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Statistical Catch-at-Age analysis *vs* ADAPT-VPA: the case of Gulf of Maine cod

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ABSTRACT

In 2003, given an estimate of the spawning stock biomass (B^{sp}) in 2001 of only 27% of the corresponding level at MSY (B^{sp}_{MSY}) on the basis of an ADAPT-VPA assessment that used data from 1982 onwards only, the Gulf of Maine cod stock was classified as "overfished" in the context of the Magnusson-Stevens Act, and a recovery plan put in place. However, an alternative Statistical Catch at Age (SCAA; alternatively termed Age Structured Production Model – ASPM) assessment at the time, which took account of survey data back to 1964, suggested that the stock was above B^{sp}_{MSY} . An independent panel appointed as part of the process to review this and other US Northeast groundfish assessments during that year recommended further investigation of this to better understand the difference. This paper addresses and discusses this issue together with a range of other (sometimes conflicting) suggestions made during a number of reviews of the assessment of this stock over the past decade. It finds that the primary reason for the different results is that the ADAPT-VPA assessment imposed asymptotically flat selectivity-at-age in circumstances where there is strong statistical evidence for dome-shaped selectivity in the data. Making allowance for this under either assessment method reverses perceptions that recent fishing mortalities have exceeded F_{MSY} , and robustly estimates B^{sp} relatively close to B^{sp}_{MSY} rather than below the threshold of 0.5 B^{sp}_{MSY} for an "overfished" ("depleted") classification. Compared to the ADAPT-VPA approach which is limited to the period for which catch-at-age data are available, the SCAA/ASPM approach allows the longer series of research survey data available to be taken into account, thus providing a better basis to estimate management quantities linked to MSY-related targets, and doubling the related precision in some cases. Given that such targets play important roles in the implementation of the Magnusson-Stevens Act, the SCAA/ASPM approach would seem to be preferred over ADAPT-VPA for assessing this stock. The calculations conducted have also pointed more generally to the need for care in treatment of the plus-group in analyses, as well as in use of the Beverton-Holt spawning biomass recruitment relationship which can lead to inappropriately low estimates of B^{sp}_{MSY} in certain circumstances, and to the importance of using flexible parametrizations of selectivity-at-age in SCAA/ASPM assessments to avoid possibly misleading impressions of the precision with which quantities such as natural mortality M can be estimated.

INTRODUCTION

Broadly speaking, there are two different approaches to the incorporation of catch-at-age information in fisheries assessments, termed Virtual Population Analysis (VPA) and Statistical Catch at Age Analysis (SCAA). When catch-at-age data are amongst those used to fit an Age Structured Production Model (ASPM), this approach can become equivalent to SCAA, so that these two names are sometimes used interchangeably. Interestingly the VPA approach tends to be the preferred method applied in many marine resource assessments on either side of the North Atlantic, whereas SCAA/ASPM is more frequently applied on the north American west coast and a number of Southern Hemisphere countries (e.g. the CASAL package originally developed for assessments of New Zealand fisheries (Bull *et al*. 2005)) as well as some international fisheries organisations (e.g. CCAMLR, CCSBT and IWC).

VPA (e.g. Gulland 1965) makes the assumption that catch-at-age data are exact (i.e. with negligible error), and requires these to be available for all the years covered by the assessment. As catch-at-age data alone do not provide sufficient information to uniquely determine abundance trends (e.g. Butterworth and Punt 1990), VPA has to be "tuned" by the incorporation of some index of relative abundance in the estimation process. Amongst the most popular of such approaches is the ADAPT-VPA approach originally introduced by Gavaris (1988).

SCAA approaches, in their simplest form, make the assumption of an invariant fishing selectivity-at-age pattern over time that determines the true age distribution of the total catch taken each year. This pattern is then estimated in the model fitting process by comparing this distribution to the observed catch-at-age data (e.g. Punt and Hilborn 1997). Doubleday (1976) was perhaps the first to implement this concept of separability of annual fishing mortality at age into age (selectivity) and year (fully selected fishing mortality) components to assist in fitting models to catch-at-age data, though Agger *et al*. (1971) applied it in a simpler form. The CAGEAN package (Deriso *et al*. 1985) constituted an early implementation of this approach. Fournier and Archibald (1982) refined the formalism with particular emphasis on the stochastic aspects to allow estimation to be set in a likelihood framework (hence the S of SCAA), and to admit the simultaneous (internal) estimation of the parameters of a spawning-stock recruitment function. A particular advantage of SCAA is that, unlike VPA, it does not require that catch-at-age data are available for every year covered by the assessment.

Thus VPA assumes that observed catch-at-age data are exact, with the fishing selectivity pattern consequently varying from year to year, whereas SCAA approaches take the selectivity pattern to be fixed in time, and consider the differences between observed and (constant selectivity) model-predicted catch-at-age data to reflect age-reading and other sources of error. More sophisticated approaches (e.g. Fournier *et al*. 1998, Butterworth *et al.* 2003) can span the range between these two extremes by allowing the possibility of the selectivity pattern varying over time through the use of time-series models.

ASPM's (e.g. Hilborn 1990, who termed them General Age-Structured Models) were a development of simpler biomass (*B*) dynamics or Age-Aggregated Production Models (AAPM), such as that of Schaefer (1957) which used the logistic form $rB(1-B/K)$ for the production function. Extending the dynamics of such models to a full age-structured form has the advantage of properly accounting for time-lags such as the period from birth to first reproduction, and expressing biomass in a form that relates directly to quantities estimated in absolute terms by survey methods (e.g. hydroacoustic survey estimates of abundance). Effectively when fitting the model to data given the values of biological parameters such as natural mortality, the estimation of the Schaefer model's *r* and *K* is replaced by that of two parameters of the spawning stock recruitment function. If that function has a stochastic component, and catch-at-age data (from either or both commercial or research survey catches) are included in the fitting process, the ASPM becomes a SCAA. A simpler form of the ASPM approach was first proposed by Kimura and Tagart (1982); they called the method Stock Reduction Analysis, and generalised it in Kimura *et al.* (1984).

But in practical terms for appropriate fisheries management advice, does it matter much which of the VPA or SCAA/ASPM (henceforth termed ASPM) approaches is used? Punt *et al*. (2002) and Radomski *et al*. (2005) conducted comparative simulation studies based upon Australia's south east fishery and the recreational walleye (*Sander vitreus*) fishery in Lake Mille Lacs, Minnesota respectively. Broadly speaking, both studies suggested better performance by the ASPM approach, though there were exceptions depending on the underlying reality and precise form of the assessment approach used.

In this paper assessments of the Gulf of Maine cod (*Gadus morhua*) stock are used to examine this question. Co-incidentally, groundfish resources off the US north-east coast are good candidates for the application of ASPM methodology because of scientific surveys which have been conducted with unchanged methodology over a very long time period (since 1964); thus (to the extent that fish distribution patterns have not changed) the age-specific estimates of abundance provided by these surveys satisfy exactly the constant selectivity assumption underlying the basic ASPM approach.

The issue of possible substantial differences in assessment results for this resource under the ADAPT-VPA and ASPM methodologies first arose during the NOAA-commissioned 2003 review of US Northeast groundfish assessments by a panel from the Center of Independent Experts (CIE: www.rsmas.miami.edu/groups/cie). Table 1 contrasts the results obtained at the time by application of the two methods: ADAPT-VPA (coupled to an externally fitted spawning stock-recruitment relationship) as detailed in NEFSC (2002), and ASPM by Butterworth *et al.* (2003) which coincidentally implemented a recommendation by the NRC (1998) that such a approach be considered for this stock in particular. Key differences are that the ADAPT-VPA approach estimated the then current spawning biomsass B^{sp} to be at only 27% of that required to harvest MSY $\left(B^{sp}_{MSY}\right)$, whereas the ASPM estimated B^{sp} to be above that level. Furthermore the ADAPT-VPA estimated the then current fishing mortality to be almost double F_{MSY}, whereas the ASPM estimated it to be below F_{MSY}. These differences are important, because the National Standard Guidelines (Federal Register 2005) associated with the Magnusson-Stevens Fishery Conservation and Management Act governing US fisheries requires fishing mortality to be reduced if it exceeds F_{MSY}. Furthermore, if B^{sp} drops below B_{lim} for which the default is 0.5 B^{sp}_{MSY}, a stock is declared "overfished" (or more recently "depleted"), a Fishery Management Plan Amendment must be put in place which aims to rebuild the stock to B^{sp}_{MSY} within a specified period.

The summary report of the CIE panel at that time (Payne 2003) found that: “Most methodologies used by the NEFSC to compute F_{MSY} and B_{MSY} are adequate” and that the ADAPT-VPA methodology provided a rigorous and adequate basis for evaluating possible fisheries management policies. In the light of the different ASPM results for Gulf of Maine cod, the panel found that “there would definitely be value in investigating the ASPM and ADAPT-based approaches to better understand the differences between them”.

Following this 2003 review, in December of that year the New England Fisheries Management Council adopted Amendment 13 to the Northeast Multispecies Fishery Management Plan (NEFMC 2003), which declared the Gulf of Maine cod stock “overfished” in 2001 on the basis of the ADAPT-VPA assessment. In consequence limits on the fishery, particularly in terms of reductions in days-at-sea allocations, were put in place to reduce effort in order to achieve estimated rebuilding targets for this stock and other species in the groundfish complex to meet the requirements of the Magnusson-Stevens Act.

Further interim analyses addressing the reasons for this difference (Butterworth *et al*. 2005) were considered through NMFS-commissioned postal reviews by four independent sources (R Cook, R Hilborn, R Mohn and CEFAS, Lowestoft) (NEFMC 2005a). Three of these sources acknowledged utility in the ASPM approach, while the fourth considered that it should be preferred to ADAPT-VPA in this case. These reviews were considered in turn by an April 2005 meeting of the Scientific and Statistical Committee (SSC) of the US New England Fisheries Management Council, which concluded that: “While the ASPM approach is worth consideration in conjunction with, or as an alternative to, the current ADAPT-VPA approach, it is premature to make management recommendations based on it at this time” (NEFMC 2005b). The SSC made certain suggestions regarding further ASPM investigations, but did not review the ADAPT-VPA approach. In the light of this report, the New England Fisheries Management Council took no immediate related action, noting that the various methods could be further considered during the next major review of groundfish assessments planned for 2008.

This paper summarises the results of further comparisons of the ADAPT-VPA and ASPM approaches for the Gulf of Maine cod stock which have been conducted since the 2005 review, which include addressing a number of comments made by the various reviewers. The data set used for the comparison is first specified, followed by details of the ASPM and ADAPT-VPA approaches (the latter as implemented by the US NEFSC, together with a modification thereof advanced by the authors of this paper). Results using these approaches are presented which, it is argued, identify the primary reasons for the original difference, and the associated wider implications are discussed.

DATA

The detailed data used for the analyses of this paper are listed in Tables SD.1 to SD.14 of the supplementary material. They comprise annual landings by mass from 1893; year-specific weights-at-age, fecundity-at-age and landings-at-age from 1982; and mean numbers-at-age per tow from various survey series, the earliest of which commenced in 1964. These data are those used for more recent ADAPT-VPA assessment of the Gulf of Maine cod stock than that of NEFSC (2002) quoted in Table 1, *viz*. Mayo and Col (2006).

As explained in the supplementary material, a slight adjustment has been made to the Mayo and Col (2006) landings-at-age matrix for the calculations of this paper, whose principal interest is a **comparative** analysis of methodologies which consequently must see such methodologies applied to the same data set. This is necessary, given the data available, to allow ASPM computations to take better account of dynamics within what the ADAPT-VPA treats as a 7+ group. The impact of this adjustment on results is discussed below.

METHODOLOGY

Appendix 1 first sets out the ADAPT-VPA methodology as implemented by the Northeast Fisheries Science Center (NEFSC) for the Gulf of Maine cod stock (Mayo and Col 2006). It then points to a mathematical inconsistency in the manner that the plus-group abundance is calculated in this approach, and indicates how this can be corrected in what is termed an "Alt-VPA" approach. This last approach also allows for flexibility in the shape of the selectivity-at-age function at larger ages through introduction of an estimable parameter α (see equation A1.16) which reflects the slope of the function at such ages. Note that α=1 corresponds (in an average sense) to the asymptotically flat selectivity assumed for the NEFSC ADAPT-VPA assessments of Gulf of Maine cod.

Appendix 1 concludes with a section specifying how MSY and associated quantities (e.g. the spawning biomass corresponding to MSY, B^{sp}_{MSY}, and the associated fully-selected fishing mortality, F_{MSY}) are calculated for both the ADAPT-VPA and ASPM approaches.

Appendix 2 details the ASPM methodology applied, including the penalised maximum likelihood criterion used to fit the model. Precision is evaluated by extending the approach to a fully Bayesian form in which the penalised maximum likelihood estimates correspond to posterior modes.

In the ASPM results that follow, total penalised negative log-likelihood $\left(-\ell n\, L\right)$ values and sometimes Bayesian probability intervals (PIs) are quoted for a number of applications of the approach. However, it needs to be remembered that the inclusion of a penalty term for residuals about the stock recruitment relationship means that these $-\ell n\, L$ values cannot strictly be used for AIC-based model selection. Although this does not compromise the Bayesian computations, for which these penalties serve as priors, there are probably some correlations amongst the data inputs which the Bayesian approach (as well as the frequentist) is treating as independent, and these will introduce some bias into the Bayesian estimates of probability intervals (PIs). Thus strictly the $-\ell n\, L$ and PI values reported are only illustrative rather than definitive in a model comparison context; but nevertheless a model options for which, say, a (pseudo-) AIC value is much higher than for others should not be accorded much weight.

RESULTS AND DISCUSSION

ASPM

To provide a focus for consideration of a potentially substantial set of results for various model options, this section is structured to address what seem to have been the major concerns raised by reviewers of earlier work (Butterworth *et al*. 2005) in NEFMC (2005a). These were:

i) the estimability of natural mortality (*M*);

ii) the choice of functional form for a spawning stock-recruitment relationship, with concerns about the implications of high estimates of steepness *h* for the Beverton-Holt form; and

iii) selectivity related questions concerning particularly the strength of evidence for a dome shape, with selectivity decreasing at older ages, and the assumption of temporal invariance for the fishery in the years prior to 1982 for which landings-at-age data are not available.

Results are reported for a Reference Case application (RC-ASPM) and a number of sensitivities (Table 2, and also Table S1 of the supplementary material). Some key choices in the specification of RC-ASPM are natural mortality M=0.2 yr^{-1}, the use of a Ricker form for the spawning stock-recruitment relationship, and initiating the analysis from as early a date as data are available rather than only in 1982 as for the NEFSC ADAPT-VPA assessments. A Reference Case (RC) assessment does not claim to be a "best" assessment, but rather a convenient choice to facilitate comparisons with alternative options. Nevertheless sensibly a RC should be chosen to be reasonably close to a likely eventual "best" selection (or set of selections), and the reasons underlying the choices listed above will become clear from the comparisons discussed below.

Estimability of M

In earlier ASPM implementations (e.g. Butterworth *et al*. 2005), likelihood profile results for *M* had suggested that this could be estimated with reasonable precision. However, these assessments had assumed the selectivity pattern in the NEFSC surveys to be linear with age on the basis of such indications from the ADAPT-VPA results. Such an assumption (Sensitivity 6 of Table 2) leads to a much inferior fit to the data compared to RC-ASPM ($-\ell n L$ larger by over 65 units) - hence the fully flexible form now used (see Appendix 2, section A2.4.1). However, when such linearity was no longer imposed, there was no longer any indication that *M* was estimable with reasonable precision. RC-ASPM therefore fixes *M*=0.2 as has been customary for NEFSC ADAPT-VPA assessment of this stock.

Bayesian posterior medians and 95% probability envelopes for historical spawning biomass (B^{sp}) trends for RC-ASPM are shown in Fig. 1. The steep decline shown over the first decade in the series should not be considered particularly reliable, as the stock had been exploited prior to 1893 contrary to the assumption of unexploited equilibrium at this time made here; estimates of recent trends in abundances and quantities of importance for management are however insensitive to this assumption. Figs 2-4 show fits to the indices of abundance and age-structure information, and do not show any obvious indications of model mis-specification. Fig. 5 shows the estimates of selectivities-at-age for both the commercial and the NEFSC surveys; the dome shape is evident, with a steeper decline at larger ages for the commercial catches compared to the surveys.

Sensitivity 2 (Table 3) explores the consequences of changing the value of *M* to 0.3, which are also illustrated in Fig. 6. This higher value is slightly preferred in likelihood terms. It results in spawning biomass estimates that are somewhat lower in absolute terms, but also an estimated current status of B^{sp}_{2004} closer to the target MSY level $\left(MSYL = B^{sp}_{MSY} / K^{sp}\right)$.

Stock-recruitment relationship

Earlier ASPM results (e.g. Butterworth *et al*. 2005) focussed on use of the Beverton-Holt spawning stock-recruitment relationship, as this had been preferred in the original NEFSC (2002) assessments. However both sets of assessments yielded estimates of steepness *h* close to the maximum of 1 that applies for this form, and concerns were raised that this yielded a very low estimate of *MSYL*, below most existing observations, which if accepted would see management targeting low abundance levels where inferred resource behaviour depended on extrapolation beyond the range of most available data.

Sensitivity 4 in Table 2 shows the results of replacing the Ricker form in RC-ASPM by a Beverton-Holt form, with the associated fits to annual estimates of recruitment (N_1) and spawning biomass shown in Fig. 7 for each case. The Ricker form achieves a better fit to the data (some 6 log-likelihood units), and also leads to an estimate of B^{sp}_{MSY} which is near the center of the range of B^{sp} values rather than close to the lower end. Further there is little indication of serial correlation in recruitment residuals about the Ricker curve where the data available allows these to be reasonably well estimated (Fig. 8). Fig. 7 indicates why the monotonically increasing Beverton-Holt form has difficulties in this case: with lowish recruitments having occurred at the highest biomass levels, the implied overall negative trend of recruitment with B^{sp} can be accommodated only by setting h as large as the form permits. All of these considerations indicate that here Ricker is the preferred of the two forms.

Actually the Ricker form is a special case of a more general form examined (see Appendix 2, equation A2.4), which includes an additional shape parameter γ. However, attempts to also estimate γ (see Sensitivity 3 in Table 2 and Fig. 6) offer neither improvements to the likelihood nor meaningful differences to the fit.

Dome-shaped selectivity

Fig. 5 shows that the RC-ASPM maximum penalised likelihood estimates of selectivity-at-age are dome-shaped for both the NEFSC surveys and the commercial catches. If these selectivities are forced to be asymptotically flat (see Sensitivity 5, Table 2), $-\ell n L$ deteriorates by 35 units. Most of this deterioration occurs for the fits of proportions at age 5 to 7+ for the commercial catches and NEFSC surveys. Fig. 9 shows residual plots for proportions-at-age fits for Sensitivity 5, and is to be compared to those for RC-

ASPM in Fig. 4. The model mis-specification in the former case (with asymptotically flat selectivity) is evident from the fact that virtually all the residuals for ages 6 and 7+ are negative (i.e. fewer older fish are observed than consistent with the flat selectivity assumption). This effect is also present, though not quite as evident, for the NEFSC autumn surveys. For RC-ASPM, the Bayesian posterior median and 95% PI estimates for S_7 / S_6 ratios are 0.52 [0.41; 0.64] and 0.72 [0.66; 0.79] for the commercial and NEFSC survey catches. If M=0.3, these estimates increase as would be expected: commercial 0.68 [0.55; 0.83] and survey 0.89 [0.82; 0.97], i.e. still not overlapping the value of 1 that corresponds to flat selectivity.

Given that 0.3 seems about as large as might enjoy general support as a realistic estimate of M for the Gulf of Maine cod stock, the results above taken together suggest strongly that the available data are not compatible with the assumption of asymptotically flat selectivity, but rather evidence this to decline at larger ages.

Selectivity prior to 1982

The ASPM requires some assumption concerning commercial selectivity-at-age prior to 1982. In the absence of landings-at-age data for any of that period, RC-ASPM sets this equal to that estimated for the 1982-1991 period (see Appendix 2, section A2.4.1) and consequently time invariant.

This assumption is certainly not correct, as for a start there were gear regulation changes during the pre-1982 period. The question though is whether incorporating such information into the analyses would substantially modify key results. Some sensitivity tests to alternative (though also time-invariant) assumed commercial selectivities-at-age pre-1982 (see Table S1 of the supplementary material) suggest very little change to estimates of current F and B^{sp} levels relative to those at MSY. Considerable experience with the ASPM approach for many other fisheries (for example in the International Whaling Commission) suggests that such effects are generally second order, with the historical sequence of total catch by weight being the much more influential factor. The likelihood that this is also the case here is supported by the trends shown in Fig. 10 of the per-recruit contribution by age to cohort biomass, taking the effects of both natural mortality and somatic growth into account. These are relativity flat over the 3-6 age range for which the commercial selectivity is relatively high, which suggests that limited changes in the age distribution of catches will have little impact on biomass and hence future resource dynamics.

A related question concerns the survey data prior to 1982, and whether concerns of their possible lack of comparability to later data should rather see analyses restricted to the use of 1982+ abundance indices and proportion-at-age data only. Sensitivities 7 and 8 in Table 2 address this, omitting pre-1982 data from the fitting criterion compared to the RC-ASPM (Ricker) and its Beverton-Holt counterpart (Sensitivity 4). In both cases there is an appreciable decrease in the precision with which certain quantities can be estimated. The ranges of the 95% PI for MSY and importantly $B^{sp}_{2004} / B^{sp}_{MSY}$ roughly double, and those for B^{sp}_{2004} in absolute terms roughly treble. .Radomski *et al*. (2005) point to the possibility of large errors if selectivity varies rather than remaining constant as assumed for this ASPM implementation, but this possibility needs to be weighed against the fact that the NEFSC surveys are perhaps the longest in the world which have focussed on maintaining the same methodology.

Comparison of ADAPT-VPA and ASPM results

A number of ADAPT-VPA assessment results are reported in Table 3, together with those for related ASPM assessments. The different spawning biomass trajectories are shown in Fig. 11, with selectivity-at-age functions plotted in Fig. 5. Note that the VPA results themselves are independent of the spawning stock-recruitment function form which is fitted externally to VPA outputs, so that the Beverton-Holt *vs* Ricker distinction affects only certain of the quantities listed in Table 3.

The Reference Case ADAPT-VPA assessment (RC-VPA) applies the same methodology as Mayo and Col (2006) (see Appendix 1), but to the slightly amended data as detailed above and in the supplementary material. There is little qualitative difference between the Mayo and Col (2006) and RC-VPA results. The Alt-VPA (α=1) method, which involves alternative treatment of the plus-group while maintaining the asymptotically flat selectivity assumption (in an average sense), produces a virtually identical spawning biomass trajectory to RC-VPA, and also a similar estimate of B^{sp}_{2004} relative to B^{sp}_{MSY} (see Table 3).

Allowing the selectivity slope at large age to be estimated ("α=est") within the Alt-VPA framework suggests dome-shaped selectivity (Fig. 5a) and a higher biomass in absolute terms (Fig. 11), together with a further increase in the estimate of B^{sp}_{2004} relative to B^{sp}_{MSY} (Table 3). When α is fixed at 1, the fits to the survey data are slightly worse for the Alt-VPA method compared to RC-VPA, but become better than those for RC-VPA when α is estimated. This holds whether the fitting criterion excludes (as for NEFSC assessments) or includes the 7+ group. However these comparisons are not entirely even-handed, as the Alt-VPA method includes a penalty term P_2 (see equation A1.15) associated with variability about the relationship between fishing mortalities for the two oldest age groups considered, whereas the corresponding relationship amongst ages 4 to 6 is forced to be exact for RC-VPA.

Comparing with ASPM results, the B^{sp} trajectory for the Alt-VPA (α=est) case is very similar to that for RC-ASPM, particularly over the last 10 years. However, that is not an entirely appropriate comparison, as the fit of RC-ASPM also take account of pre-1982 data. A better comparison is to ASPM Sensitivity 7 which excludes these earlier data, and results in B^{sp} values somewhat greater than those for Alt-VPA (α=est). Note that one would not expect exact agreement, because the ASPM takes account of dynamics within the plus-group so that average selectivity for the group as a whole changes over time because of the changing age-structure within the group, whereas the ADAPT-VPA-based methods do not make allowance for this. Fig. 12 compares some estimated fully selected fishing mortality time series for the ASPM and ADAPT-VPA approaches; the latter are appreciably higher in some recent years.

Table 3 shows that only the combination of the asymptotically flat selectivity assumption and a Beverton-Holt spawning stock recruitment relationship leads to VPA estimates showing a low value of B^{sp}_{2004} relative to B^{sp}_{MSY} and a corresponding fishing mortality in excess of F_{MSY}. If α is estimated, or a Ricker form assumed, F_{2004} is consistently estimated to be well below F_{MSY}, and all B^{sp}_{2004} relative to B^{sp}_{MSY} estimates are well above the 0.5 "overfished"/"depleted" threshold.

SOME BROADER ISSUES

The multiple recent reviews of the assessments of US Northeast groundfish assessments, and of the Gulf of Maine cod stock in particular, have led to a variety of comments of broader pertinence.

Period of data to consider in assessments

Perhaps the most interesting difference in views expressed by reviewers has related to how far back in time to incorporate data into an assessment. The NRC review (NRC 1998) was unequivocal in querying the use of short time series for assessments, stating that a longer term view achieved through increased use of historical data was needed, and singling out the Gulf of Maine cod stock in this respect. Yet some more recent reviews (Payne 2003, NEFMC 2005a,b) have appeared hesitant in this regard, expressing concerns about the necessary associated assumptions and the possibility of changes over time in underlying processes.

The two viewpoints seem to show some correlation with whether or not their exponents are closely involved in North Atlantic assessments. We posit that this may relate to personal experiences gained in circumstances of the high extent to which many North Atlantic stocks have been reduced, in contrast to the situations in some other areas. With highly depleted resources, the primary focus is to ensure that catch- or effort-related recommendations will lead to increased abundance, so that the use of data for more recent years only to better ensure comparability of abundance indices and hence obtain unbiased estimates of trend becomes paramount. Continued high fishing mortalities mean that VPA-based estimates of abundance depend little on how these mortalities might be calculated for the oldest ages. In other circumstances, however, there tends to be a greater focus on medium term targets, such as B_{MSY}^{sp} , and consequently greater emphasis on use of longer time series of data. For example, the IWC's Revised Management Procedure stresses that account be taken of catch histories that extend as far back in time as possible (IWC 1999).

Estimation of stock-recruitment relationships

Should this be internal or external to the assessment, as respectively as in the ASPM or ADAPT-VPA approaches above? By nature of its construction, ASPM must always involve internal estimation, whereas this could be external for SCAA implementations (though this might give rise to convergence difficulties for the SCAA). Proponents of the internal option will cite statistically self-consistent weighting of the various sources of information available. On the other hand, the external option ensures against being misled by a possibly inappropriate choice of functional form for the relationship.

We suggest rather that the most important consideration is to check for any evidence of systematic lack-of-fit to both the stock-recruitment function and the various abundance indices and catch-at-age data. Given indications of such lack-of-fit, the internal option is not supportable; but in the absence of such indications, internal estimation seems the logical choice. Following simulation studies of the related question of estimating the effect of environmental factors on recruitment, Maunder and Watters (2003) conclude that the internal outperforms the external estimation approach which can result in biased estimates when data are limited.

The need to choose a "best" assessment

Some reviewers have queried whether there is a need to choose a "best" method (and hence to argue whether one method is better than another), since all are approximations to reality and the use of different methods adds value through providing different perspectives. Further the merits of retaining the same method over time have been cited as reason to maintain a methodological *status quo*.

The requirement for specific decisions concerning resource and fishing mortality levels under the National Standard Guidelines for the US Magnusson-Stevens Act (Federal Register 2005) would seem to necessitate prior agreement upon decision rules, and hence on some associated "best" assessment (though this could be to take some average over a set of different assessments). Certainly once an approach has been agreed, updates of management recommendations for the immediate future should be based on an unchanged approach so that impressions gained of resource trends upon which those recommendations would be based are not artefacts of methodological changes.

However, this should not be to the exclusion of medium term review and possible change. The most important consideration is that the models used must be consistent with available data (unless cogent reasons can be advanced to query the reliability of certain data and hence to exclude them from assessments).

Simulation tests

Simulation testing has been suggested as a basis to resolve debate about the relative merits of ASPM and ADAPT-VPA for assessing the Gulf of Maine cod stock. However the difficulty with such an approach is that results will depend on the set of underlying realities chosen for inclusion in the simulation trials (e.g. Radomski *et al*. 2005). Such an approach carries the overhead of first needing to get the debating parties around a table to attempt consensus agreement on trial specifications, which is a pre-requisite to any chance to get a generally agreed interpretation of the results of such tests.

CONCLUSIONS

At a more detailed level, three general observations that arise from the debates and analyses of Gulf of Maine cod stock data are:

1) The need for care in consideration of and mathematically consistent treatment of the plus-group, particularly if there is the possibility of dome-shaped selectivity.
2) To err on the side of more flexible parametrizations of selectivity-at-age in SCAA/ASPM approaches, to avoid possibly misleading perceptions of the precision with which certain parameters (such as M) may be estimable.

3) To take care when using the Beverton-Holt spawning stock recruitment function, which will provide inappropriately low estimates of B^{sp}_{MSY} if there is an overall negative trend in estimates of recruitment when plotted against those of B^{sp}.

More specific to the Gulf of Maine cod stock, important conclusions are:

I) The primary reason for the differences shown in the results of the 2003 ADAPT-VPA and ASPM assessments shown in Table 1 that the CIE reviewers wanted understood (Payne 2003) is that the former forced asymptotically flat selectivity, whereas the latter allowed this to be estimated from the data. The differences in question reduce substantially once this constraint on the ADAPT-VPA assessment is relaxed.

II) Population modelling indicates that the assumption of asymptotically flat selectivity is inconsistent with the available catch-at-age data. Either cogent reasons need to be advanced that current ageing of older cod is unreliable, or assessments based on the assumption of asymptotically flat selectivity must be rejected.

III) Once the constraint of asymptotically flat selectivity is relaxed, estimates of recent spawning biomass as a proportion of B_{MSY} become substantially larger than the 27% of the NEFSC (2002) assessment that led to the classification of the stock as "overfished"/"depleted". Furthermore, perceptions that recent fishing mortality exceeds F_{MSY} are reversed. These results hold for both ADAPT-VPA (Table 3) and over a wide range of sensitivities for ASPM (Table 2 and Table S1).

IV) In circumstances where the implementation of the Magnusson-Stevens Act puts particular emphasis on the determination of B^{sp}_{MSY}, note that this benefits from a greater contrast in values of B^{sp} provided by considering the post-1982 period alone (note from Fig. 1 the much greater range of B^{sp} values covered when this period is extended to post-1964), precision of estimates of recent B^{sp} relative to B^{sp}_{MSY} are doubled through the inclusion of pre-1982 data in the estimation, and concerns about possible changes in selectivity pre-1982 are offset by the NEFSC research survey series being perhaps the longest in the world to have deliberately focussed on maintaining the same methodology. Consequently the ability of SCAA/ASPM approaches to take pre-1982 data into account unlike VPA would seem to render the former preferred.

By way of a concluding note, it is again important to stress that this paper has focused on a question of **methodological** comparison. It has used the summary data provided for the standard assessments of the Gulf of Maine stock for that purpose, and does not go further (as appropriate for a final assessment) in considering whether such summaries might be better alternatively developed. The ASPM Reference Case is not offered as the "best" possible assessment of the stock. Certainly independent evidence should be sought and considered for the net avoidance of trawls or emigration that might give rise to the dome-shaped selectivity identified, to better confirm the reliability of the enhanced estimates of stock status that follow, and discussions are needed to determine which of numerous options within the ASPM framework might be the best to choose for the stock. Nevertheless the broad inferences resulting from this work should facilitate the improvement of future assessments of this stock.

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Table 1: Key management quantities from NEFSC (2002) ADAPT-VPA based and the Butterworth *et al*. (2003) ASPM assessment of the Gulf of Maine cod. Biomass units are thousand tons and $MSYL = B^{sp}_{MSY} / K^{sp}$.

	NEFSC 2002	Butterworth *et al*. 2003
M	0.2	0.2
K^{sp}	274	159
$B^{sp}{}_{2001}$	22	47
$B^{sp}{}_{2001}/K^{sp}$	0.08	0.30
$B^{sp}{}_{\mathrm{MSY}}$	83	40
$B^{sp}{}_{2001}/B^{sp}{}_{MSY}$	0.27	1.17
$MSYL$	0.30	0.25
MSY	17	11
F_{MSY}	0.23	0.30
F_{2001}	0.57	0.20

Table 2: Penalised maximum likelihood estimates (followed by Bayesian posterior medians and 95% probability intervals in parenthesis) of key management quantities for the Reference Case ASPM (RC-ASPM) and seven sensitivities. Biomass units are thousand tons. The estimates given for quantities such as B^{sp}_{MSY} refer to the commercial selectivity function from 1992+. Values shown in bold are fixed on input. Negative log-likelihoods are shown in parenthesis when not comparable to that for the RC-ASPM because of data differences. See Appendix 2, section A2.4.1 for the specifications of ASPM Sensitivity 6.

	Reference Case 1) M=0.2, Ricker			2) M=0.3, Ricker			3) M=0.2, Ricker, γ estimated			4) M=0.2, Beverton-Holt		
		posterior			posterior			posterior			posterior	
	MLE	median	95% PI	MLE	median	95% PI	MLE	median	95% PI	MLE	median	95% PI
'-lnL:overall	-46.3			-48.7			-46.3			-39.9		
M	**0.20**	**0.20**	-	**0.30**	**0.30**	-	**0.20**	**0.20**	-	**0.20**	**0.20**	-
h	1.67	1.41	(1.06; 1.82)	1.39	1.20	(0.95; 1.57)	1.66	1.65	(1.11; 2.50)	0.98*	0.92	(0.78; 0.98)
γ	**1.00**	**1.00**	-	**1.00**	**1.00**	-	1.05	0.87	(0.54; 1.15)	-	-	-
K^{sp}	127.3	150.3	(121.8; 192.3)	82.3	92.9	(78.0; 108.3)	126.5	159.8	(126.3; 213.3)	205.0	234.6	(199.5; 288.1)
B^{sp}_{2004}	37.1	45.3	(33.5; 61.3)	32.4	37.0	(28.7; 46.9)	37.3	46.2	(34.2; 63.0)	37.8	49.5	(35.5; 69.1)
B^{sp}_{2004}/K^{sp}	0.29	0.30	(0.23; 0.38)	0.39	0.40	(0.31; 0.50)	0.29	0.29	(0.22; 0.37)	0.18	0.21	(0.16; 0.27)
B^{sp}_{MSY}	46.9	56.2	(45.0; 73.8)	33.5	38.0	(31.7; 44.7)	47.5	56.8	(45.8; 73.8)	36.1	46.5	(36.5; 69.4)
$B^{sp}_{2004}/B^{sp}_{MSY}$	0.79	0.80	(0.61; 1.03)	0.97	0.98	(0.75; 1.24)	0.78	0.81	(0.62; 1.06)	1.05	1.04	(0.70; 1.51)
$MSYL$	0.37	0.37	(0.36; 0.39)	0.41	0.41	(0.40; 0.42)	0.38	0.36	(0.31; 0.39)	0.18	0.20	(0.17; 0.25)
MSY	13.4	13.5	(12.0; 15.3)	12.8	12.8	(11.9; 13.8)	13.5	13.0	(11.1; 15.0)	10.5	10.9	(9.6; 12.7)
F_{MSY}	0.62	0.52	(0.39; 0.66)	0.89	0.70	(0.51; 1.05)	0.61	0.50	(0.38; 0.64)	0.65	0.52	(0.37; 0.70)
F_{2004}	0.26	0.22	(0.16; 0.30)	0.27	0.23	(0.17; 0.31)	0.26	0.22	(0.16; 0.30)	0.28	0.22	(0.16; 0.32)

	5) Flat survey and commercial selectivity for age 5+			6) Linear selectivity for NEFSC survey, M=0.2			7) Exclude pre-1982 index data, M=0.2, Ricker			8) Exclude pre-1982 index data, M=0.2, Beverton-Holt		
		posterior			posterior			posterior			posterior	
		median	95% PI		median	95% PI		median	95% PI		median	95% PI
'-lnL:overall	-11.4			19.5			(-12.6)			(-8.6)		
M	**0.20**	**0.20**	-	**0.20**	**0.20**	-	**0.20**	**0.20**	-	**0.20**	**0.20**	-
h	3.02	2.81	(2.40; 3.21)	3.74	3.46	(2.63; 4.14)	1.30	0.93	(0.56; 1.41)	0.90	0.78	(0.53; 0.94)
γ	**1.00**	**1.00**	-	**1.00**	**1.00**	-	**1.00**	**1.00**	-	-	-	-
K^{sp}	75.3	77.7	(73.6; 82.3)	73.6	76.1	(69.0; 86.3)	166.4	242.4	(168.3; 382.8)	268.7	354.5	(283.4; 482.0)
B^{sp}_{2004}	26.1	27.9	(22.3; 34.3)	27.9	29.0	(23.2; 36.2)	50.6	92.7	(54.6; 191.8)	62.1	120.1	(71.0; 217.9)
B^{sp}_{2004}/K^{sp}	0.35	0.36	(0.28; 0.45)	0.38	0.38	(0.30; 0.47)	0.30	0.38	(0.28; 0.58)	0.23	0.34	(0.23; 0.48)
B^{sp}_{MSY}	31.3	32.4	(30.2; 34.9)	28.9	30.2	(26.5; 34.0)	62.4	95.0	(62.7; 159.4)	54.3	85.8	(54.7; 148.8)
$B^{sp}_{2004}/B^{sp}_{MSY}$	0.84	0.86	(0.67; 1.07)	0.97	0.96	(0.75; 1.20)	0.81	0.98	(0.69; 1.51)	1.14	1.38	(0.84; 2.42)
$MSYL$	0.42	0.42	(0.41; 0.43)	0.39	0.39	(0.38; 0.41)	0.38	0.39	(0.37; 0.42)	0.20	0.25	(0.17; 0.33)
MSY	13.0	12.9	(12.5; 13.1)	14.1	13.9	(13.1; 14.9)	13.6	13.4	(10.4; 17.5)	11.8	12.5	(9.5; 16.8)
F_{MSY}	0.69	0.61	(0.51; 0.75)	1.20	1.00	(0.67; 1.61)	0.51	0.36	(0.20; 0.54)	0.54	0.37	(0.20; 0.59)
F_{2004}	0.25	0.23	(0.18; 0.30)	0.25	0.24	(0.19; 0.32)	0.22	0.15	(0.09; 0.23)	0.21	0.13	(0.08; 0.21)

* indicates a constraint boundary

Table 3: Estimates of key management quantities for VPA assessments of the Gulf of Maine cod. Biomass units are tons. The estimates given for quantities such as B^{sp}_{MSY} refer to an average commercial selectivity function for 1992-2004 and $MSYL = B^{sp}_{MSY} / K^{sp}$. Values shown in bold are fixed on input. Objective function (*SS*) values shown in parenthesis are not comparable to those for RC-VPA because of data differences. Note that the RC-VPA is fit to SS over ages 1-6 as in Mayo and Col (2006), whereas Alt-VPA is fit to SS over ages 1-7+. (Table S2 provides a detailed breakdown by series and age of the contributions to SS for RC-VPA.). See equation A1.15 for details of the penalty term P_2.

	Beverton-Holt						Ricker					
	as Mayo and Col, 2006	RC-VPA	Alt-VPA, α=1	Alt-VPA, α=est	ASPM, excluding pre-1982 data - Sensitivity 8	ASPM - Sensitivity 4	as Mayo and Col, 2006	RC-VPA	Alt-VPA, α=1	Alt-VPA, α=est	ASPM, excluding pre-1982 data - Sensitivity 7	RC-ASPM
VPA SR SS	(9.78)	9.88	9.89	9.95			(9.71)	9.71	9.77	9.92		
VPA fit SS 1-6	(165.99)	166.01	169.33	163.36			(165.99)	166.01	169.33	163.36		
VPA fit SS 1-7+		206.16	208.06	196.46				206.16	208.06	196.46		
Penalty P_2			4.09	9.36					4.09	9.36		
M	**0.2**	**0.2**	**0.2**	**0.2**	**0.2**	**0.2**	**0.2**	**0.2**	**0.2**	**0.2**	**0.2**	**0.2**
h	0.80	0.84	0.74	0.83	0.90	0.98*	2.08	2.18	1.90	1.73	1.30	1.67
K^{sp}	224.0	193.2	250.5	186.2	268.7	205.0	70.1	63.0	73.2	79.0	166.4	127.3
B^{sp}_{2004}	21.0	21.3	20.7	30.8	62.1	37.8	21.0	21.3	20.7	30.8	50.6	37.1
B^{sp}_{2004}/K^{sp}	0.09	0.11	0.08	0.17	0.23	0.18	0.30	0.34	0.28	0.39	0.30	0.29
B^{sp}_{MSY}	72.1	61.2	81.0	44.4	54.3	36.1	30.9	27.8	31.8	29.5	62.4	46.9
$B^{sp}_{2004}/B^{sp}_{MSY}$	0.29	0.35	0.25	0.69	1.14	1.05	0.68	0.77	0.65	1.04	0.81	0.79
$MSYL$	0.32	0.32	0.32	0.24	0.20	0.18	0.44	0.44	0.43	0.37	0.38	0.37
MSY	15.0	13.1	15.8	9.9	11.8	10.5	10.9	10.1	10.8	9.6	13.6	13.4
F_{MSY}	0.24	0.27	0.26	0.53	0.54	0.65	0.53	0.63	0.57	0.77	0.51	0.62
F_{2004}	0.38	0.36	0.44	0.35	0.21	0.28	0.38	0.36	0.44	0.35	0.22	0.26

* indicates a constraint boundary

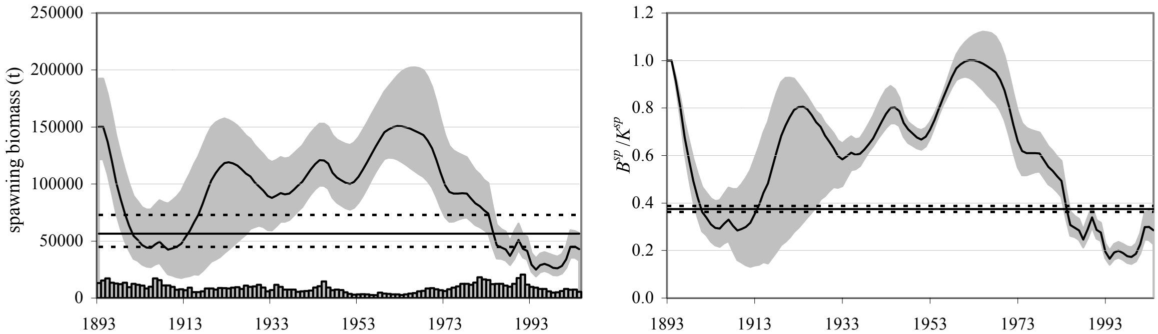

Fig. 1: Posterior medians of spawning biomass trajectories (in absolute terms and in terms of pre-exploitation level) for the ASPM Reference Case. The shaded areas represent the 95% PI envelopes. The estimated B^{sp}_{MSY} and *MSYL* are also shown, with the 95% PI as dotted lines. The bar plot shows the annual total landings (t).

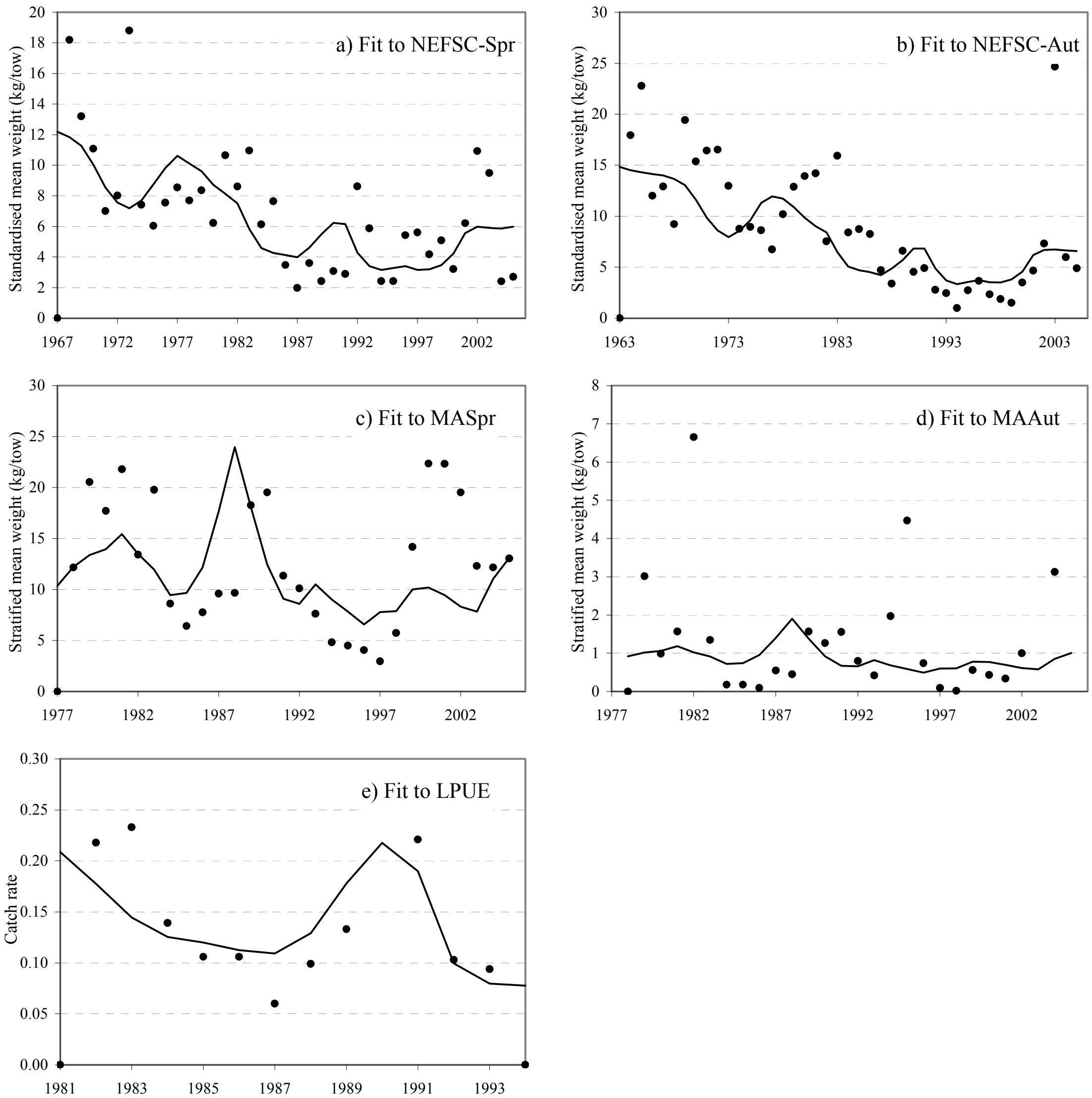

Fig. 2: RC-ASPM assessment model fits to the abundance indices (survey and CPUE).

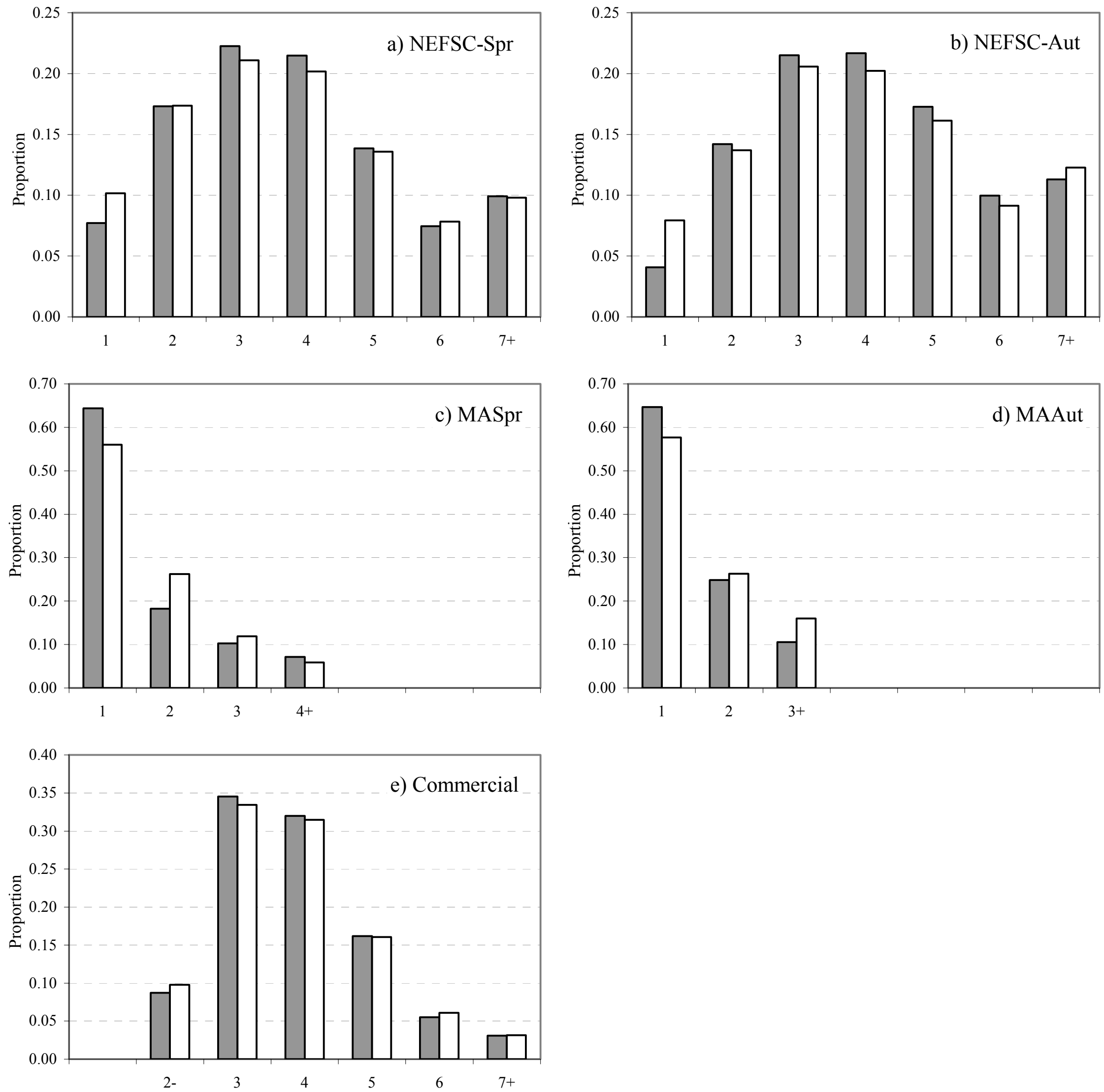

Fig. 3: RC-ASPM assessment model fits to the catch-at-age data (survey and commercial averaged over all the years with data for each data set).

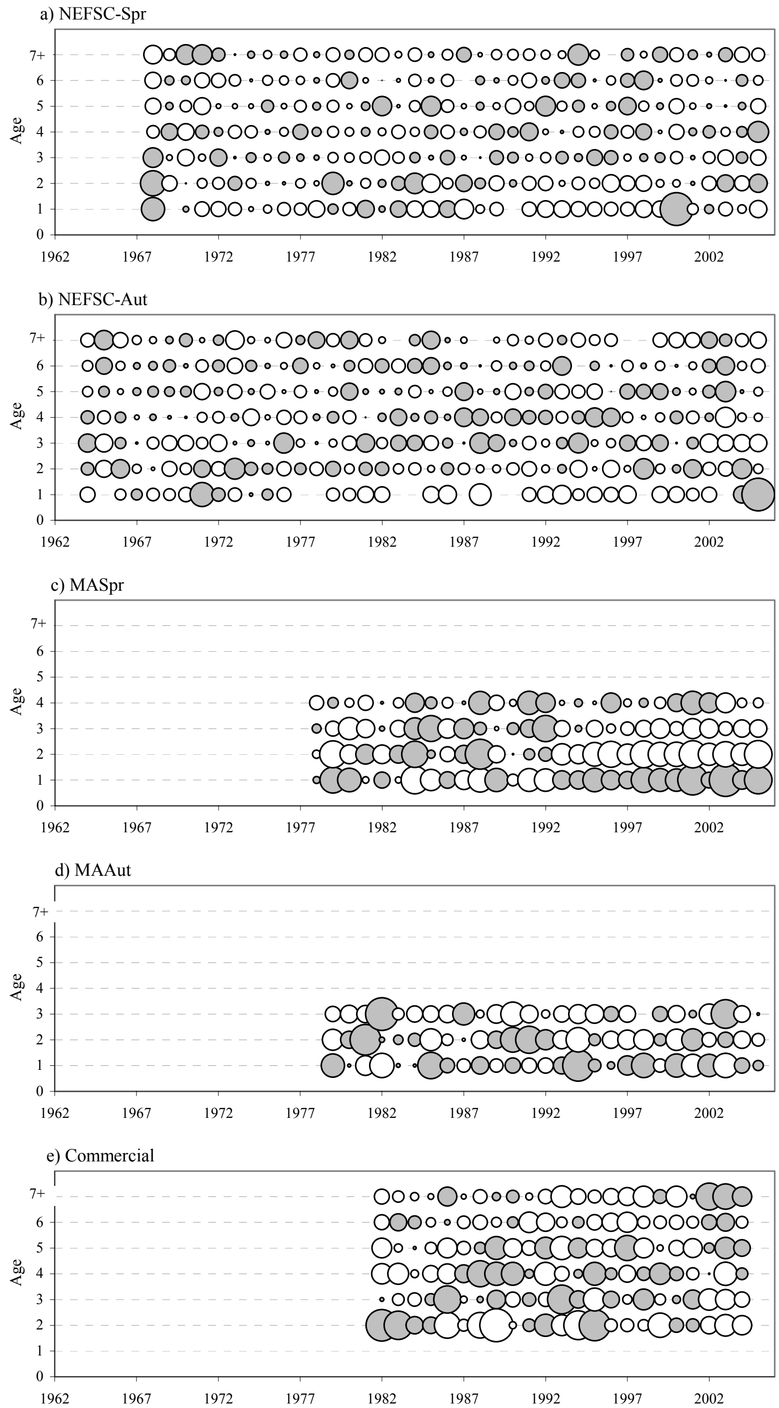

Fig. 4: Bubble plots of the standardised residuals for the catch-at-age data for the RC-ASPM assessment. The size (area) of the bubbles represents the size of the residuals. Grey bubbles represent positive residuals and white bubbles represent negative residuals.

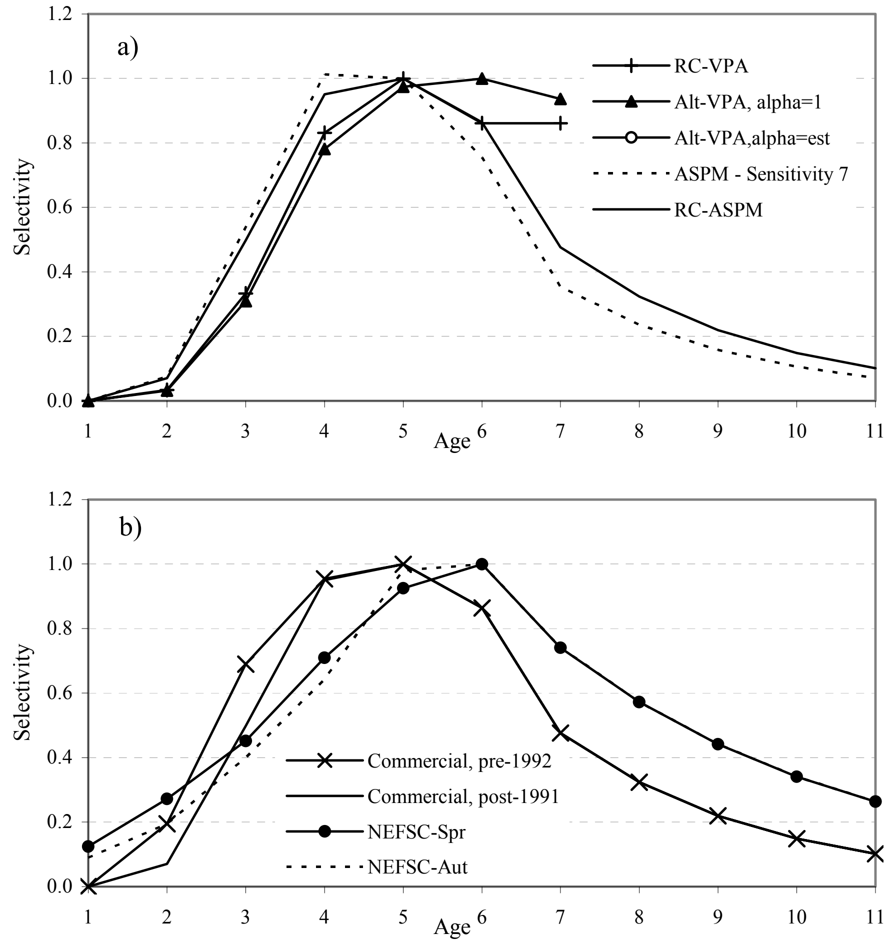

Fig. 5: a) Commercial selectivities-at-age (average over 1992-2004) for the ASPM Reference Case and Sensitivity 7 (RC except excludes pre-1982 index data), the VPA Reference Case (RC-VPA) and two of VPA sensitivities; b) commercial (pre-1992 and post-1991) and NEFSC survey selectivities-at-age for the ASPM Reference Case.

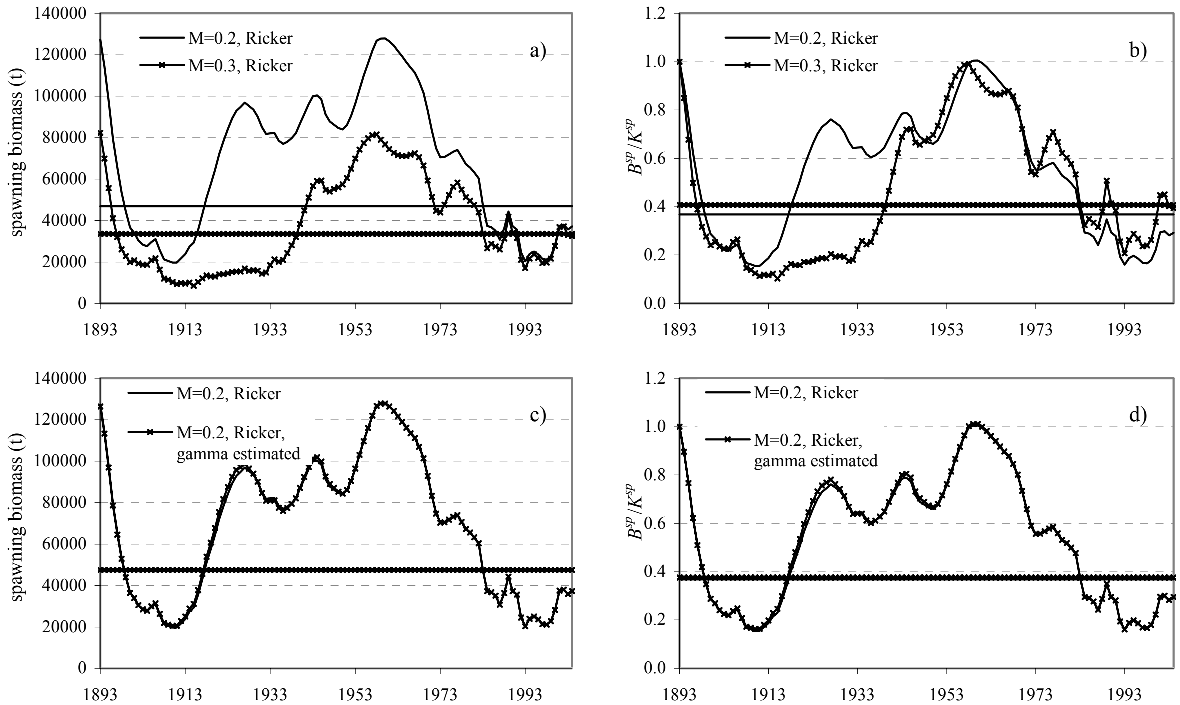

Fig. 6: Comparison of MLE ASPM spawning biomass trajectories (in absolute terms and in terms of pre-exploitation level) for Sensitivities 1 (RC-ASPM) and 2 (RC with M=0.3), and Sensitivities 1 and 3 (RC with γ estimated). The estimated B^{sp}_{MSY} and *MSYL* are also shown.

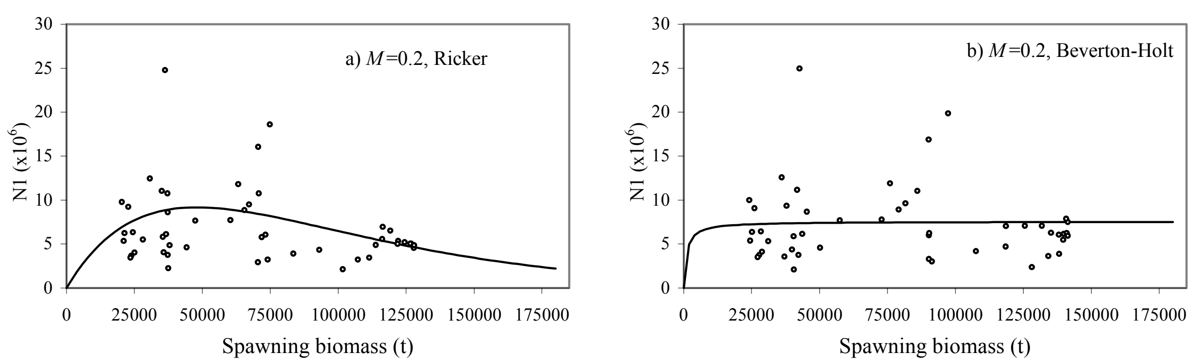

Fig. 7: The estimated stock-recruitment curve and estimated recruitments each year over the period 1956-2004 for a) RC-ASPM and b) Sensitivity 4 (RC with Beverton-Holt). (Fig. S2 shows results for further sensitivities.)

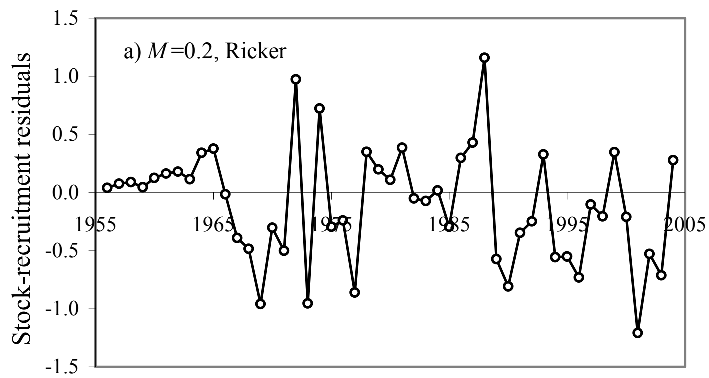

Fig. 8: Estimated stock-recruitment residuals (ς_y) for RC-ASPM.

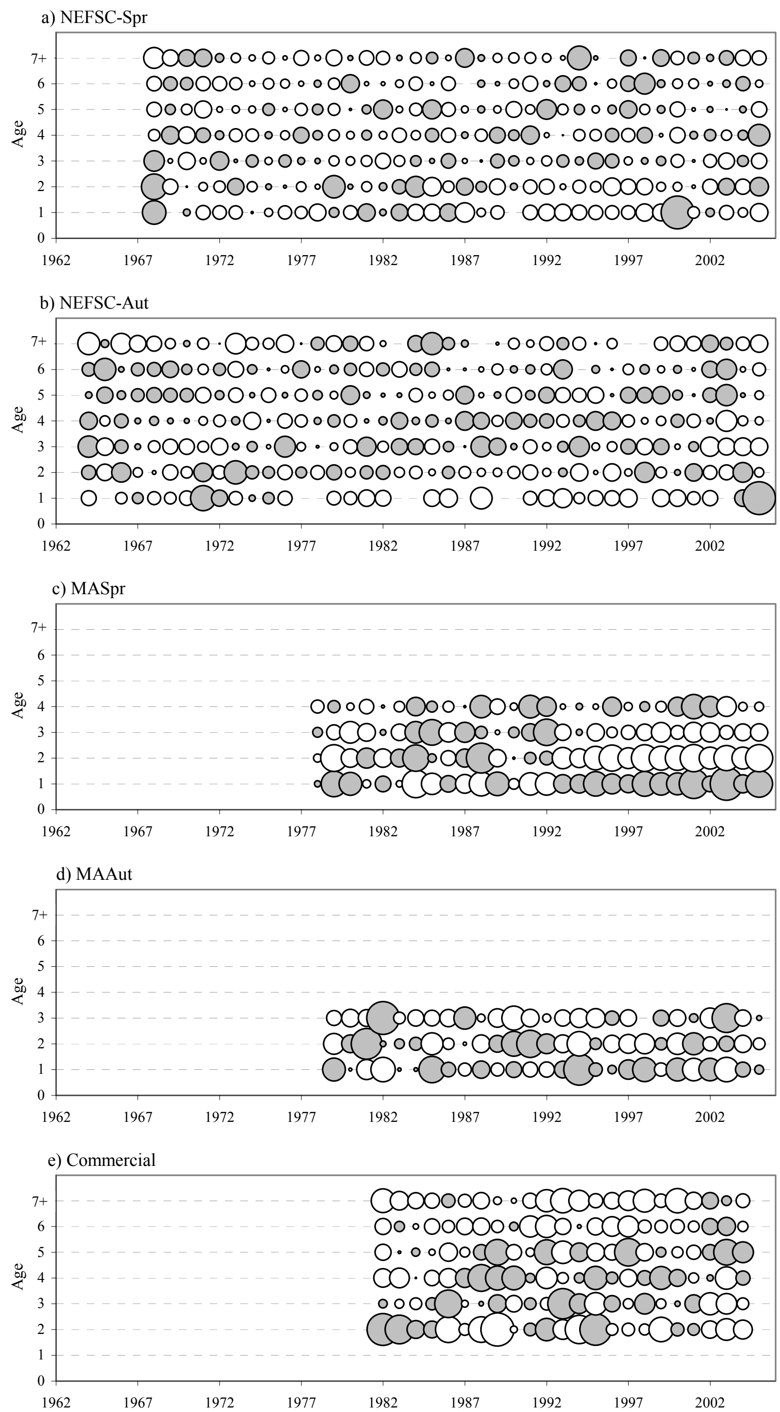

Fig. 9: Bubble plots of the standardised residuals for the catch-at-age data for ASPM Sensitivity 5 (flat commercial and NEFSC survey selectivity for age 5+) assessment. The size (area) of the bubbles represents the size of the residuals. Grey bubbles represent positive residuals and white bubbles represent negative residuals.

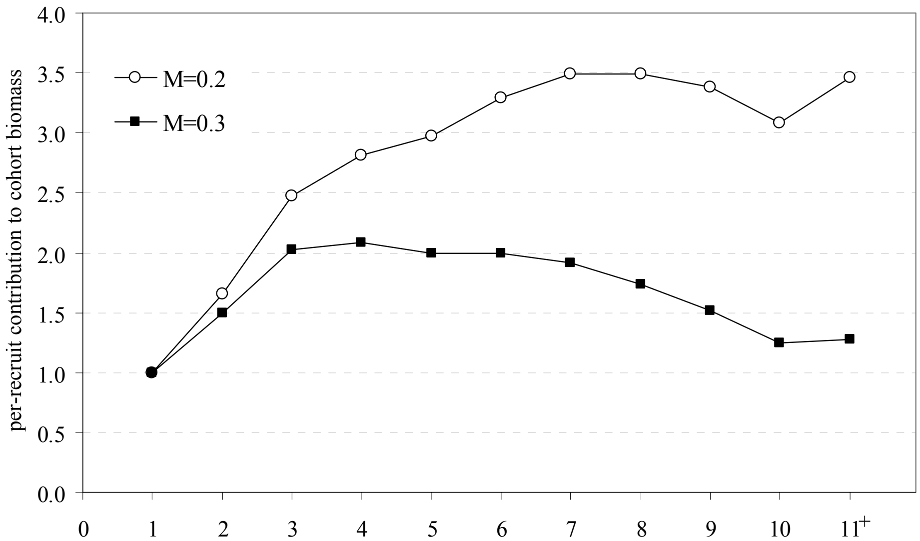

Fig. 10: Per-recruit contributions by age to cohort biomass, taking natural mortality and somatic growth into account and expressed relative to the age 1 contribution, for M=0.2 and M=0.3. Beginning of the year weights used are those for the last year available (2005). These contributions are evaluated as $w_{2005,a}^{strt} e^{[-(a-1)M]} \big/ w_{2005,1}^{strt}$.

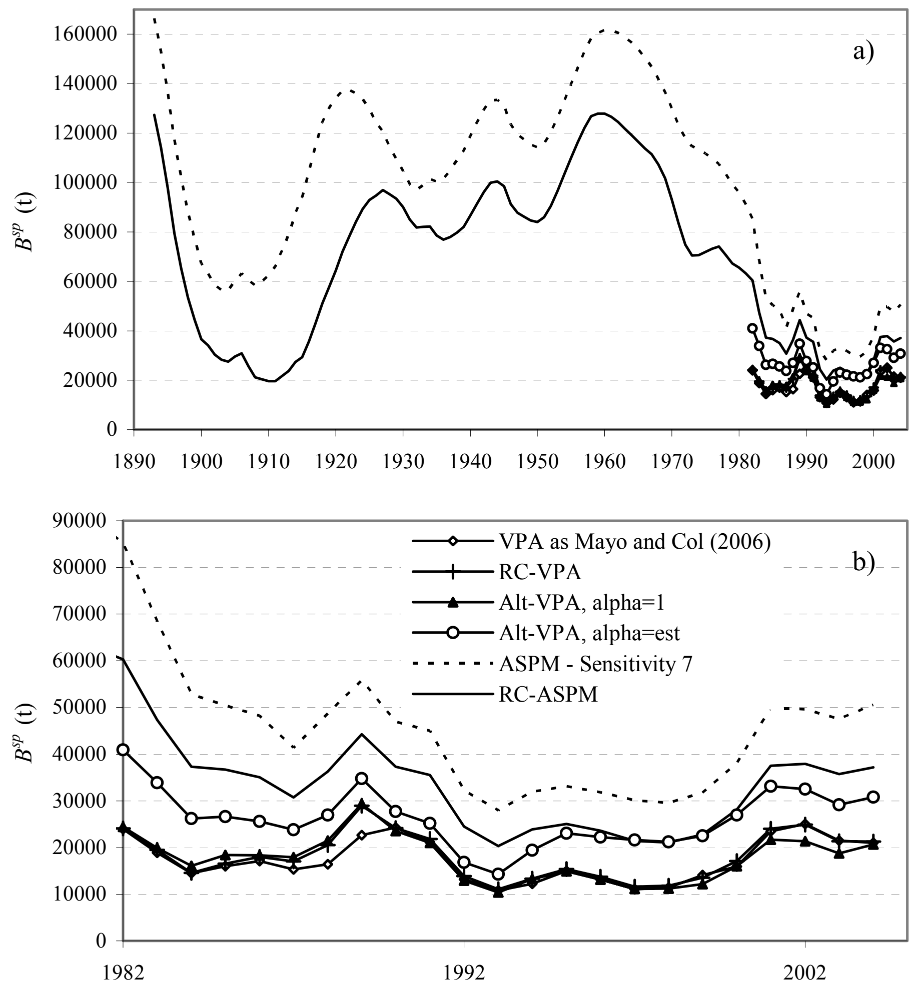

Fig. 11: Time-series of spawning biomass estimates for the VPA as in Mayo and Col (2006), the VPA Reference Case (RC-VPA) and two of VPA sensitivities, as well as for RC-ASPM and ASPM Sensitivity 7 (RC except excludes pre-1982 index data).

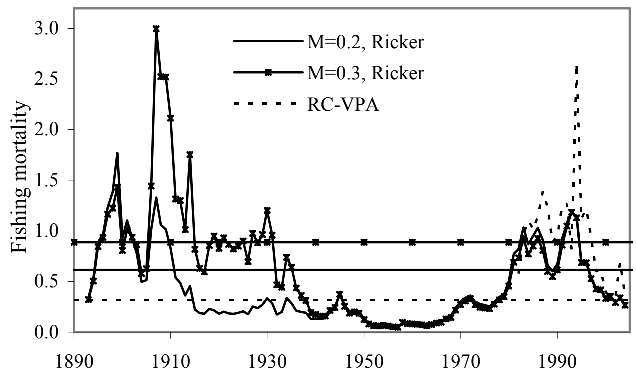

Fig. 12: Comparison of fully-selected fishing mortality trajectories for RC-ASPM and Sensitivity 2 (RC with M = 0.3) and the Reference Case VPA. Estimated F_{MSY} values are shown by the flat straight lines. (Fig. S1 shows results for further sensitivities.)

Appendix 1 - The ADAPT-VPA Model

Note that the specifications set out in the first partial section A.1.1 are not their most general form (see Anon. 2003), but rather as implemented for the Mayo and Col (2006) application to Gulf of Maine cod.

A1.1. Population Dynamics

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

$$N_{y,a} = N_{y+1,a+1}e^{M_a} + C_{y,a}e^{M_a/2} \qquad \text{for } 1 \le a \le m-2 \qquad \text{A1.1}$$

$$Z_{y,a} = \ell n\left(\frac{N_{y,a}}{N_{y+1,a+1}}\right) \qquad \text{A1.2}$$

$$F_{y,a} = Z_{y,a} - M_a \qquad \text{A1.3}$$

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 for 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 numbers of the oldest true age (*m*-1) and the plus-group (*m*) are computed as follows:

$$N_{y,a} = \frac{Z_{y,a}C_{y,a}}{F_{y,a}\left(1-e^{-Z_{y,a}}\right)} \qquad \text{for } a = m\text{-1 and } a = m \qquad \text{A1.4}$$

Fishing mortality on the oldest true age is defined as:

$$F_{y,m-1} = PR_{m-1}F_y^{full} \qquad \text{A1.5}$$

where

$F_y^{full} = \ln\left[\frac{\sum_{a\in R} N_{y,a}e^{-M_{y,a}}}{\sum_{a\in R} N_{y+1,a+1}}\right]$ 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:

$$F_{y,m} = \alpha F_{y,m-1} \qquad \text{A1.6}$$

where

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

In the RC-VPA, PR_{m-1} = 1 and α = 1; further the set of fully recruited age-classes in equation A1.5 is taken to be *R* = {4,5} where *m*=7 and $F_{y,m-1}$ set equal to F_y^{full} .

<u>Alternative approach (Alt-VPA)</u>

There is a problem with the overall approach above used to compute plus-group abundances. Essentially that approach 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 A1.4 for each year in conjunction with equation A1.6

to provide the plus-group abundance for that year. The difficulty with this is that plus-group abundance is governed by the equation:

$$N_{y+1,m} = \left(N_{y,m}e^{-M_m/2} - C_{y,m}\right)e^{-M_m/2} + \left(N_{y,m-1}e^{-M_{m-1}/2} - C_{y,m-1}\right)e^{-M_{m-1}/2} \quad \text{A1.7}$$

and results obtained from the combined application of equations A1.4 to A1.6 will not necessarily satisfy equation A1.7, because of the specification of potentially contradictory conditions. In other words, the overspecification of the approach above leads to incorrect estimates of plus-group abundance.

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 to be small. However, this is not necessarily the case in circumstances of lesser fishing mortality and particularly selectivity that declines with age at larger ages.

This problem can be rectified by replacing equation A1.4 by equation A1.7 together with the equations following:

$$Z_{y,m-1} = \ell n\left(\frac{N_{y,m-1}}{N_{y,m-1}e^{-M_{m-1}} - C_{y,m-1}e^{-M_{m-1}/2}}\right) \quad \text{A1.8}$$

and

$$F_{y,m-1} = Z_{y,m-1} - M_{y,m-1} \quad \text{A1.9}$$

and for $a=m$:

$$Z_{y,m} = \ell n\left(\frac{N_{y,m}}{N_{y,m}e^{-M_m} - C_{y,m}e^{-M_m/2}}\right) \quad \text{A1.10}$$

and

$$F_{y,m} = Z_{y,m} - M_{y,m} \quad \text{A1.11}$$

All VPA assessments of numbers-at-age $N_{y,a}$ were computed taking m=7.

A1.2. The Objective Function

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

Calculations assume that the observed abundance indices are log-normally distributed about their expected values:

$$I^i_{y,a} = \hat{I}^i_{y,a} \exp\left(\varepsilon^i_{y,a}\right) \quad \text{or} \quad \varepsilon^i_{y,a} = \ell\text{n}\left(I^i_{y,a}\right) - \ell\text{n}\left(\hat{I}^i_{y,a}\right) \qquad \text{A1.12}$$

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:

$$SS = \sum_{i,y,a} \left[\ell n\left(I^i_{y,a}\right) - \ell n\left(\hat{I}^i_{y,a}\right)\right]^2 \qquad \text{A1.13}$$

The function is minimised by treating the abundances for ages 2 to m-1 in year T+1 as estimable parameters, where T is the final year. These then define $F_{T,a}$ for a=1 to m-2, $F_{T,m-1}$ is obtained from equation A1.5, and $F_{T,m}$ from equation A1.6. Given $F_{T,m-1}$, $N_{T,m-1}$ follows from equation A1.4, and then for each year in sequence backwards $N_{T-1,m-2}$ and $F_{T-1,m-2}$ are calculated, with $F_{T-1,m-1}$ and $F_{T-1,m}$ following from equations A1.5 and A1.6 as in the preceding sentence.

Alternative approach (Alt-VPA)

With this approach, the $N_{y,m}$ are estimated directly for each year to year T and a penalty is added to the objective function so that equation A1.7 is satisfied:

$$P_1 = \sum_y \left[\ln\left(N_{y,m}\right) - \ln\left(\hat{N}_{y,m}\right)\right]^2 \Big/ 2\sigma_{plus}^2 \qquad \text{A1.14}$$

where

$$\hat{N}_{y,m} = N_{y-1,m-1}e^{-M_{m-1}} - C_{y-1,m-1}e^{-M_{m-1}/2} + N_{y-1,m}e^{-M_m} - C_{y-1,m}e^{-M_m/2}$$

and σ_{plus} is set sufficiently small to ensure the equality required.

A further penalty is added so that equation A1.6 is satisfied:

$$P_2 = \sum_y \left[\ln\left(F_{y,m}\right) - \ln\left(\hat{F}_{y,m}\right)\right]^2 \Big/ 2\sigma_F^2 \qquad \text{A1.15}$$

where

$$\hat{F}_{y,m} = \alpha F_{y,m-1} \ . \qquad \text{A1.16}$$

and σ_F is set small in the same way as σ_{plus}.

While the process for solving for $N_{y,m}$ and $F_{y.m}$ could be taken sequentially back in time in one year steps as for the previous approach, this becomes more complicated here as each time the solution to two simultaneous non-linear equations is required; thus the minimisation process immediately above is easier to implement.

In implementation, however, it was found that setting σ_F very small (i.e. forcing the equality of equation A1.16) could lead to unstable estimation behaviour. This arises because of the very small numbers of plus group fish estimated to be caught in some years (see Table SD.5). More robust behaviour was achieved by allowing some variability about the relationship of equation A1.16 by not setting σ_F too small; results presented in this paper set σ_F=0.35. Thus the relationship of equation A1.16 is achieved in an "average" sense, rather than exactly each year.

A1.3. Calculation of MSY

If the years with catch-at-age data considered in the VPA are $y=1$ to T, then the computations above provide a matrix of numbers-at-age estimates, $\{N_{y,a} : y=1,...T; a=1,...m\}$. These in turn provide a series of spawning stock-recruitment pairs $\{(B_y^{sp}, N_{y+1,1}) : y=1,...T-1\}$ where

$$B_y^{sp} = \sum_a f_{y,a} w_{y,a}^{strt} N_{y,a} e^{-(M_a+F_{y,a})/6} \qquad \text{A1.17}$$

where the formulation of this equation is to allow for cod spawning two months after the start of the year, and

$w_{y,a}^{strt}$ 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.

A stock recruit function with estimable parameters $\underset{\sim}{p} : R_y = f\left(\underset{\sim}{p}, B_y^{sp}\right)$ is then fit to these estimates by minimising:

$$SS = \sum_{y=1}^{T-1}\left[\ln\left(N_{y+1,1}\right) - \ln\left(f\left(\underset{\sim}{p}, B_y^{sp}\right)\right)\right]^2 \qquad \text{A1.18}$$

to obtain estimates of the parameters $\underset{\sim}{p}$.

The equilibrium catch for a fully selected fishing proportion F^* is then calculated as:

$$C\left(F^*\right) = \sum_a w_a^{mid} PR_a F^* N_a\left(F^*\right)e^{-(M_a/2)} \qquad \text{A1.19}$$

where numbers-at-age *a* are given by:

$$N_a\left(F^*\right)=\begin{cases} R_1 & \text{for } a=1 \\ N_{a-1}\left(F^*\right)e^{-M_{a-1}}\left(1-PR_{a-1}F^*\right) & \text{for } 1<a<m \\ \dfrac{N_{m-1}\left(F^*\right)e^{-M_{m-1}}\left(1-PR_{m-1}F^*\right)}{\left(1-e^{-M_m}\left(1-PR_mF^*\right)\right)} & \text{for } a=m \end{cases} \qquad \text{A1.20}$$

where

$$R_1=\frac{\alpha B^{sp}\left(F^*\right)}{\beta+B^{sp}\left(F^*\right)} \qquad \text{A1.21}$$

for a Beverton-Holt stock-recruitment relationship

or

$$R_1=\alpha B^{sp}\left(F^*\right)e^{-\beta\left[B^{sp}\left(F^*\right)\right]^{\gamma}} \qquad \text{A1.22}$$

for a modified Ricker stock-recruitment relationship, where the Ricker form results when fixing $\gamma=1$.

The maximum of $C\left(F^*\right)$ is then found by searching over $F*$ to give F^*_{MSY}, with the associated spawning biomass and yield given by

$$B^{sp}_{MSY}=\sum_a f_a w_a^{strt} N_a\left(F^*_{MSY}\right)e^{-M_a/6}\left(1-PR_aF^*_{MSY}/6\right) \qquad \text{A1.23}$$

$$MSY=\sum_a w_a^{mid} PR_a F^*_{MSY} N_a\left(F^*_{MSY}\right)e^{-(M_a/2)} \qquad \text{A1.24}$$

In application (for both VPA and ASPM), the maturity- (f_a) and begin-year weight-at-age (w_a^{strt}) vectors are taken as those for the last year available. The mid-year weight-at-age vector (w_a^{mid}) is taken as the average over the period with data available (1982-2004) and the partial recruitment (PR_a, equivalently selectivity S_a – see Appendix 2) is computed as:

$$PR_a = \frac{\sum_{y=1992}^{2004} F_{y,a} \Big/ 13}{\max\left(\sum_{y=1992}^{2004} F_{y,a} \Big/ 13 \right)} \qquad \text{A1.25}$$

The relationship between the fishing proportion F^* and fishing mortality F is given by:

$$F = -\ln\left(1 - F^*\right) \qquad \text{A1.26}$$

In these calculations, the plus-group is taken as 11+.

Appendix 2 - The Age-Structured Production Model

The model used for these assessments is an Age-Structured Production Model (ASPM) (e.g. Hilborn, 1990). Models of this type fall within the more general class of 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 (penalised) log-likelihood function from the different sources of data available and assumptions concerning the stock-recruitment relationship. Quasi-Newton minimization is used to minimize the total negative log-likelihood function (the package AD Model Builder™, 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 for 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. 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 groundfish 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 Ricker stock-recruitment relationship (Beverton and Holt, 1957), allowing for annual fluctuation about the deterministic relationship:

$$R_y = \alpha B_{y-1}^{sp} \exp\left[-\beta\left(B_{y-1}^{sp}\right)^{\gamma}\right] e^{(\varsigma_y - (\sigma_R)^2/2)} \qquad \text{A2.4}$$

where

α, β and γ are spawning biomass-recruitment relationship parameters,

ς_y reflects fluctuation about the expected recruitment for year y, which is assumed to be normally distributed with standard deviation σ_R (which is input in the applications considered here); these residuals are treated as estimable parameters in the model fitting process. 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_y^{sp} is the spawning biomass at the start of year y, computed as:

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

because spawning for the cod stocks under consideration is taken to occur two 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_y^{sp} in year *y*-1 to account for the fact that recruitment here refers to 1-year-old fish),

where

$w_{y,a}^{strt}$ 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:

In the fitting procedure, both *h* and K^{sp} are estimated with γ being either fixed on input or estimated as well. 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.

For sensitivities where the Beverton-Holt form is used:

$$R_y = \frac{\alpha B_{y-1}^{sp}}{\beta + B_{y-1}^{sp}} e^{(\varsigma_y - (\sigma_R)^2/2)} \qquad \text{A2.6}$$

Note: In the Beverton-Holt form, the steepness parameter *h* is constrained not to exceed 0.98.

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

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

$$C_y = \sum_{a=1}^{m} w_{y,a}^{mid}\ C_{y,a} = \sum_{a=1}^{m} w_{y,a}^{mid}\ N_{y,a}\ e^{-M_a/2}\ S_{y,a}\ F_y^* \qquad \text{A2.7}$$

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. combination of availability and 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 proportion of a fully selected age class that is fished.

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:

$$B_y^{ex} = \sum_{a=1}^{m} w_{y,a}^{mid} S_{y,a} N_{y,a} e^{-M_a/2}(1 - S_{y,a} F_y^* / 2) \qquad \text{A2.8}$$

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):

$$B_y^{surv} = \sum_{a=1}^{m} w_{y,a}^{strt} S_a^{surv} N_{y,a} \qquad \text{A2.9}$$

where

S_a^{surv} is the survey selectivity for age a, which is taken to be year-independent given that the design of NEFSC offshore trawl surveys has deliberately been maintained unchanged over time.

A2.1.4. Initial conditions

As the first year for which data (even annual catch data) are available for the cod stock considered 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.:

$$B^{sp}_{y_0} = \theta \cdot K^{sp} \qquad \text{A2.10}$$

with the starting age structure:

$$N_{y_0,a} = R_{start} N_{start,a} \qquad \text{for } 1 \le a \le m \qquad \text{A2.11}$$

where

$$N_{start,1} = 1 \qquad \text{A2.12}$$

$$N_{start,a} = N_{start,a-1} e^{-M_{a-1}} (1 - \phi S_{a-1}) \qquad \text{for } 2 \le a \le m-1 \qquad \text{A2.13}$$

$$N_{start,m} = N_{start,m-1} e^{-M_{m-1}} (1 - \phi S_{m-1}) \Big/ (1 - e^{-M_m} (1 - \phi S_m)) \qquad \text{A2.14}$$

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

A2.2. The (penalised) likelihood function

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

$$I_y^i = \hat{I}_y^i \exp\left(\varepsilon_y^i\right) \quad \text{or} \quad \varepsilon_y^i = \ell n\left(I_y^i\right) - \ell n\left(\hat{I}_y^i\right) \tag{A2.15}$$

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 $\widehat{B}_y^{ex}$ is the model estimate of exploitable resource biomass, given by equation A2.8,

$\hat{q}^i$ 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:

$$-\ell n L^{CPUE} = \sum_i \sum_y \left[\ell n\left(\sigma_y^i\right) + \left(\varepsilon_y^i\right)^2 / 2\left(\sigma_y^i\right)^2\right] \tag{A2.16}$$

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:

$$\hat{\sigma}^i = \sqrt{1/n_i \sum_y \left(\ell n(I_y^i) - \ell n(q^i \widehat{B}_y^{ex})\right)^2} \tag{A2.17}$$

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:

$$\ell n\, \hat{q}^i = 1/n_i \sum_y \left(\ln I_y^i - \ln \hat{B}_y^{ex}\right) \qquad \text{A2.18}$$

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:

$$-\ell \text{n} L^{CAA} = \sum_y \sum_a \left[\ell n\left(\sigma_{com} / \sqrt{p_{y,a}}\right) + p_{y,a}\left(\ell n\, p_{y,a} - \ell n\, \hat{p}_{y,a}\right)^2 / 2\left(\sigma_{com}\right)^2 \right] \qquad \text{A2.19}$$

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

$$\hat{C}_{y,a} = N_{y,a}\, e^{-M_a/2}\, S_{y,a}\, F_y \qquad \text{A2.20}$$

and

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

$$\hat{\sigma}_{com} = \sqrt{\sum_y \sum_a p_{y,a} \left(\ell n\, p_{y,a} - \ell n\, \hat{p}_{y,a}\right)^2 / \sum_y \sum_a 1} \qquad \text{A2.21}$$

The log-normal error distribution underlying equation A2.19 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 A2.19) 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 A2.19, for which the summation over age a is taken from age a_{minus} (considered as a minus group) to a_{plus} (a plus group).

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 A2.19) where:

$p_{y,a} = C^{surv}_{y,a} / \sum_{a'} C^{surv}_{y,a'}$ 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:

$$\hat{p}_{y,a} = S^{surv}_a N_{y,a} \Bigg/ \sum_{a'=0}^{m} S^{surv}_a N_{y,a} \qquad \text{for begin-year surveys.} \qquad \text{A2.22}$$

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:

$$-\ell nL^{pen} = \sum_{y=y1+1}^{y2}\left[\left(\frac{\lambda_y - \rho\lambda_{y-1}}{\sqrt{1-\rho^2}}\right)^2 \Big/ 2\sigma_R^2\right] \qquad \text{A2.23}$$

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 $y1$ to $y2$ (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 A2.23 omits a term in λ_{y1} for the sensitivity 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 $\rho = 0$. The years y_1 and y_2 are chosen to include periods to which age data relate and hence provide some information on the recruitment residuals.

A2.3. Estimation of precision

Where quoted, 95% probability interval estimates have been evaluated by treating this methodologically as a Bayesian estimation and using MCMC to compute posterior distributions. The contribution from equation A2.22 then corresponds to a prior on the distribution of the recruitment residual for each year. Other priors on the parameters (K^{sp}, h, M, γ and the selectivity parameters) are taken to be uniform over wide and/or feasible ranges with the intent that they be uninformative.

The estimated q for the survey abundance and CPUE series, and σ for these and the proportion-at-age data, are not integrated over priors. This corresponds to the assumption that these priors are uniform in log-space and proportional to σ^{-3} respectively (Walters and Ludwig, 1994).

A2.4. Model parameters

A2.4.1. Fishing selectivity-at-age:

The commercial fishing selectivity, S_a, as well as the fishing selectivities for the NEFSC offshore spring and autumn surveys, S_a^{NEFSC}, are estimated separately for ages 1-7. The estimated decrease from ages 6 to 7 is assumed to continue exponentially to age 11+.

In ASPM Sensitivities 6 and 12, the selectivities for the NEFSC surveys are assumed to be linear to age 7 and flat over ages 7 and above. S_1^{NEFSC} is estimated separately for each survey:

$$S_a^{NEFSC} = \begin{cases} (a-1)\left(\dfrac{1-S_1^{NEFSC}}{6}\right) + S_1^{NEFSC} & \text{for } 1 \le a \le 6 \\ 1 & \text{for } a \ge 7 \end{cases} \qquad \text{A2.24}$$

The commercial selectivity is taken to differ over the 1893-1991 and 1992+ periods. The decrease from ages 6 to 7 however is taken to be the same throughout the period. 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.

Selectivity is taken to differ for the NEFSC offshore spring and autumn surveys, but the decrease from ages 6 to 7 is taken to be the same for both surveys.

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

$$S_a^{MA} = \exp\left(-\gamma^{MA}(a-1)\right) \qquad \text{A2.25}$$

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.

A2.4.2. Other parameters

Plus-group:	
m	11
Commercial CAA:	
a_{minus}	2
a_{plus}	7
Stock-recruitment residuals:	
ρ	0, i.e. no serial correlation
σ_R	0.4
y_1	1956
y_2	2004
Natural mortality:	
M	age independent, fixed or estimated
Age-at-maturity:	
$f_{y,a}$	input, see Table S1.1
Weight-at-age:	
$w_{y,a}^{sp}$	input, see Table S1.3
$w_{y,a}^{landed}$	input, see Table S1.5
Initial conditions (unless otherwise specified):	
θ	1
ϕ	0

A2.5. Calculation of MSY

The calculation of *MSY*, F_{MSY} and B_{MSY} is as specified in Appendix 1, section A.1.3.

SUPPLEMENTARY MATERIAL

Table S1: Penalised maximum likelihood estimates of key management quantities for the ASPM Reference Case and 10 sensitivities. Biomass units are thousand tons. The estimates given for quantities such as B^{sp}_{MSY} refer to the commercial selectivity function from 1992+ and $MSYL = B^{sp}_{MSY} / K^{sp}$. Values shown in bold are fixed on input. Negative log-likelihoods are shown in parenthesis when not comparable to that for the RC-ASPM because of data differences. See Appendix 2, section A2.4.1 for the specifications of ASPM Sensitivity 12.

	1) Reference Case	9) M=0.3, Ricker, γ estimated	10) Alternative earlier commercial selectivity (pre-1982 = post-1991)	11) Alt. earlier comm. sel.: pre-1982, S_1=0, S_2=0.35, S_3=0.85 and S_4=1.0	12) Linear selectivity for survey, M estimated	13) Exclude pre-1982 index data, M estimated, Ricker
'-lnL:overall	-46.3	-49.0	-30.6	-56.5	-8.2	(-13.8)
M	**0.20**	**0.30**	**0.20**	**0.20**	0.31	0.29
h	1.67	0.75	1.66	1.70	1.52	1.12
γ	**1.00**	1.39	**1.00**	**1.00**	**1.00**	**1.00**
K^{sp}	127.3	78.1	125.8	128.7	73.0	114.6
B^{sp}_{2004}	37.1	33.5	36.3	37.3	31.7	42.6
B^{sp}_{2004}/K^{sp}	0.29	0.43	0.29	0.29	0.43	0.37
B^{sp}_{MSY}	46.9	35.2	46.1	47.3	30.6	46.0
$B^{sp}_{2004}/B^{sp}_{MSY}$	0.79	0.95	0.79	0.79	1.04	0.93
$MSYL$	0.37	0.45	0.37	0.37	0.42	0.40
MSY	13.4	13.6	13.0	13.8	12.7	13.9
F_{MSY}	0.62	0.91	0.58	0.63	1.06	0.64
F_{2004}	0.26	0.26	0.26	0.26	0.25	0.22

	14) Exclude pre-1982 index data, M estimated, Beverton-Holt	15) σ_R=0.5	16) Start in 1982, θ=1 and ϕ=0	17) Start in 1982, θ=0.3 and ϕ=0.4	18) Start in 1893, θ=0.3 and ϕ=0.4
'-lnL:overall	(-11.7)	(-62.2)	(10.0)	(2.4)	-45.5
M	0.36	**0.20**	**0.20**	**0.20**	**0.20**
h	0.86	1.94	0.76	2.37	1.62
γ	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**
K^{sp}	128.5	115.8	367.7	153.3	135.6
B^{sp}_{2004}	42.1	32.7	200.8	42.8	39.0
B^{sp}_{2004}/K^{sp}	0.33	0.28	0.55	0.28	0.29
B^{sp}_{MSY}	35.3	42.2	142.8	56.1	49.9
$B^{sp}_{2004}/B^{sp}_{MSY}$	1.19	0.77	1.41	0.76	0.78
$MSYL$	0.27	0.36	0.39	0.37	0.37
MSY	13.0	13.9	14.3	14.5	13.9
F_{MSY}	0.92	0.70	0.28	0.56	0.59
F_{2004}	0.22	0.29	0.10	0.22	0.24

Table S2: Objective function contributions for each abundance index for various sensitivities on the VPA assessments contrasted to those of the Reference Case VPA.). See equation A1.15 for details of the penalty term P_2.

	RC-VPA	Alt-VPA, α=1	Alt-VPA, α=est
NEFSC-Spr2	13.29	13.49	14.20
NEFSC-Spr3	5.48	5.71	5.30
NEFSC-Spr4	4.11	4.24	3.80
NEFSC-Spr5	8.43	8.61	6.75
NEFSC-Spr6	15.38	17.34	9.30
NEFSC-Spr7+	(25.85)	25.42	15.32
NEFSC-Aut2	8.94	9.09	9.71
NEFSC-Aut3	8.53	8.23	8.52
NEFSC-Aut4	6.14	5.73	6.34
NEFSC-Aut5	9.42	9.47	9.92
NEFSC-Aut6	7.77	6.98	9.43
NEFSC-Aut7+	(14.29)	13.31	17.79
MASpr2	7.83	7.69	8.38
MASpr3	5.04	5.21	5.31
MASpr4	11.00	11.90	11.13
MAAut2	51.94	51.48	51.57
LPUE3	1.87	1.79	1.75
LPUE4	0.44	0.44	0.39
LPUE5	0.28	0.38	0.41
LPUE6	0.12	1.55	1.18
Total SS (less 7+)	166.01	169.33	163.36
Total SS	206.16	208.06	196.46
Peanlty P_2		4.09	9.36

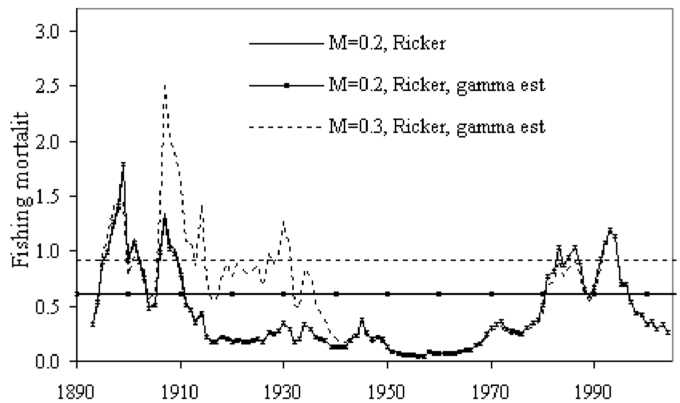

Fig S1: Comparison of fully-selected fishing mortality trajectories for RC-ASPM and Sensitivity 3 (RC with γ estimated) and Sensitivity 9 (RC with M=0.3 and γ estimated). Estimated F_{MSY} values are shown by the flat straight lines.

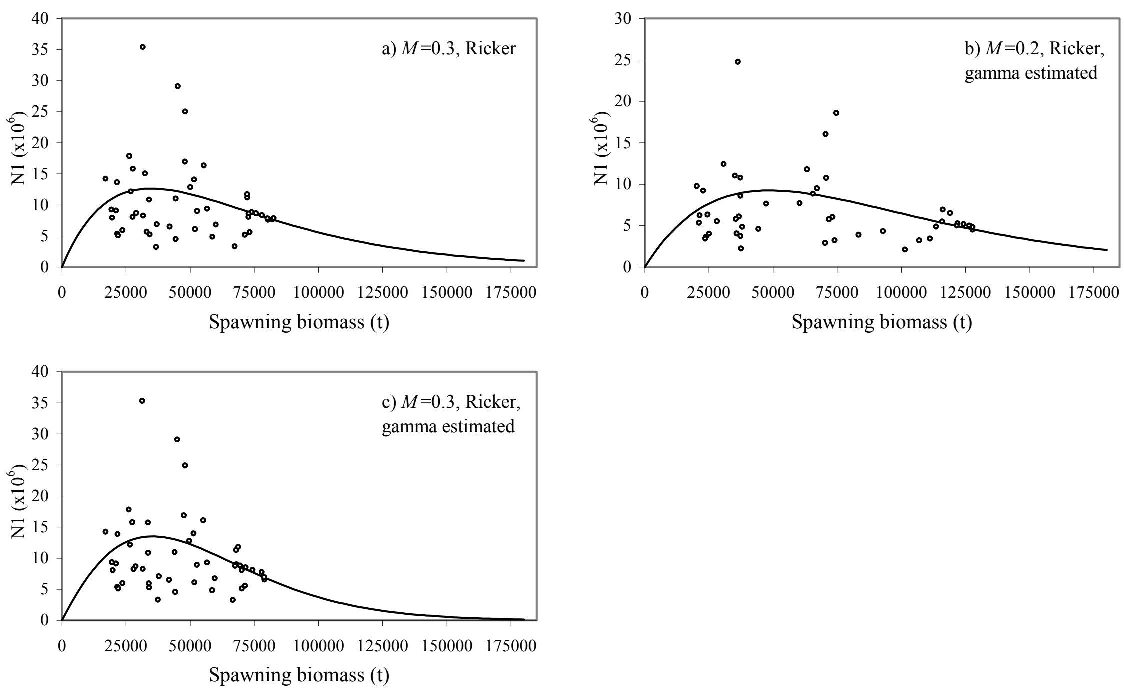

Fig. S2: The estimated stock-recruitment curve and estimated recruitments each year over the period 1956-2004 for a) Sensitivity 2 (RC with M=0.3), b) Sensitivity 3 (RC with γ estimated) and c) Sensitivity 9 (RC with M=0.3 and γ estimated).

The Data Used

The data used for the ADAPT-VPA and the ASPM Reference Case assessments, and their sensitivities, that are developed in this paper are as reported in Mayo and Col (2006).

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

The total annual catch (in metric tons) is given in Table SD.2 for the period 1893-2004.

Begin-year weights-at-age (to age 11+) used in the ASPM assessments are derived from commercial landings (only) mean weight-at-age data and are given in Table SD.3, while the corresponding mid-year weights-at-age are given in Table SD.4. In the ASPM assessment, for years prior to 1982, the weight-at-age vectors are taken to be the average over the full period available (1982-2005 for begin-year and 1982-2004 for mid-year weight-at-age).

Total (commercial and recreational) landings-at-age (in thousands of fish) for the period 1982-2004 are given in Table SD.5.

Begin-year weights-at-age (to 7+) used in the Mayo and Col (2006) VPA assessments are derived from commercial and recreational landings mean weight-at-age data and are given in Table SD.6, while the corresponding mid-year weights-at-age are given in Table SD.7.

In the ASPM assessments, the model is fit to the full catch-at-age matrix (expressed as proportions) for each index, as well as the biomass indices.

The ASPM assessments are taken to age 11+ because of the importance of allowing for dynamics within the older fish to the greatest extent possible. However, since mean weights-at-age data is not available for commercial and recreational landings up to age 11+, weights for commercial catches only (Tables SD.3 and SD.4) had to be used.

Once cannot however use commercial only weights in conjunction with landings-at-age data of Table SD.5 in VPA assessments intended to be comparable with ASPM assessments, as the latter estimate landings-at-age ($C_{y,a}$) consistent with the relationship:

$$C_y = \sum_a w_{y,a}^{mid,C} \hat{C}_{y,a} \qquad \text{S1.1}$$

where

C_y is the total landings in year y (Table SD.2), and

$w_{y,a}^{mid,C}$ the mid-year commercial weight-at-age in year y (Table SD.4).

whereas in contrast, the Mayo and Col (2006) assessments respect the relationship:

$$C_y = \sum_a w_{y,a}^{mid,C+R} C_{y,a} \qquad \text{SD.2}$$

where

$w_{y,a}^{mid,C+R}$ is the mid-year commercial plus recreational weight-at-age in year y (Table SD.7), and

$C_{y,a}$ is the landings-at-age in year y (Table S1.5).

For comparability in terms of annual total catch (by mass) then, if the commercial weight-at-age data $w_{y,a}^{mid,C}$ are used instead of $w_{y,a}^{mid,C+R}$ in the VPA-based assessments, the $C_{y,a}$ data need to be rescaled so that the relationship in equation S1.2 is preserved, i.e.:

$$C_{y,a} \rightarrow C_{y,a}^* = C_{y,a} \left[\sum_a w_{y,a}^{mid,C+R} C_{y,a} \Big/ \sum_a w_{y,a}^{mid,C} C_{y,a} \right] \qquad \text{S1.3}$$

The resultant adjusted landings-at-age data ($C^*_{y,a}$) used in the new VPA analyses of this paper are shown in Table SD.8.

These new VPA analyses require $w^{strt,C}_{y,7+}$ and $w^{mid,C}_{y,7+}$ values in addition to the values for ages *a*=1 to 6 in Tables SD.3 and SD.4. $w^{mid,C}_{y,7+}$ were taken as given in Mayo and Col (2006, Table 9b). For the begin-year weights-at-age, the plus-group weight was computed as:

$$w^{strt,C}_{y,7+} = w^{strt,C}_{y,7}\left(\frac{w^{mid,C}_{y,7}}{w^{mid,C}_{y,7+}}\right) \qquad \text{S1.4}$$

The resultant sets of 7+ weights by year are listed in Table SD.9.

Data from the surveys, including catch-at-age and biomass indices, are shown in Tables SD.10 and SD.11 for the NEFSC offshore spring (NEFSC-Spr) and autumn (NEFSC-Aut) research vessel bottom trawl surveys and in Tables SD.12 and SD.13 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 are shown in Table SD.14.

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

REFERENCES

Rivard, D. 1980. APL programs for stock assessment. *Can. Tech. Rep. Fish. Aquat. Sci*. 953:103 p.

Table SD.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
2002	0.04	0.38	0.89	0.99	1.00	1.00	1.00
2003	0.04	0.38	0.89	0.99	1.00	1.00	1.00
2004	0.04	0.38	0.89	0.99	1.00	1.00	1.00

Table SD.2: Total catch (incl. USA, DWF and recreational landings, and discards) (thousand metric tons) of Atlantic cod from the Gulf of Maine (NAFO Division 5Y), 1893-2004.

Year	Total catch	Year	Total catch	Year	Total catch
1893	13.179	1931	9.265	1969	8.484
1894	15.539	1932	5.858	1970	8.684
1895	17.256	1933	7.025	1971	7.662
1896	13.339	1934	11.619	1972	6.917
1897	12.763	1935	9.679	1973	6.146
1898	12.269	1936	7.442	1974	7.764
1899	13.420	1937	7.432	1975	9.015
1900	9.448	1938	7.547	1976	10.188
1901	12.572	1939	5.504	1977	12.426
1902	11.660	1940	5.836	1978	12.426
1903	10.895	1941	6.124	1979	11.680
1904	8.447	1942	6.679	1980	13.528
1905	10.092	1943	9.397	1981	18.083
1906	17.137	1944	10.516	1982	16.279
1907	15.706	1945	14.532	1983	15.921
1908	11.226	1946	9.248	1984	12.169
1909	11.025	1947	6.916	1985	12.549
1910	9.670	1948	7.462	1986	12.512
1911	7.344	1949	7.033	1987	10.976
1912	7.770	1950	5.062	1988	9.902
1913	6.698	1951	3.567	1989	12.575
1914	9.120	1952	3.011	1990	17.391
1915	5.130	1953	3.121	1991	20.601
1916	5.221	1954	3.411	1992	11.793
1917	5.928	1955	3.171	1993	9.675
1918	8.281	1956	2.693	1994	9.020
1919	8.324	1957	2.562	1995	7.894
1920	7.599	1958	4.670	1996	7.951
1921	8.905	1959	3.795	1997	5.790
1922	8.572	1960	3.577	1998	4.780
1923	8.475	1961	3.234	1999	5.008
1924	9.070	1962	3.072	2000	6.025
1925	9.538	1963	2.731	2001	8.019
1926	8.047	1964	3.251	2002	7.195
1927	10.931	1965	3.928	2003	7.406
1928	9.655	1966	4.392	2004	5.398
1929	10.288	1967	5.973		
1930	11.489	1968	6.421		

Table SD.3: Mean weight-at-age (kg) at the beginning of the year for the Gulf of Maine cod stock. Values derived from commercial landings mean weight-at-age data (mid-year) using procedures described by Rivard (1980).

	1	2	3	4	5	6	7	8	9	10	11+
1982	0.665	0.965	1.364	2.364	4.267	7.259	8.246	9.853	14.071	11.714	18.456
1983	0.672	0.966	1.385	2.029	3.232	5.333	6.256	9.701	10.010	11.867	17.813
1984	0.403	0.967	1.394	2.125	3.017	4.720	6.957	7.465	11.646	11.864	15.028
1985	0.634	0.862	1.423	2.178	3.486	4.507	6.826	9.544	10.468	13.135	14.523
1986	0.632	1.025	1.521	2.259	3.622	5.205	6.509	8.902	11.824	12.141	16.554
1987	0.926	1.029	1.482	2.456	3.758	5.614	7.339	8.767	11.745	13.553	14.596
1988	0.648	1.142	1.572	2.021	4.118	5.718	8.233	9.939	12.245	14.723	20.356
1989	0.699	1.003	1.501	2.373	3.062	5.017	7.919	10.889	12.835	16.499	21.521
1990	0.681	0.929	1.453	2.008	3.573	5.435	7.232	10.439	13.388	14.795	20.295
1991	0.584	0.954	1.296	2.062	3.065	5.583	8.586	11.501	13.520	19.112	21.885
1992	0.636	1.112	1.474	2.063	2.773	4.548	8.362	10.962	12.873	16.080	18.170
1993	0.601	1.021	1.702	2.198	3.438	4.347	7.071	11.518	14.786	14.469	18.170
1994	0.563	1.081	1.585	2.440	2.942	5.168	7.168	11.237	12.929	19.436	19.369
1995	0.557	1.154	1.669	2.322	4.025	5.343	8.121	10.366	14.405	16.099	18.170
1996	0.550	1.166	1.879	2.136	3.182	6.159	9.303	11.326	13.190	15.994	18.170
1997	0.640	1.182	1.941	2.534	2.754	4.118	7.938	11.845	13.281	14.716	21.356
1998	0.611	1.015	1.903	2.579	3.550	3.667	6.300	10.018	16.134	17.558	18.170
1999	0.595	1.063	1.505	2.377	3.461	4.899	5.527	8.878	12.138	17.364	18.170
2000	0.523	1.092	1.868	2.550	3.523	4.827	6.217	7.538	9.749	13.973	18.170
2001	0.618	1.242	1.931	2.912	4.265	5.503	6.633	7.551	8.438	11.414	23.960
2002	0.519	1.051	2.170	2.914	3.760	5.458	6.746	8.110	9.059	9.569	13.877
2003	0.585	1.253	1.816	2.790	3.764	4.719	6.585	7.610	9.376	10.556	12.973
2004	0.585	1.110	2.240	2.955	3.638	4.915	6.238	8.170	9.862	11.322	16.410
2005	0.563	1.138	2.075	2.886	3.721	5.031	6.523	7.963	9.433	10.482	14.420

Table SD.4: Mean weight-at-age (kg) of commercial landings (only) for the Gulf of Maine cod stock.

	1	2	3	4	5	6	7	8	9	10	11+
1982	0.801	1.156	1.664	2.764	4.770	6.739	8.944	9.931	12.922	10.618	18.456
1983	0.806	1.164	1.660	2.475	3.778	5.962	5.808	10.522	10.089	10.898	17.813
1984	0.589	1.159	1.670	2.721	3.677	5.898	8.119	9.595	12.889	13.951	15.028
1985	0.806	1.260	1.746	2.840	4.466	5.525	7.901	11.218	11.420	13.386	14.523
1986	0.806	1.304	1.837	2.923	4.619	6.067	7.669	10.030	12.463	12.907	16.554
1987	1.028	1.313	1.684	3.283	4.831	6.824	8.878	10.023	13.752	14.738	14.596
1988	0.806	1.268	1.881	2.426	5.166	6.767	9.932	11.126	14.960	15.763	20.356
1989	0.806	1.247	1.776	2.993	3.864	4.872	9.267	11.938	14.806	18.196	21.521
1990	0.806	1.071	1.692	2.271	4.265	7.645	10.734	11.758	15.015	14.784	20.295
1991	0.806	1.130	1.568	2.512	4.136	7.309	9.642	12.322	15.547	24.328	21.885
1992	0.806	1.533	1.922	2.714	3.061	5.000	9.566	12.462	13.449	16.631	18.061
1993	0.806	1.293	1.889	2.513	4.356	6.174	9.999	13.869	17.544	15.420	18.061
1994	0.806	1.450	1.943	3.151	3.444	6.132	8.321	12.628	12.052	21.532	19.369
1995	0.806	1.652	1.921	2.775	5.142	8.290	10.755	12.914	16.433	21.504	18.061
1996	0.806	1.687	2.136	2.376	3.648	7.376	10.440	11.928	13.471	15.420	18.061
1997	0.806	1.733	2.233	3.007	3.193	4.649	8.543	13.439	14.787	16.075	21.356
1998	0.806	1.277	2.089	2.979	4.191	4.211	8.538	11.747	19.369	20.847	18.061
1999	0.806	1.406	1.774	2.704	4.020	5.727	7.254	9.231	12.542	15.420	18.061
2000	0.806	1.479	2.491	3.664	4.589	5.795	6.748	7.833	10.297	15.420	18.061
2001	0.806	1.914	2.521	3.405	4.964	6.599	7.593	8.450	9.089	12.651	23.960
2002	0.806	1.371	2.459	3.367	4.153	6.002	6.896	8.663	9.712	10.074	13.877
2003	0.806	1.947	2.406	3.165	4.207	5.362	7.225	8.397	10.148	11.473	12.973
2004	0.806	1.529	2.576	3.628	4.182	5.741	7.257	9.239	11.583	12.631	16.410

Table SD.5: Total (commercial and recreational) landings-at-age (thousands of fish) of Gulf of Maine cod stock

	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	1	49	1488	1258	319	74	88
1995	0	287	1233	1348	206	14	34
1996	0	89	716	1955	368	45	10
1997	0	61	498	469	893	72	8
1998	0	112	505	627	182	214	11
1999	1	16	580	550	270	81	109
2000	0	194	540	856	198	97	23
2001	0	121	1065	643	375	102	84
2002	0	2	276	863	334	214	135
2003	0	14	111	430	786	240	189
2004	0	1	284	227	372	250	139

Table SD.6: Mean weight-at-age (kg) at the beginning of the year for the Gulf of Maine cod stock used in the Mayo and Col (2006) VPA assessments. Values derived from total (commercial and recreational landings mean weight-at-age data (mid-year) using procedures described by Rivard (1980).

	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	1.314	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	1.916	3.978	5.461	10.676
1989	0.461	0.449	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	0.072	0.403	1.242	2.020	3.030	5.509	11.106
1992	0.229	0.553	1.474	2.031	2.747	4.486	10.593
1993	0.204	0.665	1.673	2.152	3.398	4.315	10.974
1994	0.191	0.747	1.441	2.363	2.828	5.080	9.898
1995	0.190	0.796	1.619	2.206	3.920	4.860	13.367
1996	0.185	0.803	1.836	2.067	3.082	6.105	10.657
1997	0.210	0.823	1.908	2.478	2.705	4.038	8.738
1998	0.453	0.725	1.912	2.538	3.487	3.587	9.528
1999	0.166	0.862	1.564	2.403	3.480	4.865	7.706
2000	0.182	0.720	1.639	2.495	3.469	4.856	6.994
2001	0.209	0.839	1.905	2.711	4.073	5.337	7.891
2002	0.174	0.729	2.083	2.834	3.633	5.339	8.412
2003	0.198	0.877	1.810	2.720	3.670	4.644	8.678
2004	0.198	0.772	2.171	2.825	3.406	4.664	8.738
2005	0.190	0.792	2.022	2.793	3.569	4.882	8.609

Table SD.7: Mean weight-at-age (kg) of total landings (commercial and recreational) for the Gulf of Maine cod stock used in the Mayo and Col (2006) VPA assessments.

	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	0.390	1.531	1.915	2.722	3.060	5.000	10.593
1993	0.390	1.132	1.827	2.418	4.243	6.085	10.974
1994	0.390	1.429	1.835	3.056	3.307	6.081	9.898
1995	0.390	1.624	1.834	2.652	5.029	7.143	13.367
1996	0.390	1.652	2.075	2.330	3.582	7.412	10.657
1997	0.390	1.736	2.203	2.959	3.140	4.553	8.738
1998	0.625	1.348	2.105	2.923	4.110	4.098	9.528
1999	0.346	1.188	1.814	2.774	4.143	5.758	7.706
2000	0.390	1.498	2.261	3.432	4.385	5.691	6.994
2001	0.390	1.804	2.422	3.251	4.833	6.496	7.891
2002	0.390	1.360	2.406	3.317	4.059	5.897	8.412
2003	0.390	1.968	2.409	3.075	4.060	5.313	8.678
2004	0.390	1.525	2.395	3.313	3.772	5.357	8.738

Table SD.8: Modified (equation S1.3) total (commercial and recreational) landings-at-age (thousands of fish) of Gulf of Maine cod stock (see text for details).

	1	2	3	4	5	6	7+
1982	85	1935	2279	1344	695	73	235
1983	14	1313	2844	1163	673	440	166
1984	24	797	1540	1603	459	201	139
1985	47	941	2008	1067	632	126	130
1986	26	209	2757	931	276	198	190
1987	38	847	1324	1424	308	74	91
1988	6	493	2029	1089	411	48	32
1989	5	515	2220	1650	471	88	59
1990	7	290	4144	2344	482	165	104
1991	5	438	1320	4843	926	148	83
1992	0	350	600	526	2183	218	86
1993	1	148	1941	764	136	467	38
1994	1	47	1434	1212	307	71	85
1995	0	276	1187	1298	198	13	33
1996	0	87	701	1914	360	44	10
1997	0	60	488	459	875	71	8
1998	0	110	498	618	180	211	11
1999	1	16	588	558	274	82	111
2000	0	183	508	805	186	91	22
2001	0	117	1027	620	362	98	81
2002	0	2	276	862	334	214	135
2003	0	14	110	426	778	238	187
2004	0	1	265	212	347	233	130

Table SD.9: Mean weight for age 7+ (kg) at the beginning of the year for the Gulf of Maine cod stock used in the VPA assessments.

	begin-year	mid-year
1982	10.446	11.330
1983	10.507	9.755
1984	8.720	10.176
1985	8.398	9.721
1986	8.738	10.295
1987	8.466	10.241
1988	9.311	11.233
1989	10.425	12.200
1990	9.262	13.747
1991	10.195	11.449
1992	9.278	10.614
1993	7.823	11.063
1994	8.630	10.018
1995	9.793	12.969
1996	10.379	11.647
1997	11.595	12.479
1998	7.572	10.262
1999	6.020	7.901
2000	6.810	7.392
2001	7.085	8.110
2002	7.461	7.627
2003	7.485	8.212
2004	7.612	8.855
2005	7.930	

Table SD.10: 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, 1968-2005.

	Age group							Standardized mean
	1	2	3	4	5	6	7+	wt/tow (kg)
1968	0.741	1.234	1.407	0.846	0.538	0.207	0.464	18.20
1969	0.000	0.036	0.307	0.880	0.807	0.633	0.590	13.19
1970	0.159	0.124	0.053	0.091	0.271	0.465	1.028	11.08
1971	0.026	0.151	0.105	0.286	0.048	0.084	0.731	7.00
1972	0.371	0.135	0.521	0.195	0.181	0.044	0.609	8.03
1973	0.035	4.250	0.890	0.632	0.348	0.194	1.177	18.81
1974	0.475	0.103	1.503	0.172	0.235	0.075	0.338	7.42
1975	0.102	0.686	0.131	1.105	0.269	0.079	0.140	6.04
1976	0.051	0.265	1.104	0.137	0.902	0.090	0.234	7.56
1977	0.025	0.297	0.553	1.925	0.111	0.831	0.132	8.54
1978	0.048	0.110	0.308	0.351	0.744	0.095	0.394	7.70
1979	0.528	1.630	0.219	0.449	0.299	0.587	0.283	8.36
1980	0.107	0.423	0.492	0.138	0.238	0.304	0.453	6.23
1981	1.075	0.644	0.841	1.342	0.331	0.264	0.337	10.65
1982	0.373	1.007	0.476	0.655	0.988	0.087	0.177	8.62
1983	0.645	0.949	0.997	0.465	0.404	0.212	0.241	10.96
1984	0.151	1.312	1.023	0.823	0.212	0.047	0.100	6.14
1985	0.029	0.231	0.662	0.663	0.662	0.103	0.169	7.65
1986	0.537	0.248	0.754	0.237	0.091	0.035	0.056	3.48
1987	0.030	0.460	0.199	0.231	0.074	0.000	0.089	1.98
1988	0.746	0.923	0.823	0.218	0.254	0.092	0.072	3.60
1989	0.017	0.605	0.723	0.600	0.091	0.063	0.014	2.42
1990	0.000	0.208	1.365	0.637	0.102	0.032	0.018	3.08
1991	0.038	0.068	0.234	1.717	0.299	0.020	0.018	2.89
1992	0.050	0.226	0.242	0.282	1.328	0.226	0.081	8.63
1993	0.201	0.497	0.799	0.334	0.091	0.484	0.101	5.88
1994	0.015	0.316	0.388	0.215	0.094	0.049	0.194	2.43
1995	0.050	0.179	1.116	0.372	0.145	0.028	0.039	2.43
1996	0.057	0.022	0.593	1.331	0.403	0.059	0.000	5.43
1997	0.159	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	0.060	4.18
1999	0.166	0.344	0.713	0.345	0.315	0.134	0.284	5.09
2000	1.210	0.725	0.439	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	6.22
2002	0.340	0.045	0.524	1.601	0.614	0.362	0.237	10.93
2003	0.069	0.831	0.063	0.708	1.089	0.395	0.524	9.50
2004	0.136	0.045	0.221	0.118	0.191	0.232	0.038	2.41
2005	0.020	0.726	0.101	0.608	0.015	0.145	0.144	2.70

Table SD.11: 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, 1964-2005.

	Age group							Standardized mean
	1	2	3	4	5	6	7+	wt/tow (kg)
1964	0.050	0.649	1.349	1.253	0.849	0.579	1.190	17.95
1965	0.000	0.092	0.122	0.417	0.856	0.853	1.608	22.80
1966	0.002	0.850	0.880	0.824	0.750	0.496	0.693	12.01
1967	0.170	0.204	0.640	0.697	0.718	0.558	0.795	12.92
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	0.802	0.883	0.260	0.538	0.329	0.486	1.608	16.44
1972	1.319	0.179	0.276	0.219	0.578	0.478	1.313	16.53
1973	0.031	5.578	1.215	1.528	0.233	0.090	0.626	12.99
1974	0.638	0.329	2.170	0.139	0.507	0.213	0.456	8.76
1975	0.283	1.134	0.266	1.876	0.167	0.274	0.330	8.96
1976	0.047	0.177	3.045	0.138	2.333	0.259	0.144	8.62
1977	0.000	0.230	0.221	0.633	0.077	0.773	0.215	6.74
1978	0.000	0.042	0.416	0.465	1.157	0.114	0.880	10.20
1979	0.248	1.373	0.378	1.135	0.658	1.426	0.555	12.90
1980	0.002	0.381	0.588	0.145	0.708	0.337	0.984	13.93
1981	0.027	1.321	2.520	1.780	0.492	0.194	0.700	14.20
1982	0.010	0.618	0.419	0.539	0.405	0.121	0.238	7.53
1983	0.000	0.843	3.353	2.275	1.089	0.209	0.000	15.92
1984	0.000	0.317	0.916	0.828	0.197	0.227	0.302	8.42
1985	0.022	0.432	0.426	0.631	0.387	0.214	0.337	8.74
1986	0.121	0.526	0.957	0.609	0.248	0.182	0.179	8.26
1987	0.000	0.392	0.401	0.657	0.342	0.073	0.086	4.72
1988	0.128	0.578	1.380	0.592	0.243	0.075	0.000	3.39
1989	0.000	1.938	2.313	0.990	0.443	0.099	0.120	6.62
1990	0.000	0.150	2.407	1.502	0.293	0.161	0.042	4.54
1991	0.006	0.045	0.187	1.829	0.598	0.259	0.062	4.91
1992	0.009	0.144	0.139	0.223	0.633	0.081	0.023	2.78
1993	0.059	0.291	0.446	0.140	0.036	0.350	0.112	2.45
1994	0.043	0.198	0.568	0.360	0.034	0.000	0.030	1.00
1995	0.032	0.207	0.883	0.826	0.085	0.051	0.045	2.74
1996	0.008	0.068	0.285	1.228	0.325	0.082	0.011	3.67
1997	0.029	0.124	0.383	0.188	0.542	0.062	0.000	2.35
1998	0.000	0.297	0.086	0.177	0.173	0.140	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	0.367	0.586	0.243	0.132	0.022	3.51
2001	0.008	0.533	0.984	0.394	0.507	0.134	0.044	4.65
2002	0.018	0.034	0.141	0.752	0.469	0.337	0.229	7.33
2003	0.000	0.269	0.081	0.364	2.797	1.096	0.721	24.66
2004	0.542	0.455	0.198	0.185	0.529	0.450	0.172	5.99
2005	1.380	0.651	0.168	0.581	0.231	0.253	0.268	4.90

Table SD.12: 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), 1978-2005.

	Age group							Stratified mean
	1	2	3	4	5	6	7+	wt/tow (kg)
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
2001	19.080	2.780	4.810	3.630	1.860	0.410	0.160	22.33
2002	17.530	0.441	1.642	2.379	0.879	0.615	1.120	19.51
2003	807.517	9.338	0.366	1.714	1.638	0.365	0.218	12.32
2004	112.797	2.049	3.350	0.608	1.310	0.891	0.220	12.18
2005	148.826	9.363	0.675	2.575	0.230	1.313	0.551	13.05

Table SD.13: 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), 1978-2005.

	Age group							Stratified mean
	1	2	3	4	5	6	7+	wt/tow (kg)
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	0.030	0.000	0.000	0.34
2002	44.520	0.060	0.300	0.150	0.090	0.090	0.010	1.00
2003	0.990	2.500	0.300	0.550	0.770	0.910	0.160	8.66
2004	112.790	3.660	0.330	0.120	0.470	0.150	0.020	3.13
2005	39.220	14.380	1.500	2.030	0.330	0.770	0.390	8.77

Table SD.14: USA commercial LPUE index through 1993 for ages 3-6. Note that the age-specific information in this Table is not used for the ASPM fits because that would constitute double usage of information provided by Table SD.5.

	Age group				Mean LPUE,
	3	4	5	6	ages 3-6
1982	0.0738	0.0450	0.0217	0.0027	0.218
1983	0.1099	0.0422	0.0209	0.0123	0.233
1984	0.0448	0.0442	0.0118	0.0055	0.139
1985	0.0423	0.0289	0.0179	0.0036	0.106
1986	0.0688	0.0226	0.0066	0.0043	0.106
1987	0.0186	0.0260	0.0057	0.0018	0.06
1988	0.0492	0.0242	0.0093	0.0015	0.099
1989	0.0637	0.0397	0.0106	0.0023	0.133
1990	0.1595	0.0782	0.0122	0.0051	0.266
1991	0.0404	0.1355	0.0217	0.0039	0.221
1992	0.0173	0.0138	0.0515	0.0052	0.103
1993	0.0500	0.0232	0.0041	0.0140	0.094