Updated assessment of the toothfish (*Dissostichus eleginoides*) resource in the Prince Edward Islands vicinity to include data from 1997 to 2016

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ABSTRACT

The assessment of the Prince Edward Islands (PEI) toothfish (*Dissostichus eleginoides*) resource carried out by Brandão and Butterworth (2015a) is updated to take further data available for 2015 and 2016 (up to May) into account. This update again also incorporates (now updated) tag-recapture data and a new basis to estimate the extent of cetacean depredation. For the Base case and many of the assessment sensitivities the resource is estimated to be at a depletion (in relation to its average pre-exploitation level in terms of spawning biomass) in the 51-58% range (slightly better than before the new data were added, though the resource remains estimated to be decreasing in abundance). Introduction of the tag-recapture data hardly changes point estimates but does reduce estimation variance. Projections suggest that the resource would increase slowly under constant annual future catches of 500 t. This would remain the case for somewhat higher catches as well, but it remains a concern that for the last three years (2011-2013) of the longline CPUE is well below model predictions. The trotline CPUE does however show a slight increase in the 2015 compared to the 2014 index, which is the lowest in the series. Viewed overall, and pending the development of an OMP to take the assessment uncertainties into account in a better manner, a TAC increase (if any) for the 2016/17 season would seem best to be kept small.

INTRODUCTION

The assessment of the Prince Edward Islands (PEI) toothfish (*Dissostichus eleginoides*) resource carried out by Brandão and Butterworth (2015a) is updated to take further data available for 2015 and 2016 into account.

As in Brandão and Butterworth (2015a), estimates of the "split" month factors are used to provide an estimate for cetacean depredation to be used in the assessment instead of the more *ad hoc* assumptions used previously (Brandão and Butterworth, 2013). The Base case model in this paper continues to assume this value rather than the no cetacean predation scenario.

Brandão and Butterworth (2014) presented an alternative to the Base case model in which tag-recapture data are also incorporated in this Age-Structured Production Model (ASPM) assessment of the Prince Edward Islands resource. In this paper the BBase case model is the model that continues to include tagging data, and a sensitivity without tag-recapture data is run for comparison.

Sensitivity tests of the Base case model are also carried out to investigate what aspects of the assessment may not reconcile with the tag-recapture data, and also to force better fits to the CPUE indices. As for previous assessments, the biological parameter values adopted for toothfish in Subarea 48.3 (Agnew *et al.,* 2006) are assumed to apply.

As in Brandão and Butterworth (2015a), the assessments of the toothfish resource presented in this paper have been carried out on a "fishing" year rather than a calendar year as in earlier assessments, where a "fishing" year *y* is defined to extend from 1 December of year *y*-1 to 30 November of year *y*.

DATA UPDATES

Further data available for 2015 and 2016 (until May) have been incorporated in the present analyses; these were not available for previous assessments of toothfish in the Prince Edward Islands vicinity. In the interests of completeness, what follows below includes descriptions of changes made in earlier assessments as well. Where the reference is to new data or analyses related to the further data only now available, the associated text is shown in *italics*.

Since 2004, reports make no mention of vessels fishing illegally. Therefore (as agreed by the DWG) the amount of illegal take assumed from 2005 onwards is set to zero (see Brandão *et al*. (2002a, 2002b) and Brandão and Butterworth (2004) for a description of the basis for the 2004 and previous IUU estimates).

An estimate of 1.1 was obtained (Brandão and Butterworth, 2014) for the annual amount of cetacean depredation to be assumed in the assessment model for toothfish, i.e a 10% annual catch loss rather than the 50% - to 200% loss assumed in assessments prior to 2014. The Base case model assumes that the extent of toothfish predation by cetaceans from longlines increased linearly from 2000 to a saturation level from 2002 onwards, as suggested by observations made aboard the *South Princess* vessel (Brandão and Butterworth, 2005). A sensitivity test has been conducted assuming that one out of three toothfish are lost to cetaceans (referred to as 1.5x). Table 1 shows the catch (removals) figures with and without these assumed cetacean predation amounts. This basis for inflating the catch figures to account for predation was also applied to the catches estimated for illegal vessels, as it seems likely that these vessels were also longliners and would therefore have had the same problems with cetacean predation as the legal longline fishery.

From November 2004 to April 2005 one vessel in the toothfish fishery changed its fishing operations in that it began to use pots in an attempt to overcome the problem with cetacean predation. Pot data from this vessel are separated from the data obtained from the commercial longline fishery and analysed as a second fleet. This vessel has left the fishery and therefore no new data from the pot fishery are available.

From 2008 operators in the toothfish fishery began to use trotlines in some of the sets in an attempt to overcome the problem with cetacean predation. The trotline data are separated from the data obtained from the commercial longline fishery and analysed as a third fleet. In this paper the assessment of the toothfish resource considering the three fleets does not take into account the enhanced estimate obtained from a research program carried out in 2012 and 2013 in which longline and trotline sets were paired to within three nautical miles and a period of two weeks to obtain a calibration factor between longlines and trotlines.

The updated series of relative abundance indices obtained from the CPUE GLMM standardisation procedure described in Brandão and Butterworth (2016) for the trotline commercial data are listed in Table 2. The longline fleet has not operated since 2013 until 2016 (until May), so no new data for this fleet is available; therefore the GLMM standardised CPUE series for longline have not been updated and remain the same as that presented in Brandão and Butterworth, (2015b) and also given in Table 2. *Data for the 2016 season (until May) have been used in the present assessment, except for the CPUE data, for which only "full" years were considered for the GLMM standardisation of the trotline data.* Note that the longline CPUE indices are inflated by the same proportions as the longline catch to take cetacean depredation into account. Although the pot fishery operated for two years (over November 2004 to April 2005), the lack of replicate months precludes a GLM standardisation distinguishing month and year effects, so that the pot CPUE data are not incorporated in these assessments.

Catch-at-length information for the longline fishery for 1997 to 2013, for November 2004 to April 2005 for the pot fishery are included in the present assessment *as are the trotline fishery catch-at-length data for 2008 to 2015. The catch-at-length data for 2016 is not presently available for the assessment, so only the 2015 data has been updated to include data since June that is now available.* All catch-at-length proportions have been weighted by the size of the catch for the finer scale fishing areas from which they were taken. A relative weight (w_{len}) of 1.0 for the catch-at-length contribution to the log-likelihood has been applied in this paper.

Tagging of toothfish in PEI started in 2005 with the annual number of fish tagged and recaptures shown in *Table 3, which has been updated to include new information*. These data are input into the assessments that include tagging data by splitting them into numbers by age (based on the toothfish growth curve) and recaptures are also split by fleet. The original data are given as numbers by length which are converted into numbers by age using equation (A1.6) and the von Bertalanffy growth parameters given in Table 4. Note that the pot fleet operated only until 2005 and therefore no recoveries of toothfish from this fishery that have been at large for more than a year are possible.

ASSESSMENT METHODOLOGY

No changes have been made to the methodology detailed in Brandão and Butterworth (2015a), but a description thereof, together with details of some of the sensitivity tests conducted to the Base case assessment, is included below in the interests of completeness.

The generalised ASPM methodology incorporates three fleets, so that the information from the pot and trotline fisheries can be incorporated in the ASPM assessment, as in Brandão and Butterworth (2007). Appendix 1 describes the ASPM methodology for a multiple fleet fishery. As in the past, the biological parameter values assumed are based upon values adopted for toothfish in Subarea 48.3 (Table 4).

The variant that allows for annual recruitment to vary about the prediction of the Beverton-Holt stock-recruitment function, where these annual variations ("residuals", each treated as an estimable parameter) are assumed to be log-normally distributed with a CV set in this application to 0.5, has been fitted to the updated data for the toothfish off the Prince Edward Islands.

The methodology for incorporating tag-recapture data is described in Appendix 1. Some parameters values in the modelling of the tagging data have had to be assumed because of the very few data for the number of recoveries when split by fleet. These assumptions (i.e. that all tags recaptured are reported and that the fishing mortality of tagged fish during their first year at large is the same as for those that have been at large for longer) are highlighted in Appendix 1.

Four sensitivity tests have been conducted to fully understand various aspects of the assessment. These sensitivity tests are (all carried out including tag-recapture data):

i) An alternative amount of cetacean predation is assumed (one out of three toothfish is lost to cetaceans (referred to as 1.5x)).
ii) Fix K_{sp}.to 25 000 tonnes.

iii) The standard deviation (σ_R) of the annual variation in the stock-recruitment function is assumed to be 0.1 for the period until 1997 and to be 0.5 from then onwards.
iv) All CPUE indices up-weighted by a factor of 10.

RESULTS AND DISCUSSION

Table 5 shows the results for the Base case three-fleet assessment of the toothfish resource, as well as for the previous Base case model (Brandão and Butterworth, 2015a) and a sensitivity for when an alternative factor for cetacean predation is assumed. Both these updated assessments suggest the current (start of 2017) status of the resource to be at 51% of average pre-exploitation equilibrium spawning biomass, a value which is 49% for 2016. The previous Base case assessment suggests that this status of the resource at the beginning of 2016 was at 53%. The assessments carried out in 2007 suggested values in the region of 37% to 40% (Brandão and Butterworth, 2007), while those carried out in 2013 (Brandão and Butterworth, 2013) suggested very high values (in the region of 86% to 90%). Further data together with tag-recapture data now incorporated appear to have stabilised this estimate considerably.

Figure 1 shows estimated spawning biomass and recruitment trends for the Base case model.. The model estimates a large peak in recruitment in 1990 in response to the large estimated illegal catch taken in 1997, so as to better fit the trend in the CPUE abundance indices. Fits to the CPUE data are shown in Figure 2 for the Base case. The model fails to fit the comparatively very high 1997 CPUE value. The model also does not fit the last three CPUE indices for longline very well. Assuming a larger cetacean predation factor of 1.5 does improve the fit to the longline CPUE indices (see the σ_{CPUE} values in Table 5).

Fits of the Base case model to the catch-at-length distributions for the longline, pot and trotline fisheries are shown in Figure 3, and the standardised catch-at-length residuals are shown in Figure 4. From a broad perspective, the pattern of the catch-at-length residuals does not indicate model misspecification. The selectivity functions estimated for the Base case model are shown in Figure 5.

Figure 6 shows the fit to the cumulative recapture numbers of toothfish for the Base case model, combining the recaptures by longlines and trotlines.

Table 6 shows the results for three other sensitivity tests performed which are variants of the Base case model. These reflect attempts to restrain the large estimated peaks in recruitment in 1990 which result in depletion values that are much higher than obtained in many previous assessments. For comparison, results for the Base case are reproduced here as well. The one sensitivity test that achieved a lower depletion level that is in the region of depletion values obtained previously, is the one that up-weights all CPUE indices. Figure 7 compares the spawning biomass (a) and recruitment (b) for the previous Base case and the present Base case, as well as the further four sensitivity tests. Figure 7b clearly shows that only the sensitivity test that sets a lower standard deviation for recruitment (σ_R) for the years up to and including 1997 is able to reduce the large peaks in recruitment in 1990. This has been achieved by estimating a large initial pre-exploitation level but leads to worse fits to all data (Figure 8 and Table 6). Figure 8 shows fits to the CPUE indices for all models considered in this paper (including those for the previous Base case model) except for the sensitivity test that assumes an alternative value for cetacean predation. The sensitivity test that fits the first CPUE index slightly better is the one that up-weights all CPUE indices. Such up-weighting results in a better fit to the CPUE indices (see the σ_{CPUE} values in Table 6).

Table 7 compares the results between the Base case model to the equivalent without the tag-recapture data taken into account. These assessments suggest the current status of the resource to be in the region of 51% to 54% of average pre-exploitation equilibrium spawning biomass. The impact of including the tag-recapture data on the status of the resource is hence minimal in terms of point estimates, but variances are reduced (considerably so for biomass related indices).

Fixing the average pre-exploitation level of the spawning biomass at 25 000 tonnes does not result in a poorer current status of the resource; in fact this is higher than for the Base case model. This is because of two estimated high peaks in recruitment; one in 1983 and another in 1990.

Figure 9 shows the fit to the cumulative recapture numbers of toothfish for the sensitivity test that up-weights all the CPUE indices. In the previous assessment of Brandão and Butterworth (2015a), achieving a better fit to the CPUE indices resulted in an appreciable lack of fit to the tag-recapture data. This is no longer the case. Worse fits to the tag-recapture data are evident for the sensitivity test that sets a lower standard deviation for recruitment (σ_R) for the years up to and including 1997 (compare $-\ln L$ contributions from the tag recapture in Table 6).

Figure 10 shows the spawning biomass together with twenty year projections under different constant future annual catches for the Base case model with tagging data and three sensitivity tests. Projections assume that in future all catches are from the trotline fishery, as has been the case since 2014, and that there are no illegal removals. As the pot fishery has not been operational since 2005, no pot fishery is assumed in the projections.

Figures 11 and 12 provide similar results to Figure 10, but the projections are for the longline (Figure 11) and the trotline (Figure 12) exploitable components of the biomass.

CONCLUSIONS

The three-fleet model that takes the information available from the pot and trotline fisheries into account estimates the spawning biomass of the resource to be about 51% if tagging data. There has been a slight improvement in the CVs following the inclusion of the further data now available, and in absolute terms biomass estimates drop marginally throughout the period considered though in terms of resource status (relative to its pre-exploitation level) the resource is now estimated to be slightly above rather than slightly below 50% (see Table 5).

A concern with this assessment, however, remains that it is heavily influenced by the large peaks in recruitment estimated in the 1990s, and does not fully reflect the marked drop in CPUE shortly after illegal catches commenced.

Alternative fits to the data are possible under different constraints. A worse current status of 44% follows for a scenario that up-weights all the CPUE indices. In the previous assessment of Brandão and Butterworth (2015a), although this sensitivity fitted the CPUE data much better, the fit to the tag-recapture data deteriorated considerably. This bad fit to the tag-recapture data is no longer evident in the present assessment.

The impact of including the tag-recapture data on the status of the resource remains minimal in terms of point estimates; thus the tag data does not conflict with the rest of the other data, and variances (particularly for biomass-related quantities) remain reduced with their inclusion (Table 7).

Despite these uncertainties, the projections in Figures 10 to 12 would still seem to provide a basis for a TAC recommendation as last year. In all scenarios increases in spawning biomass occur in the long term under a 500 t TAC, although this is less marked for the sensitivity test in which K_{sp} is fixed at 25 000 t. While catches somewhat above 500 t might also be justified on this basis, it still remains a concern that for the last three years (2011 to 2013) the longline CPUE is well below model predictions (see Figure 7). Model fits also trend downwards through the trotline CPUE data, though those show a slight increase in the 2015 compared to the 2014 index, which is the lowest in the series.

Viewed overall, and pending the development of an OMP to take the assessment uncertainties into account in a better manner, a TAC increase (if any) for the 2016/17 season would seem best to be kept small.

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REFERENCES

Agnew, D.J., Hillary, R., Belchier, M. Clark, J. and Pearce, J. 2006. Assessment of toothfish in Subarea 48.3, 2006. Commission for the Conservation of Antarctic Marine Living Resources Subgroup on Assessment Methods Document: WG-FSA-06/53.

Brandão, A., Watkins, B.P., Butterworth, D.S. and Miller, D.G.M. 2002a. A first attempt at an assessment of the Patagonian toothfish (*Dissostichus eleginoides*) resource in the Prince Edward Islands EEZ. *CCAMLR Science* 9: 11-32.

Brandão, A., Butterworth, D.S., Watkins, B.P. and Staverees, L. 2002b. An updated assessment of the toothfish (*Dissostichus eleginoides*) resource in the Prince Edward Islands vicinity and extensions taking commercial catch-at-length data into account. Commission for the Conservation of Antarctic Marine Living Resources Document: WG-FSA-02/76.

Brandão, A. and Butterworth, D.S. 2004. Updated ASPM of the toothfish (*Dissostichus eleginoides*) resource in the Prince Edward Islands vicinity. Commission for the Conservation of Antarctic Marine Living Resources Document: WG-FSA-04/37.

Brandão, A. and Butterworth, D.S. 2005. A two-fleet ASPM assessment of the toothfish (*Dissostichus eleginoides*) resource in the Prince Edward Islands vicinity. Commission for the Conservation of Antarctic Marine Living Resources Document: WG-FSA-05/58.

Brandão, A. and Butterworth, D.S. 2007. 2007 assessment of the toothfish (*Dissostichus eleginoides*) resource in the Prince Edward Islands vicinity. Commission for the Conservation of Antarctic Marine Living Resources Document: WG-FSA-06/34.

Brandão, A. and Butterworth, D.S. 2013. Assessment of the toothfish (*Dissostichus eleginoides*) resource in the Prince Edward Islands vicinity to include data from 1997 to 2013. DAFF Branch Fisheries document: FISHERIES/2013/OCT/SWG-DEM/59.

Brandão, A. and Butterworth, D.S. 2014. Assessment of the toothfish (*Dissostichus eleginoides*) resource in the Prince Edward Islands vicinity to include data from 1997 to 2013, including tag-recapture data. DAFF Branch Fisheries document: FISHERIES/2014/OCT/SWG-DEM/49.

Brandão, A. and Butterworth, D.S. 2015a. Updated assessment of the toothfish (*Dissostichus eleginoides*) resource in the Prince Edward Islands vicinity to include data from 1997 to 2015, including tag-recapture data. DAFF Branch Fisheries document: FISHERIES/2015/OCT/SWG-DEM/40.

Brandão, A. and Butterworth, D.S. 2015b. Spanish longline and trotline standardised CPUE series for toothfish (*Dissostichus eleginoides*) in the Prince Edward Islands EEZ to be used as input for the assessment. DAFF Branch Fisheries document: FISHERIES/2015/OCT/SWG-DEM/38.

Brandão, A. and Butterworth, D.S. 2016. Updated trotline standardised CPUE series for toothfish (*Dissostichus eleginoides*) in the Prince Edward Islands EEZ to be used as input for the assessment. DAFF Branch Fisheries document: FISHERIES/2016/OCT/SWG-DEM/54.

Butterworth, D.S., Ianelli, J.N. and Hilborn, R. 2003. A statistical model for stock assessment of southern bluefin tuna with temporal changes in selectivity. *African Journal of Marine Science*, 25:331-361.

CCSBT (Commission for the Conservation of the Southern Bluefin Tuna). 2003. Report of the Second Meeting of the Management Procedure Workshop. Queenstown, New Zealand, March 2003.

Table 1. Yearly catches of toothfish (in tonnes) estimated to have been taken from the Prince Edward Islands EEZ which are used for the analyses conducted in this paper. The bases for the estimates of cetacean predation and the illegal catches for 2004 through to 2013 are detailed (or referenced) in the text. Catches (strictly "removals") from the longline fisheries (both "legal" and "illegal"), and modified to include cetacean predation (see text for the basis for this) are also given. Fishing years are defined as the period from December of the preceding year to November of the year indicated.

Fishing Year	Legal			Illegal (IUU)	Total		
	Longline fishery	Pot fishery	Trotline fishery		Without predation	With predation on longline fishery (1.1x)	With predation on longline fishery (1.5x)
1997	2 754.9	—	—	21 350	24 104.9	24 104.9	24 104.9
1998	1 224.6	—	—	1 808	3 032.6	3 032.6	3 032.6
1999	945.1	—	—	1 014	1 959.1	1 959.1	1 959.1
2000	1 577.8	—	—	1 210	2 787.8	2 880.8	3 252.5
2001	267.8	—	—	352	619.8	661.1	826.4
2002	237.3	—	—	306	543.3	597.6	815.0
2003	251.1	—	—	256	507.1	557.8	760.6
2004	182.5	34.3	—	156	372.8	410.0	559.1
2005	142.6	141.9	—	—	284.5	313.0	426.8
2006	169.1	—	—	—	169.1	186.0	253.6
2007	245.0	—	—	—	245.0	269.5	367.5
2008	88.8	—	56.4	—	145.2	154.1	189.6
2009	41.8	—	30.7	—	72.5	76.7	93.4
2010	49.2	—	174.6	—	223.7	228.7	248.4
2011	1.0	—	290.4	—	291.4	291.5	291.9
2012	70.7	—	205.5	—	276.2	283.3	311.6
2013	50.0	—	215.3	—	265.3	270.3	290.3
2014	—	—	367.5	—	367.5	367.5	367.5
2015	—	—	444.0	—	444.0	444.0	444.0
2016†	—	—	575.0	—	575.0	575.0	575.0
1997–2016 total	8 299.3	176.2	2 359.4	26 452	37 286.8	37 663.5	39 169.8

† The catch assumed for 2016 is the TAC for the year (with the whole catch assumed to come from the trotline fleet.

Table 2. Relative abundance indices for toothfish provided by the standardised commercial CPUE series for the Prince Edward Islands EEZ for the longline and trotline fishery (Brandão and Butterworth, 2015a, 2016). The CPUE indices adjusted to take cetacean predation into account are also shown. Fishing years are defined as the period from December of the preceding year to November of the year indicated.

Fishing Year	**Longline fishery**			**Trotline fishery**
	GLMM *CPUE* (no predation)	**GLMM *CPUE* including predation (1.1x)**	**GLMM *CPUE* including predation (1.5x)**	**GLMM *CPUE* (no predation)**
1997	3.412	3.412	3.412	—
1998	1.467	1.467	1.467	—
1999	1.288	1.288	1.288	—
2000	1.000	1.033	1.167	—
2001	0.581	0.620	0.775	—
2002	0.706	0.777	1.059	—
2003	0.425	0.468	0.638	—
2004	0.557	0.613	0.836	—
2005	0.735	0.809	1.103	—
2006	0.614	0.676	0.921	—
2007	0.673	0.740	1.009	—
2008	0.601	0.661	0.902	0.708
2009	0.641	0.705	0.962	0.891
2010	0.531	0.584	0.797	1.291
2011	0.159	0.175	0.239	1.000
2012	0.334	0.368	0.501	1.087
2013	0.333	0.366	0.499	0.936
2014	—	—	—	0.713
2015	—	—	—	0.769

Table 3. Summary of the number of tagged toothfish and the number of recaptures by year. The numbers in bold *italics* reflect recaptures of toothfish in the first year at large.

	2005	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**
Numbers Tagged	175	179	120	140	74	131	206	162	253	380	458	7
Recaptures												
2005	***1***											
2006	**1†**											
2007	1	1	***2***									
2008												
2009			1	2								
2010			1	1								
2011	1	1	2	2		4	***1***					
2012	1	1		1		2		**1**				
2013					1		4	1	***1***			
2014		1	1	2		1	1	6	3 (***5*†**)	***5***		
2015			1	3			1	4	9	9 (***6*†**)	***6***	
2016										1		

† These tags, even though recaptured in the following year, had not been at large for more than a year (i.e. a 12 month period).

Table 4. Biological parameter values (Agnew *et al*., 2006) assumed for the assessments conducted, based upon the values for Subarea 48.3 Note that for simplicity, maturity is assumed to be knife-edged in age.

Parameter	**Value**
Natural mortality M (yr^{-1})	0.13
von Bertalanffy growth ℓ_∞ (cm) κ (yr^{-1}) t_0 (yr)	 152.0 0.067 -1.49
Weight (in gm) length (in cm) relationship c d	 25.4×10^{-6} 2.8
Age at maturity (yr) a_m	13
Age at recruitment (yr) a_r	6
Steepness parameter (h)	0.75

Table 5. Estimates for a **Base case** three fleet (longline, trotline and pot) model that assumes different commercial selectivities for the three gears, and also a change in selectivity for the longliners between 2002 and 2003, when fitted to the CPUE and catch-at-length data for toothfish from the Prince Edward Islands EEZ. Results for a **sensitivity** to an increase to the extent of predation are also shown. The estimates shown are for the pre-exploitation toothfish spawning biomass (K_{sp}), the current spawning stock depletion (B_{sp}^{2017}) in terms of both K_{sp} and $MSYL_{sp}$, and the (longline) exploitable biomass ($B_{\exp}^{2017}$) at the beginning of the year 2017 (assuming the same selectivity as for 2016). Estimates of parameters pertinent to fitting the catch-at-length information are also shown, together with contributions to the (negative of the) log-likelihood. Numbers in brackets represent CVs. The details of the various model variants reported are given in the text.

Parameter estimates		**Model**		
		Previous Base case (tagging data; predation 1.1x)*	**Base case (tagging data; predation 1.1x)**	**Predation 1.5x**
K_{sp} (tonnes)		37 662 (0.130)	35 815 (0.118)	37 495 (0.117)
$MSYL_{sp}$ (Longline)/K_{sp}		0.244	0.244	0.244
B_{sp}^{2016}/K_{sp}		0.534 (0.096)	0.494 (0.093)	0.494 (0.093)
B_{sp}^{2017}/K_{sp}		—	0.512 (0.094)	0.512 (0.094)
B_{sp}^{1997}/K_{sp}		1.121 (0.096)	1.257 (0.095)	1.252 (0.095)
$B_{sp}^{2017}/MSYL_{sp}$(Longline)		2.189	2.102	2.102
$B_{\exp}^{2017}$ (tonnes)	Longline	15 214 (0.155)	14 246 (0.144)	14 984 (0.143)
	Pot	25 726 (0.149)	22 497 (0.128)	23 538 (0.128)
	Trotline	19 142 (0.152)	17 257 (0.132)	18 061 (0.131)
σ_{CPUE}	Longline	0.440	0.416	0.358
	Trotline	0.224	0.203	0.203
σ_R		0.500††	0.500††	0.500††
a_{50}^{97-02} (yr)		6.500	6.499	6.499
δ^{97-02} (yr^{-1})		0.020	0.020	0.020
ω^{97-02} (yr^{-1})		0.058	0.058	0.058
a_{50}^{03-16} (yr)	Longline	6.464	6.447	6.448
	Pot	8.810	8.696	8.712
	Trotline	7.372	7.347	7.349
δ^{03-16} (yr^{-1})	Longline	0.127	0.128	0.129
	Pot	0.896	0.885	0.888
	Trotline	0.246	0.292	0.292
ω^{03-16} (yr^{-1})	Longline	0.067	0.070	0.069
	Pot	0.000	0.000	0.000
	Trotline	0.031	0.033	0.033
β		0.119 (0.017)	0.118 (0.018)	0.118 (0.018)
σ_{len}	Longline	0.042	0.042	0.042
	Pot	0.035	0.035	0.035
	Trotline	0.040	0.039	0.039

†† Input value.

* The results shown for the "current" biomass-related values for the previous Base case are for 2016, and not for 2017 as for the results for present Base case model except for B_{sp}/K_{sp} .

Table 5 cont. Estimates for a **Base case** three fleet (longline, trotline and pot) model that assumes different commercial selectivities for the three gears, and also a change in selectivity for the longliners between 2002 and 2003, when fitted to the CPUE and catch-at-length data for toothfish from the Prince Edward Islands EEZ. Results for a **sensitivity** to an increase to the extent of predation are also shown. The estimates shown are for the pre-exploitation toothfish spawning biomass (K_{sp}), the current spawning stock depletion (B_{sp}^{2017}) in terms of both K_{sp} and $MSYL_{sp}$, and the (longline) exploitable biomass ($B_{\exp}^{2017}$) at the beginning of the year 2017 (assuming the same selectivity as for 2016). Estimates of parameters pertinent to fitting the catch-at-length information are also shown, together with contributions to the (negative of the) log-likelihood. Numbers in brackets represent CVs. The details of the various model variants reported are given in the text.

Parameter estimates		Model		
		Previous Base case (tagging data; predation 1.1x)*	**Base case (tagging data; predation 1.1x)**	**Predation 1.5x**
-ln *L*: Length		-815.5	-826.2	-826.1
-ln *L*: CPUE		-12.434	-15.167	-17.73
-ln *L*: Recruitment		0.858	0.163	-0.438
-ln *L*: Tagging		136.1	184.1	184.3
-ln *L*: Total		-690.9	-657.1	-660.0
MSY (tonnes)	Longline	1 514†	1 438†	1 506†
	Pot	1 675	1 590	1 665
	Trotline	1 599	1 516	1 587

† Based upon the average of the two selectivity functions estimated.

Table 6. Estimates for three **sensitivity tests** to the **Base case** model detailed in the caption to Table 5.

Parameter estimates		**Model**			
		Base case (tagging data; predation 1.1x)	**Sensitivity: varying σ_R**	**Sensitivity: fixed K_{sp}**	**Sensitivity: w_{CPUE}=10 for all years**
K_{sp} (tonnes)		35 815 (0.118)	62 821 (0.085)	25 000††	30 559 (0.110)
$MSYL_{sp}$ (Longline)/K_{sp}		0.244	0.244	0.244	0.243
B_{sp}^{2017}/K_{sp}		0.512 (0.094)	0.575 (0.044)	0.568 (0.093)	0.444 (0.096)
B_{sp}^{1997}/K_{sp}		1.257 (0.095)	1.032 (0.021)	1.528 (0.087)	1.357 (0.096)
$B_{sp}^{2017}/MSYL_{sp}$(Longline)		2.102	2.354	2.325	1.828
$B_{\exp}^{2017}$ (tonnes)	Longline	14 246 (0.144)	27 323 (0.127)	11 645 (0.120)	9 688 (0.142)
	Pot	22 497 (0.128)	43 944 (0.114)	17 309 (0.090)	6 863 (0.123)
	Trotline	17 257 (0.132)	33 722 (0.117)	14 433 (0.113)	11 589 (0.118)
σ_{CPUE}	Longline	0.416	0.469	0.408	0.364
	Trotline	0.203	0.202	0.201	0.206
σ_R		0.500††	0.1 pre 1998; 0.5 otherwise††	0.500††	0.500††
a_{50}^{97-02} (yr)		6.499	6.469	6.500	6.499
δ^{97-02} (yr^{-1})		0.020	0.020	0.020	0.020
ω^{97-02} (yr^{-1})		0.058	0.051	0.052	0.060
a_{50}^{03-16} (yr)	Longline	6.447	6.369	6.454	6.447
	Pot	8.696	8.778	8.930	8.341
	Trotline	7.347	7.252	7.352	7.323
δ^{03-16} (yr^{-1})	Longline	0.128	0.144	0.128	0.131
	Pot	0.885	0.994	0.935	0.801
	Trotline	0.292	0.289	0.294	0.290
ω^{03-16} (yr^{-1})	Longline	0.070	0.069	0.063	0.082
	Pot	0.000	0.000	0.000	0.000
	Trotline	0.033	0.033	0.026	0.041
β		0.118 (0.018)	0.113 (0.025)	0.118 (0.018)	0.117 (0.019)
σ_{len}	Longline	0.042	0.046	0.042	0.042
	Pot	0.035	0.039	0.036	0.034
	Trotline	0.039	0.038	0.039	0.039

†† Input value(s).

Table 6 cont. Estimates for three **sensitivity tests** to the Base case model detailed in the caption to Table 5.The details of the various sensitivity tests reported are given in the text.

Parameter estimates		Model			
		Base case (tagging data; predation 1.1x)	**Sensitivity: varying σ_R**	**Sensitivity: fixed K_{sp}**	**Sensitivity: w_{CPUE}=10 for all years**
-ln *L*: Length		-826.2	-750.1	-826.4	-829.4
-ln *L*: CPUE		-15.17	-13.15	-15.55	-173.1
-ln *L*: Recruitment		0.163	-46.21	4.286	9.579
-ln *L*: Tagging		184.1	191.9	185.4	187.2
-ln *L*: Total		-657.1	-617.6	-652.3	-805.6
MSY (tonnes)	Longline	1 438†	2 530†	1 009†	1 221†
	Pot	1 590	2 786	1 114	1 348
	Trotline	1 516	2 652	1 064	1 284

† Based upon the average of the two selectivity functions estimated.

Table 7. Estimates for a **sensitivity test** to the Base case model detailed in the caption to Table 6 which omits tagging data.

Parameter estimates		Model: Base case (with tagging data)	Model: Sensitivity: no tagging data)
K_{sp} (tonnes)		35 815 (0.118)	37479 (0.210)
$MSYL_{sp}$ (Longline)/K_{sp}		0.244	0.244
B_{sp}^{2017}/K_{sp}		0.512 (0.094)	0.541 (0.138)
B_{sp}^{1997}/K_{sp}		1.257 (0.095)	1.275 (0.102)
$B_{sp}^{2017}/MSYL_{sp}$(Longline)		2.102	2.220
$B_{\exp}^{2017}$ (tonnes)	Longline	14 246 (0.144)	15526 (0.296)
	Pot	22 497 (0.128)	24862 (0.298)
	Trotline	17 257 (0.132)	18180 (0.305)
σ_{CPUE}	Longline	0.416	0.422
	Trotline	0.203	0.204
σ_R		0.500††	0.500††
a_{50}^{97-02} (yr)		6.499	6.694
δ^{97-02} (yr^{-1})		0.020	0.013
ω^{97-02} (yr^{-1})		0.058	0.062
a_{50}^{03-16} (yr)	Longline	6.447	6.508
	Pot	8.696	8.650
	Trotline	7.347	7.088
δ^{03-16} (yr^{-1})	Longline	0.128	0.020
	Pot	0.885	0.836
	Trotline	0.292	0.036
ω^{03-16} (yr^{-1})	Longline	0.070	0.074
	Pot	0.000	0.000
	Trotline	0.033	0.039
β		0.122 (0.015)	0.118 (0.018)
σ_{len}	Longline	0.042	0.042
	Pot	0.035	0.035
	Trotline	0.039	0.038

Table 7 cont. Estimates for a **sensitivity test** to the Base case model detailed in the caption to Table 6 which omits tagging data.

Parameter estimates		Model	
		Base case (with tagging data)	**Sensitivity: no tagging data)**
-ln *L*: Length		-838.3	-826.2
-ln *L*: CPUE		-14.91	-15.167
-ln *L*: Recruitment		1.283	0.163
-ln *L*: Tagging		—	184.1
-ln *L*: Total		-851.9	-657.1
MSY (tonnes)	Longline	1 511†	1 438†
	Pot	1 675	1 590
	Trotline	1 595	1 516

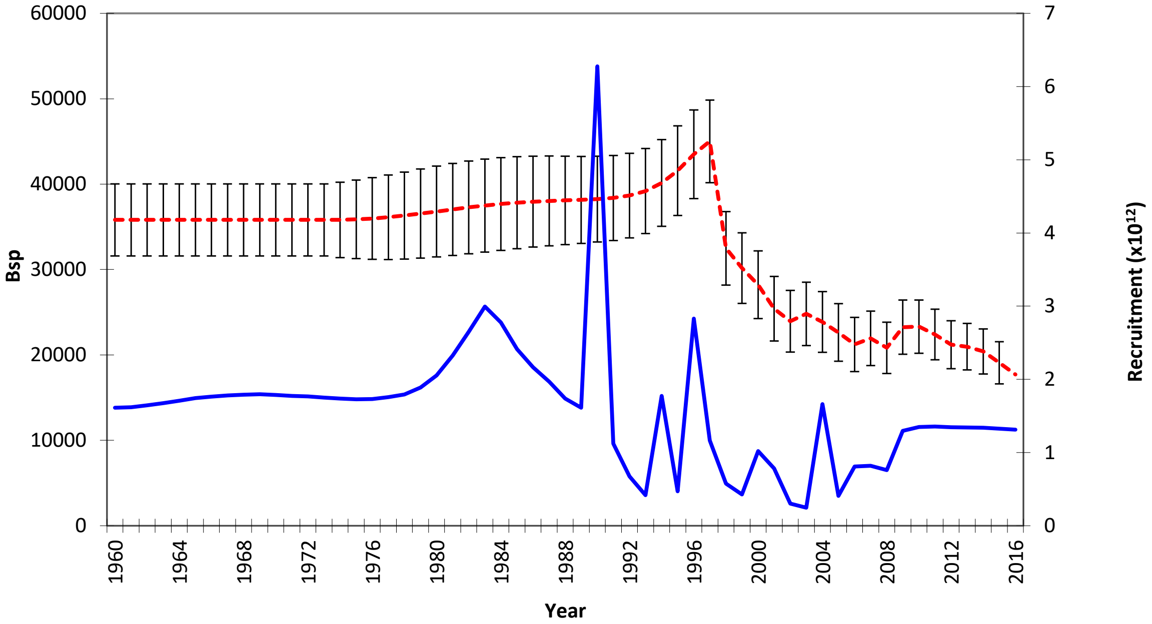
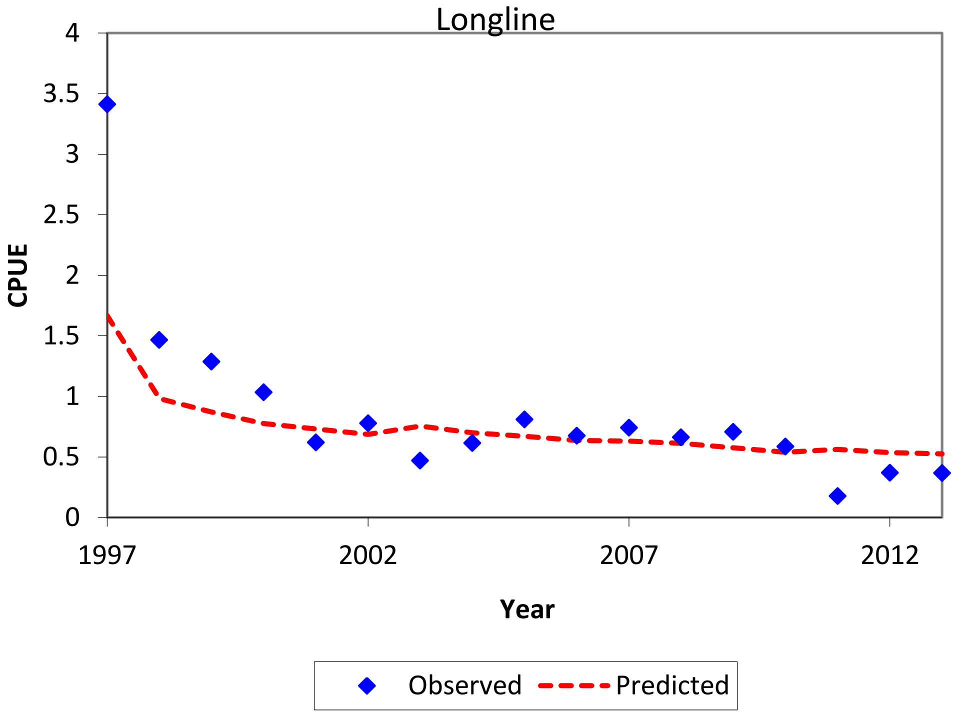


Figure 1. Spawning biomass estimates (dashed line) and estimated recruitment (full line) for the three-fleet model for the **Base case** that takes tagging data into account (with cetacean predation 1.1x). Confidence limits (Hessian-based) of one standard error for the spawning biomass are also shown.



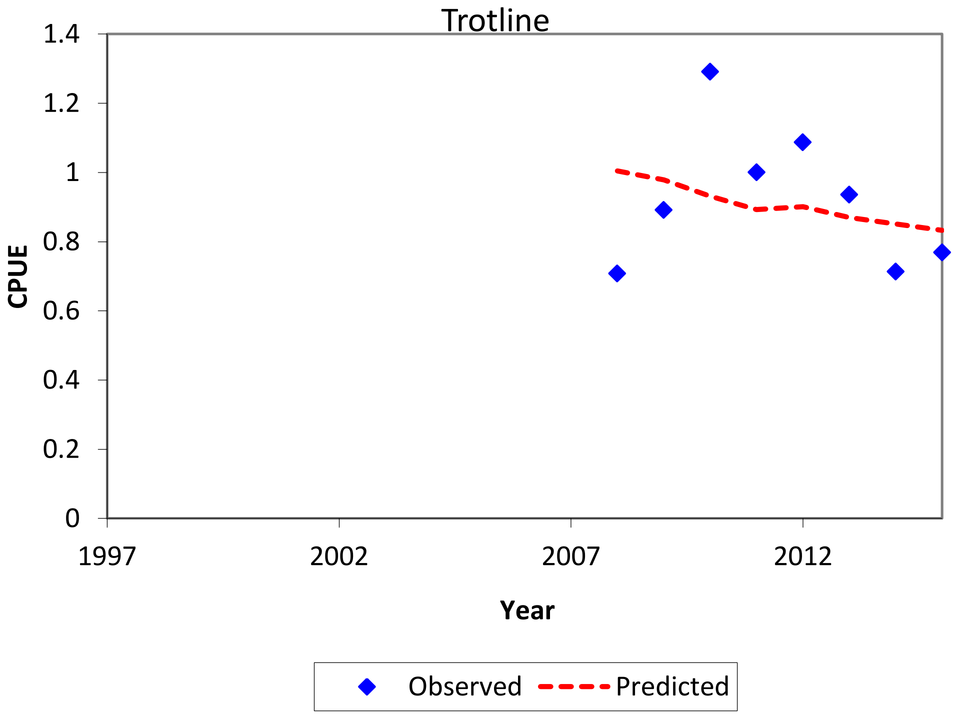


Figure 2. Exploitable biomass and the GLM-standardised CPUE indices to which the model is fit (divided by the estimated catchability *q* to express them in biomass units) for the **Base case**.

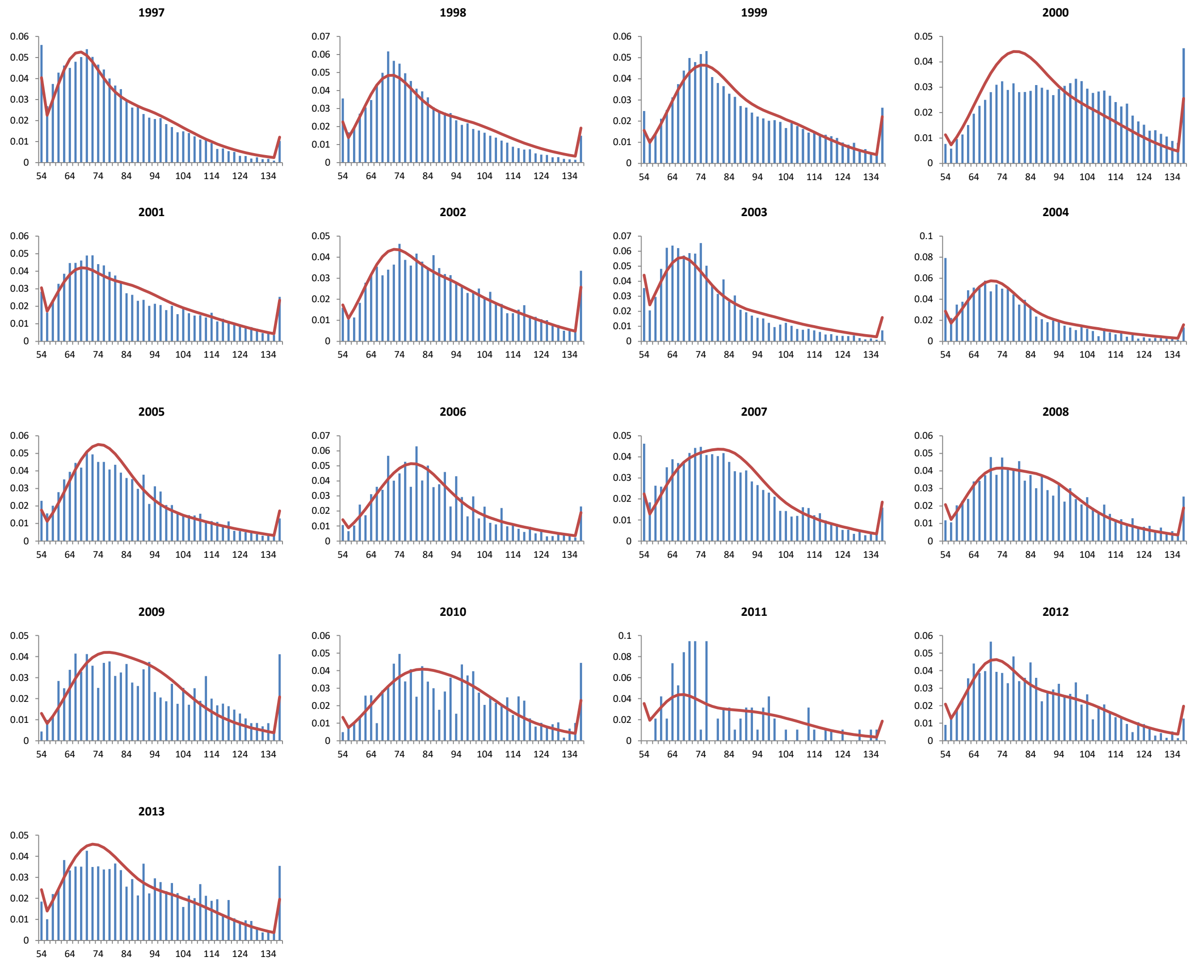


Figure 3a. Assessment predictions for the annual catch-at-length proportions in the longline fishery for the **Base case**. Note that lengths below 54 and above 138 cm are combined into minus- and plus-groups.

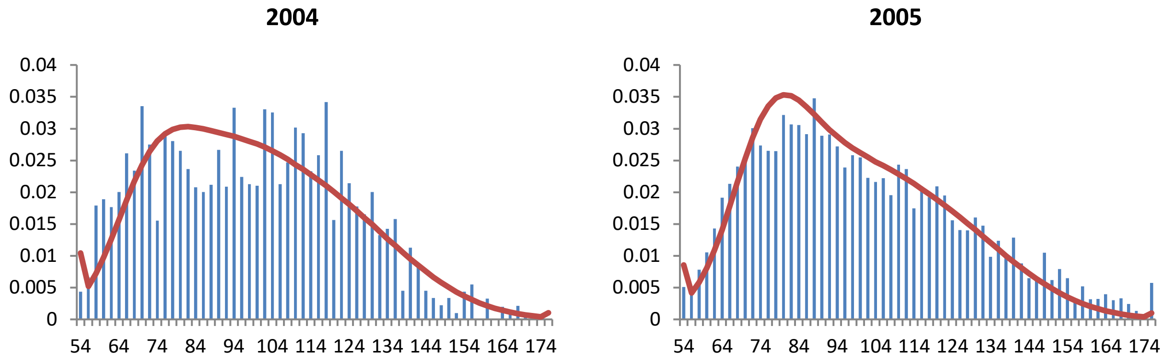


Figure 3b. Assessment predictions for the annual catch-at-length proportions in the pot fishery for the **Base case**. Note that lengths below 54 and above 176 cm are combined into minus- and plus-groups.

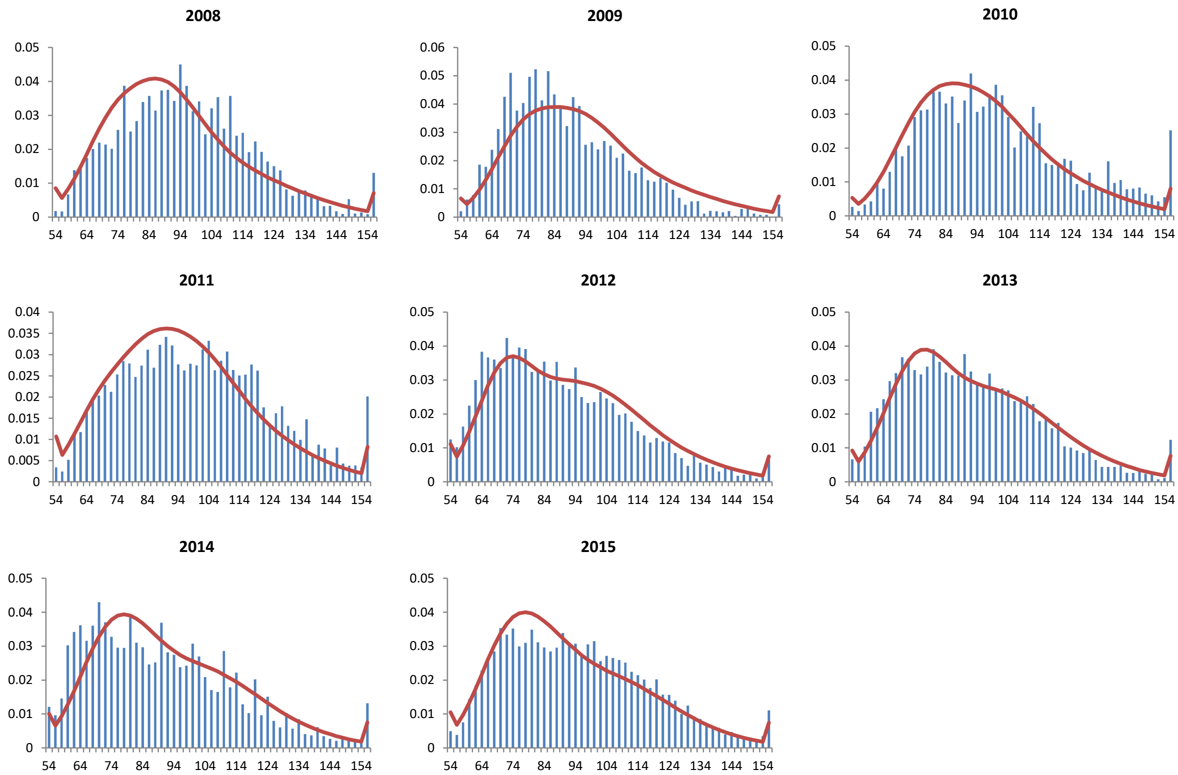


Figure 3c. Assessment predictions for the annual catch-at-length proportions in the trotline fishery for the **Base case**. Note that lengths below 54 and above 156 cm are combined into minus- and plus-groups.

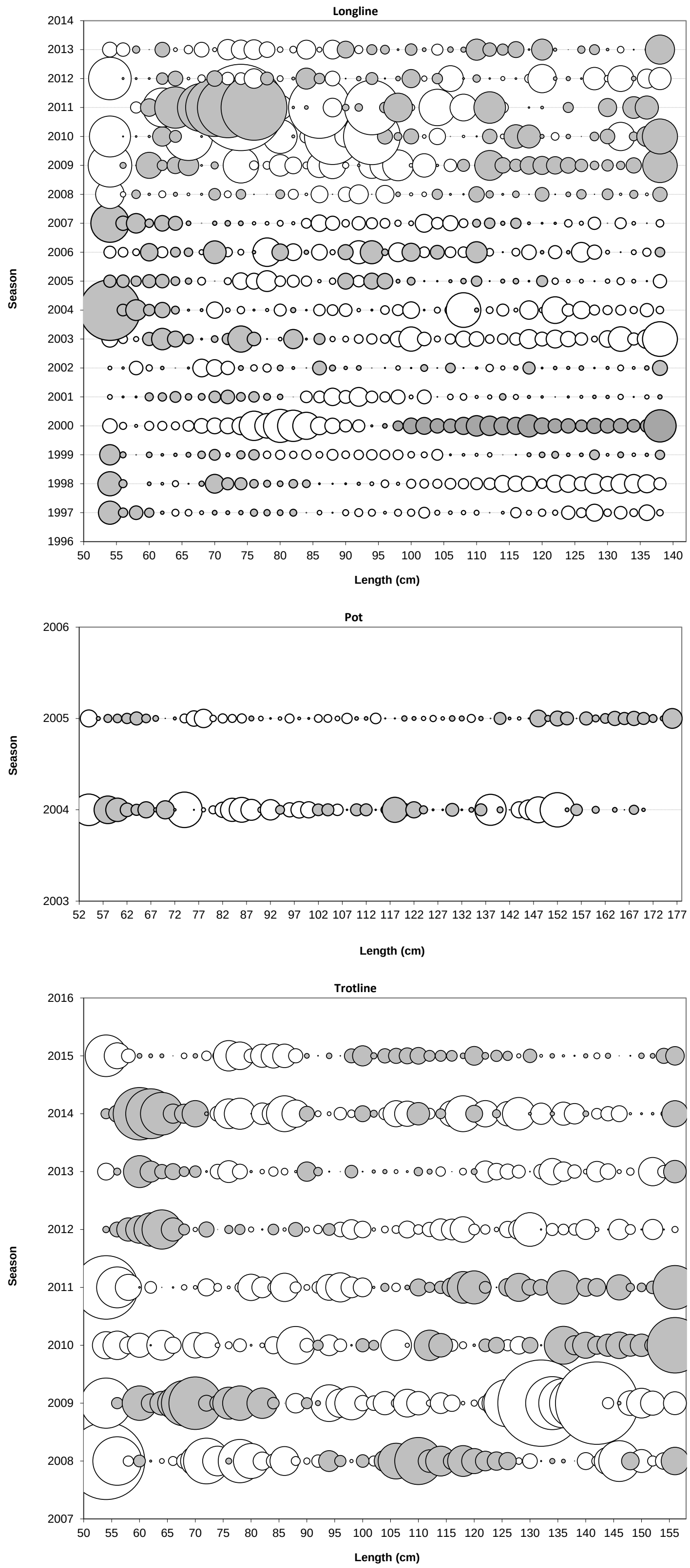


Figure 4. Bubble plots of the catch-at-length residuals for the three fisheries for the **Base case**. The size of the bubble is proportional to the corresponding standardised residual $\left(\left(\ln(obs)-\ln(pred)\right)\big/\left(\sigma/\sqrt{pred}\right)\right)$. White bubbles represent negative residuals while grey bubbles represent positives ones.

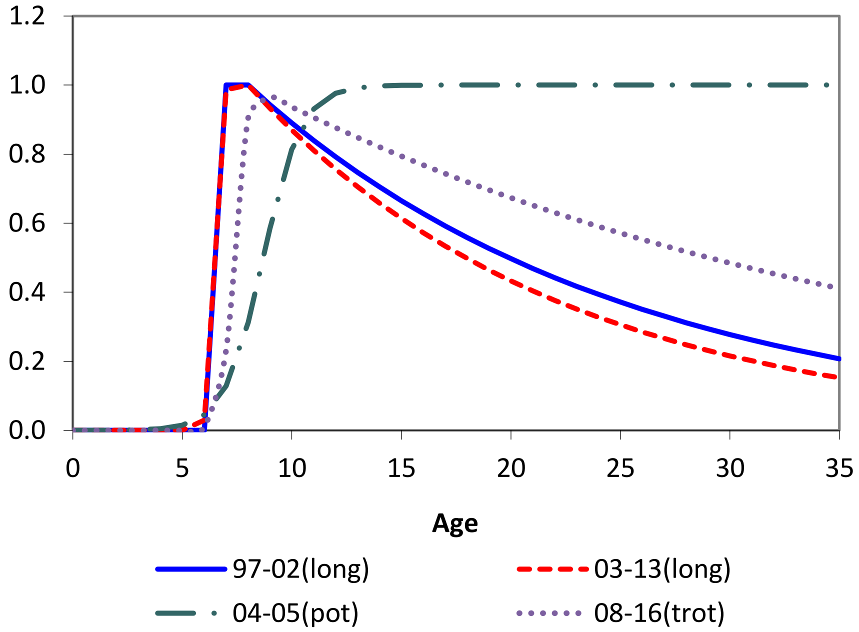


Figure 5. Estimated selectivity curves for the periods 1997–2002 and 2003–2013 for the longline fishery, for the period 2004-2005 for the pot fishery and for the period 2008–2016 for the trotline fishery. Curves are shown for the **Base case**.

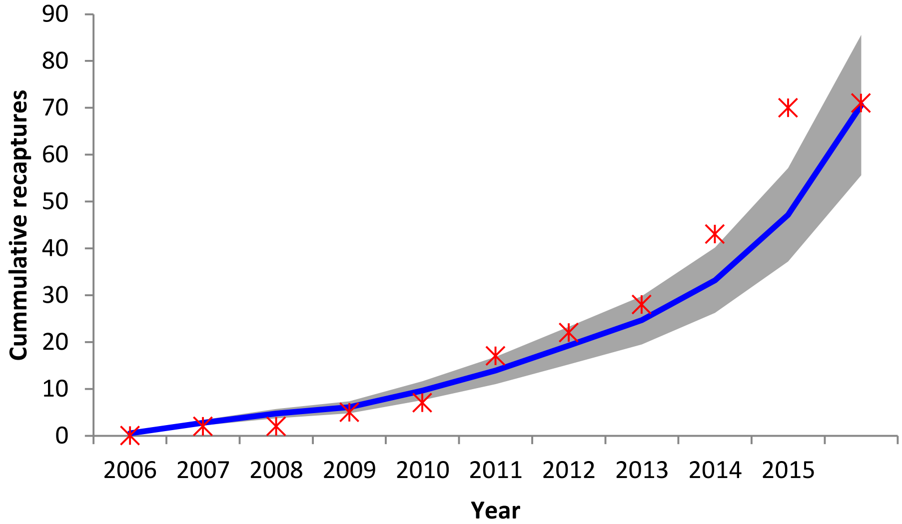


Figure 6. Observed (asterisks) and model predicted (continuous line) cumulative recapture numbers of toothfish for the **Base case** model, and combining recaptures by longlines and trotlines. The shaded area reflects the 95% confidence interval envelope.

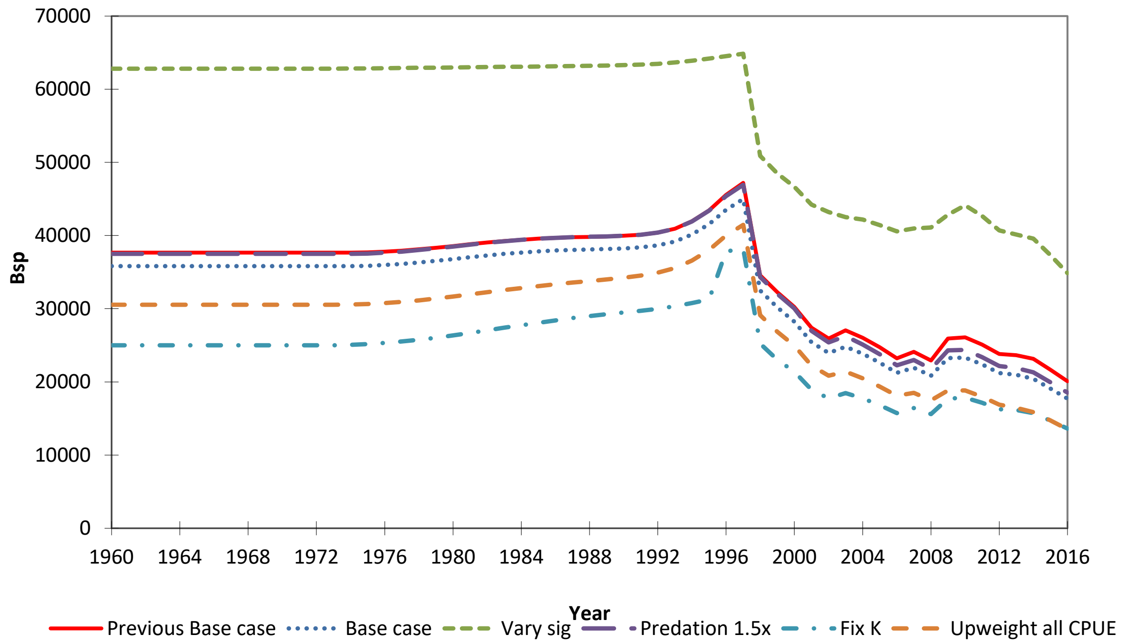


Figure 7a. Spawning biomass estimates for the **Base case** as well as four **sensitivity tests:** 1) fixes K_{sp} at 25 000, 2) varies σ_R from 0.1 pre 1998 to 0.5 otherwise, 3) assumes cetacean predation of 1.5 and 4) upweights all CPUE indices).

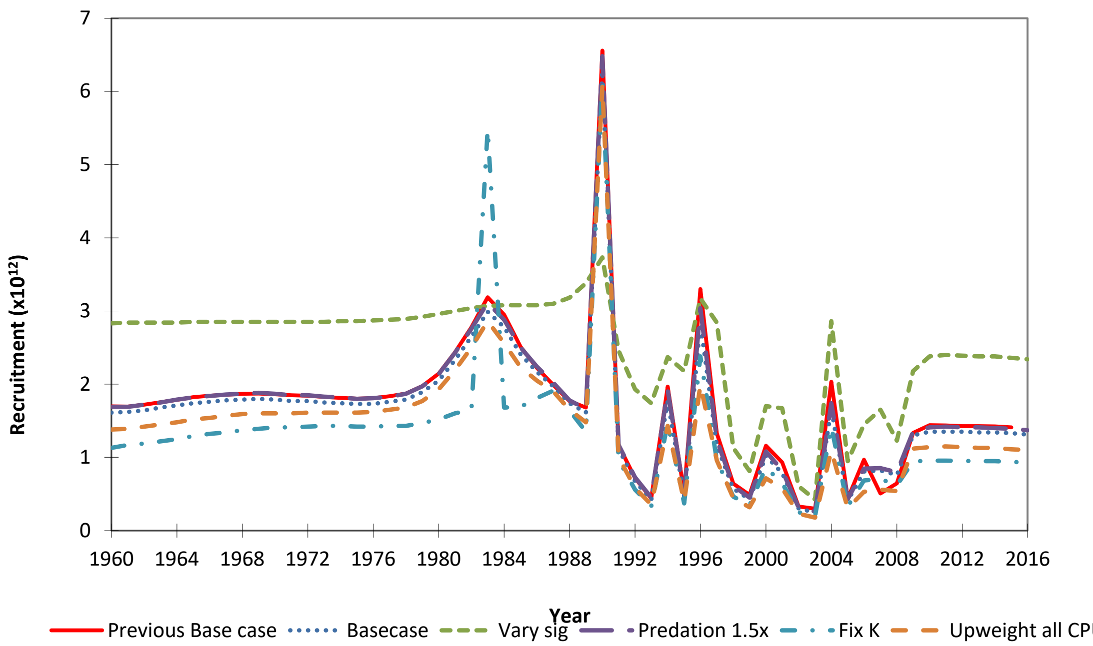


Figure 7b. Estimated recruitment for the **Base case** and the four **sensitivities** detailed in the caption to Figure 7a.

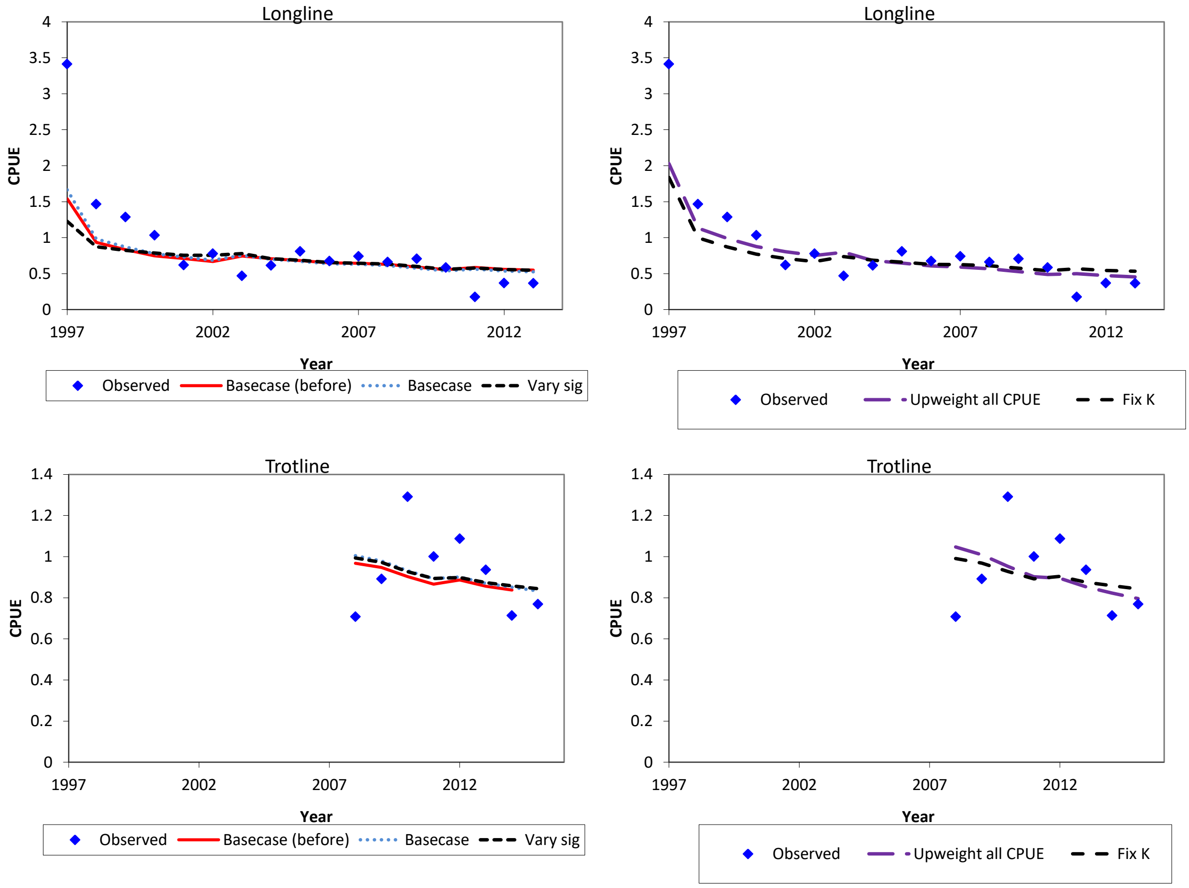


Figure 8. Exploitable biomass and the GLM-standardised CPUE indices to which the model is fit (divided by the estimated catchability q to express them in biomass units) for the previous Base case and the present **Base case** as well as three **sensitivity** tests that 1) fix K_{sp} at 25 000, 2) varies σ_R from 0.1 pre 1998 to 0.5 otherwise, and 3) up-weights all CPUE indices).

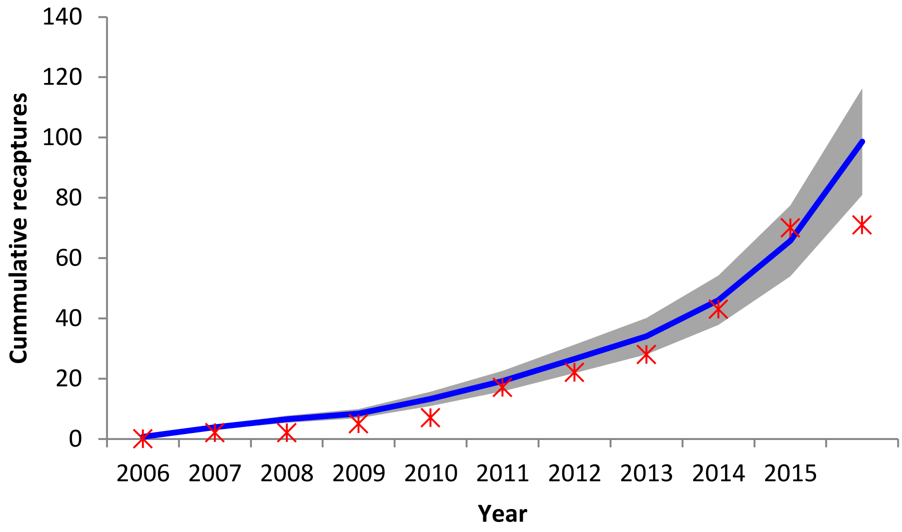


Figure 9. Observed (asterisks) and model predicted (continuous line) cumulative recapture numbers of toothfish for the **sensitivity** test that upweights all CPUE indices, compared to the Base case for which similar results are shown in Figure 6. The shaded area reflects the 95% confidence interval envelope.

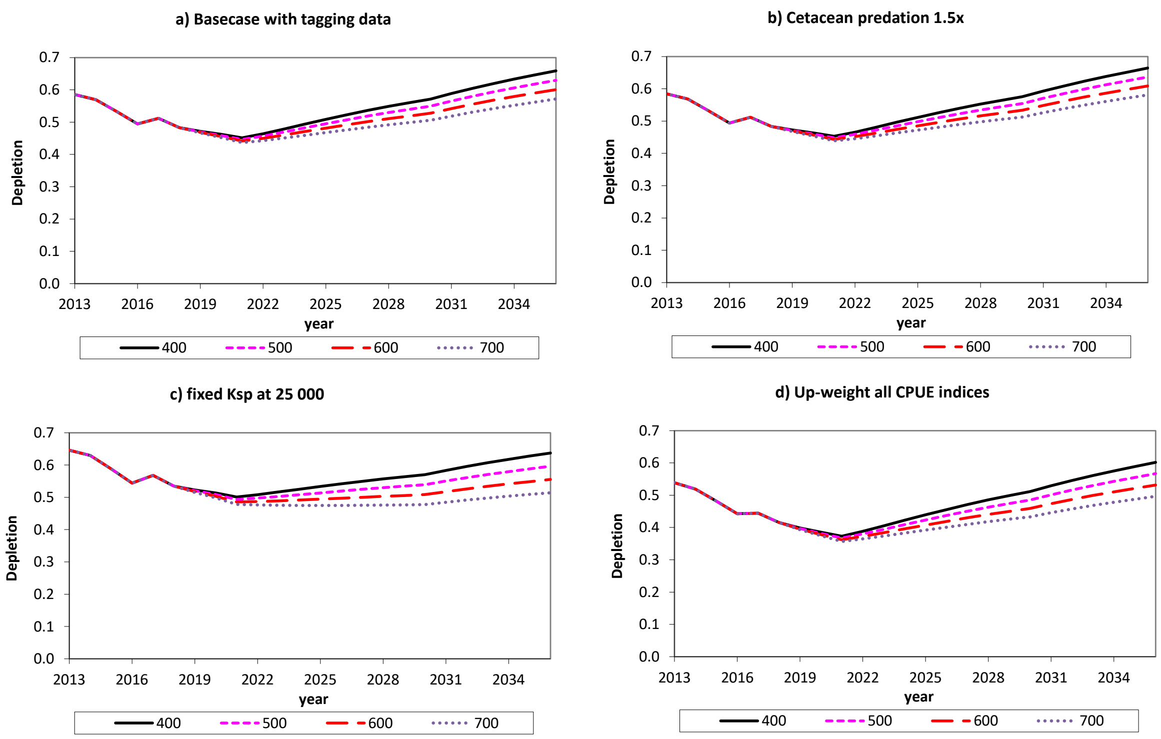


Figure 10. Spawning biomass projections under future annual catches of 400 to 700 tonnes in steps of 100 tonnes (assumed to be all from trotlines as is the case for catches taken since 2014) for the **Base case** (a) and three **sensitivity tests** ((b) assumes cetacean predation of 1.5, (c) fixes K_{sp} at 25 000, and (d) up-weights all CPUE indices).

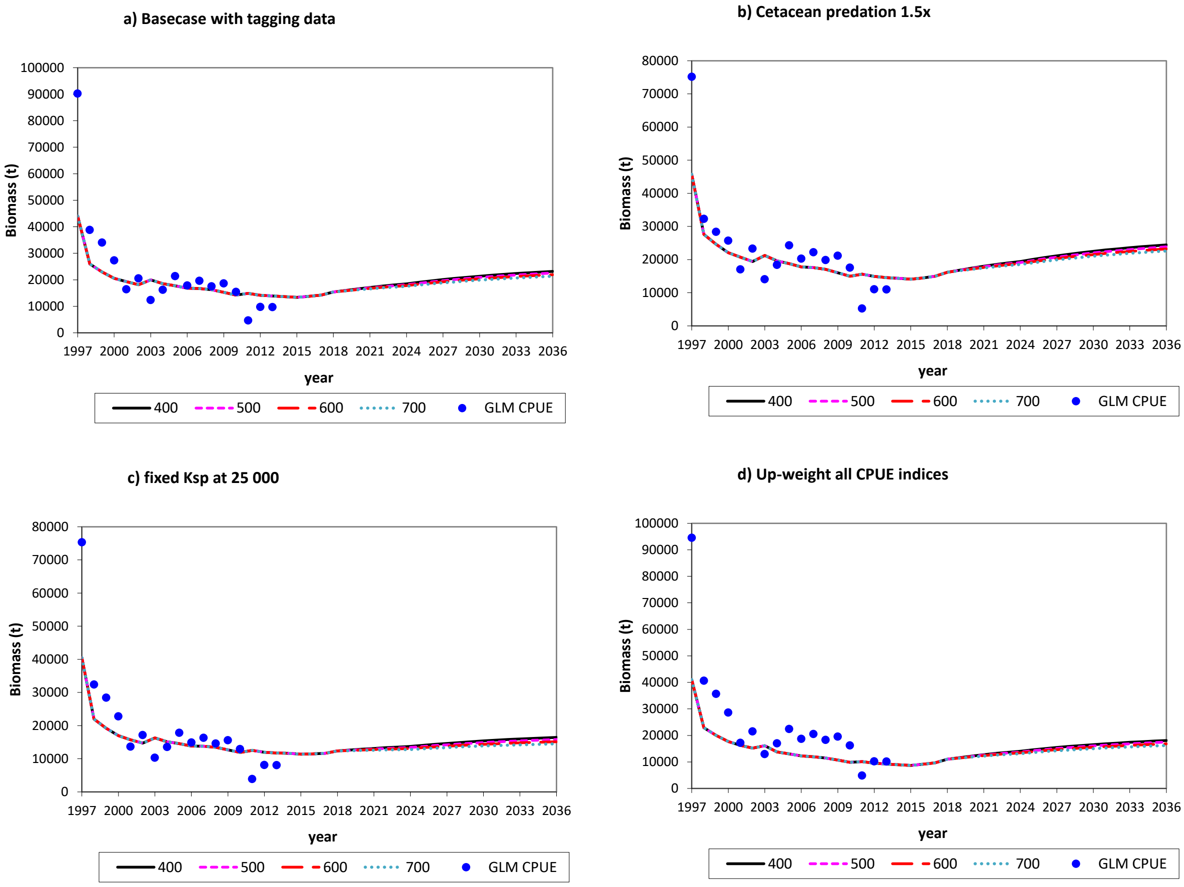


Figure 11. Exploitable biomass for the **longline** fishery and the GLM-standardised CPUE indices to which the model is fit (divided by the estimated catchability *q* to express them in biomass units), together with projections for future catches for the **Base case** and three **sensitivities** as in Figure 10.

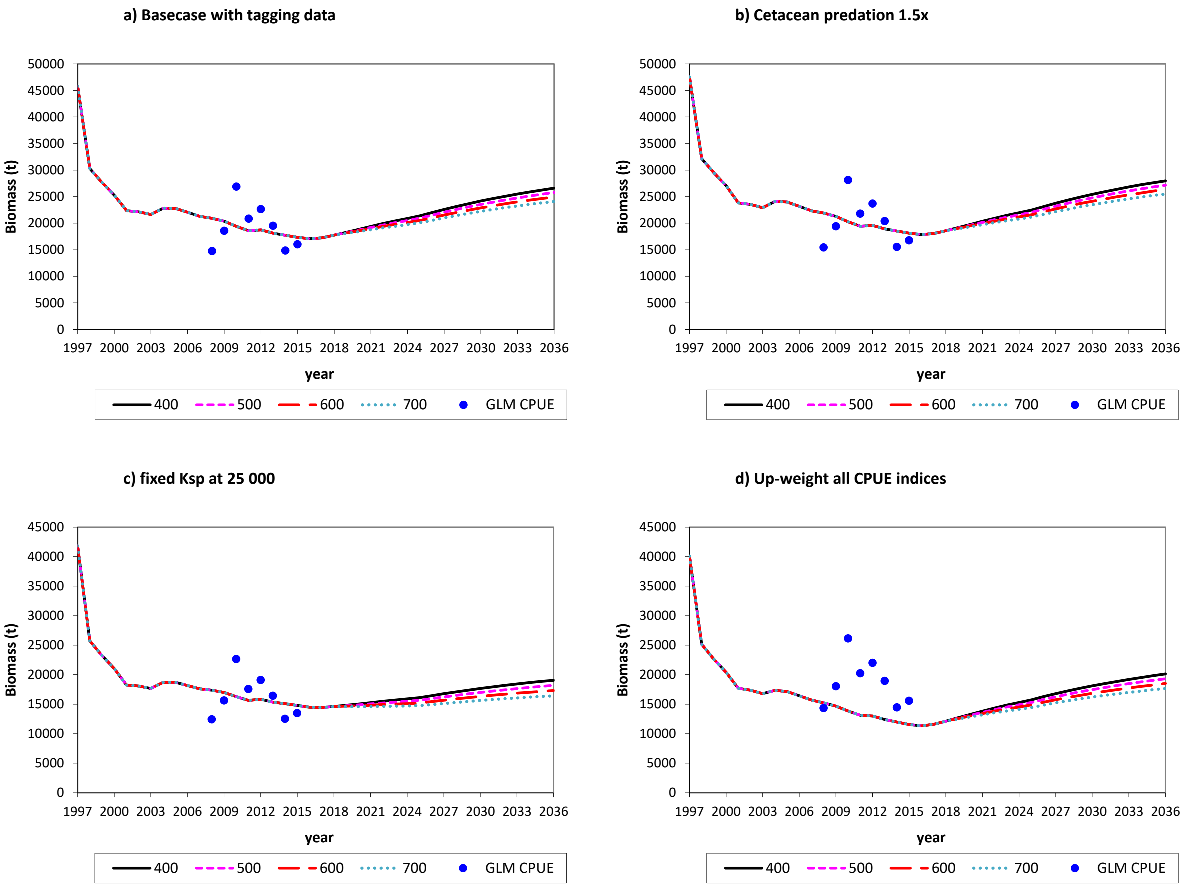


Figure 12. Exploitable biomass projections as shown in Figure 11, except here for the **trotline** rather than the longline fishery.

APPENDIX 1

THE AGE STRUCTURED PRODUCTION MODEL (ASPM) ASSESSMENT METHODOLOGY

THE BASIC DYNAMICS

The toothfish population dynamics are given by the equations:

$$N_{y+1,0} = R(B^{sp}_{y+1}) \tag{A1.1}$$

$$N_{y+1,a+1} = (N_{y,a} - C_{y,a})\, e^{-M} \qquad 0 \le a \le m\text{-}2 \tag{A1.2}$$

$$N_{y+1,m} = (N_{y,m} - C_{y,m})\, e^{-M} + (N_{y,m-1} - C_{y,m-1})\, e^{-M} \tag{A1.3}$$

where:

$N_{y,a}$ is the number of toothfish of age *a* at the start of year *y*,

$C_{y,a}$ is the number of toothfish of age *a* taken by the fishery in year *y*,

$R(B^{sp})$ is the Beverton-Holt stock-recruitment relationship described by equation (A1.10) below,

B^{sp} is the spawning biomass at the start of year *y*,

M is the natural mortality rate of fish (assumed to be independent of age), and

m is the maximum age considered (i.e. the "plus group"), taken here to be m = 35.

Note that in the interests of simplicity this approximates the fishery as a pulse fishery at the start of the year. Given that toothfish are relatively long-lived with low natural mortality, such an approximation would seem adequate.

For a three-gear (or "fleet") fishery, the total predicted number of fish of age *a* caught in year *y* is given by:

$$C_{y,a} = \sum_{f=1}^{3} C^{f}_{y,a}\ , \tag{A1.4}$$

where:

$$C^{f}_{y,a} = N_{y,a} S^{f}_{y,a} F^{f}_{y} \tag{A1.5}$$

and:

F^{f}_{y} is the proportion of the resource above age *a* harvested in year *y* by fleet *f*, and

$S^{f}_{y,a}$ is the commercial selectivity at age *a* in year *y* for fleet *f*.

The mass-at-age is given by the combination of a von Bertalanffy growth equation $\ell(a)$ defined by constants ℓ_∞, κ and t_0 and a relationship relating length to mass. Note that ℓ refers to standard length.

$$\ell(a) = \ell_\infty [1 - e^{-\kappa(a-t_0)}] \tag{A1.6}$$

$$w_a = c\left[\ell(a)\right]^d \tag{A1.7}$$

where:

w_a is the mass of a fish at age a.

The fleet-specific total catch by mass in year y is given by:

$$C_y^f = \sum_{a=0}^{m} w_a C_{y,a}^f = \sum_{a=0}^{m} w_a S_{y,a}^f F_y^f N_{y,a} \tag{A1.8}$$

which can be re-written as:

$$F_y^f = \frac{C_y^f}{\sum_{a=0}^{m} w_a S_{y,a}^f N_{y,a}} \tag{A1.9}$$

FISHING SELECTIVITY

The fleet-specific commercial fishing selectivity, $S_{y,a}^f$, is assumed to be described by a logistic curve, modified by a decreasing selectivity for fish older than age a_c. This is given by:

$$S_{y,a}^f = \begin{cases} \left[1 + e^{-\left(a - a_{50,y}^f\right)/\delta_y^f}\right]^{-1} & \text{for } a \le a_c \\ \left[1 + e^{-\left(a - a_{50,y}^f\right)/\delta_y^f}\right]^{-1} e^{-\omega_y^f (a-a_c)} & \text{for } a > a_c \end{cases} \tag{A1.10}$$

where

$a_{50,y}^f$ is the age-at-50% selectivity (in years) for year y for fleet f,

δ_y^f defines the steepness of the ascending section of the selectivity curve (in years^{-1}) for year y for fleet f, and

ω_y^f defines the steepness of the descending section of the selectivity curve for fish older than age a_c for year y for fleet f (for all the results reported in this paper, a_c is fixed at 8 yrs).

In cases where equation (A1.9) yields a value of F_y^f > 0.9 for a future year, i.e. the available biomass is less than the proposed catch for that year, F_y^f is restricted to 0.9, and the actual catch considered to be taken will be less than the proposed catch. This procedure makes no adjustment to the exploitation rate ($S_{y,a}^f$ F_y^f) of other ages. To avoid the unnecessary reduction of catches from ages where the TAC could have been taken if the selectivity for those ages had been increased, the following procedure is adopted (CCSBT, 2003):

The fishing mortality, F_y^f, is computed as usual using equation (A1.9). If $F_y^f \leq 0.9$ no change is made to the computation of the total catch, C_y^f, given by equation (A1.8). If F_y^f > 0.9, compute the total catch from:

$$C_y^f = \sum_{a=0}^{m} w_a g(S_{y,a}^f F_y^f) N_{y,a} \,. \tag{A1.11}$$

Denote the modified selectivity by $S_{y,a}^{f*}$, where:

$$S_{y,a}^{f*} = \frac{g(S_{y,a}^f F_y^f)}{F_y^f} \,, \tag{A1.12}$$

so that $C_y^f = \sum_{a=0}^{m} w_a S_{y,a}^{f*} F_y^f N_{y,a}$, where

$$g(x) = \begin{cases} x & x \leq 0.9 \\ 0.9 + 0.1\left[1 - e^{(-10(x-0.9))}\right] & 0.9 < x \leq \infty \end{cases} \,. \tag{A.1.13}$$

Now F_y^f is not bounded at one, but $g\left(S_{y,a}^f F_y^f\right) \leq 1$ hence $C_{y,a}^f = g(S_{y,a}^f F_y^f) N_{y,a} \leq N_{y,a}$ as required.

STOCK-RECRUITMENT RELATIONSHIP

The spawning biomass in year *y* is given by:

$$B_y^{sp} = \sum_{a=1}^{m} w_a f_a N_{y,a} = \sum_{a=a_m}^{m} w_a N_{y,a} \tag{A1.14}$$

where:

f_a = the proportion of fish of age *a* that are mature (assumed to be knife-edge at age a_m).

The number of recruits at the start of year *y* is assumed to relate to the spawning biomass at the start of year *y*, B_y^{sp}, by a Beverton-Holt stock-recruitment relationship (assuming deterministic recruitment):

$$R(B_y^{sp}) = \frac{\alpha B_y^{sp}}{\beta + B_y^{sp}} \,. \tag{A1.15}$$

The values of the parameters α and β can be calculated given the unexploited equilibrium (pristine) spawning biomass K^{sp} and the steepness of the curve *h*, using equations (A1.15)–(A1.19) below. If the pristine recruitment is $R_0 = R(K^{sp})$, then steepness is the recruitment (as a fraction of R_0) that results when spawning biomass is 20% of its pristine level, i.e.:

$$hR_0 = R(0.2K^{sp}) \tag{A1.16}$$

from which it can be shown that:

$$h = \frac{0.2(\beta + K^{sp})}{\beta + 0.2K^{sp}}. \tag{A1.17}$$

Rearranging equation (A1.16) gives:

$$\beta = \frac{0.2K^{sp}(1-h)}{h-0.2} \tag{A1.18}$$

and solving equation (A1.14) for α gives:

$$\alpha = \frac{0.8hR_0}{h-0.2}.$$

In the absence of exploitation, the population is assumed to be in equilibrium. Therefore R_0 is equal to the loss in numbers due to natural mortality when $B^{sp} = K^{sp}$, and hence:

$$\gamma K^{sp} = R_0 = \frac{\alpha K^{sp}}{\beta + K^{sp}} \tag{A1.19}$$

where:

$$\gamma = \left\{ \sum_{a=1}^{m-1} w_a f_a e^{-Ma} + \frac{w_m f_m e^{-Mm}}{1-e^{-M}} \right\}^{-1}. \tag{A1.20}$$

PAST STOCK TRAJECTORY AND FUTURE PROJECTIONS

Given a value for the pre-exploitation equilibrium spawning biomass (K^{sp}) of toothfish, and the assumption that the initial age structure is at equilibrium, it follows that:

$$K^{sp} = R_0 \left(\sum_{a=1}^{m-1} w_a f_a e^{-Ma} + \frac{w_m f_m e^{-Mm}}{1-e^{-M}} \right) \tag{A1.21}$$

which can be solved for R_0.

The initial numbers at each age *a* for the trajectory calculations, corresponding to the deterministic equilibrium, are given by:

$$N_{0,a} = \begin{cases} R_0 e^{-Ma} & 0 \le a \le m-1 \\ \dfrac{R_0 e^{-Ma}}{1-e^{-M}} & a = m \end{cases} \tag{A1.22}$$

Numbers-at-age for subsequent years are then computed by means of equations (A1.1)-(A1.5) and (A1.8)-(A1.14) under the series of annual catches given.

The model estimate of the fleet-specific exploitable component of the biomass is given by:

$$B_y^{\exp}(f) = \sum_{a=0}^{m} w_a S_{y,a}^f N_{y,a} \tag{A1.23}$$

THE LIKELIHOOD FUNCTION

The age-structured production model (ASPM) is fitted to the fleet-specific GLM standardised CPUE to estimate model parameters. The likelihood is calculated assuming that the observed (standardised) CPUE abundance indices are lognormally distributed about their expected value:

$$I_y^f = \widehat{I}_y^f e^{\varepsilon_y^f} \text{ or } \varepsilon_y^f = \ln\left(I_y^f\right) - \ln\left(\widehat{I}_y^f\right), \tag{A1.24}$$

where

I_y^f is the standardised CPUE series index for year *y* corresponding to fleet *f*,

$\widehat{I}_y^f$ $= \widehat{q}^f \widehat{B}_y^{\exp}(f)$ is the corresponding model estimate, where:

$\widehat{B}_y^{\exp}(f)$ is the model estimate of exploitable biomass of the resource for year *y* corresponding to fleet *f*, and

q^f is the catchability coefficient for the standardised commercial CPUE abundance indices for fleet *f*, whose maximum likelihood estimate is given by:

$$\ln\hat{q}^f = \frac{1}{n^f}\sum_y\left(\ln I_y^f - \ln\hat{B}_y^{\exp}(f)\right), \tag{A1.25}$$

where:

n^f is the number of data points in the standardised CPUE abundance series for fleet *f*, and

ε_y^f is normally distributed with mean zero and standard deviation σ^f (assuming homoscedasticity of residuals), whose maximum likelihood estimate is given by:

$$\hat{\sigma}^f = \sqrt{\frac{1}{n^f}\sum_y\left(\ln I_y^f - \ln\hat{q}^f\hat{B}_y^{\exp}(f)\right)^2}\ . \tag{A1.26}$$

The negative log likelihood function (ignoring constants) which is minimised in the fitting procedure is thus:

$$-\ln L = \sum_f\left\{\sum_y\left[\frac{1}{2(\sigma^f)^2}\left(\ln I_y^f - \ln\left(q^f B_y^{\exp}(f)\right)\right)^2\right] + n^f\left(\ln\sigma^f\right)\right\}. \tag{A1.27}$$

The estimable parameters of this model are q^f, K^{sp}, and σ^f, where K^{sp} is the pre-exploitation mature biomass. Note that the summation over *f* does not include the pot fishery for which no CPUE data are available.

EXTENSION TO INCORPORATE CATCH-AT-LENGTH INFORMATION

The model above provides estimates of the catch-at-age ($C_{y,a}^f$) by number made by the each fleet in the fishery each year from equation (A1.5). These in turn can be converted into proportions of the catch of age *a*:

$$p^f_{y,a} = C^f_{y,a} \Big/ \sum_{a'} C^f_{y,a'} \, . \tag{A1.28}$$

Using the von Bertalanffy growth equation (A1.6), these proportions-at-age can be converted to proportions-at-length – here under the assumption that the distribution of length-at-age remains constant over time:

$$p^f_{y,\ell} = \sum_a p^f_{y,a} A^f_{a,\ell} \tag{A1.29}$$

where $A^f_{a,\ell}$ is the proportion of fish of age *a* that fall in length group *ℓ* for fleet *f*. Note that therefore:

$$\sum_\ell A^f_{a,\ell} = 1 \qquad \text{for all ages } a. \tag{A1.30}$$

The *A* matrix has been calculated here under the assumption that length-at-age is normally distributed about a mean given by the von Bertalanffy equation, i.e.:

$$\ell(a) \sim \mathrm{N}^*\left[\ell_\infty\left\{1 - e^{-\kappa(a-t_0)}\right\}; \theta^f(a)^2\right] \tag{A1.31}$$

where

N* is a normal distribution truncated at ± 3 standard deviations (to avoid negative values), and

$\theta^f(a)$ is the standard deviation of length-at-age *a* for fleet *f*, which is modelled here to be proportional to the expected length at age *a*, i.e.:

$$\theta^f(\mathrm{a}) = \beta^f \ell_\infty\left\{1 - e^{-\kappa(a-t_0)}\right\} \tag{A1.32}$$

with β^f a parameter estimated in the model fitting process.

Note that since the model of the population's dynamics is based upon a one-year time step, the value of β^f and hence the $\theta^f(a)$'s estimated will reflect not only the real variability of length-at-age, but also the "spread" that arises from the fact that fish in the same annual cohort are not all spawned at exactly the same time, and that catching takes place throughout the year so that there are differences in the age (in terms of fractions of a year) of fish allocated to the same cohort.

Model fitting is effected by adding the following term to the negative log-likelihood of equation (A1.27):

$$-\ln L_{len} = w_{len} \sum_{f,y,\ell} \left\{ \ln\left[\sigma^f_{len} \Big/ \sqrt{p^f_{y,\ell}}\right] + \left(p^f_{y,\ell} \Big/ \left(2\left(\sigma^f_{len}\right)^2\right)\right)\left[\ln p^{obs}_{y,\ell}(f) - \ln p^f_{y,\ell}\right]^2 \right\} \tag{A1.33}$$

where

$p^{obs}_{y,\ell}(f)$ is the proportion by number of the catch in year *y* in length group *ℓ* for fleet *f*, and

σ^f_{len} has a closed form maximum likelihood estimate given by:

$$\left(\hat{\sigma}^f_{len}\right)^2 = \sum_{y,\ell} p^f_{y,\ell}\left[\ln p^{obs}_{y,\ell}(f) - \ln p^f_{y,\ell}\right]^2 \Big/ \sum_{y,\ell} 1 \, . \tag{A1.34}$$

Equation (A1.33) makes the assumption that proportions-at-length data are log-normally distributed about their model-predicted values. The associated variance is taken to be inversely proportional to $p^{f}_{y,\ell}$ to downweight contributions from expected small proportions which will correspond to small observed sample sizes. This adjustment (known as the Punt-Kennedy approach) is of the form to be expected if a Poisson-like sampling variability component makes a major contribution to the overall variance. Given that overall sample sizes for length distribution data differ quite appreciably from year to year, subsequent refinements of this approach may need to adjust the variance assumed for equation (A1.33) to take this into account.

The w_{len} weighting factor may be set at a value less than 1 to downweight the contribution of the catch-at-length data to the overall negative log-likelihood compared to that of the CPUE data in equation (A1.27). The reason that this factor is introduced is that the $p^{obs}_{y,\ell}(f)$ data for a given year frequently show evidence of strong positive correlation, and so would not be as informative as the independence assumption underlying the form of equation (A1.33) would otherwise suggest.

In the practical application of equation (A1.33), length observations were grouped by 2 cm intervals, with minus- and plus-groups specified below 54 and above 138 cm respectively for the longline fleet, and plus-groups above 176 cm for the pot fleet, to ensure $p^{obs}_{y,\ell}(f)$ values in excess of about 2% for these cells.

ADJUSTMENT TO INCORPORATE RECRUITMENT VARIABILIITY

To allow for stochastic recruitment, the number of recruits at the start of year *y* given by equation (A1.15) is replaced by:

$$R(B^{sp}_y) = \frac{\alpha\, B^{sp}_y}{\beta\ + B^{sp}_y} e^{\left(\zeta_y - \sigma^2_{R/2}\right)}, \qquad \text{(A1.35)}$$

where ζ_y reflects fluctuation about the expected recruitment for year *y*, which is assumed to be normally distributed with standard deviation σ_R (which is input). The ζ_y are estimable parameters of the model.

The stock-recruitment function residuals are assumed to be log-normally distributed. Thus, the contribution of the recruitment residuals to the negative log-likelihood function is given by:

$$-\ln L_{rec} = \sum_{y=1961} \left\{ \ln\sigma_R + \zeta^2_y \big/ \left(2\sigma^2_R\right) \right\}, \qquad \text{(A1.36)}$$

which is added to the negative log-likelihood of equation (A1.27) as a penalty (the frequentist equivalent of a Bayesian prior for these parameters). In the present application, it is assumed that the resource is not at equilibrium at the start of the fishery, but rather in such equilibrium in 1960 with zero catches taken until the start of the fishery in 1997 (by which time virtually all “memory” of the original equilibrium has been lost because of subsequent recruitment variability). For the computations reported in this paper $\sigma_R = 0.5$.

EXTENSION TO INCLUDE TAG-RECAPTURE DATA

The approach described by Butterworth *et al*. (2003) has been implemented in this paper to take into account tag-recapture data. The recaptures follow a Poisson distribution and therefore the following term is added to the negative log-likelihood of equation (A1.27):

$$-\ln L_{tag} = \sum_{f,y,a} \left\{ \hat{r}^f_{y,a} - r^f_{y,a} \ln \hat{r}^f_{y,a} \right\} \tag{A1.37}$$

where

$r^f_{y,a}$ is the number of recaptured tags from toothfish of age a in year y by fleet f that have been at large for more than a year, and

$\hat{r}^f_{y,a}$ is the expected number of recaptures of age a in year y by fleet f, given by:

$$\hat{r}^f_{y,a} = \zeta_{y,a} \frac{F^f_{y,a}}{M_a + F_{y,a}} \left\{ 1 - e^{-\left(M_a + F_{y,a}\right)} \right\} \sum_{k=1}^{a-1} R_{y-k,a-k} e^{-\left(M_{a-k} + F^*_{y-k,a-k}\right)} \left[\prod_{j=1,k\geq 2}^{k-1} e^{-\left(M_{a-j} + F_{y-j,a-j}\right)} \right] \tag{A1.38}$$

where

$R_{y-k,a-k}$ is the number of tags released in year *y-k* of age *a-k*,

$F_{y,a}$ is the fishing mortality for toothfish in year y of age a, which is given by the summation of the fleet specific fishing mortalities $F^f_{y,a}$,

M_a is the natural mortality rate for toothfish of age a (assumed to be independent of age),

$\zeta_{y,a}$ is the tag-reporting rate for toothfish in year y of age a (assumed to be 1 in this paper), and

$F^*_{y-k,a-k}$ is the fishing mortality of tagged toothfish in year *y-k* of age *a-k* during the first year at large. This is estimated from the number of tags recaptured by each fleet within the first year that the toothfish are at large. However in this instance, as there are minimal recaptures for longlines and none for trotlines within the first year, these fishing mortalities have been assumed to be the same as $F_{y-k,a-k}$.