# 2006 ASSESSMENT OF THE TOOTHFISH (*Dissostichus eleginoides*) RESOURCE IN THE PRINCE EDWARD ISLANDS VICINITY

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## ABSTRACT

The ASPM assessment of the Prince Edward Islands toothfish resource by Brandão and Butterworth (2005) 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 2005 and 2006. The assessment allows for a second fleet to accommodate data from a pot fishery that operated in 2004 and 2005. Updated biological parameter values for Subarea 48.3 are incorporated and lead to less optimistic results. The resource is estimated to be at about 40% 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). Specific issues raised at WG-FSA-SAM 2006 about this assessment are addressed.

## 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 (2005), further data inputs available for the last few months of 2005 and data until March 2006 are now also taken into account. The biological parameter values for toothfish in Subarea 48.3 (which are assumed to apply to the Prince Edward Islands toothfish as well) have recently been updated. Therefore the basecase model in this paper incorporates these updated parameter values.

Several sensitivities tests of the basecase model are performed to investigate the implications for the status of the resource if certain assumptions are modified. These include:

- taking into account the impact of cetacean predation,
- inclusion of year-specific weights for the CPUE indices,
- alternative assumptions about the time of year to which CPUE values best correspond, and
- adopting the “old” biological parameter values.

In addition some other issues raised at WG-FSA-SAM 2006 are also investigated:

- the length-distribution of the catch in relation to depth and area, and
- whether assessed years of greater recruitment correspond to instances of enhanced proportions of catch-at-length for smaller fish.

## DATA UPDATES

Further data available for the last months of 2005 to March 2006, 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 for 2005 and 2006 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 2006, two analyses were performed: one including CPUE data from 1997 to 2005 and another from 1997 to 2006. The trend in the standardised CPUE indices for the first three months of the latter analysis was then used to obtain an estimated CPUE index for 2006 from the 1997–2005 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.

In order to incorporate year specific weights for the CPUE indices in the assessment, a GLMM (General Linear Mixed Model) has been applied to the commercial longline fishing data. A rigorous model selection process for this approach has not been undertaken as yet, neither has time yet permitted any attempt to check model diagnostics. The particular GLMM fitted was chosen for convenience (i.e. considering all interactions with year to be random effects). The purpose of the exercise was merely to obtain year specific weights (related to inverse variances) for the CPUE indices, as the basis for an initial investigation to see their effect on the assessment of the Prince Edward Islands toothfish resource (these weights could also be obtained from the GLM fitted in the normal way, but GLM standardised indices typically have unrealistically small standard errors associated with them because the data input are not independent as this methodology assumes (a problem which is addressed by use of GLMM)). The GLMM fitted is described in Appendix 2.

Catch-at-length information for the longline fishery has also been updated to include the data available for the whole of 2005 and to March 2006. Furthermore, catch-at-length data for the pot fishery for November 2004 to April 2005 are included in the present assessment.

## 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). Appendix 1 describes the ASPM methodology for a multiple fleet fishery. In previous assessments the biological parameter values assumed were based upon the values for toothfish in Subarea 48.3 (SC-CCAMLR, 2000, Table 34). However, these parameters have since been updated for this Subarea and further these updated biological values have also been adopted for toothfish in Subareas 58.6/58.7 (Table 3); thus the basecase assessment of this paper incorporates these new biological parameters. A sensitivity test has been conducted using the previous biological parameters (values also given in 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. The relative weight accorded to the catch-at-length contribution to the log-likelihood in all computations reported is $w_{len} = 1.0$.

In addition to the sensitivity tests already mentioned above, several other issues raised at WG-FSA-SAM 2006 are investigated:

- The length-distribution of the catch in relation to depth and area.
- Whether assessed years of greater recruitment correspond to instances of enhanced proportions of catch-at-length for smaller fish.
- The sensitivity of results to the time of year to which CPUE indices are taken to correspond.

## RESULTS AND DISCUSSION

Table 4 shows the results for a two-fleet assessment of the toothfish resource, including those for the "new" basecase model (i.e. the assessment with the updated biological parameters) as well as for a number of sensitivity tests performed. Assessments based on the updated biological parameter values suggest the status of the resource to be in the region of 36% to 44% of average pre-exploitation equilibrium spawning biomass. 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 (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, for which the GLMM in any case estimates a lower and relative high variance value) and the catch-at-length data, variants which assign alternative relative weights to these two data sets have not been pursued.

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. 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 have been inflated by multiplying by three to account for future cetacean predation. Table 5 shows some summary statistics for these projections.

Including year specific weights to the CPUE indices in the assessment suggests a slightly better status for the resource. The fit to the CPUE indices improves but the fit to the stock-recruitment relationship is worse (see "Additional variance" in Table 4).

Table 6 shows the results for the sensitivity tests related to the time of year to which CPUE corresponds. These tests are based on the "old" basecase (i.e. on the old biological parameter values) as this work was completed before the new basecase model had been adopted and time restrictions precluded the models being rerun with the new biological parameter values. Making different assumptions of the relationship between CPUE and abundance (see Appendix 1) results in relatively small changes to results compared to the "old" basecase. Results for the instances where CPUE is proportional to abundance after the IUU catches have been taken (referred to as "CPUE $\propto$ after IUU" in Table 6) and where CPUE is proportional to mid year abundance (referred to as "CPUE $\propto$ mid year" in Table 6) are almost identical, except for a slight difference in the estimates of the exploitable biomass. Results for both these cases suggest a slightly better status for the resource than does the comparable (old) basecase.

Figure 1a shows high recruitments in 1994, 1996 and 1997. Given that the age at recruitment to the fishery is 6 years (corresponding to a 60 cm toothfish) these peaks should reflect instances of enhanced proportions of catch-at-length of toothfish in the range of 60 to 70 cm (i.e. 6 to 8 year olds) for the years 2001/02, 2003/04 and 2004/05 respectively. Figure 7 shows model predictions for the annual catch-at-length proportions when the recruitment series shown in Figure 1a was flattened between 1992 and 1999. For comparison, the basecase model predictions are also shown. Results clearly show that without the high recruitments in 1996 and 1997, the model is unable to match the observed high proportions of smaller toothfish in 2003 and in 2004. Flattening the 1994 peak in recruitment has a lesser impact on the fit to the 2001 and 2002 catch-at-length proportions. This is likely because the peak in 1994 was not sustained while that in 1996 was followed by another year of high recruitment.

Figures 8 and 9 show the average length and (for better discrimination) average age of toothfish caught in four areas (these areas are defined in Appendix 2, and are the areas used in the standardisation of the commercial CPUE data). Generally older fish are caught in Areas A and B. The bigger differences between Areas A and B and Areas C and D in the average age of toothfish caught occur in 1998 and 1999. Figures 10 and 11 show the average length and average age of toothfish caught by depth. Note must be taken that in the earlier years of the fishery depth was not always recorded, and in 2001 no depth records were taken. As expected larger fish occur more at deeper depths, with an average age of toothfish caught in depths shallower than 1 000 m of around eight for most years.

Figure 12 shows the proportion of the number of toothfish sampled in each area and the proportion of the total catch in each area. The weight of the fish sampled is not recorded so a comparison between the proportion of the catch of toothfish sampled and the proportion of the total catch cannot be made. However, the distribution of the proportions sampled and the proportion of toothfish caught are generally very similar, suggesting that the sampling procedure is representative and unbiased.

In 2004 and 2005 both a longline and a pot fishery were in operation, with the pot fishery catching a higher proportion of larger toothfish (Figure 3). Figure 13 compares the average length and age of toothfish sampled for the two fisheries by depth. The comparison of the proportion of numbers sampled by depth is also given. Especially in 2004 the pot fishery concentrated at deeper depths compared to the longline fishery. However, at all depths ranges where both fisheries operated, the pot fishery consistently reflected larger toothfish on average in its catch.

## 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 40% of its average pre-exploitation level. This is much lower than would have been the case had the biological parameter values not been updated. This estimate drops slightly if cetacean predation is taken into account, but improves somewhat if CPUE data points are weighted in relation to their variances.

On the basis of the MSY estimates in Table 4 together with the projections in Figures 5 and 6 (see also Table 5), it seems that a future total annual catch 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 Figures 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.

Investigations of spatially disaggregated data suggests that sampling by area is reasonably representative. There is a trend towards larger, older fish with the depth of operations.

## ACKNOWLEDGEMENTS

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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 2006 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 for 2006 are based upon data for part of a 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** | 128.5 | 103.5 | 156 | 388.0 | 580.9 |
| **2006** | 46.6 | — | 156 | 202.6 | |
| **1997–2006 total** | 7 685.1 | 176.2 | 26 764 | 34 625.3 | 40 181.2 |

**Table 2.** Relative abundance indices (normalised to their mean over 1997-2005) 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 2005) are also shown, as are the CPUE indices adjusted to take cetacean predation into account. Standardised CPUE indices obtained by fitting a GLMM to the commercial longline data are also given together with the associated standard errors in brackets. The indices for 2006 are based upon data for part of a year only.

| Year | Longline fishery | | | |
|---|---|---|---|---|
| | GLM *CPUE* (previous analysis) | GLM *CPUE* (present analysis) | GLM *CPUE* including predation | GLMM *CPUE (standard error)* |
| **1997** | 3.914 | 4.202 | 4.202 | 3.129 (0.745) |
| **1998** | 1.083 | 1.157 | 1.157 | 1.117 (0.241) |
| **1999** | 0.962 | 1.013 | 1.013 | 1.086 (0.228) |
| **2000** | 0.581 | 0.618 | 1.029 | 0.854 (0.180) |
| **2001** | 0.350 | 0.375 | 0.875 | 0.524 (0.113) |
| **2002** | 0.364 | 0.390 | 1.170 | 0.597 (0.137) |
| **2003** | 0.459 | 0.487 | 1.460 | 0.628 (0.146) |
| **2004** | 0.287 | 0.276 | 0.829 | 0.479 (0.106) |
| **2005** | 0.257 | 0.483 | 1.450 | 0.585 (0.146) |
| **2006** | — | 0.140 | 0.421 | 0.470 (0.151) |

**Table 3.** Biological parameter values previously assumed for the assessments conducted, based upon the values for Subarea 48.3 given in Table 34 of the 2000 WG–FSA report (CCAMLR, 2000). The value of *M*, however, is set to the highest value considered plausible by the August 2003 meeting of the Subgroup on Assessment Methods (CCAMLR, 2003). As the biological parameter values for Subarea 48.3 have been updated recently, these values are also now assumed for the basecase assessment conducted. Note that for simplicity, maturity is assumed to be knife-edge in age.

| Parameter | Previous value | Updated value |
|---|---|---|
| Natural mortality $M$ ($yr^{-1}$) | 0.2 | 0.13 |
| von Bertalanffy growth | | |
| $\ell_\infty$ (cm) | 194.6 | 152.0 |
| $\kappa$ ($yr^{-1}$) | 0.066 | 0.067 |
| $t_0$ (yr) | -0.21 | -1.49 |
| Weight (in gm) length relationship | | |
| $c$ | $25\times10^{-6}$ | $25.4\times10^{-6}$ |
| $d$ | 2.8 | 2.8 |
| Age at maturity (yr) | 10 | 13 |
| Age at recruitment (yr) | 6 | 6 |
| Steepness parameter ($h$) | 0.6 | 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 ($B_{sp}^{2006}/K_{sp}$) and the (longline) exploitable biomass ($B_{\exp}^{2007}$) at the beginning of the year 2007 (assuming the same selectivity as for 2006). 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** | | | |
|---|---|---|---|---|---|
| | | **Old Basecase** | **Basecase (updated biological parameters)** | **Model with predation** | **Additional variance** |
| $K_{sp}$ (tonnes) | | 30 864 | 27 922 | 33 419 | 28 332 |
| $B_{sp}^{2006}/K_{sp}$ | | 0.653 | 0.388 | 0.366 | 0.439 |
| $B_{\exp}^{2007}$ (tonnes) | Longline | 12 444 | 6 571 | 7 226 | 7 858 |
| | Pot | 23 324 | 13 877 | 15 001 | 15 875 |
| $B_{sp}^{1997}/K_{sp}$ | | 1.266 | 1.183 | 1.159 | 1.242 |
| $\sigma_{CPUE}$ | Longline | 0.548 | 0.444 | 0.382 | 0.098* |
| $\sigma_R$ | | 0.500†† | 0.500†† | 0.500†† | 0.500†† |
| $a_{50}^{97-02}$ (yr) | | 5.974 | 6.516 | 6.515 | 6.025 |
| $\delta^{97-02}$ (yr$^{-1}$) | | 0.003 | 0.024 | 0.024 | 0.001 |
| $\omega^{97-02}$ (yr$^{-1}$) | | 0.083 | 0.070 | 0.065 | 0.068 |
| $a_{50}^{03-05}$ (yr) | Longline | 5.000 | 6.505 | 6.510 | 5.087 |
| | Pot | 7.078 | 8.007 | 8.005 | 8.004 |
| $\delta^{03-05}$ (yr$^{-1}$) | Longline | 0.000 | 0.025 | 0.025 | 0.004 |
| | Pot | 0.514 | 0.351 | 0.317 | 0.582 |
| $\omega^{03-05}$ (yr$^{-1}$) | Longline | 0.180 | 0.100 | 0.097 | 0.087 |
| | Pot | 0.014 | 0.000 | 0.000 | 0.000 |
| $\beta$ | | 0.123 | 0.130 | 0.130 | 0.122 |
| $\sigma_{len}$ | Longline | 0.036 | 0.035 | 0.036 | 0.034 |
| | Pot | 0.034 | 0.032 | 0.033 | 0.033 |
| -ln $L$: Length | | -437.1 | -446.5 | -443.0 | -445.6 |
| -ln $L$: CPUE | | -1.009 | -3.114 | -4.619 | -11.67 |
| -ln $L$: Recruitment | | -7.409 | 6.965 | 2.564 | 21.37 |
| -ln $L$: Total | | -445.5 | -442.7 | -445.1 | -455.3 |
| MSY (tonnes) | Longline | 1 258† | 1 111† | 1 335† | 1 108† |
| | Pot | 1 452 | 1 239 | 1 484 | 1 254 |

† Based upon the average of the two selectivity functions estimated.
†† Input parameter.
* Estimate of additional standard deviation.

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

a) Basecase model: $\frac{B_{sp}^{2007}}{K_{sp}} = 0.386$

| | $\frac{B_{sp}^{2026}}{K_{sp}}$ | | |
|---|---|---|---|
| **Future annual catch (tonnes)** | **0** | **400** | **1000** |
| **Longline selectivity** | 0.709 | 0.542 | 0.290 |

b) Including cetacean predation: $\frac{B_{sp}^{2007}}{K_{sp}} = 0.355$

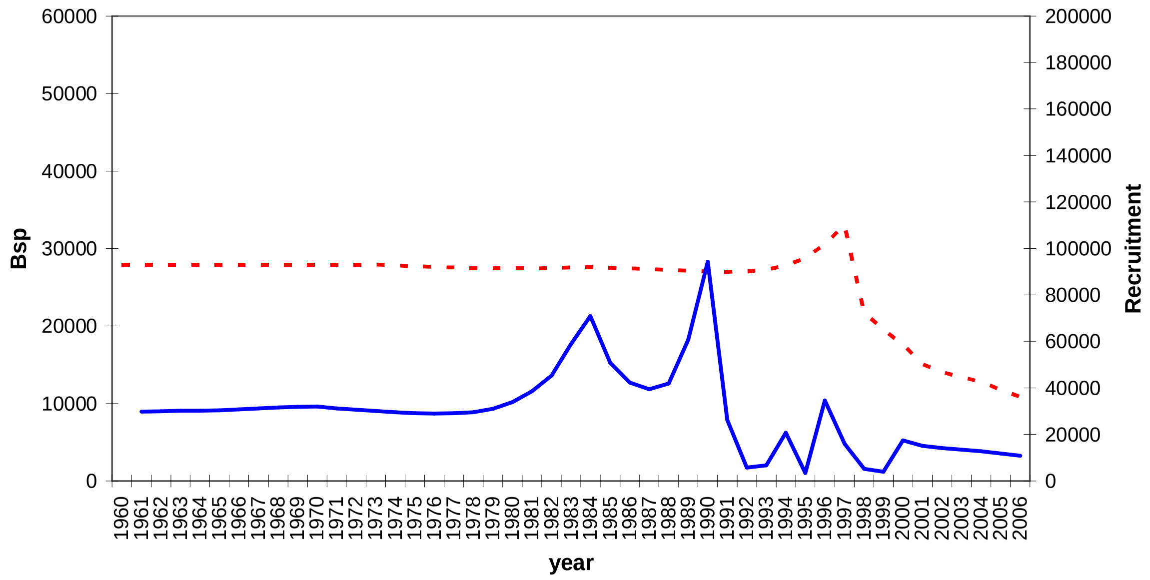
| | $\frac{B_{sp}^{2026}}{K_{sp}}$ | | |
|---|---|---|---|
| **Future annual catch (tonnes)** | **0** | **400** | **1000** |
| **Longline selectivity** | 0.691 | 0.267 | 0.000 |

**Table 6.** Estimates for a two fleet (longline and pot) model that assumes alternative assumptions to the time of year to which CPUE values correspond (and based on the old biological parameter values) 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 ($B_{sp}^{2006}/K_{sp}$) and the (longline) exploitable biomass ($B_{\exp}^{2007}$) at the beginning of the year 2007 (assuming the same selectivity as for 2006). 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 at the end of Appendix 1.

| Parameter estimates | | Model | | |
|---|---|---|---|---|
| | | **Old Basecase** | **CPUE $\propto$ mid year** | **CPUE $\propto$ after IUU** |
| $K_{sp}$ (tonnes) | | 30 864 | 39 100 | 39 100 |
| $B_{sp}^{2006}/K_{sp}$ | | 0.653 | 0.738 | 0.738 |
| $B_{\exp}^{2007}$ (tonnes) | Longline | 12 444 | 17 562 | 19 313 |
| | Pot | 23 324 | 32 893 | 36 171 |
| $B_{sp}^{1997}/K_{sp}$ | | 1.266 | 1.192 | 1.192 |
| $\sigma_{CPUE}$ | Longline | 0.548 | 0.618 | 0.618 |
| $\sigma_R$ | | 0.500†† | 0.500†† | 0.500†† |
| $a_{50}^{97-02}$ (yr) | | 5.974 | 5.511 | 5.541 |
| $\delta^{97-02}$ (yr$^{-1}$) | | 0.003 | 0.025 | 0.024 |
| $\omega^{97-02}$ (yr$^{-1}$) | | 0.083 | 0.080 | 0.080 |
| $a_{50}^{03-05}$ (yr) | Longline | 5.000 | 5.491 | 5.666 |
| | Pot | 7.078 | 7.111 | 7.111 |
| $\delta^{03-05}$ (yr$^{-1}$) | Longline | 0.000 | 0.025 | 0.017 |
| | Pot | 0.514 | 0.522 | 0.522 |
| $\omega^{03-05}$ (yr$^{-1}$) | Longline | 0.180 | 0.170 | 0.170 |
| | Pot | 0.014 | 0.007 | 0.007 |
| $\beta$ | | 0.123 | 0.123 | 0.123 |
| $\sigma_{len}$ | Longline | 0.036 | 0.036 | 0.036 |
| | Pot | 0.034 | 0.034 | 0.034 |
| -ln $L$: Length | | -437.1 | -435.8 | -435.8 |
| -ln $L$: CPUE | | -1.009 | 0.195 | 0.195 |
| -ln $L$: Recruitment | | -7.409 | -10.60 | -10.60 |
| -ln $L$: Total | | -445.5 | -446.2 | -446.2 |
| MSY (tonnes) | Longline | 1 258† | 1 599† | 1 599† |
| | Pot | 1 452 | 1 851 | 1 851 |

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

a)




b)

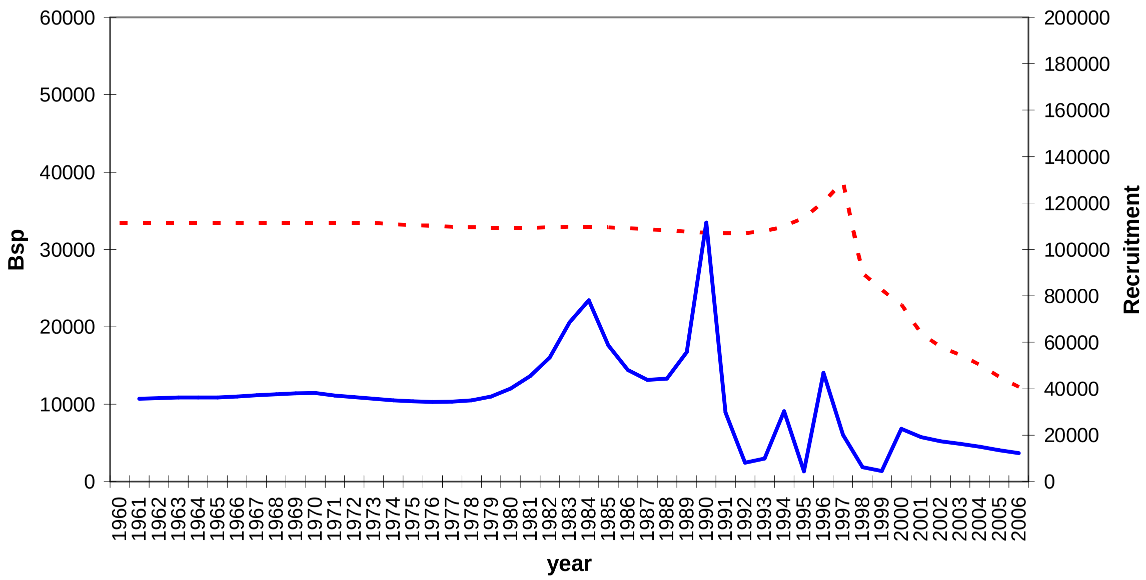
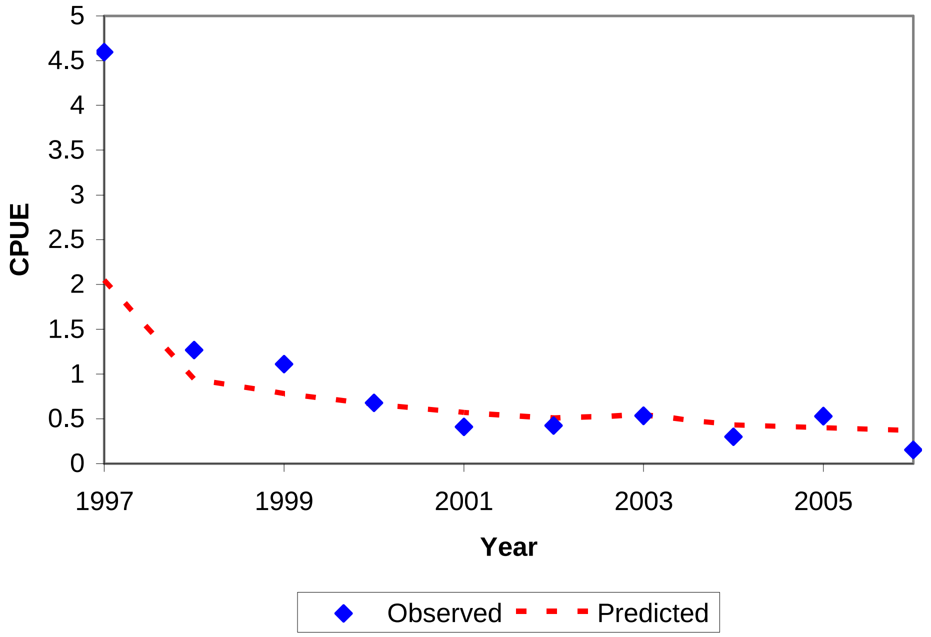



**Figure 1.** Spawning biomass estimates and estimated recruitment for the two-fleet model for a) the basecase model and b) the sensitivity test that takes cetacean predation into account.

**a)**




**b)**

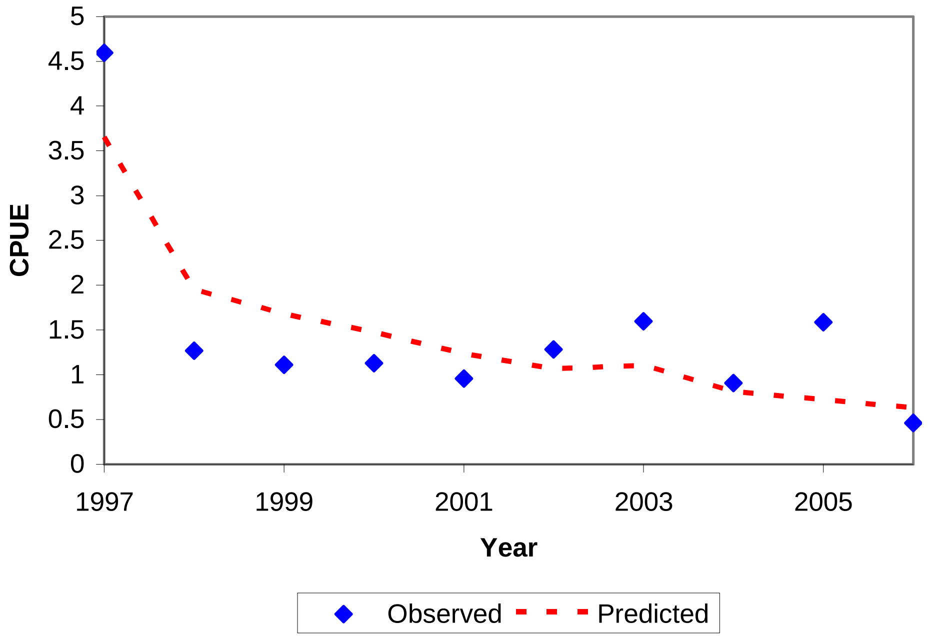



**Figure 2.** Exploitable biomass and the GLM-standardised CPUE indices to which the model is fit (divided by the estimated catchability $q$ to express them in biomass units) for a) the basecase model and b) the sensitivity test that takes cetacean predation into account.

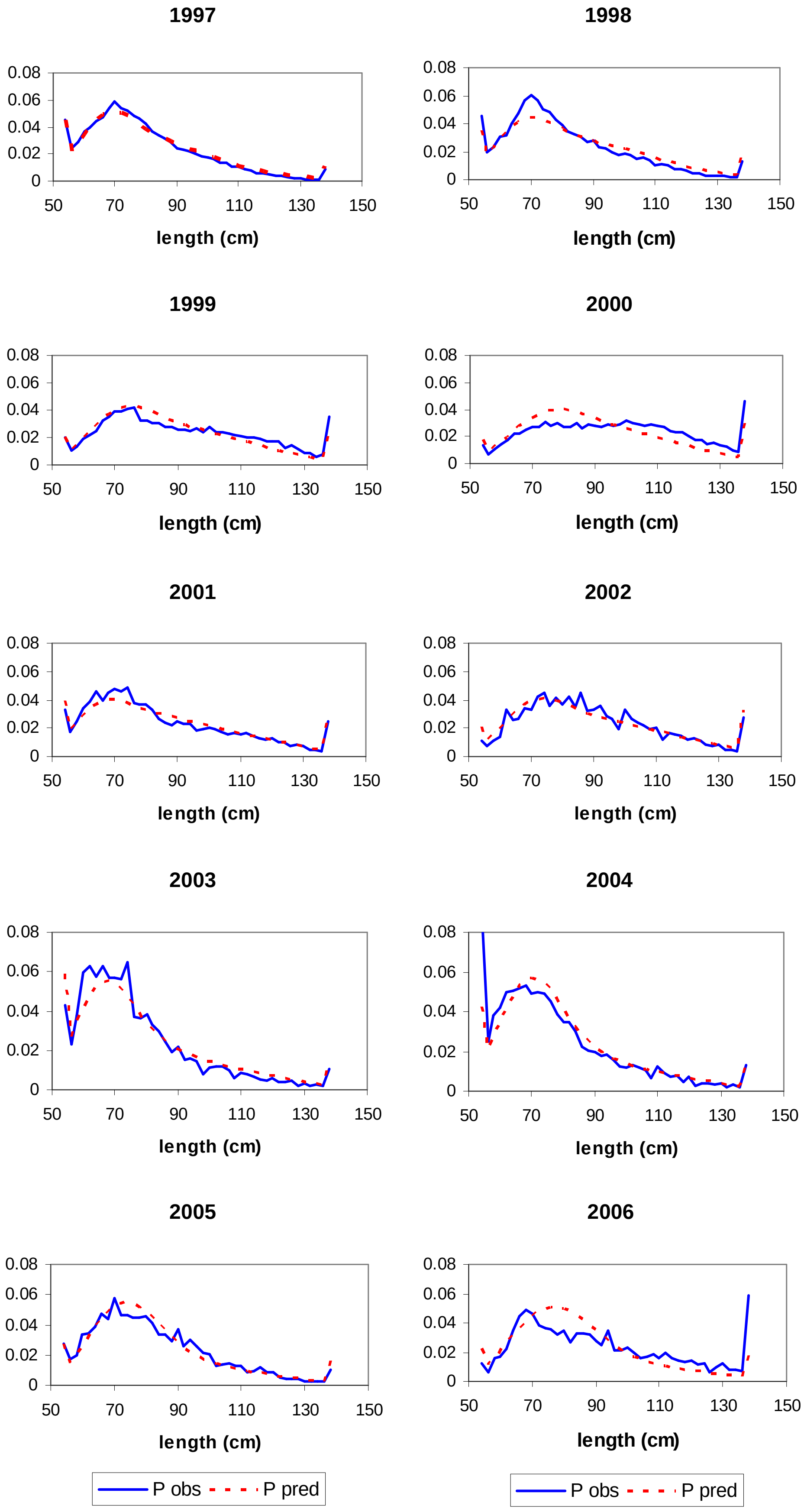



**Figure 3a.** ASPM assessment predictions for the annual catch-at-length proportions in the longline fishery for the basecase model. Note that lengths below 54 and above 138 cm are combined into minus- and plus-groups.

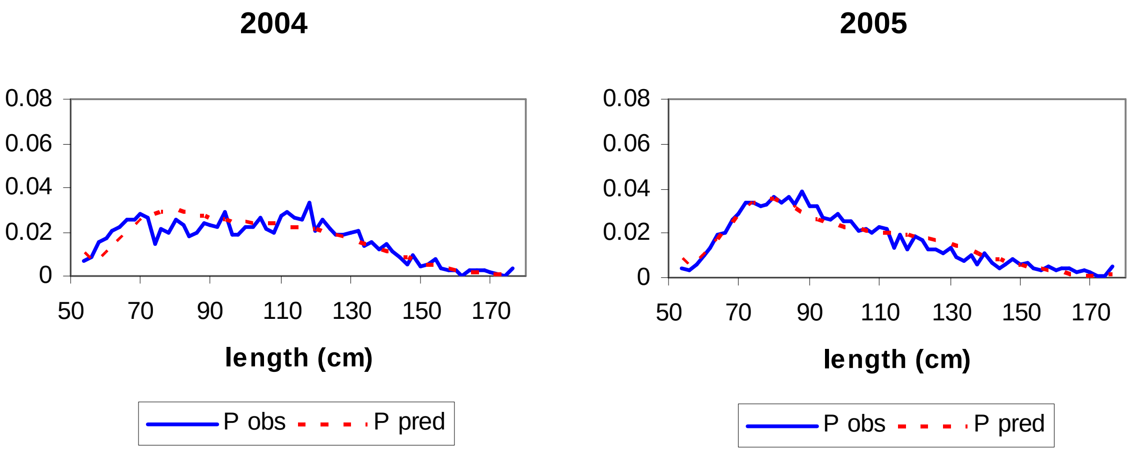
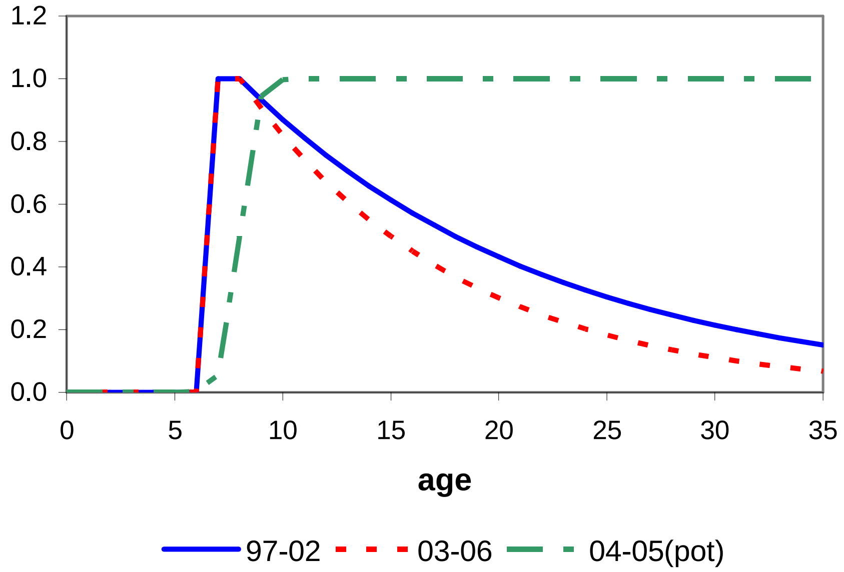



**Figure 3b.** ASPM assessment predictions for the annual catch-at-length proportions in the pot fishery for the basecase model. Note that lengths below 54 and above 176 cm are combined into minus- and plus-groups.

a)




b)

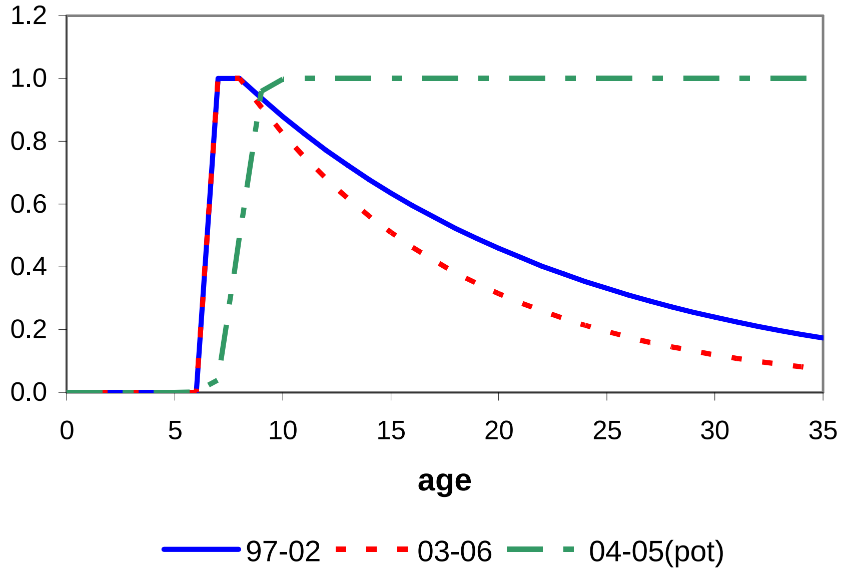



**Figure 4.** Estimated selectivity curves for the periods 1997–2002 and 2003–2005 for the longline fishery, and for the period 2004-2005 for the pot fishery. Curves are shown for a) the basecase model and b) the sensitivity test that takes cetacean predation into account.

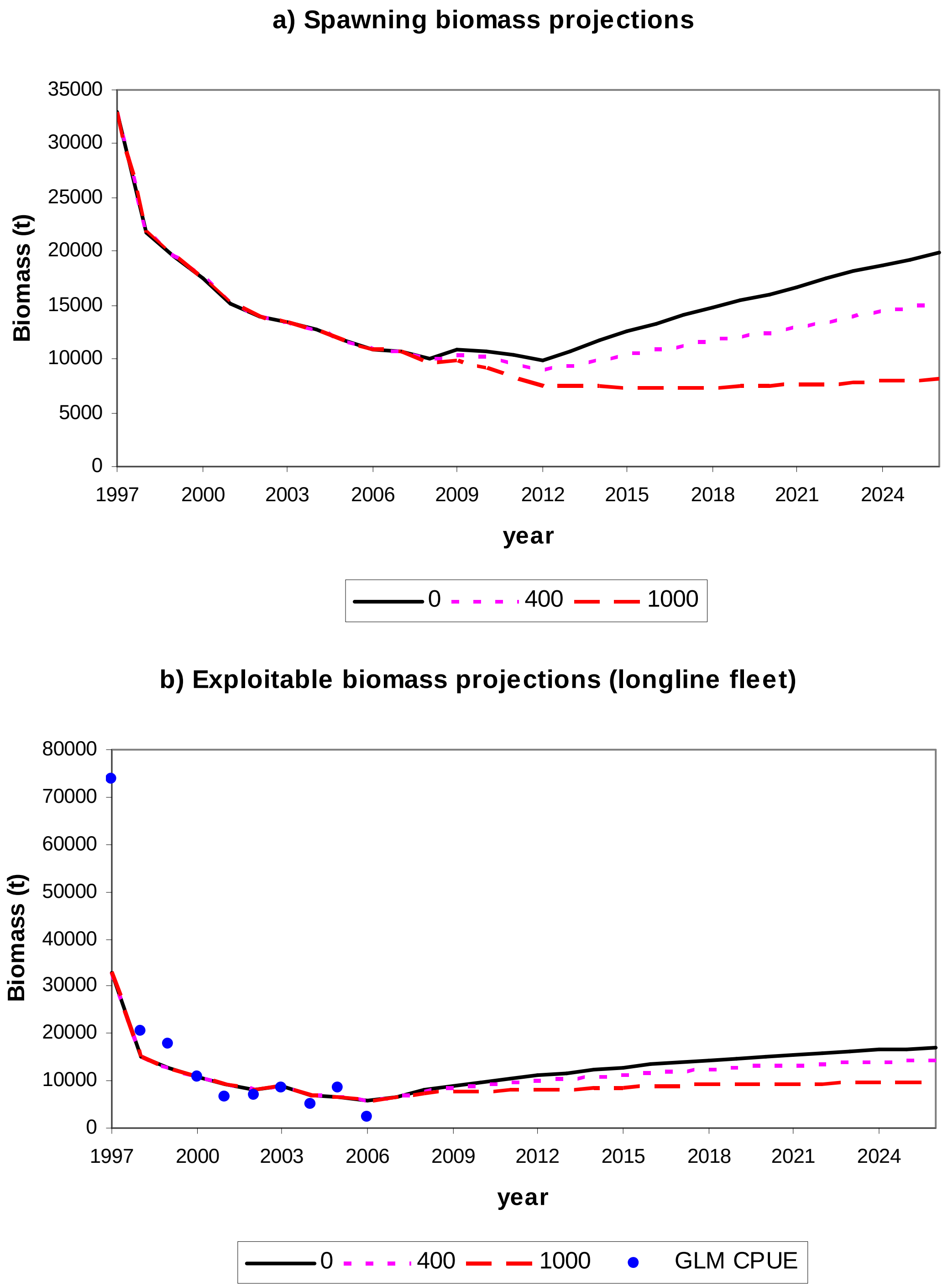
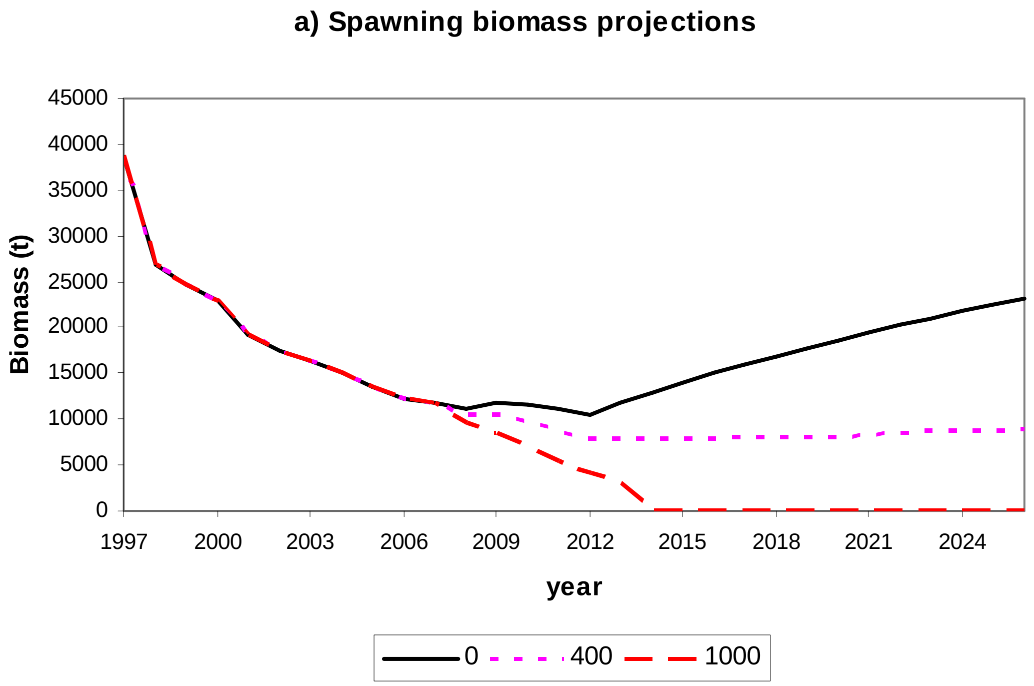



**Figure 5**. ASPM assessment results for the basecase model together with projections under future annual catches of 0, 400 and 1 000 tonnes. The top panel a) shows the spawning biomass, while the bottom panel b) shows the exploitable biomass for the longline fishery and the GLM-standardised CPUE indices 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.



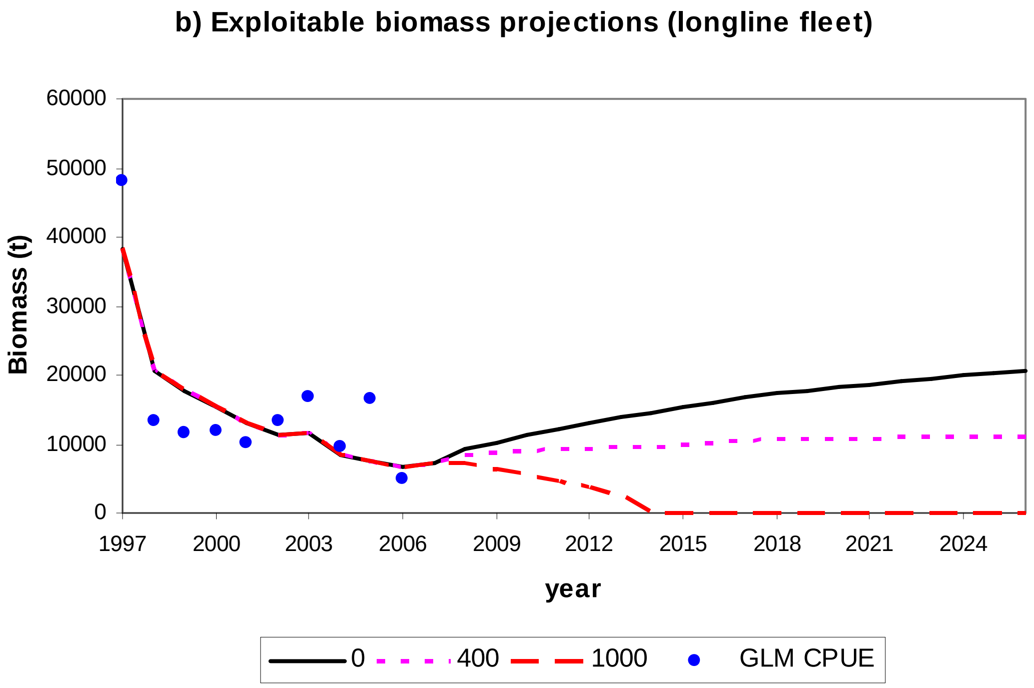




**Figure 6.** ASPM assessment results for the sensitivity test that takes cetacean predation into account, together with projections under future annual catches of 0, 400 and 1 000 tonnes. The top panel a) shows the spawning biomass, while the bottom panel b) shows the exploitable biomass for the longline 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.

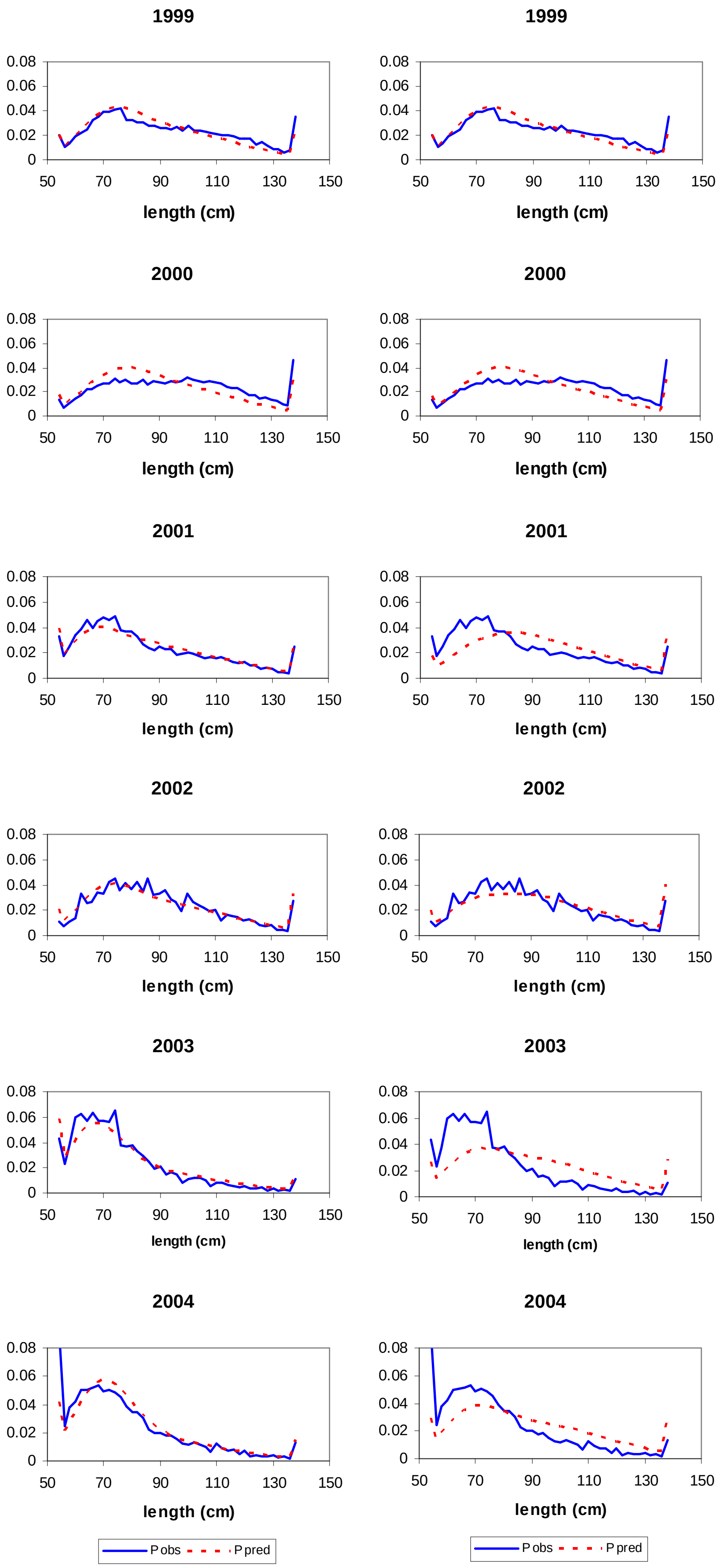



**Figure 7.** ASPM assessment predictions for the annual catch-at-length proportions in the longline fishery for the basecase model (left), and when flattening the recruitment series between 1992 and 1999 (right), to illustrate the impact on the catch-at-length distributions. Note that lengths below 54 and above 138 cm are combined into minus- and plus-groups respectively.

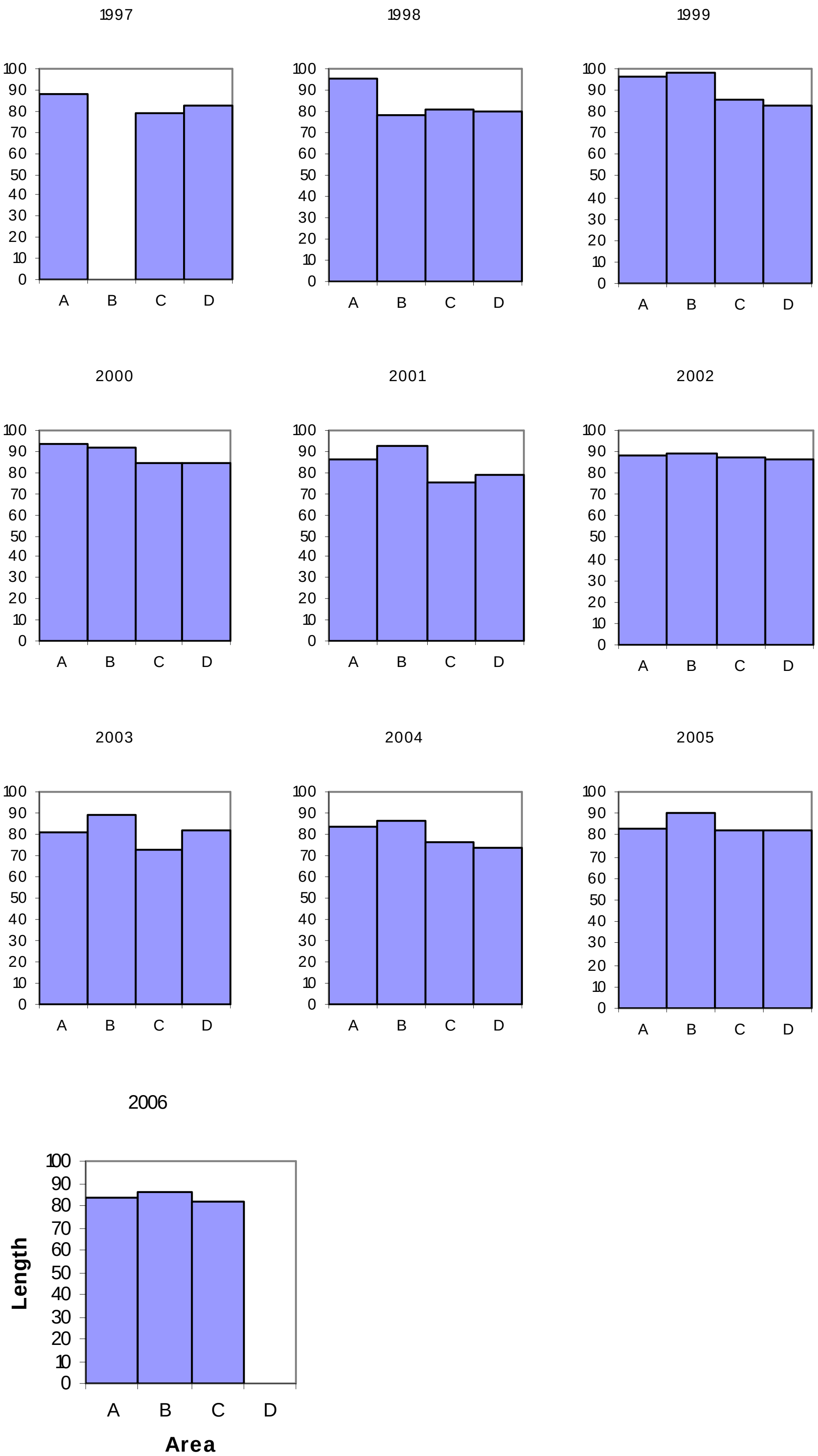



**Figure 8.** Average length (cm) of toothfish by area from the longline fishery.

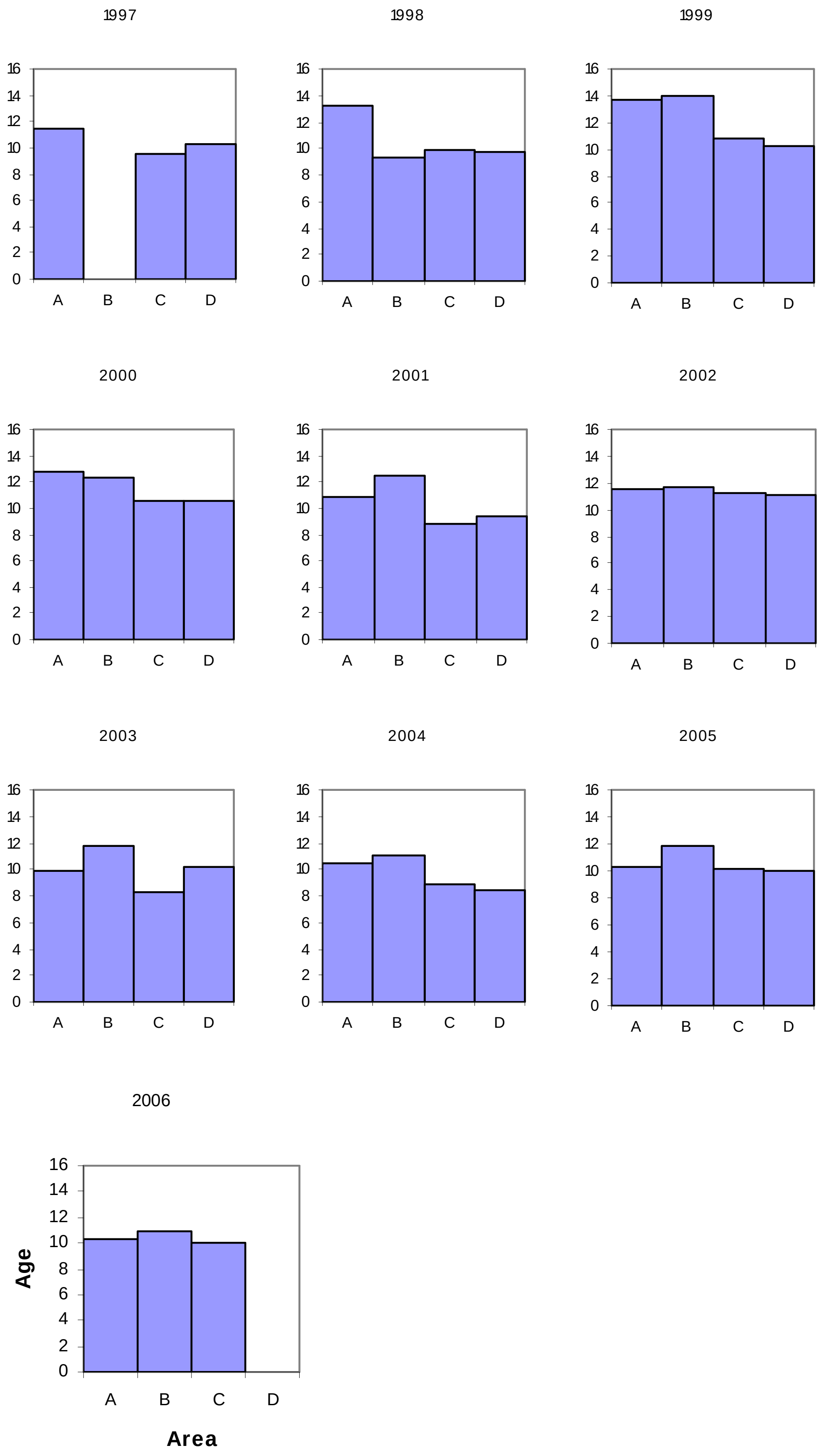



**Figure 9.** Average age (years) of toothfish by area from the longline fishery.

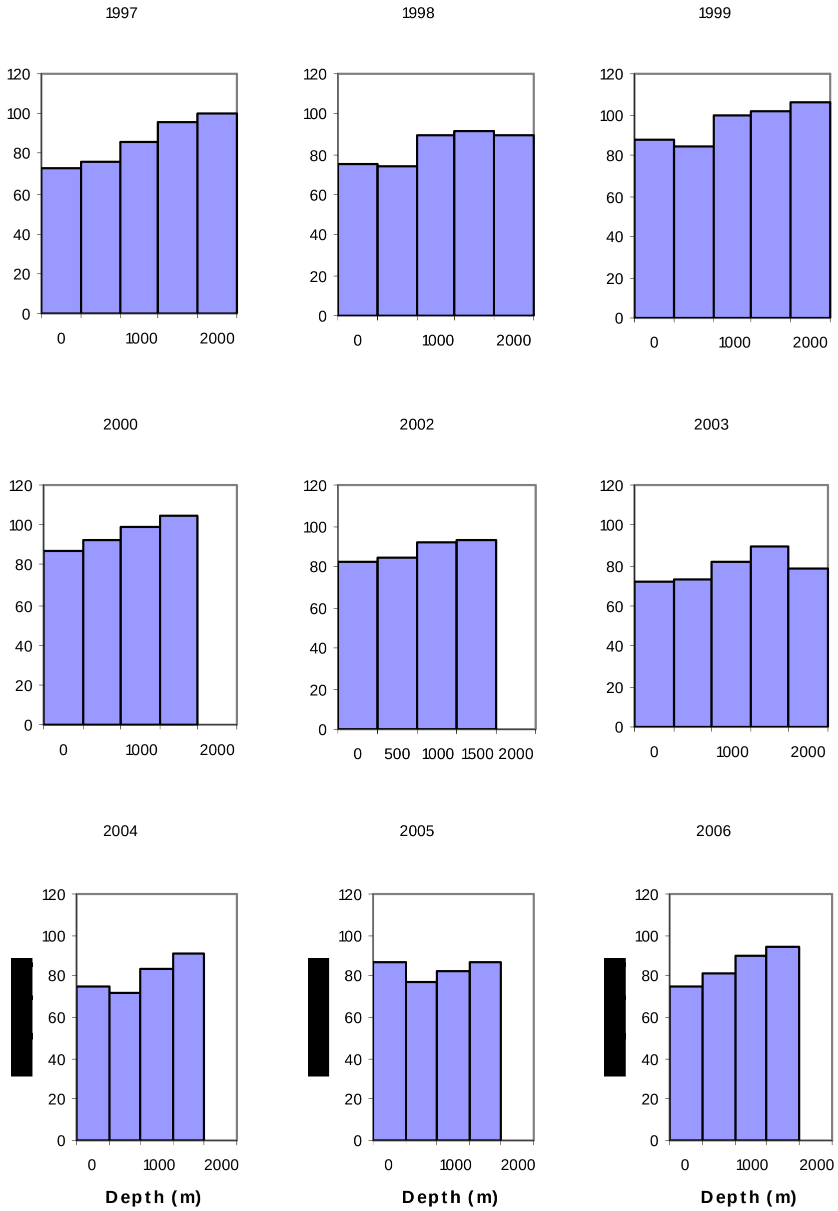



**Figure 10.** Average length (cm) of toothfish by depth from the longline fishery.

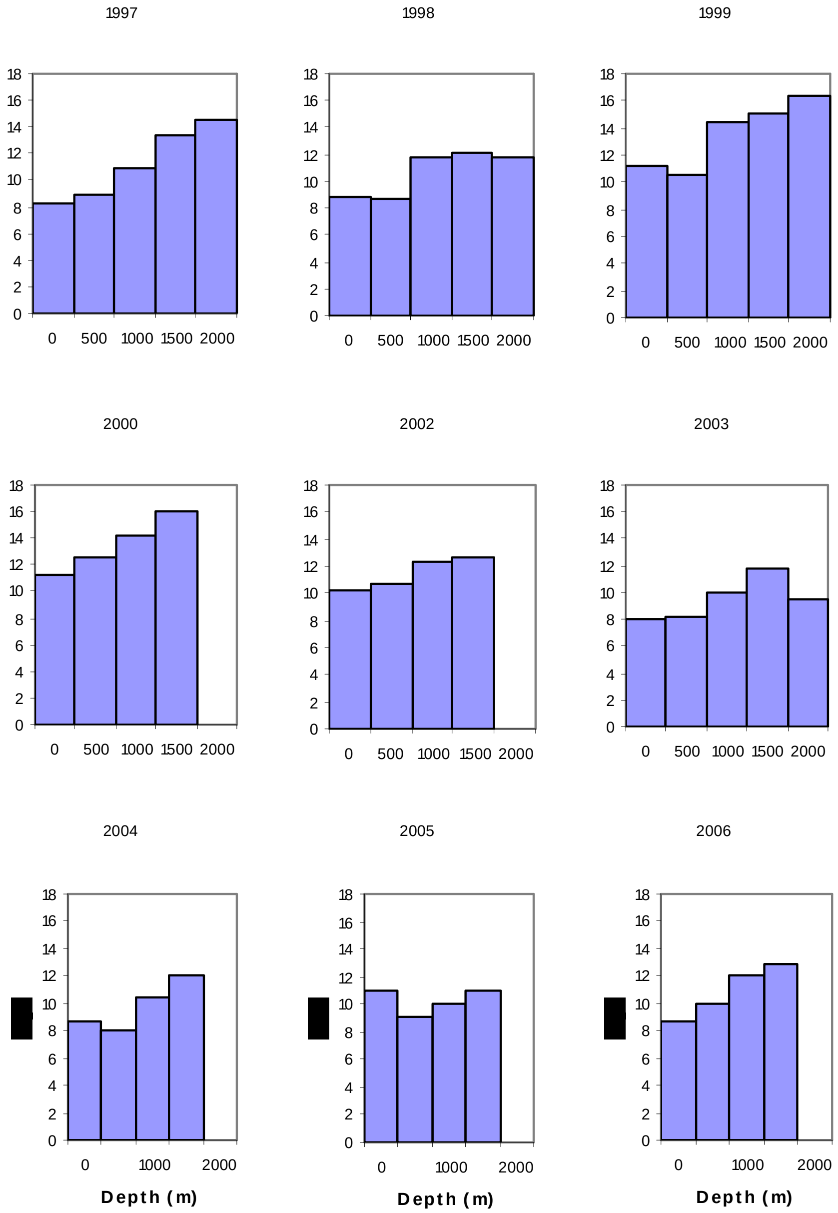



**Figure 11.** Average age (years) of toothfish by depth from the longline fishery.

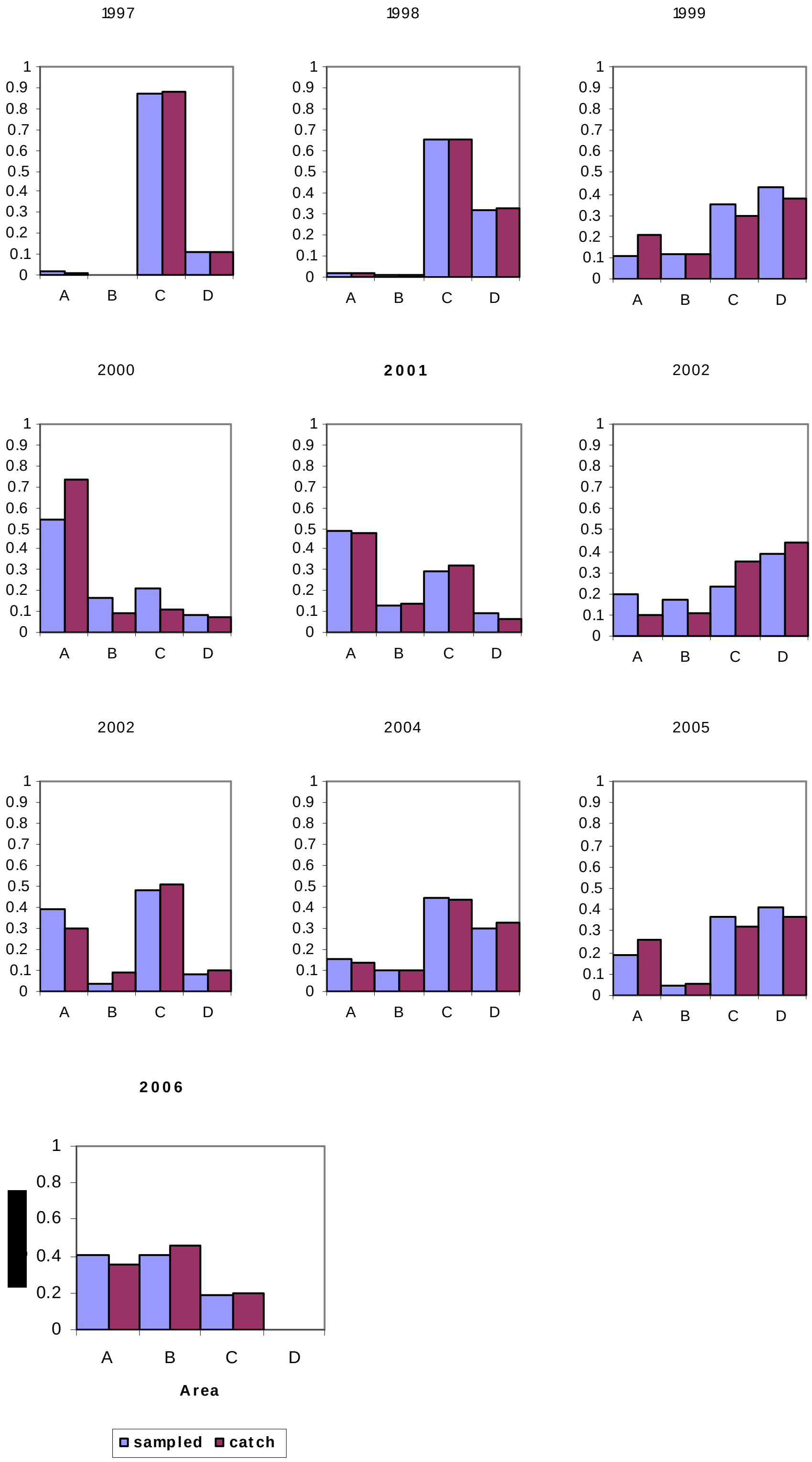



**Figure 12.** Proportion of numbers of toothfish sampled in each area. For comparison the proportion of the total catch by area is also shown.

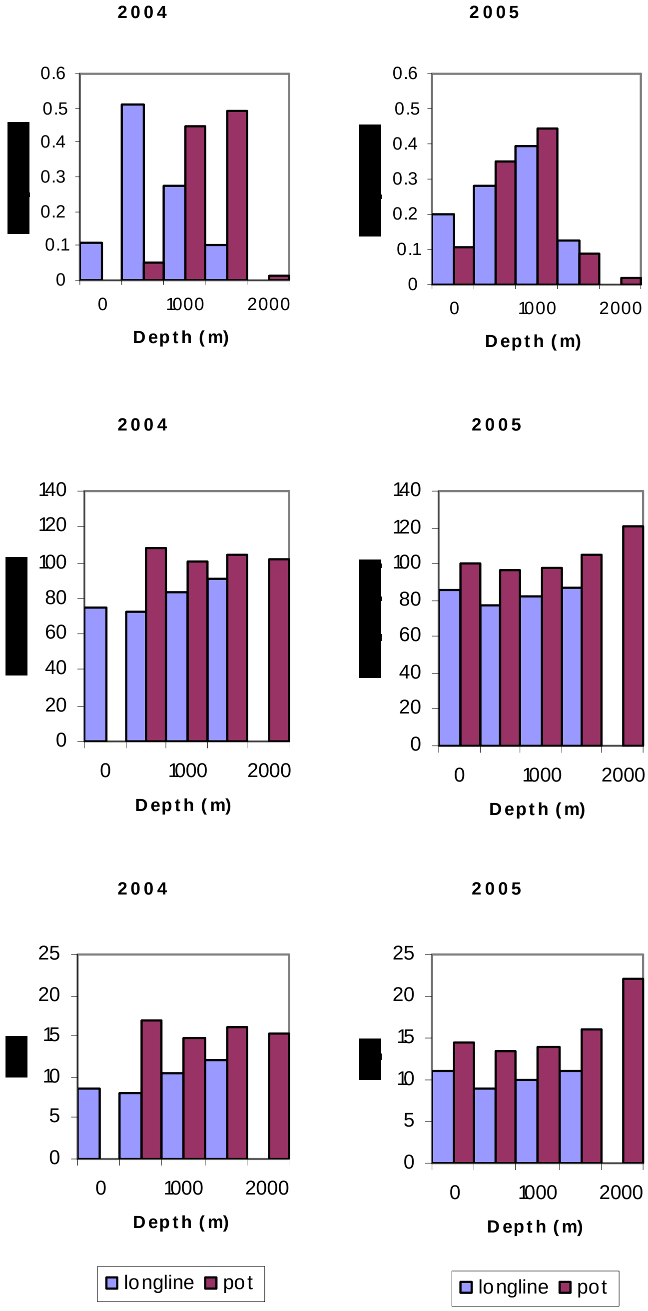



**Figure 13.** Comparison of the proportion of the number (top), the average length (middle) and average age (bottom) of toothfish sampled from the longline and pot fisheries by depth.

# 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 $\ell_\infty$, $\kappa$ and $t_0$ and a relationship relating length to mass. Note that $\ell$ refers to standard length.

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

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

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 $y$,

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

$\omega^y$ 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 $\alpha$ and $\beta$ 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 $\alpha$ 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

$\varepsilon_y^f$ is normally distributed with mean zero and standard deviation $\sigma^f$ (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 $\sigma^f$, 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 $\ell$ 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 $\beta^f$ 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 $\beta^f$ 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 $\ell$ for fleet $f$, and
- $\sigma^f_{len}$ 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:

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

where $\zeta_y$ reflects fluctuation about the expected recruitment for year *y*, which is assumed to be normally distributed with standard deviation $\sigma_R$ (which is input). The $\zeta_y$ 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:

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

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 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).

## ADJUSTMENT TO INCORPORATE YEAR SPECIFIC WEIGHTS ON CPUE

To allow for year specific weights on the CPUE indices (related to the inverse of their year-specific estimated variances), the log-likelihood function (ignoring constants) which is minimised given by equation (A1.27) is replaced by:

$$-\ln L = \sum_f \left\{ \sum_y \left[ \frac{1}{2\left((\sigma_y^f)^2 + \sigma_{add}^2\right)^2} \left(\ln I_y^f - \ln\left(q^f \; B_y^{\exp}(f)\right)\right)^2 \right] + n^f \left( \ln\left( \sqrt{\left(\sigma_y^f\right)^2 + \sigma_{add}^2} \right) \right) \right\}. \tag{A1.37}$$

Note that a further estimable parameter $\sigma_{add}$ has been introduced. This allows for the possibility that the variance of the CPUE data as estimates of relative abundance may be greater than the variance input $\left(\left(\sigma_y^f\right)^2\right)$ deduced from sampling variability considerations alone.

## Adjustments to Investigate Assumptions Concerning the Time of Year to which CPUE Relates

The assessment assumes that the (standardised) CPUE indices are proportional to the exploitable component of the resource given by equation (A1.23). This assumes that CPUE is proportional to the biomass at the beginning of the year. To investigate the effect of alternative assumptions about the time of the year providing the closest relationship between CPUE and biomass, equation (A1.23) was changed in two ways:

1) $B_y^{\exp}(f) = \sum_{a=0}^{m} w_a S_{y,a}^f \left( N_{y,a} \left( \frac{1+e^{-M}}{2} \right) - \frac{1}{2} C_{y,a} e^{-M} \right)$, i.e. assuming that CPUE is proportional to the biomass at midyear, and

2) $B_y^{\exp}(f) = \sum_{a=0}^{m} w_a S_{y,a}^f \left( N_{y,a} - C_{y,a}^{IUU} \right)$, i.e. assuming that CPUE is proportional to biomass after the IUU catch has been taken.

## APPENDIX 2

# GLM AND GLMM 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, |
| $\mu$ | is the intercept, |
| *vessel* | is a factor with 7 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*
*South Princess*
*Suidor One*

| | |
|---|---|
| *year* | is a factor with 9 levels associated with the years 1997–2005, |
| *month* | is a factor with 12 levels (January– December), |
| *area* | is a factor with 4 levels associated with the four spatially distinct fishing areas:<br>*A*: 43–48°S latitude and 32–37°E longitude,<br>*B*: 43–45.3°S latitude and 37–40.3°E longitude,<br>*C*: 45.3–48°S latitude and 37–40.3°E longitude,<br>*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 |
| $\varepsilon$ | 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:

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

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.

## GLMM MODEL TO STANDARDISE THE CPUE

The GLMM (General Linear Mixed Model) approach applied treats the year interactions of the GLM described above as random effects. Thus the model implemented has the form:

$$\ln(CPUE + \delta) = \mathbf{X}\alpha + \mathbf{Z}\beta + \varepsilon \quad \text{(A2.3)}$$

where

$\alpha$ is the unknown vector of fixed effects parameters (this vector includes the following parameters of equation (A2.1) above: the year, vessel, area and month main effects as well as the month-area interaction),

**X** is the design matrix for the fixed effects,

$\beta$ is the unknown vector of random effects parameters (here the year-area and the year-month interactions),

**Z** is the design matrix for the random effects, and

$\varepsilon$ is an error term assumed to be normally distributed and independent of the random effects.

This approach assumes that both the random effects and the error term have zero mean, i.e. E($\beta$) = E($\varepsilon$) = 0, so that E ($\Delta L$) = $\mathbf{X}\alpha$. The variance-covariance matrix for the residual errors ($\varepsilon$) is denoted by **R** and that for the random effects ($\beta$) by **G**. The analyses undertaken here assume that the residual errors as well as the random effects are homoscedastic and uncorrelated, so that both **R** and **G** are diagonal matrices given by:

$$\begin{array}{l}\mathbf{R} = \sigma_\varepsilon^2\mathbf{I} \\ \mathbf{G} = \sigma_\beta^2\mathbf{I}\end{array} \quad \text{(A2.4)}$$

where **I** denotes an identity matrix. Thus, in the mixed model, the variance-covariance matrix (**V**) for the response variable is given by:

$$\text{Cov}(\Delta L) = \mathbf{V} = \mathbf{ZGZ}^{\mathrm{T}} + \mathbf{R} \quad \text{(A2.5)}$$

where $\mathbf{Z}^{\mathrm{T}}$ denotes the transpose of the matrix **Z**.

The estimation of the variance components (**R** and **G**), the fixed effects ($\alpha$) and the random effects ($\beta$) parameters in GLMM requires two steps. First the variance components are estimated. Once estimates of **R** and **G** have been obtained, estimates for the fixed effects parameters ($\alpha$) can be obtained as well as predictors for the random effects parameters ($\beta$). Variance component estimates are obtained by the method of residual maximum likelihood (REML) which produces unbiased estimates for the variance components as it takes the degrees of freedom used in estimating the fixed effects into account.

As no fixed effects include a year interaction, the standardised CPUE indices are obtained as the sum of the year effect and the constant (here standardised on area C, the month of June and the vessel *Koryo Maru II*).