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A COMPARISON OF INITIAL STATISTICAL CATCH-AT-AGE AND CATCH-AT-LENGTH ASSESSMENTS OF WESTERN ATLANTIC BLUEFIN TUNA

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SUMMARY

A concern associated with existing Atlantic bluefin tuna age-based assessments using Virtual Population Analysis (VPA) is that the catch-at-age data inputs are obtained by the cohort-slicing method, which is approximate and might introduce appreciable bias into the results. Current custom in such circumstances is rather to fit the assessment model directly to the basic catch-at-length data available, under the assumption of invariance of the distributions of length-at-age of the fish over time, with statistical models used to formulate the likelihoods maximized in the model fitting process. Initial results are presented for a process of comparing the 2012 ICCAT SCRS VPA assessment of the western stock with first a statistical catch-at-age assessment approach which also uses the same cohort-sliced catch-at-age inputs, and then a statistical catch-at-length method which fits instead to catch-at-length distributions.

RÉSUMÉ

La crainte que suscitent les évaluations existantes basées sur l'âge du thon rouge de l'Atlantique au moyen de l'analyse de population virtuelle (VPA) est que les données de prise par âge sont obtenues par la méthode de découpage des cohortes, laquelle est approximative et pourrait introduire des biais appréciables dans les résultats. La pratique courante dans ces circonstances consiste plutôt à ajuster le modèle d'évaluation directement aux données fondamentales de prise par taille disponibles, sous le postulat d'invariance des distributions de prise par âge du poisson dans le temps, avec des modèles statistiques utilisés pour formuler les vraisemblances maximisées dans le processus d'ajustement du modèle. Les résultats initiaux sont présentés pour un processus de comparaison de l'évaluation du stock de l'Ouest au moyen de la VPA réalisée par le SCRS de l'ICCAT en 2012 avec d'abord une approche d'évaluation de la prise statistique par âge qui utilise aussi les mêmes données d'entrée de prise par âge découpées par cohorte et ensuite une méthode de prise statistique par taille qui s'ajuste plutôt aux distributions de prise par taille.

RESUMEN

Una inquietud asociada con las evaluaciones basadas en la edad del atún rojo del Atlántico existentes realizadas mediante análisis de población virtual (VPA) es que los datos de entrada de captura por edad se obtienen mediante el método de separación de cohortes, que es aproximativo y puede introducir sesgos notables en los resultados. Lo que se suele hacer en estas circunstancias es ajustar el modelo de evaluación directamente a los datos básicos de captura por talla disponibles, partiendo del supuesto de no variación de la distribución de talla por edad de los peces en el tiempo, utilizando modelos estadísticos para formular las verosimilitudes maximizadas en el proceso de ajuste del modelo. Se presentan los resultados iniciales para un proceso de comparación de la evaluación VPA del SCRS de ICCAT de 2012 del stock occidental con un enfoque de evaluación estadístico de captura por edad que utiliza las mismas entradas de captura por edad con separación de cohortes y, posteriormente, con un método estadístico de captura por talla que se ajusta a distribuciones de captura por talla.

KEYWORDS

Age composition, Biomass, Size composition, Stock assessment, Tuna fisheries

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1. Introduction

The longer-term objective of this work is the development of a two-stock assessment of the North Atlantic bluefin tuna population which takes mixing between the fish of western and of eastern origin into account, in particular by using new information from electronic tags and from otolith microchemistry in the model fitting process (*i.e.* similar to the model developed by Taylor *et al*. 2011). This should provide a more realistically-based assessment of the bluefin tuna in the North Atlantic (and Mediterranean), and would also provide Operating Models for testing candidate Management Procedures for this resource (*i.e.* in the planned Management Strategy Evaluation, or MSE, process).

However a concern with that model, and indeed with the models used currently by ICCAT that assume separate stocks, is that they are fit to catch-at-age data derived using the rather coarse approach of cohort-slicing, which might be introducing considerable bias into the results. Given the increase in computing power that has become available over the most recent decade, current custom in such circumstances is rather to fit the assessment model directly to the basic catch-at-length data available, usually under the assumption of invariance of the distributions of length-at-age of the fish over time, which considerably simplifies the analysis. Rather than utilise Virtual Population Analysis (VPA), which makes the assumption (the more poorly justified in cases where cohort-slicing is used to provide the catch-at-age values input) that the resultant catch-at-age values are error free, statistical models (Statistical Catch at Age, SCAA for age data or Statistical Catch at Length, SCAL when the length data are input directly) are used to formulate the likelihoods maximised in the model fitting process.

Thus the first step required in addressing the longer-term objective for this work is the development of SCAL assessments for the western and eastern (plus Mediterranean) components of the fishery treated as separate stocks as in current ICCAT assessments. In this paper, initial results are presented by way of comparing one of the 2012 ICCAT SCRS VPA assessments (the Continuity Run) for the western stock of North Atlantic bluefin tuna (NABFT) with first two versions of a SCAA approach which also uses the same cohort-sliced catch-at-age inputs, and then a SCAL method which fits instead to catch-at-length distributions. This follows a similar exercise carried out for the eastern (plus Mediterranean) stock (Butterworth and Rademeyer 2012).

2. Data and methods

The data utilised are documented in Appendix A. The choice of historic catch estimates that has been made is the same as used for the VPA continuity run from the 2012 ICCAT assessment meeting (ICCAT 2012).

The details of the SCAA and SCAL methodologies are provided in Appendix B, which also lists the values input for certain parameters for the associated models. Both SCAA and SCAL applications fit to the data series for both CPUE and age (or length) information in manners as similar as possible to those used in the VPA continuity run ICCAT (2012).

Some of the specific choices made within these methodologies for the analyses presented here are simpler than may eventually prove optimal, in line with the initial nature of these analyses. To mention some of the more important, which will be subject to subsequent sensitivity investigations:

- The stock–recruitment form fit is of the Beverton-Holt type, but for practical purposes reflects expected recruitment as independent of spawning biomass through fixing steepness $h = 0.98$ for the baseline runs. The standard deviation of the residuals of log recruitment about this relationship is assumed to have the value $\sigma_R = 0.6$. Thus far, sensitivities to this have been run for one of the SCAA assessments as detailed below.

- To assist stabilise estimation, the resource is assumed to be at its deterministic pre-exploitation equilibrium with the corresponding age structure at the start of the period considered (1950).

- Though one change in selectivity at age/length over time has been introduced to improve fits to the purse seine catch-at-age/length data, further changes might improve the fit further.

- A single variance for all CPUE series has been used, as is understood to have been the case for the VPA continuity run.

- Catch-at-age and catch-at-length contributions to the overall log-likelihood are downweighted by multiplicative factors of 0.1 and 0.05 respectively. This is necessary to take account of the non-independence of such data (fish of similar age or size tend to group together, so that the tuna caught in, for example, the same longline set do not constitute independent samples). However the magnitudes specified for these weights are somewhat arbitrary; the ratio of the length to the age weighting is based on the fact that there are about twice as many length classes as age classes considered in the fitting process.

For the SCAL assessment, the distributions of length-at-age are assumed to be normal with CVs of 20% about their means (**Figure 1** shows the growth curve and the distributions of length-at-age used for the SCAL run). Note that either because the data were not available or for related reasons, this “SCAL” in fact continued to fit to catch-at-age rather than catch-at-length data for a few indices.

3. Results

Two alternatives have been considered for the SCAA implementations: “SCAA-FixedS” for which the abundance indices’ selectivities are fixed to those estimated in the VPA continuity run and the selectivity of each of the fleet for the plus group is taken to be the same as that of the immediately lower age (as is done for the VPA continuity run), and “SCAA-EstS” for which all the selectivities are freely estimated (see **Table B1**). For SCAL, the selectivities are freely estimated.

A brief summary of key results for these three models is provided in **Table 1**, which includes values for the contributions of various data sources and penalties to the (penalised) log-likelihood, as well as estimates of current depletion expressed in terms of spawning biomass. The brevity of presentation is deliberate at this stage; given the initial nature of these results, it would not be appropriate to focus on more than broad features at this time.

Figure 2 compares the spawning biomass time-series estimated for the three model implementations, and also shows the results from the VPA continuity run of ICCAT (2012).

Figure 3 compares recruitment time-series, while **Figure 4** plots the stock–recruitment relationships and stock–recruitment residuals.

The fits to the various CPUE indices in **Figure 5** are not “unreasonable”, given the evident noise in these data.

Figure 6 shows the estimated selectivity-at-age vectors for the five fleets for the two SCAA runs, together with their fits (which are generally good) to the age distribution proportions averaged over years and in terms of residuals (bubble plots). The fits to the distributions of proportions of catch-at-length averaged over years under the SCAL model are similarly reasonable (**Figure 7**).

Similarly, **Figures 8, 9 and 10** show the estimated selectivities and fits to the age/length distribution proportions for the abundance indices for the SCAA-FixedS, SCAA-EstS and SCAL respectively.

Figure 11 shows spawning biomass trajectories and stock–recruit relationships for SCAA_EstS for different fixed values for steepness *h*.

4. Discussion

For the two SCAA fits, estimating selectivity (“SCAA-EstS”) provides the better fit in terms of the negative log-likelihood (**Table 1**), arising particularly from better fits to the CAA data which in turn reflect greater doming in the selectivities (**Figure 6**) and hence higher biomasses (**Figure 2**).

The SCAL assessment is closer to that of SCAA-EstS, but does not reflect the increase in spawning biomass over the more recent years that SCAA-EstS does. However prior to 1970, the SCAL results look more like those for SCAA-FixedS, with a near discontinuity at 1970 (**Figure 2**). This is a consequence of the very poor fit to the stock–recruitment "data" (**Figure 4**), which in turn allows for unrealistically large recruitments over a short period in the early 1960s which cause this near-discontinuity. It is important to note that, consistent with the VPA continuity run, there are no abundance indices or age/length composition data prior to 1970 input to these SCAA and SCAL assessments, so that those early estimates of abundance are being driven effectively entirely by the stock–recruitment relationship assumed and the implicit associated assumption of its stationarity.

Some initial sensitivities have been run for SCAA-EstS, focusing on lower values of steepness *h* which are fixed on input. As *h* is decreased, the fit improves (**Table 2**), the spawning biomass becomes lower and does not reflect a recent increase, and the Beverton-Holt curve provides a better reflection of the underlying form assumed (**Figure 11**).

There are many assumptions and value choices that have had to be made for these initial SCAA and SCAL assessment runs. Feedback from meeting participants on these, and on how they might be improved/rendered more reliable would be appreciated.

Problems with the data when moving to SCAL

A number of problems have arisen in the process of converting from a SCAA to SCAL assessment formulation:

- Age 0 is not included in VPA and SCAA—but this becomes difficult in SCAL
- The first two CAN CPUE series differ only by age groups (with 2 ages overlapping)—this cannot be effected in SCAL—this is why the SCAL fits to CAA rather than to CAL for these two series, which are not distinguished in the length information as provided
- JLL GOM: the CAA data are not properly described, so that it was not possible to determine an equivalent CAL—hence CAA were used in the SCAL for this series
- US PLL GOM: CAL grouped by length groups, but not consistent and very large grouping—hence CAA were used rather than CAL in the SCAL assessment.

Note: The "Larval zero inflated" index has been treated as an index of spawning biomass, with selectivity not estimated as in VPA.

5. Conclusion

The broad features of these results are rather similar to those found in the corresponding analysis for the eastern Atlantic Bluefin tuna (Butterworth and Rademeyer 2012). Compared to the current ICCAT VPA, biomasses are higher because the data prefer a more domed shape for the selectivity functions, and for the more recent years the SCAL suggests a more stable abundance compared to the increase suggested by the SCAA. Clearly more examination of the consequences of different assumptions for the stock–recruitment relationship is needed in further work. Immediately however, the opportunity provided by the meeting at which this paper is to be presented should be taken to resolve some remaining queries about the catch-at-length data.

Acknowledgements

We thank Laurie Kell for assistance in providing the data used to us. Shannon Cass-Calay and Clay Porch kindly assisted in clarifying some questions about these data.

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Table 1. Results for the two SCAA and the SCAL assessments of this paper with steepness *h* fixed at 0.98. Biomass units are metric tons, and K^{sp} refers to the pre-exploitation equilibrium spawning biomass. Note that the value for the overall negative log likelihood for the two SCAA assessments are comparable to each other, but not to that for the SCAL assessment.

	SCAA-FixedS	SCAA-EstS	SCAL
–lnL: overall	–3566.3	–3628.6	–1176.6
–lnL: CPUE	25.4	31.4	20.7
–lnL: fleet CAA	–2546.2	–2567.1	-
–lnL: fleet CAL	-	-	–738.0
–lnL: index CAA	–1079.0	–1121.1	–279.1
–lnL: index CAL	-	-	–219.0
–lnL: RecRes	33.4	28.1	30.3
Sel smoothing penalty	-	-	8.5
K^{sp}	82956	126945	79614
B^{sp}_{2011}	20379	48308	38456
B^{sp}_{2011}/K^{sp}	0.25	0.38	0.48

Table 2. Results for SCAA-EstS for different fixed values of steepness *h*. Biomass units are metric tons, and K^{sp} refers to the pre-exploitation equilibrium spawning biomass.

	$h = 0.98$	$h = 0.7$	$h = 0.4$
–lnL: overall	–3628.6	–3636.4	–3646.6
–lnL: CPUE	31.4	27.5	27.7
–lnL: fleet CAA	–2567.1	–2567.1	–2568.4
–lnL: index CAA	–1121.1	–1121.1	–1120.9
–lnL: RecRes	28.1	24.3	14.9
K^{sp}	126945	140240	205512
B^{sp}_{2011}	48308	33434	29484
B^{sp}_{2011}/K^{sp}	0.38	0.24	0.14

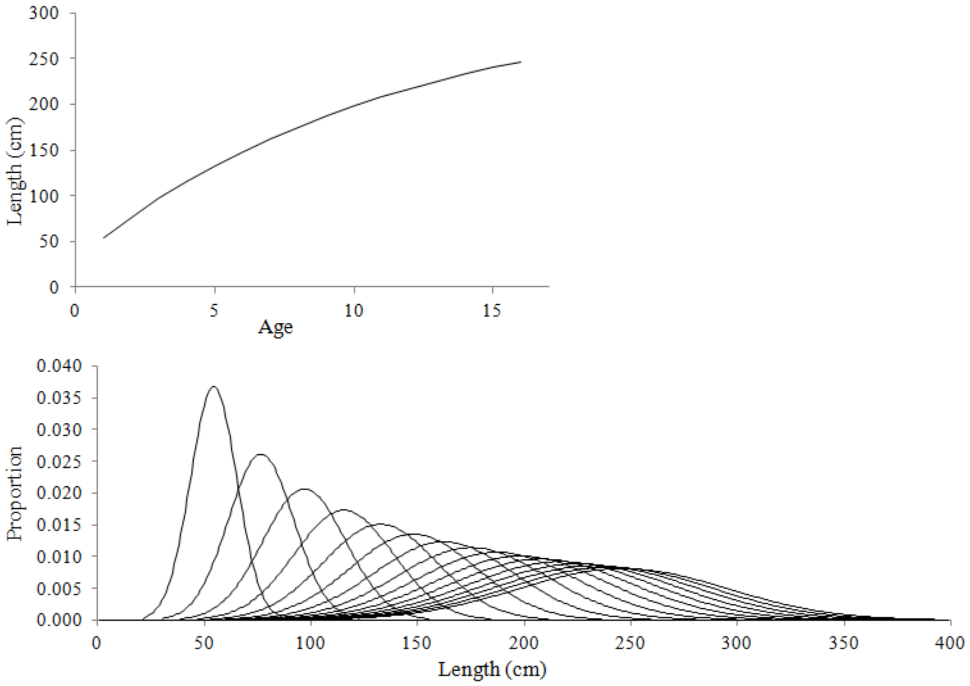

Figure 1. Growth curve and associated length-at-age distributions assumed.

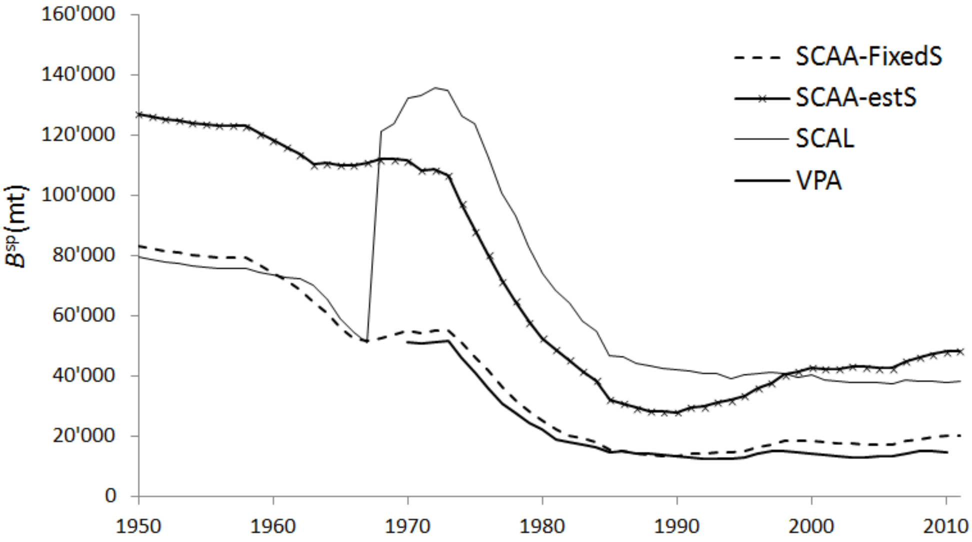

Figure 2. Spawning biomass trajectories. The notation convention used here and below is that VPA refers to Continuation Run from ICCAT (2012), SCAA_FixedS is Statistical Catch at Age with fixed selectivity for the abundance indices and commercial plus group, SCAA_EstS estimates all the selectivities, and SCAL is Statistical Catch at Length with all selectivities estimated. The SCAA and SCAL assessments fix steepness *h* at 0.98.

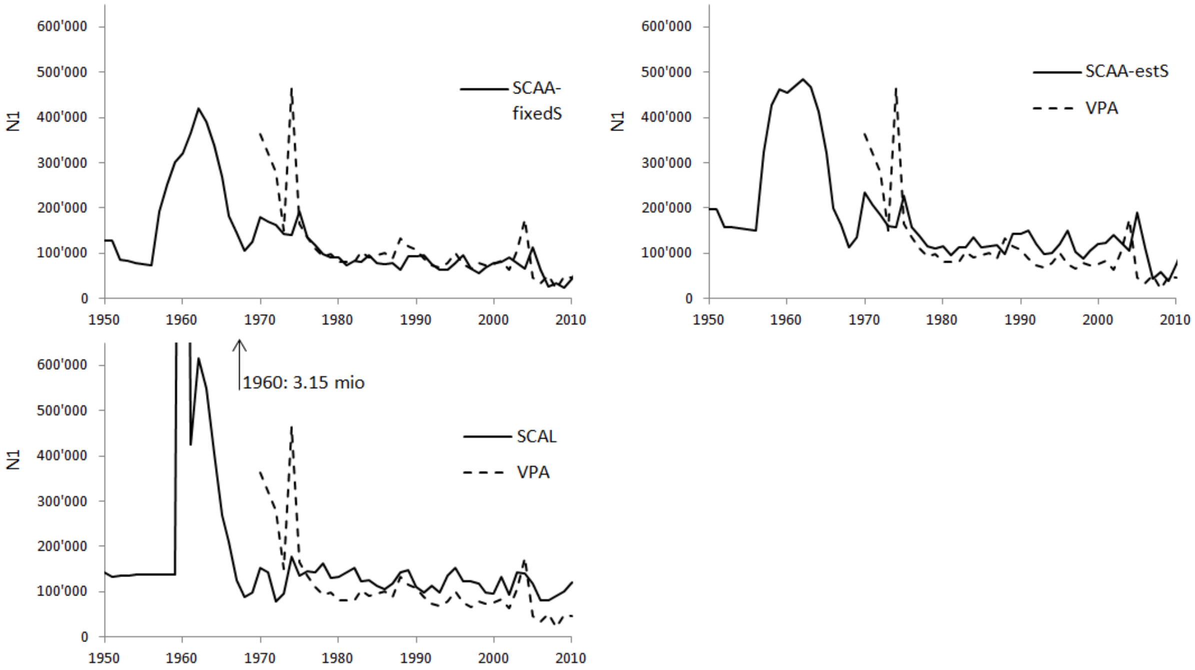

Figure 3. Recruitment (number of 1-year-olds, N_1) trajectories for the four assessments.

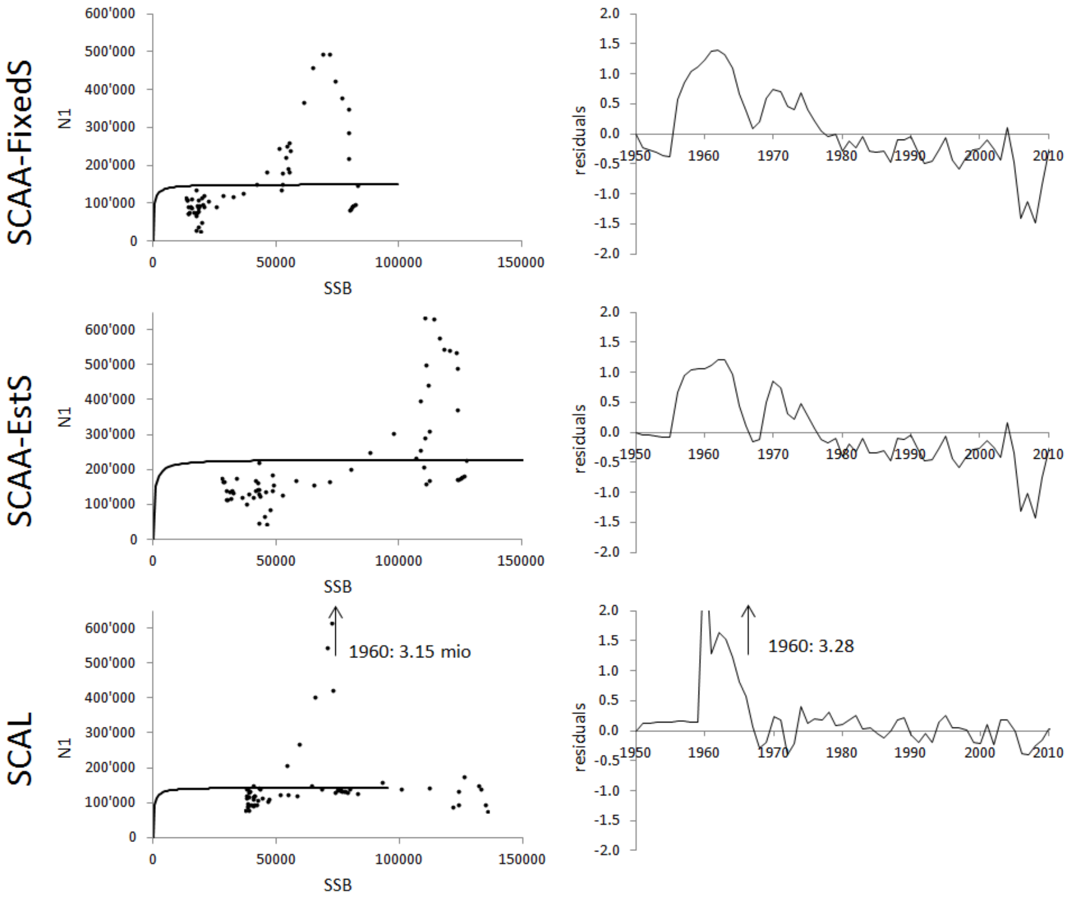

Figure 4. Stock–recruitment relationships (left-hand column) and time series of stock–recruitment residuals for the three new assessments. Spawning stock biomass (SSB) is in metric tons.

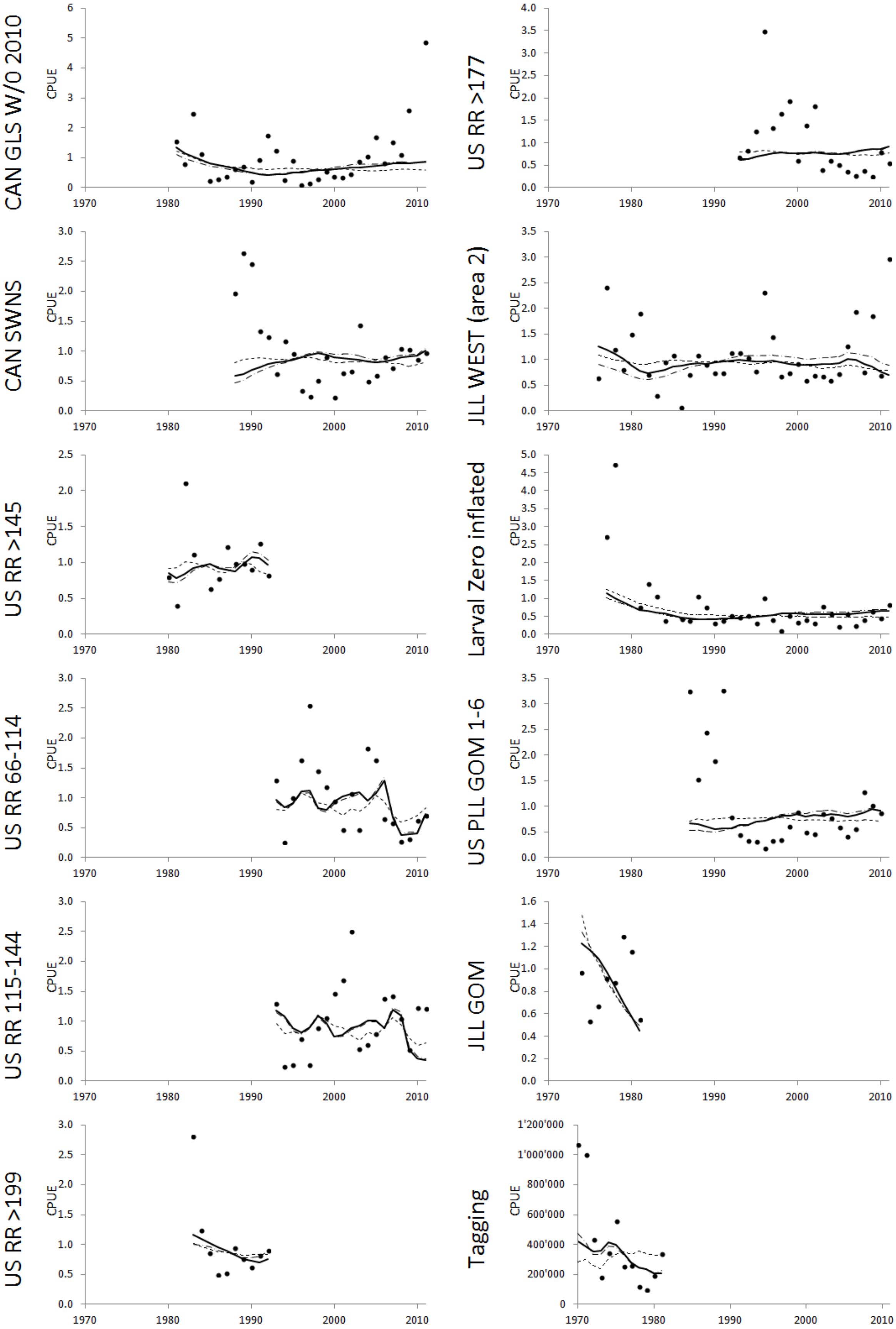

Figure 5. Fits of the new assessment models to the various CPUE series (full line=SCAA_FixedS, dashed-dot=SCAA_EstS and dashed=SCAL).

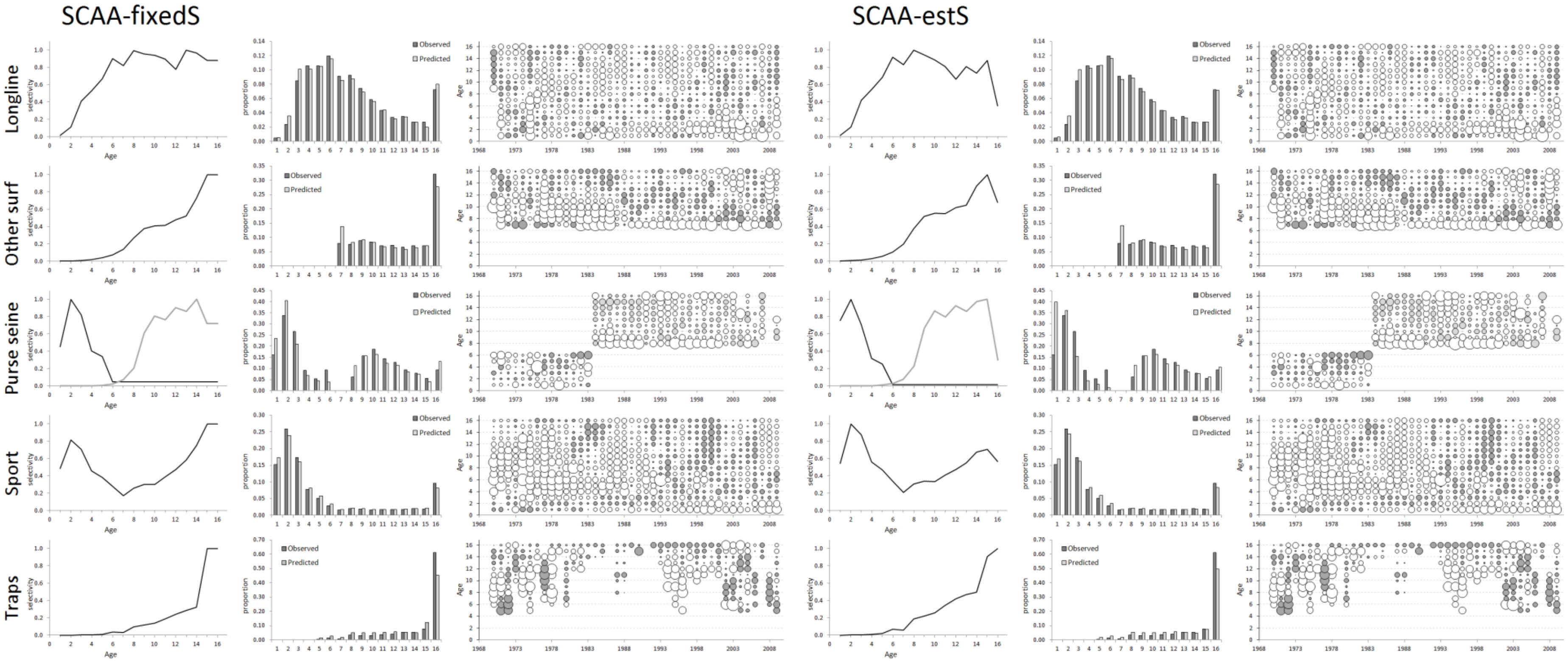

Figure 6. Estimated selectivities-at-age, fits to the CAA data (as averages over all the years with data available) and bubble plots of the CAA standardised residuals for the five fleets for the **SCAA_FixedS** (three left-hand columns) and **SCAA_EstS** (three right-hand columns) assessments. Here and below, in the bubble plots, the size (area) of the bubble is proportional to the magnitude of the corresponding standardised residual. For positive residuals the bubbles are grey, whereas for negative residuals the bubbles are white. Results for the second selectivity period for the purse seine are shown in lighter grey in the plots.

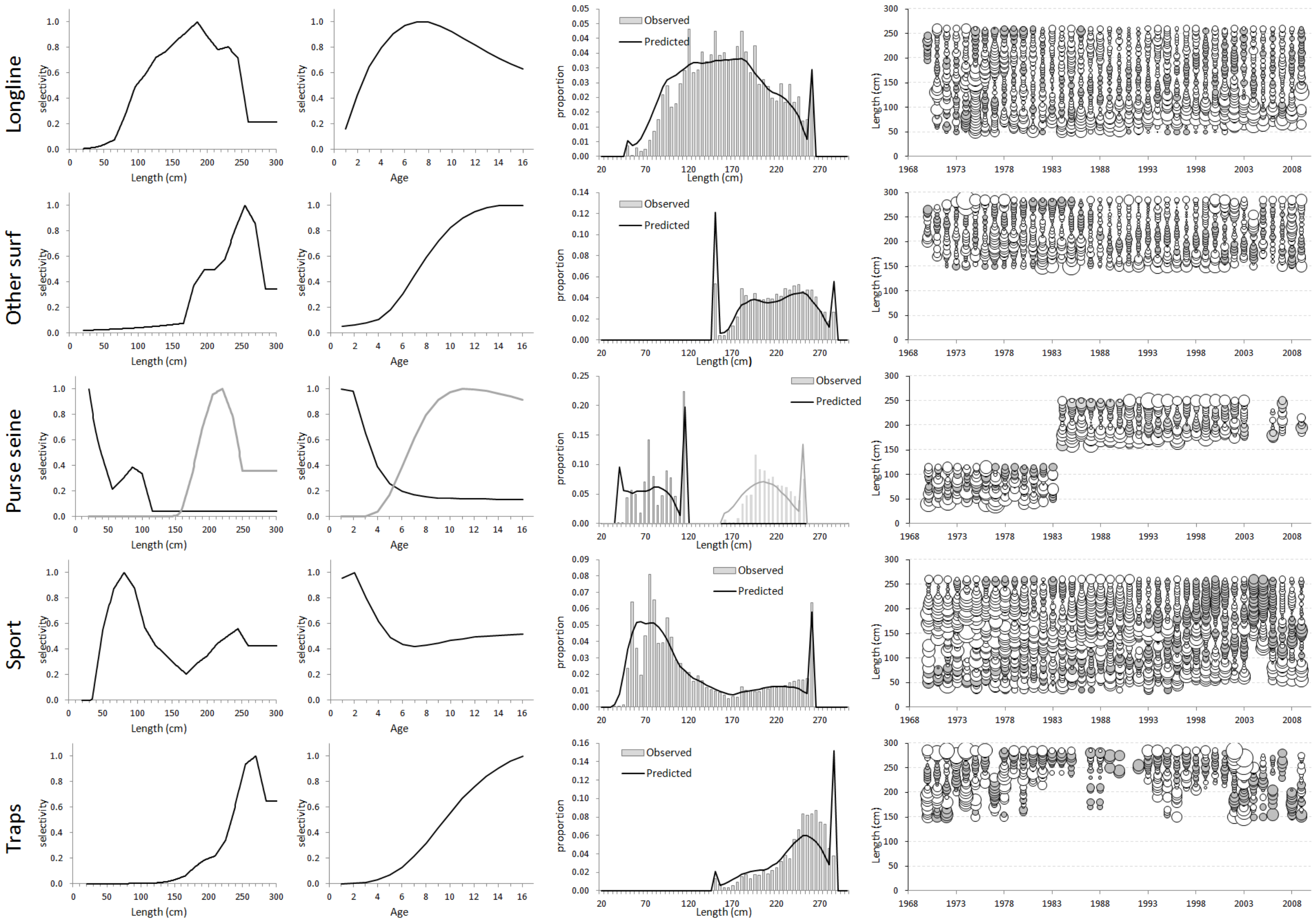

Figure 7. Estimated selectivities-at-length, the effective equivalent selectivities-at-age, fit to the CAL data (as average over all the years with data available), and bubble plots of the CAL standardised residuals for the associated fisheries for the **SCAL assessment**.

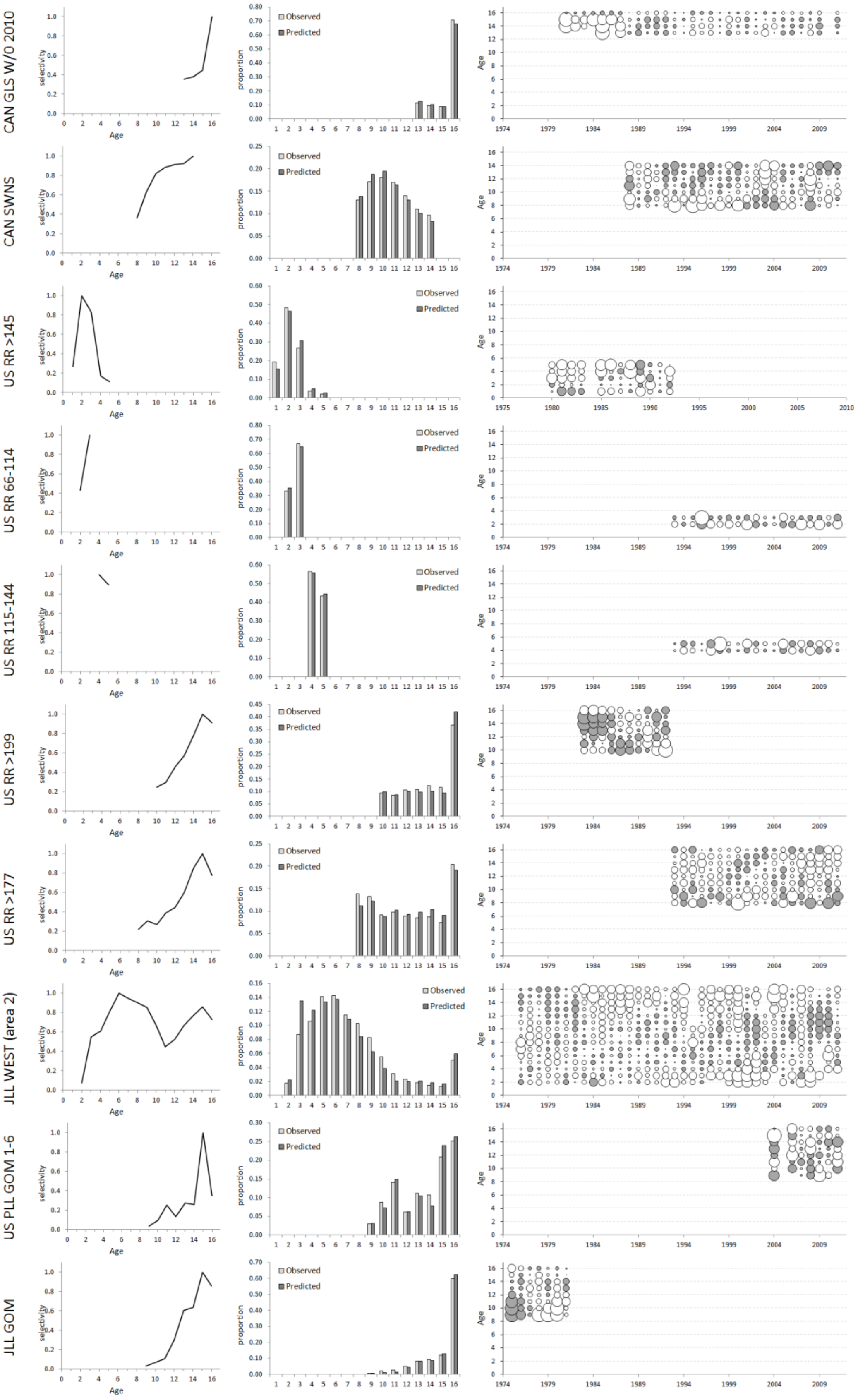

Figure 8. Estimated selectivities-at-age, fit to the CAA data (as average over all the years with data available), and bubble plots of the CAA standardised residuals for the catches associated with indices of abundance for the **SCAA_FixedS assessment**.

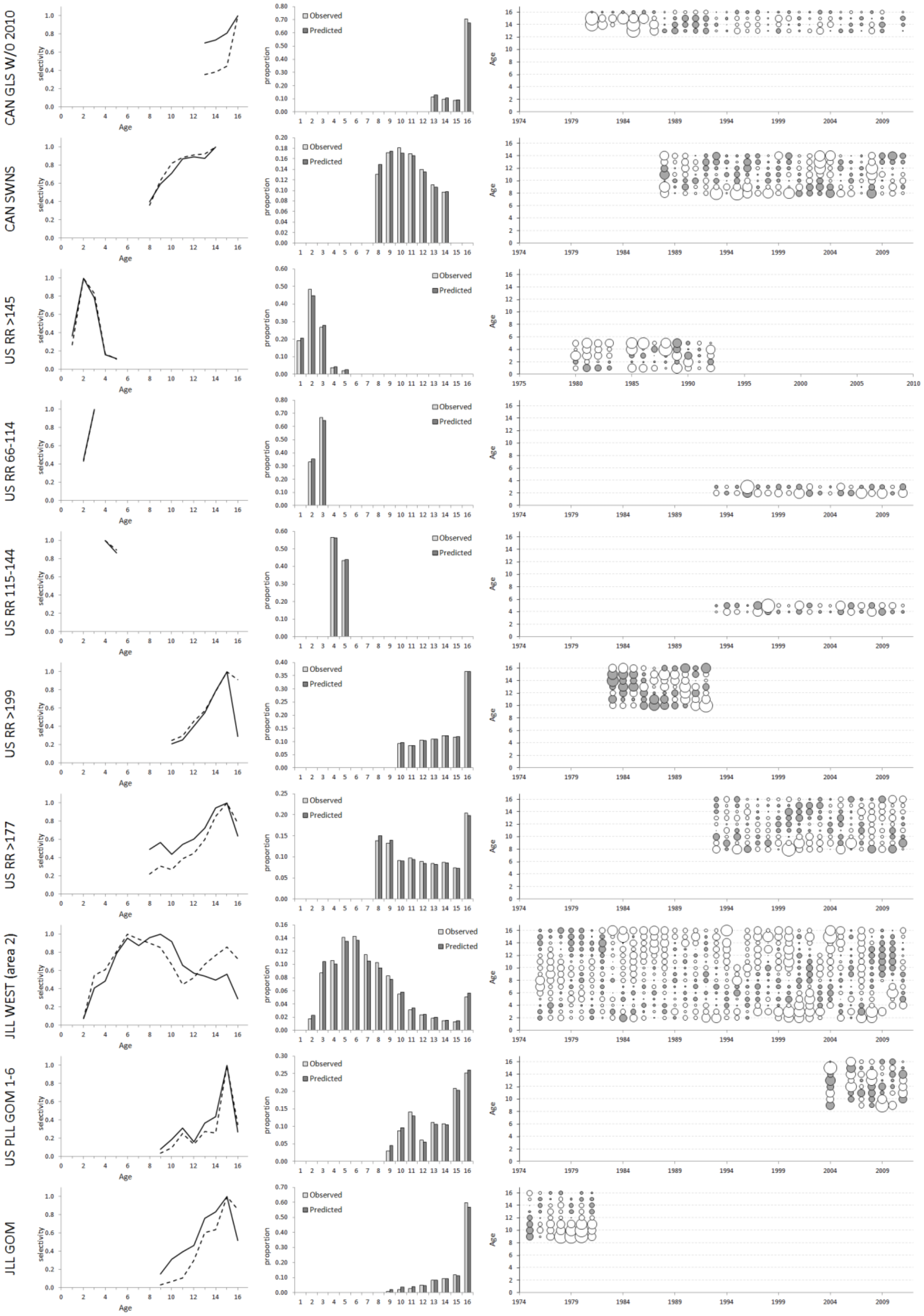

Figure 9. Estimated selectivities-at-age, fit to the CAA data (as average over all the years with data available), and bubble plots of the CAA standardised residuals for the catches associated with indices of abundance for the **SCAA_EstS assessment**. The VPA selectivities-at-age are shown as dashed lines.

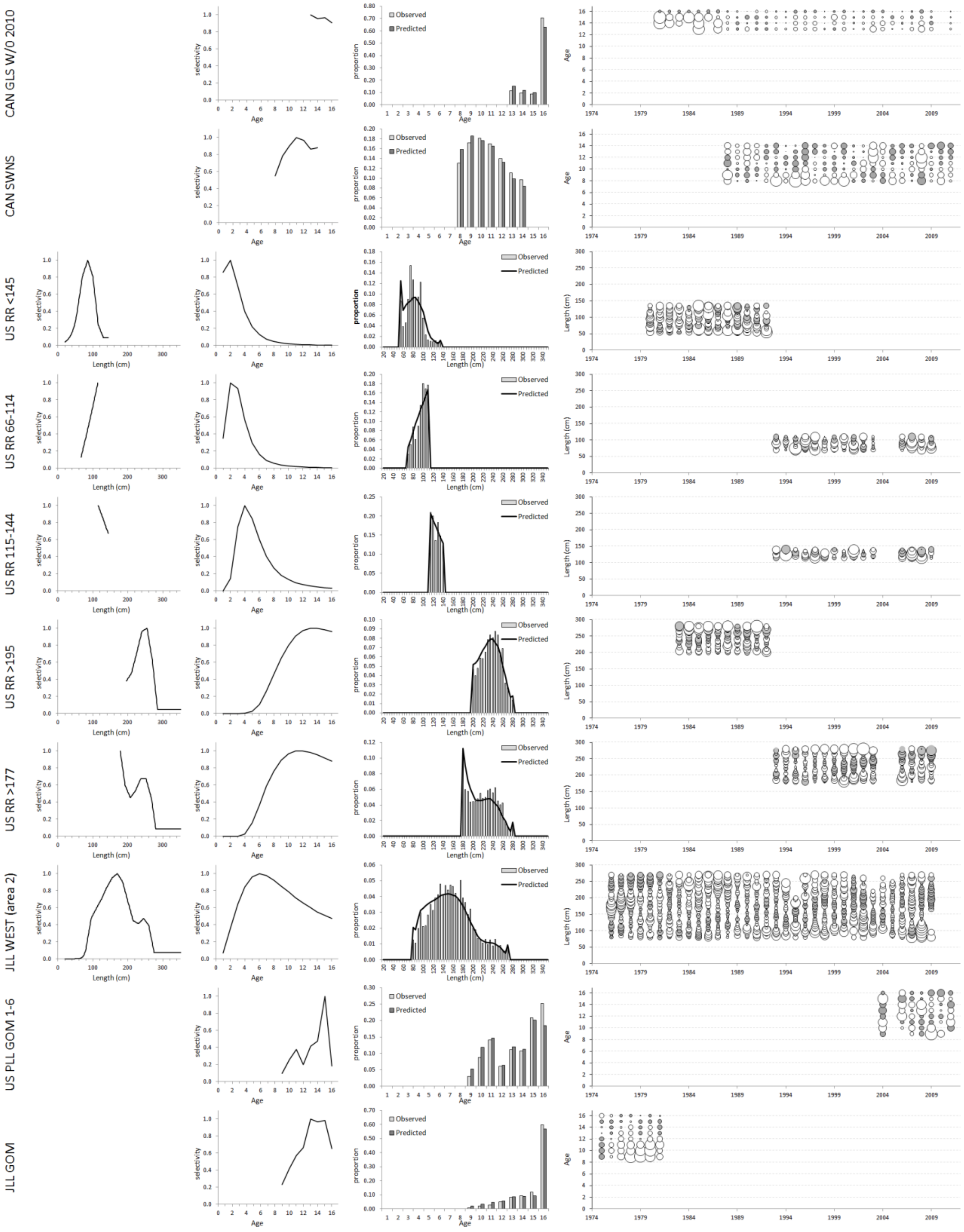

Figure 10. Estimated selectivities-at-length (where applicable), the effective equivalent selectivities-at-age, fit to the CAA/CAL data (as average over all the years with data available), and bubble plots of the CAA/CAL standardised residuals for the catches associated with indices of abundance for the **SCAL assessment**. Note that for CAN GLS W/O 2010, CAN SWNS, US PLL GOM 1-6 and JLL GOM, the model is fit to CAA data rather than CAL data.

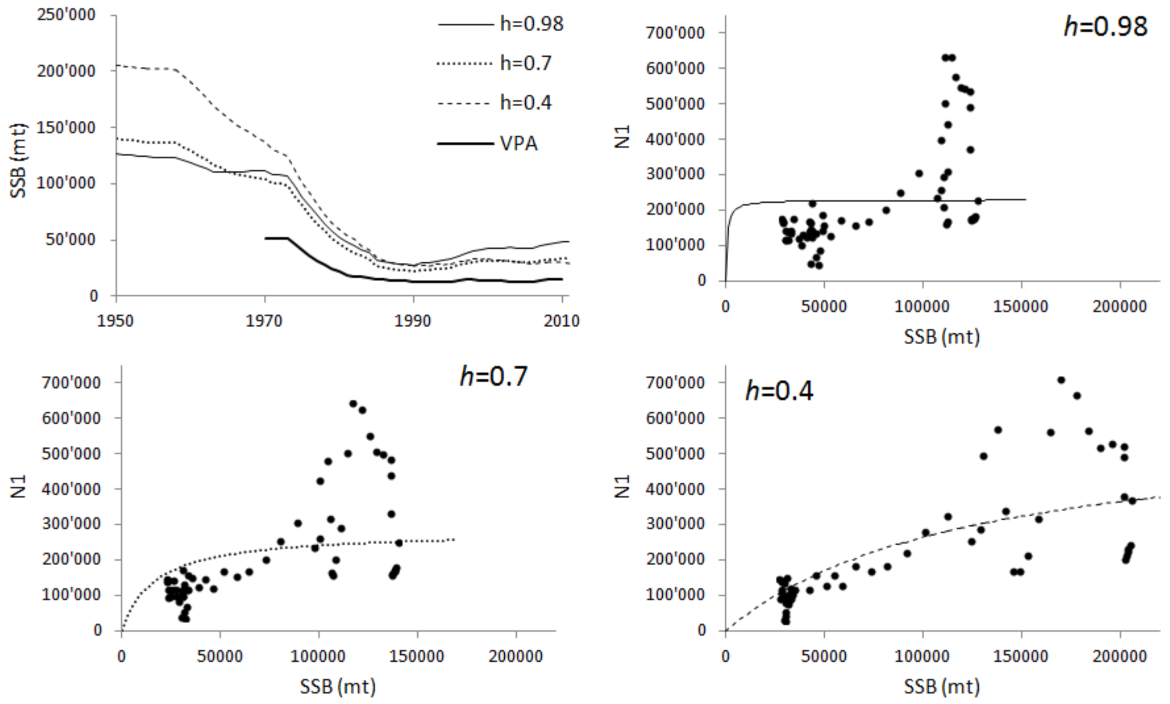

Figure 11. Spawning biomass trajectories and stock–recruit relationships for SCAA_EstS with different fixed values for steepness *h*.

Appendix A.

Data

The data listed below are from ICCAT (2012) for Continuity Run, or as kindly provided by Laurie Kell of the ICCAT Secretariat.

Table A1. Catches in metric tons.

	Longline	Other	Purse seine	Sport	Traps
1950	0.0	468.0	1.0	192.0	346.0
1951	0.0	270.0	100.0	235.0	491.0
1952	7.0	334.0	0.0	153.0	135.0
1953	1.0	198.0	0.0	119.0	766.0
1954	0.0	130.0	55.0	107.0	531.0
1955	5.0	135.0	0.0	27.0	377.0
1956	0.0	47.0	0.0	19.0	181.0
1957	46.0	58.0	0.0	38.0	404.0
1958	72.0	61.0	138.0	67.0	869.0
1959	283.0	125.0	781.0	79.0	302.0
1960	340.0	119.0	277.0	60.0	236.0
1961	373.0	78.0	903.0	108.0	158.0
1962	1351.0	44.0	3768.0	412.0	224.0
1963	6558.0	22.0	5770.0	1185.0	303.0
1964	12410.0	24.0	5150.0	608.0	479.0
1965	9469.0	58.0	3331.0	1066.0	247.0
1966	3085.0	47.0	1006.0	3731.0	221.0
1967	3126.0	58.0	2082.0	361.0	313.0
1968	1665.0	63.0	687.0	635.0	126.0
1969	593.0	32.0	1118.0	1038.0	231.0
1970	268.0	83.0	4288.0	644.0	183.0
1971	1390.0	182.0	3769.0	1144.0	106.0
1972	339.0	186.0	2011.0	1354.0	58.0
1973	1127.0	115.0	1656.0	816.0	157.0
1974	946.0	256.0	960.0	2955.0	276.0
1975	1562.4	24.0	2320.0	1022.0	144.0
1976	3066.0	311.0	1582.0	752.0	172.0
1977	3753.4	194.0	1502.0	874.0	372.0
1978	3219.1	191.0	1230.0	904.0	221.0
1979	3691.0	196.0	1381.0	956.0	31.0
1980	3972.5	131.0	758.0	893.0	47.0
1981	3879.0	133.0	910.0	808.0	41.0
1982	363.0	323.0	232.0	459.0	68.0
1983	829.0	514.0	384.0	808.0	7.0
1984	832.0	377.0	401.0	676.0	3.0
1985	1245.0	293.0	377.0	750.0	20.0
1986	1278.0	166.2	360.0	518.0	0.0
1987	1237.0	156.3	367.0	726.0	17.0
1988	1475.3	425.0	383.0	601.0	14.0
1989	817.6	769.0	385.0	786.0	1.0
1990	854.1	536.0	384.0	1004.0	2.0
1991	1023.3	578.0	237.0	1083.0	0.0
1992	885.2	509.3	300.0	586.3	1.0
1993	784.0	406.0	295.0	854.0	29.0
1994	622.0	307.2	301.0	804.0	79.0
1995	604.1	384.0	249.0	1114.0	72.0
1996	713.6	436.0	245.0	1029.0	90.0
1997	537.0	293.0	250.0	1195.3	59.0
1998	887.0	342.0	249.0	1111.0	68.0
1999	1074.5	281.0	248.0	1123.8	44.5
2000	1079.5	284.4	275.2	1119.7	16.1
2001	714.7	202.3	195.9	1655.7	15.8
2002	940.5	107.6	207.7	2035.1	28.1
2003	418.3	139.6	265.4	1398.3	84.0
2004	824.8	97.1	31.8	1138.8	32.0
2005	556.2	89.1	178.3	924.5	8.4
2006	714.4	85.3	3.6	1005.1	3.0
2007	520.3	63.1	27.9	1022.9	3.6
2008	764.7	81.9	0.0	1129.9	23.0
2009	573.5	120.7	11.4	1250.6	23.5
2010	703.1	106.7	0.0	1008.9	38.8
2011	924.4	147.8	0.0	887.3	26.3

Table A2. Commercial catches-at-age used in the SCAA.

Longline	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1970	0	0	0	0	0	0	0	0	12	182	274	182	261	199	170	80
1971	13	246	31	133	90	275	844	1551	1133	710	690	546	399	232	114	244
1972	29	54	58	17	143	55	44	103	358	206	51	72	74	66	26	119
1973	88	443	564	476	691	260	227	594	1117	696	177	287	313	271	90	249
1974	109	2668	2794	1629	518	102	471	628	542	517	460	439	407	259	270	342
1975	2	37	54	76	190	21	17	166	347	633	1180	937	881	844	864	1891
1976	184	1236	5772	2497	2630	1032	183	110	649	599	364	711	1538	1910	1750	4371
1977	59	423	5315	9521	2292	1826	1748	405	157	245	213	339	480	954	1387	6061
1978	81	192	1427	2785	2513	2673	991	394	316	174	176	324	464	471	928	6342
1979	47	340	1441	1237	685	1572	2568	1750	521	305	302	399	664	930	1129	5086
1980	135	480	1763	2676	1229	1329	2270	4609	3088	774	491	460	517	602	990	6944
1981	357	1462	8455	3354	4371	3051	2529	2055	1690	1016	456	688	604	573	480	5400
1982	82	129	178	244	160	380	399	302	155	216	150	130	146	109	58	181
1983	6	120	2151	577	569	823	602	994	595	428	257	154	161	83	65	167
1984	56	1523	602	1189	1808	1487	781	358	327	305	204	142	117	189	85	278
1985	35	128	6680	2044	3469	3697	1742	590	363	253	173	195	262	155	341	490
1986	4	133	1228	2236	1390	1119	1062	560	363	302	177	132	272	219	286	1474
1987	29	350	1547	2310	3131	3641	1171	1170	786	677	217	152	135	109	103	417
1988	85	283	3580	3747	3165	2881	2824	1351	827	431	228	127	191	144	144	452
1989	32	203	272	1062	887	1133	1022	1112	668	334	194	189	186	141	83	315
1990	36	103	834	783	1322	1410	838	735	670	502	301	186	191	111	99	372
1991	37	156	593	1334	1478	1412	1477	1079	475	371	276	294	200	153	146	438
1992	54	43	451	931	911	1273	782	1116	942	339	254	177	236	187	120	315
1993	19	50	666	1300	1165	1428	1294	650	609	545	251	122	130	71	45	219
1994	25	75	322	1566	1863	1685	601	592	530	310	157	115	80	48	37	157
1995	106	59	286	1093	689	2680	1086	250	304	188	70	58	81	46	35	125
1996	54	182	565	1356	1108	767	997	866	297	192	237	196	177	124	106	227
1997	33	8	186	601	739	755	967	670	646	230	120	62	94	69	45	113
1998	24	8	236	1059	532	1065	686	828	980	1253	391	199	108	150	35	200
1999	29	32	129	799	1138	752	670	935	652	544	494	517	538	297	199	417
2000	22	29	404	783	3293	2630	1358	1141	534	282	163	152	176	103	82	206
2001	34	33	57	120	155	344	963	1021	360	399	276	338	215	126	125	202
2002	12	34	31	90	79	237	466	1509	1201	1028	562	321	277	83	153	224
2003	2	24	17	325	262	461	185	332	185	217	222	131	189	89	163	171
2004	0	11	7	349	1445	2507	1203	768	344	367	226	183	211	140	123	207
2005	1	51	592	622	711	548	569	791	452	258	378	237	188	113	158	163
2006	4	186	355	690	468	1420	755	743	1054	840	478	350	235	150	331	377
2007	0	22	2527	2124	851	899	507	379	230	133	246	176	123	92	105	158
2008	0	32	150	518	782	457	923	997	714	573	512	298	261	110	201	230
2009	2	0	12	33	28	260	45	338	390	383	391	188	135	120	184	261

Other surf	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1970	0	0	0	0	0	0	0	0	0	1	7	62	20	19	9	169
1971	0	0	0	0	0	0	8	9	6	8	8	41	99	127	161	226
1972	4	8	6	4	18	15	9	11	43	34	30	66	100	183	109	183
1973	3	14	11	34	26	17	6	20	45	44	14	15	28	33	39	204
1974	33	214	39	64	33	4	20	36	25	36	28	40	88	139	185	351
1975	0	1	1	1	4	0	0	2	5	9	17	13	13	11	12	28
1976	4	34	84	62	43	12	10	6	23	42	48	56	97	102	134	384
1977	27	17	37	36	10	8	5	2	1	2	3	4	7	18	31	448
1978	5	8	16	27	24	18	10	5	2	6	5	15	48	85	118	272
1979	0	2	6	13	7	14	14	12	6	11	4	14	31	45	78	427
1980	0	1	6	5	3	4	6	13	13	11	7	9	12	12	19	306
1981	1	11	40	20	19	16	13	11	8	15	11	10	10	22	13	284
1982	0	0	0	0	0	0	2	4	13	17	32	53	30	27	41	698
1983	0	0	0	0	0	2	8	9	54	52	48	48	43	120	62	1052
1984	0	0	0	0	0	0	3	15	9	18	55	40	41	71	52	709
1985	0	0	0	0	0	3	3	17	14	33	29	63	71	105	113	517
1986	0	0	0	0	0	0	3	3	6	7	20	40	62	100	92	273
1987	0	1	5	13	27	32	27	41	33	42	28	33	48	57	74	239
1988	66	117	185	0	9	33	73	113	91	192	397	217	95	113	86	442
1989	22	39	62	0	4	16	69	511	600	436	301	267	227	169	174	810
1990	3	5	9	0	6	24	62	341	641	477	172	124	122	112	115	502
1991	0	0	0	3	4	26	156	343	436	551	364	194	110	135	130	456
1992	0	0	0	1	5	3	54	197	299	265	279	285	190	122	107	486
1993	0	0	0	0	0	0	73	71	153	239	208	160	156	137	101	436
1994	0	0	0	0	0	4	24	196	243	195	214	181	133	90	56	193
1995	0	0	0	0	1	12	13	104	145	343	315	240	140	112	81	277
1996	0	1	1	1	1	7	16	203	105	106	168	235	153	133	115	525
1997	0	0	0	1	2	7	20	142	251	198	58	88	104	90	82	320
1998	0	0	0	0	0	3	8	93	213	369	269	133	118	103	75	305
1999	0	0	0	0	3	3	21	205	188	274	254	232	72	54	43	167
2000	0	0	0	0	0	3	3	39	157	188	139	207	245	153	95	160
2001	0	0	0	0	1	14	191	305	60	103	99	95	99	94	61	89
2002	0	0	0	0	0	1	7	142	219	105	28	39	51	30	33	25
2003	0	0	0	0	0	0	3	82	177	151	65	43	23	16	29	166
2004	0	0	0	0	7	12	58	233	138	62	36	28	10	10	16	58
2005	0	0	0	0	0	0	1	16	33	9	31	39	24	19	34	142
2006	0	0	0	0	0	0	11	18	20	30	40	28	26	33	28	114
2007	0	0	0	0	1	4	5	52	34	16	27	28	27	26	14	68
2008	0	4	20	61	65	83	90	183	126	26	18	4	4	4	7	47
2009	0	0	0	0	0	3	5	108	183	143	62	44	25	33	28	83

Table A2 continued.

Purse seine	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1970	53799	100076	126485	17480	6528	1423	442	116	24	0	0	0	0	0	0	0
1971	48997	146315	37912	46091	354	460	424	0	0	0	0	0	0	0	0	0
1972	40900	89956	30577	2247	3412	1007	0	278	0	0	0	0	0	0	0	0
1973	4747	70245	28261	5132	1469	2018	131	17	22	0	0	0	0	0	0	0
1974	20773	15489	16422	3946	2421	1339	148	74	20	7	8	10	19	30	38	50
1975	29671	145069	6412	12799	675	677	230	70	55	100	68	47	82	91	149	379
1976	4016	17240	65387	4	0	0	0	0	13	17	29	32	69	61	92	252
1977	759	18036	3215	18850	5605	861	830	115	4	15	10	26	55	95	101	252
1978	3915	6883	17300	2048	5725	4642	383	47	77	30	17	5	7	8	14	64
1979	44	6309	13548	7292	9041	262	214	38	0	9	21	6	0	44	150	895
1980	2094	10476	7861	5247	2817	192	23	12	264	126	63	60	26	9	8	80
1981	2931	6858	7602	296	1283	364	72	125	520	1271	719	255	134	73	45	37
1982	817	514	670	145	9	5	24	66	70	152	273	257	126	49	30	14
1983	1828	0	82	9	0	0	25	22	159	199	255	269	349	242	103	130
1984	129	147	0	0	0	9	6	14	74	206	288	356	247	278	113	137
1985	0	0	0	1	0	0	2	13	37	81	162	237	258	242	233	313
1986	0	0	0	0	0	0	0	11	16	36	63	115	179	222	305	427
1987	0	0	0	0	0	0	5	21	100	233	182	157	161	186	176	382
1988	0	0	0	0	0	0	3	7	62	217	212	208	168	159	179	395
1989	0	0	0	0	0	0	1	9	72	193	216	281	174	187	160	291
1990	0	0	0	0	0	0	1	10	131	353	306	247	197	157	155	226
1991	5	1	0	0	1	1	24	166	491	323	150	52	35	22	12	18
1992	0	0	0	0	0	0	0	39	220	205	227	231	150	103	66	107
1993	0	0	0	0	0	0	5	68	794	533	129	96	44	27	11	7
1994	0	0	0	0	0	0	2	72	694	324	341	144	54	36	13	23
1995	0	0	0	0	0	0	0	5	164	588	323	129	79	47	28	25
1996	0	0	0	0	0	0	2	29	80	167	384	218	127	76	51	51
1997	0	0	0	0	0	0	0	5	175	209	154	189	191	166	100	82
1998	0	0	0	0	0	0	0	13	216	498	254	131	129	135	56	36
1999	0	0	0	0	0	0	0	14	148	485	417	240	74	42	29	20
2000	0	0	0	0	0	0	0	7	218	289	271	308	203	99	43	37
2001	0	0	0	0	0	0	0	12	36	110	168	288	178	133	51	36
2002	0	0	0	0	0	0	0	73	132	71	91	146	224	185	114	77
2003	0	0	0	0	0	0	0	311	625	434	177	88	82	82	36	45
2004	0	0	0	0	0	0	0	64	64	72	33	17	1	0	0	0
2005	0	0	0	0	0	0	0	11	32	86	163	324	136	74	34	86
2006	0	0	0	0	0	0	0	15	4	4	2	0	3	0	0	0
2007	0	0	0	0	0	0	0	0	11	5	6	8	5	16	8	50
2009	0	0	0	0	0	0	0	0	41	34	10	2	0	0	0	0

Sport	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1970	5121	4223	748	30	0	4	20	43	4	70	134	151	288	415	295	778
1971	13023	5442	0	0	7	114	74	98	41	39	100	186	491	659	634	1450
1972	4419	8293	2963	243	384	114	16	75	58	29	67	239	537	785	779	1997
1973	227	2889	1122	235	67	148	23	21	86	77	47	80	175	277	355	1549
1974	34891	1568	1176	0	0	3	0	0	7	46	368	16	40	1474	788	6503
1975	13629	2547	87	278	37	10	34	11	11	33	24	56	90	226	330	2174
1976	1328	916	607	13	70	18	7	0	16	21	39	43	99	100	178	1554
1977	663	3707	447	89	25	4	7	3	5	2	5	10	24	59	100	1988
1978	1563	3447	226	29	18	4	8	0	6	42	10	4	17	21	113	2161
1979	2737	3933	541	40	20	13	46	146	26	23	32	39	76	118	167	1942
1980	1017	5125	361	196	81	26	24	19	77	55	37	52	61	58	67	1865
1981	3001	1484	436	59	20	33	0	1	54	169	207	148	84	69	72	1563
1982	2708	3009	669	134	76	76	65	19	61	118	210	163	156	53	47	563
1983	1640	2344	858	185	46	34	71	77	146	94	123	114	186	260	233	1350
1984	941	5570	1089	304	197	82	137	64	113	114	156	207	274	325	307	657
1985	741	5267	5482	86	54	182	212	107	66	71	93	119	247	297	383	858
1986	963	5764	5250	678	48	58	71	83	51	37	44	81	94	131	184	537
1987	2297	12228	7213	2194	672	68	37	81	67	83	76	73	95	140	144	508
1988	4783	8903	7322	74	189	386	232	101	84	86	62	68	91	108	114	452
1989	788	12683	1207	2042	1628	331	529	528	275	127	124	164	129	144	159	502
1990	2954	3475	16956	1014	879	702	240	221	204	203	106	124	100	143	160	685
1991	4069	13897	9479	1744	462	45	179	139	134	213	322	364	285	274	255	602
1992	535	6045	1471	122	271	56	35	287	262	127	173	287	273	252	188	666
1993	397	1016	3719	2182	1111	1	273	442	193	324	245	191	139	123	122	599
1994	2027	645	913	574	653	139	528	658	764	253	222	352	198	218	139	518
1995	827	1288	2957	1886	2171	1562	209	251	271	466	308	208	194	193	213	961
1996	472	9166	1110	3301	2232	348	371	1218	320	168	215	248	187	143	136	549
1997	215	1095	6206	326	596	740	371	999	779	501	270	269	347	344	301	888
1998	317	881	3250	2425	121	67	62	502	912	462	436	250	308	324	286	767
1999	73	528	1817	1050	619	44	52	662	413	501	710	686	405	331	287	885
2000	76	258	648	391	305	494	299	135	367	445	477	473	467	467	264	1057
2001	1397	327	2345	4232	831	945	594	889	280	349	648	596	784	712	506	1127
2002	835	5525	4050	4438	4501	1067	512	1196	948	361	432	431	559	746	650	1302
2003	281	2680	4504	3336	1612	1005	123	544	1011	724	364	177	264	343	406	990
2004	814	2663	6937	2233	1299	386	190	455	435	497	459	314	202	155	183	851
2005	720	4839	1879	1939	371	291	119	159	322	348	417	433	301	211	178	748
2006	207	444	890	1056	1985	583	296	295	294	376	391	398	308	215	160	884
2007	65	236	4159	7160	1266	890	701	233	300	199	190	189	185	135	125	569
2008	85	752	2122	1522	5555	1065	764	574	310	214	142	113	111	159	156	782
2009	70	222	2180	1161	954	4252	1508	255	363	312	230	234	168	229	190	843

Table A2 continued.

Traps	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1970	0	0	0	0	0	3	1	2	3	7	20	41	85	99	119	271
1971	0	0	5	17	5	17	7	4	1	2	8	25	40	72	59	159
1972	0	1	1	4	6	32	23	3	6	23	38	26	19	20	15	73
1973	0	0	0	0	0	0	0	0	0	13	28	124	128	115	104	100
1974	0	0	0	0	0	0	0	1	1	3	5	12	46	126	145	608
1975	0	0	0	0	1	1	2	3	0	0	1	5	14	31	40	341
1976	0	0	0	0	0	0	0	0	0	0	0	2	0	7	23	431
1977	0	0	0	0	0	0	3	20	142	343	716	591	264	31	0	0
1978	0	0	0	0	0	5	0	0	3	0	1	0	0	2	7	485
1979	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	71
1980	0	0	0	0	0	1	4	5	4	7	2	3	4	3	4	92
1981	0	0	0	0	0	0	0	0	0	0	0	1	2	0	2	88
1982	0	0	0	0	0	0	0	0	0	0	0	1	2	3	1	149
1983	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	17
1984	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7
1985	0	0	0	0	0	0	0	0	0	0	0	0	0	2	5	45
1987	0	0	0	0	0	0	0	3	0	2	5	0	2	0	3	33
1988	0	0	0	0	0	0	0	3	0	2	4	0	2	0	3	27
1989	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3
1990	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	4
1992	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3
1993	0	0	0	0	0	0	0	0	0	0	0	0	3	3	7	65
1994	0	0	0	0	0	0	0	0	1	0	3	1	3	7	12	185
1995	0	0	0	0	0	3	2	0	1	0	1	2	11	4	9	163
1996	0	0	0	0	1	0	0	1	3	2	12	12	26	26	22	170
1997	0	0	0	0	0	0	0	0	0	0	3	2	0	2	9	145
1998	0	0	0	0	0	0	0	0	0	4	2	12	18	18	34	129
1999	0	0	0	0	0	0	0	0	0	0	3	3	8	10	19	96
2000	0	0	0	0	0	0	0	0	0	0	0	1	3	2	4	37
2001	0	0	0	0	0	0	0	0	0	0	1	2	6	5	10	27
2002	0	0	0	0	0	0	6	43	43	10	12	13	13	12	7	5
2003	0	0	0	0	0	0	16	46	157	107	27	4	28	40	14	52
2004	0	0	0	5	1	2	4	0	11	15	11	33	46	16	6	5
2005	0	0	0	0	1	1	0	1	0	1	3	8	4	7	1	7
2006	0	0	0	0	0	1	0	2	1	2	2	0	0	0	1	5
2007	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	9
2008	0	0	0	0	0	8	20	75	39	38	5	0	0	0	0	0
2009	0	0	0	0	5	22	1	10	8	3	11	7	8	5	6	30

Table A3. Commercial fleet catch-at-length used in the SCAL.

In the interests of keeping this document shorter, these data have not been listed below, but can be provided by the authors if required.

Table A4. CPUE (relative abundance) series used.

	CAN GLS W/O 2010	CAN SWNS	US RR<145	US RR 66-114	US RR 115-144	US RR>195	US RR>177	JLL WEST (area 2)	Larval zero inflated	US PLL GOM 1-6	JLL GOM	Tagging
Units	Numbers	Numbers	Numbers	Numbers	Numbers	Numbers	Numbers	Numbers	Biomass	Numbers	Numbers	Numbers
1970	-	-	-	-	-	-	-	-	-	-	-	1065132
1971	-	-	-	-	-	-	-	-	-	-	-	1001624
1972	-	-	-	-	-	-	-	-	-	-	-	431955
1973	-	-	-	-	-	-	-	-	-	-	-	183616
1974	-	-	-	-	-	-	-	-	-	-	0.968	341589
1975	-	-	-	-	-	-	-	-	-	-	0.534	554596
1976	-	-	-	-	-	-	-	0.657	-	-	0.666	253265
1977	-	-	-	-	-	-	-	2.424	2.724	-	0.913	257385
1978	-	-	-	-	-	-	-	1.200	4.733	-	0.876	121110
1979	-	-	-	-	-	-	-	0.822	-	-	1.287	98815
1980	-	-	0.799	-	-	-	-	1.508	-	-	1.158	192541
1981	1.556	-	0.399	-	-	-	-	1.912	0.770	-	0.553	337995
1982	0.796	-	2.102	-	-	-	-	0.715	1.417	-	-	-
1983	2.472	-	1.114	-	-	2.805	-	0.313	1.073	-	-	-
1984	1.112	-	-	-	-	1.246	-	0.958	0.393	-	-	-
1985	0.214	-	0.630	-	-	0.857	-	1.089	-	-	-	-
1986	0.273	-	0.778	-	-	0.503	-	0.081	0.435	-	-	-
1987	0.366	-	1.219	-	-	0.529	-	0.717	0.386	3.255	-	-
1988	0.610	1.969	0.988	-	-	0.941	-	1.089	1.063	1.533	-	-
1989	0.704	2.639	0.988	-	-	0.763	-	0.910	0.762	2.440	-	-
1990	0.188	2.459	0.904	-	-	0.626	-	0.752	0.318	1.889	-	-
1991	0.935	1.337	1.261	-	-	0.820	-	0.752	0.387	3.256	-	-
1992	1.735	1.239	0.820	-	-	0.910	-	1.148	0.530	0.797	-	-
1993	1.229	0.619	-	1.304	1.291	-	0.668	1.138	0.486	0.452	-	-
1994	0.253	1.167	-	0.265	0.237	-	0.831	1.050	0.528	0.335	-	-
1995	0.909	0.963	-	1.008	0.263	-	1.250	0.788	0.327	0.310	-	-
1996	0.090	0.344	-	1.637	0.695	-	3.489	2.317	1.019	0.183	-	-
1997	0.139	0.240	-	2.541	0.267	-	1.324	1.453	0.416	0.332	-	-
1998	0.271	0.508	-	1.448	0.886	-	1.652	0.684	0.124	0.357	-	-
1999	0.527	0.909	-	1.188	1.049	-	1.932	0.744	0.528	0.612	-	-
2000	0.359	0.230	-	0.946	1.456	-	0.602	0.934	0.352	0.884	-	-
2001	0.340	0.633	-	0.471	1.678	-	1.388	0.597	0.413	0.503	-	-
2002	0.445	0.665	-	1.079	2.490	-	1.806	0.697	0.318	0.471	-	-
2003	0.881	1.440	-	0.474	0.534	-	0.387	0.679	0.784	0.862	-	-
2004	1.048	0.499	-	1.836	0.598	-	0.600	0.608	0.581	0.783	-	-
2005	1.686	0.592	-	1.638	0.784	-	0.501	0.732	0.236	0.590	-	-
2006	0.816	0.902	-	0.657	1.377	-	0.350	1.268	0.585	0.414	-	-
2007	1.520	0.725	-	0.584	1.410	-	0.270	1.950	0.265	0.559	-	-
2008	1.083	1.050	-	0.278	1.036	-	0.369	0.768	0.411	1.283	-	-
2009	2.574	1.026	-	0.320	0.521	-	0.244	1.864	0.650	1.018	-	-
2010	-	0.869	-	0.622	1.226	-	0.792	0.696	0.459	0.881	-	-
2011	4.870	0.973	-	0.704	1.203	-	0.544	2.967	0.844	-	-	-

Table A5. Catches-at-age associated with the CPUE series used in the SCAA.

In the interests of keeping this document shorter, these data have not been listed below, but can be provided by the authors if required.

Table A6. Catches-at-length associated with the CPUE series used in the SCAL.

In the interests of keeping this document shorter, these data have not been listed below, but can be provided by the authors if required.

Appendix B.

The statistical catch-at-age model

The text following sets out the equations and other general specifications of the SCAA followed by details of the contributions to the (penalised) log-likelihood function from the different sources of data available and assumptions concerning the stock–recruitment relationship. Quasi-Newton minimization is then applied to minimize the total negative log-likelihood function to estimate parameter values (the package AD Model Builder$^{\rm TM}$ (Fournier *et al*. 2012) is used for this purpose). The description below includes more options than used in this paper, but they have been included here for completeness as they may be used in later extensions.

B.1. Population dynamics

B.1.1 Numbers-at-age

The resource dynamics are modelled by the following set of population dynamics equations:

$$N_{y+1,1} = R_{y+1} \tag{B1}$$

$$N_{y+1,a+1} = \left(N_{y,a}\, e^{-M_a/2} - \sum_f C^f_{y,a}\right) e^{-M_a/2} \qquad \text{for } 1 \le a \le m-2 \tag{B2}$$

$$N_{y+1,m} = \left(N_{y,m-1}\, e^{-M_{m-1}/2} - \sum_f C^f_{y,m-1}\right) e^{-M_{m-1}/2} + \left(N_{y,m}\, e^{-M_m/2} - \sum_f C^f_{y,m}\right) e^{-M_m/2} \tag{B3}$$

where

$N_{y,a}$ is the number of fish of age *a* at the start of year *y* (which refers to a calendar year),

R_y is the recruitment (number of 1-year-old fish) at the start of year *y*,

M_a denotes the natural mortality rate for fish of age *a*,

$C^f_{y,a}$ is the predicted number of fish of age *a* caught in year *y* by fleet *f*, and

m is the maximum age considered (taken to be a plus-group).

B.1.2. Recruitment

The number of recruits (*i.e.* new 1-year-olds) at the start of year *y* is assumed to be related to the spawning stock size (*i.e.* the biomass of mature fish) at the mid-point of the preceding year by either a modified Ricker or a Beverton-Holt stock–recruitment relationship, allowing for annual fluctuation about the deterministic relationship:

for the modified Ricker:

$$R_y = \alpha B^{\rm sp}_{y-1} \exp\left[-\beta\left(B^{\rm sp}_{y-1}\right)^{\gamma}\right] e^{(\varsigma_y - (\sigma_{\rm R})^2/2)} \tag{B4}$$

and for Beverton-Holt:

$$R_y = \frac{\alpha B^{\rm sp}_{y-1}}{\beta + B^{\rm sp}_{y-1}} e^{(\varsigma_y - (\sigma_{\rm R})^2/2)} \tag{B5}$$

where

□, □ and □ are spawning biomass–recruitment relationship parameters,

ς_y reflects fluctuation about the expected recruitment for year *y*, which is assumed to be normally distributed with standard deviation □$_{\rm R}$ (which is input in the applications considered here); these residuals are treated as estimable parameters in the model fitting process.

$B^{\rm sp}_y$ is the spawning biomass in year *y*, computed as:

$$B^{\rm sp}_y = \sum_{a=0}^{m} f_{y,a} w^{\rm sp}_{y,a} N_{y,a} e^{-M_a \frac{T_{\rm S}}{12}} \tag{B6}$$

where spawning for the stocks under consideration is taken to occur $T_{\rm S}$ months after the start of the year (here $T_{\rm S} = 6$) and some natural mortality has therefore occurred,

$w^{\text{sp}}_{y,a}$ is the mass of fish of age *a* during spawning, and

$f_{y,a}$ is the proportion of fish of age *a* that are mature.

B.1.3. Total catch and catches-at-age

The total catch by mass in year *y* is given by:

$$C_y = \sum_f \sum_{a=0}^{m} w^f_{y,a}\, C^f_{y,a} = \sum_f \sum_{a=0}^{m} w^f_{y,a}\, N_{y,a}\, e^{-M_a/2}\, S^f_{y,a}\, F^f_y \tag{B7}$$

where

$w^f_{y,a}$ denotes the mass of fish of age *a* landed in year *y* by fleet *f*,

$C^f_{y,a}$ is the catch-at-age, *i.e.* the number of fish of age *a*, caught in year *y* by fleet *f*,

$S^f_{y,a}$ is the commercial selectivity of fleet *f* (*i.e.* combination of availability and vulnerability to fishing gear) at age *a* for year *y*; when $S_{y,a} = 1$, the age class *a* is said to be fully selected, and

F^f_y is the proportion of a fully selected age class that is fished by fleet *f*.

The model estimate of the mid-year exploitable ("available") component of biomass for fleet *f* is calculated by converting the numbers-at-age into mid-year mass-at-age (using the individual weights of the landed fish) and applying natural and fishing mortality for half the year:

$$B^f_y = \sum_{a=0}^{m} w^f_{y,a} S^f_{y,a} N_{y,a} e^{-M_a/2} (1 - S^f_{y,a} F^f_y / 2) \tag{B8}$$

B.1.4. Initial conditions

For the first year (y_0) considered in the model, the numbers-at-age are estimated directly for ages 1 to a^{est}, with a parameter □ that mimics recent average fishing mortality for ages above a^{est}, *i.e.*

$$N_{y_0,a} = N_{\text{start},a} \qquad \text{for } 1 \le a \le a^{est} \tag{B9}$$

and

$$N_{\text{start},a} = N_{\text{start},a-1} e^{-M_{a-1}} (1 - \phi S_{a-1}) \qquad \text{for } a^{est} < a \le m-1 \tag{B10}$$

$$N_{\text{start},m} = N_{\text{start},m-1} e^{-M_{m-1}} (1 - \phi S_{m-1}) \Big/ (1 - e^{-M_m} (1 - \phi S_m)) \tag{B11}$$

For the applications considered here however, the population starts at its pre-exploitation equilibrium level (*K*) with an equilibrium age-structure, with:

$$N_{\text{start},1} = K^{\text{sp}} \Bigg/ \left[\sum_{a=1}^{m-1} f_{\text{start},a} w^{\text{sp}}_{\text{start},y} e^{-\frac{T_s}{12}\sum_{a'=1}^{a-1} M_{a'}} + f_{\text{start},m} w^{\text{sp}}_{\text{start},m} \frac{e^{-\frac{T_s}{12}\sum_{a'=1}^{m-1} M_{a'}}}{1 - e^{-\frac{T_s}{12} M_m}} \right] \tag{B12}$$

B.2. The (penalized) likelihood function

The model can be fit to (a subset of) CPUE, and commercial catch-at-age or catch-at-length data to estimate model parameters (which may include residuals about the stock–recruitment function, facilitated through the incorporation of a penalty function described below). Contributions by each of these to the negative of the (penalized) log-likelihood ($-\ell\text{n}L$) are as follows.

B.2.1 CPUE relative abundance data

The likelihood is calculated assuming that an observed CPUE index for a particular fishing fleet is lognormally distributed about its expected value:

$$I_y^i = \hat{I}_y^i \exp\left(\varepsilon_y^i\right) \quad \text{or} \quad \varepsilon_y^i = \ell\text{n}\left(I_y^i\right) - \ell\text{n}\left(\hat{I}_y^i\right) \qquad \text{(B13)}$$

where

I_y^i is the CPUE biomass or abundance index for year *y* for gear/flag combination *i*,

$\hat{I}_y^i = \hat{q}^i \sum^m w_{y,a}^i S_{y,a}^i N_{y,a} e^{-M_a/2}(1 - S_{y,a}^i F_y^i / 2)$ is the corresponding model estimate of biomass or

$\hat{I}_y^f = \hat{q}^f \sum^m S_{y,a}^f N_{y,a} e^{-M_a/2}(1 - S_{y,a}^f F_y^f / 2)$ is the corresponding model estimate of abundance,

$\hat{q}^i$ is the constant of proportionality (catchability) for the CPUE series, and

ε_y^i from $N\left(0, \left(\sigma^{\text{CPUE}}\right)^2\right)$.

The contribution of the CPUE data to the negative of the log-likelihood function (after removal of constants) is then given by:

$$-\ell\text{n}\, L^{\text{CPUE}} = \sum_y \left\{ \ell\text{n}\left(\sqrt{\left(\sigma^{\text{CPUE}}\right)^2 + \left(\sigma^i_{\text{Add}}\right)^2} \right) + \frac{\left(\varepsilon_y^i\right)^2}{2\left[\left(\sigma^{\text{CPUE}}\right)^2 + \left(\sigma^i_{\text{Add}}\right)^2\right]} \right\} \qquad \text{(B14)}$$

where

σ^{CPUE} is the standard deviation of the residuals for the logarithm of the indices,

σ^i_{Add} is the square root of the additional variance for the CPUE series, which can be estimated in the model fitting procedure but has been set to zero in the applications considered here.

σ^{CPUE} is estimated in the fitting procedure by its maximum likelihood value:

$$\sigma^{\text{CPUE}} = \sqrt{\sum_i \sum_y \left(\ln\left(I_y^i\right) - \ln\left(\hat{I}_y^i\right)\right)^2 \Big/ \sum_i \sum_y 1}$$

The catchability coefficient q^i for CPUE index *i* is estimated by its maximum likelihood value:

$$\ell n \hat{q}^i = 1/n_i \sum_y \left(\ln I_y^i - \ln \hat{B}_y^{\text{ex}}\right) \qquad \text{(B15)}$$

B.2.2. Commercial catches-at-age

The contribution of the catch-at-age data to the negative of the log-likelihood function under the assumption of an "adjusted" lognormal error distribution is given by:

$$-\ell\text{n}\, L^{\text{CAA}} = w_{\text{CAA}} \sum_f \sum_y \sum_a \left[\ell n\left(\sigma^f_{\text{com}} / \sqrt{p^f_{y,a}}\right) + p^f_{y,a}\left(\ell n\, p^f_{y,a} - \ell n\, \hat{p}^f_{y,a}\right)^2 / 2\left(\sigma^f_{\text{com}}\right)^2 \right] \qquad \text{(B16)}$$

where

$p^f_{y,a} = C^f_{y,a} / \sum_{a'} C^f_{y,a'}$ is the observed proportion of fish caught in year *y* by fleet *f* that are of age *a*,

$\hat{p}^f_{y,a} = \hat{C}^f_{y,a} / \sum_{a'} \hat{C}^f_{y,a'}$ is the model-predicted proportion of fish caught in year *y* by fleet *f* that are of age *a*,

where

$$\hat{C}^f_{y,a} = N_{y,a}\, S^f_{y,a}\, F^f_y e^{-M_a/2} \qquad \text{(B17)}$$

and

σ^f_{com} is the standard deviation associated with the catch-at-age data, which is estimated in the fitting procedure by:

$$\hat{\sigma}^f_{\text{com}} = \sqrt{\sum_y \sum_a p^f_{y,a}\left(\ell n\, p^f_{y,a} - \ell n\, \hat{p}^f_{y,a}\right)^2 / \sum_y \sum_a 1} \qquad \text{(B18)}$$

The lognormal error distribution underlying equation (B16) is chosen on the grounds that (assuming no ageing error) variability is likely dominated by a combination of interannual variation in the distribution of fishing effort, and fluctuations (partly as a consequence of such variations) in selectivity-at-age, which suggests that the assumption of a constant coefficient of variation is appropriate. However, for ages poorly represented in the sample, sampling variability considerations must at some stage start to dominate the variance. To take this into account in a simple manner, motivated by binomial distribution properties, the observed proportions are used for weighting so that undue importance is not attached to data based upon a few samples only.

Commercial catches-at-age are incorporated in the likelihood function using equation (B16), for which the summation over age *a* is taken from age a_{minus} (considered as a minus group) to a_{plus} (a plus group).

The w_{CAA} weighting factor may be set to a value less than 1 to downweight the contribution of the catch-at-age data (which tend to be positively correlated between adjacent ages) to the overall negative log-likelihood compared to that of the CPUE data. Here, $w_{\text{CAA}} = 0.1$.
In instances where catch-at-age data corresponding to a particular CPUE index are available, the data are treated in exactly the same manner as described above, with a specific selectivity S^i_a estimated for that index.

B.2.3. Commercial catches-at-length

Commercial catches-at-length are incorporated in the likelihood function in the same manner as the catches-at-age. When the model is fit to catches-at-length, selectivity is estimated as a function of length and then converted to selectivity-at-age:

$$S^f_{y,a} = \sum_l S^f_{y,l} A_{a,l} \qquad \text{(B19)}$$

where $A_{a,l}$ is the proportion of fish of age *a* that fall in the length group *l* (*i.e.*, $\sum_l A_{a,l} = 1$ for all ages).

The matrix $A_{a,l}$ is calculated under the assumption that length-at-age is normally distributed about a mean given by the von Bertalanffy equation, *i.e.*:

$$L_a \sim N\left(L_\infty\left(1 - e^{-\kappa(a-t_0)}\right), \theta^2_a\right) \qquad \text{(B20)}$$

where

θ_a is the standard deviation of length-at-age *a*, which is modelled to be proportional to the expected length-at-age *a*, *i.e.*:

$$\theta_a = \beta L_\infty\left(1 - e^{-\kappa(a-t_0)}\right) \qquad \text{(B21)}$$

with β fixed here to 0.2.

Furthermore, in the model fitting to CAL, the weights-at-age used to compute the CPUE indices are weighted by the selectivity for the corresponding fleet:

$$\tilde{w}^i_{y,a} = \sum_l S^f_{y,l} w_l A_{a,l} \Big/ S^i_{a,l} \qquad \text{(B22)}$$

$\tilde{w}^i_{y,a}$ is the selectivity-weighted mid-year weight-at-age *a* for fleet *f* and year *y*; and

w_l is the weight of fish of length *l*.

The following term (replacing equation (B15)) is then added to the negative log-likelihood:

$$-\ell\text{n}\, L^{\text{CAL}} = w_{\text{len}} \sum_f \sum_y \sum_l \left[\ell n\left(\sigma^f_{\text{len}} / \sqrt{p^f_{y,l}}\right) + p^f_{y,l}\left(\ell n\, p^f_{y,l} - \ell n\, \hat{p}^f_{y,l}\right)^2 \Big/ 2\left(\sigma^f_{\text{len}}\right)^2\right] \qquad \text{(B23)}$$

The w_{len} weighting factor may be set to a value less than 1 to downweight the contribution of the catch-at-length data (which tend to be positively correlated between adjacent length groups) to the overall negative log-likelihood compared to that of the CPUE data. Here, w_{len} = 0.05.

B.2.4. Stock–recruitment function residuals

The stock–recruitment residuals are assumed to be lognormally distributed. Thus, the contribution of the recruitment residuals to the negative of the (now penalized) log-likelihood function is given by:

$$-\ell nL^{\mathrm{pen}} = \sum_{y=y_1+1}^{y_2}\left[\varsigma_y^2 \big/ 2\sigma_{\mathrm{R}}^2\right] \tag{B24}$$

where

ς_y is the recruitment residual for year *y*, which is estimated for year y_1 to y_2 (see equation (B4)),

σ_{R} is the standard deviation of the log-residuals, which is input (here □$_{\mathrm{R}}$=0.4).

B.3. Model parameters

The model input parameters are given in **Table B1**.

Table B1. Input parameters (Length–weight, von Bertalanffy growth, maturity and natural mortality at age 1 to age 15 from ICCAT 2012). Length, weight and time units are centimeters, grams and years respectively.

Model plus group	16
Length–weight	a=0.00002861, b=2.929
Von Bertalanffy growth	K = 0.089, $L_\infty = 315, t_0 = -1.13$
Maturity-at-age	100% maturity at age 9
Natural mortality	0.14 yr^{-1}
Stock–recruitment	Beverton-Holt, h=0.98, □$_{\mathrm{R}}$=0.6

B.4.2. Fishing selectivity

For SCAA, the commercial fishing selectivities-at-age, $S_{y,a}^{f}$, are estimated separately for ages a_{minus} to a_{plus}. The selectivity is assumed to stay flat after a_{plus} if not otherwise specified. The selectivity is unchanged over a period, but can differ for each of specified different periods.

For SCAL, fishing selectivities-at-length are estimated rather than the selectivities-at-age. These are estimated separately for specified lengths from l_{minus} to l_{plus}, assuming linear changes from the lowest to the highest length for each length group. The selectivity is assumed to stay flat after l_{plus} if not otherwise specified. The selectivity can differ over fixed periods. Details of the fishing selectivities used for both SCAA and SCAL are shown in **Table B2**.

Table B2. Details of the selectivities estimated.

	SCAA-fixedS			SCAA-estS			SCAL					
	a_{minus} (yr)	a_{plus} (yr)	Number of parameters estimated	a_{minus} (yr)	a_{plus} (yr)	Number of parameters estimated	a_{minus} (yr)	a_{plus} (yr)	l_{minus} (cm)	l_{plus} (cm)	Number of parameters estimated	Comments
Commercial fleet:												
Longline	1	16	14	1	16	15			50	260	14	
Other	7	16	8	7	16	9			150	285	9	
Purse seine	1	6	5	1	6	5			40	115	5	First selectivity period: 1950-1983
	8	16	7	8	16	8			160	250	6	Second selectivity period: 1984-present
Sport	1	16	14	1	16	15			35	260	15	
Traps	5	16	10	5	16	11			150	285	9	
CPUE indices:												
CAN GLS W/O 2010	13*	16	-	13*	16	3	13*	16			3	
CAN SWNS	8*	14*	-	8*	14*	6	8*	14*			6	
US RR<145	1*	5*	-	1*	5*	4			55	135	5	
US RR 66-114	2*	3*	-	2*	3*	1			67	114	3	
US RR 115-144	4*	5*	-	4*	5*	1			115	144	2	
US RR>195	10*	16	-	10*	16	6			196	280	6	
US RR>177	8*	16	-	8*	16	8			178	280	7	
JLL WEST (area 2)	2*	16	-	2*	16	14			80	270	13	
Larval zero inflated	9*	16	-	9*	16	-	9*	16			-	Assume spawning biomass, i.e. age 9+
US PLL GOM 1-6	9*	16	-	9*	16	7	9*	16			7	
JLL GOM	9*	16	-	9*	16	7	9*	16			7	
Tagging	1*	3*	-	1*	3*	-	1*	3*			-	Flat selectivity for ages 1 to 3