WEST ATLANTIC BLUEFIN TUNA VIRTUAL POPULATION ANALYSIS

M. Lauretta[1], A. Kimoto [2], T. Rouyer[3], M. Ortiz[2], and J. Walter[1]

SUMMARY

This report documents the 2021 assessment of the West Atlantic bluefin tuna using virtual population analysis. The SCRS Bluefin Tuna Species Group reviewed the assessment data inputs and work plan via webinar during April 5-13, 2021. We present the base model diagnostics and results, including time series estimates of spawning stock biomass (both young and older spawning scenarios) for the period 1974 to 2020, and recruitment for the period 1974 to 2017. Model diagnostics indicate some problems with the updated model including a severe trend in the residuals for some indices and a strong retrospective bias.

RÉSUMÉ

Le présent rapport documente l'évaluation de 2021 du thon rouge de l'Atlantique Ouest au moyen de l'analyse de la population virtuelle. Le Groupe d'espèces sur le thon rouge du SCRS a examiné les données d'évaluation et le plan de travail lors d'un webinaire organisé du 5 au 13 avril 2021. Nous présentons les diagnostics et les résultats du cas de base du modèle, y compris les estimations des séries temporelles de la biomasse du stock reproducteur (scénarios de frai des jeunes et des adultes) pour la période de 1974 à 2020, et du recrutement pour la période de 1974 à 2017. Les diagnostics du modèle font état de quelques problèmes en ce qui concerne le modèle mis à jour, notamment une tendance prononcée des valeurs résiduelles pour certains indices et un fort biais rétrospectif.

RESUMEN

Este informe documenta la evaluación de 2021 del atún rojo del Atlántico oeste en la que se utilizó un análisis de población virtual. El Grupo de especies de atún rojo del SCRS revisó las entradas de datos de la evaluación y el plan de trabajo a través de un seminario web durante los días 5 a 13 de abril de 2021. Se presentan los diagnósticos y resultados del modelo del caso base, lo que incluye las estimaciones de las series temporales de la biomasa del stock reproductor (tanto de los escenarios de desove joven como de mayor edad) para el periodo de 1974 a 2020, y el reclutamiento para el periodo de 1974 a 2017. Los diagnósticos del modelo indican algunos problemas con el modelo actualizado, lo que incluye una tendencia marcada en los residuos para algunos índices y un fuerte sesgo retrospectivo.

KEYWORDS

Stock assessment, bluefin tuna, West Atlantic

[1] NOAA Fisheries, Southeast Fisheries Science Center, Sustainable Fisheries Division, 75 Virginia Beach Drive, Miami, FL, 33149-1099, USA. E-mail: matthew.lauretta@noaa.gov
[2] ICCAT Secretariat, C/Corazon de Marıa, 8, 28002, Madrid, Spain
[3] IFREMER, UMR MARBEC, Sète, France
MARBEC, Univ Montpellier, CNRS, IFREMER, IRD, Sète, France

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1. Introduction

The stock assessment of West Atlantic bluefin tuna (WBFT) applied a virtual population analysis (VPA) as one of two principal models for estimating fishery status and providing catch advice. The assessment modeled bluefin tuna abundance and fishery status in the West Atlantic stock area (i.e. mixed stocks as opposed to stock-of-origin estimates), evidenced by extensive information on stock mixing of East Atlantic bluefin tuna into the West Atlantic. The most recent WBFT benchmark assessment occurred in 2017, and the model was subsequently updated in 2020. The Bluefin Tuna Species Group (Group) of the Standing Committee on Research and Statistics (SCRS) evaluated bluefin tuna biological knowledge, available datasets, and data processing methods to select a base model parameterization for revising the VPA in 2021. This report summarizes the VPA data inputs, assumptions, provisional results, and diagnostics for written documentation of the 2021 revisions.

2. VPA Methods

SCRS Reports 2017-15 and 2017-16 (reports available here: https://www.iccat.int/en/Meetings.asp) document the methods of the 2017 benchmark assessment. SCRS Report 2020-15 summarizes the 2020 assessment update. A description of data inputs and provisional runs are presented in the following section.

2.1 VPA update methods overview

Prior to the 2021 assessment workshop, CPC analysts and ICCAT Secretariat staff compiled the indices of abundance (**Table 1**, **Figure 1**), updated the total catches-at-size (**Figure 2**), and estimated total catches-at-age (**Table 2**, **Figure 3**). The Group reviewed the indices of abundance during the intersessional Bluefin Tuna Data Preparatory Meeting, held online (April 5-13, 2021). Total catch-at-size and catch-at-age estimates closely matched the 2020 base model inputs, and included two years of additional data, 2019 and 2020 (**Figure 3**).

The assessment team then implemented the following updates to the 2020 VPA of WBFT:

- RUN0, Continuity run: Updated the 2020 VPA with the catch-at-age, partial catch-at-age and indices of abundance (the same indices and methods of indices construction as used in 2020 were applied, with 2 additional years of data added), up to and including 2020
- Corrected partial-catch-at-age of the Gulf of St Lawrence acoustic survey partial-catch-at-age (data filter correction)
- RUN 1: Replaced the US rod and reel juveniles indices (66 to 114cm and 115 to 144cm) with the combined sizeclass (66 to 144cm) index
- RUN 2: Replaced the US longline index from the Gulf of Mexico with the joint Mexico-US (MEXUS) longline index
- RUN 3: Ended the random walk on the Japan longline catchability in year 2014
- RUN 4: Included the Canada (SWNS and GSL) and US handline (US RR>177cm) indices
- RUN 5: Increased the standard deviation on vulnerability linking the terminal three years (0.5 increased to 0.6)
- RUN 6: Turned off handline indices (GSL handline, SWNS handline, and US rod and reel >177cm indices)

Base model configuration summary:

- Model years ranged 1974 to 2020
- Catch-at-age (CAA) derived by cohort slicing the total catch-at-size (CAS) estimates (provided by the Secretariat) using the Richards growth model (Ailloud *et al.* 2017)
- A plusgroup included ages 16 and older
- Natural mortality assumed a weight-based Lorenzen model scaled to equal 0.1 at age 20:

Age1 M = 0.38, Age2 M = 0.30, Age3 M = 0.24, Age4 M = 0.20, Age5 M = 0.18, Age6 M = 0.16, Age7 M = 0.14, Age8 M = 0.13, Age9 M = 0.12, Age10 M = 0.12, Age11 M = 0.11, Age12 M = 0.11, Age13 M = 0.11, Age 14+ M = 0.10

- Two alternative spawning-at-age scenarios:

Age	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16+
Young spawn	0	0	0.3	0.5	1	1	1	1	1	1	1	1	1	1	1	1
Older spawn	0	0	0	0	0	0	0	0	0.2	0.6	0.9	1	1	1	1	1

- Fisheries-dependent indices of abundance included:
  - US rod and reel <145 cm, 1980-1992
  - US rod and reel 66 to 144 cm, 1995-2020
  - US rod and reel >195 cm, 1983-1992
  - MEXUS longline Gulf of Mexico, 1994-2019
  - Japan longline Gulf of Mexico, 1974-1981
  - Japan longline early (Area 2 West), 1976-2009
  - Japan longline recent, 2010-2020
- Fisheries-independent surveys included:
  - Gulf of St Lawrence acoustic survey, 1994-2017
  - Gulf of Mexico larval survey, 1977-2019
- Index variance settings: input CV weighting of fishery-dependent indices of abundance with estimated additive variance parameters; input CVs for fishery-independent indices of abundance with a minimum annual value of 0.3 and zero additive variance
- Random-walk estimation of Japanese longline annual selectivity and catchability during 2010 to 2014
- F-ratio (annual F of plusgroup/F of age 15) set equal to 1.0
- No constraints on recruitment or spawn-recruitment relationship
- Vulnerability linked in the terminal three years, sd of penalty = 0.6 (continuity was 0.5)

The team outlined the following sensitivity analyses for model diagnostics, consistent with the previous assessment and 2021 work plan:

- jitter analysis of model random seed and parameter starting values
- an index of abundance jackknife where each index series was iteratively removed from the VPA
- a retrospective analysis to evaluate the effects of successively removing the five most recent years of data
- F-ratio parameter profiling
- Non-parametric bootstrap of the relative abundance data (each iteration replaced the index series with random draws sampled from the index residual model fits)

Using the model configuration described above, the analysts constructed a base model. They posted the data, parameter, and control files for the base models (young and older spawning assumptions), as well as diagnostic and sensitivity runs outlined above, to the assessment cloud-based server during August 2021.

2.2 VPA general specifications

The oldest age class represented a plus group of ages 16 and older combined. The fishing mortality rate on that age was specified as the product of the fishing mortality rate on the next younger age (F_{15}) and the 'F-ratio' parameter (the ratio of F_{16} to F_{15}). For the 2017 and 2020 base models, the F-ratio was fixed equal to 1.0 for the entire period. Analysts maintained this assumption in the update, as specified in the 2021 work plan.

The fishing mortality rates for each age in the last year of the VPA (except the oldest age) were estimated as free parameters, but subject to a constraint restricting the amount of change in the vulnerability pattern during the terminal three years with a standard deviation of 0.6 (see SCRS/2008/089 for more details).

The indices of abundance were fitted assuming a lognormal error structure and input CV weighting (i.e., the coefficient of variation estimated from each index standardization model). Additive variance coefficients were estimated by fleet/gear group (i.e. CAN handline, US handline, US longline, and JPN longline), for fishery dependent indices of abundance. No additive variances were applied to fishery independent surveys, however, a minimum annual CV of 0.3 was used. The catchability coefficients for each index, with exception of the Japan longline index, were assumed constant over the series duration, and estimated by the corresponding likelihood formula. A random walk of Japan longline recent period selectivity was applied to allow for cohort targeting for the period 2010 to 2014, consistent with the 2017 and 2020 base models. The catchability of the JPN LL fleet was assumed constant since 2014.

3. VPA Diagnostics

Jittering the VPA random number seed (random uniform number drawn between 1 and 999 each iteration) and starting F parameter values (random uniform number drawn between 0.001 and 3.9 separately for ages 1 to 15 each iteration) showed consistent solutions near a minimum negative log-likelihood near -9.1 (**Figure 4**). Recruitment estimates plotted by jitter iterations showed consistent long-term magnitude and trend (**Figure 5**). Model fits to the indices are shown in **Figure 6**. Model residuals (**Figure 7**) displayed a general random pattern for most data series, with exception of a lack-of-fit to the US Rod and Reel 66 to 144cm index, the JPN LL for the period prior to 2010, and the JPN LL Gulf of Mexico historical index. The trend in residuals for the US Rod and Reel 66 to 144cm index are particularly poor (Figure 7) and indicate a fairly substantial conflict between this index and the remaining information in the model.

Model sensitivities included 1) a run that included the Canada (GSL and SWNS handlines) and US (Rod and reel > 177cm) handline indices, 2) a jack-knife analysis removing individual index time series one-at-a-time, 3) five-year retrospective analysis, and 4) profiling of plusgroup F-ratio (time-invariant). In the first sensitivity, the model residuals of the handline indices showed a cyclical pattern (**Figure 8**), with Canada indices opposite in trend to the US rod and reel >177cm index. This temporal trends in residuals were similar to that observed in the 2017 assessment, which led to exclusion of the Canadian and US>177cm handline indices from the model. That decision was retained in the following runs and proposed base model.

The index jack-knife demonstrated sensitivity of current spawning stock biomass to U.S. rod and reel 66-144cm index, followed by the Gulf of Mexico larval survey and Gulf of St. Lawrence acoustic survey (**Figure 9**); the jack-knife also demonstrated high sensitivity in recruitment estimates to the US RR 66-144cm index. Estimates were less sensitive to the other fishery dependent indices of abundance due to the additive variance estimation and considerably higher overall variance compared to the fishery independent surveys. The difference in recruitment estimates across jack-knife runs further highlighted the divergent recruitment signal for the period post-2005.

The retrospective analysis indicated stable absolute scale and long-term trends in recruitment and spawning stock biomass (**Figure 10**) prior to 2005, but with high bias in the recent recruitment and level of stock rebuilding over the last decade across retrospective peels (Mohn's rho <-0.3 for recruitment estimates). Likelihood profiling of different F-ratios (**Figure 11**) provided evidence in favor of a slightly higher F-ratio than the value assumed in the base model (base model F-ratio=1.0), i.e. model information content increased at higher mortality rates of ages 16+ compared to age 15. Changes in the F-ratio assumption affected the scale of recruitment estimates, with higher F-ratios resulting in lower recruitments. The Group decided to maintain the F-ratio value of 1.0 for continuity with the previous assessments, consistent with the terms of reference.

4. VPA Results

Time series estimates of abundance from the continuity run mirrored the magnitude and trend of the prior assessment for the period prior to 2005. However, the estimates diverged notably for the terminal 15 years of the model (**Figure 12**). The continuity run demonstrated that added data (i.e. 2019 and 2020 catches-at-age and indices) significantly affected the recent recruitment and current biomass estimates. Stepwise model building from the continuity to the base indicated the replacement of the two US rod and reel juvenile indices (66-114 and 115-144cm) with a combined index (66-144cm) resulted in the largest effect on estimates of recruitment (**Figure 13**). The other changes to the model had relatively smaller effects in comparison to the data updates and the change in juvenile index. The base model estimated a similar trend in recent recruitment but at higher values compared to the continuity model, with a steady increasing trend in spawning stock biomass (**Figure 14**).

Recruitment estimates over the historical period showed consistent trends to the previous assessments, including relatively high recruitment events in 1974, 1975 and 2004 (1973, 1974, and 2003 yearclasses), as well as the lowest recruitments estimated for 2011 and 2014 (2010 and 2013 yearclasses). These high and low recruitments perpetuated clear trends of peaks and valleys in time series of abundances-at-age (**Figure 15**). Estimates of the recent recruitment (post-2005) diverged considerably from the last assessment. In particular, the model did not indicate a long-term decline over the last 15 years. In addition, above average recruitments were estimated for the most recent two-years (2016 and 2017).

Estimates of recent fishing mortality (**Table 4, Figure 16**) trended steadily downward, and were lower during the terminal year than historically for most ages. Apical fishing mortality (maximum annual F-at-age) showed the lowest rates currently compared to the entire time series (**Figure 17**). Relatively higher fishing mortality occurred on ages 9 and older compared to younger ages, but with an annual decrease observed between 2015 and 2020 for the oldest ages (**Figure 18**). The bootstrap distribution of current F (mean of 2017 to 2019 apical fishing mortality) ranged approximately from 0.05 to 0.11 (**Figure 19**), with a median equal to approximately 0.07.

Recruitment estimates showed relatively high inter-annual variability over the last 15 years (**Table 5, Figure 20**), with terminal year estimates notably higher than the preceding years. The increase in spawning biomass during the last two decades (**Table 5, Figure 21**) reflected the high recruitment events in 2004, 2009, 2010, 2013, 2015, and 2016. The estimates of spawning biomass in 2020 were of similar magnitude to the estimates at the start of the model time series. The paired spawner-recruitment estimates showed a scattered pattern, similar to estimates in previous assessments (**Figure 22**).

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References

Ailloud, L.E., Lauretta, M.V., Hoenig, J.M., Hanke, A.R., Golet, W.J., Allman, R., and Siskey, M.R. 2017. Improving growth estimates for western Atlantic Bluefin tuna using an integrated modeling approach. Fish. Res. 191: 17-24.

Table 1. Indices of relative abundance of bluefin tuna in the West Atlantic and Gulf of Mexico used in the VPA.

Series	USRR_66144		USRR>177cm		USRR<145cm		USRR>195cm		MEXUS LL		GOM Larval Su		JPN LL1		JPN LL2		JPN LL GOM		CAN Acoustic s		CAN GSL HL		CAN SWNS HL	
Year	Index	CV	Index	CV	Index	CV	Index	CV	Index	CV	Index	CV	Index	CV	Index	CV	Index	CV	Index	CV	Index	CV	Index	CV
1974	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.97	0.27	-	-	-	-	-	-
1975	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.53	0.21	-	-	-	-	-	-
1976	-	-	-	-	-	-	-	-	-	-	-	-	0.38	0.44	-	-	0.67	0.21	-	-	-	-	-	-
1977	-	-	-	-	-	-	-	-	-	-	2.45	0.46	0.97	0.34	-	-	0.91	0.22	-	-	-	-	-	-
1978	-	-	-	-	-	-	-	-	-	-	4.49	0.24	0.78	0.37	-	-	0.88	0.23	-	-	-	-	-	-
1979	-	-	-	-	-	-	-	-	-	-	-	-	0.83	0.31	-	-	1.29	0.28	-	-	-	-	-	-
1980	-	-	-	-	0.8	0.43	-	-	-	-	-	-	1.48	0.31	-	-	1.16	0.27	-	-	-	-	-	-
1981	-	-	-	-	0.4	0.52	-	-	-	-	0.79	0.44	1.21	0.29	-	-	0.55	0.24	-	-	-	-	-	-
1982	-	-	-	-	2.1	0.33	-	-	-	-	1.3	0.29	0.84	0.3	-	-	-	-	-	-	-	-	-	-
1983	-	-	-	-	1.11	0.26	2.81	0.1	-	-	1.08	0.34	0.49	0.37	-	-	-	-	-	-	-	-	-	-
1984	-	-	-	-	-	-	1.25	0.19	-	-	0.37	0.54	0.73	0.32	-	-	-	-	-	-	-	-	-	-
1985	-	-	-	-	0.63	0.64	0.86	0.3	-	-	-	-	0.91	0.29	-	-	-	-	-	-	-	-	-	-
1986	-	-	-	-	0.78	0.43	0.5	1.1	-	-	0.37	0.43	0.01	1.75	-	-	-	-	-	-	-	-	-	-
1987	-	-	-	-	1.22	0.4	0.53	0.48	-	-	0.31	0.48	0.41	0.36	-	-	-	-	-	-	-	-	-	-
1988	-	-	-	-	0.99	0.38	0.94	0.36	-	-	1.14	0.32	0.36	0.41	-	-	-	-	-	-	0.03	0.34	-	-
1989	-	-	-	-	0.99	0.43	0.76	0.36	-	-	0.75	0.37	0.74	0.33	-	-	-	-	-	-	0.03	0.35	-	-
1990	-	-	-	-	0.9	0.34	0.63	0.34	-	-	0.32	0.34	0.51	0.35	-	-	-	-	-	-	0.01	0.32	-	-
1991	-	-	-	-	1.26	0.35	0.82	0.28	-	-	0.37	0.57	0.63	0.33	-	-	-	-	-	-	0.01	0.39	-	-
1992	-	-	-	-	0.82	0.42	0.91	0.28	-	-	0.45	0.35	1.12	0.29	-	-	-	-	-	-	0.06	0.26	-	-
1993	-	-	0.53	0.13	-	-	-	-	-	-	0.45	0.65	1.06	0.3	-	-	-	-	-	-	0.1	0.2	-	-
1994	-	-	0.61	0.17	-	-	-	-	0.89	0.3	0.58	0.33	0.98	0.29	-	-	-	-	0.03	0.28	0.04	0.22	-	-
1995	1.24	0.12	1.66	0.27	-	-	-	-	0.43	0.28	0.26	0.55	0.67	0.37	-	-	-	-	0.03	0.14	0.12	0.18	-	-
1996	1.33	0.12	2.74	0.31	-	-	-	-	0.78	0.19	0.8	0.49	2.32	0.3	-	-	-	-	0.07	0.1	0.02	0.19	1.01	0.34
1997	1.97	0.1	1.17	0.21	-	-	-	-	0.22	0.53	0.33	0.38	1.71	0.29	-	-	-	-	0.04	0.12	0.02	0.19	0.75	0.34
1998	0.95	0.1	1.58	0.26	-	-	-	-	0.76	0.28	0.12	0.53	0.79	0.32	-	-	-	-	0.04	0.21	0.03	0.18	0.97	0.34
1999	0.89	0.17	1.56	0.25	-	-	-	-	0.44	0.25	0.46	0.49	1.16	0.29	-	-	-	-	0.04	0.12	0.05	0.18	1.2	0.36
2000	1.14	0.18	0.97	0.18	-	-	-	-	2.31	0.15	0.27	0.52	1.14	0.3	-	-	-	-	0.02	0.14	0.04	0.17	0.65	0.36
2001	0.76	0.11	2	0.29	-	-	-	-	0.95	0.18	0.41	0.32	0.95	0.3	-	-	-	-	0.04	0.15	0.04	0.18	0.81	0.33
2002	1.07	0.15	1.88	0.23	-	-	-	-	1.41	0.17	0.24	0.63	0.85	0.31	-	-	-	-	0.02	0.19	0.07	0.16	0.78	0.29
2003	0.66	0.09	0.54	0.15	-	-	-	-	1.16	0.15	0.72	0.38	1.28	0.32	-	-	-	-	0.04	0.14	0.08	0.16	0.85	0.31
2004	1.61	0.09	0.31	0.14	-	-	-	-	0.58	0.17	0.5	0.67	1.18	0.33	-	-	-	-	0.04	0.07	0.15	0.15	1.2	0.29
2005	1.57	0.11	0.41	0.16	-	-	-	-	0.55	0.16	0.18	0.29	1.1	0.29	-	-	-	-	0.05	0.05	0.12	0.15	1.21	0.3
2006	0.72	0.16	0.26	0.16	-	-	-	-	0.79	0.16	0.54	0.36	1.6	0.32	-	-	-	-	0.06	0.07	0.11	0.14	1.44	0.29
2007	0.7	0.09	0.27	0.14	-	-	-	-	0.5	0.15	0.44	0.37	0.95	0.44	-	-	-	-	0.04	0.13	0.18	0.15	1.29	0.29
2008	0.68	0.1	0.25	0.14	-	-	-	-	0.83	0.14	0.34	0.38	1.42	0.47	-	-	-	-	0.03	0.08	0.15	0.14	1.36	0.29
2009	0.55	0.12	0.29	0.14	-	-	-	-	0.7	0.14	0.57	0.32	2.4	0.38	-	-	-	-	0.06	0.09	0.22	0.14	2.3	0.29
2010	0.87	0.1	0.62	0.18	-	-	-	-	0.51	0.15	0.31	0.52	-	-	0.18	0.41	-	-	0.07	0.04	0.27	0.17	2.14	0.29
2011	0.77	0.12	0.74	0.18	-	-	-	-	0.94	0.16	1.04	0.39	-	-	0.64	0.29	-	-	0.05	0.08	0.19	0.15	1.79	0.29
2012	0.85	0.13	0.54	0.18	-	-	-	-	1.5	0.13	0.29	0.48	-	-	0.82	0.29	-	-	0.1	0.07	0.25	0.15	1.74	0.29
2013	1.31	0.13	0.39	0.14	-	-	-	-	0.73	0.14	1.05	0.35	-	-	0.65	0.29	-	-	0.06	0.06	0.24	0.15	1.31	0.3
2014	0.8	0.15	0.45	0.15	-	-	-	-	1.28	0.14	0.26	0.37	-	-	0.69	0.31	-	-	0.08	0.06	0.24	0.15	1.48	0.31
2015	0.39	0.14	0.8	0.19	-	-	-	-	1.88	0.13	0.38	0.3	-	-	0.45	0.29	-	-	0.08	0.1	0.2	0.14	1.48	0.3
2016	0.58	0.15	1.07	0.22	-	-	-	-	1.58	0.13	2.35	0.26	-	-	1.04	0.32	-	-	0.09	0.01	0.25	0.15	1.91	0.32
2017	0.95	0.14	1.54	0.27	-	-	-	-	1.17	0.15	0.99	0.29	-	-	1.11	0.34	-	-	0.05	0.01	0.22	0.15	1.94	0.31
2018	0.69	0.16	1.54	0.27	-	-	-	-	1.47	0.14	2.07	0.24	-	-	2.15	0.32	-	-	-	-	0.23	0.15	1.66	0.3
2019	1.26	0.13	1.76	0.3	-	-	-	-	1.62	0.14	1.59	0.29	-	-	1.88	0.31	-	-	-	-	0.24	0.15	1.94	0.3
2020	1.7	0.15	1.5	0.27	-	-	-	-	-	-	-	-	-	-	1.38	0.34	-	-	-	-	0.22	0.21	2.28	0.33

Table 2. Total catch-at-age estimates (in numbers of fish) of bluefin tuna in the West Atlantic.

Year	Age1	Age2	Age3	Age4	Age5	Age6	Age7	Age8	Age9	Age10	Age11	Age12	Age13	Age14	Age15	Age16
1974	55308	75711	1124	8430	2431	149	677	660	1975	1681	1711	701	1348	1685	1712	5592
1975	35540	154198	6787	18397	4959	212	51	288	919	1232	1237	1122	1741	1455	1123	3317
1976	8142	35472	56881	18979	3770	1651	164	297	666	634	1137	2018	2608	1818	1867	4692
1977	1124	17522	11287	18561	30915	3675	2997	414	312	367	529	742	2011	1882	1924	7818
1978	2021	9634	13353	18337	11148	9538	1179	553	450	351	446	587	1307	1092	1506	7774
1979	2148	4739	13367	15475	17152	2722	4621	1858	604	516	568	1152	1918	1479	1877	7002
1980	3480	9732	14048	10043	8728	2467	4139	6087	2111	665	667	621	718	1077	1162	6691
1981	6891	5572	25807	886	10073	4902	2545	2302	3275	1771	1142	1011	807	857	957	6006
1982	3637	2421	3093	1343	377	594	697	497	668	830	789	396	181	189	156	2159
1983	3876	1889	2249	2071	1488	1343	1517	1606	1364	843	1007	815	657	452	299	2541
1984	554	5049	3418	2239	4512	2697	1174	572	860	972	899	968	732	597	329	1533
1985	482	4261	8317	7189	4478	4843	2886	812	564	608	777	1039	1021	817	627	1517
1986	582	5518	8910	3535	6462	2654	1713	1602	756	503	520	716	648	624	450	1278
1987	1385	12118	10915	6860	7266	4562	1654	1363	1133	637	473	607	485	523	381	1088
1988	5675	4847	14914	6402	4998	4595	3901	2084	1517	945	654	676	506	523	404	1381
1989	673	5248	9080	2046	4753	1985	2826	3011	1552	1205	1010	805	583	549	396	1472
1990	1513	2968	19122	6091	3409	3255	1732	2124	2223	1024	848	647	476	539	354	1334
1991	1022	4978	22367	3891	3111	1995	2582	2411	2297	1668	1024	734	551	519	331	1008
1992	42	2045	6319	1026	2055	1831	1568	2420	1531	1266	1259	893	479	466	305	1103
1993	226	628	1392	6264	3677	1761	2630	1973	2858	1216	761	502	351	341	229	1194
1994	1017	1706	837	2081	3502	2349	1710	3315	1842	1378	868	534	310	275	189	916
1995	450	643	2555	5080	4625	3968	1183	1657	2167	1306	746	571	368	391	228	1424
1996	256	4110	7838	4184	4555	2991	1869	2206	1020	1443	1047	731	492	496	331	1218
1997	152	377	4665	3866	1916	1793	1679	2728	1765	878	902	828	567	544	283	1251
1998	219	489	2877	4512	1968	1521	1740	3277	2956	1681	898	802	656	452	249	1152
1999	35	413	997	2403	3586	2244	2163	2106	2024	2492	1775	838	499	439	273	1079
2000	54	240	860	602	2093	4088	1865	1993	2175	1507	1473	1079	734	449	326	1450
2001	1042	686	1011	5062	2631	1684	3143	2720	890	1393	1352	1241	840	657	360	1159
2002	5	4165	5749	4324	7388	2637	2305	4190	2448	1240	1083	1096	955	801	413	1139
2003	79	1257	3931	5443	2794	1779	552	1956	2340	1182	574	622	609	643	289	1142
2004	13	1728	5070	6217	3625	2452	2672	1377	1364	1222	625	474	393	309	204	1125
2005	400	4721	2721	3597	1298	826	856	1197	954	1156	1087	686	420	302	203	1090
2006	88	250	1451	1133	3277	1691	1155	1285	1286	965	803	514	482	408	235	1167
2007	58	76	986	15160	2814	2478	1380	918	542	499	400	335	287	224	153	859
2008	66	212	1379	2194	8242	1471	2142	1514	1092	823	426	307	370	261	188	1171
2009	25	81	1141	2212	1465	5871	1526	1372	1337	945	521	440	477	332	273	1058
2010	30	524	991	1694	1670	824	1615	1655	1352	1476	755	500	536	390	287	999
2011	0	92	683	2893	1729	2291	1096	4324	1275	819	797	587	394	325	240	920
2012	46	167	1050	2169	1036	815	837	1455	2163	1362	560	577	416	356	268	867
2013	9	155	300	1259	564	585	511	1363	819	1357	1048	531	407	290	190	826
2014	10	572	709	1038	534	658	209	659	1210	1268	1198	948	609	361	202	801
2015	0	2	657	948	423	342	631	887	720	1332	1317	1013	732	535	327	1065
2016	0	9	492	2317	1055	256	334	1587	1393	1307	1100	1063	695	494	269	847
2017	12	1118	1191	1261	741	893	66	1121	1699	1528	963	849	677	479	324	895
2018	10	888	948	1001	586	772	181	1109	1946	1891	1187	1002	715	508	312	869
2019	0	49	2071	2404	1464	203	1277	1463	920	1896	1744	1220	813	527	371	1017
2020	40	2694	3953	767	563	1165	427	1253	1562	1037	1266	1171	902	633	407	1152

Table 3. VPA estimated abundances-at-age of bluefin tuna in the West Atlantic. Estimates are numbers of fish at beginning of the year.

Year	Age1	Age2	Age3	Age4	Age5	Age6	Age7	Age8	Age9	Age10	Age11	Age12	Age13	Age14	Age15	Age16
1974	651059	331454	94063	54628	20059	11411	12054	17735	20115	24845	20112	18862	21228	14462	10584	34572
1975	328528	399924	181115	72999	37134	14540	9587	9849	14955	15984	20454	16400	16235	17742	11485	33924
1976	232637	195580	165928	136470	43237	26502	12195	8287	8378	12400	13018	17154	13631	12898	14671	36871
1977	187709	152407	114649	80674	94635	32679	21062	10449	6998	6805	10401	10587	13460	9749	9944	40408
1978	126960	127443	97935	80222	49364	51014	24464	15524	8788	5914	5690	8818	8783	10159	7035	36316
1979	179509	85163	86169	65263	49196	31101	34702	20170	13114	7371	4915	4676	7344	6633	8155	30421
1980	140785	120995	59033	56001	39524	25548	23995	25871	15974	11063	6052	3866	3102	4770	4599	26481
1981	126609	93420	81310	34084	36811	25080	19499	17014	17035	12183	9186	4791	2877	2101	3294	20675
1982	187132	80931	64438	41324	27106	21602	16865	14584	12788	12034	9142	7150	3338	1816	1090	15088
1983	177499	124985	57881	47955	32621	22296	17860	14013	12341	10713	9892	7444	6031	2819	1464	12440
1984	157342	118202	90972	43543	37393	25890	17763	14115	10803	9664	8709	7910	5898	4782	2122	9886
1985	183845	107145	83242	68540	33629	27124	19579	14349	11859	8773	7657	6952	6172	4592	3760	9097
1986	169628	125328	75726	58139	49635	24012	18660	14338	11840	9987	7209	6125	5247	4564	3380	9598
1987	175974	115523	88120	51706	44411	35574	18018	14628	11092	9790	8385	5966	4811	4088	3538	10102
1988	183236	119203	75224	59689	36153	30483	26116	14125	11570	8773	8084	7064	4771	3851	3202	10946
1989	191529	120649	84157	46044	43098	25647	21748	19077	10456	8836	6892	6624	5690	3796	2988	11107
1990	188742	130427	84884	58187	35850	31669	20027	16279	13938	7815	6705	5220	5173	4546	2914	10979
1991	141382	127830	94079	49951	42149	26838	23989	15799	12309	10273	5969	5205	4065	4184	3601	10967
1992	127248	95846	90435	54336	37387	32370	21033	18453	11619	8760	7545	4380	3969	3121	3293	11910
1993	106024	86985	69252	65557	43560	29354	25897	16825	13941	8867	6579	5570	3081	3103	2382	12419
1994	128633	72320	63901	53245	48025	33033	23392	20066	12930	9682	6721	5175	4515	2428	2484	12040
1995	165170	87131	52114	49526	41715	36922	25985	18744	14523	9737	7292	5201	4131	3752	1936	12093
1996	114316	112583	63997	38736	35969	30630	27810	21489	14909	10844	7408	5827	4120	3353	3023	11125
1997	92716	77965	79883	43427	27943	25896	23347	22437	16806	12264	8262	5648	4530	3226	2563	11331
1998	133636	63280	57435	58717	32069	21593	20415	18734	17151	13247	10051	6549	4277	3522	2402	11115
1999	101338	91208	46459	42637	44003	24992	16999	16129	13389	12435	10169	8156	5109	3212	2758	10899
2000	122076	69272	67215	35664	32740	33486	19230	12767	12194	9973	8689	7434	6514	4105	2490	11073
2001	143850	83439	51112	52112	28656	25439	24773	14983	9348	8772	7429	6393	5640	5142	3288	10586
2002	148741	97517	61225	39312	38102	21538	20126	18613	10615	7454	6471	5379	4556	4259	4029	11111
2003	156978	101714	68675	43086	28289	25106	15926	15353	12432	7117	5446	4775	3784	3180	3094	12224
2004	265083	107286	74274	50548	30371	21083	19755	13332	11652	8829	5202	4337	3690	2815	2267	12501
2005	169223	181269	77998	53947	35783	22066	15709	14690	10419	9053	6682	4070	3437	2934	2253	12100
2006	187668	115396	130243	58950	40923	28704	18042	12860	11779	8343	6943	4959	2998	2682	2368	11759
2007	149663	128267	85273	101169	47241	31195	22902	14610	10090	9238	6493	5461	3957	2230	2040	11451
2008	181372	102301	94957	66206	69177	36893	24300	18626	11970	8439	7724	5438	4575	3274	1805	11245
2009	214373	123979	75604	73476	52224	50275	30083	19132	14939	9590	6711	6517	4582	3749	2714	10518
2010	190283	146580	91776	58463	58160	42285	37437	24732	15516	11992	7617	5520	5422	3654	3077	10709
2011	99078	130103	108140	71316	46336	47056	35273	31043	20168	12490	9249	6110	4472	4351	2935	11253
2012	128577	67755	96303	84462	55778	37126	37988	29645	23216	16689	10308	7532	4919	3634	3628	11736
2013	193569	87891	50051	74826	67193	45644	30885	32245	24669	18557	13521	8705	6202	4013	2950	12824
2014	56316	132366	64978	39106	60126	55609	38356	26375	27039	21109	15183	11122	7296	5171	3356	13307
2015	198731	38504	97569	50486	31080	49734	46781	33151	22543	22843	17529	12469	9067	5960	4336	14123
2016	237280	135903	28523	76169	40478	25574	42065	40081	28279	19316	19007	14458	10212	7431	4885	15381
2017	309959	162265	100671	22002	60270	32848	21557	36258	33710	23771	15903	15987	11947	8492	6254	17276
2018		211958	119250	78137	16875	49666	27168	18679	30789	28300	19646	13336	13519	10063	7228	20133
2019			156262	92966	63069	13561	41611	23450	15364	25477	23321	16477	10999	11435	8622	23636
2020				121088	73944	51345	11369	34985	19222	12762	20813	19243	13608	9085	9846	27868

Table 4. Estimated fishing mortality-at-age of bluefin tuna in the West Atlantic.

Year	Age1	Age2	Age3	Age4	Age5	Age6	Age7	Age8	Age9	Age10	Age11	Age12	Age13	Age14	Age15	Age16
1974	0.11	0.30	0.01	0.19	0.14	0.01	0.06	0.04	0.11	0.07	0.09	0.04	0.07	0.13	0.19	0.19
1975	0.14	0.58	0.04	0.32	0.16	0.02	0.01	0.03	0.07	0.09	0.07	0.08	0.12	0.09	0.11	0.11
1976	0.04	0.23	0.48	0.17	0.10	0.07	0.02	0.04	0.09	0.06	0.10	0.13	0.23	0.16	0.14	0.14
1977	0.01	0.14	0.12	0.29	0.44	0.13	0.17	0.04	0.05	0.06	0.06	0.08	0.17	0.23	0.23	0.23
1978	0.02	0.09	0.17	0.29	0.28	0.23	0.05	0.04	0.06	0.07	0.09	0.07	0.17	0.12	0.25	0.25
1979	0.01	0.07	0.19	0.30	0.48	0.10	0.15	0.10	0.05	0.08	0.13	0.30	0.32	0.27	0.28	0.28
1980	0.03	0.10	0.31	0.22	0.28	0.11	0.20	0.29	0.15	0.07	0.12	0.19	0.28	0.27	0.31	0.31
1981	0.07	0.07	0.44	0.03	0.35	0.24	0.15	0.16	0.23	0.17	0.14	0.25	0.35	0.56	0.36	0.36
1982	0.02	0.04	0.06	0.04	0.02	0.03	0.05	0.04	0.06	0.08	0.10	0.06	0.06	0.12	0.16	0.16
1983	0.03	0.02	0.05	0.05	0.05	0.07	0.10	0.13	0.13	0.09	0.11	0.12	0.12	0.18	0.24	0.24
1984	0.00	0.05	0.04	0.06	0.14	0.12	0.07	0.04	0.09	0.11	0.12	0.14	0.14	0.14	0.18	0.18
1985	0.00	0.05	0.12	0.12	0.16	0.21	0.17	0.06	0.05	0.08	0.11	0.17	0.19	0.21	0.19	0.19
1986	0.00	0.05	0.14	0.07	0.15	0.13	0.10	0.13	0.07	0.06	0.08	0.13	0.14	0.16	0.15	0.15
1987	0.01	0.13	0.15	0.16	0.20	0.15	0.10	0.11	0.12	0.07	0.06	0.11	0.11	0.14	0.12	0.12
1988	0.04	0.05	0.25	0.13	0.16	0.18	0.17	0.17	0.15	0.12	0.09	0.11	0.12	0.15	0.14	0.14
1989	0.00	0.05	0.13	0.05	0.13	0.09	0.15	0.18	0.17	0.16	0.17	0.14	0.11	0.17	0.15	0.15
1990	0.01	0.03	0.29	0.12	0.11	0.12	0.10	0.15	0.19	0.15	0.14	0.14	0.10	0.13	0.14	0.14
1991	0.01	0.05	0.31	0.09	0.08	0.08	0.12	0.18	0.22	0.19	0.20	0.16	0.15	0.14	0.10	0.10
1992	0.00	0.03	0.08	0.02	0.06	0.06	0.08	0.15	0.15	0.17	0.19	0.24	0.14	0.17	0.10	0.10
1993	0.00	0.01	0.02	0.11	0.10	0.07	0.12	0.13	0.25	0.16	0.13	0.10	0.13	0.12	0.11	0.11
1994	0.01	0.03	0.02	0.04	0.08	0.08	0.08	0.19	0.16	0.16	0.15	0.12	0.08	0.13	0.08	0.08
1995	0.00	0.01	0.06	0.12	0.13	0.12	0.05	0.10	0.17	0.15	0.11	0.12	0.10	0.12	0.13	0.13
1996	0.00	0.04	0.15	0.13	0.15	0.11	0.08	0.12	0.08	0.15	0.16	0.14	0.14	0.17	0.12	0.12
1997	0.00	0.01	0.07	0.10	0.08	0.08	0.08	0.14	0.12	0.08	0.12	0.17	0.14	0.20	0.12	0.12
1998	0.00	0.01	0.06	0.09	0.07	0.08	0.10	0.21	0.20	0.14	0.10	0.14	0.18	0.15	0.12	0.12
1999	0.00	0.01	0.02	0.06	0.09	0.10	0.15	0.15	0.18	0.24	0.20	0.12	0.11	0.16	0.11	0.11
2000	0.00	0.00	0.01	0.02	0.07	0.14	0.11	0.18	0.21	0.17	0.20	0.17	0.13	0.12	0.15	0.15
2001	0.01	0.01	0.02	0.11	0.11	0.07	0.15	0.22	0.11	0.18	0.21	0.23	0.17	0.14	0.12	0.12
2002	0.00	0.05	0.11	0.13	0.24	0.14	0.13	0.27	0.28	0.19	0.19	0.24	0.25	0.22	0.11	0.11
2003	0.00	0.01	0.07	0.15	0.11	0.08	0.04	0.15	0.22	0.19	0.12	0.15	0.19	0.24	0.10	0.10
2004	0.00	0.02	0.08	0.15	0.14	0.13	0.16	0.12	0.13	0.16	0.14	0.12	0.12	0.12	0.10	0.10
2005	0.00	0.03	0.04	0.08	0.04	0.04	0.06	0.09	0.10	0.15	0.19	0.20	0.14	0.11	0.10	0.10
2006	0.00	0.00	0.01	0.02	0.09	0.07	0.07	0.11	0.12	0.13	0.13	0.12	0.19	0.17	0.11	0.11
2007	0.00	0.00	0.01	0.18	0.07	0.09	0.07	0.07	0.06	0.06	0.07	0.07	0.08	0.11	0.08	0.08
2008	0.00	0.00	0.02	0.04	0.14	0.04	0.10	0.09	0.10	0.11	0.06	0.06	0.09	0.09	0.12	0.12
2009	0.00	0.00	0.02	0.03	0.03	0.14	0.06	0.08	0.10	0.11	0.09	0.07	0.12	0.10	0.11	0.11
2010	0.00	0.00	0.01	0.03	0.03	0.02	0.05	0.07	0.10	0.14	0.11	0.10	0.11	0.12	0.10	0.10
2011	0.00	0.00	0.01	0.05	0.04	0.05	0.03	0.16	0.07	0.07	0.10	0.11	0.10	0.08	0.09	0.09
2012	0.00	0.00	0.01	0.03	0.02	0.02	0.02	0.05	0.10	0.09	0.06	0.08	0.09	0.11	0.08	0.08
2013	0.00	0.00	0.01	0.02	0.01	0.01	0.02	0.05	0.04	0.08	0.09	0.07	0.07	0.08	0.07	0.07
2014	0.00	0.01	0.01	0.03	0.01	0.01	0.01	0.03	0.05	0.07	0.09	0.09	0.09	0.08	0.07	0.07
2015	0.00	0.00	0.01	0.02	0.02	0.01	0.02	0.03	0.03	0.06	0.08	0.09	0.09	0.10	0.08	0.08
2016	0.00	0.00	0.02	0.03	0.03	0.01	0.01	0.04	0.05	0.07	0.06	0.08	0.08	0.07	0.06	0.06
2017	0.00	0.01	0.01	0.07	0.01	0.03	0.00	0.03	0.06	0.07	0.07	0.06	0.06	0.06	0.06	0.06
2018	0.00	0.01	0.01	0.01	0.04	0.02	0.01	0.07	0.07	0.07	0.07	0.08	0.06	0.05	0.05	0.05
2019	0.00	0.00	0.02	0.03	0.03	0.02	0.03	0.07	0.07	0.08	0.08	0.08	0.08	0.05	0.05	0.05
2020	0.00	0.00	0.05	0.01	0.01	0.03	0.04	0.04	0.09	0.09	0.07	0.07	0.07	0.08	0.04	0.04

Table 5. VPA estimates of bluefin tuna spawning stock biomass and recruitment in the West Atlantic.

Year	SSB (young_spawn)	SSB (older_spawn)	Recruitment (Age 1)
1974	39698	29924	651059
1975	36492	28387	328528
1976	34753	26752	232637
1977	31807	23357	187709
1978	29197	19816	126960
1979	25967	16212	179509
1980	22761	13088	140785
1981	19770	11397	126609
1982	18378	10381	187132
1983	18189	10235	177499
1984	17996	9964	157342
1985	16661	9320	183845
1986	17935	9349	169628
1987	18188	9507	175974
1988	18071	9616	183236
1989	18001	9404	191529
1990	17840	9115	188742
1991	18376	9119	141382
1992	18055	8953	127248
1993	18437	8949	106024
1994	18285	9035	128633
1995	19431	9321	165170
1996	19295	9396	114316
1997	19228	9614	92716
1998	19190	10055	133636
1999	19425	10522	101338
2000	18557	10501	122076
2001	18043	9873	143850
2002	16860	9243	148741
2003	16462	8705	156978
2004	15729	8543	265083
2005	15772	8547	169223
2006	16706	8514	187668
2007	18099	8866	149663
2008	20750	9304	181372
2009	21410	9410	214373
2010	23057	9783	190283
2011	24161	10466	99078
2012	26902	11730	128577
2013	28859	13326	193569
2014	31707	15173	56316
2015	33427	17015	198731
2016	35089	18738	237280
2017	36255	20556	309959
2018	37115	22809	-
2019	38490	24501	-
2020	40370	25303	-

Indices of Relative Abundance

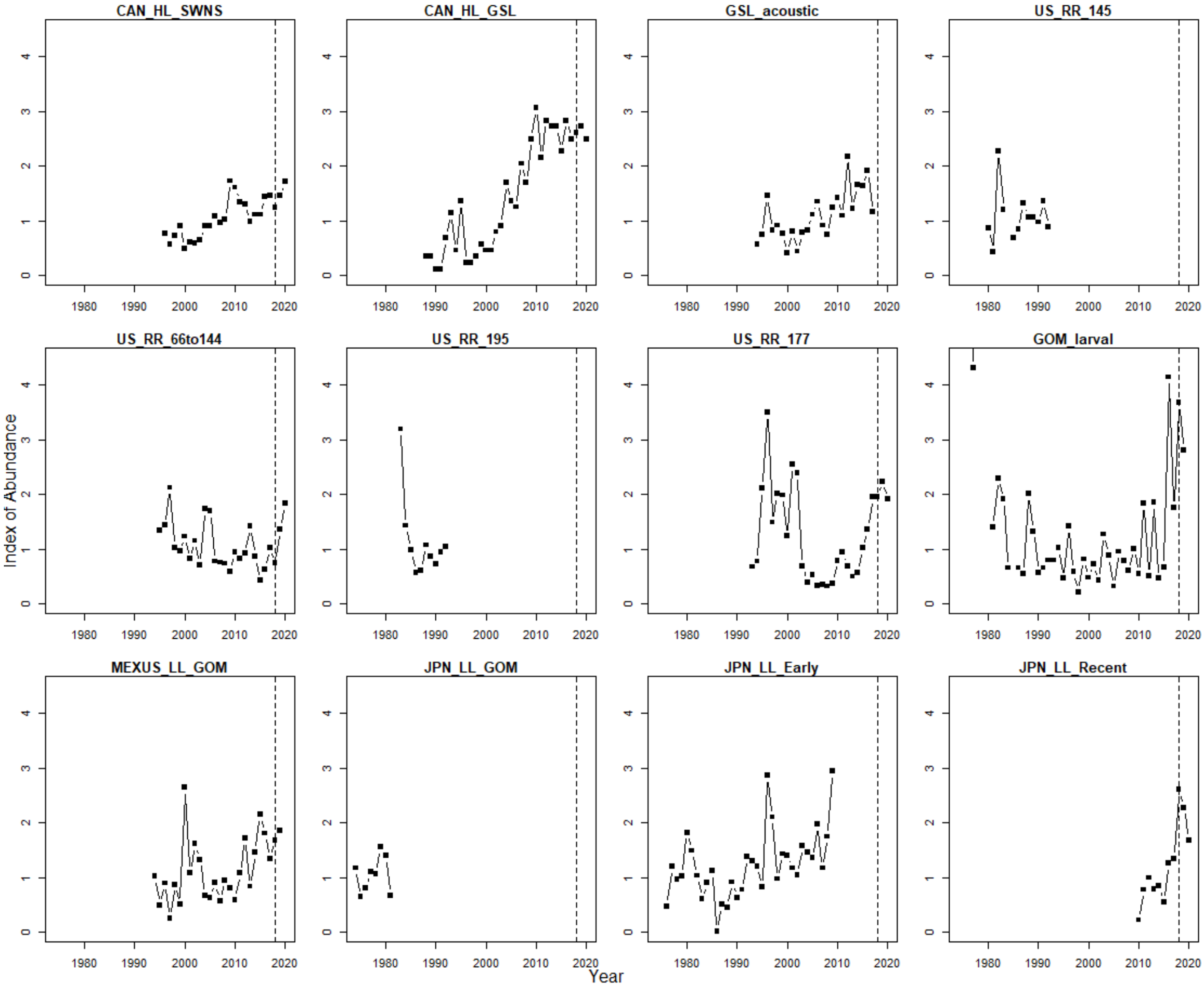


Figure 1. Indices of relative abundance of bluefin tuna in the West Atlantic used in the VPA. The dashed vertical line denotes 2018, the terminal year of the last assessment, and the data points to the right of that line are the additional years of data, 2019 and 2020 (when available).

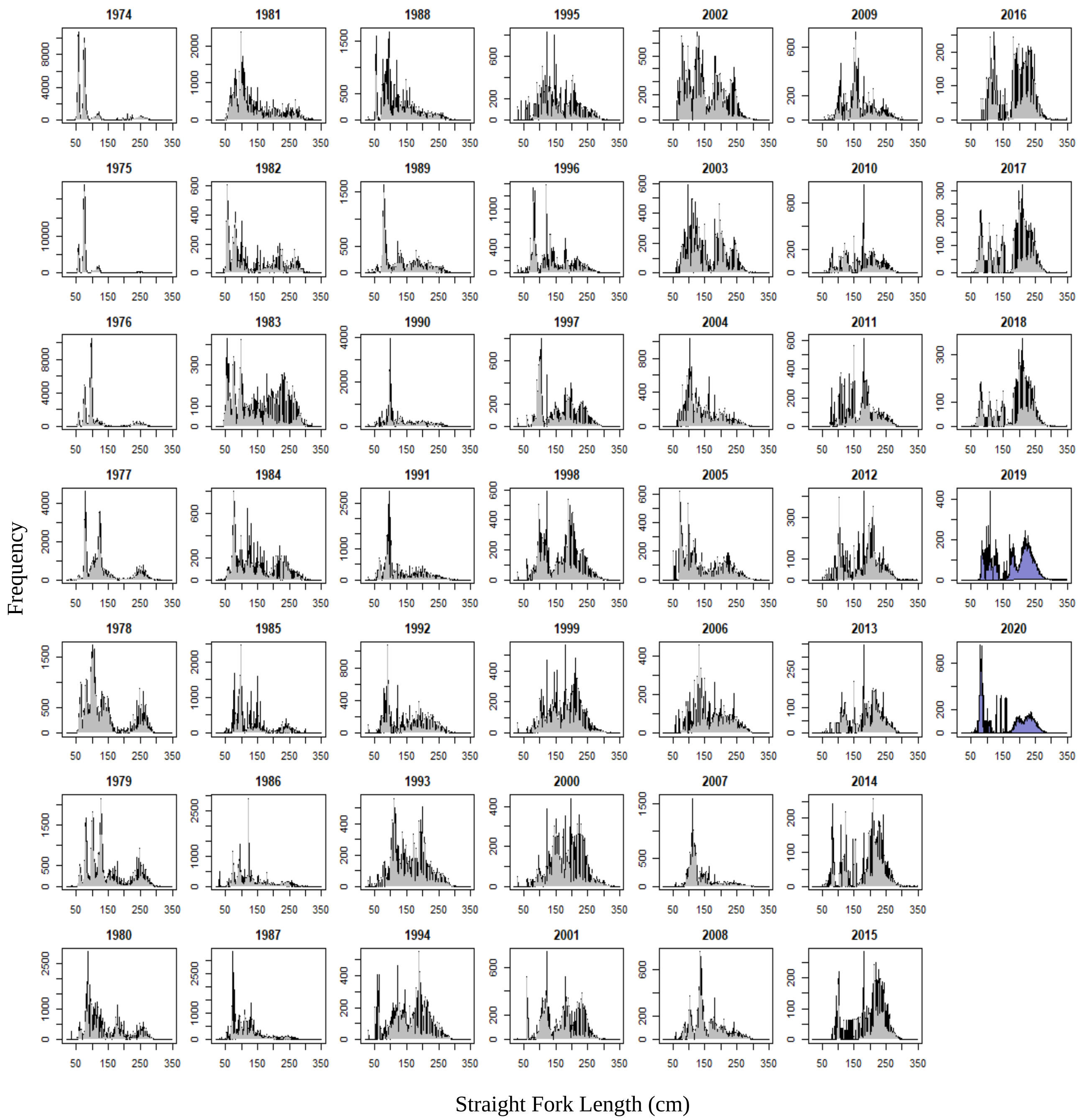


Figure 2. Total catch-at-size estimates of bluefin tuna in the West Atlantic.

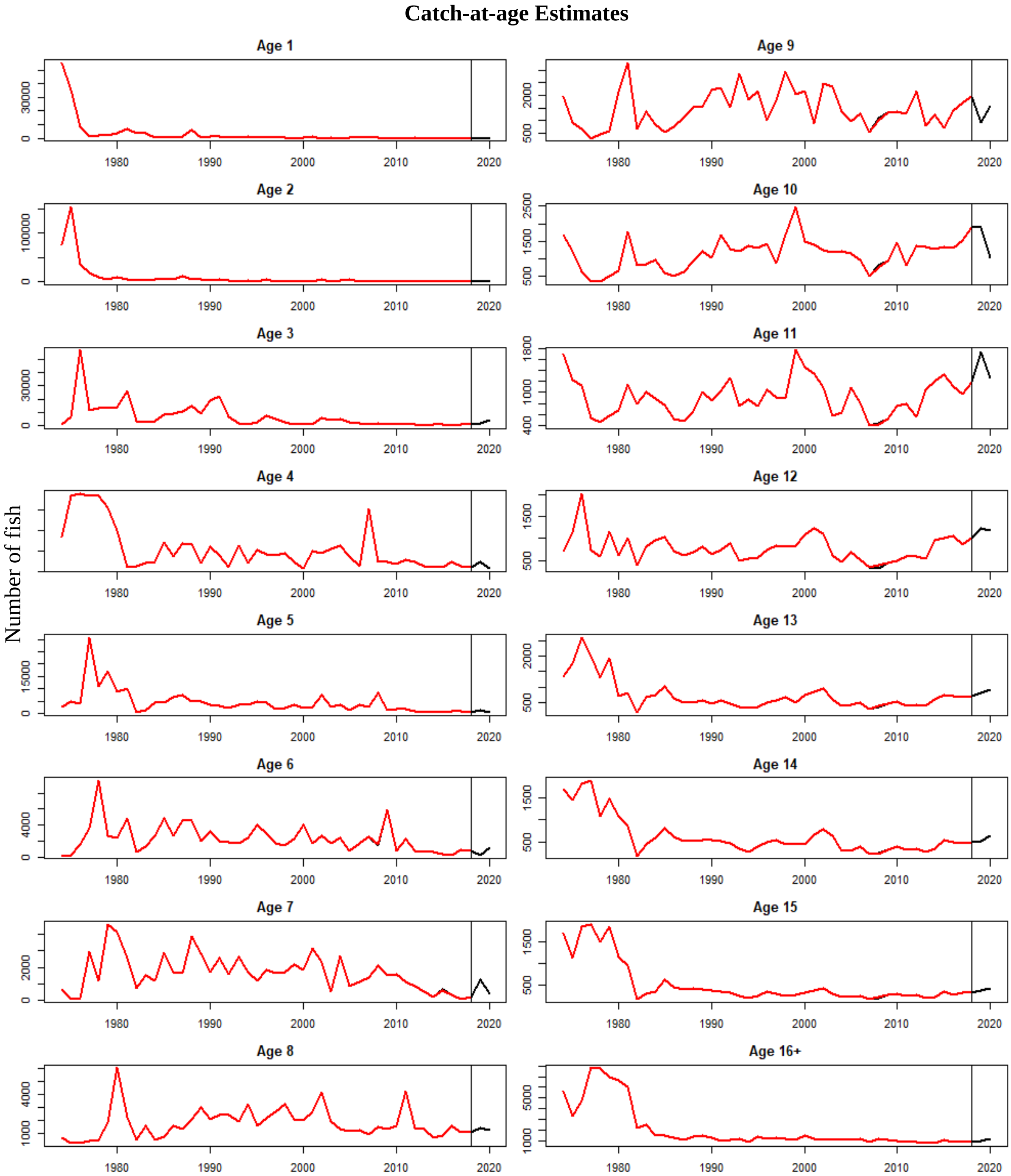


Figure 3. Catch-at-age estimates (in total numbers of fish) of bluefin tuna in the West Atantic, based on cohort slicing of total catches-at-size. The red lines shows the catch estimates by ageclass in the 2020 base assessment and the black lines show the updated time series.

Model convergence across Jitter Iterations

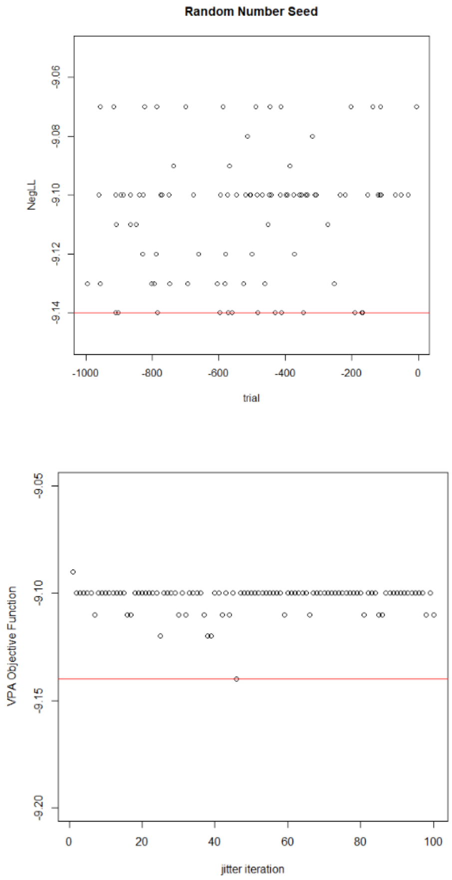


Figure 4. Final objective function values (negative log-likelihood) across random starting seed (upper panel) and jittered starting F parameters (lower panel). The red line shows the minimum negative log-likelihood solution of the base model.

Recruitment estimates by Jitter Iteration

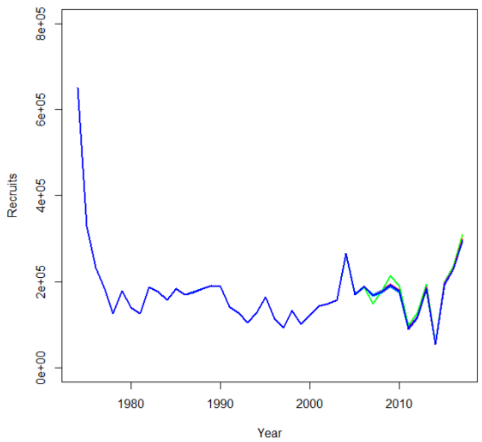


Figure 5. Estimates of recruitment of bluefin tuna in the West Atlantic, plotted across trials (n=100) with random starting seed and jittered terminal F parameter starting values.

VPA fits to Indices of Abundance

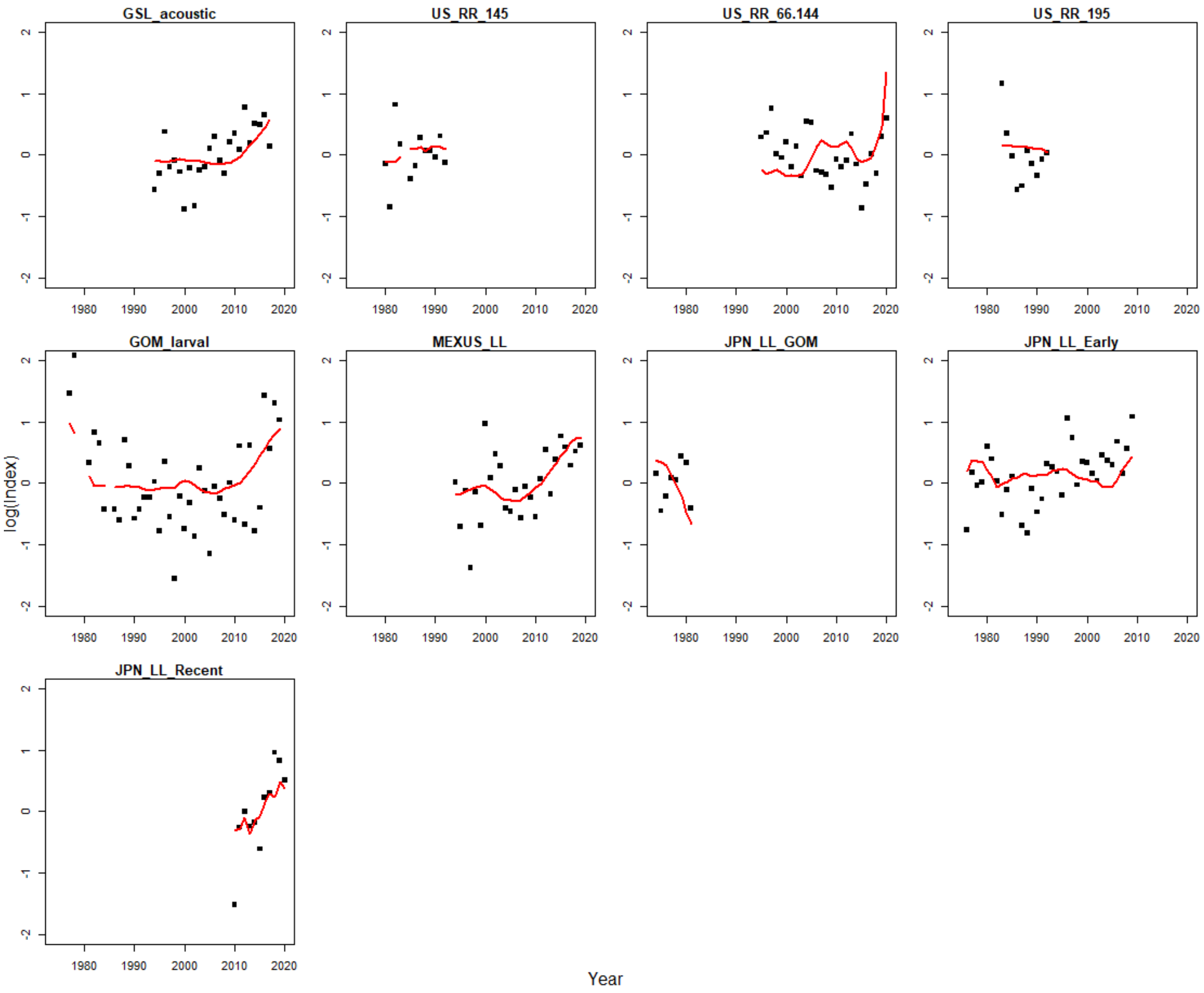


Figure 6. VPA base model fits (red lines) to indices of relative abundance (black points).

VPA residuals

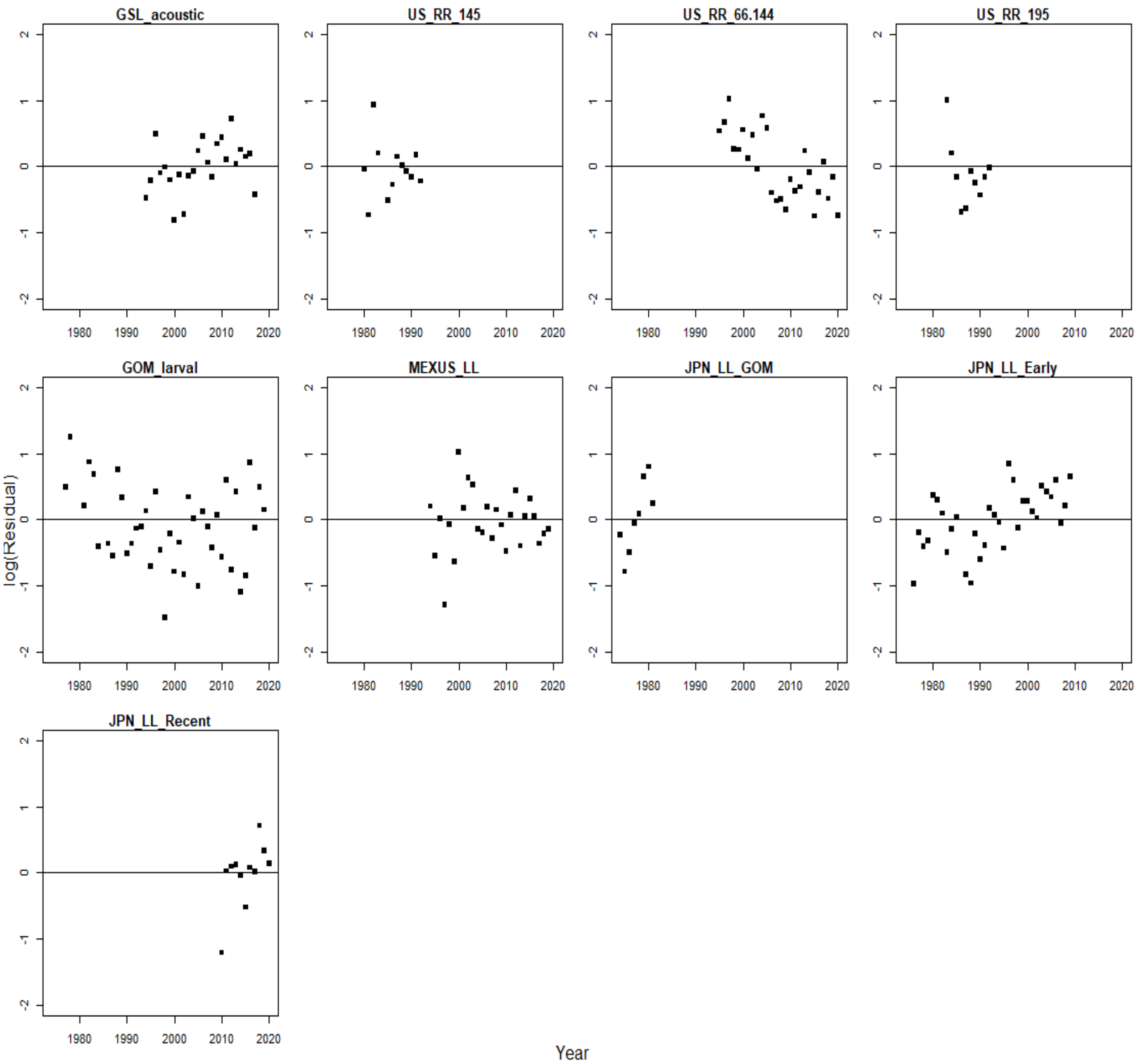


Figure 7. Residual errors (log-e scale) of base model fits to the indices of relative abundance.

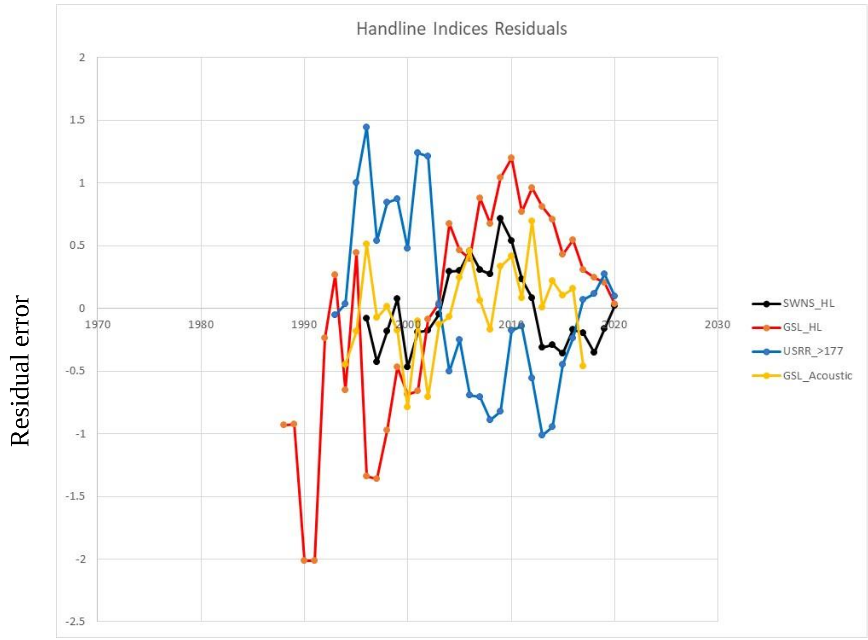


Figure 8. VPA residual error to handline (Canada GS la SWNS, and US RR>177cm) indices and the GSL acoustic index. Estimates from the sensitivity run that included all indices in **Table 1**, including the US and Canada handlines which were excluded from the continuity and proposed base runs.

Index Jackknife Analysis

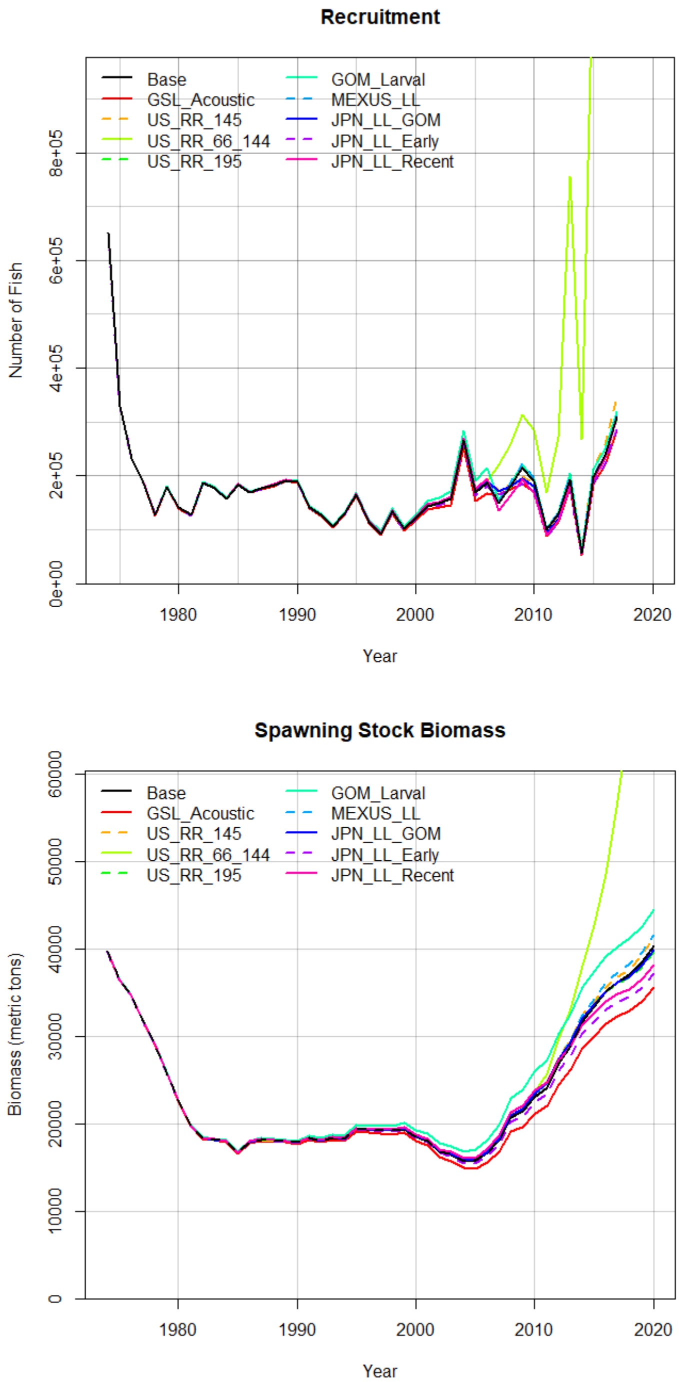


Figure 9. Index jackknife effects on estimates of bluefin tuna recruitment and spawning stock biomass (young spawning scenario) in the West Atlantic.

Retrospective Analysis

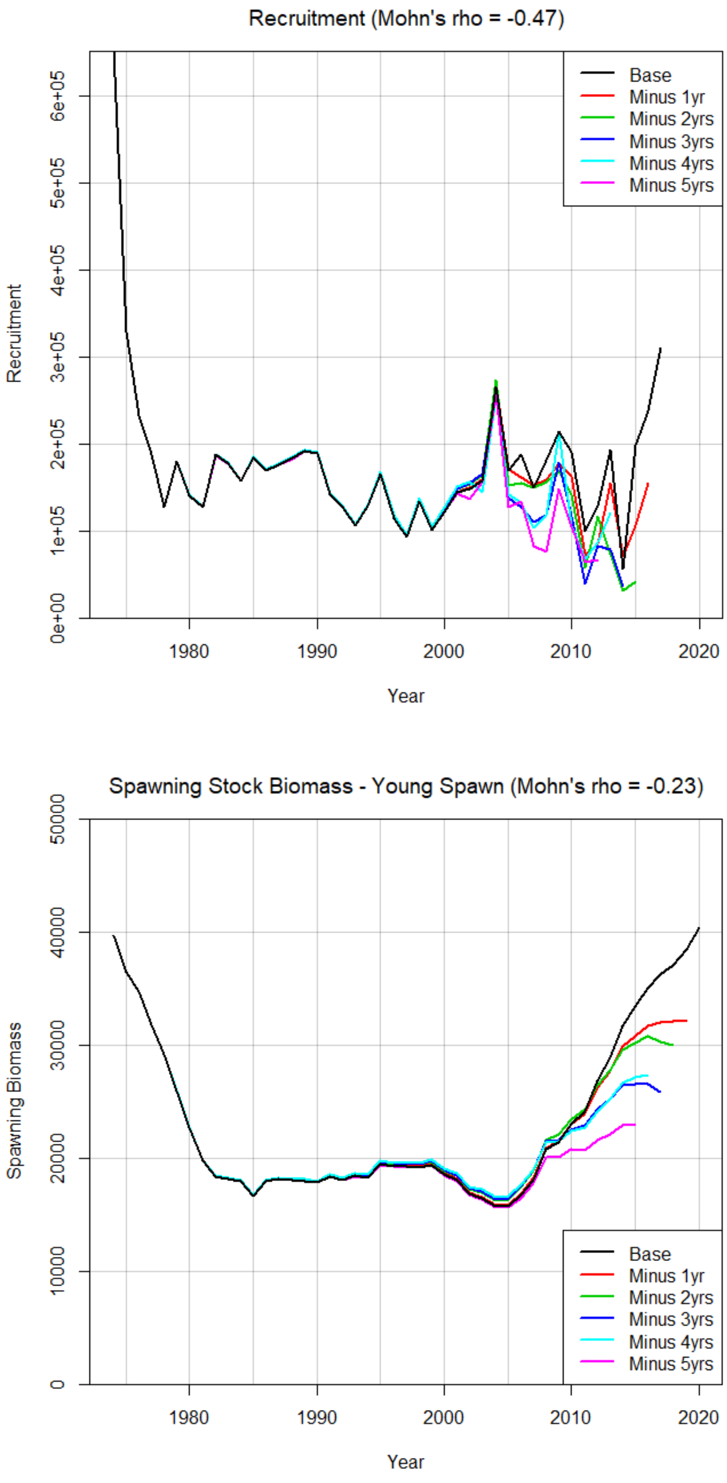


Figure 10. Retrospective estimates of bluefin tuna recruitment (upper panel) and spawning stock biomass (young spawn scenario, lower panel) in the West Atlantic.

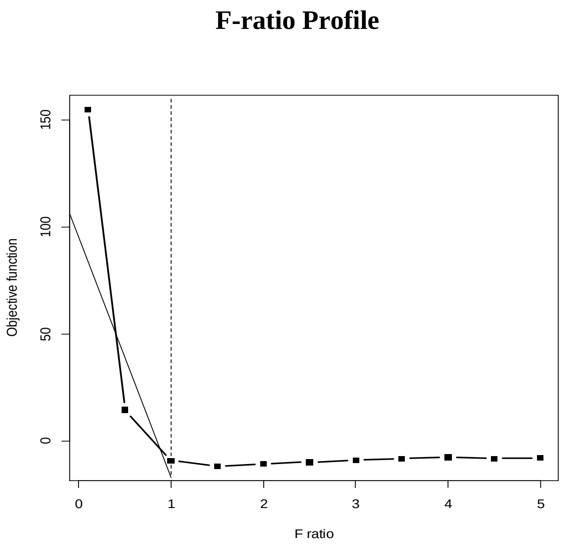


Figure 11. VPA likelihood profile of the F-ratio parameter.

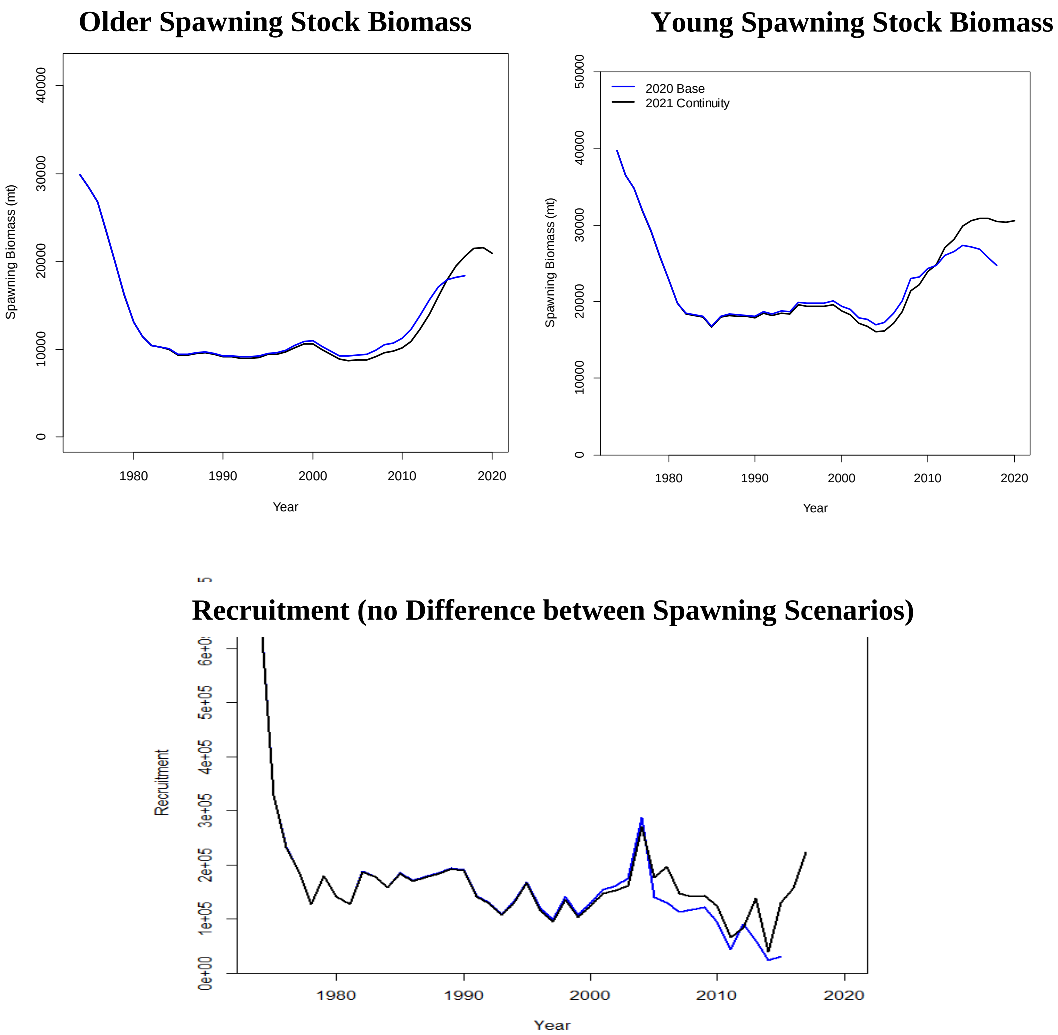


Figure 12. Spawning stock biomass (upper panels, left = older spawning scenario, right=young spawning scenario) and recruitment estimates (lower panel) of bluefin tuna in the West Atlantic continuity model (black lines) compared to the 2020 assessment (blue lines).

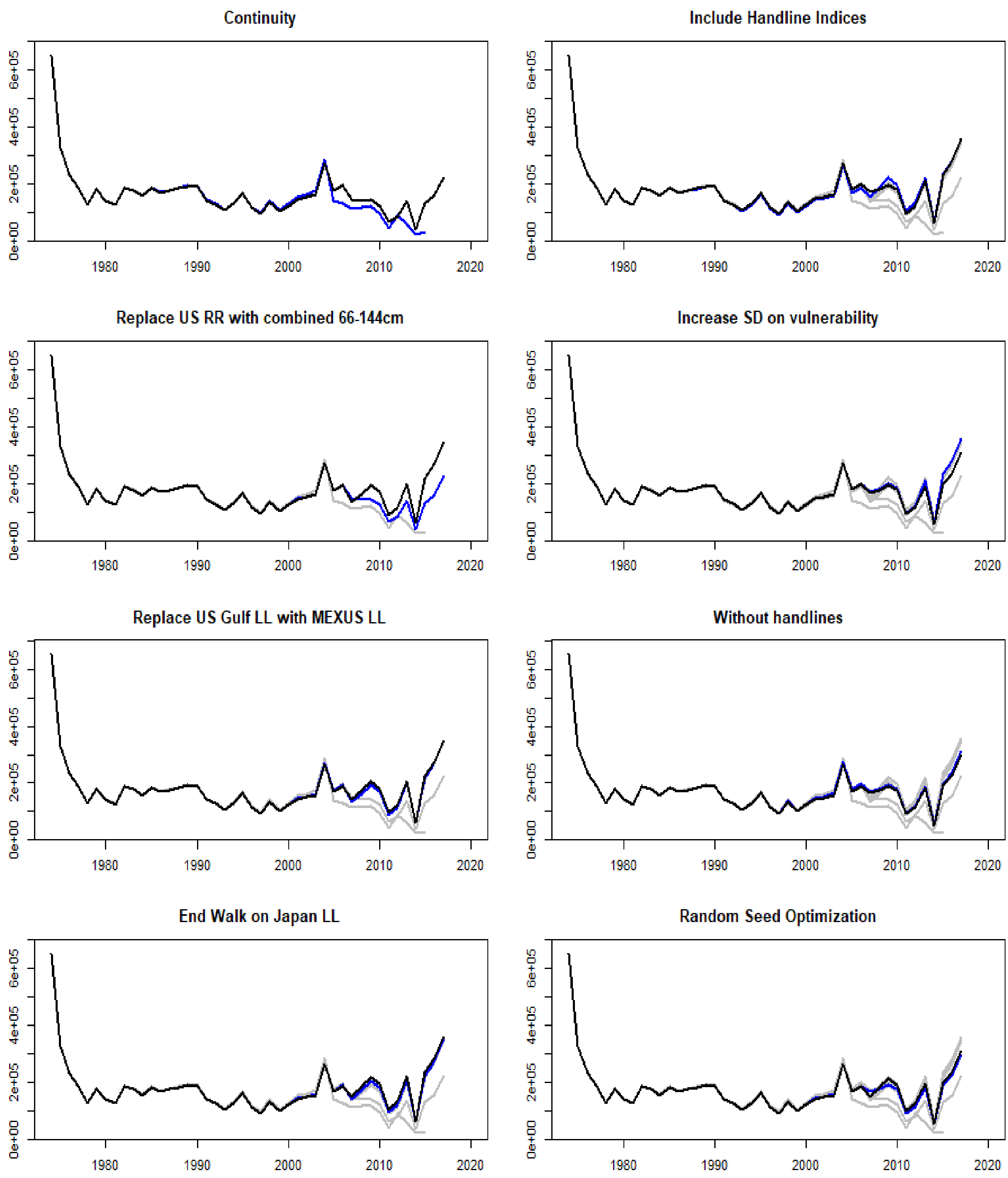


Figure 13. Estimates of bluefin tuna recruitment in the West Atlantic by stepwise model iteration (moving down by column in each step) from the continuity to the proposed base model. The black line shows the updated run in each step, the blue lines shows the run from the previous step, and the gray lines show all other prior runs.

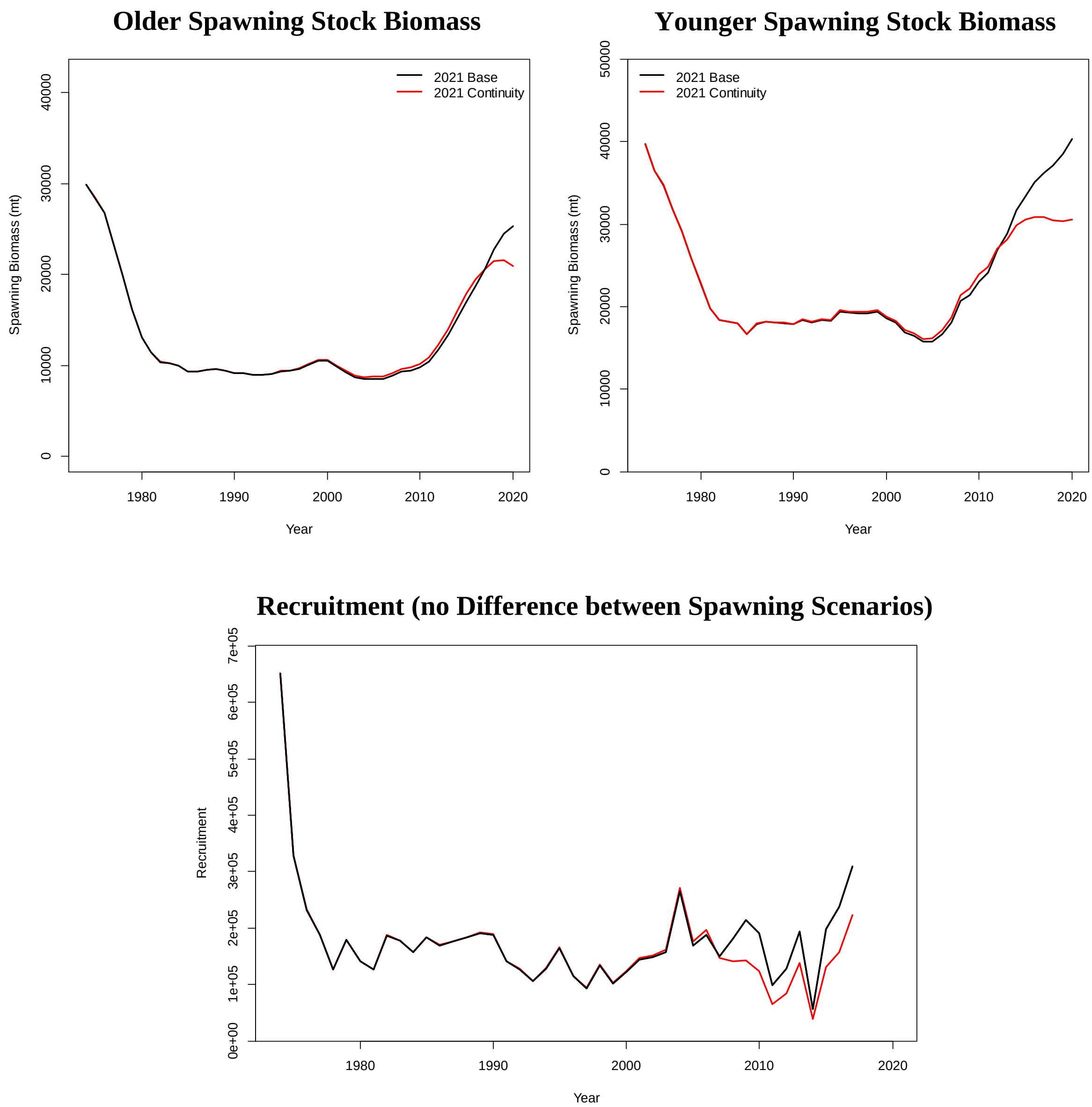


Figure 14. Spawning stock biomass (upper panels, left = older spawning scenario, right=young spawning scenario) and recruitment estimates (lower panel) of bluefin tuna in the West Atlantic base model (black lines) compared to the 2021 continuity (red lines).

Bootstrap Estimates of Abundance

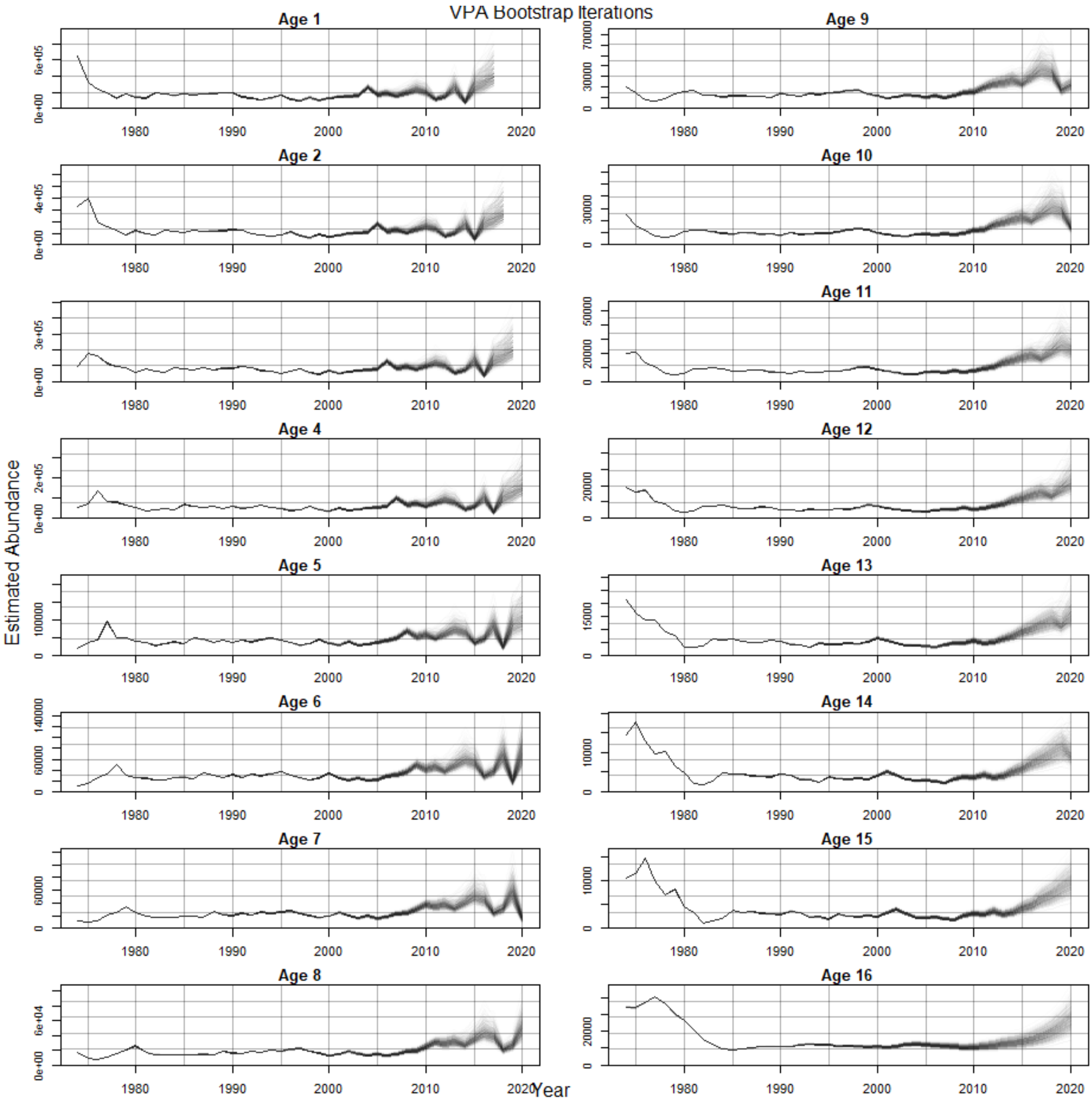


Figure 15. Estimated abundance-at-age of West Atlantic bluefin tuna. Each gray line shows the annual estimates from one of the 500 bootstrap iteration of the base VPA.

Bootstrap Estimates of Fishing Mortalities

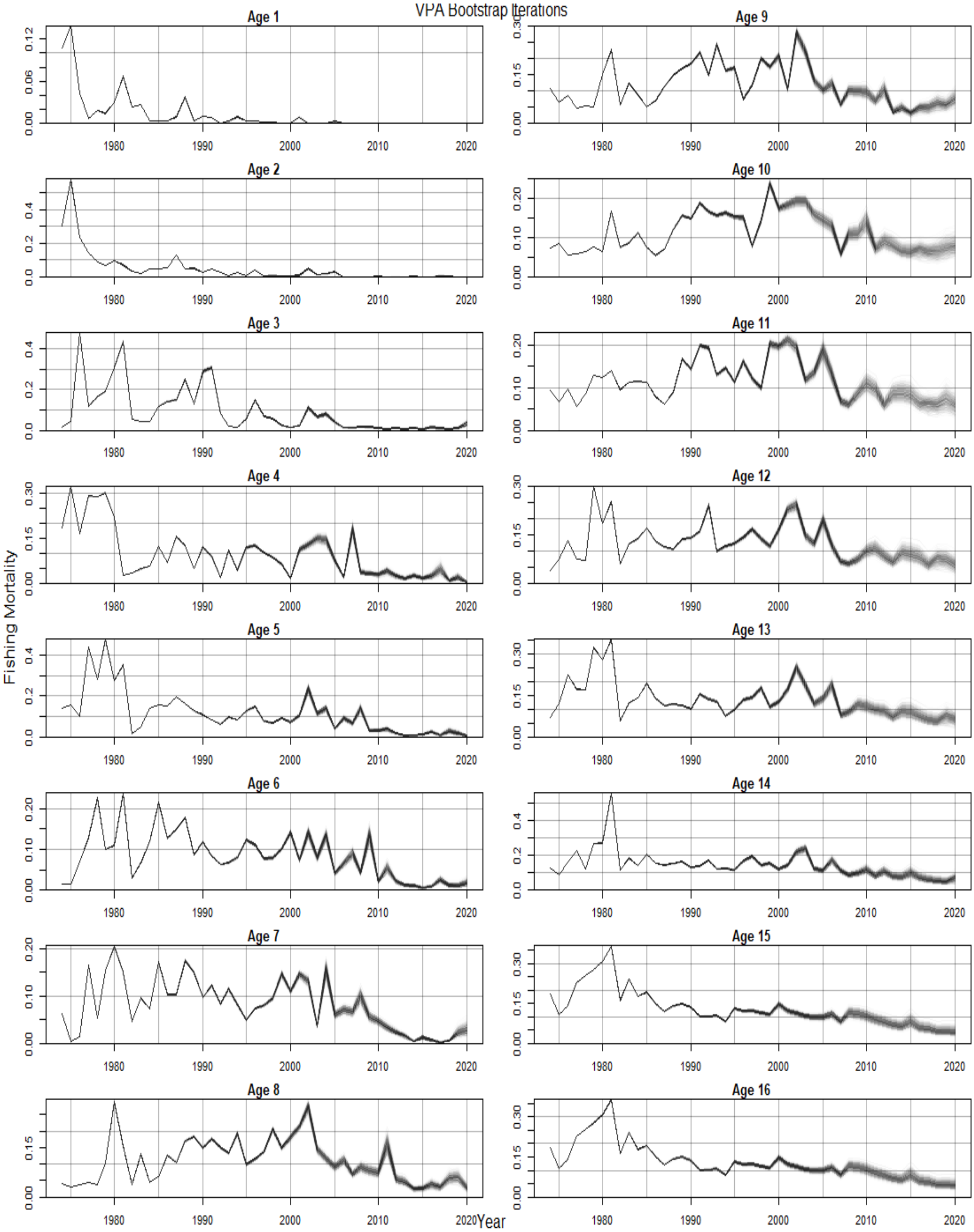


Figure 16. Estimated fishing mortalities-at-age of bluefin tuna in the West Atlantic. Each gray line shows the annual estimates from one of the 500 bootstrap iteration of the base VPA.

Apical Fishing Mortality

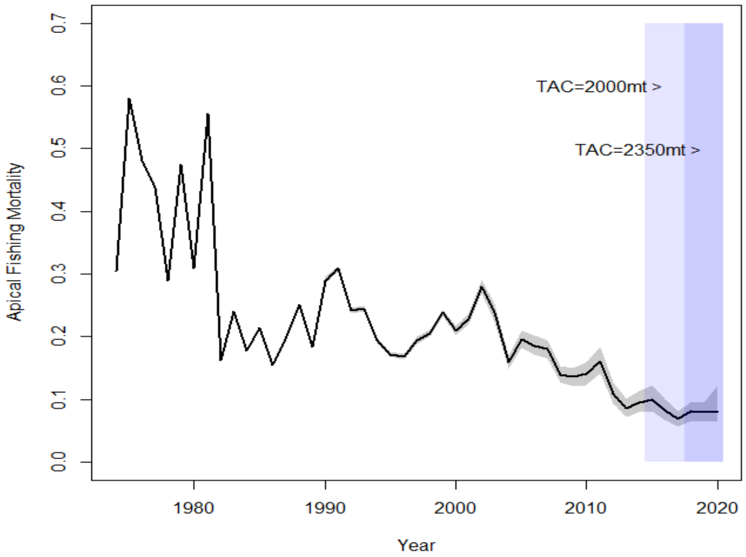


Figure 17. Estimated apical fishing mortality (maximum annual F-at-age) of bluefin tuna in the West Atlantic. The black line shows the median of the bootstraps, and the gray shaded area represents the 80% confidence intervals. The total allowable catch (TAC) periods over the last two assessment cycles are shaded blue.

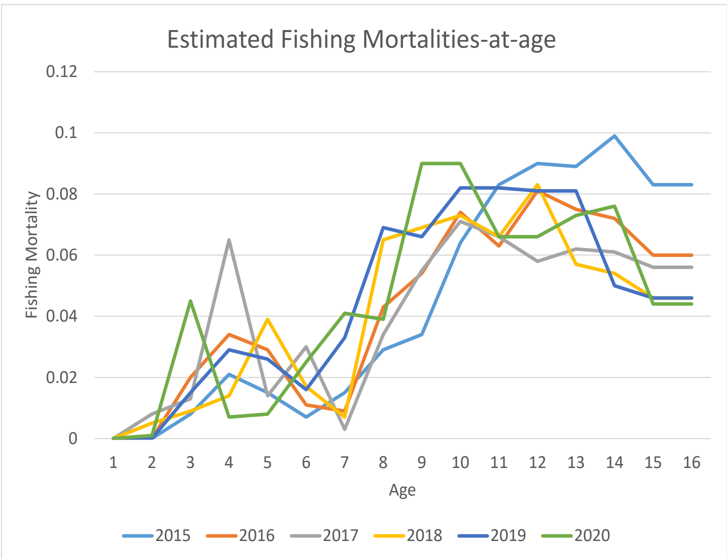


Figure 18. Fishing mortality-at-age estimates of bluefin tuna in the West Atlantic during 2015 to 2020.

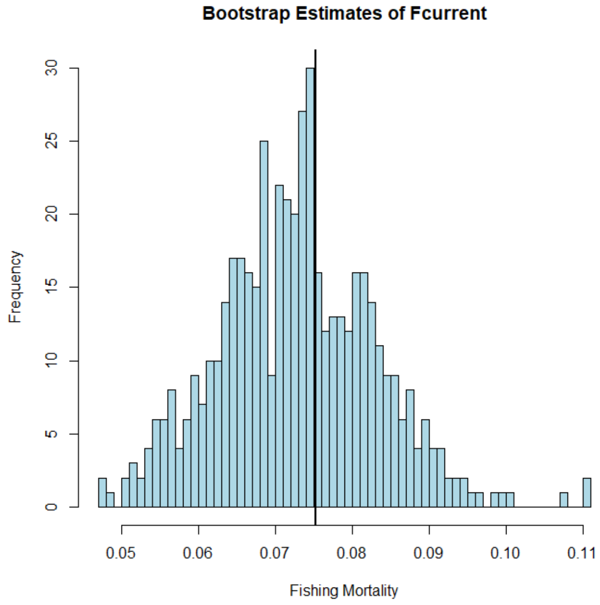
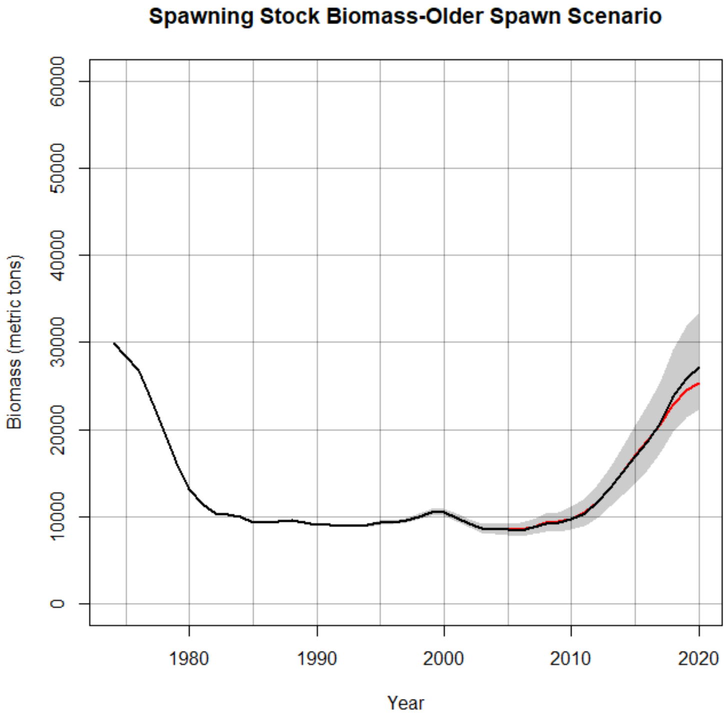


Figure 19. Estimated current fishing mortality (2017 to 2019 mean apical F) of bluefin tuna in the West Atlantic. The blue histogram shows the distribution of estimates across bootstraps, and the vertical black line shows the deterministic run estimate.

Figure 20. Estimated recruitment of bluefin tuna in the West Atlantic. The black line shows the median of the bootstrap trials, and the gray shaded area shows the 80% confidence intervals.



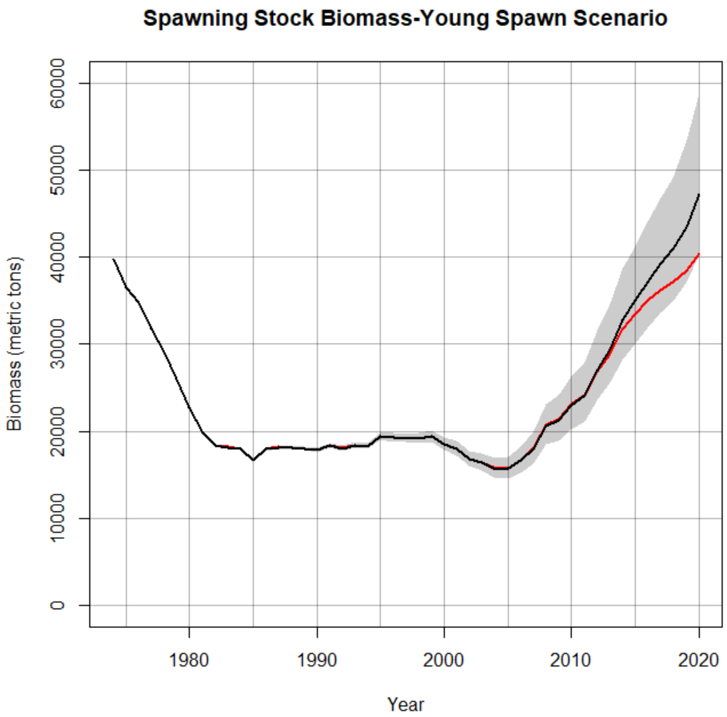


Figure 21. Estimated spawning stock biomass of bluefin tuna in the West Atlantic. The red line shows the deterministic estimates, black line shows the median of the bootstrap trials, and the gray shaded area shows the 80% confidence intervals.

Stock-Recruitment Plot

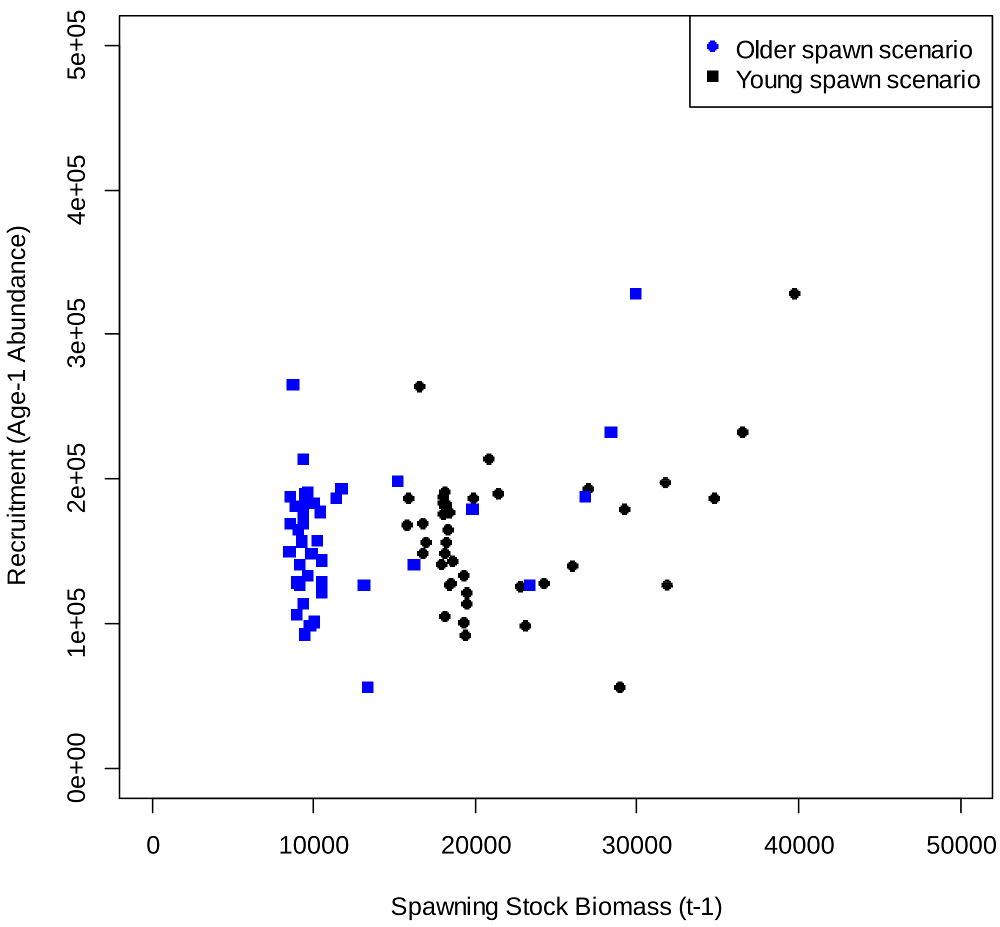


Figure 22. VPA stock-recruitment estimates. The black points show the young spawning scenario and the blue points show the older spawning scenario. The estimates cover the period 1974 to 2017.