Fisheries and Oceans Canada Pêches et Océans Canada
Science Sciences

C S A S **S C C S**

Canadian Science Advisory Secretariat **Secrétariat canadien de consultation scientifique**

Research Document 2012/034
Document de recherche 2012/034

Gulf Region
Région du Golfe

Revised population model for Atlantic cod (*Gadus morhua*) in the southern Gulf of St. Lawrence

Révision d'un modèle de population de la morue franche (*Gadus morhua*) du sud du golfe du Saint-Laurent

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ISSN 1499-3848 (Printed / Imprimé)
ISSN 1919-5044 (Online / En ligne)

Canada

Correct citation for this publication:
La présente publication doit être citée comme suit :

Swain, D.P. 2012. Revised population model for Atlantic cod (*Gadus morhua*) in the southern Gulf of St. Lawrence. DFO Can. Sci. Advis. Sec. Res. Doc. 2012/034. iii + 39 p.

ABSTRACT

The status of Atlantic cod (*Gadus morhua*) in the southern Gulf of St. Lawrence (4T cod) has been assessed using sequential population analysis (SPA) implemented using the ADAPT software. In order to accommodate large changes in the instantaneous rate of natural mortality (*M*) experienced by 4T cod, recent assessments have fixed age-aggregated (2+) *M* at 0.2 in 1971-1979 and at 0.4 in 1994-1997 and estimated it in 5-7 year blocks in other years. The February 2009 assessment of this stock identified discrepancies between the observed abundance indices and those predicted by the assessment model. A revised population model has been developed to address this problem. The revised model, implemented using the AD Model Builder software, estimates separate trends in *M* for ages 2-4 and 5+ years, starting from fixed values in 1971-1976. *M* is estimated either in blocks of years or using a random walk. Both approaches to estimating *M* produce similar results. Estimated *M* of 5+ cod increased sharply in the late 1980s and early 1990s, and remained at a high level throughout the 1990s and 2000s. In contrast, estimated *M* of cod aged 2-4 years decreased in the early 1990s and remained at a relatively low level in the following years. The revised model provided a much better fit to the abundance indices than did models that used age-aggregated (2+) *M*. Retrospective patterns were negligible for the revised model. Like earlier models, the revised model indicated that the abundance and biomass of 4T cod are at record low levels and are declining.

RÉSUMÉ

L'état du stock de la morue franche (*Gadus morhua*) du sud du golfe du Saint-Laurent (4T) a jusqu'à récemment été évalué avec des modèles d'analyse séquentielle dans le logiciel ADAPT. Pour tenir compte des grands changements dans le taux instantané de la mortalité naturelle (*M*) de la morue dans 4T, les dernières évaluations ont fixé *M* à un taux de 0,2 pour tous les âges 2+ pendant la période de 1971 à 1979, à un taux de 0,4 pour la période 1994 à 1997, et le taux a été estimé par bloque de cinq à sept ans pour les années par après. Durant l'évaluation tenue en février 2009, on a noté des inconsistances dans les prédictions des indices d'abondance par rapport aux indices observés avec ce modèle. Une révision au modèle d'évaluation est proposée pour adresser ce problème. La révision du modèle, construit dans le logiciel AD Model Builder, permet d'estimer des tendances séparées de *M* pour le groupe d'âge 2 à 4 et celui de 5 ans et plus. Les valeurs de *M* sont fixées par groupe d'âge pour la période 1971 à 1976. Par après, *M* est estimée soit par bloque d'années ou selon une marche aléatoire. Ces deux approches donnent des estimations de *M* similaires. La mortalité (*M*) de la morue âgée de 5 ans et plus a rapidement augmenté à la fin des années 80s et le début des années 90s, et est demeurée élevée durant les années 90s et 2000s. Par contre, la mortalité (*M*) pour la morue âgée de 2 à 4 ans a diminué au début des années 90s et est demeurée relativement basse par après. Le modèle révisé produit un meilleur ajustement aux indices d'abondance que les modèles d'âges agrégées (2+) pour *M*. Pour le modèle révisé, les patrons retrospectifs étaient négligeables. Comme les modèles précédents, le modèle révisé indique que l'abondance et la biomasse de la morue franche de 4T sont à des niveaux bas records et continuent à diminuer.

INTRODUCTION

COSEWIC (Committee on Status of Endangered Wildlife in Canada) assessed as Endangered four Designatable Units of Atlantic Cod (*Gadus morhua*) in eastern Canada (COSEWIC 2010). In response, a Recovery Potential Assessment (RPA) Zonal Advisory Process meeting was held in February 2011. Population models were required to address the terms of reference for the RPA meeting. Where peer-reviewed models were not available, or were no longer appropriate, peer review of new or alternate models was required prior to the RPA meeting. A framework zonal advisory process meeting was conducted December 6-8, 2010, in part to review alternate population models proposed for the cod stock in the southern Gulf of St. Lawrence (herein referred to as 4T cod) (DFO 2011).

The status of the 4T cod stock is assessed using sequential population analysis (SPA), implemented using the ADAPT software (Gavaris 1988) and calibrated using abundance indices from an annual research vessel (RV) survey, a number of fishing-industry surveys and a commercial catch rate index (e.g., Swain et al. 2009). Normally a fixed level is assumed in SPA for the instantaneous rate of natural mortality (*M*). However, it is clear that *M* increased for 4T cod between the 1970s and 1990s (Sinclair 2001). Starting in assessments conducted in the late 1990s, *M* was assumed to be 0.2 up to 1985 and 0.4 since 1986 (Sinclair et al. 1998). Using a simulation study, Chouinard et al. (2005a) demonstrated that SPA can also be used to estimate trends in *M*. Following this work, recent assessments of this stock have estimated *M* for various blocks of years, starting from a fixed value of 0.2 in the 1970s. A zonal review of *M* in the Gulf cod stocks also recommended that *M* should be fixed at 0.4 in 1994-1997 in SPA models for the 4T stock (DFO 2007). In all these models, *M* was assumed not to vary with age over the range of ages used in the models (ages 2 years and older).

The most recent assessment of this stock identified a number of discrepancies between the RV survey indices at age and the abundances at age predicted by the standard assessment model with age-aggregated *M* (Swain et al. 2009). These discrepancies could be eliminated by using a model that estimated separate trends in *M* for different age groups of cod. Nonetheless, it was decided to retain the standard model as the basis for advice on stock status, pending further work on estimated age-disaggregated patterns in *M*. Additional work on population models using age-disaggregated time trends in *M* was presented at the zonal review of seal impacts on fish populations in October 2010 (Swain 2011*a*). This work provided further support for the conclusion that the time trends in *M* differ between young and old 4T cod.

This document describes additional work on the appropriate *M* structure for the 4T cod population model. Models estimating separate time trends in *M* for ages 2-4 and 5+ years are recommended. In addition, results are compared between equivalent models implemented in ADAPT or AD Model Builder (ADMB, http://admb-project.org/) ; ADMB is preferred due to its greater flexibility. An update of the abundance indices to 2009 or 2010 is also provided so that the updated indices can be used in modelling for the RPA.

UPDATED ABUNDANCE INDICES

Detailed information on the abundance indices used to calibrate population models for 4T cod is given by Swain et al. (2009). Three of these indices are currently updated annually: the September RV survey, a sentinel bottom-trawl survey conducted each August and a sentinel longline survey.

The mean number of cod per tow in the September RV survey increased in 2009 whereas the mean weight per tow remained at about the 2008 level (Fig. 1). This increase in the abundance index was due to increased catches of cod less than 40 cm (Fig. 2), corresponding to fish aged 3 and 4 years (Fig. 3). In contrast, the catch rate of cod aged 5 years and older decreased slightly in 2009 (Fig. 3). In 2010, both the abundance and biomass indices declined to record-low levels, about half the 2009 level (Fig. 1).

The 2009 catch rate index for the sentinel bottom-trawl survey increased slightly in terms of abundance and decreased slightly in terms of biomass (Fig. 4). As in the RV survey, the slight increase in the abundance index in 2009 was due to increased catch rates for 3 and 4 year old cod; catch rates of cod aged 5 years and older decreased slightly in 2009 (Fig. 5).

Standardized catch rates in the longline sentinel survey were the lowest on record in 2009 (Fig. 6). Catch rates in this survey have declined each year after 2004. There is a concern that this index may show “hyperdepletion”, declining more rapidly than population abundance. Catch rates in both the RV and mobile sentinel surveys have also declined since 2004, but not as sharply and steadily as in the longline survey. One potential source of hyperdepletion in the longline survey is increasing predation of the catch by seals and other predators/scavengers (e.g., hagfish). Another potential cause of hyperdepletion is shifts in the distribution of cod. Unlike the RV and mobile sentinel surveys, which are synoptic surveys covering virtually the entire area occupied by 4T cod during August and September, fishing in the longline survey is restricted to nearshore areas. Thus, any offshore shift in cod distribution (e.g., to avoid inshore areas where the risk of seal predation is high) would result in hyperdepletion of this index. Investigation of these potential causes of hyperdepletion is at a preliminary stage, and conclusions regarding the likelihood of hyperdepletion have not yet been reached.

LANDINGS UPDATE

The directed fishery for cod was closed in 2009. Reported landings amounted to 147 t.

POPULATION MODELS WITH AGE-AGGREGATED (2+) *M*

In this section, results from the standard model (Model 1) from the February 2009 assessment are compared with results from the same model with the 2009 data added. These models estimate abundance for ages 3-15 yr in the terminal year (2009 or 2010) and age 15 in the most recent eight years. In other years, the instantaneous rate of fishing mortality (*F*) on the oldest age is assumed to be equal to the average of the two previous ages. *M* is assumed to be 0.2 in 1971-1979 and 0.4 in 1994-1997, and estimated separately in 1980-1986, 1987-1993, 1998-2002 and 2003-2008 (or 1998-2003 and 2004-2009 in the model including 2009 data).

Calibration indices are:

- the RV indices for ages 2-10 in 1971 – 2008 or 2009, excluding 2003. The reasons for excluding the 2003 indices are that the survey in that year started late, had a low sampling intensity with some strata sampled by only one tow or missed entirely, and was conducted by an uncalibrated vessel (the *Wilfred Templeman*). Stratified mean catch rates at age have been calculated for 2003 using predicted values for the catches in unsampled strata. These predicted values were obtained from generalized linear models fit to the data from the 2003 September RV survey and the 2003 August sentinel survey (which uses the same stratification scheme as the RV survey). However, these corrected indices for 2003 have not been used in previous cod assessments due to the other issues with the 2003 survey (e.g., the uncalibrated vessel).

- a fishery catch rate index for otter trawls, ages 5-12 yr, 1982-1993. Catchability is assumed to have a linear time trend, with a separate slope parameter estimated for each age.

- the longline sentinel index, ages 5-11, 1995 – 2008 or 2009

- the August bottom-trawl sentinel index, ages 2-12, 2003 – 2008 or 2009

- a Danish seine sentinel index with liner, ages 2-10, 1995-2002

- a Danish seine sentinel index without liner, ages 5-11, 1995-2002

- an otter trawl sentinel index with liner, ages 2-10, 1995-2002

- an otter trawl sentinel index without liner, ages 5-10, 1995-2002

- a gillnet sentinel index, ages 7-10, 1996-2002

The total mortality rate (Z) during the fishing moratorium in 1994-1997 was estimated to be 0.57 (95% CI 0.47-0.66) for ages 7-11 based on the RV survey catch rates (Swain et al. 2009). Given the very low fishing effort during this period, this estimate suggests that *M* may have been greater than 0.4 then. Two additional models with age-aggregated *M* were fit with the 2009 data. These models did not fix *M* in 1994-1997. In model 1b, *M* was fixed at 0.2 in 1971 – 1979, and estimated separately in the following blocks of years: 1980-1986, 1987-1993, 1994-1998, 1999-2003, 2004-2009. In model 1c, *M* was fixed at 0.2 in 1971 – 1976, and estimated separately in the following blocks of years: 1977-1982, 1983-1989, 1990-1995, 1996-2002, 2003-2009. These models are described in more detail in Swain (2011*a*), where they are referred to as models 1 and 2.

In summary, four models were tested: model 1 with data up to 2008 or 2009, and models 1b and 1c, which included data up to 2009 but estimated *M* in different blocks of years. Residual patterns in the fit to the RV data become more severe when the 2009 data are added to model 1 (Fig. 7). Residuals tend to be negative (observed index less than predicted index) for older ages (5+) in the 1970s and early to mid 1980s and for younger ages (2-4) in the 1990s and 2000s. A band of positive residuals occurs for cohorts produced in the mid to late 1980s. Strong residual patterns also occur for models 1b and 1c, though the fit to the RV data is substantially improved for these models; the sum of squared residuals from the RV data is 105.6 for model 1 and 86.5 and 83.4 for models 1b and 1c, respectively.

Adding the 2009 data to model 1 results in a slight reduction in estimated M in the 1980s and early 1990s and an increase in estimated M in the late 1990s and 2000s (Fig. 8). Estimates of *M* for 1994-1997 from models 1b and 1c are higher than 0.4. Model 1b suggests a steady increase in M in the 1980s and early 1990s whereas model 1c suggests a period of rapid increase in the late 1980s and early 1990s. Random walk models for *M* (Swain 2011*a*) are more consistent with model 1c than 1b.

All four models indicate that spawning stock biomass (SSB) is currently at a record low level, is well below the limit reference point for this stock (LRP = 80,000 t of SSB) and is declining (Fig. 9). Details of the estimated past trajectory of SSB differ between models, reflecting the differences in estimated *M*. A period of increasing SSB in the mid 1990s is indicated by the models that fix M at 0.4 in 1994-1997 (model 1-08 and -09) whereas SSB is roughly stable during this period based on the models that estimate *M* during this period (models 1b and 1c).

Figure 10 compares estimated recruitment rates (the number of age-3 recruits produced per unit of spawning stock biomass) among models and with model-independent estimates based directly on the RV data. All four models estimate that recruitment rates were very high in the 1990s and 2000s, much higher than the rates at the start of the time series and approaching the exceedingly high rates of the mid to late 1970s. In contrast, the RV data indicate that recruitment rates in the 1990s and 2000s were much lower than those in the mid to late 1970s and were comparable to those observed in the early 1970s (1971 and 1972 year-classes).

Further diagnostics of the fit of models with age-aggregated *M* are given by Swain (2011*a*).

POPULATION MODELS WITH AGE-DISAGGREGATED *M* (2-4 AND 5+ YEARS)

Models which estimate separate time trends in *M* for ages 2-4 and 5+ provide a much better fit to the RV survey data (Swain 2011*a*). Several models with age-disaggregated *M* were examined by Swain (2011*a*). Models with a 12+ group provided the best fit to the data, and it is proposed that this model structure (12+ group, separate M values and trends for ages 2-4 and 5+) should be used to provide advice on 4T cod at the February 2011 recovery potential assessment for cod.

The models with age-disaggregated *M* examined by Swain (2011*a*) were fit only to the RV survey indices, and included the 2003 indices that are normally excluded from model calibration. In this section, results are examined for the proposed model calibrating with the traditional set of indices. (Because this model has a 12+ group, age 12 has been excluded from indices that traditionally include this age.) Effects of particular indices on model results were examined by removing single indices from the full calibration set.

Two types of models were examined by Swain (2011*a*): ADAPT models that estimated *M* in blocks of years and ADMB models that estimated *M* using random walks. These two types of models are again compared here. In addition, the ADAPT *M*-block models were implemented in ADMB to obtain access to certain model outputs for projections. For all models described here, *M* was fixed at a constant value for 1971-1976, either 0.5 or 0.65 for ages 2-4 years and either 0.1 or 0.15 for ages 5+. The values chosen for ages 5+ were based on earlier studies that estimated *M* to be 0.07-0.2 for 4T cod in the 1970s and earlier (see Swain 2011*a*). Appropriate values to use for younger cod are more uncertain. Based on a review of empirical estimates of *M* for marine and brackish water fishes, Gislason et al. (2010) recommended the following formula for estimating *M* from length and growth characteristics:

$\ln(M) = 0.55 - 1.61\ \ln(L) + \ln(L4) + \ln(K)$

where *L* is fish length (cm) and *L*4 and *K* are the von Bertalanffy growth parameters. Using the size at age and growth characteristics of 4T cod in the 1970s, this formula yields an unweighted average *M* of 0.65 for ages 2-4 yr (Fig. 11). The effect of the level chosen for *M* in 1971-1976 on models results is also examined below.

In the random walk models, *M* was modeled as follows:

$M_{j,y} = M\text{fix}_j$ if y = 1971-1976

$M_{j,y} = M_{j,y-1} * \exp(M\text{dev}_{j,y})$ if $y > 1976$

where *y* indexes year and *j* indexes age class (2-4 or 5+).

For the ADMB *M*-block models, the objective function to be minimized was:

$$\text{f}_1 = 0.5 \cdot \sum\nolimits_{a,y,i} (\log(I_{a,y,i} / (q_{a,i} N_{a,y})) / s_{a,y,i})^2 + \sum\nolimits_{a,y,i} \log(s_{a,y,i})$$

where

$$s_{a,y,i} = (\log(1 + cv_{a,y,i}^2))^{0.5}$$

where *I* is an abundance index, *N* is estimated population abundance, *q* is catchability, *cv* is the coefficient of variation for index *i, a* indexes age, *y* indexes year and *i* indexes abundance index. *cv* was set to a constant value of 0.3, and thus had no effect on the minimization (except in the random walk models described below, where this value affects the weight attributed to this component of the objective function).

For the random walk models, the objective function to be minimized was:

$$\text{f}_2 = \text{f}_1 + 0.5 \cdot (\sum\nolimits_{j,y} M\text{dev}_{j,y}^2) / sd^2$$

The value of *sd* affects the degree to which the random walk is constrained. If it is too large, estimated *M* will tend to fluctuate erratically in response to year-effects. For the analyses presented by Swain (2011*a*), which were fit to the RV data only, *sd* was set at 0.1. For the models examined here, which were fit to 7 additional sets of indices, a value of 0.1 was too large and *sd* was set at 0.075.

UPDATED POPULATION MODELS WITH AGE-DISAGGREGATED M

In this section, the proposed population models for 4T cod are updated with the indices traditionally used to calibrate the 4T cod model. These models estimate separate time trends in *M* for ages 2-4 and 5+, and will be referred to here as “2M” models. Seven sentinel fishery indices are included in the calibration and the 2003 values are omitted from the RV index used in calibration. The ninth traditional index, the fishery CPUE index, could be included in ADAPT models but not in ADMB models. In the traditional formulation this index is fit assuming an age-dependent linear trend in catchability. Attempts to include this index in the ADMB models were not successful at the time of the December 2010 meeting[1]. Excluding this index has a negligible effect on model results (see below). *M* in 1971-1976 was fixed at 0.65 and 0.15 for ages 2-4 and 5+ respectively. The models include a 12+ group and are fit using the F-ratio method, as described in the ADAPT manual. The F-ratio was estimated in 2004-2009 and set to 1 in earlier years.

Residuals from the RV index were similar between M-block and random walk models, and were similar to those reported by Swain (2011*a*) for 2M models fit to the RV data only (Fig. 12). Residual patterns were considerably less severe than in the 1M models (Fig. 12), and fit to the RV data was much improved over that of the 1M models (sum of squared residuals for corresponding 1M and 2M models were 86.6 and 52.8, respectively).

Residuals from the other indices are shown in Figures 13-15 for the 2M models. Residuals were again very similar between M-block and random walk models. Residuals from the longline index tended to be positive in the early 2000s and negative in the late 2000s, indicating that the index declined more sharply than estimated population abundance during this period (Fig. 13). Residuals from the unlined seine index tended to be negative early in the 1995-2002 period and positive late in this period (Fig. 14). Residuals from the gillnet index showed the opposite pattern (Fig. 15).

Estimated time trends in M were similar between M-block and random walk models, especially for ages 5+ (Fig. 16). Estimated *M* was virtually identical for M-block models fit using ADAPT versus ADMB, again particularly for ages 5+ (Fig. 16). For ages 5+, estimated *M* increased gradually in the late 1970s and early 1980s and sharply in the late 1980s and early 1990s; 5+ *M* remained at a high level throughout the 1990s and 2000s. Estimated *M* for ages 2-4 showed the opposite pattern, declining in the late 1980s and early 1990s.

Estimated SSB was very similar between M-block and random-walk models (Fig. 17). ADAPT and ADMB models produced nearly identical results. SSB estimated using 2M models was somewhat higher than that estimated by the previous 1M assessment model in most years since 1980. The revised 1M model that estimated *M* in 1994-1997 produced SSB estimates that were similar to those produced by the 2M models until the mid 1990s. For years since the mid 1990s, SSB estimates from both 1M models were lower than those from the 2M models.

Estimated abundance of ages 2-4 was very similar between M-block and random-walk models, except in the late 1980s when the random walk model produced somewhat higher estimates (Fig. 18). ADAPT and ADMB models again produced nearly identical results. Abundance estimates for ages 2-4 in the 1970s and 1980s were much higher from the 2M models than from the 1M models. This reflects the much higher *M* for these ages in the 2M models during this period.

Estimated 5+ abundance was very similar among 2M models, except in the early 1990s when the random walk model produced somewhat lower estimates (Fig. 19). Trends in 5+ abundance were similar between 2M and 1M models, though abundance estimated by the 2M models was higher than that estimated by the 1M models from the mid 1990s to the present.

[1] Subsequent to the December 2010 meeting the programming error that prevented the incorporation of the fishery CPUE index in ADMB models was identified, and this index was included in the RPA model.

Time trends in estimated exploitation rate were similar among models, though the previous 1M assessment model indicated a considerably higher exploitation rate in the early 1990s than is indicated by the other models (Fig. 20).

Estimated trends in recruitment rate contrast sharply between 1M and 2M models (Fig. 21). The 1M models indicate that recruitment rate was strong in the 1990s and 2000s, more than 2-3 times the rate at the start of the time series. The 2M models indicate that recruitment rate was weaker in the 1990s and 2000s, about equal to the rate at the start of the time series. The time trend in the RV data is more like that produced by the 2M models than that produced by the 1M models.

The catchability coefficients estimated by the 2M models are shown in figures 22 and 23.

EFFECTS OF SENTINEL AND CPUE INDICES ON MODEL RESULTS

Effects of particular indices on the model results were examined by comparing results with these indices omitted to results of a model calibrated using all indices. The M block models were used for this analysis. Effects of removing single indices (or all the short 1995-2002 sentinel indices) on estimates of *M* were generally very minor (Fig. 24). The largest effect on 5+ *M* was a decline in the estimate for the 2003-2009 time block from 0.74 to 0.70 when the longline index was omitted. For 2-4 *M*, the largest effects were changes in the estimates in the 1990s and 2000s when the longline index or the five 1995-2002 sentinel indices were omitted; these changes did not alter the general time trend in estimated 2-4 *M*. Omitting the fishery CPUE index resulted in declines in the estimates of 5+ M that ranged from a decline of 0.007 in the 2003-2009 time block to a decline of 0.022 in the 1977-1982 block. Omitting this index also resulted in very minor increases in estimated 2-4 *M*. Effects of removing all indices except the RV index were more substantial, though the general time trends in estimated *M* remained unchanged.

Trends in estimated SSB were similar calibrating with all indices or with various indices omitted from calibration (Fig. 25). Estimated SSB was somewhat lower in the 1980s based on the model with the fishery cpue index omitted from the calibration. Among the models compared, estimated SSB at the start of 2010 was lowest if the cpue index was omitted from the calibration and highest if the longline index was omitted from the calibration, though differences were relatively minor.

EFFECTS OF THE VALUE ASSUMED FOR *M* IN 1971-1976

In the 2M models described above, *M* in 1971-1976 was fixed at 0.65 for ages 2-4 and 0.15 for ages 5+. Changing the initial fixed value for 5+ *M* to 0.1 had no effect on the estimates of *M* for ages 2-4 and little effect on the estimates of 5+ *M* (Fig. 26). Estimated 5+ M declined by 0.02 in the first two time blocks and by 0.006 in the last two time blocks. A further change reducing the initial fixed value for 2-4 M from 0.65 to 0.5 had no noticeable effect on the estimates of 5+ M but resulted in a corresponding change in the estimates of 2-4 *M* (i.e., reducing the initial fixed value by 0.15 resulted in a reduction in the estimated values of 2-4 *M* by about 0.15).

Reducing the initial fixed value for 5+ M from 0.15 to 0.1 resulted in a decline in estimated SSB (Fig. 27). Estimated SSB declined by from 7% in the 1970s to 6% in the 2000s. A further change reducing the initial fixed value for 2-4 M from 0.65 to 0.5 resulted in little additional decline in SSB (though this changed resulted in a substantial decline in estimated abundance of ages 2-4).

ADJUSTMENT FOR BIAS

The ADAPT results reported in previous assessments of 4T cod have been bias adjusted. No bias adjustment was applied to the results of the ADMB models used here. The effect of bias adjustment on the ADAPT results is negligible (Fig 28).

RETROSPECTIVE PATTERNS

Retrospective patterns were examined by sequentially dropping the most recent year of data and re-fitting models. Retrospective patterns were negligible for both M-block and random walk models (Fig. 29 and 30).

CONCLUSIONS

Recent assessments of the 4T cod stock have used an ADAPT model which estimated age-aggregated (2+) *M* in blocks of years, except for 1971-1979 and 1994-1997 when *M* was fixed at 0.2 and 0.4, respectively. In the February 2009 assessment, a number of discrepancies were noted between the predictions of this model and the data. These discrepancies became more severe with the addition of the 2009 data. The following changes to the assessment model were proposed and accepted at the review meeting:

1) *M* should not be fixed at 0.4 in 1994-1997. Models which estimate *M* during this period provide a substantially better fit to the data. *M* during this period appears to be higher than 0.4.

2) Models which estimate separate trends in *M* for ages 2-4 and 5+ provide a substantially improved fit to the data. Such a 2M model should be used for the assessment of this stock. The proposed model includes a 12+ group and fixes *M* in the 1971-1976 period only, provisionally at 0.65 for ages 2-4 yr and 0.15 for ages 5+.

3) ADMB provides greater flexibility in model structure than does ADAPT, and permits access to various model outputs for projections. Use of ADMB instead of ADAPT for the 4T cod assessment model was proposed and accepted.

4) Bias correction has a negligible impact on 4T cod model results and has not yet been implemented in ADMB models for this stock. The use of results without bias adjustment was proposed and accepted.

5) All of the indices traditionally used to calibrate the 4T cod assessment model should be included in calibration of the revised model (except indices at age 12, due to the use of a 12+ group). There is a concern that the sentinel longline index may show hyperdepletion, but this index should be retained for calibration until this issue is investigated further. Omission of single indices from the calibration, including the omission of the sentinel longline index, had only minor effects on model estimates.

ACKNOWLEDGEMENTS

ADMB programs used here evolved from code originally provided by Bob Mohn; I thank Bob for this code and for discussion and advice during the course of this work. I thank Tom Hurlbut for updated figures of the RV survey data, Luc Savoie for updated figures of the sentinel survey data, Éliane Aubry for other technical assistance, and Ghislain Chouinard for discussion and advice.

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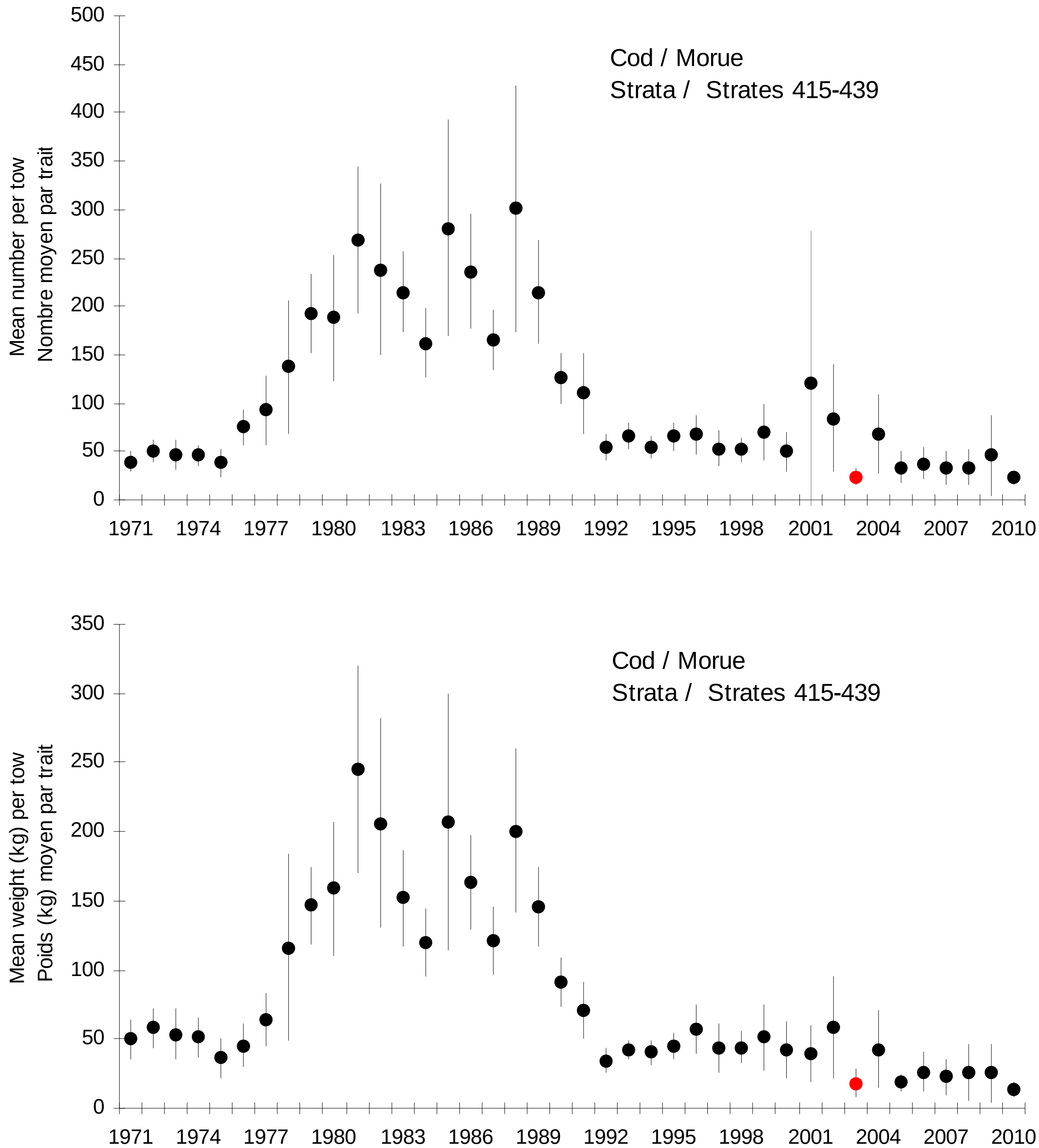

Figure 1. Mean number and weight of cod per tow in the September research vessel survey of the southern Gulf of St. Lawrence. Vertical lines are ±2SD. Note that the 2003 survey (denoted by the red symbol) started late, had a low sampling intensity with some strata sampled by only one tow or missed entirely, and was conducted by an uncalibrated vessel (the Wilfred Templeman); the mean values in missed strata were estimated as described in Chouinard et al 2005b.

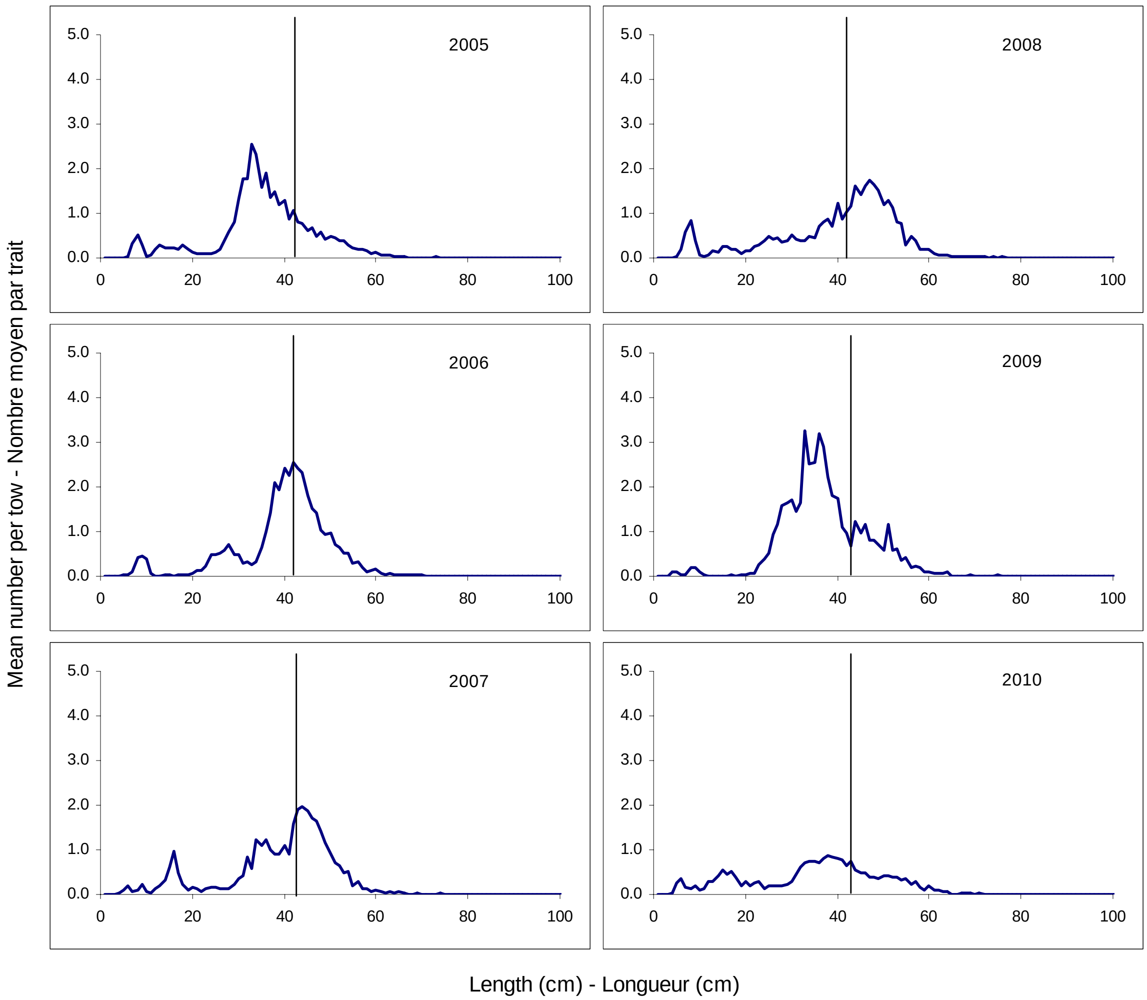

Figure 2. Length distribution of cod catches in recent September surveys.

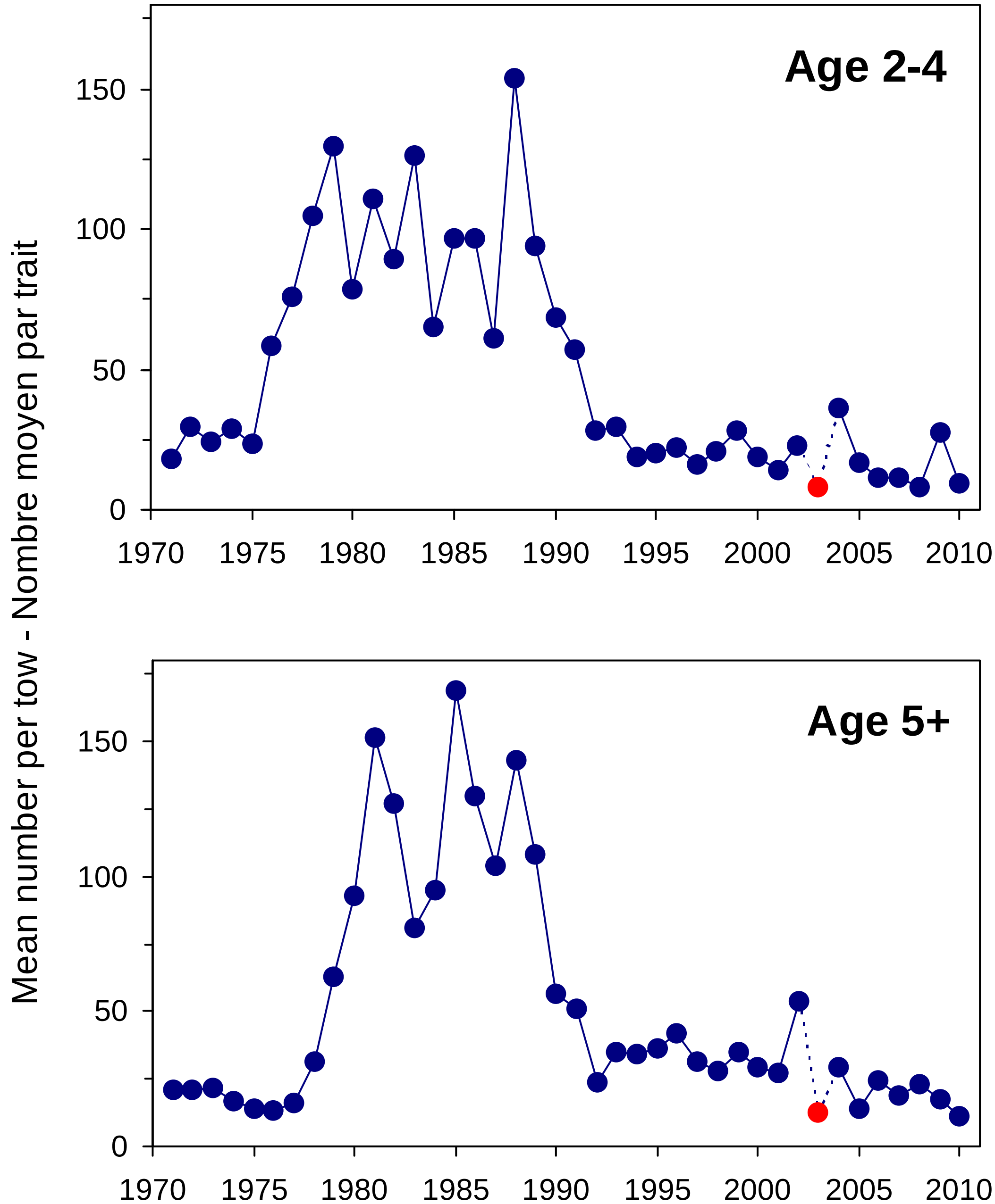

Figure 3. Mean catch rate of cod in the September RV survey by age class. The 2003 indices, denoted by red symbols, are normally excluded from population model calibration for the reasons outlined n the caption to Figure 1.

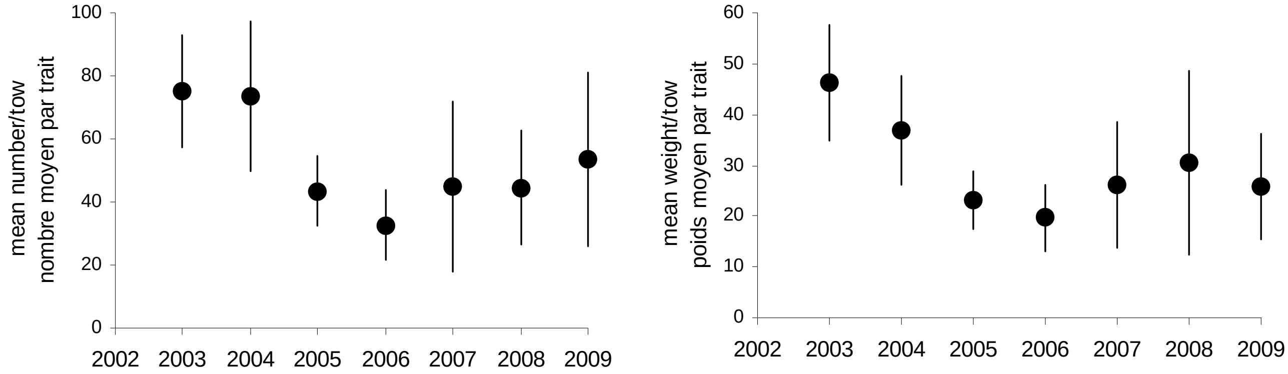

Figure 4. Mean number and weight of cod per tow in the August sentinel trawl survey of the southern Gulf of St. Lawrence. Catch rates are adjusted for differences between vessels in fishing efficiency. Error bars indicate approximate 95% confidence intervals.

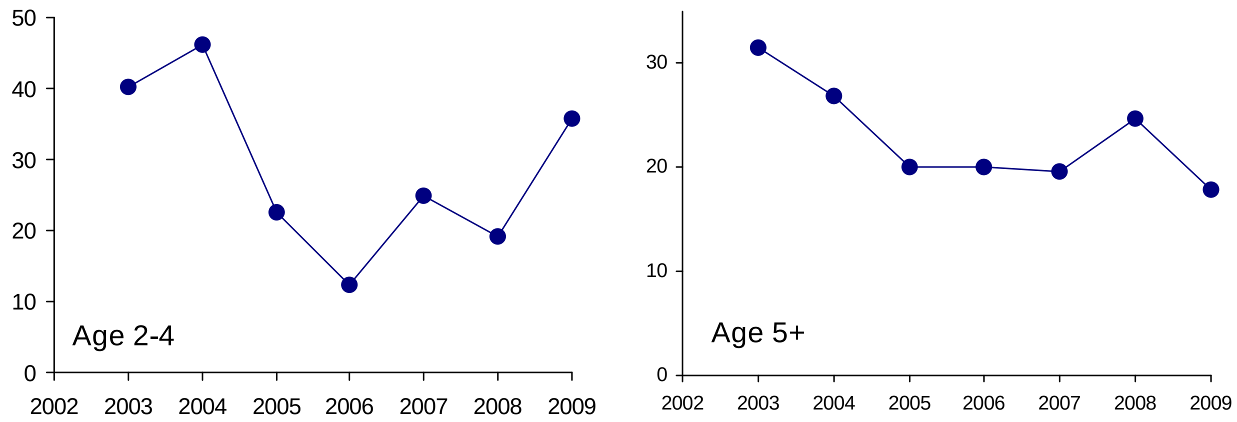

Figure 5. Mean catch rate of cod (number/tow) in the August sentinel trawl survey by age class.

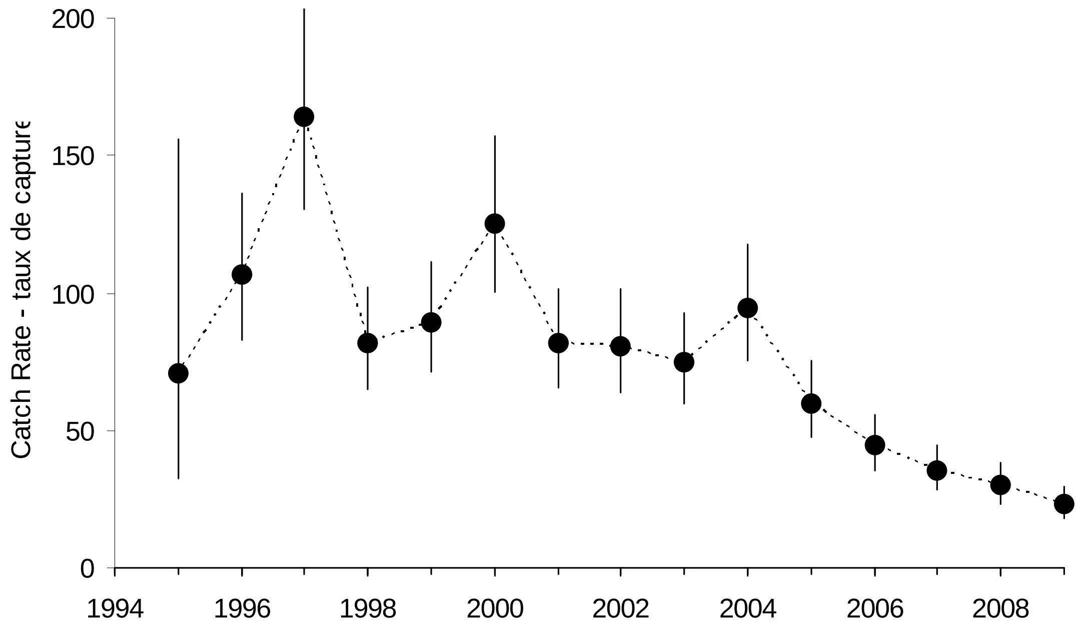

Figure 6. Standardized catch rates in the longline sentinel surveys in the southern Gulf of St. Lawrence, 1995 to 2009. Error bars indicate approximate 95% confidence intervals.

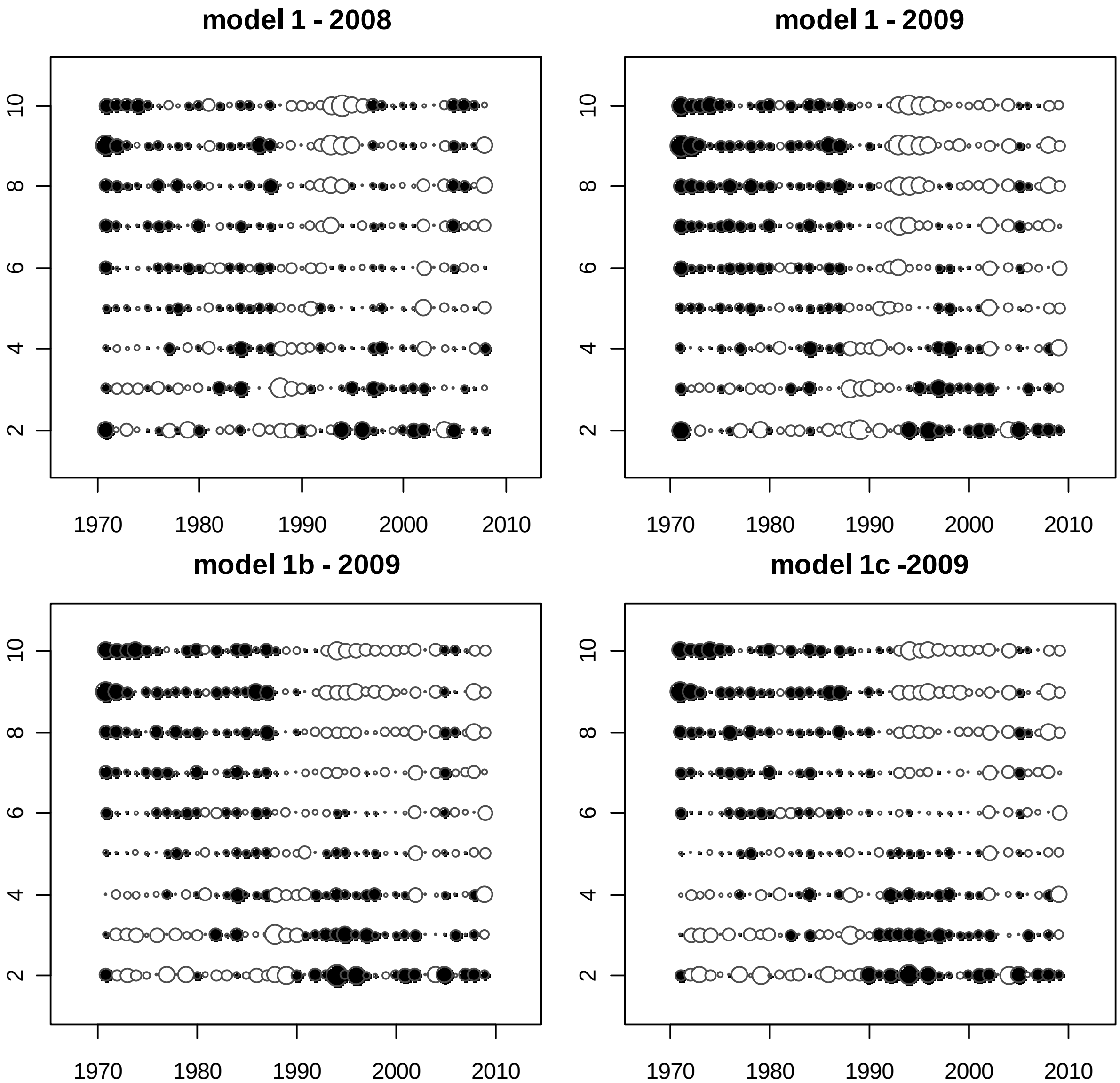

Figure 7. Residuals for the RV survey indices for age-aggregated M models. Black circles indicate negative residuals (i.e., observed index < predicted index).

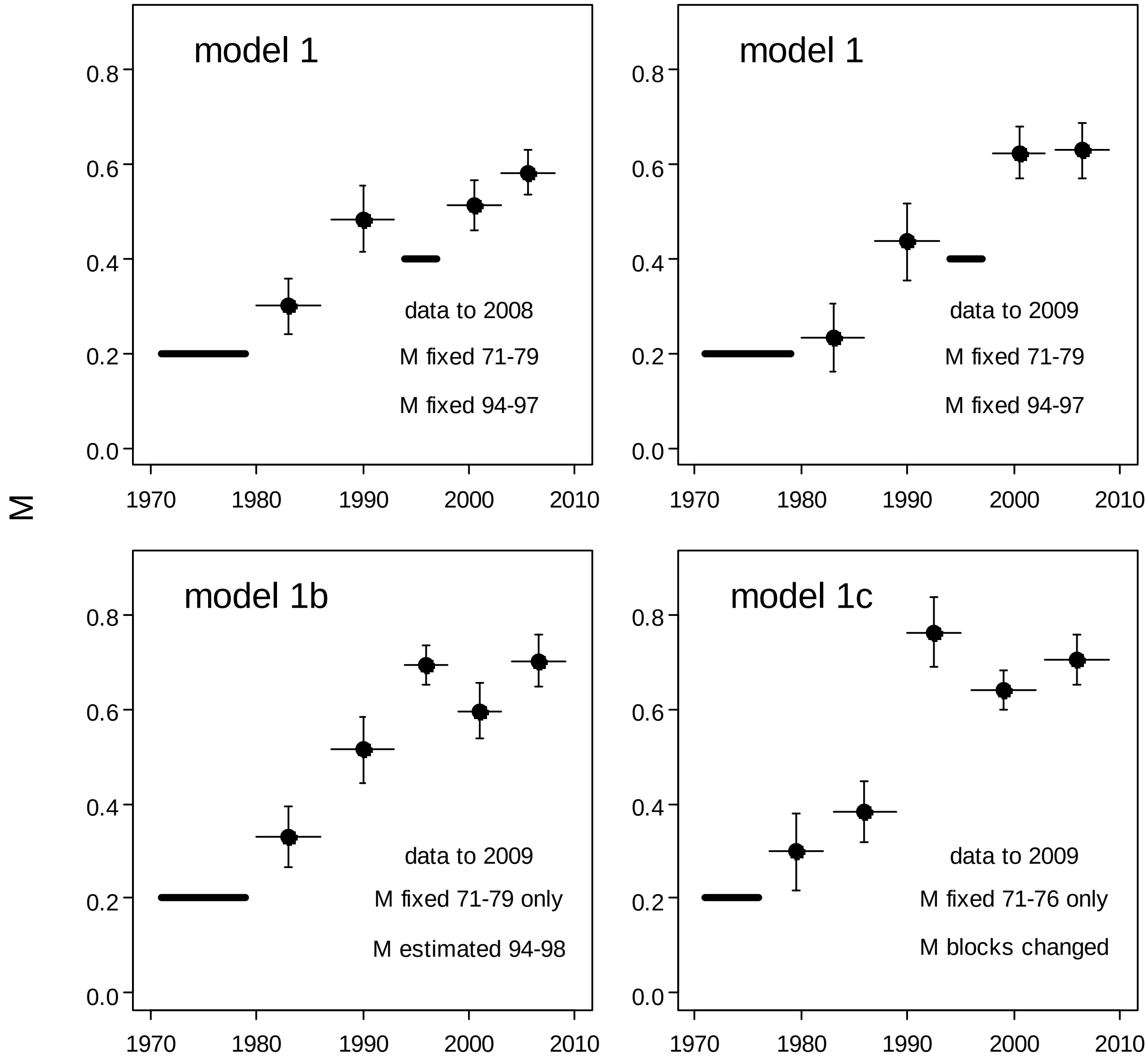

Figure 8. Estimates of age-aggregated (2+) M. Heavy horizontal line is an assumed value. Light horizontal lines indicate the time period for each estimate. Vertical lines are $\pm$*2SE.*

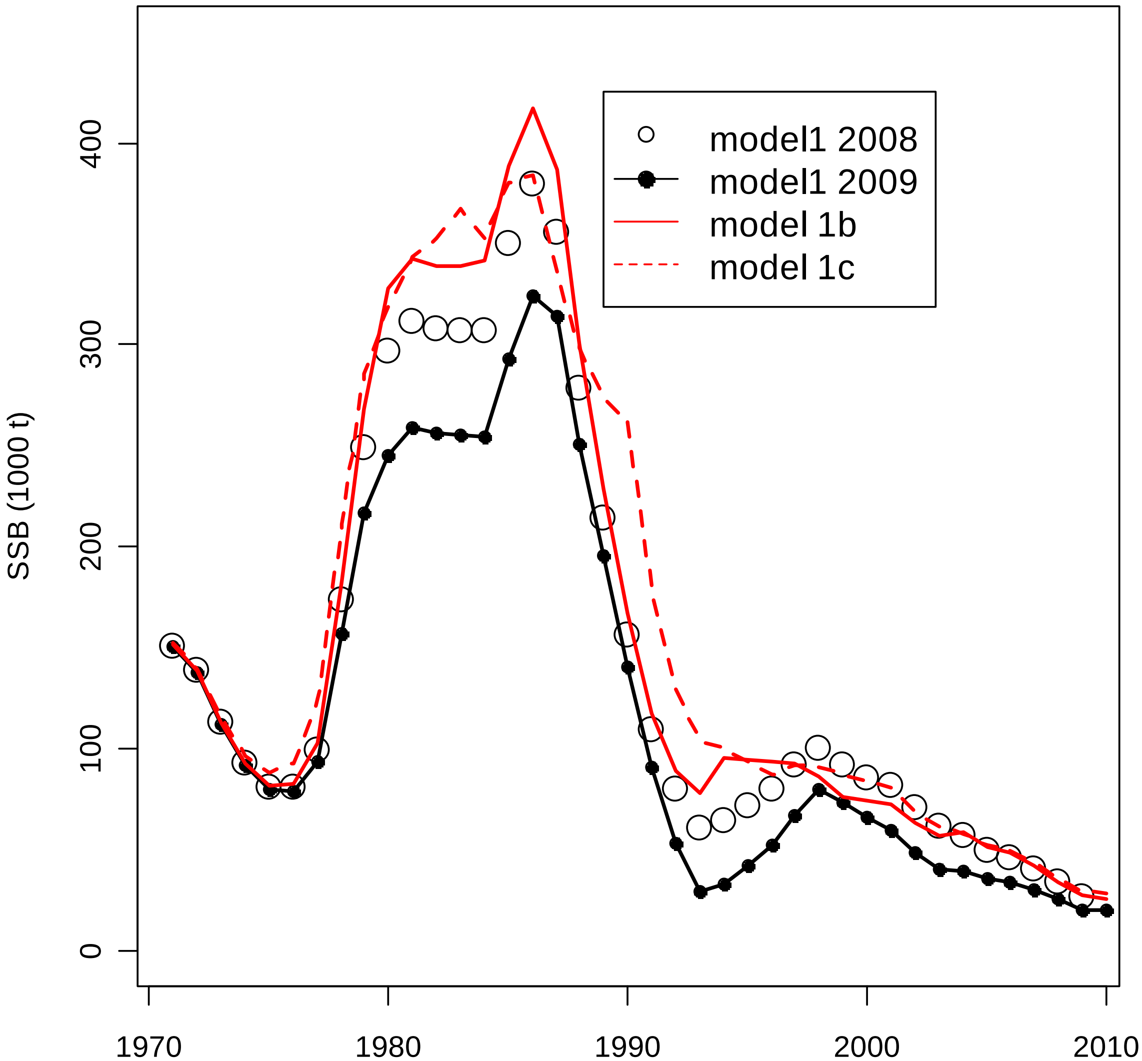

Figure 9. Estimates of spawning stock biomass (SSB) from models with age-aggregated M.

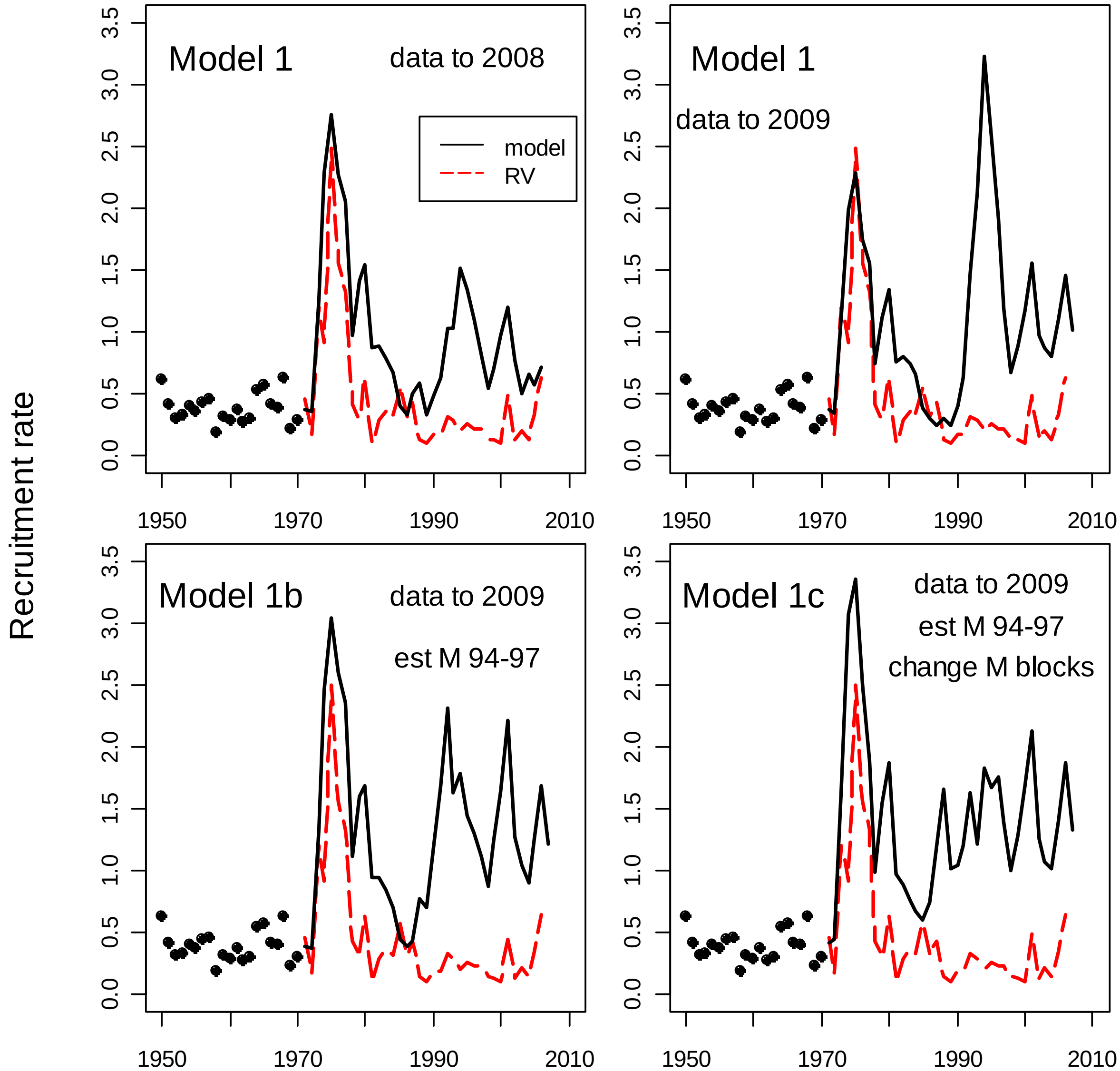

Figure 10. Recruitment rate (the number of age-3 recruits produced per unit of spawning stock biomass) estimated by models with age-aggregated M (solid black line) or from the survey data (dashed red line). Circles are the rates from an earlier SPA model which assumed an age-aggregated M of 0.2 (Maguire et al. 1983). (Note that maturity schedules for years prior to 1971 have been revised following Swain (2011b), so the recruitment rates for the 1950-1970 year-classes differ slightly from values presented earlier.)

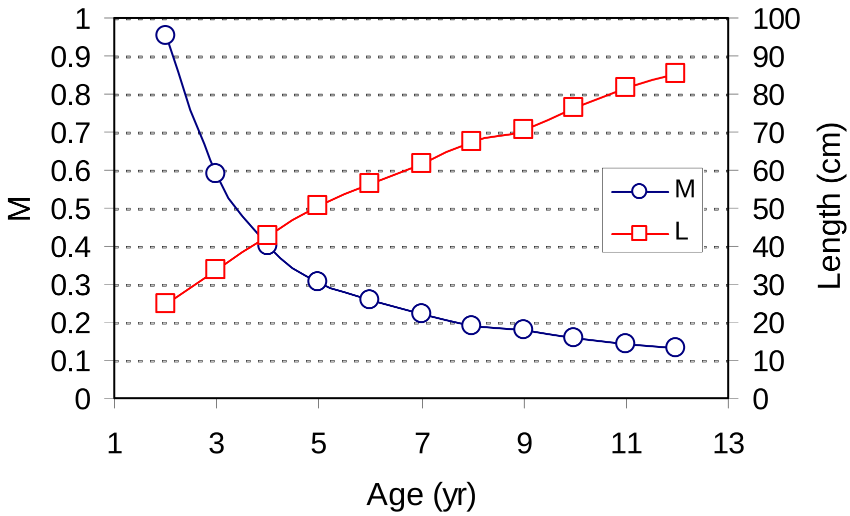

Figure 11. Mean length at age of 4T cod in the 1970s and the corresponding estimates for M at age from the formula of Gislason et al. (2010).

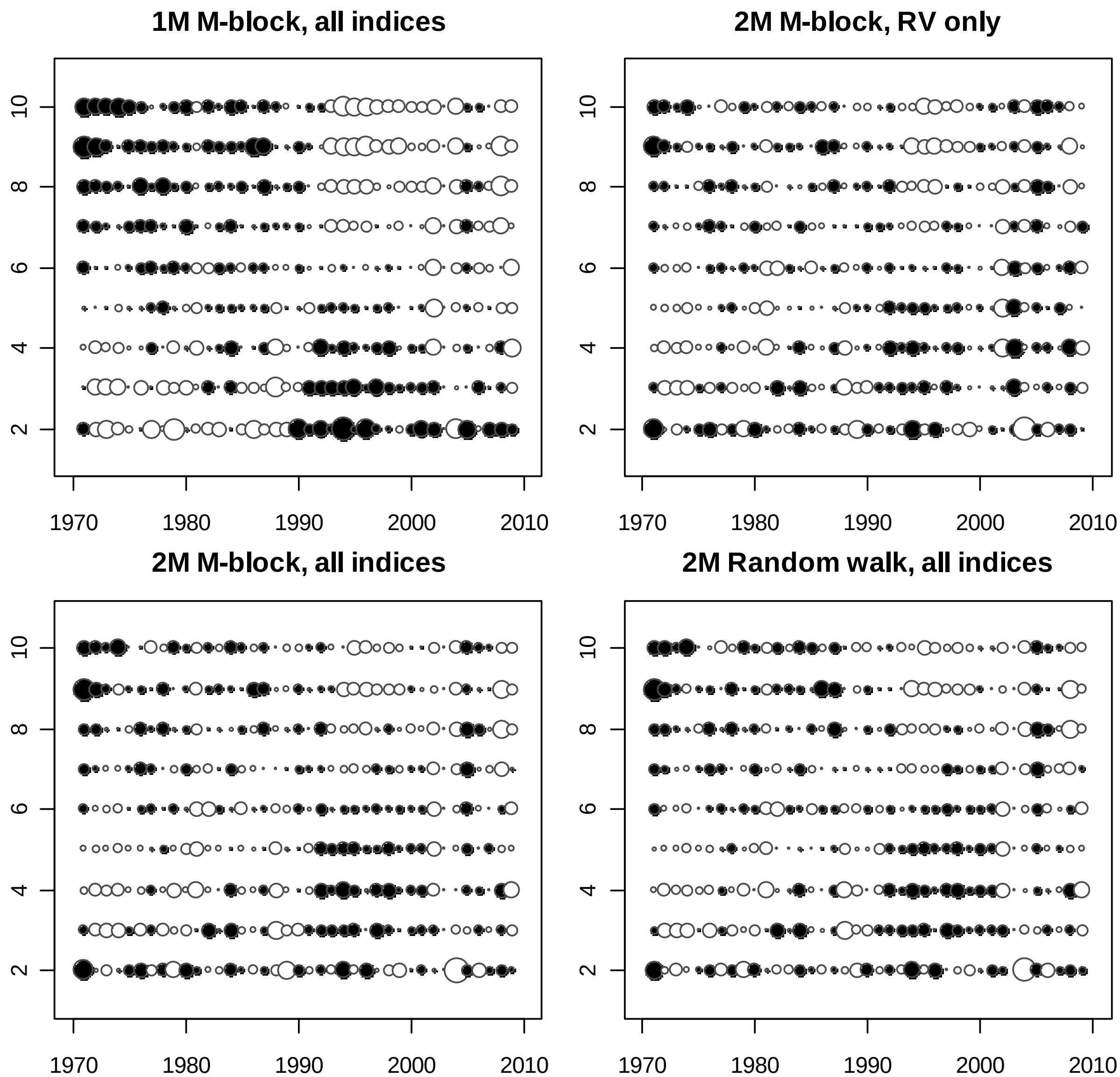

Figure 12. Residuals from the RV data for the 2-M (ages 2-4 and 5+) models fit to all indices but the fishery cpue compared to the residuals for a 2-M model fit to the RV data only and a 1-M model fit to all indices. Models in the upper panels were fit using the ADAPT software and those in the lower panels are ADMB models.

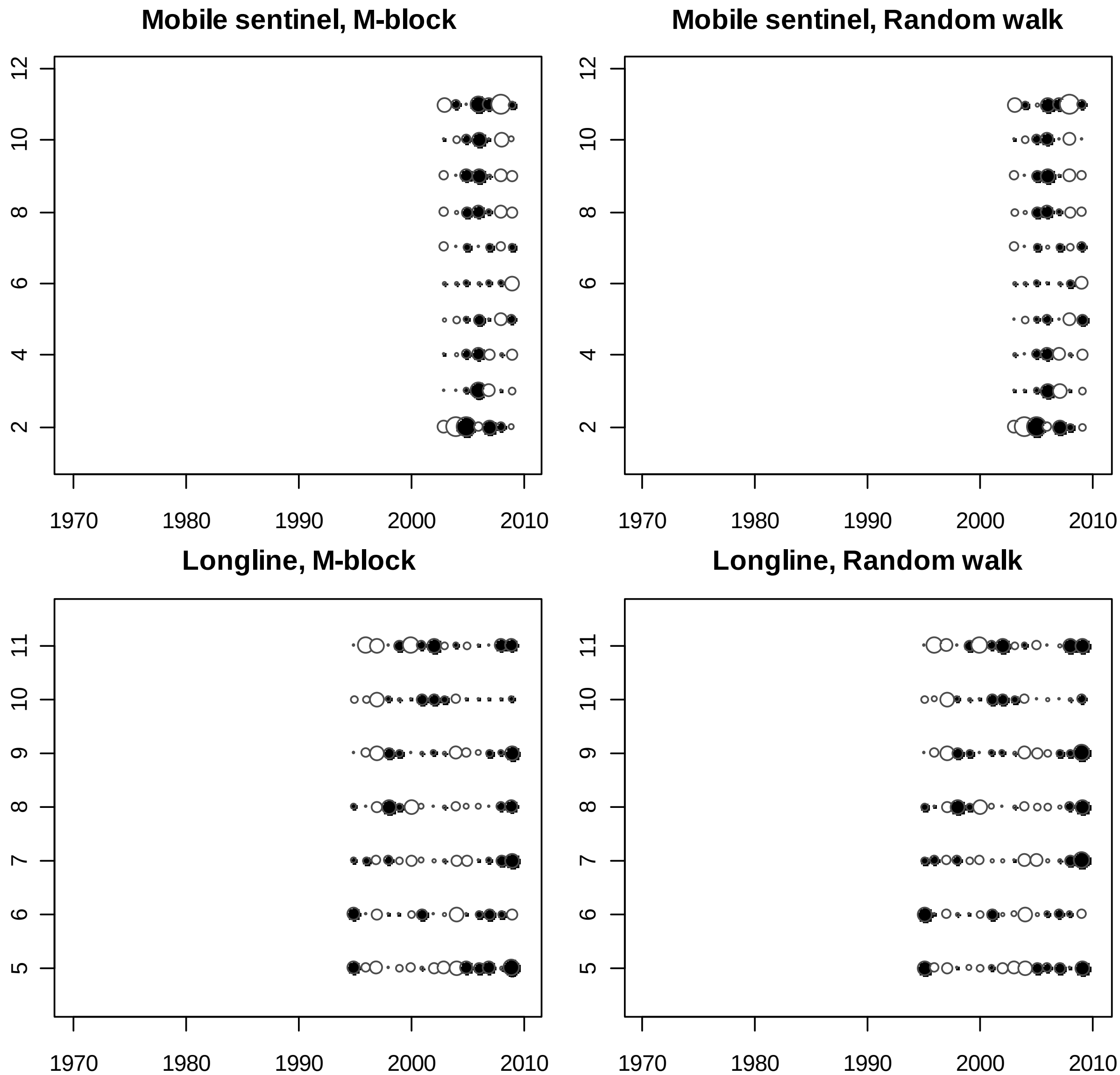

Figure 13. Residuals from the mobile sentinel and longline sentinel indices for the 2-M (ages 2-4 and 5+) models fit using all indices but the fishery cpue.

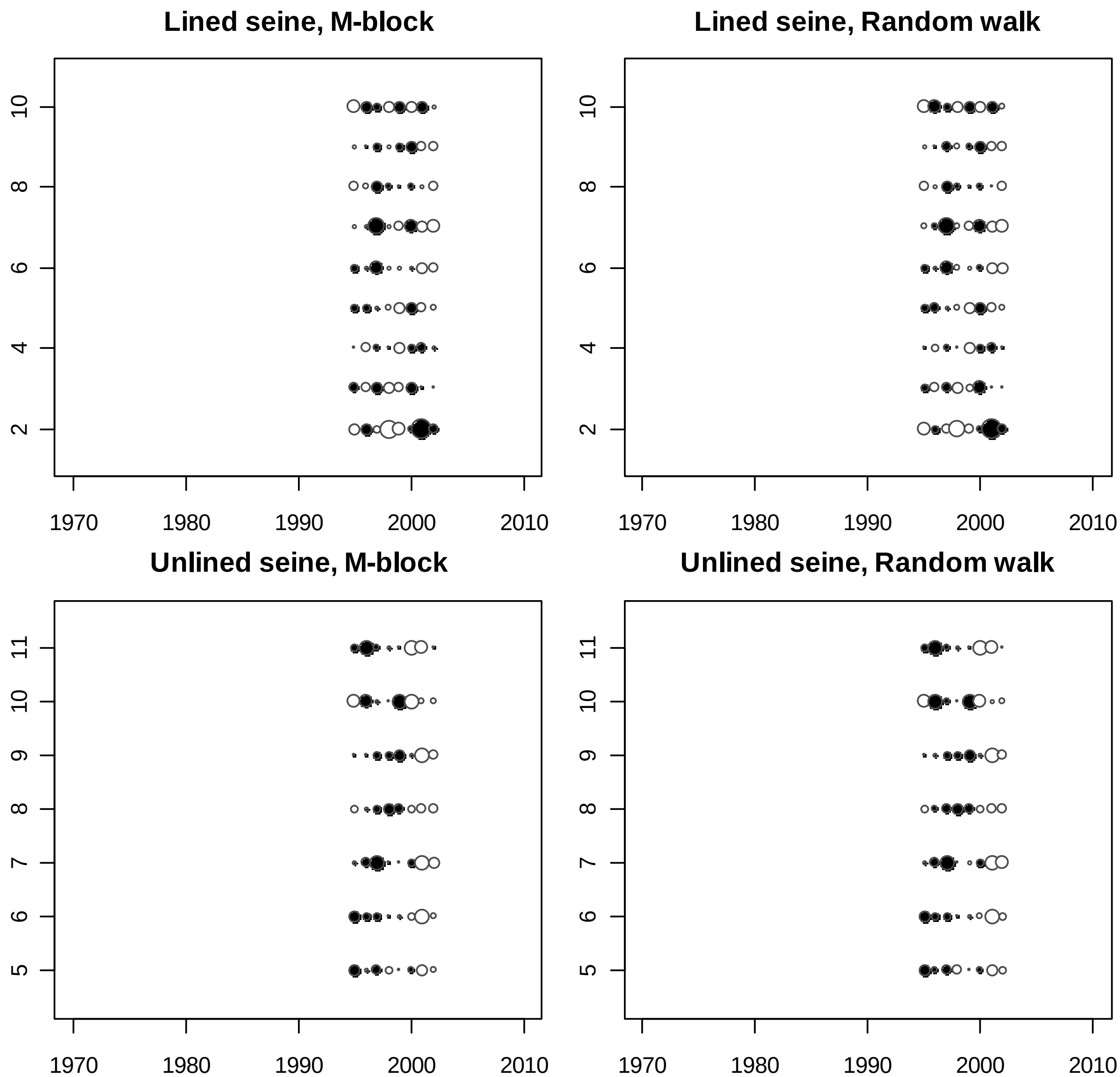

Figure 14. Residuals from the seine sentinel indices for the 2-M (ages 2-4 and 5+) models fit using all indices but the fishery cpue.

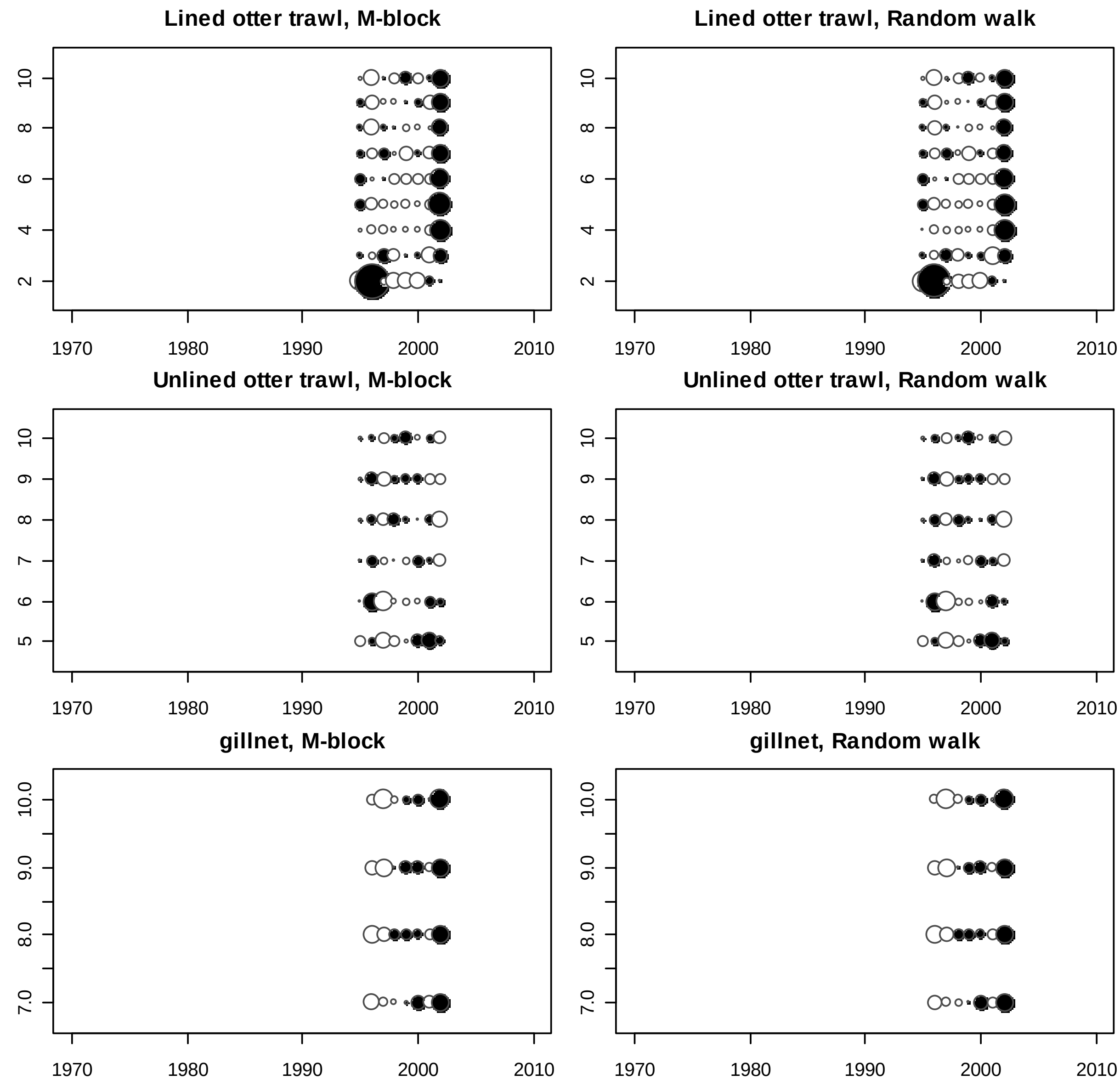

Figure 15. Residuals from the otter trawl and gillnet sentinel indices for the 2-M (ages 2-4 and 5+) models fit using all indices but the fishery cpue.

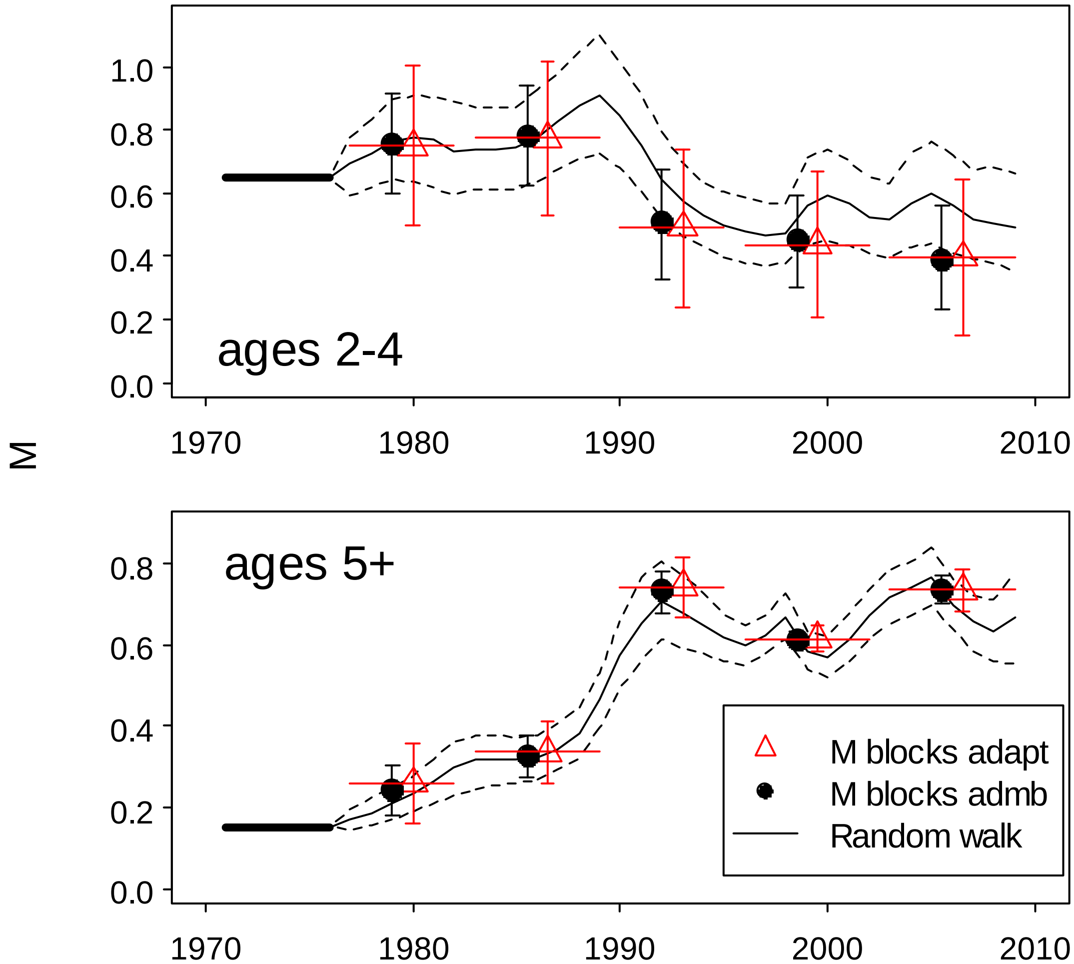

Figure 16. Estimated M from 2M models fit to all indices except fishery cpue. Heavy horizontal lines are assumed values. Light horizontal lines indicate the time period for each M block. Vertical lines are ± 2SE (ADAPT) or the 2.5th and 97.5th percentiles of 1000 MCMC samples (ADMB). For the random walk, the solid line is the median and dashed lines the 2.5th and 97.5th percentiles of 1000 MCMC samples (every 50th sample from 50000 samples).

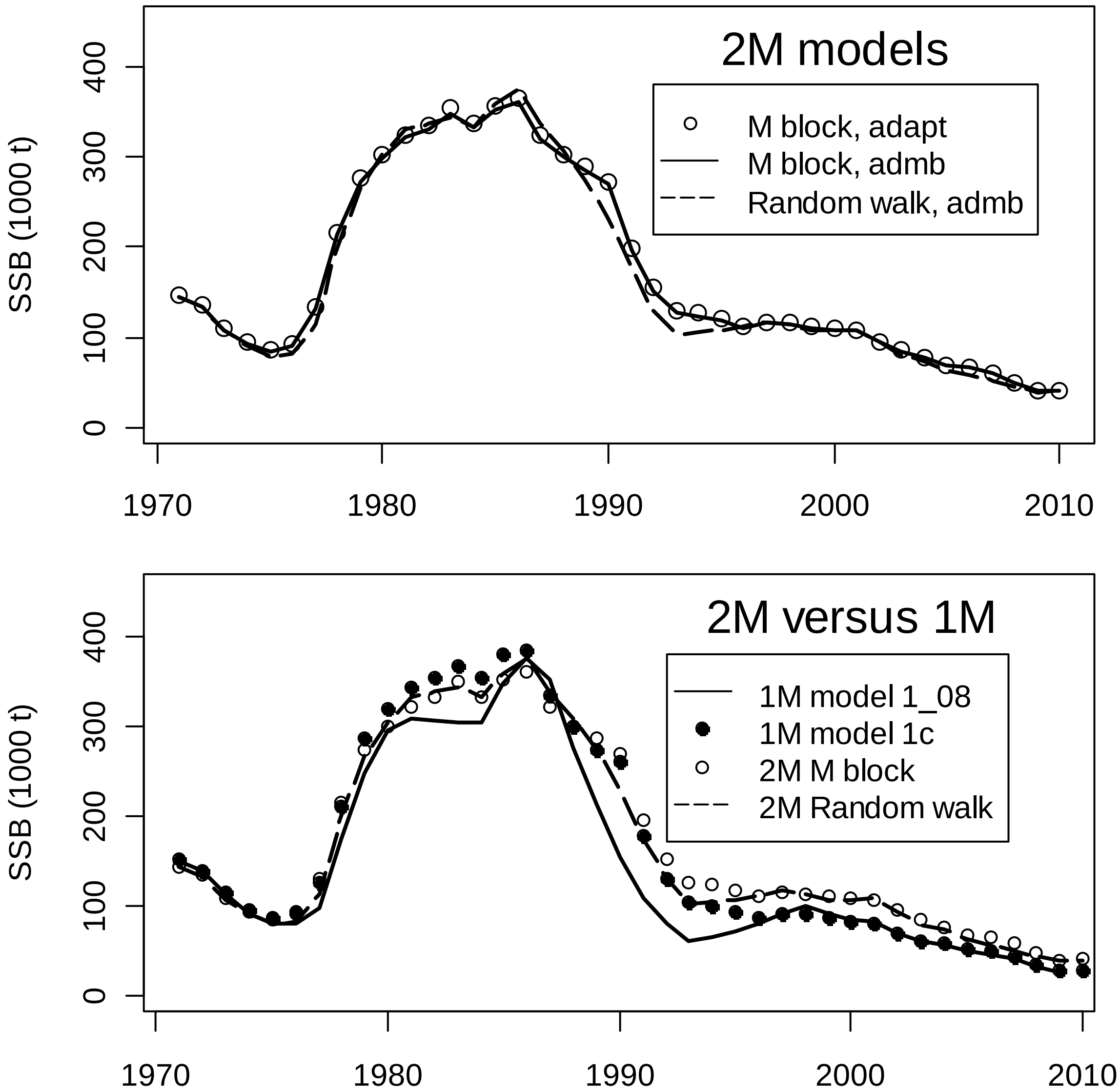

Figure 17. Spawning stock biomass (SSB) compared between models.

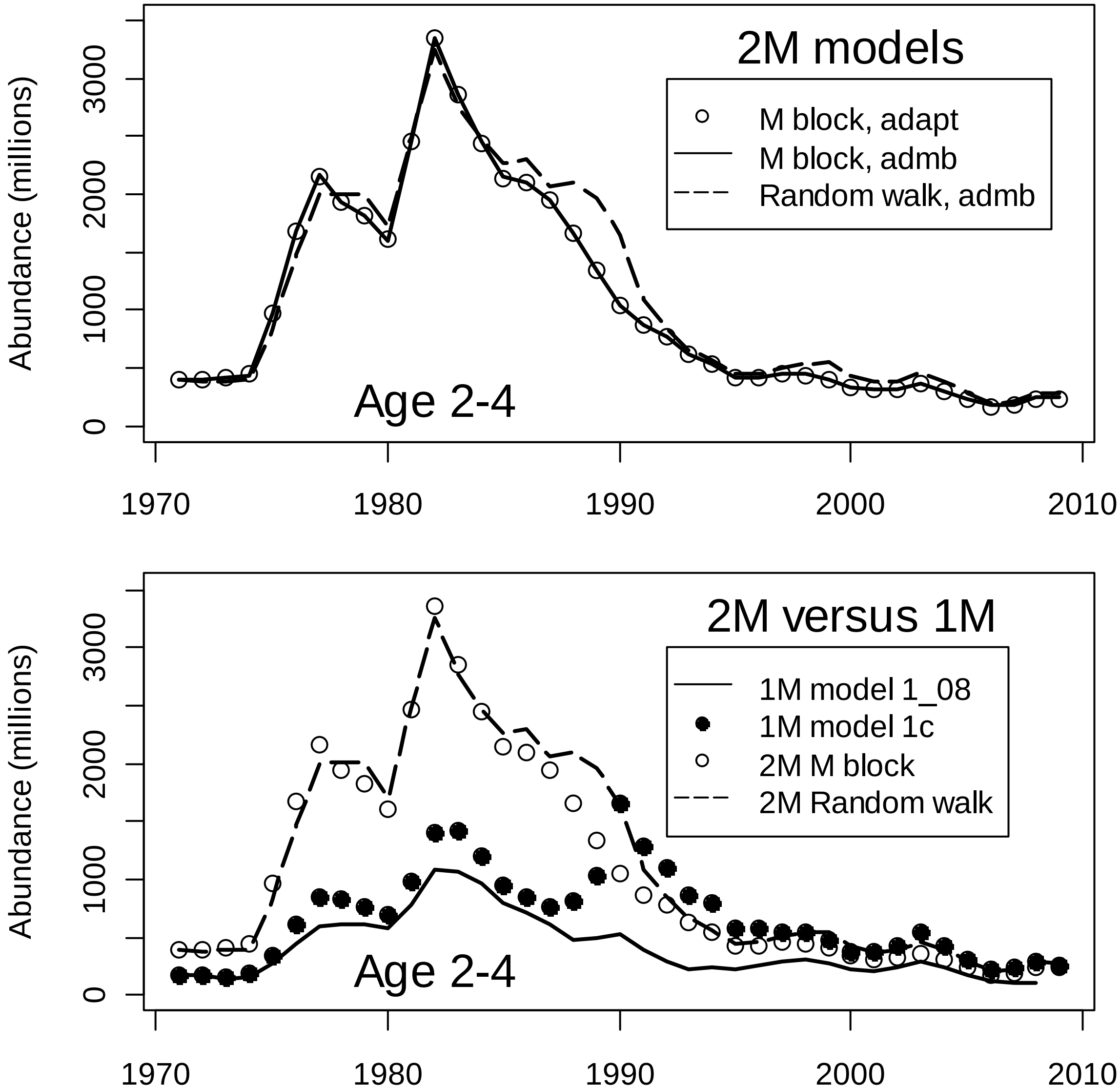

Figure 18. Abundance of cod aged 2-4 yr compared between models.

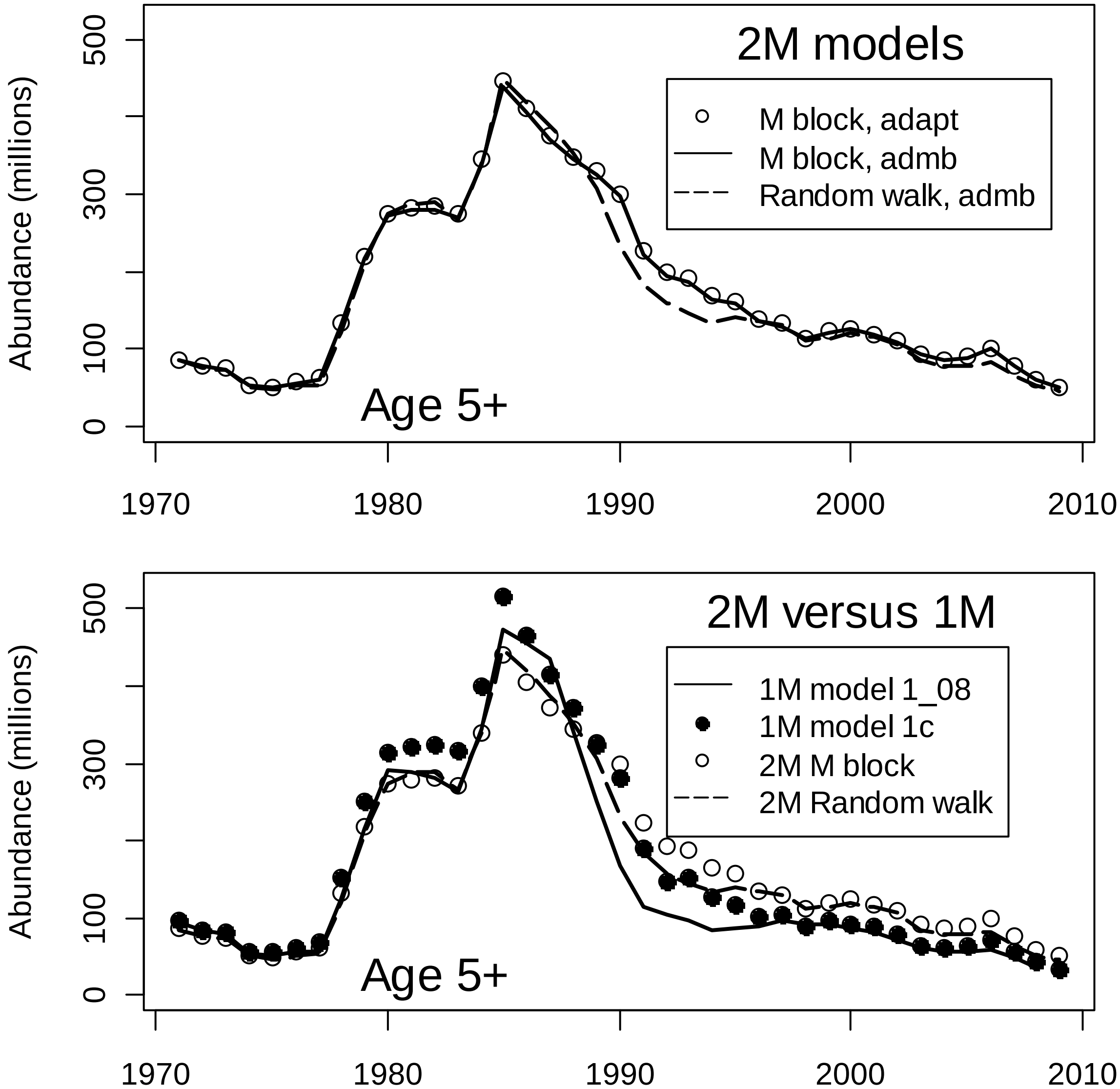

Figure 19. Abundance of cod aged 5 years and older compared between models.

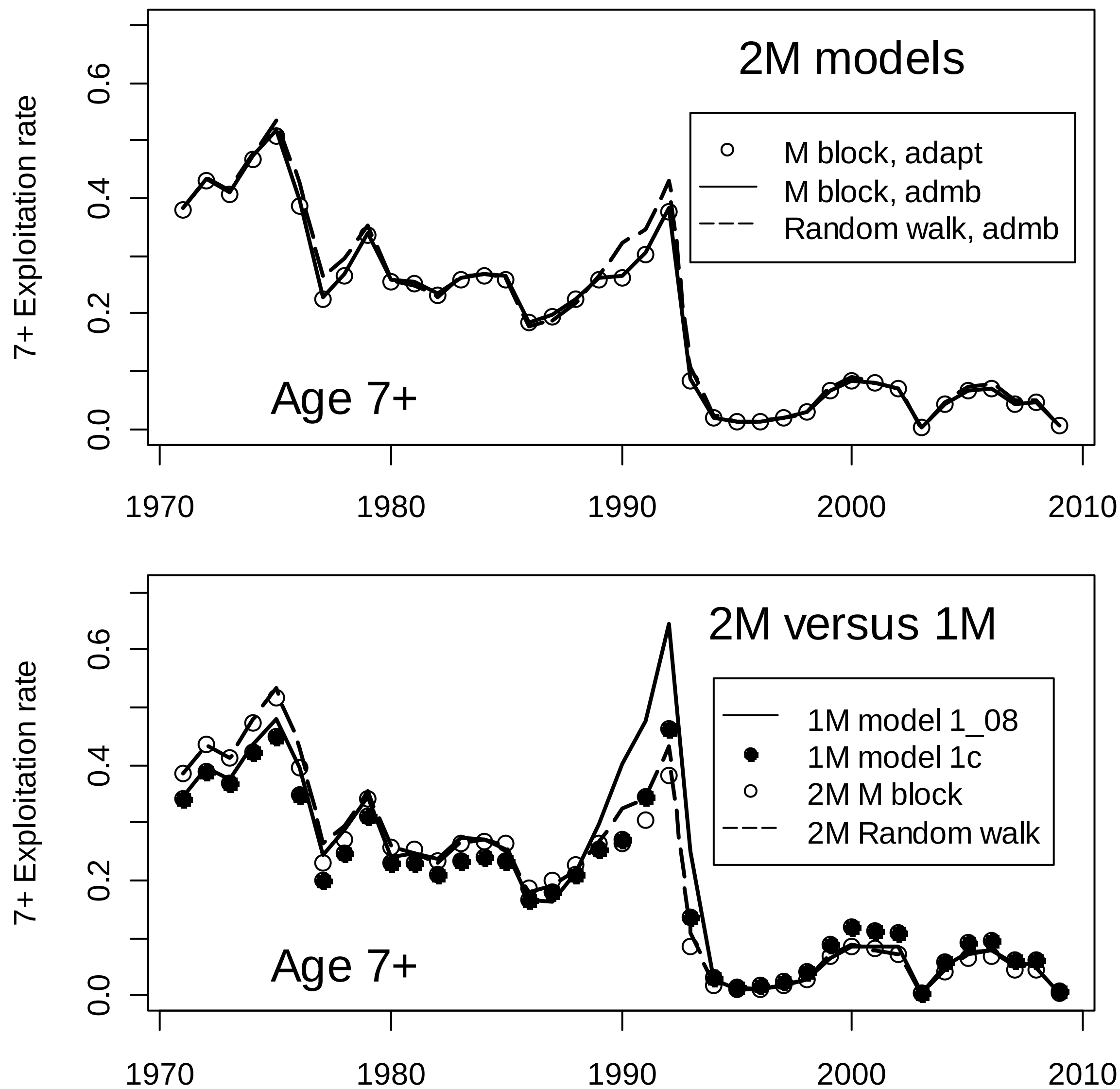

Figure 20. Exploitation rate of cod aged 7 years and older compared between models.

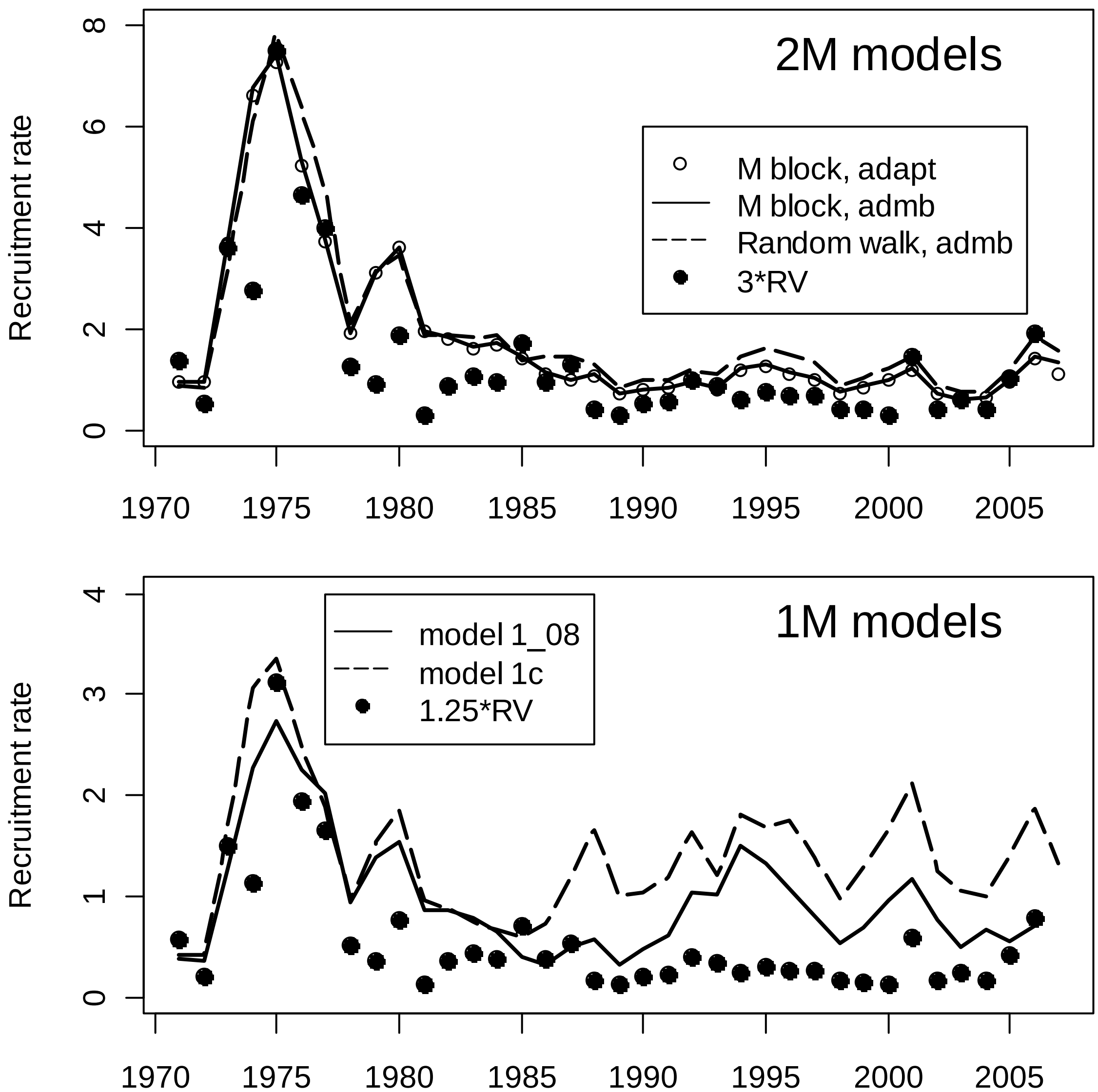

Figure 21. Recruitment rate of cod aged 3 years compared between models and the RV survey data. Note the difference in vertical axis scale between panels. RV rates are scaled to be roughly comparable to model rates in the early to mid 1970s.

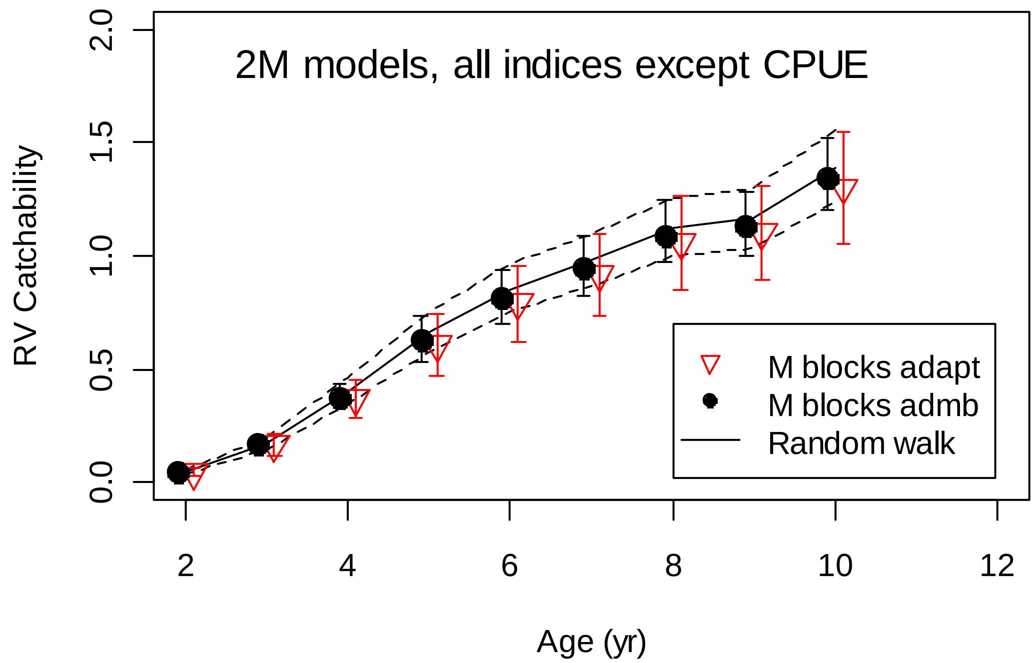

Figure 22. Catchability to the RV survey estimated by 2M models. Dashed and vertical lines are ±2SE (adapt model) or the 2.5th and 97.5th percentiles of 1000 MCMC samples (admb models).

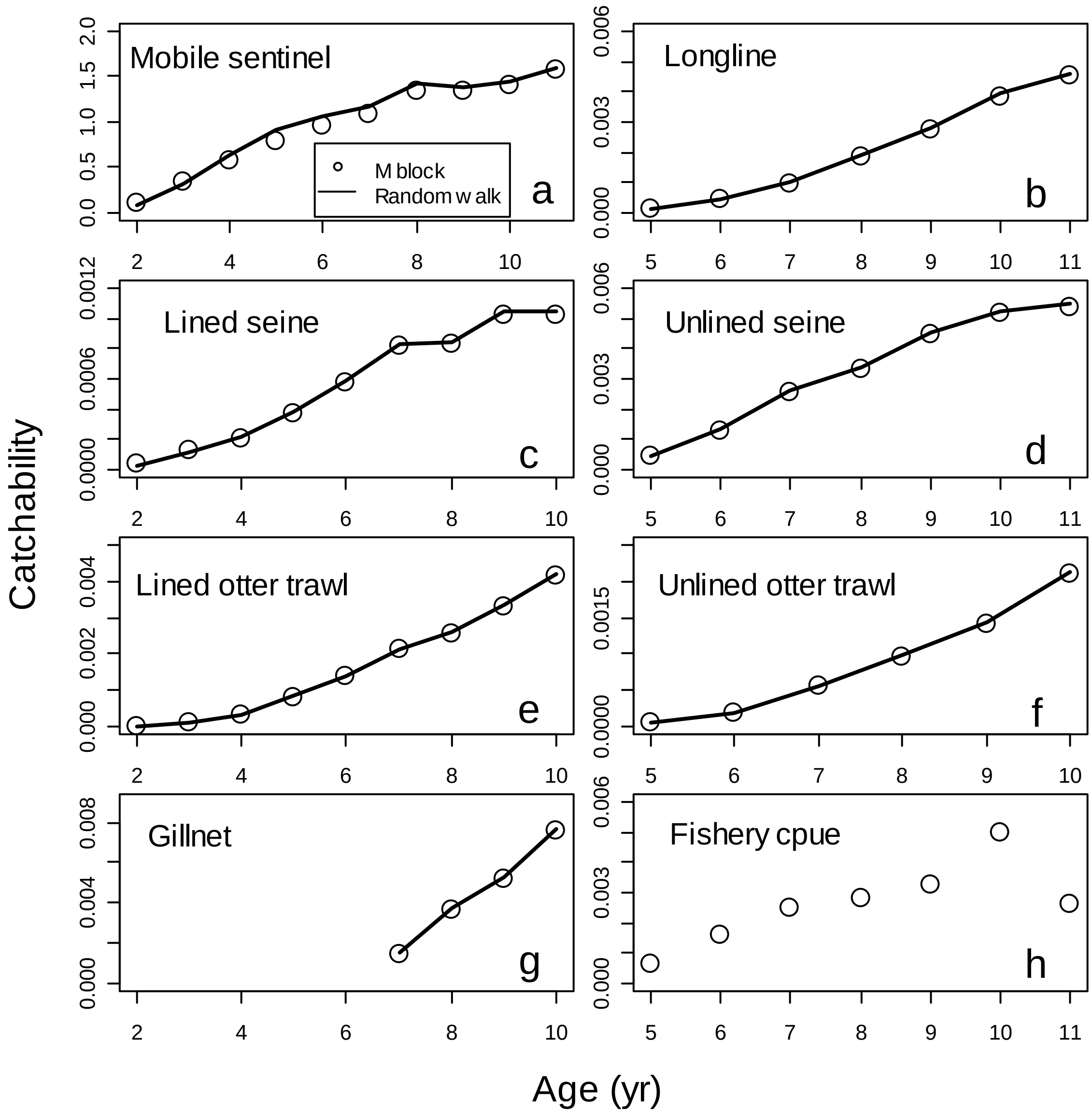

Figure 23. Estimated catchability coefficients from the 2M models (see Fig. 22 for the RV coefficients). Models included all indices except the cpue index for panels a-g. The model for panel h included all indices.

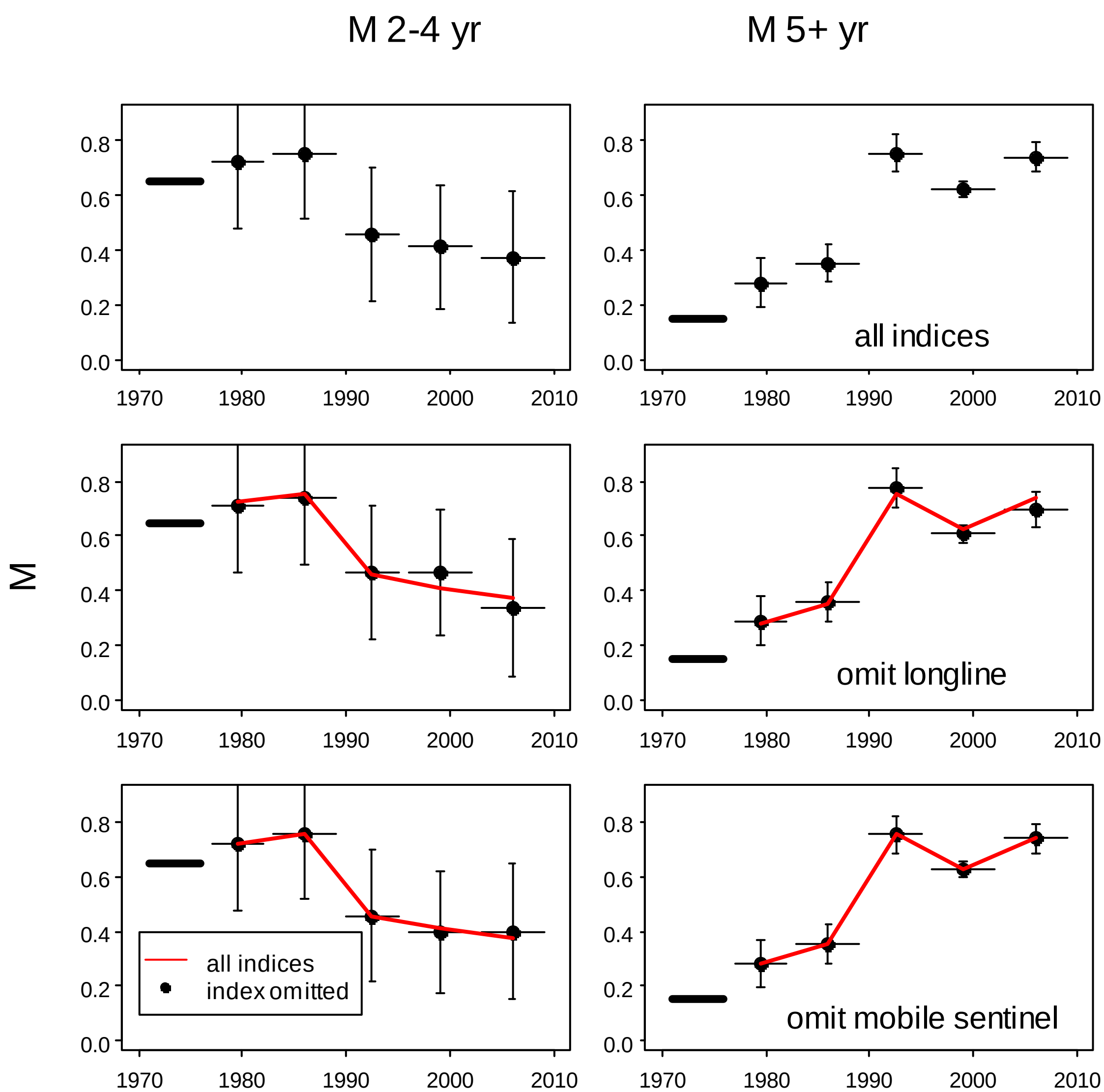

Figure 24. Effect of omitting indices on M estimates.

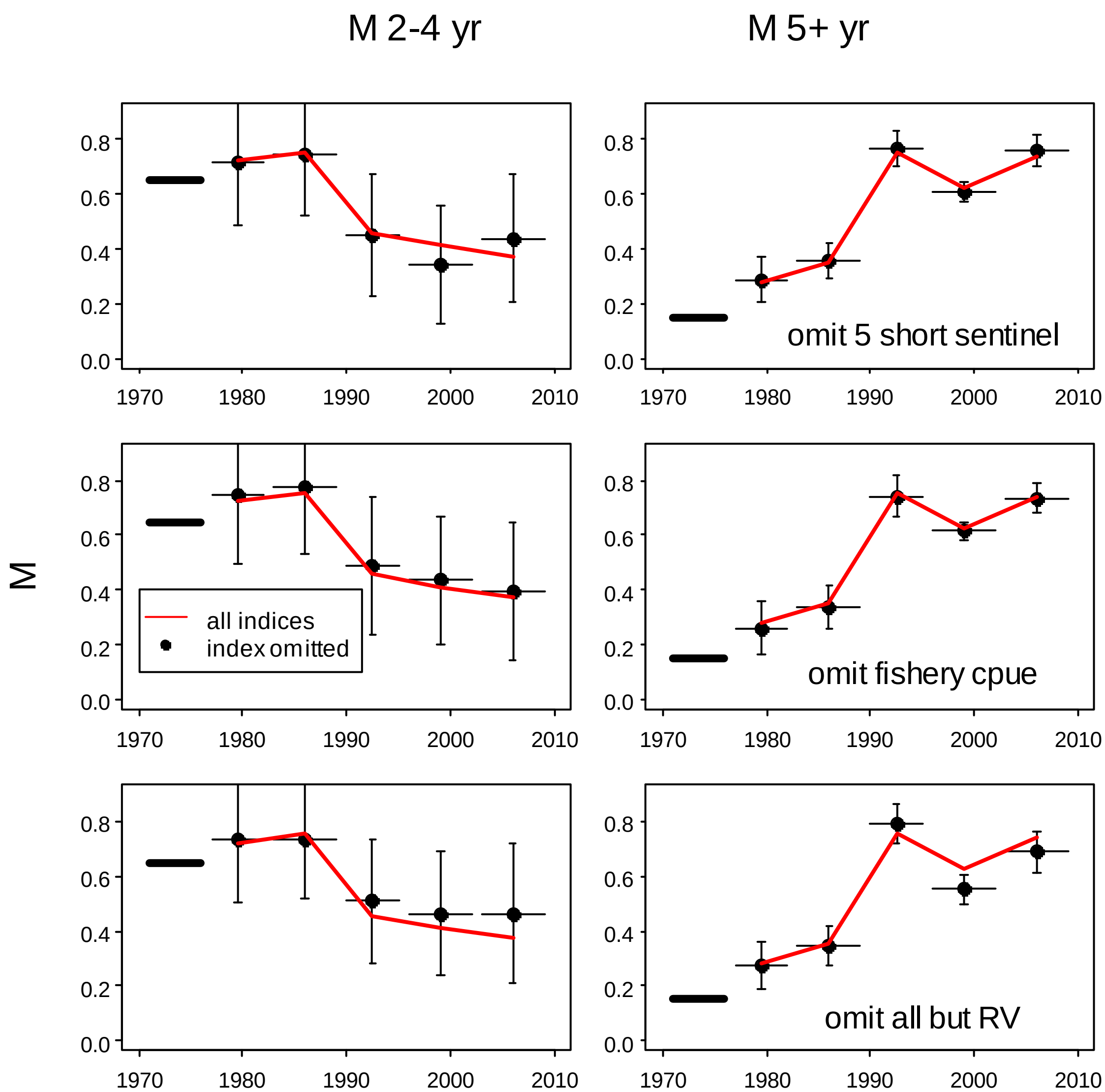

Figure 24 continued.

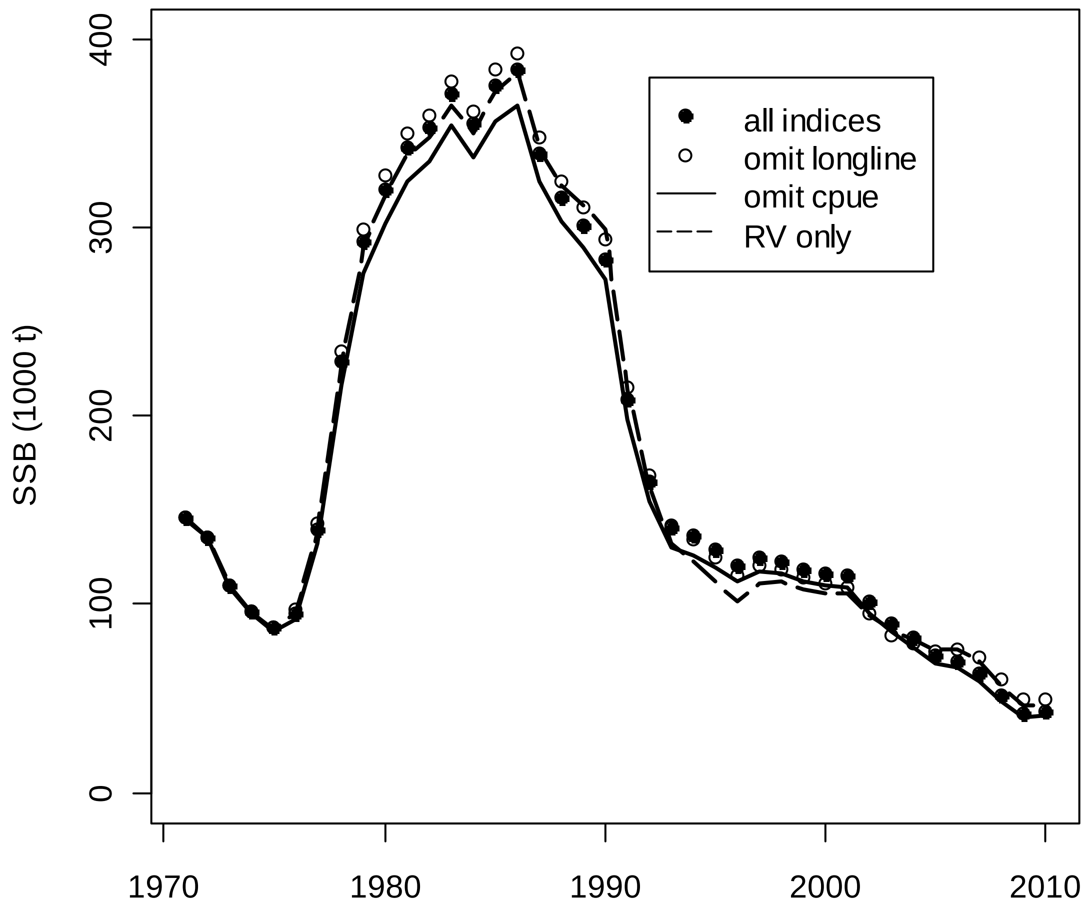

Figure 25. Estimated spawning stock biomass (SSB) from 2M models calibrated with all indices or with various indices omitted.

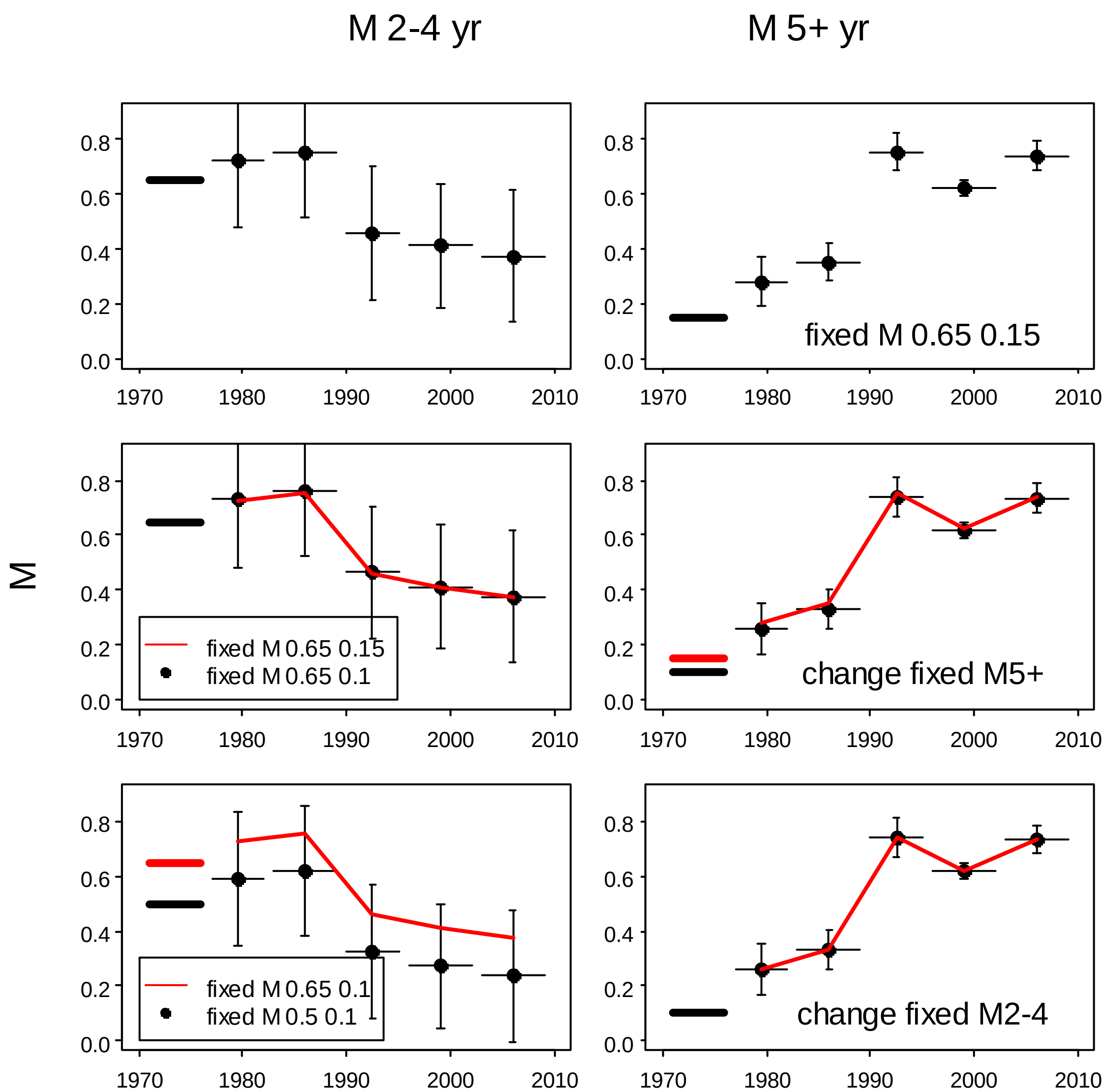

Figure 26. Effects of initial fixed values on M estimates.

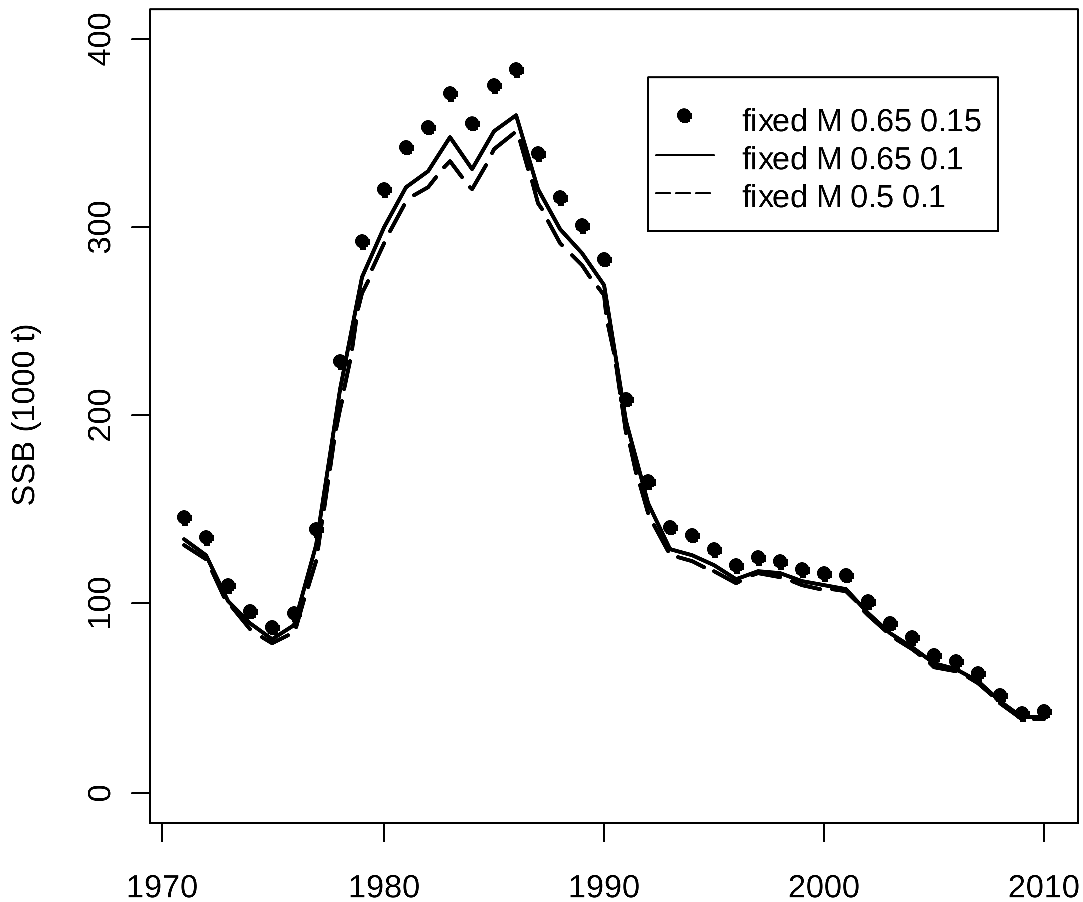

Figure 27. Effects of initial fixed values for M on estimated SSB.

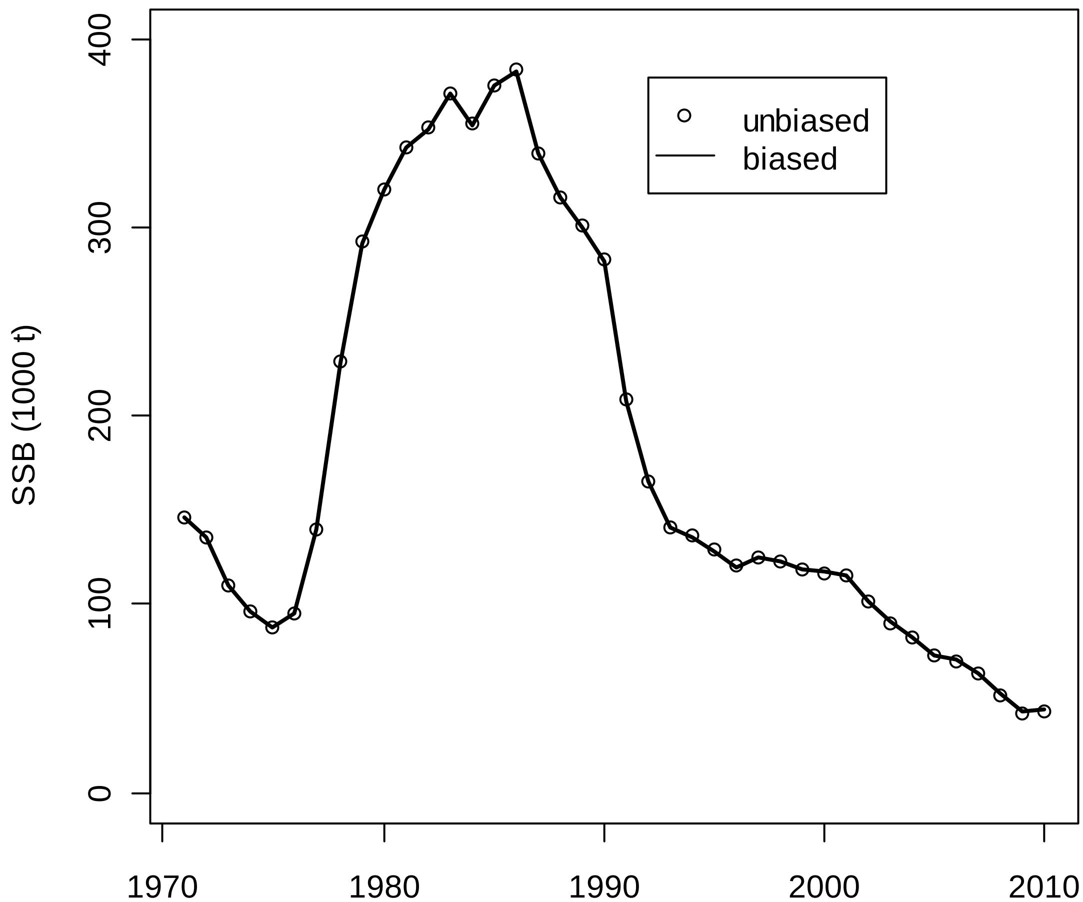

Figure 28. Effect of bias correction on the spawning stock biomass (SSB) estimated by a 2M M-block model.

Figure 29. Retrospective pattern for the model estimating M of age 2-4 and 5+ cod in blocks of years.

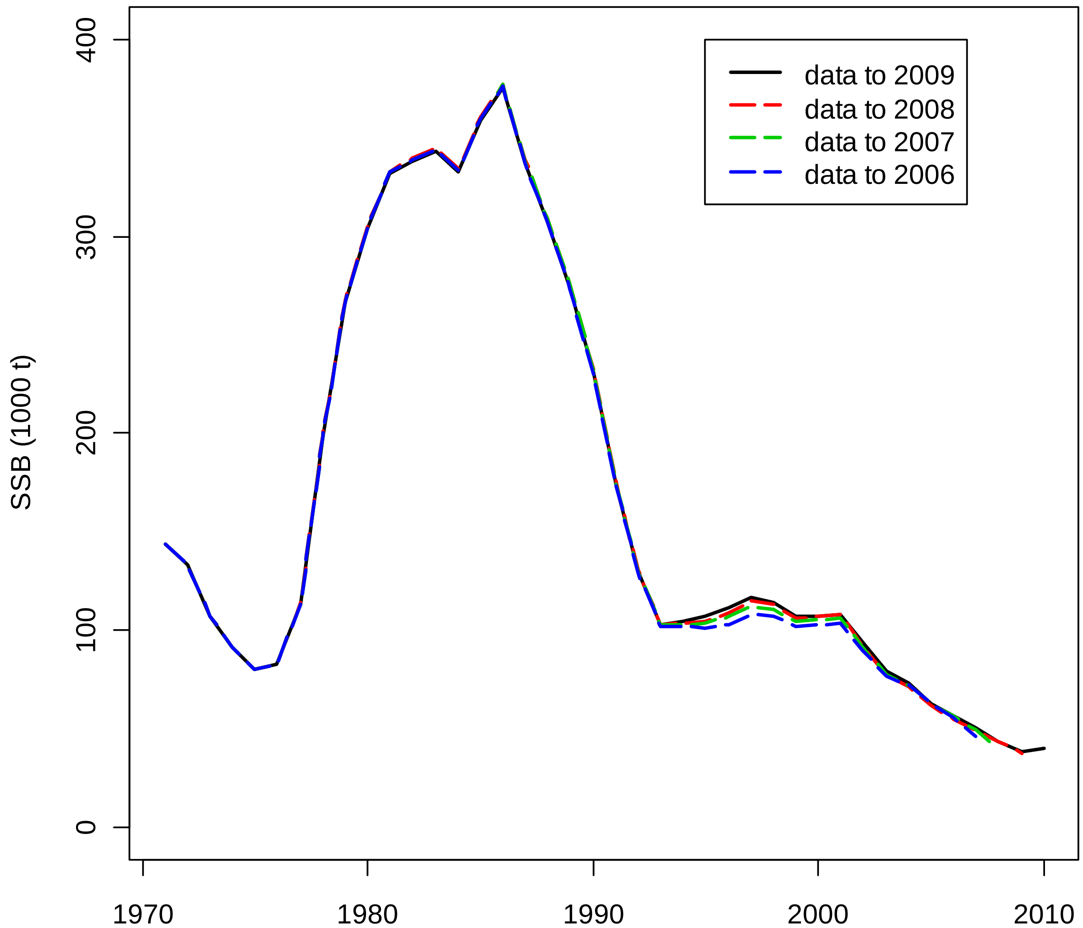

Figure 30. Retrospective pattern for the model estimating separate time trends in M of cod aged 2-4 and 5+ years using random walks in M.