WESTERN ATLANTIC BLUEFIN TUNA VIRTUAL POPULATION ANALYSIS BASE MODEL DIAGNOSTICS AND RESULTS[1]

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SUMMARY

This report documents the 2020 update of the West Atlantic bluefin tuna virtual population analysis. The SCRS Bluefin Tuna Species Group reviewed the assessment model assumptions, results and diagnostics via webinar during May 14-22, 2020. 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 2018, and recruitment for the period 1974 to 2015. The 2003 year class showed the largest recruitment event over the last few decades, reflected in the time series of estimated abundances-at-age. A recent decline in abundance resulted from the period of lower recruitment following the 2003 year class. Analysts posted the assessment files and results to the Bluefin Tuna Species Group Meeting cloud-based drive on May 15, 2020.

RÉSUMÉ

Ce rapport documente la mise à jour 2020 de l'analyse de population virtuelle de thon rouge de l'Atlantique Ouest. Le groupe d'espèces sur le thon rouge du SCRS a examiné les hypothèses, les résultats et les diagnostics du modèle d'évaluation via un webinaire du 14 au 22 mai 2020. 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 2018, et du recrutement pour la période de 1974 à 2015. La classe d'âge de 2003 a montré l'événement de recrutement le plus important de ces dernières décennies, reflété dans la série temporelle des abondances estimées par âge. Le récent déclin de l'abondance résultait de la période de plus faible recrutement qui a suivi la classe d'âge de 2003. Les analystes ont publié les fichiers et les résultats de l'évaluation sur le dossier cloud de la réunion du Groupe d'espèces sur le thon rouge le 15 mai 2020.

RESUMEN

Este informe documenta la actualización de 2020 del análisis de población virtual del atún rojo del Atlántico occidental. El Grupo de especies de atún rojo del SCRS revisó los supuestos, los resultados y los diagnósticos del modelo de evaluación virtualmente durante el 14-22 de mayo de 2020. Presentamos el diagnóstico del caso base del modelo y los resultados, incluidas las estimaciones de la serie temporal de la biomasa del stock reproductor (escenarios de reproductores jóvenes y mayores) para el periodo 1974 a 2019, y el reclutamiento para el periodo 1974 a 2015. La clase anual de 2003 presentó el mayor evento de reclutamiento de las últimas décadas, reflejado en las series temporales de las abundancias estimadas por edad. Se produjo un reciente descenso en la abundancia como resultado del periodo de menor reclutamiento posterior a la clase anual de 2003. Los analistas publicaron los archivos y los resultados de la evaluación para la reunión del Grupo de especies de atún rojo en el archivo basado en la nube el 15 de mayo de 2020.

KEYWORDS

Stock assessment, bluefin tuna, West Atlantic

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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, during which, 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, and compiled a list of sensitivity analyses. Recently, the Group outlined a set of specifications for updating the base VPA in the 2020 work plan. Specifically, they provided guidelines to the update "*The same model parameter settings (F-ratio) and variance scaling will be used for VPA and the same model structure will be used for Stock Synthesis. The BFT Species Group will also do standard diagnostic of models and if problems arise, they will be dealt with appropriately. This gives the modelers the ability to handle problems/issues that can arise when things are changed. For continuity a model with data up to 2015 (mimic 2017 end date) and then up-to 2018 (new time)*". The Group reviewed the assessment model assumptions, results and diagnostics via webinar during May 14-22, 2020, and determined the VPA base model inputs. This report summarizes the VPA data inputs, assumptions, results, and diagnostics for written documentation of the 2020 assessment update.

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.

2.1 VPA update methods overview

Prior to the 2020 assessment workshop, CPC analysts and ICCAT Secretariat staff updated the indices of abundance (**Table 1**, **Figure 1**), total catches-at-size, and estimated catches-at-age (**Table 2**, **Figure 2**). The Group reviewed the final data inputs during the intersessional Bluefin Tuna Species Group online meeting (May 14-22, 2020). Total catch-at-size and catch-at-age estimates closely matched the 2017 base model inputs, and included three years of additional data, 2016 to 2018 (**Figure 2**).

The assessment team then implemented the following updates to the 2017 VPA of WBFT:

- Updated the VPA data file with the catch-at-age, partial catch-at-age and indices of abundance, up to and including 2018
- Corrected partial-catch-at-age of the Japanese longline fleet (data filter code correction)
- Removed the 2018 data point of the Gulf of St. Lawrence acoustic survey

Base model configuration summary:

- Model years ranged 1974 to 2018
- 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 for the oldest age class:
  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 114 cm, 1993-2018
    - US rod and reel 115 to 144 cm, 1993-2018
    - US rod and reel >195 cm, 1983-1992
    - US longline Gulf of Mexico, 1992-2018
    - Japan longline Gulf of Mexico, 1974-1981
    - Japan longline Area 2 West, 1976-2009
    - Japan longline recent, 2010-2018
- Fisheries-independent surveys included:
    - Gulf of St Lawrence acoustic survey, 1994-2018
    - Gulf of Mexico larval survey, 1977-2018
- Index variance settings combined 1) input CV weighting of fishery-dependent indices of abundance with additive variance parameters estimated in the VPA, and 2) input CVs for fishery-independent indices of abundance (or minimum value of 0.3, when applicable)
- Random-walk estimation of Japanese longline recent period annual selectivity and catchability
- F-ratio (annual F of plusgroup/F of age 15) set equal to 1.0
- No constraints on recruitment or spawn-recruitment relationship

The team outlined the following sensitivity analyses for model diagnostics, consistent with the previous assessment and 2020 work plan:

- jitter analysis of model random seed and parameter starting values
- an index of abundance jackknife where each index series is 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
- bootstrap resampling of the relative abundance data (each iteration replaced the index data with random lognormal draws assuming the input means and defined variances (i.e. input CVs, plus additional variance estimated for fishery dependent indices)

Using the model configuration described above, the analysts constructed a base model using the same set of indices and model specifications as the 2017 VPA base-case assessment. 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 on May 15, 2020.

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 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 2020 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 0.5 (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. 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, consistent with the 2017 base model.

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 that model convergence occurred around two distributions of the final objective function (**Figure 3**). The different solutions highlighted a trade-off between alternative fits to indices with conflicting trends (**Figure 4**), namely the juvenile relative abundances versus larger fish indices. One set of solutions showed improved fits to the juvenile indices (US RR indices), compared to the alternative solution set (maximum likelihood estimate included) with improved fit to the indices of larger fish (GoM larval, U.S. GoM LL, GSL acoustic). Recruitment estimates plotted by jitter iterations showed consistent long-term magnitude and trend (**Figure 5**), but also illustrated the divergent pattern in recruitment for the period 2005 to 2009. Model residuals displayed a general random pattern for most data series, with exception of the historic JPN longline index and Gulf of Mexico larval survey, where clustering occurred in time blocks (**Figure 6**).

Model sensitivities included 1) a jack-knife analysis removing individual index time series one-at-a-time, 2) five-year retrospective analysis, and 3) profiling of plusgroup F-ratio (time-invariant). The index jack-knife demonstrated sensitivity of historic recruitments and current spawning stock biomass to the Gulf of Mexico larval survey and Gulf of St. Lawrence acoustic survey (**Figure 7**), with contrast in the direction of the effect. Estimates were less sensitive to the 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 2005 to 2009. The retrospective analysis indicated stable absolute scale and long-term trends in recruitment and spawning stock biomass (**Figure 8**), but with notable uncertainty in the recent recruitment and level of stock rebuilding that occurred since the mid-2000s. Likelihood profiling of different F-ratios (**Figure 9**) provided evidence in favor of a higher F-ratio than the value assumed in the base model (base model Fratio=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 (**Figure 10**). The Group decided to maintain the F-ratio value of 1.0 for continuity with the 2017 assessment, consistent with the terms of reference.

4. VPA Results

Time series estimates of abundance mirrored the magnitude and trend of the prior assessment, with exception of recruitment estimates from 2005 to 2009 (**Figure 11**). The 2003 year class showed the largest recruitment event over the last few decades, observed as a distinct peak in estimated abundances-at-age (**Table 3, Figure 12)**. The recent decrease in abundance of some age classes (ages 5 to 9, in particular) resulted from the steady decline in recruitments following the 2003 year class.

Estimates of fishing mortality (**Table 4**) on ages 1-7 and ages 13-16 for the terminal years trended lower than historical periods; however, we observed an increasing trend in recent fishing mortality estimates of ages 8 to 12, with terminal year estimates approaching historical levels (**Figure 13**). Apical fishing mortality rates (maximum annual F across age-classes) declined to a low in 2013, but increased since that time (**Figure 14**). Higher fishing mortality occurred on ages 4 and ages 10-12 compared to other ages, with an annual increase observed between 2013 and 2018 (**Figure 15**). The bootstrap distribution of current F (mean of 2015 to 2017 apical fishing mortality) ranged approximately from 0.07 to 0.16 (**Figure 16**), with a median equal to 0.10.

Recruitment estimates declined steadily over the last decade (**Table 5, Figure 17**). The decrease in spawning biomass (young spawning scenario) during the terminal two years (**Table 5, Figure 18**) reflected the recent lower recruitments. The abundance of old fish in the population (ages 15 and 16+) increased during 2014 to 2018 to the highest abundance since 1980, with the 2003 year class expected to have aged to that group in 2019. However, a lag effect of lower recruitment on the abundance of older age classes is expected (i.e. a future decline in the abundance and biomass of spawners of age 16 and older). **Figure 19** plots the paired spawner-recruitment estimates.

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References

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

Year	GSL acoustic	CV	USRR <145	CV	USRR 66to114	CV	USRR 115to144	CV	USRR >195	CV	JPNLL historic	CV	GoM Larval	CV	USLL GoM	CV	JPNLL GoM	CV	JPNLL Recent	CV
1974	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.97	0.27	-	-
1975	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.53	0.21	-	-
1976	-	-	-	-	-	-	-	-	-	-	0.39	0.41	-	-	-	-	0.67	0.21	-	-
1977	-	-	-	-	-	-	-	-	-	-	0.89	0.32	2.49	0.45	-	-	0.91	0.22	-	-
1978	-	-	-	-	-	-	-	-	-	-	0.73	0.34	4.55	0.30	-	-	0.88	0.23	-	-
1979	-	-	-	-	-	-	-	-	-	-	0.81	0.28	-	-	-	-	1.29	0.28	-	-
1980	-	-	0.80	0.43	-	-	-	-	-	-	1.39	0.28	-	-	-	-	1.16	0.27	-	-
1981	-	-	0.40	0.52	-	-	-	-	-	-	1.11	0.26	0.78	0.44	-	-	0.55	0.24	-	-
1982	-	-	2.10	0.33	-	-	-	-	-	-	0.79	0.28	1.31	0.30	-	-	-	-	-	-
1983	-	-	1.11	0.26	-	-	-	-	2.81	0.10	0.46	0.35	1.12	0.35	-	-	-	-	-	-
1984	-	-	-	-	-	-	-	-	1.25	0.19	0.67	0.29	0.38	0.53	-	-	-	-	-	-
1985	-	-	0.63	0.64	-	-	-	-	0.86	0.30	0.83	0.27	-	-	-	-	-	-	-	-
1986	-	-	0.78	0.43	-	-	-	-	0.50	1.10	0.01	1.66	0.38	0.43	-	-	-	-	-	-
1987	-	-	1.22	0.40	-	-	-	-	0.53	0.48	0.38	0.34	0.31	0.48	-	-	-	-	-	-
1988	-	-	0.99	0.38	-	-	-	-	0.94	0.36	0.34	0.37	1.13	0.32	-	-	-	-	-	-
1989	-	-	0.99	0.43	-	-	-	-	0.76	0.36	0.68	0.30	0.78	0.37	-	-	-	-	-	-
1990	-	-	0.90	0.34	-	-	-	-	0.63	0.34	0.48	0.32	0.30	0.34	-	-	-	-	-	-
1991	-	-	1.26	0.35	-	-	-	-	0.82	0.28	0.60	0.30	0.37	0.56	-	-	-	-	-	-
1992	-	-	0.82	0.42	-	-	-	-	0.91	0.28	1.09	0.27	0.45	0.35	1.14	0.35	-	-	-	-
1993	-	-	-	-	1.67	0.19	2.80	0.21	-	-	0.98	0.27	0.42	0.64	0.64	0.36	-	-	-	-
1994	0.03	0.30	-	-	0.32	0.31	0.60	0.37	-	-	0.90	0.27	0.60	0.33	0.47	0.39	-	-	-	-
1995	0.03	0.30	-	-	1.53	0.17	1.05	0.22	-	-	0.59	0.34	0.27	0.55	0.44	0.39	-	-	-	-
1996	0.07	0.30	-	-	1.85	0.17	1.44	0.21	-	-	2.21	0.27	0.79	0.49	0.25	0.40	-	-	-	-
1997	0.04	0.30	-	-	3.55	0.13	0.23	0.34	-	-	1.61	0.26	0.33	0.39	0.47	0.36	-	-	-	-
1998	0.04	0.30	-	-	1.34	0.15	0.84	0.17	-	-	0.75	0.30	0.12	0.53	0.50	0.37	-	-	-	-
1999	0.04	0.30	-	-	1.44	0.26	1.37	0.31	-	-	1.12	0.26	0.44	0.48	0.84	0.33	-	-	-	-
2000	0.02	0.30	-	-	1.02	0.35	1.09	0.38	-	-	1.11	0.27	0.29	0.53	1.25	0.33	-	-	-	-
2001	0.04	0.30	-	-	0.57	0.18	2.14	0.20	-	-	0.91	0.27	0.40	0.32	0.71	0.38	-	-	-	-
2002	0.02	0.30	-	-	1.03	0.15	2.36	0.17	-	-	0.77	0.28	0.26	0.65	0.66	0.39	-	-	-	-
2003	0.04	0.30	-	-	0.64	0.10	0.85	0.13	-	-	1.20	0.29	0.67	0.38	1.20	0.32	-	-	-	-
2004	0.04	0.30	-	-	2.46	0.10	0.72	0.15	-	-	1.10	0.31	0.49	0.67	1.09	0.32	-	-	-	-
2005	0.05	0.30	-	-	2.09	0.10	0.68	0.16	-	-	0.98	0.26	0.18	0.30	0.82	0.34	-	-	-	-
2006	0.06	0.30	-	-	0.78	0.23	1.16	0.16	-	-	1.51	0.29	0.55	0.37	0.58	0.39	-	-	-	-
2007	0.04	0.30	-	-	0.52	0.08	0.99	0.11	-	-	0.96	0.41	0.42	0.37	0.78	0.38	-	-	-	-
2008	0.03	0.30	-	-	0.35	0.09	1.52	0.11	-	-	1.34	0.45	0.33	0.38	1.79	0.33	-	-	-	-
2009	0.06	0.30	-	-	0.29	0.09	0.36	0.14	-	-	2.30	0.35	0.55	0.32	1.46	0.35	-	-	-	-
2010	0.07	0.30	-	-	0.52	0.09	1.07	0.12	-	-	-	-	0.31	0.52	1.23	0.34	-	-	0.59	0.38
2011	0.05	0.30	-	-	0.59	0.10	0.64	0.16	-	-	-	-	1.06	0.40	1.10	0.48	-	-	2.00	0.26
2012	0.10	0.30	-	-	0.47	0.11	0.60	0.17	-	-	-	-	0.29	0.48	3.41	0.37	-	-	2.50	0.27
2013	0.06	0.30	-	-	0.60	0.12	1.30	0.15	-	-	-	-	1.05	0.35	1.23	0.42	-	-	1.89	0.26
2014	0.08	0.30	-	-	0.47	0.14	0.50	0.21	-	-	-	-	0.25	0.37	0.96	0.44	-	-	2.34	0.28
2015	0.08	0.30	-	-	0.32	0.13	0.23	0.24	-	-	-	-	0.39	0.30	1.02	0.47	-	-	1.43	0.27
2016	0.09	0.30	-	-	0.35	0.12	0.75	0.16	-	-	-	-	2.27	0.30	1.11	0.47	-	-	3.58	0.29
2017	0.05	0.30	-	-	0.56	0.12	0.64	0.18	-	-	-	-	0.99	0.30	0.82	0.48	-	-	3.57	0.31
2018	-	-	-	-	0.66	0.13	0.07	0.41	-	-	-	-	2.05	0.30	1.04	0.51	-	-	6.50	0.30

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	2193	8243	1535	2132	1518	1027	765	422	396	389	238	203	1158
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	650	938	418	339	627	886	720	1332	1317	1013	732	535	327	1064
2016	0	9	486	2290	1043	254	332	1585	1393	1307	1100	1062	695	494	269	847
2017	12	1105	1177	1246	732	883	66	1120	1698	1528	963	849	677	479	323	895
2018	10	891	952	1005	588	773	180	1108	1946	1891	1187	1002	714	508	312	869

Table 3. VPA estimated abundances-at-age of bluefin tuna in the West Atlantic.

Year	Age 1	Age 2	Age 3	Age 4	Age 5	Age 6	Age 7	Age 8	Age 9	Age 10	Age 11	Age 12	Age 13	Age 14	Age 15	Age 16+
1974	651429	331702	94215	54737	20101	11430	12064	17754	20132	24865	20124	18874	21242	14471	10591	34592
1975	328926	400179	181299	73118	37223	14575	9603	9858	14972	15999	20472	16411	16245	17755	11494	33949
1976	233091	195853	166117	136615	43334	26576	12225	8301	8386	12414	13031	17170	13641	12908	14683	36900
1977	188348	152718	114851	80821	94754	32760	21126	10475	7011	6812	10414	10599	13475	9758	9953	40444
1978	127606	127880	98165	80382	49485	51113	24533	15579	8811	5925	5696	8829	8793	10172	7043	36356
1979	180031	85605	86493	65443	49326	31201	34786	20230	13162	7391	4925	4681	7355	6643	8166	30464
1980	141386	121351	59361	56256	39671	25656	24081	25944	16026	11106	6070	3875	3107	4779	4608	26532
1981	127119	93831	81574	34341	37019	25202	19591	17088	17099	12230	9224	4807	2885	2106	3303	20728
1982	188039	81280	64742	41531	27316	21775	16970	14665	12853	12090	9183	7184	3352	1823	1094	15143
1983	178367	125606	58139	48195	32790	22472	18008	14104	12412	10771	9943	7481	6062	2832	1470	12494
1984	158260	118796	91432	43746	37589	26032	17912	14244	10883	9726	8761	7955	5931	4809	2133	9941
1985	185030	107773	83682	68901	33795	27288	19700	14479	11972	8843	7712	6998	6212	4622	3785	9157
1986	170821	126138	76191	58485	49931	24151	18800	14443	11954	10088	7272	6175	5288	4601	3407	9675
1987	177799	116340	88720	52072	44694	35821	18137	14750	11184	9891	8474	6023	4855	4125	3570	10196
1988	185764	120451	75829	60161	36453	30719	26326	14228	11677	8854	8174	7144	4822	3891	3236	11061
1989	193705	122377	85081	46518	43485	25897	21950	19260	10546	8931	6965	6704	5761	3841	3024	11241
1990	190513	131915	86165	58914	36240	31992	20240	16454	14098	7895	6789	5285	5245	4610	2954	11133
1991	143325	129041	95181	50957	42743	27163	24264	15984	12462	10416	6040	5280	4123	4249	3659	11143
1992	129502	97175	91332	55202	38210	32866	21310	18692	11782	8896	7671	4444	4037	3173	3352	12121
1993	108191	88527	70237	66262	44269	30042	26320	17066	14151	9011	6700	5683	3138	3164	2429	12664
1994	132743	73802	65044	54019	48603	33625	23978	20434	13141	9868	6849	5283	4616	2479	2539	12304
1995	168913	89942	53212	50425	42349	37404	26490	19253	14846	9924	7457	5316	4228	3842	1982	12381
1996	119536	115143	66080	39600	36704	31159	28221	21928	15356	11131	7574	5975	4222	3440	3105	11427
1997	98794	81536	81779	45065	28650	26510	23798	22794	17192	12660	8516	5796	4662	3318	2642	11677
1998	140808	67436	60080	60208	33410	22184	20939	19126	17465	13588	10403	6776	4410	3641	2486	11499
1999	107292	96114	49539	44717	45224	26112	17503	16584	13733	12713	10472	8471	5313	3331	2865	11323
2000	129429	73343	70848	38087	34443	34506	20184	13204	12593	10278	8935	7705	6796	4288	2598	11553
2001	154606	88467	54128	54970	30639	26861	25641	15812	9732	9126	7700	6614	5883	5395	3453	11117
2002	161774	104873	64950	41685	40441	23194	21338	19368	11343	7795	6785	5621	4753	4477	4257	11742
2003	174741	110627	74125	46015	30230	27059	17338	16406	13094	7762	5748	5056	4001	3357	3290	13002
2004	286768	119434	80877	54835	32769	22705	21419	14559	12577	9416	5774	4607	3941	3009	2427	13383
2005	139686	196098	86998	59141	39291	24068	17090	16136	11496	9873	7203	4582	3679	3160	2429	13043
2006	129310	95197	141227	66029	45175	31635	19748	14060	13049	9299	7670	5426	3457	2899	2572	12772
2007	113486	88357	70310	109809	53036	34746	25399	16093	11145	10364	7340	6112	4375	2641	2236	12552
2008	117322	77561	65392	54436	76247	41734	27326	20796	13272	9374	8723	6197	5159	3648	2177	12419
2009	121061	80178	57277	50219	42589	56178	34149	21772	16841	10806	7595	7415	5177	4253	3074	11915
2010	94808	82769	59328	44046	39120	34237	42467	28267	17834	13679	8695	6311	6227	4187	3533	12299
2011	43040	64811	60867	45792	34533	31152	28415	35415	23272	14546	10745	7076	5181	5072	3418	13104
2012	90175	29433	47934	47276	34881	27268	24436	23682	27055	19441	12131	8872	5784	4269	4280	13847
2013	59827	61630	21661	36778	36749	28190	22485	20464	19434	21961	15962	10338	7403	4788	3525	15323
2014	24036	40906	45523	16774	28974	30180	23483	19072	16694	16466	18202	13308	8759	6247	4057	16087
2015	29947	16429	29814	35183	12797	23714	25111	20220	16130	13669	13411	15173	11026	7271	5309	17275
2016		20478	12169	22877	27958	10307	19895	21247	16926	13629	10871	10770	12635	9185	6070	19114
2017			15163	9143	16666	22401	8549	16987	17174	13702	10859	8699	8644	10662	7842	21729
2018				10888	6363	13253	18275	7371	13868	13635	10716	8817	6990	7104	9192	25601

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

Year	Age 1	Age 2	Age 3	Age 4	Age 5	Age 6	Age 7	Age 8	Age 9	Age 10	Age 11	Age 12	Age 13	Age 14	Age 15	Age 16+
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	0.01	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	0.47	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	0.27	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	0.04	0.05	0.05	0.07	0.10	0.13	0.12	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	0.05	0.08	0.13	0.14	0.15	0.15	0.15
1987	0.01	0.13	0.15	0.16	0.20	0.15	0.10	0.10	0.11	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	0.15	0.17	0.14	0.11	0.16	0.15	0.15
1990	0.01	0.03	0.29	0.12	0.11	0.12	0.10	0.15	0.18	0.15	0.14	0.14	0.10	0.13	0.13	0.13
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	0.16	0.19	0.24	0.13	0.17	0.10	0.10
1993	0.00	0.01	0.02	0.11	0.10	0.07	0.11	0.13	0.24	0.15	0.13	0.10	0.13	0.12	0.10	0.10
1994	0.01	0.03	0.02	0.04	0.08	0.08	0.08	0.19	0.16	0.16	0.14	0.11	0.07	0.12	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	0.11	0.13	0.13
1996	0.00	0.04	0.14	0.12	0.15	0.11	0.07	0.11	0.07	0.15	0.16	0.14	0.13	0.16	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	0.16	0.14	0.19	0.12	0.12
1998	0.00	0.01	0.06	0.09	0.07	0.08	0.09	0.20	0.20	0.14	0.10	0.13	0.17	0.14	0.11	0.11
1999	0.00	0.01	0.02	0.06	0.09	0.10	0.14	0.15	0.17	0.23	0.20	0.11	0.10	0.15	0.11	0.11
2000	0.00	0.00	0.01	0.02	0.07	0.14	0.10	0.18	0.20	0.17	0.19	0.16	0.12	0.12	0.14	0.14
2001	0.01	0.01	0.02	0.11	0.10	0.07	0.14	0.20	0.10	0.18	0.21	0.22	0.16	0.14	0.12	0.12
2002	0.00	0.05	0.11	0.12	0.22	0.13	0.12	0.26	0.26	0.19	0.18	0.23	0.24	0.21	0.11	0.11
2003	0.00	0.01	0.06	0.14	0.11	0.07	0.04	0.14	0.21	0.18	0.11	0.14	0.18	0.22	0.10	0.10
2004	0.00	0.02	0.07	0.13	0.13	0.12	0.14	0.11	0.12	0.15	0.12	0.12	0.11	0.11	0.09	0.09
2005	0.00	0.03	0.04	0.07	0.04	0.04	0.06	0.08	0.09	0.13	0.17	0.17	0.13	0.11	0.09	0.09
2006	0.00	0.00	0.01	0.02	0.08	0.06	0.07	0.10	0.11	0.12	0.12	0.11	0.16	0.16	0.10	0.10
2007	0.00	0.00	0.02	0.17	0.06	0.08	0.06	0.06	0.05	0.05	0.06	0.06	0.07	0.09	0.08	0.08
2008	0.00	0.00	0.02	0.05	0.13	0.04	0.09	0.08	0.09	0.09	0.05	0.07	0.08	0.07	0.10	0.10
2009	0.00	0.00	0.02	0.05	0.04	0.12	0.05	0.07	0.09	0.10	0.08	0.07	0.10	0.09	0.10	0.10
2010	0.00	0.01	0.02	0.04	0.05	0.03	0.04	0.06	0.08	0.12	0.10	0.09	0.10	0.10	0.09	0.09
2011	0.00	0.00	0.01	0.07	0.06	0.08	0.04	0.14	0.06	0.06	0.08	0.09	0.08	0.07	0.08	0.08
2012	0.00	0.01	0.03	0.05	0.03	0.03	0.04	0.07	0.09	0.08	0.05	0.07	0.08	0.09	0.07	0.07
2013	0.00	0.00	0.02	0.04	0.02	0.02	0.03	0.07	0.05	0.07	0.07	0.06	0.06	0.07	0.06	0.06
2014	0.00	0.02	0.02	0.07	0.02	0.02	0.01	0.04	0.08	0.09	0.07	0.08	0.08	0.06	0.05	0.05
2015	0.00	0.00	0.03	0.03	0.04	0.02	0.03	0.05	0.05	0.11	0.11	0.07	0.07	0.08	0.07	0.07
2016	0.00	0.00	0.05	0.12	0.04	0.03	0.02	0.08	0.09	0.11	0.11	0.11	0.06	0.06	0.05	0.05
2017	0.00	0.01	0.09	0.16	0.05	0.04	0.01	0.07	0.11	0.13	0.10	0.11	0.09	0.05	0.04	0.04
2018	0.00	0.00	0.01	0.11	0.11	0.07	0.01	0.17	0.16	0.16	0.12	0.13	0.11	0.08	0.04	0.04

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

Year	SSB (young_spawn)	SSB (older_spawn)	Recruitment (Age 1)
1974	39730	29945	651429
1975	36526	28410	328926
1976	34792	26776	233091
1977	31851	23382	188348
1978	29249	19842	127606
1979	26026	16240	180031
1980	22832	13121	141386
1981	19852	11437	127119
1982	18473	10427	188039
1983	18296	10289	178367
1984	18116	10026	158260
1985	16787	9390	185030
1986	18084	9432	170821
1987	18353	9603	177799
1988	18254	9724	185764
1989	18208	9523	193705
1990	18073	9245	190513
1991	18650	9265	143325
1992	18363	9115	129502
1993	18785	9130	108191
1994	18663	9236	132743
1995	19868	9550	168913
1996	19776	9658	119536
1997	19761	9918	98794
1998	19794	10405	140808
1999	20129	10923	107292
2000	19349	10949	129429
2001	18951	10352	154606
2002	17879	9769	161774
2003	17647	9291	174741
2004	17025	9207	286768
2005	17254	9310	139686
2006	18462	9396	129310
2007	20103	9897	113486
2008	23052	10484	117322
2009	23268	10724	121061
2010	24364	11292	94808
2011	24694	12235	43040
2012	26067	13823	90175
2013	26564	15621	59827
2014	27401	17103	24036
2015	27205	17886	29947
2016	26865	18225	-
2017	25749	18414	-
2018	24780	18572	-

Indices of Relative Abundance

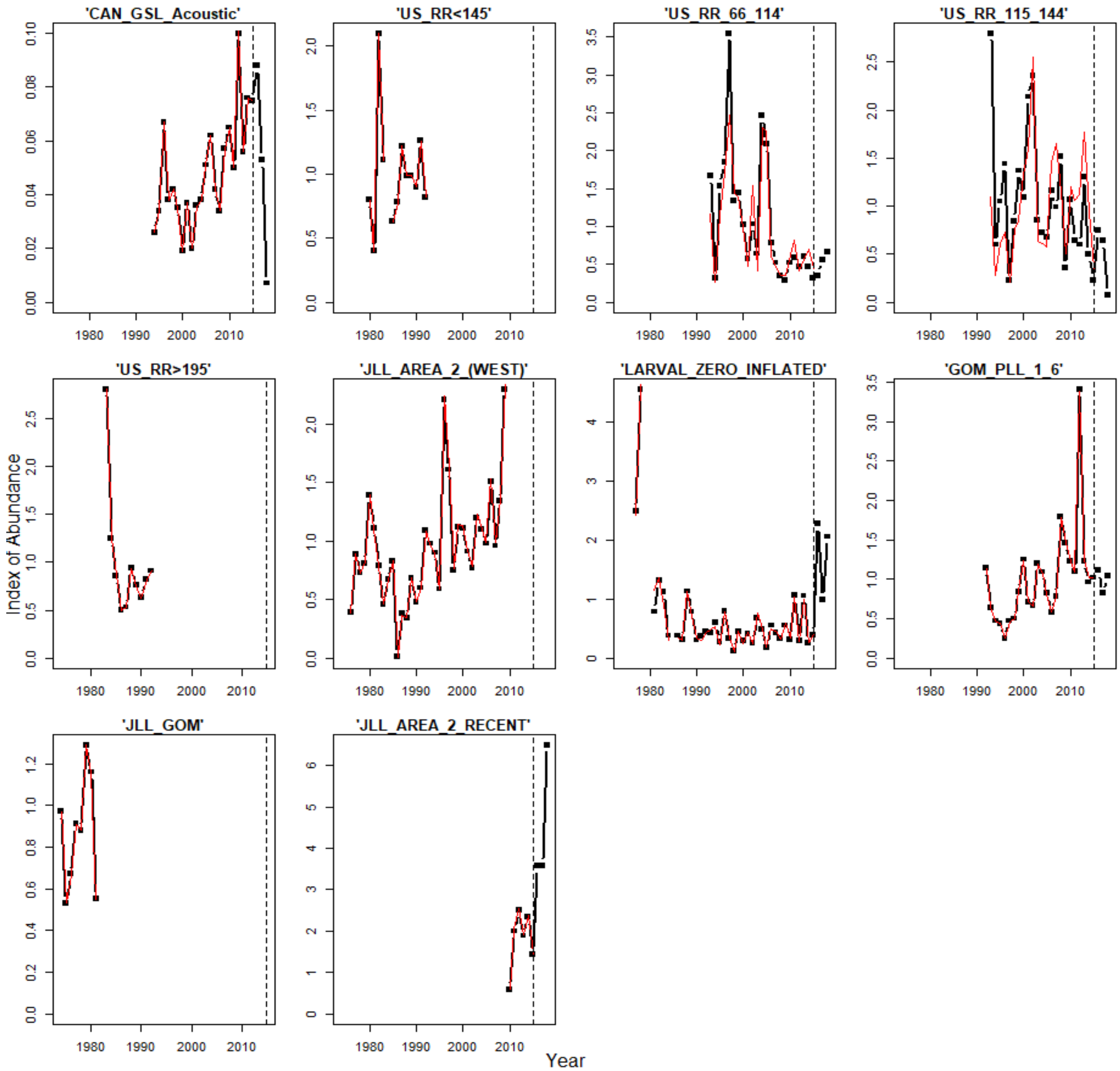


Figure 1. Indices of relative abundance of bluefin tuna in the West Atlantic used in the VPA. The red line shows the time series in the 2017 base VPA, and the black lines show the updated time series.

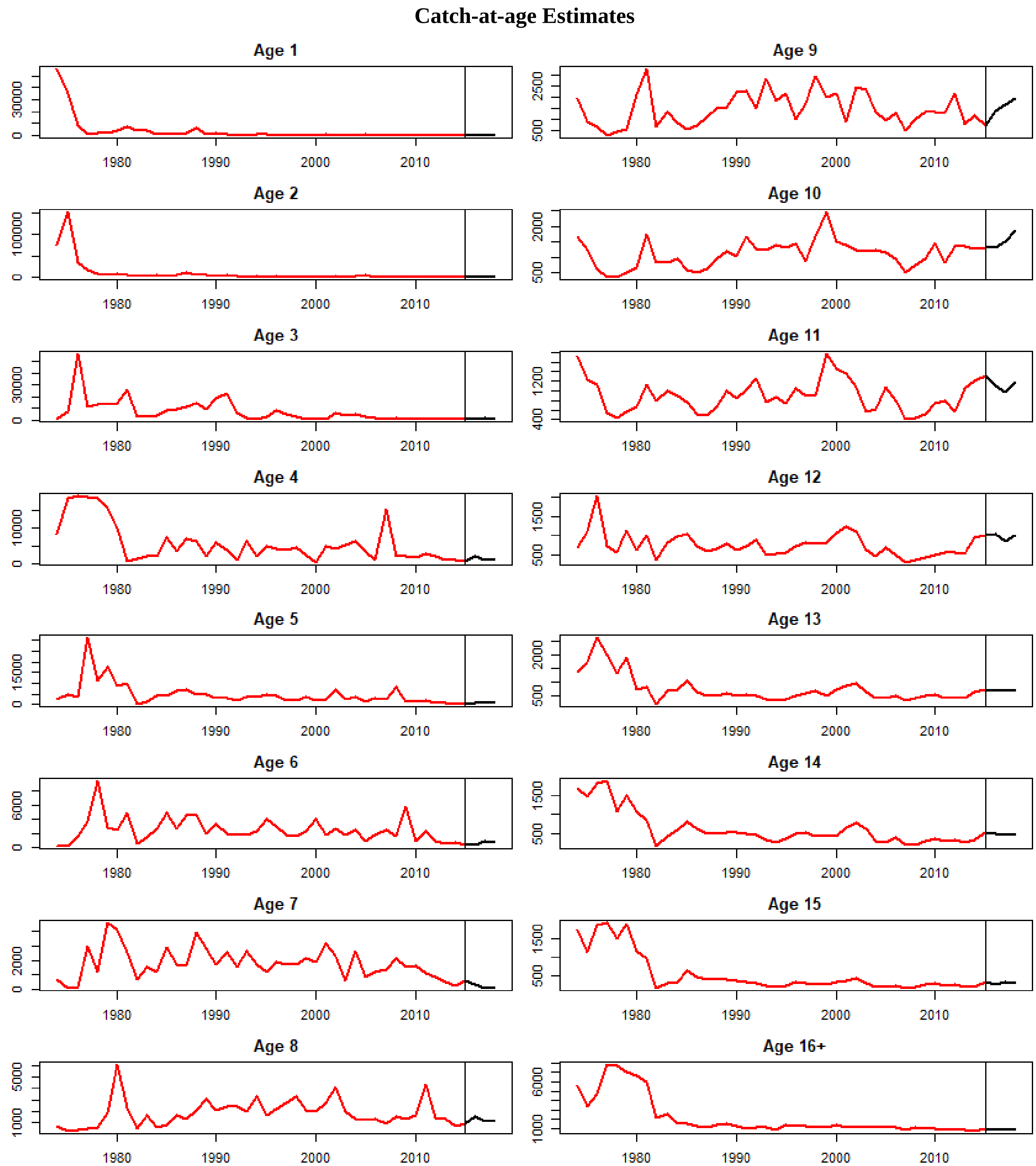


Figure 2. Catch-at-age estimates of bluefin tuna in the West Atantic, based on cohort slicing of total catches-at-size. The red lines shows the catch estimates by ageclass in the 2017 base assessment and the black lines show the updated time series.

Model convergence across Jitter Iterations

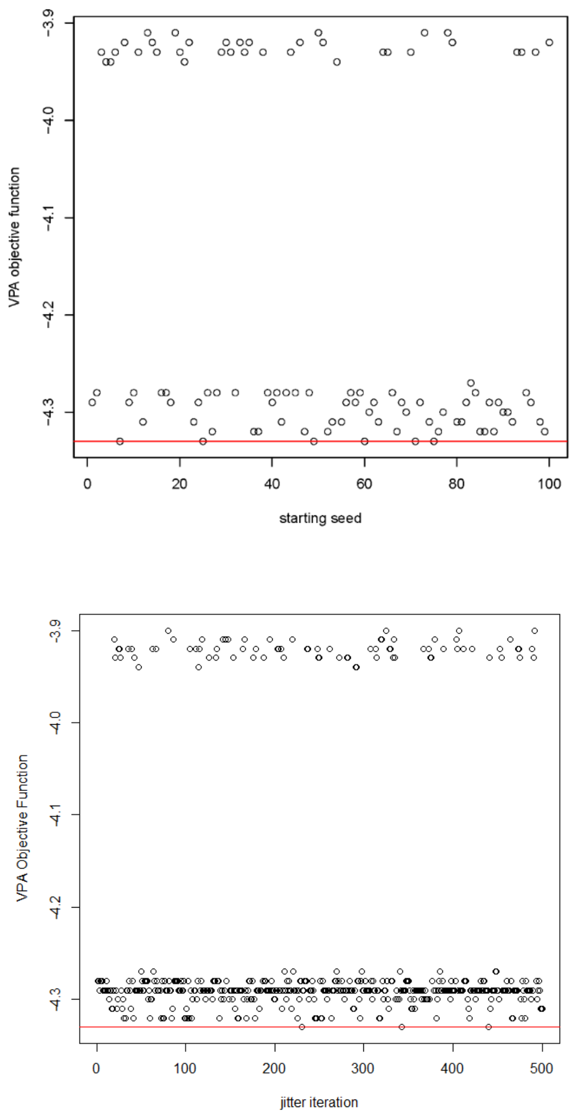


Figure 3. Final objective function values (negative log-likelihood) across random starting seed (upper panel) and jittered starting F parameters (lower panel). The red line shows the minimum negative log-likelihood solution of the base model.

VPA fits to Indices of Abundance

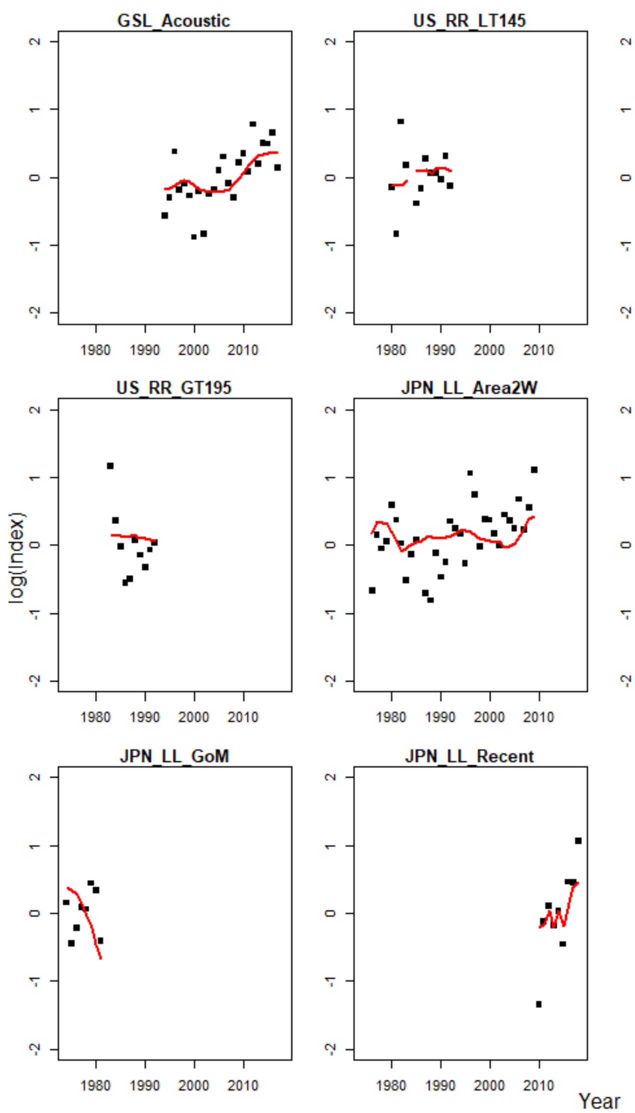


Figure 4. VPA base model fits (red lines) to indices of relative abundance (black points).

Recruitment estimates by Jitter Iteration

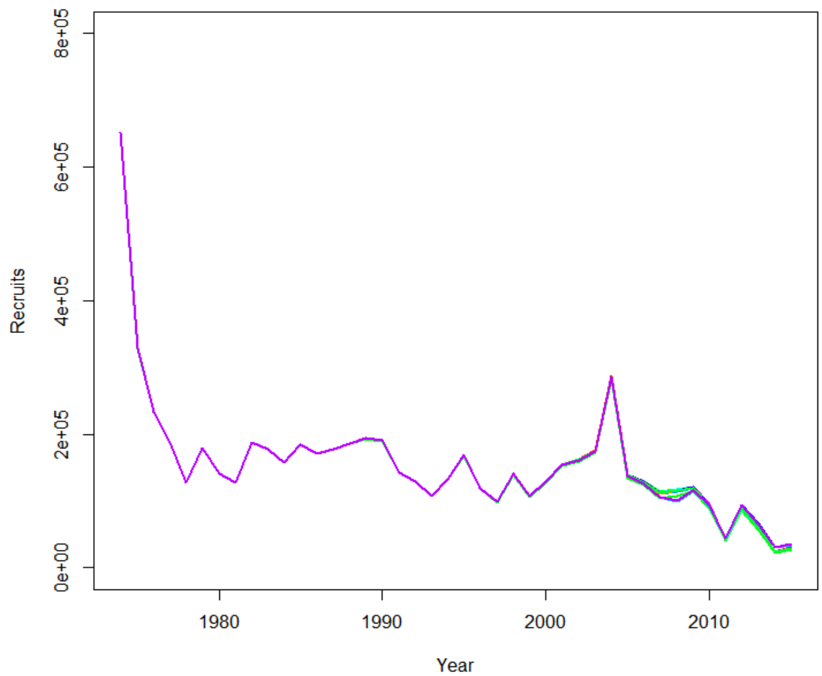


Figure 5. Estimates of recruitment of bluefin tuna in the West Atlantic, plotted across trials (n=500) with random starting seed and jittered terminal F parameter starting values.

VPA residuals

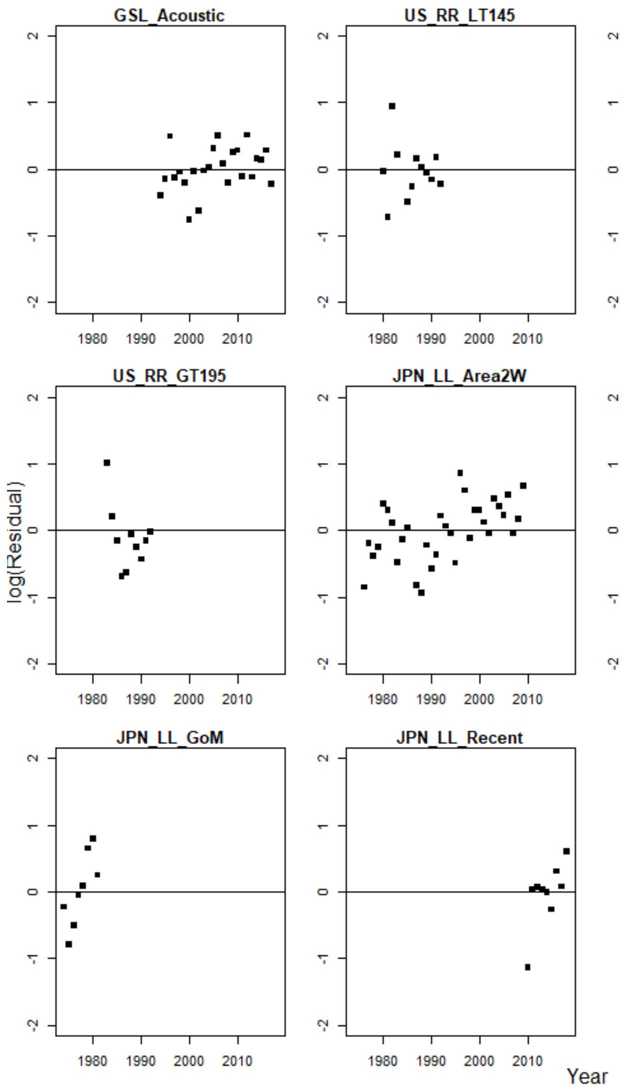
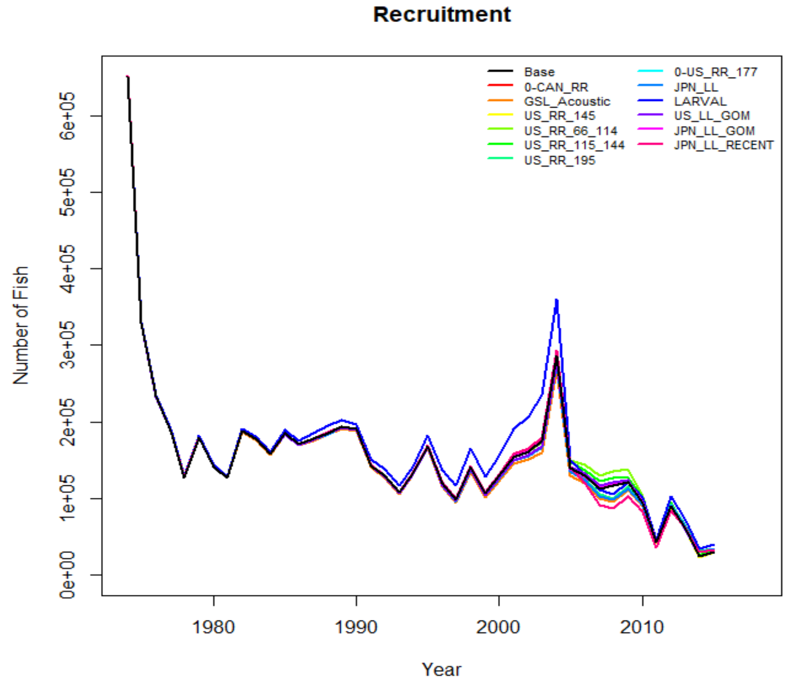


Figure 6. Residual errors (log-e scale) of base model fits to the indices of relative abundance.

Index Jackknife Analysis



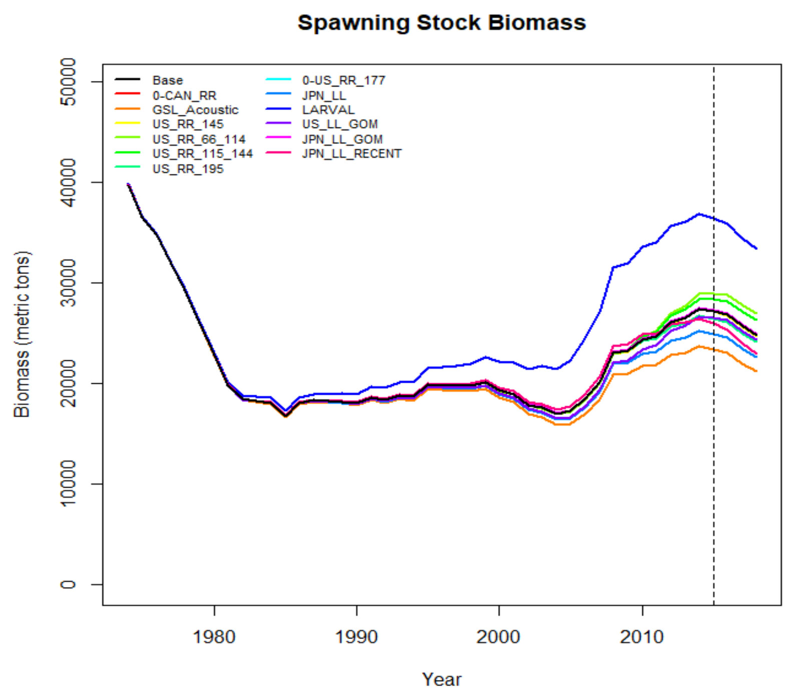


Figure 7. Index jackknife effects on estimates of bluefin tuna recruitment and spawning stock biomass (young spawning scenario) in the West Atlantic.

Retrospective Analysis

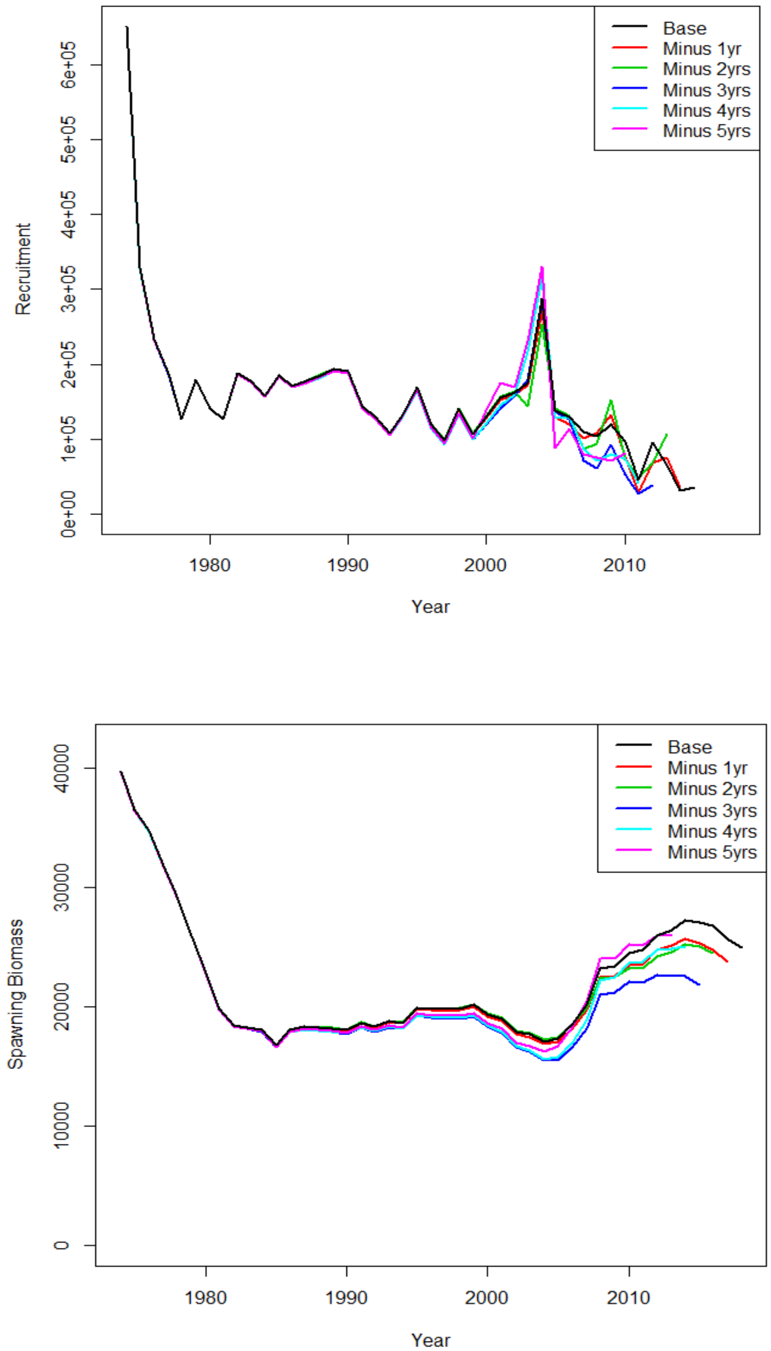


Figure 8. Retrospective estimates of bluefin tuna recruitment (upper panel) and spawning stock biomass (young spawn scenario, lower panel) in the West Atlantic.

F-ratio Profile

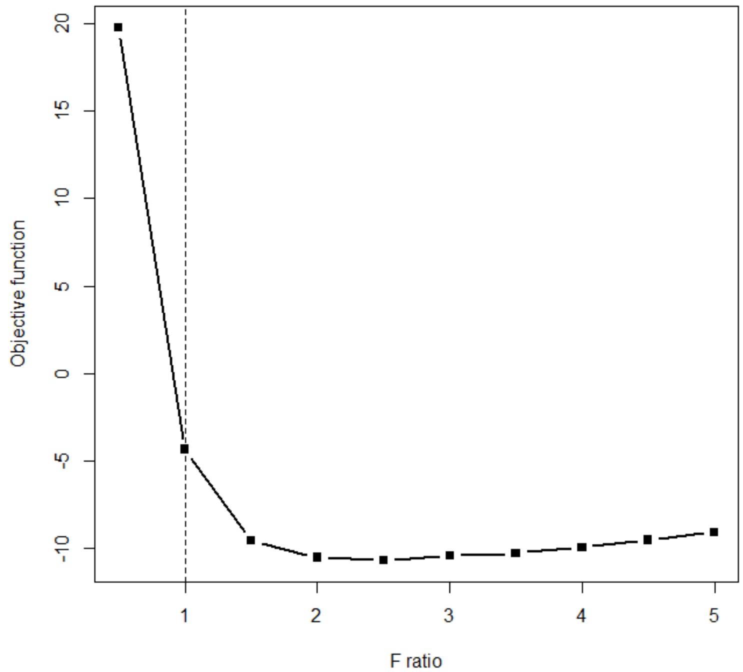


Figure 9. VPA likelihood profile of the F-ratio parameter.

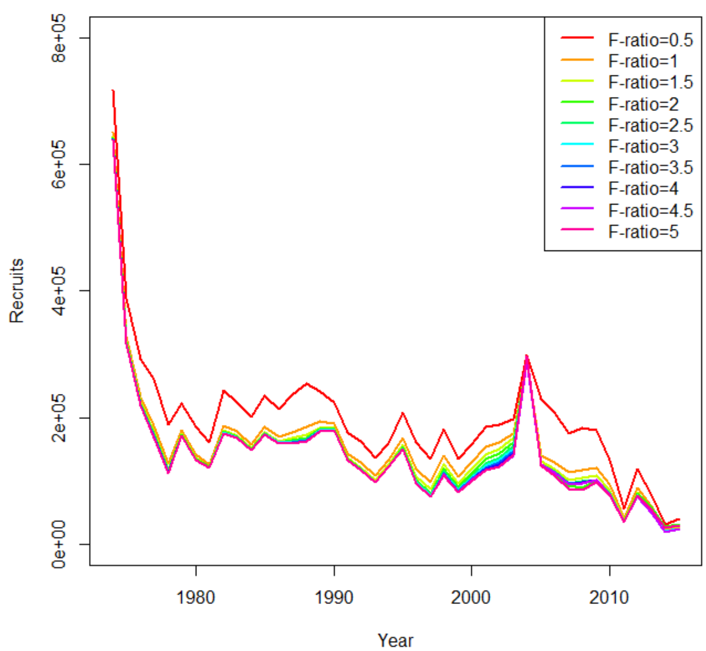


Figure 10. Sensitivity of West Atlantic bluefin tuna recruitments to alternative F-ratios (base model value = 1.0).

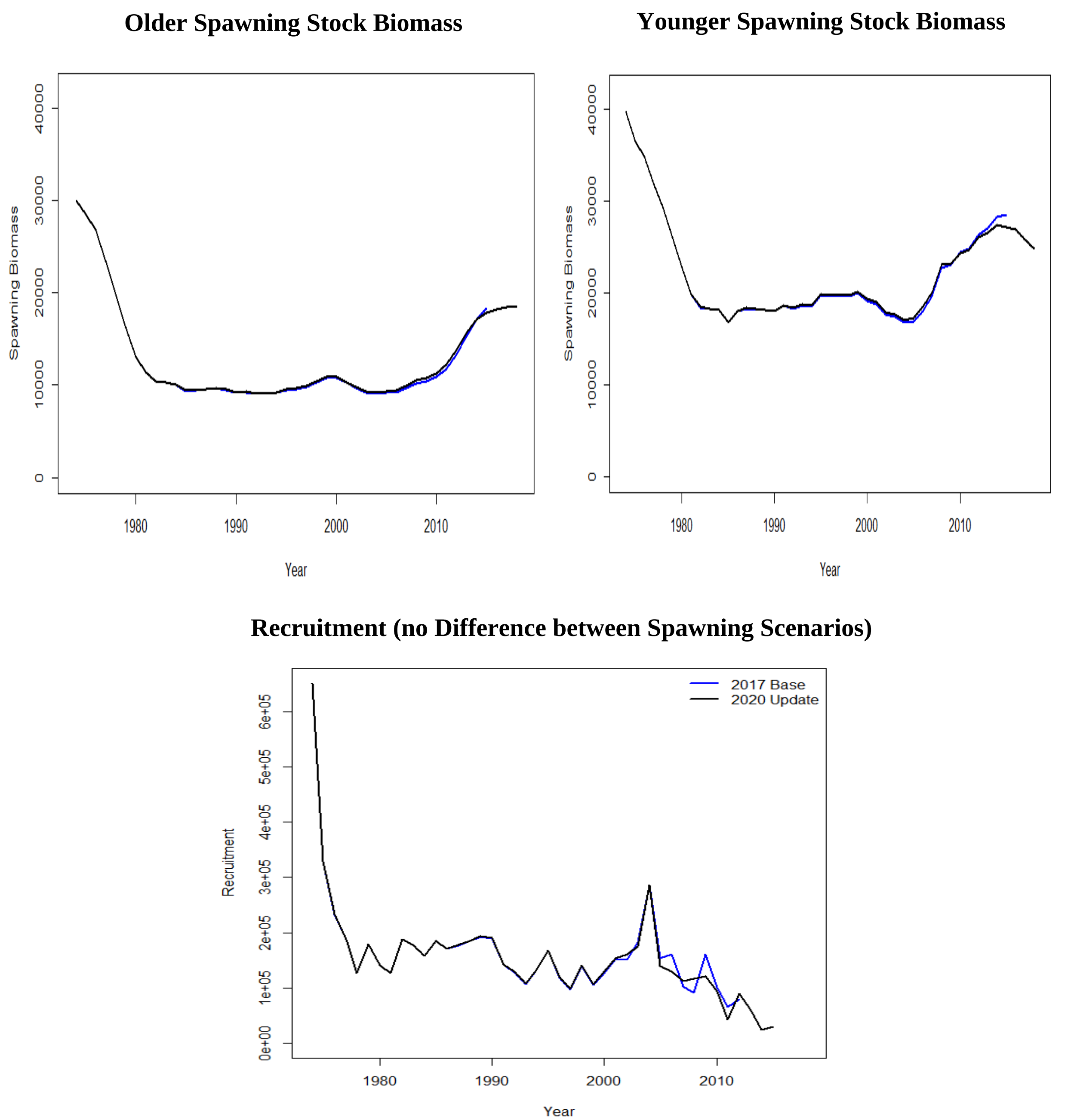


Figure 11. Spawning stock biomass (upper panels, left = older spawning scenario, right=young spawning scenario) and recruitment estimates (lower panel) of bluefin tuna in the West Atlantic compared to the 2017 assessment (blue lines).

Bootstrap Estimates of Abundance

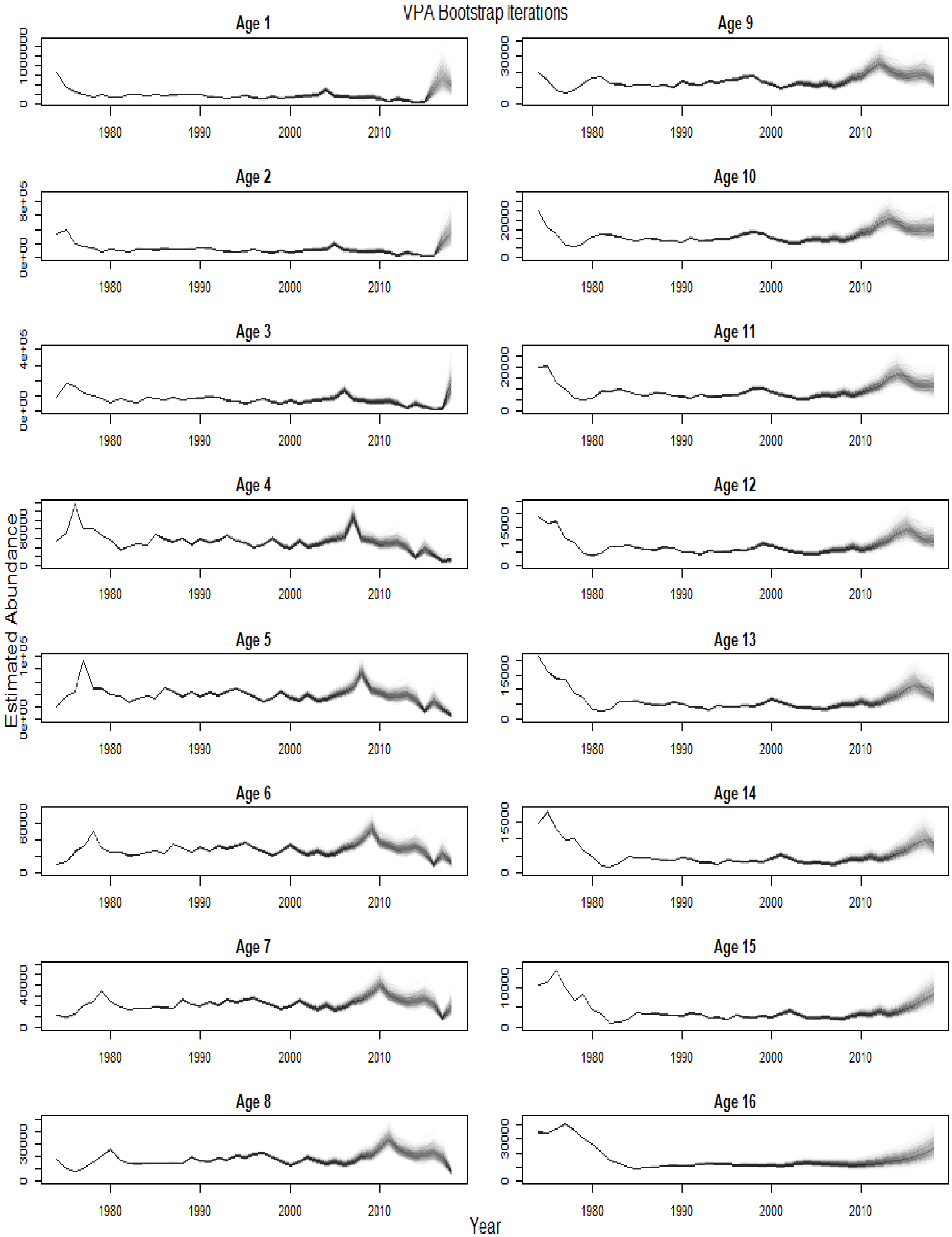


Figure 12. Estimated abundance-at-age of West Atlantic bluefin tuna. Each gray line shows the annual estimates from one of the 500 bootstrap iteration of the base VPA.

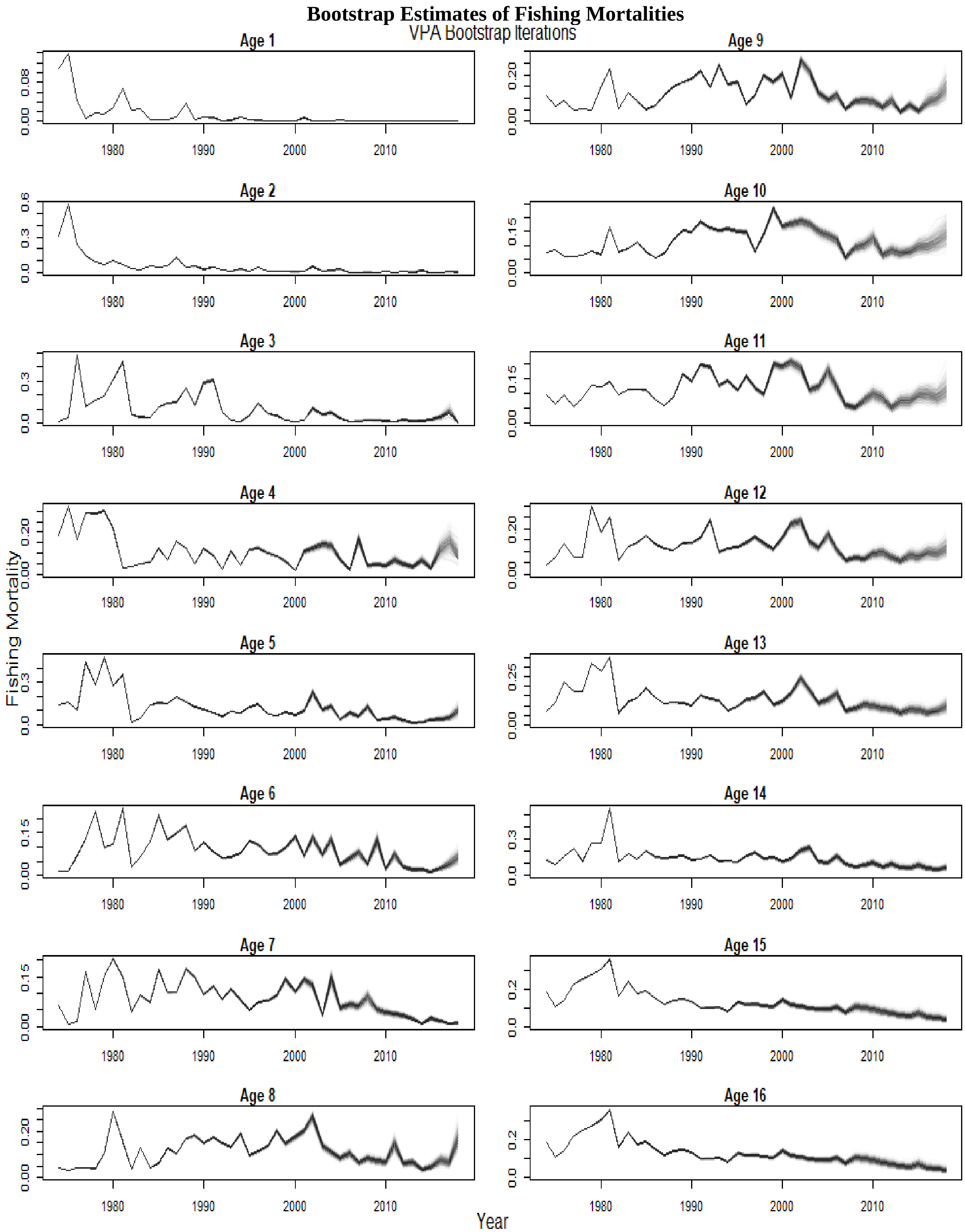


Figure 13. Estimated fishing mortalities-at-age of bluefin tuna in the West Atlantic. Each gray line shows the annual estimates from one of the 500 bootstrap iteration of the base VPA.

Apical Fishing Mortality

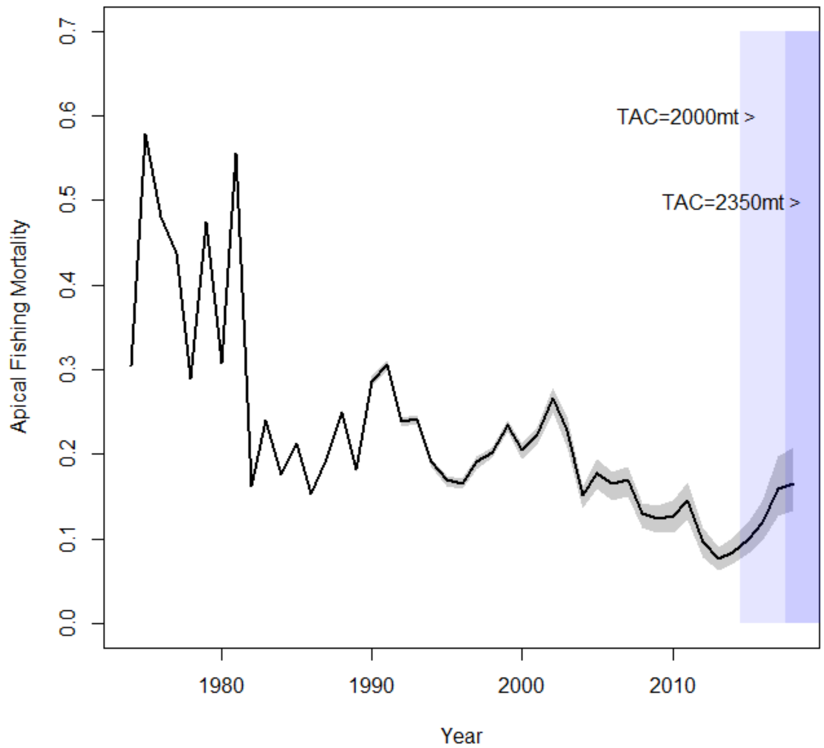


Figure 14. Estimated apical fishing mortality (maximum annual F-at-age) of bluefin tuna in the West Atlantic. The black line shows the median of the bootstraps, and the gray shaded area represents the 80% confidence intervals. The total allowable catch (TAC) periods over the last two assessment cycles are shaded blue.

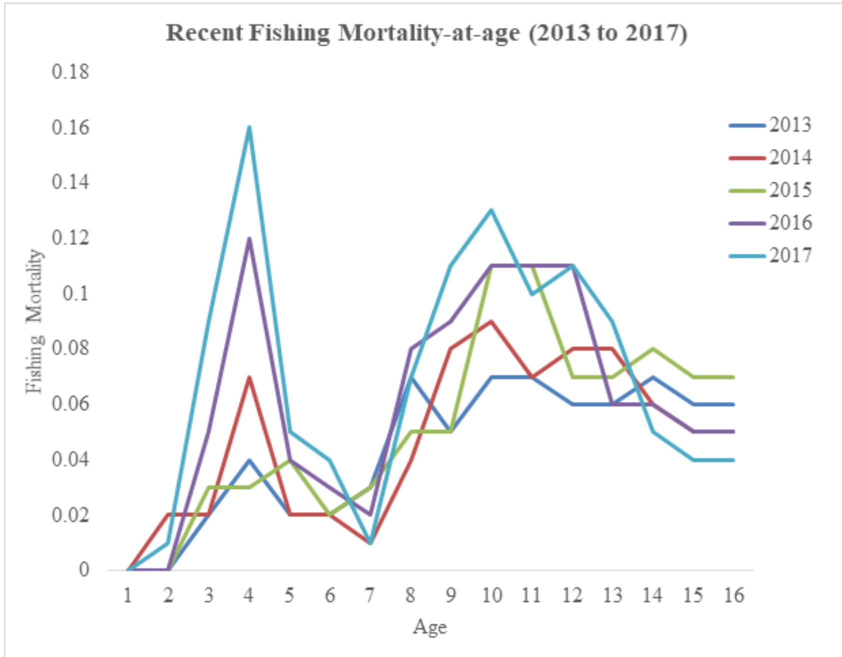


Figure 15. Fishing mortality-at-age estimates of bluefin tuna in the West Atlantic during 2013 to 2017.

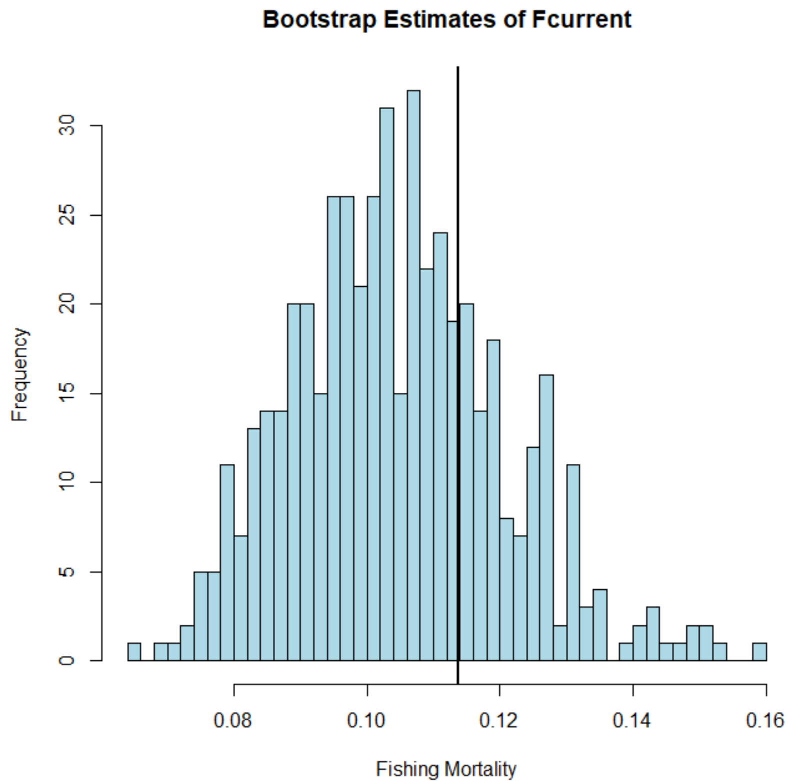
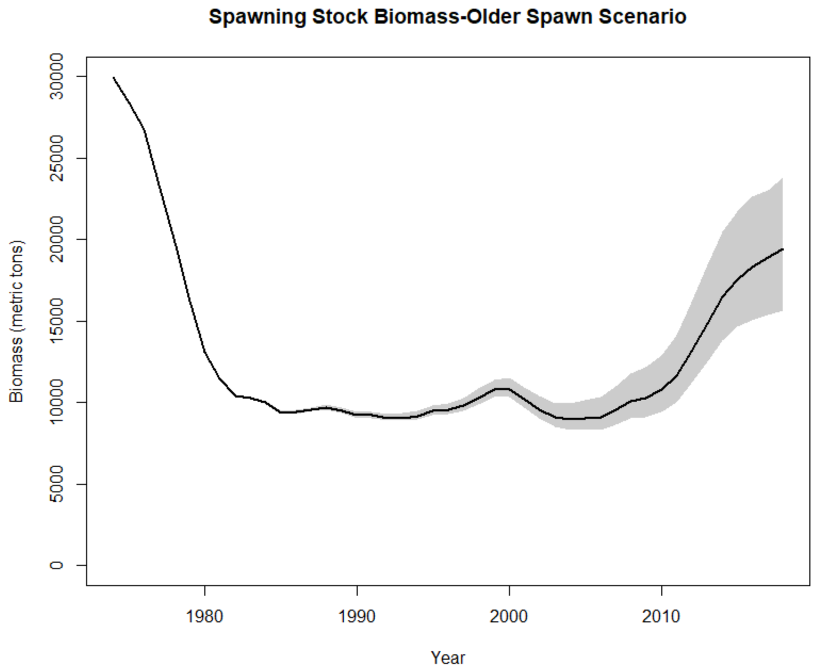


Figure 16. Estimated current fishing mortality (2015 to 2017 mean apical F) of bluefin tuna in the West Atlantic. The blue histogram shows the distribution of estimates across bootstraps, and the vertical black line shows the deterministic run estimate.

Figure 17. 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.



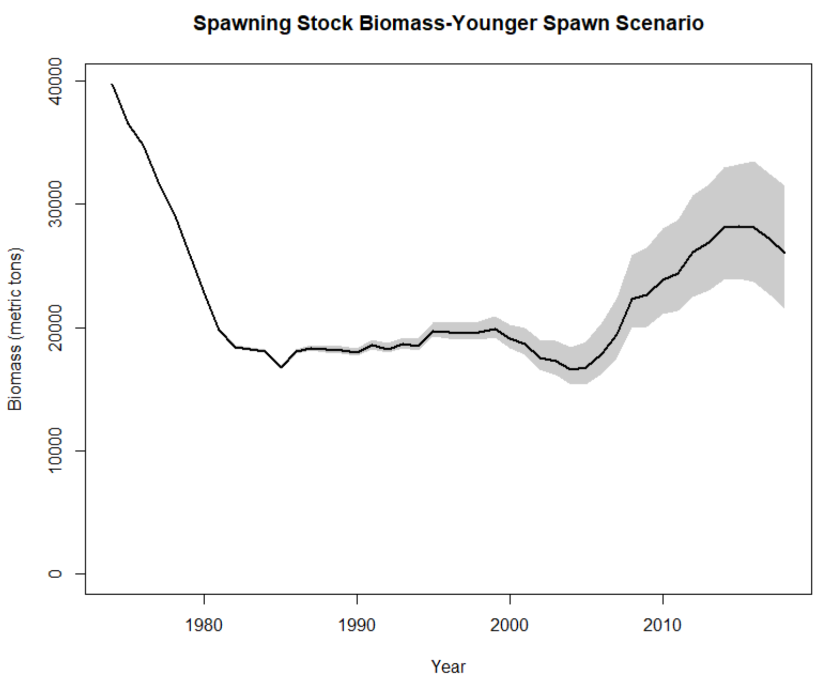


Figure 18. Estimated spawning stock biomass of bluefin tuna in the West Atlantic. The black line shows the median of the bootstrap trials, and the gray shaded area shows the 80% confidence intervals.

Stock-Recruitment Plot

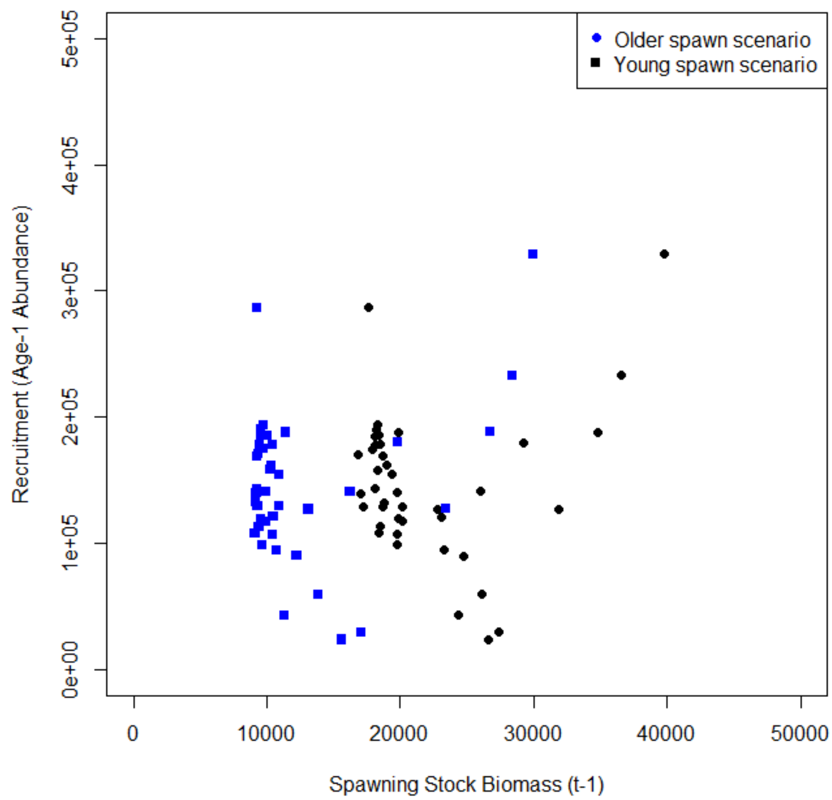


Figure 19. VPA stock-recruitment estimates. The black points show the young spawning scenario and the blue points show the older spawning scenario.