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2013 Benchmark Assessment of Eastern Georges Bank Atlantic Cod (*Gadus morhua*)

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ABSTRACT

The assessment model formulations for the Eastern Georges Bank Atlantic Cod management unit was last established at the Transboundary Resources Assessment Committee (TRAC) benchmark review conducted in 2009. In recent years the model results exhibited consistent and severe retrospective patterns which indicated that contemporary estimates of biomass were consistently lower than previously estimated. A benchmark review to examine alternative model formulations was conducted in April 2013.

The total mortality of ages 6+ calculated from the fishery and survey data has been high despite the decreased relative F (fishery catch/survey abundance indices) since the mid-1990s, which implies that natural mortality increased since the mid-1990s at ages 6+, or hypothesized with very high levels of unreported catch, which is considered unlikely. The VPA model formulations were explored, letting the model estimate mortality (M) and assigning various values for M starting from different ages. Model fit diagnostics provided convincing selection to the “M 0.8” Virtual Population Analysis (VPA) model, a model with $M=0.8$ for ages 6+ since 1993.

For the “M 0.8” VPA assessment model, the fishing mortality reference point was calculated from the age-disaggregated Sissenwine-Shepherd production model with a proposed value $F=0.11$.

Although the results were not accepted at the meeting, it was agreed that the current $F_{ref}=0.18$ was not consistent with the VPA “M 0.8” model, and that a lower reference point for this model would be expected. The TRAC agreed that projections would be run at the current F_{ref} of 0.18 and at a value less than the F_{ref} , and the assessment leads should pick the most meaningful values for the projection. Further investigation will be required to determine an appropriate recommendation for an exploitation rate for the VPA “M 0.8” model.

A consequence analysis to understand the risks associated with assumptions in the projection of the VPA “M 0.8” model and an alternative model (Age Structured Assessment Program [ASAP] “M 0.2” model also reviewed at the 2013 benchmark meeting) with an assumption of constant $M=0.2$, will be conducted to provide catch advice.

Évaluation du point de référence en 2013 pour la morue franche (*Gadus morhua*) de l'est du banc de Georges

RÉSUMÉ

Les formules de modèle d'évaluation pour la zone de gestion de la morue franche de l'est du banc de Georges ont été établies la dernière fois à l'occasion de l'examen des points de référence du Comité d'évaluation des ressources transfrontalières (CERT) mené en 2009. Au cours des dernières années, les résultats du modèle ont affiché des tendances rétrospectives constantes et graves selon lesquelles les estimations actuelles de la biomasse étaient invariablement plus faibles que les estimations précédentes. En avril 2013, on a mené un examen des points de référence en vue d'étudier d'autres formules de modèle.

Depuis le milieu des années 1990, la mortalité totale des morues âgées de 6 ans et plus, calculée à partir de données dérivées de relevés et des pêches, a été élevée malgré la baisse de la valeur relative de F (prises des pêches/indices d'abondance des relevés), ce qui signifie que la mortalité naturelle a augmenté chez les morues âgées de 6 ans et plus depuis ou qu'il pourrait y avoir des niveaux très élevés de prises non déclarées. La dernière hypothèse est toutefois peu probable. On a étudié les formules du modèle d'analyse de population virtuelle (APV). On l'a alors utilisé pour estimer la mortalité (M) et on a attribué diverses valeurs pour M à partir de différents âges. Les diagnostics d'ajustement de modèle ont fourni une sélection convaincante pour le modèle d'APV « $M = 0,8$ », selon lequel $M = 0,8$ pour les morues âgées de 6 ans et plus depuis 1993.

Pour le modèle d'évaluation APV « $M = 0,8$ », le point de référence relatif à la mortalité par pêche a été calculé au moyen du modèle de production Sissenwine-Shepherd sans regroupement par âge avec une valeur proposée de $F = 0,11$.

Bien que les résultats n'aient pas été acceptés lors de la réunion, on a convenu que le taux de mortalité par pêche de référence $F_{\text{réf}} = 0,18$ n'était pas conforme au modèle d'APV « $M = 0,8$ » et que l'on pourrait s'attendre à un point de référence inférieur pour ce modèle. Le CERT a convenu que les projections seraient effectuées à l'aide du taux de mortalité par pêche de référence $F_{\text{réf}} = 0,18$, à une valeur inférieure au $F_{\text{réf}}$, et que les responsables de l'évaluation devraient sélectionner les valeurs les plus significatives en vue des projections. De plus amples recherches devront être effectuées pour déterminer le taux d'exploitation recommandé pour le modèle d'APV « $M = 0,8$ ».

Afin de fournir des recommandations de prises, on mènera une analyse des conséquences pour comprendre les risques associés aux hypothèses de la projection du modèle d'APV « $M = 0,8$ » et d'un autre modèle (le modèle du Programme d'évaluation selon la structure d'âge [PESA] « $M = 0,2$ » a aussi fait l'objet d'un examen lors de la réunion de 2013 portant sur le point de référence) avec l'hypothèse d'un taux de mortalité constant de $M = 0,2$.

INTRODUCTION

Following declarations of exclusive economic zones by coastal states in 1977, Atlantic Cod on Georges Bank have been exploited by only Canadian and USA fisheries. Cod are now considered transboundary with respect to the Canada/USA maritime boundary that was established by the International Court of Justice in 1984. The Transboundary Resources Assessment Committee (TRAC) was established in 1998 to conduct joint Canada/USA peer review of assessments for transboundary resources in the Georges Bank/Gulf of Maine area and thus provide a common understanding of resource status. While stock assessment results are needed routinely to serve the management system, it is not practical to evaluate the assessment approach each time the assessment is conducted. The TRAC review process is two tiered, with annual assessment reviews undertaken between more intensive, periodic benchmark reviews.

The basis and background for the delineation of management units of cod on Georges Bank and the vicinity were reviewed and summarized at the 2009 Eastern Georges Bank cod benchmark assessment meeting (O'Brien and Worcester 2009). For the purpose of a sharing agreement and consistent management by Canada and the USA, agreement was reached that the transboundary management unit for Atlantic cod would be limited to the eastern portion of Georges Bank (DFO Statistical Unit Areas 5Zej and 5Zem; USA Statistical Areas 551, 552, 561 and 562) (DFO 2002). The management area is shown in Figure 1. The USA has a requirement for management advice for the Georges Bank cod stock (5Z + SubArea 6). The status quo has been to use an assessment of cod in 5Zjm for transboundary management advice and an assessment of cod in 5Z+6 for USA domestic management advice. There is concern that development of fisheries management advice from potentially differing assessment approaches arrived at through independent reviews may make reconciliation of results difficult.

The assessment model formulations for Eastern Georges Bank cod were last established in a benchmark review conducted in 2009 (O'Brien and Worcester 2009). At the June 2012 assessment meeting, concerns were expressed about the model formulations established by the 2009 benchmark assessment (Wang and O'Brien 2012). In recent years, the model results exhibited consistent and severe retrospective patterns which indicated that contemporary estimates of biomass were consistently lower than previously estimated. A benchmark review to examine alternative model formulations was recommended.

This manuscript documents the supporting analyses in respect to the Virtual Population Analysis (VPA) assessment model formulation presented during the benchmark review conducted in 2013.

FISHERY

Combined Canada/USA catches averaged 17,198 mt between 1978 and 1993, declined to 1,683 mt in 1995, then fluctuated around 3,000 mt until 2004 and subsequently declined again. Catches in 2011 were 1,030 mt, including 62 mt of discards (Table 1, Figure 2). Catches include USA and Canadian discards in all years where discard estimates were available.

Canadian catches peaked at 17,898 mt in 1982 and declined to 1,140 mt in 1995 (Table 1, Figure 3). Since 1995, with lower cod quotas, the fishery has reduced targeting for cod through changes in fishing practices, including the introduction of the cod separator panel for bottom trawls in 1999.

Canadian regulations prohibit the discarding of undersized fish from the groundfish fishery. For the Canadian groundfish fishery on Eastern Georges Bank during 1978 – 1996, a review was

conducted at the 2013 benchmark meeting to evaluate cod discards (unreported catch). Comparison of length frequencies of observer and port samples did not provide evidence of discarding. Since there was little quota regulation of the Canadian Georges Bank cod fishery prior to 1995 and landings generally were well below the quota, it was concluded that there was no indication of discarding before 1996 (Claytor and O'Brien 2013). The ratio of sums method, which uses the difference in ratio of cod to haddock from the observed and unobserved trips, was applied to estimate discards of cod from groundfish fishery. Since 1996, the Canadian scallop fishery has not been permitted to land cod. The 3-month moving average observed discard rate has been applied to scallop effort to estimate discards from scallop fishery since 2005.

USA catches increased from 5,502 mt in 1978 to 10,550 mt in 1984. With the implementation of the International boundary (the 'Hague Line') between Canada and the USA in 1984, catches declined and subsequently fluctuated around 6,000 mt between 1985 and 1993 (Table 1, Figure 3). Since December 1994, a year-round closure of Area II has been in effect, with the exception of a Special Access Program for haddock that started in 2004 (from August 1st to the following January 31st). Minimum mesh size limits were increased in 1994, 1999 and 2002. Quotas were introduced in May 2004. Limits on sea days, as well as trip limits, have also been implemented. With the implementation of a catch share system in 2010, most of the fleets are now managed by quotas.

Discards by USA groundfish fleets occur because of trip limits and minimum size restrictions. Cod discarded in the Eastern Georges Bank area by otter trawl and scallop fisheries were estimated using the Northeast Fisheries Science Center (NEFSC) Observer data from 1989-2011. A ratio of discarded cod to total kept of all species (d:k) was estimated on a trip basis. Total discards (mt) were estimated from the product of d:k and total commercial landings (Table 1, Figure 3). In the 2012, the 55th Northeast Regional Stock Assessment Workshop (55th SAW) Georges Bank cod benchmark meeting, 'Delphi' determined mortality rates (otter trawl: 75%) were applied to the final estimates of USA discards (Table 1)

The combined Canada/USA fishery catch at age was obtained by pooling Canadian landings at age, discards at age from the groundfish fishery and discards at age from the scallop fishery with USA landings at age and discards at age (Table 2, Figure 4). The number of fish captured by the fishery for all the ages has declined substantially since 1995. The proportion of age composition in the catch at age has tended to decrease for ages 2-3 and increase for ages 4-6. Both number and proportion of catch at ages 9 and older are lower in more recent years (Figure 4).

SURVEY INDICES

Surveys on Georges Bank have been conducted by DFO each year (February) since 1986 and by the National Marine Fisheries Service (NMFS) each autumn (October) since 1963 and each spring (April) since 1968. All surveys use a stratified random design (Figures 5 and 6).

Survey catch at younger ages from all three surveys declined substantially since the early 1990s (Tables 3-5, Figures 7-9). In contrast, the abundance indices for ages 4-6 fluctuate without trend since the early 1990s. Abundance indices for ages 9 and older are currently very low. Survey biomass indices have been lower since the mid-1990s and continue to decline (Figure 10).

The coefficient of variation (CV) of stratified mean catch number per tow for the three surveys is shown in Figure 11. The CV values were similar between the DFO and NMFS spring surveys

and smaller compared to the NMFS fall survey values. After the mid-1990s, the higher CV values might be caused by patchy distribution at low abundance.

Population weight at age for the beginning of year was derived from the DFO and NMFS spring survey results (1978-1985: DFO weight length relationship applied to NMFS 1978-1985 spring average length at age; 1986-1992: DFO weight at age; 1992-2012: sample numbers weighted average of DFO weight at age and NMFS spring weight at age). Figure 12 shows the smoothed weight at age which displays a clearly declining trend since the early 1990s.

STOCK STATUS DETERMINATION

The adaptive framework, ADAPT, (Gavaris 1988) was used to calibrate the virtual population analysis with the research survey indices. The observed data used in the models were:

$C_{a,t}$ = catch at age for ages $a = 1$ to 10+ and time $t = 1978$ to 2011, where t represents the year during which the catch was taken

$I_{1,a,t}$ = DFO survey for ages $a = 1$ to 8 and time $t = 1986.16, 1987.16 \dots 2011.16, 2012.00$

$I_{2,a,t}$ = NMFS spring survey (Yankee 41) for ages $a = 1$ to 8 and time $t = 1978.29, 1979.29, 1980.29, 1981.29$

$I_{3,a,t}$ = NMFS spring survey (Yankee 36), for ages $a = 1$ to 8 and time $t = 1982.29, 1983.29 \dots 2011.29, 2012.00$

$I_{4,a,t}$ = NMFS autumn survey, ages $a = 1$ to 5 and time $t = 1978.69, 1979.69 \dots 2011.69$.

For model fitting, the population numbers at the time of year the surveys occurred were derived by applying the fishing and natural mortality to the numbers at the beginning of the year. Since the fishing mortality rate for 2012 was not known, the DFO survey and the NMFS spring survey were designated as beginning of year for 2012 only. This deviation was not considered to have an appreciable impact as the catch prior to the surveys being conducted was small in recent years.

All model formulations assumed that observation errors for the catch at age data were negligible. Observation errors for the abundance indices at age were assumed to be independent and identically distributed after taking natural logarithms of the values. Zero observations for abundance indices were treated as missing data as the logarithm of zero was not defined. Numbers and fishing mortality for the 10+ age group were derived by aggregating the survivors for ages 9 and 10+ in the previous year.

Estimation was based on minimization of the objective function:

$$\sum_{s,a,t} \left(\ln I_{s,a,t} - \left(\hat{\kappa}_{s,a} + \ln N_{a,t} \right) \right)^2,$$

where s indexed survey and N was population abundance.

Statistical properties of estimators were determined using conditional non-parametric bootstrapping of model residuals (Efron and Tibshirani 1993, Rivard and Gavaris 2003a). Retrospective analyses were used to detect any patterns to consistently overestimate or underestimate fishing mortality, biomass and recruitment relative to the terminal year estimates.

CONTEXT

BASIC VPA CALIBRATION

For a basic VPA calibration, the annual natural mortality rate, M , was assumed constant and equal to 0.2 for all ages in all years. Fishing mortality on age 9 for 1978 to 2011 was assumed to be equal to the population number weighted average fishing mortality on ages 7 and 8. The estimated model parameters were survey catchability for ages 1 to 8 of DFO and NMFS spring surveys, ages 1 to 5 of NMFS fall survey, population abundance for ages 2 to 9 at the terminal year.

The basic VPA calibration displayed notable age and time residual patterns (Figure 13). However, greatest concern was caused by the persistent and strong retrospective patterns (Figure 14) which indicated the current estimate of biomass was consistently lower than previously estimated. The survey catchability estimates showed temporal trends and were considered problematic (Figure 15).

2002 BENCHMARK FORMULATION

The 2002 benchmark meeting examined the concerns about residual patterns and retrospective patterns from the assessment. The benchmark formulation was otherwise similar to the basic formulation except that it also estimated population abundance at age 10 for 1999 onwards ('around the corner'). The residuals from the 2002 benchmark formulation were somewhat improved compared to the basic formulation, but age and time patterns persisted. The retrospective pattern was greatly improved with contemporary estimates of biomass being either slightly lower or higher than previously estimated.

This benchmark formulation resulted in a somewhat domed fishery partial recruitment (PR) (Figure 16). In view of relatively flat survey catchability at older ages (Figure 16), this feature was not considered a concern. Further, a domed shaped fishery partial recruitment was not inconsistent with the decline in Canadian catches during the first quarter, when larger cod were more prevalent. The resulting fishing mortality trend from the benchmark formulation also appeared to better reflect the trends in catches.

With the inclusion of more recent survey and fishery data, the tendency for a dome-shaped fishery PR with a more steeply descending limb (Figure 17), dome-shaped survey catchability at age (Figure 17) and high estimates of population at older ages raised concerns. The resulting assessment generated appreciable 'cryptic' biomass that could not be observed by either the fishery or the surveys.

2009 BENCHMARK FORMULATION

At the 2009 benchmark meeting, an examination of the implications of eliminating the first quarter fishery indicated that the magnitude of those removals was not large enough to appreciably alter the annual size composition. Therefore, a marked change in fishery PR after the mid-1990s, a key feature of the 2002 benchmark model formulation, was not supported. In principle, it is considered a good practice to favour a flat age pattern at older ages for fishery PR and survey catchability unless there is compelling evidence to suggest otherwise.

The "split M 0.2" model, a model that split the survey time series in 1993/1994 and set $M=0.2$ for all the ages and years, appreciably reduced the time residual patterns (Figure 18) and addressed the strong trends in survey catchability (Figure 19), reduced retrospective patterns as compared to the basic VPA (Figure 20). The survey catchability changes were suspected as

possible differences in vertical structure of cod aggregations in relation to changes in abundance.

The second model, the “split M 0.5” model, split the survey time series in 1993/1994 and set $M=0.5$ for ages 6+ from 1994 onward. Relative to the “split M 0.2” model, the diagnostics showed reduced retrospective patterns (Figure 20), flatter survey catchability at older ages (Figure 21), smaller changes in survey catchability at all ages (Figures 19 and 21), flatter fishery partial recruitment at older ages (Figure 22), and fishing mortality time trends that were intuitively more consistent with effort regulations (Figure 23).

Fit statistics (AIC and BIC) favored a natural mortality of 0.5 over 0.2 for the age/time block and M between 0.4-0.6 accounted for about 80% of the probability in the fit statistics (Wang *et al.*, 2009).

While models with higher M for ages 6+ during 1994-2007 were supported, persistence of higher M was questionable. There was consensus that the “split M 0.5” model was indicated by fit diagnostics as the basis for management advice; however, it was recommended during the 2009 benchmark review meeting that the results from the comparable model “split M 0.2” model also be considered. Until the fate of the 2003 year class has been documented (ages 6+) it would be necessary to use these two models to adequately account for uncertainty in the assessment. Doing so acknowledged that there was considerable uncertainty about selection of a single appropriate model. It was also notable that domestic USA management of NAFO Divisions 5Z+6 was based on a model with split survey time series and $M=0.2$ (O’Brien and Worcester 2009).

However, with inclusion of more recent survey and fishery data, both models started to show persistent and strong retrospective pattern (Figure 24). The retrospective analysis showed a tendency to overestimate biomass and underestimate fishing mortality in recent years (Table 6, Figure 24). Meanwhile, mechanisms that would explain the abrupt change of survey catchability between the 1993 to 1994 time periods could not be established (Figure 25). Furthermore, catches in recent years have not reduced F below F_{ref} based on these models, which is not consistent with quotas set by fishery management (Figure 26).

DATA FEATURES THAT MODELS NEED TO FIT/EXPLAIN

Despite poor recruitment since the mid-1990s, survey indices at age 5 and 6 did not show obvious temporal changes (Figures 7 and 8) and can be explained by the reduced fishery catches (Figure 27). In contrast, fish older than 6 did not increase subsequently as expected with severely reduced fishing after mid-1990s (Figures 7 and 8).

At the 2009 benchmark meeting, TRAC agreed that documenting the fate of the 2003 year class, the only above average year class since the 1990 year class, over the next few years should be informative about M at older ages. Based on catch curve analysis, the calculated total mortality (Z) for the 2003 year class, ages 6+, was appreciably high; 2.25 derived from the DFO survey abundance indices at age (ages 6-9), 1.38 from the NMFS spring survey abundance indices at age (ages 6-8, no fish were caught at age 9) and 1.46 from the fishery catch at age (ages 6-8) (Figure 28). Furthermore, the calculated Z for ages 6+ from other cohorts suggested that total mortality was currently as high or higher compared to before the mid-1990s (Figure 29). A modified catch curve analysis based on a 4-year moving window covariance analysis (Sinclair 2001) showed the similar trend (Figure 30).

Total mortality among different age groups was also compared. The estimated Z from fishery data showed a clear upward trend for ages 6-9 compared with the younger ages groups

(Figure 31). In the equations below, Z_{45} and Z_{678} were referred to as the approximation to total mortality of ages 4-5 and ages 6-8 in year i , respectively.

$$Z_{45} = \ln\left(\frac{\sum \text{age 4+age 5 for years } i}{\sum \text{age 5+age 6 for years } i+1}\right)$$

$$Z_{678} = \ln\left(\frac{\sum \text{age 6+age 7+age 8 for years } i}{\sum \text{age 7+age 8+age 9 for years } i+1}\right)$$

Figure 32 showed the estimated Z and the smoothed line with LOESS method (Cleveland 1979). Z was appreciably higher for ages 6-8 compared to ages 4-5 since the mid-1990s. The relative F (fishery catch / survey abundance indices) suggested that fishing mortality decreased substantially in the mid-1990s (Figure 33). This would imply that M increased or unreported catch or discards happened since the mid-1990s.

The possibility of higher proportion of unreported catch or discards after mid-1990s was examined. Canadian landings accounts for an average of 70% of total catch since 1994. During this period, the Canadian fishery monitoring system was believed to have improved greatly with the implementation of mandatory dockside monitoring and hauls, and a Vessel Monitoring System (VMS) was required on all fishing vessels on the Eastern Georges Bank (EGB) since 2006. The target of observer coverage was 10% up until at least 2003 but achieved higher percentages on some fleets in some years. Since 2003, coverage has been generally 20-25% and at times has been mandatory. The estimate of discards from scallop fishery and groundfish fishery have been calculated and included in the total catch. Considering these measures, it was difficult to rationalize such a high proportion of missing catch for the Canadian fishery. It was also considered unlikely that the unaccounted catches of this magnitude could have occurred for the USA fishery catches.

In summary, the following observations can be made:

- Total mortality calculation showed that it has remained high for ages 6+.
- Total mortality appeared higher for ages 6+ compared to ages 4-5.
- Relative F indicated a decline beginning in the mid-1990s.
- The indication for total mortality, coupled with relative exploitation, implied that natural mortality increased since the mid-1990s and that M may be higher at ages 6+.

MODEL OPTIONS

“SPLIT M 0.2” AND “SPLIT M 0.5” MODELS

The strong retrospective pattern has been one of the major issues with both models. To investigate the possible reasons for retrospective pattern, the cohort effect and the year effect from the survey catch were investigated, respectively.

Considering that the retrospective analysis indicated that the 2003 year class has been overestimated for the younger ages 1-3 (Table 6), the cohort effect was examined in a VPA run by excluding the 2003 year class abundance indices of ages 1-3 from all the three surveys. In this run, the retrospective pattern was improved a bit for both models, but the retrospective pattern still strong (Table 7).

To examine the survey year effect, VPA runs calibrated with the CV - weighted survey abundance indices were conducted. The retrospective pattern was slightly improved for the “split M 0.2” model, but not for the “split M 0.5” model (Table 8).

Due to the unresolved retrospective pattern (Figure 24), and abrupt changes of survey catchability, q , after 1994 (Figure 25), the models with split survey were not worth pursuing further.

NO SPLIT HIGH M MODEL

The starting year for an increase in natural mortality was selected as 1994, the date when new management measures were introduced which led to the dramatic decline of fishery catch, and the date when the residual patterns appeared.

Models were set up as:

- F for age 9 was calculated as the weighted average of F on age 7 and 8 during 1978 - 2011
- In 2012, population number was estimated for ages 2-9

Evaluation of model explorations did not rely on a single criterion. A suite of diagnostics was used to compare how well the models fit the data and how their results conformed to conventional perceptions of fisheries dynamics. The model with the following features was favored:

- Residuals: better age, time, cohort patterns.
- Survey catchability: flatter survey catchability at older ages, no time patterns
- Fishery partial recruitment (PR): flatter fishery PR.
- Time trends of fishing mortality: more consistent with fishing effort and catch in the past.
- Better retrospective patterns of 3+ biomass and fishing mortality.
- Model-goodness-of-fit statistics: with the minimum mean squared residuals (MSR), and the minimum Akaike Information Criterion corrected for sample size (AICc) (Burnham and Anderson 2002):

$$AICc = 2k - 2 \ln(L) + \frac{2k(k+1)}{n-k-1}$$

where k is the number of parameters in the model, n is the sample size, and L is the maximum value of the likelihood function for the estimated model. The differences between the AICc value for each model and that for the model with the lowest AICc ($\Delta AICc$) provided a means of ranking the model fits. Models with $\Delta AICc > 10$ were omitted from further consideration. The Akaike Weight (w_i) was used to interpret the relative likelihood of a model (Burnham and Anderson 2002):

$$w_i = \frac{e^{(-\frac{1}{2}\Delta_i)}}{\sum_{r=1}^R e^{(-\frac{1}{2}\Delta_r)}}$$

Estimating age and year specific M was challenging in ADAPT due to its correlation with other parameters. M was estimated in age and time blocks in the model exploration.

The first step was to specify M for recent years (post-1994) as a parameter while M for earlier years (pre-1994) was assigned a constant value 0.2. The data analysis indicated that a $M > 0.2$ for the older age group was more appropriate as the model assumption. Therefore, the age blocks and appropriate M were developed in a stepwise fashion beginning with the selection of

a starting age (A) of the group (A-10+) for which M changed and the value of M to be estimated in the 1994-2011 time block. The VPA runs were conducted starting at different ages from 4 to 8. The model with changing M starting from age 6 had the lowest MSR (Figure 34), with a more flat topped fishery PR (Figure 35), and more flat topped survey catchability (Figure 36). The estimated M for ages 6+ in post-1994 was 0.8. The AICc comparison showed that this model accounted for 95% of the probability between the five models (Table 9). Ages 6+ were selected as the age group in which M has changed since 1994.

The second step was to evaluate the effect of fixing M at 0.2 for the older age groups in the early time block (1978-1993) through a VPA sensitivity run. In this run, M values for the older age groups (6+) were estimated simultaneously for the 2 time blocks (1978-1993, 1994-2011). The estimated M value was 0.03 with a CV of 5.53 in pre-1994 and 0.78 with a CV of 0.07 in post-1994. It showed that M in recent years was well above the early time block. Fixing M at 0.2 for ages 6+ in pre-1994 or estimating it had little impact on the estimated value of M for ages 6+ in post-1994. The estimated values were 0.8 and 0.78, respectively. Given the high uncertainties associated with the estimate in the early years, fixing M for ages 6+ in pre-1994 at 0.2 was assumed appropriate.

To test the reliability of estimated M from VPA, another sensitivity analysis was done by fixing M at ages 6+ for post-1994 at different values. The M values ranged from 0.2 to 0.9, respectively. The model with M 0.8 had the lowest mean square residuals (Figure 37) with a more flat topped fishery PR (Figure 38), and more flat topped survey catchability (Figure 39). The AICc comparison showed that this model accounts for more than 99% of the probability in the fit statistics between the eight models (Table 10). The survey catchability of DFO survey was above 1.0 when the M value was fixed between 0.2 and 0.6 (Figure 39).

The final exploration was estimating M at younger age groups in post-1994. Due to the difficulties of reliable estimation of M at very young ages, the trial runs were focused on estimating M at ages 4-5 only. The first run was done by estimating M at ages 4-5 and M at ages 6+ in post-1994 simultaneously. The M at ages 4-5 was estimated as 0.14 with a CV of 0.71 and 0.82 with a CV of 0.04 for ages 6+. Considering the higher CV with the estimated M at age 4-5, M at ages 4-5 and 6+ were fixed at different values. The combination of different M values for the 2 age groups is shown in Table 11. M = 0.2 for ages 4-5 and M = 0.8 for ages 6+ had the lowest mean square residuals (Table 11). This model (referred to as "M 0.8") was selected as the proposed model for EGB cod. In this model, M was fixed at 0.8 for ages 6+ for post-1994 and 0.2 for all other ages in other years.

Tables 12 to 14 show the assessment results from the "M 0.8" model formulation. This model produces a 3+ biomass of about 10,000 mt in 2012. The average of fishing mortalities (F) for the 3 time blocks (1978-1993, 1994-2006 and 2007-2011) were around 0.5, 0.21 and 0.08 (Figure 40), respectively. The survey catchability q at fully recruited age 5 was 0.8 for DFO, 0.4 for NMFS spring, and 0.1 for NMFS fall (Figure 41).

The following model outputs from the "M 0.8" were compared with the "basic VPA" model.

Model-goodness-of-fit: Compared to the "basic VPA model", the "M 0.8" model had much lower mean square residuals (Figure 37) and accounts for more than 99% of the probability in AICc analysis (Table 10). The uncertainties in the model parameter estimation are lower than "basic VPA" (Table 15).

Time trend of fishing mortality: The average fishing mortalities (F) from the "basic VPA" model for the 3 time blocks (1978-1993, 1994-2006 and 2007-2011) were 0.57, 0.62 and 0.2, respectively (Figure 40), which was not consistent with the effort regulations. On the USA side, a year-round closure of area II has been effect since 1994, quotas were introduced in May

2004, and limits on sea days, as well as trip limits, had also been implemented during that time. On Canadian side, the quota has been low since the mid-1990s, and the winter fishery was closed from January to the end of May for 1994 to 2004, and from February to May since 2005. Due to the low ratio of cod to haddock quota, a mandatory cod separator panel has been in effect for otter trawls since 1999, in order to catch more haddock while avoiding cod, and fixed gear has changed to smaller hook size.

Using fishing days as an approximate estimation of fishing effort, Figure 42 compares the fishing days of the Canadian mobile gear and the fixed gear fishery with the F from the “M 0.8” and “basic VPA” models. The calculated F from the “M 0.8” model was more consistent with the fishing effort trend. Further, the trend of exploitation rate (fishery catch at age/population number at age) from the “M 0.8” model was much closer to the relative exploitation rate (fishery catch at age/survey abundance indices) (Figures 33 and 43).

Survey catchability: In the 3 surveys, the DFO survey has the highest survey catchability. Based on survey experiments, a value of survey catchability below or close to 1 is considered plausible. For the DFO survey, the survey catchability was around 2.0 with fully recruited at age 6 from the “basic VPA” model and around 0.8 with fully recruited at age 5 from the “M 0.8” model (Figure 41).

Time and age pattern of residuals: Figures 13 and 44 show the residual patterns from “basic VPA” model and the “M 0.8” model. Although there were year effects for both models, there was some improvement in the time pattern for the “M 0.8” model compared with the “basic VPA” model. The estimated survey q at age from the VPA compared with the observed values from the three surveys (Figures 15 and 45), indicate fewer time trends over r in the “model 0.8” model.

Retrospective analysis: The persistent strong retrospective pattern has been a major issue with the “basic VPA” model (Figure 14). For the “M 0.8” model, the retrospective pattern was greatly improved (Figure 46), the Mohn’s rho with 7-years peel was -0.02 for 3+ biomass, and 0.01 for fishing mortality (Table 16). The retrospective analysis back 14 years showed the no retrospective pattern (Table 17, Figure 47). There was negligible retrospective pattern in survey q from the “M 0.8” model compared with the “basic VPA” model (Figure 48).

Another retrospective analysis was conducted by estimating M at ages 6+ by an additional year of data was removed from the stock assessment; this analysis was back to 1998. The estimated M ranged between 0.62 and 0.81 from 1998 to 2012 are used, despite the estimated M for ages 6+ was not stable when different years of data are used, but has been high, and higher estimates of M are associated with lower CV (Table 18, Figure 49). This confirmed the possibility of high natural mortality for ages 6+.

FISHING REFERENCE POINTS

The Transboundary Management Guidance Committee (TMGC) has adopted a strategy to maintain a low to neutral risk of exceeding the current fishing mortality limit reference, $F_{ref}=0.18$ (TMGC meeting in December, 2002). When stock conditions are poor, fishing mortality rates should be further reduced to promote rebuilding. The current F_{ref} was derived from yield or spawner per recruit analysis with an assumption of $M=0.2$, and by coincidence $F_{40\%Spr}=F_{0.1}=0.18$.

Changes in M would potentially invoke a re-negotiation of F_{ref} . The output from the “M 0.8” model was used as data input for fishing reference points calculation. The average PR for 1994-2011, average fishery weight at age for 1994-2011 and spawning stock weight at age from the DFO and NMFS spring surveys from 1994-2012 were used for the per recruit analysis (Table 19). The calculated $F_{0.1}$ was 0.46 and $F_{40\%Spr}$ was 0.53, a value well above the current

$F_{ref}=0.18$ (Figure 50). In this type of per recruit analysis, M only impacts the trade-off between the gains from leaving fish in the water to grow bigger and the losses of fish over time due to natural mortality. When there is a positive stock-recruitment (SR) relationship, per recruit analyses will tend to overestimate fishing reference points due to not considering the feedback between conserving biomass in the water to increase recruitment and obtaining yield later (Duplisea 2013).

When M was high, the SR relationship had a profound influence on characterizing productivity and evaluating reference points. There did not appear to be any time trends in recruits per spawner that might be associated with compensatory processes in response to either higher M or reduced biomass (Figure 51). The SR points for EGB cod showed two clouds and there appeared to be a tendency for higher recruitment at biomass levels above about 25,000 mt (Figure 52). For the SR relationship analysis, the parametric Beverton-Holt SR model did not fit the observed data in a meaningful way (Figure 52); the spawning stock biomass (SSB) which could produce the maximum recruitment was far beyond the range of the observed SSB values. This left us with trying to understand the SR relationship with non-parametric tools.

A non-parametric LOESS smoother (Cleveland 1979) was applied to characterize the SR relationship. In the fitting with the non-parametric method, extra caution was made about extrapolations outside the observed range. For biomass less than any observed value, recruitment would be expected to decline with biomass and eventually go to the origin (0, 0). For biomass greater than the observed value, a parsimonious assumption would be to expect recruitment to neither increase nor decrease. Figure 53 shows the SR plot with the fitted LOESS curve. The LOESS fitted “S” shape curve joined the two clouds of SR points of this stock in a depensation like manner. It is noteworthy that almost all the SR observations since the mid-1990s fall in the lower cloud.

The age-disaggregated Sissenwine-Shepherd production model (Sissenwine and Shepherd 1987) was used to investigate production dynamics under various F rates. Figure 53 shows the fitted SR curve and replacement lines under different F . For $F_{40\%spr}$, calculated under an $M=0.8$ scenario, there was no intersection with the SR curves, which provides no equilibrium yield, so that fishing at $F_{40\%spr}=0.53$ would lead to stock collapse. For the replacement line at the current $F_{ref}=0.18$, the intersection with SR curve was at the lowest observed SSB. This implies that the SSB at equilibrium would stay at a very low level even if fishing at $F_{ref}=0.18$, which is contrary to the goal of stock rebuilding.

Beverton (1992) suggested that F_{95} could be used as a more conservative proxy for an F reference point. F_{95} is a fishing rate around 80% of F_{MSY} that could produce 95% of MSY . It is not only more attractive in economic terms, F_{95} also makes a significant contribution to conservation since it implies appreciably less stock depletion than at F_{MSY} . The replacement line of F_{95} intersects the SR curve at multiple points (Figure 53). Given the uncertainties regarding the SR relationship and the changes to natural mortality, $F_{95}=0.11$ is recommended as the F reference point for EGB cod VPA 0.8 model under the current elevated M scenario. If F is reduced below $F_{95}=0.11$, there could be a chance of allowing the stock to rebuild to the upper biomass cloud, while maintaining F as high as $F_{95}=0.11$ could trap the stock in its current low recruitment mode. While M remains elevated, fishing above $F_{95}=0.11$ could result in further stock decline and fishing below $F_{95}=0.11$ is necessary for, but does not guarantee, stock increase.

PROJECTION AND RISK ANALYSIS

This outlook was provided in terms of consequences with respect to the harvest reference points for alternative catch quotas in 2013 (Gavaris and Sinclair 1998, Rivard and Gavaris

2003b). Uncertainty about current biomass generates uncertainty in forecast results, which is expressed here as the risk of exceeding the proposed $F_{95}=0.11$, and the probability of changes in adult biomass from 2013 to 2014. The risk calculations assist in evaluating the consequences of alternative catch quotas by providing a general measure of the uncertainties. However, they are dependent on the data and model assumptions and did not include uncertainty due to variations in weight at age, partial recruitment to the fishery, natural mortality, systematic errors in data reporting or the possibility that the model may not reflect stock dynamics closely enough, and/or retrospective bias.

For projections, the 2009-2011 average values were assumed for the fishery weight at age. The 2010-2012 survey average values were assumed for the beginning of year population weights at age in 2013-2014. However, for the slower growing 2003 year class, fishery weight at age 9 in 2012 was based on a cohort regression. The 2007-2011 average partial recruitment was assumed for the partial recruitment pattern in 2012 and 2013. The 2007-2011 geometric mean of recruitment at age 1 from the VPA 0.8 was used for 2012-2014 projections. Catch in 2012 was assumed to be equal to the 675 mt quota.

Illustrative projections were conducted to evaluate how differences in stock status and catch determination using different F rates in 2013, at $F_{95}=0.11$ and $F=0$. Deterministic (Table 20) and stochastic projections (Figures 54-56) are provided from the model results. At $F_{95}=0.11$, the "M 0.8" model generates a fairly high catch of 1,300 mt but results in very high risk of biomass decline (Table 20, Figures 54 and 55). If there was no catch in 2013, the 2014 adult biomass would increase by 11.3% (Table 20, Figure 56).

SUMMARY

The consensus during the benchmark assessment review in 2013 was to provide advice based on a VPA "M 0.8" model (Claytor and O'Brien 2013). It was agreed that the current $F_{ref}=0.18$ is not consistent with the VPA "M 0.8" model given that it was derived based on models with an $M=0.2$. Although no consensus was reached as to what an appropriate fishing reference point would be for the VPA "M 0.8" model, it was agreed that it should be lower than the current $F_{ref}=0.18$. The TRAC agreed that projections would be run at the current F_{ref} of 0.18 and at a value less than the F_{ref} , and the assessment leads should pick the most meaningful values for the projection. Further investigation will be required to determine an appropriate recommendation for an exploitation rate for the VPA "M 0.8" model.

A consequence analysis to understand the risks associated with assumptions in the projection of the VPA "M 0.8" model and an alternative model (ASAP "M 0.2" model also reviewed at the 2013 benchmark) with an assumption of constant $M=0.2$, will be conducted to provide catch advice.

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TABLES

Table 1. Catches from Canadian and USA fisheries on Eastern Georges Bank.

Year	Canada			USA			Total	
	Landings	Discards Scallop	Discards Grnfish	Total	Landings	Discards		Total
1978	8,777	98		8,875	5,502		5,502	14,377
1979	5,979	103		6,082	6,408		6,408	12,490
1980	8,066	83		8,149	6,418		6,418	14,567
1981	8,508	98		8,606	8,092		8,092	16,698
1982	17,827	71		17,898	8,565		8,565	26,463
1983	12,131	65		12,196	8,572		8,572	20,769
1984	5,761	68		5,829	10,550		10,550	16,379
1985	10,442	103		10,545	6,641		6,641	17,186
1986	8,504	51		8,555	5,696		5,696	14,251
1987	11,844	76		11,920	4,793		4,793	16,713
1988	12,741	83		12,824	7,645		7,645	20,470
1989	7,895	76		7,971	6,182	84	6,267	14,238
1990	14,364	70		14,434	6,414	69	6,483	20,917
1991	13,467	65		13,532	6,353	112	6,464	19,997
1992	11,667	71		11,738	5,080	176	5,256	16,995
1993	8,526	63		8,589	4,019	57	4,076	12,665
1994	5,277	63		5,340	998	5	1,003	6,343
1995	1,102	38		1,140	543	<0	544	1,683
1996	1,924	56		1,980	676	1	677	2,657
1997	2,919	58	428	3,405	549	5	554	3,958
1998	1,907	92	273	2,272	679	6	685	2,957
1999	1,818	85	253	2,156	1,195	9	1,204	3,360
2000	1,572	69		1,641	772	16	788	2,429
2001	2,143	143		2,286	1,488	146	1,634	3,920
2002	1,278	94		1,372	1,688	9	1,697	3,069
2003	1,317	200		1,528	1,851	84	1,935	3,462
2004	1,112	145		1,257	1,006	57	1,063	2,321
2005	630	84	144	859	171	199	370	1,228
2006	1,096	112	237	1,445	131	94	225	1,671
2007	1,108	114		1,222	234	279	513	1,735
2008	1,390	36	103	1,529	224	20	244	1,773
2009	1,003	69	137	1,209	433	146	580	1,789
2010	748	44	48	840	357	97	454	1,294
2011	702	29	13	743	267	20	287	1,030
Minimum	630	29	13	743	131	1	225	1,030
Maximum	17,827	200	428	17,898	10,550	279	10,550	26,463
Average	5,751	82	182	5,881	3,535	71	3,585	9,466

Table 2. Catch at age numbers (thousands) from Canadian and USA fisheries on Eastern Georges Bank.

Year/Age	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16+	Total
1978	1	8	108	3,643	1,167	394	163	127	22	23	6	2	1	0	0	0	0	5,667
1979	1	15	890	734	1,520	543	182	74	61	11	3	2	1	0	1	0	0	4,037
1980	2	6	973	1,650	301	968	354	97	26	46	16	4	1	0	0	0	0	4,445
1981	3	35	860	1,866	1,337	279	475	181	96	59	21	3	1	0	0	0	0	5,216
1982	0	15	3,516	1,971	1,269	1,087	195	399	155	49	14	22	6	3	4	1	0	8,707
1983	10	22	783	2,510	1,297	562	398	118	182	102	25	28	12	1	3	1	0	6,055
1984	0	17	231	805	1,354	546	377	279	39	90	38	17	7	2	3	0	1	3,806
1985	33	9	2,861	1,409	661	987	271	110	110	21	27	3	4	1	1	0	0	6,509
1986	1	41	451	2,266	588	343	456	68	48	29	4	8	1	0	0	0	0	4,303
1987	2	22	4,116	846	1,148	163	132	174	41	24	8	3	1	0	0	0	0	6,680
1988	1	23	289	4,190	680	855	130	116	182	52	21	13	4	1	0	0	0	6,556
1989	1	8	689	812	1,984	228	373	56	40	59	15	7	5	0	0	0	0	4,278
1990	1	11	728	3,111	1,039	1,374	145	153	12	12	24	3	2	1	0	0	0	6,617
1991	0	55	997	1,008	1,930	904	746	105	69	21	11	8	4	2	0	1	0	5,862
1992	0	49	2,596	1,379	462	889	314	315	45	34	3	5	2	1	0	0	0	6,095
1993	0	8	497	1,899	909	299	359	133	97	25	17	2	0	0	0	0	0	4,245
1994	1	5	183	483	788	270	45	61	30	21	2	1	0	0	0	0	0	1,889
1995	3	1	57	237	94	105	18	7	4	4	0	0	0	0	0	0	0	531
1996	0	5	40	234	398	79	60	13	4	3	0	0	0	0	0	0	0	837
1997	1	8	146	206	358	358	83	37	13	4	1	1	0	0	0	0	0	1,217
1998	0	4	102	314	161	158	134	23	13	4	1	0	1	0	0	0	0	915
1999	0	6	80	484	337	109	61	57	14	2	1	0	0	0	0	0	0	1,151
2000	1	2	64	111	381	151	37	22	12	3	0	0	0	0	0	0	0	785
2001	1	3	95	524	210	398	105	32	17	7	1	0	0	0	0	0	0	1,394
2002	1	0	10	126	447	108	156	30	9	6	2	1	0	0	0	0	0	895
2003	13	0	25	154	246	406	82	89	19	4	1	0	0	0	0	0	0	1,040
2004	0	20	10	142	152	148	139	35	30	7	1	1	0	0	0	0	0	685
2005	0	1	67	44	205	52	32	39	11	5	1	0	0	0	0	0	0	458
2006	0	2	20	223	79	194	49	18	17	2	1	0	0	0	0	0	0	607
2007	0	1	44	61	430	35	86	12	7	7	0	0	0	0	0	0	0	683
2008	0	1	41	145	61	249	15	33	4	2	1	0	0	0	0	0	0	553
2009	1	1	51	206	138	42	136	9	11	1	1	0	0	0	0	0	0	597
2010	0	1	25	107	215	74	15	35	3	2	0	0	0	0	0	0	0	477
2011	0	4	44	77	93	115	26	12	7	0	0	0	0	0	0	0	0	379

Table 3. Indices of swept area abundance (thousands) for Eastern Georges Bank cod from the DFO survey.

Year/Age	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16+	Total
1986	0	770	3,538	3,204	331	692	445	219	35	66	0	10	0	0	0	0	0	9,311
1987	0	48	1,791	642	753	162	89	181	89	13	13	0	13	16	0	0	0	3,812
1988	0	148	450	5,337	565	838	95	79	179	18	12	4	0	16	0	0	0	7,741
1989	0	350	2169	764	1,706	258	332	42	85	112	5	32	8	5	0	0	0	5,868
1990	20	106	795	3,471	1,953	4,402	535	1,094	144	157	289	65	52	37	0	0	5	13,125
1991	0	1,198	1,019	1,408	1,639	882	1,195	148	249	38	45	30	12	5	8	0	0	7,876
1992	0	48	2,049	1,221	409	643	451	300	93	38	0	3	3	18	0	0	0	5,276
1993	0	31	355	1,723	622	370	754	274	268	51	31	0	20	6	0	0	0	4,504
1994	0	13	629	691	1,289	477	182	363	84	119	12	0	0	0	8	5	0	3,871
1995	0	32	187	1,240	757	520	186	44	67	28	18	8	6	0	0	0	0	3,093
1996	0	90	203	1,744	4,337	1,432	1,034	445	107	149	39	4	0	0	5	0	0	9,590
1997	0	30	376	568	1,325	1,262	216	50	35	23	17	0	3	0	0	0	0	3,905
1998	0	6	582	831	322	317	238	56	29	7	8	3	4	0	0	0	0	2,402
1999	0	3	156	1,298	1,090	449	317	190	10	28	5	9	0	3	0	0	0	3,561
2000	0	0	423	1,294	4,967	2,157	1,031	510	317	20	23	12	0	0	0	0	0	10,754
2001	0	3	37	802	519	1,391	645	334	224	225	36	24	7	0	0	0	0	4,248
2002	0	0	118	477	2,097	694	1,283	458	188	63	76	7	0	0	0	0	0	5,462
2003	0	0	8	200	510	867	194	219	69	12	0	0	0	0	0	0	0	2,078
2004	0	427	40	246	381	422	353	59	108	25	5	0	3	0	0	0	0	2,069
2005	0	25	1,025	1,398	7,149	1,766	816	743	60	87	8	4	0	0	0	0	0	13,082
2006	0	0	41	1,500	673	1,779	757	217	216	83	34	10	15	0	0	0	0	5,325
2007	0	18	130	549	2,606	379	653	119	81	53	0	4	0	0	0	0	0	4,591
2008	0	12	147	1,027	755	2,978	194	392	41	4	20	0	0	0	0	0	0	5,569
2009	0	11	51	2,487	2,261	519	2,955	0	82	0	0	0	18	0	0	0	0	8,384
2010	0	5	92	956	4,105	1,781	703	1,828	65	84	5	0	0	0	0	0	0	9,623
2011	0	193	271	766	952	1,324	256	67	112	14	8	2	0	0	0	0	0	3,965
2012	0	9	149	327	315	195	158	7	18	4	0	0	0	0	0	0	0	1,182

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Table 4. Indices of swept area abundance (thousands) for Eastern Georges Bank cod from the NMFS spring survey. Conversion factors to account for vessel and trawl door changes have been applied. During 1973-1981 a Yankee 41 net was used rather than the standard Yankee 36 net.

Year/Age	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16+	Total
1970	0	354	1,115	302	610	73	263	48	0	71	24	0	48	0	0	0	0	2,907
1971	0	185	716	503	119	326	124	257	227	40	40	79	0	0	0	0	0	2,615
1972	56	1,578	1,856	2,480	393	114	136	60	88	73	18	14	0	0	14	0	0	6,879
1973	0	665	37,880	5,474	6,109	567	467	413	0	163	231	0	0	0	95	0	0	52,064
1974	0	461	5,877	4,030	759	2,001	360	91	267	45	48	54	0	0	0	0	0	13,991
1975	0	0	467	3,061	4,348	446	960	79	0	122	0	0	0	0	0	0	0	9,483
1976	84	1,733	1,111	620	444	759	0	167	35	0	0	0	0	48	0	0	0	5,001
1977	0	0	2,358	736	354	307	334	22	35	0	0	0	0	0	0	0	0	4,145
1978	373	187	0	2,825	615	916	153	787	62	43	40	0	0	0	0	0	0	6,001
1979	71	339	1,332	122	1,430	543	176	91	130	0	0	0	0	0	0	0	0	4,234
1980	0	11	2,251	2,168	169	1,984	410	78	48	31	0	47	0	0	0	0	0	7,197
1981	283	1,956	1,311	2,006	1,093	43	453	197	59	0	0	0	0	0	0	0	0	7,399
1982	44	455	6,642	13,614	12,667	9,406	0	3,088	992	120	0	0	0	0	0	0	0	47,027
1983	0	389	2,017	3,781	779	608	315	106	98	0	70	0	0	0	0	0	35	8,197
1984	0	103	117	344	483	92	182	74	18	105	0	0	0	0	0	0	0	1,518
1985	58	36	2,032	633	1,061	1,518	328	217	213	83	116	34	23	0	0	0	0	6,352
1986	97	619	339	1,132	298	427	536	20	109	142	0	0	0	0	0	0	0	3,719
1987	0	0	1,194	247	568	0	152	148	30	54	0	0	0	0	0	0	0	2,394
1988	138	320	243	2,795	274	461	51	5	67	0	0	10	0	0	0	0	0	4,364
1989	0	174	1,238	338	1,685	234	396	99	12	36	48	24	0	0	0	0	0	4,284
1990	24	45	360	1,687	586	634	152	164	19	0	0	24	0	0	0	0	0	3,696
1991	217	725	620	514	903	460	382	44	17	0	24	53	0	0	0	0	0	3,957
1992	0	81	666	349	103	261	152	159	27	52	0	0	0	0	0	0	0	1,850
1993	0	0	462	1,284	262	46	182	46	43	46	12	0	0	0	0	0	0	2,382
1994	38	54	194	152	185	44	11	33	0	8	0	0	0	0	0	0	0	720
1995	384	70	294	927	495	932	191	253	0	68	0	0	0	0	0	0	0	3,614
1996	0	139	300	990	1,343	121	94	28	0	0	0	0	0	0	0	0	0	3,016
1997	271	54	218	48	402	519	53	126	57	0	0	0	0	0	0	0	0	1,747
1998	54	0	1,040	1,985	995	983	609	30	31	0	0	0	0	0	0	0	0	5,729
1999	22	22	145	673	624	370	172	107	34	8	0	0	0	0	0	0	0	2,176
2000	36	0	304	643	1,348	492	138	52	20	0	0	0	0	0	0	0	0	3,032
2001	0	0	64	889	96	350	109	0	12	10	0	0	0	0	0	0	0	1,530
2002	36	0	121	470	1081	175	214	61	0	0	0	0	0	0	0	0	0	2,158
2003	0	0	125	287	812	1,154	135	78	9	0	0	0	0	0	0	0	0	2,599
2004	0	549	10	838	2,091	2,105	1,351	239	382	29	0	0	0	0	0	0	0	7,595
2005	36	15	345	70	747	287	190	131	34	0	0	0	0	0	0	0	0	1,855
2006	0	37	73	952	411	1,007	340	151	79	0	0	0	0	0	0	0	0	3,050
2007	0	0	369	308	2,258	239	291	47	28	0	0	0	0	0	0	0	0	3,540
2008	43	37	112	675	372	1,385	51	66	0	0	0	0	0	0	0	0	0	2,741
2009	0	61	86	875	408	219	377	24	12	15	0	0	0	0	0	0	0	2,078
2010	0	25	126	367	667	168	44	147	0	12	0	0	0	0	0	0	0	1,556
2011	0	88	164	164	266	144	56	9	24	0	0	0	0	0	0	0	0	914
2012	0	0	280	413	545	188	123	14	0	0	0	0	0	0	0	0	0	1,563

Table 5. Indices of swept area abundance (thousands) for Eastern Georges Bank cod from the NMFS fall survey. Conversion factors to account for vessel and trawl door changes have been applied.

Year/Age	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16+	Total
1970	348	1,416	836	208	412	11	0	0	5	25	0	0	0	0	0	0	0	3,261
1971	203	1,148	900	181	232	130	142	14	0	0	0	0	0	0	0	0	0	2,951
1972	1,110	3,299	614	667	24	40	0	0	0	0	0	0	0	0	0	0	0	5,753
1973	46	2,435	2,947	997	979	93	0	25	63	0	0	0	0	0	0	0	0	7,584
1974	77	196	399	622	54	31	15	0	0	0	0	0	0	0	0	0	0	1,394
1975	414	660	177	414	764	27	46	0	0	0	0	0	0	0	0	0	0	2,501
1976	0	8,260	362	144	0	91	0	48	0	0	0	0	0	0	0	0	0	8,904
1977	51	0	3,475	714	184	156	178	3	0	0	0	0	0	0	0	0	0	4,760
1978	113	1,519	58	3,027	417	58	63	77	0	0	0	0	0	0	0	0	0	5,330
1979	182	1,704	1,695	116	1,522	243	48	20	11	18	0	0	0	0	0	0	0	5,557
1980	315	782	409	649	22	184	14	17	20	0	0	0	0	0	0	0	0	2,412
1981	360	2,352	1,208	933	269	15	29	0	0	0	53	0	0	0	0	0	0	5,220
1982	0	549	718	54	59	0	0	27	0	0	0	0	0	0	0	0	0	1,406
1983	948	73	267	567	24	8	8	0	23	0	0	0	0	0	0	0	0	1,917
1984	29	1,805	120	690	1,025	23	32	0	0	9	0	0	0	0	0	0	0	3,734
1985	1,245	209	993	161	18	5	9	0	0	0	4	0	0	0	0	0	0	2,645
1986	119	3,018	56	198	0	0	6	0	0	0	0	0	0	0	0	0	0	3,396
1987	156	129	845	121	100	0	0	0	0	0	0	0	7	0	0	0	0	1,357
1988	95	561	177	1,182	163	206	0	30	41	10	0	0	0	0	0	0	0	2,464
1989	318	570	1,335	222	607	78	24	0	0	0	0	0	0	0	0	0	0	3,154
1990	198	403	442	831	120	204	20	0	15	0	0	0	0	0	0	0	0	2,232
1991	0	158	60	71	10	24	0	0	0	0	0	0	0	0	0	0	0	322
1992	0	205	726	154	0	37	12	0	0	0	0	0	0	0	0	0	0	1,134
1993	0	81	104	158	19	0	0	0	0	0	0	0	0	0	0	0	0	362
1994	10	78	282	220	143	13	26	0	0	0	0	0	0	0	0	0	0	771
1995	223	28	122	304	66	29	7	0	0	0	0	0	0	0	0	0	0	779
1996	10	291	76	293	211	53	28	0	0	0	0	0	0	0	0	0	0	961
1997	0	161	394	181	58	84	29	0	0	0	0	0	0	0	0	0	0	907
1998	0	171	684	480	65	109	0	0	29	0	0	0	0	0	0	0	0	1,538
1999	0	15	14	249	124	32	0	0	0	0	0	0	0	0	0	0	0	434
2000	30	55	204	68	89	46	0	0	0	0	0	0	0	0	0	0	0	493
2001	25	74	106	257	38	75	12	12	0	0	0	0	0	0	0	0	0	598
2002	122	110	635	712	2,499	170	211	17	0	0	0	0	0	0	0	0	0	4,476
2003	76	0	24	100	70	17	0	6	0	0	0	0	0	0	0	0	0	293
2004	108	422	68	840	385	545	436	103	30	0	30	0	0	0	0	0	0	2,969
2005	21	29	508	114	251	43	0	10	0	0	0	0	0	0	0	0	0	976
2006	0	146	123	530	37	263	16	16	16	16	0	0	0	0	0	0	0	1,162
2007	60	22	136	7	69	0	7	0	0	0	0	0	0	0	0	0	0	302
2008	0	74	170	55	15	98	15	15	0	0	0	0	0	0	0	0	0	442
2009	54	37	194	280	39	18	11	0	0	0	0	0	0	0	0	0	0	633
2010	434	27	79	74	121	20	0	0	0	0	0	0	0	0	0	0	0	755
2011	126	600	472	260	177	110	32	0	0	0	0	0	0	0	0	0	0	1,776

Table 6. Mohn's rho calculations for the "split M 0.2" and the "split M 0.5" models. The numbers highlighted with yellow are the highest retrospective bias among the 7 years peels.

Peel	"Split M 0.2"			"Split M 0.5"		
	Age 1	3+ Biomass	F	Age 1	3+ Biomass	F
1	-0.18	0.23	-0.24	-0.17	0.21	-0.22
2	0.22	0.84	-0.54	0.25	0.67	-0.43
3	0.09	0.96	-0.49	0.11	0.64	-0.31
4	-0.27	1.57	-0.54	-0.25	1.04	-0.40
5	1.55	1.56	-0.47	1.83	1.09	-0.46
6	0.75	1.54	-0.39	0.67	1.16	-0.39
7	3.77	0.51	-0.46	2.64	0.53	-0.46
Mohn's Rho	0.85	1.03	-0.45	0.73	0.76	-0.38

Table 7. Mohn's rho calculations for the "split M 0.2" and the "split M 0.5" models for the cohort effect examination.

Peel	"Split M 0.2"			"Split M 0.5"		
	Age 1	3+ Biomass	F	Age 1	3+ Biomass	F
1	-0.14	0.28	-0.26	-0.12	0.26	-0.24
2	0.30	0.80	-0.49	0.34	0.75	-0.42
3	0.21	0.76	-0.33	0.24	0.60	-0.22
4	-0.20	1.02	-0.25	-0.17	0.79	-0.18
5	1.71	0.70	-0.47	2.02	0.57	-0.49
6	0.87	0.51	-0.39	0.80	0.35	-0.41
7	0.15	0.50	-0.46	-0.16	0.56	-0.46
Mohn's Rho	0.41	0.65	-0.38	0.42	0.55	-0.35

Table 8. Mohn's rho calculations for the "split M 0.2" and the "split M 0.5" models for the year effect examination.

Peel	"Split M 0.2"			"Split M 0.5"		
	Age 1	3+ Biomass	F	Age 1	3+ Biomass	F
1	0.28	0.58	-0.37	0.33	0.60	-0.39
2	0.56	1.01	-0.54	0.61	1.03	-0.52
3	0.17	0.78	-0.27	0.19	0.78	-0.31
4	-0.21	1.61	-0.55	-0.16	1.66	-0.57
5	1.59	1.44	-0.43	1.80	1.45	-0.47
6	0.39	1.31	-0.27	0.27	1.33	-0.31
7	3.52	0.07	-0.24	3.41	0.14	-0.27
Mohn's Rho	0.90	0.97	-0.38	0.92	1.00	-0.41

Table 9. The AICc comparison results for models when M was estimated starting at different ages during 1994-2011.

Starting Ages	MSR	AICc	Akaike Weight
Age 6	0.907	-19.9	0.95
Age 5	0.916	-13.8	0.04
Age 7	0.925	-7.7	<0.01
Age 8	0.940	2.6	<0.01
Age 4	0.950	9.7	<0.01

Table 10. The AICc comparison results for models when M for ages 6+ is fixed at different values in 1994-2011.

M at Ages 6+	MSR	AICc	Akaike Weight
0.8	0.906	-21.9	>0.99
0.9	0.927	-7.0	<0.01
0.7	0.928	-6.7	<0.01
0.6	0.968	20.2	<0.01
0.5	1.015	50.2	<0.01
0.4	1.064	79.7	<0.01
0.3	1.112	107.5	<0.01
0.2	1.157	133.0	<0.01

Table 11. The mean square residuals (MSR) when fixing M at different values for 2 age groups of ages 4-5 and ages 6+ in post-1994. The highlighted with yellow showed the minimum value of MSR.

fix M ages 45	M ages 6+	MSR
0.1	0.8	0.907
0.2	0.8	0.906
0.3	0.8	0.909

fix M ages 45	M ages 6+	MSR
0.1	0.7	0.935
0.2	0.7	0.928
0.3	0.7	0.924
0.4	0.7	0.925

fix M ages 45	M ages 6+	MSR
0.1	0.6	0.979
0.2	0.6	0.968
0.3	0.6	0.960
0.4	0.6	0.955
0.5	0.6	0.953
0.6	0.6	0.957

Table 12. Beginning of year population abundance (numbers in 000s) for Eastern Georges Bank cod using the "M 0.8" model formulation.

Year/Age	1	2	3	4	5	6	7	8	9	10+	1+
1978	12,459	3,342	10,752	3,989	1,312	714	619	105	111	100	33,503
1979	10,451	10,193	2,639	5,537	2,218	721	438	392	66	143	32,798
1980	10,052	8,543	7,543	1,501	3,169	1,328	427	292	266	156	33,277
1981	17,483	8,225	6,117	4,692	958	1,725	769	262	216	286	40,733
1982	5,694	14,283	5,958	3,335	2,641	534	986	467	128	335	34,361
1983	5,109	4,648	8,534	3,111	1,594	1,190	262	450	243	291	25,433
1984	14,266	4,163	3,101	4,734	1,387	801	617	109	206	283	29,668
1985	5,279	11,665	3,200	1,815	2,661	647	320	256	55	258	26,156
1986	24,093	4,314	6,980	1,361	894	1,294	288	163	111	204	39,702
1987	8,263	19,688	3,126	3,682	588	425	651	174	90	221	36,910
1988	14,188	6,745	12,417	1,800	1,985	335	229	377	106	223	38,405
1989	5,150	11,596	5,262	6,410	864	861	158	84	146	189	30,719
1990	7,528	4,209	8,872	3,577	3,469	503	371	79	33	198	28,837
1991	9,712	6,153	2,790	4,475	1,996	1,611	281	167	53	151	27,390
1992	3,751	7,902	4,140	1,381	1,939	827	652	136	75	124	20,929
1993	4,898	3,027	4,142	2,154	716	794	396	253	71	122	16,573
1994	3,822	4,003	2,030	1,695	950	319	329	205	121	118	13,594
1995	2,229	3,125	3,112	1,228	684	536	115	109	73	92	11,303
1996	3,909	1,824	2,507	2,335	921	465	229	47	46	72	12,354
1997	6,199	3,196	1,457	1,842	1,553	682	170	94	19	51	15,263
1998	2,553	5,068	2,484	1,007	1,185	950	253	53	34	28	13,615
1999	5,991	2,087	4,057	1,751	679	828	340	99	15	24	15,872
2000	2,466	4,899	1,636	2,886	1,131	458	333	117	35	15	13,976
2001	1,582	2,017	3,953	1,240	2,019	790	182	135	44	21	11,983
2002	4,288	1,292	1,566	2,764	826	1,295	287	61	50	24	12,453
2003	835	3,510	1,049	1,169	1,861	578	481	110	22	27	9,643
2004	13,399	684	2,851	720	735	1,158	207	159	37	18	19,971
2005	1,119	10,952	550	2,207	453	469	431	71	52	19	16,324
2006	1,687	915	8,906	411	1,622	324	190	168	25	28	14,276
2007	2,932	1,379	732	7,090	265	1,153	114	74	65	21	13,824
2008	1,809	2,400	1,089	544	5,417	185	463	44	29	34	12,012
2009	1,669	1,480	1,928	761	390	4,210	74	186	17	26	10,741
2010	1,703	1,366	1,166	1,393	499	282	1,803	27	77	18	8,333
2011	5,950	1,393	1,096	858	947	342	117	787	10	41	11,542
2012		4,868	1,101	828	618	672	137	45	349	23	8,640

Table 13. Annual fishing mortality rate for Eastern Georges Bank cod using the “M 0.8” model formulation.

Year/Age	1	2	3	4	5	6	7	8	9	10+	F4-9
1978	0.00	0.04	0.46	0.39	0.40	0.29	0.26	0.26	0.26	0.11	0.36
1979	0.00	0.10	0.36	0.36	0.31	0.32	0.20	0.19	0.20	0.05	0.33
1980	0.00	0.13	0.27	0.25	0.41	0.35	0.29	0.10	0.21	0.16	0.33
1981	0.00	0.12	0.41	0.37	0.38	0.36	0.30	0.51	0.35	0.10	0.37
1982	0.00	0.31	0.45	0.54	0.60	0.51	0.58	0.45	0.54	0.18	0.56
1983	0.00	0.20	0.39	0.61	0.49	0.46	0.67	0.58	0.62	0.30	0.55
1984	0.00	0.06	0.34	0.38	0.56	0.72	0.68	0.49	0.65	0.31	0.48
1985	0.00	0.31	0.66	0.51	0.52	0.61	0.47	0.63	0.55	0.17	0.53
1986	0.00	0.12	0.44	0.64	0.54	0.49	0.30	0.39	0.33	0.07	0.53
1987	0.00	0.26	0.35	0.42	0.36	0.42	0.35	0.29	0.34	0.06	0.40
1988	0.00	0.05	0.46	0.53	0.64	0.55	0.81	0.75	0.77	0.20	0.61
1989	0.00	0.07	0.19	0.41	0.34	0.64	0.50	0.73	0.58	0.17	0.44
1990	0.00	0.21	0.48	0.38	0.57	0.38	0.60	0.19	0.53	0.18	0.47
1991	0.01	0.20	0.50	0.64	0.68	0.70	0.52	0.60	0.55	0.22	0.65
1992	0.01	0.45	0.45	0.46	0.69	0.54	0.75	0.45	0.70	0.11	0.60
1993	0.00	0.20	0.69	0.62	0.61	0.68	0.46	0.54	0.49	0.19	0.61
1994	0.00	0.05	0.30	0.71	0.37	0.22	0.31	0.23	0.28	0.03	0.50
1995	0.00	0.02	0.09	0.09	0.19	0.05	0.09	0.05	0.07	0.00	0.10
1996	0.00	0.02	0.11	0.21	0.10	0.21	0.09	0.12	0.09	0.01	0.17
1997	0.00	0.05	0.17	0.24	0.29	0.19	0.37	0.22	0.32	0.05	0.26
1998	0.00	0.02	0.15	0.19	0.16	0.23	0.14	0.44	0.19	0.11	0.19
1999	0.00	0.04	0.14	0.24	0.19	0.11	0.27	0.23	0.26	0.05	0.20
2000	0.00	0.01	0.08	0.16	0.16	0.12	0.10	0.16	0.12	0.06	0.15
2001	0.00	0.05	0.16	0.21	0.24	0.21	0.29	0.20	0.25	0.08	0.23
2002	0.00	0.01	0.09	0.20	0.16	0.19	0.16	0.23	0.17	0.21	0.19
2003	0.00	0.01	0.18	0.26	0.27	0.23	0.30	0.28	0.30	0.09	0.27
2004	0.00	0.02	0.06	0.26	0.25	0.19	0.28	0.31	0.29	0.18	0.23
2005	0.00	0.01	0.09	0.11	0.14	0.10	0.14	0.25	0.15	0.12	0.12
2006	0.00	0.02	0.03	0.24	0.14	0.24	0.14	0.15	0.15	0.10	0.17
2007	0.00	0.03	0.09	0.07	0.16	0.11	0.16	0.15	0.15	0.04	0.08
2008	0.00	0.02	0.15	0.13	0.05	0.12	0.11	0.14	0.11	0.04	0.06
2009	0.00	0.04	0.12	0.21	0.12	0.05	0.20	0.08	0.12	0.04	0.08
2010	0.00	0.02	0.10	0.18	0.17	0.07	0.03	0.16	0.03	0.03	0.10
2011	0.00	0.03	0.07	0.12	0.13	0.11	0.15	0.01	0.03	0.01	0.10

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Table 14. Beginning of year population abundance (numbers in 000s) for Eastern Georges Bank cod using the "M 0.8" model formulation.

Year/Age	1	2	3	4	5	6	7	8	9	10+	1+	3+
1978	1,391	2,963	17,457	14,216	7,104	4,461	5,337	944	1,134	1,463	56,471	52,117
1979	1,174	8,843	4,591	16,585	10,125	3,741	4,220	4,266	727	2,096	56,368	46,351
1980	2,778	6,032	14,274	4,181	16,615	8,341	2,525	2,623	3,133	2,286	62,788	53,978
1981	1,654	7,011	11,171	15,681	4,762	11,839	6,296	3,329	2,431	4,179	68,353	59,688
1982	524	12,413	13,224	10,172	10,866	3,433	7,952	4,124	1,381	4,903	68,990	56,054
1983	1,144	5,257	15,972	7,040	4,992	7,151	2,138	3,897	2,561	4,252	54,403	48,003
1984	719	2,421	6,059	11,567	3,744	3,300	3,635	982	2,117	4,141	38,685	35,545
1985	460	7,540	6,162	5,817	10,061	3,774	2,803	2,527	774	3,776	43,694	35,695
1986	3,161	3,322	12,157	4,378	4,398	7,374	2,140	1,463	1,188	2,992	42,574	36,091
1987	1,239	16,637	5,318	9,889	3,338	3,179	4,872	1,162	914	3,241	49,789	31,912
1988	2,160	6,276	22,168	5,435	8,275	2,100	1,933	3,288	1,312	3,270	56,217	47,781
1989	732	9,646	8,971	17,686	3,722	5,535	1,203	654	1,653	2,772	52,575	42,196
1990	1,616	3,314	16,350	10,369	15,132	3,018	3,184	750	445	2,896	57,074	52,144
1991	852	5,518	5,445	14,174	8,470	7,884	2,121	1,678	533	2,210	48,886	42,516
1992	476	6,686	8,469	3,858	8,073	5,067	4,554	1,165	740	1,819	40,907	33,745
1993	344	2,889	7,640	6,261	3,232	4,675	2,771	1,869	659	1,788	32,129	28,895
1994	547	2,629	2,910	4,456	3,758	2,379	2,412	1,777	1,069	1,730	23,668	20,492
1995	408	2,482	4,940	2,757	2,376	2,516	767	861	868	1,352	19,327	16,437
1996	342	1,528	3,893	6,062	3,598	2,845	1,249	565	551	1,051	21,684	19,813
1997	1,177	2,290	2,467	4,008	4,998	4,231	1,056	921	191	745	22,085	18,617
1998	199	3,295	3,433	2,274	3,596	4,289	1,474	410	277	408	19,656	16,162
1999	663	2,089	5,477	3,918	2,020	3,837	2,218	817	129	348	21,516	18,763
2000	149	4,387	2,597	6,713	3,656	2,043	2,163	957	408	226	23,300	18,764
2001	16	1,556	5,605	3,203	7,273	4,020	1,255	1,020	456	241	24,643	23,072
2002	68	640	1,901	6,271	2,921	5,677	1,683	516	495	281	20,453	19,746
2003	13	1,547	1,198	2,200	5,668	1,944	2,465	736	167	320	16,257	14,697
2004	289	197	4,145	1,763	2,537	4,733	893	1,008	392	215	16,172	15,685
2005	65	6,449	643	3,905	1,347	1,547	1,696	540	338	226	16,754	10,241
2006	52	281	10,252	647	4,251	1,031	878	789	142	325	18,646	18,313
2007	158	863	785	12,505	695	4,725	661	503	517	244	21,654	20,634
2008	83	1,384	1,580	1,110	13,566	641	1,926	347	287	395	21,318	19,851
2009	191	1,072	2,833	1,890	1,053	14,849	329	1,041	147	304	23,710	22,447
2010	135	897	1,837	3,084	1,594	986	7,145	145	559	210	16,592	15,560
2011	227	672	1,307	1,747	2,565	1,224	429	3,531	52	482	12,236	11,337
2012		2,493	1,300	1,763	1,786	2,533	697	283	1,851	267	12,974	10,481

Table 15. The CV values of the estimated population number in terminal year from the “M 0.8” model and the “basic VPA” model.

Parameter	CV M 0.8	CV basic VPA
N[2012 2]	0.47	0.57
N[2012 3]	0.37	0.45
N[2012 4]	0.33	0.39
N[2012 5]	0.31	0.39
N[2012 6]	0.30	0.46
N[2012 7]	0.33	0.57
N[2012 8]	0.31	0.51
N[2012 9]	0.18	0.29

Table 16. Mohn’s rho calculations for the “basic VPA” and the “M 0.8” models for the 7 years peels.

Peel	"basic VPA"			"M 0.8"		
	Age 1	3+ Biomass	F	Age 1	3+ Biomass	F
1	-0.31	0.04	-0.14	-0.31	0.01	-0.01
2	-0.13	0.67	-0.40	-0.16	0.02	0.11
3	-0.27	0.69	-0.30	-0.33	-0.17	0.37
4	-0.60	1.02	-0.34	-0.63	-0.09	0.25
5	0.99	1.35	-0.69	0.54	-0.01	-0.22
6	0.13	1.19	-0.62	-0.22	0.02	-0.15
7	0.96	2.27	-0.74	0.05	0.10	-0.28
Mohn's Rho	0.11	1.03	-0.46	-0.15	-0.02	0.01

Table 17. Mohn's rho calculations for 14-years retrospective analysis of 3+ biomass for the "M 0.8" and "basic VPA" model.

M 0.8	3+ biomass	Mohn's rho	basic VPA	3+ biomass	Mohn's rho
2011	0.01		2011	0.04	
2010	0.02		2010	0.67	
2009	-0.17		2009	0.69	
2008	-0.09		2008	1.02	
2007	-0.01		2007	1.35	
2006	0.02	7 years peel	2006	1.19	7 years peel
2005	0.10	-0.02	2005	2.27	1.03
2004	-0.21	-0.05	2004	1.40	1.22
2003	-0.19	-0.08	2003	1.16	1.30
2002	-0.26	-0.09	2002	0.97	1.33
2001	-0.18	-0.10	2001	1.05	1.34
2000	0.06	-0.09	2000	1.73	1.39
1999	-0.02	-0.10	1999	1.72	1.47
1998	-0.01	-0.12	1998	1.83	1.41
average		-0.07	average		1.22

Table 18. The value of estimated M for ages 6+ in 1994-2011 in the retrospective analysis for the years of 1998-2012.

Year	M	CV
1998	0.62	0.242
1999	0.67	0.167
2000	0.75	0.112
2001	0.7	0.104
2002	0.72	0.088
2003	0.7	0.079
2004	0.74	0.067
2005	0.73	0.063
2006	0.76	0.054
2007	0.75	0.051
2008	0.78	0.056
2009	0.8	0.042
2010	0.78	0.041
2011	0.80	0.036
2012	0.80	0.036
Average	0.74	

Table 19. Data input for per recruit analysis using assessment result from the "M 0.8" model.

Age	M	PR	Fishery Weight	Spawning Weight	Maturity
1	0.2	0.01	0.37	0.07	0
2	0.2	0.1	1.16	0.63	0
3	0.2	0.6	1.93	1.37	1
4	0.2	1	2.81	2.19	1
5	0.2	1	3.80	3.14	1
6	0.8	1	4.88	4.39	1
7	0.8	1	6.10	5.39	1
8	0.8	1	7.41	7.40	1
9	0.8	1	8.85	8.74	1
10+	0.8	1	11.65	11.65	1

Table 20. Projection results for Eastern Georges Bank cod using "M 0.8" model under different fishing mortality rates.

a. Projected population biomass (mt)

F=0.11												
Year/Age	1	2	3	4	5	6	7	8	9	10+	1+	3+
2012	74	2482	1299	1763	1787	2532	698	283	1850	267	13036	10480
2013	123	1109	5194	1825	1864	1720	1204	311	111	1834	15295	14062
2014	123	1109	2132	5284	1841	1689	813	616	137	894	15638	14406

F=0												
Year/Age	1	2	3	4	5	6	7	8	9	10+	1+	3+
2012	74	2482	1299	1763	1787	2532	698	283	1850	267	13036	10480
2013	123	1109	5194	1825	1864	1720	1204	311	111	1834	15295	14062
2014	123	1110	2180	5862	2055	1885	907	687	152	923	16885	15652

b. Projected catch (mt) at F=0.11

Year/Age	1	2	3	4	5	6	7	8	9	10+	1+	3+
2012	1	68	94	127	122	117	29	12	103	2	675	606
2013	1	49	572	223	213	140	103	26	13	28	1368	1318

FIGURES

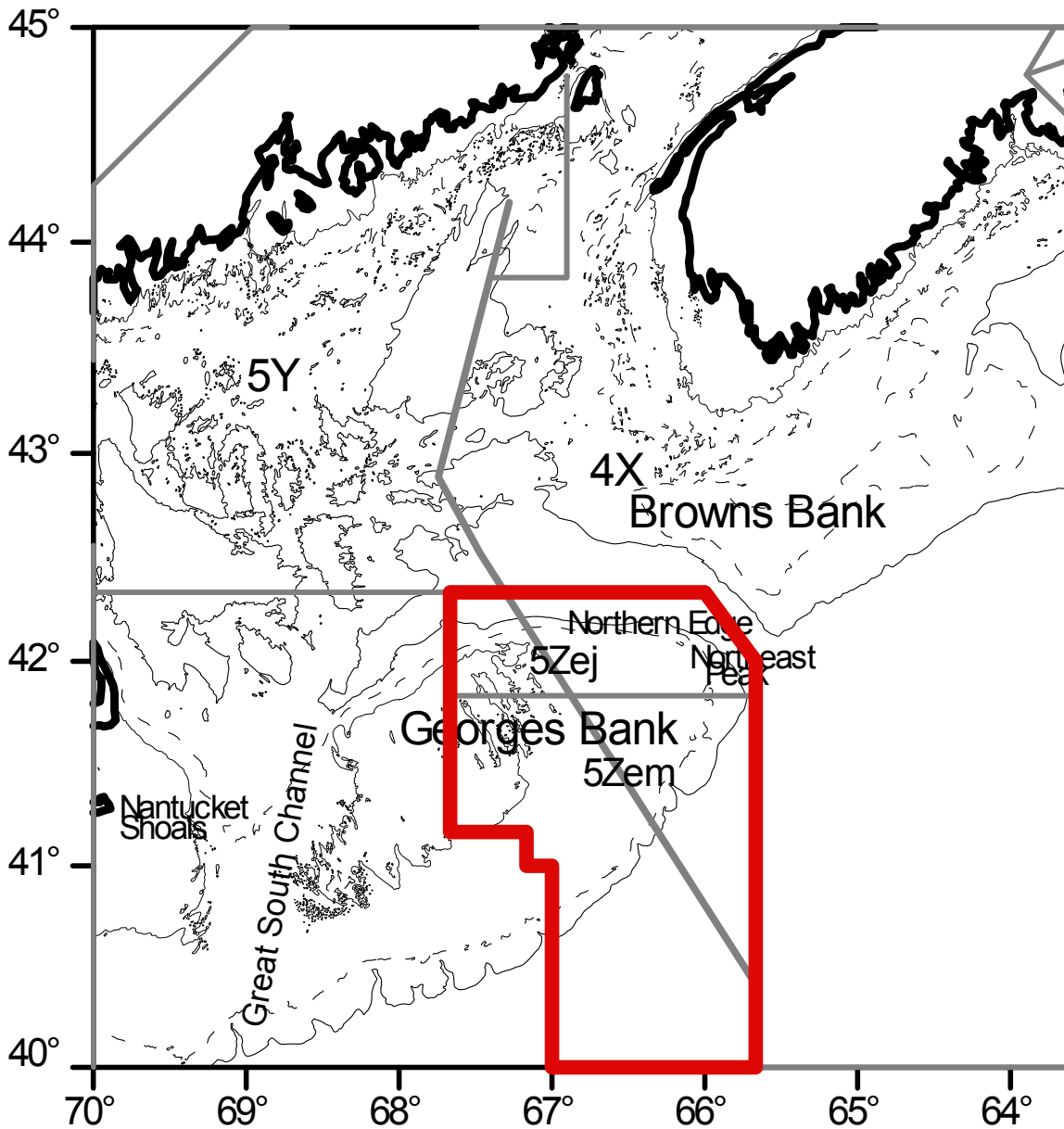


Figure 1. Transboundary management unit area of Atlantic Cod on Eastern Georges Bank shown in red line.

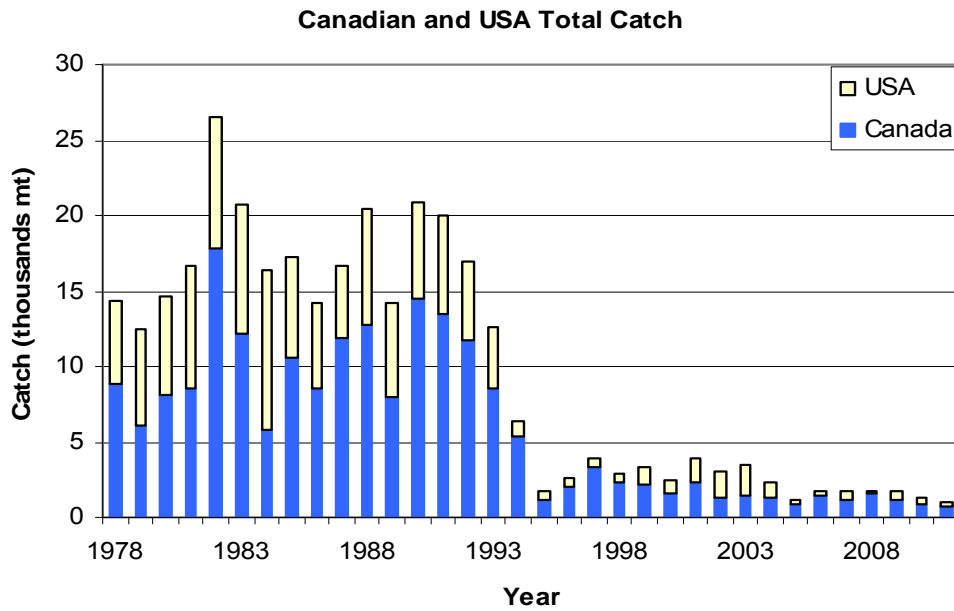


Figure 2. Fishery catches (landings + discards) of cod on Eastern Georges Bank.

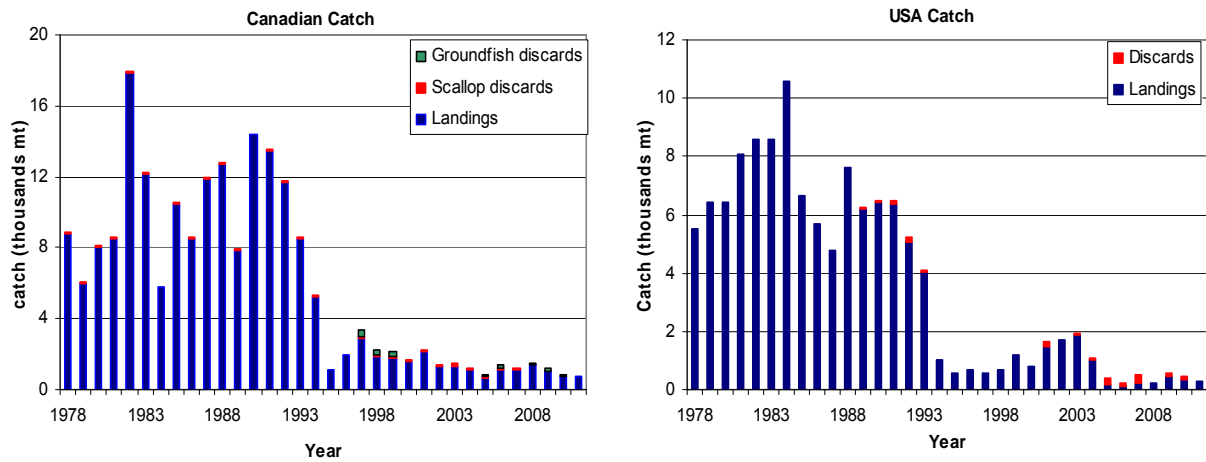


Figure 3. Canadian and USA catch of cod on Eastern Georges Bank.

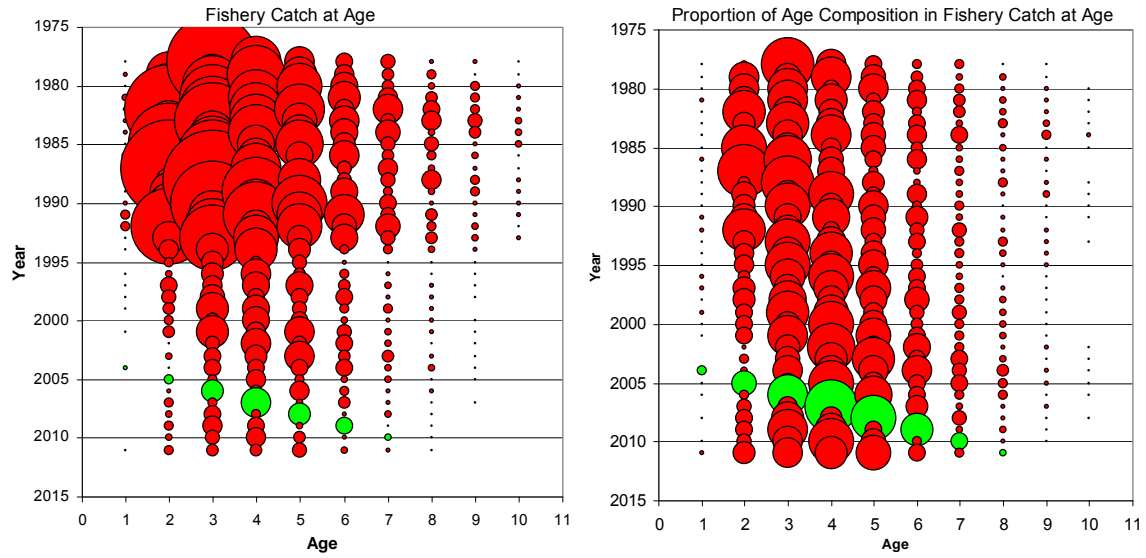


Figure 4. Fishery catch at age of Eastern Georges Bank cod during 1978-2011. The 2003 year class is identified with green bubbles.

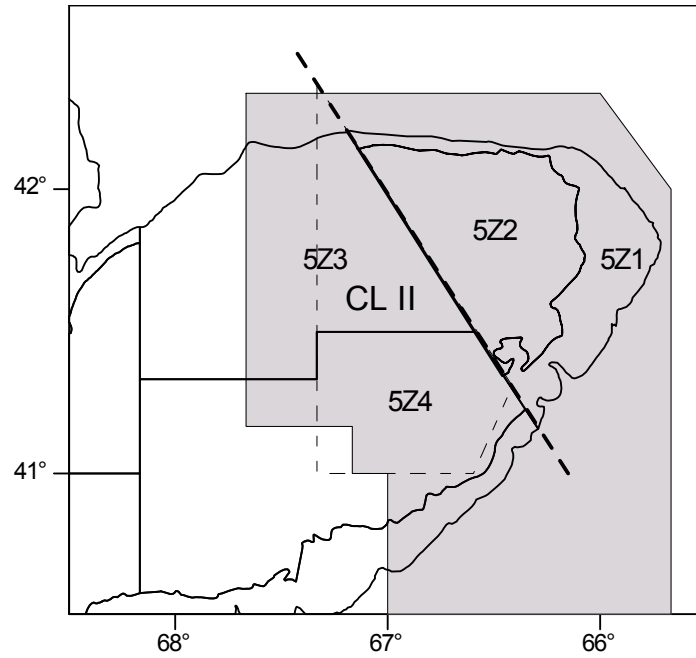


Figure 5. Stratification used for the DFO survey. The eastern Georges Bank management unit is indicated by shading. CL II is the closed area II.

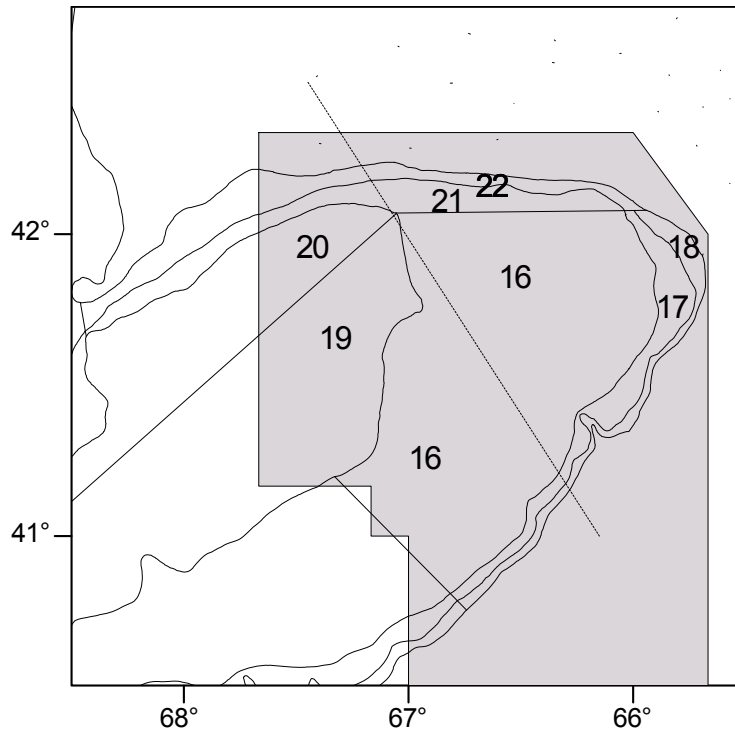


Figure 6. Stratification used for the NMFS surveys.

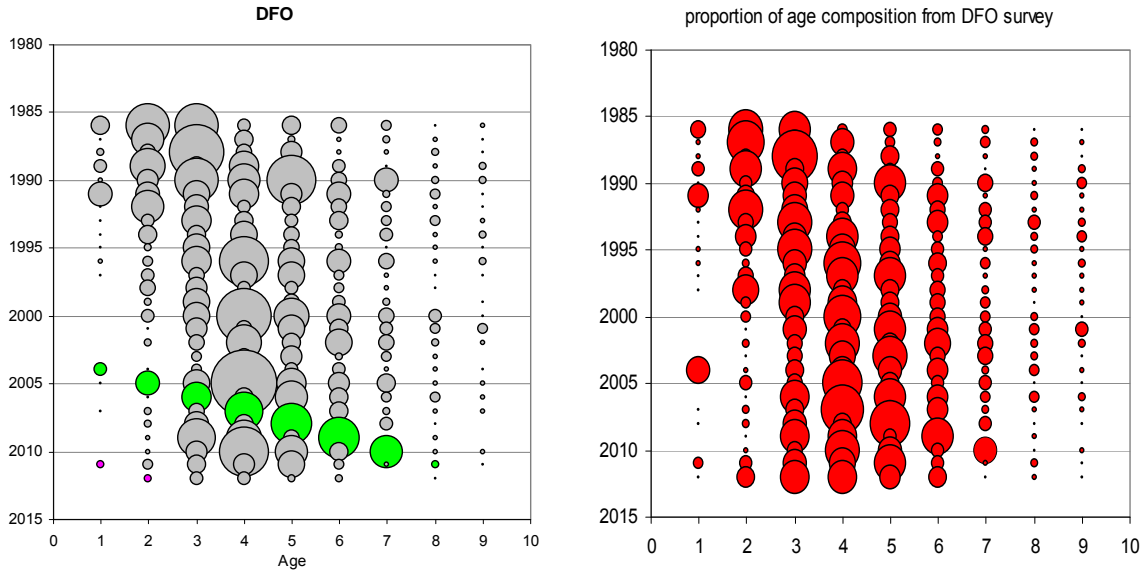


Figure 7. DFO survey abundance at age (numbers) and proportion at age (1986-2012) of Eastern Georges Bank cod. The bubble area is proportional to the magnitude. The 2003 year class is identified with green bubbles.

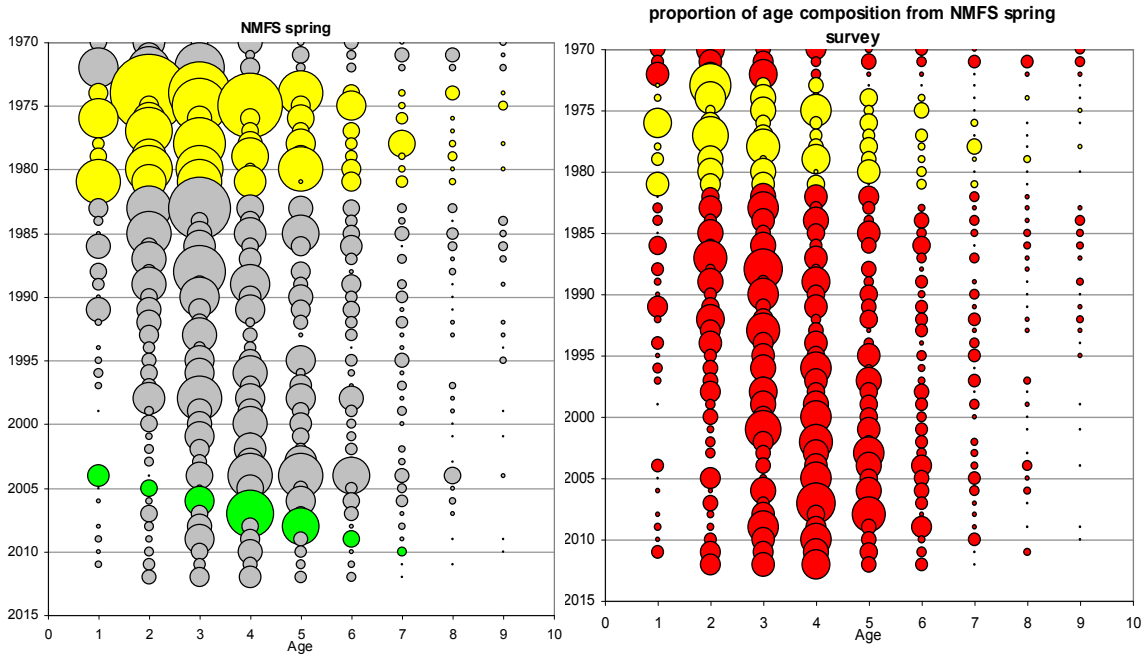


Figure 8. NMFS spring survey abundance at age (numbers) and proportion at age (1970-2012) of Eastern Georges Bank cod. The bubble area is proportional to the magnitude. The NMFS spring survey was conducted using a modified Yankee 41 during 1978 to 1981 (yellow bubbles). Conversion factors to account for changes in door type and survey vessel were applied to the NMFS spring survey. The 2003 year class is identified with green bubbles.

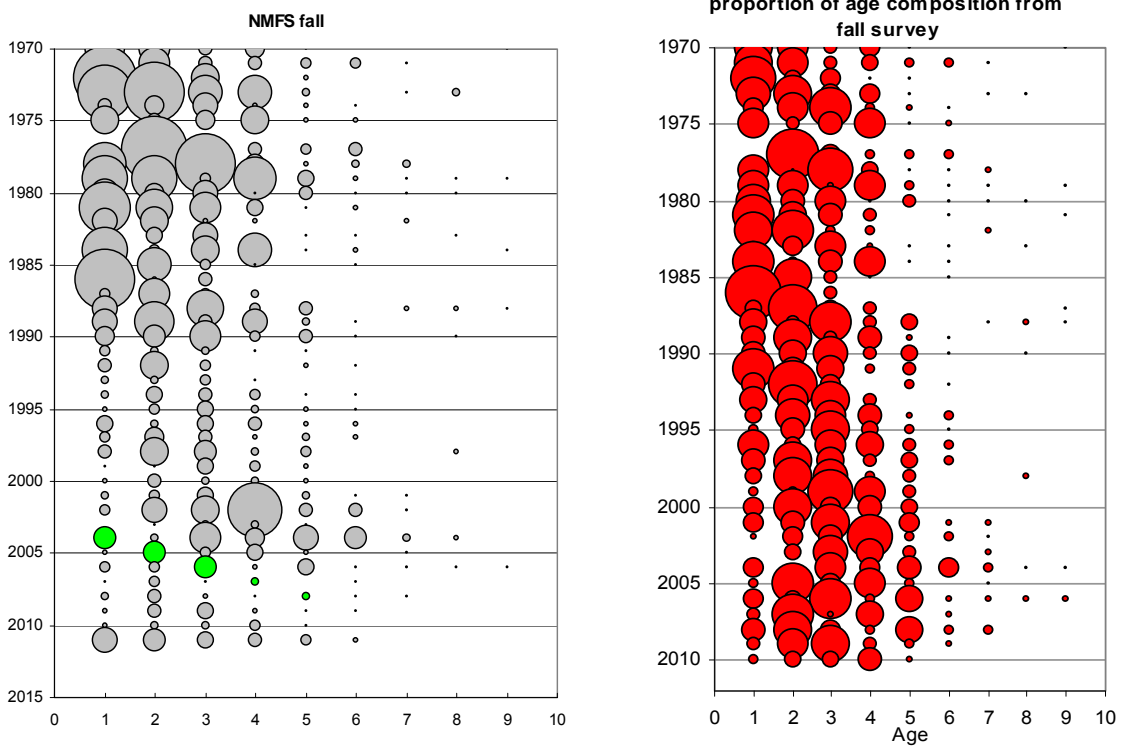


Figure 9. NMFS fall survey abundance at age (numbers) and proportion at age (1970-2011) of Eastern Georges Bank cod. The bubble area is proportional to the magnitude. Conversion factors to account for changes in door type and survey vessel were applied to the NMFS spring survey. The 2003 year class is identified with green bubbles.

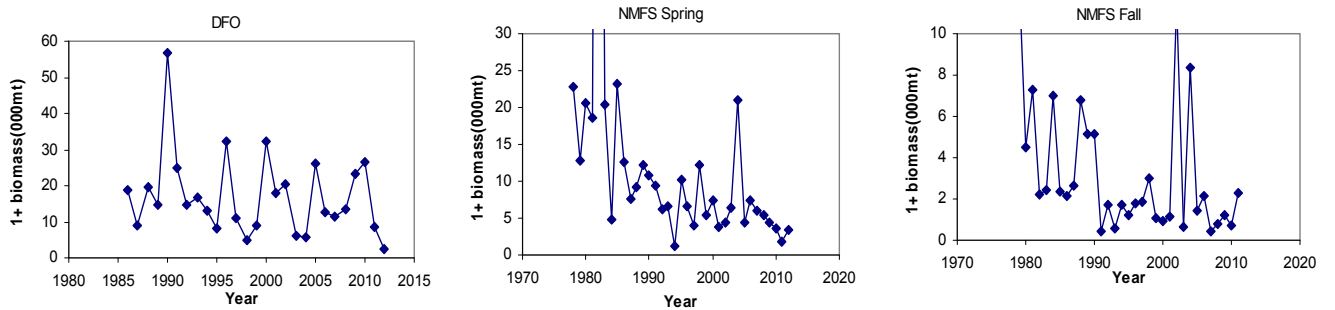


Figure 10. Swept area survey biomass of Eastern Georges Bank cod from 3 surveys.

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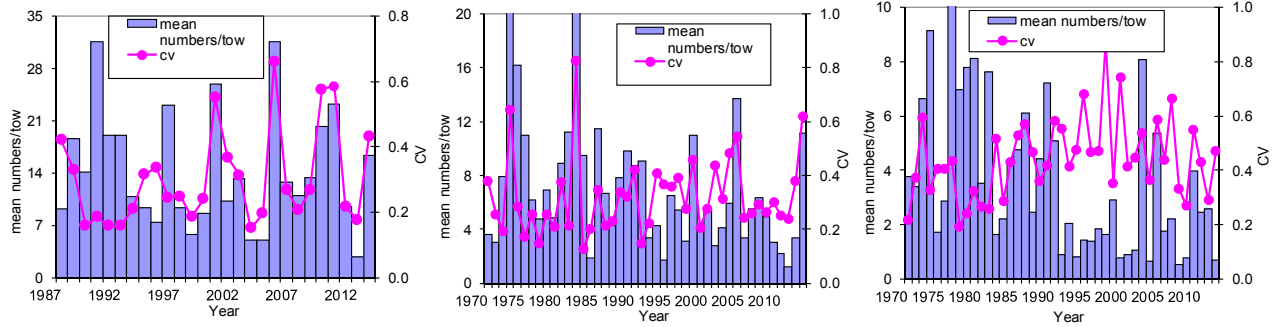


Figure 11. The mean number/tow and coefficient of variation (CV) for the DFO (left panel), NMFS spring (middle panel) and fall survey (right panel) catch of Eastern Georges Bank cod.

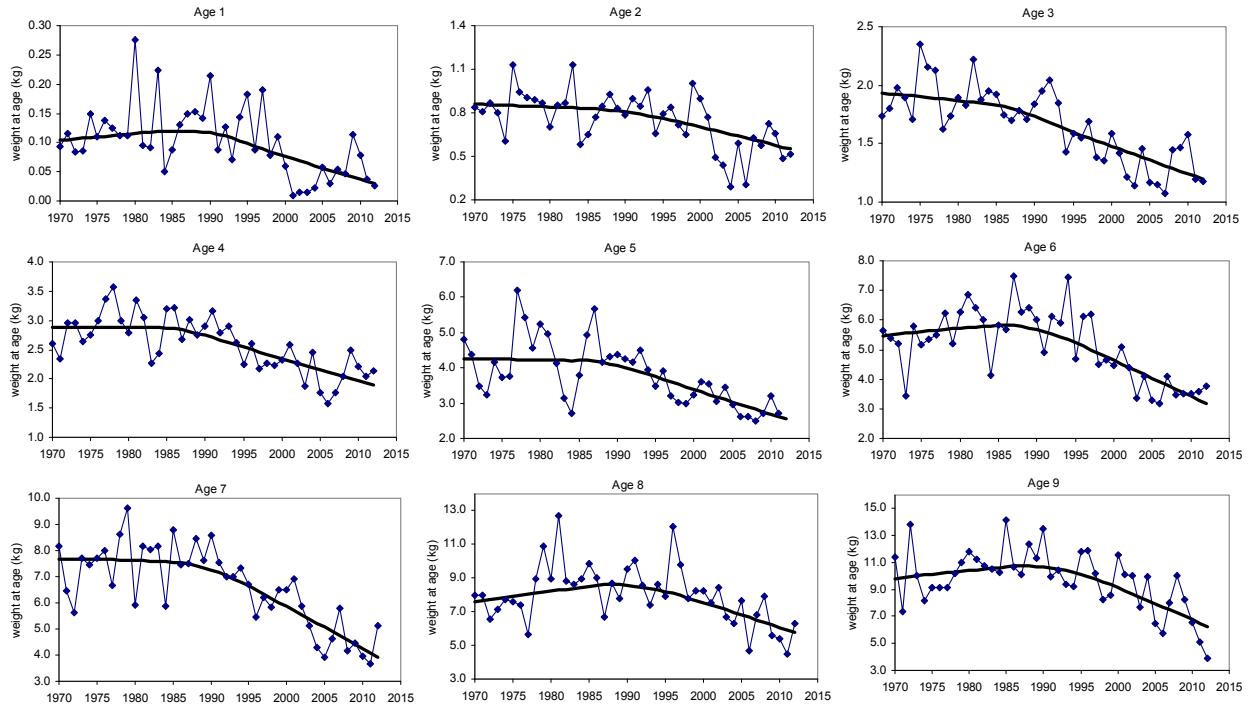


Figure 12. Beginning of year weight at age of Eastern Georges Bank cod from DFO and NMFS spring surveys. The lines show the smoothed values using LOESS method.

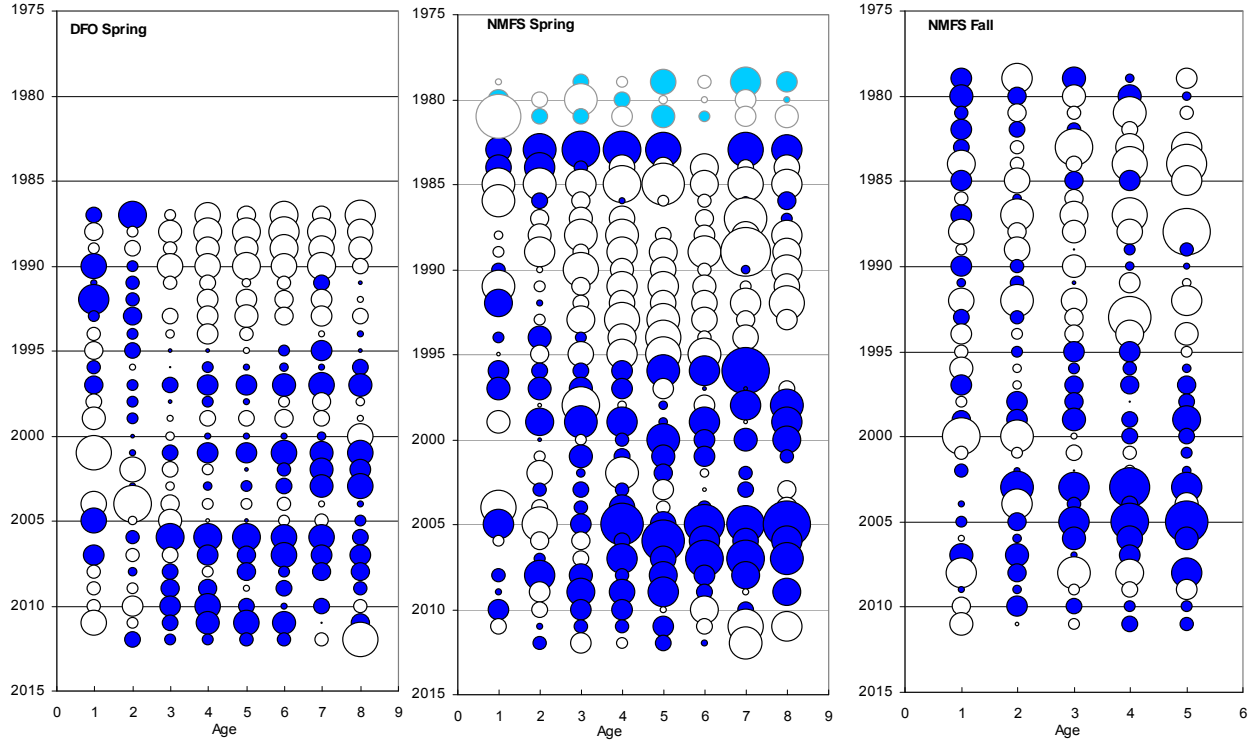


Figure 13. Residuals from the “basic VPA” model. Solid bubbles indicate positive values, open bubbles indicate negative values and the bubble area is proportional to magnitude. The NMFS spring survey was conducted using a modified Yankee 41 from 1978 to 1981 (pale blue bubbles).

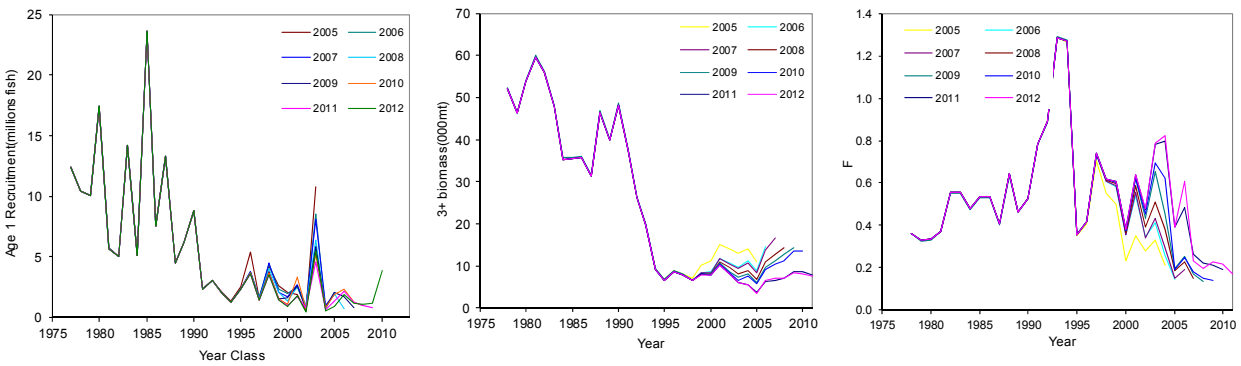
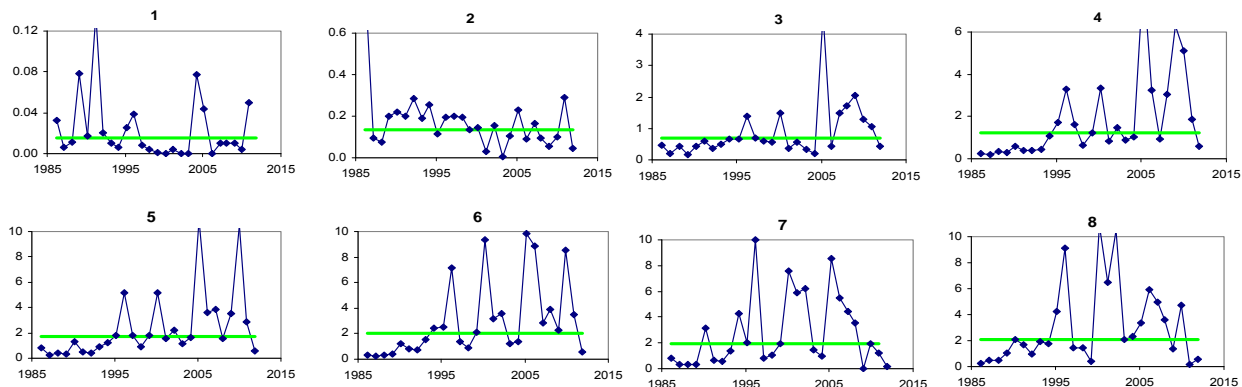
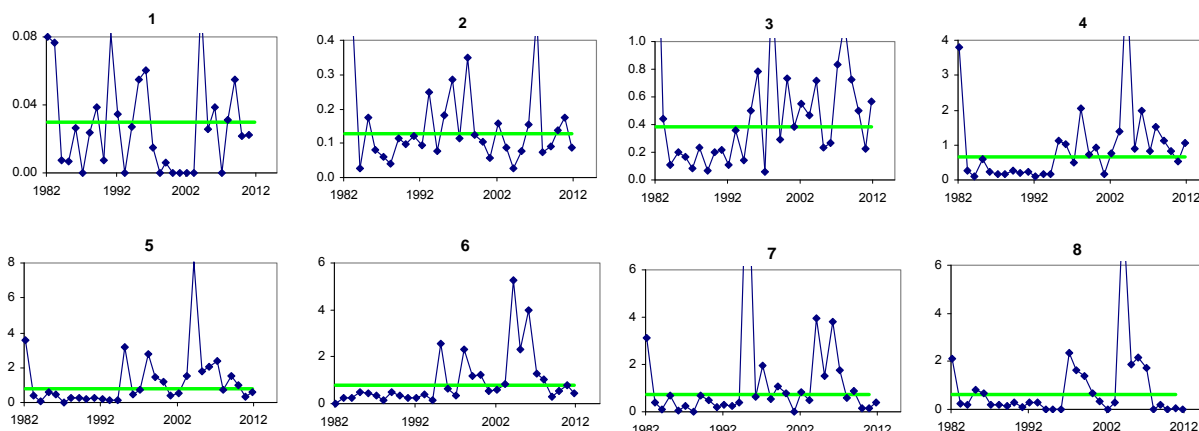


Figure 14. Retrospective pattern from the “basic VPA “ model.

a) DFO Survey



b) NMFS Spring Survey



c) NMFS Fall Survey

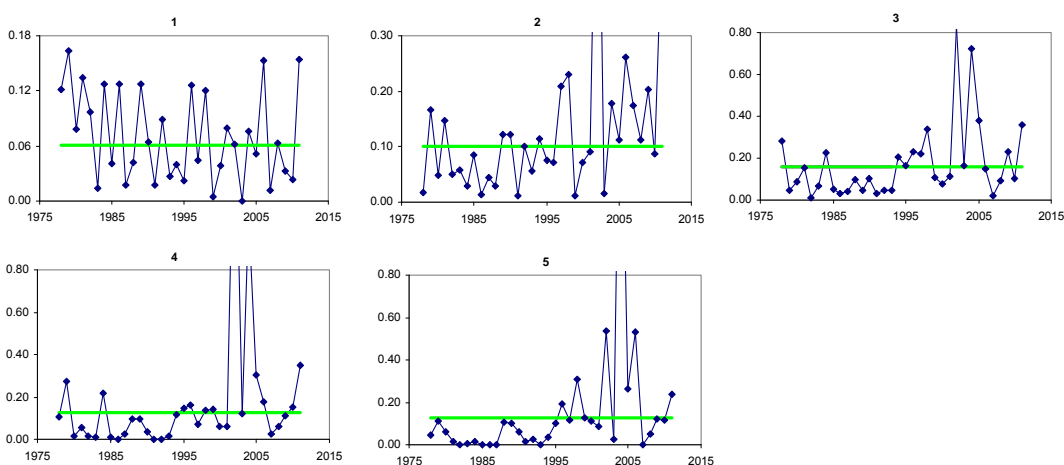


Figure 15. Time trends in survey catchability at age of cod on Eastern Georges Bank, estimated (horizontal line) and calculated (survey abundance indices at age/estimated population abundance at age, diamonds) from the “basic VPA” model: a) DFO survey, b) NMFS spring survey, c) NMFS fall survey.

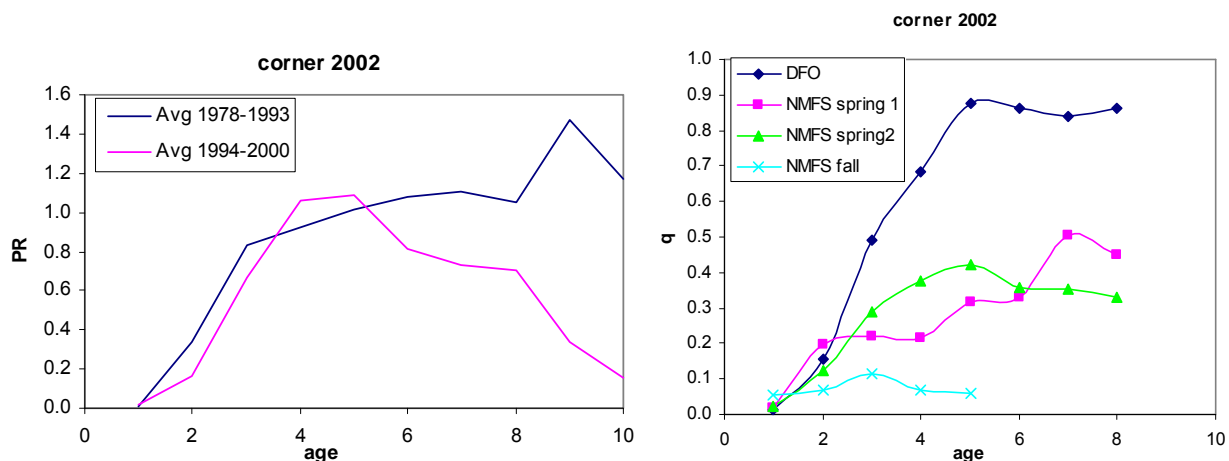


Figure 16. Fishery partial recruitment and survey catchability from the 2002 benchmark formulation when using data up to 2002 only.

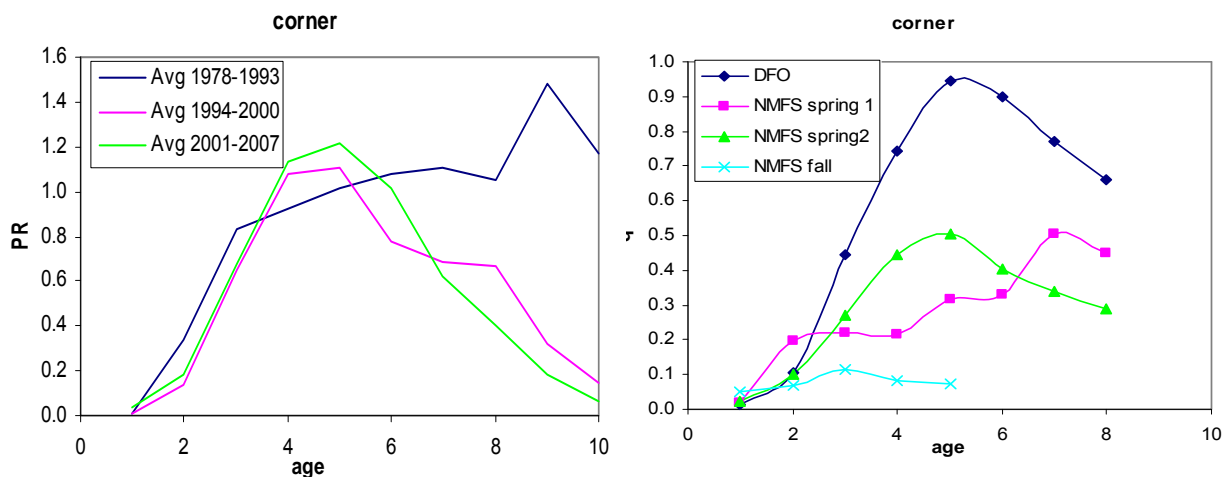


Figure 17. Fishery partial recruitment and survey catchability from the 2002 benchmark formulation when using data up to 2008.

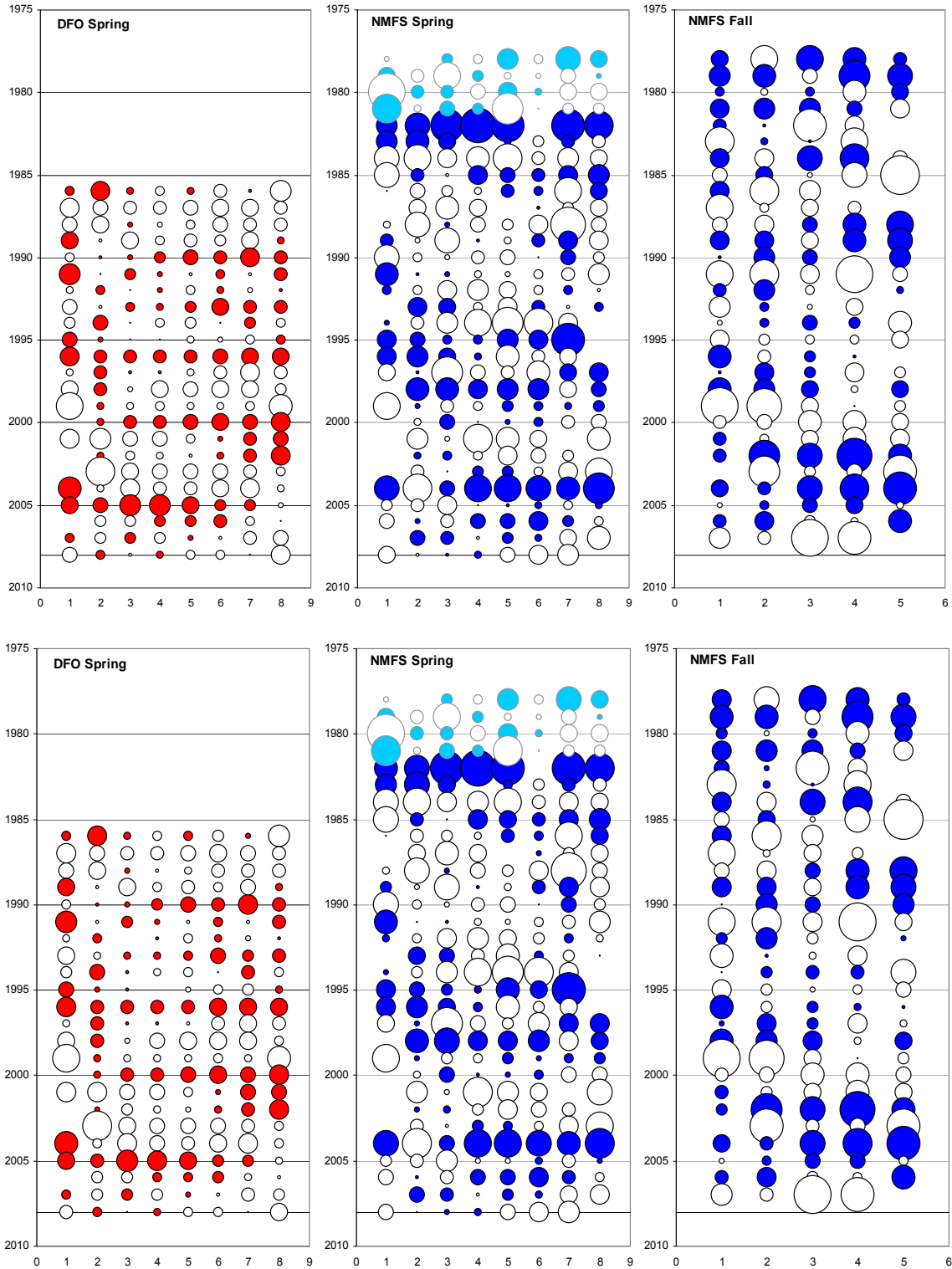
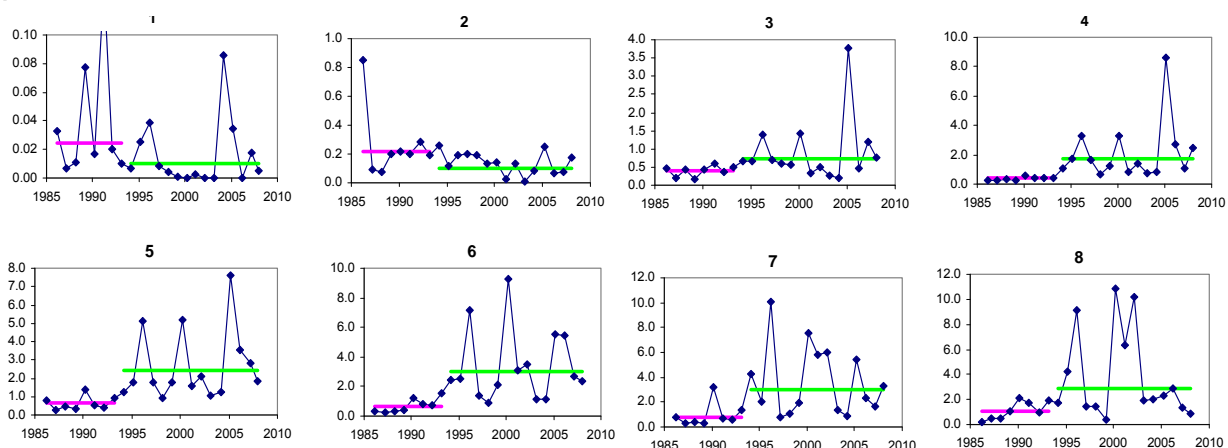
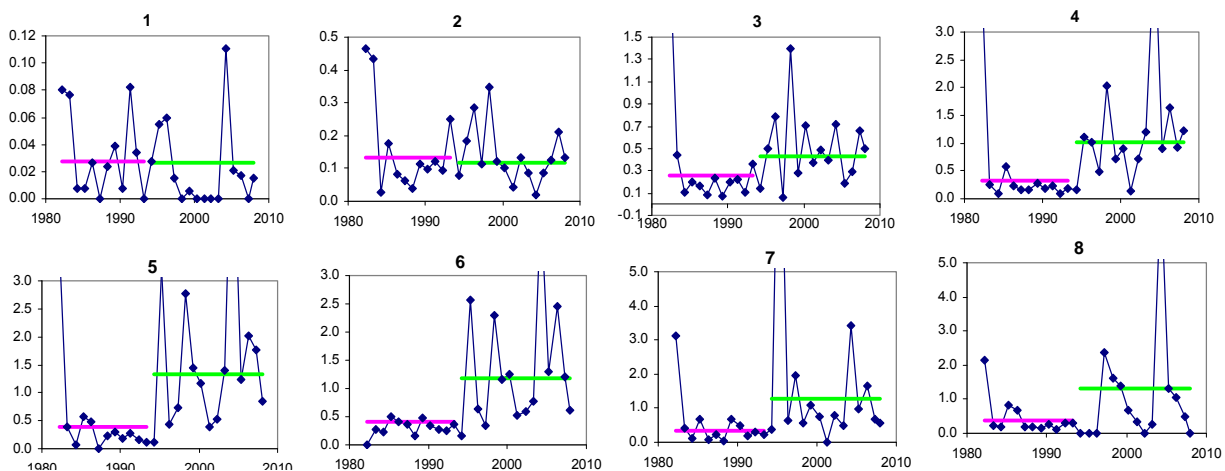


Figure 18. Residuals by year and age group from survey indices for Eastern Georges Bank cod using data up to 2008 only. Solid bubbles indicate positive values, open bubbles indicate negative values and the bubble area is proportional to magnitude. The NMFS spring survey was conducted using a modified Yankee 41 from 1978 to 1981 (pale blue bubbles). The upper figures are from the “split M 0.2” model and the lower figures are from the “split M 0.5” model.

a) DFO



b) NMFS Spring



c) NMFS Fall

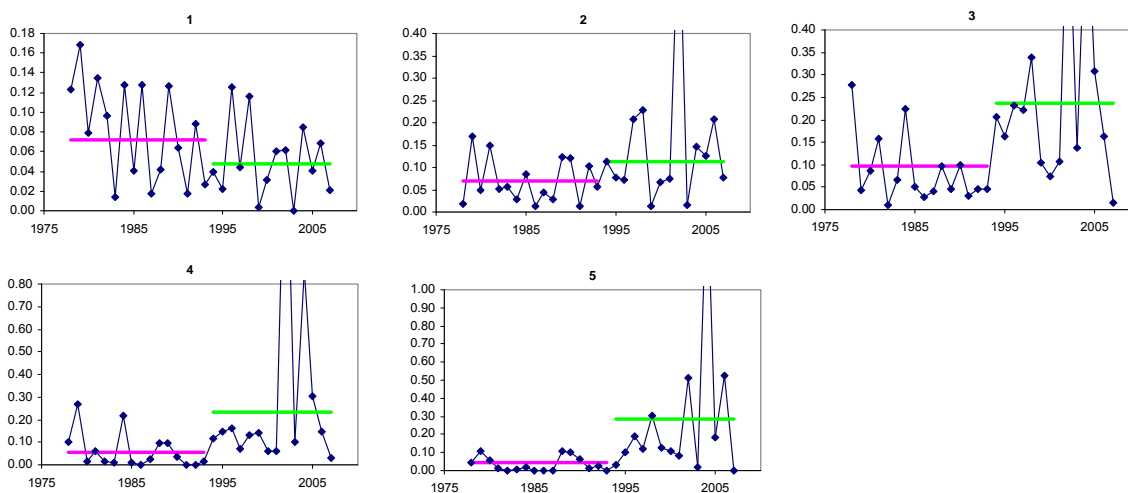
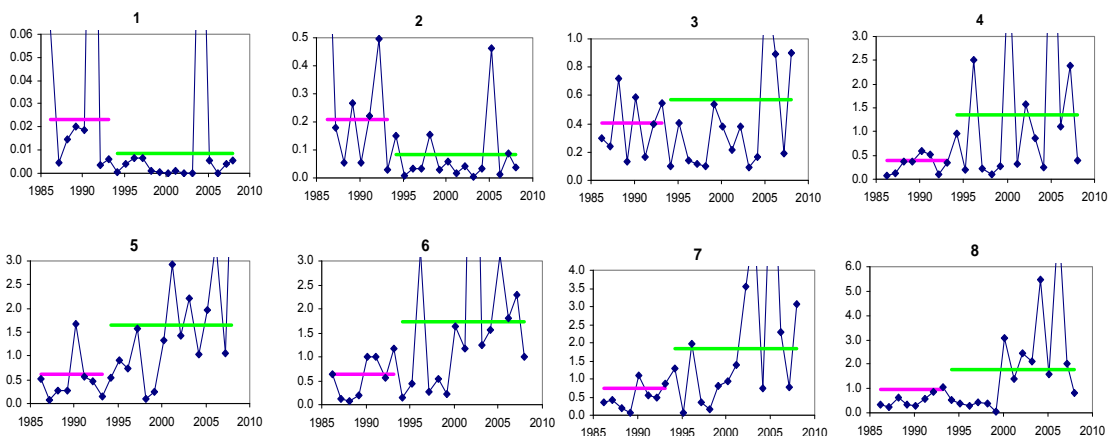
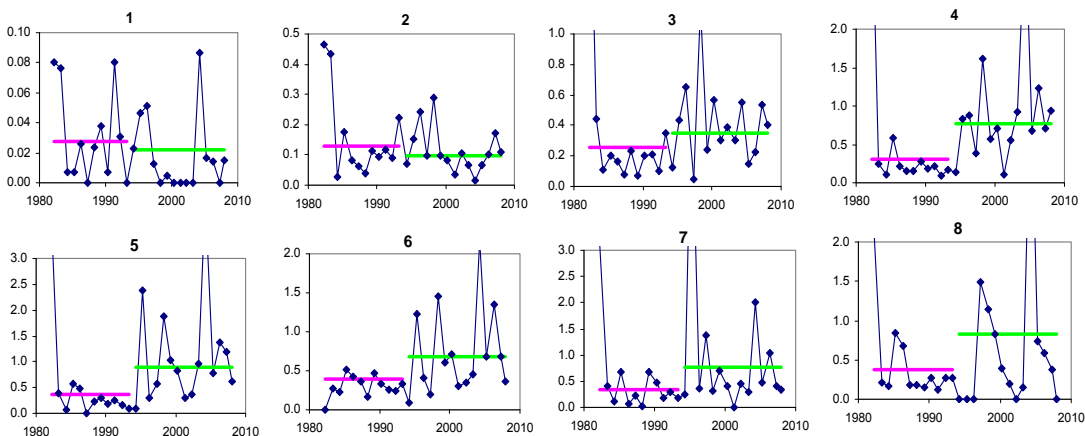


Figure 19a. Time trends in survey catchability at age of cod on Eastern Georges Bank, estimated (horizontal line) and calculated (diamonds) from the “split M 0.2” model formulation using data up to 2008 only.

a) DFO Survey



b) NMFS Spring Survey



c) NMFS Fall Survey

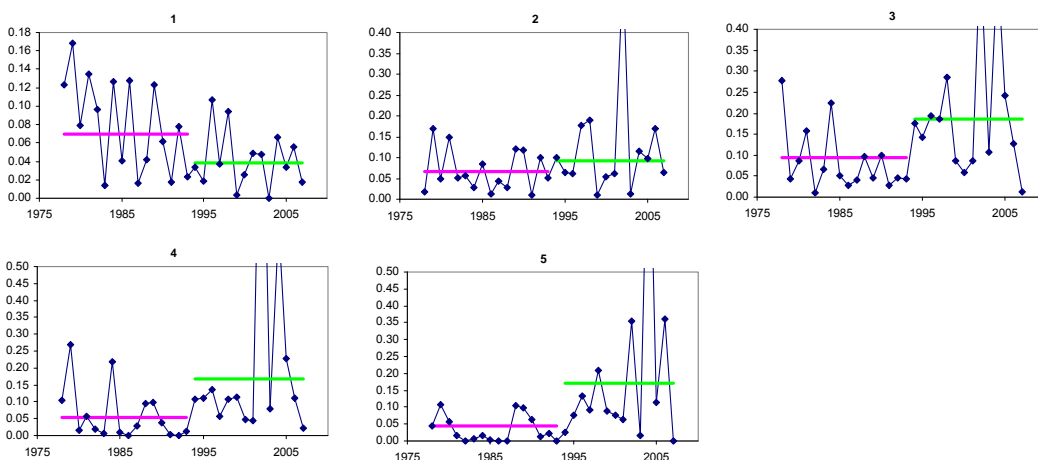


Figure 19b. Time trends in survey catchability at age of cod on Eastern Georges Bank, estimated (horizontal line) and calculated (survey abundance indices at age/estimated population abundance at age, diamonds) from the “split M 0.5” model formulation using data up to 2008 only

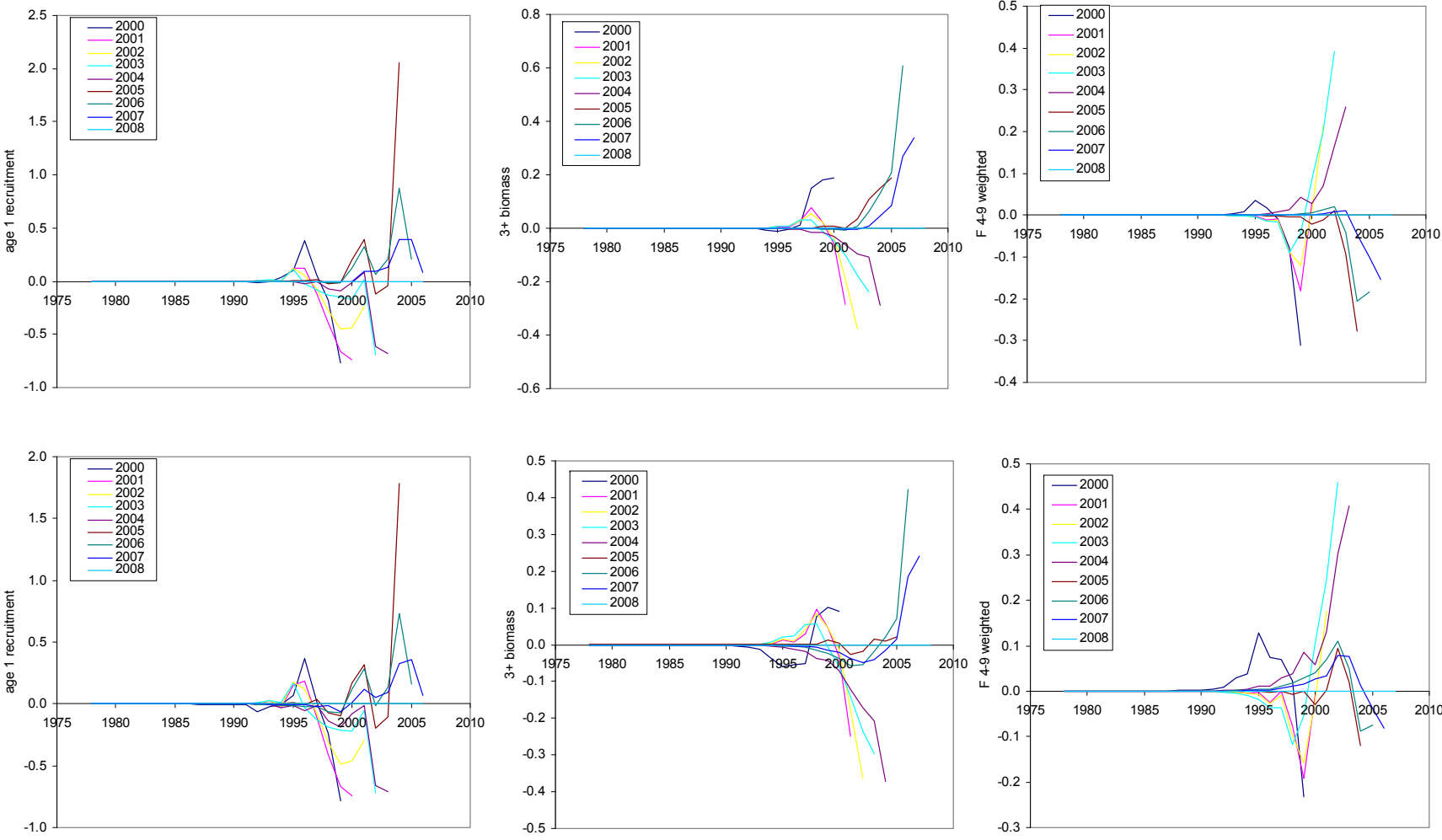


Figure 20. Relative retrospective patterns for “split M 0.2” model (top), and “split M 0.5” model (bottom) for cod on Eastern Georges Bank using data up to 2008 only.

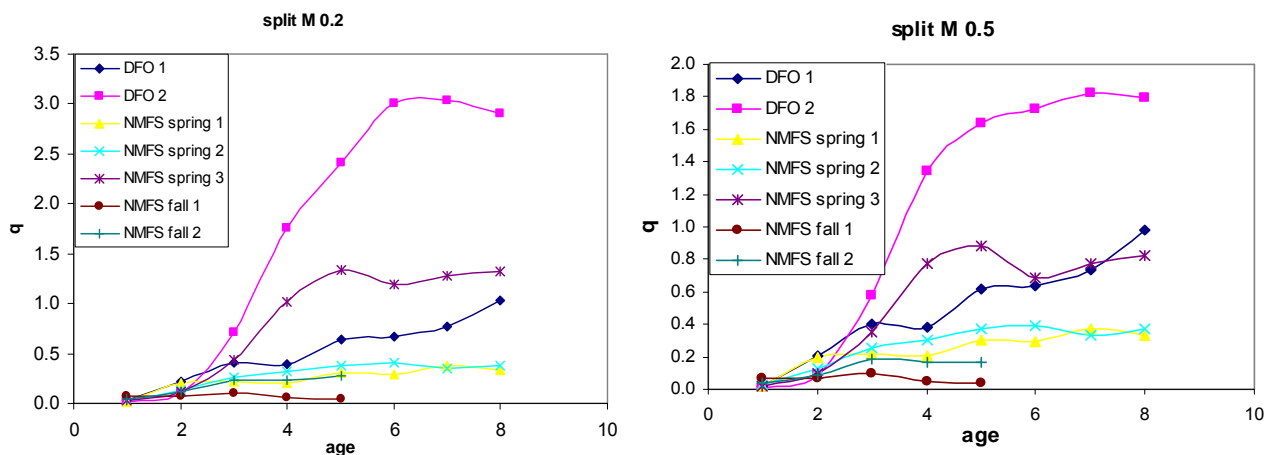


Figure 21. Survey catchability (q) for the DFO, NMFS spring and NMFS fall surveys from the “split M 0.2” and “split M 0.5” model formulations using data up to 2008 only.

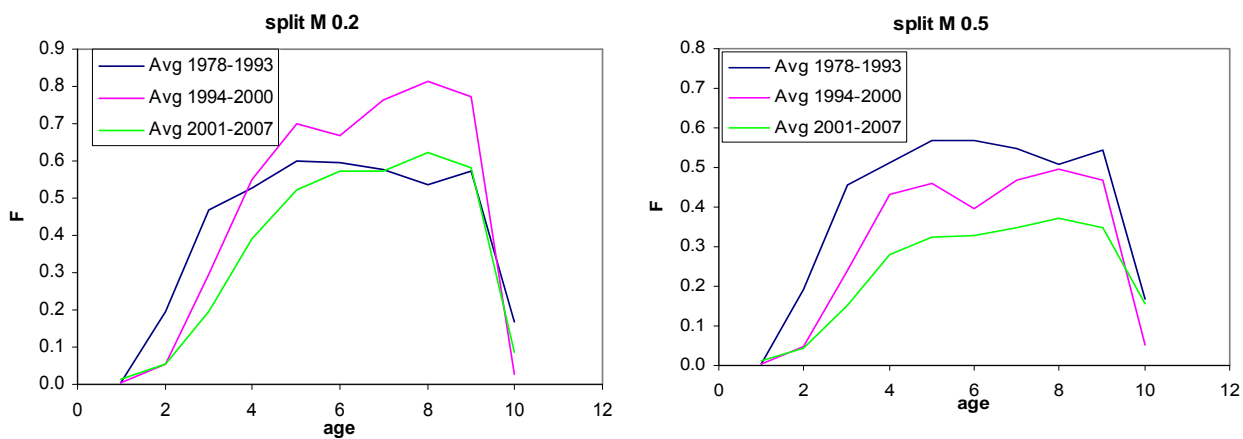


Figure 22. Fishing mortality from the “split M 0.2” and the “split M 0.5” model formulation using data up to 2008.

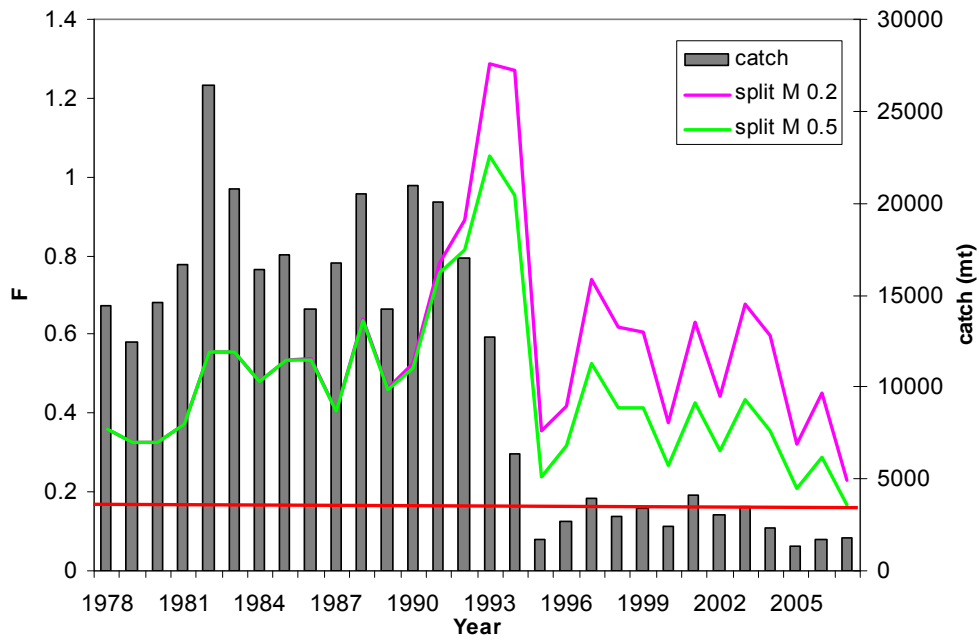


Figure 23. Fishing mortality from the “split M 0.2” and the “split M 0.5” model with fishery catch for cod on Eastern Georges Bank using data up to 2008. The red line shows the current $F_{ref}=0.18$.

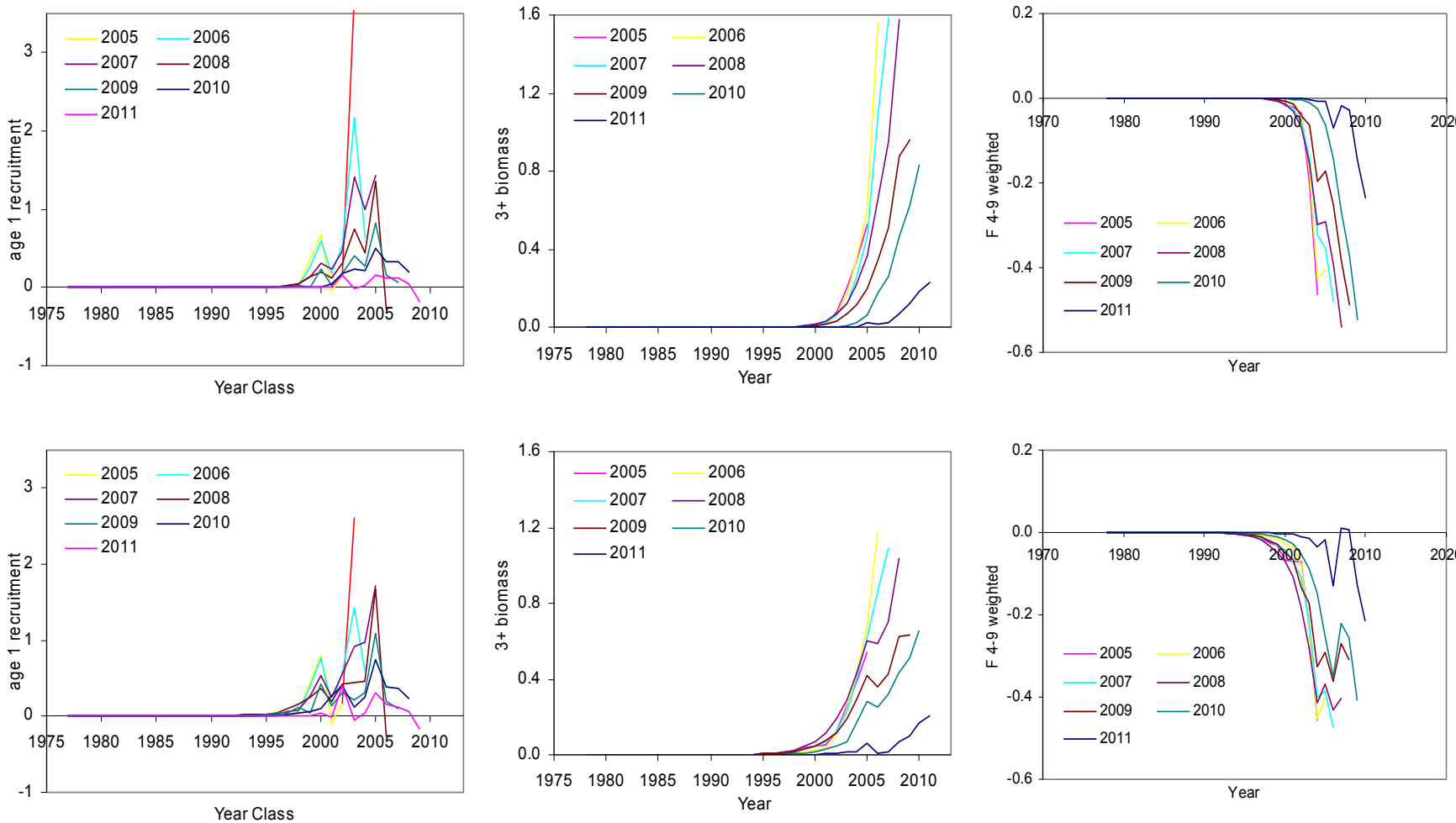


Figure 24. Relative retrospective patterns for the "split M 0.2" model (top), and the "split M 0.5" model (bottom) using data up to 2012.

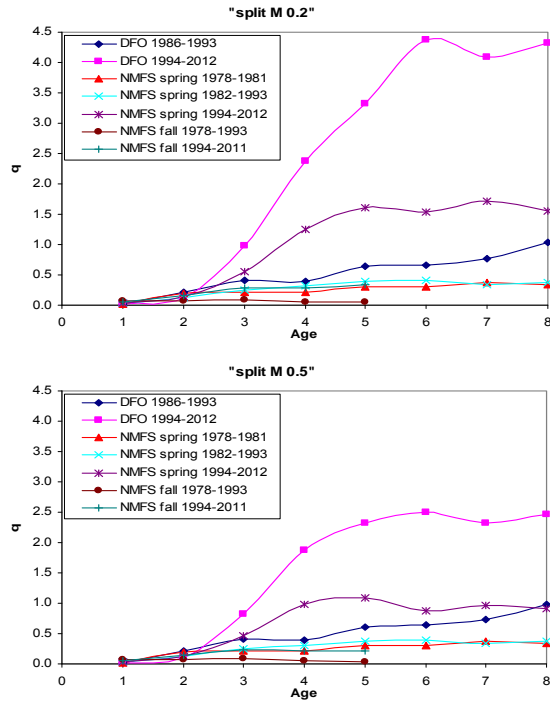


Figure 25. Survey catchability (q) for the DFO, NMFS spring and NMFS fall surveys from the “split M 0.2” and the “split M 0.5” model using data up to 2012.

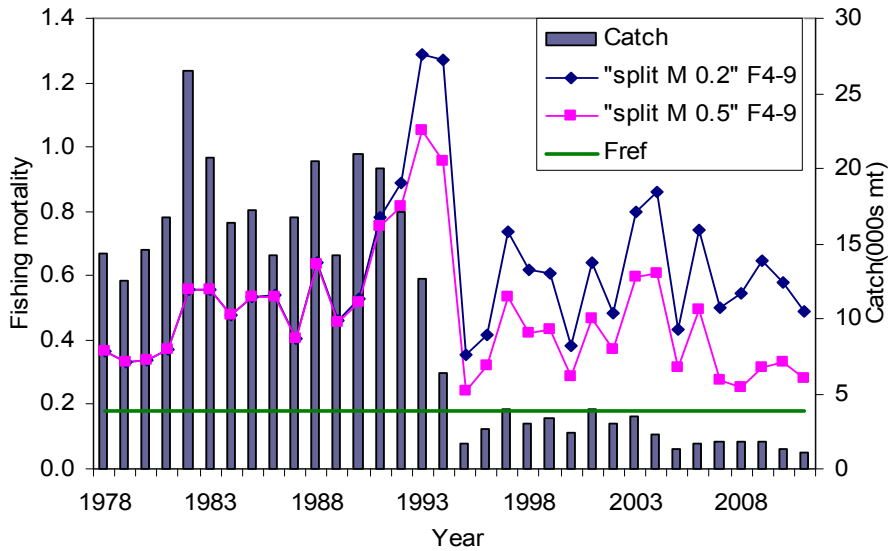


Figure 26. Fishing mortality from the two models with fishery catch for cod on Eastern Georges Bank using data up to 2012. The green line showed the current $F_{ref}=0.18$.

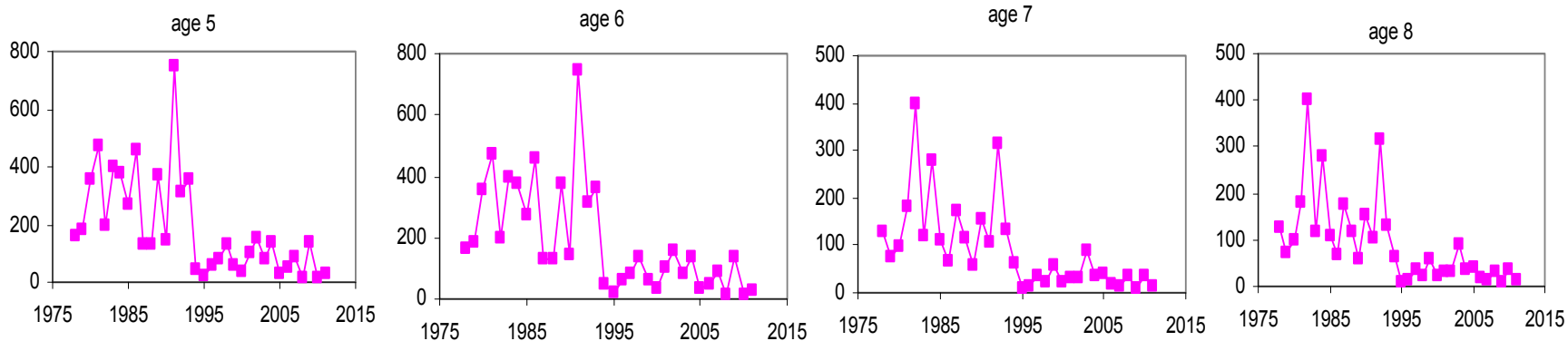


Figure 27. Fishery catch at ages 5-8 of cod on Eastern Georges Bank from 1978 to 2011.

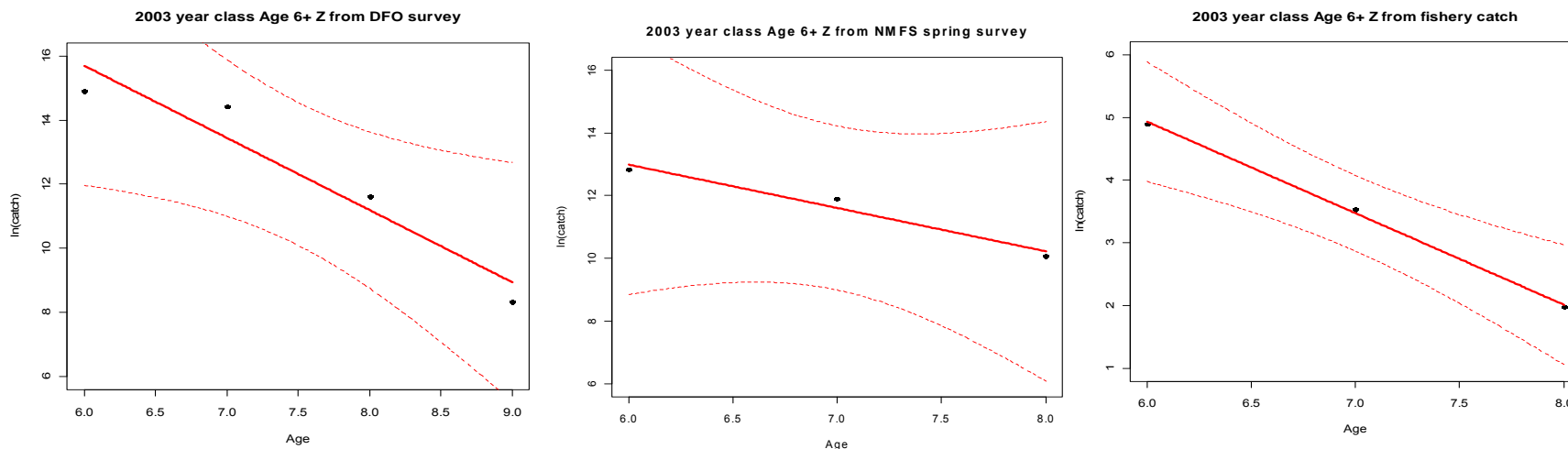


Figure 28. Calculated total mortality Z for ages 6+ from the 2003 year class using the DFO and NMFS spring surveys and fishery catch at age of cod on Eastern Georges Bank. The slope of each figure indicates the value of Z .

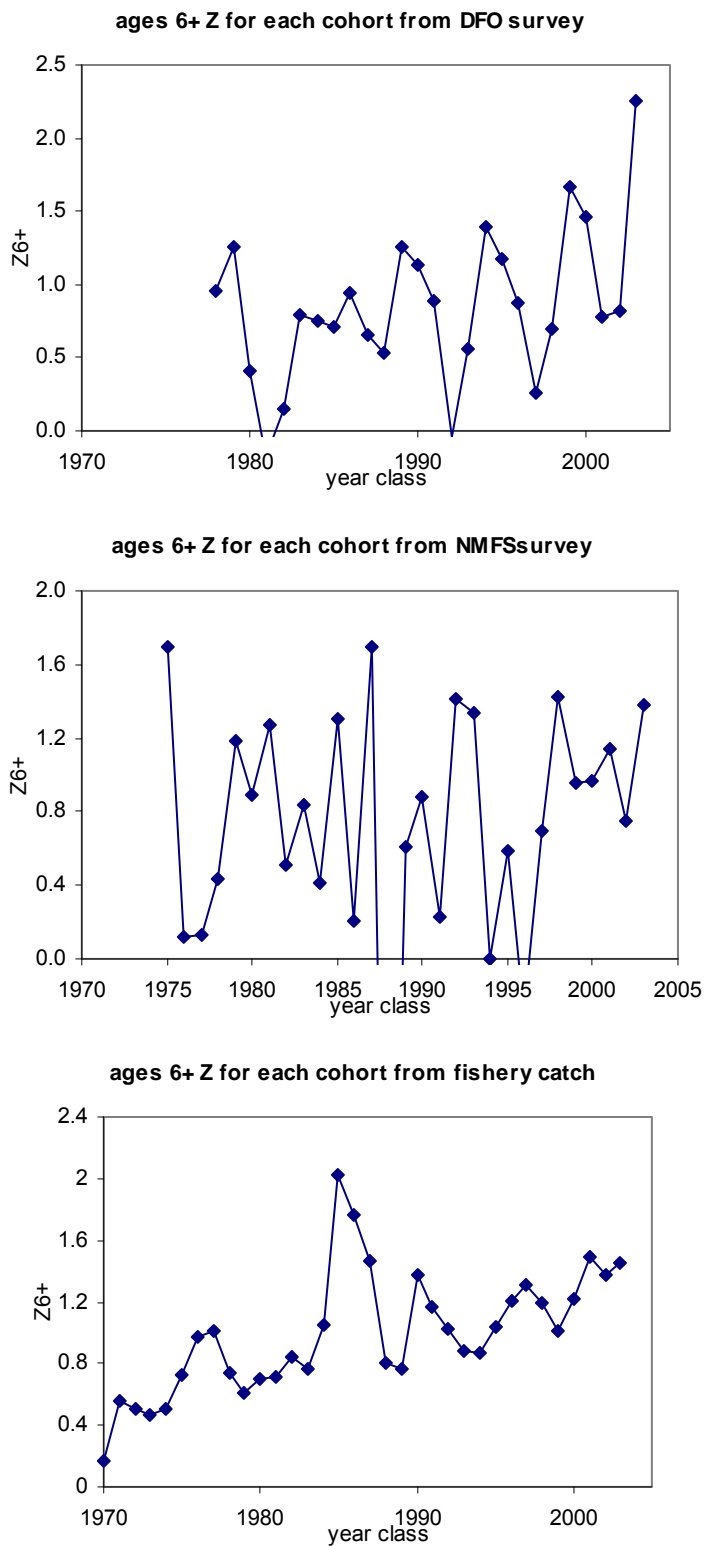


Figure 29. Calculated total mortality Z for ages 6+ from each cohort using DFO and NMFS spring surveys and fishery catch at age of cod on Eastern Georges Bank.

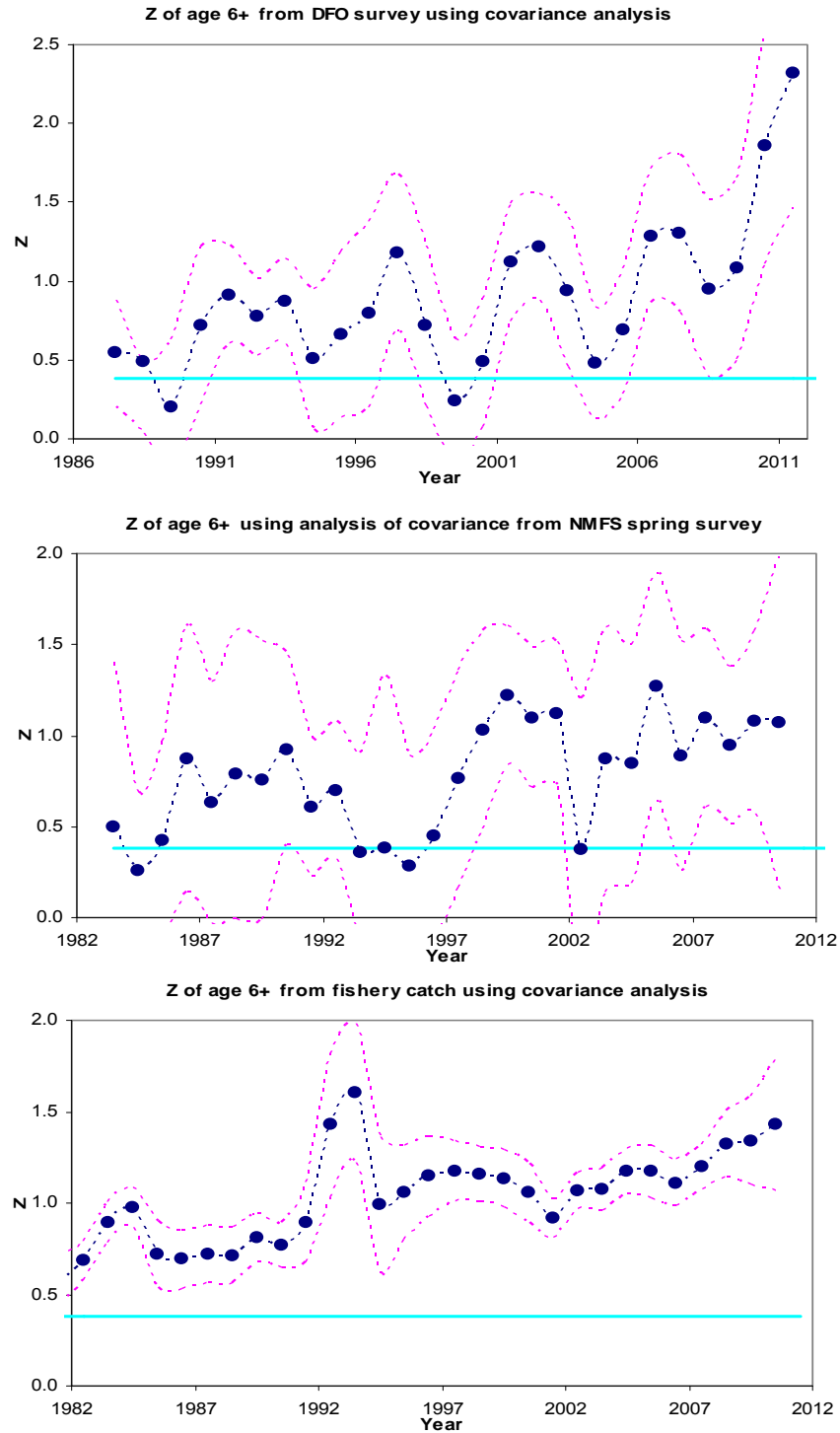


Figure 30. Calculated total mortality Z with 95% confidence intervals for ages 6+ from the covariance analysis using DFO and NMFS spring surveys and fishery catch at age of cod on Eastern Georges Bank. The blue line shows the $Z=(0.2+0.18)=0.38$, where 0.2 was the assumed natural mortality, 0.18 is the current F_{ref} .

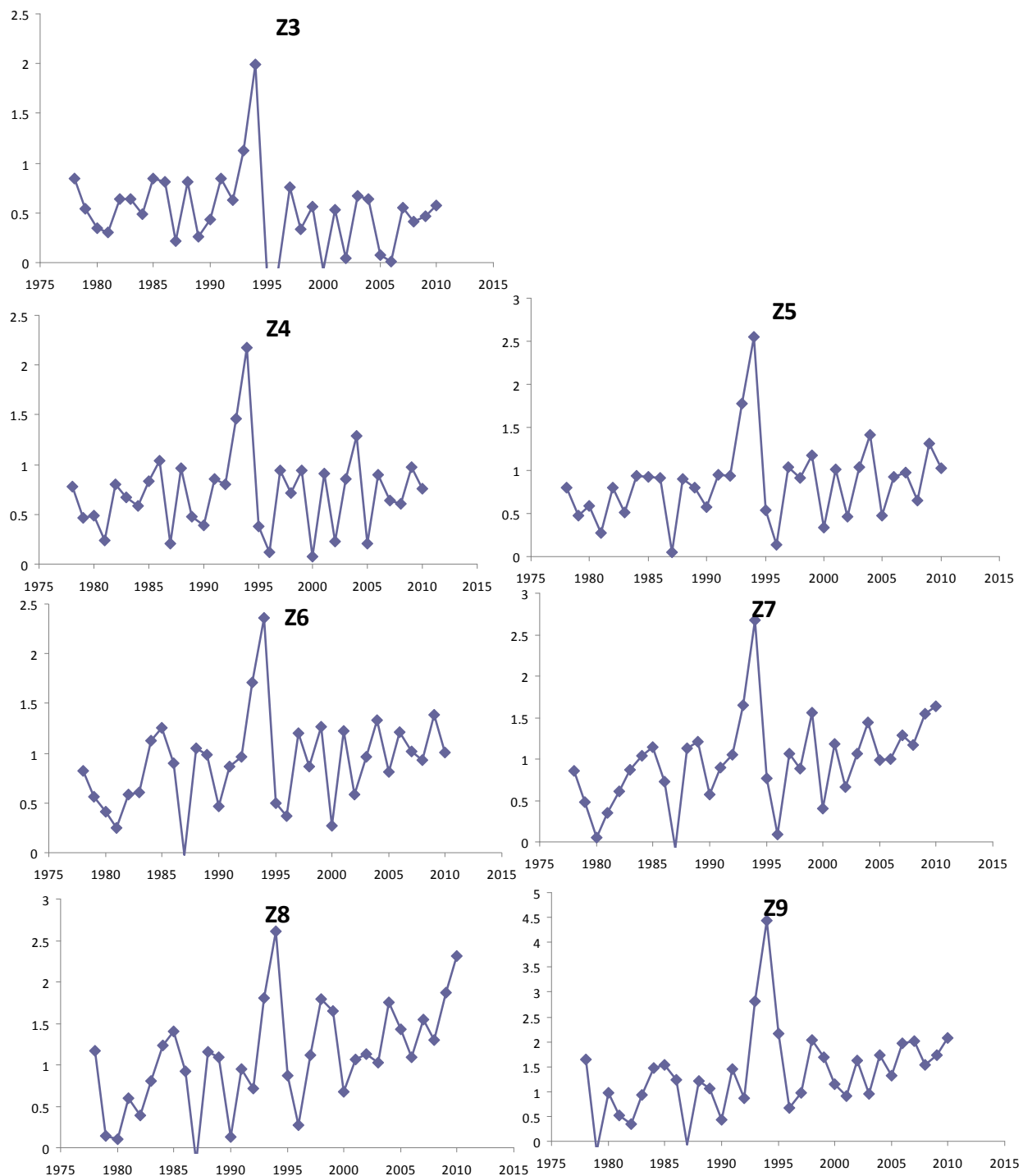


Figure 31. Calculated total mortality Z for different ages using fishery catch at age of cod on Eastern Georges Bank.

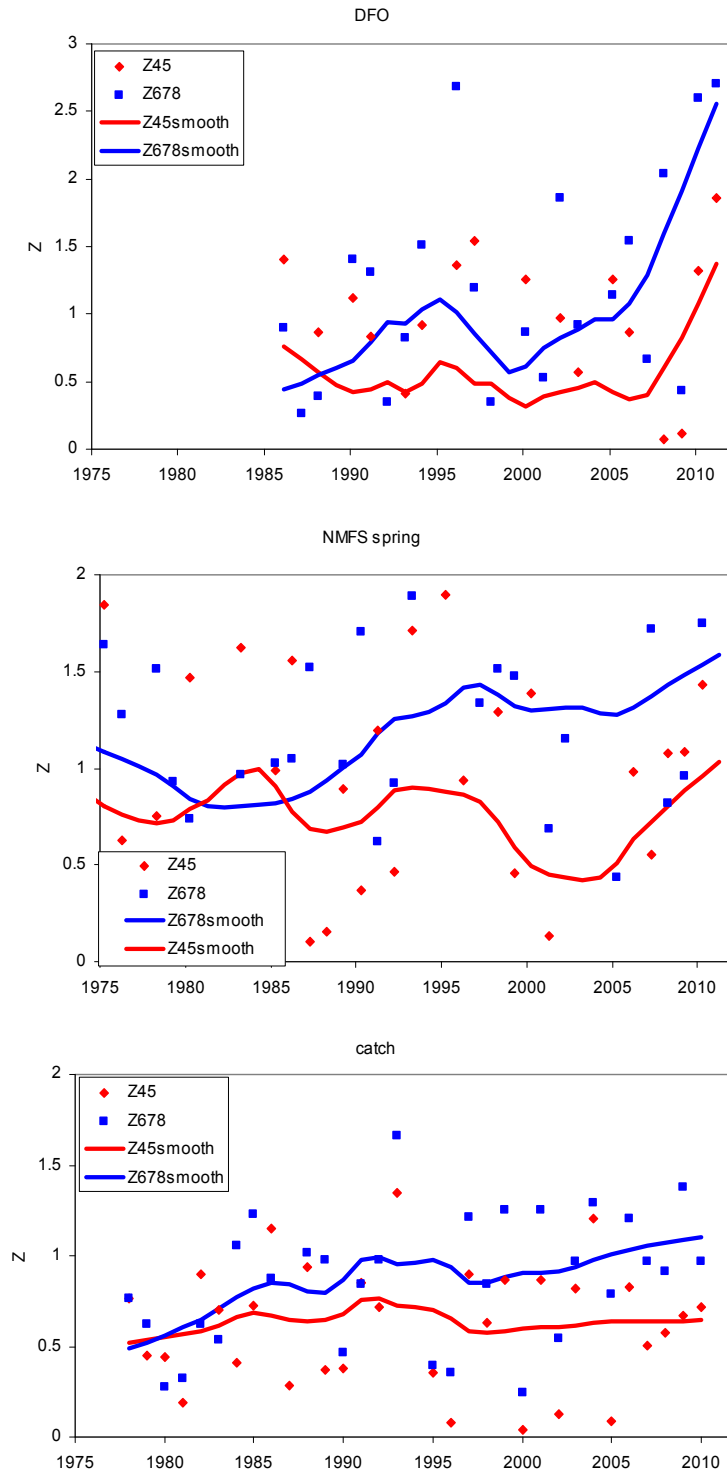


Figure 32. Total mortality Z calculations for age groups 4-5 and 6-8 from the fishery catch, DFO survey and NMFS spring survey for cod on Eastern Georges Bank.

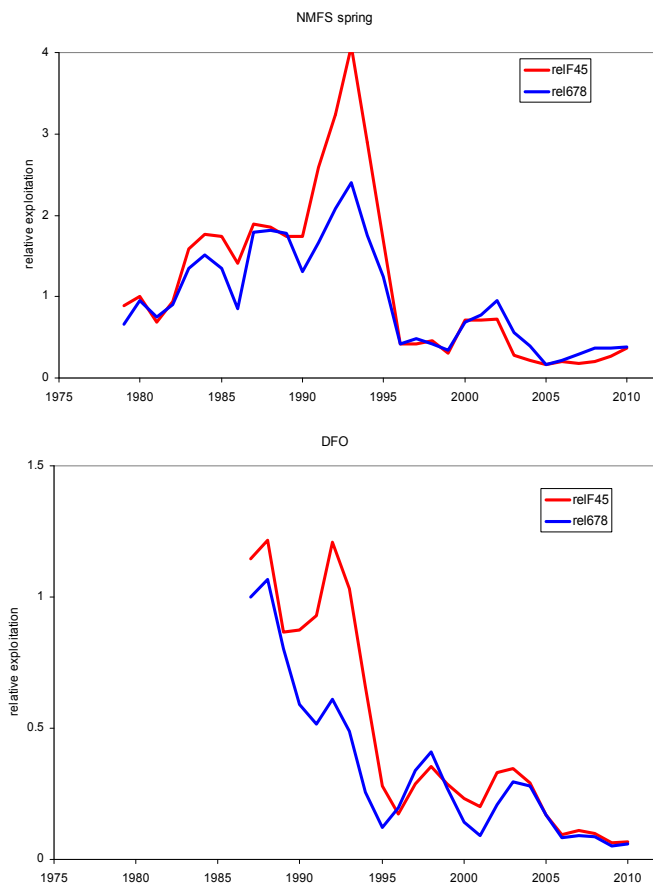


Figure 33. The relative F of cod on Eastern Georges Bank using the ratio of fishery catch to the catch from the DFO survey and NMFS spring survey.

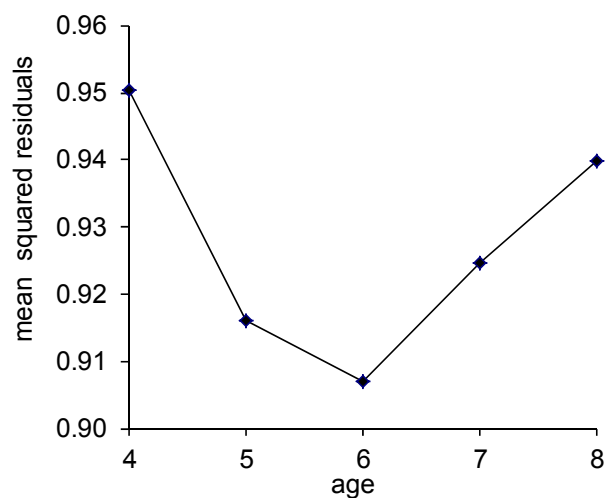


Figure 34. The mean squared residuals for models that M was estimated starting at different ages.

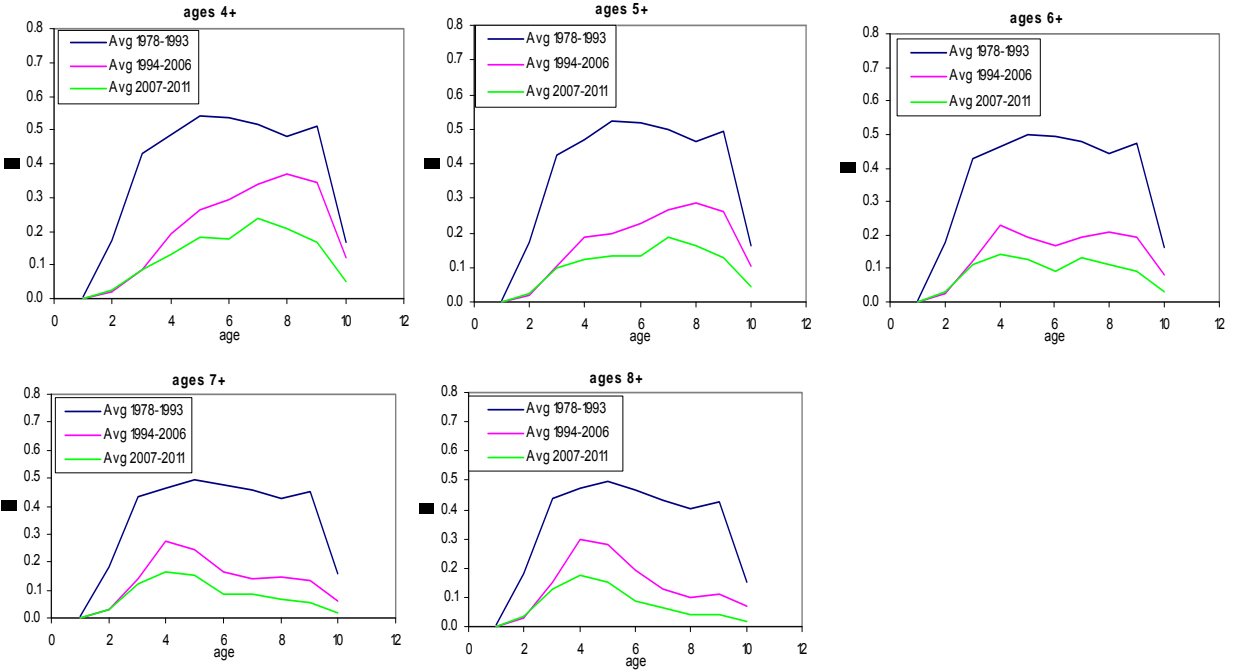


Figure 35. Fishing mortality comparison for models when M was estimated starting at different ages in 1994-2011.

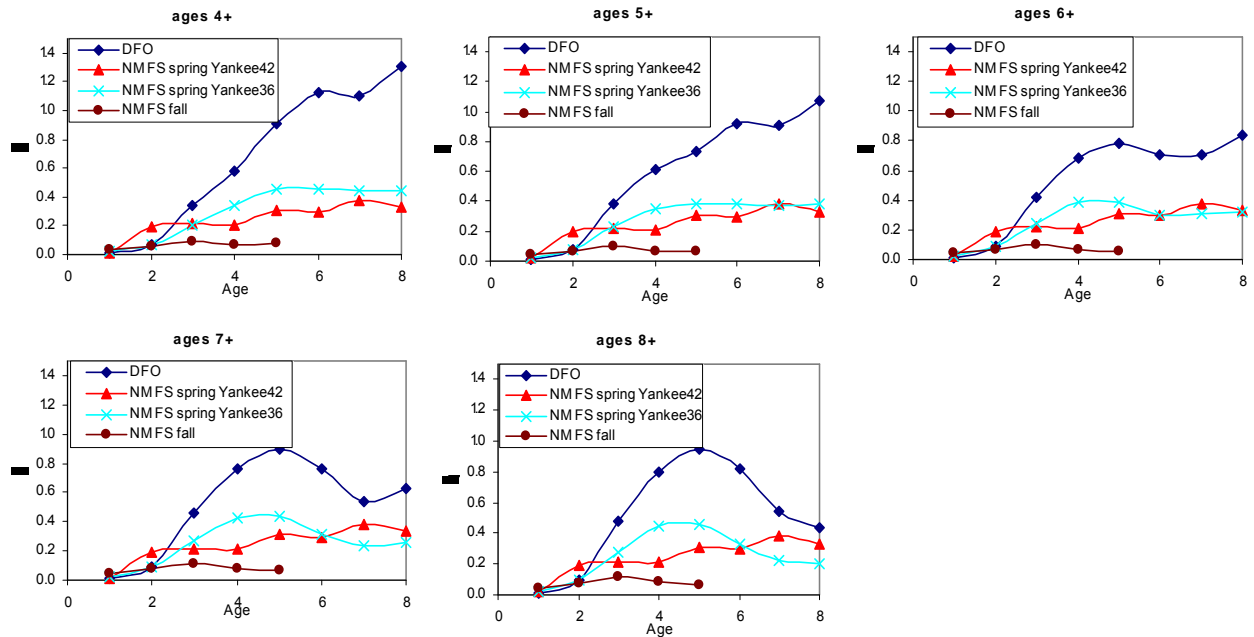


Figure 36. Survey catchability comparison for models when M was estimated starting at different ages during 1994-2011.

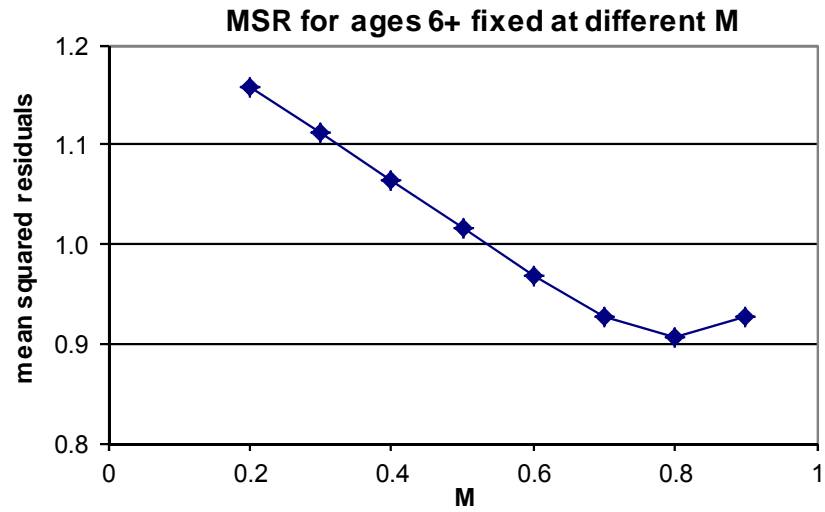


Figure 37. Mean square residuals for models with M for ages 6+ fixed at different values from 0.2 to 0.9 during 1994-2011.

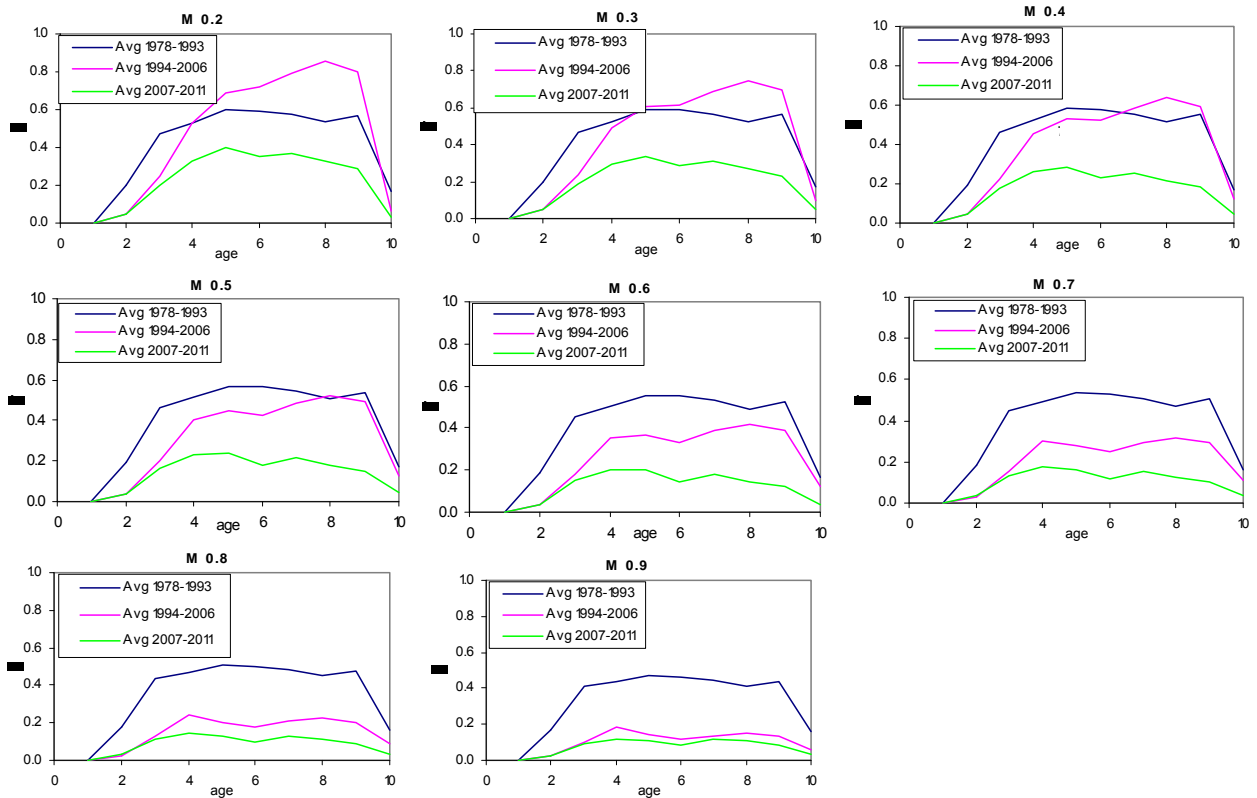


Figure 38. Fishing mortality comparison for models when M for ages 6+ in 1994-2011 was fixed at different values.

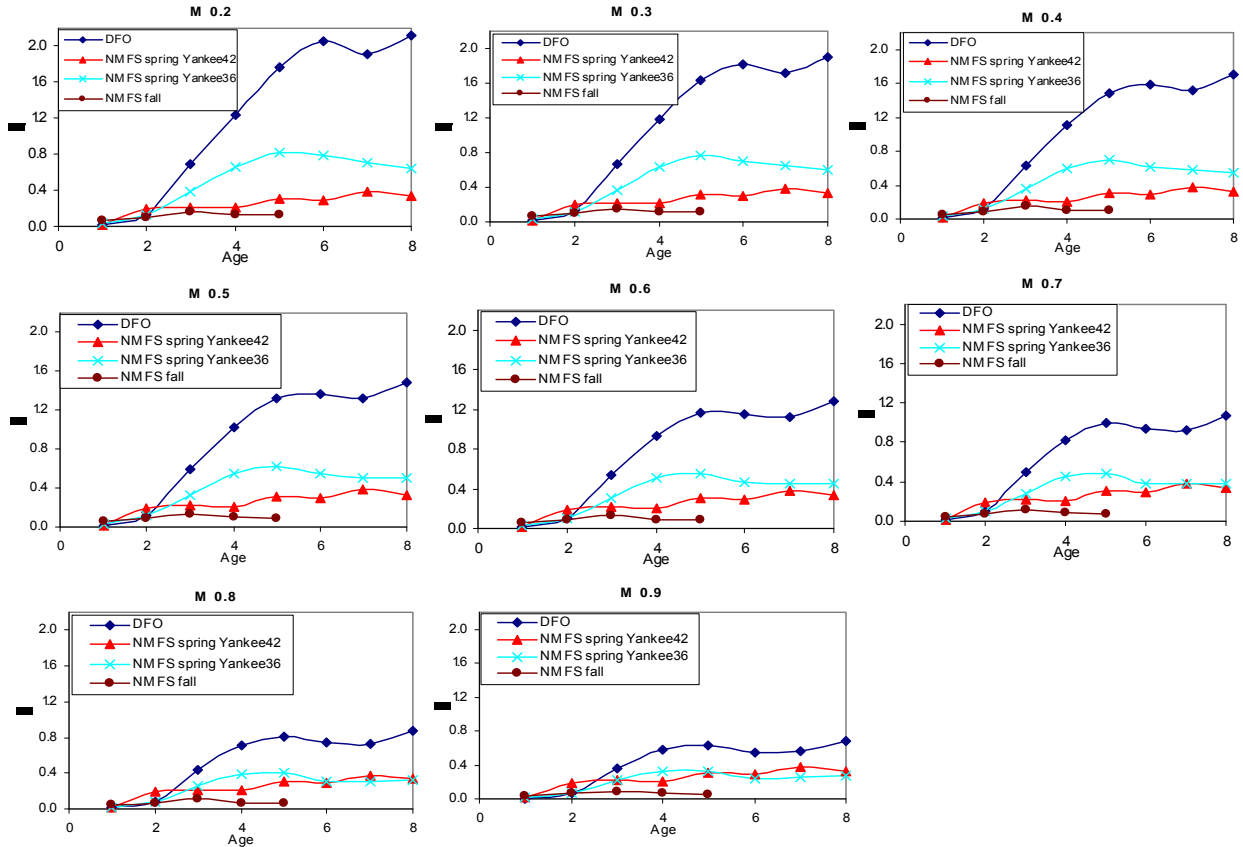


Figure 39. Survey catchability comparison for models when M at ages 6+ was fixed at different values.

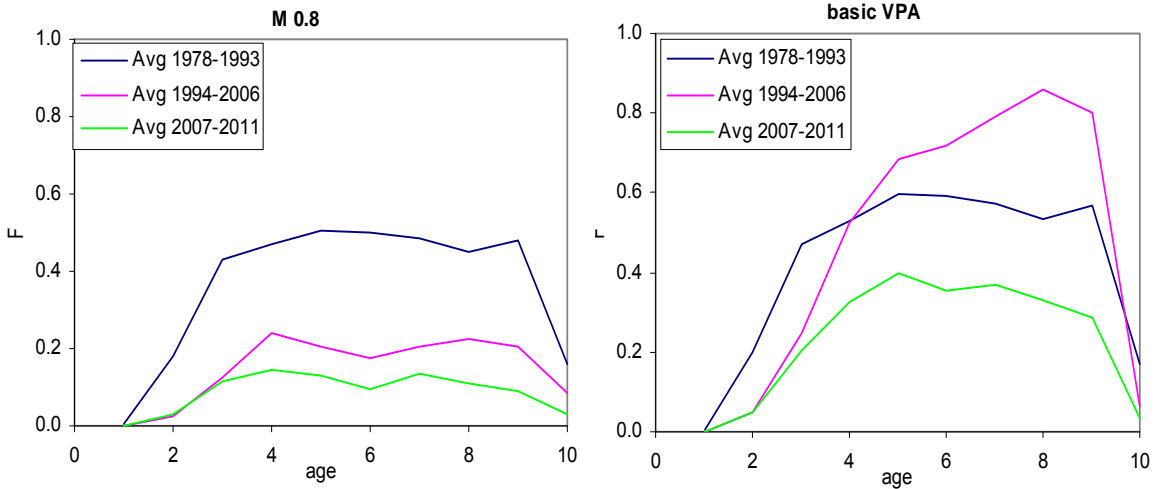


Figure 40. Fishing mortality from the "M 0.8" model and the "basic VPA" model.

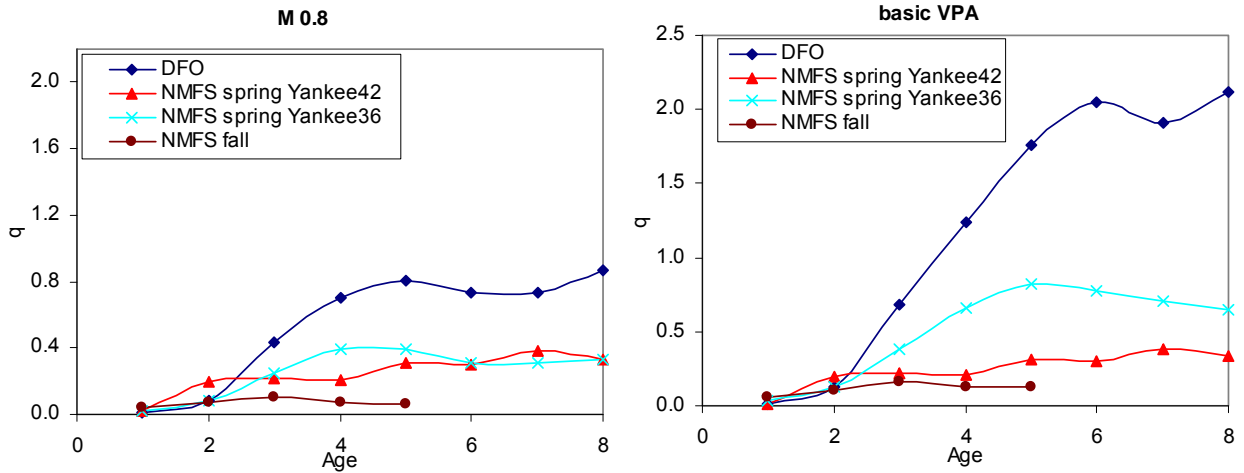


Figure 41. Survey catchability from the "M 0.8" model and the "basic VPA" model.

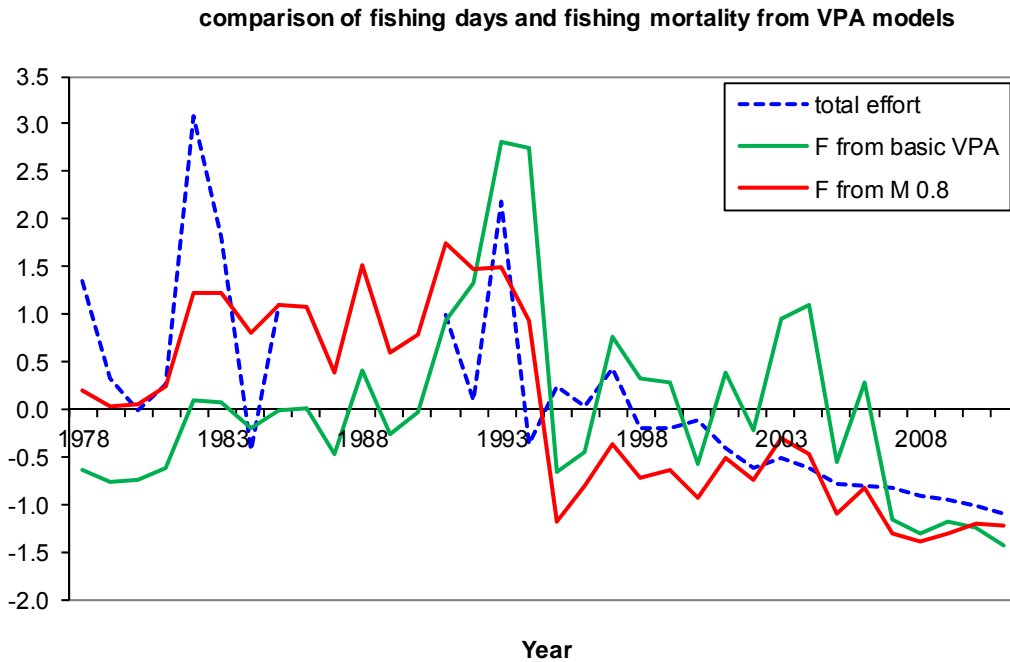


Figure 42. Trend comparison of fishing mortality from the "M 0.8" model and the "basic VPA" model to fishing days of Canadian mobile gear and fixed gear cod fishery on Eastern Georges Bank. The mobile gear fishing days were standardized using fixed gear CPUE with some missing records for 1986-1990 in the database. For trend comparison, the time series of fishing mortality and total fishing effort were normalized using their mean and standard deviation.

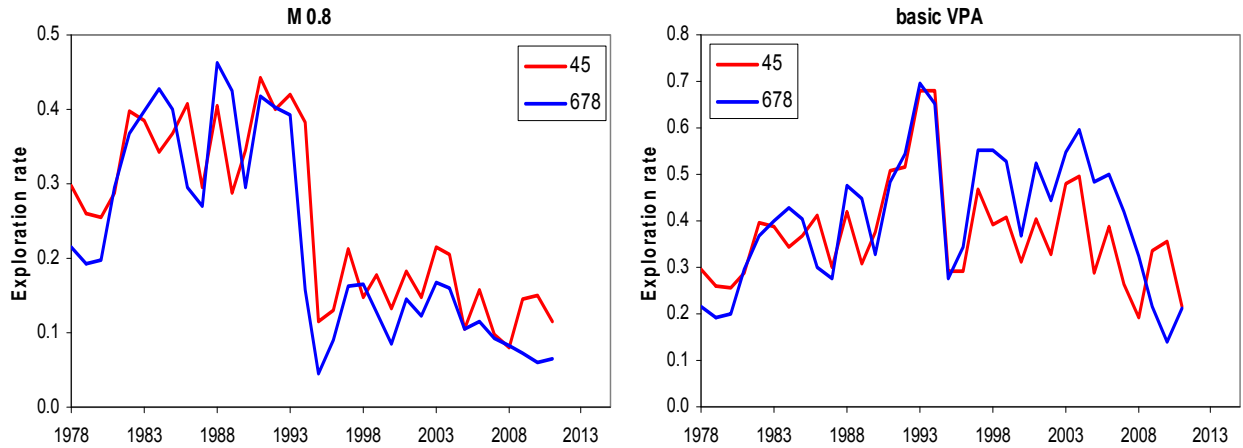


Figure 43. Fishery exploitation from the "M 0.8" model and the "basic VPA" model.

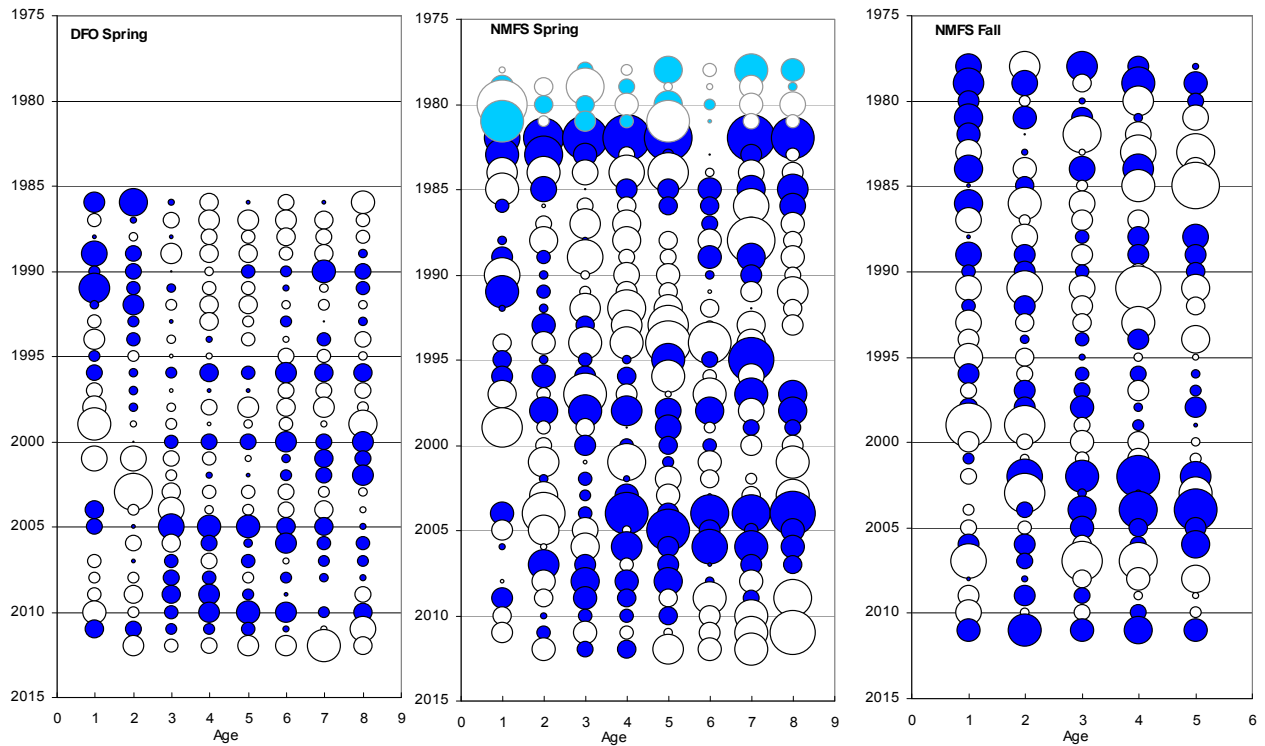
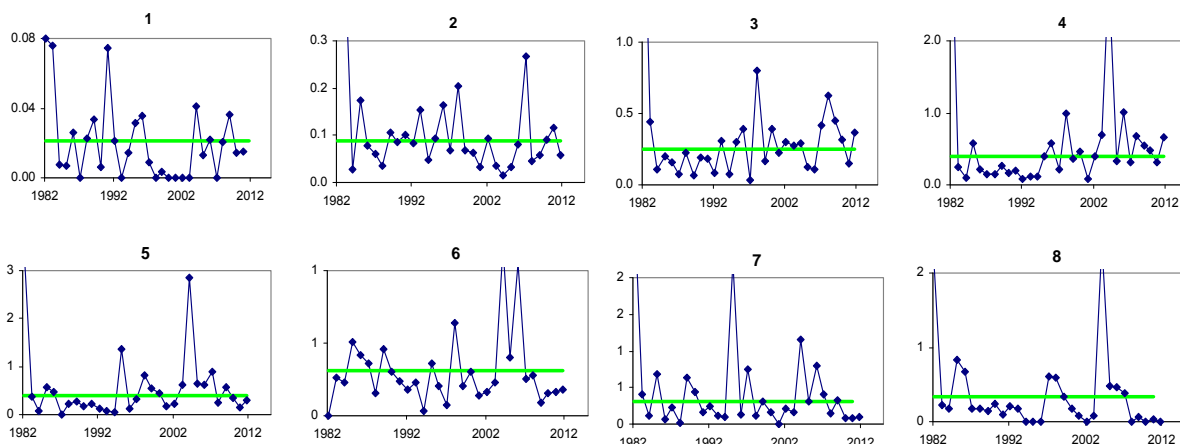
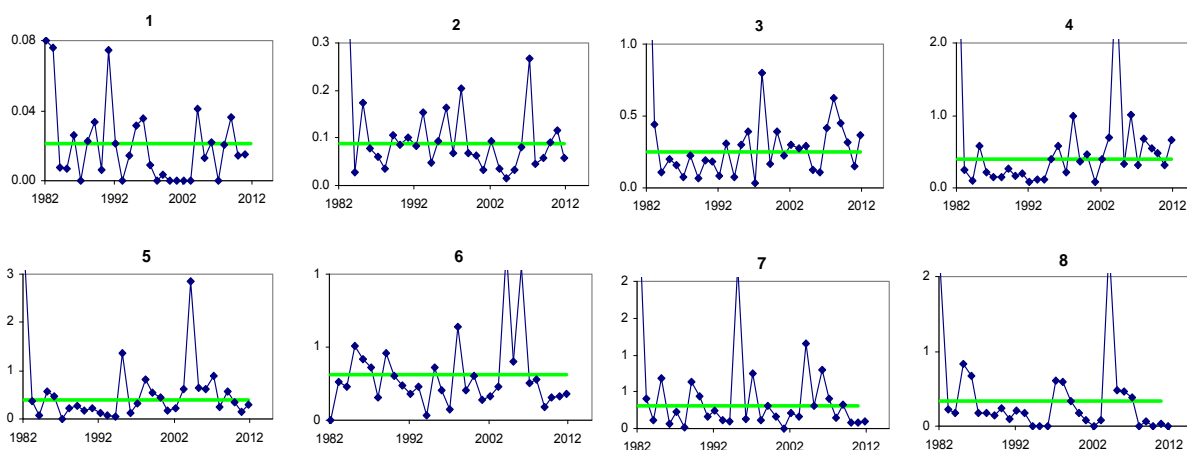


Figure 44. Residuals from the "M 0.8" model.

a) DFO



b) NMFS Spring



c) NMFS Fall

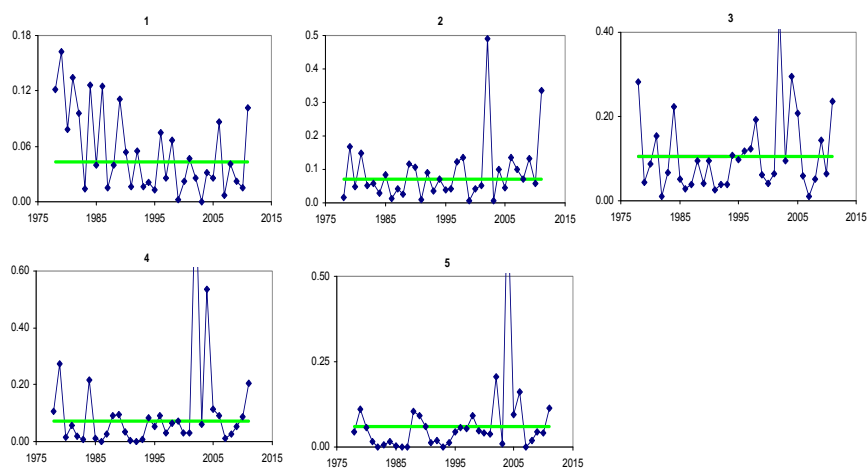


Figure 45. Time trends in survey catchability at age of cod on Eastern Georges Bank. The estimated (horizontal line) and calculated (survey abundance indices at age/estimated population abundance at age, diamonds) from the “M 0.8” model formulation. a): DFO survey, b): NMFS spring survey, c): NMFS fall survey.

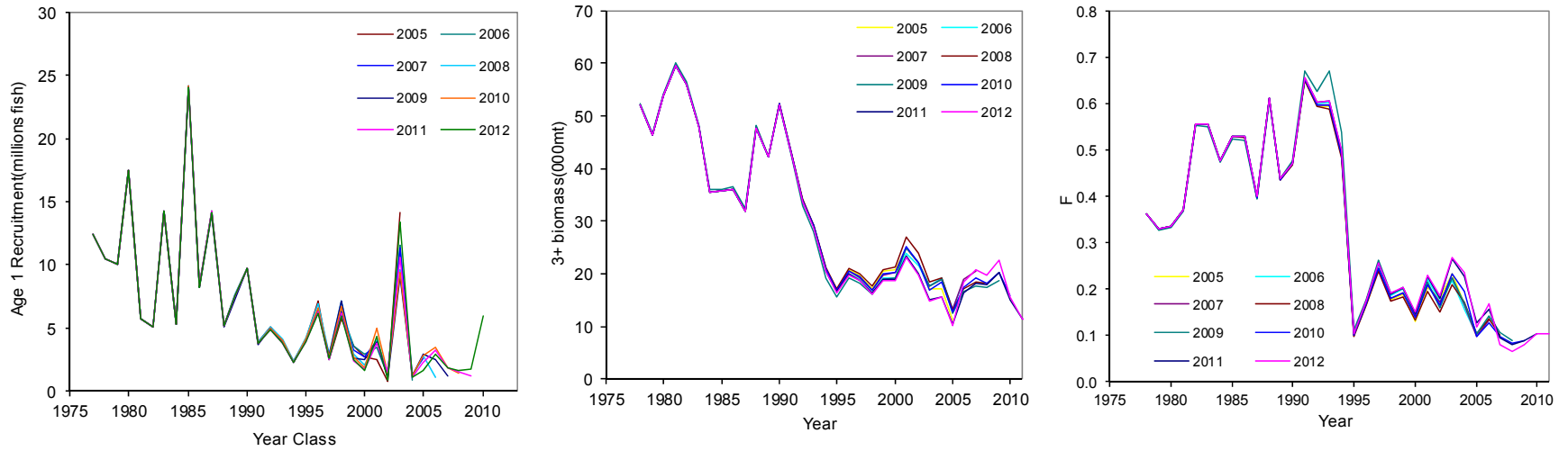


Figure 46. The retrospective pattern from the "M 0.8" model.

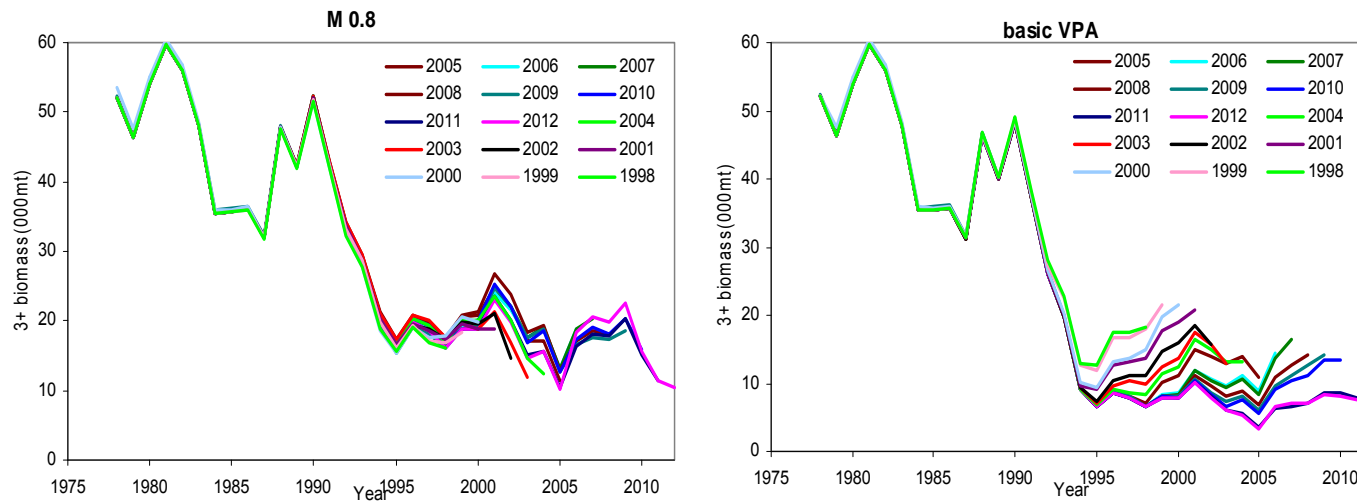


Figure 47. The 14-years peel retrospective analysis of 3+ biomass from the "M 0.8" model and the "basic VPA" model.

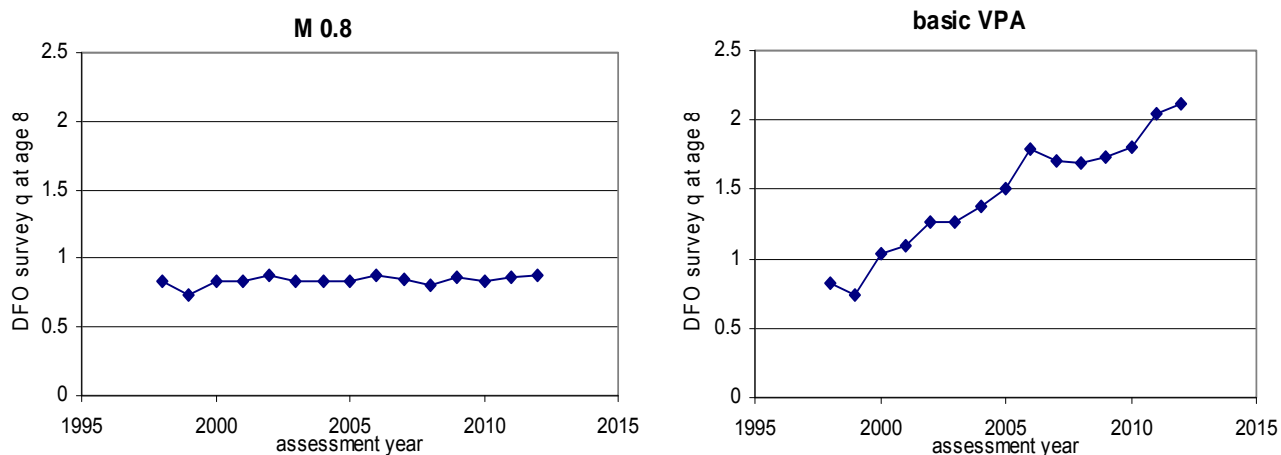


Figure 48. The 14-years peel retrospective analysis of q from the "M 0.8" model and the "basic VPA" model.

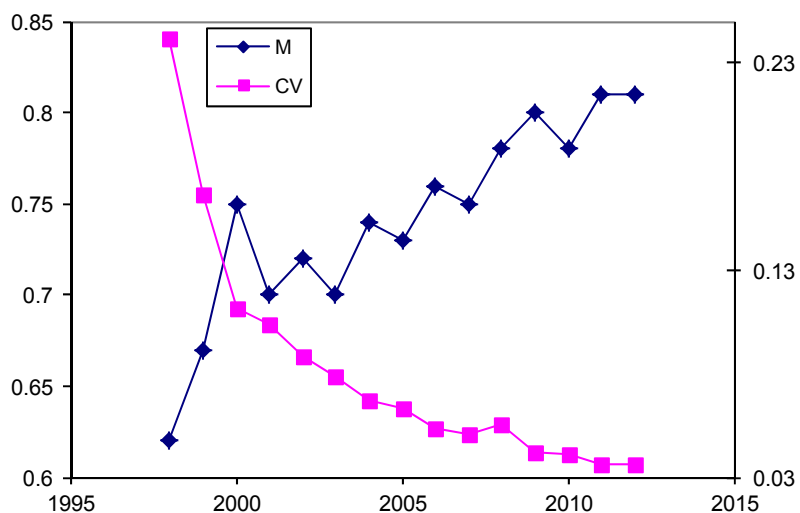


Figure 49. The 14-years peel retrospective analysis of M for ages 6+ in 1994-2011 from the model with M estimated.

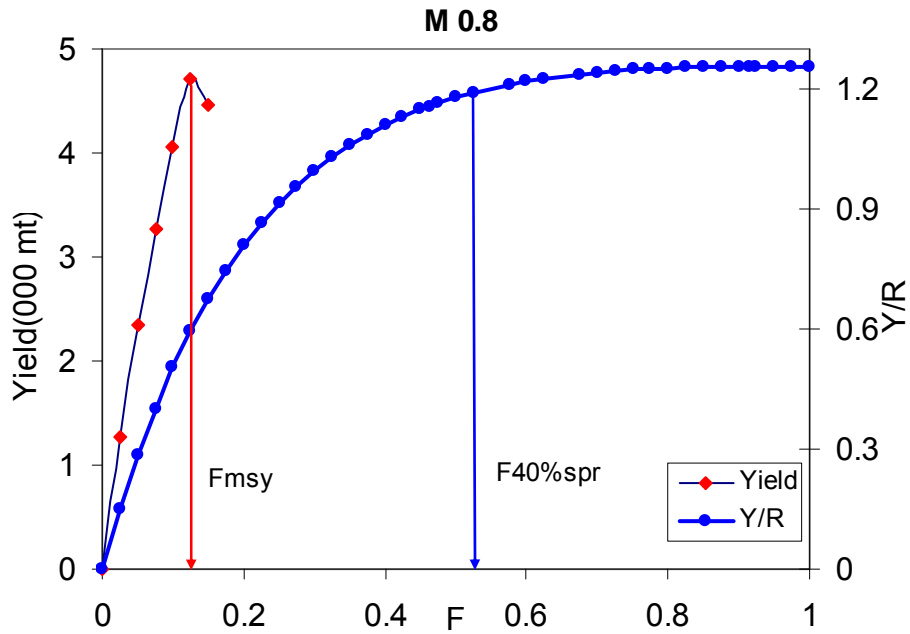


Figure 50. Yield per recruit from dynamic pool model and yield at equilibrium from production model using assessment result from the “M 0.8” model.

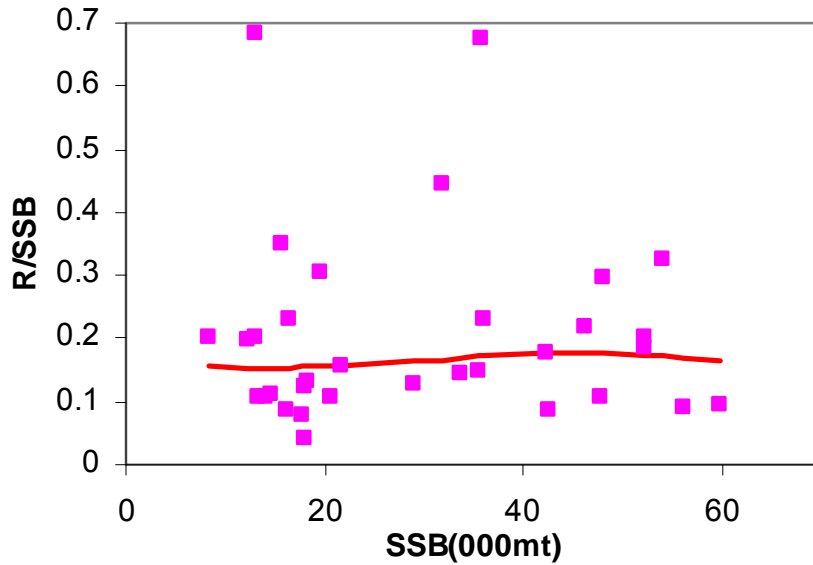


Figure 51. Recruitment per spawner scatter plot and LOESS smoothed line using assessment result from the “M 0.8” model.

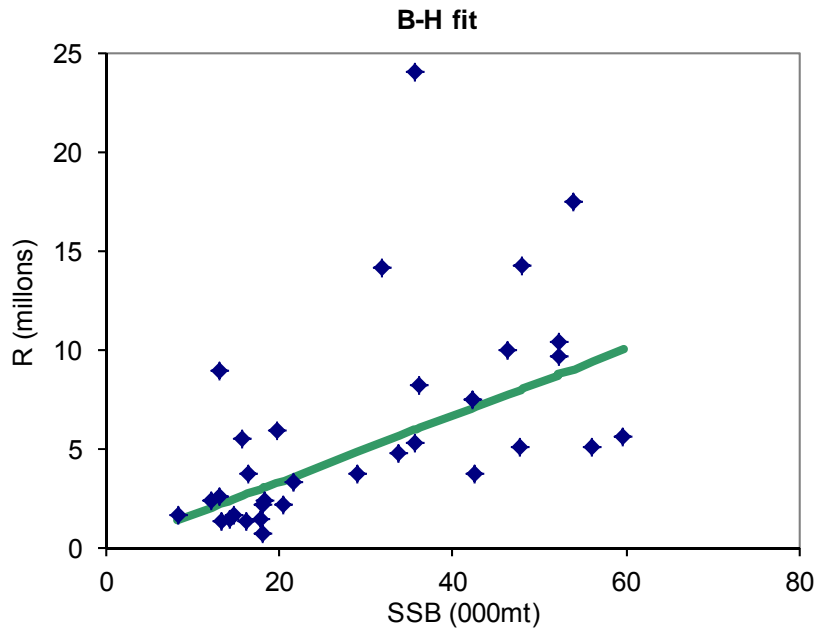


Figure 52. Spawning stock biomass (SSB) to recruitment (R) relationship fit with a Beverton-Holt (B-H) model (solid line) using results from the “M 0.8” model for Eastern Georges Bank cod.

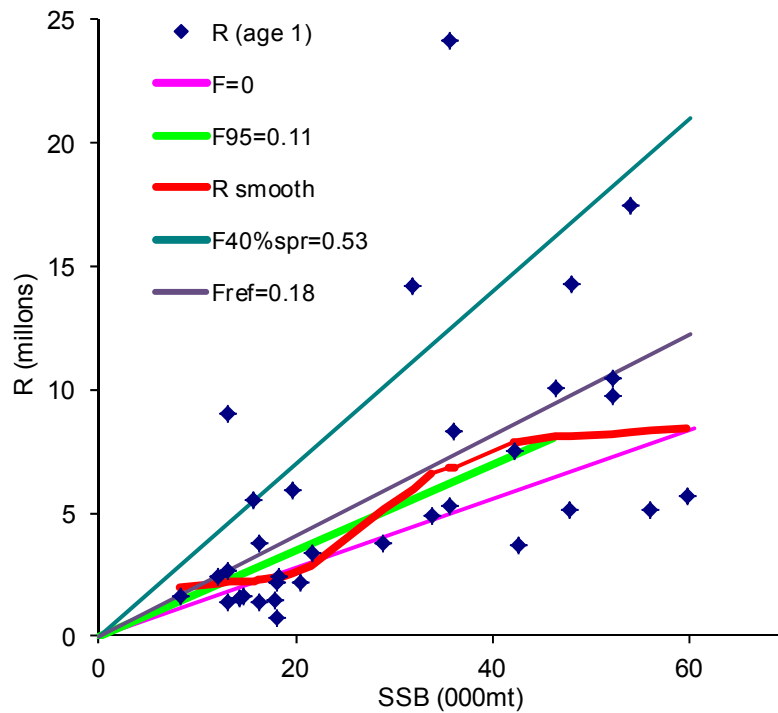


Figure 53. Spawning stock biomass (SSB) to recruitment (R) relationship with LOESS smooth fit using assessment result from the “M 0.8” model for Eastern Georges Bank cod. The lines show the replacement line under different fishing levels.

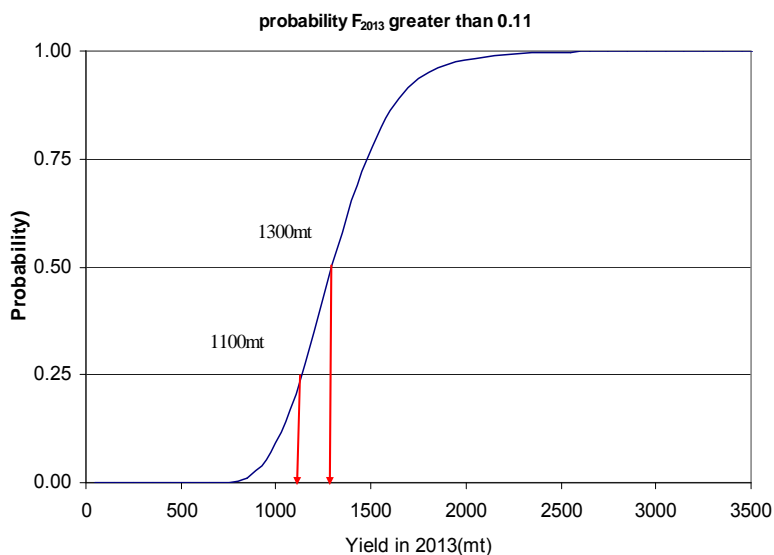


Figure 54. The probability of fishing mortality will exceed $F=0.11$ for alternative total yields of Eastern Georges Bank cod in 2013 from risk analysis of the “M 0.8” model.

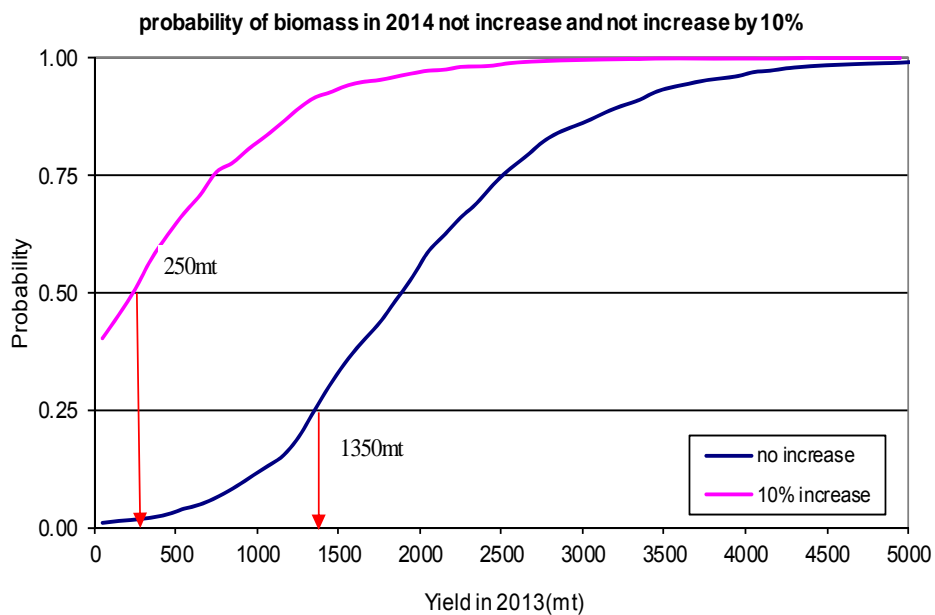


Figure 55. Risk of 3+ biomass in 2014 not increasing, and not increasing by 10% from 2013 for alternative total yields of Eastern Georges Bank cod in 2013, from risk analysis of the “M 0.8” model.

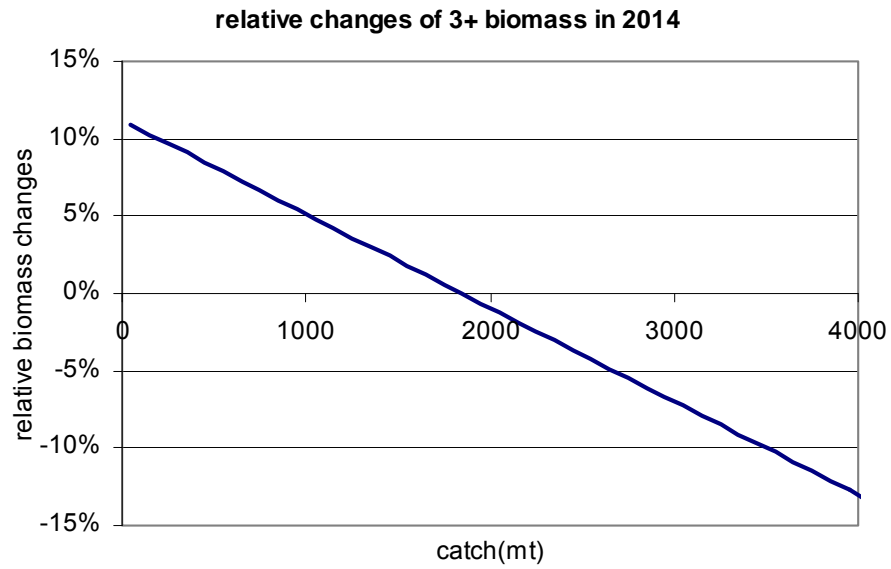


Figure 56. Relative change of 3+ biomass in 2014 compared to 2013 for alternative total yields of Eastern Georges Bank cod in 2013, from projection of the "M 0.8" model.