2007 ASSESSMENT OF THE TOOTHFISH (*Dissostichus eleginoides*) RESOURCE IN THE PRINCE EDWARD ISLANDS VICINITY

A. Brandão and D.S. Butterworth

MARAM (Marine Resource Assessment and Management Group)
Department of Mathematics and Applied Mathematics,
University of Cape Town, Rondebosch 7701, South Africa

ABSTRACT

The ASPM assessment of the Prince Edward Islands toothfish resource by Brandão and Butterworth (2006) that permitted annual fluctuations about a deterministic stock-recruitment relationship is updated to take account of further catch, GLM standardised CPUE and catch-at-length information that has become available for the years 2006 and 2007. The assessment allows for a second fleet to accommodate data from a pot fishery that operated in 2004 and 2005. Biological parameter values adopted for Subarea 48.3 are used. The resource is estimated to be at about 37% of its average pre-exploitation level in terms of spawning biomass. It is suggested that it would be prudent to restrict annual legal catches to 500 tonnes or less, unless a large proportion of the catch is to be taken by pots (which avoid the cetacean predation associated with longlining).

INTRODUCTION

An updated two fleet Age-Structured Production Model (ASPM) assessment of the Prince Edward Islands (PEI) toothfish (*Dissostichus eleginoides*) resource is presented in this paper. Compared to the previous assessment of Brandão and Butterworth (2006), further data inputs available for the last few months of 2006 and data until June 2007 are now also taken into account. 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 a) the impact of cetacean predation is taken into account and b) the 1997 CPUE index is omitted.

DATA UPDATES

Further data available for the last months of 2006 to June 2007, 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. However, these reports cover only times when the legal vessels were operating, and it is not obvious that the same situation can be assumed during periods when no monitoring was possible. Therefore the same amount of illegal take is assumed from 2005 onwards as for 2004 (see Brandão and Butterworth (2004) for a description of the basis for the 2004 IUU estimate). Brandão and Butterworth (2005) conducted a sensitivity test assuming zero illegal catches in 2005, but this had minimal effects on the basecase results.

A sensitivity test has 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). Table 1 shows the catch figures with and without this assumed cetacean predation. 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.

The CPUE GLM standardisation procedure described in Appendix 1 of Brandão and Butterworth (2003) (see also Appendix 2 of this paper) has been reapplied to the longline commercial data, resulting in the revised series of relative abundance indices listed in Table 2. To include the CPUE for the first part of 2007, two analyses were performed: one including CPUE data from 1997 to 2006 and another from 1997 to 2007. The trend in the standardised CPUE indices for the first six months of the latter analysis was then used to obtain an estimated CPUE index for 2007 from the 1997–2006 standardised indices. Note that for the sensitivity test 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 incorporation of these CPUE data in assessments must await further pot fishing. As a sensitivity test, the 1997 CPUE index has been omitted, because it appears potentially highly influential.

Catch-at-length information for the longline fishery has also been updated to include the data available for the whole of 2006 and to June 2007. Catch-at-length data for the pot fishery for November 2004 to April 2005 are included in the present assessment as in Brandão and Butterworth (2005, 2006). 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 two fleets, so that the information from the pot fishery can be incorporated in the ASPM assessment, is as in Brandão and Butterworth (2005, 2006). 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 of the toothfish off the Prince Edward Islands.

RESULTS AND DISCUSSION

Table 4 shows the results for a two-fleet assessment of the toothfish resource, including those for the basecase model as well as when cetacean predation is taken into account and when the 1997 CPUE index is omitted. For comparison, the previous results for the basecase model from Brandão and Butterworth (2006) are also given. These assessments suggest the status of the resource to be in the region of 37% to 40% of average pre-exploitation equilibrium spawning biomass. The sensitivity test which omits the 1997 CPUE data point reflects little differences in results compared to the basecase. 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. Fits to the CPUE data are shown in Figure 2 for these two assessments. 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 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 and pot fisheries are shown in Figure 3. The selectivity functions estimated for the basecase model and the sensitivity that allows for cetacean predation are shown in Figure 4. In previous papers, model variants which place different relative weights on seemingly contradictory CPUE and catch-at-length data have been reported. However, as the models reported here show reasonable fits to both the CPUE (except perhaps the initial value) and the catch-at-length data, variants which assign alternative relative weights to these two data sets have not been pursued here.

Figure 5 shows both the spawning and the longline exploitable components of the biomass, together with twenty year projections under different constant future annual catches for the basecase model. Note that the catch as specified covers both legal and illegal removals. Projections assume the longline fishery selectivity to apply in the future as the pot fishery has not been operational recently. Figure 6 provides similar results to Figure 5, but for the sensitivity test that takes cetacean predation into account. Here the future catches as indicated have been inflated by multiplying by three in the computations to account for future cetacean predation. Table 5 shows some summary statistics for these projections.

CONCLUSIONS

The two-fleet model that takes the information available from the pot fishery into account estimates the spawning biomass of the resource to be about 37% of its average pre-exploitation level. This estimate improves to 40% if cetacean predation is taken into account.

On the basis of the MSY estimates in Table 4 together with the projections in Figures 5 and 6 and the fact that the resource is estimated to be well above its MSY level, it seems that a future total annual catch (by both legal and illegal operators) of some 1 000 tonnes would be sustainable, unless taken entirely by longlining (which would increase the effective catch to 3 000 tonnes as a result of cetacean predation – see Figure 6). Unless a large proportion of any catch is to be taken by pots, it seems prudent to restrict the annual legal catch not to exceed about 500 tonnes.

ACKNOWLEDGEMENTS

Financial support for this work from Marine and Coastal Management and the South African National Antarctic Programme of the Department of Environment Affairs and Tourism is acknowledged. Pheobius Mullins of Marine and Coastal Management and CAFISH are thanked for providing the data. The estimation software used, AD Model Builder, is a trademark of Otter Research Ltd., P O Box 265, Station A, Nanaimo, B.C. V9R 5K9, Canada.

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. 2002. 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. and Butterworth, D.S. 2003. Progress on the application of an Age-Structured Production Model fitted to commercial catch-rate and catch-at-length data to assess the toothfish (*Dissostichus eleginoides*) resource in the Prince Edward Islands vicinity. Commission for the Conservation of Antarctic Marine Living Resources Subgroup on Assessment Methods Document: WG-FSA-03/97.

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. 2006. 2006 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-06/58.

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 2007 are detailed in the text. Catches from the longline fisheries ("legal" and "illegal") modified to include cetacean predation (see text for basis) are also given. The catches given for 2007 are estimates based upon data for part of that year only.

Year	***Legal***		***Illegal***	***Total***	
	Longline fishery	**Pot fishery**		**Without predation**	**With predation on longline fishery**
1997	2 921.2	—	21 350	24 271.2	24 271.2
1998	1 010.9	—	1 808	2 818.9	2 818.9
1999	956.4	—	1 014	1 970.4	1 970.4
2000	1 561.6	—	1 210	2 771.6	4 619.4
2001	351.9	—	352	703.9	1 642.4
2002	200.2	—	306	506.2	1 518.5
2003	312.9	—	256	568.9	1 706.7
2004	194.9	72.6	156	423.6	1 052.8
2005	131.2	103.5	156	390.7	861.6
2006	166.9	—	156	322.9	968.7
2007	112.2	—	156	268.2	804.7
1997–2007 total	7 920.3	176.2	26 920	35 016.5	42 235.3

Table 2. Relative abundance indices (normalised to their mean over 1997-2006) for toothfish provided by the standardised commercial CPUE series for the Prince Edward Islands EEZ for the longline fishery. For comparison, indices from the previous analysis (Brandão and Butterworth 2006) are also shown, as are the CPUE indices adjusted to take cetacean predation into account. The indices for 2007 are based upon data for part of that year only.

Year	**Longline fishery**		
	GLM *CPUE* (previous analysis)	**GLM *CPUE* (present analysis)**	**GLM *CPUE* including predation**
1997	4.597	4.665	4.665
1998	1.265	1.229	1.229
1999	1.108	1.071	1.071
2000	0.676	0.623	1.038
2001	0.410	0.381	0.890
2002	0.427	0.393	1.180
2003	0.532	0.503	1.508
2004	0.302	0.286	0.857
2005	0.529	0.531	1.594
2006	0.153	0.317	0.952
2007	—	0.427	1.280

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 relationship	
c	25.4×10^{-6}
d	2.8
Age at maturity (yr)	13
Age at recruitment (yr)	6
Steepness parameter (h)	0.75

Table 4. Estimates for a two fleet (longline and pot) model that assumes different commercial selectivities for the two 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}^{2008}) in terms of both K_{sp} and $MSYL_{sp}$, and the (longline) exploitable biomass ($B_{\exp}^{2008}$) at the beginning of the year 2008 (assuming the same selectivity as for 2007). Note that these estimates for the previous basecase apply to 2007 rather than 2008. 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: Previous Basecase	Model: Updated Basecase	Model: Model with predation	Model: Basecase (omit 1997 CPUE)
K_{sp} (tonnes)		27 922	28 111	41 878	29 655
$MSYL_{sp}$ (Longline)/K_{sp}		0.205	0.202	0.213	0.204
B_{sp}^{2008}/K_{sp}		0.386	0.366	0.398	0.381
$B_{sp}^{2008}/MSYL_{sp}$(Longline)		1.887	1.809	1.867	1.868
$B_{\exp}^{2008}$ (tonnes)	Longline	6 571	6 894	11 503	7 601
	Pot	13 877	13 994	22 701	15 417
B_{sp}^{1997}/K_{sp}		1.183	1.197	1.136	1.186
σ_{CPUE}	Longline	0.444	0.358	0.350	0.269
σ_R		0.500††	0.500††	0.500††	0.500††
a_{50}^{97-02} (yr)		6.516	6.515	6.515	6.515
δ^{97-02} (yr^{-1})		0.024	0.024	0.024	0.024
ω^{97-02} (yr^{-1})		0.070	0.070	0.071	0.071
a_{50}^{03-07} (yr)	Longline	6.505	6.521	6.526	6.521
	Pot	8.007	8.103	8.188	8.112
δ^{03-07} (yr^{-1})	Longline	0.025	0.025	0.025	0.025
	Pot	0.351	0.456	0.469	0.457
ω^{03-07} (yr^{-1})	Longline	0.100	0.104	0.098	0.104
	Pot	0.000	0.000	0.000	0.000
β		0.130	0.128	0.128	0.128
σ_{len}	Longline	0.035	0.034	0.035	0.034
	Pot	0.032	0.032	0.032	0.032
-ln L: Length		-446.5	-501.9	-485.9	-500.6
-ln L: CPUE		-3.114	-5.802	-6.051	-8.141
-ln L: Recruitment		6.965	9.896	-0.186	8.260
-ln L: Total		-442.7	-497.8	-492.1	-500.5
MSY (tonnes)	Longline	1 111†	1 117†	1 667†	1 178†
	Pot	1 239	1 249	1 864	1 318

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

Table 5. Some summary statistics for the 20–year spawning biomass projections.

a) Basecase: $\frac{B_{sp}^{2008}}{K_{sp}} = 0.366$

	Longline selectivity		
Future annual catch (tonnes)	**0**	**400**	**1000**
$\frac{B_{sp}^{2027}}{K_{sp}}$	0.716	0.551	0.300

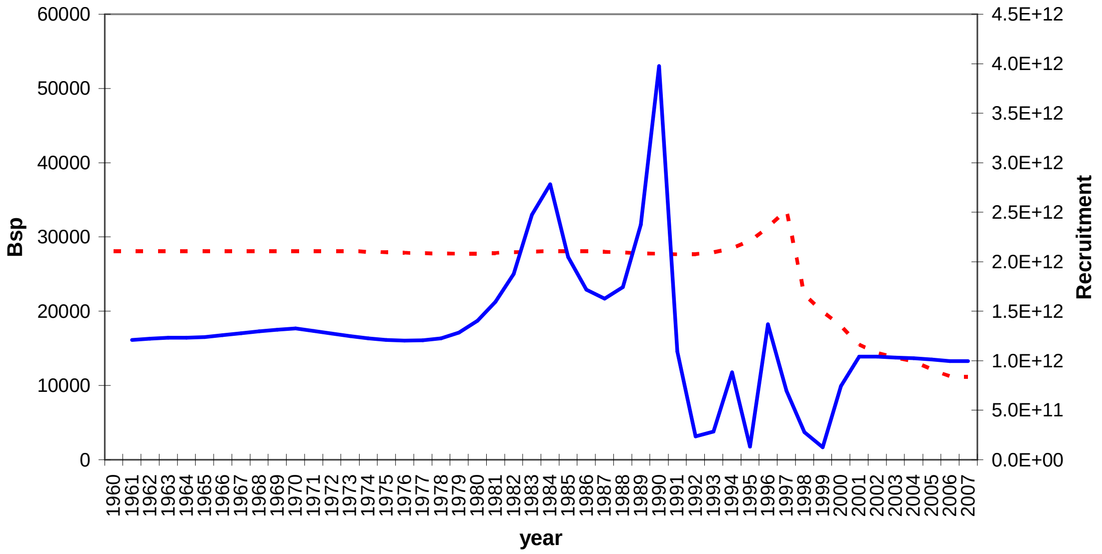
b) Including cetacean predation: $\frac{B_{sp}^{2008}}{K_{sp}} = 0.398$

	Longline selectivity		
Future annual catch (tonnes)	**0**	**400**	**1000**
$\frac{B_{sp}^{2027}}{K_{sp}}$	0.736	0.405	0.000

c) Basecase model (omitting 1997 CPUE index): $\frac{B_{sp}^{2008}}{K_{sp}} = 0.381$

	Longline selectivity		
Future annual catch (tonnes)	**0**	**400**	**1000**
$\frac{B_{sp}^{2027}}{K_{sp}}$	0.725	0.569	0.333

a)



b)

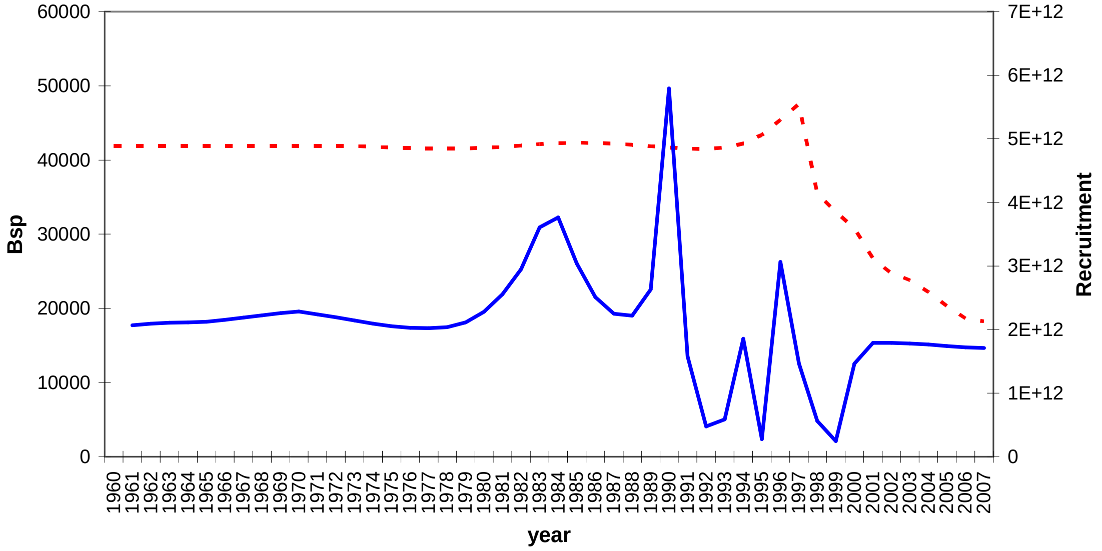
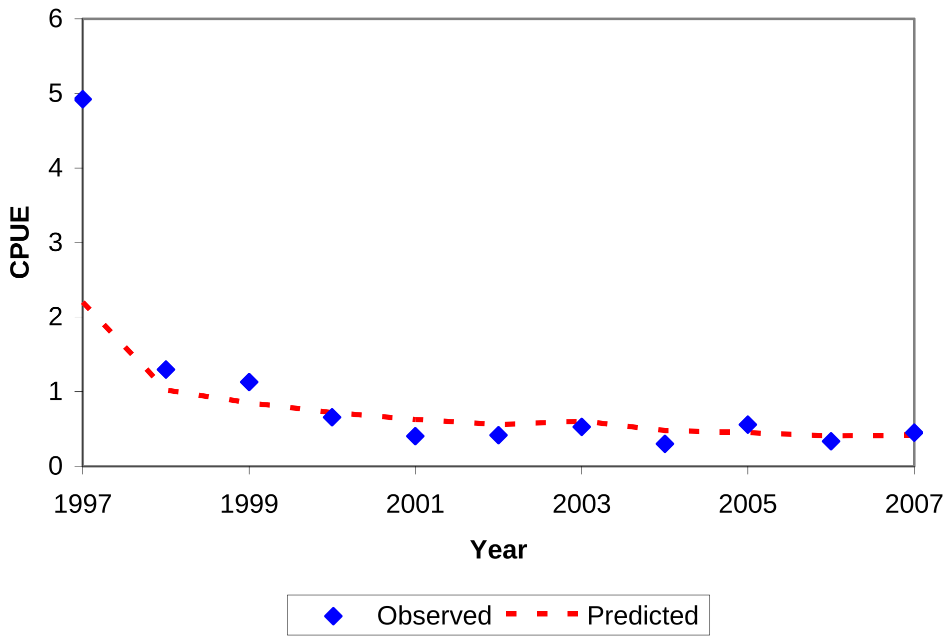


Figure 1. Spawning biomass estimates (dashed line) and estimated recruitment (full line) for the two-fleet model for a) the basecase and b) the sensitivity test that takes cetacean predation into account.

a)



b)

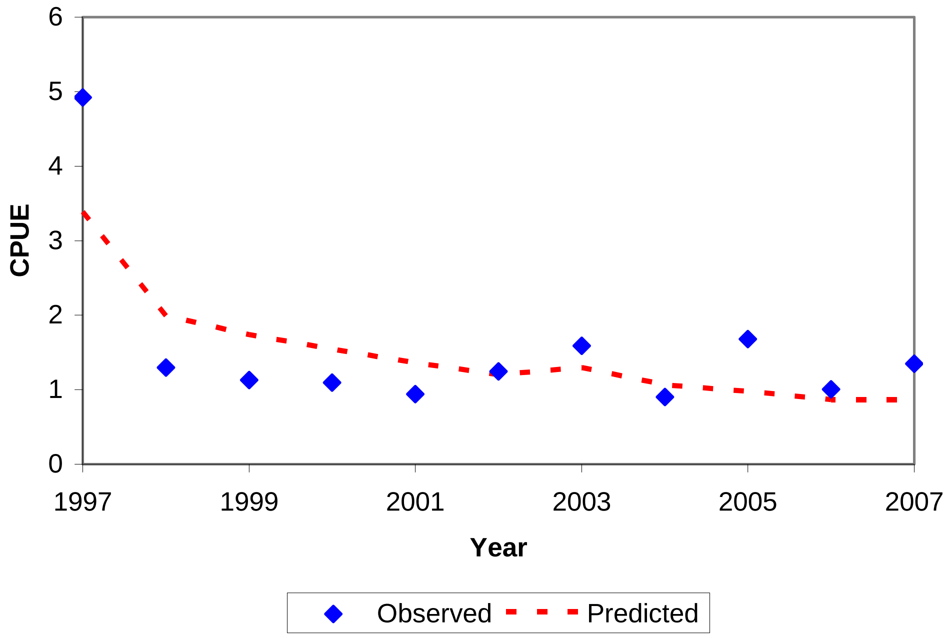


Figure 2. Exploitable biomass and the GLM-standardised CPUE indices to which the model is fit (divided by the estimated catchability q to express them in biomass units) for a) the basecase and b) the sensitivity test that takes cetacean predation into account.

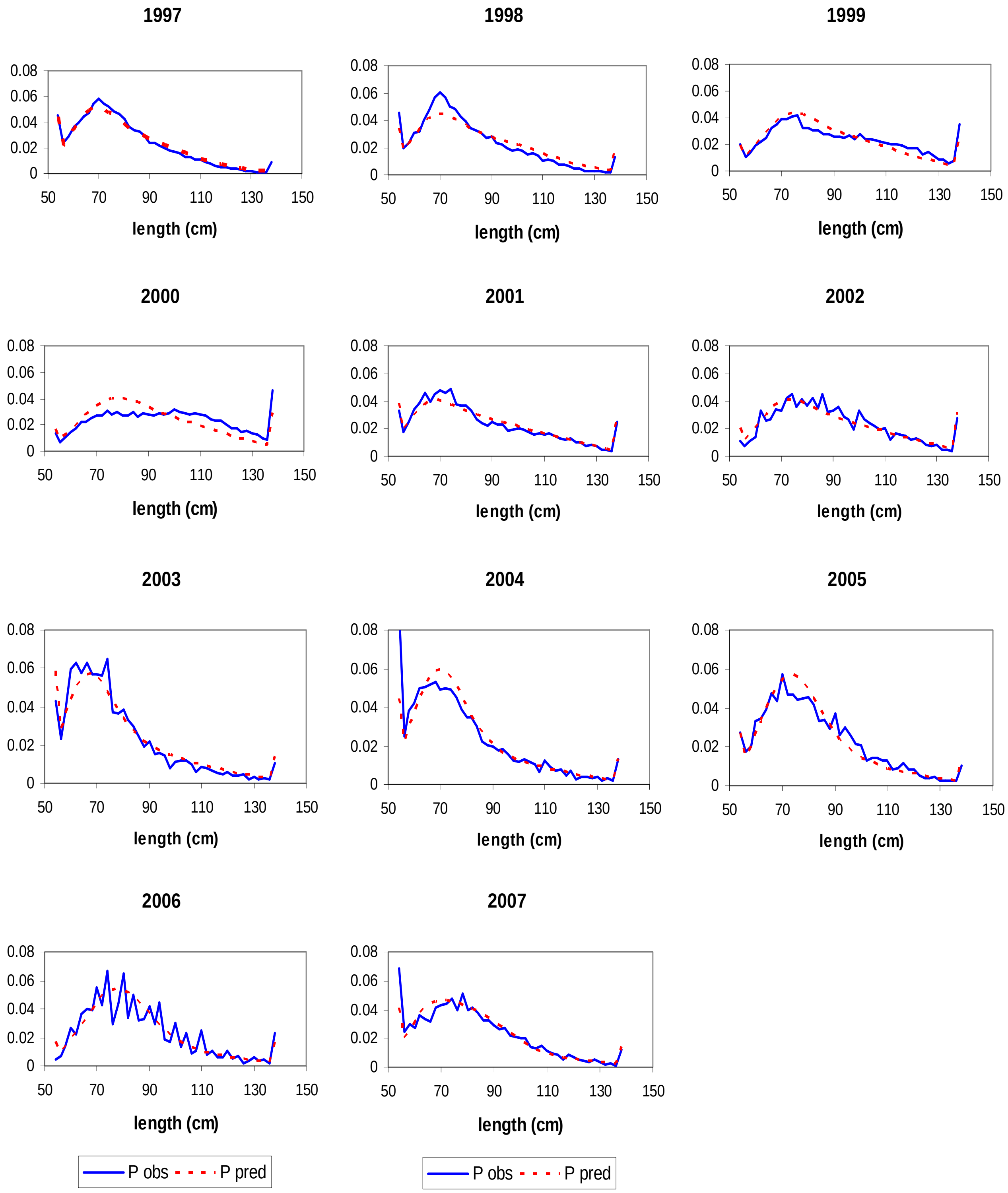
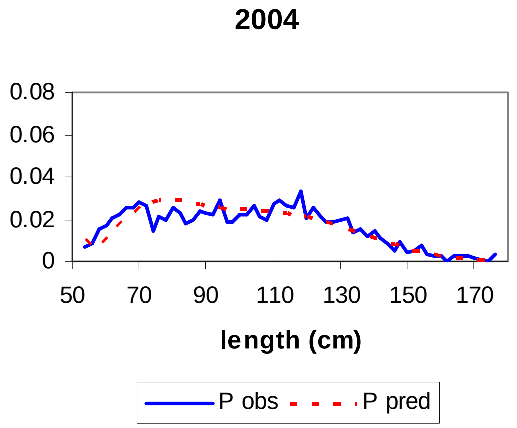


Figure 3a. Assessment predictions for the annual catch-at-length proportions in the longline fishery for the basecase. Note that lengths below 54 and above 138 cm are combined into minus- and plus-groups.



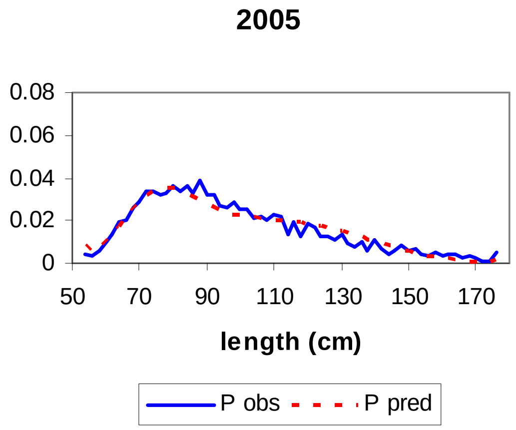
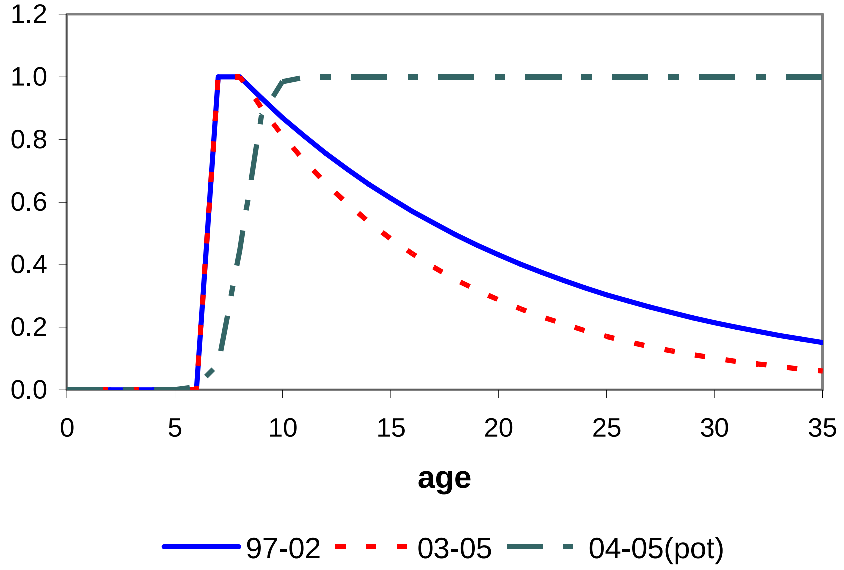


Figure 3b. Assessment predictions for the annual catch-at-length proportions in the pot fishery for the basecase. Note that lengths below 54 and above 176 cm are combined into minus- and plus-groups.

a)



b)

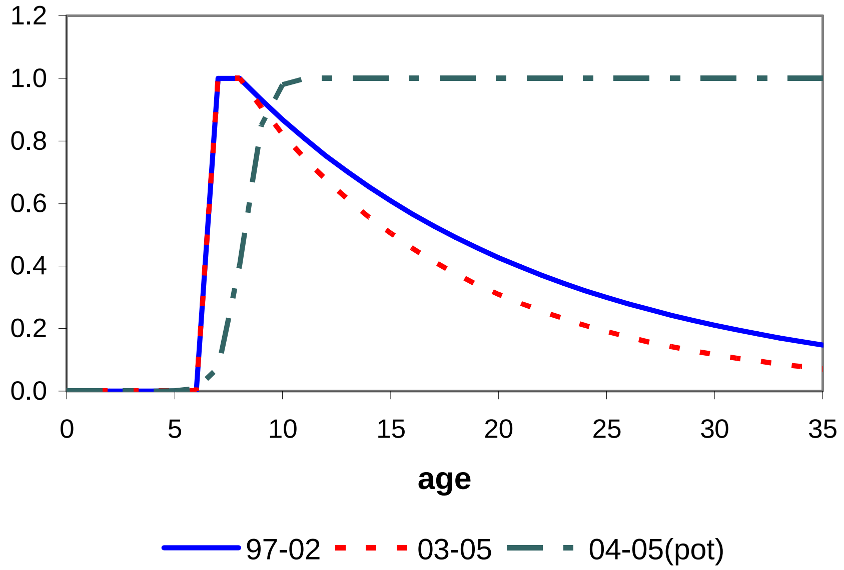


Figure 4. Estimated selectivity curves for the periods 1997–2002 and 2003–2007 for the longline fishery, and for the period 2004-2005 for the pot fishery. Curves are shown for a) the basecase and b) the sensitivity test that takes cetacean predation into account.

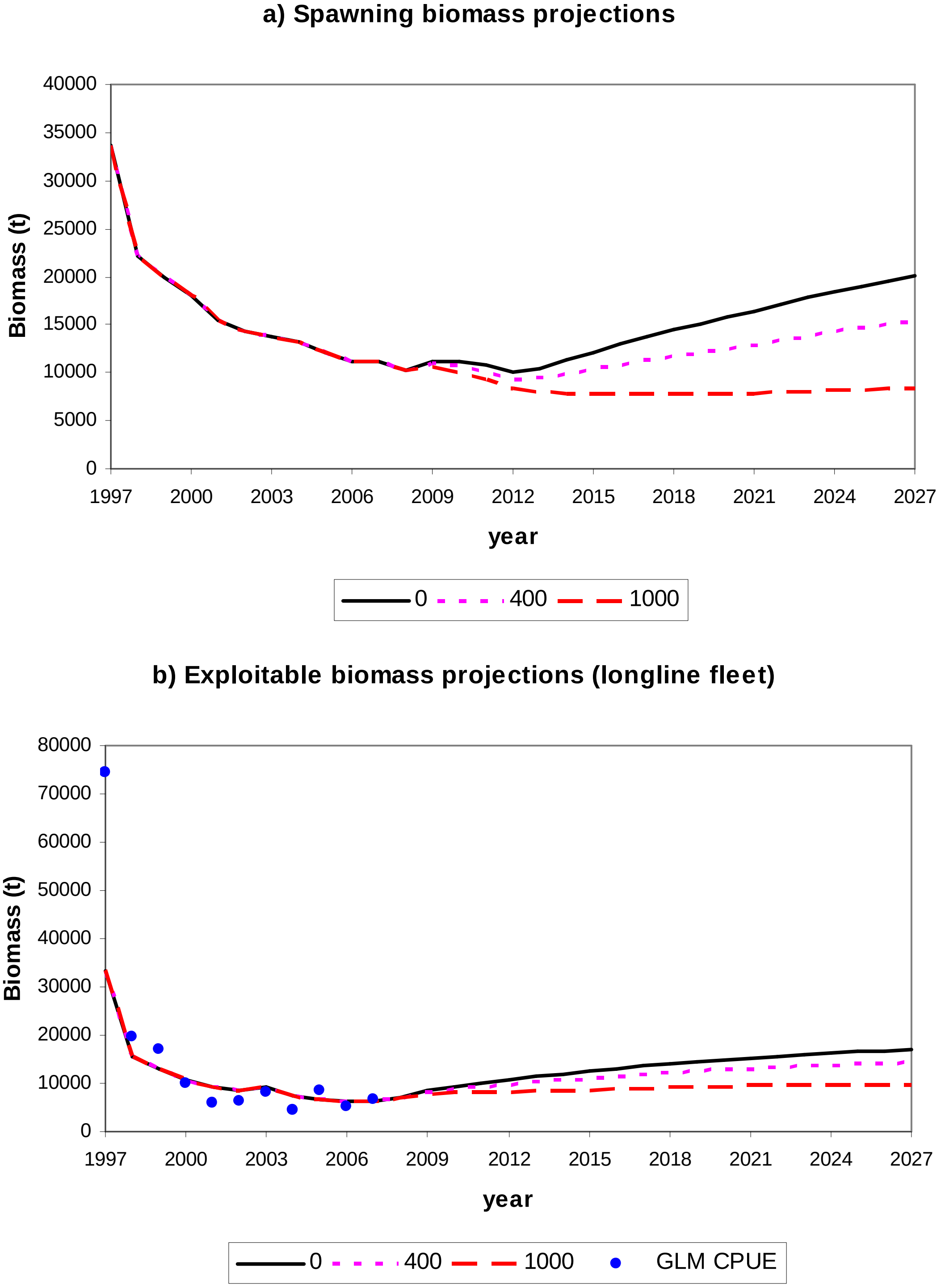


Figure 5. Assessment results for the basecase together with projections under future annual catches of 0, 400 and 1 000 tonnes. The top panel a) shows the spawning biomass, while the bottom panel b) shows the exploitable biomass for the longline fishery and the GLM-standardised CPUE indices to which the model is fit (divided by the estimated catchability *q* to express them in biomass units). The current longline selectivity is assumed to apply in the future.

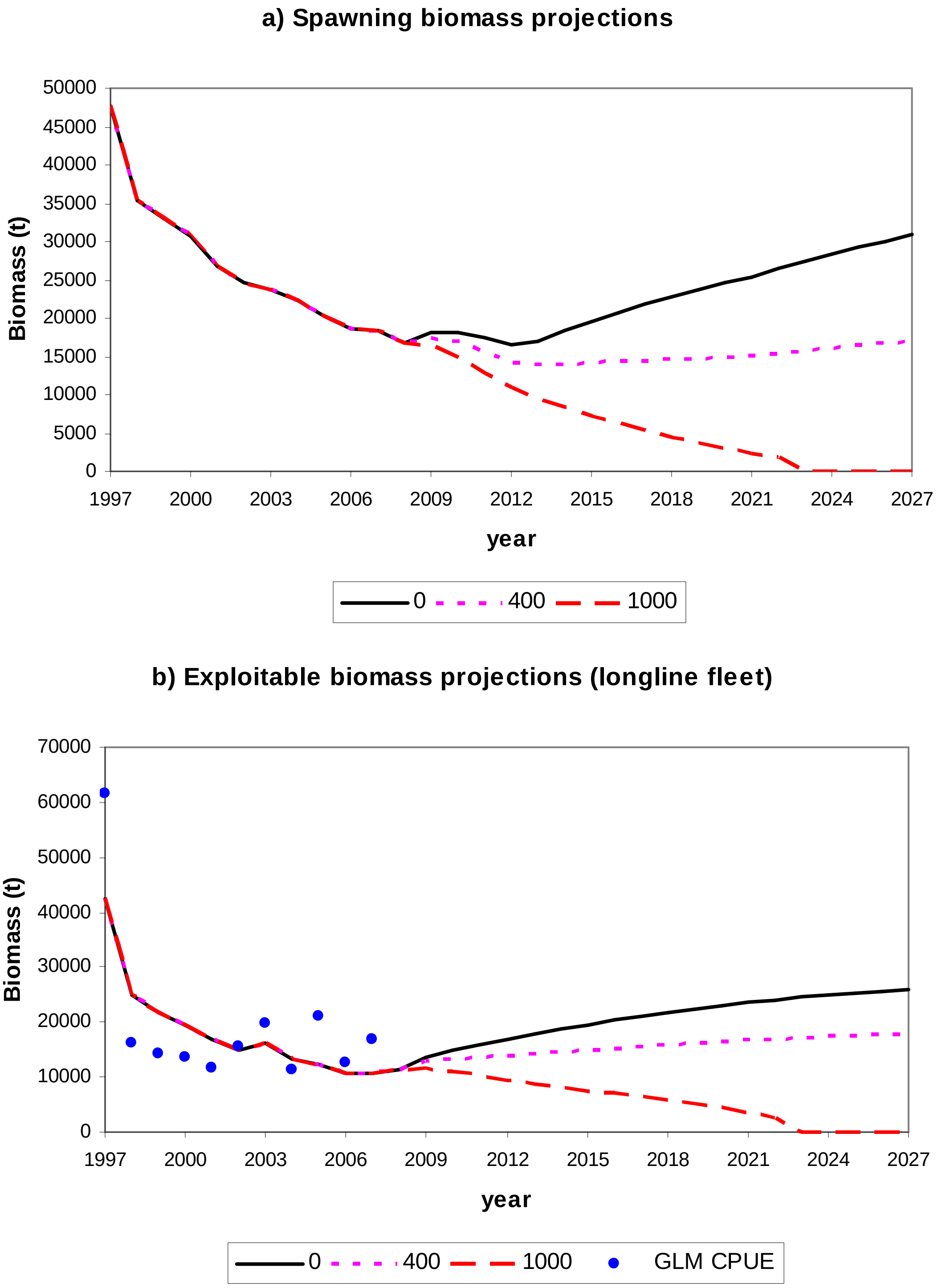


Figure 6. Assessment results for the sensitivity test that takes cetacean predation into account, together with projections under future annual catches of 0, 400 and 1 000 tonnes. The top panel a) shows the spawning biomass, while the bottom panel b) shows the exploitable biomass for the longline fishery and the GLM-standardised CPUE indices to which the model is fit (divided by the estimated catchability *q* to express them in biomass units). 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:

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

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

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

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”).

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

$$C_{y,a} = \sum_{f=1}^{2} C^f_{y,a}\ , \tag{A1.4}$$

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:

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

where

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

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

ω^y defines the steepness of the descending section of the selectivity curve for fish older than age a_c for year y (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 $F_y^f > 1$ for a future year, i.e. the available biomass is less than the proposed catch for that year, F_y^f is restricted to 0.9, and the actual catch considered to be taken will be less than the proposed catch. This procedure makes no adjustment to the exploitation rate ($S_{y,a}^f F_y^f$) of other ages. To avoid the unnecessary reduction of catches from ages where the TAC could have been taken if the selectivity for those ages had been increased, the following procedure is adopted (CCSBT, 2003):

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

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

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

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

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

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

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

STOCK-RECRUITMENT RELATIONSHIP

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

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

where:

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

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

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

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

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

from which it can be shown that:

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

Rearranging equation (A1.16) gives:

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

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

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

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

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

where:

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

PAST STOCK TRAJECTORY AND FUTURE PROJECTIONS

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

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

which can be solved for R_0.

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

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

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

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

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

THE LIKELIHOOD FUNCTION

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

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

where

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

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

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

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

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

where:

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

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

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

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

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

The estimable parameters of this model are q^f, K^{sp}, and σ^f, where K^{sp} is the pre-exploitation mature biomass.

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.:

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

where

- N* is a normal distribution truncated at ± 3 standard deviations (to avoid negative values), and
- $\theta^f(a)$ is the standard deviation of length-at-age *a* for fleet *f*, which is modelled here to be proportional to the expected length at age *a*, i.e.:

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

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

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

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

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

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 (originally suggested to us by A.E. Punt) 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 VARIABILIITY

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

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

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

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

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

which is added to the negative log-likelihood of equation (A1.27) as a penalty (the frequentist equivalent of a Bayesian prior for these parameters). In the present application, it is assumed that the resource is not at equilibrium at the start of the fishery, but rather that the resource was at deterministic 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).

APPENDIX 2

GLM STANDARDISATION OF LONGLINE CPUE DATA

GLM MODEL TO STANDARDISE THE CPUE

The “base case” General Linear Model (GLM) of Brandão *et al.* (2002) has been applied to standardise the longline CPUE data for toothfish in Prince Edward Islands EEZ. This model includes the main effects of all the explanatory variables for which data are available (excluding depth since its effect on the GLM fit was not significant), as well as some interactions.

The base case model

The base case model considered for the longline CPUE data is given by:

$$\ln(CPUE+\delta)=\mu+\alpha_{vessel}+\beta_{year}+\gamma_{month}+\lambda_{area}+\eta_{year\times area}+\theta_{year\times month}+\varphi_{month\times area}+\varepsilon \quad \text{(A2.1)}$$

where:

CPUE is the longline catch per unit effort in kg per hook,

μ is the intercept,

vessel is a factor with 8 levels associated with each of the vessels that have operated in the fishery (to an appreciable extent):

Aquatic Pioneer
Arctic Fox
Eldfisk
Isla Graciosa
Koryo Maru
Ross Mar
South Princess
Suidor One

year is a factor with 11 levels associated with the years 1997–2007,

month is a factor with 12 levels (January– December),

area is a factor with 4 levels associated with the four spatially distinct fishing areas:

A: 43–48°S latitude and 32–37°E longitude,
B: 43–45.3°S latitude and 37–40.3°E longitude,
C: 45.3–48°S latitude and 37–40.3°E longitude,
D: 43–48°S latitude and 40.3–43.3°E longitude,

year×area is the interaction between year and area (this allows for the possibility of different trends for the different areas),

year×month is the interaction between year and month,

month×area is the interaction between month and area,

δ is a small constant (0.022) added to the toothfish CPUE to allow for the occurrence of zero CPUE values, and

ε is an error term assumed to be normally distributed.

The standardised CPUE for the base case model is calculated by summing over the four areas within a year and month, weighting by the total area, and then averaging over the months:

$$CPUE_y = \sum_{month} \left[\sum_{area} \left\{ \exp\begin{bmatrix} \mu + \overline{\alpha} + \beta_{year} + \gamma_{month} + \lambda_{area} + \eta_{year \times agg} \\ + \theta_{year \times month} + \varphi_{month \times area} \end{bmatrix} - \delta \right\} * A_{area} \right] \Big/ 12 \qquad \text{(A2.2)}$$

where

$\overline{\alpha}$ is the median vessel estimate, and

A_{area} is the size of the respective area (values for the size of each area (A_{area}) are given in Appendix 1 of Brandão *et al*. (2002)).

Thus equation (A2.2) is taking CPUE to provide an index of local density and effectively integrating over area to obtain an index of overall abundance. In some instances there were insufficient data to estimate all the interaction terms. Such missing values were then computed by linear interpolation from adjacent values.