Assessment of the toothfish (*Dissostichus eleginoides*) resource in the Prince Edward Islands vicinity to include data from 1997 to 2013, including tag-recapture data

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ABSTRACT

The assessment of the Prince Edward Islands (PEI) toothfish (*Dissostichus eleginoides*) resource carried out by Brandão and Butterworth (2013) is updated to take into account further data available for 2013 and a revised CPUE standardisation in which several desirable improvements have been made. 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 55-60% range. 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 the longline CPUE is well below model predictions. In these circumstances, perhaps recommendations to increase the TAC beyond 500 t should first await further trotline CPUE data.

INTRODUCTION

The assessment of the Prince Edward Islands (PEI) toothfish (*Dissostichus eleginoides*) resource carried out by Brandão and Butterworth (2013) is updated to take into account further data available for 2013 and a revised CPUE standardisation in which several desirable improvements have been made. These include: a) using a finer scale definition of fishing areas that reflect the preferred depth zones for the occurrence of toothfish more closely, b) include different fixed month effects prior- and post-2000 (the year when cetacean depredation first became noticeable) rather than including the year-month interaction as a random effect, to provide a quantitative surrogate for the extent of cetacean depredation on longlines, and c) assumes that the two *Koryo Maru* vessels are identical in terms of power (rendered reasonable by the fact that the same skipper operated on both vessels considered) (Brandão and Butterworth, 2014a-c).

Estimates of the "split" month factor 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 now assumes this value rather than the no cetacean predation scenario.

As an alternative to the base case model, tag-recapture data are also incorporated in this Age-Structured Production Model (ASPM) assessment of the Prince Edward Islands resource. Sensitivity tests of this alternative base case model are carried out to investigate what aspects of the assessment may not reconcile with the tag-recapture data and others to force better fits to the CPUE indices The biological parameter values adopted for toothfish in Subarea 48.3 (Agnew *et al.,* 2006) are assumed to apply.

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 previous 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 the last few months of 2013 (since July) have been incorporated in the present analyses, which were not available for previous assessments of toothfish in the Prince Edward Islands vicinity. 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).

Using the post-2000 month estimates obtained from the new “split” month factor of the CPUE standardisation, the additional cetacean take in a month as a proportion of the landed catch can be calculated and the estimate of the total catch as a proportion of this landed catch can be used as an estimate for the annual amount of cetacean depredation to be assumed in the assessment model for toothfish. An estimate of 1.1 has been obtained in the present analysis, i.e a 10% annual catch loss rather than the 50% - to 200% loss assumed in previous assessments. 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 initial attempt at assessing 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 revised series of relative abundance indices obtained from the CPUE GLMM standardisation procedure described in Brandão and Butterworth (2014a-c) for the longline and trotline commercial data are listed in Table 2. These indices have changed slightly from those reported in Brandão and Butterworth (2014c) as an error in the levels of the "split" month factor was detected and has since been corrected. 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 the assessments.

Catch-at-length information for the longline fishery has also been updated to include the data available up to 2013. Catch-at-length data for the pot fishery for November 2004 to April 2005 are included in the present assessment as are the trotline fishery catch-at-length data for 2008 to 2013. 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 to 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. These data are input into the assessments that include tagging data by splitting them into numbers by age 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 only operated until 2005 and therefore no recoveries of toothfish that have been at large for more than a year are possible.

ASSESSMENT METHODOLOGY

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. 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.

A variant to the base case model has been conducted in which tag-recapture data are taken into account. 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 minimal data in 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.

Five 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.
v) Variant of (iv) above in which only the last three CPUE indices are up-weighted by a factor of 10.

RESULTS AND DISCUSSION

Table 5 shows the results for a three-fleet assessment of the toothfish resource, including those for the base case model as well as when tag-recapture data are taken into account and when an alternative factor of cetacean predation is assumed. These assessments suggest the current status of the resource to be in the region of 57% to 59% of average pre-exploitation equilibrium spawning biomass. 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%).

Figure 1 shows estimated spawning biomass and recruitment trends for the base case model and the sensitivity test that takes tagging data into account. Both models estimate a large peak in recruitment in 1991 in response to the large estimated illegal catch taken in 1997, so as to better fit the trend in the CPUE abundance indices. Figure 2 shows the comparison of depletion trends between the base case model and the sensitivity tests that take tagging data into account. The impact of including the tag-recapture data on the status of the resource is minimal in terms of point estimates, but variances are reduced. Fits to the CPUE data are shown in Figure 3 for the base case and the sensitivity test that takes tagging data into account. Both models fail to fit the comparatively very high 1997 CPUE value. The models also do not fit the last three CPUE indices for longline very well. Overall, the base case model has a slightly better fit to the longline CPUE indices (see the σ_{CPUE} values in Table 5). Assuming a larger cetacean predation factor of 1.5 does improve the fit to the longline CPUE (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 4, and the standardised catch-at-length residuals are shown in Figure 5. 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 and the sensitivity that takes tag-recapture data into account are shown in Figure 6. In previous papers, model variants which place different relative weights on seemingly contradictory CPUE and catch-at-length data have been reported.

Figure 7 shows the fit to the cumulative recapture numbers of toothfish for the base case model which takes tagging data into account, combining the recaptures by longlines and trotlines.

Tables 6 and 7 show the results for the five sensitivity tests performed which are variants of the base case model that takes tag-recapture data into account. These reflect attempts to restrain the large estimated peaks in recruitment in 1997 which result in depletion values that are much higher than obtained in many previous assessments. For comparison, results for the base case with tagging data 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 and was able to remove the large peak in recruitment is the sensitivity test that sets a lower standard deviation for recruitment (σ_R) for the years up to and including 1997 and fixes the pre-exploitation level (K_{sp}) at a much lower value. Figure 8 compares the spawning biomass (a) and recruitment (b) for the base case and the base case with tagging data, as well as the further five sensitivity tests. Figure 8b clearly shows that only the one sensitivity test was able to reduce the large peaks in recruitment in 1991. This has been achieved by estimating a large initial pre-exploitation level but leads to worse fits to all data (Figure 9 and Table 6). Figure 9 shows fits to the CPUE indices for all models considered in this paper 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-weight all CPUE indices or fix the pre-exploitation level at a lower value. Up-weighting all CPUE indices results in a better fit to the CPUE indices (see the σ_{CPUE} values in Table 7). Up-weighting the last three CPUE indices forces the fit to go through the last two indices but at the expense of a much worse fit to the other CPUE indices (Figure 9 and Table 7).

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 slightly higher than for the base case model. This is because of two estimated high peaks in recruitment; one in 1984 and another in 1991.

Figure 10 shows the fit to the cumulative recapture numbers of toothfish for the sensitivity test that up-weights all the CPUE indices. To achieve a better fit to the CPUE indices results in an appreciable lack of fit to the tag-recapture data. Similar results are also shown for the sensitivity test that fixes the pre-exploitation level at a lower value.

Figure 11 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 in 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 12 and 13 provide similar results to Figure 11, but the projections are for the longline (Figure 12) and the trotline (Figure 13) 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 57% of its average pre-exploitation level and at about 58% if tagging data is taken into account.

A concern with this assessment, however, is that it is heavily influenced by large peaks in recruitment 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 46% follows for a scenario that up-weights all the CPUE indices. However, although this fits the CPUE data much better, the fit to the tag-recapture data deteriorates considerably.

Despite these uncertainties, the projections in Figures 11 to 13 might provide a basis for a TAC recommendation. In all scenarios increases in spawning biomass occur in the long term under a 500 t TAC, except for the sensitivity test in which K_{sp} is fixed at 25 000 t. In this case, the spawning biomass is only slightly less than the current biomass at the end of the twenty year projection period. While catches somewhat above 500 t might also be justified on this basis, it remains a concern that for the last three years the longline CPUE is well below model predictions (see Figure 8). In these circumstances, perhaps recommendations to increase the TAC beyond 500 t should first await further trotline CPUE data.

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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. 2014a. Standardisation of the CPUE series for toothfish (Dissostichus eleginoides) in the Prince Edward Islands EEZ using finer scale fishing areas. DAFF Branch Fisheries document: FISHERIES/2014/JUN/SWG-DEM/17.

Brandão, A. and Butterworth, D.S. 2014b. Further results for the standardisation of the CPUE series for toothfish (Dissostichus eleginoides) in the Prince Edward Islands EEZ using finer scale fishing areas. DAFF Branch Fisheries document: FISHERIES/2014/JUL/SWG-DEM/28.

Brandão, A. and Butterworth, D.S. 2014c. Final 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/2014/AUG/SWG-DEM/32.

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 for the analyses conducted in this paper. The bases for the estimates of the illegal catches for 2004 through to 2013 are detailed (or referenced) in the text. Catches (strictly "removals") from the longline fisheries ("legal" and "illegal") 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	24104.9	24104.9
1998	1 224.6	—	—	1 808	3 032.6	3032.6	3032.6
1999	945.1	—	—	1 014	1 959.1	1959.1	1959.1
2000	1 577.8	—	—	1 210	2 787.8	2880.8	3252.5
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	159.7	217.8
2009	41.8	—	30.7	—	72.5	79.7	108.7
2010	49.2	—	174.6	—	223.7	246.1	335.6
2011	1.0	—	323.9	—	324.8	357.3	487.2
2012	70.7	—	205.5	—	276.1	303.8	414.2
2013	50.0	—	215.3	—	265.3	291.8	397.9
2014†	0	—	400	—	400	440.0	600.0
1997–2014 total	8 299.3	176.2	1 406.3	26 452	36 333.8	36 851.0	38 919.7

† The catch for 2014 is the expected catch for the year (with the whole catch assumed to come from the trotline fleet (Richard Ball pers. comm.).

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, 2014c corrected for an error). 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	3.453	3.453	3.453	—
1998	1.458	1.458	1.458	—
1999	1.285	1.285	1.285	—
2000	1.000	1.033	1.167	—
2001	0.570	0.608	0.760	—
2002	0.693	0.763	1.040	—
2003	0.421	0.463	0.631	—
2004	0.553	0.609	0.830	—
2005	0.730	0.803	1.095	—
2006	0.607	0.668	0.911	—
2007	0.669	0.735	1.003	—
2008	0.595	0.655	0.893	0.872
2009	0.640	0.704	0.960	0.986
2010	0.525	0.578	0.788	1.527
2011	0.167	0.183	0.250	1.000
2012	0.341	0.375	0.511	0.995
2013	0.346	0.381	0.519	0.934

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**
Numbers Tagged	175	179	120	140	74	137	200	162	254
Recaptures									
2005	***1***								
2006	**1†**								
2007	1	1	***2***						
2008									
2009			1	1					
2010			1	1					
2011			1	1		4	***1***		
2012		1		1		2			
2013					1		4		

† This tag, even though recaptured in the following year, had not been at large for more than a year.

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 three fleet (longline, trotline and pot) model that assumes different commercial selectivities for the three gears, and also a change for the longliners between 2002 and 2003, when fitted to the CPUE data and catch-at-length data for toothfish from the Prince Edward Islands EEZ. The estimates shown are for the pre-exploitation toothfish spawning biomass (K_{sp}), the current spawning stock depletion (B_{sp}^{2014}) in terms of both K_{sp} and $MSYL_{sp}$, and the (longline) exploitable biomass ($B_{\exp}^{2014}$) at the beginning of the year 2014 (assuming the same selectivity as for 2013). 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		
		Base case	**Base case (tagging data)**	**Base case (tagging data; predation 1.5x)**
K_{sp} (tonnes)		36 868 (0.205)	39 627 (0.152)	42 730 (0.152)
$MSYL_{sp}$ (Longline)/K_{sp}		0.243	0.243	0.243
B_{sp}^{2014}/K_{sp}		0.568 (0.130)	0.584 (0.103)	0.592 (0.102)
B_{sp}^{1997}/K_{sp}		1.266 (0.101)	1.232 (0.096)	1.221 (0.096)
$B_{sp}^{2014}/MSYL_{sp}$(Longline)		2.334	2.401	2.433
$B_{\exp}^{2014}$ (tonnes)	Longline	14 066 (0.290)	15 992 (0.190)	17 595 (0.186)
	Pot	25 046 (0.285)	27 671 (0.186)	30 228 (0.186)
	Trotline	16 299 (0.299)	19 136 (0.189)	21 004 (0.186)
σ_{CPUE}	Longline	0.403	0.419	0.361
	Trotline	0.197	0.195	0.196
σ_R		0.500††	0.500††	0.500††
a_{50}^{97-02} (yr)		6.694	6.500	6.500
δ^{97-02} (yr^{-1})		0.013	0.020	0.020
ω^{97-02} (yr^{-1})		0.062	0.060	0.060
a_{50}^{03-13} (yr)	Longline	6.508	6.496	6.496
	Pot	8.581	8.659	8.678
	Trotline	7.115	7.079	7.078
δ^{03-07} (yr^{-1})	Longline	0.020	0.020	0.020
	Pot	0.824	0.853	0.857
	Trotline	0.038	0.034	0.034
ω^{03-07} (yr^{-1})	Longline	0.075	0.072	0.071
	Pot	0.000	0.000	0.000
	Trotline	0.043	0.038	0.038
β		0.122 ()	0.121 (0.015)	0.121 (0.015)
σ_{len}	Longline	0.042	0.042	0.042
	Pot	0.035	0.035	0.035
	Trotline	0.038	0.038	0.038

†† Input value.

Table 5 cont. Estimates for sensitivity tests of a three fleet (longline, trotline and pot) model that assumes different commercial selectivities for the three gears, and also a change for the longliners between 2002 and 2003, when fitted to the CPUE data and catch-at-length data for toothfish from the Prince Edward Islands EEZ. The estimates shown are for the pre-exploitation toothfish spawning biomass (K_{sp}), the current spawning stock depletion (B_{sp}^{2014}) in terms of both K_{sp} and $MSYL_{sp}$, and the (longline) exploitable biomass ($B_{\exp}^{2014}$) at the beginning of the year 2014 (assuming the same selectivity as for 2013). 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		
		Base case	**Base case (tagging data)**	**Base case (tagging data; predation 1.5x)**
-ln *L*: Length		-765.8	-764.6	-763.9
-ln *L*: CPUE		-13.699	-13.083	-15.619
-ln *L*: Recruitment		3.557	0.671	-0.567
-ln *L*: Tagging		—	61.613	61.782
-ln *L*: Total		-775.9	-715.4	-718.3
MSY (tonnes)	Longline	1 485†	1 589†	1 714†
	Pot	1 646	1 759	1 897
	Trotline	1 566	1 676	

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

Table 6. Estimates for a three fleet (longline, trotline and pot) model that assumes different commercial selectivities for the three gears, and also a change for the longliners between 2002 and 2003, when fitted to the CPUE data and catch-at-length data for toothfish from the Prince Edward Islands EEZ. The estimates shown are for the pre-exploitation toothfish spawning biomass (K_{sp}), the current spawning stock depletion (B_{sp}^{2014}) in terms of both K_{sp} and $MSYL_{sp}$, and the (longline) exploitable biomass ($B_{\exp}^{2014}$) at the beginning of the year 2014 (assuming the same selectivity as for 2013). Estimates of parameters pertinent to fitting the catch-at-length information are also shown, together with contributions to the (negative of the) log-likelihood (values in brackets give the difference in log-likelihood for models when K_{sp} is estimated or fixed). Numbers in brackets represent CVs. The details of the various sensitivity tests reported are given in the text.

Parameter estimates		**Model**		
		Base case (tagging data)	**Varying σ_R**	**Base case (tagging data; fixed K_{sp})**
K_{sp} (tonnes)		39 627 (0.152)	91 248 (0.145)	25 000
$MSYL_{sp}$ (Longline)/K_{sp}		0.243	0.244	0.244
B_{sp}^{2014}/K_{sp}		0.584 (0.103)	0.713 (0.043)	0.600 (0.108)
B_{sp}^{1997}/K_{sp}		1.232 (0.096)	1.024 (0.021)	1.515 (0.088)
$B_{sp}^{2014}/MSYL_{sp}$(Longline)		2.401	2.928	2.455
$B_{\exp}^{2014}$ (tonnes)	Longline	15 992 (0.190)	43 271 (0.168)	11 112 (0.133)
	Pot	27 671 (0.186)	77 642 (0.177)	17 882 (0.106)
	Trotline	19 136 (0.189)	52 992 (0.166)	13 441 (0.136)
σ_{CPUE}	Longline	0.419	0.486	0.391
	Trotline	0.195	0.195	0.194
σ_R		0.500††	0.1 pre 1998; 0.5 otherwise††	0.500††
a_{50}^{97-02} (yr)		6.500	6.468	6.500
δ^{97-02} (yr^{-1})		0.020	0.019	0.020
ω^{97-02} (yr^{-1})		0.060	0.054	0.053
a_{50}^{03-13} (yr)	Longline	6.496	6.178	6.496
	Pot	8.659	8.594	8.870
	Trotline	7.079	7.087	7.081
δ^{03-07} (yr^{-1})	Longline	0.020	0.035	0.020
	Pot	0.853	0.905	0.904
	Trotline	0.034	0.041	0.035
ω^{03-07} (yr^{-1})	Longline	0.072	0.074	0.066
	Pot	0.000	0.000	0.000
	Trotline	0.038	0.040	0.032
β		0.121 (0.015)	0.119 (0.020)	0.121 (0.015)
σ_{len}	Longline	0.042	0.046	0.041
	Pot	0.035	0.038	0.035
	Trotline	0.038	0.038	0.038

†† Input value(s).

Table 6 cont. Estimates for sensitivity tests of a three fleet (longline, trotline and pot) model that assumes different commercial selectivities for the three gears, and also a change for the longliners between 2002 and 2003, when fitted to the CPUE data and catch-at-length data for toothfish from the Prince Edward Islands EEZ. The estimates shown are for the pre-exploitation toothfish spawning biomass (K_{sp}), the current spawning stock depletion (B_{sp}^{2014}) in terms of both K_{sp} and $MSYL_{sp}$, and the (longline) exploitable biomass ($B_{\exp}^{2014}$) at the beginning of the year 2014 (assuming the same selectivity as for 2013). Estimates of parameters pertinent to fitting the catch-at-length information are also shown, together with contributions to the (negative of the) log-likelihood (values in brackets give the difference in log-likelihood for models when K_{sp} is estimated or fixed). Numbers in brackets represent CVs. The details of the various model variants reported are given in the text.

Parameter estimates		**Model**		
		Base case (tagging data)	**Varying σ_R**	**Base case (tagging data; fixed K_{sp})**
-ln *L*: Length		-764.6	-690.0	-767.0
-ln *L*: CPUE		-13.083	-10.563	-14.328
-ln *L*: Recruitment		0.671	-54.362	7.449
-ln *L*: Tagging		61.613	67.676	63.794
-ln *L*: Total		-715.4	-687.3	-710.1
MSY (tonnes)	Longline	1 589†	3 666†	1 008†
	Pot	1 759	4 039	1 113
	Trotline	1 676	3 852	1 062

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

Table 7. Estimates for a three fleet (longline, trotline and pot) model that assumes different commercial selectivities for the three gears, and also a change for the longliners between 2002 and 2003, when fitted to the CPUE data and catch-at-length data for toothfish from the Prince Edward Islands EEZ. The estimates shown are for the pre-exploitation toothfish spawning biomass (K_{sp}), the current spawning stock depletion (B_{sp}^{2014}) in terms of both K_{sp} and $MSYL_{sp}$, and the (longline) exploitable biomass ($B_{\exp}^{2014}$) at the beginning of the year 2014 (assuming the same selectivity as for 2013). Estimates of parameters pertinent to fitting the catch-at-length information are also shown, together with contributions to the (negative of the) log-likelihood (values in brackets give the difference in log-likelihood for models when K_{sp} is estimated or fixed). Numbers in brackets represent CVs. The details of the various sensitivity tests reported are given in the text.

Parameter estimates		Model		
		Base case (tagging data)	**Base case (tagging data; w_{CPUE}=10 for all years)**	**Base case (tagging data; w_{CPUE}=10 for last 3 years)**
K_{sp} (tonnes)		39 627 (0.152)	26 934 (0.119)	39 153 (0.151)
$MSYL_{sp}$ (Longline)/K_{sp}		0.243	0.243	0.243
B_{sp}^{2014}/K_{sp}		0.584 (0.103)	0.457 (0.105)	0.574 (0.103)
B_{sp}^{1997}/K_{sp}		1.232 (0.096)	1.358 (0.103)	1.515 (0.088)
$B_{sp}^{2014}/MSYL_{sp}$(Longline)		2.401	1.878	2.364
$B_{\exp}^{2014}$ (tonnes)	Longline	15 992 (0.190)	7 733 (0.138)	14 259 (0.185)
	Pot	27 671 (0.186)	14 624 (0.147)	26 748 (0.186)
	Trotline	19 136 (0.189)	8 939 (0.123)	16 992 (0.182)
σ_{CPUE}	Longline	0.419	0.341	0.469
	Trotline	0.195	0.200	0.086
σ_R		0.500††	0.500††	0.500††
a_{50}^{97-02} (yr)		6.500	6.476	6.527
δ^{97-02} (yr^{-1})		0.020	0.020	0.020
ω^{97-02} (yr^{-1})		0.060	0.059	0.062
a_{50}^{03-13} (yr)	Longline	6.496	6.630	6.574
	Pot	8.659	8.382	8.473
	Trotline	7.079	7.077	7.069
δ^{03-07} (yr^{-1})	Longline	0.020	0.015	0.017
	Pot	0.853	0.786	0.812
	Trotline	0.034	0.035	0.031
ω^{03-07} (yr^{-1})	Longline	0.072	0.080	0.078
	Pot	0.000	0.000	0.000
	Trotline	0.038	0.046	0.044
β		0.121 (0.015)	0.120 (0.015)	0.121 (0.016)
σ_{len}	Longline	0.042	0.041	0.042
	Pot	0.035	0.034	0.035
	Trotline	0.038	0.038	0.038

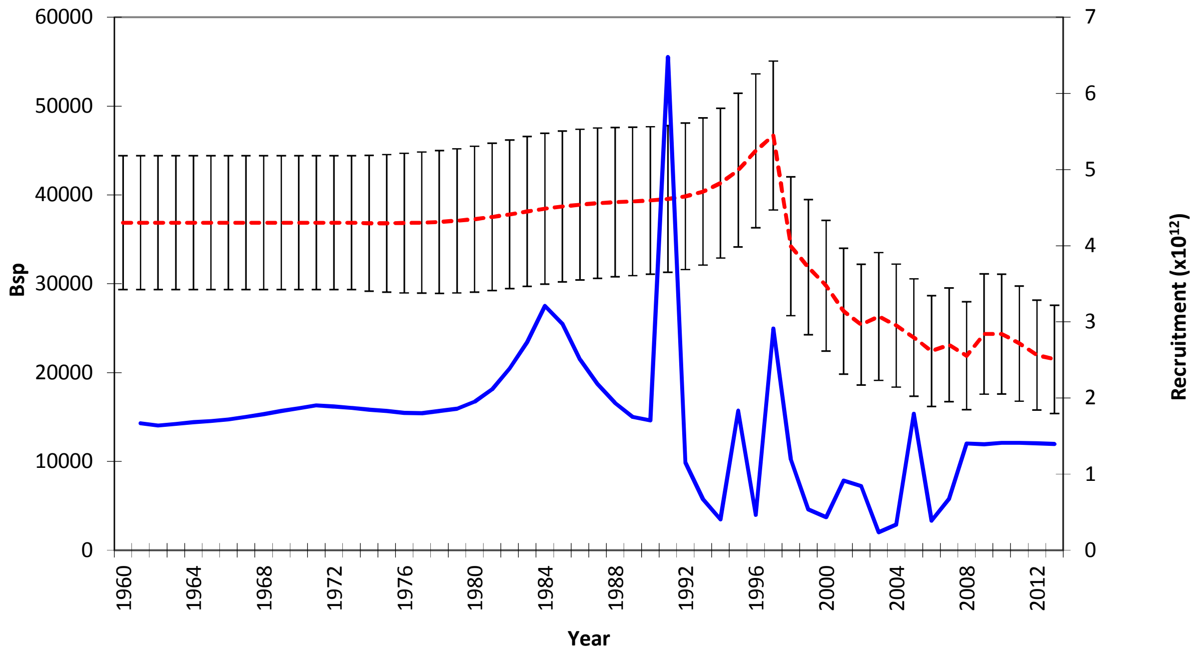
†† Input value(s).

Table 7 cont. Estimates for sensitivity tests of a three fleet (longline, trotline and pot) model that assumes different commercial selectivities for the three gears, and also a change for the longliners between 2002 and 2003, when fitted to the CPUE data and catch-at-length data for toothfish from the Prince Edward Islands EEZ. The estimates shown are for the pre-exploitation toothfish spawning biomass (K_{sp}), the current spawning stock depletion (B_{sp}^{2014}) in terms of both K_{sp} and $MSYL_{sp}$, and the (longline) exploitable biomass ($B_{\exp}^{2014}$) at the beginning of the year 2014 (assuming the same selectivity as for 2013). Estimates of parameters pertinent to fitting the catch-at-length information are also shown, together with contributions to the (negative of the) log-likelihood (values in brackets give the difference in log-likelihood for models when K_{sp} is estimated or fixed). Numbers in brackets represent CVs. The details of the various model variants reported are given in the text.

Parameter estimates		Model		
		Base case (tagging data)	Base case (tagging data; w_{CPUE}=10 for all years)	Base case (tagging data; w_{CPUE}=10 for last 3 years)
-ln *L*: Length		-764.6	-772.4	-765.8
-ln *L*: CPUE		-13.083	-164.5	-75.764
-ln *L*: Recruitment		0.671	15.466	3.375
-ln *L*: Tagging		61.613	68.722	61.676
-ln *L*: Total		-715.4	-852.7	-776.5
MSY (tonnes)	Longline	1 589†	1 077†	1 565†
	Pot	1 759	1 190	1 732
	Trotline	1 676	1 132	1 648

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

a)



b)

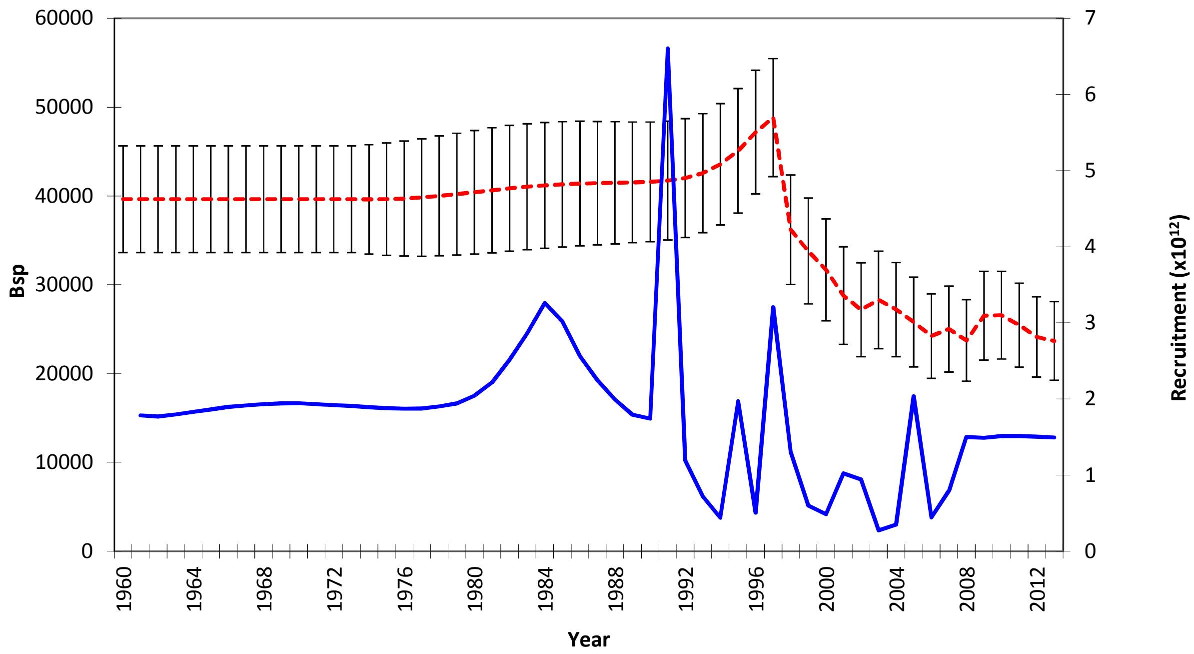


Figure 1. Spawning biomass estimates (dashed line) and estimated recruitment (full line) for the three-fleet model for a) the base case (cetacean predation 1.1x) and b) the sensitivity test that takes tagging data into account. Confidence limits of one standard error for the spawning biomass are also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

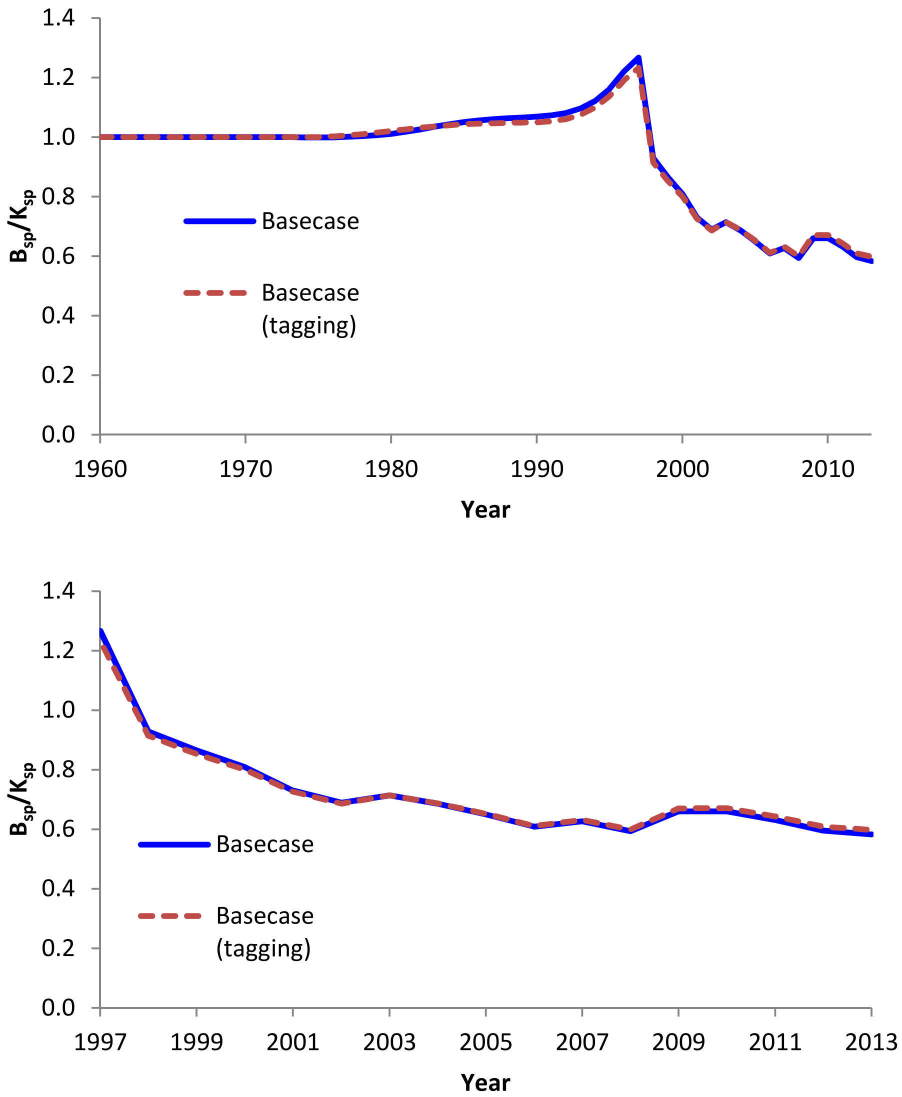


Figure 2. Spawning biomass estimates (in terms of pre-exploitation level) for the three-fleet model for the base case (cetacean predation 1.1x) and the sensitivity test that take tagging data into account. The bottom plot zooms in the later part of the trajectories.

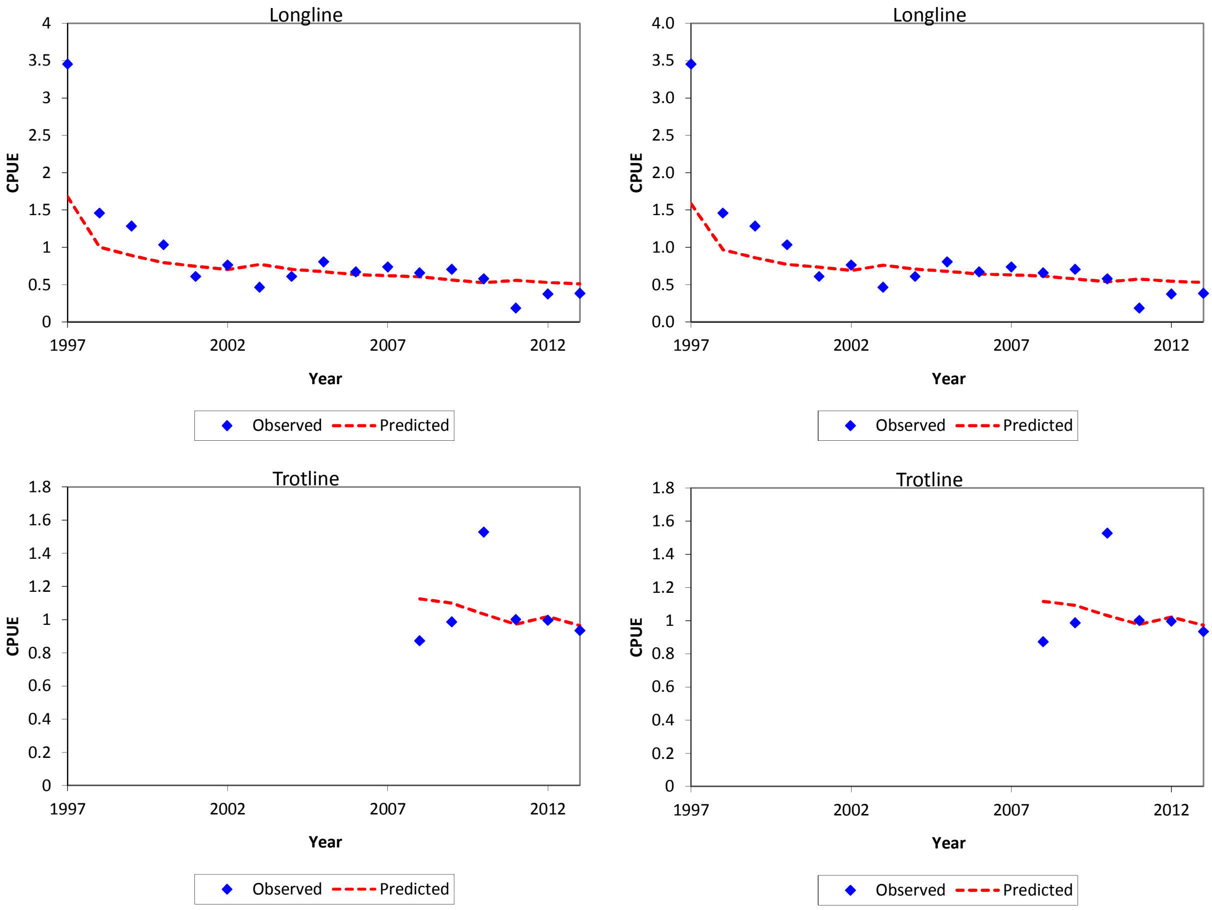


Figure 3. Exploitable biomass and the GLM-standardised CPUE indices to which the model is fit (divided by the estimated catchability q to express them in biomass units) for the base case (left) and the sensitivity test that takes tagging data into account (right).

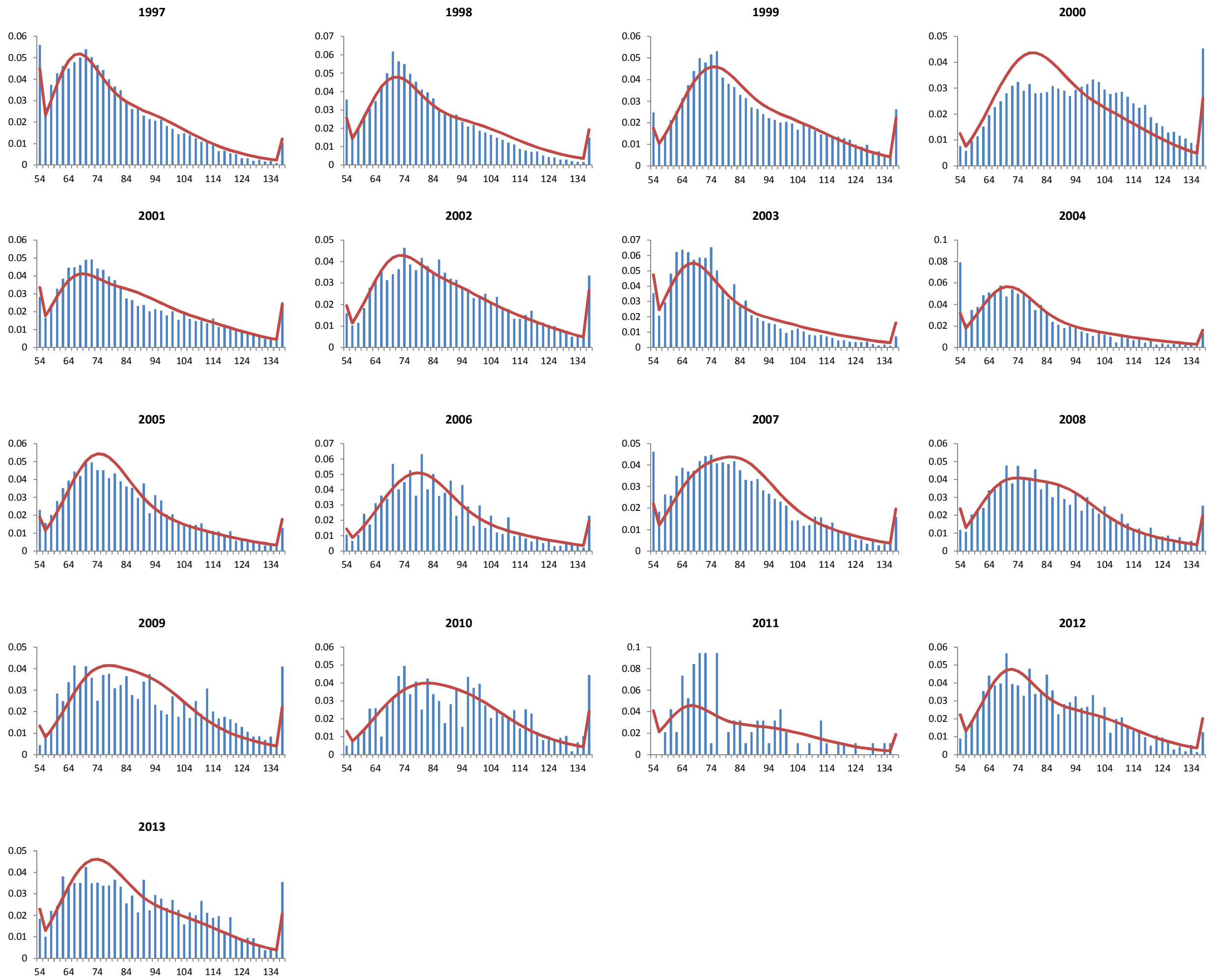


Figure 4a. Assessment predictions for the annual catch-at-length proportions in the longline fishery for the base case. Note that lengths below 54 and above 138 cm are combined into minus- and plus-groups.

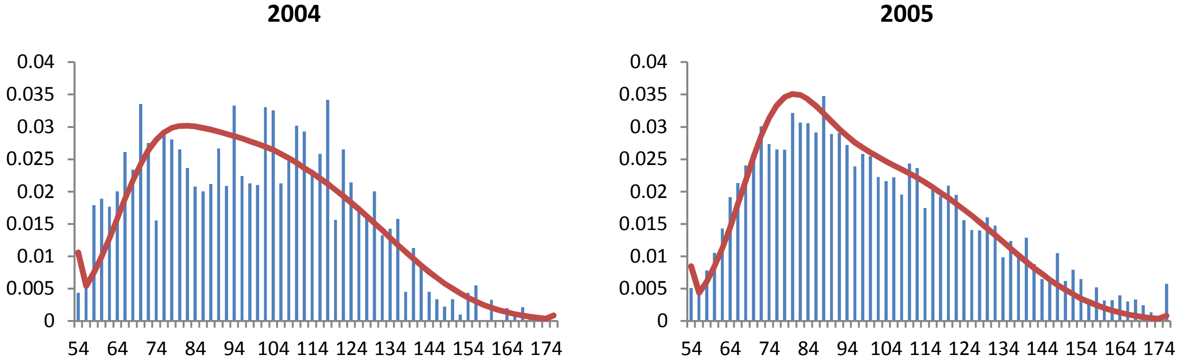


Figure 4b. Assessment predictions for the annual catch-at-length proportions in the pot fishery for the base case. Note that lengths below 54 and above 176 cm are combined into minus- and plus-groups.

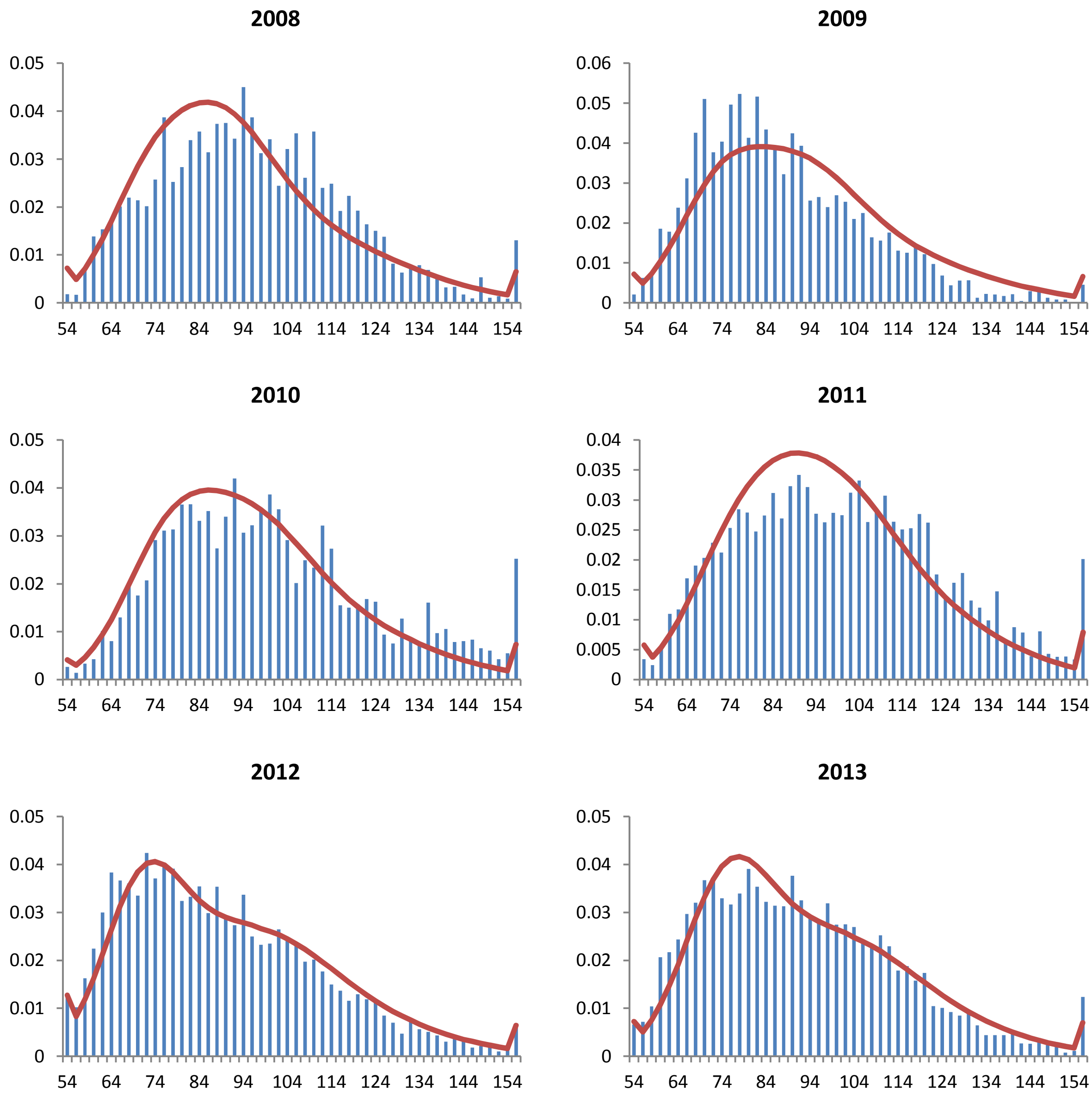


Figure 4c. Assessment predictions for the annual catch-at-length proportions in the trotline fishery for the base case. Note that lengths below 54 and above 156 cm are combined into minus- and plus-groups.

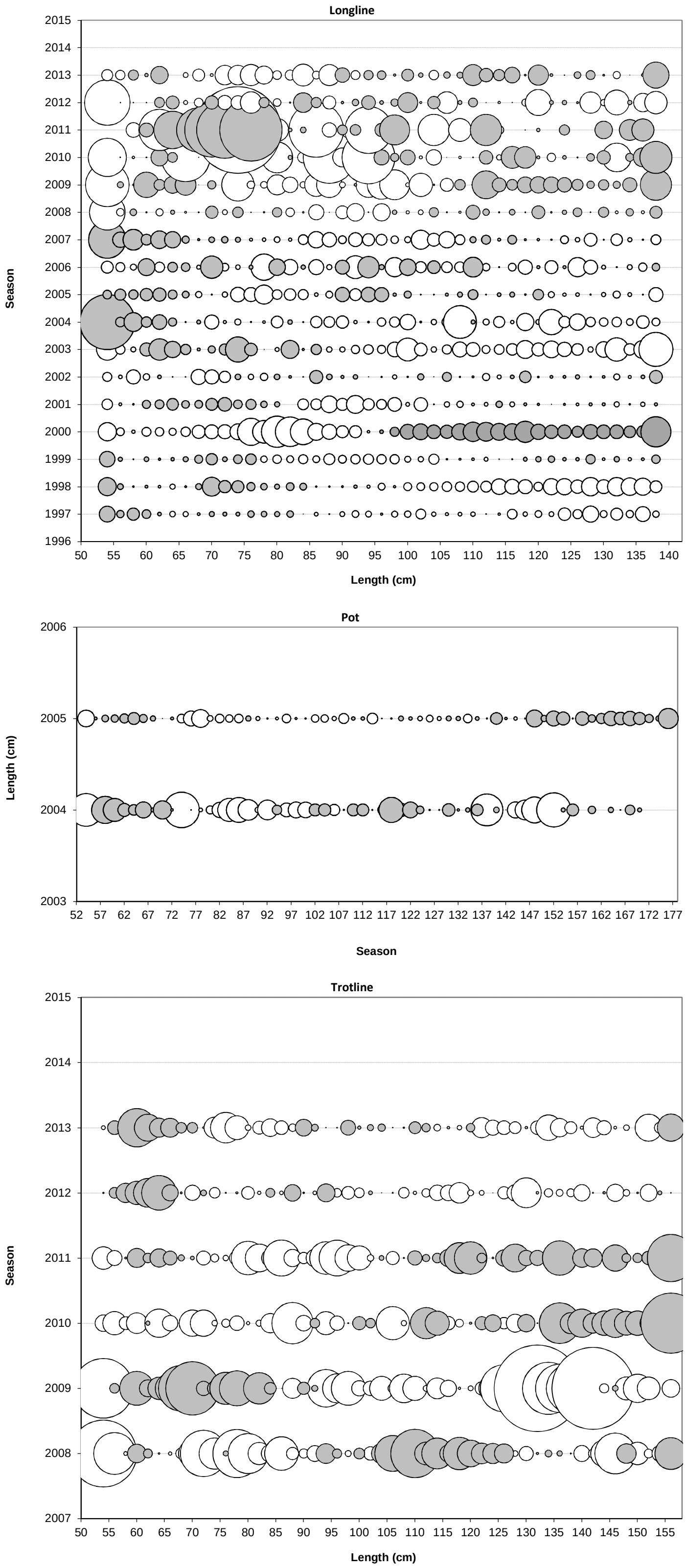
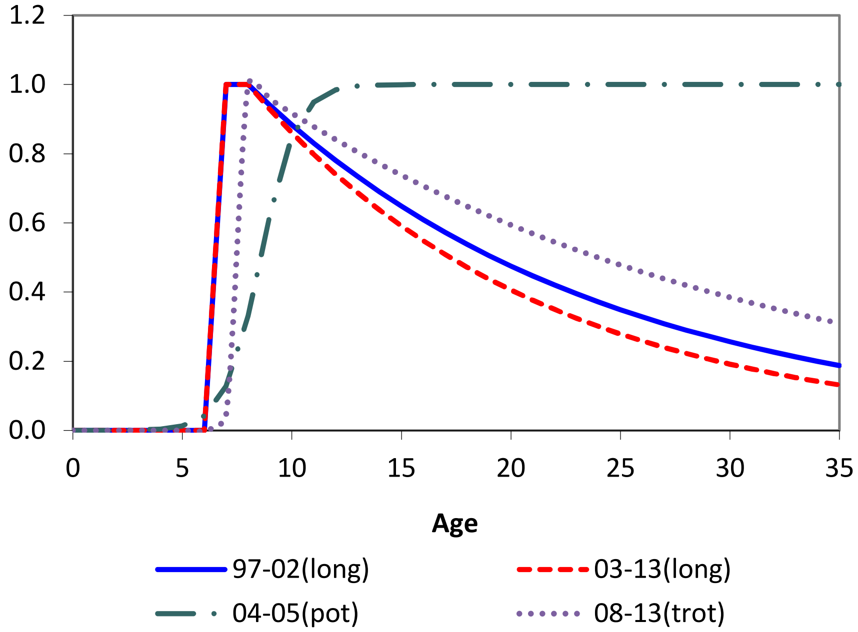


Figure 5. Bubble plots of the catch-at-length residuals for the three fisheries for the base case. The size of the bubble is proportional to the corresponding standardised residual $\left(\left(\ln(obs)-\ln(pred)\right)\Big/\left(\sigma\big/\sqrt{pred}\right)\right)$. White bubbles represent negative residuals while grey bubbles represent positives ones.

a)



b)

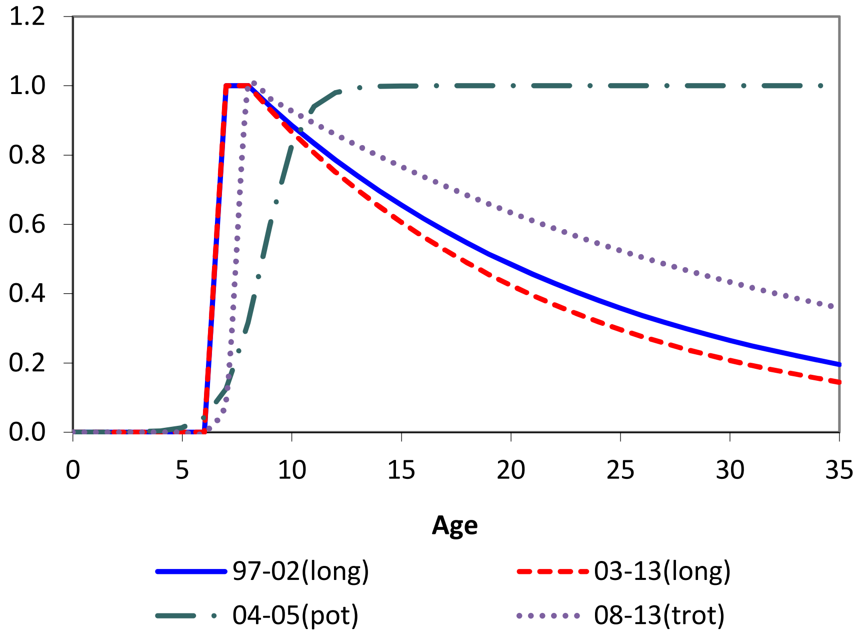


Figure 6. Estimated selectivity curves for the periods 1997–2002 and 2003–2013 for the longline fishery, for the period 2004-2005 for the pot fishery and for the period 2008–2013 for the trotline fishery. Curves are shown for a) the base case and b) the sensitivity test that takes tagging data into account.

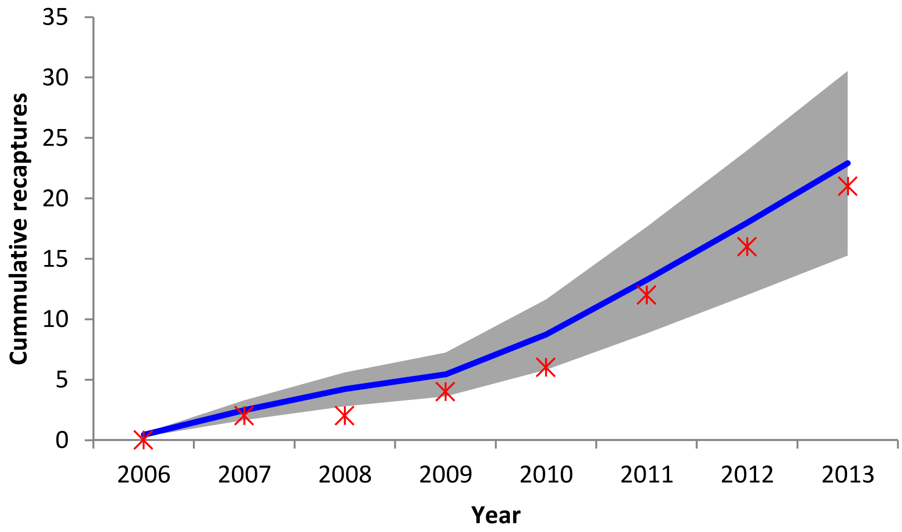


Figure 7. Observed (asterisks) and model predicted (continuous line) cumulative recapture numbers of toothfish for the base case model which takes tagging data into account, and combining recaptures by longlines and trotlines. The shaded area reflects the 95% confidence interval envelope.

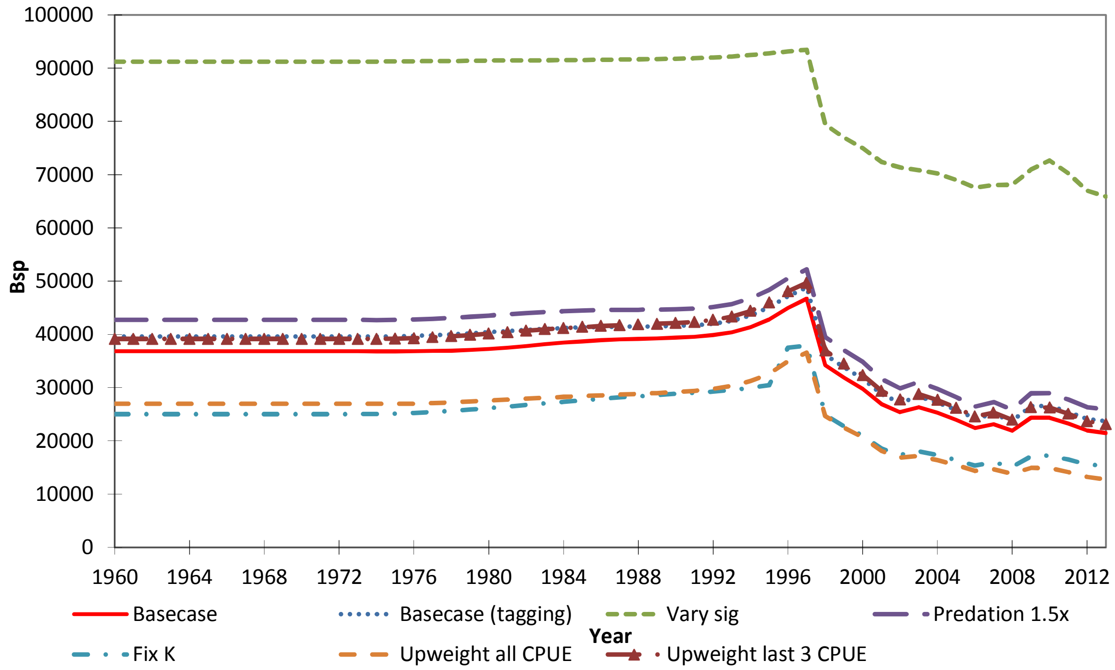


Figure 8a. Spawning biomass estimates for the three-fleet model for the base case and the base case with tagging data as well as five sensitivity tests (variants of the base case with tagging data that 1) fixes K_{sp} at 25 000, 2) varies σ_R from 0.1 pre 1998 to 0.5 otherwise, 3) assumes cetacean predation of 1.5, 4) upweights all CPUE indices and 5) upweights the last three CPUE indices).

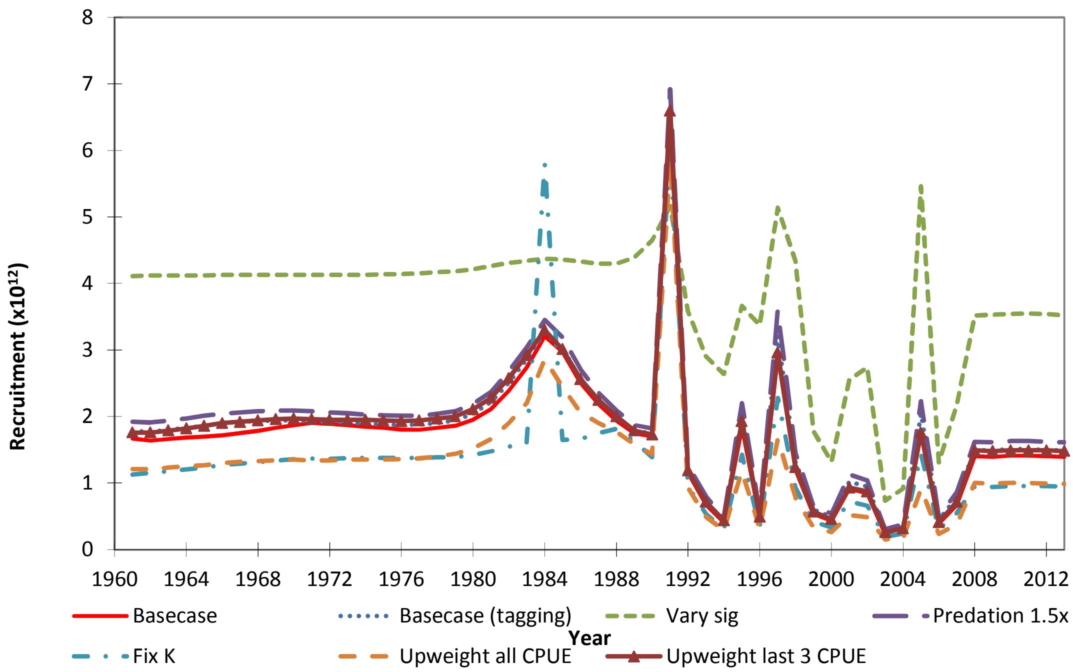


Figure 8b. Estimated recruitment for the three-fleet model for the base case and the base case with tagging data as well as five sensitivity tests (variants of the base case with tagging data that 1) fixes K_{sp} at 25 000, 2) varies σ_R from 0.1 pre 1998 to 0.5 otherwise, 3) assumes cetacean predation of 1.5, 4) upweights all CPUE indices and 5) upweights the last three CPUE indices).

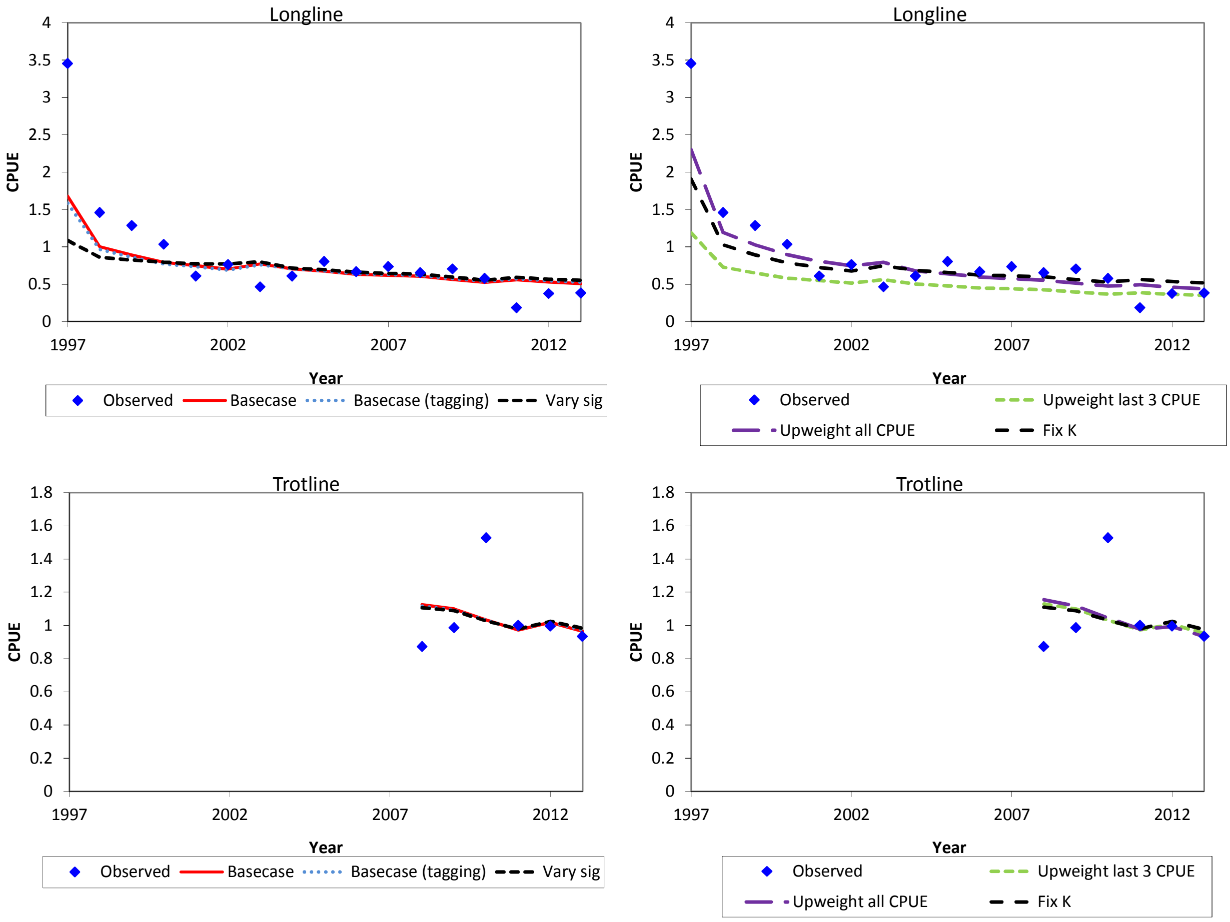


Figure 9. Exploitable biomass and the GLM-standardised CPUE indices to which the model is fit (divided by the estimated catchability q to express them in biomass units) for the base case and the base case with tagging data as well as four sensitivity tests (variants of the base case with tagging data that 1) fixes K_{sp} at 25 000, 2) varies σ_R from 0.1 pre 1998 to 0.5 otherwise, 3) upweights all CPUE indices and 4) upweights the last three CPUE indices).

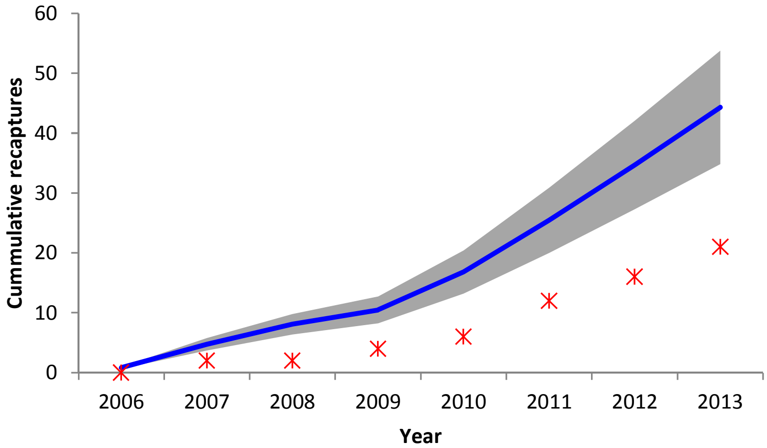


Figure 10. Observed (asterisks) and model predicted (continuous line) cumulative recapture numbers of toothfish for the sensitivity test that upweights all CPUE indices, and combining recaptures by longlines and trotlines. The shaded area reflects the 95% confidence interval envelope.

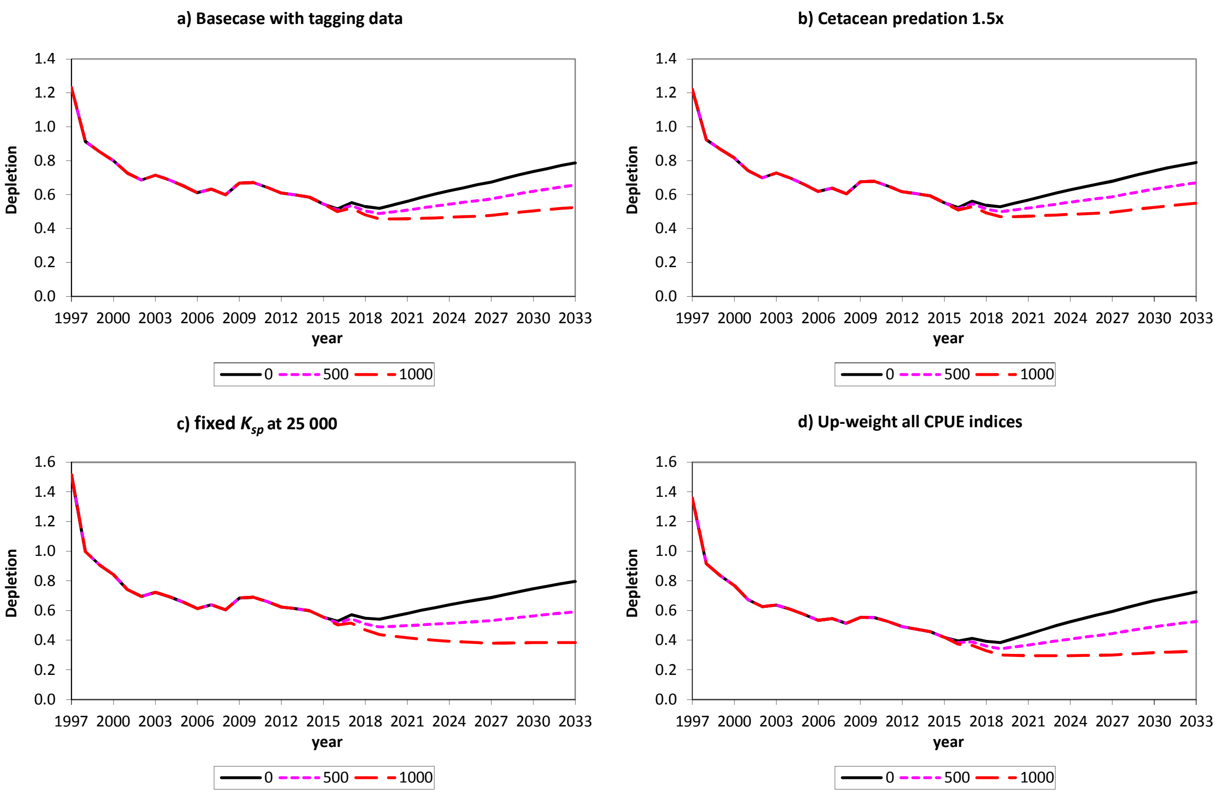


Figure 11. Spawning biomass projections under future annual catches of 0, 500 and 1 000 tonnes (assumed to be all from trotlines as is the case for catches taken in 2014) for the base case with tagging data (a) and three sensitivity tests ((b) accounts for cetacean predation of 1.5x, (c) a variant of the base case that fixes K_{sp} at 25 000, and (d) a variant of the base case that varies σ_R from 0.1 pre 1998 to 0.5 otherwise.

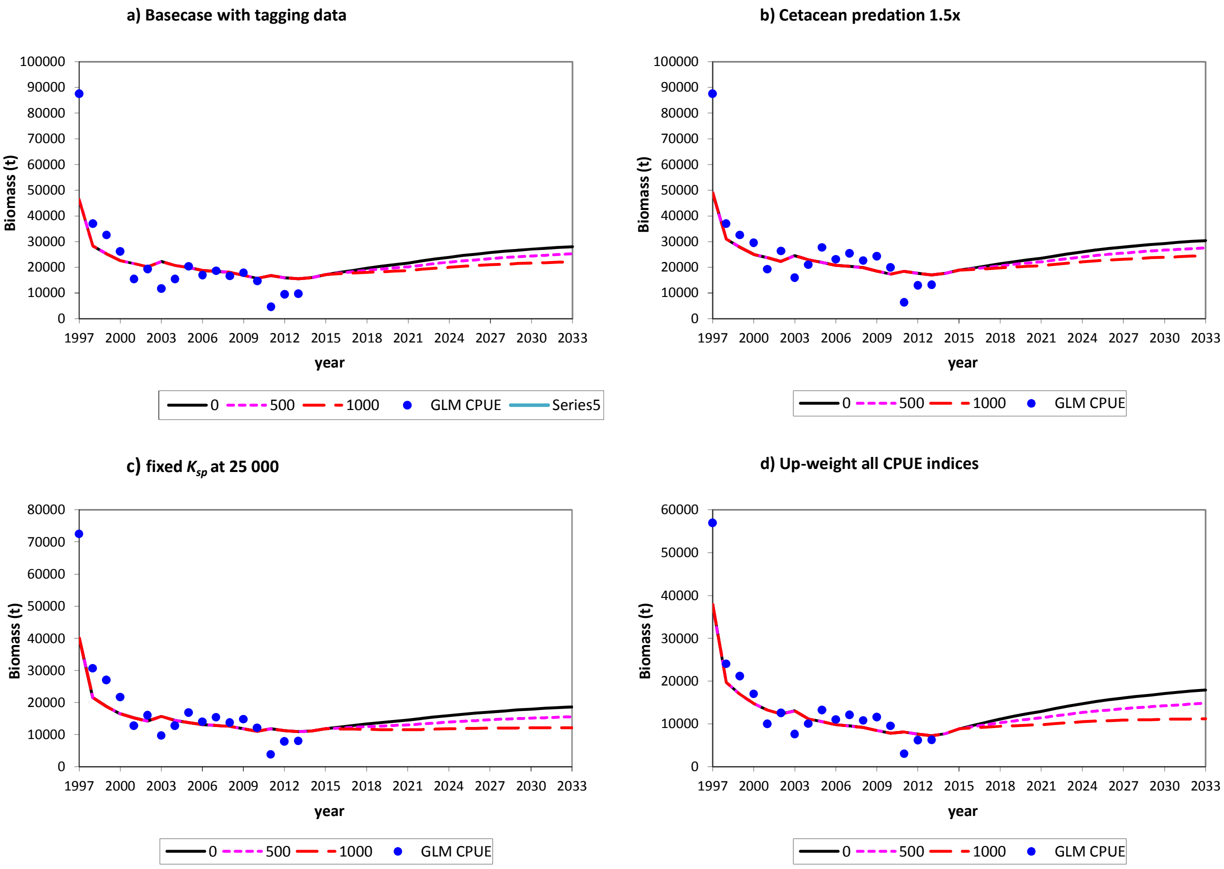


Figure 12. Exploitable biomass for the longline fishery and the GLM-standardised CPUE indices to which the model is fit (divided by the estimated catchability q to express them in biomass units), together with projections under future annual catches of 0, 500 and 1 000 tonnes (assumed to be all from trotlines as is the case for catches taken in 2014) for the base case with tagging data (a) and three sensitivity tests ((b) accounts for cetacean predation of 1.5x, (c) a variant of the base case that fixes K_{sp} at 25 000, and (d) a variant of the base case that varies σ_R from 0.1 pre 1998 to 0.5 otherwise.

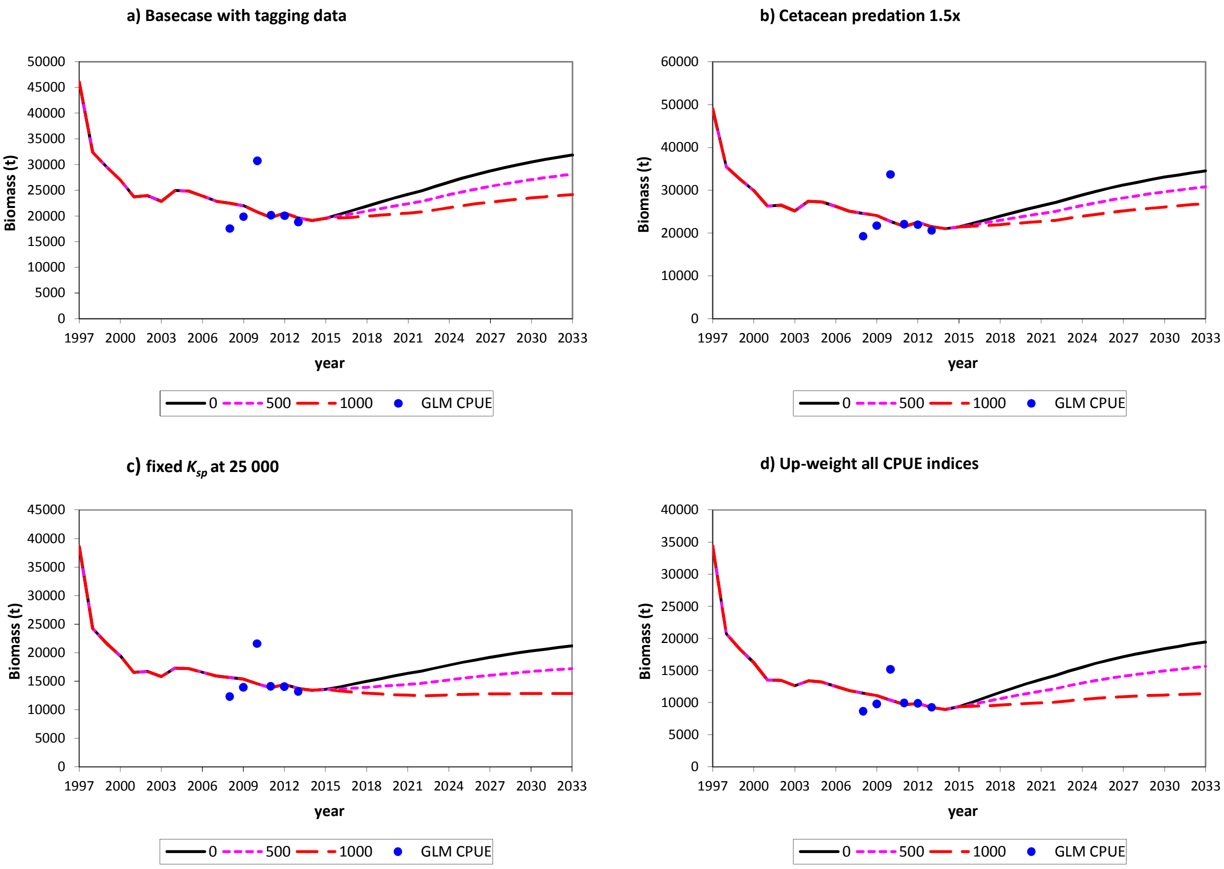


Figure 13. Exploitable biomass for the trotline fishery and the GLM-standardised CPUE indices to which the model is fit (divided by the estimated catchability *q* to express them in biomass units), together with projections under future annual catches of 0, 500 and 1 000 tonnes (assumed to be all from trotlines as is the case for catches taken in 2014) for the base case with tagging data (a) and three sensitivity tests ((b) accounts for cetacean predation of 1.5x, (c) a variant of the base case that fixes K_{sp} at 25 000, and (d) a variant of the base case that varies σ_R from 0.1 pre 1998 to 0.5 otherwise.

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:

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

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.:

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

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:

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

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:

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

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:

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

(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 $F_{y-k,a-k}$.