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AN INVESTIGATION OF THE TREND IN THE ESTIMATED RECRUITMENT FOR BIGEYE TUNA IN THE EASTERN PACIFIC OCEAN

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1. SUMMARY

The average level of recruitment, the relationship between spawning stock size and recruitment, and the temporal variability in recruitment are important determinants of yield and stock status. There are some notable characteristics in the time series of estimated recruitments for bigeye tuna in the eastern Pacific Ocean (EPO). In particular, a two-stage pattern can be identified, which consists of an early period of low recruitments (pre-1994), followed by a period of relatively larger recruitments (post-1994) (Figure 1). The estimates prior to 1994 are also more uncertain and less variable. This is due to the lack of length-frequency data for small-size bigeye prior to 1994, since the floating object fishery exploiting juvenile bigeye was relatively small and restricted to the inshore area, so only one floating object fishery was modeled. As the floating object fishery began its expansion in the mid-1990s, more data is available on recently recruited bigeye and recruitment estimates become higher, more variable and less uncertain (Figure 1).

This paper presents a critical evaluation of a series of alternative hypothesis advanced by the IATTC staff and other colleagues to explain the bigeye recruitment pattern in the EPO, and similar recruitment patterns found with tuna stocks in other regions of the Pacific Ocean. The hypotheses presented so far include: 1) an environmental regime shift, 2) underestimated catches, 2) higher natural mortality rates, 3) density dependent-growth, 4) changes of migratory patterns, and 5) the "spatial mismatch hypothesis".

2. HYPOTHESES

There are several hypotheses that could account for the trend in recruitment. However, the only analyses that "corrected" the trend are those that had possibly unrealistically high natural mortality for the medium and large bigeye, and the spatial analysis which is presented in detail elsewhere (Aires-da-Silva and Maunder, 2010b). However, results from a cohort analysis also presented in this paper don't support the hypothesis that the trend in recruitment is caused by spatial changes in the fishery.

2.1. Hypothesis 1: An environmental regime shift

A first hypothesis to explain the observed shift to higher recruitments is that the bigeye stock experienced an environmental regime shift in the EPO during the mid-1990s. There have been multidecadal changes in the Pacific Ocean, one of which consisting of a shift from a warm "sardine regime" to cool "anchovy regime" in the mid- to late-1990s (Chavez et al., 2003). This hypothesis, however, seems less likely than any of the hypothesis presented below, considering that similar patterns are not observed in the recruitment time series for other tuna species in the EPO, particularly yellowfin. However, a similar pattern is seen for bigeye tuna in the western and central Pacific Ocean (Harley et al. 2009).

2.2. Hypothesis 2: Underestimated floating-object catches for the early period (Fonteneau and Ariz, 2008)

Fonteneau and Ariz (2008) argue that "there are still significant/major uncertainties in the levels of the historical bigeye catches taken by purse seiners in the EPO". In particular, the authors claim that the purse seine catches have been largely underestimated for the early period (pre-1994 years), in comparison to the ad hoc estimates produced for the 1994-1999 period, and those derived from the IATTC purse seine species composition sampling which begun in 2000 (Figure 2a).

In their overview of the IATTC bigeye stock assessments, Fonteneau and Ariz (2008) propose that the early (pre-1994 period) floating-object catches be corrected by applying species composition ratios that are similar to those obtained from recent species composition sampling (2000-present) (**Figure 2b**). However, the early purse-seine fishery operating around floating objects - on natural logs or flotsam, rather than artificial floating objects, as in the later period - was mainly restricted to the inshore region of the EPO, in which bigeye catches have been historically low, in comparison to other regions (see Figure 3 in BET-01-02b).

The IATTC staff believes that the early floating-object catch estimates assumed in the bigeye stock assessment are the best available estimates, and that the correction proposed by Fonteneau and Ariz (2008) is not appropriate. Nonetheless, their hypothesis can be subject to debate and a sensitivity analysis was made to investigate the effect of assuming higher floating-object catches on the recruitment pattern. In this sensitivity, the official bigeye catch levels for the early period (pre-1994) of the floating-object fishery were raised by applying the average ratio of the bigeye catch to the total tuna catch (skipkack, bigeye and yellowfin) by purse seiners derived from the IATTC species composition program (Figure 2b). The official and raised bigeye catches are shown on Figure 2a.

Increased floating-object catches during the early period did not eliminate the recruitment pattern. The recruitment estimates for the early period did slightly increase to explain the assumed higher catches (Figure 3a), but this change was not sufficient to eliminate the pattern (Figure 3b). These results, however, are conditional on the current model structure, and may change for other assumptions (e.g., different natural mortality estimates).

2.3. Hypothesis 3: Higher natural mortality rates (Fonteneau and Ariz, 2008)

A mis-specification of natural mortality (*M*) could also explain the observed pattern of bigeye recruitment. In particular, the lower recruitment estimates in the early period may be caused by underestimated natural mortality levels. Two sensitivity analyses were conducted to investigate the effect on the recruitment estimates by increasing the natural mortality rates on juveniles and adult bigeye, respectively.

Fonteneau and Ariz (2008) proposed that natural mortality rates of juvenile bigeye should be higher than those assumed in the base case mode. A sensitivity analysis for juvenile *M* investigated the effect of variations in shape of the young segment of the *M* schedules assumed for males and females (Figure 4). In the bigeye assessment, natural mortality is set on a quarterly basis so high values may appear lower than one would expect if not converted into an annual bases (i.e. multiply by 4). The sensitivity analyses were conducted by assuming one of two different levels of *M* for age-0 fish (0.25 and 0.50 quarter-1), and a linear decreasing trend of *M* between age-0 and one of three possible young ages (5, 10 and 13 quarters of age). The sensitivity analysis for adult *M* explored the effect on the recruitment estimates from assuming several scenarios of higher *M* for adult females and males (Figure 5). For consistency with the estimates obtained from the sex-ratio data, as in the base case model, the absolute difference of adult *M* between females and males was kept constant across scenarios.

For changes in juvenile natural mortality, the two-stage recruitment pattern was greatly minimized only when two extreme cases of increased juvenile *M* were considered (juvenile sensitivities 4 and 5; Figure 4). However, quarterly natural mortality rates between 0.2 and 0.3 for bigeye of 5-10 quarters of age seem unreasonable biologically. These are medium size fish ranging between 70 and 105 cm.

With respect to the analysis assuming increased levels of adult natural mortality, the recruitment pattern was also minimized for only two extreme cases (adult sensitivities 4 and 5). Adult quarterly natural mortality rates between 0.2 and 0.25 for both adult females and males seem extremely high and unrealistic for larger bigeye, even when the potential effects of energy loss due to reproduction or starvation in the open ocean are considered.

2.4. Hypothesis 4: Density-dependent growth (S. Hoyle, SPC)

Density-dependent growth mechanisms could explain the recruitment pattern as well. In particular, bigeye growth rates could increase in overexploited areas. Faster growth rates would imply greater proportions of larger fish, which, without density dependent growth, the model might explain by increased recruitment.

2.5. Hypothesis 4: Changes of migratory patterns (S. Harley, SPC)

A change in the migratory patterns of the stock, or segment of the stock, could also explain the recruitment pattern. For example, if availability of larger fish greatly increased due to immigration of adult bigeye to the fishing grounds, the model could try to explain higher observed proportions of large fish by increasing recruitment. Emigration of juvenile fish could have the same effect, since the juveniles would be vulnerable to purse seine but not to longline.

2.6. Hypothesis 5: The “spatial mismatch” hypothesis

The recruitment pattern could also be explained by a spatial mis-specification in the model. For example, the recruitment issue could be due to a model artifact caused by a major change in the spatial distribution of the fishery around the mid-1990s, when the historic period of higher recruitment estimates begins.

Such hypothesis seems to be consistent with major historic events that happened in the bigeye fishery in the EPO. In particular, the recruitment shift coincided with the expansion of the purse-seine fishery on floating-objects throughout the equatorial EPO region in the mid-1990s. This very rapid expansion of the floating-object fishery resulted in strong competition with the longline fishery which was already established along the equatorial grounds for a few decades. Decreased catch rates for the longline fishery (see Aires-da-Silva and Maunder, 2010b), and negative gear interactions with purse-seines, stimulated a gradual exodus of longliners away from the central equatorial grounds into the westernmost offshore waters, southern or northern grounds.

It is possible that longliners shifted their fishing effort to less exploited fishing grounds or even distinct sub-stocks of bigeye in the EPO after the mid-1990s. Considering the restricted movements and poor mixing of bigeye in the EPO (Schaefer and Fuller, 2009), it is also possible that juvenile bigeye exploited by the floating-object fishery, recently developed along the equatorial grounds, do not become vulnerable later on in their life to longliners, on newly occupied fishing grounds. This hypothesis is corroborated by the low tag return rate by longliners of juvenile bigeye caught and tagged on purse-seines in the central fishing grounds (Figure 7). The underlying assumption in the previous explanation is that the tag reporting rates by longliners are high, which can be subject to debate.

A spatially-structured bigeye assessment should minimize, or even eliminate the recruitment pattern if the spatial mismatch hypothesis is valid. A preliminarily evaluation of spatial structure in the bigeye assessment is presented by Aires-da-Silva and Maunder (2010b). In particular, separate assessments for four bigeye sub-stocks in the EPO are made. The spatial analysis greatly reduced the recruitment pattern

(Figure 8)

Future research should include fine-scale spatial analysis of the distribution of catch, effort and bigeye length compositions of the longline and purse-seine fisheries in order to validate, or reject, this "spatial mismatch" hypothesis.

3. COHORT ANALYSIS

Cohort analysis, particularly with the assumption that all fish die after the last age used in the model, calculates recruitment directly from the catch at age (calculated from the length data outside the model) and the natural mortality that the cohort would have experienced before it was caught. Under these assumptions, the recruitment can then be associated with the catch at a particular age or from a particular gear. We use this methodology to investigate the impact of changes in the catch by the longline and purse seine fisheries on estimated recruitment. The results of the bigeye cohort analysis are presented in Appendix A. Recruitment associated with the longline fishery's catch has remained fairly constant over time, while the recruitment associated with the purse seine fishery's catch increased as the floating object fishery expanded. Recruitment associated with the purse seine fishey's catch after 1993 is higher than the recruitment associated with the longline fishery's catch prior to 1993. These results do not support the hypothesis that the trend in recruitment is caused by spatial changes in the fishery.

4. CONCLUSION

There are several hypotheses that could account for the trend in recruitment. However, the only analyses that "corrected" the trend are those that had possibly unrealistically high natural mortality for the medium and large bigeye. The spatial analysis which is presented in detail elsewhere (Aires-da-Silva and Maunder, 2010b) also partially corrected the trend.

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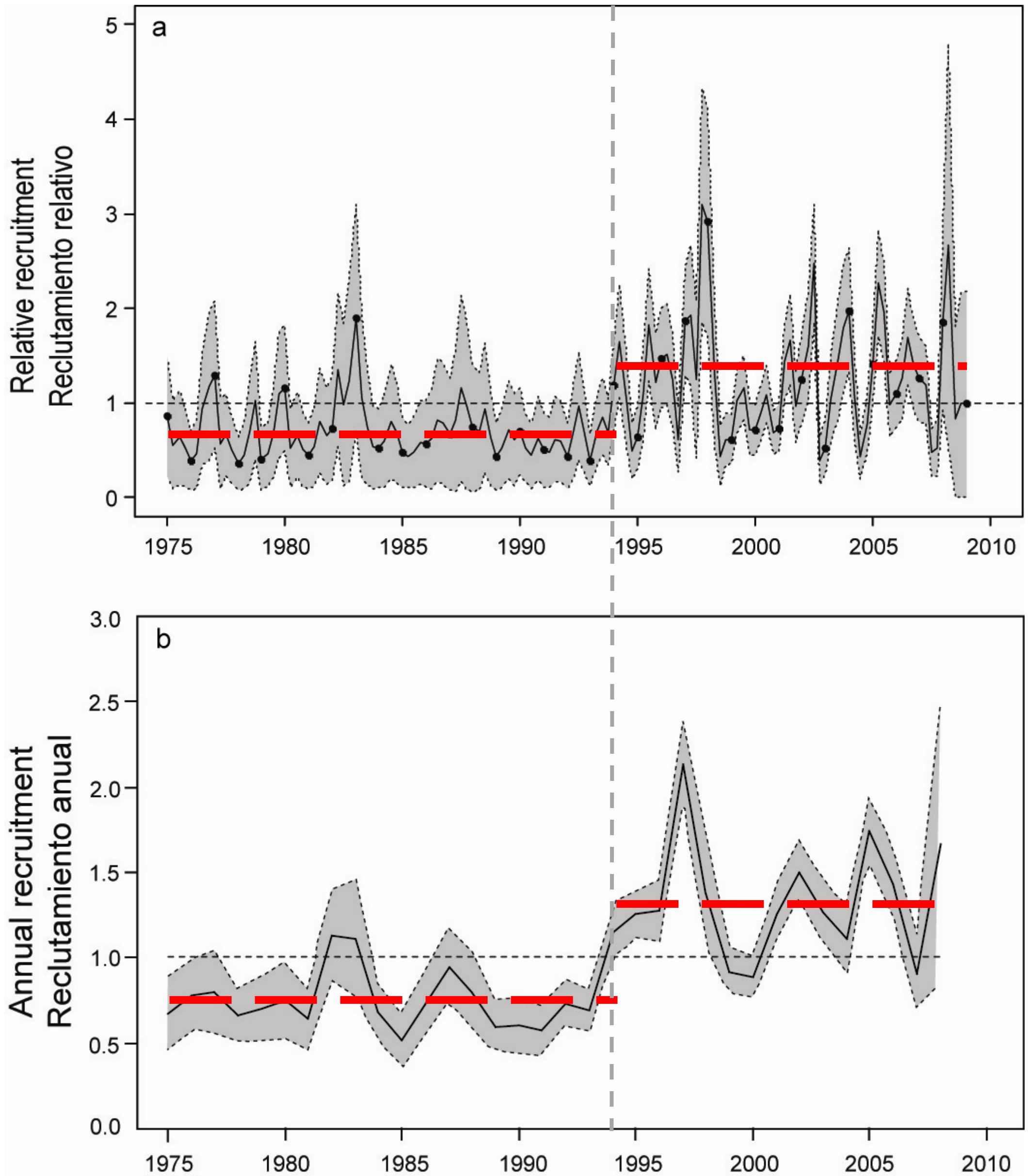

FIGURE 1. Estimated recruitment of bigeye tuna to the fisheries of the EPO: a) quarterly recruitment; b) annual recruitment. The estimates are scaled so that the estimate of virgin recruitment is equal to 1.0. The bold line illustrates the maximum likelihood estimates of recruitment, and the grey area marks the confidence intervals (±2 standard deviations) around those estimates. The thin dashed horizontal line represents the average recruitment for the period (1975-2008); the thick dashed horizontal lines indicate the average recruitment for two consecutive periods: 1975-1993 and 1994-2008. The vertical dashed line marks the beginning of the expansion of the purse-seine fishery on floating objects in 1994.

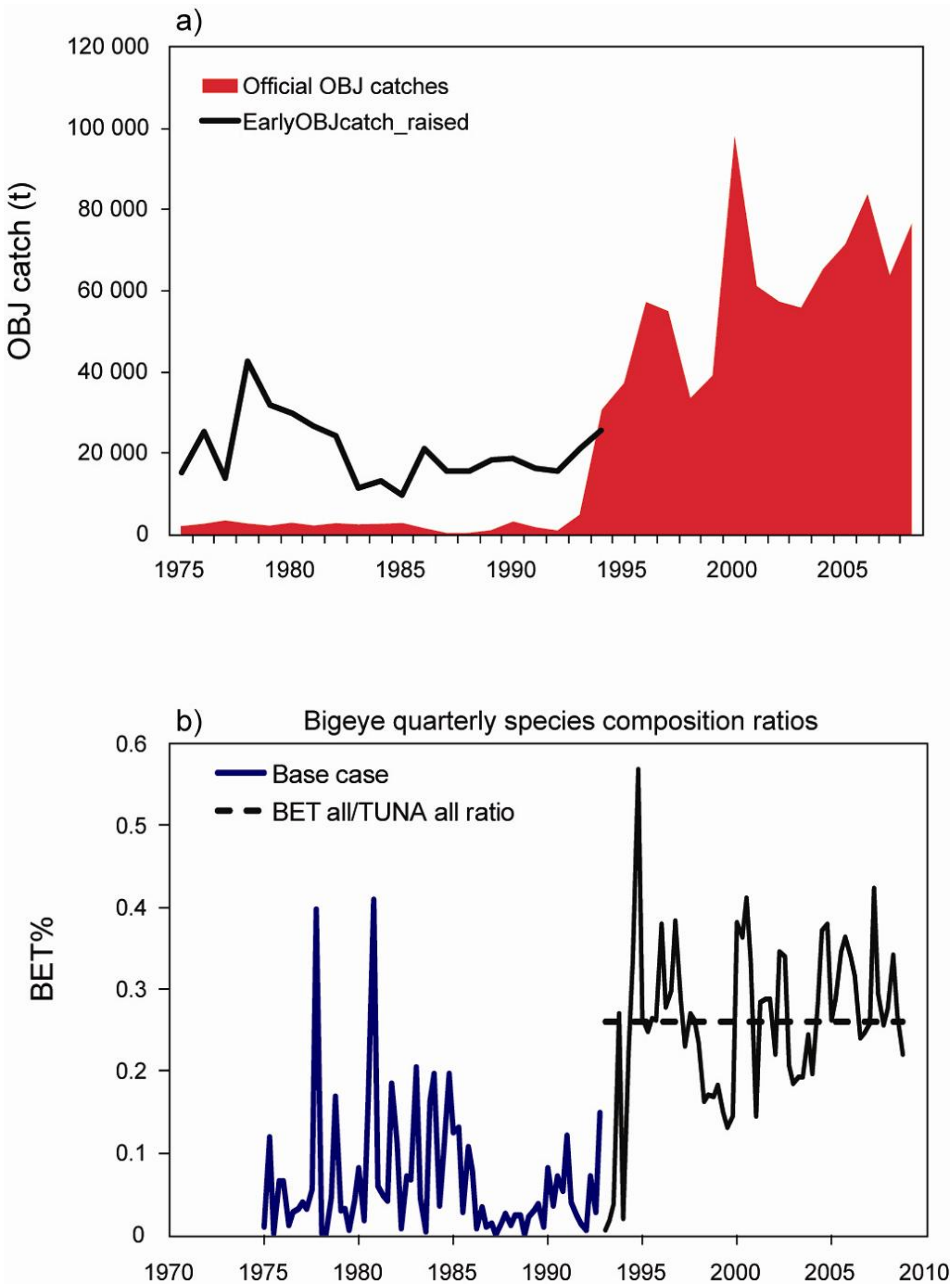

FIGURE 2. a) Official and raised annual bigeye catches in the EPO. b) Proportions of bigeye catch to total catches of tuna (skipjack, yellowfin and bigeye) by quarterly time step in the EPO assumed in the base case model for the early period (prio-1994), and derived from the IATTC species composition sampling for the later period.

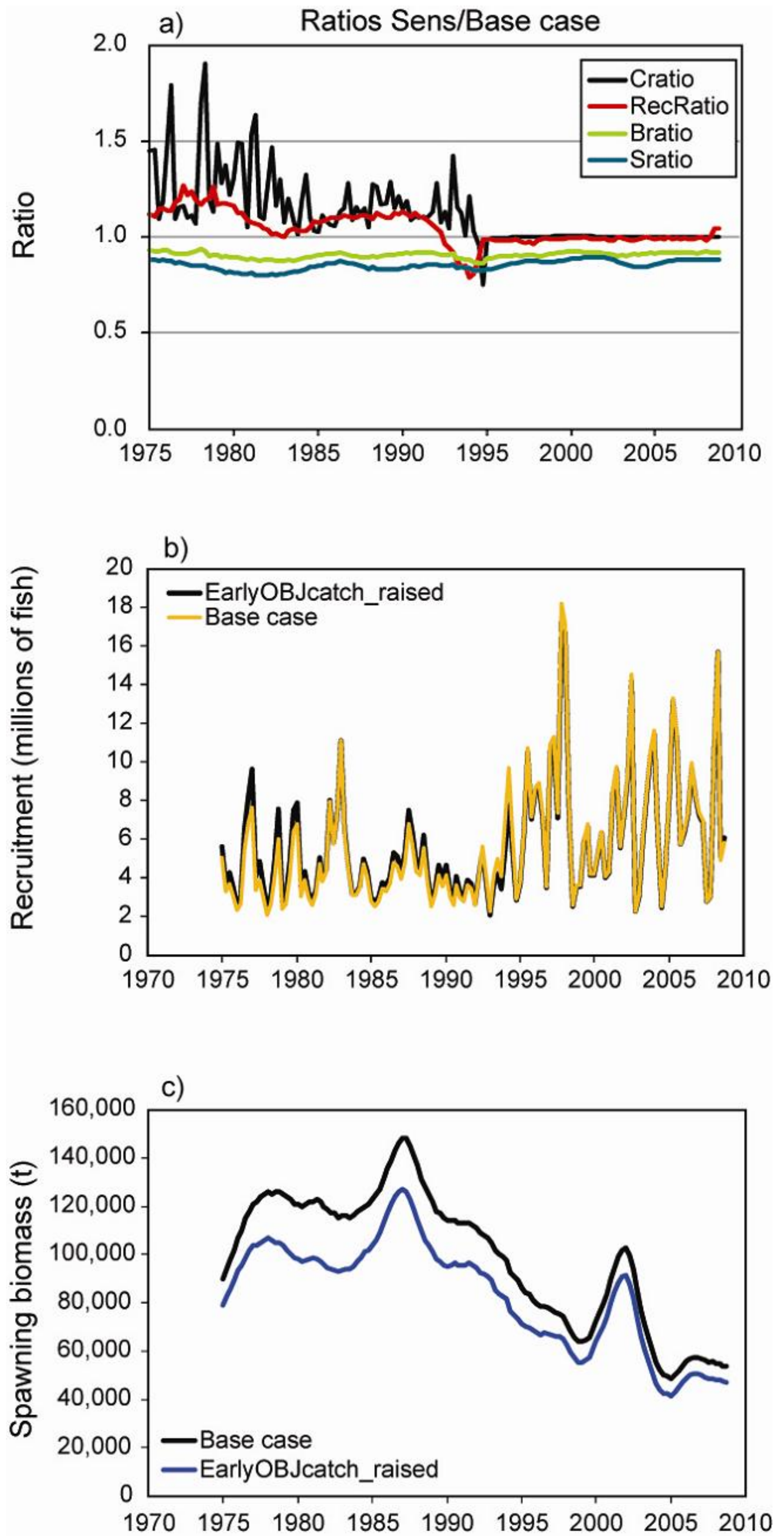

FIGURE 3. a) Ratios of the catch levels, recruitment, summary biomass and spawning biomass estimates between the sensitivity analysis assuming raised floating-object catches for the early period (EarlyOBJcatch_raised) and the base case. b) estimated recruitments for the sensitivity and the base case model, c) estimated spawning biomasses for the sensitivity and the base case model.

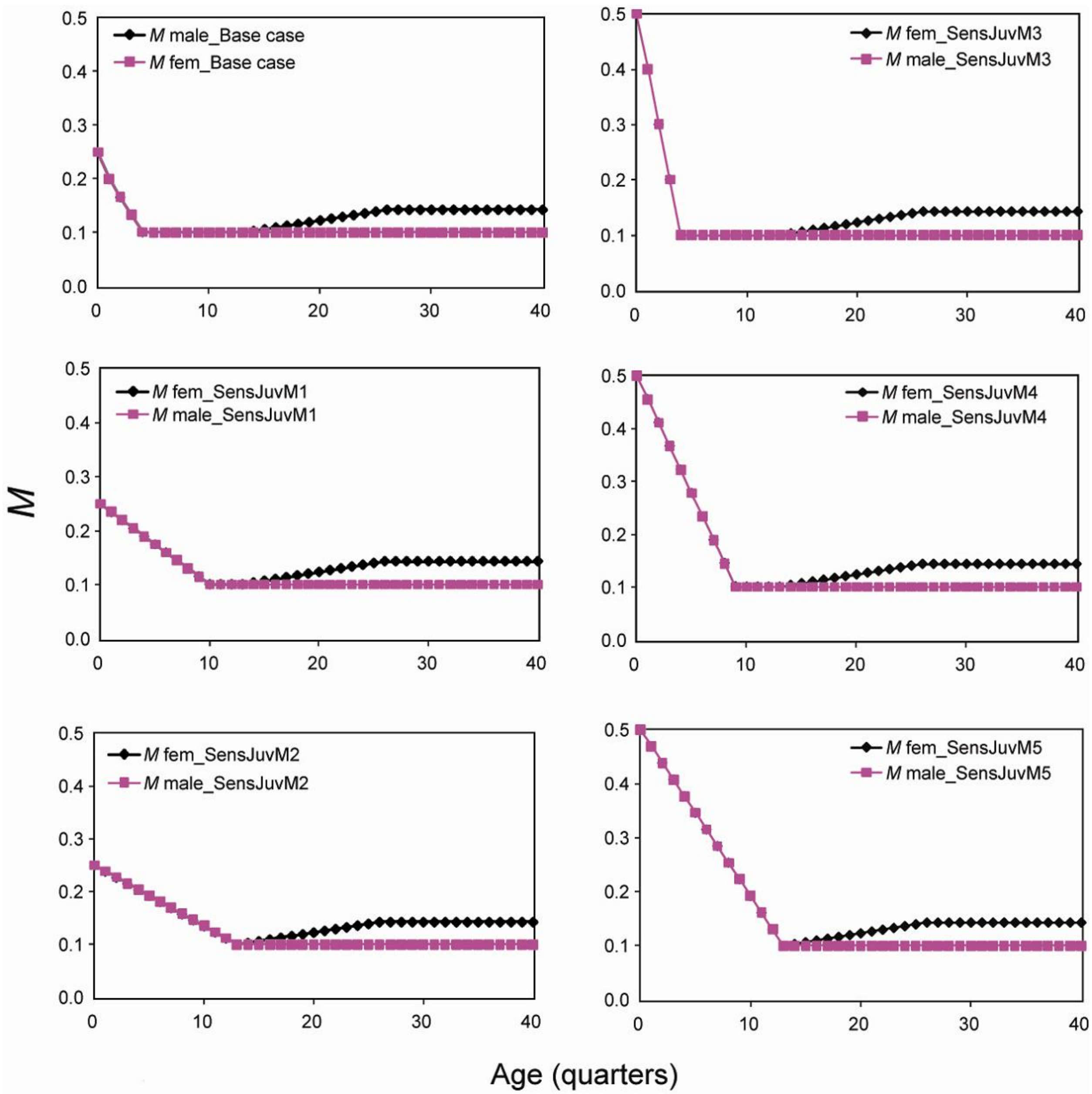

FIGURE 4. Natural mortality (*M*) schedules for female and male bigeye investigated in the sensitivity to higher *M* values for juveniles.

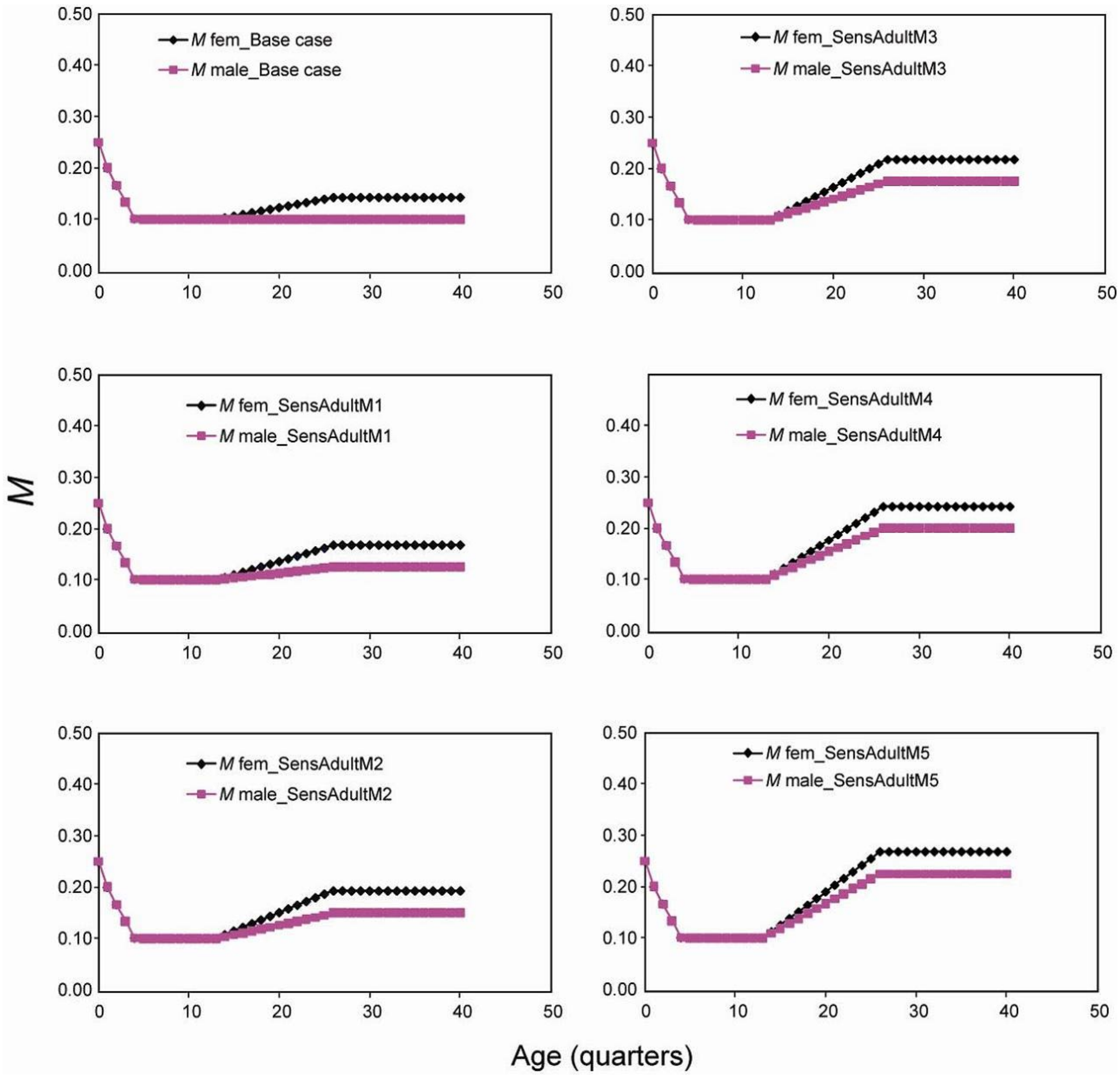

FIGURE 5. Natural mortality (*M*) schedules for female and male bigeye investigated in the sensitivity to higher *M* values for adults.

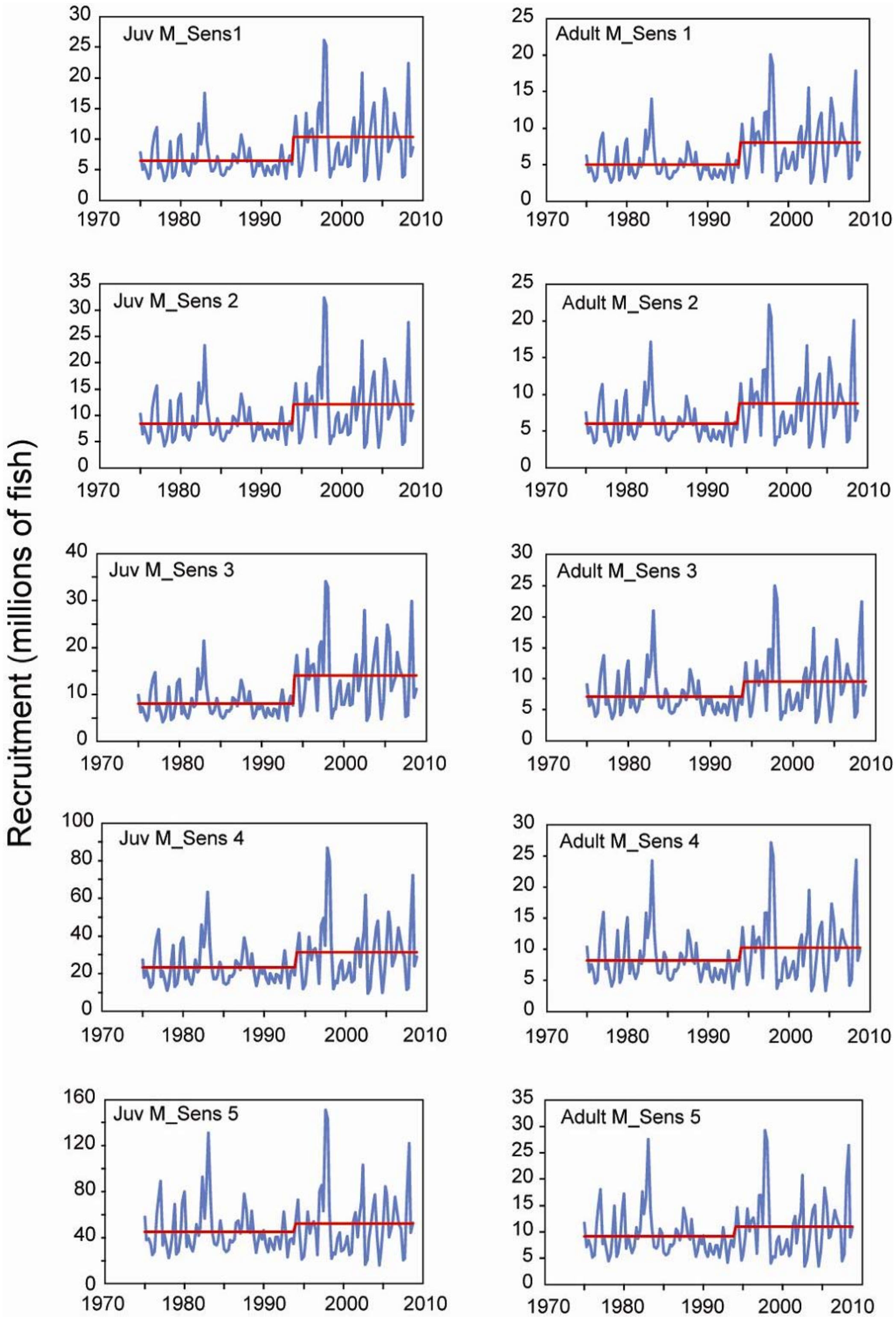

FIGURE 6. Estimated quarterly recruitments of bigeye for the sensitivity model runs assuming different levels of natural mortality (*M*): left – sensitivities to higher juvenile M, right – sensitivities to higher adult *M*. The horizontal lines mark the average recruitment levels during the pre-1994 and post-1994 periods. See Figures 4 and 5 for the *M* schedules used in the juvenile and adult *M* sensitivities, respectively.

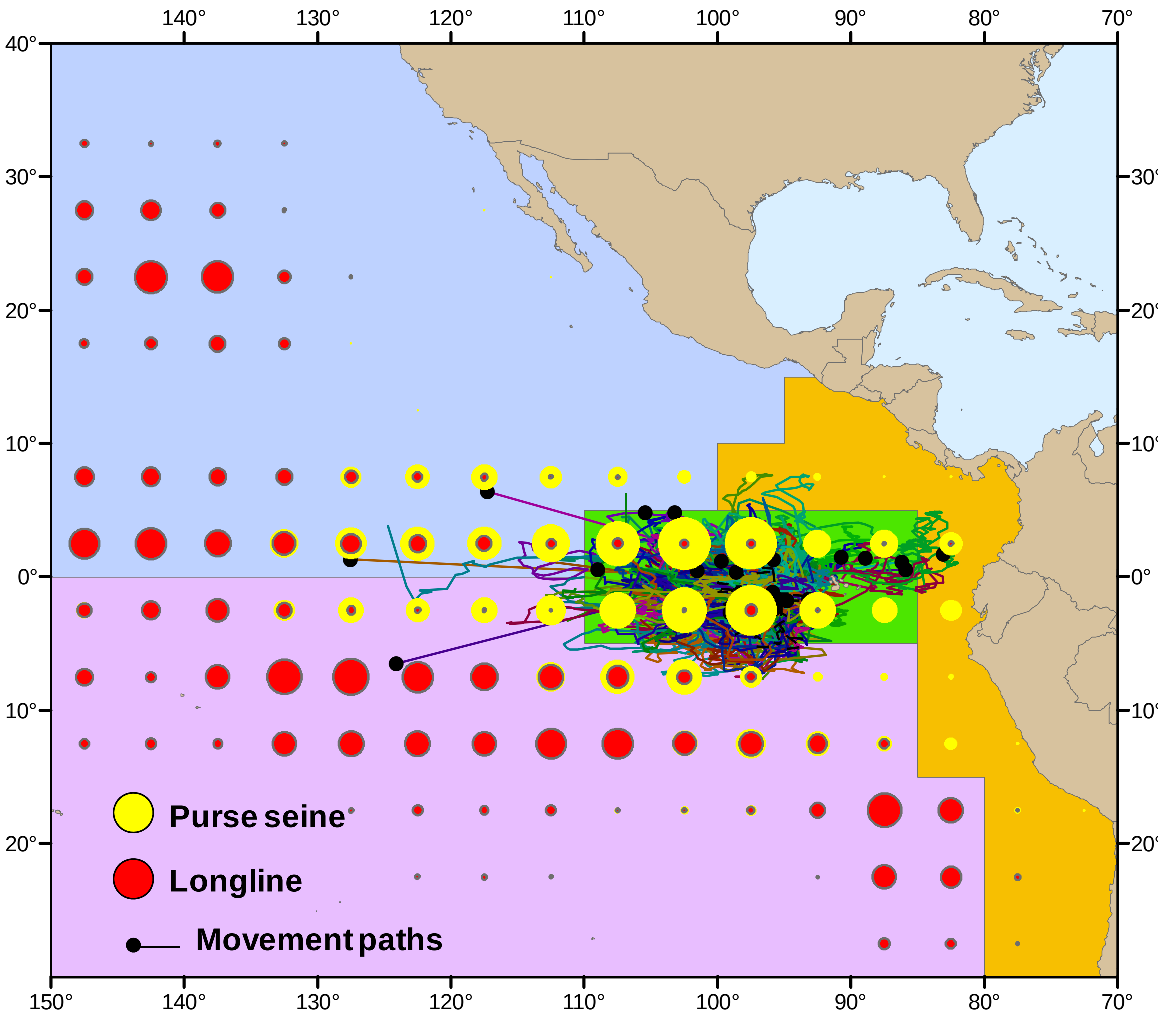

FIGURE 7. Comparison of archival tag movement tracks with spatial distribution of longline (dark circles) and purse seine (light circles) catches. The catch is the average over 2000-2006. The archival tag movement paths are based on data for 2000-2006 (Schaefer and Fuller 2009).

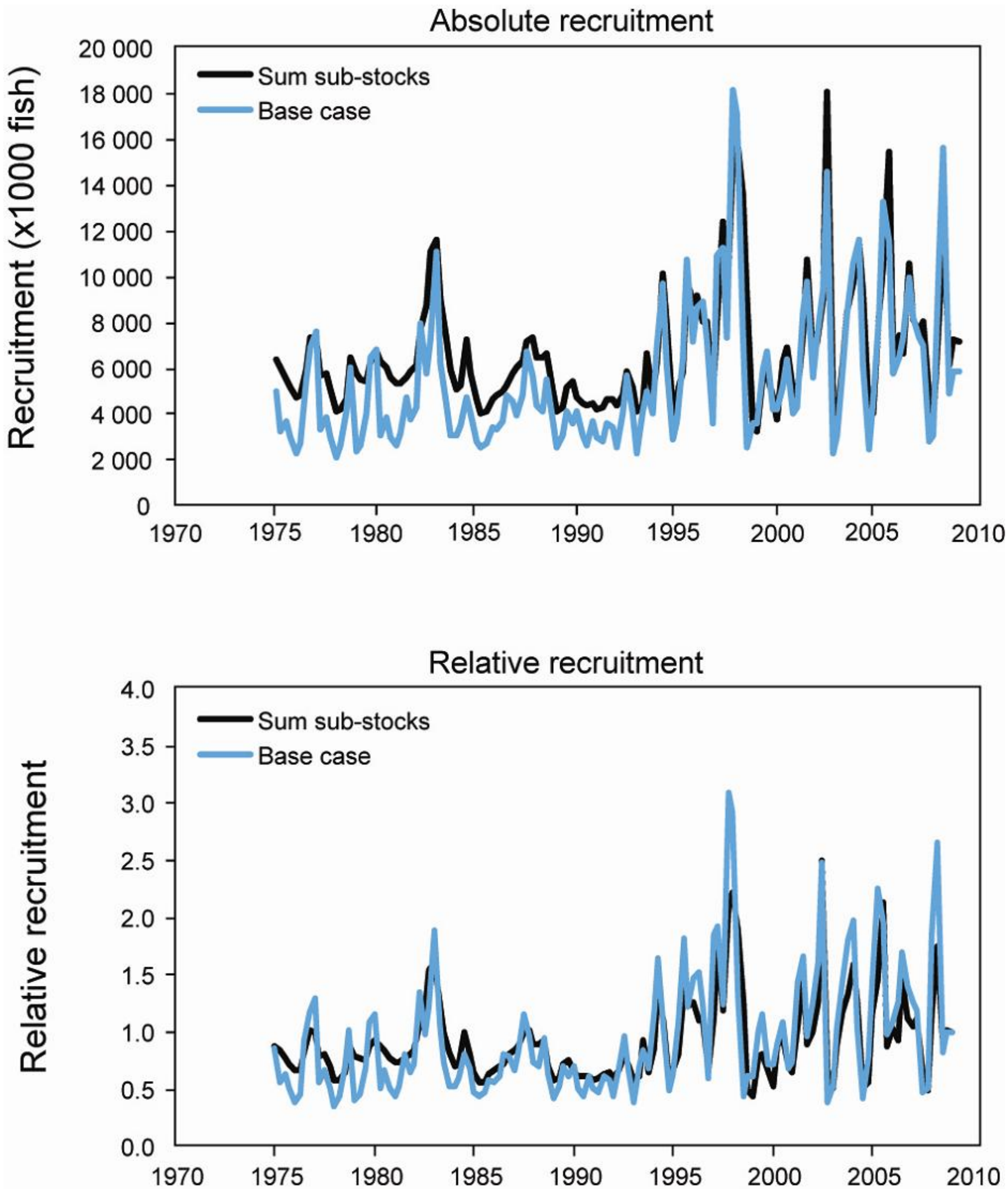

FIGURE 8. Time series of absolute and relative recruitment of bigeye in the EPO estimated from two methods: 1) summing across the results from individual EPO sub-stock assessments (see Aires-da-Silva and Maunder, 2010b); 2) results from the single EPO stock base case model (Aires-da-Silva and Maunder, 2010).

APPENDIX A: EVALUATION OF THE RECRUITMENT TREND BY CALCULATING THE RECRUITMENT ASSOCIATED WITH DIFFERENT COMPONENTS OF THE CATCH

Cohort analysis, particularly with the assumption that all fish die after the last age used in the model, calculates recruitment directly from the catch at age (calculated from the length data outside the model) and the natural mortality that the cohort would have experienced before it was caught. Under these assumptions, the recruitment can then be associated with the catch at a particular age or from a particular gear. We use this methodology to investigate the impact of changes in the catch by the longline and purse seine fisheries on estimated recruitment.

First, simply calculating the recruitment associated with each fishery's catch shows that the recruitment associated with the longline fishery's catch has remained fairly constant over time, while the recruitment associated with the purse seine fishery's catch increased as the floating object fishery expanded (Figure A1). It also shows that the recruitment associated with the purse seine fishey's catch after 1993 is higher than the recruitment associated with the longline fishery's catch prior to 1993. This indicates that the purse seine fishery is not simply replacing the longline fishery in the central area and forcing the longline fishery into unexploited areas. In other words, the results don't support the hypothesis that the trend in recruitment is caused by spatial changes in the fishery.

The Stock Synthesis stock assessment differs from the above cohort analysis in that it estimates the catch at age simultaneously with the other parameters and that it estimates the number of individuals alive that are older than the maximum age (i.e. the numbers in the plus group). The above cohort analysis was insensitive to the assumption about the size of the oldest fish, while the Stock Synthesis analysis was sensitive to this assumption. By accounting for the cumulative fishing and natural mortality over the lifespan of fish that are caught and for the fishing mortality associated with catching those fish, all the fish caught from a cohort in a given year can be used to estimate the recruitment of that cohort (Figure A3). Since the cumulative mortality is very high for the old fish (Figure A2) a small change in the numbers of old fish caught, which is influenced by the average length of the plus group, can have a large influence on the results.

The Stock Synthesis results can also be used to assign recruitment estimates to catch at age data (Figures A4 and A5). These results also show that recruitment estimated from the catch of small bigeye by the floating object fishery increases after 1993, while estimates of recruitment from large fish declined.

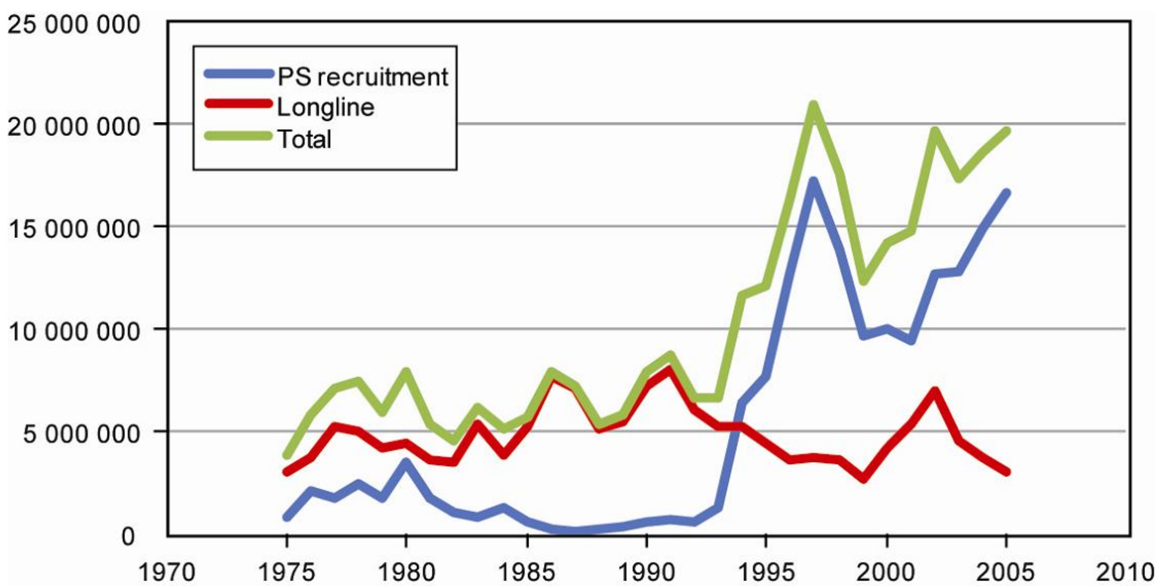

FIGURE A1. Recruitment calculated by cohort analysis associated with the catch by gear in a given year.

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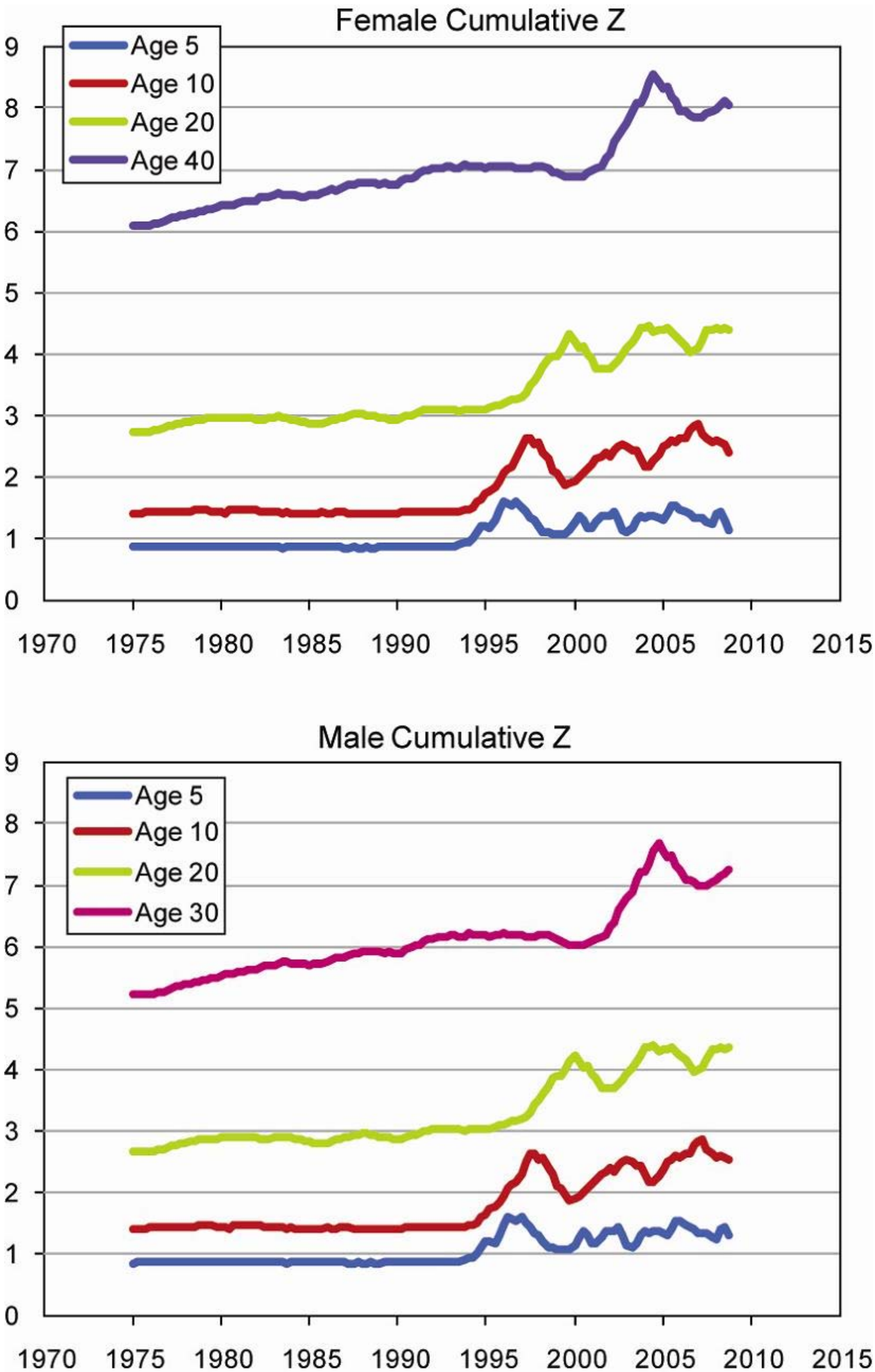

FIGURE A2. Cumulative total quarterly mortality by quarterly age group.

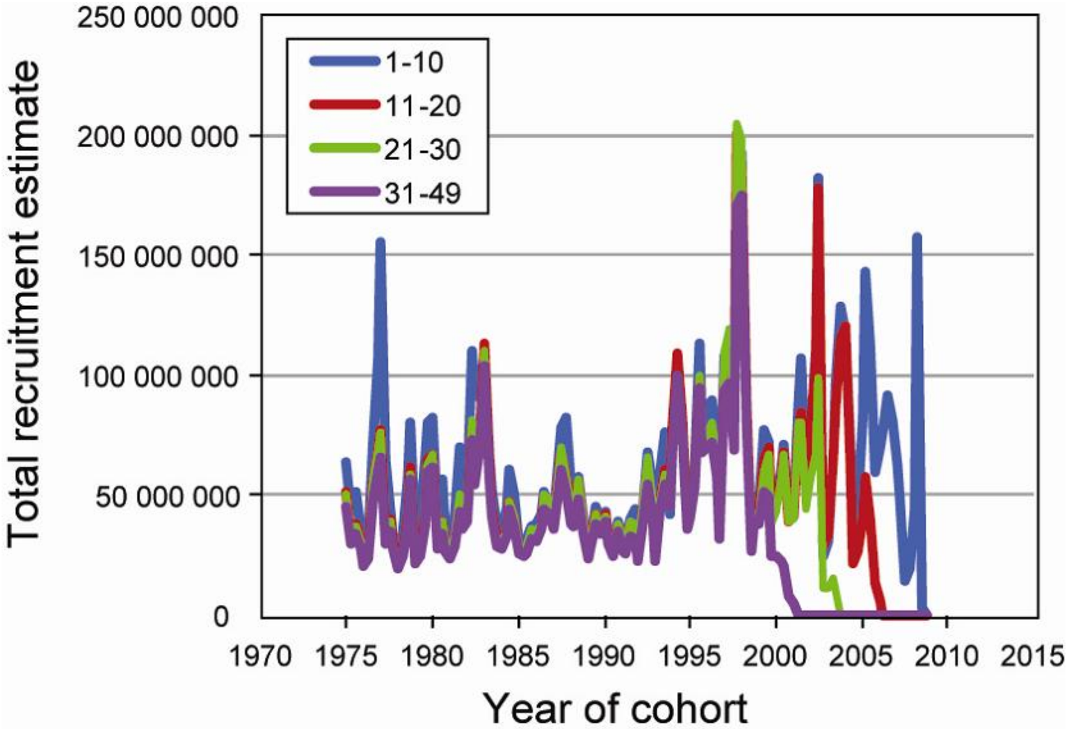

FIGURE A3. Total recruitment estimated from catch of quarterly age groups plotted by year of the cohort. The estimates are incomplete for the later years because the cohorts have yet to age into the older age groups.

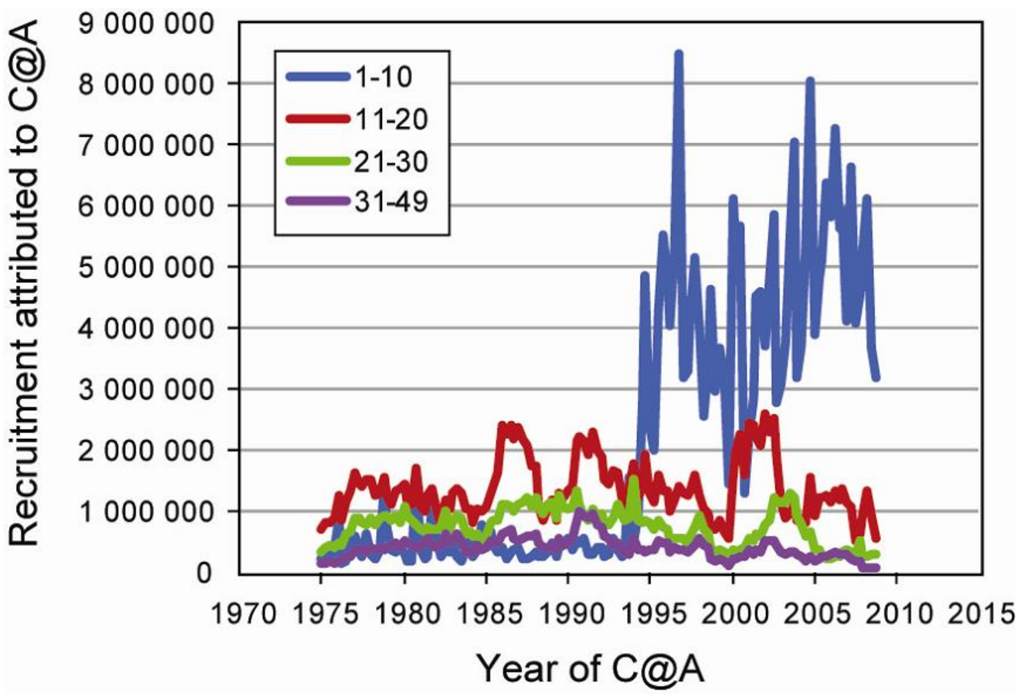

FIGURE A4. Recruitment attributed to catch of quarterly age groups plotted by year of the catch at age data.

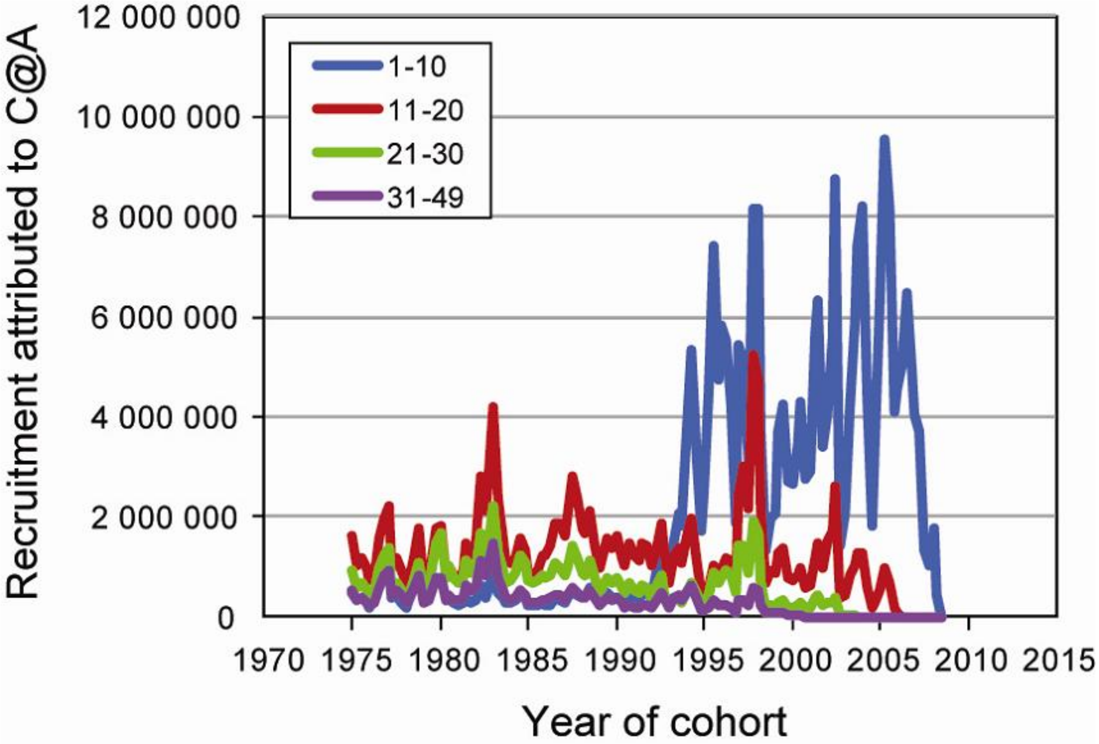

FIGURE A5. Recruitment attributed to catch of quarterly age groups plotted by year of the cohort. The estimates are incomplete for the later years because the cohorts have yet to age into the older age grow.