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An integrated stock assessment for the Heard Island and the McDonald Islands Patagonian toothfish (Dissostichus eleginoides) fishery in Division 58.5.2

P. Ziegler and D. Welsford (Australia)

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An integrated stock assessment for the Heard Island and the McDonald Islands Patagonian toothfish (*Dissostichus eleginoides*) fishery in Division 58.5.2

Philippe Ziegler and Dirk Welsford

Australian Antarctic Division
Department of the Environment
203 Channel Highway, Kingston, Tasmania 7050, Australia
Email: philippe.ziegler@aad.gov.au

Abstract

This paper presents an updated assessment for the Patagonian toothfish (*Dissostichus eleginoides*) fishery at the Heard Island and the McDonald Islands in CCAMLR Division 58.5.2 with data until end of July 2015. The updated assessment model is based on the best available estimates of model parameters, the use of abundance estimates from a random stratified trawl survey (RSTS), longline tag-release data from 2012-2014 and longline tag-recapture data from 2013-2015, and auxiliary commercial composition data to aid with the estimation of year class strength and selectivity functions of the trawl, longline and trap sub-fisheries.

Compared to the 2014 assessment that was accepted by WG-FSA-14 to be used for management advice, this assessment takes into account the recommendations of WG-FSA-2014 and WG-SAM-2015, and incorporates (a) new fishery observations up to 2015 including new ageing data from the 2014-2015 RSTS and commercial fishery from 2009-2014, (b) tag-releases from 2014 and tag-recaptures from 2014 (complete) and 2015 (partial), (c) an updated growth model, (d) changes in priors for survey catchability *q*, unfished spawning biomass B_0 and year class strength, and (e) a split of the trawl sub-fishery into two periods. All model runs were conducted with the CASAL version 2.30-2012-03-21 that was agreed on by WG-SAM-14.

The updated assessment model leads to a smaller estimate of the virgin spawning stock biomass B_0 than that obtained in 2014, with an MCMC estimate of 87 077 tonnes (95% CI: 78 500-97 547 tonnes). Estimated *SSB* status in 2015 was 0.64 (95% CI: 0.59-0.69). Using this model, a catch limit of 3405 tonnes satisfies the CCAMLR decision rules. Similarly to the 2014 assessment, the projected stock remains above the target level for the entire projection period.

1. Introduction

A number of stock assessments have been developed in recent years for the fishery for Patagonian toothfish (*Dissostichus eleginoides*) at the Heard Island and the McDonald Islands (HIMI) in CCAMLR Division 58.5.2 (Candy and Constable 2008, Candy and Welsford 2009, Candy and Welsford 2011, Ziegler et al. 2013, Ziegler et al. 2014).

At WG-FSA-14, a series of research papers presented new information for consideration in the development of the stock assessment for 2014. These papers centred around recommendations on the assessment from WG-FSA-13, SC-CAMLR-XXXII and WG-SAM-14, describing:

- The spatial distribution of *D. eleginoides* using data collected from the fishery and research surveys in Division 58.5.2 since 1997 (Péron and Welsford 2014 - WG-FSA-14/42);
- The spatial structure, mortality, movement rates and growth analysed from data of tagged and recaptured *D. eleginoides* within Division 58.5.2 between 1997 and 2014 (Welsford et al. 2014 - WG-FSA-14/43);
- Information gained from new aging data for *D. eleginoides* in Division 58.5.2 (Farmer et al. 2014 - WG-FSA-14/45);
- A revised estimate of the ageing error matrix (Burch et al. 2014 - WG-FSA-14/46); and
- A step-wise development of a new base-case assessment model for *D. eleginoides* starting from the previous assessment model presented in WG-FSA-13/24 (Ziegler et al. 2014 - WG-FSA-14/34).

The proposed assessment model in WG-FSA-14/34 incorporated, *inter alia*, new ageing data, a Beverton-Holt stock recruitment relationship, an updated error matrix, an updated growth model, and an externally estimated prior for the catchability q of the Random Stratified Trawl Survey (RSTS). The paper also compared MCMC runs with covariance matrix resampling for stock projections for this stock.

WG-FSA-14 noted that the base-case model presented in WG-FSA-14/34 indicated a high correlation between survey q and spawning stock biomass B_0, and that the precision in the estimate of B_0 was relatively poor (WG-FSA-14, para. 4.26). This contrasted with the well-defined B_0 estimate that resulted from the inclusion of the two most recent years of tagging data as presented in WG-FSA-14/43. In addition, the low year class strengths (*YCS*) estimated by the model presented in WG-FSA-14/34 for the years 1982–1985 were poorly determined in the observations. WG-FSA-14 recommended that the model including tag-releases for 2012 and 2013 and fixed *YCS* before 1986 at 1.0 be used to provide management advice (WG-FSA-14, para. 4.27).

WG-FSA-14 also recommended to (Table 1):

- Re-estimate growth parameters, particularly as more data characterising size-at-age in older year classes become available (WG-FSA-14, para. 4.30); and
- Estimate survey catchability q in the model and present to WG-SAM along with sensitivities around these calculations, and investigate the inclusion of survey data as biomass and proportions-at-age in future model runs (WG-FSA-14, para. 4.31).

In response to these recommendations, de la Mare et al. (2015) presented analyses that considered potential biases in the calculation of priors for survey catchability q using abundance estimates from a random trawl survey and tag-recapture data as recommended by WG-FSA-14 (para. 2.3). WG-SAM-15 concluded that such estimates of q using these data were likely to be biased (WG-SAM-15, para. 2.10).

Table 1: Recommendations from WG-FSA-2014 and WG-SAM-2015 and their implementation.

Recommendation	Source	Implementation
Re-estimate growth parameters, particularly as more data characterising size at age in older year classes become available	WG-FSA-14, para. 4.30	Chapter 3.6
Estimate survey catchability *q* in the model and present to WG-SAM along with sensitivities around these calculations	WG-FSA-14, para. 4.31	De la Mare et al. (2015)
Investigate the inclusion of survey data as biomass and proportions at age in future model runs	WG-FSA-14, para. 4.31	Chapter 4.4

This paper presents a revised integrated stock assessment for *D. eleginoide*s in Division 58.5.2, using the CASAL assessment model framework (Bull et. al., 2012). As in Ziegler et al. (2014), a bridging analysis was conducted starting with the assessment model that was used to provide management advice in 2014 (WG-FSA-14, para. 4.27). This bridging analysis updates model data and parameter estimates, and improves the model structure, leading step-wise to the proposed 2015 assessment model.

This stock assessment uses again survey and tag-based information to estimate fish biomass. Candy and Constable (2008) investigated the inclusion of tag-releases and recaptures from the trawl sub-fishery in the stock assessment, but concluded that these tag-recapture data were likely to only estimate the local biomass in the relatively small fishing area where trawl had been concentrated, rather than that of the population biomass in the entire Division 58.5.2. Longline fishing started in 2003 and since then has expanded over some parts of the fishable area in the Division (Welsford et al. 2014, Burch et al. 2015). A research project is currently underway with the aim to include further tag-recapture data in the assessment and develop approaches that will allow accounting for potential biases in biomass estimates from tag-recapture data that may arise from the spatial heterogeneity in the distribution of fish population and fishing effort (Welsford and Ziegler 2012, Burch et al. 2015).

2. Data

2.1. Catch data

Commercial fishery data from the Patagonian toothfish fishery in Division 58.5.2 were available for the period from 1997-2015. The haul-by-haul data from longline, trawl and trap included information on *inter alia* fishing date, haul latitude and longitude, fishing depth, gear type, effort, and total catch in weight and numbers. Relevant biological data collected by observers included the total length and weight of all sampled fish. Biological data were excluded if the quality of the record had been flagged as being poor. Observers also collected fish otoliths that were used for ageing fish.

Table 2 presents the estimated catches from 1996 to the end of July 2015. For the assessment, catches were summarised by sub-fishery and fishing season, and it was assumed that the catch limit in 2014/2015 of 4410 tonnes would be reached.

Table 2: Catch limits, reported catch for RSTS, trawl, longline and trap, estimated IUU catch and total removals in tonnes by calendar year for Division 58.5.2.

	Catch	Reported catch					Estimated	Total
Year	**limits[a]**	**RSTS**	**Trawl**	**Longline**	**Trap**	**Total**	**IUU catch**	**removals**
1996	297	0	0	0	0	0	3000	3000
1997	3800	0	1866	0	0	1866	7117	8983
1998	3700	1	3784	0	0	3785	4150	7935
1999	3690	93	3452	0	0	3545	427	3972
2000	3585	9	3556	0	0	3565	1154	4719
2001	2995	45	2933	0	0	2978	2004	4982
2002	2815	35	2717	0	0	2752	3489	6241
2003	2879	13	2580	270	0	2863	1274	4137
2004	2873	65	2218	566	0	2849	531	3380
2005	2787	21	2040	636	0	2697	265	2962
2006	2584	12	1785	659	72	2528	112	2640
2007	2427	12	1775	625	0	2412	0	2412
2008	2500	4	1612	825	0	2441	0	2441
2009	2500	20	1268	1173	13	2474	0	2474
2010	2550	28	1239	1216	32	2515	0	2515
2011	2550	6	1142	1317	33	2498	0	2498
2012	2730	41	1322	1356	0	2719	0	2719
2013	2730	8	555	2116	40	2719	0	2719
2014	2730	13	93	2638	0	2744	0	2744
2015	4410	26	118	1496	0	1640	0	1640 [b]

[a] Catch limits for fishing seasons with (1 December - 30 November) do not completely overlap with calendar years.

[b] Incomplete fishing season. For the assessment, it was assumed that the catch limit for 2015 would be reached, with 26 tonnes from the RSTS, 118 tonnes from trawl, and 4266 tonnes from longline.

2.2. Length and ageing data

A large number of toothfish have been measured annually for length in the RSTS and the commercial fishery (Table 3). Since the last assessment (Ziegler et al. 2014), an additional 1721 otoliths collected from the surveys and commercial fishery have been aged, helping to create a dataset of almost 14 000 age estimates. All ages have been estimated by technicians that have been trained following the recommendation of the 2012 toothfish ageing workshop (SC-CAMLR 2012) and the protocols for thin sectioning developed at the Australian Antarctic Division (AAD; Welsford et al. 2012, Farmer et al. 2014). Samples of otoliths from all RSTS until 2014 where otoliths are available have now been aged (Table 3 and Figure 1). For the 2015 survey, 200 fish have been aged so far, and an additional 1150 fish have been aged that have been caught by the commercial fishery from 2009-2014.

Table 3: Number of toothfish measured for length or age and used in the assessment for the RSTS and commercial fisheries. Where numbers are in bold, the ages have been used to calculate age-length keys (ALKs). Length samples and ages of sampled otoliths in 2015 are incomplete.

Year	**Length**			**Age**		
	RSTS	**Commercial**	**Total**	**RSTS**	**Commercial**	**Total**
1997	0	11 387	11 387	0	**55**	55
1998	169	11 229	11 398	0	**286**	286
1999	2294	14 623	16 917	2	**623**	625
2000	2258	20 483	22 741	20	**807**	827
2001	2505	27 079	29 584	2	**909**	911
2002	2965	18 476	21 441	4	**829**	833
2003	2301	27 298	29 599	13	**675**	688
2004	2462	33 509	35 971	4	**336**	340
2005	2355	28 899	31 254	1	**370**	371
2006	2081	31 427	33 508	**119**	**1100**	1219
2007	2050	22 843	24 893	**547**	**588**	1135
2008	1281	31 475	32 756	**652**	**107**	759
2009	1922	44 342	46 264	**642**	**77**	719
2010	5893	30 485	36 378	**918**	**129**	1047
2011	2484	35 568	38 052	**520**	**142**	662
2012	6062	37 026	43 088	**549**	**140**	689
2013	2912	42 736	45 648	**266**	**1249**	1515
2014	2769	50 417	53 186	**571**	**526**	1099
2015	3869	18 661	22 530	**200**	3	203
Total	48 632	537 966	586 598	5031	8951	13982

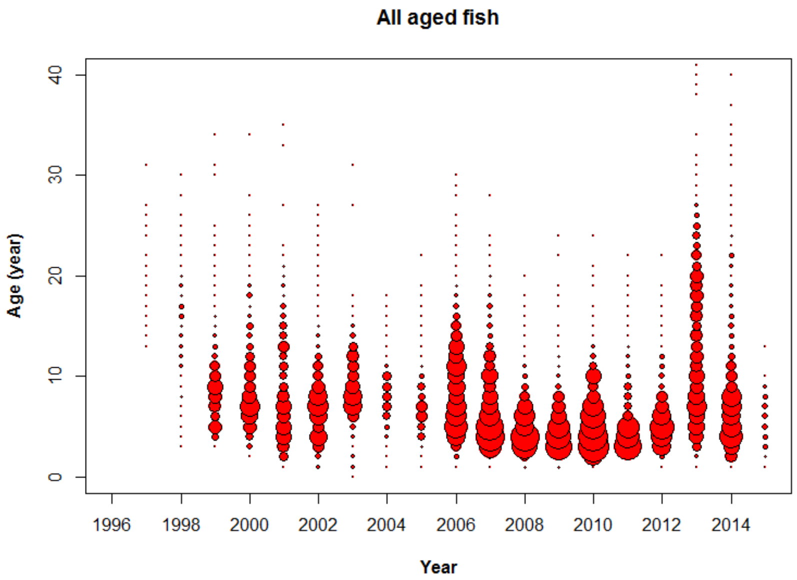


Figure 1: Bubble plots for the overall number of fish aged. The numbers of aged fish are relative to the diameter of the circles.

3. Methods

3.1 Model population dynamics

Basic descriptions of the CASAL model population dynamics can be found in Candy and Constable (2008), Candy and Welsford (2009, 2011) and Ziegler et al. (2013, 2014). The single-sex CASAL assessment model (Bull et al. 2012) was age-structured with age classes from 1-35 years. Natural mortality was assumed to be 0.155 (Candy et al. 2011) and constant across all age classes. CASAL 2.30-2012-03-21 rev. 4648 was used in all instances, following the recommendation of WG-SAM-14 (WG-SAM-14, para. 2.29).

The assessment models were run for the period from 1982-2015. The annual cycle was divided into three time steps or seasons during which (1) fish recruitment, the first half of natural mortality, and fishing, (2) the second part of natural mortality and spawning, and (3) ageing occurred.

3.2. Random stratified trawl surveys (RSTS)

Random stratified trawl surveys (RSTS) have been conducted around Division 58.5.2 to estimate the abundance and size structure of *D. eleginoides* and *Champsocephalus gunnari* (mackerel icefish) in 1990, 1992, 1993, and annually from 1997-2015. However, the structure and intensity of the surveys has varied over these years as the objective for the surveys has changed, and information for survey design and power has improved (Welsford et al. 2006). For example, the initial three surveys in the early 1990s were conducted to gain a basic understanding of the distribution and abundance of fish stocks in the region, occurred at different seasons, and used a relatively small number of trawls. The surveys in 1997-1998 targeted icefish and are not suitable to estimate toothfish abundance. Major surveys incorporating a wider range of toothfish habitats started in 1999, although for the first four years different stratum plans based on specific research questions for toothfish and icefish within the annual allocation of ship-time resulted in varying effort to survey toothfish. The large shallow strata sampled in the 1999 survey were subdivided in 2001 and the deeper strata in 2002, after which the strata boundaries have been stable. In 2000, only a relative small area was surveyed, and the northern plateaus were not sampled in 2003. After reviewing the statistical power of the surveys in 2003, trawl allocation to strata with greater fish abundance was increased (Candy et al. 2004).

An annual survey consists of between 120-160 trawl hauls, each taking approximately 30 mins to complete. The entire fishable area in Division 58.5.2 down to 1000 m is divided into ten strata (of which one is excluded from sampling since it is closed to fishing) that each cover areas of similar depth and/or fish abundance (Nowara et al. 2015). A list of random co-ordinates for starting position and prescribed headings for each station in each stratum is provided to the fishing vessel conducting the survey, including first choice and reserve positions. In the surveys until 2014, the sampling area of the main trawl fishing ground, which is around 450 km^2, was subdivided into squares of 2 x 2.4 nautical miles (0.5 x 0.5 degrees). Sampling occurred in a randomly selected subset of 20 out of the total of 30 of these squares, with details provided in the survey instructions. For the 2015 survey, the main trawling ground was subdivided into two sub-strata, and as in the other strata vessels were provided with random co-ordinates for starting positions and headings. The number of stations in the main trawl ground has also been increased to 25.

For the assessment, observations from the survey years 2001-2002 and 2004-2015 were used (‘Survey group 1’ in Ziegler et al. 2014). In the assessments up to 2013, this survey group had been assumed to fully sample the fish stock vulnerable to the fishing gear as quantified by the fishing selectivity function, with survey catchability *q* set to 1. For the 2014 assessment, catchability for this survey group had been estimated using a prior that was derived from comparing abundance estimates of the survey with abundance estimates calculated from the tag-recaptures data on the main trawl ground (Ziegler et al. 2014).

In response to comments by WG-FSA-14, de la Mare et al. (2015) further investigated the ability to estimate survey *q* from survey and tag-based abundance estimates. Simulations indicated that a potential bias in the estimate of survey catchability could arise from the need to concurrently estimate fishing selectivity and that this potential bias could not be corrected given the available data. While de la Mare et al. (2015) recommend a prior with uniform distribution for survey *q*, a uniform-log prior was used in this assessment to account for the multiplicative space within which catchability is applied (Punt and Hilborn 2001).

For surveys from 2001-2002 and 2004-2005, estimates of abundance-at-length and their corresponding CVs were obtained using a bootstrap procedure, retaining the stratification and length composition in a haul during the bootstrap (Constable et al. 2006).

For all surveys from 2006-2015, catch-at-length data were used to estimate proportions-at-length, weighted by stratum-area. These were then converted to proportions-at-age, using age-length keys (ALKs) as described in Candy (2009), along with a Monte Carlo sampling method for estimating effective sample size (ESS) for use as the nominal multinomial sample size. The proportions-at-age ESS took into account uncertainty due to haul-level variability in proportions-at-length (Candy 2008), ALK sampling error, and random ageing error (see below). The ALKs used for each of these years were restricted to fish aged from the surveys of that particular year. Table A.1 shows the overall age-length relationship for the survey catch by an ALK obtained by pooling data of all years from 2006-2015. Catch-at-length proportions and ALKs were grouped by 50 mm length bins from 150 to 2000 mm.

Abundances-at-age were obtained by multiplying proportions-at-age with the estimated total population abundance vulnerable to the survey. Assuming a lognormal distribution, the CV of abundance-at-age estimates was obtained using the variance of the proportions-at-age and the variance of estimated total vulnerable population size (i.e. the variance for a stratified random sample, Cochran 1977), as described in Appendix 2 of Candy and Welsford (2011). No process error component was calculated for the survey abundance-at-length and abundance-at-age data, as a heuristic way of giving extra statistical weight to the survey data to account for the fact that the data are fisheries-independent.

3.3. Commercial fishery

Length-frequency distributions (LFD) of fish in hauls may show systematic trends that are caused by gear-specific selectivity and fish availability. In integrated assessments, hauls with similar LFD data are usually pooled into groups, here termed ‘sub-fisheries’, with individual selectivity functions to achieve a better model fit. These definitions of sub-fisheries are typically based on gear types and fishing locations.

Following the method developed by Candy et al. (2013), the fishery structure was evaluated in a similar way as in the 2014 assessment and remained unchanged for this assessment. This method takes account of the shape of the entire LFD of single or grouped hauls and fits a Generalised Additive Mixed Model (GAMM) with cubic smoothing splines for a combination of covariates (e.g. gear type, depth strata and region). The analysis showed that a split between all gear types and some further splits for longline hauls were appropriate for the toothfish fishery in Division 58.5.2 (Figure 2). Alternative depth and regional splits of longline hauls indicated that depth splits at 1250 m or 1500 m provided similar results, with significantly different splines between shallow and deep hauls. For the assessment model here, a depth split at 1500 m was used. Splines from the respective depth strata on eastern and western fishing grounds were similar, indicating that a separation of longline hauls by fishing regions would not be needed in an assessment.

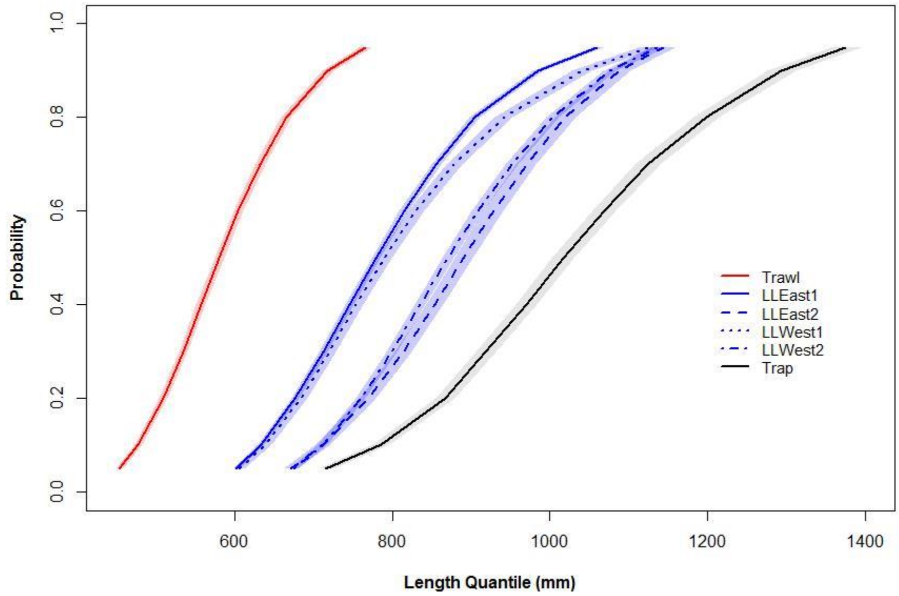


Figure 2: Predicted splines for length quantiles of trap, trawl and longline (LL). The shaded areas represent the 95% confidence intervals (or two standard errors) of the spline for trawl (red) and trap (black), or of the difference between pairs of splines for longline (blue). The analysis is based on hauls pooled by block size of 1/8° latitude * 1/4° longitude (about 4 * 4 nm). Longline hauls were split into eastern and western fishing areas, and into depth stratum 1 (depths <1500 m) and stratum 2 (depths >1500 m).

Based on this analysis, the commercial sub-fishery structure for the assessment consisted of a trawl, trap, a shallow longline LL1 and a deep longline sub-fishery LL2 (however, see bridging analysis below). IUU catches from Table 2, which were included in the assessment, were assumed to have been taken by longline, with a selectivity function similar to that of the longline sub-fishery LL1.

For all years with commercial fishing (1997-2015), catch-at-length data were used to estimate catch proportions-at-length. To account for over-dispersion of the proportions-at-length data relative to a multinomial distribution, the actual number of fish sampled across bins were replaced with estimated ESS (excluding process error) which were calculated following the method described in Candy (2008). Year-specific ALKs were calculated from age-length samples across all sub-fisheries (Table 3). For the year 1997, the relatively low age-length sample sizes were pooled with those from 1998. Table A.2 shows an ALK obtained by pooling data over all years showing the overall age-length relationship for the commercial catch.

Proportions-at-age for commercial sub-fisheries were calculated in the same way as those for surveys, following the method of Candy (2009). Again, the proportions-at-age ESS took into account uncertainty due to haul-level variability in proportions-at-length (Candy 2008), ALK sampling error, and random ageing error. Catch proportions-at-length and ALKs were again grouped by 50 mm length bins from 150 to 2000 mm.

3.4 Selectivity functions

Either double-normal (DN) or double-normal-plateau (DNP) fishing selectivity functions were fitted for the survey and each sub-fishery. The DNP function was calculated as $f(x)$ for age x (Bull et al. 2012):

$$f(x)=\begin{cases} a_{\max}2^{-\left[(x-a_1)/\sigma_L\right]^2} & x\le a_1 \\ a_{\max} & a_1<x\le a_1+a_2 \\ a_{\max}2^{-\left[\{x-(a_1+a_2)\}/\sigma_U\right]^2} & x>a_1+a_2 \end{cases} \quad (0.1)$$

where a_1 and a_1+ a_2 define the age range at which the ogive takes the value a_{max}, and σ_L and σ_R define the shape of the left-hand and right-hand side of the DNP function such that the ogive takes the value $0.5a_{max}$ at $a = a_1 - \sigma_L$ and $a = a_1 + a_2 + \sigma_R$. In all cases, a_{max} was not estimated but set to 1, i.e. only four parameters were estimated for all DNPs. When the parameter a_2 is estimated to be very small (~ 0.1 year), the DNP collapses to a DN and was replaced with a DN function in the assessment model. This was the case for the survey and the trawl sub-fishery, while all longline and the trap sub-fisheries were fitted with DNP functions.

3.5 Tagging data

Longline-caught fish that have been tagged and released from 2012-2014 and their subsequent recaptures by longline in the years 2013-2015 have been used in this assessment (Table 4). Within-season recaptures were excluded. Recaptures from 2015 were included in the model, although longline fishing had not been completed for this season. In the model, the tag-detection rate incorporated tag-shedding rate and was estimated to be 0.993 for longline (Candy and Constable 2008), tag-release mortality was assumed to be 0.1, and a no-growth period after tagging of 0.5 years was assumed. Tag-dispersion ϕ_j was estimated for each recapture event j following the method in Mormede et al. (2013):

$$\phi_j = var\left(\frac{O_{lj} - E_{lj}}{\sqrt{E_{lj}(1-p_{lj})}}\right)$$

where O_{lj} was the observed number of recaptures, E_{lj} was the expected number of recaptures, and p_{lj} was the expected probability of recapture in each length bin l. The log-likelihood for tagging data was then modified by multiplying by $1/\phi$.

Table 4: Numbers of tag-releases, tag-recaptures and scanned fish that were used in the assessment. Data for 2015 is incomplete.

Releases		**Recaptures**			
Year	**Numbers**	**2013**	**2014**	**2015**	**Total**
2012	1434	22	40	22	84
2013	1473		52	36	88
2014	1809			31	31

Scanned fish		**2013**	**2014**	**2015**	**Total**
		357 576	412 287	240 798	1 010 661

3.6 Length-at-age

The method to re-estimate length-at-age was presented by Ziegler and Welsford (2014) and endorsed by WG-SAM-14 (SC-CCAMLR 2014). Length-at-age data was re-estimated using all available data of fish collected from 1997-2015. Fish records with a poor quality flag, missing data, doubtful length measurements, or poor age reads (e.g. a poor readability score) were excluded. For otoliths with multiple reads, the median age was taken (rounded to the next integer age).

Similarly to the 2014 assessment (Ziegler et al. 2014), a von Bertalanffy (VB) growth function was re-estimated following the approach of Candy et al. (2007). The definition of the likelihood function was based on variable probability (VP) sampling due to the pre-specified length-dependent fishing selectivity function and the effect of length-bin sampling on sampling probabilities. Accounting for a dome-shaped selectivity function reflected the combined effects of fish selection by the trawl, longline and trap gear, with lower selectivity of fish smaller than about 500 mm and larger than 1200 mm (Ziegler and Welsford 2014; Figure 3a). Accounting for length-bin sampling was needed because aged fish were not randomly selected from the catch, with an over-representation of aged fish smaller than 500 mm and fish between 1000-1500 mm compared to the catch (Figure 3b).

Compared with the growth model estimated in 2014, the updated growth model predicted marginally lower estimates of length-at-age for older fish (Figure 4 and Table 5).

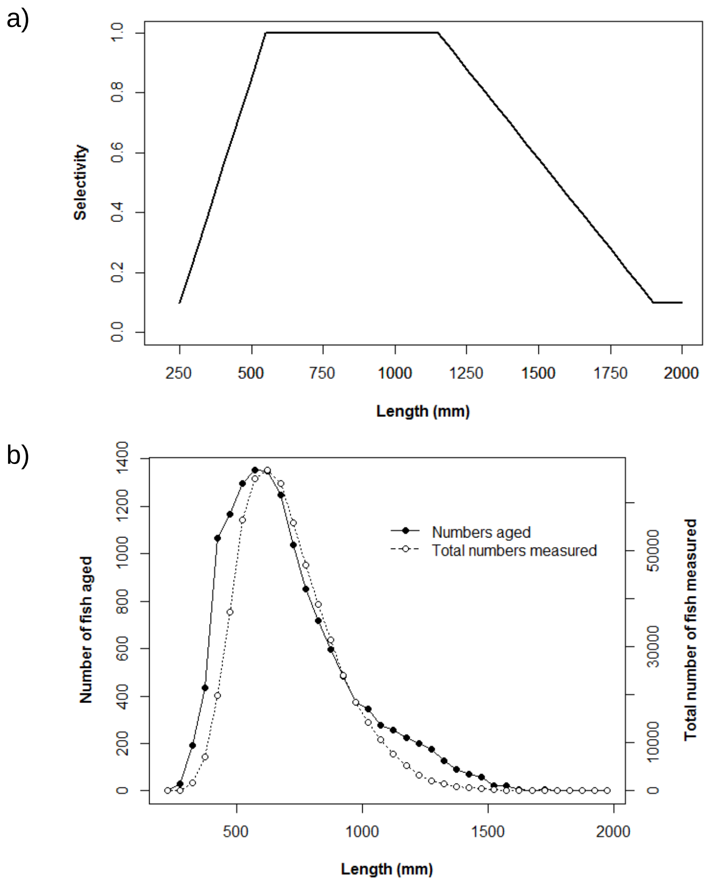


Figure 3: (a) Selectivity function used in the estimation of growth, and (b) number of fish sampled by 50 mm length bins for ageing (black circles and solid line) and overall in the fishery (open circles and dotted line).

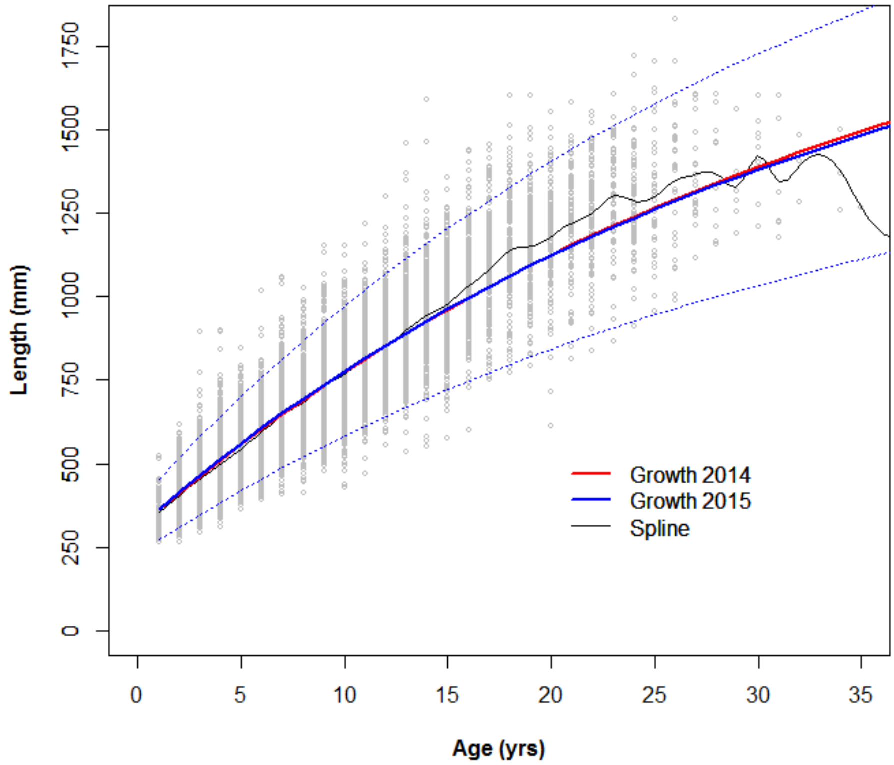


Figure 4: Length-at-age data (grey), spline (black line) and fitted von Bertalanffy growth functions that accounted for dome-shaped selectivity and length-bin sampling for 2014 (Ziegler et al. 2014; red line) and 2015 (blue line) with approximate 95% confidence intervals of the data based on *CV* (blue dotted lines). Sample size *N* = 12620.

Table 5: Parameters estimates of the von Bertalanffy growth functions that accounted for dome-shaped selectivity and length-bin sampling.

Model	L_∞	***K***	t_0	**CV**
Model 2014 (Ziegler et al. 2014)	2190	0.028	-5.37	0.129
Model 2015	2116	0.030	-5.31	0.128

3.7 Ageing error matrix

In 2014, the method of Candy et al. (2012) to estimate the ageing error matrix (AEM) was revised by Burch et al. (2014) to address some issues regarding true ages not being the mode at the extremes of the matrix and a lack of smoothness in the probabilities for ages above 25 years. At the same time, the reference collection was expanded to include an additional 50 otoliths, read by four or more readers, that had a mean fish age of 25 years or greater. For this assessment, the ageing error matrix was updated with new otolith reads which resulted in slightly flatter tails in the error of each age (Table A.3).

3.8 Model estimating procedure

The assessment models estimated unfished spawning biomass B_0, survey catchability *q*, annual year class strength (*YCS*), and the parameters of the selectivity functions for the survey and all sub-fisheries.

All models included penalties for *YCS* and catch. A penalty for *YCS* was intended to force the average of estimated *YCS* towards 1. Strong catch penalties prohibited the model from returning an estimated fishable biomass for which the catch in any given year would exceed the maximum exploitation rate set at $U = 0.995$ for each sub-fishery.

When fitting the models, process error was included to reduce the weight of the initial ESS for the commercial proportions-at-length and proportions-at-age observations in parameter estimation. A number of iterations were run for each model using the method described in Candy (2008) to account for process error until the ESS stabilised with no further reductions of practical significance.

Initially, a point estimate (maximum posterior density MPD) and its approximate covariance matrix for all free the parameters as the inverse Hessian matrix were estimated. For the final model, these estimates were used as starting point for Monte Carlo Markov Chains (MCMCs) sampling. For the MCMCs, the first 500 000 iterations were dismissed (burn-in), and every 1000th sample taken from the next 1 million iterations. MCMC trace plots were used to determine evidence of non-convergence.

3.9 Bridging analysis

A bridging analysis was conducted, starting with the 2014 assessment model that was used to provide management advice (WG-FSA-14, para. 4.27) and leading step-wise to the proposed 2015 assessment model (Table 6).

The starting point of the bridging analysis, the 2014 assessment model, included survey abundance-at-length and abundance-at-age, tag-releases for 2012 and 2013, and catch-at-age from sub-fisheries for trawl, longline LL1 and LL2, and trap. Year class strength was estimated for the period from 1986-2009 (Table 7).

In Step 1, first the model was extended to 2015 and the AEM was updated (Model 1a), then data were step-wise added, i.e. catch data (Model 1b), complete 2014 and partial 2015 abundance-at-age from the survey (Model 1c), and catch-at-age from the commercial sub-fisheries from 2009-2014 (Model 1d). Next, the last estimated *YCS* was extended from 2009 to 2010 (Model 1e). Extending *YCS* estimation to 2011 was also evaluated (Figure 5), but there was little information in the data and model results were almost identical.

Finally, tagging data was added, first complete tag-recaptures in 2014 for tagged and released fish in 2012-2013 (Model 1f), then partial tag-recaptures in 2015 for tagged and released fish in 2012-2013 (Model 1g), and finally tag-releases in 2014 and their partial recaptures in 2015 (Model 1h).

In Step 2, the updated growth function was included (Table 5).

In Step 3, the prior for survey catchability *q* was changed from that estimated by Ziegler et al. (2014) to a uniform-log prior. While de la Mare et al. (2015) recommend a prior with uniform distribution for survey *q*, a uniform-log prior was used in this assessment to account for the multiplicative space within which catchability is applied (Punt and Hilborn 2001). The differences in model results when using a uniform-log instead of a uniform prior were small, with e.g. an increase in the MPD estimates of virgin biomass B_0 of only 194 tonnes. The parameter bounds were retained at 0.1-1.5 to be able to fully account for the collective effects of the various fishing-related processes and how the survey is represented in the stock assessment model.

In Step 4, the distribution of the prior for B_0 was change from uniform to uniform-log to account for the multiplicative space within which B_0 is applied and to provide a consistent approach for the estimation of survey q and B_0.

In Step 5, the distribution of the prior for *YCS* was changed from uniform to lognormal with μ = 1 and *CV* = 0.6 in an attempt to stabilise *YCS* (WG-FSA-14, para. 4.27).

In Step 6, a split of trawl into two periods was re-introduced. In past assessments, the trawl fishery had been split into the periods 1997-2006 and 2007-2014 based on changes in targeting of fish by trawl, and but then the two periods were amalgamated into one trawl period in the 2014 assessment (Ziegler et al. (2014). The re-introduction of two trawl periods was conducted as a response to model diagnostics indicating a poorer fit with one trawl period only (see below), with a split in trawl from 1997-2004 (Trawl1) and 2005-2015 (Trawl2) based on model fits.

Table 6: Step-wise (cumulative) changes from the 2014 assessment model to the proposed 2015 assessment model (Model 6).

Step		Description
0		2014 Assessment model (as in Ziegler et al. 2014 and WG-FSA-14 report)
1		Update model structure and data:
	a)	Extend model to 2015 and update AEM
	b)	Add catches
	c)	Add numbers-at-age from survey (complete 2014 and partial 2015)
	d)	Add catch-at-age from commercial fishery (2009- 2014)
	e)	Extend last estimated *YCS* from 2009 to 2010
	f)	Add complete tag-recaptures in 2014
	g)	Add partial tag-recaptures in 2015
	h)	Add tag-releases in 2014 and their partial tag-recaptures in 2015
2		Update growth parameters
3		Prior for survey catchability q: change from estimated prior (Ziegler et al. 2014) to uniform-log
4		Prior for B_0: change from uniform to uniform-log
5		Prior for *YCS*: change from uniform to log-normal with μ=1 and *CV*=0.6
6		Split trawl into two periods (1997-2004 and 2005-2015)

Table 7: Population parameters and their values for all evaluated Models 1 to 6 in the bridging analysis. New changes in each model are highlighted in bold with grey shading. All introduced changes were maintained for subsequent model steps.

Parameters	**2014 Model**	**1: Updated data**	**2: Update growth**	**3: Prior for *q***	**4: Prior for B_0**	**5: Prior for *YCS***	**6: Split trawl**
Assessment period	1982-2014	1982-**2015**	1982-2015	1982-2015	1982-2015	1982-2015	1982-2014
B_0 and recruitment:							
B_0	Estimated	Estimated	Estimated	Estimated	Estimated	Estimated	Estimated
Mean recruitment R_0	Derived from B_0	Derived from B_0	Derived from B_0	Derived from B_0	Derived from B_0	Derived from B_0	Derived from B_0
Period of estimated *YCS*	1986-2009	1986-**2010**	1986-2010	1986-2010	1986-2010	1986-2010	1986-2009
σ_R for projections	Calculated from *YCS* 1992-2009	Calculated from *YCS* 1992-**2010**	Calculated from *YCS* 1992-2010	Calculated from *YCS* 1992-2010	Calculated from *YCS* 1992-2010	Calculated from *YCS* 1992-2010	Calculated from *YCS* 1992-2010
Stock–recruitment and steepness *h*	Beverton-Holt *h* = 0.75	Beverton-Holt *h* = 0.75	Beverton-Holt *h* = 0.75	Beverton-Holt *h* = 0.75	Beverton-Holt *h* = 0.75	Beverton-Holt *h* = 0.75	Beverton-Holt *h* = 0.75
Age classes	1 - 35 y	1 - 35 y	1 - 35 y	1 - 35 y	1 - 35 y	1 - 35 y	1 - 35 y
Length classes	300 - 2000 mm (50 mm bins)	300 - 2000 mm (50 mm bins)	300 - 2000 mm (50 mm bins)	300 - 2000 mm (50 mm bins)	300 - 2000 mm (50 mm bins)	300 - 2000 mm (50 mm bins)	300 - 2000 mm (50 mm bins)
Size-at-age:	Von Bertalanffy	Von Bertalanffy	Von Bertalanffy	Von Bertalanffy	Von Bertalanffy	Von Bertalanffy	Von Bertalanffy
$L\infty$	2190	2190	**2116**	2116	2116	2116	2116
K	0.028	0.028	**0.030**	0.030	0.030	0.030	0.030
t0	-5.37	-5.37	**-5.31**	-5.31	-5.31	-5.31	-5.31
CV	0.129	0.129	**0.128**	0.128	0.128	0.128	0.128
Ageing error matrix	Burch et al. (2014)	**Burch et al. (2014)**	Burch et al. (2014)	Burch et al. (2014)	Burch et al. (2014)	Burch et al. (2014)	Burch et al. (2014)
Weight at length *L* (mm to t)	*c* = 2.59E-12, *d* = 3.2064	*c* = 2.59E-12, *d* = 3.2064	*c* = 2.59E-12, *d* = 3.2064	*c* = 2.59E-12, *d* = 3.2064	*c* = 2.59E-12, *d* = 3.2064	*c* = 2.59E-12, *d* = 3.2064	*c* = 2.59E-12, *d* = 3.2064
Maturity: Range 5 - 95%	11 - 17 y	11 - 17 y	11 - 17 y	11 - 17 y	11 - 17 y	11 - 17 y	11 - 17 y
Natural mortality *M*	0.155	0.155	0.155	0.155	0.155	0.155	0.155
Survey *q*	Estimated	Estimated	Estimated	Estimated	Estimated	Estimated	Estimated
Tagging data							
Tag-shedding & detection	0.993	0.993	0.993	0.993	0.993	0.993	0.993
Tag-release mortality	0.1	0.1	0.1	0.1	0.1	0.1	0.1
No-growth period	0.5 y	0.5 y	0.5 y	0.5 y	0.5 y	0.5 y	0.5 y

Table 7: Continued.

Estimated parameters	2014 Model	1: Updated data	2: Update growth	3: Prior for *q*	4: Prior for B_0	5: Prior for *YCS*	6: Split trawl
Priors and bounds							
B_0 Starting value Bounds	Prior: uniform 90 000 30 000 - 250 000	Prior: uniform 90 000 30 000 - 250 000	Prior: uniform 90 000 30 000 - 250 000	Prior: uniform 90 000 30 000 - 250 000	Prior: **uniform-log** 90 000 30 000 - 250 000	Prior: uniform-log 90 000 30 000 - 250 000	Prior: uniform 90 000 30 000 - 250 000
Survey *q*	Prior: Lognormal μ = 0.423 *CV* = 0.257 Bounds: 0.1 – 1.5	Prior: Lognormal μ = 0.423 *CV* = 0.257 Bounds: 0.1 – 1.5	Prior: Lognormal μ = 0.423 *CV* = 0.257 Bounds: 0.1 – 1.5	Prior: **uniform-log** Bounds: 0.1 – 1.5	Prior: uniform-log Bounds: 0.1 – 1.5	Prior: uniform-log Bounds: 0.1 – 1.5	Prior: uniform-log Bounds: 0.1 – 1.5
YCS Starting value Bounds	Prior: uniform 1 0.001 – 200	Prior: uniform 1 0.001 – 200	Prior: uniform 1 0.001 – 200	Prior: uniform 1 0.001 – 200	Prior: uniform 1 0.001 – 200	Prior: **lognormal** **μ = 1, *CV* = 0.6** 0.001 – 200	Prior: lognormal μ = 1, *CV* = 0.6 0.001 – 200
Fishing selectivities:							
Double-normal: Sub-fisheries	Prior: uniform Survey, Trawl	Prior: uniform Survey, Trawl	Prior: uniform Survey, Trawl	Prior: uniform Survey, Trawl	Prior: uniform Survey, Trawl	Prior: uniform Survey, Trawl	Prior: uniform Survey, **Trawl1, Trawl2**
Starting values (bounds)	a_1: 4 (1 - 20) σ_L: 1 (0.1 - 20) σ_R: 7 (0.1 - 20)	a_1: 4 (1 - 20) σ_L: 1 (0.1 - 20) σ_R: 7 (0.1 - 20)	a_1: 4 (1 - 20) σ_L: 1 (0.1 - 20) σ_R: 7 (0.1 - 20)	a_1: 4 (1 - 20) σ_L: 1 (0.1 - 20) σ_R: 7 (0.1 - 20)	a_1: 4 (1 - 20) σ_L: 1 (0.1 - 20) σ_R: 7 (0.1 - 20)	a_1: 4 (1 - 20) σ_L: 1 (0.1 - 20) σ_R: 7 (0.1 - 20)	a_1: 4 (1 - 20) σ_L: 1 (0.1 - 20) σ_R: 7 (0.1 - 20)
Double plateau normal: Sub-fisheries Starting values (bounds)	Prior: uniform LL1, LL2, Trap a_1: 10 (1 - 20) a_2: 6 (0.1 - 20) σ_L: 1 (0.1 - 20) σ_R: 3 (0.1 - 20) a_{max}: 1 (1 - 1)	Prior: uniform LL1, LL2, Trap a_1: 10 (1 - 20) a_2: 6 (0.1 - 20) σ_L: 1 (0.1 - 20) σ_R: 3 (0.1 - 20) a_{max}: 1 (1 - 1)	Prior: uniform LL1, LL2, Trap a_1: 10 (1 - 20) a_2: 6 (0.1 - 20) σ_L: 1 (0.1 - 20) σ_R: 3 (0.1 - 20) a_{max}: 1 (1 - 1)	Prior: uniform LL1, LL2, Trap a_1: 10 (1 - 20) a_2: 6 (0.1 - 20) σ_L: 1 (0.1 - 20) σ_R: 3 (0.1 - 20) a_{max}: 1 (1 - 1)	Prior: uniform LL1, LL2, Trap a_1: 10 (1 - 20) a_2: 6 (0.1 - 20) σ_L: 1 (0.1 - 20) σ_R: 3 (0.1 - 20) a_{max}: 1 (1 - 1)	Prior: uniform LL1, LL2, Trap a_1: 10 (1 - 20) a_2: 6 (0.1 - 20) σ_L: 1 (0.1 - 20) σ_R: 3 (0.1 - 20) a_{max}: 1 (1 - 1)	Prior: uniform LL1, LL2, Trap a_1: 10 (1 - 20) a_2: 6 (0.1 - 20) σ_L: 1 (0.1 - 20) σ_R: 3 (0.1 - 20) a_{max}: 1 (1 - 1)
Number of parameters	44	44	44	44	44	44	47

Table 7: Continued.

Data	**2014 Model**	**1: Updated data**	**2: Update growth**	**3: Prior for *q***	**4: Prior for B_0**	**5: Prior for *YCS***	**6: Split trawl**
RSTS:	Survey	Survey	Survey	Survey	Survey	Survey	Survey
Survey numbers-at-length	2001-2002, 2004-2005	2001-2002, 2004-2005	2001-2002, 2004-2005	2001-2002, 2004-2005	2001-2002, 2004-2005	2001-2002, 2004-2005	2001-2002, 2004-2005
Survey numbers-at-age	2006-2014	2006-**2015**	2006-2015	2006-2015	2006-2015	2006-2015	2006-2015
Commercial sub-fisheries:	Trawl, LL1, LL2, Trap	Trawl, LL1, LL2, Trap	Trawl, LL1, LL2, Trap	Trawl, LL1, LL2, Trap	Trawl, LL1, LL2, Trap	Trawl, LL1, LL2, Trap	**Trawl1, Trawl2,** LL1, LL2, Trap
Proportions-at-age	1997-2008, 2013	1997-**2014**	1997-2014	1997-2014	1997-2014	1997-2014	1997-2014
Estimated sample size (ESS)	Estimated, except set to 1 for Trap	Estimated, except set to 1 for Trap	Estimated, except set to 1 for Trap	Estimated, except set to 1 for Trap	Estimated, except set to 1 for Trap	Estimated, except set to 1 for Trap	Estimated, except set to 1 for Trap
Tagging data							
Tag-releases							
Sub-fisheries	LL1, LL2	LL1, LL2	LL1, LL2	LL1, LL2	LL1, LL2	LL1, LL2	LL1, LL2
Years	2012-2013	2012-**2014**	2012-2014	2012-2014	2012-2014	2012-2014	2012-2014
Tag-recaptures							
Sub-fisheries	LL1, LL2	LL1, LL2	LL1, LL2	LL1, LL2	LL1, LL2	LL1, LL2	LL1, LL2
Years	2013-2014	2013-**2015**	2013-2015	2013-2015	2013-2015	2013-2015	2013-2015

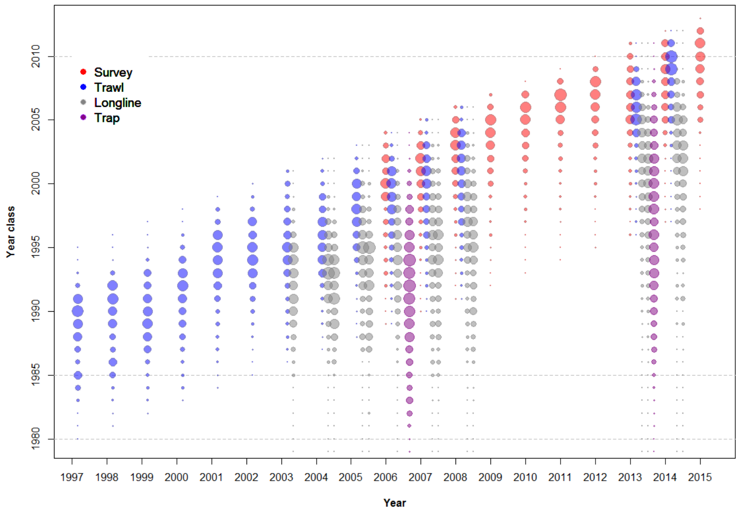


Figure 5: Bubble plot of age observations by year for the survey (red), trawl (blue), longline (LL1 and LL2, grey) and trap (purple).

3.10 Calculations of catch limits

Catch projection trials accounted for uncertainty surrounding parameter estimates of the model as well as future recruitment variability. In order to integrate across uncertainty in the model parameters, MCMC samples were used for CASAL's projection procedure to obtain 1000 random time series samples of estimated numbers of age-1 recruits for the period from 1982-2010, corresponding to *YCS* estimates from 1981-2009. The median of the square root of the variance of the yearly numbers of these age-1 recruits from 1992-2010 provided a robust estimate of the σ_R for recruitment required for the lognormal random recruitment generation.

The estimated *CVs* were used to generate the random recruitment from 2011 until the end of the 35-year projection period. Based on this sample of projections for spawning stock biomass, long-term catch limits were calculated following the CCAMLR decision rules:

- Choose a yield γ_1, so that the probability of the spawning biomass dropping below 20% of its median pre-exploitation level over a 35-year harvesting period is 10% (depletion probability).
- Choose a yield γ_2, so that the median escapement of the spawning biomass at the end of a 35-year period is 50% of the median pre-exploitation level.
- Select the lower of γ_1 and γ_2 as the yield.

The depletion probability was calculated as the proportion of samples from the Bayesian posterior where the predicted future spawning biomass was below 20% of B_0 in the respective sample at any time over the 35-year projected period. The level of escapement was calculated as the proportion of samples from the Bayesian posterior where the projected future status of the spawning biomass was below 50% of B_0 in the respective sample at the end of the 35-year projection period.

Catch limit estimates were based on the assumption of constant annual catches. Future surveys were assumed to be conducted every year with a catch of 20 tonnes. The entire remaining future catch was assumed to be taken by longline, with a catch split based on the catch distribution of longline sub-fisheries in 2014. This meant that 50% of the total catch was attributed to LL1 and 50% to LL2.

4. Results

4.1 Bridging analysis and MPD estimates

Updating the model in Step 1 with data available up to end of July 2015 on catches, survey abundance-at-age, commercial catch-at-age, and tag-recaptures from 2014 and 2015 and tag-releases from 2014, and estimating *YCS* in 2010 reduced the estimated B_0 from 108 154 tonnes as estimated in the 2014 assessment to 93 832 tonnes (Table 8 and Figure 6). This reduction was driven by both tag-recaptures in 2014 and 2015.

Updating the model with the new growth parameters in Model 2 reduced the estimated B_0 to 89 632 tonnes. Using a uniform-log prior for survey catchability q instead of the estimated prior by Ziegler et al. (2014) in Model 3 had only a small effect on B_0, with a reduction in the estimated B_0 to 89 044 tonnes. Using a uniform-log prior for B_0 in Model 4 and a log-normal prior for *YCS* in Model 5 had little effect on the estimated B_0, however the latter reduced extreme values in the *YCS* time series (Figure 7). Splitting the trawl observations into two periods was in response to the lack of fits of median age for trawl, but it also improved the model fits to most other data (Figure 8 and Table 9). This final Model 6 estimated a B_0 of 88 020 tonnes.

Compared to the 2014 assessment model, the estimated current *SSB* status remained almost identical at 0.64 in Model 6.

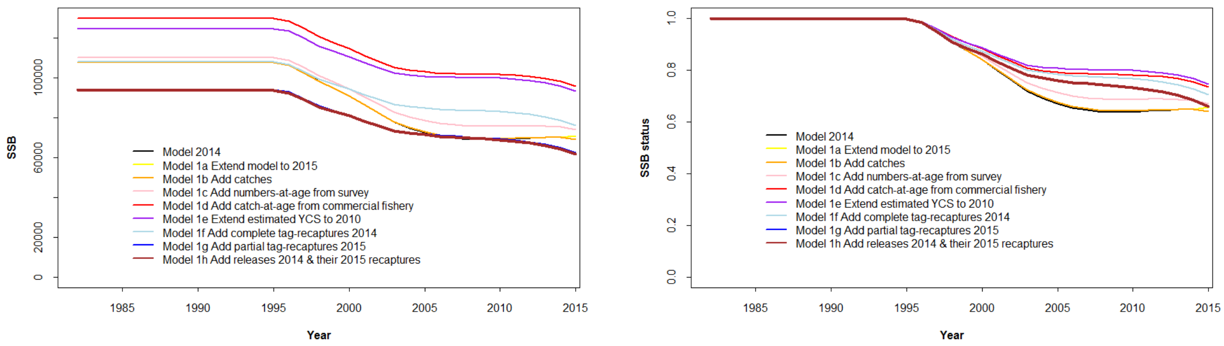
Table 8: MPD estimates of unfished spawning stock biomass B_0 in tonnes, *SSB* status in 2015, and R_0 (mean recruitment in millions that gives rise to B_0), the number of estimated parameters (*N* Para), and the total objective function (ObjF). * *SSB* status is for 2014.

Step	Description	B_0	*SSB* status	R_0	*N* Para	ObjF
0	Assessment 2014	108 154	0.65*	8.04	43	1942
1a	Extend model to 2015	107 816	0.66	8.01	43	1915
1b	Add catches	107 816	0.64	8.01	43	1915
1c	Add survey numbers-at-age	110 212	0.67	8.19	43	2159
1d	Add commercial catch-at-age	129 855	0.74	9.65	43	3104
1e	Last estimated *YCS* in 2010	124 848	0.75	9.28	44	3093
1f	Add tag-recaptures 2014	108 064	0.71	8.03	44	3097
1g	Add tag-recaptures 2015	94 268	0.66	7.01	44	3142
1h	Add tag-releases 2014	93 832	0.66	6.97	44	3143
2	Update growth parameters	89 632	0.64	6.71	44	3116
3	Survey q: Uniform-log prior	89 044	0.64	6.66	44	3141
4	B_0: Uniform-log prior	88 861	0.64	6.65	44	3152
5	*YCS*: Log-normal prior	89 564	0.64	6.70	44	3159
6	Split trawl into two periods	88 020	0.64	6.59	47	3104

Table 9: Contributions to the objective function for Models 1h to 6.

Component	Model 1h	Model 2	Model 3	Model 4	Model 5	Model 6
Surv1A	765.8	768.2	771.1	771.1	771.3	762.8
Surv1L	256.4	257.3	258.3	258.3	258.5	249.2
Catch_LL1A	799.6	790.3	801.7	801.7	803.5	784.6
Catch_LL2A	632.0	616.0	633.1	633.1	634.1	620.6
Catch_TrapA	5.1	5.1	5.1	5.1	5.1	5.2
Catch_Trawl1A	594.9	594.2	594.4	594.4	595.6	255.6
Catch_Trawl2A						337.7
Tags2012	41.2	37.8	35.6	35.4	35.7	34.9
Tags2013	35.6	34.4	32.0	31.7	32.1	31.2
Tags2014	10.9	11.0	10.4	10.3	10.4	10.2
meanYCS_1	0	0	0	0	1.9	1.9
Prior B0	0	0	0	11.4	11.4	11.4
Other priors	1.9	2.1	-0.3	-0.3	-0.7	-0.9
Penalties	0	0	0	0	0	0
Total	3143	3116	3141	3152	3159	3104

a)



b)

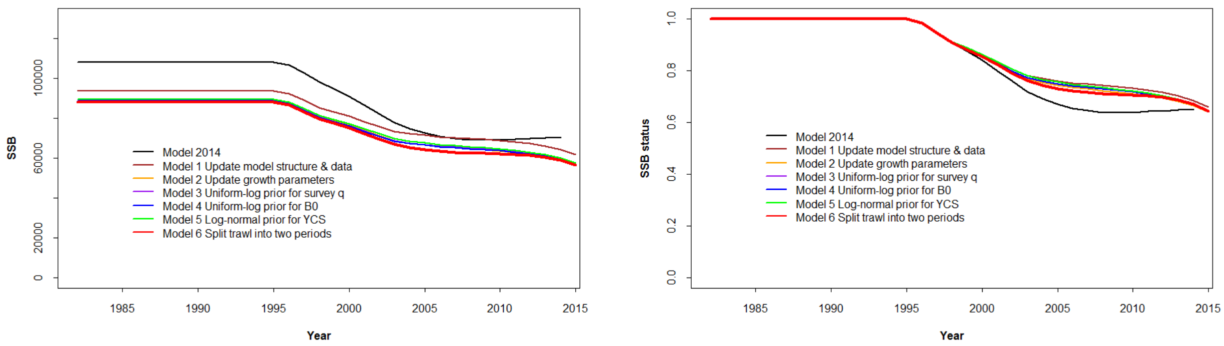


Figure 6: Estimated spawning biomass trajectories (*SSB*, left) and spawning stock status (*SSB* status, right) for (a) the 2014 assessment model and Models 1a to 1h; and (b) the 2014 assessment model and Models 1h to 6.

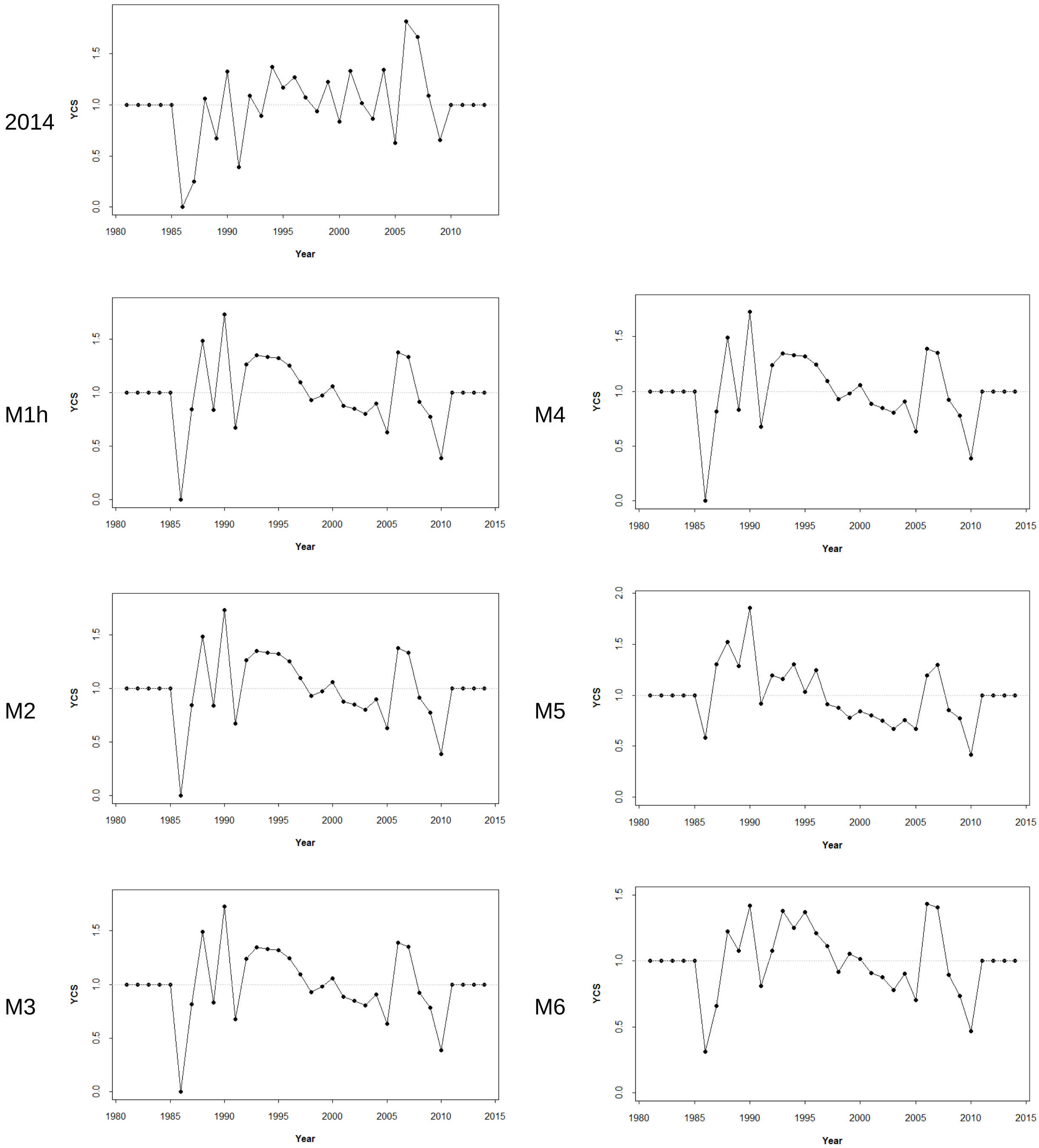


Figure 7: MPD estimates of *YCS* for the 2014 assessment model (2014), Model 1h with all updated data (M1h), Model 2 with updated growth estimated (M2), Model 3 with uniform-log prior for survey *q* (M3), Model 4 using a uniform-log prior for B_0 (M4), Model 5 using log-normal prior for *YCS* (M5), and Model 6 with split trawl (M6).

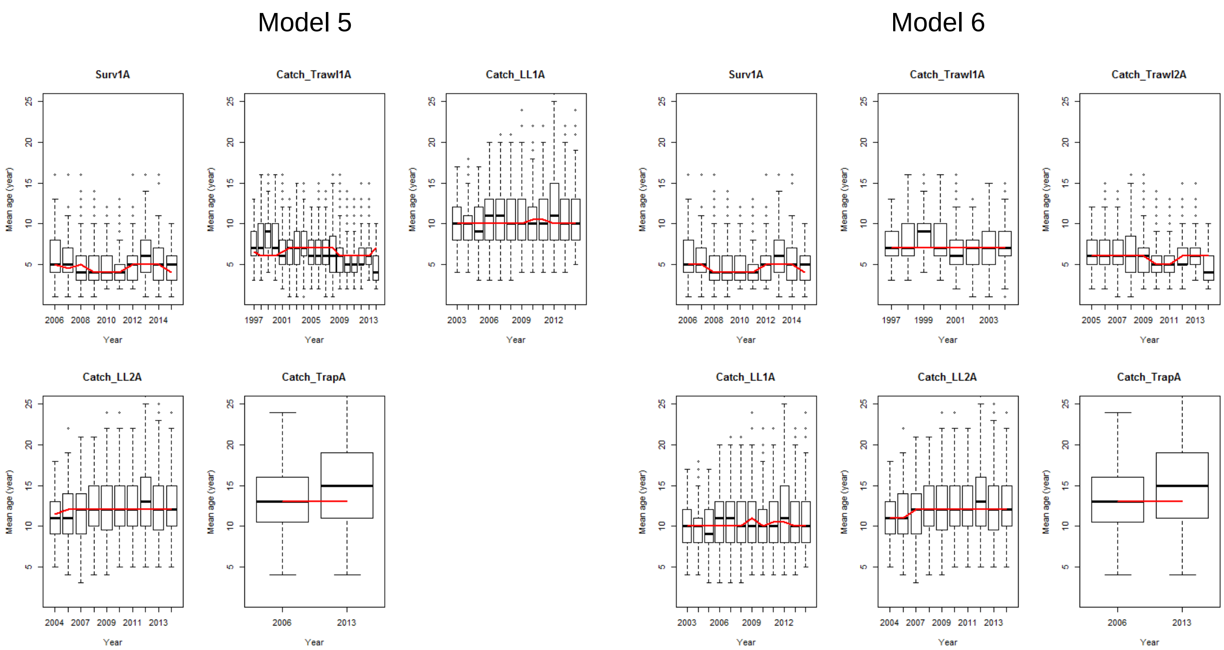


Figure 8: Boxplots of observed age by fishery and predicted median age (red line) for Model 5 and Model 6.

4.2 Model fits

Compared to all other models evaluated here, Model 6 provided the best overall fit and best fits to survey observations and tagging data (Table 9). Fits by the commercial sub-fisheries were also the best although not strictly comparable since slightly different ESS were estimated for each model step.

The model fits of Model 6 to the survey observations were generally acceptable despite strong inter-annual variability in survey abundance data between some years (Figures A.1 and A.2).

Generally good fits were obtained for the proportions-at-age datasets of the commercial sub-fisheries (Figures A.3 to A.12, with the respective final ESS in Table A.4 and tag dispersion in Table A.5). The split into two trawl periods in Model 6 improved the fits to trawl data, however there still remained some trend in the residuals during the period 1997-2004 (Figure A.8). The good fits to proportions-at-age for both longline sub-fisheries LL1 and LL2 indicated that the subdivision of longline hauls into these two sub-fisheries, defined by a split at 1500 m depth, was also reasonable. Fits to the trap sub-fishery were reasonable, despite the fact that the ESS of this sub-fishery was set to 1 (the information content of the data was considered poor due to high inter-annual variability in areas and depths fished).

The likelihood profile for Model 6 is shown in Figure 9. Tag-releases from 2012 and 2014 indicating that a B_0 of around 85 000 tonnes was most likely, while tag-releases from 2013 indicated that a B_0 of around 65 000 tonnes was most likely. The survey abundance data indicated that a B_0 of over 100 000 tonnes was most likely. Catch-at-age proportions from trawl and longline generally suggested that large levels B_0 were more likely.

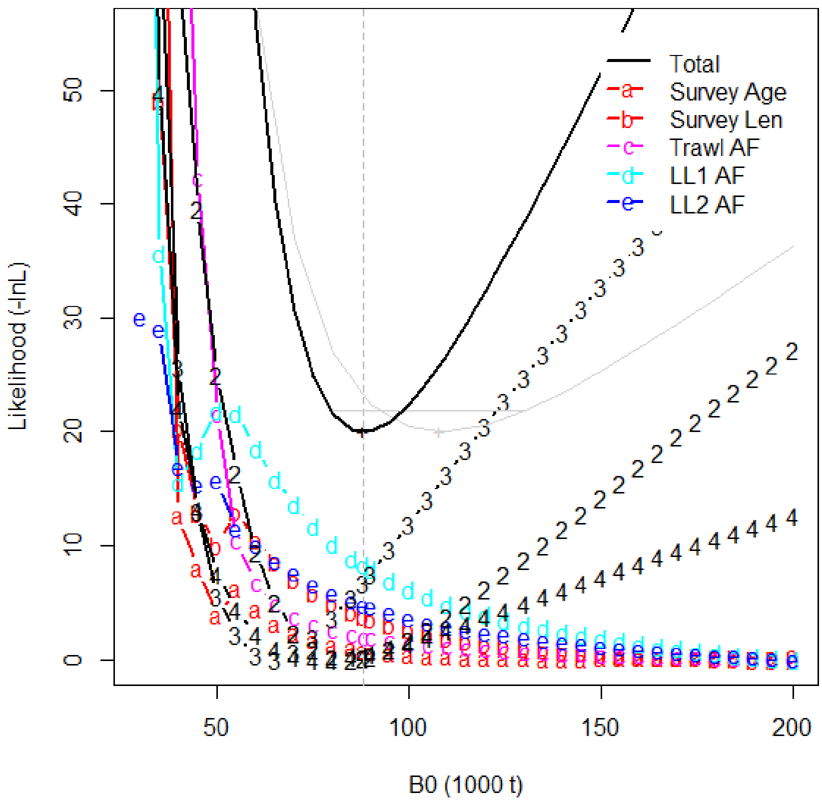


Figure 9: Likelihood profiles (-2 log-likelihood) across a range of B_0 values for Model 6. To create these profiles, B_0 values were fixed while only the remaining parameters were estimated. Values for each data set were rescaled to have a minimum of 0, while the total objective function was rescaled to 20. The dotted grey line indicates the MPD estimate. The solid grey lines indicate the total objective function from the 2014 stock assessment and the 95% confidence intervals for both likelihood profiles.

4.3 MCMC estimates

The updated assessment model leads to a smaller estimate of the virgin spawning stock biomass B_0 than that obtained in 2014, with an MCMC estimate of 87 077 tonnes (95% CI: 78 500-97 547 tonnes). Estimated *SSB* status in 2015 was 0.64 (95% CI: 0.59-0.69) (Table 10).

The estimated *YCS* and selectivity functions are shown in Figures 10 and 11. The estimated selectivity functions differed distinctly between the survey and the trawl, longline and trap sub-fisheries. The trawl surveys and the commercial trawl sub-fisheries observed predominantly young fish, while the longline and trap sub-fisheries concentrated on older fish, with LL2 in waters deeper than 1500 m catching older fish compared to LL1 in waters shallower than 1500 m. Trap was estimated to catch mainly fish older than 15 years.

Table 10: MCMC results with 95% confidence intervals.

Model	B_0	***SSB* Status**	***Survey q***
2014 Assessment	108 586 (92 263-132 167)	0.65 (0.59-0.71)	0.48 (0.39-0.58)
2015 Assessment (Model 6)	87 077 (78 500-97 547)	0.64 (0.59-0.69)	0.72 (0.62-0.83)

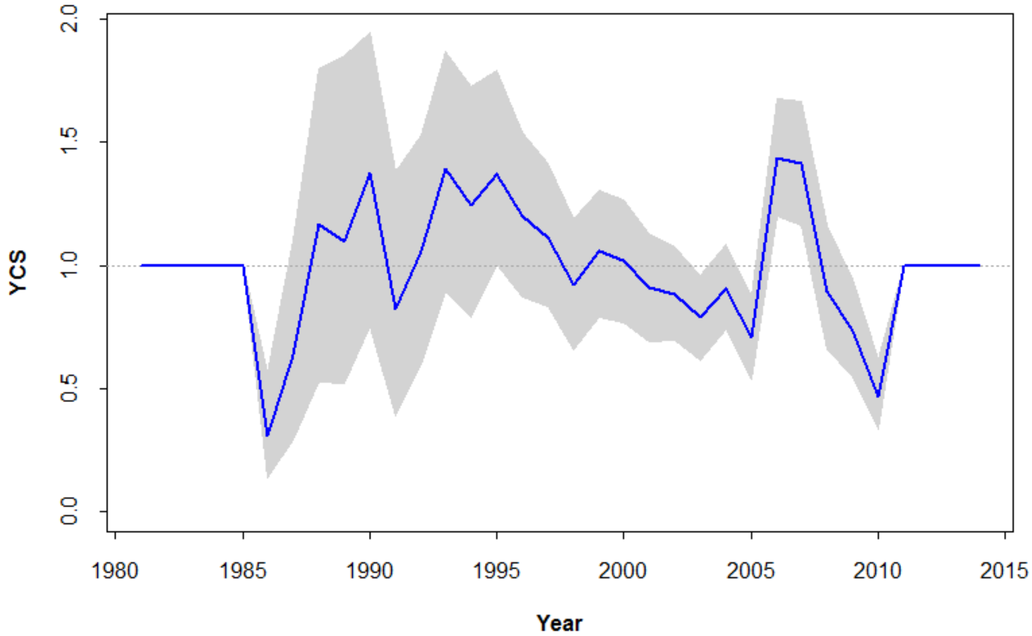


Figure 10: Estimated *YCS* for Model 6 showing 95% confidence bounds obtained from the MCMC sample.

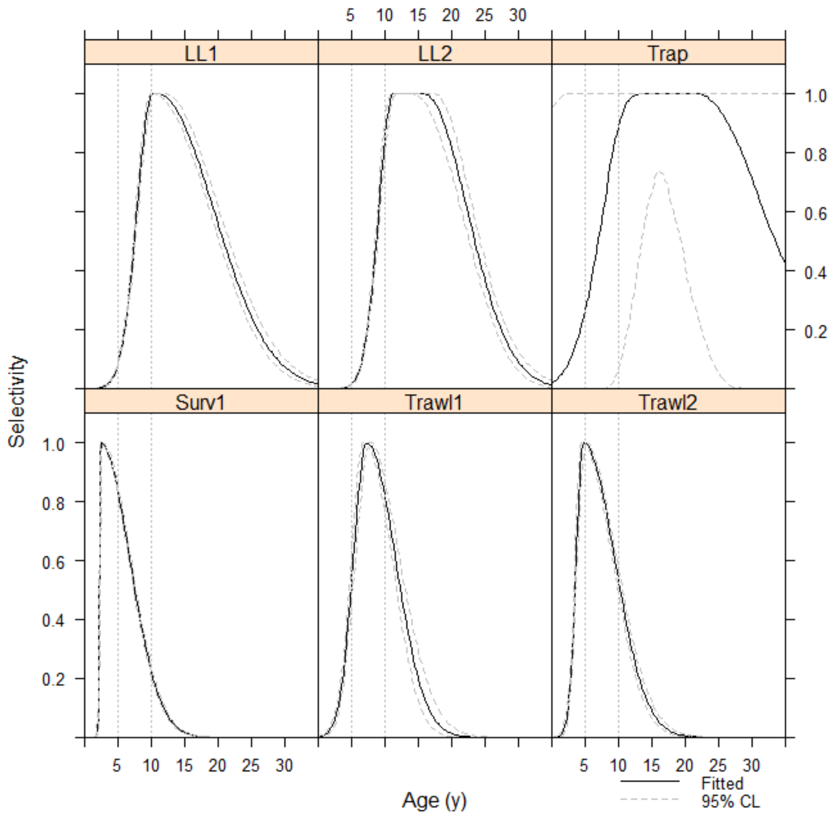


Figure 11: Estimated double-normal-plateau and double-normal fishing selectivity functions for the survey (Surv1) and commercial sub-fisheries in Model 6, showing 95% confidence bounds obtained from the MCMC samples. Trawl1 is trawl from 1997-2004, Trawl2 is trawl from 2005-2015, LL1 and LL2 are longline in <1500 m and >1500 m depth, respectively. Vertical reference lines are shown at ages 5 and 10.

The trace plots of the MCMCs for all free parameters showed little evidence of non-convergence (Figures 12 and 13, and Appendix Figures A.13 and A.14). The trace plots for B_0, survey q, the selectivity parameters of all sub-fisheries, and all estimated *YCS* showed good mixing behaviour. There was some evidence of correlations in selectivity parameters of the survey, but this was likely to be due to the model bounds at the minimum age. There was also some evidence for poor mixing within the selectivity parameters of LL1 and trap, however the resulting selectivity estimates for LL1 were tight (Figure 11). While the trace plots for trap selectivity looked poor, this was likely to be without substantial consequences, since data from the trap fishery have little effect on biomass and *YCS* estimates.

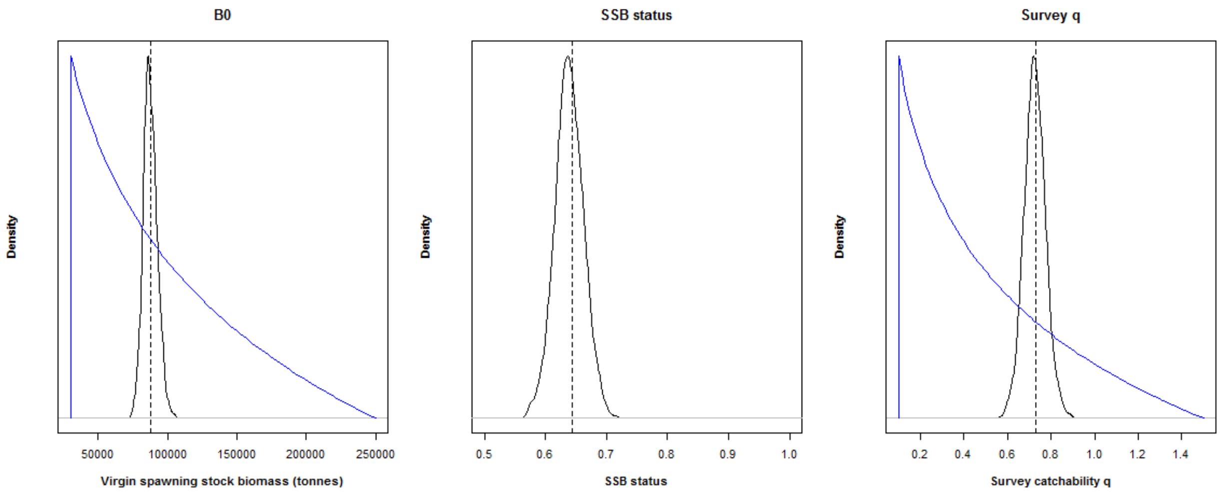


Figure 12: MCMC posterior distribution of B_0, *SSB* status in 2015, and survey catchability *q* (black), and prior distributions (blue) for Model 6. Vertical dashed lines indicate the MPD estimates.

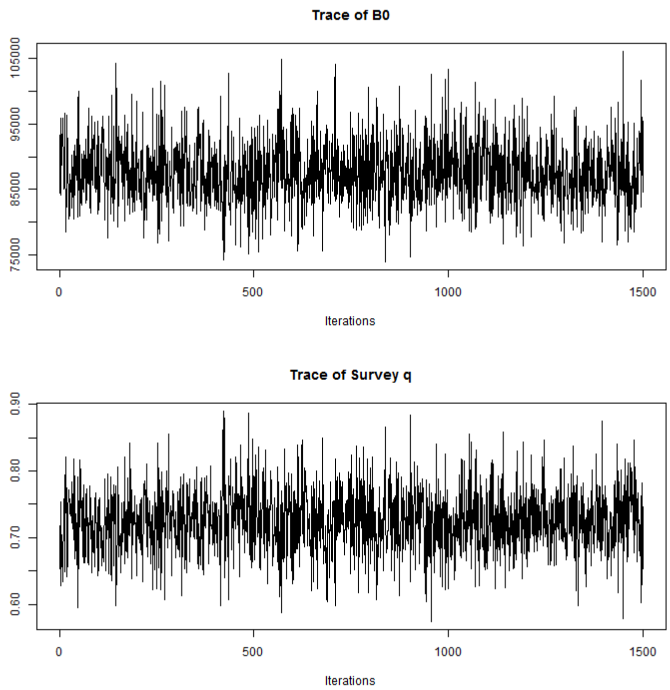


Figure 13: MCMC posterior trace plots for B_0 and survey catchability *q* for Model 6.

4.4 Model sensitivity runs

A number of scenarios were run to evaluate the sensitivity of the stock assessment model to some model parameters and assumptions (Table 11).

Separating the trawl survey data into an index of survey abundance (total weight) and either proportions-at-length or age from the survey (*sensu* WG-FSA-14, para. 4.31) had little effect on the estimated B_0, but changed some *YCS* estimates. By summarising the weights of all age or length classes to an overall biomass index and using deterministic survey catch proportions, this approach effectively down-weighted the survey as an important source of information on *YCS* and lost any information on the variability in age or length classes. We consider that this is not a valid approach to incorporating the information contained in the survey as it loses information from the randomised fishery-independent survey which is fitted well in the reference Model 6. Further evaluation of the effect of such an approach to randomised surveys would be best addressed through a formal management strategy evaluation.

Assuming an alternative value for natural mortality $M = 0.13$ as e.g. used in the assessments of the Patagonian toothfish fishery in South Georgia (Scott 2013) and the Antarctic toothfish fishery in the Ross Sea (Mormede et al. 2013) increased the estimates for B_0 to 126 518 tonnes. The improvement of model fits to the commercial catch data was compensated by a worse fit to the survey data. Overall, the model had a larger (i.e. poorer) objective function due to higher contributions from the penalty for mean *YCS* (mean *YCS* was 0.9999997) and the prior for *YCS*, although the pattern of *YCS* itself did not differ substantially from that in Model 6.

There was little information in the data regarding the value of steepness *h* of the stock-recruitment relationship, with little changes in model estimates and the objective function when alternative fixed values were used.

Table 11: MPD results of Model 6 and sensitivity analyses, with estimates of unfished spawning stock biomass B_0 in tonnes, *SSB* status in 2015, and R_0 (mean recruitment in millions that gives rise to B_0), the number of estimated parameters (*N* Para), and the components of the total objective function. * Objective function cannot be compared to that of the other models.

Sensitivity run	B_0	***SSB***	R_0	***N***	**Objective Function**					
		status		**Para**	**Survey**	**Catch-at**	**Tag**	**meanYCS**	**Other**	**Total**
Reference: Model 6	88 020	0.64	6.59	47	1012	2004	76	2	10	3104
Survey index and survey proportions-at-length & age	87 360	0.70	6.54	47	506*	2002	48	1	14	2572*
Natural mortality $M = 0.13$	126 518	0.67	5.20	47	1033	1980	68	39	98	3218
Steepness $h = 0.5$	91 227	0.64	6.82	47	1015	2004	78	2	10	3110
Steepness $h = 0.9$	86 952	0.64	6.51	47	1011	2003	76	2	11	3103

4.5 Calculations of catch limits

The median CV estimated for the *YCS* period from 1992-2010 in Model 6 were used to generate the random recruitment from 2011-2015 and the 35-year projection period from 2016-2050 (σ_R = 0.32). The maximum catches that satisfy the CCAMLR harvest control rules were estimated based on the assumption of future constant annual catches taken entirely by an annual survey of 20 tonnes and by longline (50% LL1 and 50% LL2).

The maximum yield for the Model 6 was estimated at 3405 tonnes (Table 12 and Figure 14).

Table 12: Estimates of catch limits in tonnes based on MCMC sampling that satisfy the CCAMLR harvest control rules, with (i) a median escapement of the spawning biomass at the end of the 35-year projection period of at least 50% of the median pre-exploitation level ('Target'), and (ii) a less than 10% risk of the spawning biomass dropping below 20% of its median pre-exploitation level at any time over the 35-year projection period ('Depletion').

Model	Catch limit	Target	Depletion
2014 Assessment	4410		
2015 Assessment (Model 6)	3405	0.502	0.00

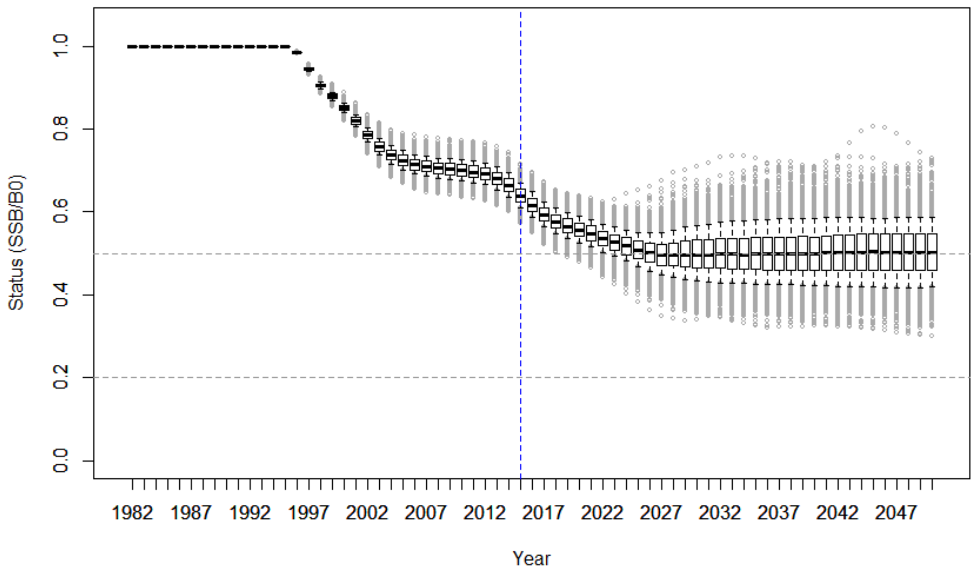


Figure 14: Projected *SSB* status relative to B_0 for the assessment Model 6 using MCMC samples and future random lognormal recruitment from 2011-2050 with annual constant catches. Boxplots represent the distribution of the estimates across 1000 projection trials. Dotted lines show the 50% and 20% status levels used in the CCAMLR decision rules.

5. Discussion

This paper presents an updated assessment for Patagonian toothfish (*Dissostichus eleginoides*) at the Heard Island and the McDonald Islands in Division 58.5.2 with data until end of July 2015. Starting with the 2014 assessment model that was used to provide management advice (WG-FSA-14, para. 4.27), this paper presents a bridging analysis and proposes a new assessment model for 2015. The new model is based on the best available estimates of model parameters, the use of abundance estimates from a random stratified trawl survey, longline tag-release data from 2012-2014 and longline tag-recapture data from 2013-2015, an estimated survey catchability coefficient *q*, and auxiliary commercial composition data to aid with the estimation of year class strength and selectivity functions of the sub-fisheries.

Compared to the 2014 assessment, this assessment incorporates (a) new fishery observations up to July 2015 including new ageing data from the 2014-2015 RSTS and the commercial fishery from 2009-2014, (b) tag-releases from 2014 and tag-recaptures from 2014 (complete) and 2015 (partial), (c) an updated growth model, (d) changes in priors for survey catchability *q*, unfished spawning biomass B_0 and year class strength, and (e) a split of the trawl fishery into two periods. All model runs were conducted with the CASAL version that was agreed on by WG-SAM-14.

The updated assessment model leads to a smaller estimate of the virgin spawning stock biomass B_0 than that obtained in 2014, with an MCMC estimate of 87 077 tonnes (95% CI: 78 500-97 547 tonnes). Estimated *SSB* status in 2015 was 0.64 (95% CI: 0.59-0.69). Using this model, a catch limit of 3405 tonnes satisfies the CCAMLR decision rules. Similarly to the 2014 assessment, the projected stock remains above the target level for the entire projection period.

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Appendix A

Table A.1: Length-age frequency of otoliths samples from all surveys combined over the years from 2006-2015.

Age class (year)	Length bin (mm)											
	251-350	351-450	451-550	551-650	651-750	751-850	851-950	951-1050	1051-1150	1151-1250	1251-1350	1351-1450
1	29	25	5	0	0	0	0	0	0	0	0	0
2	45	262	60	6	0	2	0	0	0	0	0	0
3	20	395	339	59	4	0	0	0	0	0	0	0
4	7	223	417	174	19	2	1	0	0	0	0	0
5	0	85	295	261	48	6	0	0	0	0	0	0
6	0	23	149	293	108	11	1	0	0	0	0	0
7	0	5	52	242	146	27	2	0	0	0	0	0
8	0	4	22	128	166	43	2	1	0	0	0	0
9	0	0	5	55	109	51	10	3	1	0	0	0
10	0	2	3	19	62	73	22	6	0	0	0	0
11	0	0	0	11	42	46	20	6	0	0	0	0
12	0	0	0	6	24	44	18	5	1	0	0	0
13	0	0	1	1	4	12	19	11	2	1	0	0
14	0	0	0	0	6	8	9	6	3	0	0	0
15	0	0	0	0	4	7	5	11	4	0	1	0
16	0	0	0	1	1	6	5	3	2	2	0	1
17	0	0	0	0	0	2	2	2	3	3	0	2
18	0	0	0	0	0	1	0	0	1	2	0	0
19	0	0	0	0	0	1	0	1	2	1	1	0
20	0	0	0	1	0	0	0	0	1	0	1	0
21	0	0	0	0	0	0	1	0	2	1	1	0
22	0	0	0	0	0	0	0	0	1	0	0	0
23	0	0	0	0	0	0	0	0	0	0	0	0
24	0	0	0	0	0	0	0	0	0	0	0	0
25	0	0	0	0	0	0	0	0	0	0	0	0
26	0	0	0	0	0	0	0	0	0	0	0	0
27	0	0	0	0	0	0	0	0	0	0	1	0
28	0	0	0	0	0	0	0	0	0	0	0	0
29	0	0	0	0	0	0	0	0	0	0	0	0
30	0	0	0	0	0	0	0	0	0	0	0	0
31	0	0	0	0	0	0	0	0	0	0	0	0
32	0	0	0	0	0	0	0	0	0	0	0	0
33	0	0	0	0	0	0	0	0	0	0	0	0
34	0	0	0	0	0	0	0	0	0	0	0	0
35	0	0	0	0	0	0	0	0	0	0	0	0
Total	101	1024	1348	1257	743	342	117	55	23	10	5	3

Table A.2: Length-age frequency of otoliths samples from all commercial sub-fisheries combined over the years from 1997-2015.

Age class (year)	Length bin (mm)											
	251-350	351-450	451-550	551-650	651-750	751-850	851-950	951-1050	1051-1150	1151-1250	1251-1350	1351-1450
1	42	10	1	0	0	0	0	0	0	0	0	0
2	31	88	20	6	0	0	0	0	0	0	0	0
3	9	111	140	18	5	1	1	0	0	0	0	0
4	0	83	283	139	18	3	1	0	0	0	0	0
5	0	18	290	276	51	6	0	0	0	0	0	0
6	0	8	146	343	171	13	1	1	0	0	0	0
7	0	1	52	348	299	75	11	1	2	0	0	0
8	0	1	21	197	340	135	22	4	0	0	0	0
9	0	0	8	82	271	208	48	14	0	1	0	0
10	0	0	11	34	204	224	100	21	6	0	0	0
11	0	0	2	10	95	209	154	49	9	4	0	0
12	0	0	0	4	49	141	173	73	15	7	1	0
13	0	0	0	4	23	94	145	89	30	12	4	2
14	0	0	0	4	11	43	100	81	62	20	5	1
15	0	0	0	1	6	32	57	81	68	33	11	1
16	0	0	0	0	2	11	47	66	68	33	16	1
17	0	0	0	0	2	7	30	55	68	47	20	10
18	0	0	0	0	0	5	11	38	51	44	32	13
19	0	0	0	0	0	2	12	28	34	45	36	14
20	0	0	0	0	1	1	5	12	29	45	31	14
21	0	0	0	0	0	2	3	9	25	27	36	15
22	0	0	0	0	0	1	3	11	17	26	36	21
23	0	0	0	0	0	0	2	1	6	18	17	12
24	0	0	0	0	0	0	2	4	7	24	20	16
25	0	0	0	0	0	0	0	2	7	7	9	10
26	0	0	0	0	0	0	0	2	4	5	5	10
27	0	0	0	0	0	0	0	0	2	2	7	6
28	0	0	0	0	0	0	0	0	1	3	5	0
29	0	0	0	0	0	0	0	0	0	1	3	2
30	0	0	0	0	0	0	0	0	0	1	1	3
31	0	0	0	0	0	0	0	0	0	4	1	0
32	0	0	0	0	0	0	0	0	0	0	2	1
33	0	0	0	0	0	0	0	0	0	0	1	1
34	0	0	0	0	0	0	0	0	1	0	1	1
35	0	0	0	0	0	0	0	0	3	2	7	4
Total	82	320	974	1466	1548	1213	928	642	515	411	307	158

Table A.3: Ageing error matrix for an average readability score of 3.

True Age	Read Age																																		
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35
1	0.697	0.252	0.042	0.008	0.001	0.001	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0.204	0.548	0.204	0.035	0.007	0.001	0.001	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0.036	0.200	0.519	0.200	0.036	0.007	0.001	0.001	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	0.008	0.038	0.200	0.505	0.200	0.038	0.008	0.001	0.001	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0.001	0.008	0.041	0.202	0.494	0.202	0.041	0.008	0.001	0.001	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	0.002	0.002	0.009	0.043	0.203	0.482	0.203	0.043	0.009	0.002	0.002	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	0	0.002	0.002	0.010	0.045	0.205	0.472	0.205	0.045	0.010	0.002	0.002	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0	0.002	0.002	0.011	0.048	0.206	0.461	0.206	0.048	0.011	0.002	0.002	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9	0	0	0	0.002	0.003	0.012	0.050	0.207	0.451	0.207	0.050	0.012	0.003	0.002	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0.003	0.003	0.013	0.053	0.208	0.441	0.208	0.053	0.013	0.003	0.003	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0.003	0.003	0.014	0.056	0.209	0.430	0.209	0.056	0.014	0.003	0.003	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0.004	0.004	0.015	0.058	0.209	0.420	0.209	0.058	0.015	0.004	0.004	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	0	0	0	0	0	0	0	0.004	0.004	0.016	0.061	0.210	0.410	0.210	0.061	0.016	0.004	0.004	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
14	0	0	0	0	0	0	0	0	0.005	0.005	0.017	0.064	0.210	0.400	0.210	0.064	0.017	0.005	0.005	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0	0	0	0.005	0.006	0.018	0.067	0.209	0.389	0.209	0.067	0.018	0.006	0.005	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
16	0	0	0	0	0	0	0	0	0	0	0.006	0.006	0.020	0.070	0.209	0.379	0.209	0.070	0.020	0.006	0.006	0	0	0	0	0	0	0	0	0	0	0	0	0	0
17	0	0	0	0	0	0	0	0	0	0	0	0.007	0.007	0.021	0.072	0.208	0.370	0.208	0.072	0.021	0.007	0.007	0	0	0	0	0	0	0	0	0	0	0	0	0
18	0	0	0	0	0	0	0	0	0	0	0	0	0.007	0.008	0.022	0.075	0.207	0.360	0.207	0.075	0.022	0.008	0.007	0	0	0	0	0	0	0	0	0	0	0	0
19	0	0	0	0	0	0	0	0	0	0	0	0	0	0.008	0.009	0.024	0.078	0.206	0.350	0.206	0.078	0.024	0.009	0.008	0	0	0	0	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.009	0.010	0.025	0.081	0.205	0.341	0.205	0.081	0.025	0.010	0.009	0	0	0	0	0	0	0	0	0	0
21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.010	0.011	0.026	0.083	0.203	0.331	0.203	0.083	0.026	0.011	0.010	0	0	0	0	0	0	0	0	0
22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.012	0.012	0.028	0.086	0.201	0.322	0.201	0.086	0.028	0.012	0.012	0	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.013	0.014	0.029	0.089	0.199	0.313	0.199	0.089	0.029	0.014	0.013	0	0	0	0	0	0	0
24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.014	0.015	0.031	0.091	0.197	0.304	0.197	0.091	0.031	0.015	0.014	0	0	0	0	0	0
25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.016	0.017	0.032	0.094	0.194	0.295	0.194	0.094	0.032	0.017	0.016	0	0	0	0	0
26	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.018	0.018	0.033	0.096	0.191	0.286	0.191	0.096	0.033	0.018	0.018	0	0	0	0
27	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.019	0.020	0.035	0.098	0.189	0.278	0.189	0.098	0.035	0.020	0.019	0	0	0
28	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.021	0.022	0.036	0.100	0.185	0.270	0.185	0.100	0.036	0.022	0.021	0	0
29	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.023	0.024	0.037	0.102	0.182	0.261	0.182	0.102	0.037	0.024	0.023	0
30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.025	0.027	0.038	0.104	0.179	0.253	0.179	0.104	0.038	0.027	0.025
31	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.027	0.029	0.040	0.106	0.175	0.245	0.175	0.106	0.040	0.056
32	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.030	0.031	0.041	0.108	0.172	0.238	0.172	0.108	0.102
33	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.032	0.034	0.042	0.109	0.168	0.230	0.168	0.217
34	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.035	0.037	0.043	0.110	0.164	0.223	0.389
35	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.007	0.013	0.020	0.037	0.061	0.863

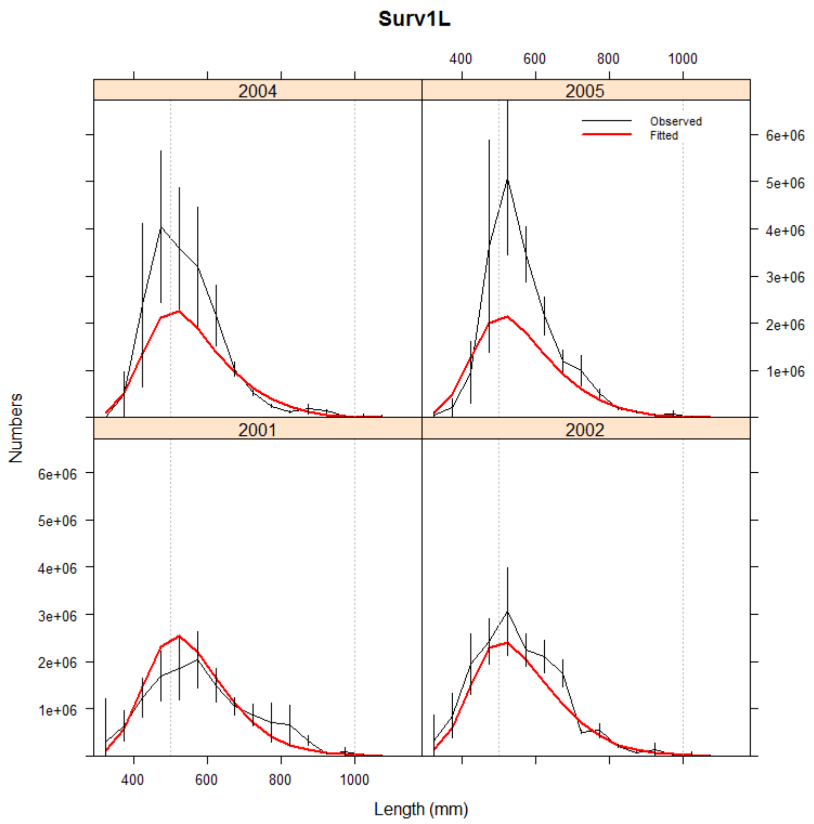
Table A.4: Final effective sample sizes (ESS) for proportions-at-age (1997-2014) of each commercial sub-fishery and fishing year in Model 6. ESS of Trap was set to 1.

Year	**Trawl**		**Longline**		**Trap**
	Trawl1	**Trawl2**	**LL1**	**LL2**	
1997	27				
1998	27				
1999	125				
2000	183				
2001	289				
2002	184				
2003	130		371		
2004	85		220	164	
2005	195		182	133	
2006	340		951		1
2007	348		364	329	
2008	442		498	342	
2009	98		139	99	
2010	105		176	109	
2011	142		131	101	
2012	250		1278	1731	
2013	180		1159	1697	1
2014	47		355	444	

Table A.5: Tag-dispersion ϕ estimated following the method in Mormede et al. (2013).

Step	**Description**	ϕ
0	Assessment 2014	1
1a	Extend model to 2015	1
1b	Add catches	1
1c	Add survey numbers-at-age	1
1d	Add commercial catch-at-age	1
1e	Last estimated *YCS* in 2010	1
1f	Add tag-recaptures 2014	1.021
1g	Add tag-recaptures 2015	1.105
1h	Add tag-releases 2014	1.119
2	Update growth parameters	1.158
3	Survey *q*: Uniform-log prior	1.221
4	B_0: Uniform-log prior	1.229
5	*YCS*: Log-normal prior	1.218
6	Split trawl into two periods	1.244

a)



b)

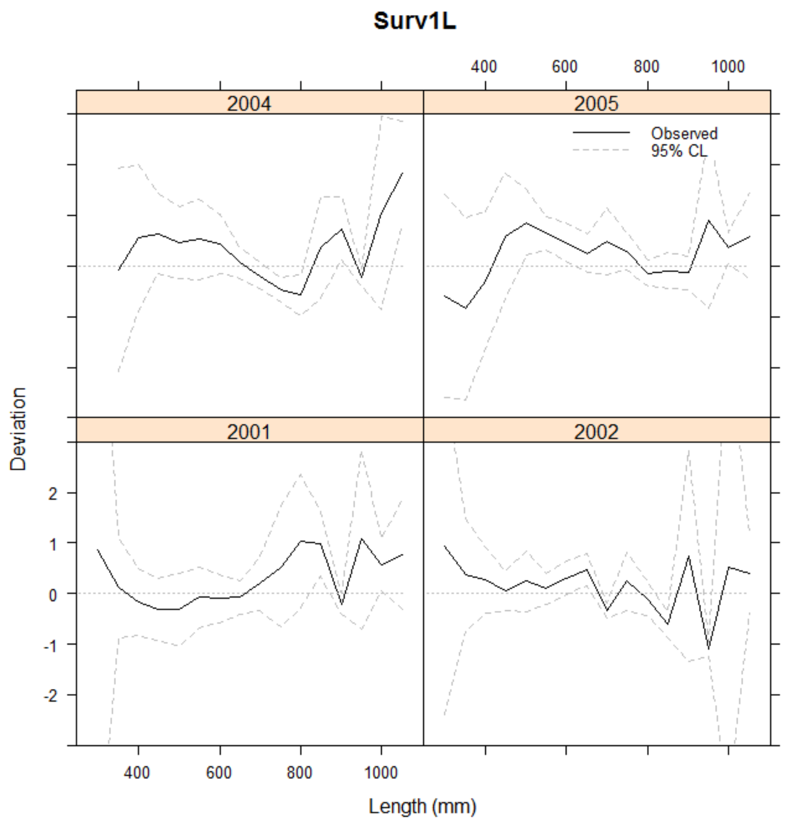
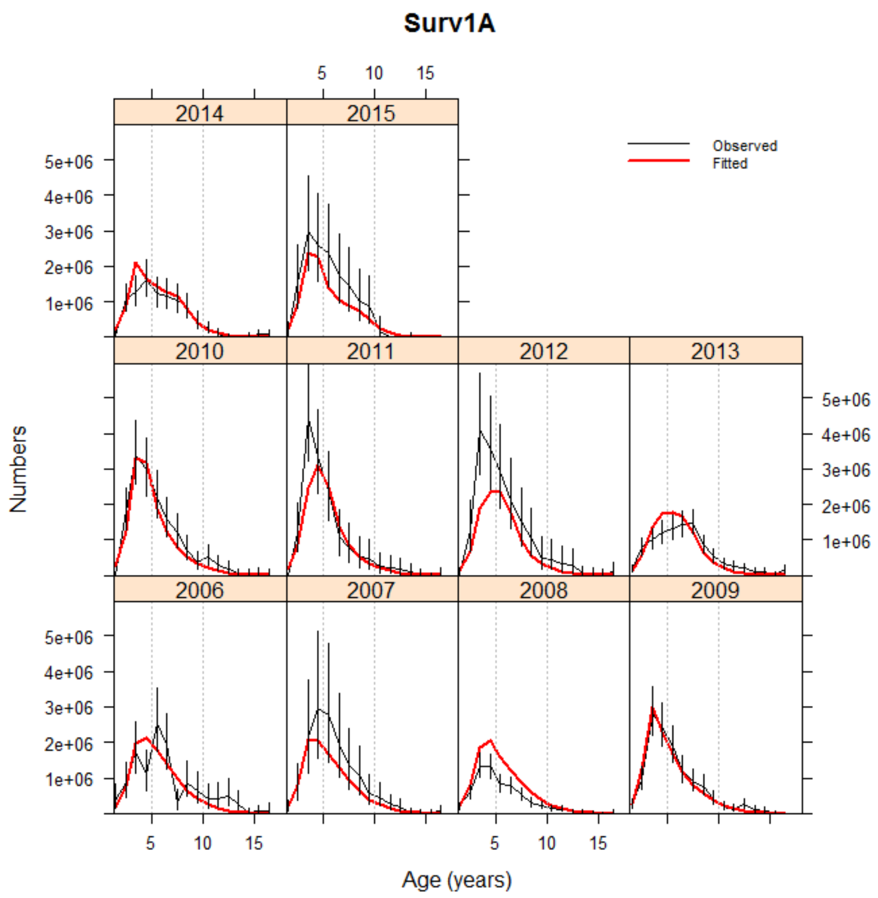


Figure A.1: (a) Observed (black lines with approximate 95% CI) and expected (red lines) abundance-at-length; and (b) observed minus expected log abundances (deviation) with 95% confidence bounds (dashed lines) for the Survey in Model 6. Note that the years are not consecutive.

a)



b)

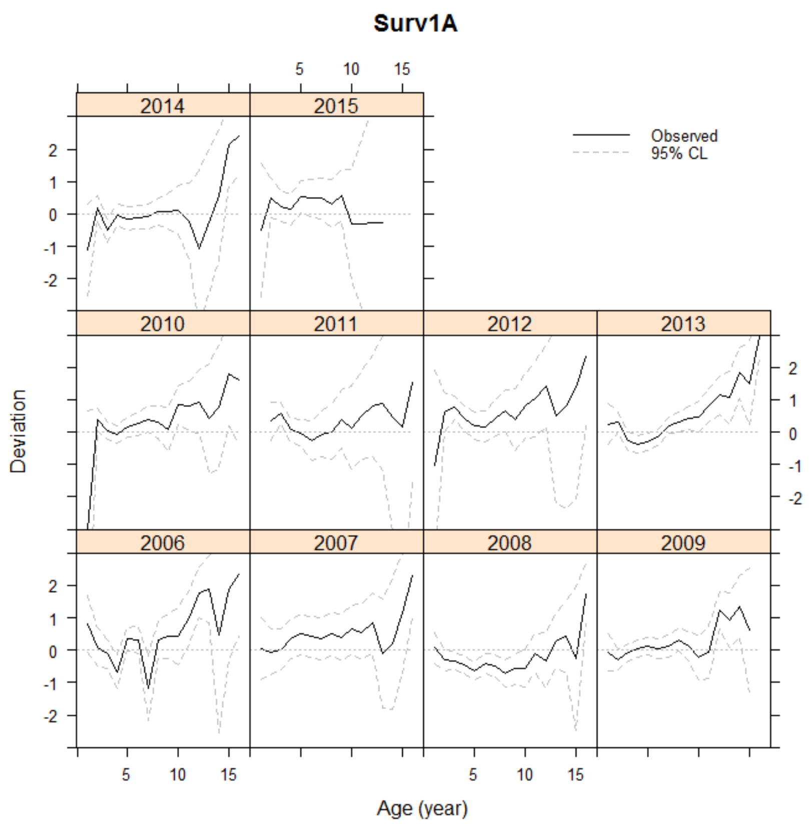
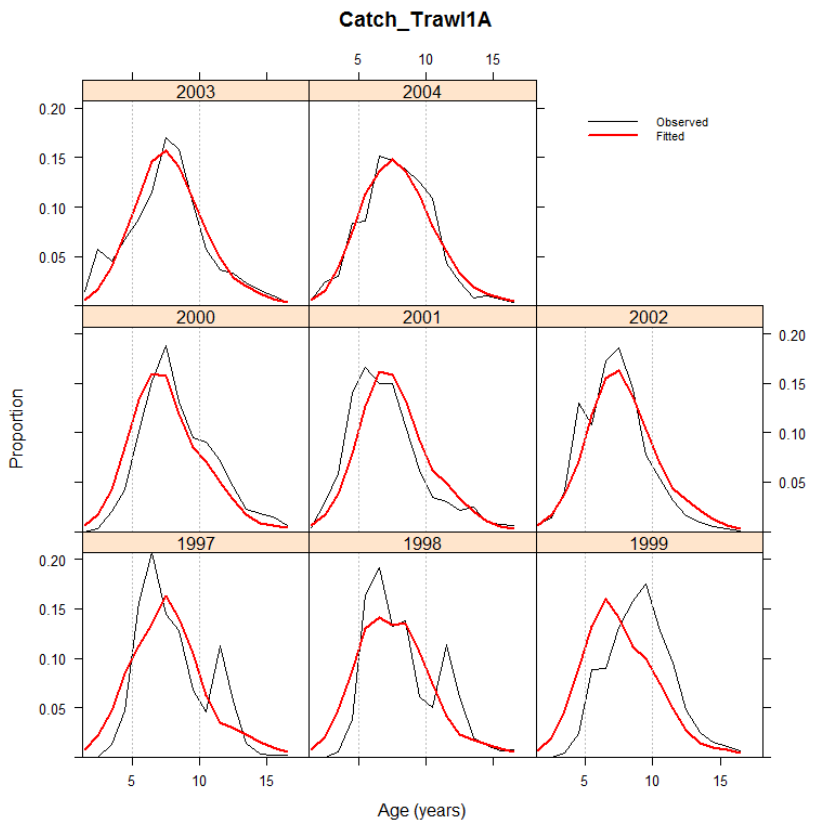


Figure A.2: (a) Observed (black lines with approximate 95% CI) and expected (red lines) abundance-at-age; and (b) observed minus expected log abundances (deviation) with 95% confidence bounds (dashed lines) for the Survey in Model 6.

a)



b)

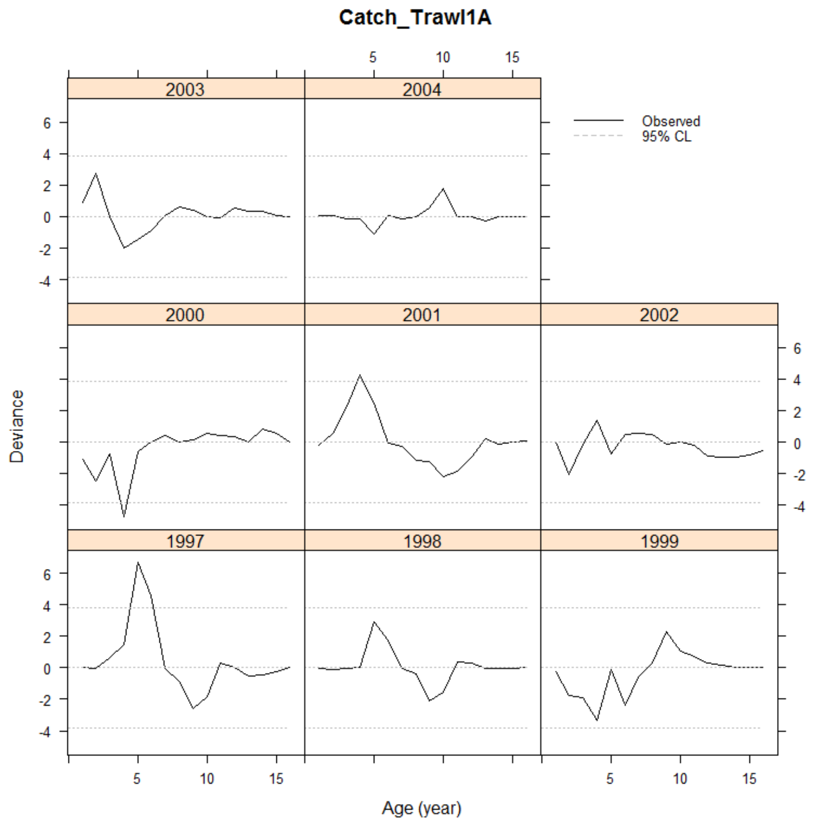
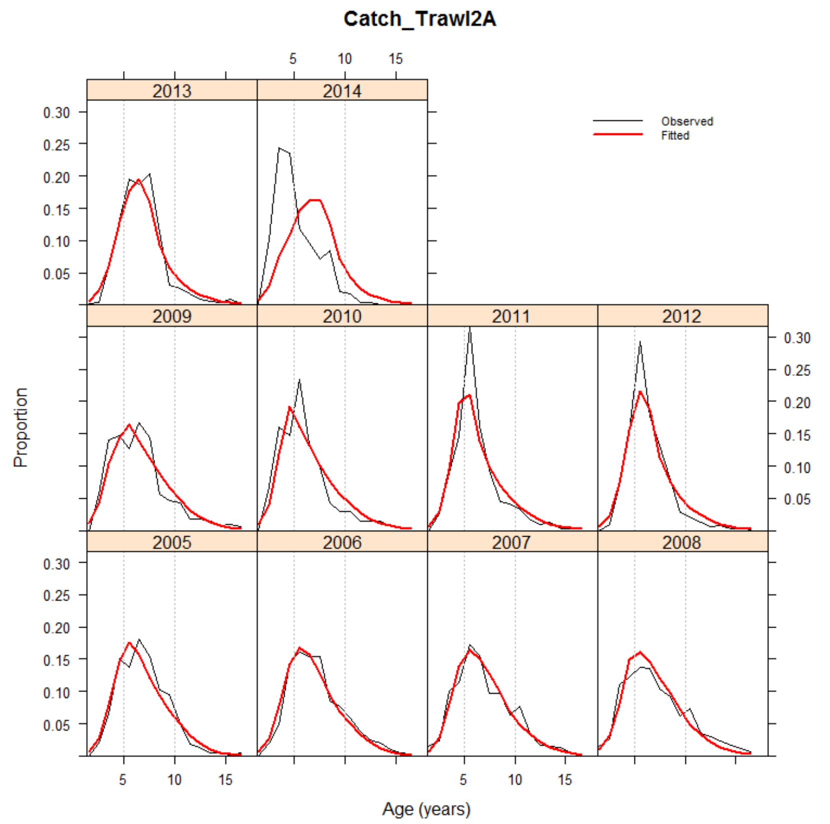


Figure A.3: (a) Observed (black lines) and expected (red lines) proportions-at-age; and (b) deviance residuals from systematic lack-of-fit (SLOF) with approximate 95% confidence bounds (dashed lines) for Trawl1 in Model 6.

a)



b)

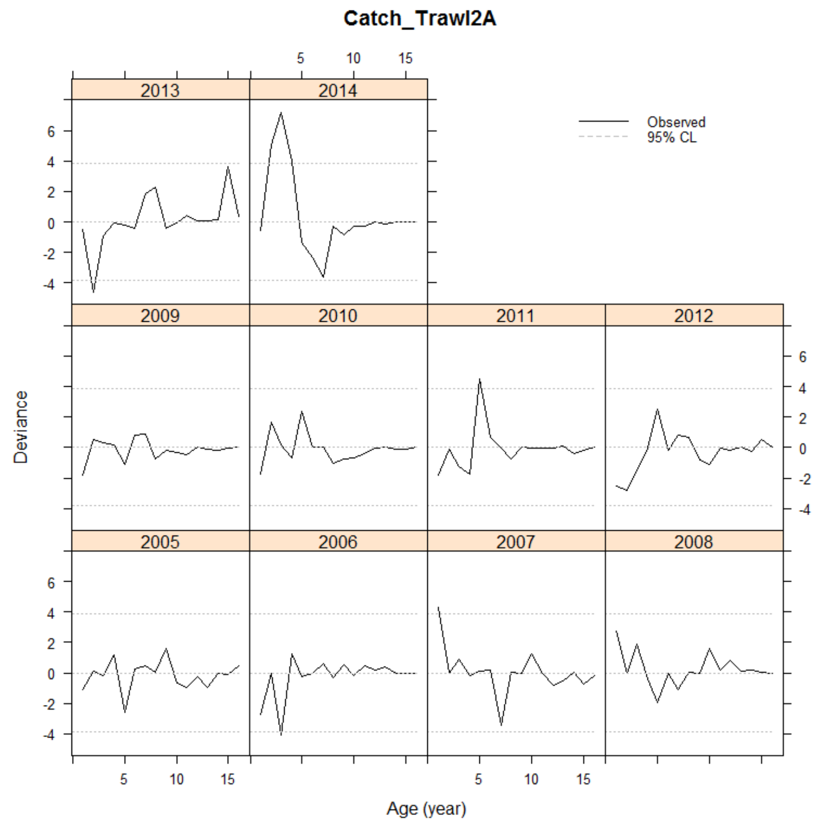


Figure A.4: (a) Observed (black lines) and expected (red lines) proportions-at-age; and (b) deviance residuals from systematic lack-of-fit (SLOF) with approximate 95% confidence bounds (dashed lines) for Trawl2 in Model 6.

a) b)

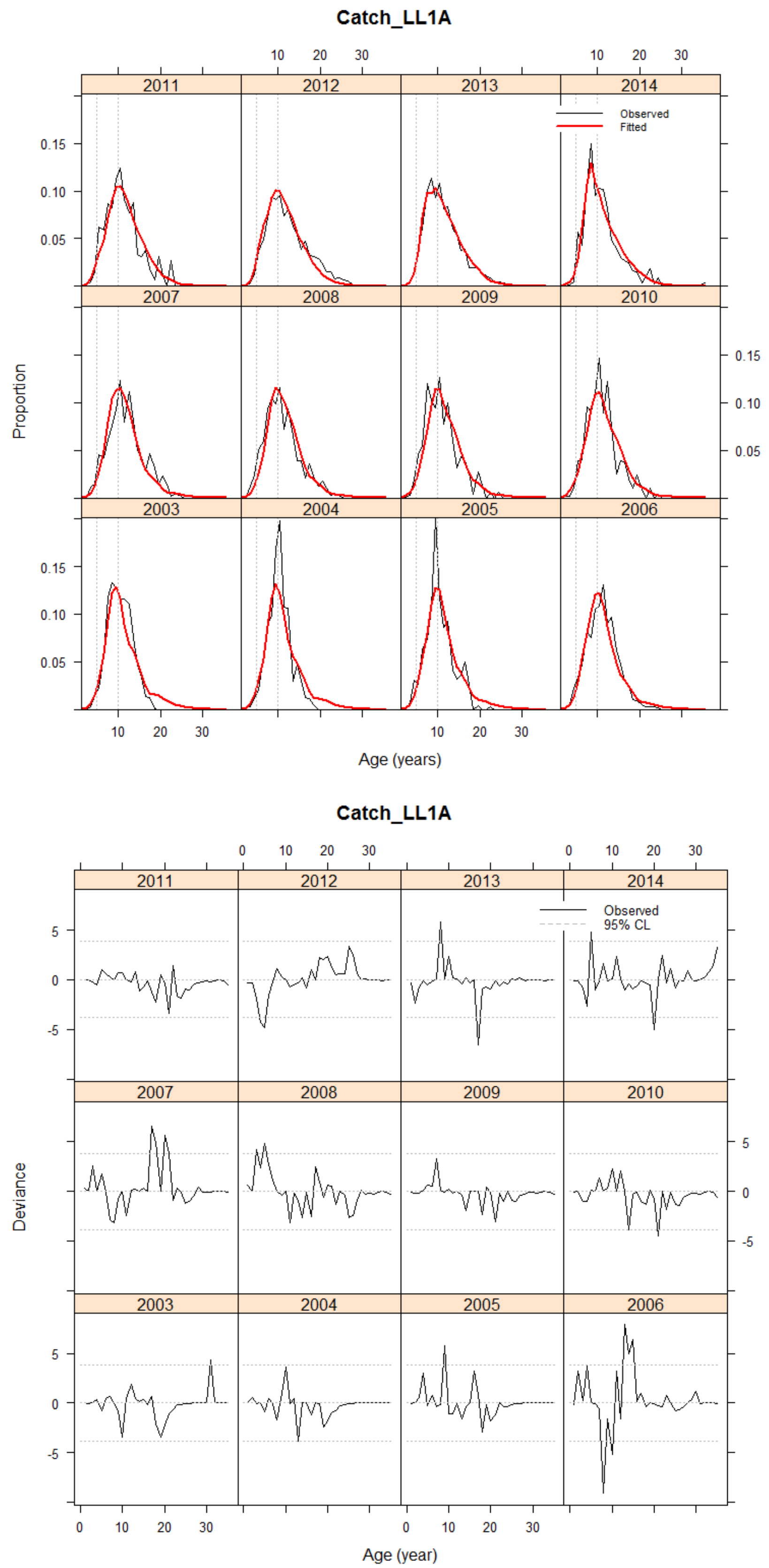
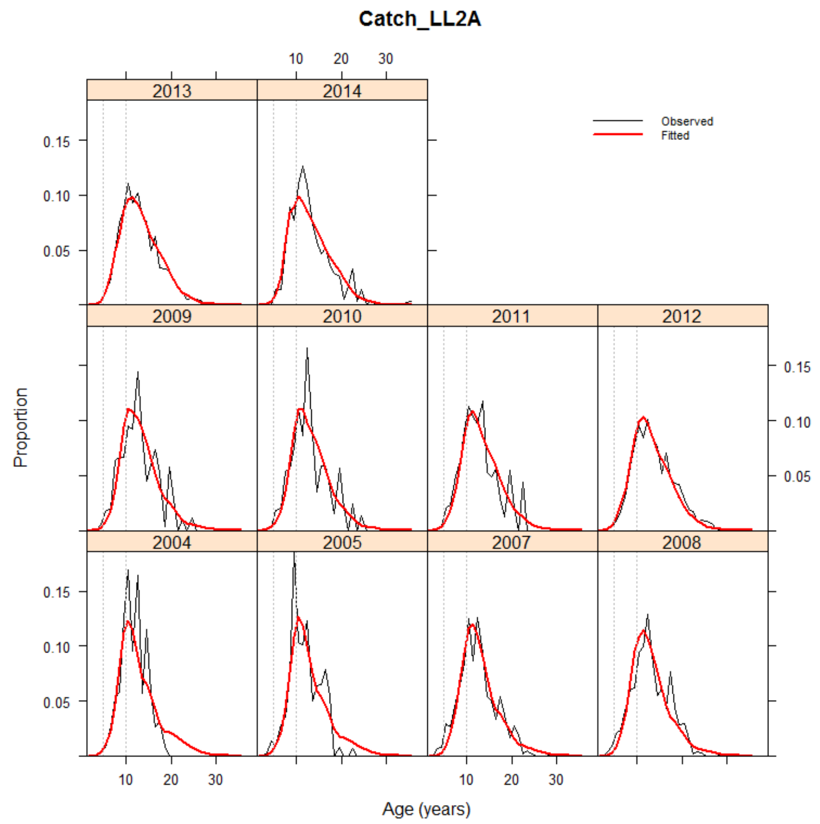


Figure A.5: (a) Observed (black lines) and expected (red lines) proportions-at-age; and (b) deviance residuals from systematic lack-of-fit (SLOF) with approximate 95% confidence bounds (dashed lines) for LL1 in Model 6.

a)



b)

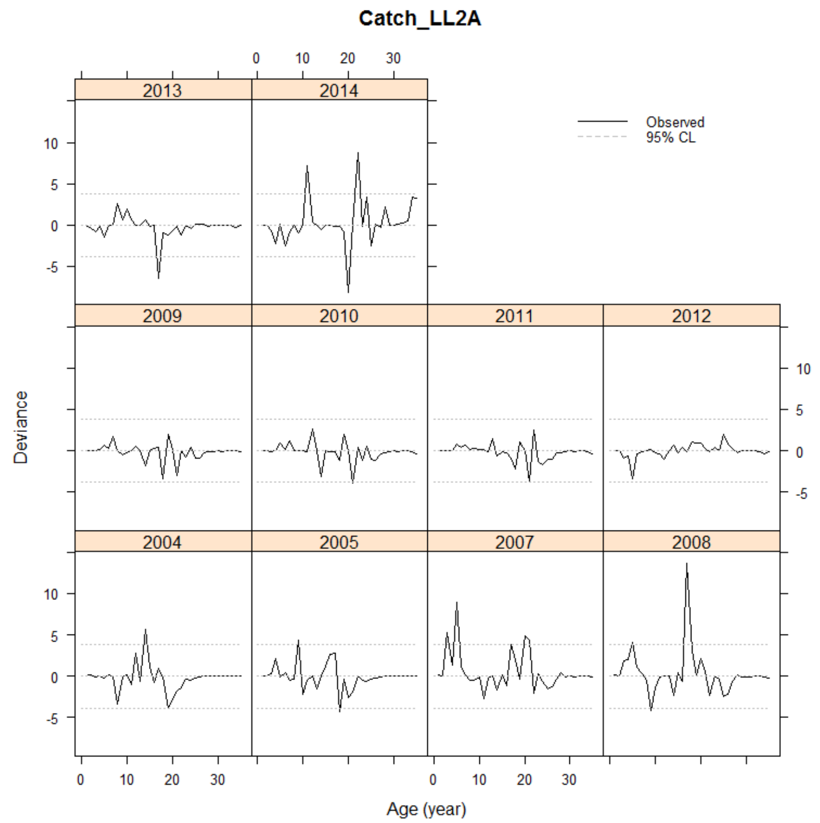
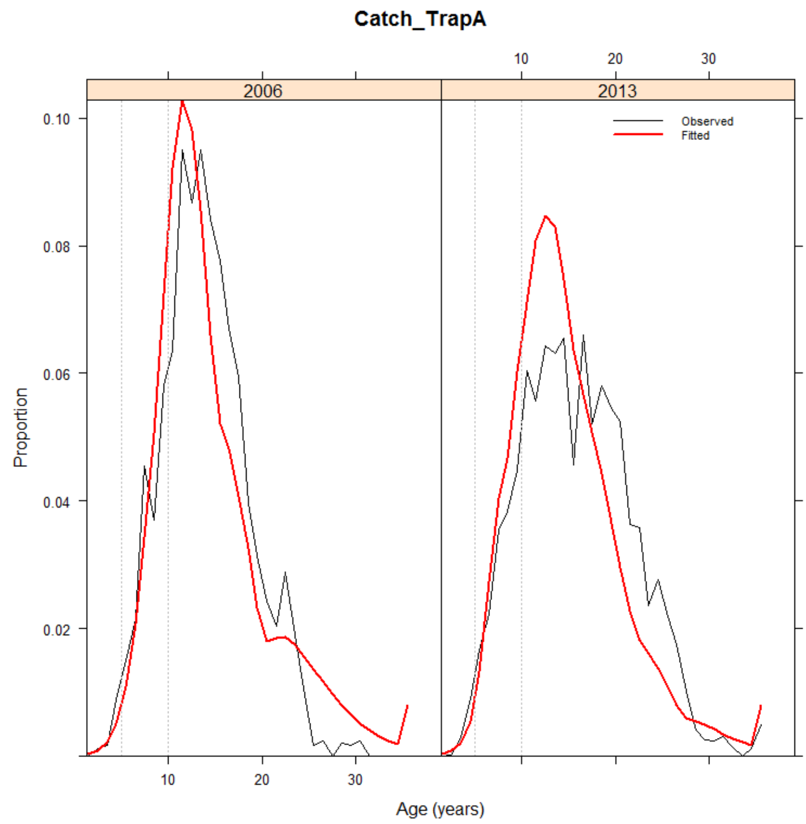


Figure A.6: (a) Observed (black lines) and expected (red lines) proportions-at-age; and (b) deviance residuals from systematic lack-of-fit (SLOF) with approximate 95% confidence bounds (dashed lines) for LL2 in Model 6.

a)



b)

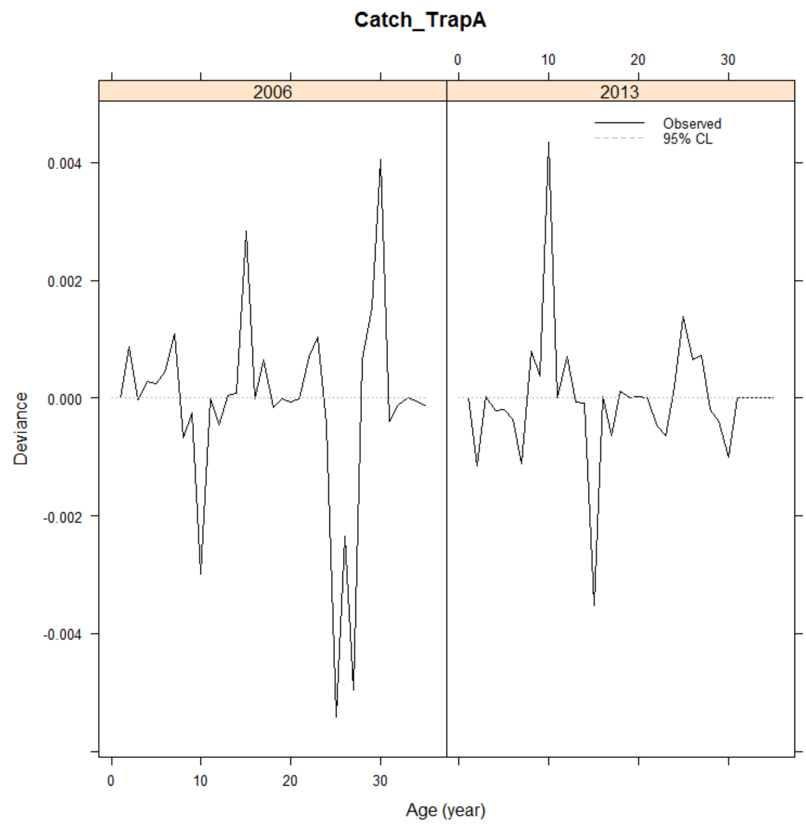


Figure A.7: (a) Observed (black lines) and expected (red lines) proportions-at-age; and (b) deviance residuals from systematic lack-of-fit (SLOF) with approximate 95% confidence bounds (dashed lines) for Trap in Model 6. Note that years are not consecutive.

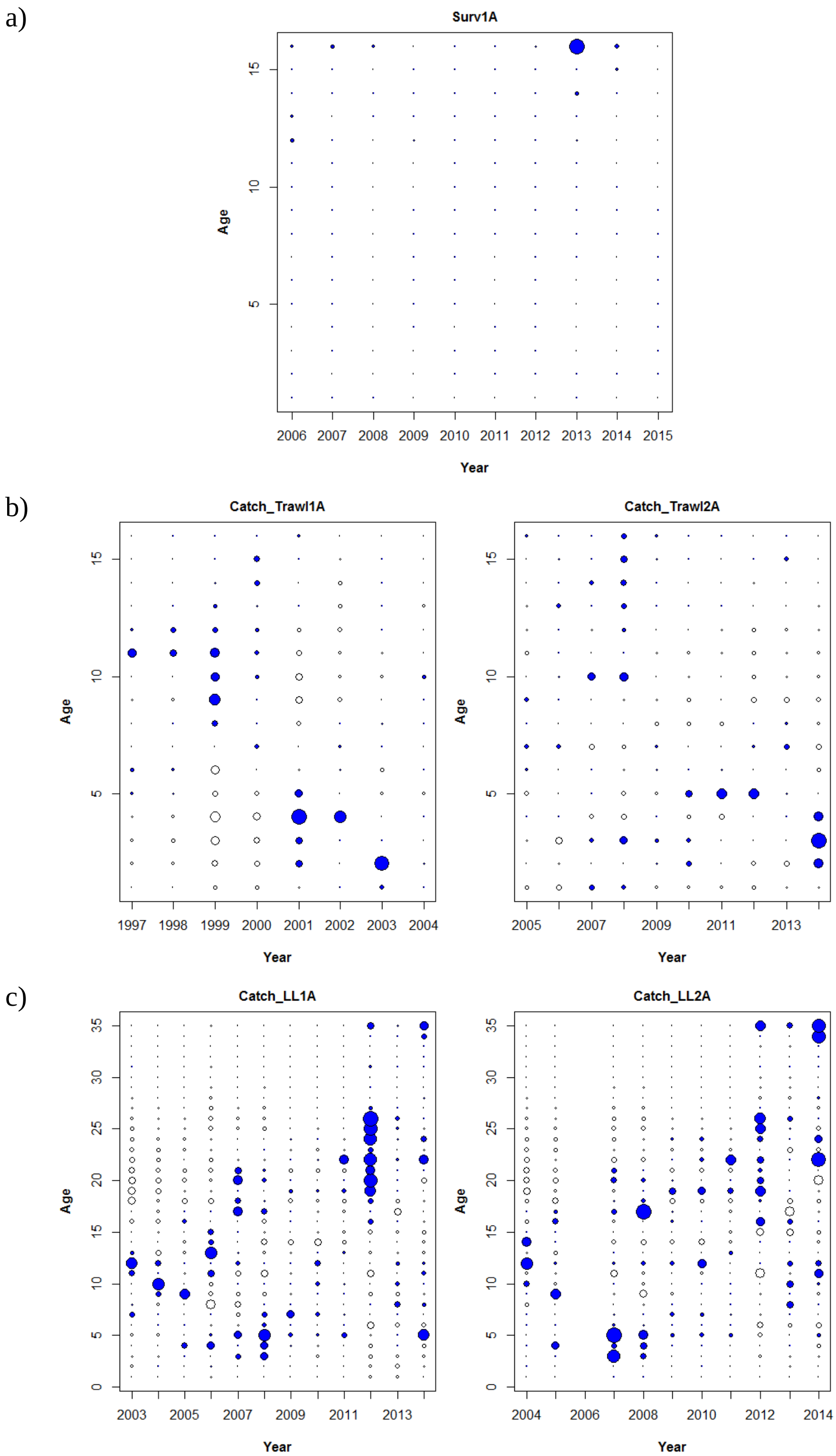


Figure A.8: Pearson's residuals of MPD fits by age and year for the survey and commercial sub-fisheries in Model 6.

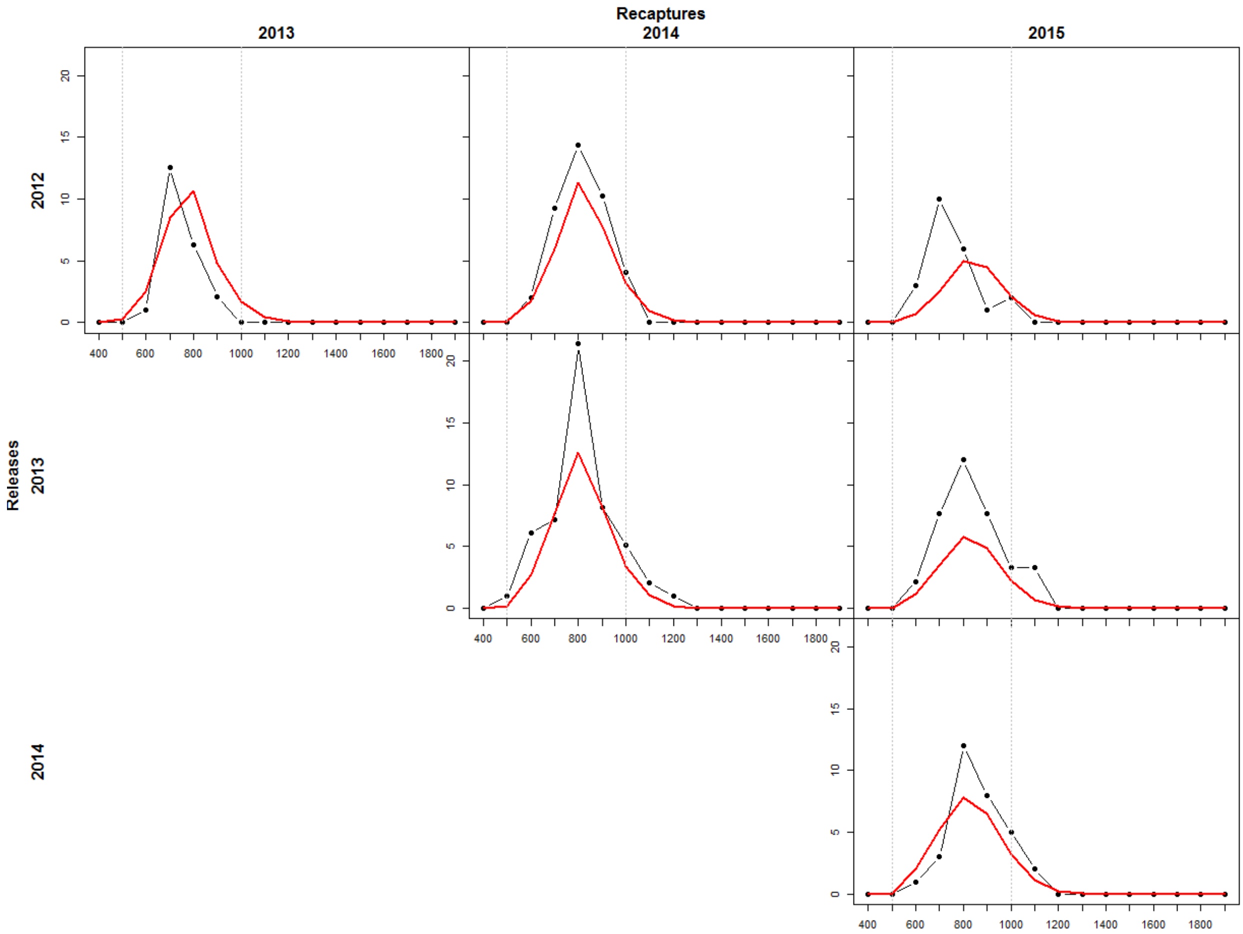


Figure A.9: Observed (black lines) and expected (red lines) tag-recaptures by 100 mm length for tag-releases in 2012-2014 and tag-recaptures in 2013-2015 in Model 6.

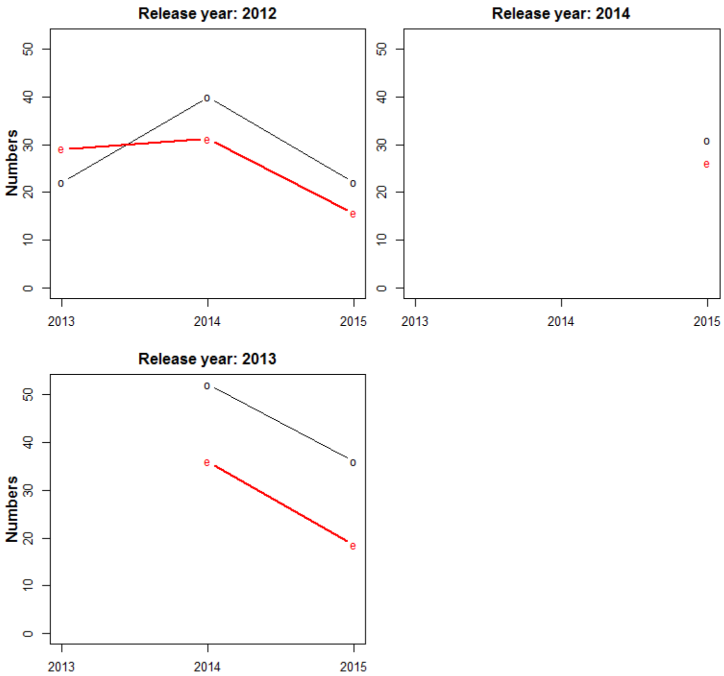


Figure A.10: Observed (black lines) and expected (red lines) total tag-recaptures by recapture year for tag-releases in 2012-2014 and tag-recaptures in 2013-2015 in Model 6.

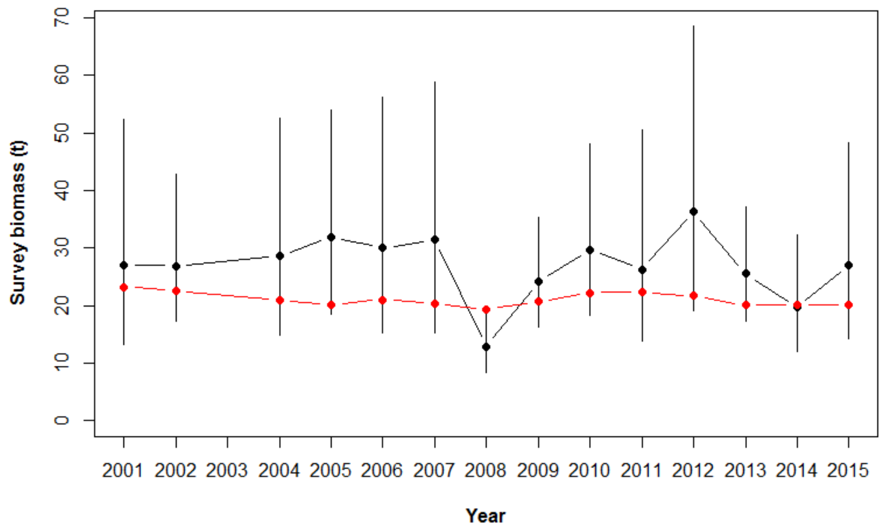


Figure A.11: Calculated survey biomass (with indicative 95% CI) of observed survey numbers (black) and expected survey numbers (red) in Model 6.

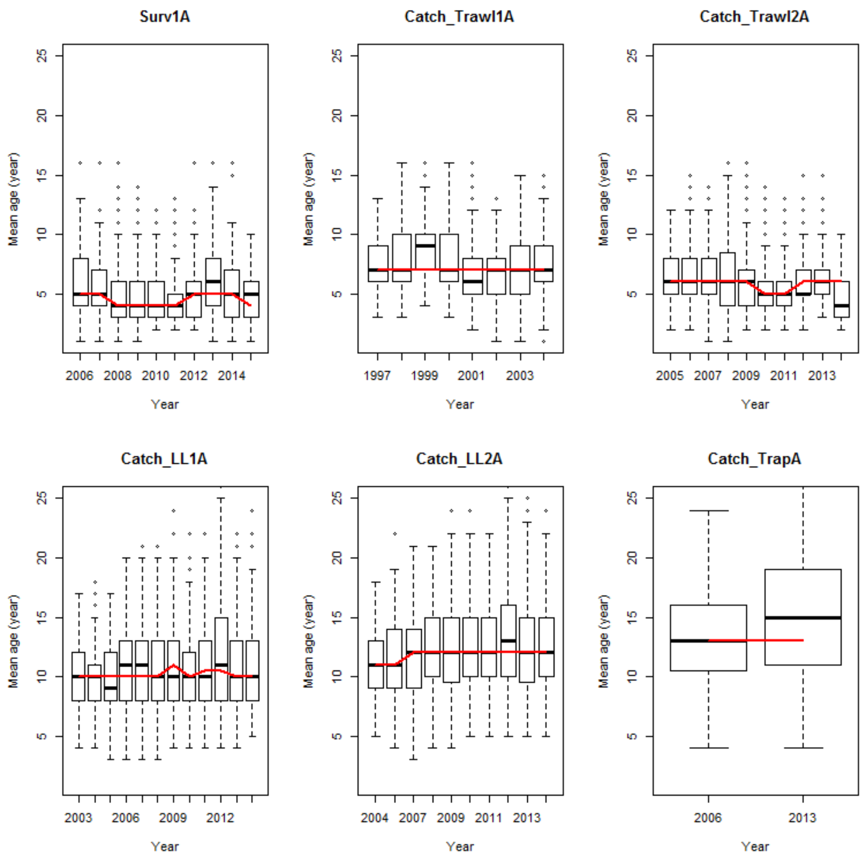


Figure A.12: Boxplots of observed age by sub-fishery and expected median age (red line) in Model 6.

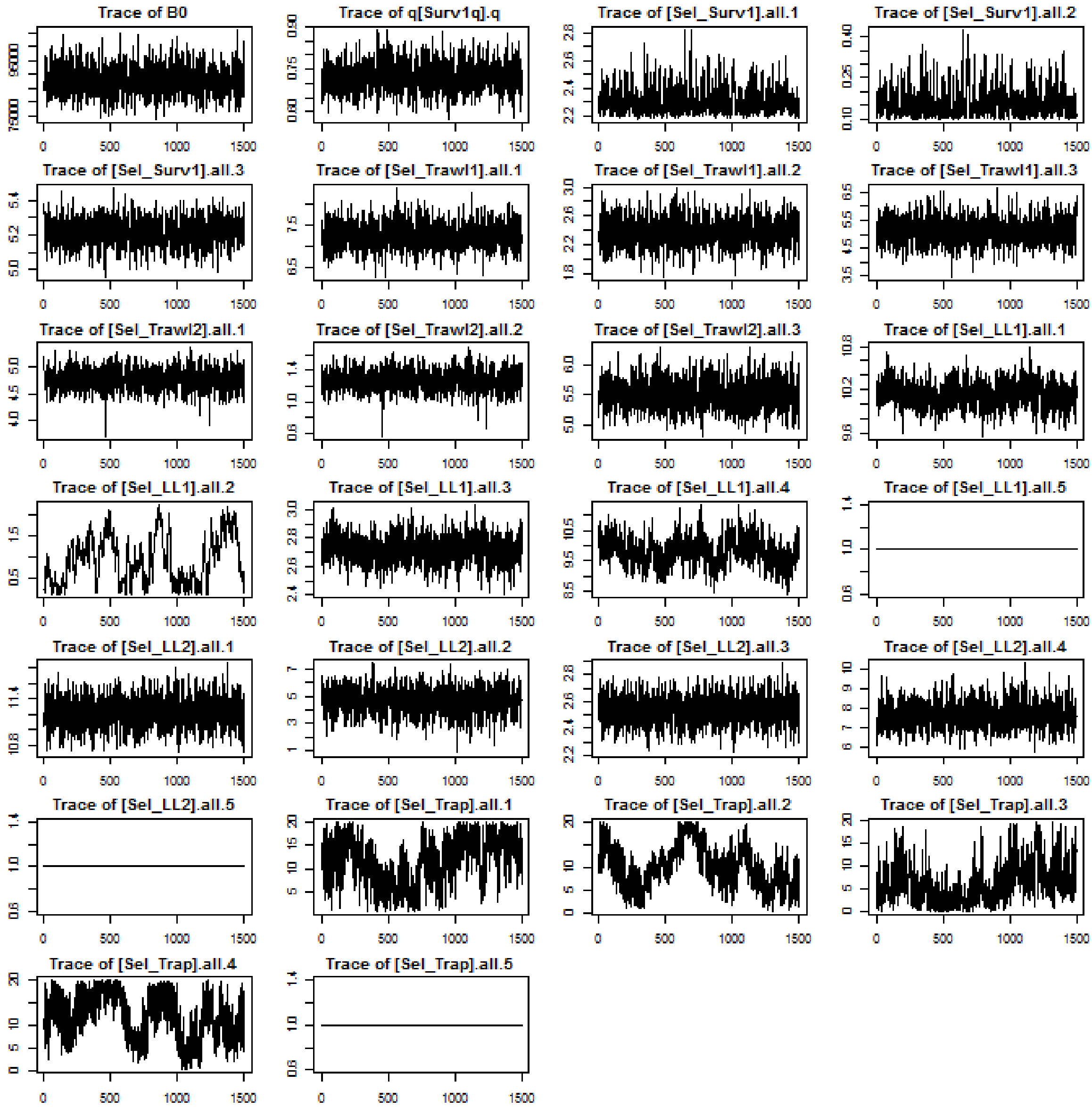


Figure A.13: MCMC posterior trace plots for B_0, survey catchability q, and all selectivity parameters in Model 6.

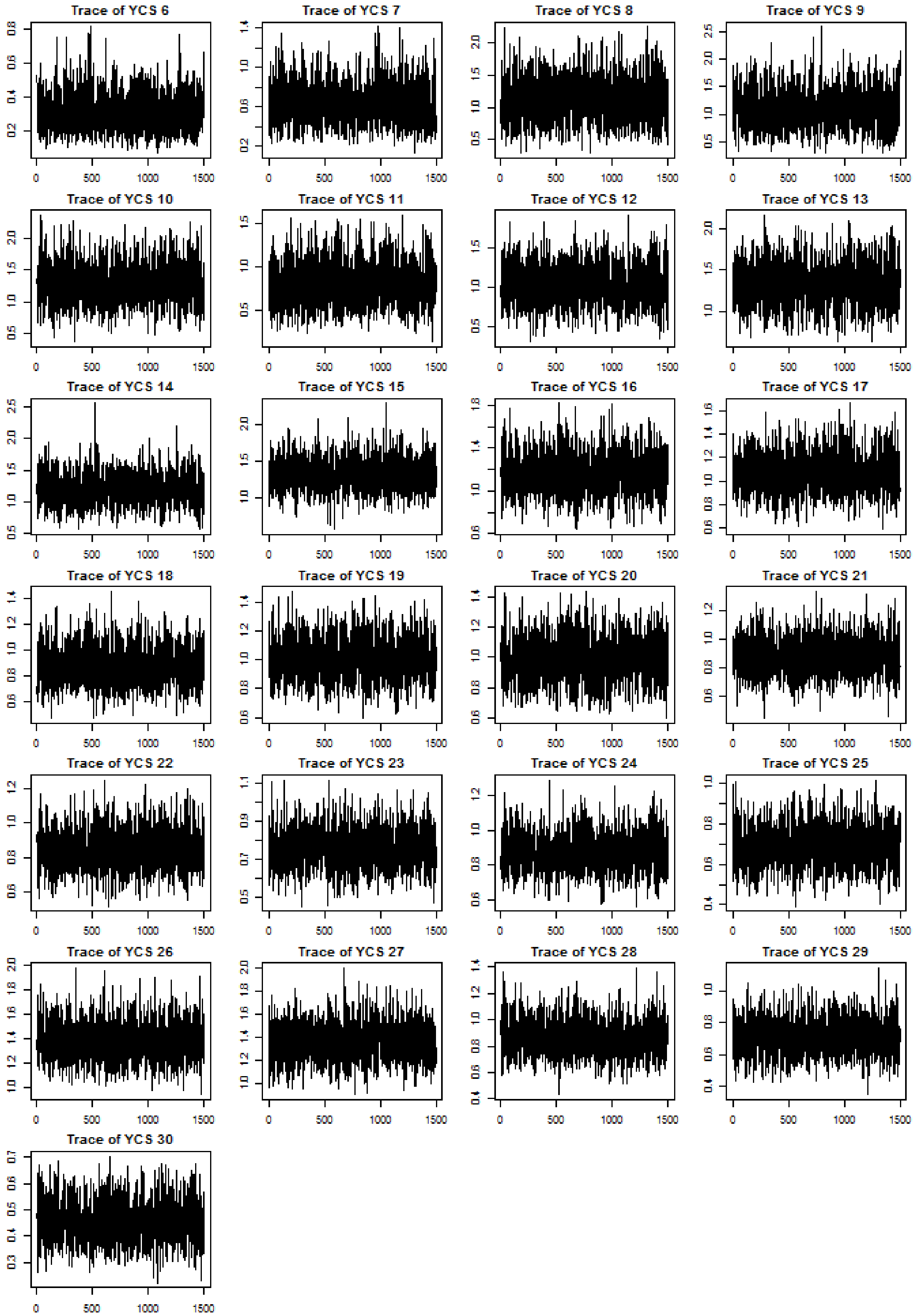


Figure A.14: MCMC posterior trace plots for all *YCS* parameters in Model 6.