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CATCH-AT-AGE ESTIMATES OF ATLANTIC BLUEFIN TUNA FROM COMBINED FORWARD-INVERSE AGE-LENGTH KEYS

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SUMMARY

Estimates of catch-at-age are presented for the western and eastern stocks of Atlantic bluefin tuna using a combined forward-inverse age-length key for the period 1974 to 2015 and 1968 to 2015, respectively. Results indicated signals of strong and weak cohorts with the 2002 year class standing out as a relatively strong cohort. Convergence issues caused by missing samples and/or poor data quality were identified and further work is needed to resolve the issues. Specifically, a systematic error in age readings between spines and otoliths was apparent, with otolith younger ages potentially overestimated due to the occurrence of false band deposition. This bias correction along with increased sampling (e.g., back processing of eastern samples for the recent years) are expected to increase the reliability of catch-at-age estimates produced by the combined forward-inverse age-length key.

RÉSUMÉ

Les estimations de la prise par âge sont présentées pour les stocks occidentaux et orientaux de thon rouge de l'Atlantique à l'aide d'une clé combinée âge-taille inverse-vers l'avant pour la période 1974 à 2015 et 1968 à 2015, respectivement. Les résultats ont indiqué des signaux de fortes et faibles cohortes, la classe d'âge de 2002 se démarquant comme une cohorte relativement forte. Des problèmes de convergence causés par des échantillons manquants et/ou la mauvaise qualité des données ont été identifiés et des travaux supplémentaires sont nécessaires pour résoudre les problèmes. Plus précisément, une erreur systématique dans les lectures de l'âge entre les épines et les otolithes est apparue, les âges plus jeunes des otolithes étant potentiellement surestimés en raison de la présence de faux dépôts de bandes. Cette correction des biais ainsi qu'un échantillonnage accru (p. ex., traitement rétroactif d'échantillons de l'Est au cours des années récentes) sont censés augmenter la fiabilité des estimations de prise par âge produites par la clé combinée âge-taille inverse-vers l'avant.

RESUMEN

Se presentan estimaciones de captura por edad para los stocks oriental y occidental de atún rojo del Atlántico utilizando una clave edad-talla que combina hacia delante e inversa para el periodo de 1974 a 2015 y de 1968 a 2015, respectivamente. Los resultados indicaban señales de cohortes fuertes y débiles, y la clase anual de 2002 destacaba como cohorte relativamente fuerte. Se identificaron problemas de convergencia causados por las muestras faltantes y/o por la escasa calidad de los datos, y es necesario llevar a cabo más trabajos para resolver estos problemas. De manera específica, quedó claro un error sistemático en las lecturas de edad entre espinas y otolitos, produciéndose posiblemente una sobreestimación en las edades más jóvenes estimadas a partir de otolitos debido a la existencia de deposición de bandas falsas. Se espera que esta corrección del sesgo junto con un mayor muestreo (por ejemplo, procesar hacia atrás las muestras orientales de años recientes) incremente la fiabilidad de las estimaciones de captura por edad producidas por la clave edad-talla que combina hacia delante e inversa.

KEYWORDS

Bluefin tuna, catch-at-age, age composition, age length keys

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1. Introduction

Cohort slicing has been routinely used to produce catch-at-age estimates for the assessment of the eastern and western stocks of Atlantic bluefin tuna (ABT). While this method is useful for converting catch-at-size into catch-at-age when no age data are available, it makes the strong assumption that there is no variability in length-at-age. Failure of this assumption can result in strong biases in estimates of age structure. Several authors have shown that when applied to stock assessment, these bias result in underestimation of recruitment variability (Mohn 1994; Restrepo 1995), resulting from negative bias in the proportion of younger fish and positive bias in the proportion of older fish in the population (Kell and Kell 2011; Goodyear 1987; Ailloud *et al.* 2015).

In this study, several alternative methods were considered as potential replacements for cohort slicing: 1. a hybrid age length key (ALK) approach (combining forward ALKs and cohort slicing), 2. a pooled ALK (pooling data from multiple years to construct a single forward ALK that is applied to each year) and 3. the method of Hoenig *et al.* (2002) which combines forward and inverse ALKs in a maximum likelihood framework). Results from a previous simulation study (SCRS/P/2017/003) aimed at comparing the relative performance of each method (alongside cohort slicing) indicated that the combined forward-inverse ALK outperformed the other methods. For this reason, the estimates of catch-at-age presented in this document were produced using the combined forward-inverse ALK.

2. Materials and Methods

2.1 Western data

A total of 4,283 age-length samples (99.9% otoliths, 0.1% spines) collected in the Western Atlantic were used for this analysis (**Table 1a**, **Figure 1a**), with the earliest samples dating back to 1974. All samples were aged following the standardized reading protocol and ages were adjusted for proper year class assignment (Luque *et al.,* 2014; Busawon *et al*., 2015; Rodriguez-Marin *et al*., 2016). Sample sizes by age and year are presented in **Table 1a**. Of those samples, only 5% were associated with fish whose sizes were directly measured as straight fork length (SFL), for the remaining fish measurements were obtained from converted length (i.e. curved fork length, snout length, etc.) or weight measurements. Apparent outliers (39 records of fish with sizes falling beyond 3 standard deviations of the mean of the sample for each age – shown in **Figure 1a**) were removed for the analysis as they were thought to be unrealistic and could have a negative impact on the estimation process.

2.2 Eastern data

A total of 9,459 age-length samples (90% spines, 10% otoliths) collected in the Eastern Atlantic were used for this analysis (**Table 2b**, **Figure 2b**), with the earliest samples dating back to 1984. All samples were aged following the standardized reading protocol and ages were adjusted for proper year class assignment (Luque *et al.,* 2014; Busawon *et al*., 2015; Rodriguez-Marin *et al*., 2016). Sample sizes by age and year are presented in **Table 2b**. Of those samples, 95% were associated with fish whose sizes were directly measured as straight fork length. No outliers were apparent in the eastern dataset.

2.3 The Forward-Inverse Key

The method of Hoenig *et al.* (2002) combines forward and inverse ALKs. The forward ALK looks at the age composition in a length interval and applies the proportions to those fish in the length interval that have not been aged. Thus, it uses estimated probabilities $P(i|j)$, where i refers to ages and j to length bins. These probabilities can only be applied to a population with the same age composition as the aged sample. For example, in one year we might have for a particular length interval that $P(i = 3|j) = 0.4$ and $P(i = 4|j) = 0.6$. If the next year, there is a complete failure of the year class that should be age 3, then the probabilities should be $P(i = 3|j) = 0$ and $P(i = 4|j) = 1$. But, if the ALK from the previous year is applied to the current fish in the length bin, then 40% would be assigned to age 3.
The inverse key looks at the distribution of size for each length given age to obtain estimates of $P(j|i)$. It is assumed that these probabilities do not change over time so that an inverse key developed from data from one (or more) year(s) can be applied to any year. One thinks of the logic of the method as finding the weighting factors for the separate length at age distributions that cause the sum of the distributions to match the overall length-frequency distribution as closely as possible, the weighting factors being the age composition.

Hoenig *et al.* (2002) showed that the $P(j|i)$ can be expressed in terms of $P(i|j)$ and vice versa using Bayes Rule. Consequently, the forward and inverse approaches can be combined in one likelihood and the catch-at-age can be estimated for both years with age data and years without age data as well as for years where only incomplete age data is available.

The objective function (Λ_g) is defined as follows:

$$\Lambda_g \propto \prod_{i=1}^{I}\prod_{j=1}^{J}\prod_{k=1}^{K}[P(j|i)P(i)_k]^{n_{ijk}} \prod_{j=1}^{J}\prod_{k=1}^{K}[\sum_{i=1}^{I} P(j|i)P(i)_k]^{y_{jk}} \prod_{j=1}^{J}\prod_{k=1}^{K} P(i)_k^{x_{ik}} \quad (1)$$

where *i*, *j*, and *k* refer to age (0-16+ in the West, 0-10+ in the East), length bin (20:349cm SFL in 17cm bins in the West and 20cm bins in the East) and year (1974-2015 in the West, 1968-2015 in the East), respectively. n_{ijk} is the sample size of fish that were both aged and measured for any combination of age, length bin and year, y_{jk} is the sample size of fish that were only measured for any combination of length bin and year, and x_{ik} is the sample size of fish that were only aged for any combination of age and year. (Note that, in the base run, all x_{ik} were set to zero but this was later changed, see section 3.1). The optimization resulted in estimates of probability of size given age (the inverse age length key matrix, $P(j|i)$) and estimates of probability of age by year ($P(i)_k$). In the West, because of the lack of samples of fish of age 0, $P(i=0|j)$ was fixed to probabilities calculated from the Ailloud *et al.* (2017) growth curve.

The optimization was carried out in AD Model Builder.

3. Results & Discussion

3.1 Convergence

A systematic problem was detected in aging estimation, with certain year classes appearing, disappearing and reappearing in the catch. This was only an issue in years with little to no age data. This problem occurred when two adjacent ages were equally likely to be assigned catch and the model chose to assign all the catch to one age group and none to the other rather than splitting catches between the two age groups. We solved this problem by adding synthetic data to the likelihood using the x_{ik} term from equation 1. x_{ik}, which defines the number of samples of fish of age I in year k that was aged but not measured, was set equal to 1 for all for ages 2 to the plus group, essentially acting as a weak prior on the likelihood to keep $P(i)_k$ estimates off zero. For age 0, $x_{i=0,k}$ were left at zero since it was not obvious that age 0 fish appeared in the catch every year. The validity of this trick was tested using a dummy dataset and found to perform as expected: it kept estimates of $P(i)_k$ off zero and brought them closer to the true $P(i)_k$ values while having no effect on estimates of $P(j|i)$.

3.2 Western results

The model was fitted to data from 1974 to 2015 using different starting values. While many of the runs appeared to have converged (no error messages were produced and standard errors were correctly estimated), they resulted in different negative log likelihoods, suggesting they may have converged on a local minimum. Convergence issues were likely a result of having too much noise is the data. Looking at length-at-age distributions in different years revealed evidence of measurement error that are likely to affect the estimation process as they blur the distinction between the size distributions of adjacent age classes (**Figure 2**). We therefore ran the model with over 200 different starting values, retaining only runs that had a reasonably low final maximum gradient component (<0.1), to see if we would begin the see the appearance of a global minimum. The negative log likelihoods for these runs are presented in **Figure 3a** and estimated proportions-at-age in each year for the best 5 runs are shown in **Figure 4a**. The top 5 runs showed nearly identical results, suggesting the best result is likely close to or at the global minimum. Corresponding estimates of catch-at-age plotted against catch-at-age estimates from cohort slicing are shown in **Figure 5a**.

3.3 Eastern results

The model was fitted to data from 1968 to 2015 using different starting values. The model had more difficulty converging with the eastern data than with the western data, likely due to the scarcity of samples pertaining to older individuals (10+) and the lack of age data in the last 3 years of the analysis (2013-2015) where there are large catches of intermediate to large sized individuals. As such, over 1,200 different starting values were attempted and the negative log likelihoods for these runs are presented in **Figure 3b**. The top 5 runs showed nearly identical estimates of proportions-at-age in each year (**Figure 4b**), however, a surprising result was the fact that, in certain years, the model estimated higher catches of age 9 compared to catches in the 10+ plus group. This raises suspicion on the validity of the results for the eastern stock. Estimates of catch-at-age plotted against catch-at-age estimates from cohort slicing are shown in **Figure 5b**.

3.4 Tracking strong and weak cohorts

There was evidence of both strong and weak cohorts in the catch-at-age estimates in both the East and the West, though they were more pronounced in the West (**Table 2a** and **Table 2b**). With the West, there was an apparent strong 2002 year class moving through the catch, while in the East, it was unclear if the strong cohort belonged to the 2002 or 2003 year class. This difference is likely due to a discrepancy in age readings between spines and otoliths, where otolith ages are more likely to be overestimated due to the occurrence of false band deposition at younger ages (Rodriguez-Marin, pers. comm.). Further investigation into this problem is needed to settle the issue.

4. Conclusion

The combined forward-inverse ALK produced reasonable estimates of catch-at-age but significant data quality concerns remain. The extent to which issues in the data are affecting the results is unknown, we therefore recommend exercising caution when interpreting results from this analysis. We recommend that improvements be made to the data collection and ageing analysis so that more representative and reliable samples be made available for use in ALKs. Samples must be representative of the catch in terms of area covered and range of lengths observed. A length stratified sampling design with fixed sample sizes in each length bin could efficiently help achieve the goal. Moreover, any issues related to the interpretation of false band deposition in otoliths must be addressed. This will likely to resolve some of the issues at hand (e.g. origin of the strong year class signals) and improve convergence to the global minimum. If these changes alone do not result in proper convergence, the method may need to be further modified to allow for more flexibility in dealing with poor quality of input data, such as allowing error in the ages or lengths of the samples, and using priors to limit the solution space.

While the extent and magnitudes of errors in the catch-at-age estimates produced using the forward-inverse ALK remain unknown, there are known and important biases associated with using cohort slicing to produce catch-at-age estimates. We therefore stress the importance that the analyst maintain a level of skepticism of the estimates produced by cohort slicing, especially at older ages, since the method was shown to perform poorly in the simulations previously carried out (SCRS/P/2017/003).

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Table 1a. Western age-length samples used for the forward-inverse ALK (fish captured in the West Atlantic/Gulf of Mexico).

AGE/YEAR	**1974**	**1975**	**1976**	**1977**	**1978**	**1996**	**1997**	**1998**	**1999**	**2000**	**2002**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**Grand Total**
0																			
1		26					1	8											35
2		53		1		1	12	6	10	1				15	8	1	16	4	128
3		9	11	3		4	5	6	3	3				50	63	13	38	21	229
4		4	5	6				9	6	2			3	65	90	37	30	90	347
5		3	4	3		1	4	8	1			1	10	67	58	34	35	24	253
6	2	1	5	1		3	3	3				5	4	51	30	16	14	10	148
7			1	1		12	2	2	1		2	7	22	52	49	11	22	6	190
8		1				15	3	1			3	9	54	100	57	47	24	1	315
9		3	1			15	2				3	10	83	184	55	51	29	11	447
10		1	2	1		16	1				8	5	78	111	65	51	54	17	410
11		4		2	1	2					8	8	39	63	44	62	59	37	329
12		2	1		1	2	1				7	9	23	32	32	45	41	51	247
13		1	1	1	4	1					11	8	16	27	17	33	32	39	191
14		1		1	7						5	11	12	20	12	26	19	26	140
15		2			4						2	9	19	23	11	6	16	20	112
16		3	3		2	1					2	16	15	27	24	13	12	7	125
17		8	3	1	2						3	1	11	38	15	27	5	7	121
18		8	3		6	1						4	4	16	20	32	13	7	114
19		9	6		2						1	6	10	10	12	18	11	8	93
20		3	3	1	4							3	9	16	4	14	12	9	78
21		3	1		6	1						1	3	20	9	15	7	4	70
22		2	2		9							1	3	15	11	7	3	6	59
23		4	4		10								1	4	3	11	3	2	42
24		2	7		5									1	2	9	7		33
25		1	2	2	6											3	3	1	18
26			1		8											2	1	3	15
27		2	1	2	4														9
28					7														7
29			1		5								1	1		1			9
30					2							1							3
31																			
32					2														2
33																			
34					1									1	1				3
Grand Total	**2**	**156**	**68**	**26**	**98**	**75**	**34**	**43**	**21**	**6**	**55**	**115**	**420**	**1009**	**692**	**585**	**506**	**411**	**4322**

Table 1b. Eastern age-length samples used for the forward-inverse ALK (fish captured in the East Atlantic/Mediterranean).

AGE/YEAR	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	…
0																				
1		76	130	108	136	62	57	57	32	46	33	37	79	116	63	6	88		30	…
2		201	116	116	123	60	70	92	109	66	65	94	79	65	132	53	46	87	53	…
3		175	119	50	102	38	64	84	71	60	58	83	106	107	90	17	36	20	47	…
4		72	93	52	70	31	49	45	16	51	38	15	57	67	70	29	10	16	2	…
5	2	46	48	59	40	20	29	29	14	18	9	2	17	19	14	44	10	8	4	…
6	27	7	19	9	26	13	5	6	4	6			4	2	6	7	6	11	3	…
7	21		15	5	6	4	2	2	1	2	1		3	1		4	1	8	12	…
8	11		1	2	3	1	11	1		2	2	1	4			2		10	11	…
9	22		1		1	1	7											4	6	…
10	34					1	17											5	1	…
11	39						16												1	…
12	22						9												1	…
13	21						11											1	2	…
14																				…
15																				…
16																				…
17																				…
18																				…
Grand Total	**199**	**577**	**542**	**401**	**507**	**231**	**347**	**316**	**247**	**251**	**206**	**232**	**349**	**377**	**375**	**162**	**197**	**170**	**173**	…

AGE/YEAR	…	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	Grand Total
0	…	28	1	26				8	30	25	14				132
1	…	39	97	73	34	46	34	2	5	43	20		1	1	1551
2	…	29	56	40	4	39	92	25	64	96	35				2107
3	…	15	5	75	10	11	50	53	19	96	47				1708
4	…	12	23	22	1	13	39	25	8	157	48				1131
5	…	12	11	8	5	3	29	25	6	141	40			1	713
6	…	13	8	9	23	8	18	16	19	63	40	6		5	389
7	…		13	9	10	29	21	15	33	71	47	2		7	345
8	…	1	4	26	4	17	46	12	29	88	52	1		5	347
9	…		10	44	2	8	29	6	25	87	57			4	314
10	…	4	7	59		2	13	2	28	65	37	4	1		280
11	…	1	2	34		2	10	3	16	42	43	3			212
12	…		2	25			3		10	23	14	7	1	3	120
13	…			4		1	2	1	6	13	10	6			78
14	…								2	5	6	1			14
15	…									4	4				8
16	…									3	2				5
17	…								1	1	1				3
18	…										2				2
Grand Total	…	**154**	**239**	**454**	**93**	**179**	**386**	**193**	**301**	**1023**	**519**	**30**	**3**	**26**	**9459**

Table 2a. Catch-at-age estimates for the western stock. Lighter colors indicate lower catches and darker colors indicate higher catches. A strong 2002 cohort is clearly apparent.

Year/Age	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16+
1974	38	12232	57133	72101	87	1296	290	5	189	399	1491	3635	104	3488	6946	833	695
1975	2	2938	44858	170357	337	1250	227	115	37	106	1634	1383	1135	3562	3471	457	712
1976	0	855	10362	37339	75381	246	449	246	342	22	647	82	3976	3570	5676	773	898
1977	29	266	1912	29912	8350	18986	25525	1512	77	29	231	225	343	2755	9026	1823	1113
1978	55	108	7507	11009	17694	12309	7931	9425	137	26	64	208	575	324	7327	3081	1547
1979	5	85	3945	12437	14909	4840	21531	111	3061	2170	10	38	87	4582	4525	3214	1654
1980	320	0	4164	14468	13397	9674	5452	1679	3077	8858	1482	31	38	421	5743	2952	945
1981	0	1024	6924	12545	14208	9765	5457	4795	3191	1680	4196	1646	43	76	148	1862	7256
1982	0	1952	2745	3838	1510	745	4	628	969	236	796	1584	145	10	10	1695	1182
1983	0	2918	1160	2668	2762	794	1091	1821	1308	1639	1828	751	1216	117	127	1135	2697
1984	28	197	1260	6933	2642	1664	3347	2004	2341	80	622	1202	1525	1118	27	649	1496
1985	5	872	57	6918	13761	431	4009	5722	2166	28	24	247	1705	2021	1039	13	1223
1986	565	0	2073	5686	8725	1659	8221	1550	1866	1735	709	57	672	1684	930	113	769
1987	65	1584	1442	14720	7196	7722	7806	3188	1839	1284	1261	235	402	1352	729	101	675
1988	69	3131	3659	10329	12676	3805	3351	5136	4851	1811	990	626	572	1191	884	261	732
1989	93	592	533	14494	1631	117	5365	1353	2705	3627	1788	1362	619	1227	751	674	475
1990	129	935	1909	3835	22397	1626	3776	1367	3142	1441	3254	699	534	899	1050	249	531
1991	111	310	4597	4259	21763	2337	1937	1675	3270	2397	3348	1800	523	1091	499	455	201
1992	98	0	640	3887	5129	218	1484	1726	2410	2280	1747	1731	1236	707	625	444	341
1993	133	7	443	1061	1569	7048	1804	2392	2755	1804	4643	212	332	307	641	739	227
1994	77	607	2198	213	1056	3017	2717	2155	1889	3312	2411	1515	225	414	292	587	201
1995	281	349	924	484	2672	4539	4357	4141	1816	1176	3200	1174	411	171	531	866	658
1996	205	238	548	11655	1209	3196	5280	2408	836	3383	576	2325	563	1045	365	599	592
1997	75	0	322	689	7400	999	1458	1811	2164	2590	2819	143	1259	932	597	683	328
1998	54	18	475	789	3601	4133	1301	785	2605	2645	5445	703	707	881	195	641	525
1999	64	0	136	486	1484	1751	2275	3640	1696	2786	2575	3905	807	114	19	26	1668
2000	49	0	135	276	962	395	2308	3654	3076	1467	2609	1527	2105	34	9	18	2410
2001	13	0	1814	3	1323	5214	2712	695	2753	4171	562	1748	2104	1080	188	35	1470
2002	0	0	1119	6024	4636	2651	8096	2833	908	4400	4207	514	1340	1689	294	142	1083
2003	0	0	214	2309	3465	4952	2674	1675	517	1623	4330	438	206	1138	545	117	989
2004	0	0	856	2636	5255	5082	3975	1782	3004	1084	1552	1344	494	110	739	369	588
2005	0	652	242	5718	3100	2687	574	854	1175	627	1087	2083	991	115	542	507	560
2006	0	0	253	401	1347	1298	3006	2299	650	1665	1358	1076	626	686	116	698	712
2007	0	0	87	118	3613	15759	168	2296	1556	558	497	544	471	175	86	200	1040
2008	0	0	96	825	1539	803	7776	3507	309	2875	1251	567	430	151	43	392	1313
2009	0	0	79	94	1376	2162	767	5155	4682	169	1389	695	388	550	483	275	811
2010	0	0	72	1269	573	1515	1738	608	1070	2837	1653	1553	399	563	634	241	574
2011	0	0	7	490	762	3189	1230	2490	790	4870	1628	700	553	404	422	141	778
2012	0	35	81	175	1793	1604	979	265	1494	951	3461	1121	520	361	502	68	734
2013	0	13	36	128	339	1484	383	581	370	1537	932	2084	819	350	360	41	759
2014	0	10	90	1245	110	963	582	487	224	388	1801	1533	1980	552	285	119	617
2015	0	0	1	31	1390	252	225	427	602	974	536	2115	1727	1235	508	241	657

Table 2b. Catch-at-age estimates for the eastern stock. Lighter colors indicate lower catches and darker colors indicate higher catches.

Year/Age	0	1	2	3	4	5	6	7	8	9	10+
1968	7359	13	6988	87474	43043	29110	31	13669	1063	2989	31289
1969	539	6622	35622	132979	543	12699	15716	4402	14029	4521	33847
1970	1162	13437	126327	49733	668	6539	13406	13301	7907	4560	17894
1971	809	12943	67608	89205	15	6814	968	3932	30713	41	16993
1972	15	10123	28980	174873	28354	2266	3103	6797	3212	9672	15921
1973	114	2608	108200	106287	9796	2728	735	5293	27399	1125	13078
1974	267	58999	48962	83573	51734	41816	1635	2219	32630	11246	28889
1975	509	17172	103900	116587	3679	19269	6976	6391	2870	3203	62815
1976	148	2593	31517	103480	43399	32557	10343	8873	8274	4818	59842
1977	161956	51929	16795	148896	33700	13100	9824	8282	555	595	50114
1978	88347	22894	171275	32799	17978	21597	3404	3903	2513	412	41477
1979	84400	9271	10641	62798	33510	14520	3893	6313	6239	3257	28771
1980	60074	15344	73637	15781	40123	15036	5523	8241	2332	7000	35975
1981	51221	24340	164517	46364	18017	8884	5963	12135	11097	11208	24574
1982	166410	81515	179804	84104	70601	16943	10193	13993	13351	13426	43206
1983	0	172166	358035	29491	45283	18156	8370	12746	11621	19547	37899
1984	171	11908	107559	230147	41340	34632	18356	14202	17850	19812	39438
1985	0	23601	135274	142650	152690	20499	16741	5115	5218	9590	41718
1986	0	87077	234006	59701	76765	11262	17287	11193	2539	6369	40966
1987	19	43791	244802	169444	29266	32762	13441	10888	5383	13922	26078
1988	0	285255	198410	130692	124898	19604	13325	21576	7704	14007	35942
1989	0	50541	453096	48865	95068	35542	2464	21166	8738	7114	31356
1990	0	182529	142344	154662	96049	74324	5239	17868	12966	17083	25835
1991	24478	266457	58669	219851	146815	46181	26018	9469	16605	32285	20699
1992	18	173504	168687	502642	166064	3473	34866	17570	11257	26582	28822
1993	1993	231941	312684	596288	146031	36599	40034	22170	7187	18475	25600
1994	318195	371496	583219	108052	174724	26037	57450	34175	23696	44794	59175
1995	18024	152853	634225	128840	146350	41255	58281	30679	25305	22686	78866
1996	3	209462	951152	64477	338439	77590	28218	14857	23398	32253	64187
1997	0	142362	591501	333070	155775	102940	51990	17512	36021	62494	41315
1998	70800	289402	259627	489797	309130	147125	11745	15980	30965	36784	40482
1999	63615	376203	573029	236351	370547	31214	27889	40660	18630	79656	21520
2000	0	7444	345135	139824	327624	6233	47823	33154	39841	112026	12323
2001	0	1485	253339	253751	389994	11839	53336	34800	35896	64585	40228
2002	62	3813	249663	521139	209682	24837	49513	21776	22184	36908	81461
2003	3533	7146	295288	289168	117332	31021	71488	28354	19864	67770	72158
2004	0	12170	311748	121266	147905	22882	25818	74002	2753	95796	61391
2005	203	8316	279905	49037	58051	44232	37186	32306	31263	70756	95520
2006	11	797	93783	73302	84444	106303	51762	34285	56350	63956	68620
2007	314	39261	1802	124855	111399	310451	113733	24479	30464	51930	84257
2008	0	3012	88157	68354	62572	91778	37370	23104	24393	19584	21399
2009	452	3246	2268	37433	22772	27026	57700	43682	9425	16266	20989
2010	57	1618	4684	29233	14116	39997	25450	24731	11981	6047	6961
2011	0	56	1114	6229	14104	23686	16543	4418	12082	8461	15290
2012	0	30	127	1281	14664	18551	10135	7727	12818	15132	16212
2013	0	420	24429	1807	10685	22819	7719	15378	17965	20556	15616
2014	0	2	24372	885	13181	22000	1886	2398	11939	32575	18175
2015	7	80	32087	7397	26565	30125	1548	1982	13094	30508	29101

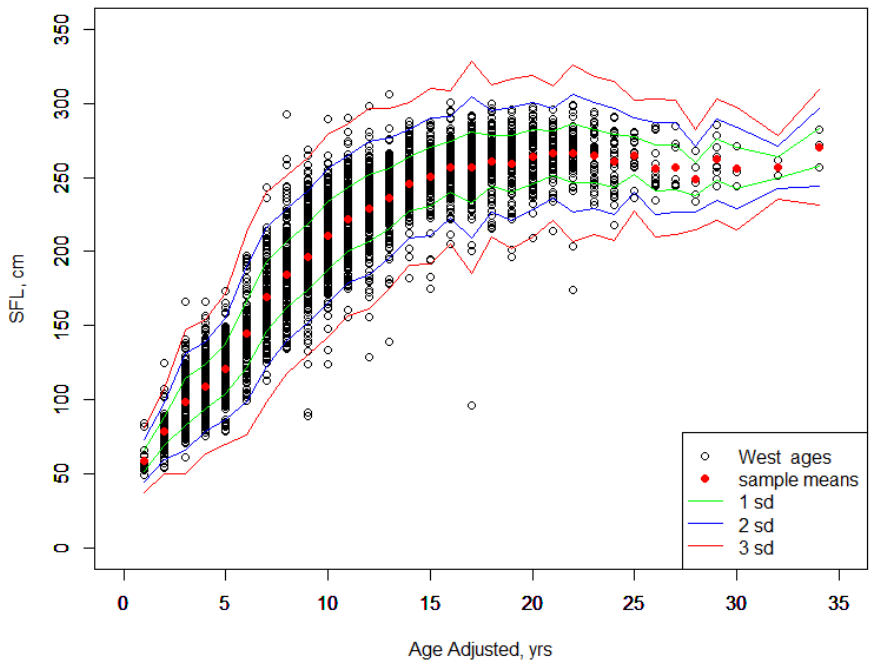

Figure 1a. Age-length samples available for the West Atlantic. Records falling beyond 3 standard deviations of the mean (red line) were excluded from the analysis.

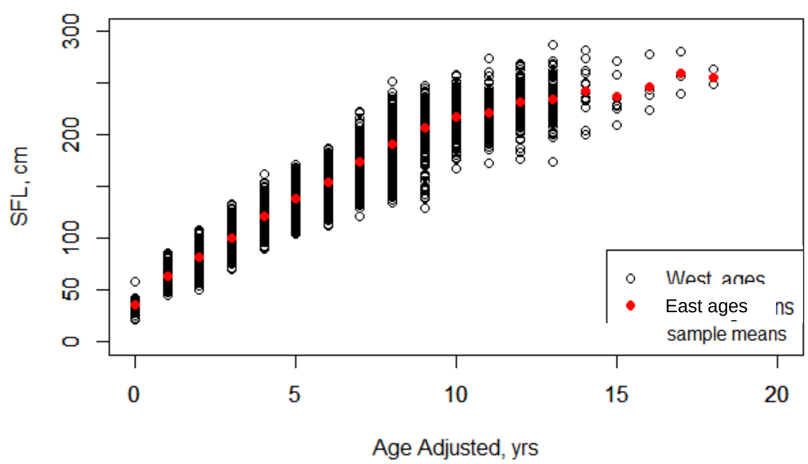

Figure 1b. Age-length samples available for the East Atlantic.

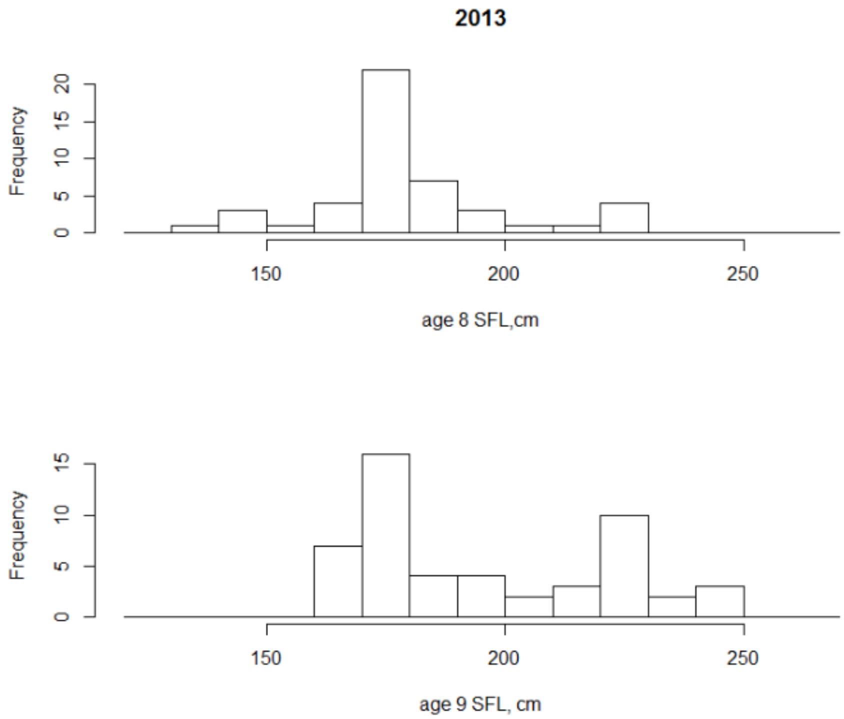

Figure 2. Histogram of length records for fish sampled in the West Atlantic in 2013 that have been assigned to ages 8 and 9. A bimodal distribution is apparent and likely to be a reflection of measurement and/or ageing error.

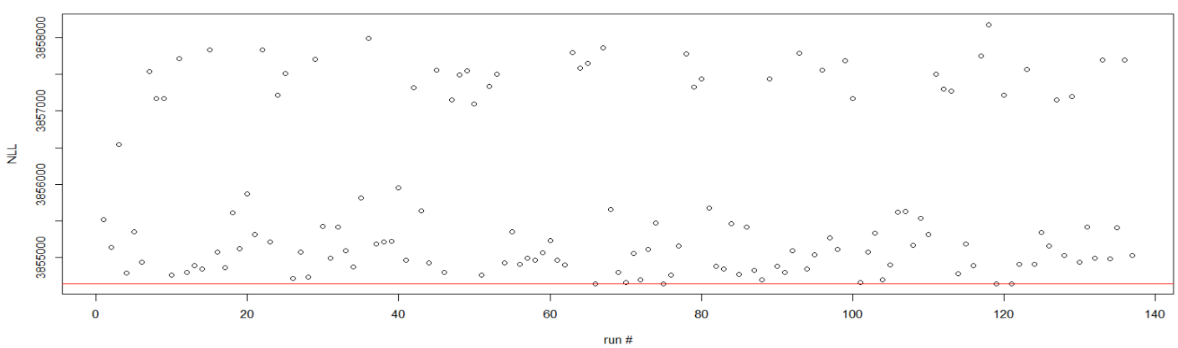

Figure 3a. Negative log likelihoods of the different runs (different starting values) for the western data.

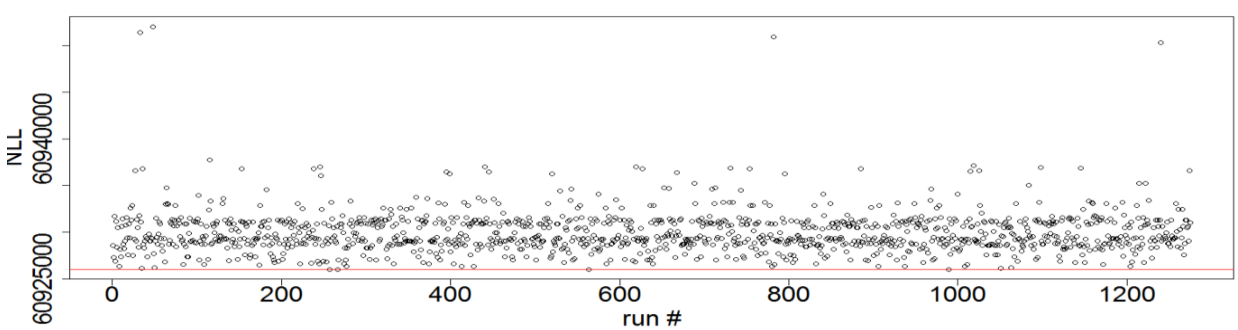

Figure 3b. Negative log likelihoods of the different runs (different starting values) for the eastern data.

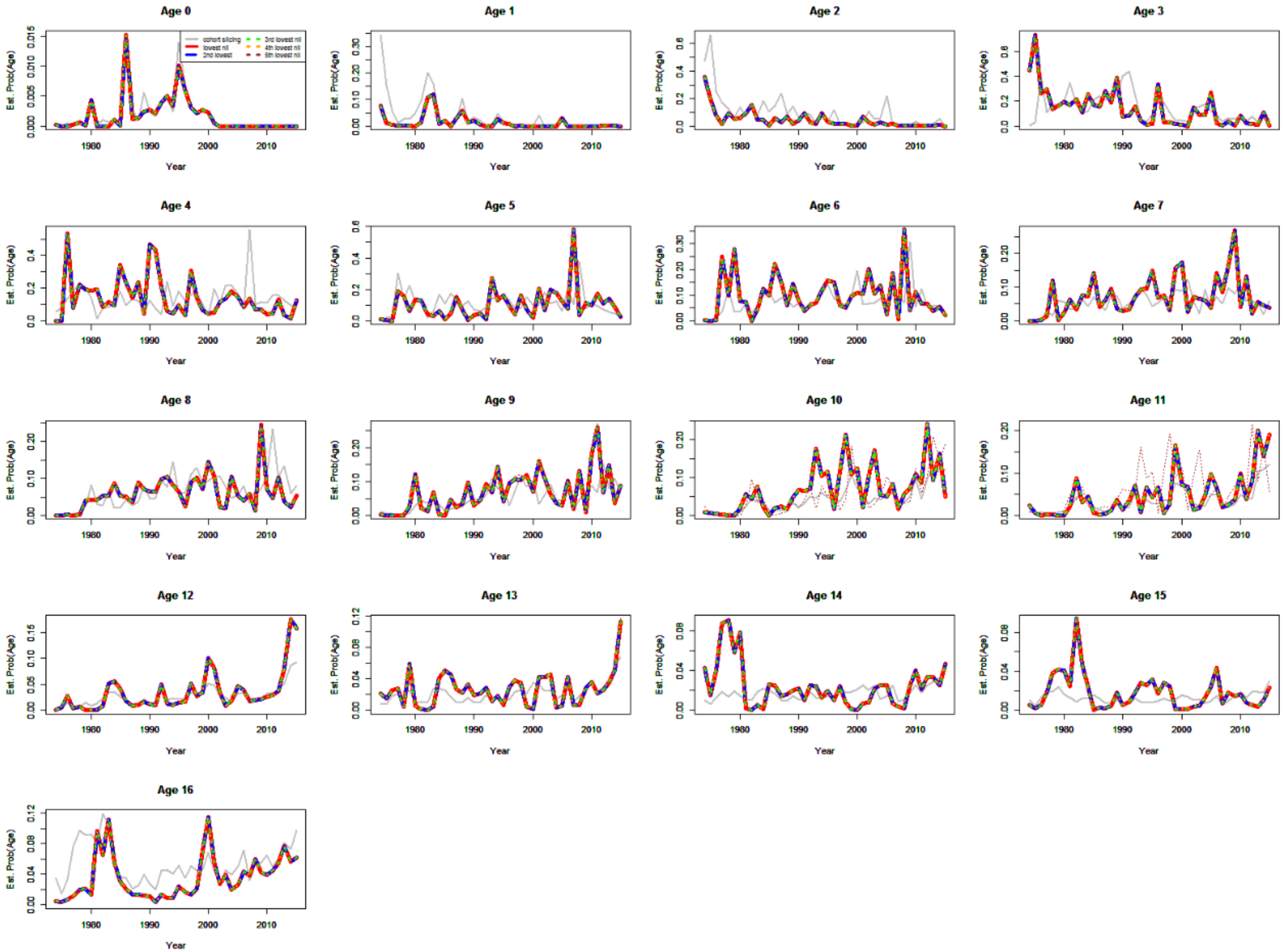

Figure 4a. Estimated proportions-at-age by year for the top 5 runs of western ABT plotted against estimates from cohort slicing for the West (grey solid line).

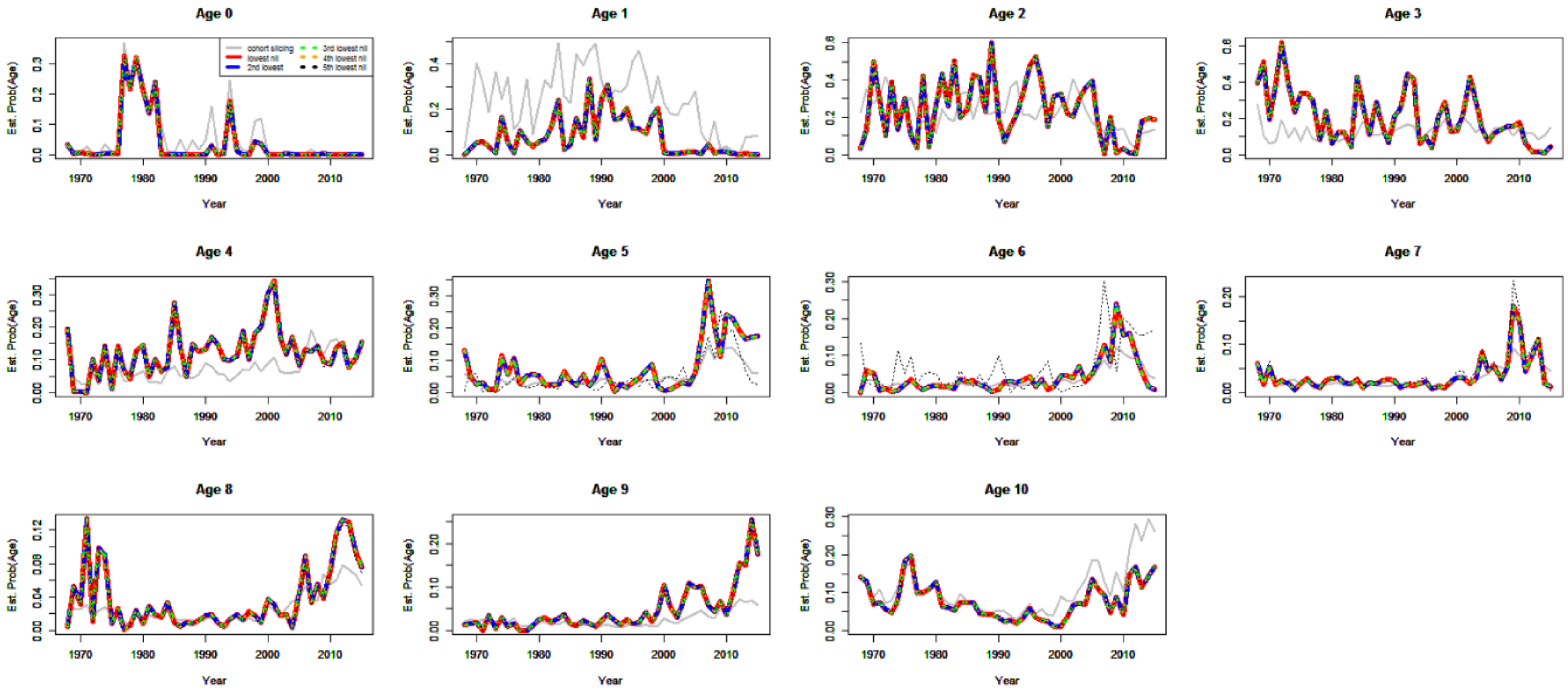

Figure 4b. Estimated proportions-at-age by year for the top 5 runs of eastern ABT plotted against estimates from cohort slicing (solid grey line) for the East.

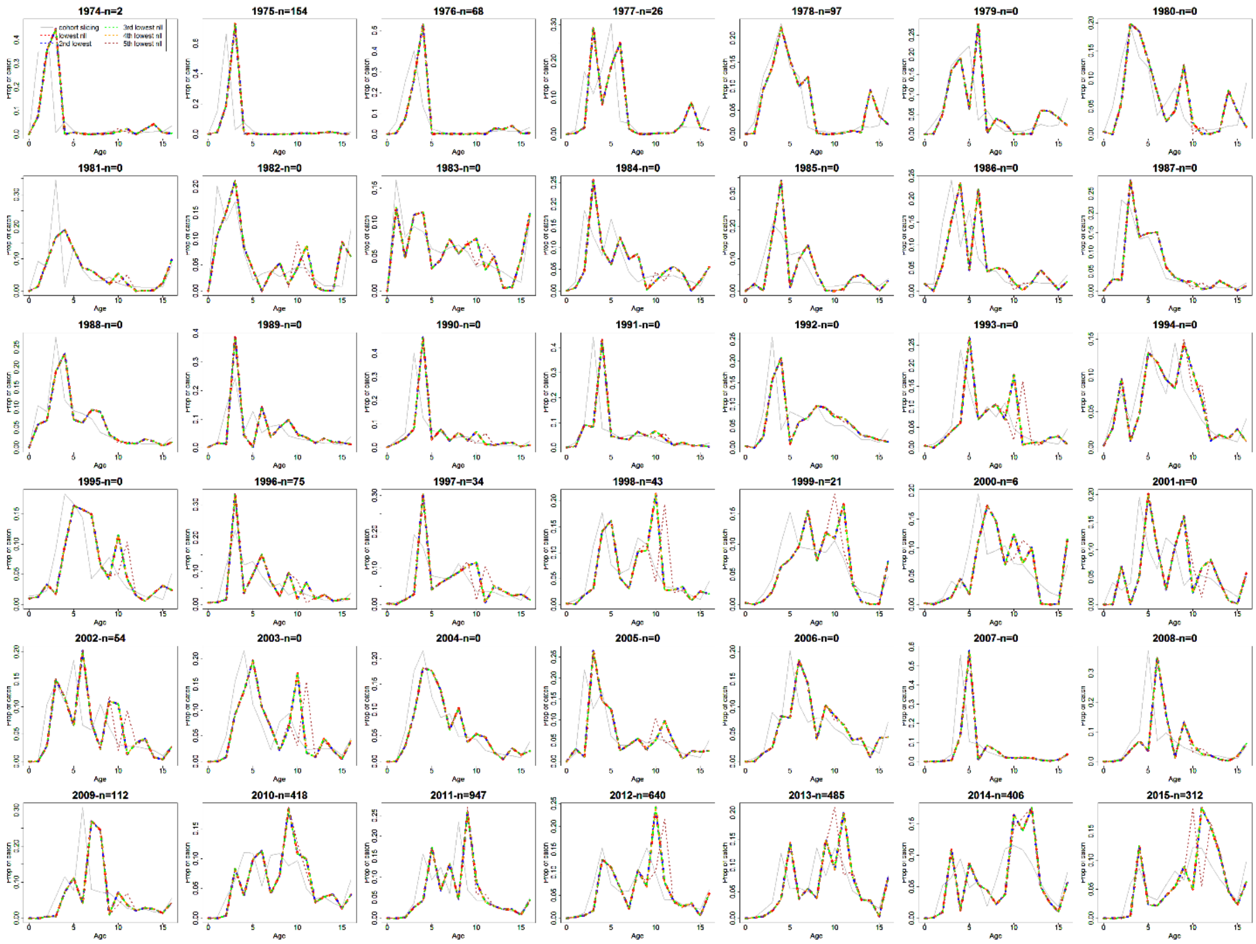

Figure 5a. Catch-at-age estimates for western ABT obtained using the forward-inverse ALK plotted against the cohort sliced estimates (solid grey line). Sample sizes of age data in each year are shown.

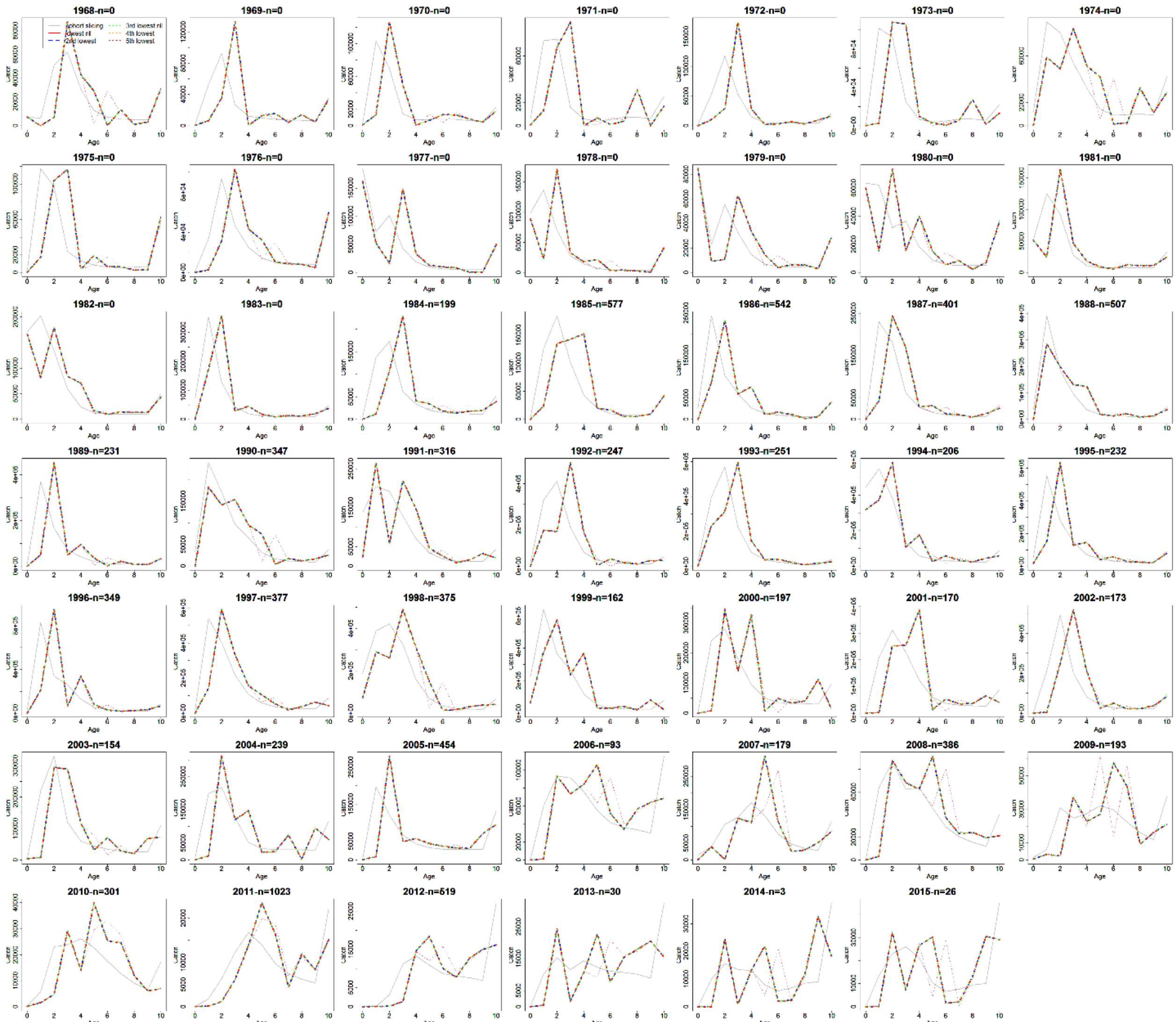

Figure 5b. Catch-at-age estimates for eastern ABT obtained using the forward-inverse ALK plotted against the cohort sliced estimates (solid grey line). Sample sizes of age data in each year are shown.