuild}$	N/A		N/A		N/A		N/A		N/A		N/A		N/A		N/A	
F_{2007}	0.20	(0.16)	0.19	(0.15)	0.19	(0.15)	0.23	(0.16)	0.20	(0.15)	0.19	(0.15)	0.18	(0.15)	0.19	(0.15)
F_{2007} (av ages 4-5)	0.19	(0.15)	0.18	(0.14)	0.17	(0.14)	0.22	(0.15)	0.19	(0.14)	0.18	(0.14)	0.18	(0.14)	0.18	(0.14)
$F_{40\%}$	0.21	(0.00)	0.27	(0.00)	0.39	(0.00)	0.14	(0.00)	0.23	(0.00)	0.38	(0.00)	0.33	(0.00)	0.35	(0.00)
B^{*sp}_{MSY}_40%	70.2	(0.07)	44.1	(0.06)	33.5	(0.04)	60.6	(0.05)	40.4	(0.04)	32.9	(0.04)	33.4	(0.04)	32.9	(0.04)
*MSY**_40%	9.0	(0.03)	9.8	(0.03)	11.1	(0.03)	9.3	(0.03)	9.3	(0.02)	10.9	(0.03)	10.8	(0.03)	10.8	(0.03)
C_{2008}	**5.6**	-	**5.6**	-	**5.6**	-	**5.6**	-	**5.6**	-	**5.6**	-	**5.6**	-	**5.6**	-
C_{2009} (F_{MSY})	19.9	(0.17)	21.2	(0.16)	23.8	(0.15)	22.6	(0.16)	25.1	(0.15)	25.9	(0.15)	23.3	(0.15)	23.8	(0.15)
C_{2009} ($F_{status\ quo}$)	7.0	(0.04)	6.8	(0.04)	6.6	(0.04)	7.1	(0.03)	6.8	(0.03)	6.6	(0.04)	6.9	(0.04)	6.7	(0.04)
C_{2009} ($F_{rebuild}$)	N/A		N/A		N/A		N/A		N/A		N/A		N/A		N/A	
q spring	0.35	(0.12)	0.35	(0.11)	0.35	(0.10)	0.48	(0.08)	0.40	(0.10)	0.36	(0.10)	0.32	(0.10)	0.34	(0.10)
q autumn	0.38	(0.10)	0.37	(0.10)	0.38	(0.09)	0.51	(0.06)	0.43	(0.09)	0.38	(0.09)	0.34	(0.08)	0.36	(0.10)
Slope_com 7/8	0.59	(0.18)	0.39	(0.29)	0.20	(0.62)	0.09	(0.86)	0.19	(0.62)	0.16	(0.76)	0.12	(1.18)	0.16	(0.83)
Slope_surv 7/8	0.47	(0.11)	0.26	(0.18)	0.06	(0.79)	**0.00**	-	**0.00**	-	**0.00**	-	**0.00**	-	**0.00**	-
σ_R out	0.53	(0.03)	0.53	(0.03)	0.53	(0.03)	0.59	(0.03)	0.55	(0.03)	0.53	(0.03)	0.54	(0.03)	0.53	(0.03)
M1	**0.20**		**0.30**		**0.40**		**0.20**		**0.30**		**0.40**		**0.20**		**0.30**	
M2	**0.20**		**0.30**		**0.40**		**0.20**		**0.30**		**0.40**		**0.20**		**0.30**	
M3	**0.20**		**0.30**		**0.40**		**0.20**		**0.30**		**0.40**		**0.20**		**0.30**	
M4	**0.20**		**0.30**		**0.40**		**0.20**		**0.30**		**0.40**		**0.20**		**0.30**	
M5	**0.20**		**0.30**		**0.40**		**0.20**		**0.30**		**0.40**		0.25		0.33	
M6	**0.20**		**0.30**		**0.40**		**0.20**		**0.30**		**0.40**		0.30		0.36	
M7	**0.20**		**0.30**		**0.40**		**0.20**		**0.30**		**0.40**		0.37		0.39	
M8	**0.20**		**0.30**		**0.40**		**0.20**		**0.30**		**0.40**		0.46		0.42	
M9	**0.20**		**0.30**		**0.40**		**0.20**		**0.30**		**0.40**		0.56		0.46	
M10	**0.20**		**0.30**		**0.40**		**0.20**		**0.30**		**0.40**		0.69		0.50	
M11+	**0.20**		**0.30**		**0.40**		**0.20**		**0.30**		**0.40**		0.85		0.55	

* Constraint boundary

Table 3b: Estimates of management quantities for the Gulf of Maine cod with a Beverton-Holt stock-recruitment curve. The symbols are defined in the Results section of the text. Values in bold are inputs, and those in parentheses are Hessian based CV's. Mass units are '000 tons.

	Domed survey selectivity						Flat survey selectivity						*M* incr with age			
	M=0.2		*M*=0.3		*M*=0.4		*M*=0.2		*M*=0.3		*M*=0.4		*M*(4)=0.2		*M*(4)=0.3	
	A		*B*		*C*		*D*		*E*		*F*		*G*		*H*	
'-lnL:overall	25.0		22.3		23.9		62.1	0.0	35.9		25.6		26.7		25.0	
'-lnL:Survey	-12.2		-12.9		-12.9		-7.8		-11.9		-13.2		-12.8		-13.1	
'-lnL:CAA	-39.3		-39.3		-38.4		-35.8		-37.8		-38.2		-39.2		-38.8	
'-lnL:CAAsurv	33.5		33.1		35.3		54.4		40.7		36.2		37.0		36.1	
'-lnL:RecRes	43.1		41.3		39.9		51.3		44.9		40.7		41.8		40.9	
h	0.94	(0.15)	0.96	(0.16)	0.98*	-	0.98*	-	0.98*	-	0.98*	-	0.95	(0.20)	0.98*	-
γ	**1.00**	-	**1.00**	-	**1.00**	-	**1.00**	-	**1.00**	-	**1.00**	-	**1.00**	-	**1.00**	-
θ	0.65	(0.08)	0.80	(0.16)	0.95*	-	0.24	(0.12)	0.49	(0.10)	0.83	(0.11)	0.81	(0.17)	0.88	(0.15)
ϕ	**0.10**	-	**0.10**	-	**0.10**	-	**0.10**	-	**0.10**	-	**0.10**	-	**0.10**	-	**0.10**	-
K^{sp}	201.2	(0.13)	118.5	(0.12)	86.5	(0.07)	164.0	(0.07)	105.8	(0.07)	83.5	(0.07)	85.0	(0.12)	81.9	(0.08)
B^{sp}_{2007}	53.6	(0.15)	50.3	(0.14)	51.3	(0.13)	31.1	(0.14)	39.8	(0.13)	48.5	(0.13)	43.6	(0.13)	46.4	(0.13)
B^{sp}_{2007}/K^{sp}	0.27	(0.15)	0.42	(0.16)	0.59	(0.11)	0.19	(0.14)	0.38	(0.13)	0.58	(0.12)	0.51	(0.17)	0.57	(0.13)
MSYL^{sp}	0.14	(0.14)	0.12	(0.31)	0.17	(0.03)	0.18	(0.04)	0.10	(0.04)	0.17	(0.03)	0.19	(0.23)	0.15	(0.08)
B^{sp}_{MSY}	27.9	(0.11)	14.3	(0.23)	15.1	(0.08)	29.6	(0.08)	11.0	(0.08)	14.6	(0.08)	16.2	(0.16)	12.5	(0.08)
B^{*sp}_{MSY}	32.6	(0.11)	16.6	(0.23)	17.5	(0.08)	35.6	(0.08)	12.9	(0.08)	16.9	(0.08)	18.8	(0.16)	14.5	(0.08)
$B^{sp}_{2007}/B^{*sp}_{\text{MSY}}$	1.64	(0.15)	3.04	(0.25)	2.94	(0.12)	0.87	(0.14)	3.08	(0.13)	2.86	(0.12)	2.32	(0.18)	3.20	(0.13)
MSY	10.1	(0.09)	11.3	(0.23)	13.3	(0.07)	9.7	(0.07)	10.5	(0.07)	12.8	(0.07)	11.2	(0.15)	12.2	(0.08)
MSY^*	11.8	(0.09)	13.1	(0.23)	15.3	(0.07)	11.6	(0.07)	12.4	(0.07)	14.8	(0.07)	13.1	(0.15)	14.2	(0.08)
F_{MSY}	0.48	(0.00)	1.12	(0.00)	2.30	(0.00)	0.30	(0.00)	1.92	(0.00)	2.30	(0.00)	0.76	(0.00)	2.01	(0.00)
$F_{rebuild}$	N/A		N/A		N/A				N/A		N/A		N/A		N/A	
F_{2007}	0.20	(0.16)	0.20	(0.15)	0.19	(0.15)	0.25	(0.17)	0.22	(0.15)	0.20	(0.15)	0.19	(0.15)	0.19	(0.15)
F_{2007} (av ages 4-5)	0.19	(0.15)	0.19	(0.14)	0.18	(0.14)	0.37	(0.16)	0.21	(0.15)	0.18	(0.14)	0.18	(0.14)	0.18	(0.14)
$F_{40\%}$	0.22	(0.00)	0.27	(0.00)	0.39	(0.00)	0.14	(0.00)	0.23	(0.00)	0.38	(0.00)	0.33	(0.00)	0.37	(0.00)
B^{*sp}_{MSY}_40%	71.0	(0.07)	44.5	(0.06)	34.0	(0.04)	60.0	(0.06)	40.2	(0.04)	32.8	(0.04)	32.9	(0.04)	32.2	(0.05)
MSY^*_40%	9.0	(0.03)	9.8	(0.03)	11.2	(0.03)	9.4	(0.05)	9.2	(0.02)	10.9	(0.03)	10.9	(0.03)	11.1	(0.03)
C_{2008}	**5.6**	-	**5.6**	-	**5.6**	-	**5.6**	-	**5.6**	-	**5.6**	-	**5.6**	-	**5.6**	-
C_{2009} (F_{MSY})	23.0	(0.17)	40.5	(0.15)	52.9	(0.15)	13.8	(0.17)	47.9	(0.16)	51.8	(0.15)	33.9	(0.15)	52.7	(0.15)
C_{2009} ($F_{\text{status quo}}$)	6.9	(0.04)	6.7	(0.04)	6.6	(0.04)	7.1	(0.03)	6.8	(0.04)	6.6	(0.04)	6.8	(0.04)	6.7	(0.04)
C_{2009} (F_{rebuild})	N/A		N/A		N/A				N/A		N/A		N/A		N/A	
q spring	0.33	(0.12)	0.33	(0.12)	0.33	(0.09)	0.51	(0.09)	0.41	(0.10)	0.35	(0.11)	0.31	(0.12)	0.32	(0.12)
q autumn	0.36	(0.10)	0.35	(0.12)	0.36	(0.09)	0.53	(0.08)	0.43	(0.09)	0.37	(0.10)	0.33	(0.10)	0.34	(0.11)
Slope_com 7/8	0.61	(0.18)	0.42	(0.27)	0.23	(0.50)	0.03	(4.41)	0.19	(0.60)	0.18	(0.67)	0.11	(1.28)	0.15	(0.86)
Slope_surv 7/8	0.48	(0.11)	0.28	(0.18)	0.10	(0.46)	**0.00**	-	**0.00**	-	**0.00**	-	**0.00**	-	**0.00**	-
$\sigma_R$out	0.56	(0.03)	0.55	(0.03)	0.54	(0.03)	0.61	(0.03)	0.57	(0.03)	0.54	(0.03)	0.55	(0.03)	0.55	(0.03)
M1	**0.20**		**0.30**		**0.40**		**0.20**		**0.30**		**0.40**		**0.20**		**0.30**	
M2	**0.20**		**0.30**		**0.40**		**0.20**		**0.30**		**0.40**		**0.20**		**0.30**	
M3	**0.20**		**0.30**		**0.40**		**0.20**		**0.30**		**0.40**		**0.20**		**0.30**	
M4	**0.20**		**0.30**		**0.40**		**0.20**		**0.30**		**0.40**		**0.20**		**0.30**	
M5	**0.20**		**0.30**		**0.40**		**0.20**		**0.30**		**0.40**		0.25		0.33	
M6	**0.20**		**0.30**		**0.40**		**0.20**		**0.30**		**0.40**		0.31		0.37	
M7	**0.20**		**0.30**		**0.40**		**0.20**		**0.30**		**0.40**		0.38		0.40	
M8	**0.20**		**0.30**		**0.40**		**0.20**		**0.30**		**0.40**		0.48		0.45	
M9	**0.20**		**0.30**		**0.40**		**0.20**		**0.30**		**0.40**		0.59		0.49	
M10	**0.20**		**0.30**		**0.40**		**0.20**		**0.30**		**0.40**		0.74		0.54	
M11+	**0.20**		**0.30**		**0.40**		**0.20**		**0.30**		**0.40**		0.91		0.60	

* Constraint boundary

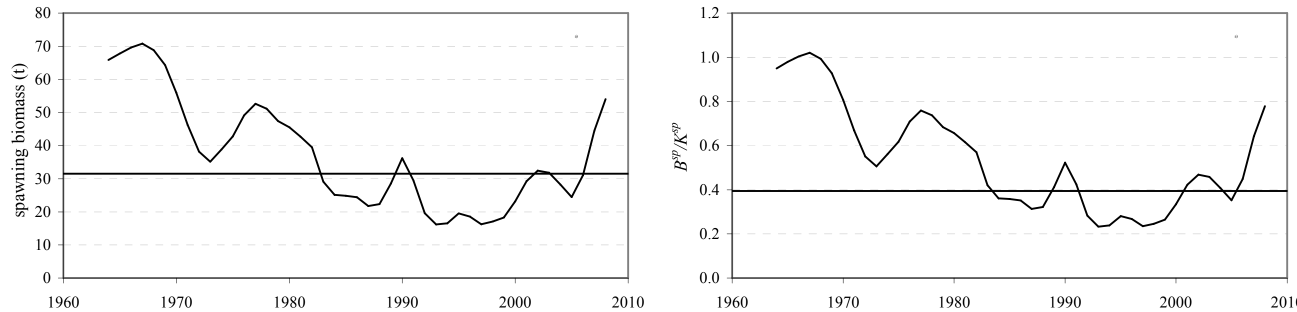

Fig. 1: Spawning biomass trajectories (in absolute terms and in terms of pre-exploitation level) for assessment Ricker G. The estimated B^{*sp}_{MSY} and MSYL are also shown.

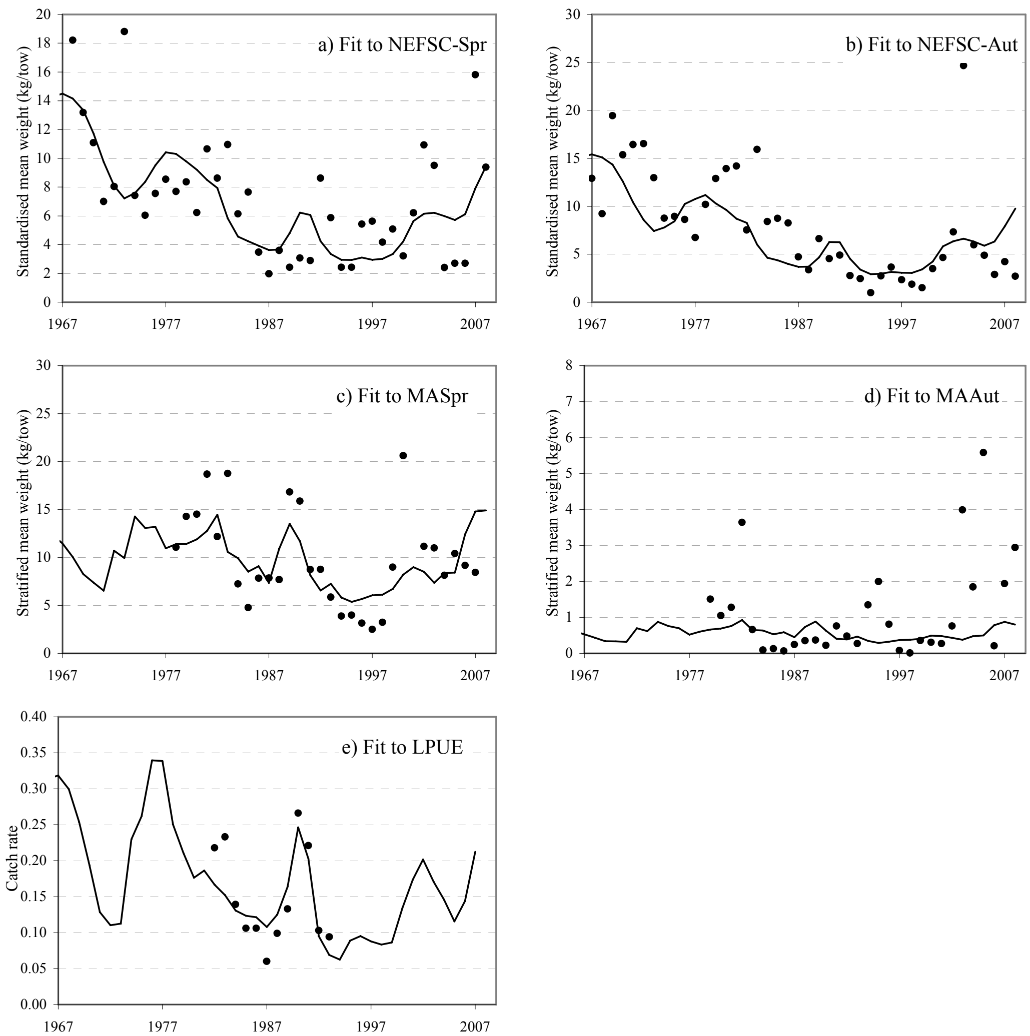

Fig. 2: Model fits to the abundance indices (survey and CPUE) for assessment Ricker G.

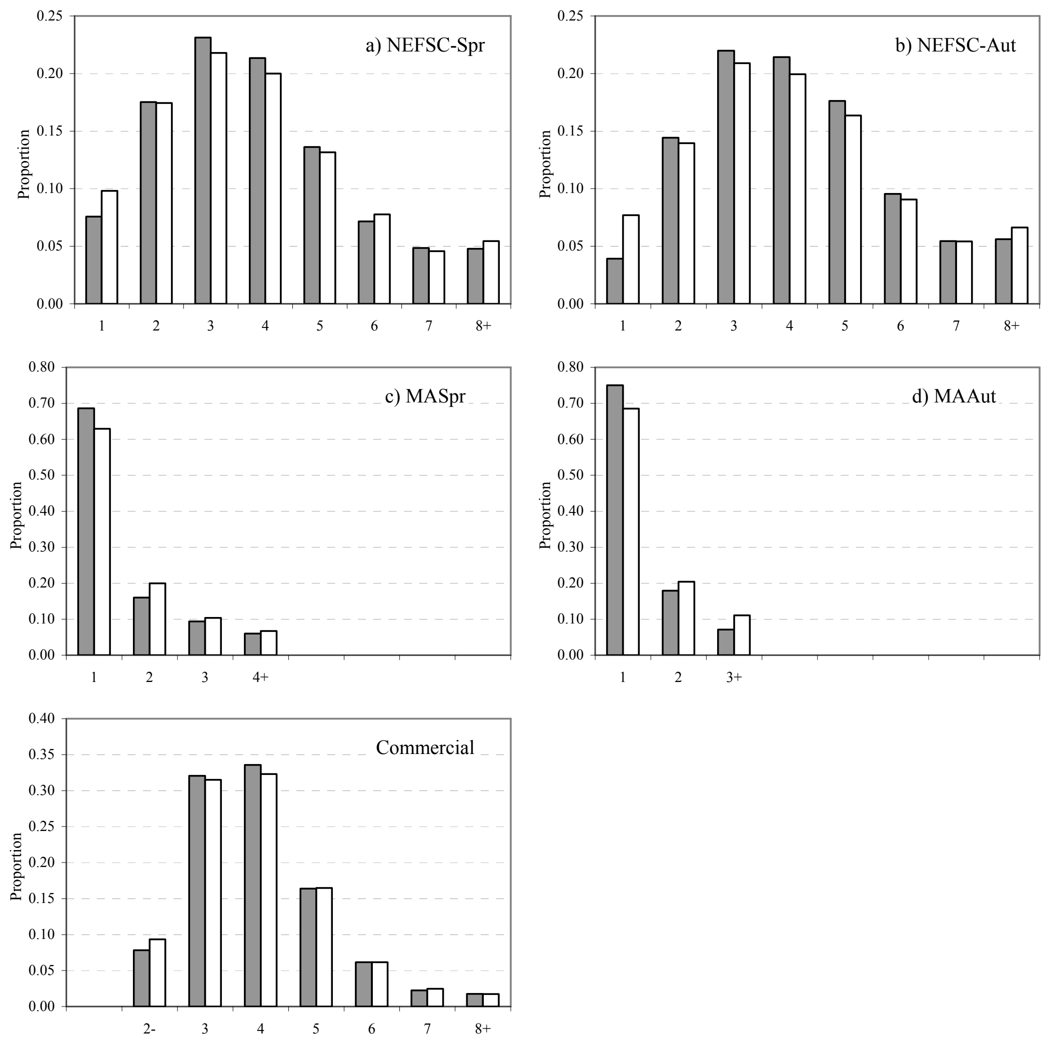

Fig. 3: Fits to the catch-at-age data (survey and commercial averaged over all the years with data for each data set) for assessment Ricker G. The dark bars are the data and the white bars the model estimates.

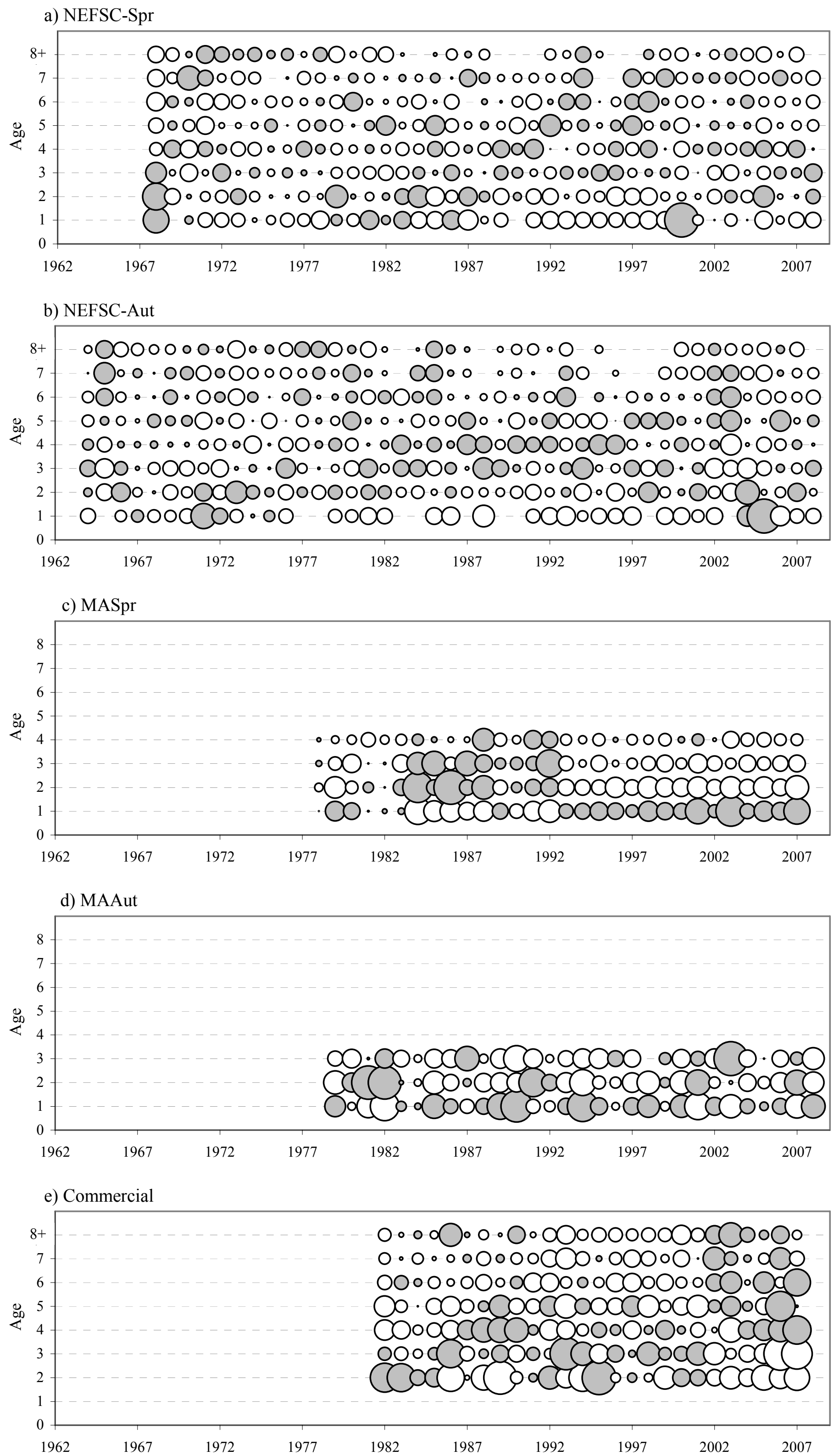

Fig. 4: Bubble plots of the standardised residuals for the catch-at-age data for assessment Ricker G. The size (area) of the bubbles represents the size of the residuals. Grey bubbles represent positive residuals and white bubbles represent negative residuals.

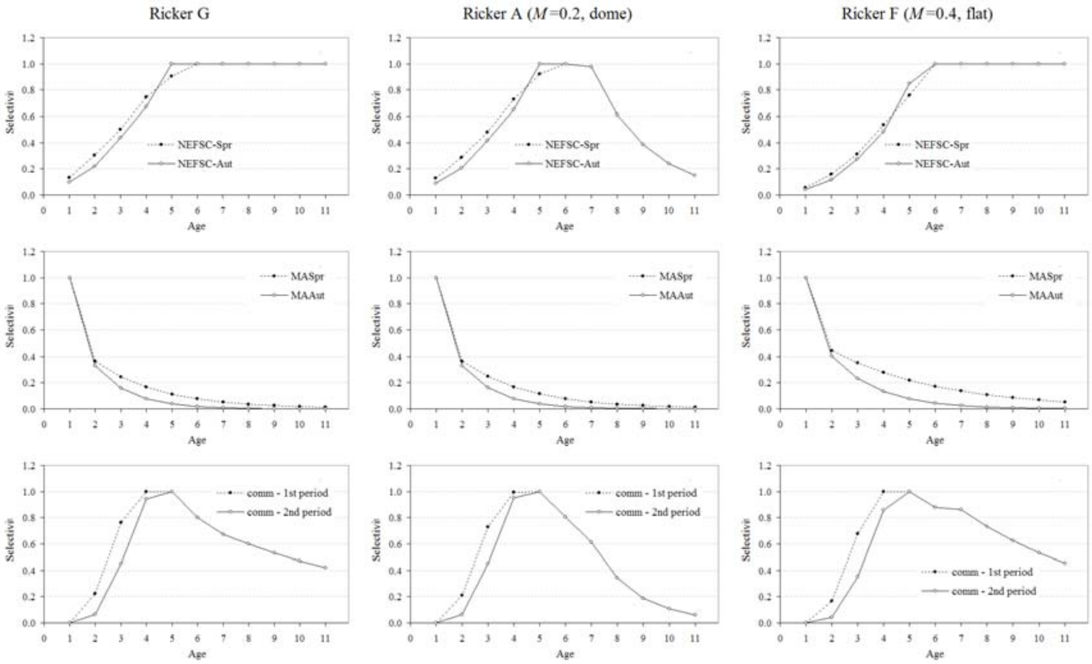

Fig. 5: Survey and commercial selectivities-at-age for three Ricker assessments.

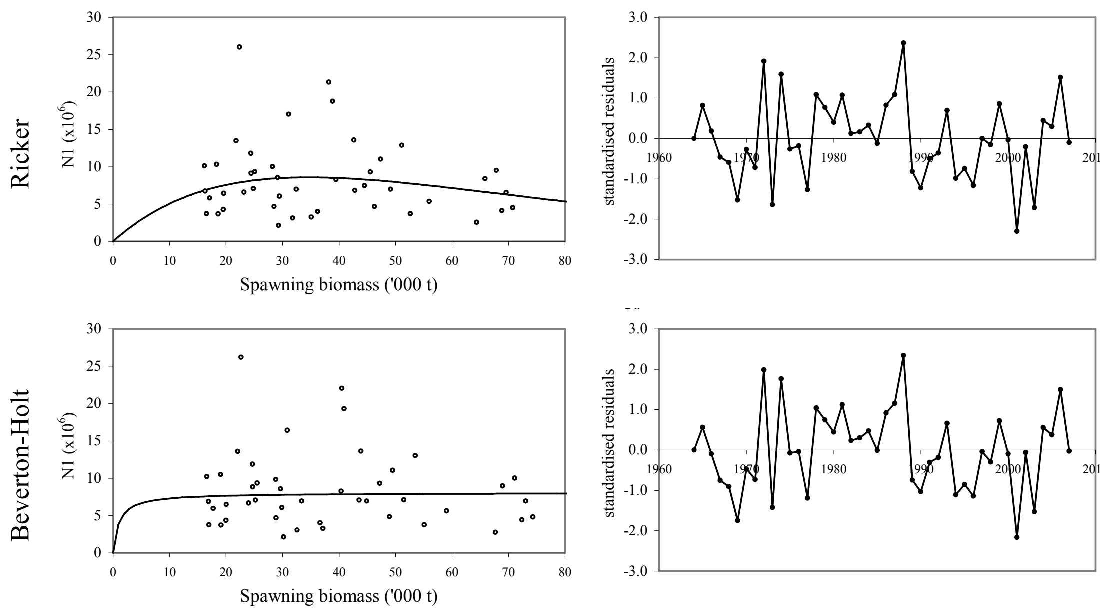

Fig. 6: The estimated stock-recruitment curve and estimated recruitment and spawning biomass each year for assessments Ricker and Beverton-Holt G. The plots to the right show the time series of standardised stock-recruitment residuals.

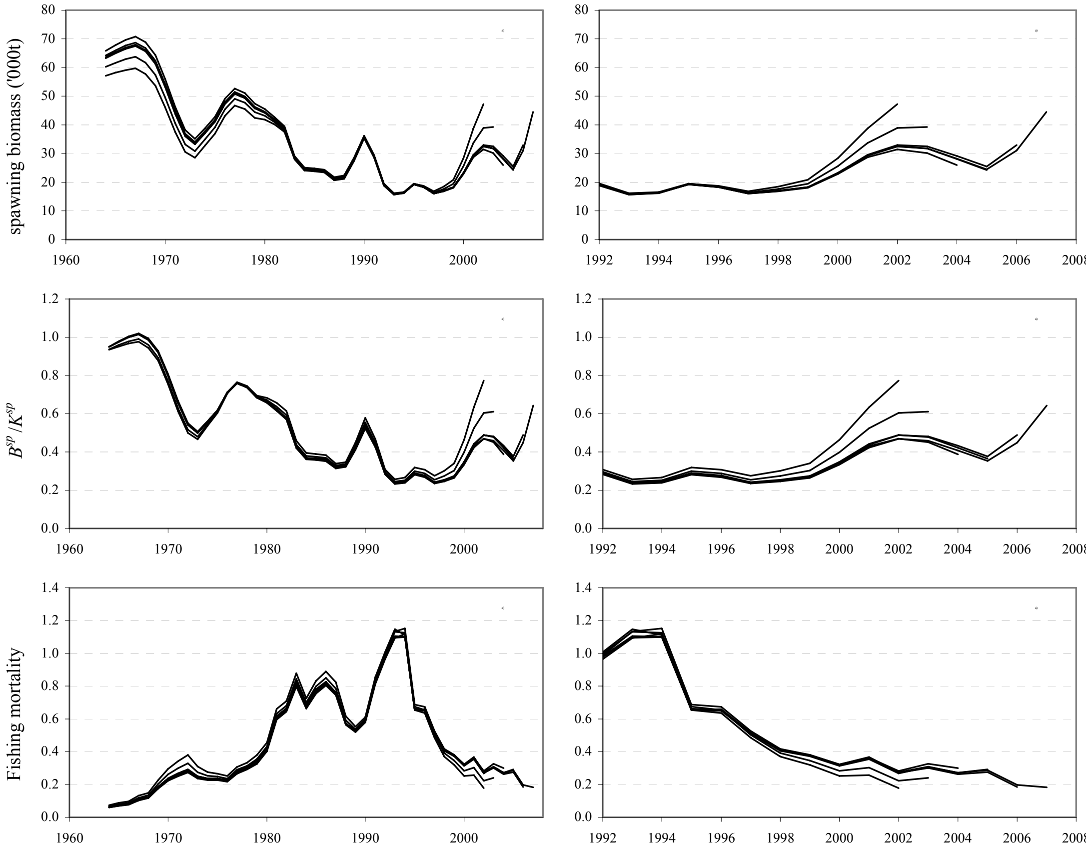

Fig. 7: Retrospective analysis of Gulf of Maine cod for assessment Ricker G for spawning biomass (in absolute terms, top panels, and relative to pre-exploitation levels, middle panels) and fully selected fishing mortality (lower panels).