Assessment of the toothfish (*Dissostichus eleginoides*) resource in the Prince Edward Islands vicinity to include data from 1997 to 2017

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September2017

ABSTRACT

The assessment of the Prince Edward Islands (PEI) toothfish (*Dissostichus eleginoides*) resource carried out by Brandão and Butterworth (2017) is updated to take further data now available for 2017 into account. This update also incorporates 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 36-42% range. If the model is forced to fit the trotline CPUE indices and the tag-recapture data as well, the estimated average pre-exploitation level in terms of spawning biomass is in the range of 12-26%, but this requires an assumption of very high levels of tag loss.

INTRODUCTION

The assessment of the Prince Edward Islands (PEI) toothfish (*Dissostichus eleginoides*) resource carried out by Brandão and Butterworth (2017) is updated to take further data now available for 2017 into account.

As in Brandão and Butterworth (2017), estimates of the "split" month factors are used to provide an estimate for cetacean depredation (applied to longlines only) 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 to adopt 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 Base case model is the model that continues to include tagging data. Sensitivity tests of the Base case model are also carried out to investigate what aspects of the assessment may conflict 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 (2017), 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 2017 have been incorporated in the present analyses; these were not available for previous assessments of toothfish in the Prince Edward Islands vicinity. No data for 2018 were available for the present assessment. 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 is 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 (2018) for the trotline commercial data which now include 2017 data is listed in Table 2. The longline fleet has not operated since 2013 until 2016, 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, (2015a) and also given in Table 2. 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 2017.* 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 from 2017*. 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 (2017), 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.

Eight sensitivity tests have been conducted to fully understand various aspects of the assessment. These sensitivity tests are:

i) An alternative amount of cetacean predation is assumed (one out of three toothfish is lost to cetaceans (referred to as 1.5x)).
ii) Assume a tag-reporting rate of 0.8 instead of 1.
iii) Double the 1997 IUU estimate.
iv) The last two indices (2016 and 2017) of trotline CPUE are up-weighted by a factor of 10.
v) All CPUE indices from 2010 up-weighted by a factor of 10.
vi) Omit the 2008 and 2009 trotline CPUE indices.
vii) Repeat of sensitivity (v) but applied to sensitivity (vi).
viii) Tag loss of 0.75 (i.e. 75% of the tags are lost) applied to sensitivity (vii).
ix) All CPUE indices from 2010 up-weighted by a factor of 5 and a tag loss of 0.5, applied to sensitivity (vi).

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, 2017) and a sensitivity for when an alternative factor for cetacean predation is assumed. Both these updated assessments suggest the current (start of 2019) status of the resource to be at 38% of average pre-exploitation equilibrium spawning biomass, a value which has decreased from 40% for the start of 2018. The previous Base case assessment suggests that this status of the resource at the beginning of 2018 was at 41%. 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 slightly the fit to the longline CPUE indices (see the σ_{CPUE} values in Table 5). The model does not fit the latest two low CPUE indices for the trotline fishery well.

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.

Tables 6 and 7 shows the results for five other sensitivity tests performed which are variants of the Base case model. These reflect attempts to improve the fit to the trotline CPUE indices, as well as to address some concerns about some of the assumptions made in the Base case model. For comparison, results for the Base case are reproduced in these Tables as well. The two sensitivity tests that achieved a lower depletion levels are the one that doubles the 1997 IUU estimate and the one that assumes a reporting rate of 0.8. Figure 7 compares the spawning biomass (a) and recruitment (b) for the previous Base case and the present Base case, as well as the five sensitivity tests reported in Tables 6 and 7. Figure 7b clearly shows that the sensitivity test that doubles the 1997 IUU estimates sets an even larger peak in recruitment in 1990, as well as two other peaks prior to that. Figure 8 shows fits to the CPUE indices for these sensitivity tests (including those for Base case as well as the previous Base case models) except for the sensitivity test that assumes an alternative value for cetacean predation. The sensitivity tests that fit the first CPUE index slightly better are the ones that up-weights all CPUE indices since 2010 and that doubles the 1997 IUU estimate. Such up-weighting results in a better fit to the trotline CPUE indices but has a worse fit to the longline CPUE indices (see the σ_{CPUE} values in Table 7).

Table 8 shows the results for the remaining three sensitivity tests that attempt to improve the fit to the trotline CPUE indices and the tagging data. All these sensitivity tests are applied to the variant of the Base case in which the 2008 and 2009 trotline CPUE indices are omitted (and the results are reproduced here for comparison). The sensitivities that try to fit to both the trotline CPUE and the tagging data estimate much lower values of spawning biomass. Figure 9 compares the spawning biomass (a) and recruitment (b) for the Base case model as well as these four sensitivity tests reported in Table 8. Figure 9b shows that all sensitivity tests that up-weight the CPUE indices estimate two large peaks of recruitment, one in 1983 and another in 1990. Figure 10 shows fits to the CPUE indices for these sensitivity tests (including those for Base case model).

Figure 11a shows the fit to the cumulative recapture numbers of toothfish for the sensitivity test that up-weights all the CPUE indices and omits the 2008 and 2009 trotline CPUE indices (top) and for the sensitivity when the 1997 IUU estimate is doubled. Figure 11b compares this fit to the sensitivity tests that try to improve the fit to the trotline CPUE indices. To force the model to fit the trotline very well (see the σ_{CPUE} values in Table 8 and Figure 10), a tag loss of 0.75 was required. The sensitivity test with a lower weight factor applied to the CPUE indices and a tag loss of 0.5 was run to see what the results would be to the fit of the trotline CPUE indices and the tagging data if a lower tag loss was assumed. This sensitivity test is capable of fitting to the initial high longline CPUE index, while the sensitivity test that fits well to the trotline CPUE overestimates this initial estimate considerably (Figure 10).

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 38% of its average pre-exploitation level if tagging data are taken into account. There has been a slight improvement in the CV estimates following the inclusion of the further data now available, and in absolute terms biomass estimates have dropped throughout the period considered. In terms of status (relative to its pre-exploitation level) the resource is now estimated to be slightly below 40% rather than slightly above 40% (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. To achieve a better fit to the trotline CPUE indices, the fit to the tagging data deteriorates and a tag loss of 0.75 was needed to improve the fit to the tagging data as well as the trotline CPUE indices.

ACKNOWLEDGEMENTS

Deon Durholtz of DAFF is thanked for providing the data. The estimation software used, AD Model Builder, is a trademark of Otter Research Ltd., P O Box 265, Station A, Nanaimo, B.C. V9R 5K9, Canada.

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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	406.6	542.0
2005	142.6	141.9	—	—	284.5	298.8	355.8
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	76.6	93.4
2010	49.2	—	174.6	—	223.7	228.7	248.3
2011	1.0	—	290.4	—	291.4	291.5	291.9
2012	52.4	—	223.5	—	275.9	281.1	302.1
2013	49.7	—	215.6	—	265.3	270.3	290.2
2014	—	—	366.9	—	366.9	366.9	366.9
2015	—	—	431.3	—	431.3	431.3	431.3
2016	—	—	298.0	—	298.0	298.0	298.0
2017	—	—	110.8	—	110.8	110.8	110.8
2018†	—	—	575.0	—	575.0	575.0	575.0
1997–2018 total	8 280.7	176.2	2 773.2	26 452	37 682	38 039.1	39 467.5

† The catch assumed for 2018 is the TAC for the year (with the whole catch assumed to have 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 fisheries (Brandão and Butterworth, 2015a, 2017). 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	0.690
2009	0.641	0.705	0.962	0.862
2010	0.531	0.584	0.797	1.231
2011	0.159	0.175	0.239	1.000
2012	0.334	0.368	0.501	1.129
2013	0.333	0.366	0.499	0.901
2014	—	—	—	0.761
2015	—	—	—	0.813
2016	—	—	—	0.538
2017	—	—	—	0.520

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**	**2017**
Numbers Tagged	175	179	120	140	75	131	206	162	253	379	458	324	115
Recaptures													
2005	***1***												
2006	**1†**												
2007	1	1	***1***										
2008													
2009			1	2									
2010			1	1									
2011		1	2	2		4	***1***						
2012	1	1		1		2							
2013					1		4		***1***				
2014		1	1	2		1	1	3	3 (***5†***)	***5***			
2015			1	3			1	3	9	9 (***6†***)	***6***		
2016				1	1	2		3		13	1(**7†**)	***1***	
2017							1	1	5	9	6	***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, catch-at-length data and tag-recapture 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 $\left(B_{sp}^{2019}\right)$ in terms of both K_{sp} and $MSYL_{sp}$, and the (longline) exploitable biomass $\left(B_{\exp}^{2019}\right)$ at the beginning of the year 2019 (assuming the same selectivity as for 2018). 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)*	Model: Base case (tagging data; predation 1.1x)	Model: Predation 1.5x
K_{sp} (tonnes)		28 711 (0.108)	27 618 (0.105)	29 069 (0.104)
$MSYL_{sp}$ (Longline)/K_{sp}		0.244	0.243	0.243
B_{sp}^{2018}/K_{sp}		0.408 (0.096)	0.398 (0.095)	0.398 (0.095)
B_{sp}^{2019}/K_{sp}		—	0.377 (0.094)	0.379 (0.094)
B_{sp}^{1997}/K_{sp}		1.337 (0.099)	1.360 (0.099)	1.348 (0.098)
$B_{sp}^{2019}/MSYL_{sp}$(Longline)		1.677	1.550	1.556
$B_{sp}^{2019}/MSYL_{sp}$(Trotline)		1.661	1.536	1.542
$B_{\exp}^{2019}$ (tonnes)	Longline	10 202 (0.148)	10 199 (0.131)	10 910 (0.130)
	Pot	15 347 (0.125)	14 681 (0.117)	15 483 (0.116)
	Trotline	11 949 (0.134)	11 697 (0.120)	12 451 (0.119)
σ_{CPUE}	Longline	0.370	0.357	0.325
	Trotline	0.221	0.239	0.241
σ_R		0.500††	0.500††	0.500††
a_{50}^{97-02} (yr)		6.499	6.499	6.499
δ^{97-02} (yr^{-1})		0.020	0.020	0.020
ω^{97-02} (yr^{-1})		0.057	0.057	0.057
a_{50}^{03-18} (yr)	Longline	6.424	6.403	6.404
	Pot	8.582	8.489	8.532
	Trotline	7.263	7.214	7.216
δ^{03-18} (yr^{-1})	Longline	0.131	0.134	0.135
	Pot	0.872	0.862	0.872
	Trotline	0.273	0.270	0.270
ω^{03-18} (yr^{-1})	Longline	0.074	0.076	0.074
	Pot	0.000	0.000	0.000
	Trotline	0.037	0.039	0.038
β		0.116 (0.019)	0.115 (0.020)	0.115 (0.019)
σ_{len}	Longline	0.042	0.042	0.042
	Pot	0.035	0.035	0.035
	Trotline	0.038	0.036	0.036

†† Input value.

* The results shown for the "current" biomass-related values for the previous Base case are for 2018, and not for 2019 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, catch-at-length data and tag-recapture 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 $\left(B_{\exp}^{2019}\right)$ in terms of both K_{sp} and $MSYL_{sp}$, and the (longline) exploitable biomass $\left(B_{\exp}^{2019}\right)$ at the beginning of the year 2019 (assuming the same selectivity as for 2018). 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		-880.0	-930.3	-930.1
-ln *L*: CPUE		-17.48	-18.29	-19.84
-ln *L*: Recruitment		9.813	12.97	11.66
-ln *L*: Tagging		178.0	200.4	202.4
-ln *L*: Total		-709.6	-735.2	-735.9
MSY (tonnes)	Longline	1 152†	1 106†	1 165†
	Pot	1 271	1 221	1 286
	Trotline	1 209	1 159	1 221

† 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. The details of the various sensitivity tests reported are given in the text.

Parameter estimates		Model: Base case (tagging data; predation 1.1x)	Model: Sensitivity: Double IUU in 1997	Model: Sensitivity: Omit first 2 years of trotline CPUE	Model: Sensitivity: w_{CPUE}(trotline)=10 for last 2 years
K_{sp} (tonnes)		27 618 (0.105)	35 021 (0.121)	27 726 (0.105)	27800 (0.106)
$MSYL_{sp}$ (Longline)/K_{sp}		0.243	0.243	0.243	0.243
B_{sp}^{2018}/K_{sp}		0.398 (0.095)	0.375 (0.102)	0.398 (0.095)	0.400 (0.096)
B_{sp}^{2019}/K_{sp}		0.377 (0.094)	0.357 (0.101)	0.377 (0.094)	0.377 (0.095)
B_{sp}^{1997}/K_{sp}		1.360 (0.099)	1.468 (0.134)	1.371 (0.099)	1.412 (0.099)
$B_{sp}^{2019}/MSYL_{sp}$(Longline)		1.550	1.466	1.551	1.552
$B_{sp}^{2019}/MSYL_{sp}$(Trotline)		1.536	1.455	1.538	1.541
B_{exp}^{2019} (tonnes)	Longline	10 199 (0.131)	12 138 (0.137)	10 048 (0.133)	9376 (0.134)
	Pot	14 681 (0.117)	17 676 (0.122)	14 735 (0.117)	14616 (0.118)
	Trotline	11 697 (0.120)	13 785 (0.124)	11 485 (0.121)	10603 (0.121)
σ_{CPUE}	Longline	0.357	0.345	0.355	0.349
	Trotline	0.239	0.241	0.229	0.194
σ_R		0.500††	0.500††	0.500††	0.500††
a_{50}^{97-02} (yr)		6.499	6.499	6.499	6.499
δ^{97-02} (yr^{-1})		0.020	0.020	0.020	0.020
ω^{97-02} (yr^{-1})		0.057	0.055	0.058	0.061
a_{50}^{03-18} (yr)	Longline	6.403	6.399	6.402	6.397
	Pot	8.489	8.428	8.440	8.290
	Trotline	7.214	7.212	7.214	7.208
δ^{03-18} (yr^{-1})	Longline	0.134	0.134	0.135	0.135
	Pot	0.862	0.851	0.850	0.811
	Trotline	0.270	0.269	0.270	0.271
ω^{03-18} (yr^{-1})	Longline	0.076	0.078	0.077	0.082
	Pot	0.000	0.000	0.000	0.000
	Trotline	0.039	0.041	0.040	0.045
β		0.115 (0.020)	0.115 (0.002)	0.115 (0.020)	0.115 (0.020)
σ_{len}	Longline	0.042	0.042	0.042	0.042
	Pot	0.035	0.035	0.035	0.034
	Trotline	0.036	0.036	0.036	0.036

†† 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: Double IUU in 1997**	**Sensitivity: Omit first 2 years of trotline CPUE**	**Sensitivity: w_{CPUE}(trotline)=10 for last 2 years**
-ln *L*: Length		-930.3	-931.6	-930.8	-931.7
-ln *L*: CPUE		-18.29	-18.82	-16.87	-41.31
-ln *L*: Recruitment		12.97	24.80	13.84	16.97
-ln *L*: Tagging		200.4	202.2	200.2	199.2
-ln *L*: Total		-735.2	-723.3	-733.6	-756.8
MSY (tonnes)	Longline	1 106†	1 403†	1 110†	1 109†
	Pot	1 221	1 546	1 225	1 225
	Trotline	1 159	1 468	1 162	1 161

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

Table 7. Estimates for two **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)	Model: Sensitivity: w_{CPUE}(trotline)=10 for all years	Model: Sensitivity: reporting rate 0.8
K_{sp} (tonnes)		27 618 (0.105)	28 230 (0.108)	24 584 (0.103)
$MSYL_{sp}$ (Longline)/K_{sp}		0.243	0.242	0.244
B_{sp}^{2018}/K_{sp}		0.398 (0.095)	0.418 (0.098)	0.361 (0.099)
B_{sp}^{2019}/K_{sp}		0.377 (0.094)	0.387 (0.098)	0.340 (0.098)
B_{sp}^{1997}/K_{sp}		1.360 (0.099)	1.581 (0.100)	1.398 (0.103)
$B_{sp}^{2019}/MSYL_{sp}$(Longline)		1.550	1.602	1.397
$B_{sp}^{2019}/MSYL_{sp}$(Trotline)		1.536	1.597	1.385
B_{exp}^{2019} (tonnes)	Longline	10 199 (0.131)	7 605 (0.142)	8 368 (0.135)
	Pot	14 681 (0.117)	14 867 (0.122)	11 822 (0.121)
	Trotline	11 697 (0.120)	8 208 (0.121)	9 445 (0.123)
σ_{CPUE}	Longline	0.357	0.419	0.343
	Trotline	0.239	0.181	0.235
σ_R		0.500††	0.500††	0.500††
a_{50}^{97-02} (yr)		6.499	6.474	6.499
δ^{97-02} (yr^{-1})		0.020	0.022	0.020
ω^{97-02} (yr^{-1})		0.057	0.071	0.055
a_{50}^{03-18} (yr)	Longline	6.403	6.384	6.404
	Pot	8.489	7.745	8.496
	Trotline	7.214	7.200	7.220
δ^{03-18} (yr^{-1})	Longline	0.134	0.137	0.134
	Pot	0.862	0.641	0.865
	Trotline	0.270	0.270	0.270
ω^{03-18} (yr^{-1})	Longline	0.076	0.100	0.076
	Pot	0.000	0.000	0.000
	Trotline	0.039	0.064	0.039
β		0.115 (0.020)	0.115 (0.020)	0.115 (0.019)
σ_{len}	Longline	0.042	0.042	0.042
	Pot	0.035	0.033	0.035
	Trotline	0.036	0.036	0.036

†† Input value(s).

Table 7 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: w_{CPUE}(trotline)=10 for all years**	**Sensitivity: reporting rate 0.8**
-ln *L*: Length		-930.3	-932.3	-932.9
-ln *L*: CPUE		-18.29	-118.7	-19.18
-ln *L*: Recruitment		12.97	30.27	18.08
-ln *L*: Tagging		200.4	197.7	200.3
-ln *L*: Total		-735.2	-823.0	-733.7
MSY (tonnes)	Longline	1 106†	1 114†	986†
	Pot	1 221	1 232	1 087
	Trotline	1 159	1 161	1 032

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

Table 8. Estimates for four **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**			
		Sensitivity: Omit first 2 years of trotline CPUE	**Sensitivity: Omit first 2 years of trotline CPUE and w_{CPUE}(trotline)=10 for all years**	**Sensitivity: Omit first 2 years of trotline CPUE and w_{CPUE}(trotline)=10 for all years and 75% of tags lost**	**Sensitivity: Omit first 2 years of trotline CPUE and w_{CPUE}(trotline)=5 for all years and 50% of tags lost**
K_{sp} (tonnes)		27 726 (0.105)	27 648 (0.122)	11 381 (0.098)	17 065 (0.119)
$MSYL_{sp}$ (Longline)/K_{sp}		0.243	0.241	0.244	0.243
B_{sp}^{2018}/K_{sp}		0.398 (0.095)	0.447 (0.115)	0.155 (0.161)	0.290 (0.127)
B_{sp}^{2019}/K_{sp}		0.377 (0.094)	0.411 (0.113)	0.123 (0.162)	0.259 (0.127)
B_{sp}^{1997}/K_{sp}		1.371 (0.099)	1.778 (0.129)	2.170 (0.102)	1.853 (0.114)
$B_{sp}^{2019}/MSYL_{sp}$(Longline)		1.551	1.706	0.503	1.067
$B_{sp}^{2019}/MSYL_{sp}$(Trotline)		1.538	1.704	0.503	1.067
B_{exp}^{2019} (tonnes)	Longline	10 048 (0.133)	6 810 (0.156)	1 688 (0.149)	3 700 (0.177)
	Pot	14 735 (0.117)	15 206 (0.124)	1 994 (0.151)	6 134 (0.157)
	Trotline	11 485 (0.121)	7 128 (0.137)	1 483 (0.074)	3 718 (0.164)
σ_{CPUE}	Longline	0.355	0.415	0.431	0.394
	Trotline	0.229	0.151	0.079	0.138
σ_R		0.500††	0.500††	0.500††	0.500††
a_{50}^{97-02} (yr)		6.499	6.497	6.506	6.498
δ^{97-02} (yr^{-1})		0.020	0.021	0.021	0.021
ω^{97-02} (yr^{-1})		0.058	0.077	0.044	0.058
a_{50}^{03-18} (yr)	Longline	6.402	6.383	6.323	6.400
	Pot	8.440	7.487	8.478	7.995
	Trotline	7.214	7.209	7.344	7.254
δ^{03-18} (yr^{-1})	Longline	0.135	0.137	0.021	0.134
	Pot	0.850	0.531	0.844	0.721
	Trotline	0.270	0.270	0.269	0.273
ω^{03-18} (yr^{-1})	Longline	0.077	0.111	0.080	0.093
	Pot	0.000	0.000	0.000	0.000
	Trotline	0.040	0.076	0.052	0.061
β		0.115 (0.020)	0.116 (0.021)	0.118 (0.005)	0.116 (0.019)
σ_{len}	Longline	0.042	0.042	0.040	0.041
	Pot	0.035	0.033	0.034	0.034
	Trotline	0.036	0.036	0.036	0.036

†† Input value(s).

Table 8 cont. Estimates for four **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			
		Sensitivity: Omit first 2 years of trotline CPUE	**Sensitivity: Omit first 2 years of trotline CPUE and w_{CPUE}(trotline)=10 for all years**	**Sensitivity: Omit first 2 years of trotline CPUE and w_{CPUE}(trotline)=10 for all years and tag loss 0.75**	**Sensitivity: Omit first 2 years of trotline CPUE and w_{CPUE}(trotline)=5 for all years and tag loss 0.5**
-ln *L*: Length		-930.8	-931.1	-955.6	-945.9
-ln *L*: CPUE		-16.87	-131.4	-181.1	-73.46
-ln *L*: Recruitment		13.84	38.84	72.13	49.89
-ln *L*: Tagging		200.2	198.3	168.8	197.0
-ln *L*: Total		-733.6	-825.4	-895.9	-772.5
MSY (tonnes)	Longline	1 110†	1 085†	459†	679†
	Pot	1 225	1 201	503	748
	Trotline	1 162	1 128	475	705

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

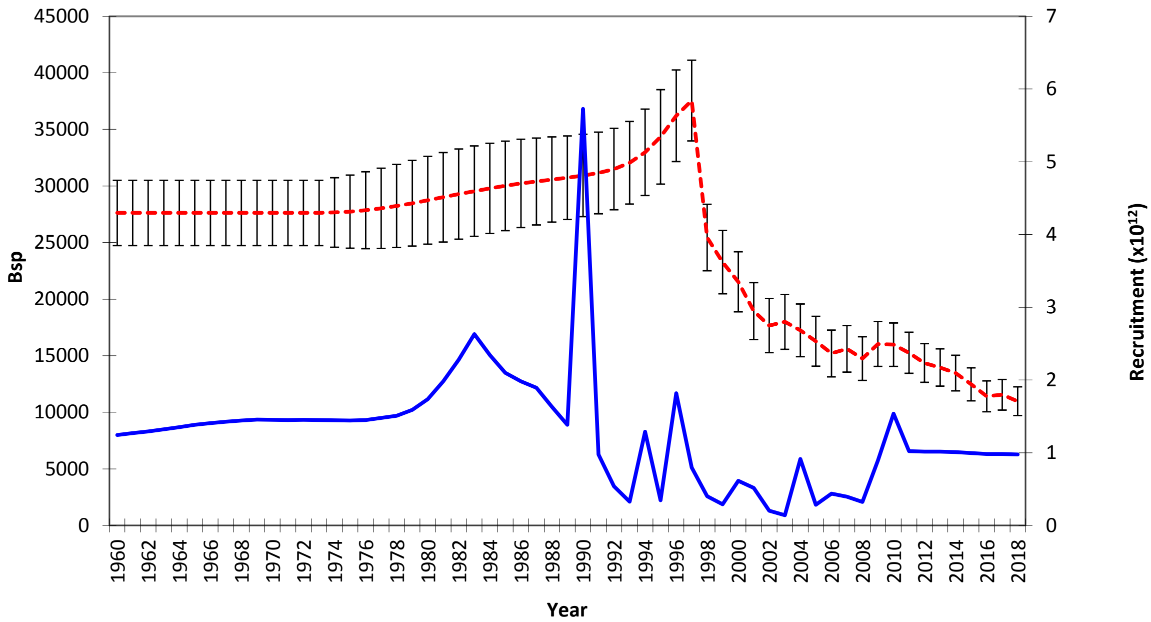

Figure 1. Spawning biomass estimates (dashed line) and estimated recruitment (full line) for the three-fleet model for the **Base case** that takes tagging data into account (with cetacean predation 1.1x). Confidence limits (Hessian-based) of one standard error for the spawning biomass are also shown.

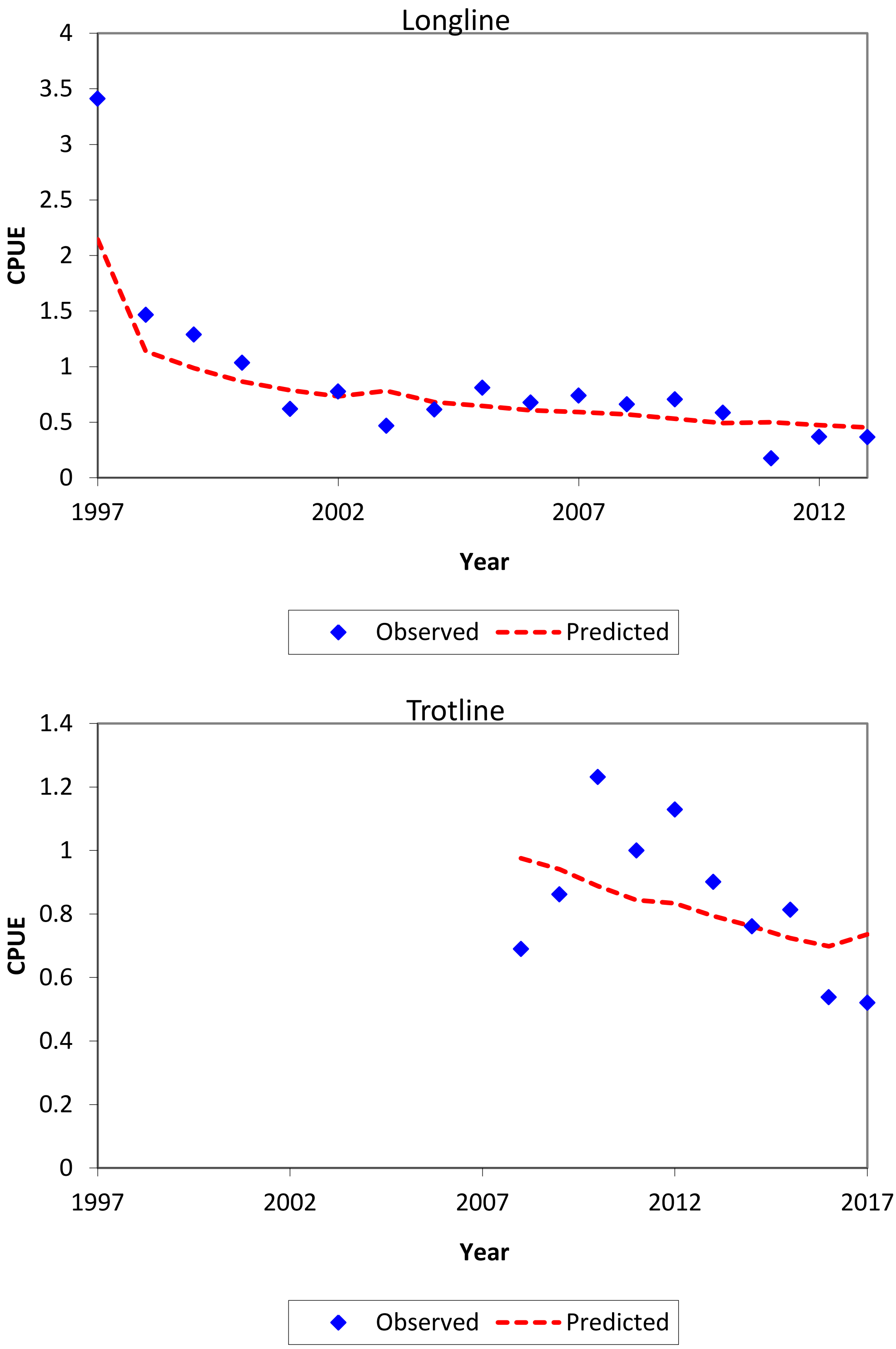

Figure 2. Exploitable biomass and the GLM-standardised CPUE indices to which the model is fit (divided by the estimated catchability q to express them in biomass units) for the **Base case**.

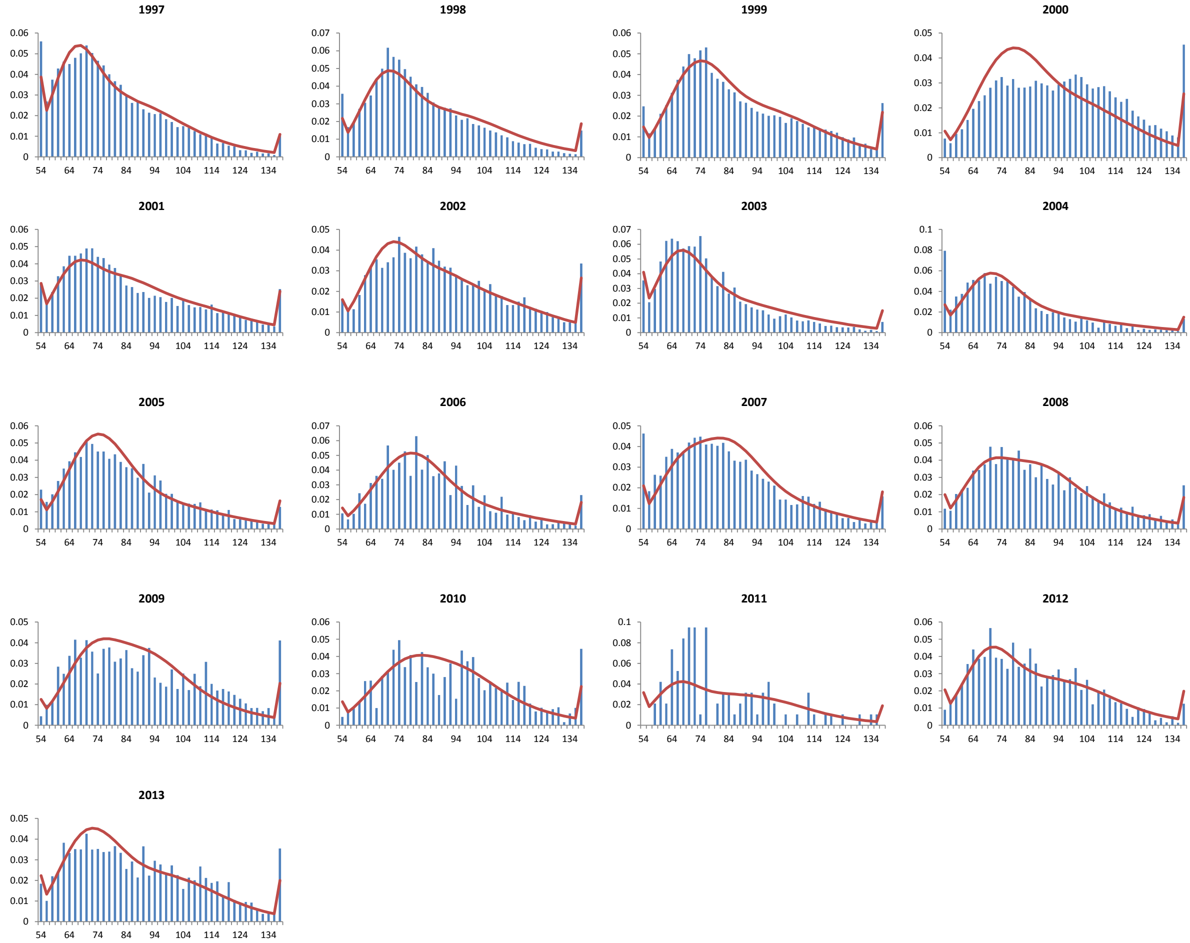

Figure 3a. Assessment predictions for the annual catch-at-length proportions in the longline fishery for the **Base case**. Note that lengths below 54 and above 138 cm are combined into minus- and plus-groups respectively.

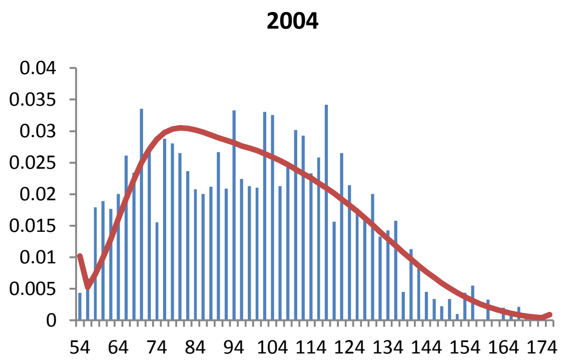

Figure 3b. Assessment predictions for the annual catch-at-length proportions in the pot fishery for the **Base case**. Note that lengths below 54 and above 176 cm are combined into minus- and plus-groups.

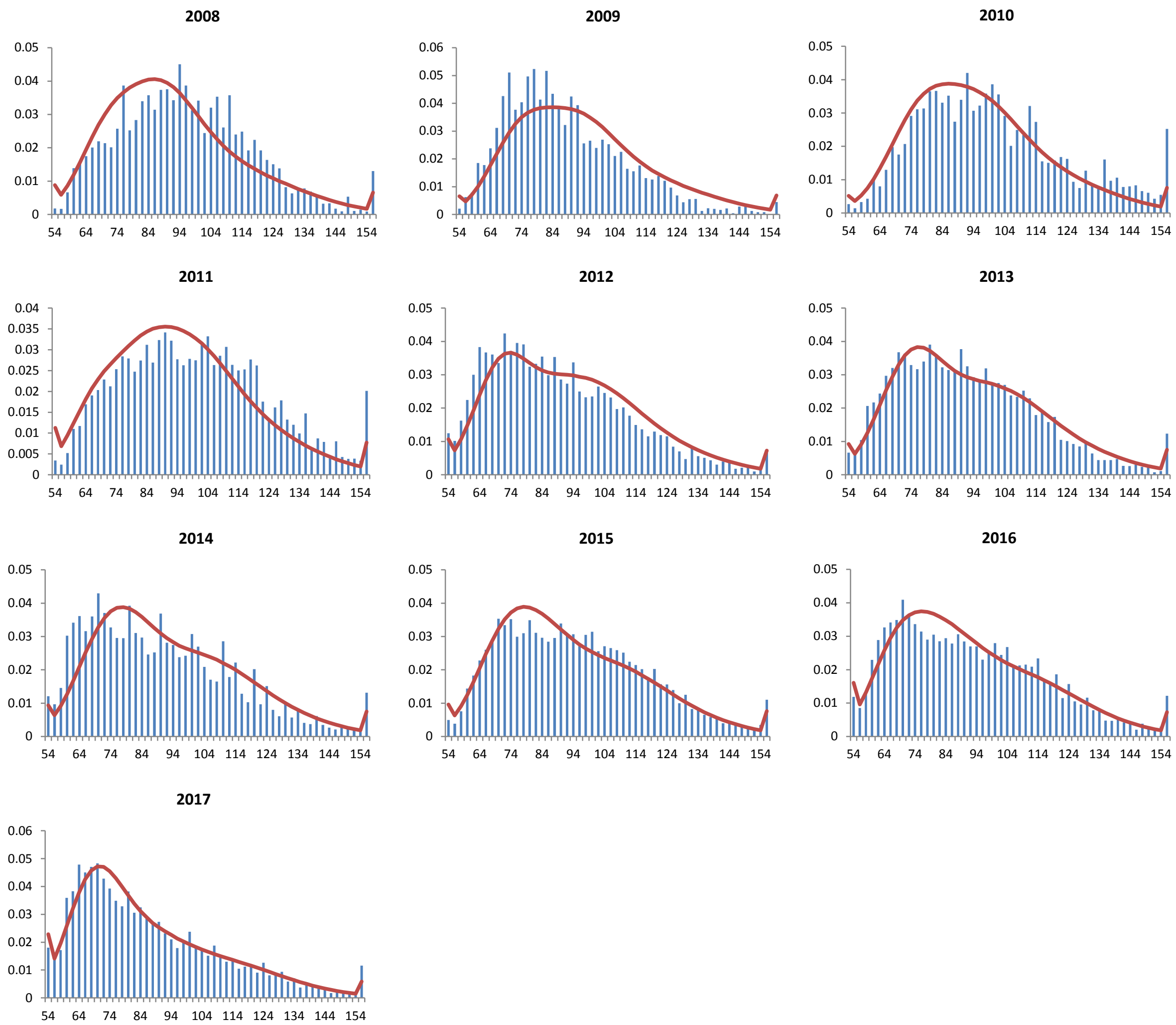

Figure 3c. Assessment predictions for the annual catch-at-length proportions in the trotline fishery for the **Base case**. Note that lengths below 54 and above 156 cm are combined into minus- and plus-groups respectively.

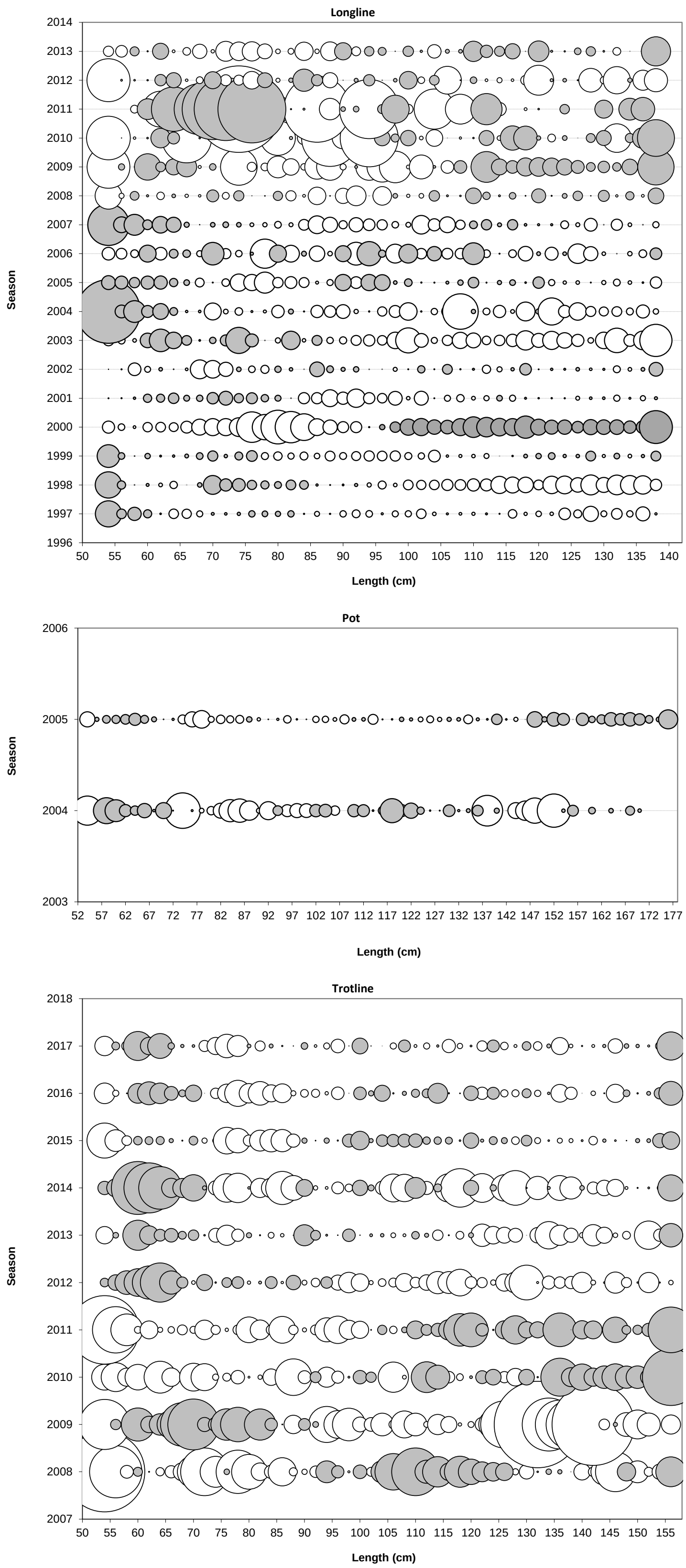

Figure 4. Bubble plots of the catch-at-length residuals for the three fisheries for the **Base case**. The size of the bubble is proportional to the corresponding standardised residual $\left(\left(\ln(obs)-\ln(pred)\right)\Big/\left(\sigma\big/\sqrt{pred}\right)\right)$. White bubbles represent negative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

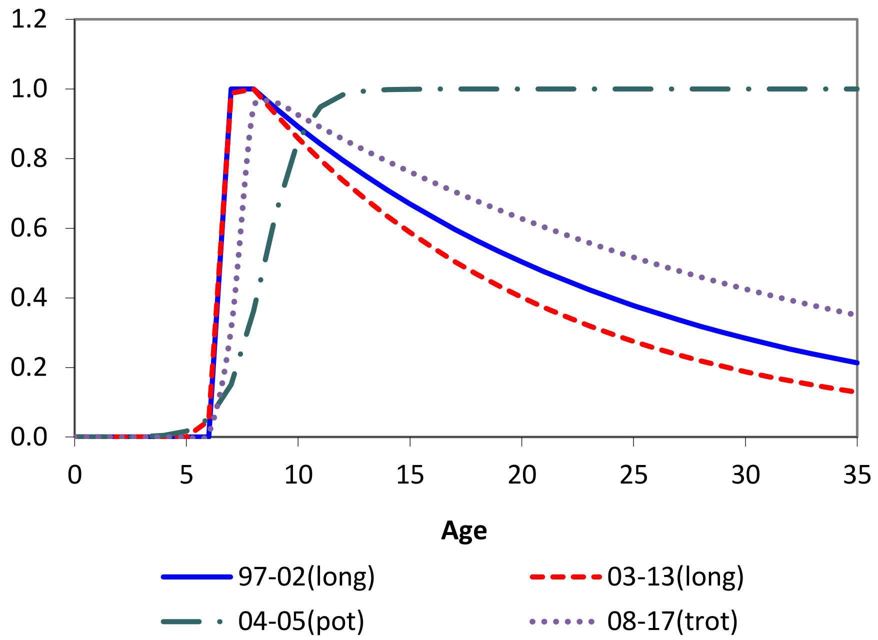

Figure 5. Estimated selectivity curves for the periods 1997–2002 and 2003–2013 for the longline fishery, for the period 2004-2005 for the pot fishery and for the period 2008–2016 for the trotline fishery. Curves are shown for the **Base case**.

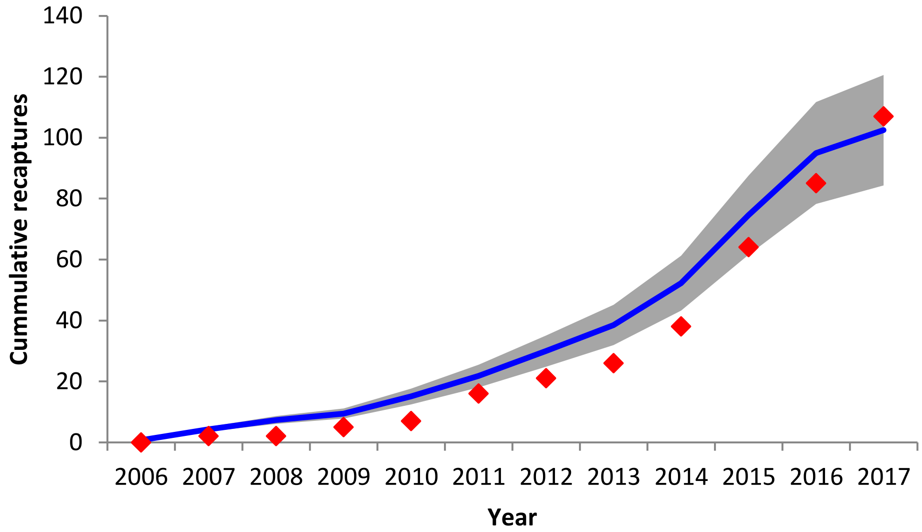

Figure 6. Observed (diamonds) and model predicted (continuous line) cumulative recapture numbers of toothfish for the **Base case** model, and combining recaptures by longlines and trotlines. The shaded area reflects the 95% confidence interval envelope.

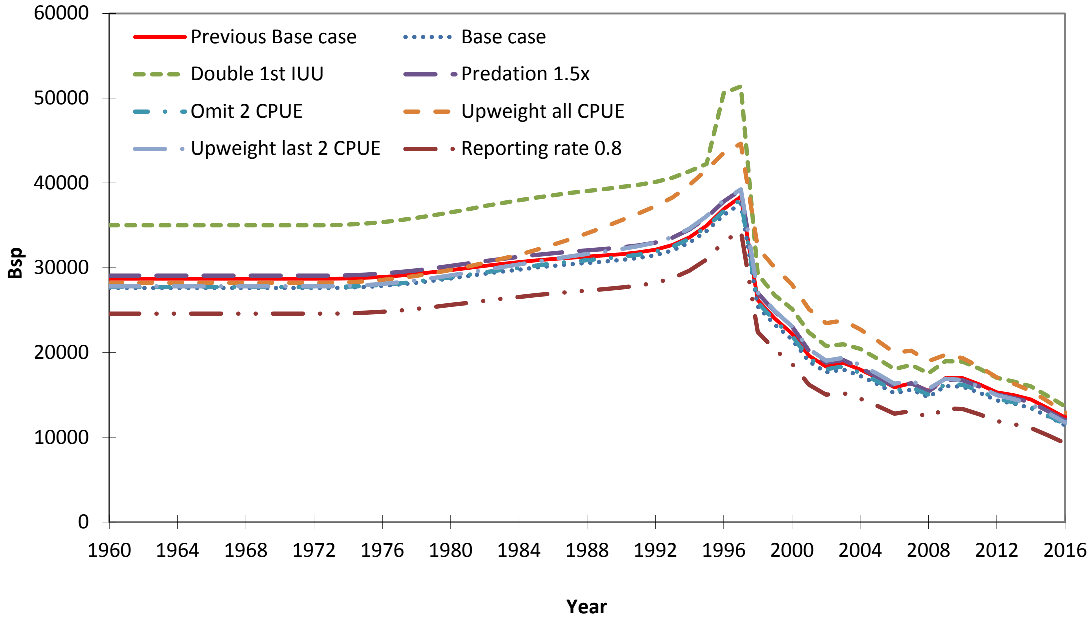

Figure 7a. Spawning biomass estimates for the **Base case** (and the previous Base case) as well as six **sensitivity tests:** 1) doubles 1997 IUU estimate, 2) omits 2008 and 2009 trotline CPUE indices, 3) assumes cetacean predation of 1.5, 4) up-weights last two trotline CPUE indices, 5) up-weights all CPUE indices from 2010 and 6) assumes a reporting rate of 0.8.

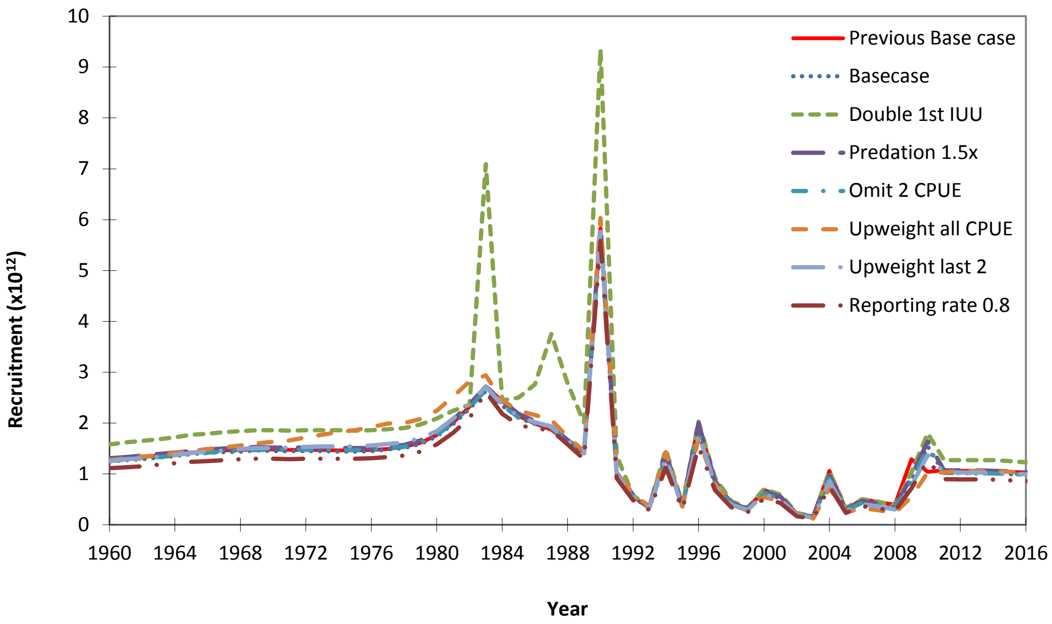

Figure 7b. Estimated recruitment for the **Base case** and the four **sensitivities** detailed in the caption to Figure 7a.

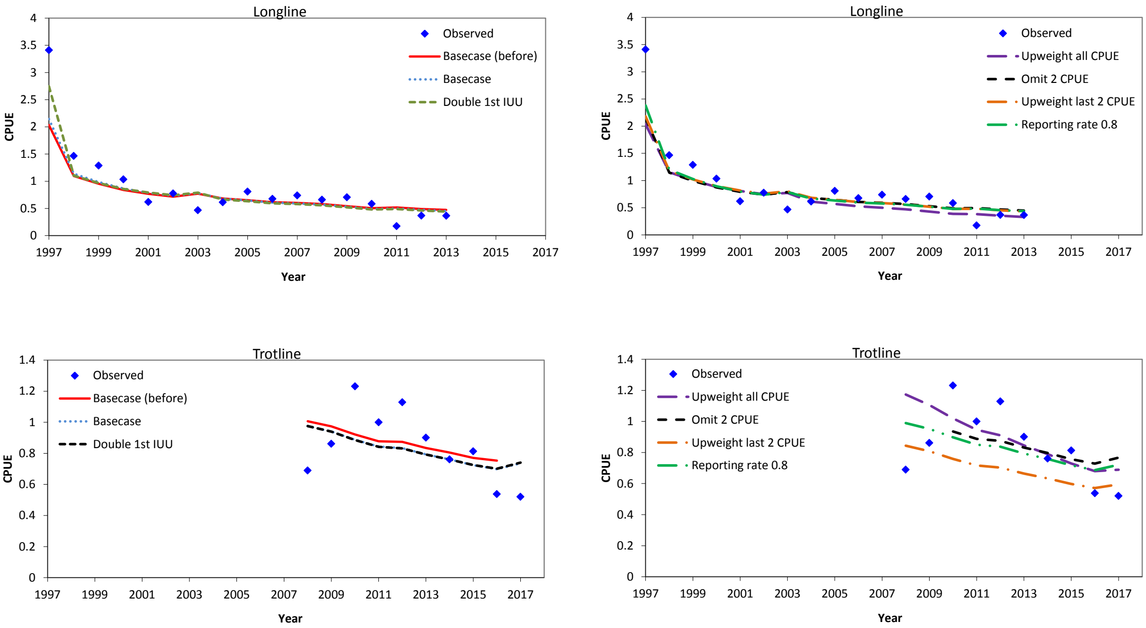

Figure 8a. Exploitable biomass and the GLM-standardised CPUE indices to which the model is fit (divided by the estimated catchability *q* to express them in biomass units) for the previous Base case and the present **Base case** as well as five **sensitivity** tests that 1) doubles 1997 IUU estimate, 2) omits 2008 and 2009 trotline CPUE indices, 3) up-weights last two trotline CPUE indices, 4) up-weights all CPUE indices from 2010 and 5) assumes a reporting rate of 0.8.

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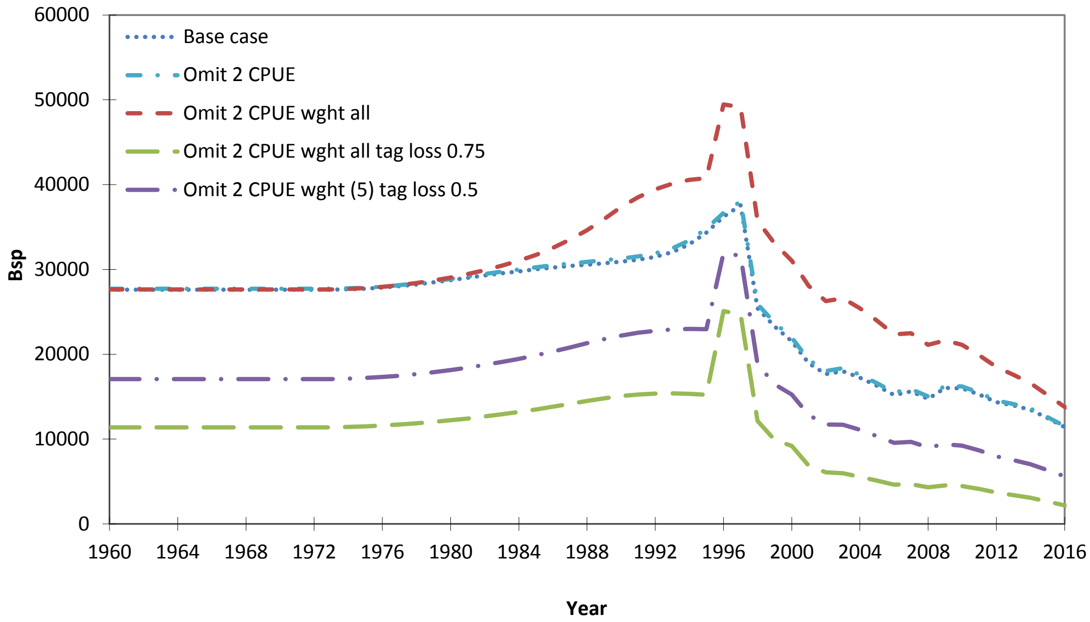

Figure 9a. Spawning biomass estimates for the **Base case** as well as four **sensitivity tests:** 1) omit the 2008 and 2009 trotline CPUE indices, 2) sensitivity (1) with up-weighting all CPUE indices from 2010, 3) sensitivity (2) with tag loss of 0.75 and 4) sensitivity (3) with lower weighting and tag loss.

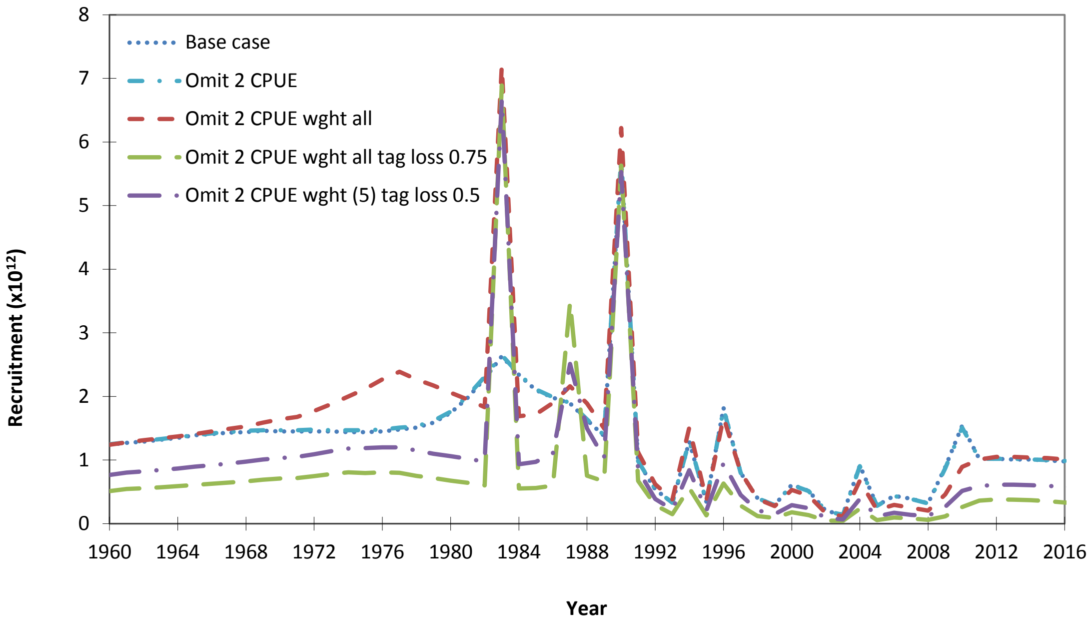

Figure 9b. Estimated recruitment for the **Base case** and the four **sensitivities** detailed in the caption to Figure 9a.

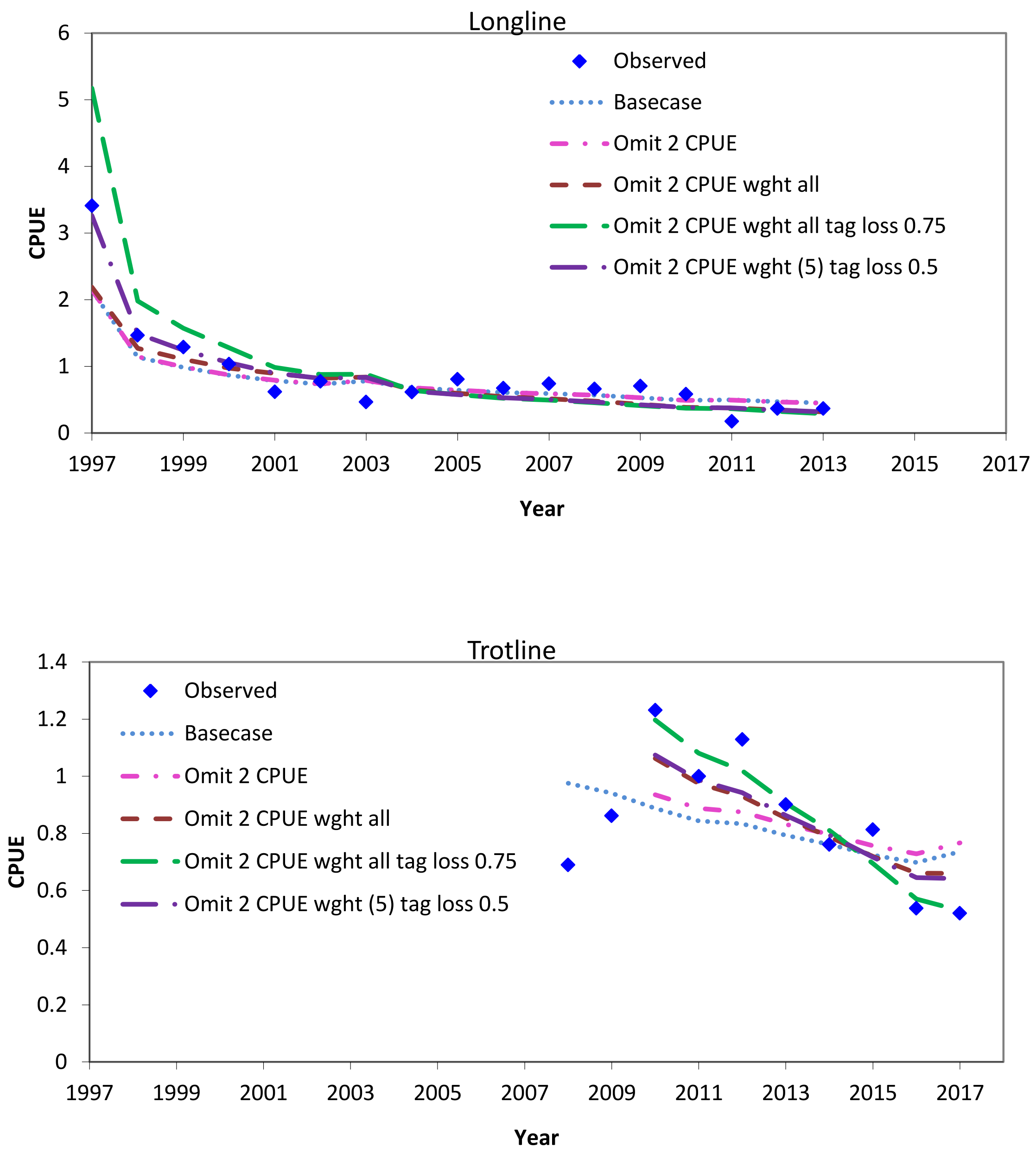

Figure 10. Exploitable biomass and the GLM-standardised CPUE indices to which the model is fit (divided by the estimated catchability *q* to express them in biomass units) for the **Base case** as well as four **sensitivity** tests that 1) omit the 2008 and 2009 trotline CPUE indices, 2) sensitivity (1) with up-weighting all CPUE indices from 2010, 3) sensitivity (2) with tag loss of 0.75 and 4) sensitivity (3) with lower weighting and tag loss.

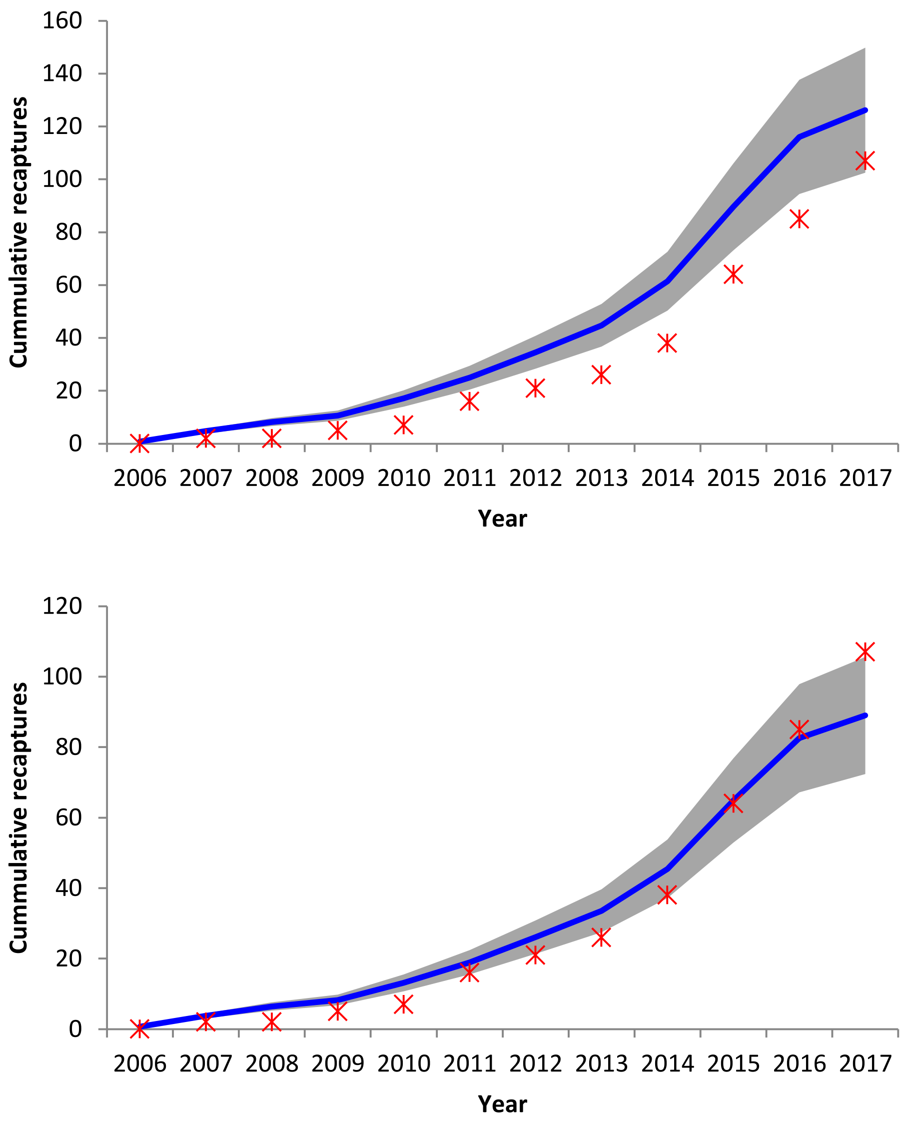

Figure 11a. Observed (asterisks) and model predicted (continuous line) cumulative recapture numbers of toothfish for the **sensitivity** tests that 1) up-weights all CPUE indices from 2010 and omits the 2008 and 2009 trotline CPUE indices (top) and 2) doubles the 1997 IUU estimate (bottom), compared to the Base case for which similar results are shown in Figure 6. The shaded area reflects the 95% confidence interval envelope.

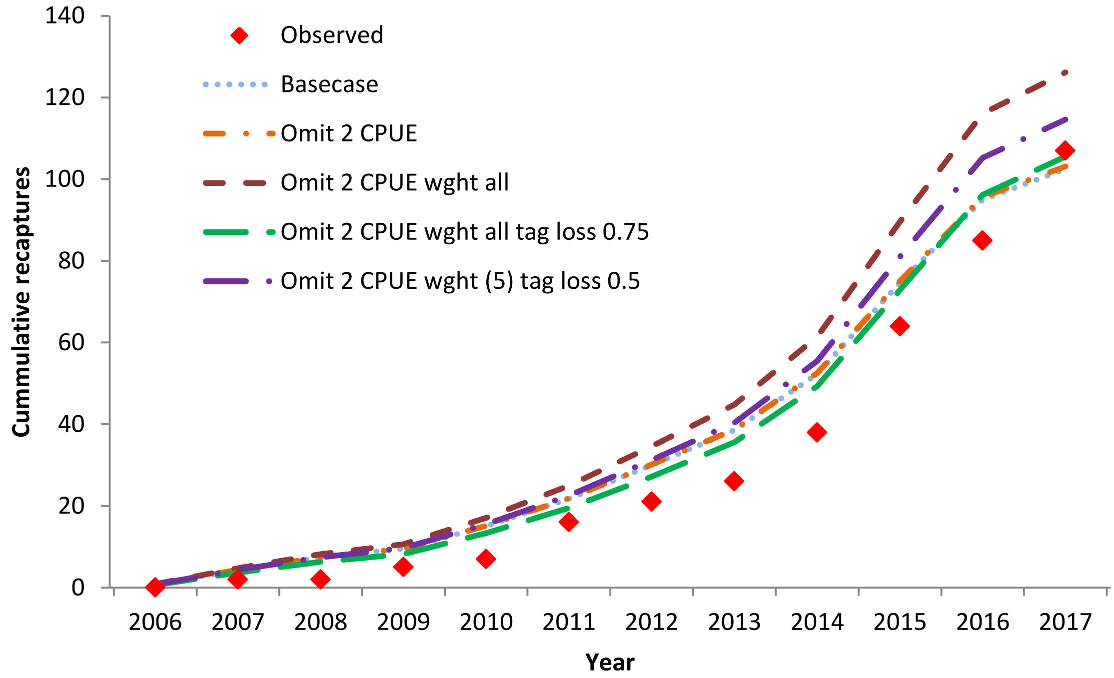

Figure 11b. Observed (asterisks) and model predicted cumulative recapture numbers of toothfish for the **Base case** model and for four **sensitivity** tests that 1) omit the 2008 and 2009 trotline CPUE indices, 2) sensitivity (1) with up-weighting all CPUE indices from 2010, 3) sensitivity (2) with tag loss of 0.75 and 4) sensitivity (3) with lower weighting and tag loss.

APPENDIX 1

THE AGE STRUCTURED PRODUCTION MODEL (ASPM) ASSESSMENT METHODOLOGY

THE BASIC DYNAMICS

The toothfish population dynamics are given by the equations:

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

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

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

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:

$$C_{y,a} = \sum_{f=1}^{3} C^f_{y,a} \ , \quad \text{(A1.4)}$$

where:

$$C^f_{y,a} = N_{y,a} S^f_{y,a} F^f_y \quad \text{(A1.5)}$$

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:

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

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 ($C^f_{y,a}$) 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:

$$p^f_{y,a} = C^f_{y,a} \Big/ \sum_{a'} C^f_{y,a'} \; . \qquad \text{(A1.28)}$$

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:

$$p^f_{y,\ell} = \sum_a p^f_{y,a} A^f_{a,\ell} \qquad \text{(A1.29)}$$

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:

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

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.:

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

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.:

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

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):

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

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:

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

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):

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

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:

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

(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 for trotlines within the first year, these fishing mortalities have been assumed to be the same as $F_{y-k,a-k}$.