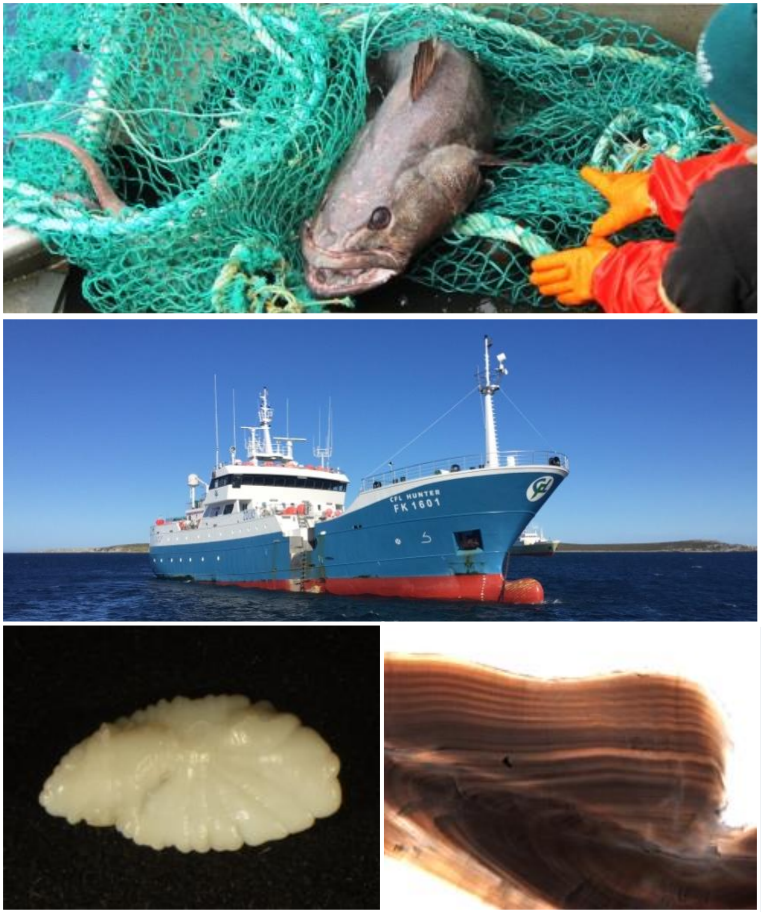
Stock Assessment Report – 2017

Patagonian Toothfish
(*Dissostichus eleginoides*)



Thomas J. Farrugia
Andreas Winter

Falkland Islands Government
Directorate of Natural Resources
Fisheries Department
Stanley, Falkland Islands

17 April 2018

SA – 2017 – TOO

Participating Scientific Staff

Dr Thomas J. Farrugia (Toothfish Stock Assessment Scientist)
Dr Andreas Winter (Senior Stock Assessment Scientist)

Acknowledgements

We thank all of the observers and researchers that have contributed to the data used in this stock assessment report. We also thank Consolidated Fisheries Ltd., and the Captain and crew of the *CFL Hunter* for their assistance and support.

For citation purposes this publication should be referenced as follows:

Farrugia T.J., Winter A. (2018). 2017 Stock Assessment Report for Patagonian Toothfish, Fisheries Report TOO-2017-SA. Stanley, Fisheries Department, Directorate of Natural Resources, Falkland Islands Government.

Table of Contents

List of Tables

List of Figures

Summary

1. Toothfish stock assessment was calculated using an age-structured production model in CASAL software. The stock assessment model was revised for 2017 by: a) adjusting the maturity data to take into account that “immature” and “mature resting” fish are not distinguishable, b) changing the gear type of six longline sets in 2013 that were conducted with a Spanish-system longline rather than an umbrella-system longline, c) using a lower whale depredation rate in line with the most up-to-date data, and d) including ageing data through the end of the stock assessment year (2017).
2. The stock assessment calculated toothfish total biomass of 31,891 tonnes and spawning stock biomass of 11,293 tonnes in 2017. The ratio of SSB_{2017}:SSB_0 (current spawning stock biomass to unfished spawning stock biomass) was 0.482. Maximum sustainable yield was estimated by the stock assessment model at 1,932 tonnes, assuming a catch / bycatch split of 75.9% toothfish longline, 21.9% finfish trawl, and 2.2% calamari trawl.
3. The recommendation for the toothfish longline fishery is to maintain total allowable catch (TAC) at 1040 tonnes, same as last year. The recommendation is based on the SSB_{2017}:SSB_0 ratio being above the trigger point, but still showing signs that it may decrease in the future.
4. Forward-calculation of the age-structured production model projected that spawning stock biomass will decrease until 2024, reaching a minimum $SSB_{current}$:SSB_0 ratio of 0.436 (95% CI: 0.355 - 0.586) before increasing back above the upper target reference point of 0.45 by 2029.

Introduction

A commercial longline fishery targeting Patagonian toothfish (*Dissostichus eleginoides*) has been operating in Falkland Islands waters since 1992, and specifically licensed since 1995 (des Clers et al. 1996, Laptikhovsky and Brickle 2005). Important quantities of toothfish are also caught in two other Falklands fisheries: finfish trawl, of which toothfish is not a target but commercially valuable bycatch, and calamari (*Doryteuthis gahi*) squid trawl, of which toothfish is also bycatch, but individuals caught in this fishery are too small to be commercially valuable. The fisheries access different parts of the toothfish population in different areas: longlining occurs on the slope and in deep water, finfish trawling on the shelf primarily north and west of the Falkland Islands, and calamari trawling also on the shelf, east of the Falkland Islands (Figure 1).

The current stock assessment of Falkland Islands toothfish was calculated with updated catch and effort through 2017, 169,256 length measurements between 1988 and 2017, and 5,742 age measurements from otolith readings sampled between 2007 and 2017. Reported toothfish catch in 2017 totalled 1520.1 tonnes, of which 67.9% by weight was caught by longline (191 vessel-days), 30.3% by finfish trawl (2431 vessel-days), and 1.9% by calamari trawl (2079 vessel-days). Longline vessel-days in 2017 were the lowest since 1993, due to operational scheduling by the quota holder. Despite this, a relatively high catch per unit effort (CPUE) in 2017 led to a slight increase in reported longline catches compared to 2016.

Methods

The stock assessment was calculated as an age-structured production model in CASAL software (C++ Algorithmic Stock Assessment Laboratory; Bull et al. 2012, Dichmont et al. 2016). This stock assessment was based on the objective function comprising relative annual abundance indices (longline CPUE), and catch-at-age distributions of the toothfish longline, finfish trawl (including skate and surimi licenses), and calamari trawl fisheries. Jig and pot fisheries catch negligible quantities of toothfish and have no toothfish observer data to determine catch-at-age distributions. Finfish trawl and calamari trawl fisheries were modelled separately because the small mesh permitted solely for calamari fishing results in different toothfish catch-at-age distributions. The two calamari seasons per year (Arkhipkin et al. 2008) were combined. The use of only longline CPUE as a relative abundance index is motivated by the inconsistency of CPUE in fisheries where toothfish is a bycatch and not a target; toothfish bycatch may change just because those fisheries are switching targets, areas, or seasonality, rather than by any factors related to the toothfish stock.

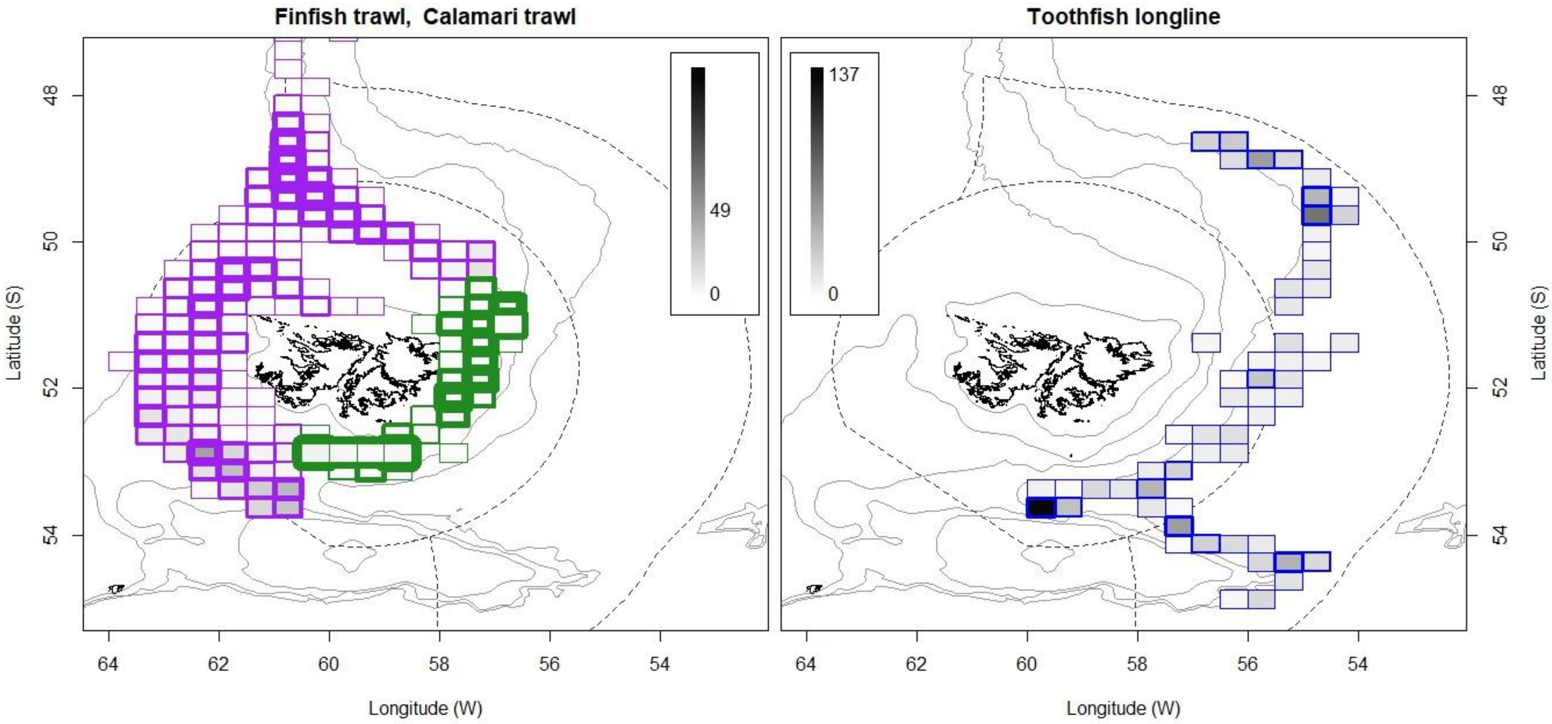


Figure 1. Distribution of toothfish catches in 2017 by Falkland zone grid. Thickness of grid lines is proportional to the number of vessel-days, grey-scale is proportional to the toothfish catch biomass. Left: finfish trawls (purple; max. 127 vessel-days and max. 49.5 tonnes toothfish in one grid square), Falkland calamari trawls (green; max. 320 vessel-days and max. 5.9 tonnes toothfish in one grid square). Right: toothfish longline (blue; max. 15 vessel-days and max. 137.4 tonnes toothfish in one grid square).

Yearly index values were weighted for the CASAL optimization using Francis’ (2011) two-stage approach. First, to address observation error an effective sample size (N) of age-class data per year in each fishery was calculated based on data fit to the multinomial distribution, using the function ‘Neff.obs’ in R package ‘DataWeighting’ (Francis 2013). Second, to address process error, effective sample sizes were multiplied by a weighting factor calculated as the inverse of the variance of difference between observed and expected mean age classes, standardized for the variance of the expected age distributions (Method TA1.8 in Table A.1, Francis 2011). The two components of the objective function (relative annual abundance indices of the longline fishery, and catch-at-age distributions of the toothfish longline, finfish trawl, and calamari trawl fisheries) were then re-weighted, as catch-at-age data may disproportionately influence a stock assessment model (Maunder and Langley 2004). The relative annual abundance indices include 24 independent years of data (Spanish-system longline 13 years: 1996-2007, 2013; umbrella-system longline 11 years: 2007-2017).

The catch-at-age distributions include 77 independent years of data (Spanish-system longline 16 years: 1992, 1994-2007, 2013; umbrella-system longline 11 years: 2007-2017; finfish trawl 25 years: 1988-1989, 1991-1994, 1997-1999, 2002-2017; and calamari trawl 25 years: 1989-1995, 1998-1999, 2002-2017). Accordingly, the effective sample sizes of the catch-at-age distributions were further multiplied by a factor of 24/77 = 0.3117.

The age structure input to the CASAL model together with maturity estimation informs the spawning stock biomass (SSB), which controls how much recruitment to the population can be expected in successive years. An important starting parameter is SSB_0, defined as the SSB that would exist with recruitment each year in the absence of fishing (Bull et al. 2012). SSB_0 is optimized within CASAL and was initialized with a value of 40,000 tonnes, approximately the average from an earlier stock assessment (Payne et al. 2005). A Beverton-Holt stock-recruitment function (Haddon 2001) was used in the model, and the steepness parameter of the stock-recruitment function (fraction of recruitment from the unfished population when spawning stock biomass declines to 0.2 of its unfished level; Mangel et al. 2013) was set to the commonly used reference value of 0.75 (Brandão and Butterworth 2009, Day et al. 2014, Mormede et al. 2014). Recruitment variability was set to 0.6 (Mormede et al. 2014). The variability distributions of optimized quantities such as total biomass and spawning stock biomass in the age-structured production model were calculated by Monte-Carlo Markov Chain (MCMC).

Model changes

The following changes from last year were effected in modelling the toothfish stock:

1. An adjustment to the proportion of mature fish at each age was made. The previous proportions were problematic because the scale used to describe maturity could not distinguish between “immature” and “mature resting” fish as those two states look very similar macroscopically. Therefore, the maturity at any length where some of the fish were mature was likely underestimated as some of the “mature resting” fish were classified as “immature”. To rectify this, a generalized linear model was used to predict the proportion of fish at each length that should be immature and stochastically remove the number of data points necessary to bring the observations in line with the prediction (see ‘Maturity’ section below for details).

2. It was recently discovered that a few longlines set in 2013 by a chartered longline were incorrectly coded in the database. These six longline sets were actually a Spanish-system longline, like the one used in the Falkland Islands up to 2007, rather than an umbrella-system longline. Therefore, the data from these six lines were attributed to the Spanish system, which now has data running from 1996-2007, plus 2013.

3. A recent report (Tixier and Arnould, 2017) on the rates of whale depredation on the longline fishery in the Falkland Islands suggests that since 2012 the annual biomass of toothfish depredated by whales varies between 40.14 and 77.7 t, representing between 3.35% and 7.47% of the annual total allowable catch, respectively. This rate is lower than assumed in the previous stock assessment model (Winter, 2017), and therefore assumed whale depredation rates were adjusted down for the 2017 stock assessment model (see below).

4. During 2017 and early 2018, much effort has been dedicated to ‘catching up’ on reading otolith and ageing toothfish. The result has been that for the first time, the stock assessment includes ageing data up to the year of the stock assessment (in this case 2017).

In previous stock assessments, ageing data stopped at the year prior to the stock assessment year. This improvement makes the stock assessment more current.

Data

Catch totals and catch-at-age proportions were used from all available years, going back to 1987. Catch reports that list fishing effort as “trawl and jig time” (listed under various licenses until 1996) were considered trawls if the unit effort was ≤ 1440; the number of minutes in 24 hours. Trawl catch reports under experimental license were considered calamari trawls if >50% of the catch was calamari, or if the report was within 7 days of a report by the same vessel that did catch >50% calamari. Otherwise, experimental-license trawls were considered finfish.

Longline CPUE indices were restricted to years since 1996. Earlier years were considered compromised by high levels of IUU fishing (Payne et al. 2005), and the composition of the longline fishing fleet changed from 1996 onwards. Before 1996, longline fishing was conducted mostly by Chilean vessels, after 1996, mostly by Falklands and Korean vessels; a difference which would have caused a disproportionate vessel effect in the standardization model.

Toothfish age and maturity data were restricted to measurements that had been processed by FIFD staff and observers, and restricted to ages >0. Length data were restricted to measurements that had been sampled randomly. Age / length distributions were summarized for the longline, finfish trawl, and calamari trawl fisheries separately. As far as possible[1], observer age / length data were matched to catch reports, and the same criteria as above were used to distinguish between finfish trawls and calamari trawls.

Input analyses

For the age-structured production model, catch proportions-at-age in the longline, finfish and calamari fisheries were calculated by assigning ages to all length measurements by conditional probability of the age-at-length distributions. To mitigate stochasticity, the conditional probability algorithm was iterated 10000 times. Ages ≥ 31 years were assigned to a ‘31+’ class. Longline CPUE (kg / 1000 hooks) was standardized as described in Appendix 1. Catch selectivity-at-age was modelled as a logistic function in the longline fishery, but as a double-normal function in the finfish and calamari fisheries because toothfish bycatches in these fisheries first increase then decrease with age. The length-weight relationship was calculated in the format $W = a \cdot L^b$ (Froese 2006), and length-at-age was modelled by the von Bertalanffy equation $L = L_{inf} \times (1 - e^{-K(t - t0)})$ in R package ‘fishmethods’ (Nelson 2015). Length-weight and size-at-age distributions are plotted in Figure 2; parameters are summarized in Appendix 2.

---

[1] Based on date and vessel call sign. Catch reports and observer data entries do not use cross-referenced identification codes.

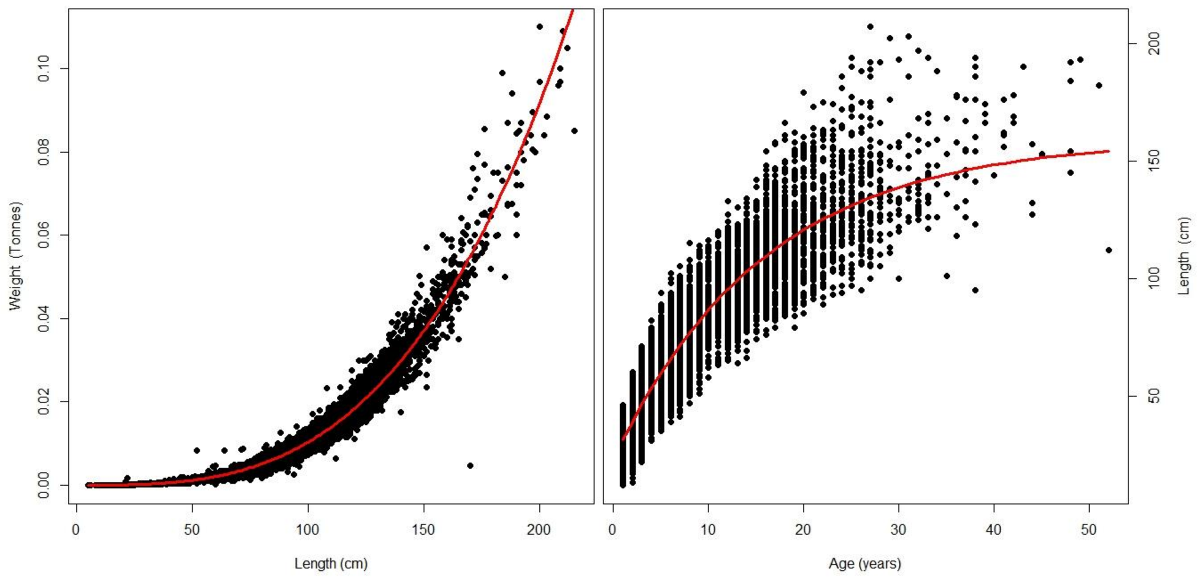


Figure 2. Length-weight and length-at-age relationships. Both the length-weight (left) and the length-at-age (right) relationships were calculated from observer data. Equation parameters are summarized in Appendix 2.

Maturity

Maturity was scored on an 8-point scale, and toothfish are considered mature from stage 3 (Laptikhovsky et al. 2006, 2008). However, once toothfish have started spawning, they occasionally enter a "resting" stage, possibly during times of skip spawning, when mature toothfish spawn one year and don't spawn the next (Collins et al. 2010, Brendon Lee FIFD pers. comm.). While in this "resting" stage, the gonads look very similar macroscopically to stage 2 gonads that are considered immature. Therefore, a number of bigger, older fish are erroneously assigned as immature because they were resting and were considered stage 2 when observed.

To address this discrepancy, the raw length maturities were plotted as the proportion of fish in stage 2 at each length (Figure 3). The data show a clear bell-shaped curve as expected until about 130 cm, after which the data become more erratic. This is what would be expected if larger individuals were erroneously assigned to stage 2 while they were resting, artificially inflating the proportion of stage 2 fish at larger sizes.

We used a generalized additive model (GAM) to model the stage 2 maturities until 130 cm, after which we used the predicted continuation to determine what proportion of fish should be stage 2 at larger lengths. We then corrected the data above 130 cm by removing the appropriate number of random fish at each stage to bring the stage-2 proportions into agreement with the GAM prediction. This process was accomplished in a loop of 10,000 iterations. At each iteration, ages were first assigned to each length, and then the appropriate number of fish was removed to bring the data in line with the predictions. The next step within each iteration was fitting a maturity ogive (proportion ≥ stage 3 per age) using a different GAM. This was used instead of the more typical logistic function because even after the stage 2 correction was made, the oldest ages still had maturity proportions significantly less than 1 (Figure 3), an outcome that is likely related to skipped spawning. At the end of the 10,000 iterations, the GAM-predicted maturity proportions at each age were averaged to obtain one age-maturity curve (Figure 4).

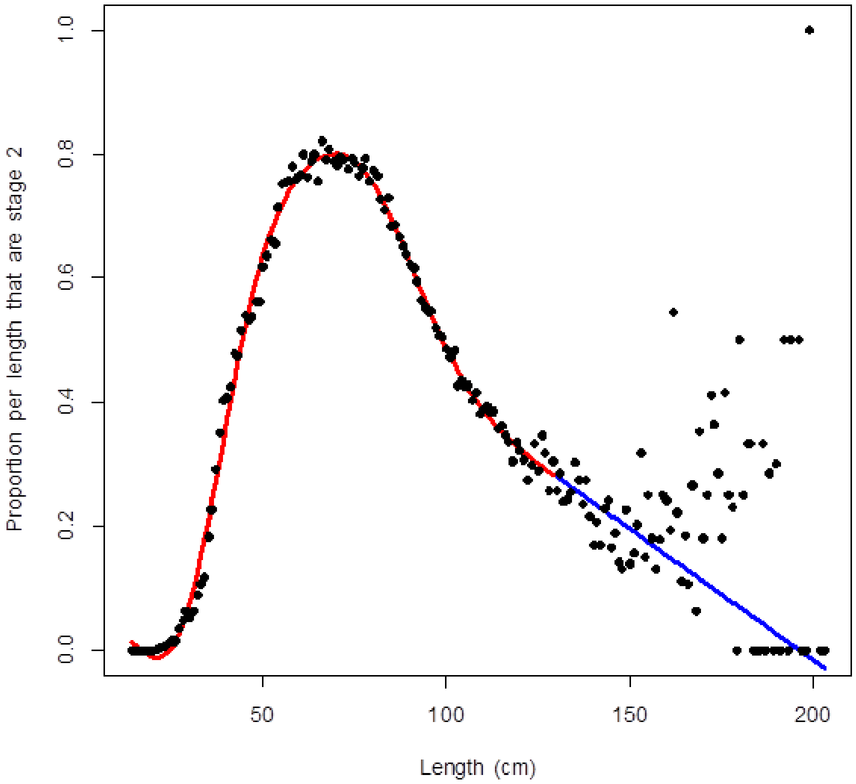


Figure 3. Proportion of stage 2 toothfish at each length. Red line: generalized additive model fit to data <130 cm length. Blue line: extrapolated proportion of stage 2 fish at lengths >130 cm. Data are from the observer database.

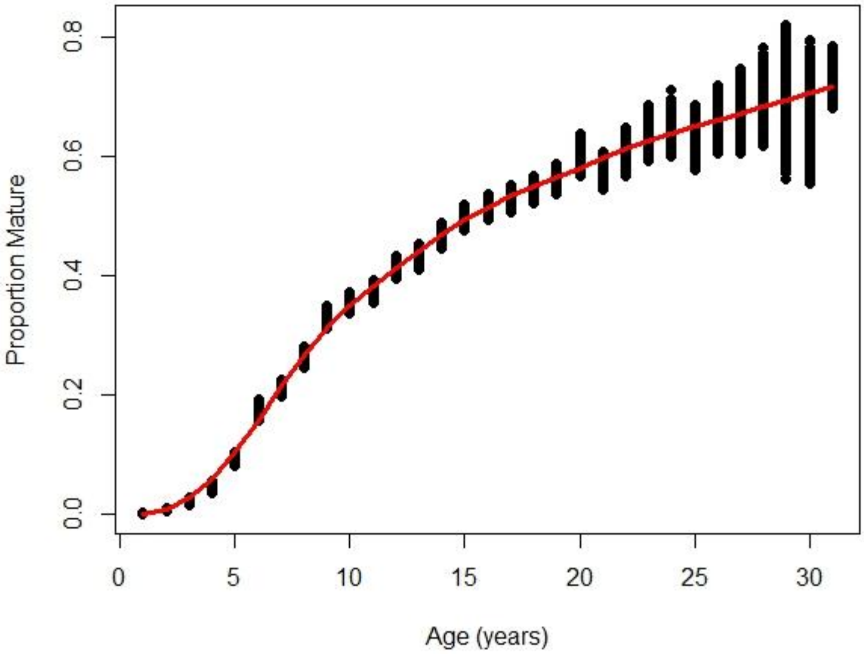


Figure 4. Proportion of mature toothfish at each age. Black dots: proportion of mature fish (maturity stage ≥3) by age from 1 to 31+, after the stage 2 correction (from FIFD observer data). Red line: average maturity ogive fitted by a generalized additive model.

Unreported fishing and whale depredation

A base model of the toothfish stock assessment was calculated incorporating all reported catches in the Falkland Islands fishing zone. Reported catches do not however include catches of vessels unlicensed by the FIG, or catches lost to undetected whale depredation.

Unreported fishing includes illegal and unregulated fishing (IUU), but may also include fishing near the Falklands zone by vessels that are foreign-licensed and do not report to the FIG. Unreported fishing is inherently difficult to estimate (Pitcher et al. 2002, Ainsworth and Pitcher 2005, Agnew et al. 2009). For the Falkland Islands toothfish stock, we utilized data from two publications: Table 1 in Agnew (2000), which gives estimated total toothfish catches in Falkland waters from 1987 to 1999, and Table 2 in Agnew et al. (2009), which gives estimated percentages of illegal / unreported fishing by region and averaged by 5-year period between 1980 and 2003. The data of the Antarctic region in Table 2 of Agnew et al. (2009) were used as these data pertain specifically to toothfish. For years since 2003, we took grey-literature estimations (e.g., CCAMLR 2010) that illegal / unreported fishing in the southern oceans has decreased significantly, and extrapolated unreported fishing 2% lower than the period up to 2003. The proportion of unreported fishing on the Falklands toothfish stock was estimated as the maximum – in each year – of either Table 1 (Agnew 2000) or Table 2 (Agnew et al. 2009 and extrapolation) multiplied by the base model catches.

Whale depredations are included in longline catch report totals when they are evident as toothfish hauled up damaged or destroyed by bite-marks. However, toothfish taken entirely by whales before hauling cannot be accounted. Winter and Pompert (2016) developed a model-differencing algorithm to predict the proportions of toothfish catches that are invisibly depredated. These proportions were extrapolated from observed longline sets to all commercial longlines. In the previous stock assessment, two measures of whale depredation were explored, with the more precautionary measure adjusting depredation rates upwards by dividing the depredation ratio from the algorithm by its 2.5% quantile. For the current assessment, the more precautionary measure was used, but the adjustment was changed to using the 5% quantile (decreasing the depredation ratio) to bring the depredation rates more in line with the results from a recent depredation study (Tixier and Arnould, 2017).

A precautionary model of the toothfish stock assessment was defined as the base model plus the margin of estimated unreported fishing plus the margin of estimated undetected whale depredation. Unreported fishing was included in the annual catch totals, but not in the CPUE indices, as estimates of unreported effort are not available. Effectively, this assumes that unreported catches have equivalent average CPUE to reported catches. Undetected whale depredation was included in both the annual catch totals and CPUE indices. The estimated proportions of whale depredation were applied to both reported and estimated unreported catch totals. Effectively, this assumes that unreported catches experience the same average rate of whale depredation as reported catches.

Harvest control measures

The age-structured production model in CASAL generates annual estimates of total biomass and spawning stock biomass (SSB), and can calculate forward projections of these estimates pursuant to assumptions of future catches. Based on the CASAL model output, the following decision matrix of harvest control rules has been established to manage the Falkland Islands toothfish longline fishery.

Expansion range: If the ratio of $SSB_{current}:SSB_0$ has remained above the upper target reference point (0.45) for 3 consecutive years and the SSB projection with the current

TAC shows no decrease below 0.45 for at least 10 years (one generation) under precautionary assumptions, the Director may authorize an increase in longline TAC to a level that continues to show no projected $SSB_{current}:SSB_0$ decrease to below 0.4 (trigger point) for at least 10 years under precautionary assumptions.

Target range: If the ratio of $SSB_{current}:SSB_0$ is between 0.4 and 0.45 (within the target range), current longline TAC is reviewed in relation to stock trends. Current TAC may be maintained if $SSB_{current}:SSB_0$ has increased from the previous assessment, or if the SSB ratio projection shows a level status under precautionary assumptions. TAC may not be increased, but it may be decreased if age-structure distributions anticipate weak recruitment.

Trigger point and range: If the ratio of $SSB_{current}:SSB_0$ falls to ≤ 0.4 (trigger point), longline TAC will be decreased to a level that projects an increasing SSB trend under precautionary assumptions. The magnitude of the proposed TAC reduction will be examined using three methods (adapted from ICES, 2017):

a. Indexed to the reduction of the MSY estimates
    i. $TAC_{year} = TAC_{year-1} * (MSY_{year} / MSY_{year-1})$
b. Indexed to the reduction of the SSB estimates
    i. $TAC_{year} = TAC_{year-1} * (SSB_{year} / SSB_{year-1})$
c. Indexed to the reduction in SSB ratios
    i. $TAC_{year} = TAC_{year-1} * (\text{SSB ratio}_{year} / \text{SSB ratio}_{year-1})$

TACs obtained from all three methods will be projected forward in the stock assessment model and the trends in SSB will be compared. The final method will be chosen based on it returning the SSB ratio to above 0.4 within 10 years (one generation) of the SSB ratio falling below 0.4. If more than one method meets this requirement, the chosen method will also depend on discussions between the Fisheries Department and industry.

Limit reference point: If the ratio of $SSB_{current}:SSB_0$ is ≤ 0.2, the longline fishery will be closed pending comprehensive evaluation of conditions required to rebuild the stock. The Director may authorize test fishing to measure biological parameters of the stock, subject to close monitoring by the Fisheries Department.

Results

Catches

Since 2008, the first full year of umbrella-system longlining, reported annual toothfish catches in the target longline fishery have ranged from 943 to 1469 tonnes, with a general downward trend over the past five years. Average (unstandardized) CPUE in the longline fishery increased steadily over the same period, from 3.1 to 5.4 t / vessel / day (Figure 5 - top panel).

Annual toothfish bycatch in finfish trawls reached an initial peak in 2010, the year that rock cod (*Patagonotothen ramsayi*) first attained predominance in the finfish trawl fishery (FIG 2011). However, the highest toothfish CPUEs in finfish trawls were obtained in the last two years (2016 and 2017), when both toothfish bycatch and CPUE increased by several times over the years before (Figure 5 - middle panel). With the recent large decrease in rock cod abundance (FIFD 2016), finfish trawlers targeted other species and fished deeper. In 2015, the weighted average depth of finfish toothfish bycatch was 234 m, and 46.1% of toothfish was taken in trawls of which the primary catch was rock cod. In 2016, the weighted average depth of finfish toothfish bycatch was 298 m, and 5.1% of toothfish was taken in trawls of which the primary catch was rock cod. In 2017, the weighted average depth of finfish toothfish bycatch was 440 m, and 1% of toothfish was taken in trawls of which the primary catch was rock cod. By contrast, the proportion of toothfish bycatch taken in trawls in which the primary catch was grenadier increased from 2.8% in 2015, to 17.2% in 2016 to 50.8% in 2017.

Annual toothfish bycatch as well as CPUE in calamari trawls reached their highest levels in 2016, with several times' increase over the year before (Figure 5 - bottom panel). The increase may be due to increased recruitment of toothfish as shown by the catch proportions of finfish and calamari trawls (Figure A2), but could also relate to the decrease of rock cod abundance (FIFD 2016). Fewer small rock cod may allow more juvenile toothfish to inhabit the zone occupied by the calamari fishery, and may also result in more accurate reporting of toothfish bycatch, as small rock cod and juvenile toothfish are mistakable for crews that have no commercial interest in either. In 2017, calamari trawls captured fewer toothfish, possibly as a result of the previous year's strong year class increasing in length beyond the size selectivity of the calamari trawl nets.

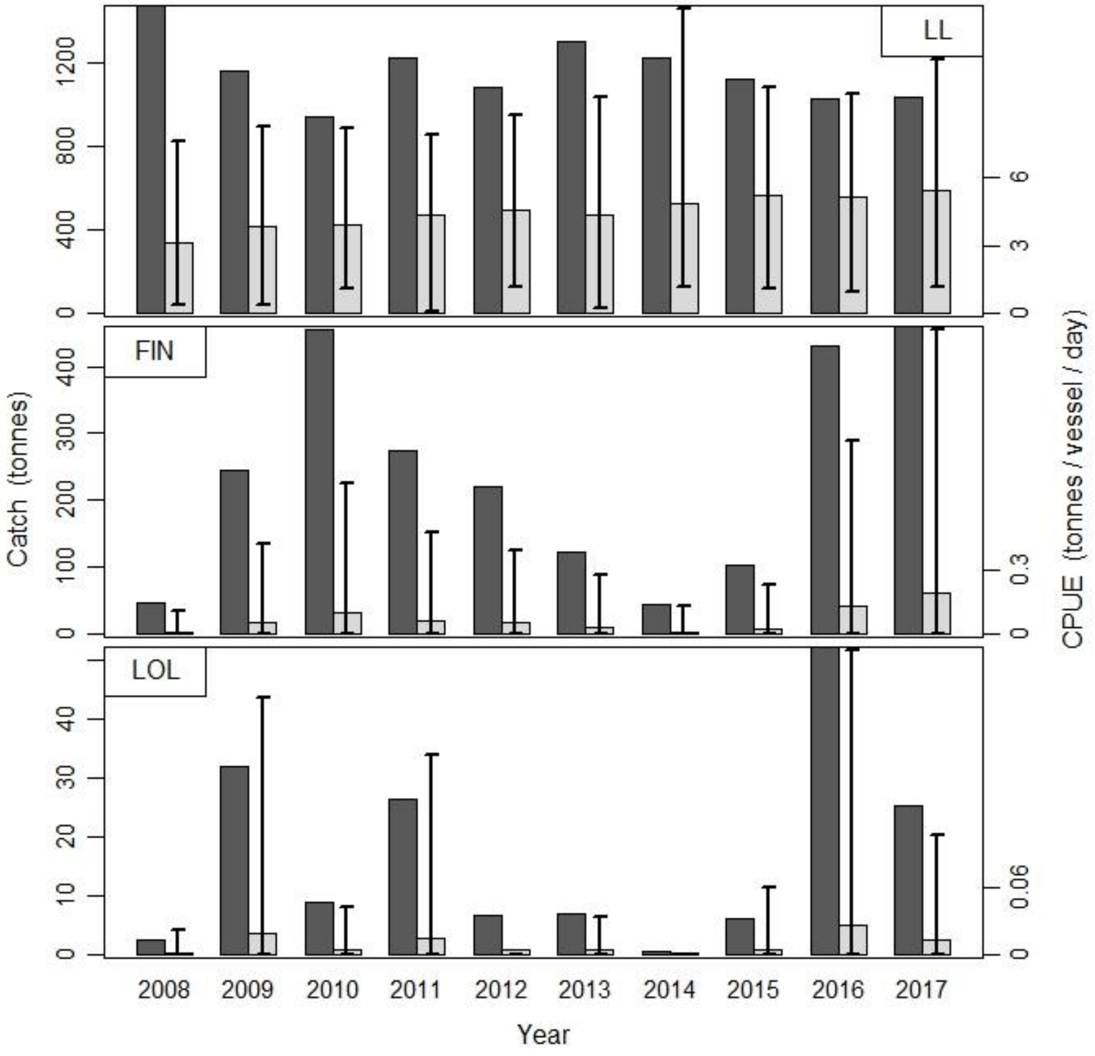


Figure 5. Annual catches and unstandardized CPUE of toothfish per fishery. Dark bars: catches (tonnes), light bars: unstandardized CPUE (tonnes / vessel / day) with 95% intervals. Data are shown for the toothfish longline (LL), finfish trawl (FIN) and calamari trawl (LOL) fisheries since 2008 (first full year of umbrella-system longlining).

Model estimates

The precautionary model version of the CASAL age-structured production model (Winter, 2017) was computed. Estimated yearly unreported catches and whale depredation that were included in the precautionary model version are shown in Table A4. Results from sensitivity analyses in the previous stock assessment report (Winter, 2017) indicate that the CASAL age-structured production model is robust to uncertainties in unreported catch and undetected whale depredation.

Statistically significant model co-variates for standardizing CPUE indices were, for Spanish-system longline: month, individual vessel, fishing region, and soak duration; for umbrella-system longline: month, individual vessel, soak duration, and depth. Optimized model fits of the precautionary model are shown in Figures A1 and A2. As a comparison of model fits within the objective functions, proportions were calculated of the optimizations that fell within the 95% confidence intervals of LOESS smooths of each data series (the data were not otherwise modelled on LOESS). For the Spanish-system CPUE index, 10 of 12 (83%) optimizations fell within the 95% confidence intervals of the LOESS smooth, and for the umbrella-system CPUE index, 10 of 11 (91%) optimizations fell within the 95% confidence intervals of the LOESS smooth. Among catch-at-age distributions (Figure A2), for Spanish-system longline data by year, 12.9% - 100% of optimizations fell within the 95% confidence intervals of the LOESS smooth, for umbrella-system longline 25.8% - 60.0%, for finfish trawls 67.7% - 96.8%, and for calamari trawls 64.5% - 87.1%.

The precautionary model estimates the biomass time series shown in Figure 6; toothfish biomass having decreased from 63,727 t in 1987 to 31,891 t in 2017, of which the spawning stock biomass decreased from 23,446 t in 1987 to 11,293 t in 2017 (Table 1). The precautionary model-estimated natural mortality of M = 0.174 is nearly equivalent to the natural mortality used for toothfish in South Georgia (Hillary et al. 2006), and previously in the Falkland Islands as a composite average (Payne et al. 2005). This is expectedly lower than the base model estimated natural mortality M = 0.180 (Winter, 2017), as M in the base model has to absorb the unseparated removals of unreported catch and undetected whale depredation. MSY is the maximum constant annual catch that can be sustained under deterministic recruitment and the assumed constant catch partition. Deducting from 1,932 t (Table 1), 300 t for finfish trawl and 30 t for calamari trawl leaves 1,602 t, well above the current longline toothfish TAC (1,040 t). MCMC distributions showed high variability and strong positive skewness for stock parameters, as the parameters are naturally lower-bounded at zero (Figure A3). 95% confidence intervals from selected MCMC distributions are shown in Table 1.

Table 1. Output parameters of the toothfish stock assessment from the CASAL age-structured production model. MSY was based on the anticipated future catch partition of 1,040 t longline, 300 t finfish trawl, and 30 t calamari trawl. Lower and upper 95% confidence interval from MCMC distributions are based on 5,000 iterations.

Parameter	Output	Lower 95% CI	Upper 95% CI
SSB_0	23,450 t	21,524 t	94,865 t
SSB_{1987}	23,446 t	21,518 t	94,861 t
SSB_{2017}	11,293 t	9,230 t	83,615 t
SSB_{2017}:SSB_0	0.482	0.422	0.908
B_{1987}	63,727 t	57,562 t	303,230 t
B_{2017}	31,891 t	26,991 t	256,319 t
MSY	1,932 t	1,773 t	7,815 t
$M_{natural}$	0.174 yr^{-1}	0.160 yr^{-1}	0.232 yr^{-1}

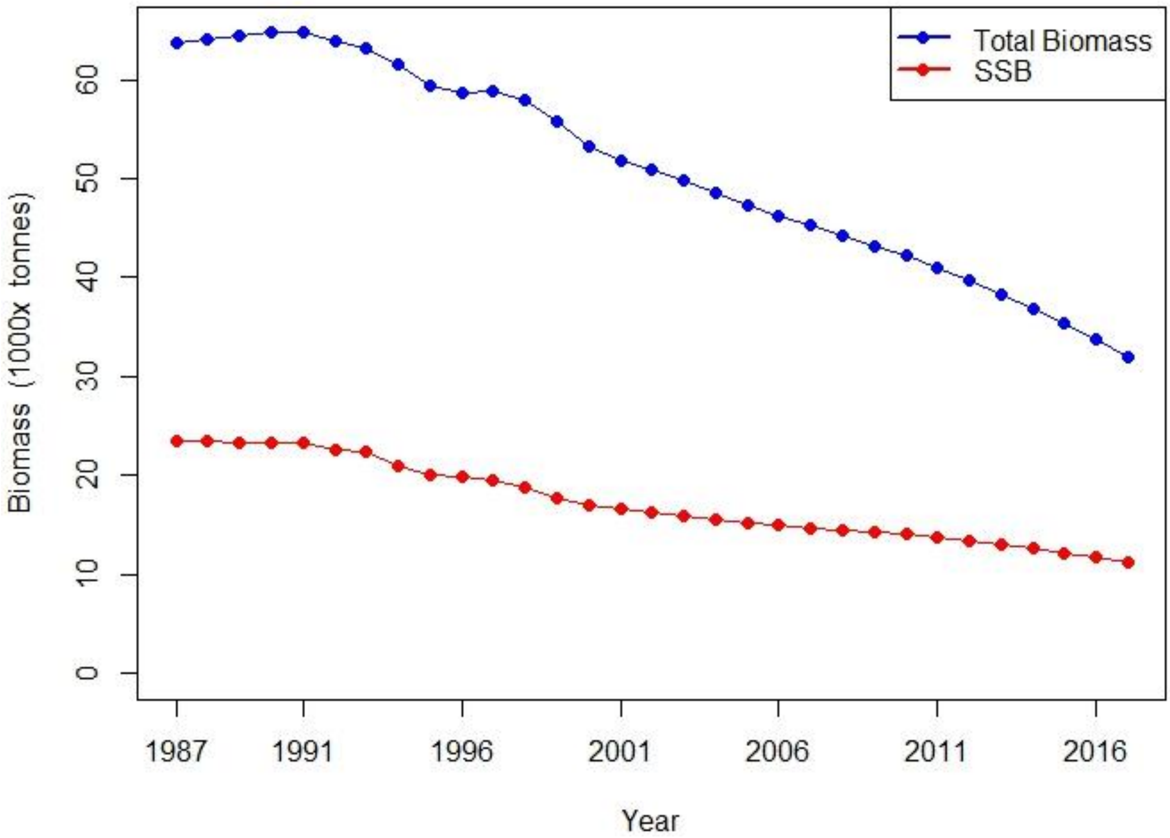


Figure 6. Toothfish annual total and spawning stock biomass 1987-2017. The estimates are from the CASAL age-structured production model.

In the longline fishery, modal toothfish catch ages by year fitted with the CASAL age-structured production model (ages at which highest proportions were caught; corresponding to the maximum of red lines in Figure A2 plots) show a slight but significantly increasing trend in the longline fishery since about 2003 (Figure 7). This trend suggests that the stock is currently being 'fished up', i.e., largely the same cohort is taking most of the fishing pressure in successive years.

Recommendation and model projections

The ratio SSB_{2017}:SSB_0 = 0.482 places the precautionary model within the 'Expansion rage' range of the Harvest Control Measures (above). Spawning stock biomass is currently projected to continue decreasing until 2024 (Figure 8), at which point it will be 0.436 of SSB_0 (95% CI: 0.355 - 0.586).

Thus, current assessment projects the stock to stay above the 'Trigger' range that would require additional conservation measures. From the minimum in 2024, SSB is projected to increase back above $SSB_{current}$:SSB_0 = 0.45 by 2029. It is important to note that a projection (forecast from the exact current stock parameters) does not mean prediction (consideration of limits and potential variability in future stock parameters). However, the long life-span of toothfish and restricted conditions of the licensed longline fishery allow projections to be informative of the relative status of the population.

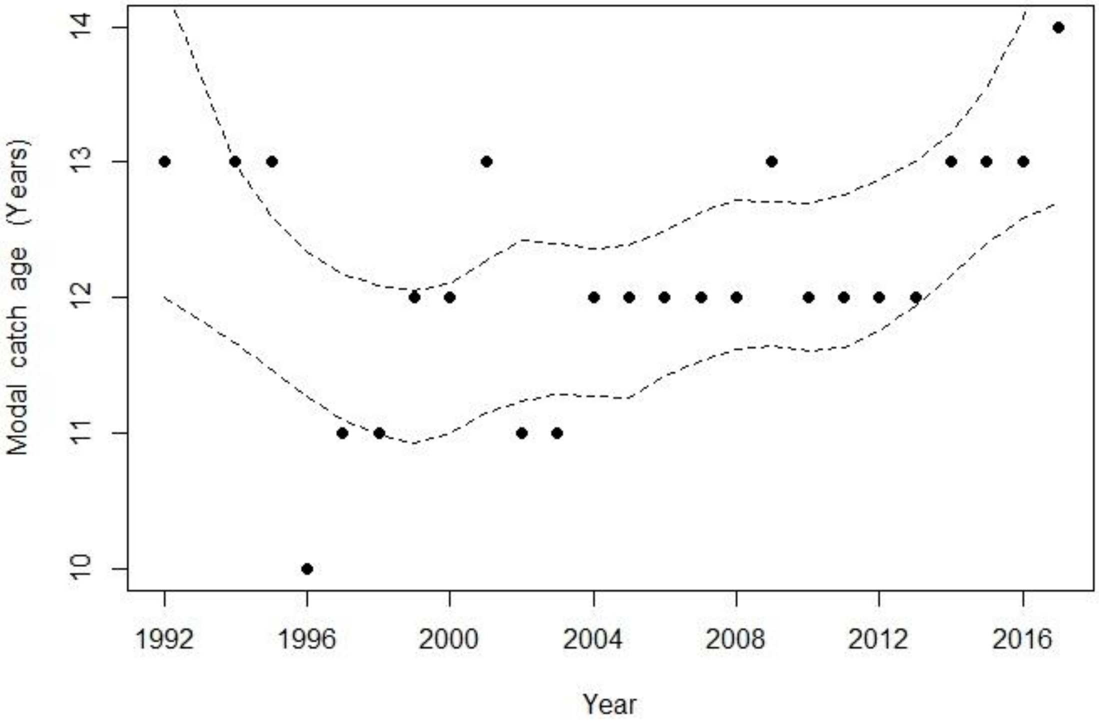


Figure 7. Modal catch ages of toothfish by year in the longline fishery. Broken lines: 95% confidence intervals of LOESS smooth of the time series.

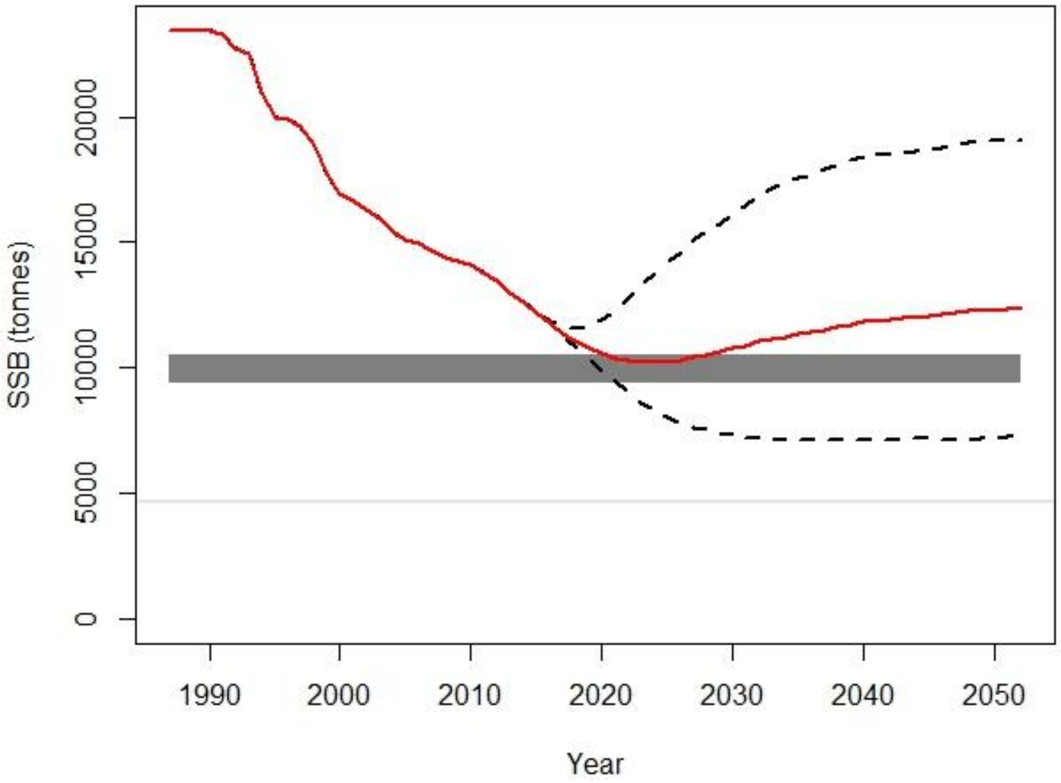


Figure 8. Projected SSB from 1987 to 2052. Red line: projection is stochastic insofar as year-class strengths are randomized. Black dashed lines: 95% interval of 5,000 iterations of the projection. Horizontal light grey field: the level of SSB that is 0.4 to 0.45 of SSB_0. Horizontal grey line: SSB that is 0.2 of the SSB_0.

A Markov chain Monte Carlo (MCMC) projection 35 years into the future shows that the SSB ratio is likely to stay above 0.45 under the current TAC (Figure 9). In fact, between 2018 and 2052, the SSB ratio projections fall below the 0.2 threshold between 0 - 0.1% of the time in the MCMC (Figure 10). Over the next 35 years, the probabilities that the SSB ratio falls below the management thresholds of 0.4 and 0.45 show dome-shaped relationships, where the probability reaches a peak between the years 2022 and 2026 before declining (Figure 10). The highest likelihood that the SSB ratio falls below the trigger point of 0.4 (25.9% of the MCMC runs) is projected to take place in 2026, and by 2052, this probability decreases to 14.1%. The stock is projected to be below the expansion range (SSB ratio of 0.45) 61.3% of the time in 2022 and 2023, which then decreases to 25.7% by 2052. Over 74% of the projections show that the SSB ratio will be above 0.45 by 2052.

Therefore the recommendation from this stock assessment is to maintain the toothfish annual TAC for longline fishing at its current level of 1,040 tonnes. A second recommendation is to develop a strategy to address the bycatch of toothfish in the trawl fisheries, specifically the finfish fishery. There has been a shift in fishing behaviour of the finfish fishery in the last two years, which had led that fishery to catch much more toothfish than in previous years. The shift may be due to a lack of fishing opportunities in the traditional fishing grounds, pushing vessels deeper and further south in the FICZ to capture grenadier, and in doing so they are encountering more toothfish. To minimize the threat to the toothfish stock from bycatch, this change in behaviour could be addressed by closing certain areas or depths to trawling.

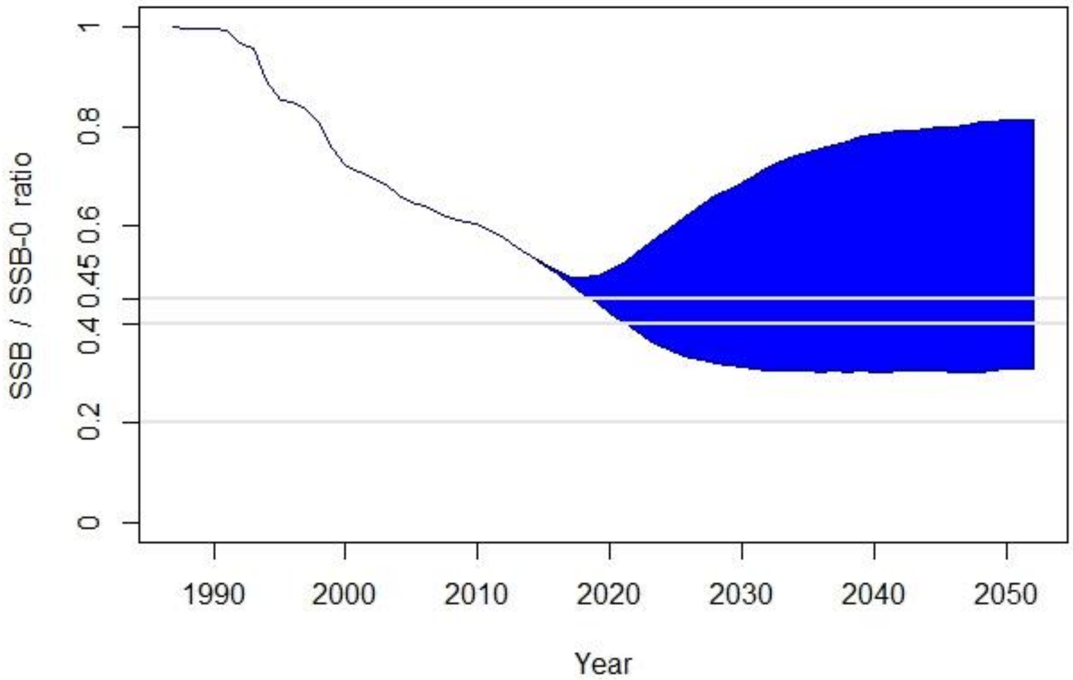


Figure 9. Markov chain Monte Carlo (MCMC) projection of the SSB ratio. Blue trace: 95% interval of 5,000 model runs from 1987 to 2052. Horizontal grey lines: SSB ratios of 0.2, 0.4 and 0.45.

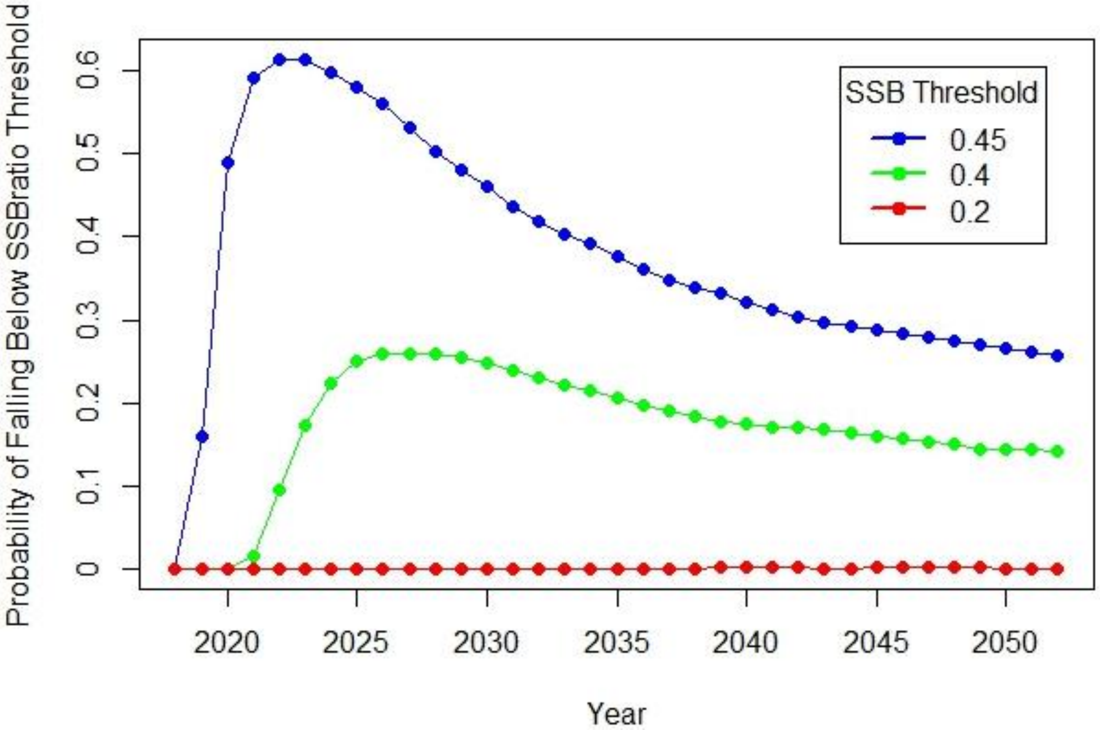


Figure 10. Probability of falling below SSB ratio thresholds in MCMC projections. Probabilities that the SSB ratio will fall below the thresholds of 0.45 (blue), 0.4 (green) and 0.2 (red), projected by the 5,000 MCMC iterations.

References

Agnew D.J. (2000) The illegal and unregulated fishery for toothfish in the Southern Ocean, and the CCAMLR catch documentation scheme. *Marine Policy* 24, 361-374.

Agnew D.J., Pearce J., Pramod G., Peatman T., Watson R., Beddington J.R., Pitcher T.J. (2009) Estimating the worldwide extent of illegal fishing. *PLoS ONE* 4, e4570.

Ainsworth C.H., Pitcher T.J. (2005) Estimating illegal, unreported and unregulated catch in British Columbia's marine fisheries. *Fisheries Research* 75, 40-55.

Arkhipkin A.I., Middleton D.A., Barton J. (2008) Management and conservation of a short-lived fishery resource: *Loligo gahi* around the Falkland Islands. *American Fisheries Society Symposium* 49, 1243-1252.

Brandão A., Butterworth D.S. (2009) A proposed management procedure for the toothfish (*Dissostichus eleginoides*) resource in the Prince Edward Islands vicinity. *CCAMLR Science* 16, 33-69.

Bull B., Francis R.I.C.C., Dunn A., McKenzie A., Gilbert D.J., Smith M.H., Bian R., Fu D. (2012) CASAL (C++ algorithmic stock assessment laboratory): CASAL user manual v2.30-2012/03/21. *NIWA Technical Report 135*, 280 pp.

CCAMLR (2010) Estimation of IUU catches of toothfish inside the convention area during the 2009/10 fishing season. WG-FSA-10/6 Rev. 1, 12 pp.

Collins M.A., Brickle P., Brown J., Belchier M. (2010) The Patagonian toothfish: biology, ecology, and fishery. *Advances in Marine Biology* 58, 227-300.

Day J., Wayte S., Haddon M., Hillary R. (2014) Stock assessment of the Macquarie Island fishery for Patagonian toothfish (*Dissostichus eleginoides*) using data up to and including August 2013. *Report to SARAG* 48, 1 April 2014. CSIRO, Australia.

des Clers S., Nolan C.P., Baranowski R., Pompert J. (1996) Preliminary stock assessment of the Patagonian toothfish longline fishery around the Falkland Islands. *Journal of Fish Biology* 49, 145-156.

Dichmont C.M., Deng R.A., Punt A.E., Brodziak J., Chang Y.-J., Cope J.M., Ianelli J.N., Legault C.M., Methot Jr. R.D., Porch C.E., Prager M.H., Shertzer K.W. (2016) A review of stock assessment packages in the United States. *Fisheries Research* 183, 447-460.

FIFD (2016) Finfish fisheries based on rock cod, Patagonotothen ramsayi. In: *Vessel Units, Allowable Effort, and Allowable Catch 2017 – Part 2 Stock Assessment*. Fisheries Department, Directorate of Natural Resources, Falkland Islands Government, 17 pp.

FIG (2011) Fisheries Department Fisheries Statistics. *Volume 15, 2010*. Fisheries Department, Directorate of Natural Resources, Falkland Islands Government, 72 pp.

Francis R.I.C.C. (2011) Data weighting in statistical fisheries stock assessment models. *Canadian Journal of Fisheries and Aquatic Sciences* 68, 1124-1138.

Francis R.I.C.C. (2013) DataWeighting: A set of R functions for evaluating and calculating data weights for CASAL. R package version 1.0.

Francis R.I.C.C., Hurst R.J., Renwick J.A. (2003) Quantifying annual variation in catchability for commercial and research fishing. *Fishery Bulletin* 101, 293-304.

Froese R. (2006) Cube law, condition factor and weight–length relationships: history, meta-analysis and recommendations. *Journal of Applied Ichthyology* 22, 241-253.

Haddon M. (2001) Modelling and quantitative methods in fisheries. Chapman & Hall / CRC, Boca Raton FL, 406 p.

Hillary R.M., Kirkwood G.P., Agnew D.J. (2006) An assessment of toothfish in subarea 48.3 using CASAL. *CCAMLR Science* 13, 65-95.

ICES (2017) Report of the workshop on evaluation of the adopted harvest control rules for Icelandic summer spawning herring, link and tusk (WKICEMSE), 21-25 April 2017, Copenhagen, Denmark. ICES CM 2017/ACOM:45. 196 pp.

Laptikhovsky V., Arkhipkin A., Brickle P. (2006) Distribution and reproduction of the Patagonian toothfish *Dissostichus eleginoides* Smitt around the Falkland Islands. *Journal of Fish Biology* 68, 849-861

Laptikhovsky V., Arkhipkin A., Brickle P. (2008) Life history, fishery, and stock conservation of the Patagonian toothfish around the Falkland Islands. *American Fisheries Society Symposium* 49, 1357-1363.

Laptikhovsky V., Brickle P. (2005) The Patagonian toothfish fishery in Falkland Islands' waters. *Fisheries Research* 74, 11-23.

Mangel M., MacCall A.D., Brodziak J., Dick E.J., Forrest R.E., Pourzand R., Ralston S. (2013). A perspective on steepness, reference points, and stock assessment. *Canadian Journal of Fisheries and Aquatic Sciences* 70, 930-940.

Manning M. (2011) CPUE: A collection of functions for standardised CPUE analysis. R package version 1.1.

Maunder M.N., Langley A.D. (2004) Integrating the standardization of catch-per-unit-of-effort into stock assessment models: testing a population dynamics model and using multiple data types. *Fisheries Research* 70, 389-395.

Maunder M.N., Punt A.E. (2004) Standardizing catch and effort data: A review of recent approaches. *Fisheries Research* 70, 141-159.

Maunder M.N., Starr P.J. (2003) Fitting fisheries models to standardised CPUE abundance indices. *Fisheries Research* 63, 43-50.

Mormede S., Dunn A., Hanchet S.M. (2014) A stock assessment model of Antarctic toothfish (*Dissostichus mawsoni*) in the Ross Sea region incorporating multi-year mark-recapture data. *CCAMLR Science* 21, 39-62.

Nelson G.A. (2015) Package 'fishmethods': Fishery science methods and models from published literature and contributions from colleagues. R package version 1.9-0.

Payne A.G., Agnew D.J., Brandão A. (2005) Preliminary assessment of the Falklands Patagonian toothfish (*Dissostichus eleginoides*) population: Use of recruitment indices and the estimation of unreported catches. *Fisheries Research* 76, 344-358.

Pitcher T.J., Watson R., Forrest R., Valtýsson H.Þ., Guénette S. (2002) Estimating illegal and unreported catches from marine ecosystems: a basis for change. *Fish and Fisheries* 3, 317-339.

Shono H. (2005) Is model selection using Akaike's information criterion appropriate for catch per unit effort standardization in large samples? *Fisheries Science* 71: 978-986.

Tixier P., Arnould J. (2017) Study on whale depredation: Falkland Islands. Technical Report, COLTO, 24 pp.

Winter A. (2017) Stock assessment for Patagonian toothfish in the Falkland Islands. Fisheries Department, Directorate of Natural Resources, Falkland Islands Government, 34 pp.

Winter A., Pompert J. (2016) Initial analyses of whale depredation in the Falkland Islands toothfish longline fishery. Fisheries Department, Directorate of Natural Resources, Falkland Islands Government, 18 pp.

Appendix

1. CPUE standardization

Spanish-system and umbrella-system longline CPUE series were standardized to remove the effect of co-variates other than yearly abundance (Maunder and Punt 2004). Co-variate effects were estimated by fitting CPUE to a generalized linear model (GLM) in log scale with normal error distribution, as CPUE is usually log-normally distributed (Maunder and Starr 2003). Significant co-variates were added to the year effect by forward selection using the function 'stepCPUE' in R package 'CPUE' (Manning 2011). Because AIC can bias co-variate effects (Shono 2005), the criterion for co-variate significance was set instead by the r^2 of the GLM fit, at an increase of 0.5%. Error of the indices was expressed as the coefficients of variation (cv) calculated from the covariance matrices, plus 20% to account for process error (Francis et al. 2003): $\sqrt{cv^2 + 0.20^2}$. Standardization co-variates tested were the individual vessel, month, soak duration of the reported catch, depth, and fishing region (3 regions: north or south of 53.5° within the Falklands zone, or outside the Falklands zone[2]). The 53.5° S demarcation separates the Burdwood Bank spawning area from fishing further north (Payne et al. 2005). For the umbrella-system longline index two additional co-variates were tested: umbrella spacing (which was changed from 40 m between umbrellas to 22 m between umbrellas after November 2014), and numbers of hooks per umbrella (which was progressively decreased from 10 hooks initially to 8 hooks in December 2007, to 7 hooks in March 2014, to 6 hooks in June 2016).

2. Model input parameters

Table A1. Length-weight model ($W (t) = a \cdot L (cm)^b$):

a	5.06238×10^{-9}
b	3.154409
N	28,762

Table A2. von Bertalanffy length-at-age model ($L (cm) = L_{inf} \times (1 - e^{-K(t - t0)})$):

K	0.06292
t_0	-2.46533
L_{inf}	159.279
cv	0.19294
N	5,742

Table A3. Maturity proportions at age:

Age	N	Prop. Mature	Age	N	Prop. Mature
1	13,364	0.000	17	5,766	0.534
2	11,528	0.007	18	5,218	0.550
3	6,653	0.027	19	3,900	0.566
4	5,258	0.059	20	2,999	0.582
5	6,751	0.104	21	2,762	0.597
6	6,730	0.158	22	1,907	0.613
7	7,995	0.214	23	1,318	0.627
8	6,457	0.267	24	1,052	0.640
9	6,768	0.313	25	1,061	0.651

---

[2] Although deemed 'out-of-zone' catches were not included in the CPUE indices, a few reports gave coordinate positions marginally outside the Falklands Conservation Zones, and these were recorded as such.

10	6,463	0.350	26	916	0.662
11	6,246	0.383	27	568	0.673
12	7,237	0.412	28	426	0.684
13	6,918	0.441	29	200	0.695
14	6,790	0.469	30	174	0.706
15	7,254	0.494	31	1,037	0.718
16	6,381	0.516			

Table A4. Annual toothfish catches (tonnes). Longline catches that are reported to the FIG, and additional quantities estimated unreported to FIG and lost to whale depredation are used in the current model. Year 2007 was the switch from Spanish-system to umbrella-system longlining, and some Spanish-system longlining took place in 2013; catches under either system are shown separately for those years (Spanish-system/umbrella system).

Year	Reported	Est. unreported	Est. depredation
1992	111.49	797.51	164.49
1993	7.73	386.27	84.17
1994	2,733.17	229.83	418.66
1995	1,745.52	322.48	334.78
1996	512.75	173.25	116.48
1997	998.05	196.95	217.77
1998	1,700.40	255.06	292.39
1999	2,405.01	360.75	421.65
2000	1,976.00	138.32	302.64
2001	1,444.73	101.13	251.65
2002	1,472.40	103.07	225.82
2003	1,517.62	106.23	323.98
2004	1,807.87	90.39	346.74
2005	1,614.55	80.73	309.79
2006	1,303.92	65.20	228.47
2007	566.49/984.03	28.32/49.20	120.07/158.87
2008	1,469.41	73.47	201.33
2009	1,159.04	57.95	117.06
2010	942.88	47.14	103.49
2011	1,225.61	61.28	163.03
2012	1,085.06	54.25	184.61
2013	13.94/1,289.41	0.70/64.47	2.04/227.31
2014	1,221.38	61.07	168.77
2015	1,123.23	56.16	194.74
2016	1,022.93	51.15	184.05
2017	1,031.61	51.58	136.19

3. Model optimization

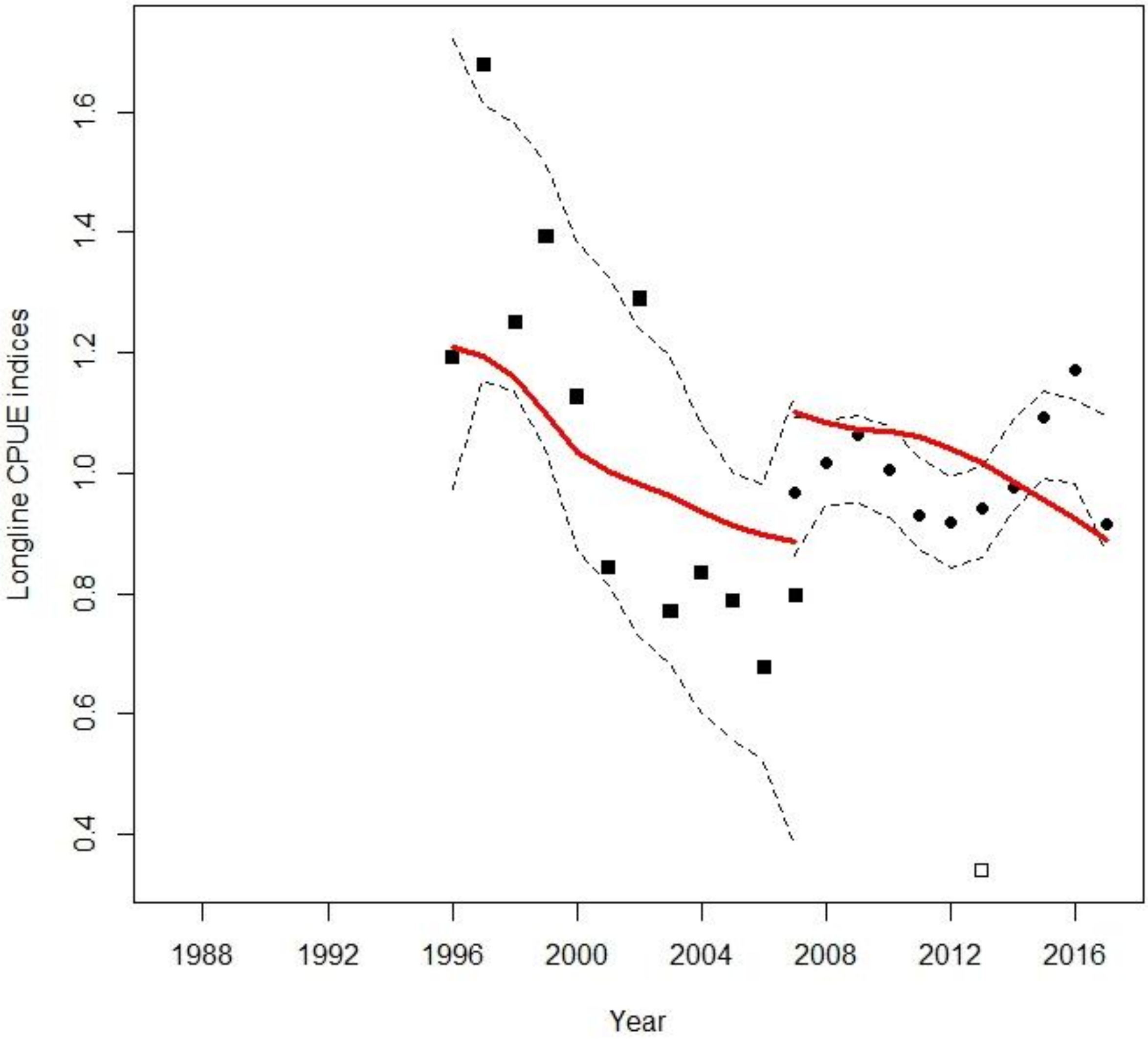


Figure A1. Standardized toothfish CPUE indices in the longline fishery. Black squares: Spanish-system 1996-2007 standardized indices. Black circles: umbrella system 2007-2016 standardized indices. Red lines: age-structured production model optimizations. Broken lines: 95% confidence limits of LOESS smooths through either data time series, for visual comparison. Open square: Spanish-system 2013 standardized index (not included in the optimization due to very low number of lines and catch).

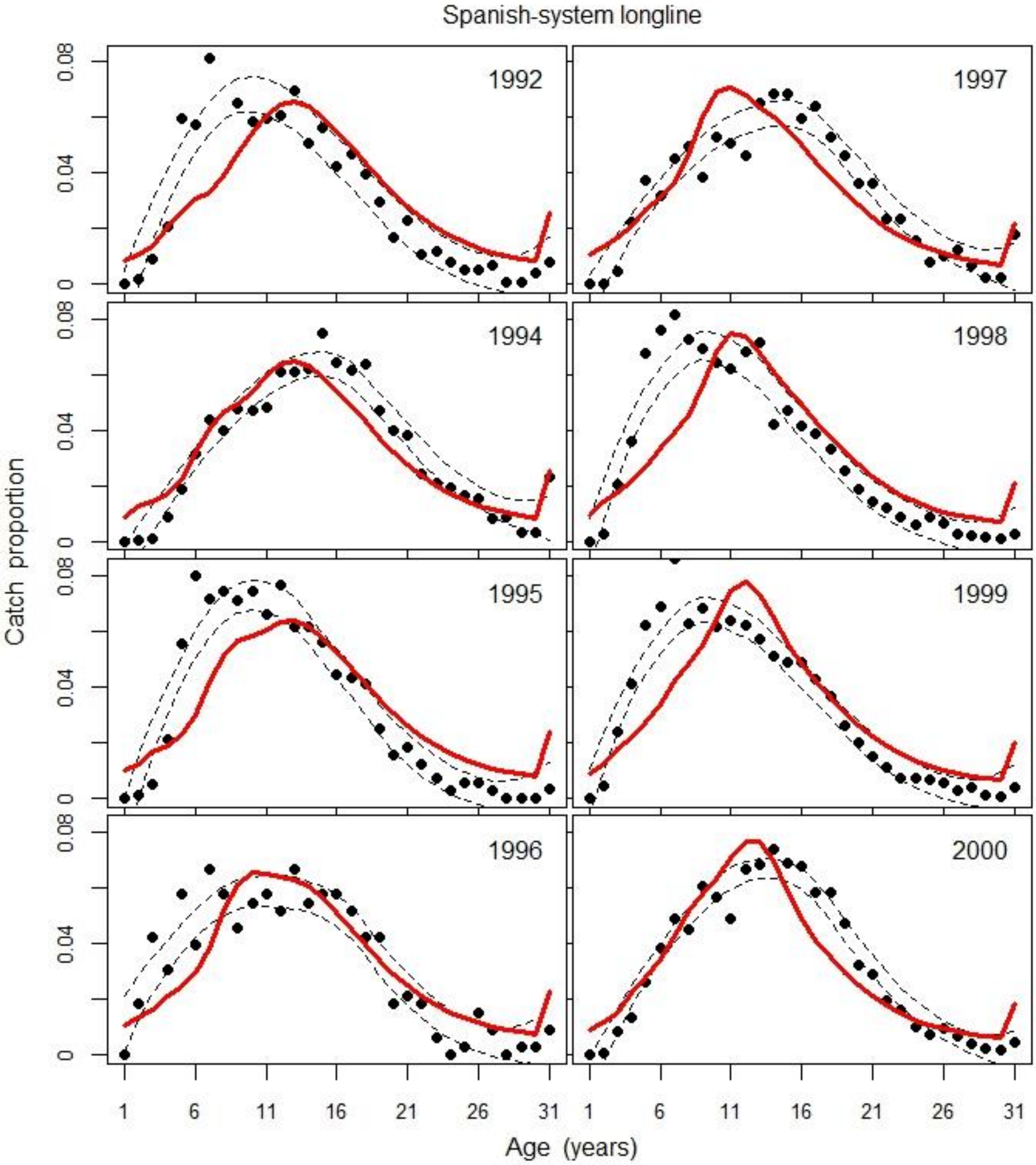


Figure A2. Catch proportions by age per year and per fishery. Each year of available data is shown for each fishery catching toothfish: Spanish-system longline, umbrella-system longline, finfish trawl, calamari trawl. Black circles: empirical catch-at-age proportions, red lines: age-structured production model optimizations. Note that the trend increases at age = 31 years reflect that this is the cumulative ‘plus’ group. Broken lines: 95% confidence limits of LOESS smooths through each data series, for visual comparison.

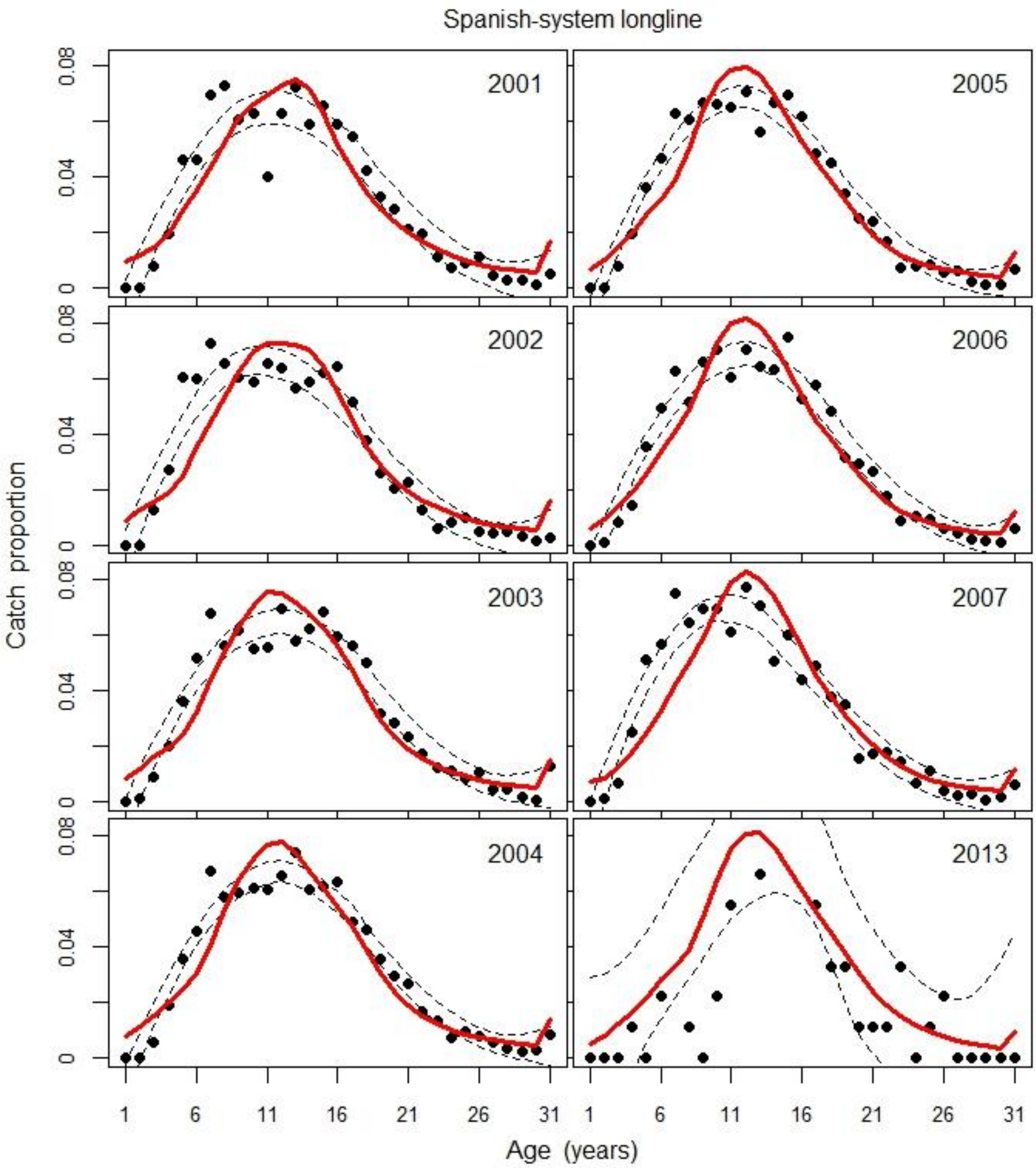


Figure A2. Continued.

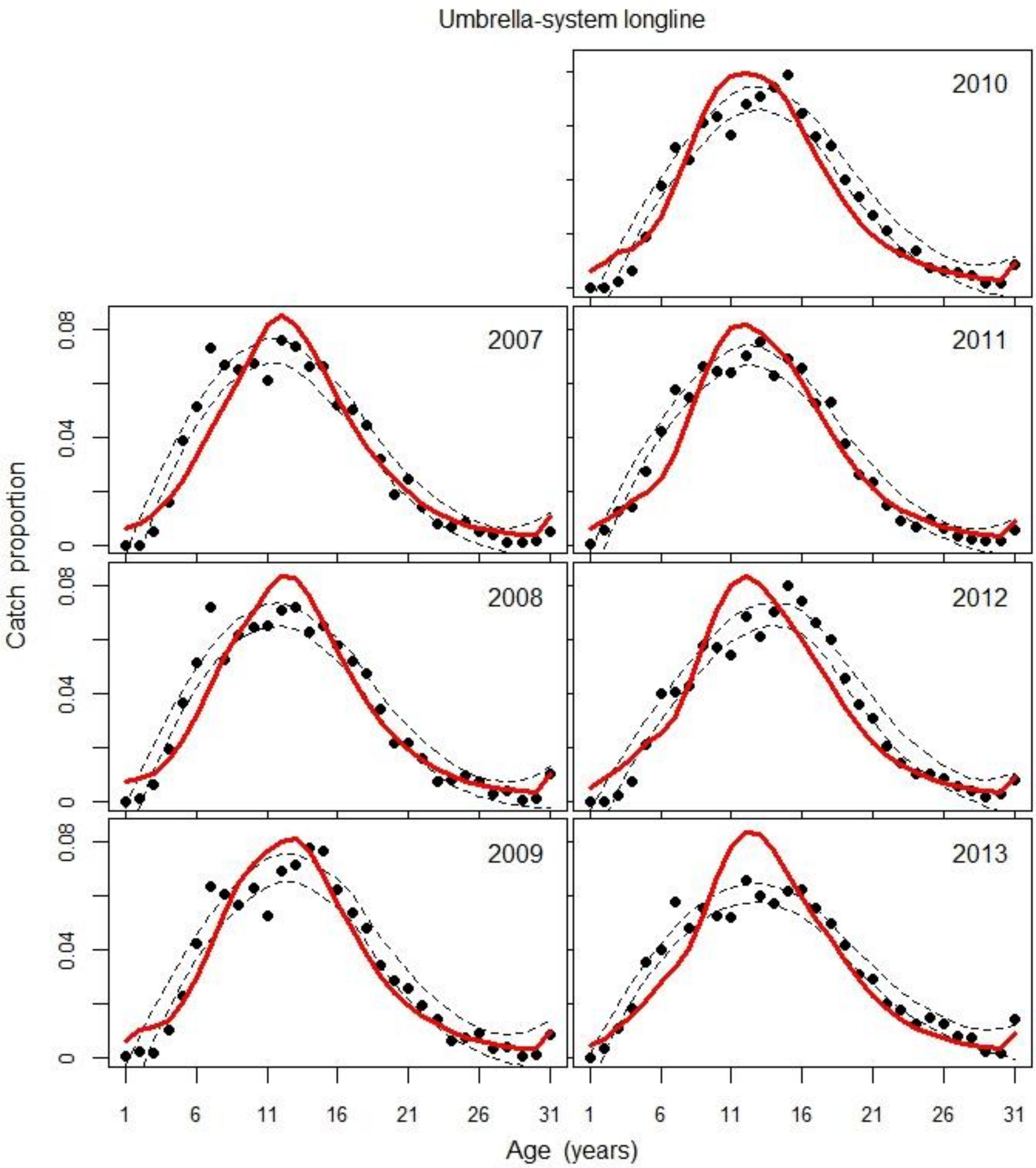


Figure A2. Continued.

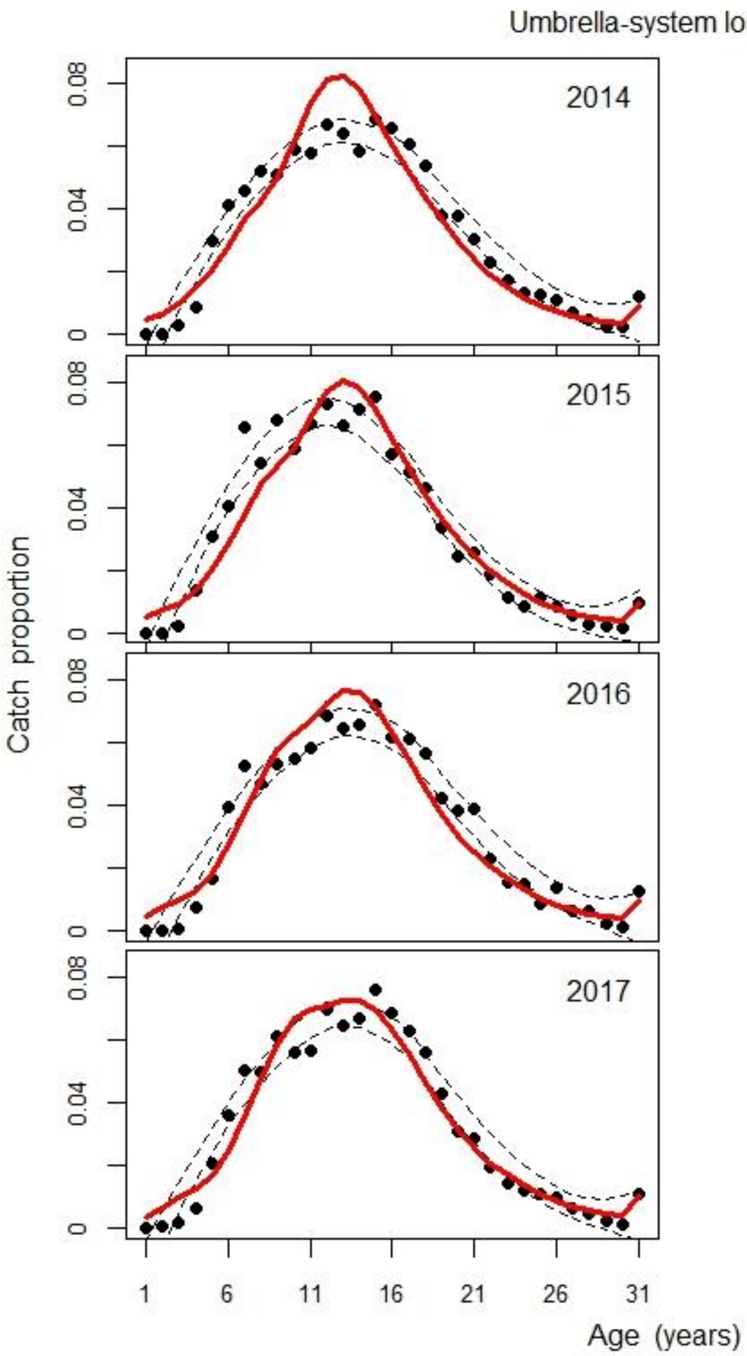


Figure A2. Continued.

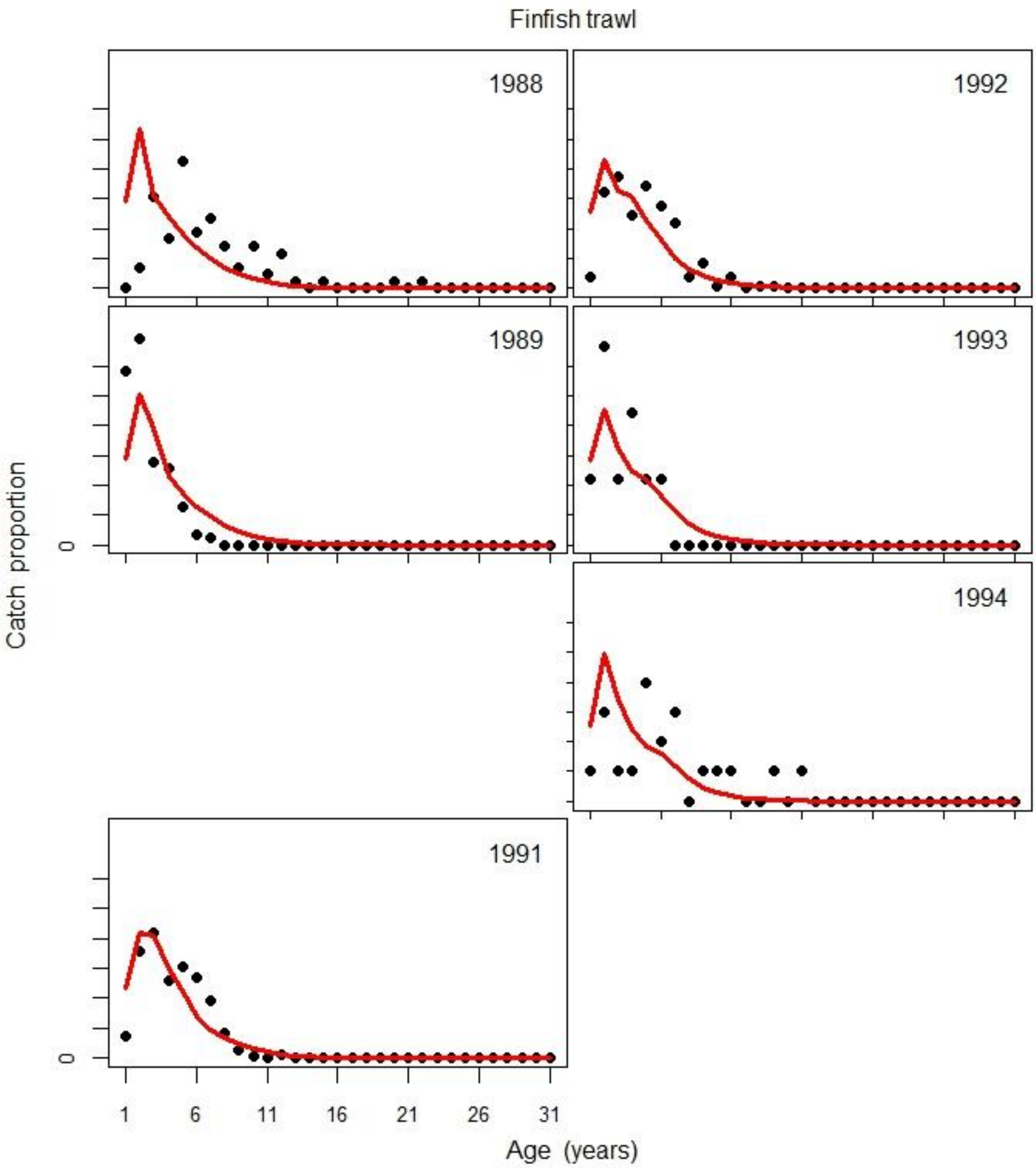


Figure A2. Continued.

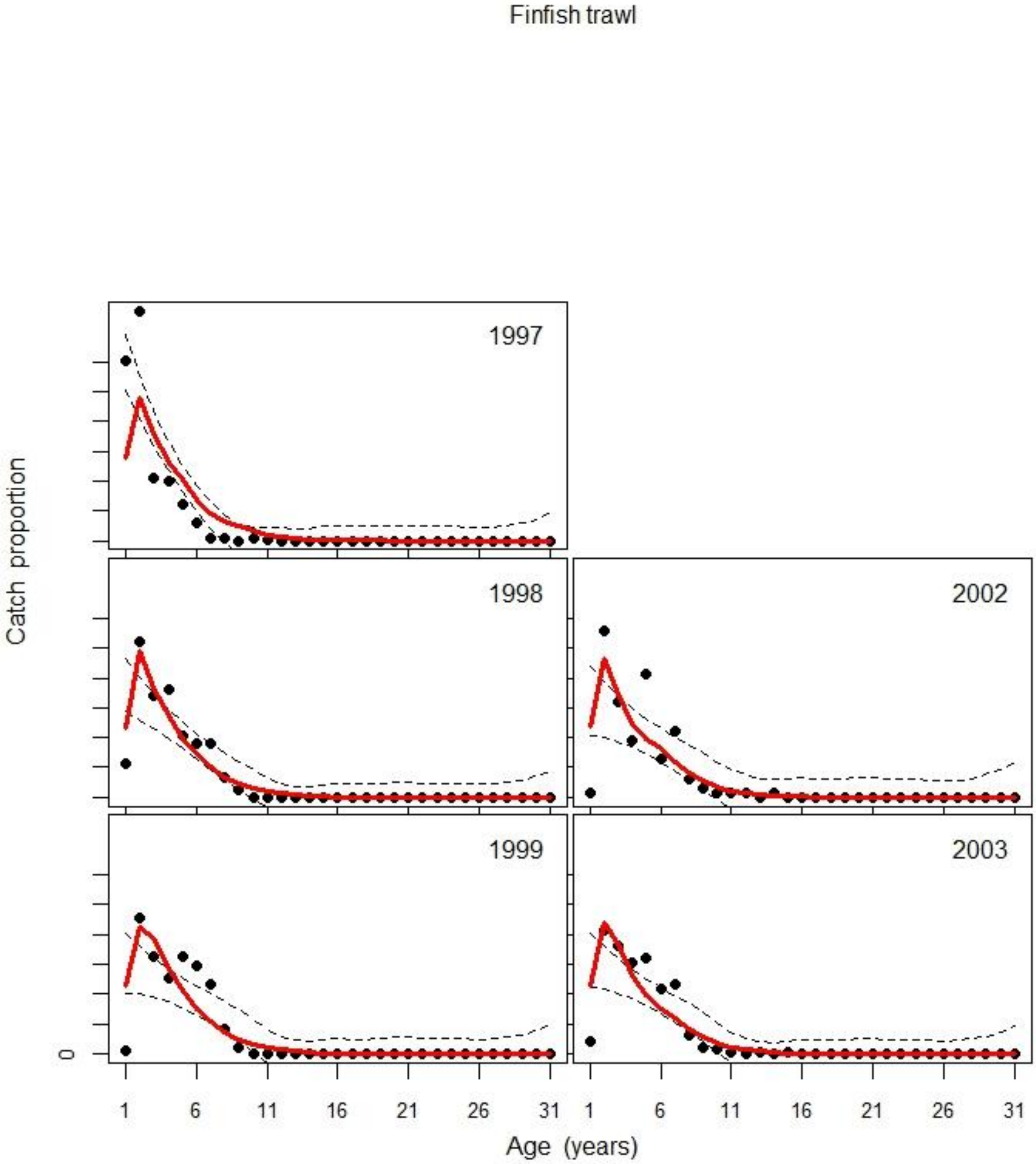


Figure A2. Continued.

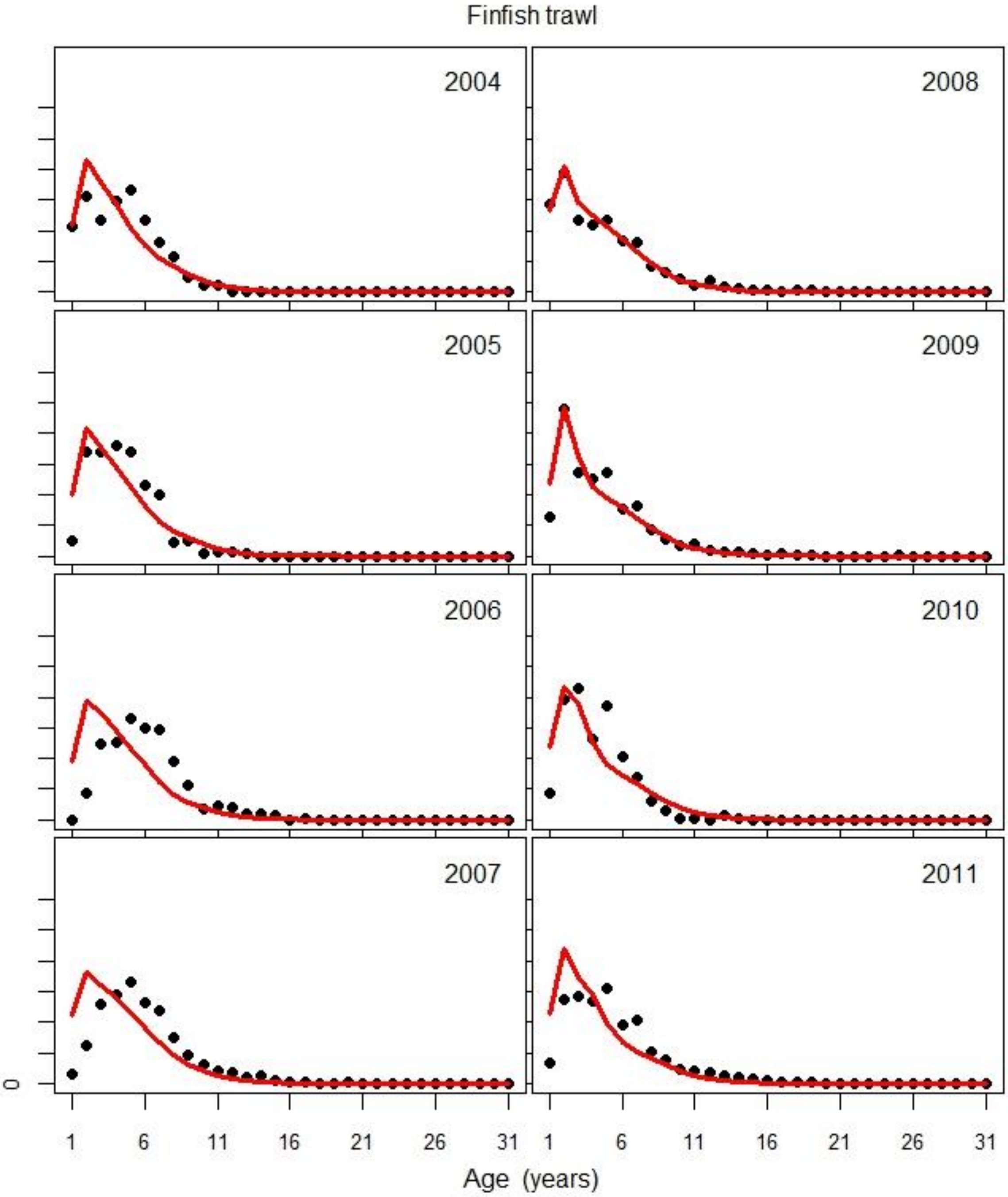


Figure A2. Continued.

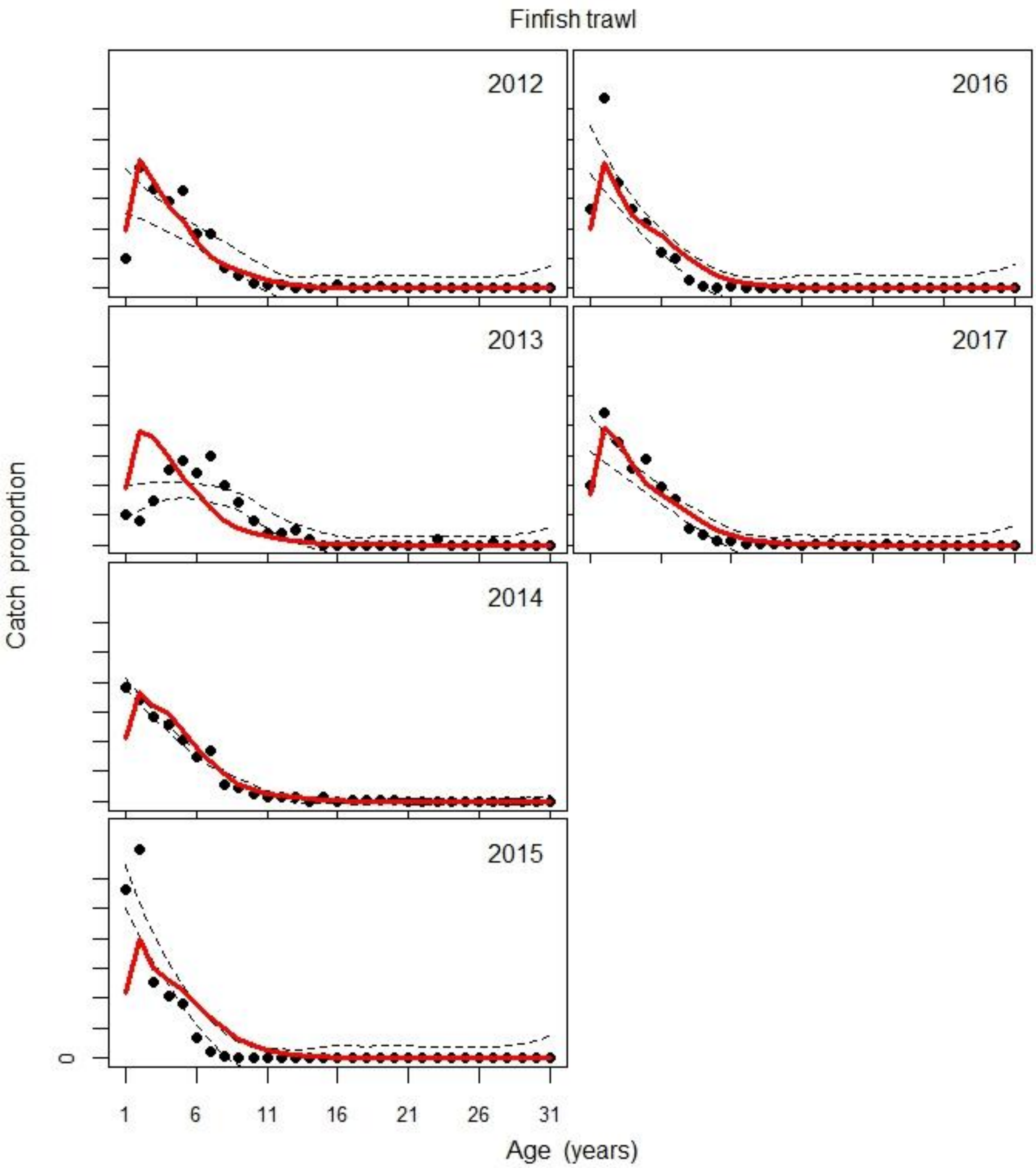


Figure A2. Continued.

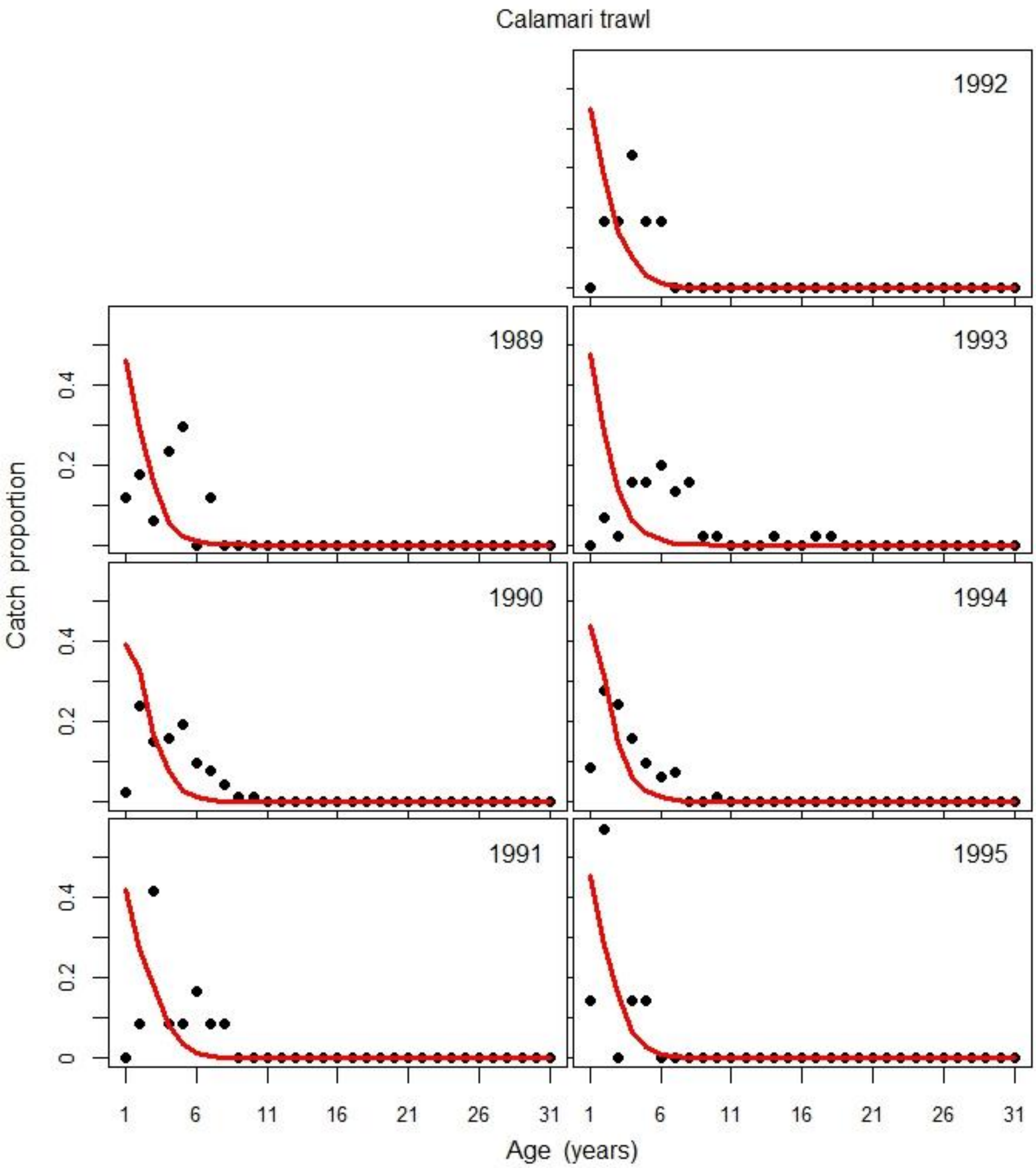


Figure A2. Continued.

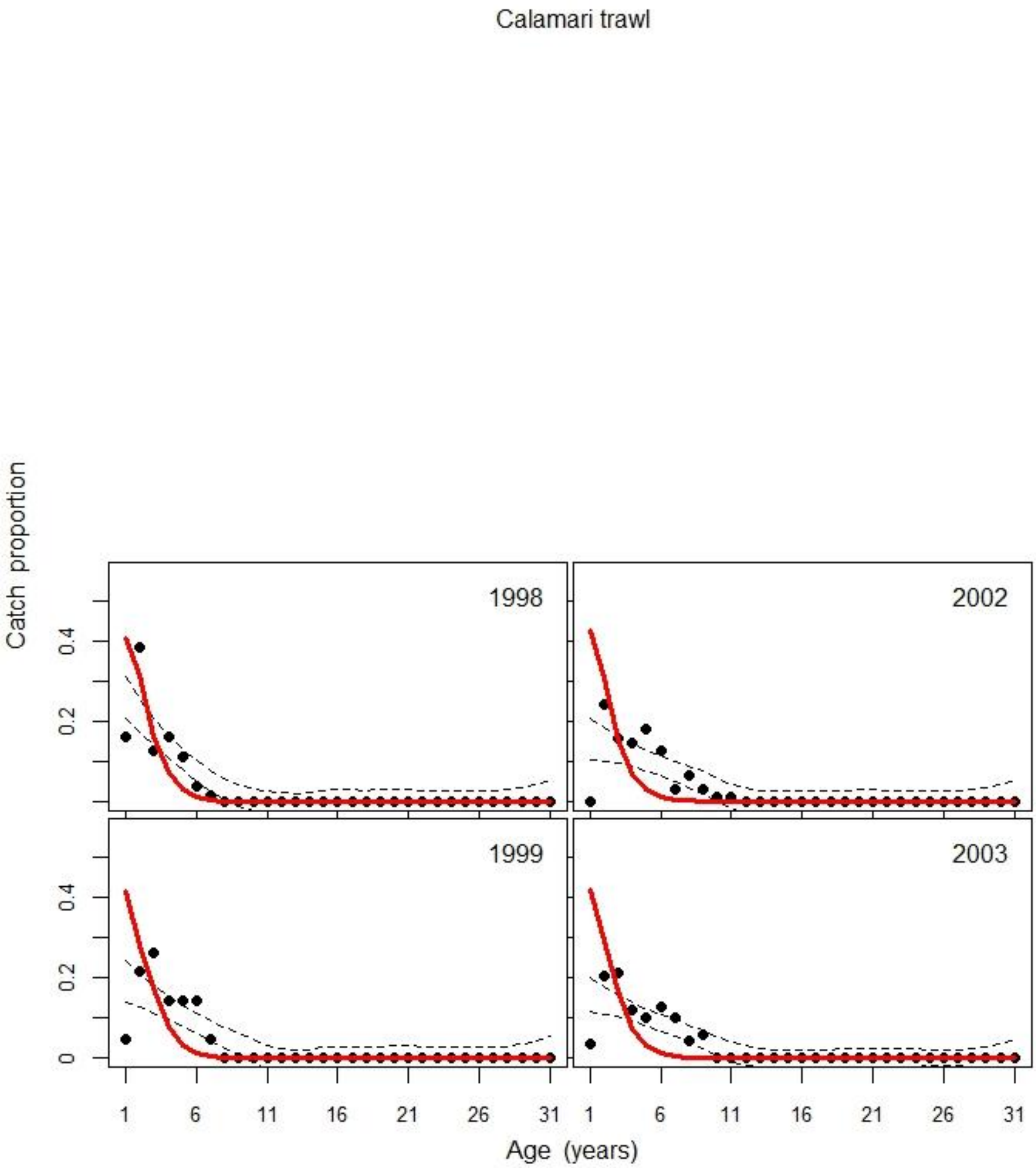


Figure A2. Continued.

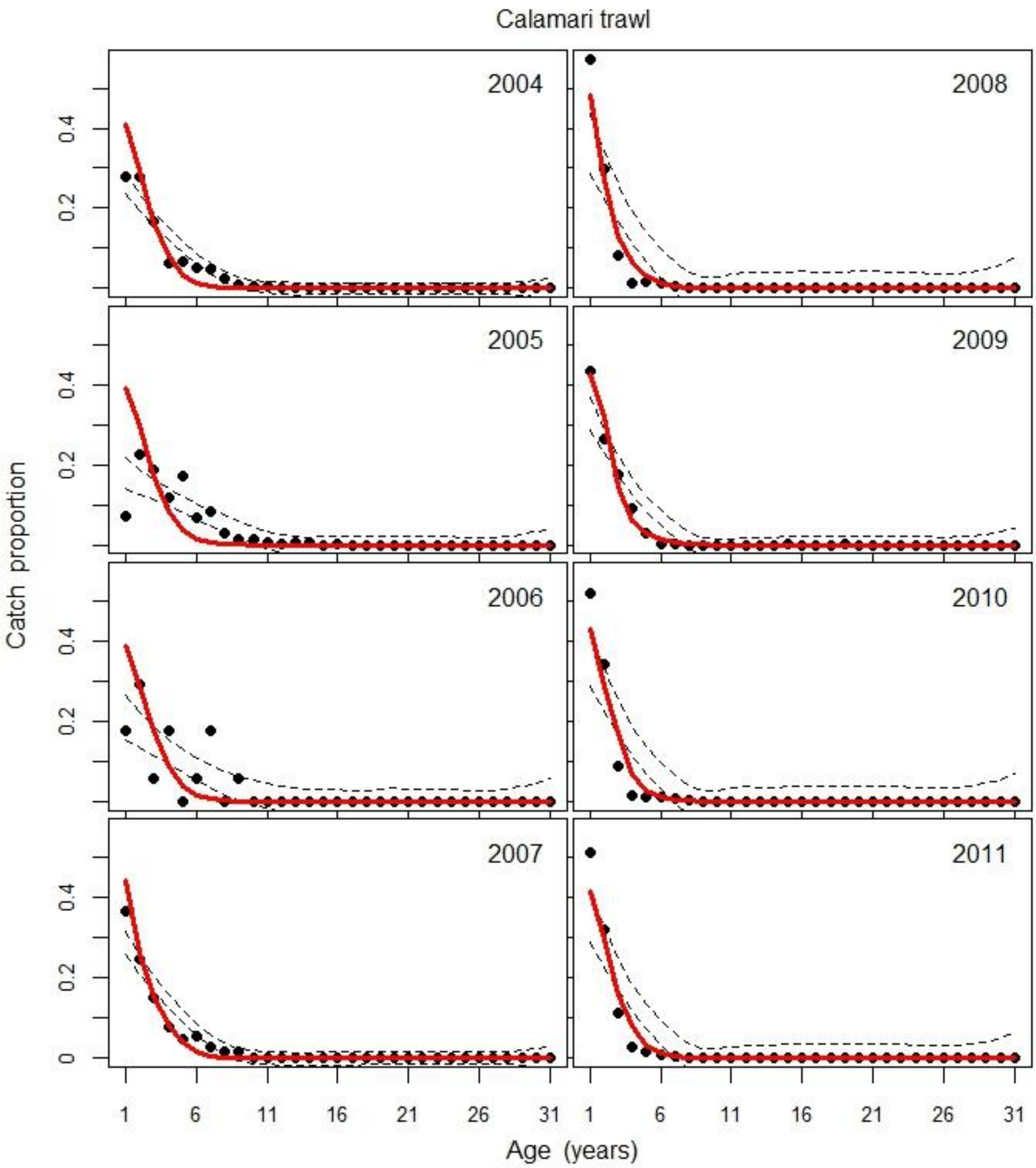


Figure A2. Continued.

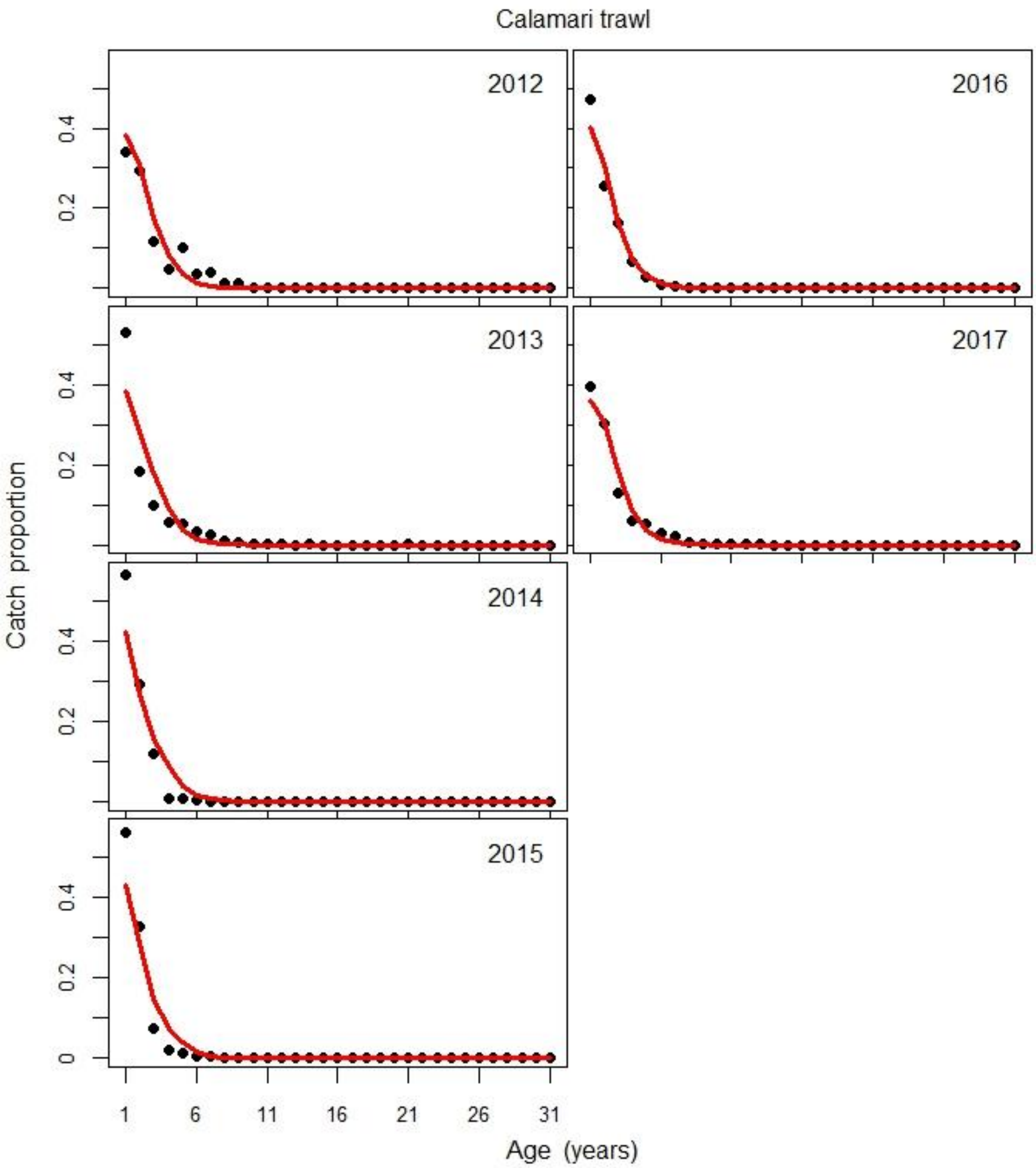


Figure A2. Continued.

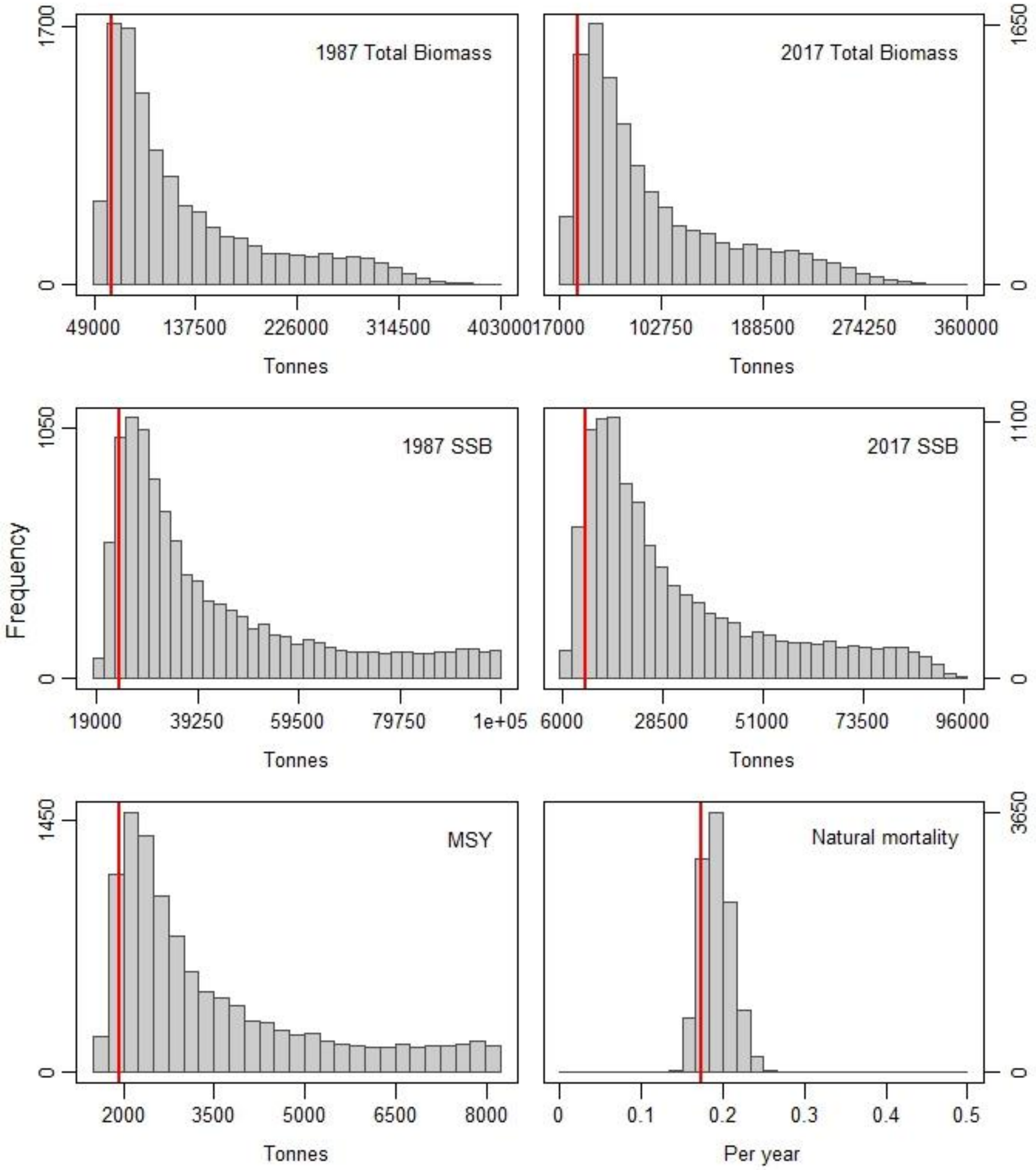


Figure A3. MCMC distributions of CASAL model estimates. Estimates include toothfish total biomass and spawning stock biomass spawning in start year 1987 and current year 2017, maximum sustainable yield, and instantaneous natural mortality. Vertical red lines: empirical model estimate of each parameter.