2022 ASAP STOCK ASSESSMENT OF THE EASTERN ATLANTIC AND MEDITERRANEAN BLUEFIN TUNA

C. Carrano[1], J.-J. Maguire[2], L. Kerr[3], J. Walter[4], M. Lauretta[4], T. Rouyer[5], and S.X. Cadrin[1]

SUMMARY

The Age Structured Assessment Program (ASAP) was applied to Eastern Atlantic and Mediterranean Atlantic Bluefin tuna for the 2022 stock assessment. Previous single-fleet applications of ASAP for the 2017 and 2020 Atlantic Bluefin tuna assessments were updated and revised, and alternative models with fleet structure were explored. The single-fleet ASAP runs generally fit the data well, and were retrospectively consistent, but residual patterns in age composition and uncertainty in selectivity parameters could not be resolved. Model estimates suggest a substantial change in selectivity in the late 1990s. Multi-fleet ASAP models were developed to fit catch data and estimate selectivity for each index fleet and the Mediterranean purse seine fleet. Multi-fleet-based runs were also retrospectively consistent and fit the available data well, with some residual patterns, but catch data by fleet need revision. Status determination from single-fleet and provisional multi-fleet runs was similar: The stock recovered over the last decade from strong recruitment and low fishing mortality, the estimate of 2020 fishing mortality was much less than $F_{0.1}$, and the estimate of 2020 spawning biomass was much greater than $SSB_{F0.1}$.

RÉSUMÉ

Le programme d'évaluation structuré par âge (ASAP) a été appliqué au thon rouge de l'Atlantique Est et de la Méditerranée pour l'évaluation du stock de 2022. Les applications précédentes d'ASAP à flottille unique pour les évaluations du thon rouge de l'Atlantique de 2017 et 2020 ont été mises à jour et révisées et des modèles alternatifs avec une structure de la flottille ont été étudiés. Les scénarios de ASAP à flottille unique s'ajustent généralement bien aux données et sont rétrospectivement cohérents, mais les schémas résiduels de la composition par âge et l'incertitude des paramètres de sélectivité n'ont pas pu être résolus. Les estimations du modèle suggèrent un changement substantiel de la sélectivité à la fin des années 1990. Des modèles ASAP pluri-flottilles ont été développés pour ajuster les données de captures et estimer la sélectivité de chaque flottille des indices et pour la flottille des senneurs de la Méditerranée. Les scénarios pluri-flottilles étaient également rétrospectivement cohérents et s'ajustaient bien aux données disponibles avec certains schémas résiduels, mais les données de capture par flottille ont dû être révisées. La détermination de l'état à partir des scénarios à flottille unique et à flottilles multiples provisoires était similaire, à savoir : le stock s'est rétabli au cours de la dernière décennie grâce à un fort recrutement et à une faible mortalité par pêche, l'estimation de la mortalité par pêche en 2020 était bien inférieure à $F_{0,1}$ et l'estimation de la biomasse reproductrice en 2020 était bien supérieure à $SSB_{F0,1}$.

RESUMEN

Se aplicó el Programa de evaluación estructurada por edad (ASAP) al atún rojo del Atlántico este y Mediterráneo para la evaluación de stock de 2022. Se actualizaron y revisaron las aplicaciones previas de ASAP de una sola flota para las evaluaciones de atún rojo del Atlántico

[1] University of Massachusetts School for Marine Science & Technology, 836 South Rodney French Boulevard, New Bedford MA 02744 USA, scadrin@umassd.edu
[2] 1450 Godefroy, Quebec City, Qc, G1T2E4 Canada
[3] Gulf of Maine Research Institute, 350 Commercial Street, Portland, ME 04101 USA
[4] NOAA Fisheries, Southeast Fisheries Science Center, Sustainable Fisheries Division, 75 Virginia Beach Drive, Miami, FL, 33149, USA.
[5] IFREMER, UMR MARBEC, Sète, France; MARBEC, Univ Montpellier, CNRS, IFREMER, IRD, Sète, France

de 2017 y 2020, y se exploraron modelos alternativos con una estructura de la flota. En general, los ensayos de ASAP de una sola flota se ajustaron bien a los datos y fueron coherentes desde el punto de vista retrospectivo, pero no se pudieron resolver los patrones residuales en la composición por edad y la incertidumbre en los parámetros de selectividad. Las estimaciones del modelo sugieren un cambio importante en la selectividad a finales de la década de 1990. Se desarrollaron modelos ASAP multiflota para ajustar los datos de captura y estimar la selectividad para cada flota del índice y la flota de cerco del Mediterráneo. Los ensayos basados en múltiples flotas también fueron coherentes desde el punto de vista retrospectivo y se ajustaron bien a los datos disponibles, con algunos patrones residuales, pero los datos de captura por flota necesitan ser revisados. La determinación del estado a partir de ensayos de una sola flota y de múltiples flotas provisiones fueron similares: El stock se recuperó durante la última década gracias a un fuerte reclutamiento y a una baja mortalidad por pesca, la estimación de la mortalidad por pesca de 2020 fue mucho inferior a $F_{0.1}$ *y la estimación de la biomasa reproductora de 2020 fue mucho superior a* $SSB_{F0.1}$.

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KEYWORDS

Eastern Atlantic Bluefin Tuna, Stock Assessment, Fleets

Introduction

The Age Structured Assessment Program (ASAP) is a statistical catch-at-age model that was initially applied to the stock assessment of western Atlantic bluefin tuna (Legault and Restrepo 1998). ASAP has since been widely applied to a range of U.S. and international fisheries (Dichmont *et al.* 2016). ASAP offers a model of intermediate complexity for the stock assessment of eastern Atlantic and Mediterranean bluefin tuna.

Recent iterations of eastern Atlantic and Mediterranean bluefin tuna stock assessments developed a range of assessment models, including Virtual Population Analysis (VPA, Porch 2003), Stock Synthesis (SS3, Methot & Wetzel 2013), and ASAP. At the 2017 ICCAT assessment meetings, various data decisions were considered for ASAP applications (e.g., starting year) as well as alternative model configurations (e.g., selectivity periods, inclusion of abundance indices, changes in catchability; Maguire *et al.* 2017). ASAP generally provided similar estimates of stock trends and magnitude as the 2014 and 2017 VPAs. The SS3 application to eastern Atlantic bluefin tuna had unresolved problems in 2017 (ICCAT 2017) and was not updated in 2020 (ICCAT 2020).

The 2020 updated VPA for eastern Atlantic and Mediterranean bluefin tuna produced unstable estimates of biomass in the historical period (ICCAT 2020). The VPA was revised by assuming values for relative fishing mortalities at the oldest ages, which produced more stable estimates of historical biomass but had a large retrospective pattern and did not provide a reliable basis for management advice (ICCAT 2020). Therefore, the 2017 ASAP applications were updated, and model revisions were explored to evaluate model sensitivity and uncertainties (Maguire & Cadrin 2020). ASAP fit the updated and revised data well and provided similar perspectives as other models, and further development of ASAP applications was recommended.

Further ASAP model development was explored to improve the performance for routine application and updates. For example, the initial application of ASAP to western Atlantic bluefin tuna included fleet structure (Legault & Restrepo 1998), but the 2017 and 2020 applications modeled the fishery as a single fleet (Maguire *et al.* 2017, Maguire & Cadrin 2020). In principle, fleet structure should have several advantages for stock assessment modeling. Fleet structure is expected to improve the estimation of fishery selectivity, because each fleet has different gear selectivity and spatial overlap with the stock (Maunder *et al.* 2014), and fleet-specific selectivity can be informed by age composition data. Fleet structure can also improve the performance of index fleets for informing relative abundance by estimating selectivity of index fleets. We collaborated with other ICCAT scientists to improve ASAP applications to Eastern Atlantic and Mediterranean bluefin tuna for consideration in the 2022 stock assessment.

1. Data

ASAP requires a time series of observed catch, catch-at-age, and indices of abundance, and can account for years with missing data. Assumed natural mortality rate was age-specific, decreasing from 0.38 at age-1 to 0.10 at ages-10+ (**Table 1**). Maturity was assumed to begin at age-3 (25%), with 50% maturity at age-4 and 100% maturity at ages-5+ (**Table 1**). Weight at age was assumed from age composition sampling. Spawning is assumed to occur at mid-year.

Several alternative ASAP configurations were developed with varying degrees of data aggregation:
1. Single fleet (updated and revised from Maguire & Cadrin 2020)
2. Five fleets (four index fleets and a composite fleet for the remaining catch)
3. Six fleets (four index fleets, Mediterranean purse seine fleet, and a composite fleet for the remaining catch)

Two 'base runs' for single-fleet and multi-fleet ASAP configurations were developed based on two alternative catch-at-age data sets: 1) the data available at the 2022 Eastern Atlantic and Mediterranean Bluefin Tuna Data Preparatory Meeting (18-26 April 2022), and 2) revised data that assigned inflated catch (not elsewhere included, NEI-inflated, 1998-2007) to the Mediterranean purse seine fleet (PS_MED_pre2008), shifting age composition to older ages in that period. The six-fleet model was developed with the original catch-at-age, and then revised with the revised catch-at-age. A single-fleet sensitivity analysis was fit to a third alternative catch-at-age series based on a Richards's growth function (Sampedro *et al.* 2022).

Index fleets accounted for 22% of the 1968-2020 catch (11% to 42% of annual catch). The Mediterranean purse seine fleet accounted for 18% of the total catch (7% to 65% of annual catch). Other fleets accounted for 60% of the total catch (22-66% of annual; **Figure 1**).

The 1968-2020 catch for was mostly ages 1-12 (>84% in each year) and there was little catch older than age-15 (catch at age 16+ was 0-5% in each year; **Figure 2**). There was a shift in age composition of the catch in the mid-2000s associated with fishing regulations, in which 1968-2006 catch was mostly ages 1-4, but since 2007, there was little catch at age-1 and less catch at age-2. The revised catch at age suggests intermediate age composition during the period of inflated catch (1998-2007). Weight at age was relatively stable, suggesting good sampling for ages 1-15, with some interannual variation in age-16+ suggesting sampling variability (**Figure 3**). Correlations of catch at age within year-classes and among ages suggest good cohort tracking, with moderate to strong correlations from one year to the next (r=0.50-54 between ages 1 and 2, r=0.62-83 for ages 2+), and most correlations were slightly greater for revised data (**Figure 4**). Therefore, age composition was modeled for ages 1-15 and age-16+.

At the 2022 Eastern Atlantic and Mediterranean Bluefin Tuna Data Preparatory Meeting (18-26 April 2022), eleven stock indices were updated and ten were proposed for inclusion in stock assessment models. Seven were fishery catch rate indices:

1. Moroccan-Spanish Traps (MOR_SP_TP) 1981-2011,
2. Moroccan-Portuguese traps (MOR_POR_TP) 2012-2020,
3. Japanese Eastern Atlantic and Mediterranean longline (JPN_LL_EastMed, 1975-2009),
4. Japanese Northeast Atlantic longline (JPN_LL1_NEA) 1990-2009,
5. Japanese Northeast Atlantic longline (JPN_LL2_NEA) 2010-2019,
6. Spanish baitboat (SP_BB1) 1968-2006,
7. Spanish baitboat (SP_BB2) 2007-2014.

The French aerial survey was split into two indices (FR_AER1 2000-2003 and FR_AER2 2009-2020). The Western Mediterranean larval survey (WMED_LARV) was modeled as an index of spawning biomass. The Western Mediterranean GBYP Aerial survey (WMedGBYPAerial) was included as a stock index in a sensitivity run.

2. Analysis

2.1 Population Model

ASAP is a forward projecting model, using age-based process equations to model population dynamics. Technical details and AD Model Builder code are available online (https://nmfs-fish-tools.github.io/ASAP) and in the ICCAT Software Catalog (https://github.com/ICCAT/software/wiki/2.6-ASAP). Annual recruitment (abundance at age-1) can be derived from an annual deviation from a Beverton-Holt stock recruitment relationship, but steepness was assumed to be 1.0 for application to eastern Atlantic and Mediterranean bluefin tuna, making estimated recruitment an annual deviation from a time series average.

Abundance at age *a* was derived survival from the previous age (*a*-1) from continuous exponential rates of natural mortality (*M*), and fishing mortality at age, the product of estimated annual fishing mortality of fully-selected ages (*F*) is estimated selectivity (*s*) at age for each fleet *j*:

$$N_{t,a} = N_{t-1,a-1} e^{-\left[M_{t-1,a-1} + \sum_j \left(\widehat{F_{t-1,J}} s_{t-\widehat{1,a-}1,J}\right)\right]}$$

and abundance of the oldest ages (16+ for eastern Atlantic and Mediterranean bluefin tuna) were derived as an aggregate 'plus group', *A*:

$$N_{t,A} = N_{t-1,A-1} e^{-\left[M_{t-1,A-1} + \sum_j \left(\widehat{F_{t-1,J}} s_{t-\widehat{1,A-}1,J}\right)\right]} + N_{t-1,A} e^{-\left[M_{t-1,A} + \sum_j \left(\widehat{F_{t-1,J}} s_{t-\widehat{1,A},J}\right)\right]}$$

Selectivity was estimated as individual parameters for each age or as a function of age (logistic or double logistic).

Spawning biomass was derived from abundance at age, assumed maturity (*m*) at age, spawning weight at age (*w*), and spawning season (*p*, portion of annual mortality that occurs before spawning):

$$SSB_t = \sum_{a=1}^{a=A} \left\{ N_{t,a} m_{t,a} w_a e^{-\left\{p\left[M_{t,a} + \sum_j \left(\widehat{F_{t,J}} \widehat{s_{t,a,J}}\right)\right]\right\}} \right\}$$

2.2 Observation Model

Model predictions of observed stock indices *j* were derived from the corresponding abundance at the time of year the index is observed (*p*), catchability (*q*), index selectivity (s) and index weight at age (*w*, if the index is in biomass units):

$$I_{t,j} = q \sum_{a=1}^{a=A} \left\{ N_{t,a} s_{t,a,j} w_a e^{-\left\{p\left[M_{t,a} + \sum_j \left(\widehat{F_{t,J}} \widehat{s_{t,a,J}}\right)\right]\right\}} \right\}$$

The predicted catch in numbers of fish for each fleet, year, and age were derived from Baranov's catch equation:

$$C_{t,a} = N_{t,a} \left\{ 1 - e^{-\left[M_{t,a} + \sum_j \left(\widehat{F_{t,J}} \widehat{s_{t,a,J}}\right)\right]} \right\} \frac{\sum_j \left(\widehat{F_{t,J}} \widehat{s_{t,a,J}}\right)}{M_{t,a} + \sum_j \left(\widehat{F_{t,J}} \widehat{s_{t,a,J}}\right)}$$

and the predicted total weight of landings (*Y*, yield) was derived from catch at age and catch weight at age (*w*):

$$Y_{t,j} = \sum_{a=1}^{a=A} \left(C_{t,a,j} w_{t,a} \right)$$

2.3 Statistical Model

The estimation of abundance at age in the first year, average recruitment, annual recruitment deviations, annual fishing mortality, fishery selectivity parameters, index catchability and selectivity parameters were estimated using AD Model Builder. The objective function was the sum of several likelihood components. Likelihood components for total yield and indices assumed lognormal error and likelihoods. Total yield and indices included an input coefficient of variation (CV) that determined emphasis for each lognormal likelihood component. Likelihood components for age composition assumed multinomial error, and the multinomial negative log likelihood was multiplied by effective sample size in the objective function.

Design-based CVs provided for each index were maintained for index likelihoods. Other assumed CVs were iteratively revised so that the assumed variance approximated the variance of model residuals for each component using the RMSE~1 diagnostic. Effective sample size for fishery age composition was assumed based on initial model predictions from age composition residuals and multinomial error (Francis 2011). Model diagnostics described by Carvalho *et al.* (2021) were applied for model comparison and development.

2.4 Single-Fleet ASAP configuration

The single fleet ASAP application developed for the 2020 stock assessment (Maguire & Cadrin 2020) was updated and revised according to decisions at the 2022 Eastern Atlantic and Mediterranean Bluefin Tuna Data Preparatory Meeting (18 - 26 April 2022). Catch was assumed to be relatively precise (CV=0.1), except the assumed CV for the period of inflated catch (1998-2007), which was iteratively increased to 0.17 for the unrevised data and 0.20 for the revised data, based on a constraint for predicted catch to be greater than reported catch. Effective sample size of fishery age composition was 25 for 1968-1995 and 50 for 1996-2020 for unrevised data; 50 for 1968-2020 for revised data (**Figure 5**). A CV of 0.5 was assumed for annual recruitment deviations based on their resulting root mean square from initial runs. A fifth selectivity period was added to the four periods in the 2020 application to improve fit to recent age composition. Age-specific selectivity was estimated. ASAP requires that selectivity is assumed to be 1 for at least one age, so selectivity at each age was initially estimated, then selectivity was assumed to be 1 for all ages estimated to have full selectivity or to have the greatest estimated selectivity. For the unrevised catch at age, selectivity was modeled in five periods:

- 1968-1982 (estimated selectivity at age, except age-2 selectivity assumed to be 1)
- 1983-1998 (estimated selectivity at age, except age-3 selectivity assumed to be 1)
- 1999-2005 (estimated selectivity at age, except age-12 selectivity assumed to be 1)
- 2006-2014 (estimated selectivity at age, except ages 12-13 selectivity assumed to be 1)
- 2015-2020 (estimated selectivity at age, except ages 9-11 selectivity assumed to be 1)

For the revised catch at age, selectivity was modeled in five periods:

- 1968-1982 (estimated selectivity at age, except age-2 selectivity assumed to be 1)
- 1983-1998 (estimated selectivity at age, except age-3 selectivity assumed to be 1)
- 1999-2004 (estimated selectivity at age, except age-12 selectivity assumed to be 1)
- 2005-2014 (estimated selectivity at age, except age-12 selectivity assumed to be 1)
- 2015-2020 (estimated selectivity at age, except age-10 selectivity assumed to be 1)

Fishing mortality estimates were reported as apical F and average F for ages 9-11 based on recent selectivity.

Sensitivity analyses were explored for an additional index (Western Mediterranean GBYP Aerial survey WMedGBYPAerial), alternative selectivity assumptions, deriving index selectivity from the partial catch-at-age,alternative catch-at-age based on Richards growth, and assumed CV for catch.

2.5 Fleet-structured ASAP configurations

Fleet-structured ASAP models were developed using an iterative model building approach in which each index fleet was modeled separately in a series of two-fleet models to explore appropriate selectivity models for index fleets. A five-fleet model was then developed that included each index fleet and all others. A six-fleet model was developed to model the Mediterranean purse seine fleet separately.

The five-fleet model included four index fleets and a composite fleet for remaining catch:

- Fleet One (“Other”) - all catch not accounted for by four index fleets
- Fleet Two (“Traps”) - catch using traps by Morocco and Spain from 1968-2011; Morocco and Portugal 2012-2020
- Fleet Three (“BB”) - catch by Spanish bait boats 1968-2020
- Fleet Four (“JPN_LL_EastMed”) - catch by Japanese longline vessels in Mediterranean Sea 1972-2009. Years 1968-1971 and 2010-2020 were input as zero reported catch and selectivity periods were assigned with selectivity fixed at 0 for all ages.
- Fleet Five (“JPN_LL_NEA”) - catch by Japanese longline vessels in Northeast Atlantic Ocean 1971-2020. A small amount of catch at age was reported for 1968-1971, but total weight estimates were not available for this time period, so the catch at age was reassigned to the “other” fleet so that fleet five showed zero CAA and total weight for this period.

The six-fleet model included four index fleets, the Mediterranean purse-seine fleet, and a composite fleet for the remaining catch:

- Fleet One ("Other") - all catch not accounted for by four index fleets and PS_MED
- Fleet Two ("Traps") - same as five fleet model
- Fleet Three ("BB") - same as five fleet model
- Fleet Four ("JPN_LL_EastMed") - same as five fleet model
- Fleet Five ("JPN_LL_NEA") - same as five fleet model
- Fleet Six ("PS_MED") - catch by purse-seine vessels in Mediterranean Sea, excluding catch by Croatia.

Selectivity models were initially based on the two-fleet models for each index fleet, with minor adjustments for the five and six-fleet models:

- Fleet One ("Other") - two selectivity periods: 1968-2008 (estimated selectivity at age, except age 12-16 selectivity assumed to be 1), 2008-2020 (estimated selectivity at age, except age 4-5 selectivity assumed to be 1)
- Fleet Two ("Traps") - one selectivity period:1968-2020 (double logistic selectivity estimated)
- Fleet Three ("BB") - two selectivity periods:1968-2006 (estimated selectivity at age, except age 2 selectivity assumed to be 1), 2007-2020 (estimated selectivity at age, except age 4 selectivity assumed to be 1)
- Fleet Four ("JPN_LL_EastMed") - one selectivity period:1972-2009 (logistic selectivity estimated)
- Fleet Five ("JPN_LL_NEA") - one selectivity period: 1971-2020 (logistic selectivity estimated)
- Fleet Six ("PS_MED") - three selectivity periods: 1968-2004 (estimated selectivity at age, except age 2-3 selectivity assumed to be 1), 2005-2012 (estimated selectivity at age, except age 4-5,11-13 selectivity assumed to be 1), 2013-2020 (estimated selectivity at age, except age 9-12 selectivity assumed to be 1)

Fishing mortality estimates were reported as apical F and average F for ages 11-13 based on recent selectivity.

Effective sample sizes were set to be consistent with mean age as described in Francis (2011). Final ESS assumptions for the six-fleet model were:

- Fleet One ("Other") ESS=25 (1968-2005), ESS=50 (2006-2020)
- Fleet Two ("Traps") ESS=50
- Fleet Three ("BB") ESS=20
- Fleet Four ("JPN_LL_EastMed") ESS=25
- Fleet Five ("JPN_LL_NEA") ESS=20
- Fleet Six ("PS_MED") ESS=25

CVs for catch data were adjusted to bring the root mean square error (RMSE) value close to 1. The catch CV for fleet six was adjusted upwards during the period 1997-2007 to allow the model some flexibility in fitting the data during this period of inflated catch. Due to relatively small, but highly variable catch in some of the index fleets, higher CVs were necessary to improve the RMSE diagnostic:

- Fleet One ("Other"): CV=0.2
- Fleet Two ("Traps"): CV=0.4
- Fleet Three ("BB"): CV=0.5
- Fleet Four ("JPN_LL_EastMed"): CV=0.5
- Fleet Five ("JPN_LL_NEA"): CV=0.5
- Fleet Six ("PS_MED"): CV= 0.2 (1968-1996, 2008-2020), CV=0.3 (1997-2007)

A revised six-fleet model with the revised CAA used for the single-fleet base2 run. The six-fleet models with revised and unrevised data had the same model configuration except for the PS_Med fleet selectivity model. The revised configuration maintained three selectivity periods, but selectivity in the second period, 2005-2012, had estimated selectivity at age, except age 11-13 selectivity assumed to be 1), and selectivity in the third period, 2013-2020 had estimated selectivity at age, except age 9-11 selectivity assumed to be 1.

2.6 Status Determination and Projections

ASAP derives integrated estimates of reference points for each application. The application of ASAP to eastern Atlantic and Mediterranean bluefin tuna fixed steepness at 1, so reference points based on yield-per-recruit (F_{max}, $F_{0.1}$) or maximum spawning potential (e.g., $F_{40\%MSP}$) may be more appropriate.

ASAP derives deterministic F-based projections using the same process equations. Short-term projections assumed 2021 catch was 30,937 mt (as estimated by the 2022 Eastern Atlantic and Mediterranean Bluefin Tuna Data Preparatory Meeting, 18-26 April 2022), and 2022 catch equaled the TAC (36,000 mt). Alternative projections for 2022-2025 assumed status quo fishing mortality, status quo TAC or F0.1.

3. Results and conclusions

3.1 Single-Fleet ASAP Configurations

The base1 model run (with unrevised data) and base2 run (with revised data) fit the data relatively well. Both model runs fit the fishery catch well, except for the period of inflated catch, when the models were allowed to deviate more within the constraint of reported catch and estimated catch was between the reported and inflated catch in each year (**Figure 6**). Both model runs also fit stock indices relatively well, generally within the design-based confidence intervals (**Figure 7**). There were some large age composition residuals at age-1 and patterns of smaller residuals at older ages that could not be resolved by additional selectivity periods (**Figure 8**). Retrospective analyses produced relatively consistent estimates of SSB (rho=0.01 for base 1 and 0.02 for base 2; Mohn 1999; **Figure 9**) and age 7-10 F (rho=-0.02 for base 1 and -0.08 for base 2).

Model parameters were generally well estimated by both base 1 and base 2 model runs. The total likelihood profile suggests relatively precise estimation of mean recruitment (**Figure 10**). Gradients of each likelihood component were similar but suggest that stock indices are most informative, followed by age composition then catch, with constraint from the likelihood penalty for recruitment deviations. Both base models converged on the same or a similar solution for all runs with moderately jittered starting values for estimated parameters (abundance in the first year, average recruitment, catchabilities, ...). The model solution was somewhat sensitive to the starting guesses for recent selectivity of young ages but estimates of stock size were less sensitive (within 8% of the estimate and confidence limits). An alternative run with naïve starting values (0.5 for all estimated selectivities) produced a similar stock estimate (within 1%; **Figures 11 and 15**). Another alternative run with four selectivity periods (i.e., combining 2006-2020 into a single selectivity period), similar to the 2020 application (Maguire and Cadrin 2020) was also explored to evaluate sensitivity to recent selectivity estimation.

Estimates of selectivity from base1 and base2 model runs suggest a substantial change from bimodal selectivity in the early selectivity periods (full selection of ages 2 or 3 and partial selection of older ages before 1999), to relatively low selectivity of young fish (ages 1-8) and full selection of older fish (ages 9-12) since 1999 (**Figure 12**). Results from both model runs suggest that the stock decreased from the 1970s to the early 2000s then recovered over the last decade from recent strong recruitment and low fishing mortality (**Figure 13**). Recruitment estimates were relatively low for the early part of the assessment series (1968-1987), but above average since then, with strong recruitment in the early 1990s and 2013-2017. Fishing mortality estimates gradually increased from the early 1980s to 2007, then sharply declined to less than candidate reference points based on yield or spawner per recruit that assume recent selectivity and weight at age (**Table 2**). Model estimates suggest that SSB gradually declined from the late 1970s to 2007 then rapidly increased to be greater than candidate biomass reference points. Estimates of SSB, F and age-1 recruitment were relatively precise (CV<0.25), except for recruitment in the last two years (CV=0.35 and 0.47 from base 2). The stock-recruit relationship is not strong but suggests that the stock has more than enough productivity to replace itself if fished at the candidate reference points (**Figure 14**). The estimate of 2020 fishing mortality was much less than $F_{0.1}$, and the estimate of 2020 spawning biomass was much greater than $SSB_{F0.1}$.

Results were generally robust to alternative data and model decisions (**Figure 15**). Estimates from base run 1 (unrevised data) and base run 2 (revised data) produced similar results, except for 1999-2005 fishing mortality estimates which were during the period of inflated catch. Estimates of SSB were most sensitive to estimating selectivity at the oldest ages (as in the base runs) vs. assuming asymptotic selectivity (‘flat-topped’), but asymptotic selectivity did not fit the data well and cannot be considered a candidate model. Estimates of recent spawning stock biomass were somewhat sensitive to the Richards’s catch-at-age, but estimates of selectivity were more sharply domed with that data (**Figure 16**). The Western Mediterranean GBYP Aerial survey (WMedGBYPAerial) had a residual pattern in which the survey suggests a steeper recent stock increase than the model (Figure 16). Estimates of SSB and F were not sensitive to other selectivity models, and alternative models had similar sensitivity to starting parameter values for young ages in the recent period and significantly greater AIC.

Short-term projections (2021-2025) suggest continued increases in the stock and catch at the current F, modest increase in the stock at the current TAC, and modest stock decrease from substantial increase in catch at $F_{0.1}$ (**Figure 17**).

3.2 Fleet-Structured ASAP Configurations

Both the five-fleet and six-fleet ASAP runs fit the data relatively well. In the five-fleet run, selectivity was estimated well for the four index fleets and composite "other" fleet (**Figure 18**). Age composition residuals showed a pattern of positive residuals around 2006-2008 that was not resolved by an additional selectivity period. The trap fleet also showed a few large age composition residuals at younger ages due to sporadic large catches of young fish among a consistent catch of older fish (age 7-14) over the time series. Age composition residuals did not show any obvious patterns for the Spanish baitboat or Mediterranean Japanese longline fleet. The northeast Atlantic Japanese Longline fleet did show some residual patterns during the period 2008-2020 (**Figure 19**). Retrospective analyses with 7-year peels were very consistent for SSB (Mohn's rho= -0.09) and age 7-10 F (rho= -0.02) (**Figure 20**).

The six-fleet run had similar estimates of selectivity for the four index fleets, and selectivity for the Mediterranean purse-seine fleet was also well estimated, despite shifting catch compositions over the time series (e.g., during the inflated period). Estimates for the composite "other" fleet also showed a slightly more realistic selectivity pattern, although selectivity was still bimodal due to the mixed-gear nature of the fleet. The pattern in age composition residuals for the "other" fleet in the 2006-2008 period was improved in the six-fleet model (**Figure 21**). The same residual pattern observed for the northeast Atlantic longline fleet was also seen in the six-fleet model (**Figure 22**) and could not be resolved with an additional selectivity period without causing other diagnostic issues such as gradient warnings. Retrospective analyses for the six-fleet run were also moderately consistent in their estimates of SSB (rho= -0.13) and age 7-10 F (rho= 0.12).

The six-fleet run with revised catch-at-age data did not differ greatly from the other six-fleet model. It showed a slightly decreased selectivity for age 4-5 fish during the second selectivity period and a slightly decreased selectivity of age 12 fish during the most recent period (**Figure_23**). Age composition residuals for the six-fleet revised data were similar to the other six-fleet run (**Figure 24**). Retrospective inconsistency was slightly higher with the new data: SSB (rho= -0.15) and age 7-10 F (rho= 0.19) (**Figure 25**).

Model results from the five and six-fleet runs were similar, but the multi-fleet ASAP runs offer a somewhat different perspective on historical stock development than the single ASAP fleet runs. For the multi-fleet models, estimates of SSB are low for the 1970s and 1980s, gradually increase during the 1990s, then rapidly increase in the last decade. By contrast, single-fleet runs show a steady decrease from the 1970s to around 2007 (**Figure 26**). Estimates of fishing mortality are slightly higher early in the time series for the multi-fleet runs (**Figure 26**). The six-fleet model runs with revised and unrevised data estimated similar fishing mortality and spawning stock biomass (SSB). All models exhibited a similar stock increase with low fishing mortality in recent years. Recruitment estimates from both multi-fleet runs were similar to those from the single-fleet run, suggesting relatively weak recruitment in the early part of the time series, with episodes of high recruitment in the early 1990's and the most recent decade (**Figure 26**).

Reference point calculations from the 6-fleet ASAP model were similar to those from the single-fleet ASAP runs (**Table 2**). Status determination from single-fleet and multi-fleet runs was similar: The estimate of 2020 fishing mortality was much less than $F_{0.1}$, and the estimate of 2020 spawning biomass was much greater than $SSB_{F0.1}$. Projected SSB moderately increased at $F_{0.1}$, increased then decreased at the current TAC or the current fishing mortality. Projected fishing mortality is slightly greater at $F_{0.1}$ and the current TAC. Projected yield is relatively constant at the current fishing mortality and decreases slightly at $F_{0.1}$ (**Figure 27**).

3.3 Discussion

Retrospective consistency of these and previous ASAP applications to Eastern Atlantic and Mediterranean Atlantic Bluefin tuna is greater than previous VPA applications (e.g., ICCAT 2020). Although statistical catch at age models are subject to retrospective patterns, the improvement from VPA appears to result from allowing for error in the catch-at-age and modeling selectivity of the oldest age simultaneously with younger ages rather than assuming an oldest-age selectivity or attempting to estimate it as a function of selectivity at younger ages. Assuming no error in the catch-at-age is a major concern for Atlantic bluefin tuna VPAs because of sampling error and the cohort-slicing method (Ailloud *et al.* 2015).

The common statistical catch-at-age assumption of constant selectivity within multi-annual periods may not be valid for mixed-gear fisheries like Atlantic bluefin tuna. Changes in fishery management, fishing behavior or fleet composition can be accounted for by time-varying estimates of selectivity or periods of constant selectivity (e.g., Legault & Restrepo 1998, Maguire & Cadrin 2020). The selectivity assumption is more valid within fleets, and the 6-fleet model appears to provide the most realistic estimates of selectivity. Future explorations of the single-fleet ASAP application should be extended to include random effects for process errors in recruitment as well as selectivity, survival, and natural mortality using the state-space Woods Hole Assessment Method (WHAM), which has similar population model structure and can efficiently use ASAP input files (Stock & Miller 2021).

The different perspectives of historical stock development (i.e., 1970s-2000s; **Figure 26**) from the single-fleet and multi-fleet runs stock in appear to result from fleet structure. Examination of results from provisional two-fleet and three-fleet runs produced in the iterative model building process suggest that modeling the two Japanese longline fleets separately (JPN_LL_EastMed and JPN_LL_NEA) produce the perception that the stock was depleted at the beginning of the assessment period (Figure 28). Two and Three-fleet model runs with baitboat and trap fleets produce historical stock estimates that are more similar to those from the single-fleet runs (i.e., stock depletion from the 1970s to the early 2000s). Those two fleets were also the more challenging to model. The different perceptions may result from fleets with different spatial dynamics (i.e., 'areas-as-fleets', Hurtado-Ferro *et al.* 2014, Waterhouse *et al.* 2014),

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Table 1. Biological assumptions.

Age	natural mortality	proportion mature
1	0.38	0.00
2	0.30	0.00
3	0.24	0.25
4	0.20	0.50
5	0.18	1.00
6	0.16	1.00
7	0.14	1.00
8	0.13	1.00
9	0.12	1.00
10+	0.10	1.00

Table 2. Fishing mortality reference points and associated long-term biomass reference points derived from single-fleet and six-fleet ASAP applications to Eastern Atlantic and Mediterranean Atlantic Bluefin tuna with unrevised data (Base1) and revised data (Base2). Fishing mortality reference points are for fully-selected ages (ages 9-11 for single-fleet models; ages 11-13 for six-fleet models).

Reference Point	1-Fleet Base1 F(9-11)	1-Fleet Base1 SSB (kt)	1-Fleet Base2 F(9-11)	1-Fleet Base2 SSB (kt)	6-Fleet Base1 F(11-13)	6-Fleet Base1 SSB (kt)	6-Fleet Base2 F(11-13)	6-Fleet Base2 SSB (kt)
$F_{0.1}$	0.15	385	0.15	390	0.12	370	0.11	368
F_{max}	0.24	239	0.25	241	0.20	230	0.19	229
$F_{30\%MSP}$	0.18	332	0.18	334	0.16	289	0.15	287
$F_{40\%MSP}$	0.13	443	0.13	445	0.11	385	0.10	383
2020	0.09	583	0.09	627	0.06	494	0.06	487

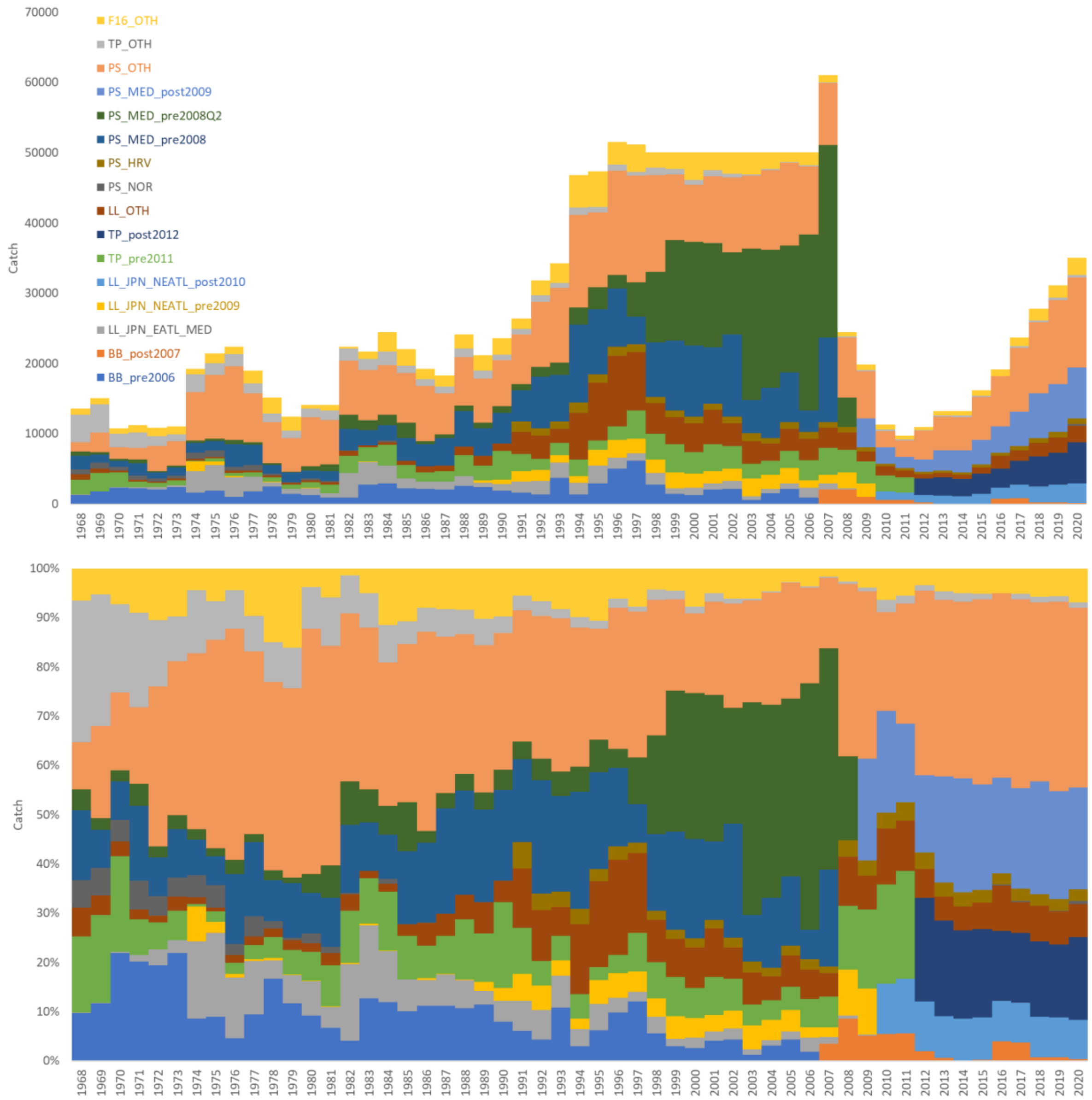

Figure 1. Catch (mt) of Eastern Atlantic and Mediterranean Atlantic Bluefin tuna by fleet.

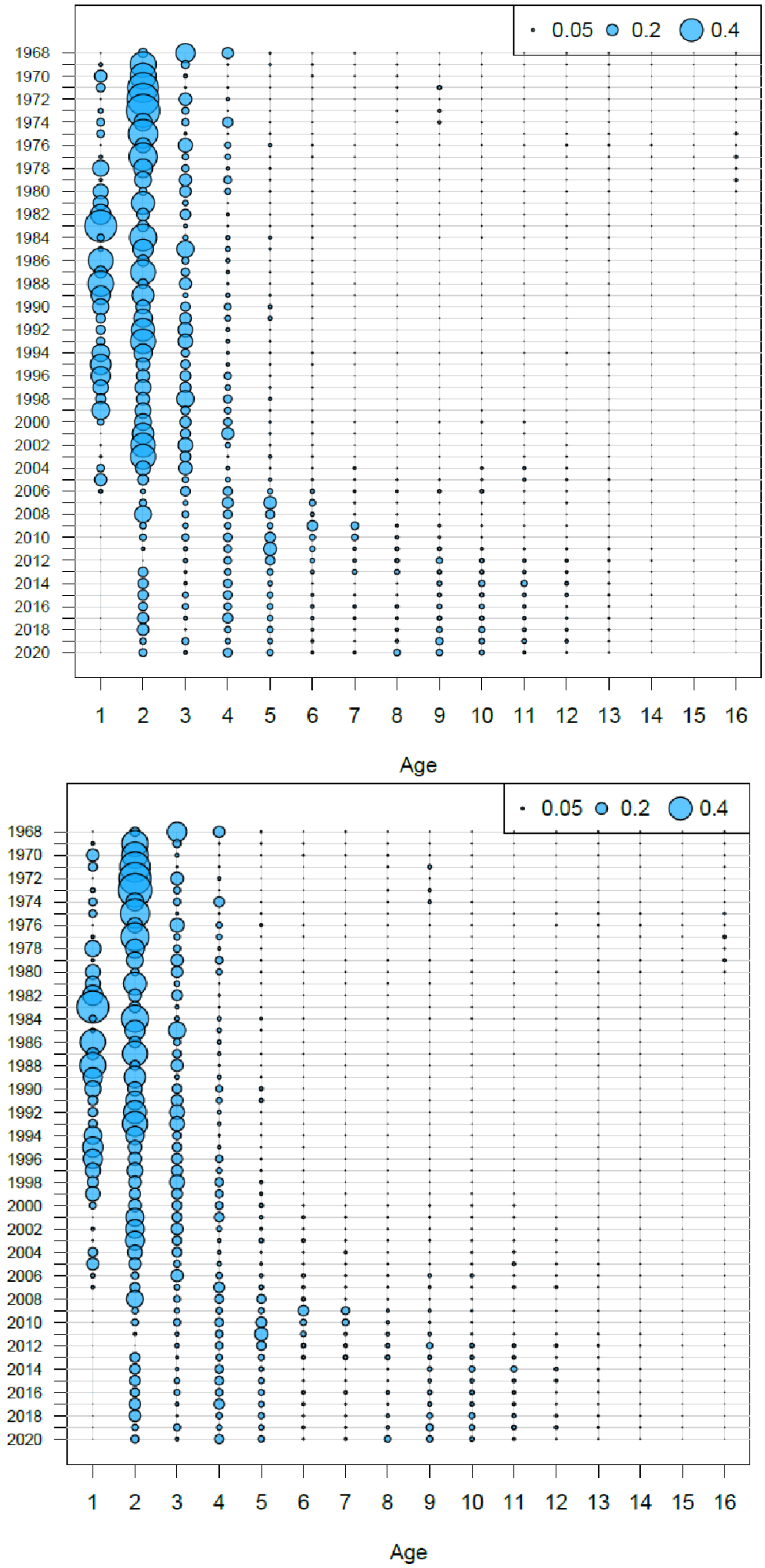

Figure 2. Age composition of Eastern Atlantic and Mediterranean Atlantic Bluefin tuna catch; unrevised data (top) and revised data (bottom).

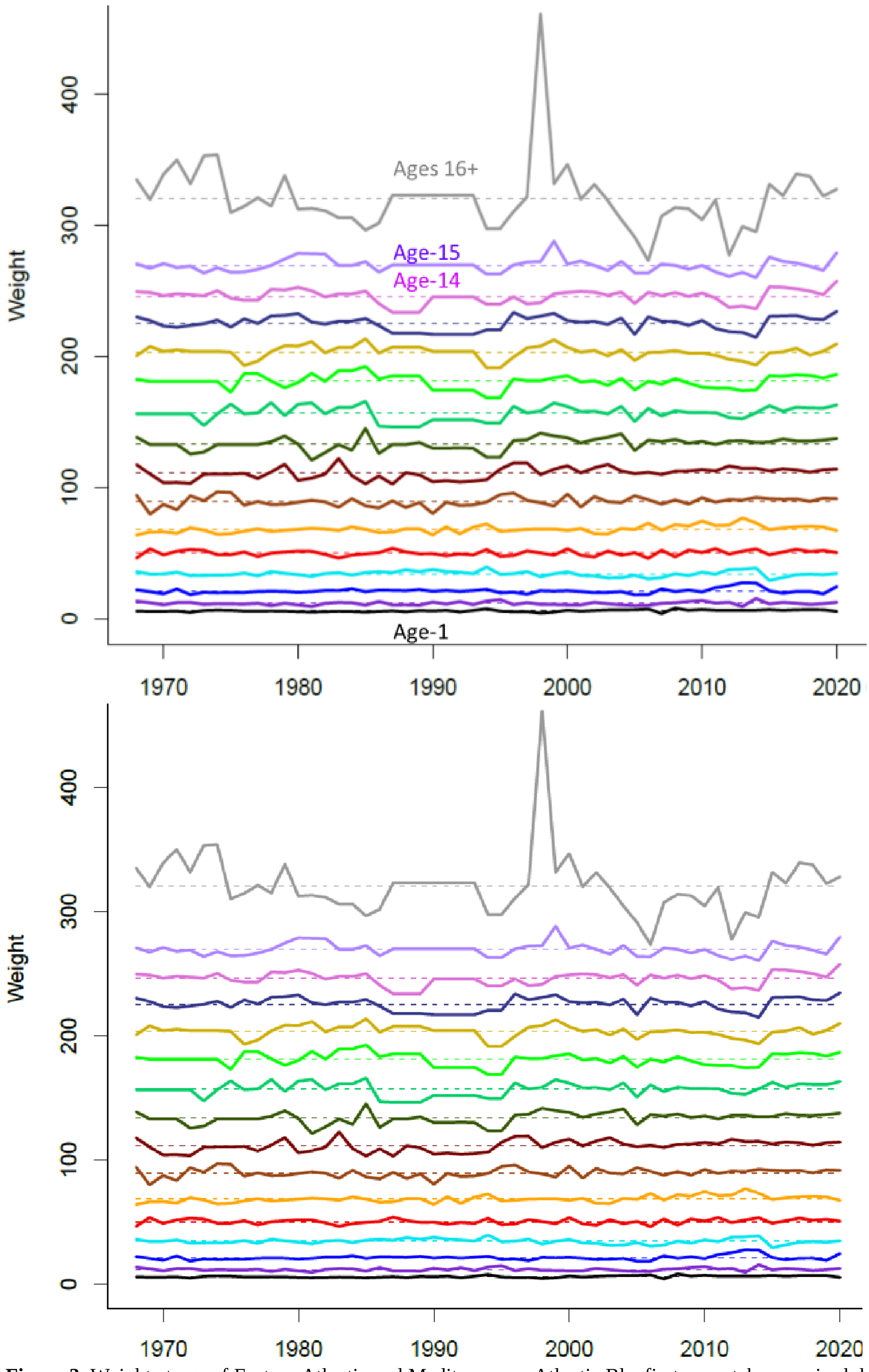

Figure 3. Weight at age of Eastern Atlantic and Mediterranean Atlantic Bluefin tuna catch; unrevised data (top) and revised data (bottom).

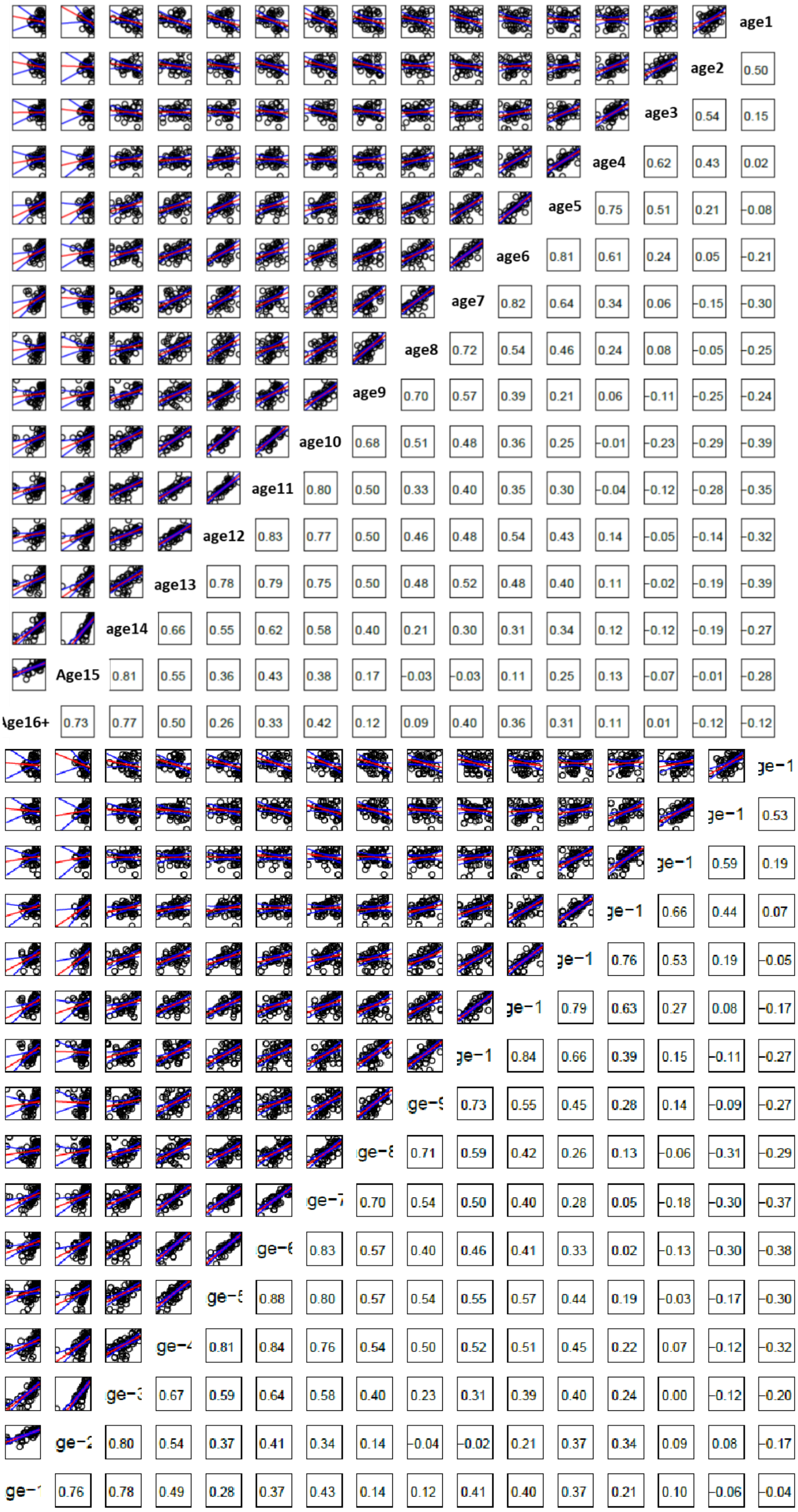

Figure 4. Correlation of catch at age of Eastern Atlantic and Mediterranean Atlantic Bluefin tuna among ages by year-class; unrevised data (top) and revised data (bottom).

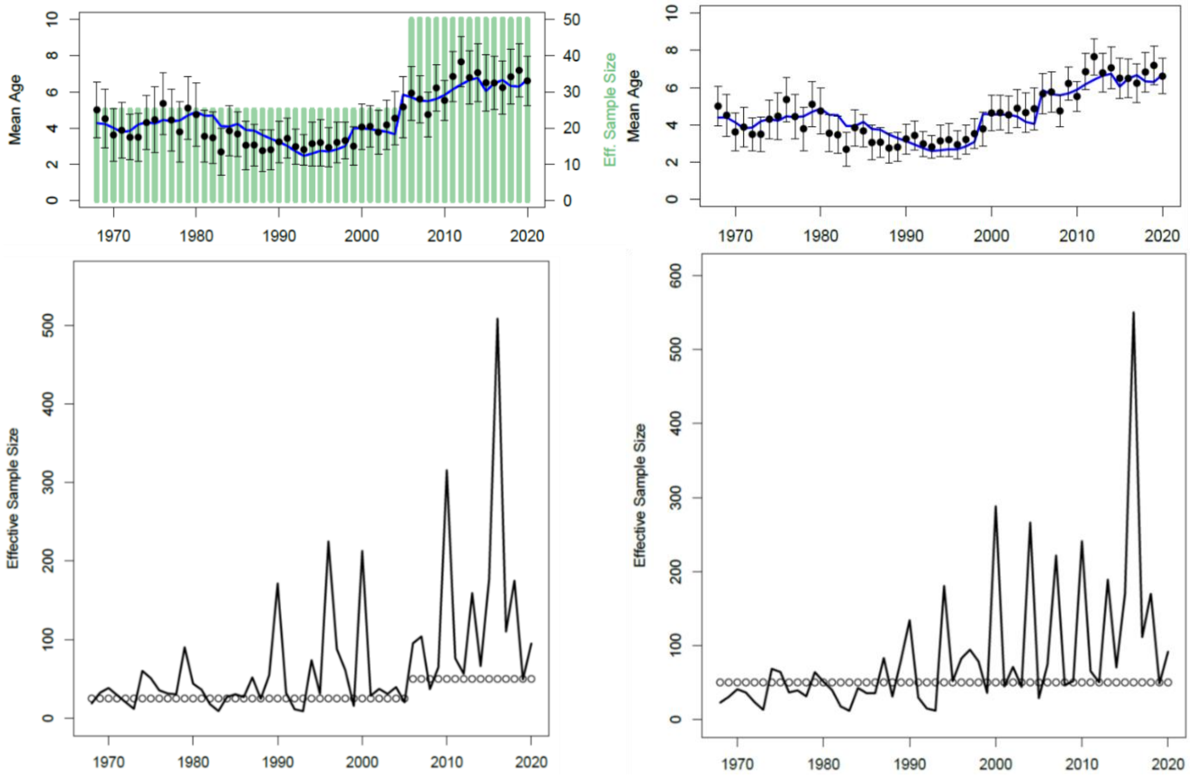

Figure 5. Assumed effective sample size for fishery age composition (green bars, top; open circles, bottom), observed mean age (closed circles and error bars, top) and model estimates of mean age (blue line, top) and effective sample size (black line, bottom) from the single-fleet ASAP application to Eastern Atlantic and Mediterranean Atlantic Bluefin tuna; unrevised data (left) and revised data (right).

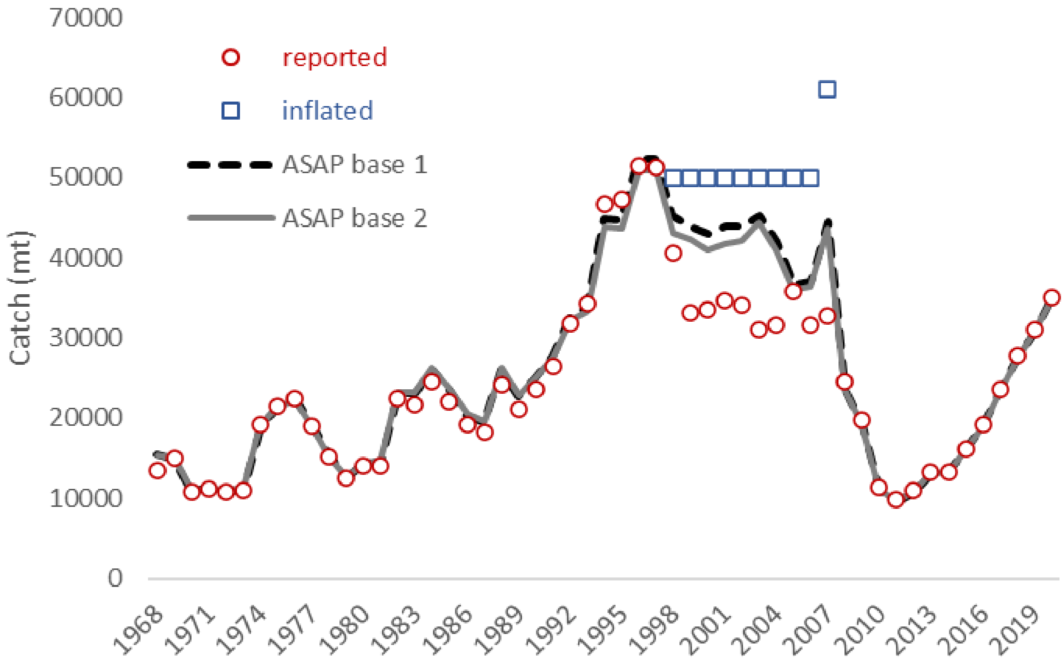

Figure 6. Predictions of catch (black line), reported catch (red circles), and inflated catch for 1998-2007 (blue squares) from the single-fleet ASAP configuration application to Eastern Atlantic and Mediterranean Atlantic Bluefin tuna, with unrevised data (base 1) and revised data (base 2).

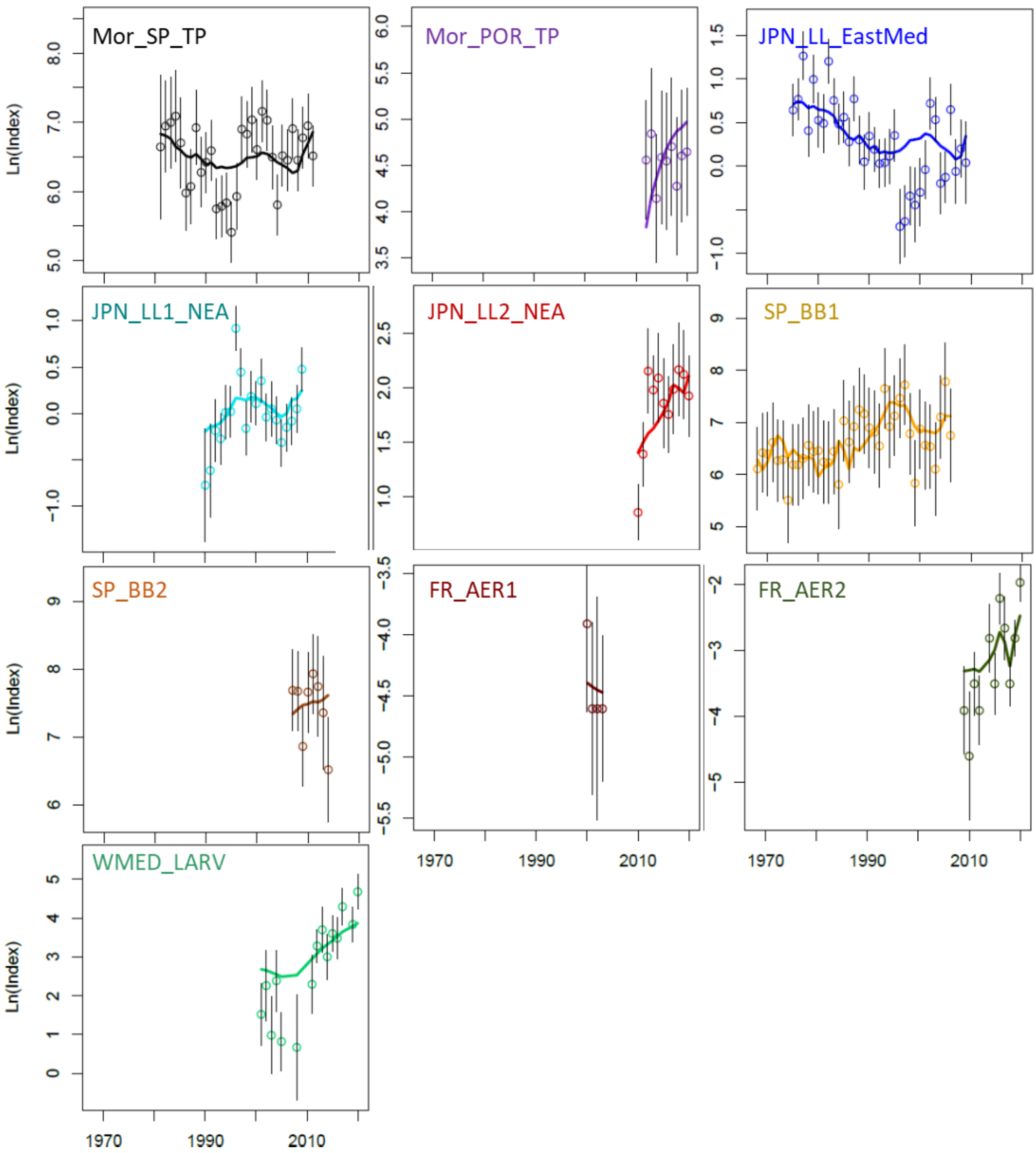

Figure 7. Stock index predictions (lines) and observed values (circles with confidence limits) from the single-fleet ASAP application to Eastern Atlantic and Mediterranean Atlantic Bluefin tuna (base run 2).

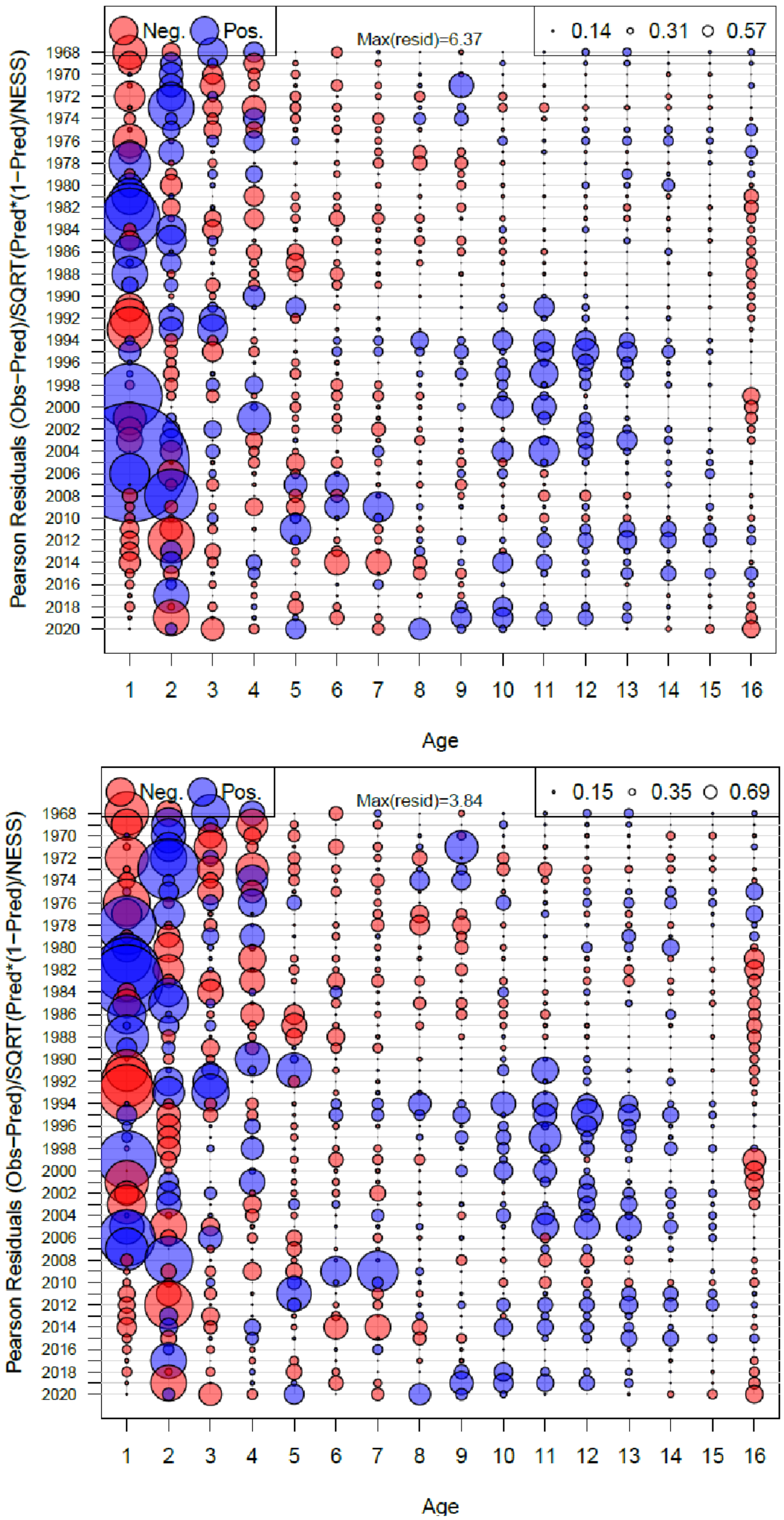

Figure 8. Pearson residuals of fishery age composition from single-fleet ASAP application to Eastern Atlantic and Mediterranean Atlantic Bluefin tuna, from unrevised data (base1, top) and revised data (base2, bottom).

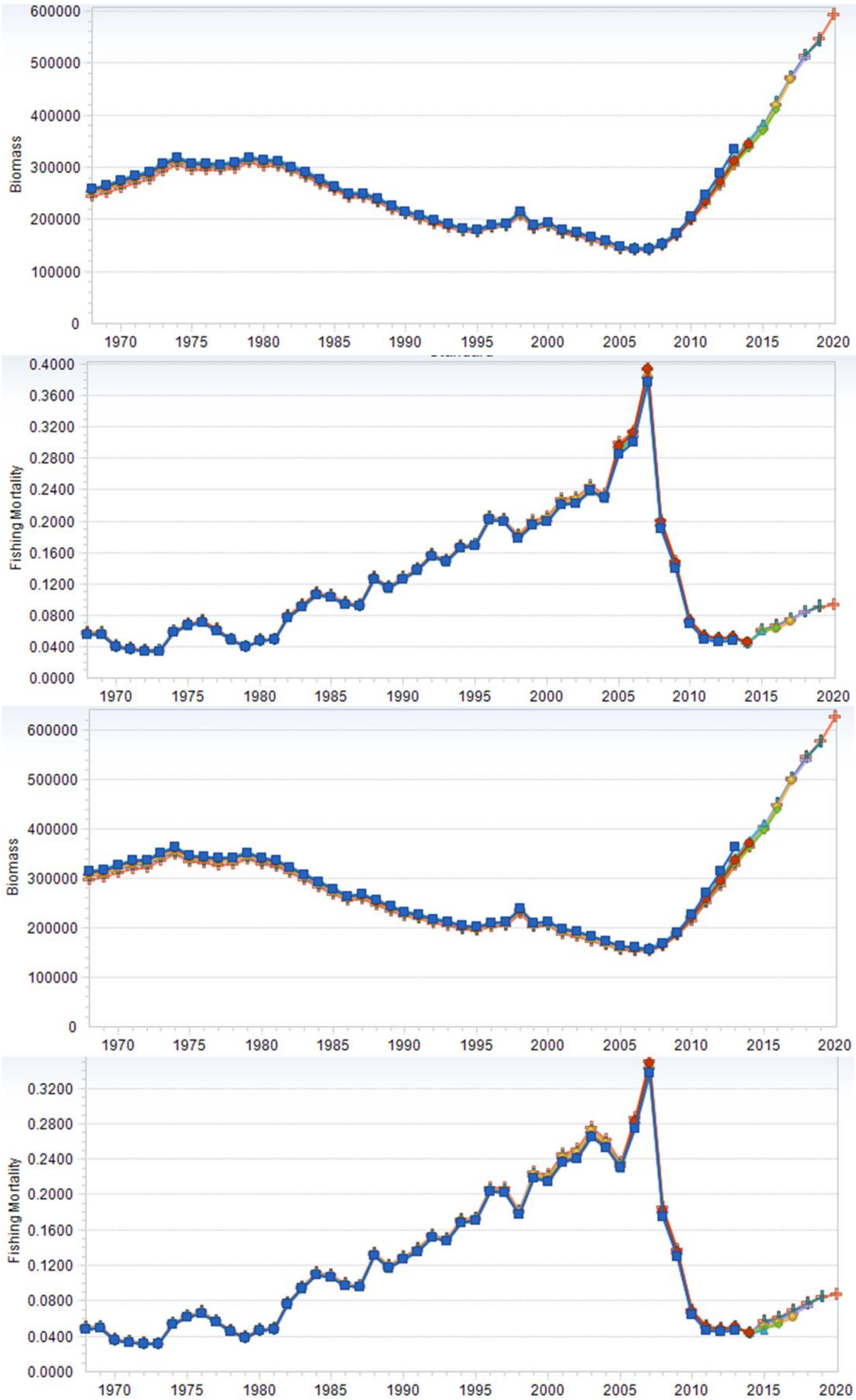

Figure 9. Retrospective estimates of SSB and age 9-11 fishing mortality from single-fleet ASAP application to Eastern Atlantic and Mediterranean Atlantic Bluefin tuna; model with unrevised data (base1, top panels), and revised data (base2, bottom panels).

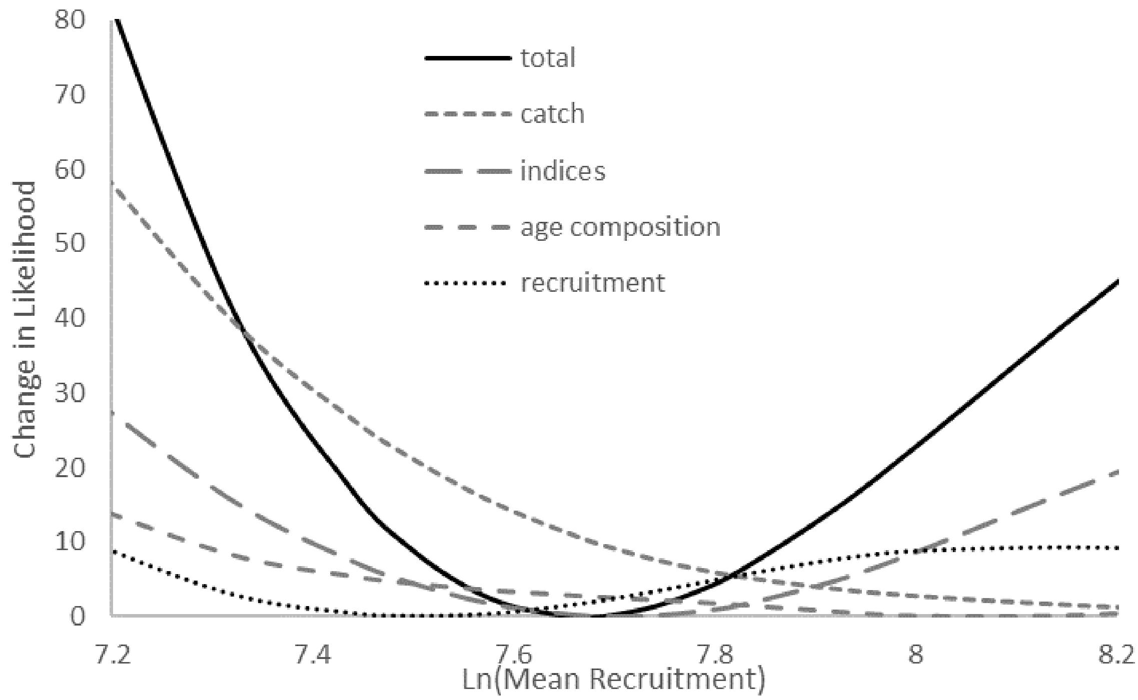

Figure 10. Likelihood profiles for the estimate of mean recruitment for the data components of the single-fleet ASAP application to Eastern Atlantic and Mediterranean Atlantic Bluefin tuna (base 2 run).

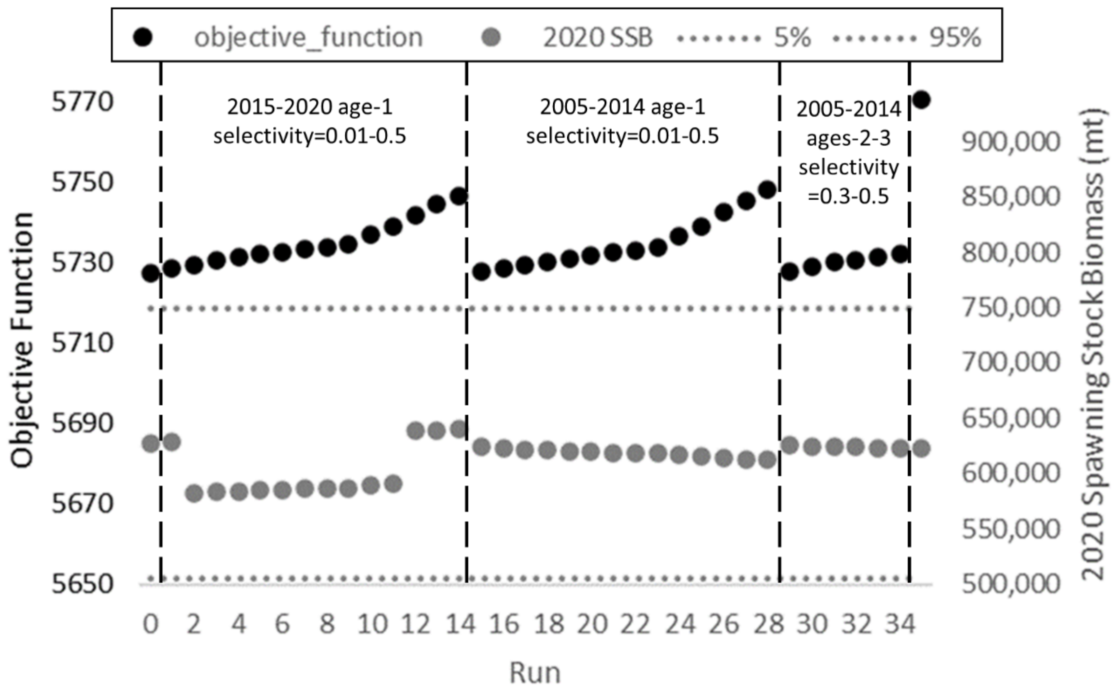

Figure 11. Sensitivity of objective function (black dots) to starting values for recent selectivity of young ages and terminal stock estimates (grey dots) with 90% confidence limits of base estimate (dotted horizontal lines). Run 0 is the single-fleet ASAP base2 run and run 35 is an alternative run with naïve starting values (0.5) for all selectivity estimates.

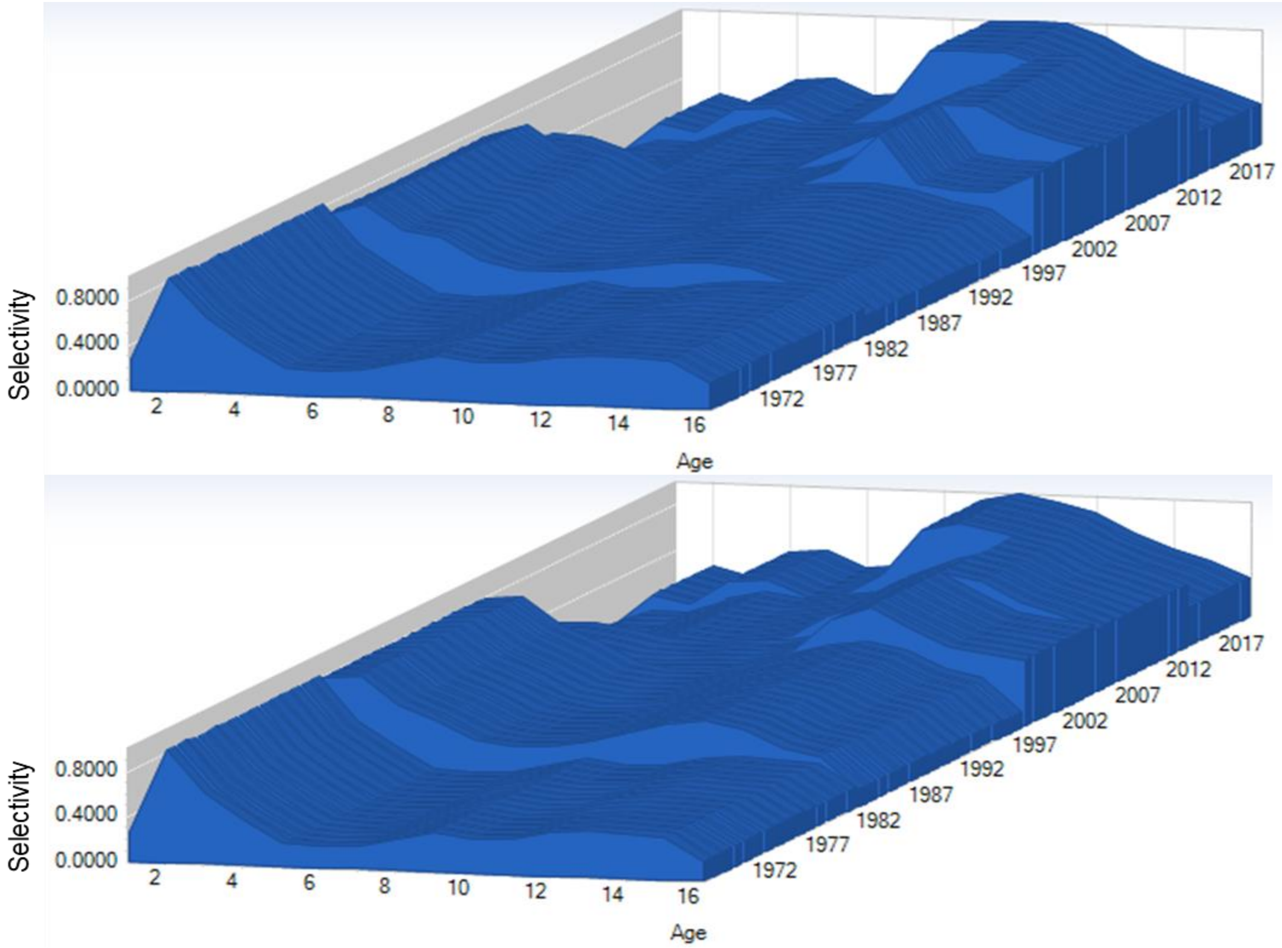

Figure 12. Estimates of selectivity from single-fleet ASAP application to Eastern Atlantic and Mediterranean Atlantic Bluefin tuna with unrevised data (base1, above), and revised data (base2, below).

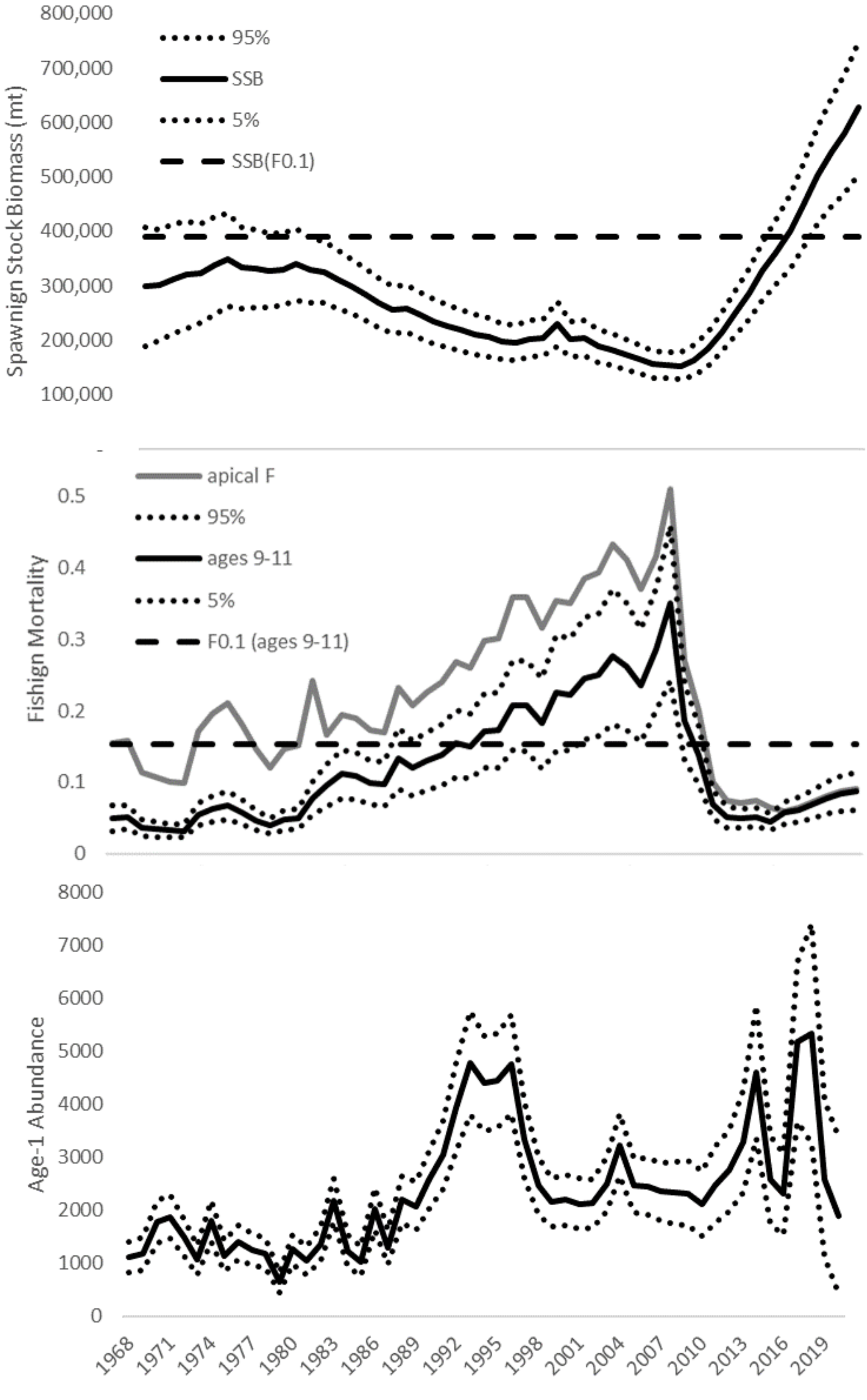

Figure 13. Estimates of SSB (top), fishing mortality (middle) and recruitment (bottom) with 90% confidence intervals and candidate reference points from the single-fleet ASAP application to application to Eastern Atlantic and Mediterranean Atlantic Bluefin tuna (base 2 run).

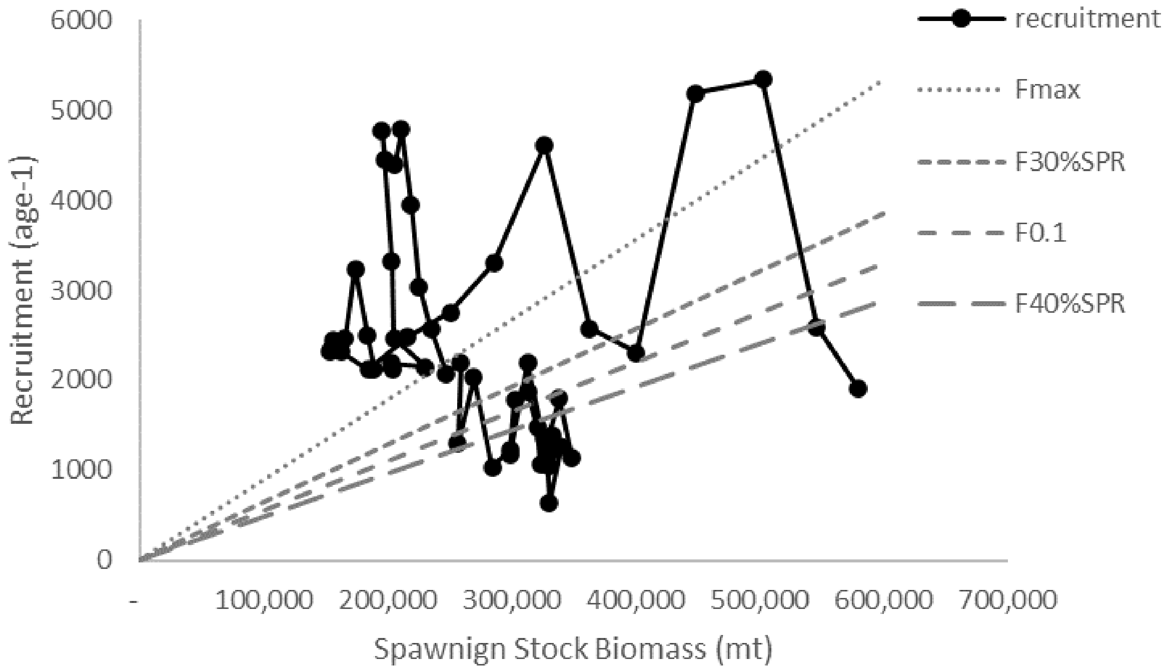

Figure 14. Stock recruit relationship with year-class labels and replacement lines for candidate reference points from the single-fleet ASAP application to Eastern Atlantic and Mediterranean Atlantic Bluefin tuna (base 2 run).

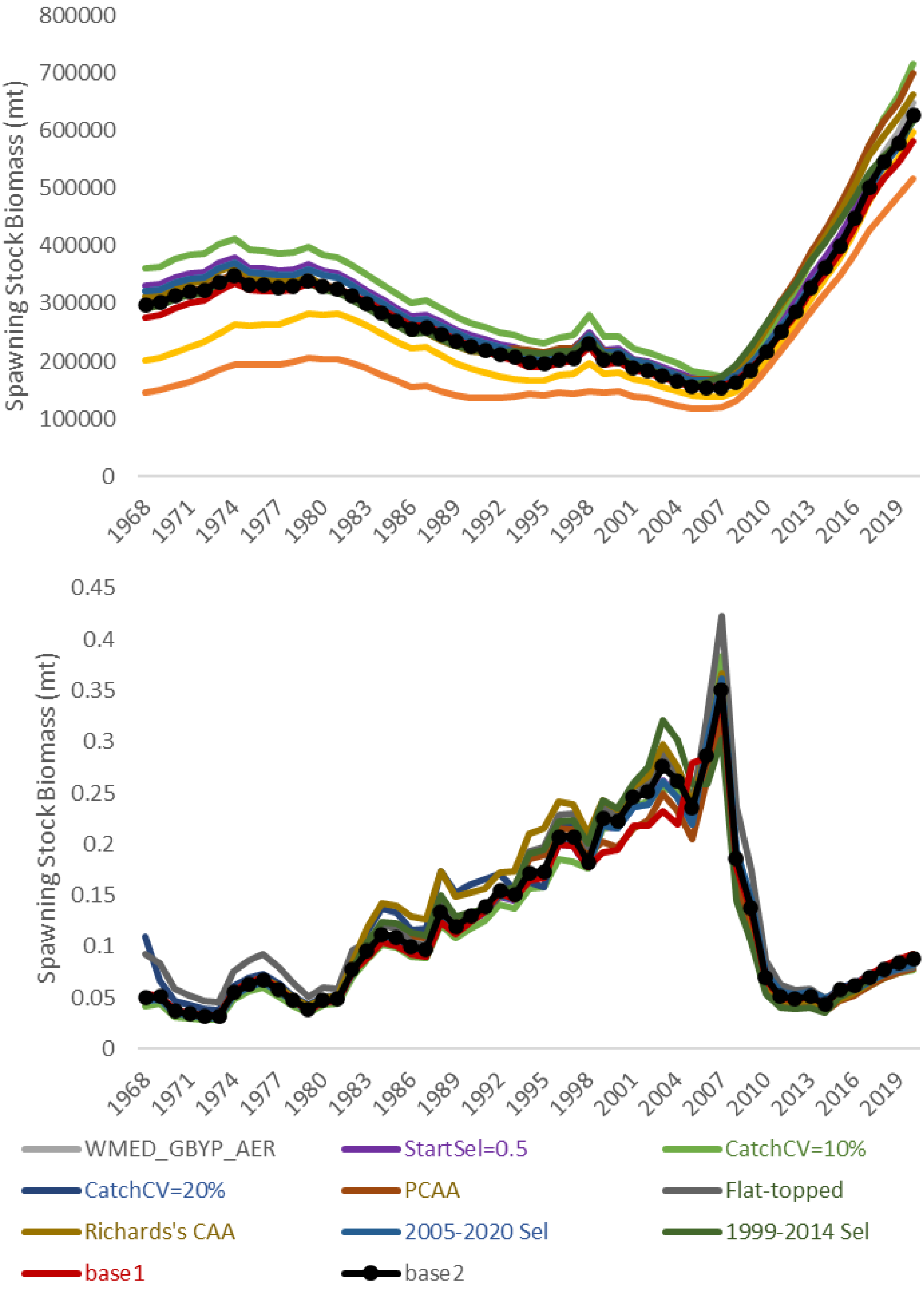

Figure 15. Sensitivity of SSB (top) and fishing mortality (bottom) to unrevised catch-at-age data (base1), revised data (base2), an additional stock index (WMED_GBYP_AER), naïve starting values for selectivity parameters (StartSel=0.5), combining the two recent selectivity periods (2005-2020 Sel), combining the previous two selectivity periods (1999-2014 Sel), deriving index selectivity from partial catch-at-age (PCAA), using the Richards's catch-at-age, catch CV=10% for all years, catch CV=20% for all years, including years of inflated catch).

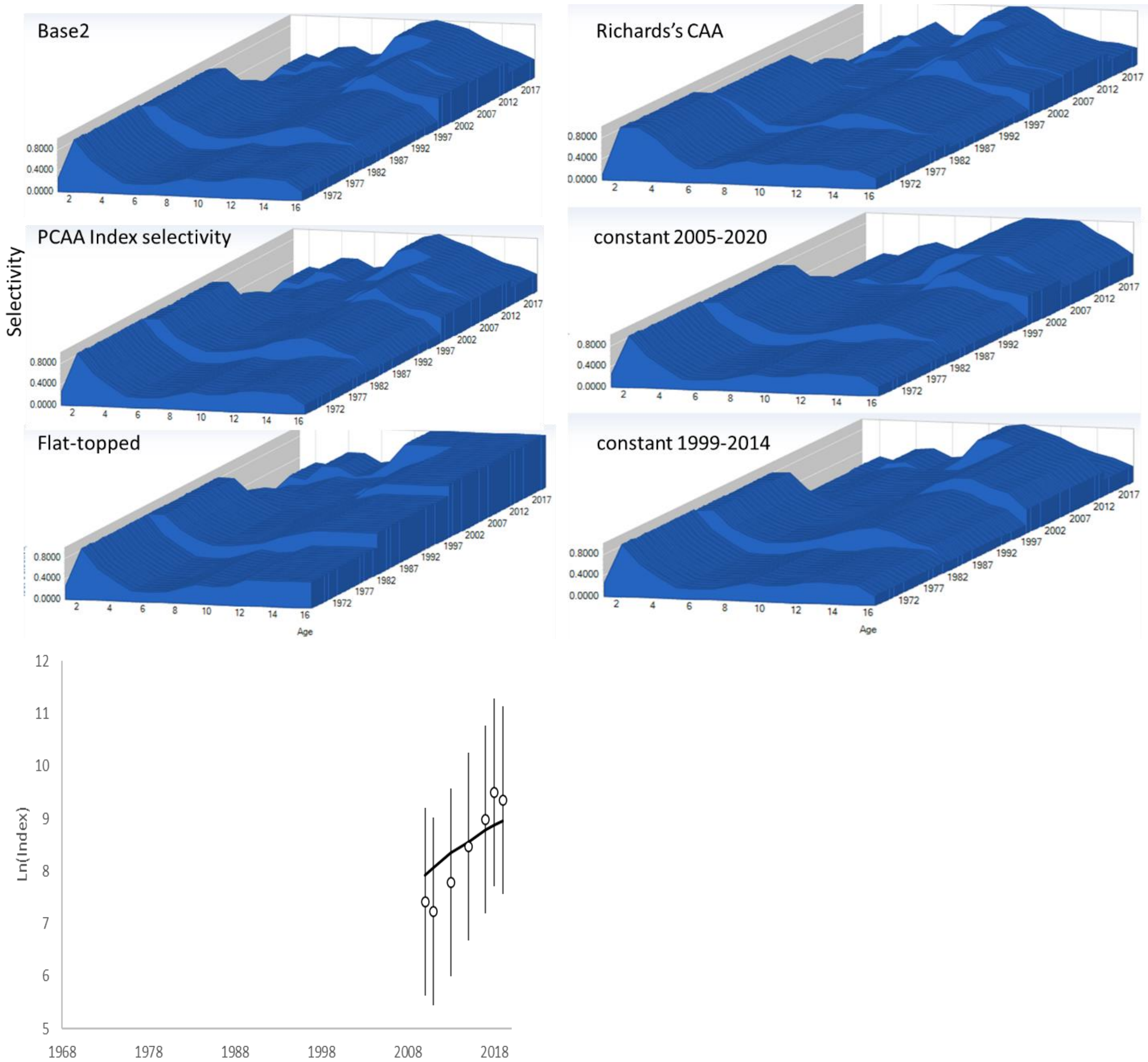

Figure 16. Selectivity estimates from single-fleet ASAP sensitivity runs (top panels) and sensitivity run fit to the Western Mediterranean GBYP Aerial survey (WMedGBYPAerial, bottom panel) with stock index predictions (bold line) and observed values (circles with confidence limits).

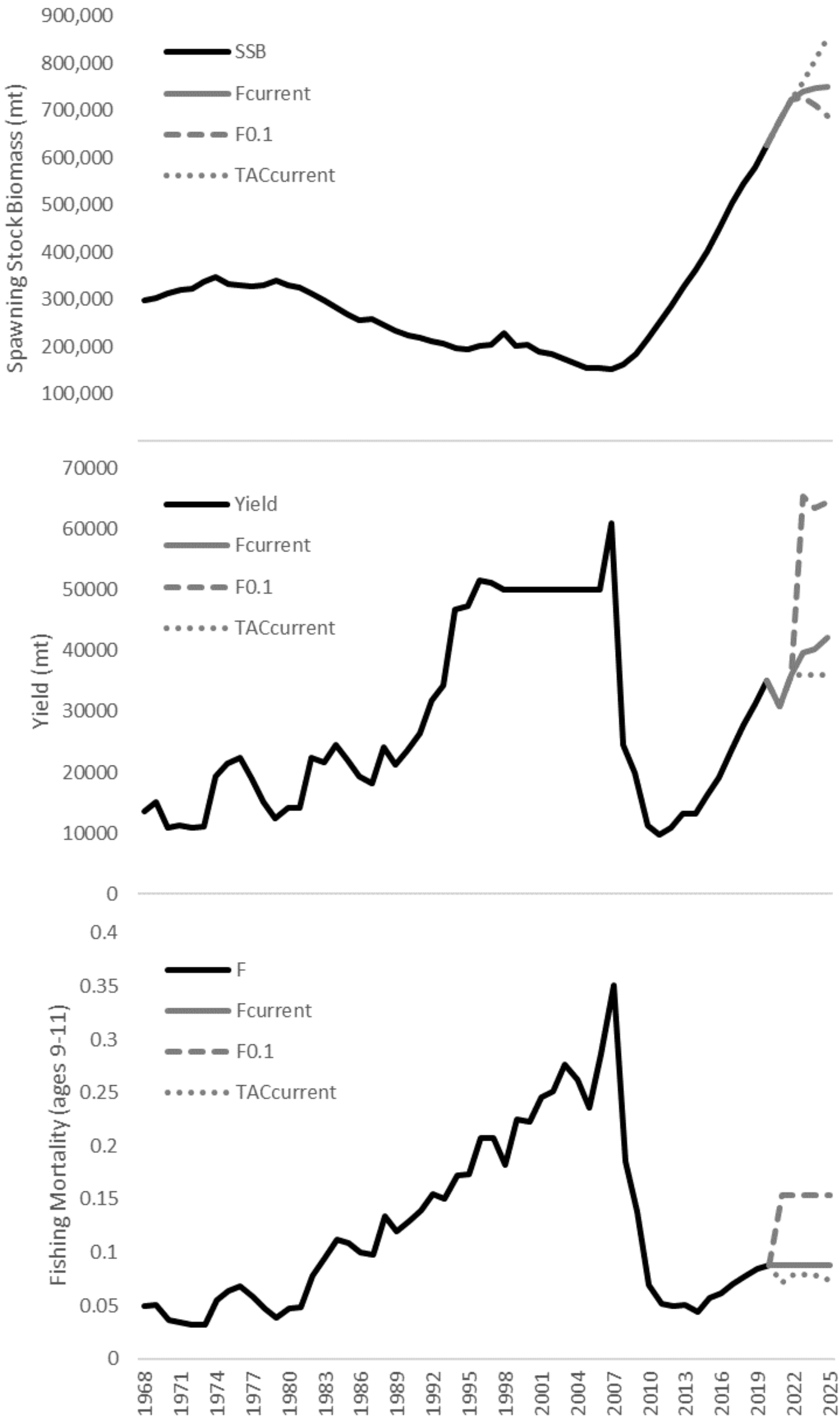

Figure 17. Estimates (black line) and projected values (grey lines) of SSB (top), yield (middle), and fishing mortality (bottom), with alternative projections at the current fishing mortality (Fcurrent), the current TAC (TACcurrent) and $F_{0.1}$ from the single-fleet ASAP application to Eastern Atlantic and Mediterranean Atlantic Bluefin tuna base run 2.

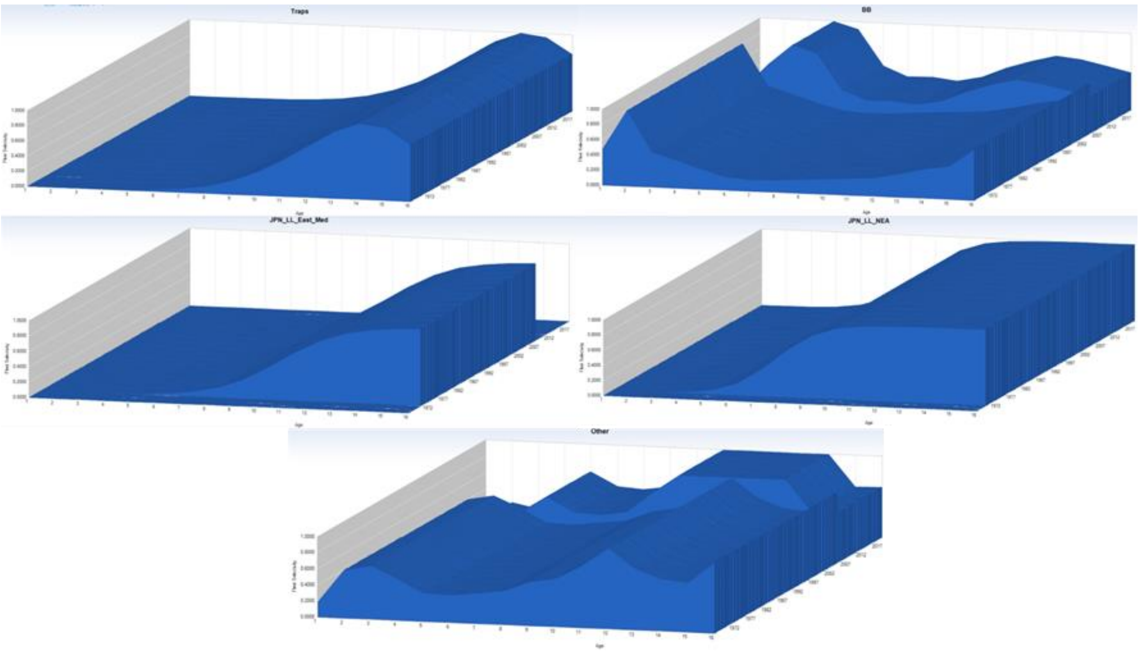

Figure 18. Selectivity estimates from five-fleet ASAP application to Eastern Atlantic and Mediterranean Atlantic Bluefin tuna showing the trap fleet (top left), Spanish baitboat (top right), JPN_LL_EastMed (middle left), JPN_LL_NEA (middle right) and the composite "other" fleet (bottom).

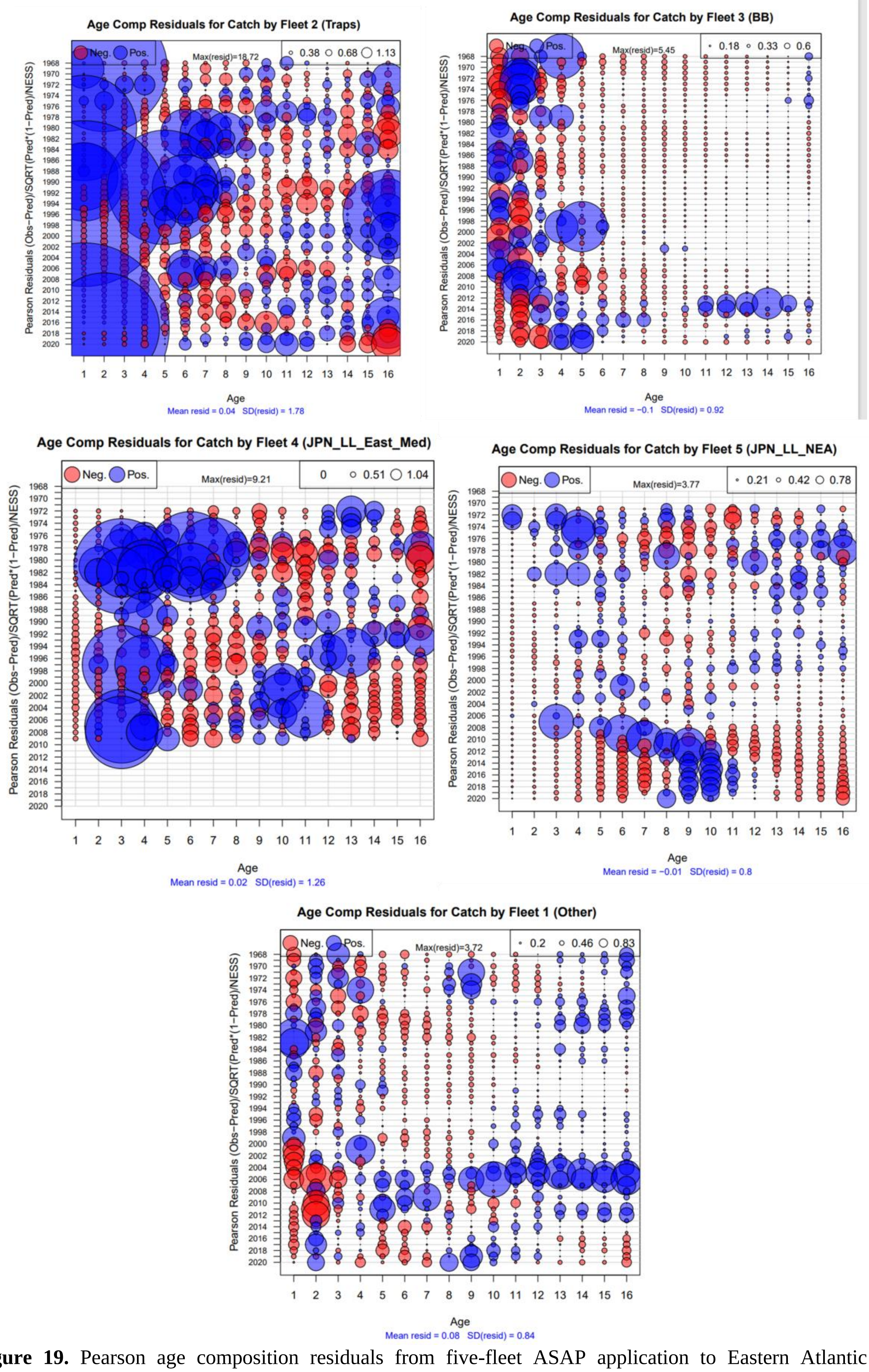

Figure 19. Pearson age composition residuals from five-fleet ASAP application to Eastern Atlantic and Mediterranean Atlantic Bluefin tuna showing the trap fleet (top left), Spanish baitboat (top right), JPN_LL_EastMed (middle left), JPN_LL_NEA (middle right) and the composite “other” fleet (bottom).

Figure 20. Retrospective estimates of SSB (top) and age 11-13 fishing mortality (bottom) from five-fleet ASAP application to Eastern Atlantic and Mediterranean Atlantic Bluefin tuna.

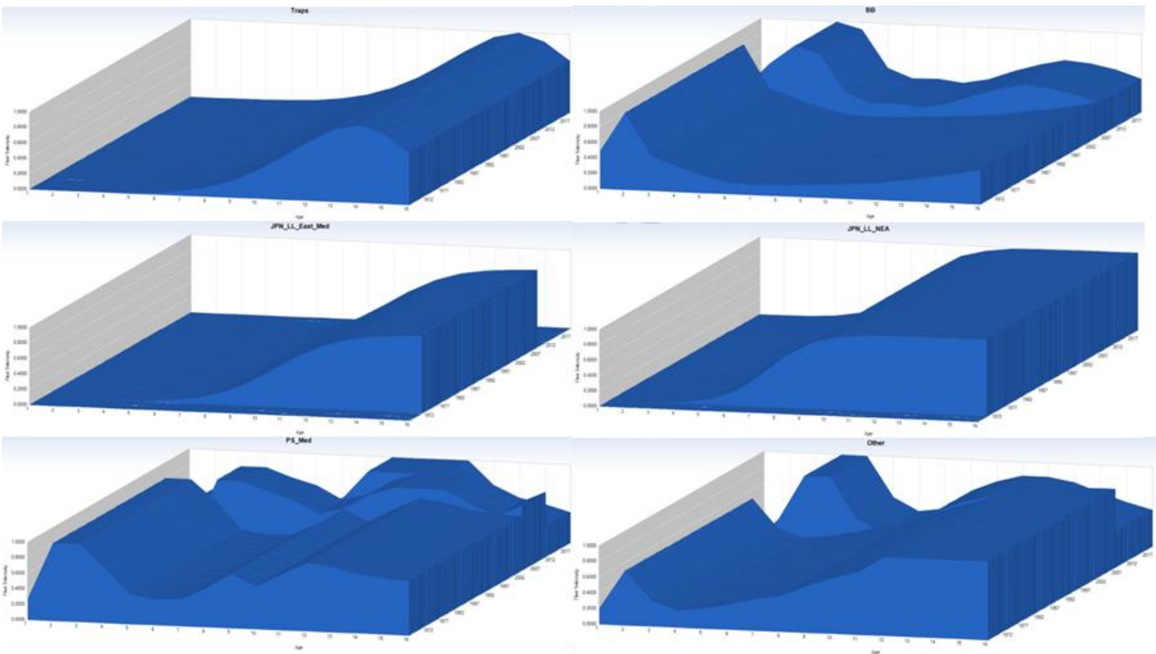

Figure 21. Selectivity estimates from six-fleet ASAP application to Eastern Atlantic and Mediterranean Atlantic Bluefin tuna showing the trap fleet (top left), Spanish baitboat (top right), JPN_LL_EastMed (middle left), JPN_LL_NEA (middle right), Mediterranean purse-seine (bottom left), and the composite “other” fleet (bottom right).

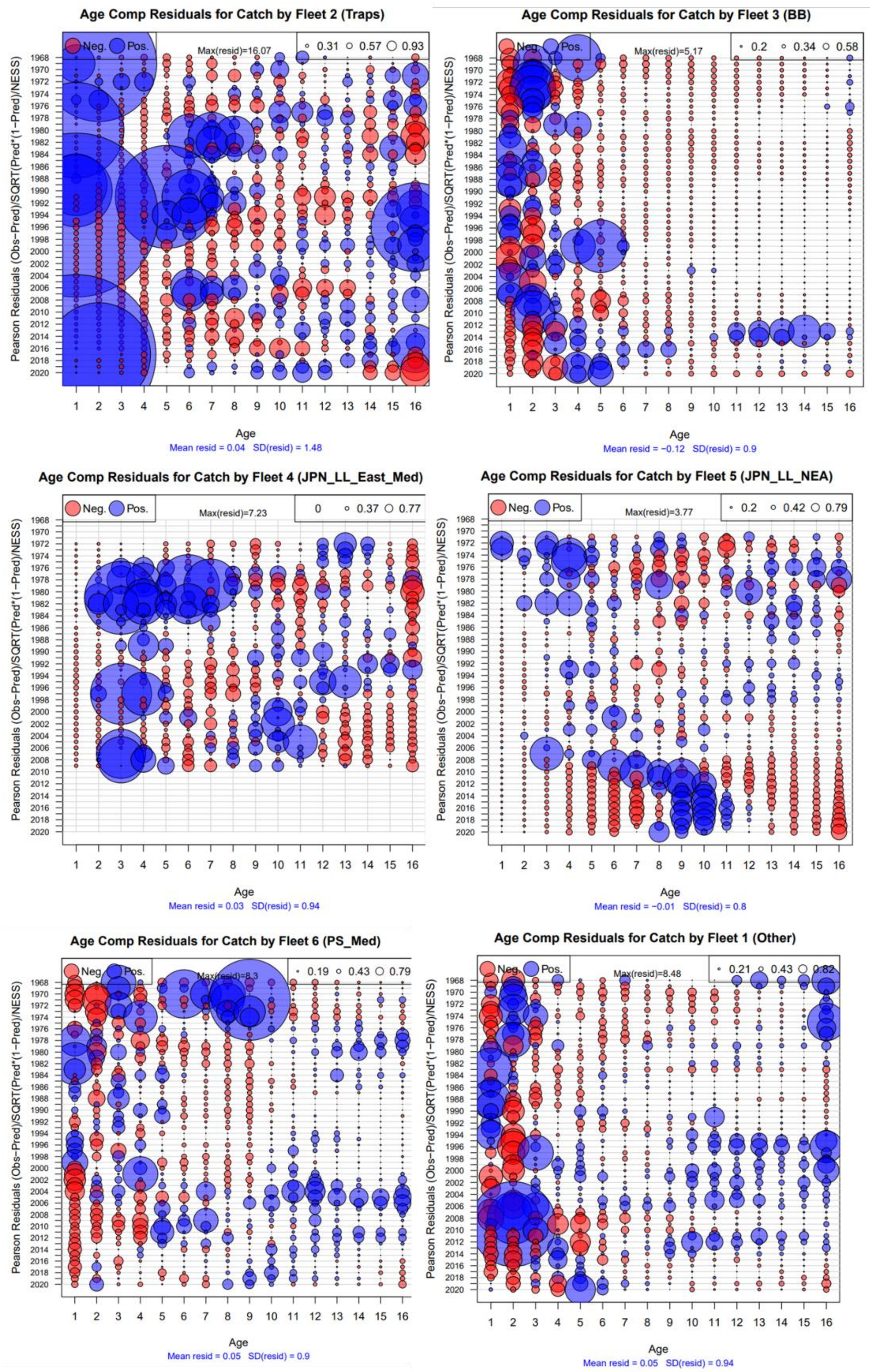

Figure 22. Pearson age composition residuals from six-fleet ASAP application to Eastern Atlantic and Mediterranean Atlantic Bluefin tuna showing the trap fleet (top left), Spanish baitboat (top right), JPN_LL_EastMed (middle left), JPN_LL_NEA (middle right), Mediterranean purse-seine (bottom left), and the composite “other” fleet (bottom right).

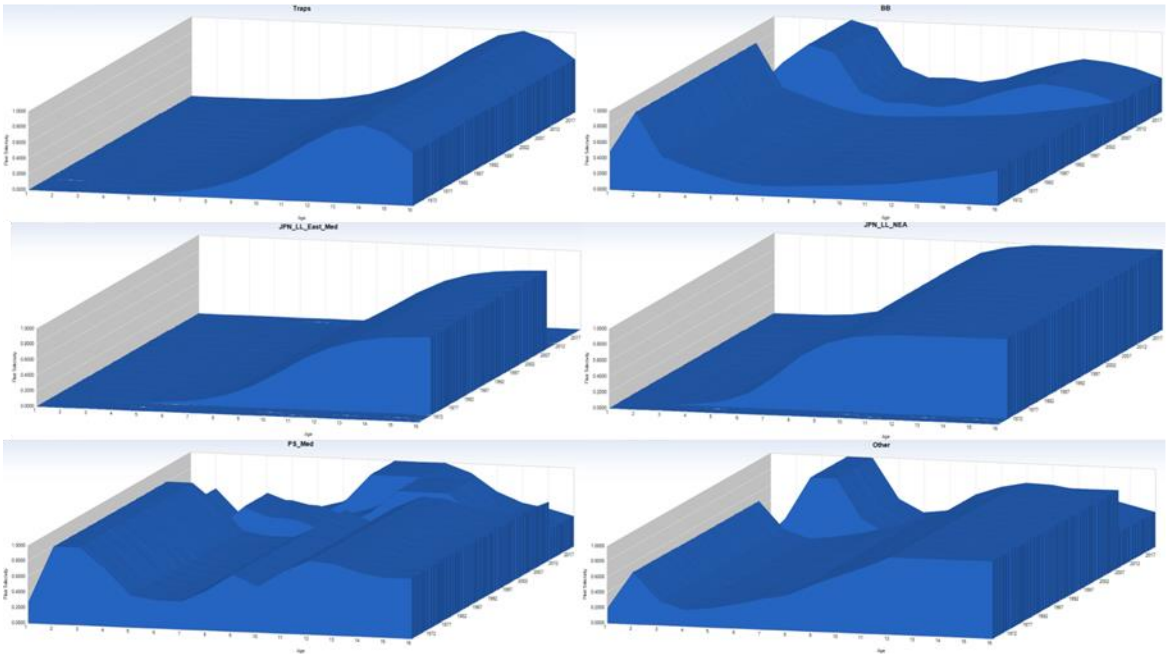

Figure 23. Selectivity estimates from six-fleet (revised data) ASAP application to Eastern Atlantic and Mediterranean Atlantic Bluefin tuna showing the trap fleet (top left), Spanish baitboat (top right), JPN_LL_EastMed (middle left), JPN_LL_NEA (middle right), Mediterranean purse-seine (bottom left), and the composite "other" fleet (bottom right).

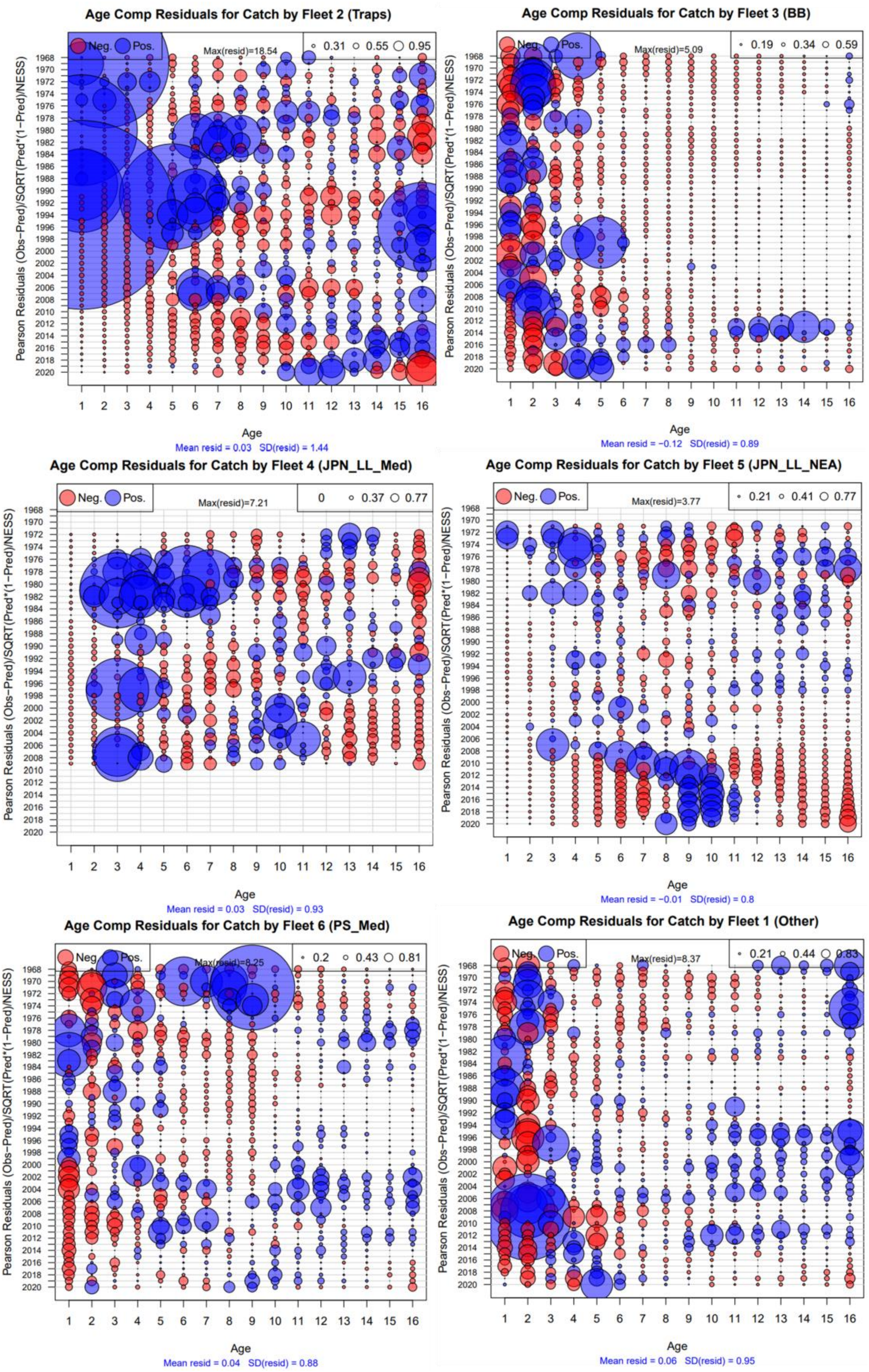

Figure 24. Pearson age composition residuals from six-fleet (revised data) ASAP application to Eastern Atlantic and Mediterranean Atlantic Bluefin tuna showing the trap fleet (top left), Spanish baitboat (top right), JPN_LL_EastMed (middle left), JPN_LL_NEA (middle right), Mediterranean purse-seine (bottom left), and the composite "other" fleet (bottom right).

Figure 25. Retrospective estimates of SSB (top) and age 11-13 fishing mortality (bottom) from six-fleet ASAP application (revised data) to Eastern Atlantic and Mediterranean Atlantic Bluefin tuna.

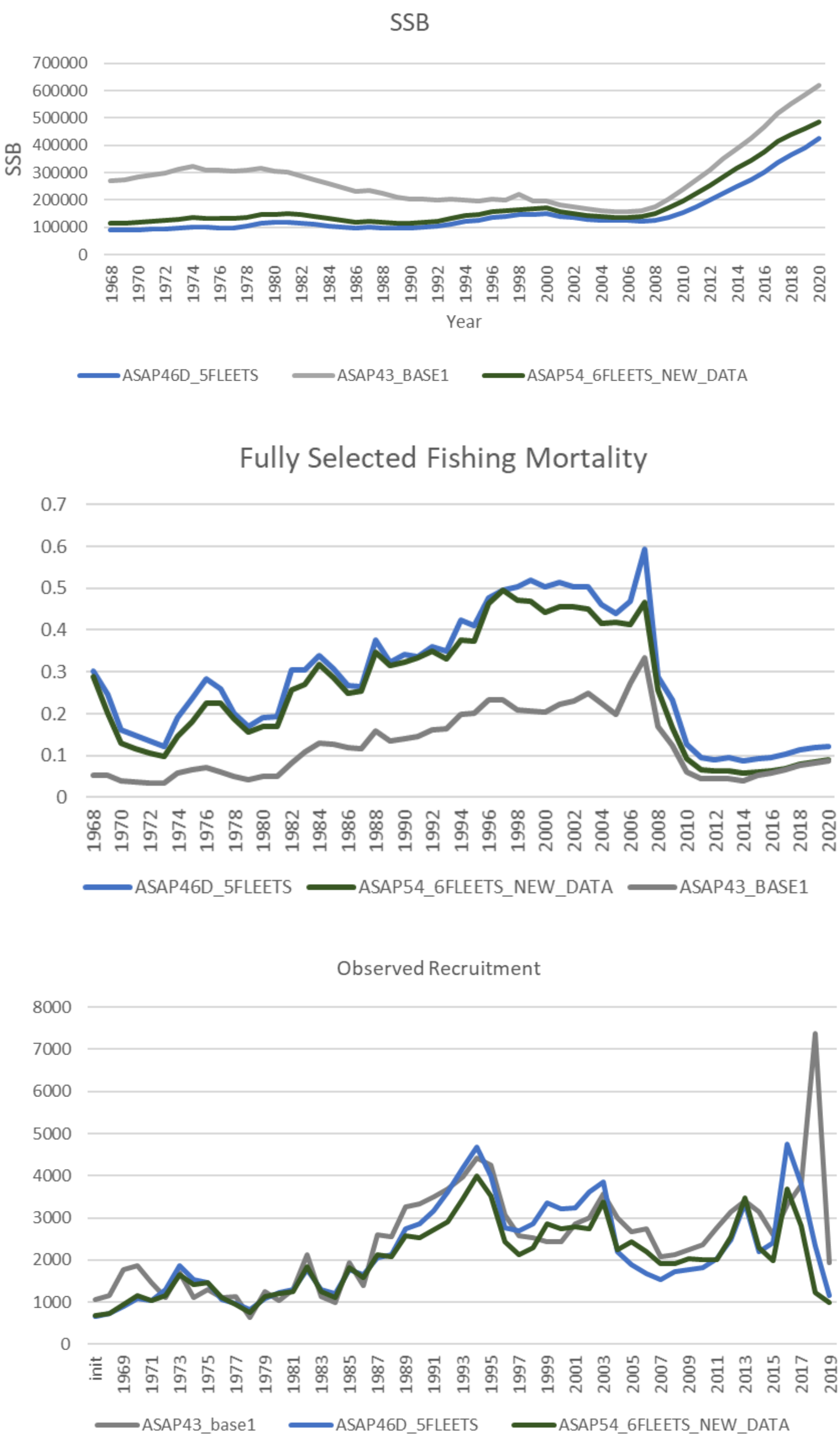

Figure 26. Model estimates of SSB (top) and fully-selected fishing mortality (middle), and recruitment (bottom) for the single-fleet base 1 (gray line), five-fleet (blue line), and six-fleet (revised data; green line) ASAP applications to Eastern Atlantic and Mediterranean Atlantic Bluefin tuna.

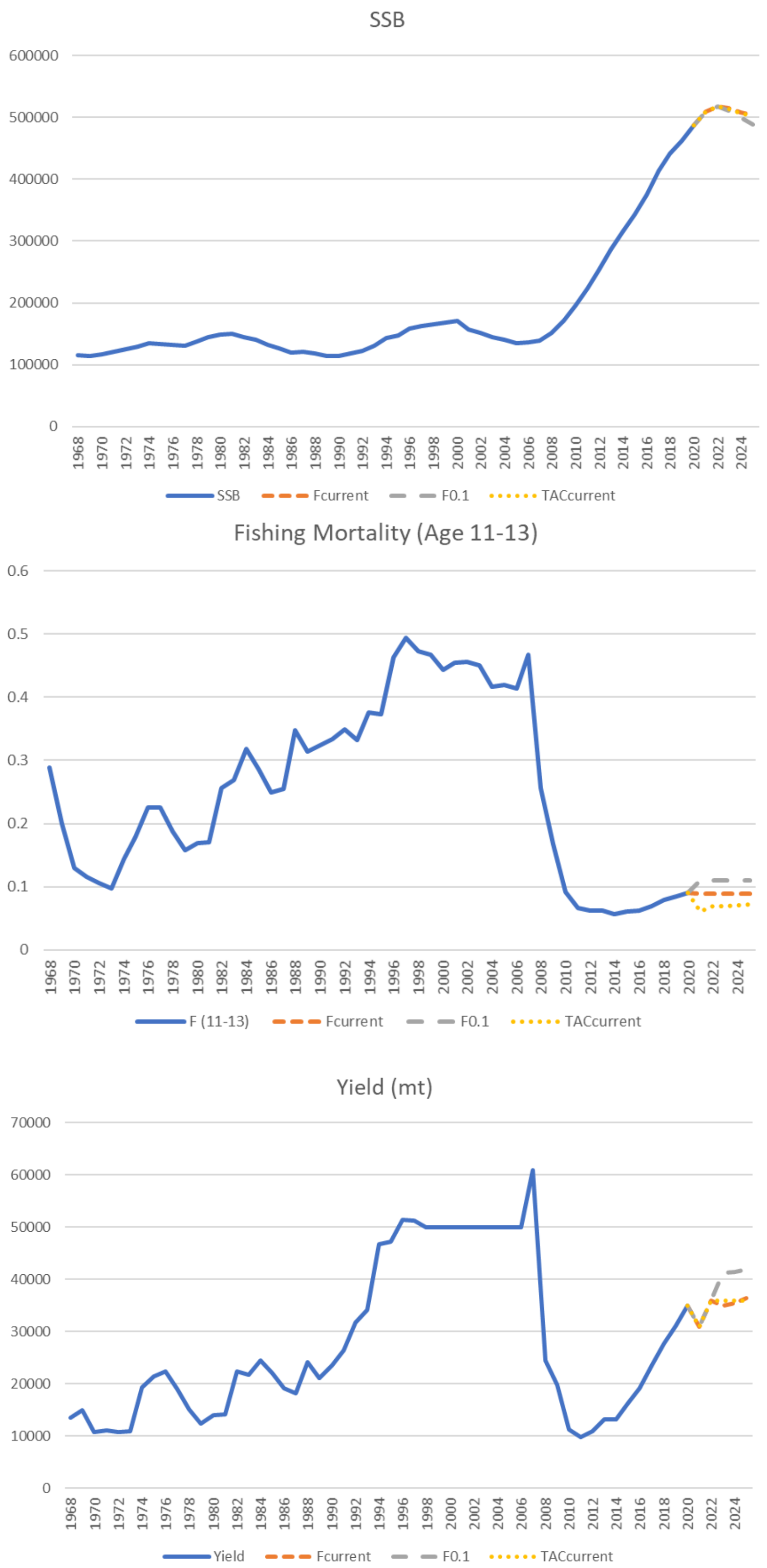

Figure 27. Estimates (solid line) and projected values (broken lines) of SSB (top), yield (middle), and fishing mortality (bottom), with alternative projections at the current fishing mortality (Fcurrent), the current TAC (TACcurrent) and $F_{0.1}$ from the six-fleet (revised data) ASAP application to Eastern Atlantic and Mediterranean Atlantic Bluefin tuna base run 2.

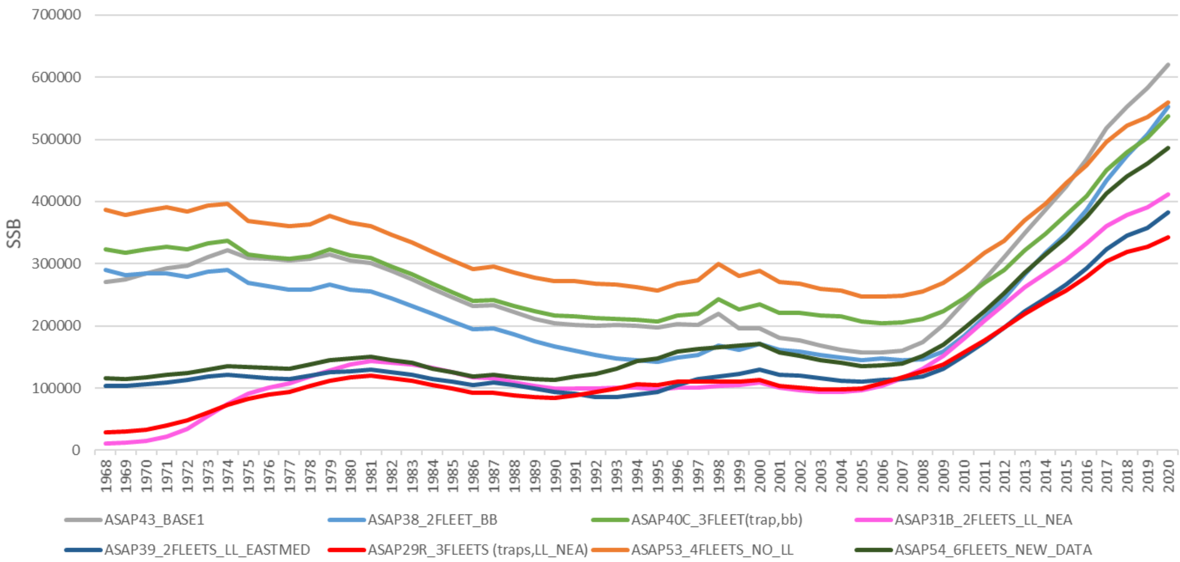

Figure 28. Provisional estimates of SSB from multi-fleet ASAP applications to Eastern Atlantic and Mediterranean Atlantic Bluefin tuna.