

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

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ABSTRACT

The ASPM assessment of the Prince Edward Islands toothfish resource by Brandão and Butterworth (2007) that permitted annual fluctuations about a deterministic stock-recruitment relationship is updated to take account of further catch, GLMM standardised CPUE and catch-at-length information that has become available for the years 2007 to 2013. The assessment allows for three fleets to accommodate data from a pot fishery that operated in 2004 and 2005 and a trotline fishery since 2008 in addition to the Spanish longline operations. Biological parameter values adopted for Subarea 48.3 are used. The resource is estimated to be at a depletion of about 87% of its average pre-exploitation level in terms of spawning biomass, but this requires large recruitment pulses in the 1990s and does not reflect the large CPUE decline when the fishery commenced. Imposing alternative constraints lead to a depletion of about 43%. These different assessments imply rather different sustainable yields, though all suggest medium term abundance increases for a TAC of 500 t.

INTRODUCTION

The last assessment of the Prince Edward Islands (PEI) toothfish (*Dissostichus eleginoides*) resource was carried out in 2007 (see Brandão and Butterworth, 2007). Since then, apart from further data inputs being now available, a data verification process has been carried out resulting in an extensive change to the data, especially to the commercial CPUE data (Brandão and Butterworth, 2012, 2013). Another change that has occurred in the fishery is the introduction of operations using trotlines in 2008. All this new information is incorporated in a three fleet Age-Structured Production Model (ASPM) assessment of the Prince Edward Islands resource which is presented in this paper. The biological parameter values adopted for toothfish in Subarea 48.3 (Agnew *et al.*, 2006) are assumed to apply.

Two sensitivity tests of the basecase model are performed to investigate the implications for the status of the resource if the impact of cetacean predation is taken into account. A further three

sensitivity tests are carried out to inform what aspects of this updated assessment are having the most influence on the higher estimate of current depletion than obtained previously.

DATA UPDATES

Further data available for the last few months of 2007 and continuing to July 2013, which were not available for previous assessments of toothfish in the Prince Edward Islands vicinity, have been incorporated in the present analyses. 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 and Butterworth (2004) for a description of the basis for the 2004 IUU estimate).

Two sensitivity tests have again been conducted assuming 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). Different amounts of cetacean predation are assumed in each sensitivity test; in a) the assumption of one out of three toothfish is lost to cetaceans (referred to as 1.5x), and in b) that two out of three toothfish are lost to cetaceans (referred to as 3x). 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 are 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 (2013) for the longline and trotline commercial data are listed in Table 2. Note that for the sensitivity tests including cetacean predation, the longline CPUE indices are inflated by the same proportions as the longline catch. 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 until July 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 July 2013. A relative weight (w_{len}) of 1.0 to the catch-at-length contribution to the log-likelihood has been applied in this paper.

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 3).

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 updated assessment of the toothfish resource presented in this paper is not merely the usual routine update of an assessment by incorporating further data available. Substantial changes have taken place since the last assessment was carried out in 2007. First a large amount of further data is now available (six years’ worth); secondly the commercial CPUE data has undergone verification process which resulted in a marked difference in the standardised CPUE series (see Brandão and Butterworth, 2013), in particular the large decline in the CPUE indices from 1997 to 1998 is no longer as sharp; and thirdly a new trotline fishery has been introduced since 2008.

These changes in the input data to the assessment have produced results that are markedly different from those obtained in previous assessments (Brandão and Butterworth, 2002, 2003, 2004, 2005, 2006, 2007) and which may be unrealistically optimistic. To fully understand the impact of the changes on the status of the toothfish resource, a considerable investigation needs to be undertaken. Unfortunately, due to time constraints, this could not be done immediately. As an initial investigation, three further sensitivity tests have been conducted:

- i) The basecase model but with a fixed K_{sp} .
- ii) Variant of the basecase model in which 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.
- iii) The same variant as (ii) above but with a fixed K_{sp} .

RESULTS AND DISCUSSION

Table 4 shows the results for a three-fleet assessment of the toothfish resource, including those for the basecase model as well as when cetacean predation is taken into account. These assessments suggest the current status of the resource to be in the region of 86% to 90% 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). Figure 1 shows estimated spawning biomass and recruitment trends for the basecase model and the sensitivity test that takes cetacean predation into account. Both models estimate 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. However both models also show an even larger peak in recruitment 1997 resulting in the current status of the resource being very healthy. Figure 2 shows the comparison of depletion trends between the basecase model and the sensitivity tests that take cetacean predation into account. Even assuming that two out of three toothfish are lost to cetaceans, the impact on the status of the resource is minimal. Fits to the CPUE data are shown in Figure 3 for the basecase and the sensitivity test that takes a 3x cetacean predation into account. The basecase model fails to fit the

comparatively very high 1997 CPUE value. The sensitivity test which takes cetacean predation into account fits this initial CPUE point marginally better, but at the expense of a worse fit to the other indices (however, overall it has a slightly better fit to the CPUE indices (see the σ_{CPUE} values in Table 4)). Fits of the basecase 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. The model overestimates the proportion of smaller toothfish in the last year but underestimates in the previous two years, in both the longline and the trotline fisheries. In general, the pattern of the catch-at-length residuals does not indicate model misspecification. The selectivity functions estimated for the basecase model and the sensitivity that allows for a 3x cetacean predation 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. A very low relative weight to the catch-at-length data has been tried to see if this would force the model to fit the first CPUE index and consequently obtain results more similar to those obtained previously. However, this was not the case and so this has not been pursued further here.

Table 5 shows the results for the three sensitivity tests performed which are variants of the basecase model. 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 previous assessments. For comparison, the basecase results 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 7 compares the spawning biomass (a) and recruitment (b) between the basecase and the further three sensitivity tests. Figure 7b clearly shows that only the one sensitivity test was able to reduce the large peaks in recruitment in 1997 and in 1990. This has been achieved by fitting the first CPUE index better (Figure 8 and Table 5) but a worse fit to the length data (Table 5).

Figure 9 shows the spawning biomass together with twenty year projections under different constant future annual catches for the basecase model and all sensitivity tests, except for the one assuming a cetacean predation of 1.5x. Projections assume a 50:50 split in future catches between the longline and the trotline fisheries and zero illegal removals. As the pot fishery has not been operational since 2005, no pot fishery is assumed in the projections.

Figure 10 provides similar results to Figure 9, but the projections are for the longline-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 87% of its average pre-exploitation level. This estimate is even higher if cetacean predation is taken into account. MSY estimates are in the four thousand tonnes range.

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

Alternative fits to the data are possible under different constraints. A poorer current status of 43% follows for a scenario that limits the extent of recruitment variability prior to the start of the fishery

and fixes the average pre-exploitation level of the spawning biomass at 25 000 tonnes. However, although this fits the CPUE data much better, the fit to the length composition data deteriorates considerably.

Despite these uncertainties, the projections in Figures 9 and 10 might provide a basis for a TAC recommendation. It is notable that these indicate medium term increases in spawning biomass under a 500 t TAC for all the scenarios considered.

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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 in the text. Catches (strictly “removals”) from the longline fisheries (“legal” and “illegal”) modified to include cetacean predation (see text for basis) are also given. The catches given for 2013 are estimates based upon data for part of that year only.

Year	Legal			Illegal (IUU)	Total		
	Longline fishery	Pot fishery	Trotline fishery		Without predation	With predation on longline fishery (1.5x)	With predation on longline fishery (3x)
1997	2 908.2	—	—	21 350	24 258.2	24258.2	24258.2
1998	1 102.1	—	—	1 808	2 910.1	2910.1	2910.1
1999	966.8	—	—	1 014	1 980.8	1980.8	1980.8
2000	1 548.2	—	—	1 210	2 758.2	3217.9	4597.1
2001	251.5	—	—	352	603.5	804.6	1408.1
2002	231.0	—	—	306	537.0	805.4	1610.9
2003	251.1	—	—	256	507.1	760.6	1521.3
2004	194.9	72.6	—	156	423.6	526.4	1052.8
2005	130.1	103.5	—	—	233.7	195.2	390.3
2006	169.1	—	—	—	169.1	253.6	507.2
2007	245.0	—	—	—	245.0	367.5	735.1
2008	88.8	—	58.0	—	146.9	133.3	266.5
2009	41.8	—	29.1	—	70.8	62.6	125.3
2010	49.2	—	182.3	—	231.4	73.7	147.5
2011	1.0	—	302.5	—	303.4	1.5	2.9
2012	48.6	—	207.7	—	256.4	72.9	145.8
2013	37.2	—	128.2	—	165.5	55.8	111.7
1997–2013 total	8 264.5	176.2	907.8	26 452	35 800.5	36 480.2	41 771.5

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, 2013). The CPUE indices adjusted to take cetacean predation into account are also shown. The indices for 2013 are based upon data for part of that year only.

Year	Longline fishery			Trotline fishery
	GLMM CPUE (no predation)	GLMM CPUE including predation (1.5x)	GLMM CPUE including predation (3x)	GLMM CPUE (no predation)
1997	0.551	0.551	0.551	—
1998	0.194	0.194	0.194	—
1999	0.201	0.201	0.201	—
2000	0.239	0.279	0.399	—
2001	0.059	0.078	0.137	—
2002	0.129	0.193	0.386	—
2003	0.027	0.041	0.082	—
2004	0.145	0.218	0.436	—
2005	0.134	0.200	0.401	—
2006	0.073	0.109	0.218	—
2007	0.100	0.149	0.299	—
2008	0.128	0.192	0.383	0.578
2009	0.096	0.145	0.289	0.845
2010	0.100	0.150	0.299	1.062
2011	0.054	0.081	0.162	0.969
2012	0.055	0.083	0.166	0.666
2013	0.050	0.075	0.151	0.821

Table 3. Biological parameter values as recently updated (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-edge in age.

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

Table 4. 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. The details of the various model variants reported are given in the text.

Parameter estimates		Model			
		Basecase (no predation)	Model with predation (1.5x)	Model with predation (3x)	Basecase with $w_{len}=0.186$
K_{sp} (tonnes)		79 182	81 660	108 283	153 325
$MSYL_{sp}$ (Longline)/ K_{sp}		0.245	0.245	0.245	0.246
B_{sp}^{2014}/K_{sp}		0.869	0.864	0.898	0.955
B_{sp}^{1997}/K_{sp}		1.193	1.192	1.169	0.961
$B_{sp}^{2014}/MSYL_{sp}$ (Longline)		3.555	3.535	3.671	3.875
B_{exp}^{2014} (tonnes)	Longline	47 452	48 819	68 941	122 004
	Pot	76 530	78 503	108 196	166 072
	Trotline	65 386	67 151	94 798	173 259
σ_{CPUE}	Longline	0.648	0.544	0.459	0.705
	Trotline	0.224	0.224	0.223	0.211
σ_R		0.500 ^{††}	0.500 ^{††}	0.500 ^{††}	0.500 ^{††}
a_{50}^{97-02} (yr)		6.852	6.798	6.744	6.779
δ^{97-02} (yr ⁻¹)		0.007	0.004	0.011	0.010
ω^{97-02} (yr ⁻¹)		0.065	0.065	0.065	0.047
a_{50}^{03-13} (yr)	Longline	6.741	6.739	6.558	6.626
	Pot	8.989	8.992	9.039	9.260
	Trotline	7.760	7.758	7.600	7.688
δ^{03-07} (yr ⁻¹)	Longline	0.003	0.011	0.019	0.015
	Pot	0.803	0.803	0.810	0.924
	Trotline	0.007	0.010	0.018	0.013
ω^{03-07} (yr ⁻¹)	Longline	0.053	0.052	0.050	0.040
	Pot	0.000	0.000	0.000	0.000
	Trotline	0.015	0.015	0.013	0.000
β		0.128	0.128	0.128	0.124
σ_{len}	Longline	0.052	0.052	0.052	0.055
	Pot	0.033	0.033	0.033	0.037
	Trotline	0.053	0.053	0.053	0.054

†† Input value.

Table 4 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. The details of the various model variants reported are given in the text.

Parameter estimates		Model			
		Basecase (no predation)	Model with predation (1.5x)	Model with predation (3x)	Basecase with $w_{len}=0.186$
-ln L: Length		-519.6	-519.5	-517.8	-85.42
-ln L: CPUE		-4.849	-7.823	-10.730	-3.793
-ln L: Recruitment		2.395	2.340	0.417	-25.89
-ln L: Total		-522.1	-525.0	-528.1	-115.1
MSY (tonnes)	Longline	3 216 [†]	3 317 [†]	4 403 [†]	6 313 [†]
	Pot	3 566	3 678	4 881	6 927
	Trotline	3 442	3 551	4 714	6 739

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

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 (values in brackets give the difference in log-likelihood for models when K_{sp} is estimated or fixed). The details of the various sensitivity tests reported are given in the text.

Parameter estimates		Model			
		Basecase	Basecase (fixed K_{sp})	Varying σ_R	Varying σ_R (fixed K_{sp})
K_{sp} (tonnes)		79 182	36 000	184 566	25 000
$MSYL_{sp}$ (Longline)/ K_{sp}		0.245	0.245	0.244	0.250
B_{sp}^{2014}/K_{sp}		0.869	0.746	0.848	0.427
B_{sp}^{1997}/K_{sp}		1.193	1.340	1.016	1.135
$B_{sp}^{2014}/MSYL_{sp}$ (Longline)		3.555	3.043	3.472	1.711
B_{exp}^{2014} (tonnes)	Longline	47 452	19 640	88 469	11 057
	Pot	76 530	29 912	173 741	10 795
	Trotline	65 386	26 764	123 427	12 569
σ_{CPUE}	Longline	0.648	0.587	0.616	0.531
	Trotline	0.224	0.223	0.232	0.212
σ_R		0.500 ^{††}	0.500 ^{††}	0.1 pre 1998; 0.5 otherwise ^{††}	0.1 pre 1998; 0.5 otherwise ^{††}
a_{50}^{97-02} (yr)		6.852	6.985	6.737	6.987
δ^{97-02} (yr ⁻¹)		0.007	0.001	0.011	0.010
ω^{97-02} (yr ⁻¹)		0.065	0.058	0.053	0.017
a_{50}^{03-13} (yr)	Longline	6.741	6.509	6.525	6.787
	Pot	8.989	9.114	8.504	11.71
	Trotline	7.760	7.470	7.588	7.600
δ^{03-07} (yr ⁻¹)	Longline	0.003	0.020	0.019	0.008
	Pot	0.803	0.840	0.809	1.529
	Trotline	0.007	0.023	0.017	0.017
ω^{03-07} (yr ⁻¹)	Longline	0.053	0.049	0.070	0.023
	Pot	0.000	0.011	0.000	0.000
	Trotline	0.015	0.015	0.028	0.000
β		0.128	0.127	0.125	0.128
σ_{len}	Longline	0.052	0.052	0.055	0.058
	Pot	0.033	0.034	0.039	0.045
	Trotline	0.053	0.053	0.052	0.052

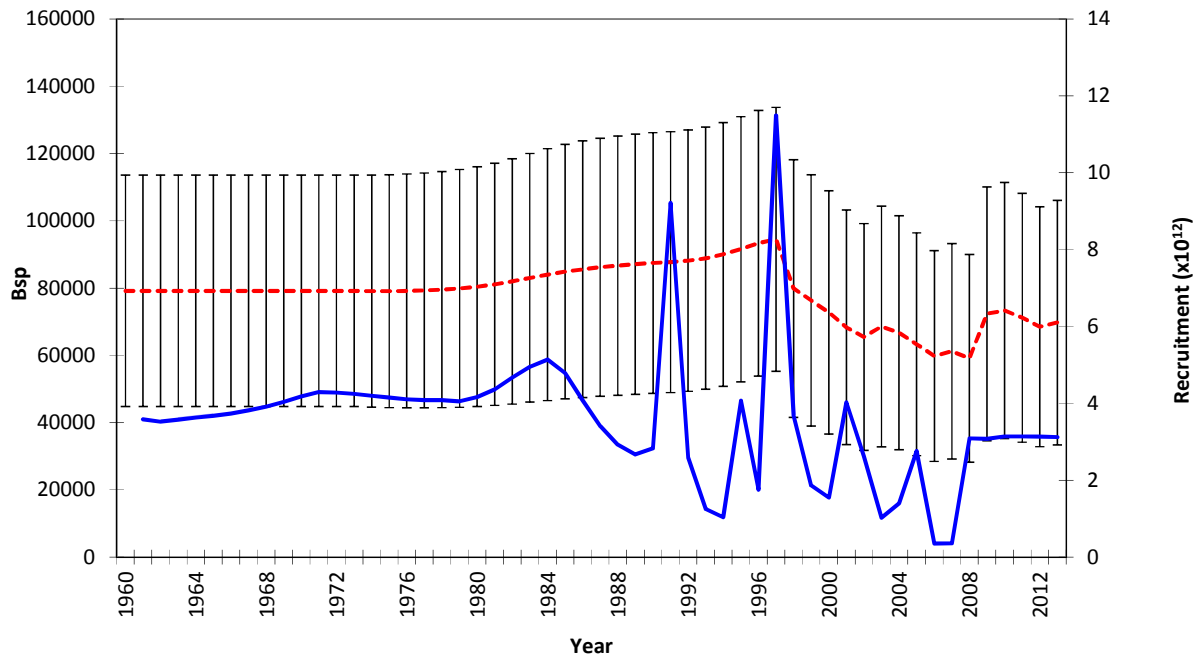
†† Input value(s).

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 (values in brackets give the difference in log-likelihood for models when K_{sp} is estimated or fixed). The details of the various model variants reported are given in the text.

Parameter estimates		Model			
		Basecase	Basecase (fixed K_{sp})	Varying σ_R	Varying σ_R (fixed K_{sp})
-ln L: Length		-519.6	-522.0 (-2.40)	-460.1	-399.8 (60.3)
-ln L: CPUE		-4.849	-6.579 (-1.73)	-5.504	-8.568 (-3.06)
-ln L: Recruitment		2.395	9.947 (7.55)	-50.78	7.958 (58.7)
-ln L: Total		-522.1	-518.7 (3.40)	-516.4	-400.4 (116)
MSY (tonnes)	Longline	3 216 [†]	1 469 [†]	7 482 [†]	1 054 [†]
	Pot	3 566	1 624	8 227	1 166
	Trotline	3 442	1 569	7 942	1 099

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

a)



b)

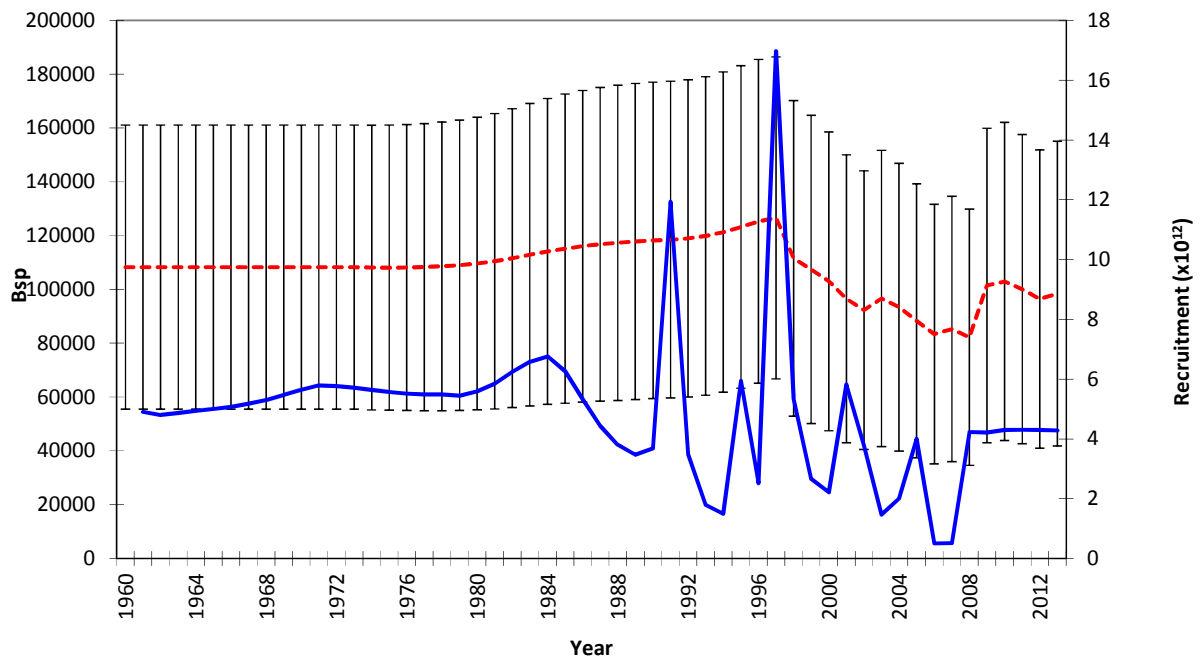


Figure 1. Spawning biomass estimates (dashed line) and estimated recruitment (full line) for the three-fleet model for a) the basecase (no predation) and b) the sensitivity test that takes a 3x cetacean predation into account. Confidence limits of one standard error for the spawning biomass are also shown.

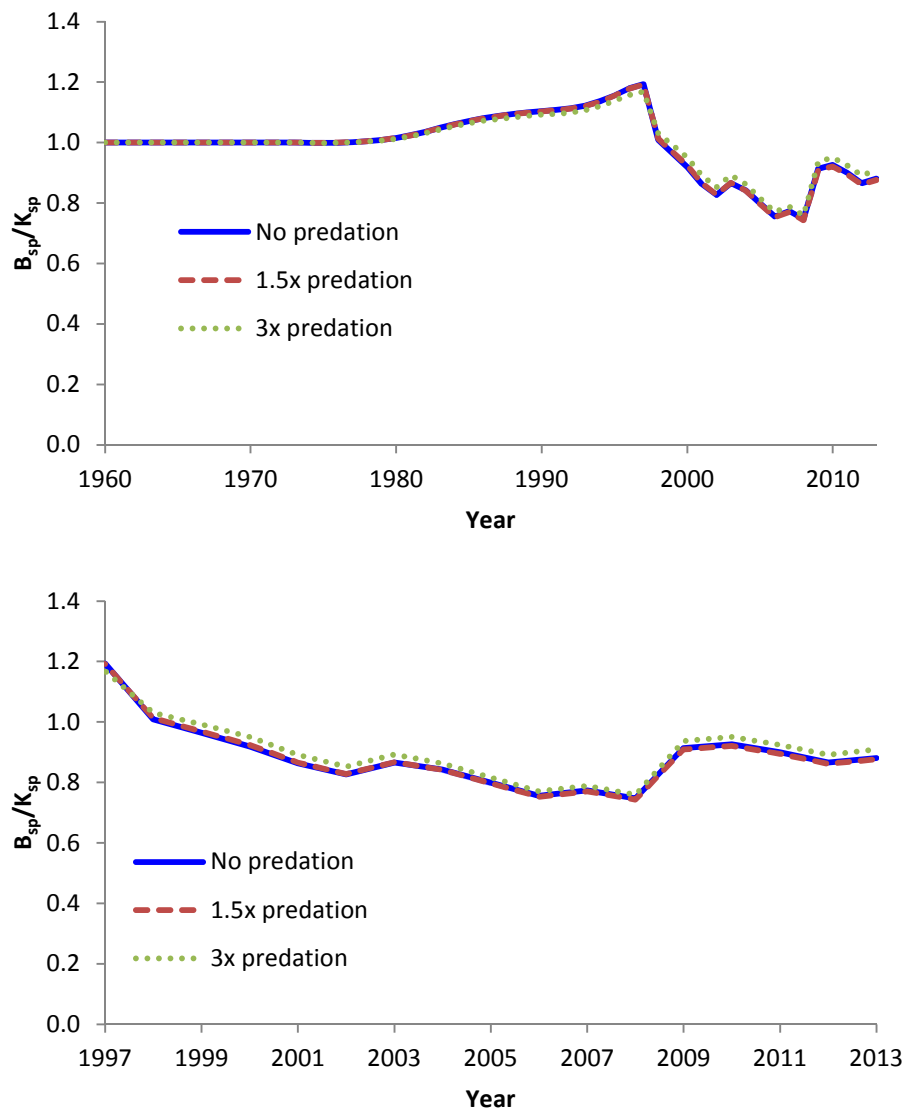


Figure 2. Spawning biomass estimates (in terms of pre-exploitation level) for the three-fleet model for the basecase (no predation) and the sensitivity tests that take a 1.5x and a 3x cetacean predation into account. The bottom plot zooms in the later period of the trajectories.

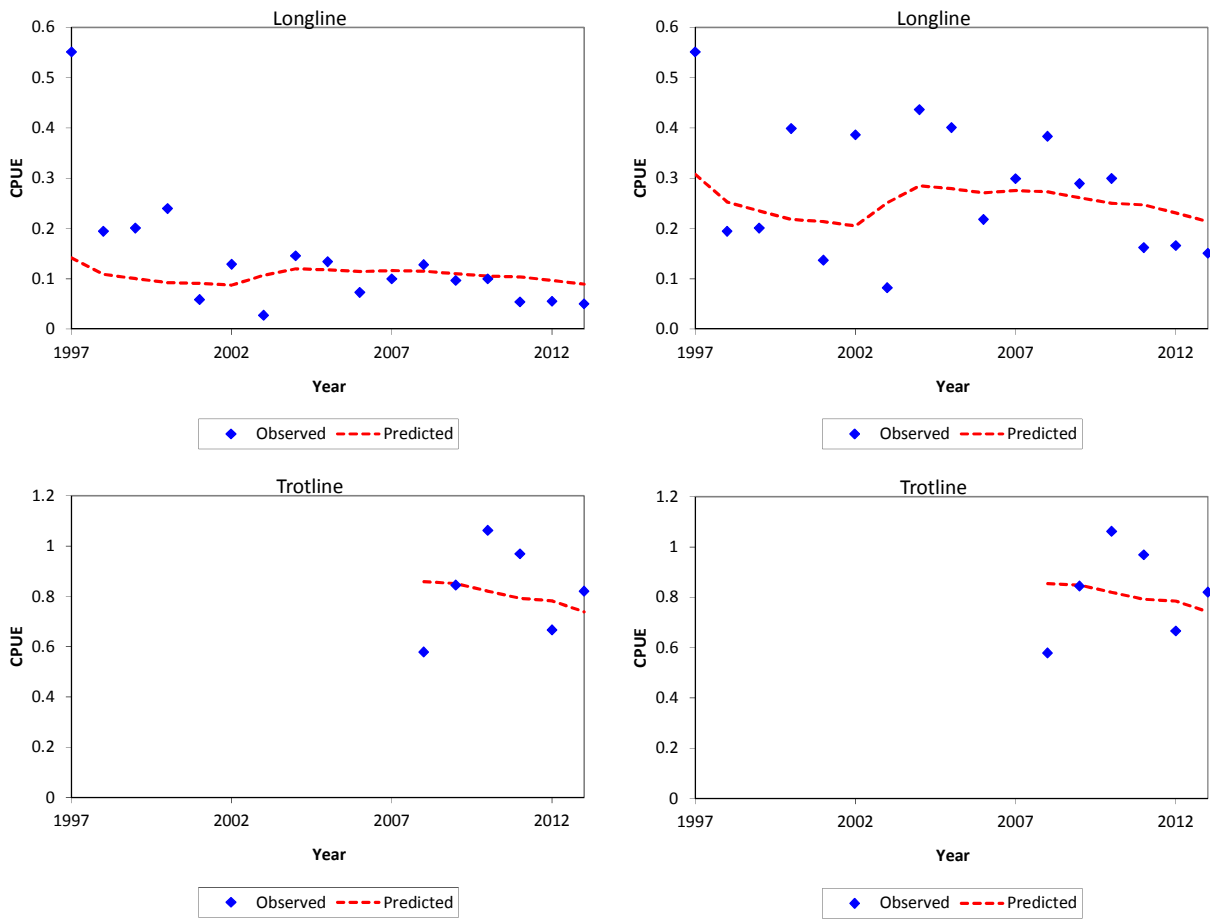


Figure 3. Exploitable biomass and the GLM-standardised CPUE indices to which the model is fit (divided by the estimated catchability q to express them in biomass units) for the basecase (left) and the sensitivity test that takes a 3x cetacean predation into account (right).

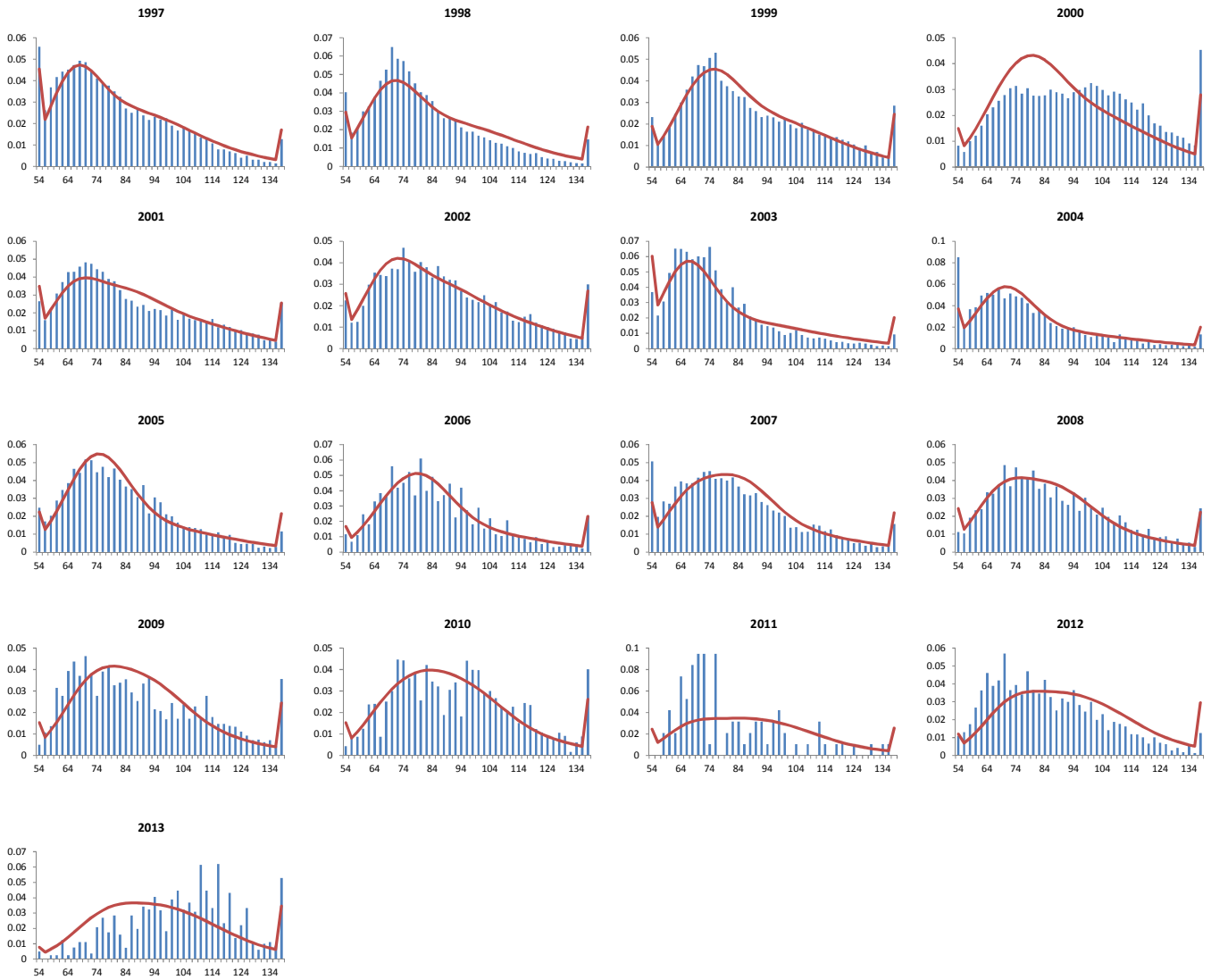


Figure 4a. Assessment predictions for the annual catch-at-length proportions in the longline fishery for the basecase. Note that lengths below 54 and above 138 cm are combined into minus- and plus-groups.

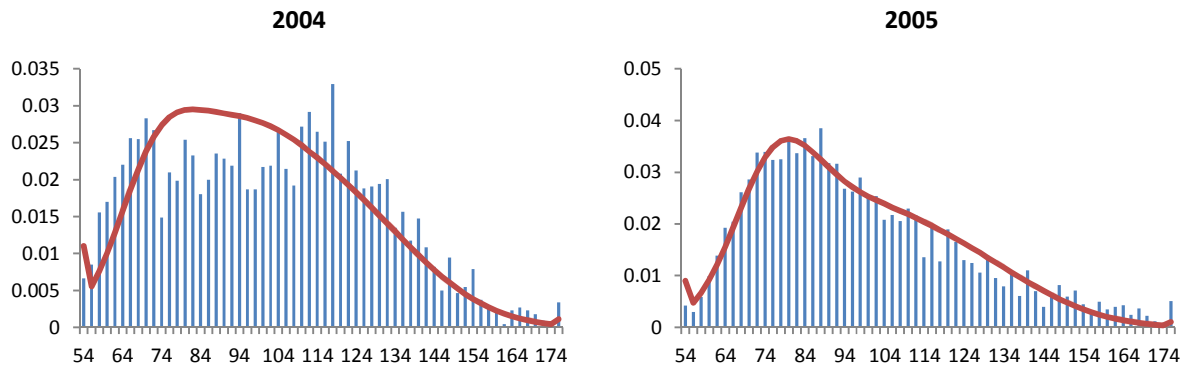


Figure 4b. Assessment predictions for the annual catch-at-length proportions in the pot fishery for the basecase. Note that lengths below 54 and above 176 cm are combined into minus- and plus-groups.

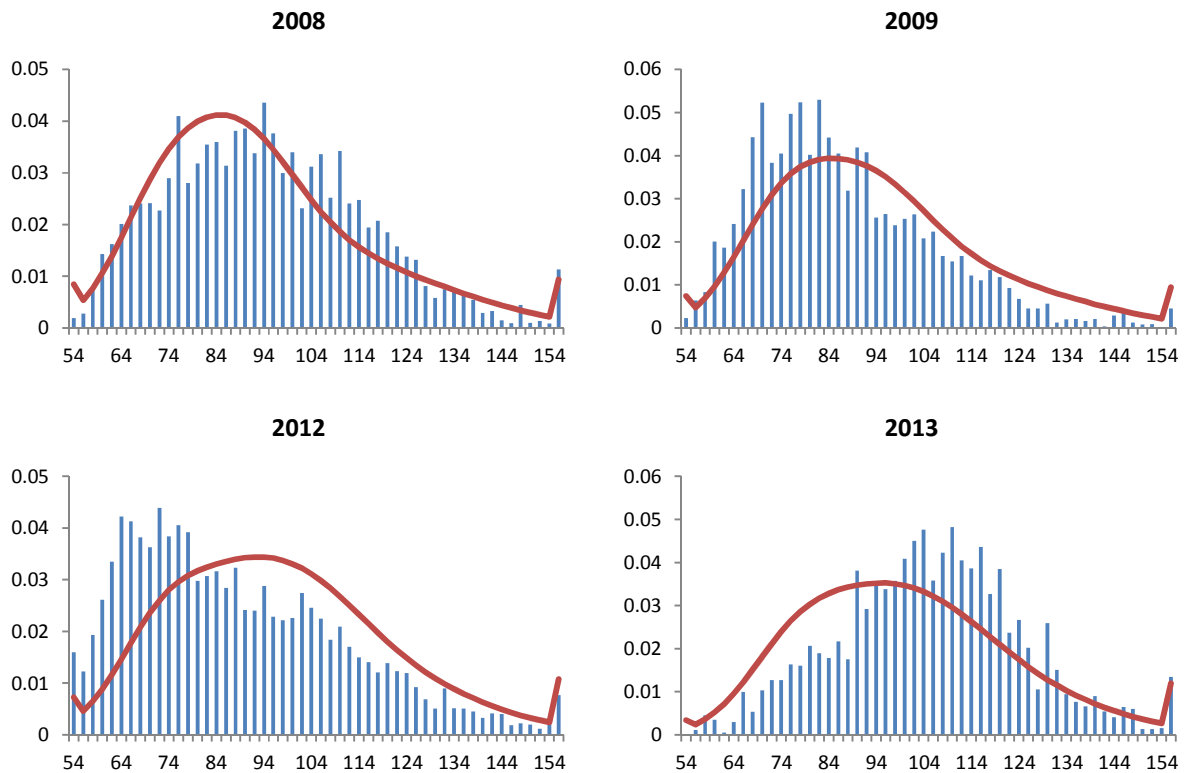


Figure 4c. Assessment predictions for the annual catch-at-length proportions in the trotline fishery for the basecase. Note that lengths below 54 and above 156 cm are combined into minus- and plus-groups.

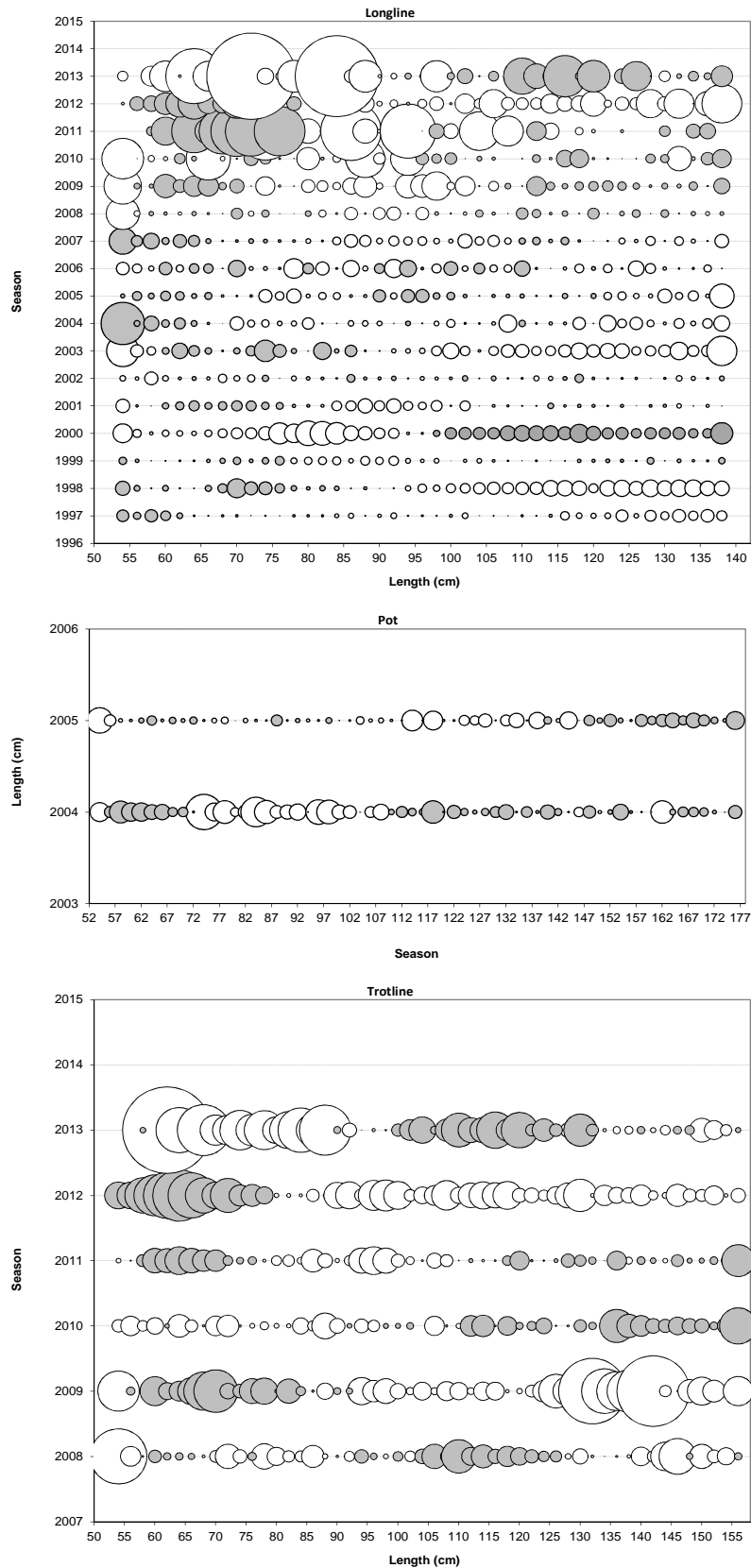
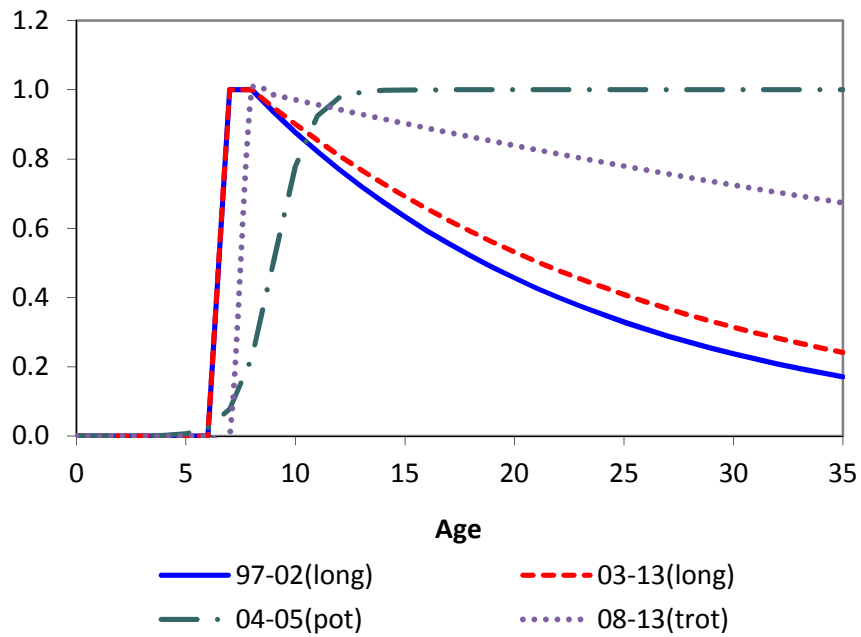


Figure 5. Bubble plots of the catch-at-length residuals for the three fisheries for the basecase. The size of the bubble is proportional to the corresponding standardised residual $(\ln(obs) - \ln(pred)) / (\sigma / \sqrt{pred})$. White bubbles represent negative residuals while grey bubbles represent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

a)



b)

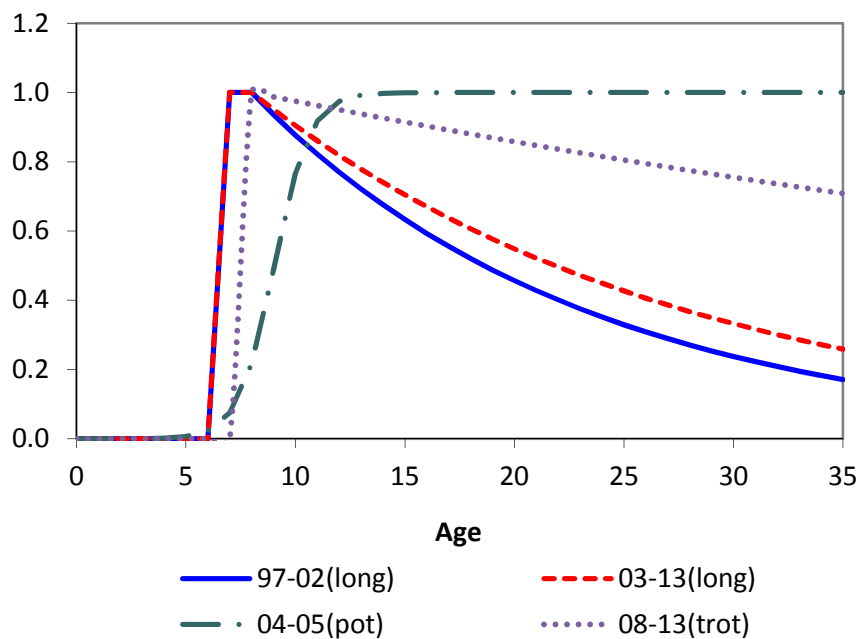


Figure 6. Estimated selectivity curves for the periods 1997–2002 and 2003–2013 for the longline fishery, for the period 2004–2005 for the pot fishery and for the period 2008–2013 for the trotline fishery. Curves are shown for a) the basecase and b) the sensitivity test that takes a 3x cetacean predation into account.

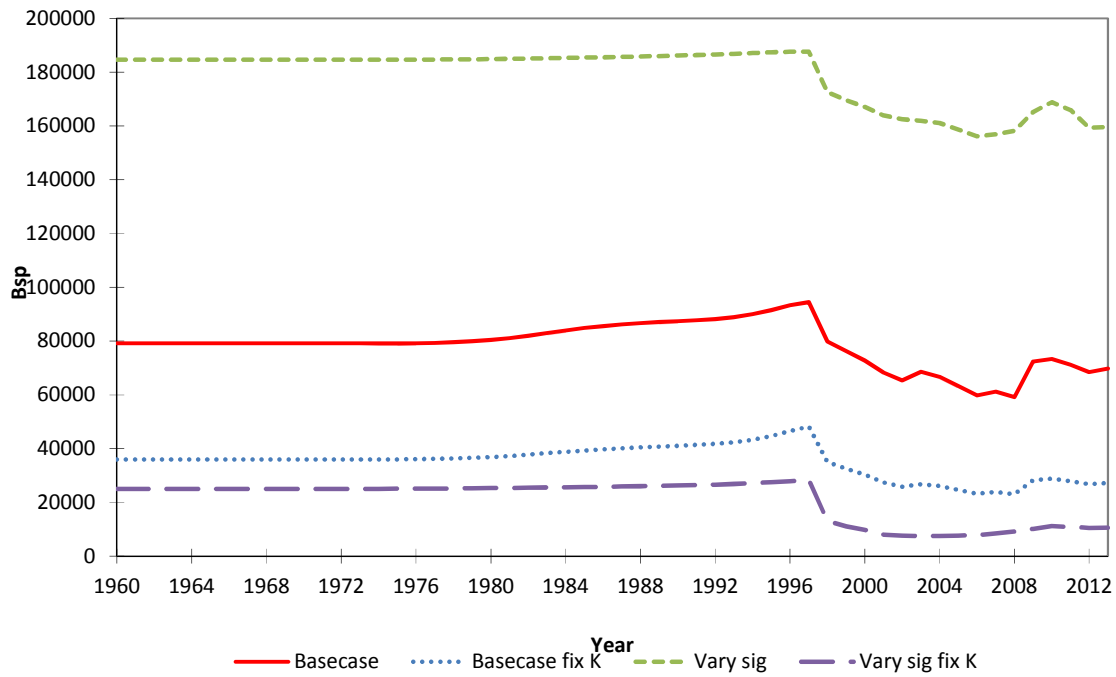


Figure 7a. Spawning biomass estimates for the three-fleet model for the basecase (no predation) and three sensitivity tests (a variant of the basecase that fixes K_{sp} at 36 000, a variant of the basecase that varies σ_R from 0.1 pre 1998 to 0.5 otherwise, and a variant of the previous sensitivity test which in addition fixes K_{sp} at 25 000).

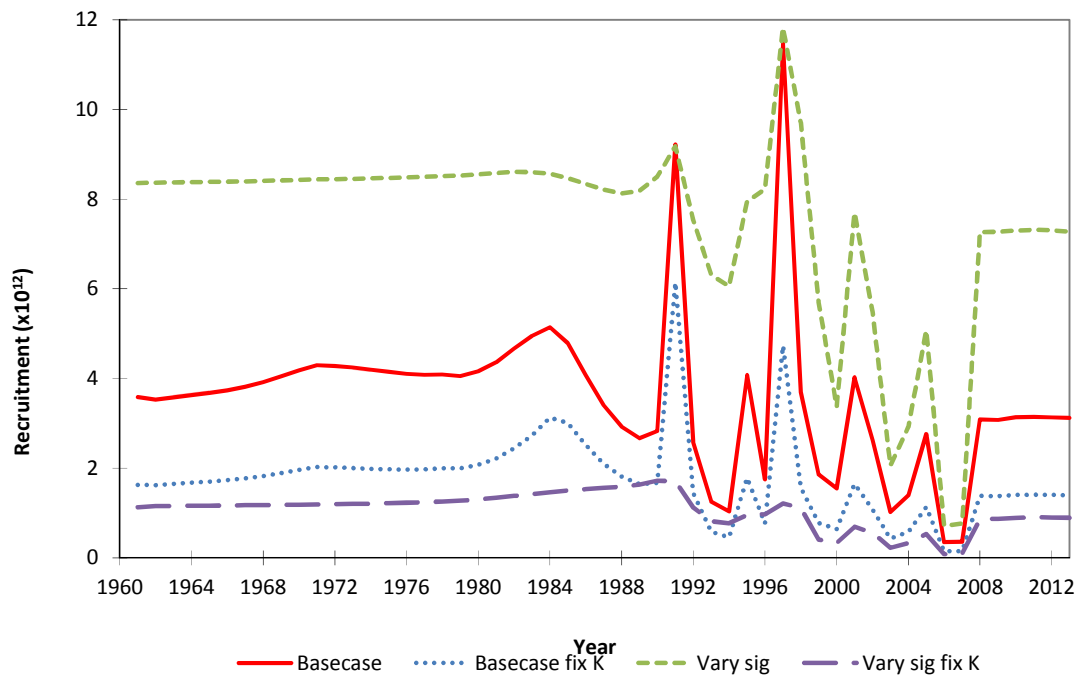


Figure 7b. Estimated recruitment for the three-fleet model for the basecase (no predation) and three sensitivity tests (a variant of the basecase that fixes K_{sp} at 36 000, a variant of the basecase that varies σ_R from 0.1 pre 1998 to 0.5 otherwise, and a variant of the previous sensitivity test which in addition fixes K_{sp} at 25 000).

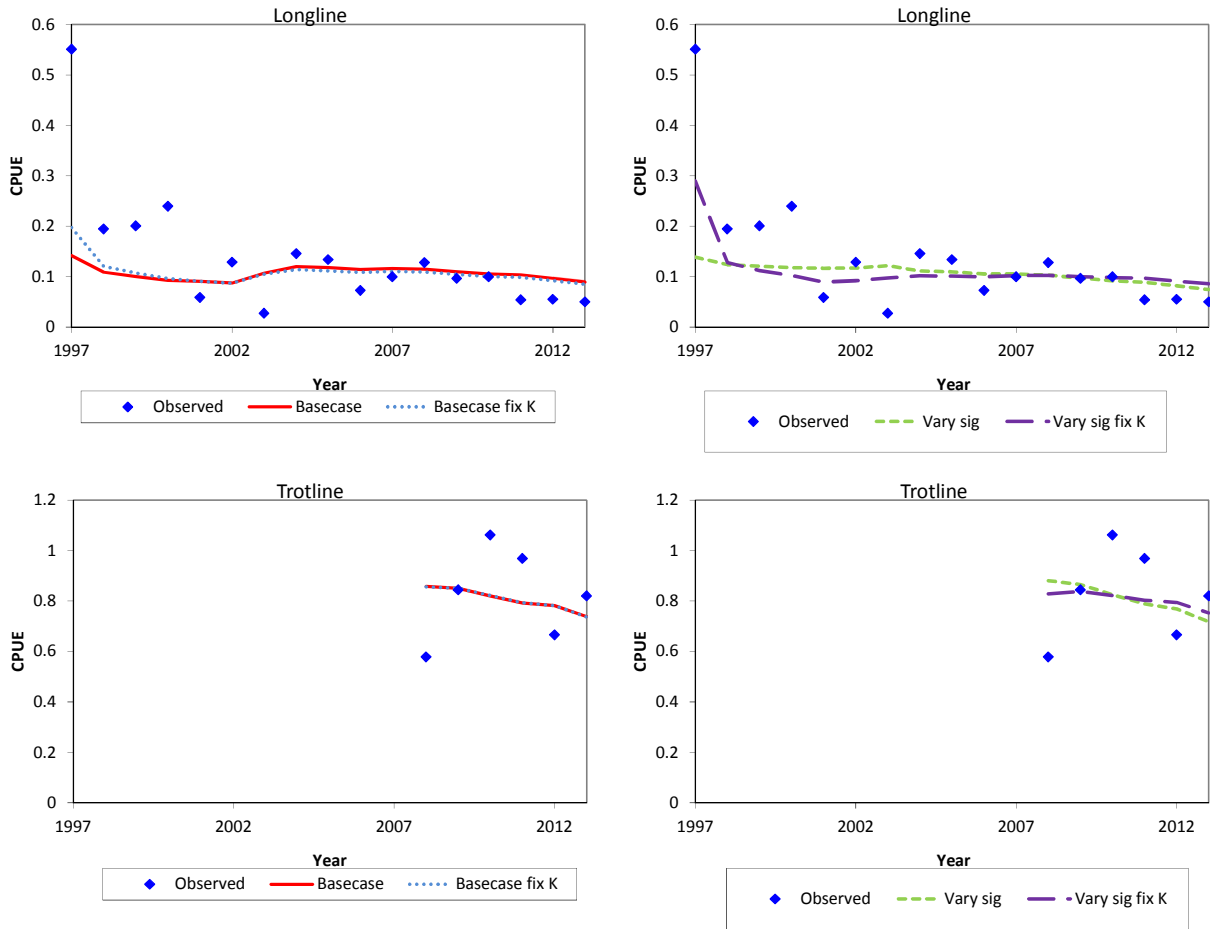


Figure 8. Exploitable biomass and the GLM-standardised CPUE indices to which the model is fit (divided by the estimated catchability q to express them in biomass units) for the basecase (no predation) and three sensitivity tests (a variant of the basecase that fixes K_{sp} at 36 000, a variant of the basecase that varies σ_R from 0.1 pre 1998 to 0.5 otherwise, and a variant of the previous sensitivity test which in addition fixes K_{sp} at 25 000).

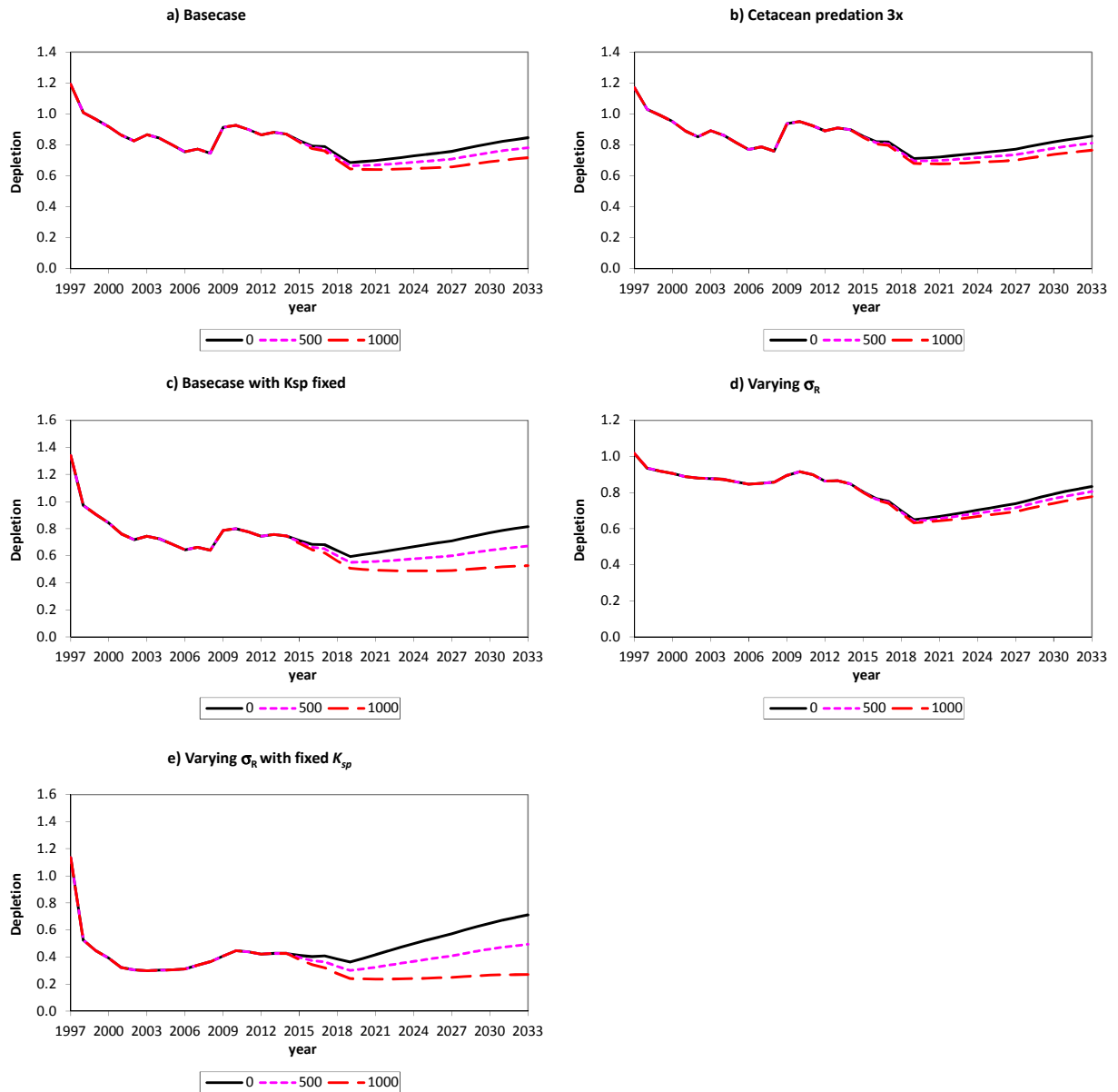


Figure 9. Spawning biomass projections under future annual catches of 0, 500 and 1 000 tonnes (split 50:50 between longlines and trotlines) for the basecase (a) and four sensitivity tests ((b) accounts for cetacean predation of 3x, (c) a variant of the basecase that fixes K_{sp} at 36 000, (d) a variant of the basecase that varies σ_R from 0.1 pre 1998 to 0.5 otherwise, and (e) a variant of the previous sensitivity test which in addition fixes K_{sp} at 25 000). For the longline fishery, the current longline selectivity is assumed to apply in the future.

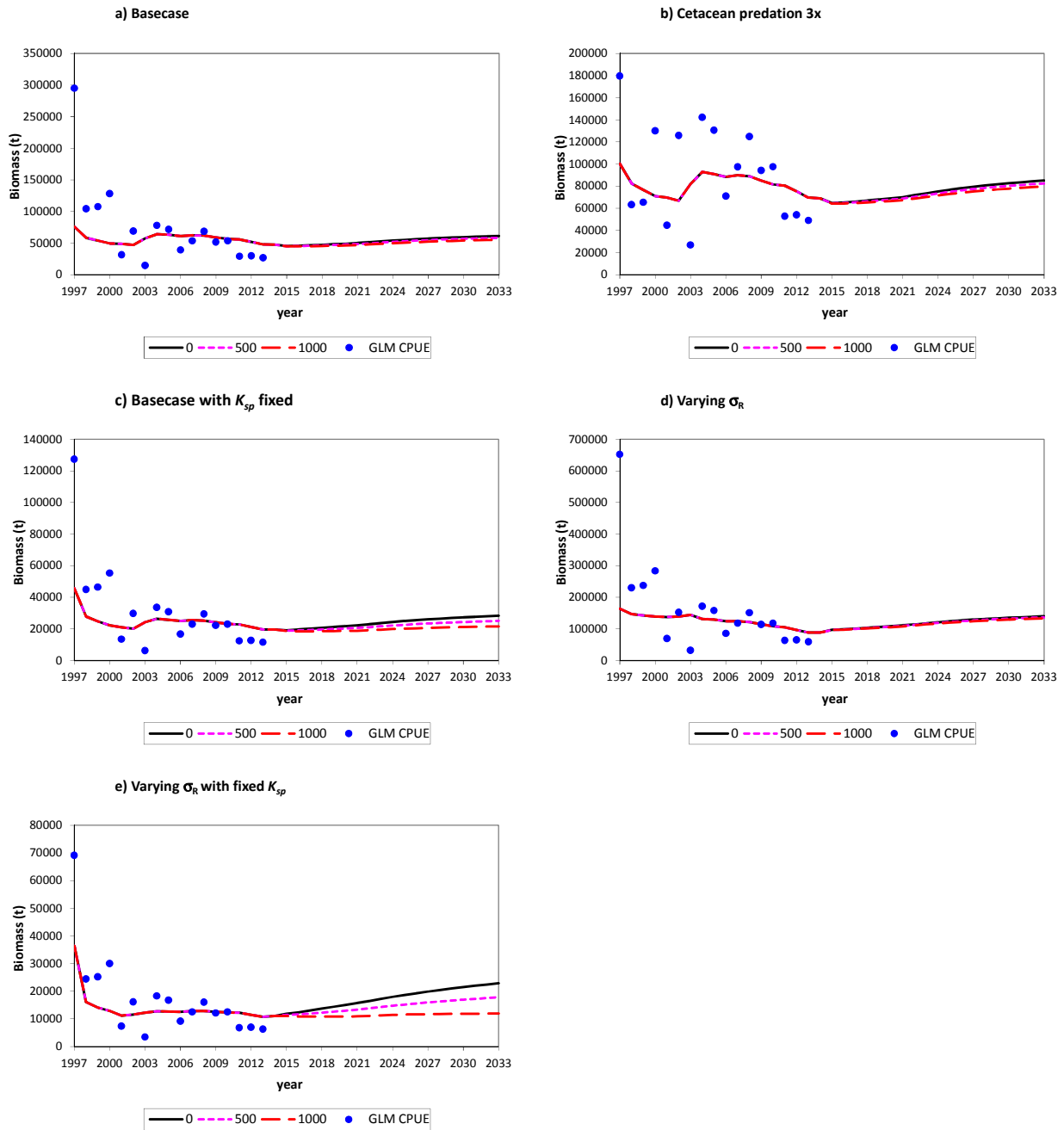


Figure 10. Exploitable biomass for the longline fishery and the GLM-standardised CPUE indices to which the model is fit (divided by the estimated catchability q to express them in biomass units), together with projections under future annual catches of 0, 500 and 1 000 tonnes (split 50:50 between longlines and trotlines) for the basecase (a) and four sensitivity tests ((b) accounts for cetacean predation of 3x, (c) a variant of the basecase that fixes K_{sp} at 36 000, (d) a variant of the basecase that varies σ_r from 0.1 pre 1998 to 0.5 otherwise, and (e) a variant of the previous sensitivity test which in addition fixes K_{sp} at 25 000). For longline fishery, the current longline selectivity is assumed to apply in the future.

APPENDIX 1

THE AGE STRUCTURED PRODUCTION MODEL (ASPM) ASSESSMENT METHODOLOGY

THE BASIC DYNAMICS

The toothfish population dynamics are given by the equations:

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

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

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

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:

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

where:

$$C_{y,a}^f = N_{y,a} S_{y,a}^f F_y^f \quad (A1.5)$$

and:

- F_y^f is the proportion of the resource above age a harvested in year y by fleet f , and
- $S_{y,a}^f$ 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.

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

$$w_a = c [\ell(a)]^d \quad (A1.7)$$

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:

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

which can be re-written as:

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

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:

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

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:

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

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

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

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

$$g(x) = \begin{cases} x & x \leq 0.9 \\ 0.9 + 0.1[1 - e^{(-10(x-0.9))}] & 0.9 < x \leq \infty \end{cases}. \quad (\text{A1.13})$$

Now F_y^f is not bounded at one, but $g(S_{y,a}^f F_y^f) \leq 1$ 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:

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

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):

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

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.:

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

from which it can be shown that:

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

Rearranging equation (A1.16) gives:

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

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:

$$\gamma K^{sp} = R_0 = \frac{\alpha K^{sp}}{\beta + K^{sp}} \quad (\text{A1.19})$$

where:

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

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:

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

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:

$$N_{0,a} = \begin{cases} R_0 e^{-Ma} & 0 \leq a \leq m-1 \\ \frac{R_0 e^{-Ma}}{1 - e^{-M}} & a = m \end{cases} \quad (\text{A1.22})$$

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:

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

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:

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

where

I_y^f is the standardised CPUE series index for year y corresponding to fleet f ,
 $\hat{I}_y^f = \hat{q}^f \hat{B}_y^{\text{exp}}(f)$ is the corresponding model estimate, where:
 $\hat{B}_y^{\text{exp}}(f)$ 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:

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

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:

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

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

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

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 :

$$p_{y,a}^f = C_{y,a}^f / \sum_a C_{y,a}^f. \quad (\text{A1.28})$$

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:

$$p_{y,\ell}^f = \sum_a p_{y,a}^f A_{a,\ell}^f \quad (\text{A1.29})$$

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

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

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.:

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

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.:

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

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):

$$-\ln L_{len} = w_{len} \sum_{f,y,\ell} \left\{ \ln \left[\frac{\sigma_{len}^f}{\sqrt{p_{y,\ell}^f}} \right] + \left(\frac{p_{y,\ell}^f}{2(\sigma_{len}^f)^2} \right) \left[\ln p_{y,\ell}^{obs}(f) - \ln p_{y,\ell}^f \right]^2 \right\} \quad (\text{A1.33})$$

where

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

σ_{len}^f has a closed form maximum likelihood estimate given by:

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

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 $p_{y,\ell}^f$ 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 $p_{y,\ell}^{obs}(f)$ 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 $p_{y,\ell}^{obs}(f)$ values in excess of about 2% for these cells.

ADJUSTMENT TO INCORPORATE RECRUITMENT VARIABILITY

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

$$R(B_y^{sp}) = \frac{\alpha B_y^{sp}}{\beta + B_y^{sp}} e^{(\zeta_y - \sigma_R^2/2)}, \quad (\text{A1.35})$$

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:

$$-\ln L_{rec} = \sum_{y=1961} \left\{ \ln \sigma_R + \zeta_y^2 / (2\sigma_R^2) \right\}, \quad (\text{A1.36})$$

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 $\sigma_R = 0.5$.