A PROPOSED MANAGEMENT PROCEDURE FOR THE TOOTHFISH (*Dissostichus eleginoides*) RESOURCE IN THE PRINCE EDWARD ISLANDS VICINITY

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ABSTRACT

Four Operating Models (OMs) reflecting an “Optimistic”, “Intermediate”, “Less Pessimistic” and a “Pessimistic” current status for the toothfish resource in the Prince Edward Islands region are developed which take account of the different selectivities of past longline and pot fisheries. These models are used for trials of a candidate Management Procedure (MP) which could provide future TAC recommendations for this resource. The MP uses two data sources: the recent trend in longline CPUE and the mean length of the catches made. A specific MP, with its associated control parameter values, is proposed for implementation based upon the results of the trials. Given the importance of an adequate catch rate for the economic viability of the fishery, the choice of control parameter values focused primarily on a reasonable probability of securing a catch rate increase, whatever the current resource status. MP performance is reasonably robust across a range of sensitivity tests, though does deteriorate in conservation terms if steepness *h* is low. These tests also indicate that monitoring of future catch-at-length information would be necessary to guard against a change in selectivity towards greater catches of older fish.

INTRODUCTION

Previous assessments of the toothfish (*Dissostichus eleginoides*) resource in the waters surrounding the Prince Edward Islands have yielded wide-ranging results (Brandão and Butterworth 2002a, b, 2003, 2004a, b). Even when possible recruitment fluctuations in years before any (legal or IUU) harvesting commenced are taken into account, the absence of much change over time in the catch-at-length structure information available for this resource suggests that it has hardly been impacted by catches, whereas the CPUE data in isolation indicate the resource to have been heavily depleted by those catches.

These circumstances lead to major difficulties in making scientific recommendations for appropriate catch limits for this resource. Therefore investigations were initiated to ascertain whether a “Management Procedure” (MP) approach might provide a way forward. The fundamental idea is that while the two “alternative hypotheses” above cannot at present be reliably distinguished, data from future catches would hopefully enable them to be so. Thus the potential of alternative algorithms for setting catch limits is to be examined using simulation tests to determine which best ensures that the resource is hardly likely be further depleted (and indeed preferably shows some recovery) if the “Pessimistic” assessment is correct, while allowing catches to be increased if future data indicate support for the more “Optimistic” appraisal.

These computer simulation tests are based on “Operating Models” (OMs) which reflect possible true underlying dynamics of the resource to enable future data (both catch-at-length distributions and CPUEs) to be generated that are compatible with past data. These generated future data are then used by the algorithms to compute projected future catch limits for the candidate MPs to be examined. Clearly complete compatibility with *all* past data is impossible given the highly conflicting assessment results that follow from varying the weights given to these different data types. Accordingly, to develop some initial trials to initiate an MP evaluation process, Brandão and Butterworth (2005a) followed an approach which eliminated some of either the earlier CPUE data and/or the earlier catch-at-length data, so that the population model for toothfish is able to fit both (reduced) sets satisfactorily (here "satisfactorily" means, in particular, *without any systematic trends in the residuals*; this is essential as the relationships so estimated are to be used to generate future data in the projections of the OM for the MP testing, and one is assuming that the same process that generated such data in the past continues unchanged to generate them in the future, so that the fit to the past data must be such as ensures that such a self-consistency assumption can be made defensibly). Brandão and Butterworth (2005a) implemented this approach to develop three OMs, one reflecting an "Optimistic" and one a "Pessimistic" status for current abundance, and one that reflected a status intermediate between these two extremes. The implicit assumption that they made is thus that for some reason, some or other of such earlier CPUE and catch-at-length data are unreliable in the context of the assumptions associated with their use in the population model used for assessment, given their mutual incompatibility demonstrated in past assessments.

Subsequently Brandão and Butterworth (2007a) considered stochastic projections under the "Optimistic", "Intermediate" and "Pessimistic" scenarios that took into account data from both the past longline and pot fisheries, though no account was taken of cetacean depredation. These OMs were then used to investigate the performance of a candidate MP that took into account the trend in future CPUE indices and the mean length of the longline catches (which provides a surrogate index to indicate whether biomass is above or below MSYL) to provide future TACs.

In this paper, these OMs are further updated to include further CPUE and catch-at-length data and to take cetacean depredation into account. A further OM is also developed which reflects a "Less Pessimistic" scenario for the current status of the toothfish fishery that is about midway between the status estimated for the "Intermediate" and "Pessimistic" scenarios for a more complete coverage of the range of possible present resource status. These four OMs form a reference set which is used to generate future data to test candidate MPs to provide future TAC recommendations for the toothfish resource in the Prince Edward Islands vicinity.

On the basis of these reference set tests, augmented by further robustness tests to address other aspects of uncertainty, an MP is proposed for the provision of future TAC advice for the fishery.

OPERATING MODELS AND PROJECTIONS

Assessment component

A reference set of four Operating Models (OMs) reflecting an "Optimistic", an "Intermediate", a "Less Pessimistic" and a "Pessimistic" current status for the toothfish resource in the Prince Edward Islands region are used in this paper to generate future data to test a candidate MP. These OMs are developed in a similar way as in Brandão and Butterworth (2005a) in that the implicit assumption is made that for some reason, some or other of the earlier CPUE and/or length data are unreliable in the context of the assumptions associated with their use in the population model used for assessment, given their mutual incompatibility demonstrated in past assessments. The "Optimistic", "Intermediate" and "Pessimistic" OMs reflect the spawning biomass depletion at the start of 2007 to be at 68%, 57% and 15% respectively. A relative weight (w_{len}) of 0.2 was applied to the catch-at-length contribution to the log-likelihood. This value of w_{len} is given by approximately the ratio of the (about) 8 age-classes that make substantial contributions to the catches each year and the 43 length classes included in the likelihood. However to be able to reflect a current depletion as low as 15% in the "Pessimistic" scenario, a value of w_{len} of 0.1 had to be used, as using the same weight as for the other scenarios produced results that were not too different from the "Intermediate" scenario. A "Less Pessimistic" scenario was also developed to lie approximately half way between the "Intermediate" and the "Pessimistic" scenarios. This was obtained by applying a w_{len} value of 0.165 to the catch-at-length data, which provides a depletion of 37% at the start of 2007. The OMs developed are Age-Structured Production Models (ASPMs) and the methodology applied to fit ("condition") these models to updated data together with the associated results are given in Appendix 1.

For simplicity, the OMs considered by Brandão and Butterworth (2005a, 2006a) did not take the pot "fleet" into account and treated pot catches as if they had the same selectivity as the longliners. In this paper, all four reference set OMs differentiate the selectivities for the longline and pot fisheries.

Furthermore, the OMs considered by Brandão and Butterworth (2005a, 2006a, 2007a) did not take the impact of cetacean depredation into account. In this paper, as in the assessments of Brandão and Butterworth (2005b, 2006b, 2007b) it is assumed that the extent of toothfish depredation by cetaceans from longlines increased linearly from 2000 to a saturation level from 2002 onwards, as suggested in discussions with industry members. Observations abroad the *South Princess* vessel suggested that two of every three toothfish caught on longlines were thieved by cetaceans, i.e. that cetacean depredation should be calculated as a multiplying factor z = 2 of the landed longline catch. As this factor appears somewhat extreme, however, given accounts elsewhere in the Antarctic of this effect, the reference set OMs all assume z = 1 (i.e. cetacean depredation equal to landed longline catch). Robustness tests are conducted for alternative possible choices for z. This basis for inflating the catch figures to account for depredation is 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.

Projections component

The MP investigated here assumes that commercial longline CPUE and catch-at-length data will continue to be available annually for the longline fishery. As the pot fishery has not been in operation since April 2005, it is assumed that this fishery will not operate in the future.

The evaluation of the MP requires the simulation of future longline CPUE and catch-at-length data from projections for the population. These projections are effected using the following procedure:

1. Numbers-at-age ($N_{y',a}$) for the start of the year in which projections commence (i.e. y' = 2007) are estimated by applying equations (A1.1)–(A1.3). To allow for variation in biomass projections initially (as the stochastic effects enter later only through variability in future recruitment which takes a period to propagate through to the exploitable component of the biomass), the numbers-at-age for the first seven years are allowed to fluctuate, where these fluctuations are simulated by generating $\varphi_{y'}$ factors distributed as N(0, σ_R^2), where $\sigma_R = 0.5$. The reason for this is that the catch-at-length data to which the OMs are fitted provides no information on recruitment residuals $\zeta_{y'}$ for these year classes which have yet to enter the fishery, so that these $\zeta_{y'}$ are estimated to be zero in the assessments. Thus, for ages 1–7, the numbers-at-age are given by $N_{y',a}e^{\left(\varphi_{y'}-\sigma_R^2/2\right)}$. The future catches-at-age ($C_{y',a}$) are obtained from equations (A1.4) and (A1.5). Such future catch-at-age values are generated assuming that the commercial selectivity function remains the same as that for the last year of the assessment. Future recruitments are obtained from the stock-recruitment relationship given by equation (A1.35), which allows for fluctuations about this relationship. These fluctuations are computed for each future year simulated by generating $\zeta_{y'}$ factors also distributed as N(0, σ_R^2), where $\sigma_R = 0.5$.

2. Future spawning and exploitable biomasses are calculated using equations (A1.14) and (A1.23). Given the exploitable biomass for longliners, the expected (longliner) CPUE abundance index $I_{y'}^{CPUE}$ is first generated using equation (A1.23); then log-normal observation error is added to this expected value, i.e.:

$$I_{y'}^{CPUE} = qB_{y'}^{\exp} e^{\varepsilon_{y'}} ,$$

where $\varepsilon_{y'}$ is normally distributed with a mean zero and a standard deviation σ which is the estimate obtained for the operating model (from equation (A1.26)), as is *q* (from equation (A1.25)), for the longline fishery.
3. The TAC for the starting year 2007 (TAC_{2007}) is set to be 250 tonnes. For future years (i.e. 2008, 2009, etc. for year *y'*), the generated longline CPUE abundance indices and longline catch mean length data (see Step 5 following) are used to compute future TACs ($TAC_{y'+1}$) from the TACs for the current year ($TAC_{y'}$) as described in the next section which specifies the MP.
4. The numbers-at-age for year *y'* are projected forward under a true catch given by the sum of $TAC_{y'}$ (the legal component) and any assumed illegal component, together with the assumed level of cetacean depredation which is taken to remain at its correct level, by means of the operating model to obtain $C_{y',a}$ and $N_{y'+1,a}$. The same assumptions about the commercial selectivity function and recruitment fluctuations as made in step (1) above are made.
5. Given the catch-at-age $C_{y',a}$ for longliners, the mean length ($\bar{\ell}_{y'}$) of toothfish for year *y'* caught by longliners is given by:

$$\bar{\ell}_{y'} = \frac{\sum_{\ell} \ell C_{y',\ell} \left(e^{\eta_{y',\ell} - \sigma^2_{y',\ell}/2} \right)}{\sum_{\ell} C_{y',\ell} \left(e^{\eta_{y',\ell} - \sigma^2_{y',\ell}/2} \right)} = \frac{\sum_{\ell} \ell \left(\sum_{a} C_{y',a} A_{a,\ell} \right) \left(e^{\eta_{y',\ell} - \sigma^2_{y',\ell}/2} \right)}{\sum_{\ell} C_{y',\ell} \left(e^{\eta_{y',\ell} - \sigma^2_{y',\ell}/2} \right)} ,$$

where:

$A_{a,\ell}$ is the proportion of fish of age *a* that fall in length group ℓ (equations (A1.29)–(A1.30)) for longliners,

$C_{y',\ell}$ is the catch-at-length ℓ for longliners in year *y'*,

ℓ is the length class (where the minus group is to 54 cm and the plus group is from 138 cm, in steps of 2 cm, and these values are used for the minus and plus group lengths in the averaging process), and

$\eta_{y',\ell}$ is a factor distributed as N(0, $\sigma^2_{y',\ell}$), where $\sigma_{y',\ell} = \frac{\hat{\sigma}_{len}}{\sqrt{\sum_{a} C_{y',a} A_{a,\ell}}}$, and $\hat{\sigma}_{len}$ is given by equation (A1.34) for the longline fishery.
6. Steps (2)–(5) are repeated for each future year considered.
7. This projection procedure is replicated 100 times, to provide probability distributions for projection results arising from uncertainties in future recruitment and observation errors for CPUE and catch-at-length data.

In Brandão and Butterworth (2007a), the future observed $\bar{\ell}_{y'}$ values were taken to equal the model values exactly (i.e. no observation error was considered for these data). In this paper future observed $\bar{\ell}_{y'}$ values are stochastic as indicated in Step 5 above.

THE MP CONSIDERED

A simple candidate for an MP is one where the TAC is modified in synchrony with the trend in a resource abundance index (such as CPUE). However, although future increases in CPUE trends would imply increases in catches, a decrease in CPUE trend does not necessarily mean a need for decreased catches. This would depend on whether or not the biomass is above or below MSYL (if the biomass is above MSYL one is happy, from a biological standpoint, to have catches increase even though the biomass drops to some extent). The mean length of catches is used here as a surrogate for MSYL. A mean length above a certain length (ℓ *) indicates (crudely) that biomass is above MSYL, and below this length that biomass is below MSYL. Figure 1 depicts the structure underlying the formulation of an MP that takes this reasoning into account. The “+” and “-“ signs depict the increase or decrease in catches depending on the trend in CPUE and whether the mean length is above or below ℓ *. In each quadrant the formula of the control rule is also shown. In instances when the CPUE trend is increasing and the mean length is above ℓ *, TACs are increased (using both values to set the extent of the increase). If the CPUE is decreasing and the mean length is below ℓ *, then the TAC decreases (again using both values to set the extent of the decrease). If the trend in CPUE is decreasing but mean length is above ℓ * (the surrogate for MSYL), the TAC is increased (ignoring the CPUE trend), while if the mean length is below ℓ *, the catches are increased (ignoring the specific value of the mean length) but only if the CPUE trend is increasing.

This specific control rule of the MP is:

$$TAC_{y+1} = TAC_y \left[1 + \Psi\right] \quad (1)$$

where:

$$\Psi = \begin{cases} \lambda s_{CPUE} + \mu\left(\left(\ell_{mean} - \ell^*\right)/\ell^*\right) & \text{if} \quad s_{CPUE} \geq 0 \quad \text{and} \quad \ell_{mean} - \ell^* \geq 0 \\ \lambda s_{CPUE} & \text{if} \quad s_{CPUE} \geq 0 \quad \text{and} \quad \ell_{mean} - \ell^* \leq 0 \\ \lambda s_{CPUE} + \mu\left(\left(\ell_{mean} - \ell^*\right)/\ell^*\right) & \text{if} \quad s_{CPUE} \leq 0 \quad \text{and} \quad \ell_{mean} - \ell^* \leq 0 \\ \mu\left(\left(\ell_{mean} - \ell^*\right)/\ell^*\right) & \text{if} \quad s_{CPUE} \leq 0 \quad \text{and} \quad \ell_{mean} - \ell^* \geq 0 \end{cases}$$

where s_{CPUE} is the slope of a log-linear regression of the abundance index against time for the last (in the case implemented) 5 years and ℓ_{mean} is the average of mean length ($\bar{\ell}_{y'}$) over the last 5 years. The λ, μ and ℓ * are control parameters. This MP also constrains TACs to a maximum inter-annual change of 15%.

Figure 2 shows typical deterministic projections for CPUE, CPUE slope and the mean length of the catch for the four operating models of the reference set which are obtained under one particular set of choices of the control parameter values for this control rule. These behave as anticipated under the reasoning given above.

RESULTS

The performances of different candidate MPs were considered in term of future projections over a 20 year period, and in particular the following four statistics which were intended to capture key features of the trade-off choices to be made:

<u>Catches achieved</u>

Average annual catch: $\overline{C^s} = \frac{1}{20}\sum_{y=2007}^{2026} C_y^s$, where *s* represents simulation *s*.

<u>Risk to resource</u>

Final resource size: $B_{2026}^{sp(s)} / K^{sp(s)}$

<u>Industrial stability</u>

Average annual catch variation: $AAV^s = \frac{1}{20}\sum_{y=2007}^{2026}\frac{\left|C_y^s - C_{y-1}^s\right|}{C_{y-1}^s}$

Economic viability

CPUE relative to recent level: $\frac{CPUE_{2026}^s}{\frac{1}{3}\sum_{y=2004}^{2006} CPUE_y^s}$.

Over the simulations *s* there is a distribution for each of these statistics, and performance is reported in terms of statistics of those distributions (typically the median and 90% probability interval).

Experimentation with different values of the three control parameters led to the selections $\lambda = 1$, $\mu = 1$ and $\ell^* = 81$ cm for the MP of equation (1). For economic viability reasons, the major concern of the industry is that the *CPUE* not decline. Thus, the control parameters were chosen in consultation with the industry, keeping this concern as a priority.

Testing this MP for the four reference set scenarios yields the results shown in Table 1 and Figure 3 by the left most point, with the bars representing the 90% percentiles. Figure 4 shows the performance of this MP under the reference set OMs. These results broadly reflect the performance features sought: TACs increase faster for the “Optimistic” than for the “Pessimistic” scenario, and there is some recovery in abundance for the latter case coupled with a low probability of any further decline which would compromise catch rates and hence the economic viability of the fishery.

Robustness tests

Table 2 describes the various robustness tests carried out whose results are shown in Figure 3, together with the abbreviations used to represent them.

The reference set OMs assume that cetacean depredation is known to be equal ($z = 1$) to the catch landed and that it continues at this same level in the future. As robustness tests, the multiplicative factor *z* is increased to 2 and decreased to 0.5. The results of these two robustness tests are shown in Figure 3 for the “Intermediate” and the “Pessimistic” OMs. For $z = 2$, final stock status is better for the “Pessimistic” scenario compared to results for the reference set, but there are no other changes of much note.

Given the critical value played by the mean length of the catch in the MP investigated, it is important to check whether performance is reasonably robust to changes in longline selectivity (e.g. through the area fished changing), which would alter the mean length of the catch without any change to the status of the resource. A third robustness test therefore considers the implications if the longline selectivity function of the earlier years (1997 to 2002) of the fishery is assumed to apply in the future. As this selectivity function is only estimable for the “Optimistic” OM, to apply this robustness test to the other OMs, the same proportion of change estimated between the earlier and later selectivity functions of the “Optimistic” OM is assumed for these other OMs. The results in Figure 3 show that future catches increase somewhat, but for the “Less Pessimistic” and “Pessimistic” scenarios there is a slight deterioration in the extent of resource recovery achieved.

Two further robustness tests are considered in which future selectivity changes. In one, a lower age at 50% selectivity ($a_{50} = 5.5$ years) was introduced after three years (i.e. in 2010) to examine the MP performance in case the fishery targets for more smaller fish to a greater extent. Another robustness test considers the opposite scenario in which the fishery targets for more bigger fish and the age at 50% selectivity is set at 7.5 years from 2010. Note that a change in selectivity confounds the relationship between exploitable biomass and CPUE (see equations (A1.23, 24), likely resulting in a consequential change in catchability q. To keep computations simple here, this factor was ignored by applying equation (A1.23) to compute exploitable biomass as if a_{50} had not changed, though naturally taking the change into account when future catch-at-length data are generated. The change in selectivity to more smaller fish decreases the catches for all four scenarios (Figure 3). Under the "Pessimistic" scenario, a change in selectivity to more larger fish reduces the extent of recovery of the stock and the catch rate (particularly the associated lower 5% percentile). Thus if the MP proposed is implemented, monitoring of future catch-at-length distributions will still be needed to check that such a change in selectivity is not occurring.

Another robustness test considers the steepness parameter of the stock-recruitment curve to be 0.6 instead of 0.75, with the productivity of the resource consequentially being lower. Under the "Less Pessimistic" and particularly the "Pessimistic" scenario, a lower value for the steepness parameter would give rise to concerns in terms of a probable drop in catch rate and further depletion of the resource (Figure 3).

The last robustness test considers the possibility that the development of technology to stop cetacean depredation from longlines (see Kock *et al*. 2008) is successful and that in two years time (i.e. from 2010) no further cetacean depredation occurs. Figure 5 shows the performance of the MP under these circumstances for the "Pessimistic" scenario. It is clear from the results that a solution to the cetacean depredation problem would be of considerable benefit to both the resource (in terms of a faster recovery rate) as well as to the fishery (in terms of higher catch rates and higher catches).

CONCLUDING REMARKS

The MP of equation (1), with control parameters set as $\lambda = 1$, $\mu = 1$ and $\ell^* = 81$ cm, and an inter-annual TAC change constraint of 15%, is put forward as a future basis for TAC recommendations for the toothfish fishery in the Prince Edward Islands region. For economic reasons, the choice of control parameter values focused primarily on a reasonable probability of securing a catch rate increase, whatever the current resource status. MP performance is reasonably robust across a range of sensitivity tests, though does deteriorate in conservation terms if steepness h is appreciably less than the reference set value of 0.75 assumed. Furthermore monitoring of future catch-at-length information would be necessary to guard against a change in selectivity towards greater catches of older fish.

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. The estimation software used, AD Model Builder, is a trademark of Otter Research Ltd., P O Box 265, Station A, Nanaimo, B.C. V9R 5K9, Canada.

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Table 1. Projected median average annual legal (longline) catches of toothfish (in tonnes) for the period 2007 to 2026, the median spawning biomass depletion at the start of the year 2026, average annual variation (AAV) in catch and the median CPUE index in 2026 as a proportion of the average of the 2004 to 2006 CPUE indices, for the four reference set OMs. The 90% percentiles are also shown in parenthesis. These results assume illegal (longline) catches will continue in the future at a constant rate of 150 tonnes per year.

Scenario	Performance statistic			
	$\bar{C}_{2007-2026}$	B^{sp}_{2026}/K^{sp}	**AAV**	$\frac{CPUE_{2026}}{\overline{CPUE}_{04-06}}$
"Optimistic"	399 (358; 451)	0.775 (0.637; 0.936) [2007 value: 0.677]	0.076 (0.064; 0.092)	1.116 (0.740; 1.561)
"Intermediate"	400 (366; 455)	0.692 (0.561; 0.876) [2007 value: 0.572]	0.078 (0.067; 0.092)	1.439 (0.901; 2.300)
"Less Pessimistic"	430 (374; 488)	0.453 (0.327; 0.631) [2007 value: 0.374]	0.088 (0.073; 0.108)	1.591 (0.823; 3.070)
"Pessimistic"	400 (359; 461)	0.174 (0.089; 0.297) [2007 value: 0.149]	0.079 (0.066; 0.098)	1.277 (0.749; 2.145)

Table 2. Reference set and robustness tests carried out to test the performance of the proposed MP, together with abbreviations for these used in Figure 3.

Robustness test	Description
Ref set	Reference set
z = 2	Cetacean depredation is equal to twice the longline catch landed
z = 0.5	Cetacean depredation is equal to half the longline catch landed
early sel	The longline selectivity function of the earlier years (1997-2002) of the fishery is assumed to apply in the future
a_{50} = 5.5	The age at 50% selectivity is lowered to 5.5 years from 2010
a_{50} = 7.5	The age at 50% selectivity is increased to 7.5 years from 2010
h = 0.6	Stock-recruitment steepness value is lowered to 0.6

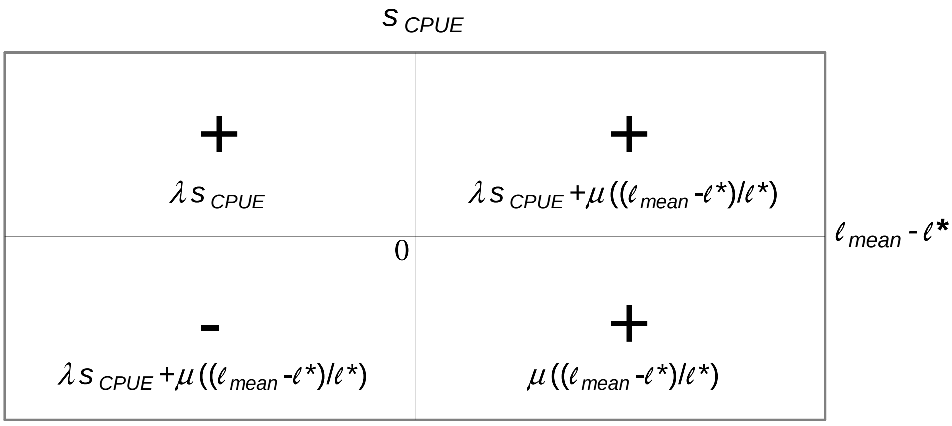

Figure 1. The structure in the formulation of an MP that takes into account the trend in CPUE indices, but reacts differently to this trend depending on whether biomass is above or below MSYL (for which a mean length at capture of ℓ^* acts as a surrogate). The “+” and “-“ signs indicate whether an increase or decrease in catches is required, depending on the trend in CPUE (given by slope s_{CPUE}) and whether the mean length of catches ℓ_{mean} is above or below ℓ^*. The formula of the control rule to be applied is also shown in each quadrant.

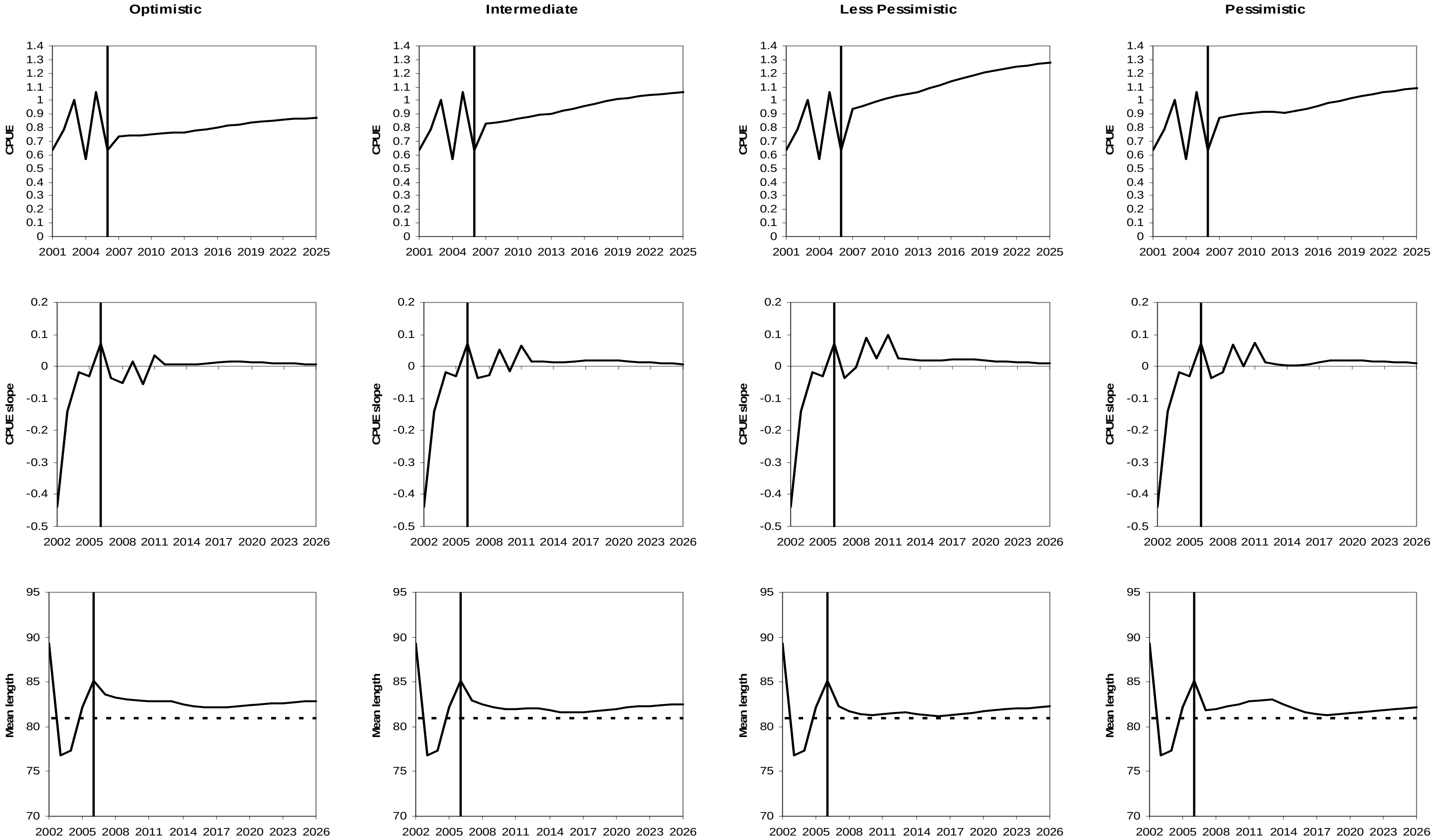

Figure 2. Deterministic projections of CPUE, CPUE slope (s_{CPUE}) and mean length trends under the "Optimistic", "Intermediate", "Less Pessimistic" and "Pessimistic" operating models (shown to the right of the vertical line). The values to the left of this line reflect past data from longline operations. The horizontal dashed line in the lowest set of plots show the value of ℓ^* = 81 selected for the MP control rule.

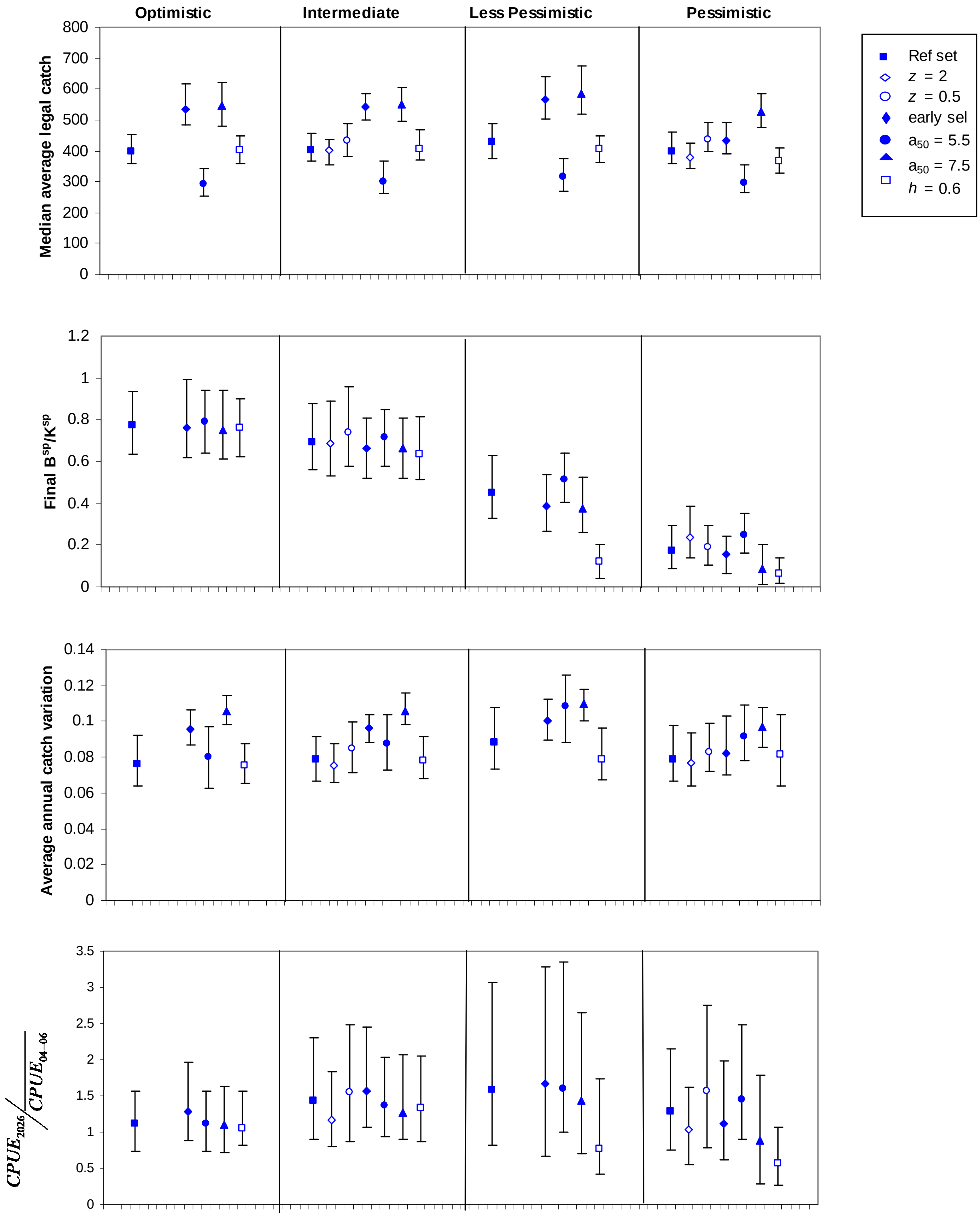

Figure 3. Projected median (and 90% percentiles) of the average annual legal (longline) catches of toothfish (in tonnes) for the period 2007 to 2026, the spawning biomass depletion at the start of 2026, the average annual variation in catch and the CPUE index in 2026 as a proportion of the average of the 2004 to 2006 CPUE indices for the four OMs for various robustness tests in the following order: reference set, cetacean depredation z = 2 and z = 0.5, earlier longline selectivity applies in the future, age at 50% selectivity of 5.5 and 7.5 yrs, and steepness parameter h = 0.6. Note that for the "Optimistic" and "Less Pessimistic" OMs, not all robustness tests are shown.

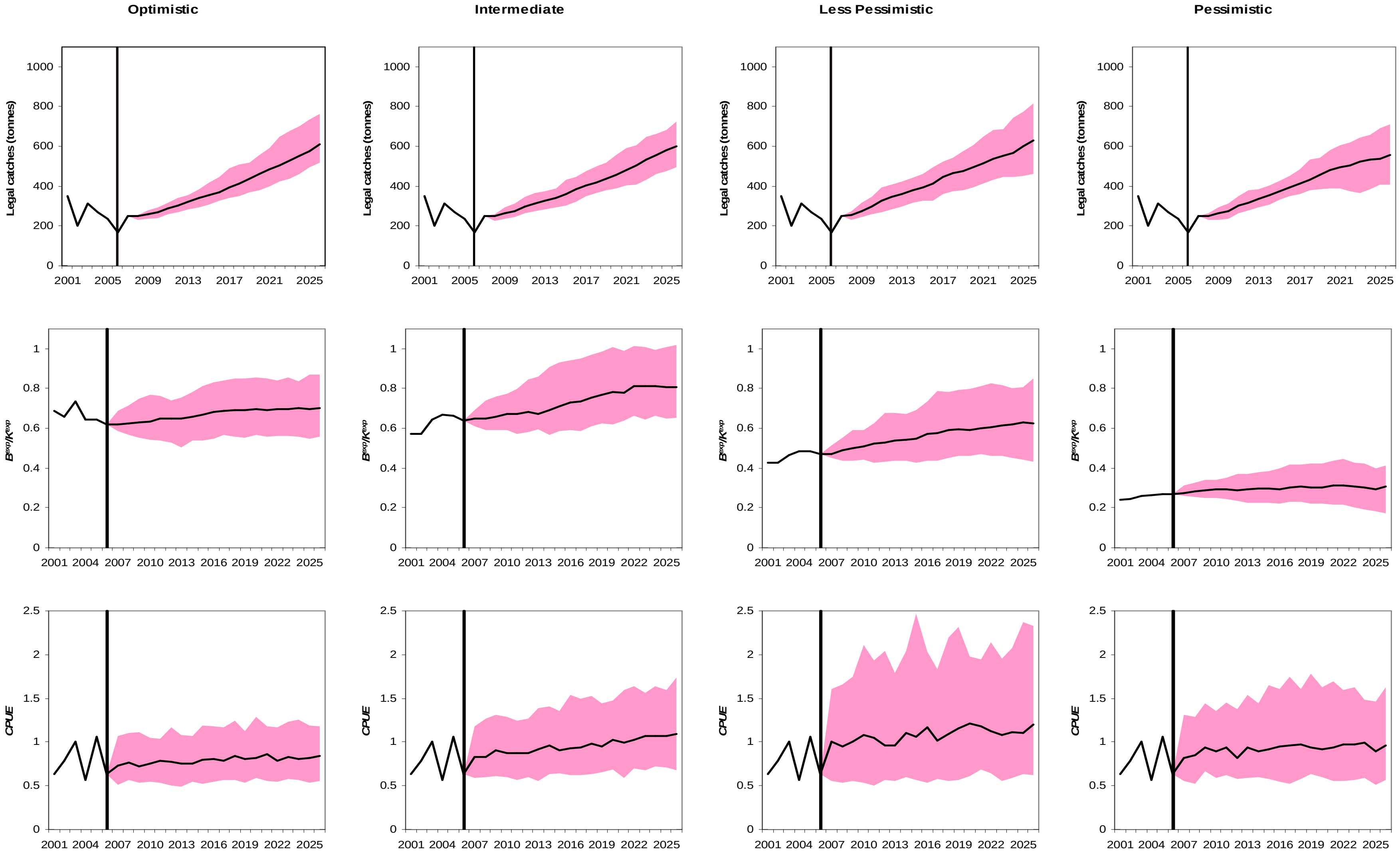

Figure 4. Median trajectories of legal annual catches by longliners (in tonnes), exploitable biomass depletion and CPUE trends under the proposed empirical MP for the "Optimistic", "Intermediate", "Less Pessimistic" and "Pessimistic" Operating Models (OMs). Projections (medians) commence to the right of the vertical lines and the shaded areas represent 90% probability envelopes. These results assume that illegal catches continue at a constant rate of 150 tonnes per year and that cetacean depredation continues in the future at the same level as in the immediate past (*z* = 1, i.e. equal to the longline catch landed).

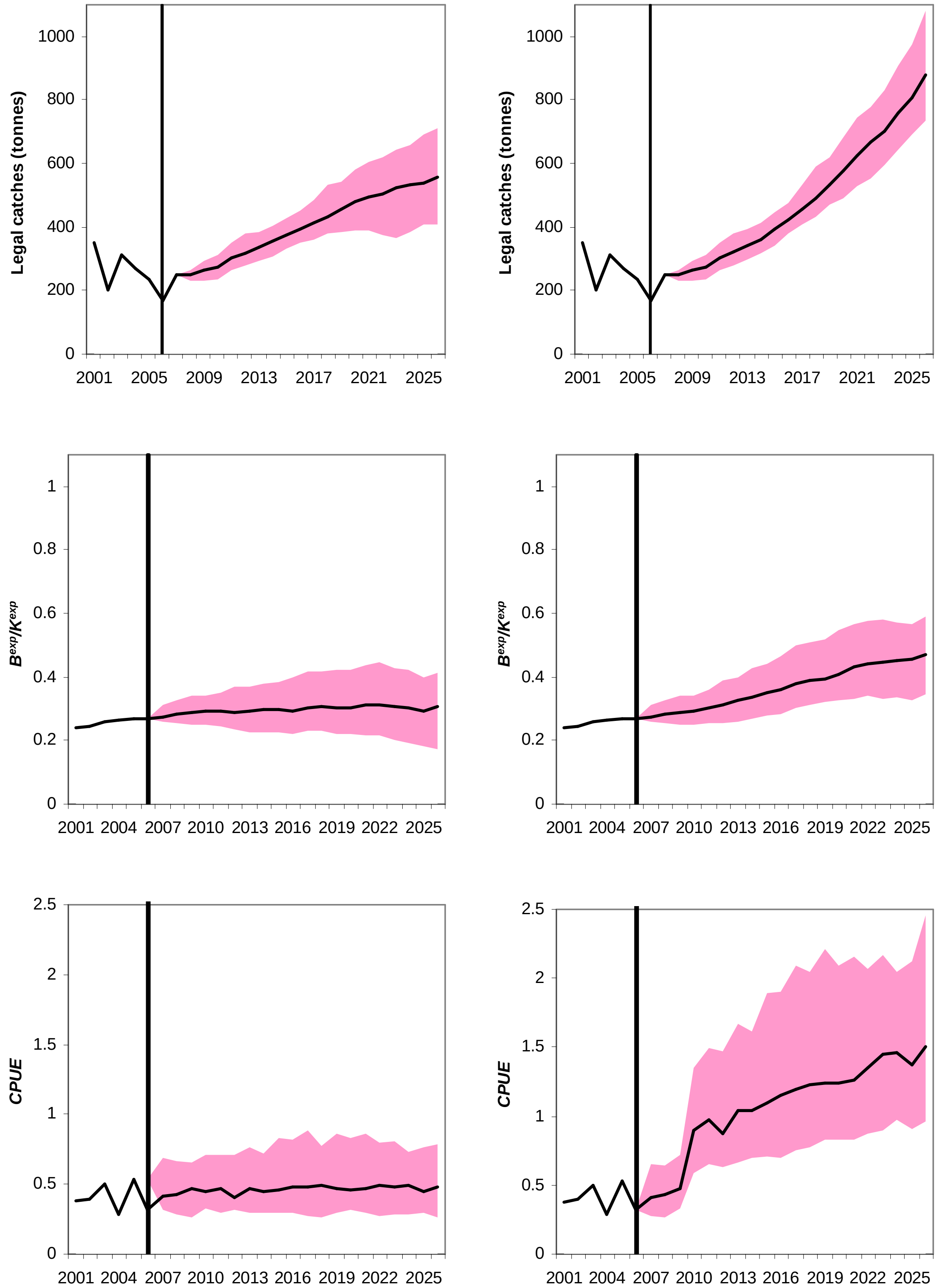

Figure 5. Median trajectories of legal annual catches by longliners (in tonnes), exploitable biomass depletion and CPUE trends under the proposed empirical MP for the "Pessimistic" Operating Model (OM) for the robustness test that assumes that cetacean depredation will cease from 2010 (right). For comparison the corresponding reference set trajectories are also shown (left). Projections (medians) commence to the right of the vertical lines and the shaded areas represent 90% probability envelopes. These results assume that illegal catches continue at a constant rate of 150 tonnes per year. Note that CPUE as shown here is that realised by the vessels (i.e. is not adjusted to incorporate loses to depredation as in Table A.2)

APPENDIX 1

THE AGE-STRUCTURED PRODUCTION MODEL (ASPM) METHODOLOGY UNDERLYING THE OPERATING MODELS

Brandão and Butterworth (2005a) developed three Operating Models (OMs) to be used in the simulation testing process for candidate toothfish Management Procedures (MPs). The OMs used to describe the dynamics of the toothfish resource are ASPMs. In this paper, these OMs are refined and a total of four are considered as a reference set for MP testing. These are fitted to subsets of the data and applying different relative weights to the catch-at-length data to reflect “Optimistic”, “Intermediate”, “Less Pessimistic” and “Pessimistic” scenarios, with the first and last corresponding respectively to a resource respectively well above and well below MSYL.

METHODOLOGY

The toothfish population dynamics in the OMs are given by the equations:

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

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

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

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 of equation (A1.15) 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.

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

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

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:

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

which to solve for F_y^f can be re-written as:

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

FISHING SELECTIVITY

The fleet-specific commercial fishing selectivity, $S_{y,a}^f$, is assumed to be described by a logistic curve, modified by a decreasing selectivity for fish older than age a_c. This is given by:

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

where:

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

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

ω^y specifies 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 could for example be restricted to 0.9, and the actual catch considered to be taken would be less than the proposed catch. This procedure alone would however make 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 $F_y^f > 0.9$, however, compute the total catch from:

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

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

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

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

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

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:

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

where:

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

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

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

The values of the parameters α and β can be calculated given the unexploited equilibrium (pristine) spawning biomass K^{sp} and the steepness of the curve *h*, using equations (A1.16)–(A1.20) 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.:

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

from which it can be shown that:

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

Rearranging equation (A1.17) gives:

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

and solving equation (A1.15) 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:

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

where:

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

PAST STOCK TRAJECTORY AND FUTURE PROJECTIONS

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

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

which can be solved for R_0.

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

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

Numbers-at-age for subsequent years are then computed by means of equations (A1.1)-(A1.5) and (A1.8)-(A1.15) under the series of annual catches given.

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

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

THE LIKELIHOOD FUNCTION

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

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

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:

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

where:

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

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

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

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

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

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

EXTENSION TO INCORPORATE CATCH-AT-LENGTH INFORMATION

The model above provides estimates of the catch-at-age ($C_{y,a}^f$) by number made by the each fleet in the fishery each year from equation (A1.5). These in turn can be converted into proportions of the catch of age *a*:

$$p_{y,a}^f = C_{y,a}^f \Big/ \sum_{a'} C_{y,a'}^f \; . \qquad \text{(A1.28)}$$

Using the von Bertalanffy growth equation (A1.6), these proportions-at-age can be converted to proportions-at-length – here under the assumption that the distribution of length-at-age remains constant over time:

$$p^f_{y,\ell} = \sum_a p^f_{y,a} A^f_{a,\ell} \tag{A1.29}$$

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.:

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

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

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

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

where:

- $p^{obs}_{y,\ell}(f)$ is the proportion by number of the catch in year *y* in length group ℓ for fleet *f*, and
- σ^f_{len} has a closed form maximum likelihood estimate given by:

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

Equation (A1.33) makes the assumption that proportions-at-length data are log-normally distributed about their model-predicted values. The associated variance is taken to be inversely proportional to $p^f_{y,\ell}$ to downweight contributions from expected small proportions which will correspond to small observed sample sizes. This adjustment is of the form to be expected if a Poisson-like sampling variability component makes a major contribution to the overall variance. Given that overall sample sizes for length distribution data differ quite appreciably from year to year, subsequent refinements of this approach may need to adjust the variance assumed for equation (A1.33) to take this into account.

The w_{len} weighting factor may be set at a value less than 1 to downweight the contribution of the catch-at-length data to the overall negative log-likelihood compared to that of the CPUE data in equation (A1.27). The reason that this factor is introduced is that the $p^{obs}_{y,\ell}(f)$ data for a given year frequently show evidence of strong positive correlation (unsurprisingly, as for lower lengths in particular, samples for neighbouring lengths come from the same cohort), and so would not be as informative as the independence assumption underlying the form of equation (A1.33) would otherwise suggest.

In the practical application of equation (A1.33), length observations were grouped by 2 cm intervals, with minus- and plus-groups specified below 54 and above 138 cm respectively for the longline fleet, and plus-groups above 176 cm for the pot fleet, to ensure $p^{obs}_{y,\ell}(f)$ values in excess of about 2% for these cells.

ADJUSTMENT TO INCORPORATE RECRUITMENT VARIABILIITY

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

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

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:

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

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). A value of σ_R = 0.5 is assumed for fits of the model presented in this paper.

DATA AND IMPLEMENTATION

Four OMs (one reflecting an "Optimistic", one an "Intermediate", one a "Less Pessimistic" and one a "Pessimistic" current status for the toothfish resource) have been developed and are described in the main paper. Commencing November 2004 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 depredation. The OMs considered in this paper take this new "fleet" into account. Table A.1 shows the annual catches broken down into the two fleets (longline and pot), as well as estimates for illegal catches (see Brandão and Butterworth (2005b, 2006b) for a description of the basis for the estimates of illegal catches for 2004 to 2006).

The CPUE GLM standardisation procedure described in Appendix 1 of Brandão and Butterworth (2003) has been reapplied to the longline commercial data, resulting in the revised series of relative abundance indices listed in Table A.2. Only data for complete years are used in the analysis, thus CPUE data from 1997 to 2006 are used to obtain the standardised CPUE indices.

The values in both Table A.1 and Table A.2 make allowance for the appreciable impact caused by toothed cetaceans thieving fish from lines as they are hauled.

Catch-at-length information has also been updated to include the data now available for 2006. Table A.3 shows the basic biological updated parameter values which are as used for the most recent assessment (Brandão and Butterworth, 2007b).

The ASPM 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 0.47 corresponding to σ_R = 0.5.

A relative weight (w_{len}) ranging between 0.2 and 0.1 has been applied to the catch-at-length contribution to the log-likelihood. Clearly a value of 1 is too high, as there is correlation between the catch numbers-at-length given that the length classes included in the likelihood are generally of 2cm width only and number 43 in total, and amounts to overweighting such data. Inspection of the selectivity curves suggests that (for most fits considered) effectively only about 8 age-classes contribute to the catches each year. The somewhat crude basis for the choice for w_{len} then is the ratio of these two numbers, i.e. effectively treating the information from each such age-class as independent.

The "Optimistic" OM is fitted to all the 2001–2006 catch-at-length data but omits the two initial CPUE indices (1997 and 1998), whereas the "Intermediate" OM is fitted to only the last four years (2003–2006) catch-at-length data, with the first two initial CPUE indices omitted. For both the "Optimistic" and the "Intermediate" OMs, a relative weight of 0.2 has been applied to the catch-at-length data. The "Pessimistic" OM omits the catch-at-length distributions for the initial years (i.e. for 1997–2002) but includes all the CPUE indices, and a relative weight of 0.1 has been applied to the catch-at-length data. The "Less Pessimistic" OM is fitted to the same data as the "Pessimistic" OM but a relative weight of 0.165 has been applied to the catch-at-length data to yield a current spawning biomass depletion roughly half way between those for the "Intermediate" and "Pessimistic" OMs.

RESULTS

Table A.4 reports the parameter estimates for the four scenarios considered. Figure A.1 shows estimated spawning biomass trends and fits to the CPUE data are shown in Figure A.2. Fits of the four OMs to the catch-at-length distributions for the longline fishery for the years 2003 to 2006 are shown in Figure A.3. The selectivity functions estimated are shown in Figure A.4.

Note (Table A.4) that these four OMs span a range from 0.15 to 0.68 for spawning biomass depletion (B^{sp}_{2007}/K^{sp}).

Table A.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 Brandão and Butterworth (2005b, 2006b). The total catches shown include both legal (longline and pot) and estimated IUU catches and reflect various multiplicative factors (*z*) of the recent landed catch for the cetacean depredation assumed in this paper.

Year	Total catches			
	***z* = 0 (none)**	***z* = 0.5**	***z* = 1**	***z* = 2**
1997	24271.2	24271.2	24271.2	24271.2
1998	2818.9	2818.9	2818.9	2818.9
1999	1970.4	1970.4	1970.4	1970.4
2000	2771.6	3233.5	3695.5	4619.3
2001	703.9	938.5	1173.2	1642.4
2002	506.2	759.3	1012.4	1518.5
2003	568.9	853.3	1137.8	1706.7
2004	423.6	635.4	847.2	1270.8
2005	390.7	586.1	781.5	1172.2
2006	322.9	484.4	645.8	968.7
1997–2006 total	34 748.3	36 551.0	38 353.8	41 959.2

Table A.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. Note that the values shown reflect the CPUEs which would have been achieved had there been no cetacean depredation over recent years (this depredation is assumed to increase linearly from zero to its maximum level over 2000–2002, see text).

Year	Longline fishery *CPUE*			
	***z* = 0 (none)**	***z* = 0.5**	***z* = 1**	***z* = 2**
1997	4.665	4.665	4.665	4.665
1998	1.229	1.229	1.229	1.229
1999	1.071	1.071	1.071	1.071
2000	0.623	0.727	0.831	1.038
2001	0.381	0.508	0.635	0.890
2002	0.393	0.590	0.787	1.180
2003	0.503	0.754	1.005	1.508
2004	0.286	0.428	0.571	0.857
2005	0.531	0.797	1.062	1.594
2006	0.317	0.476	0.635	0.952

Table A.3. Biological parameter values assumed for the assessments conducted, based upon the recently updated values for Subarea 48.3 (Agnew *et al.* 2006). 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) κ (yr^{-1}) t_0 (yr)	 152.0 0.067 -1.49
Weight (in gm) length relationship c d	 25.4×10^{-6} 2.8
Age at maturity (yr)	13
Age at recruitment (yr)	6
Stock-recruitment steepness (h)	0.75

Table A.4. Estimates for a two fleet (longline and pot) model that assumes possibly different logistic commercial longline selectivities (with declining slopes at larger ages), one for the years 1997 and 2002 and another for 2003 to 2006, when fitted to the CPUE and catch-at-length data for toothfish from the Prince Edward Islands EEZ. For the "Optimistic" scenario, both these longline selectivity functions are estimated; for the other cases, only the 2003–2006 catch-at-length data are fitted, and the associated estimated longline selectivity function is assumed to have applied also to earlier years. The estimates shown are for the pre-exploitation toothfish spawning biomass (K_{sp}), the current spawning stock depletion (B_{sp}^{2007}/K_{sp}) and the 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 log-likelihood (where the catch-at-length contribution includes the down-weighting factors discussed in the text). The results shown assume a cetacean depredation factor z = 1, i.e. recent loses to cetacean depredation are equal to the landed longline catch.

Parameter estimates		**Model**			
		"Optimistic" scenario (97-98 CPUE omitted; only 01-06 length data fitted; w_{len} = 0.2**)**	**"Intermediate" scenario (97-98 CPUE omitted; only 03-06 length data fitted;** w_{len} = 0.2**)**	**"Less Pessimistic" scenario (all CPUE fitted; only 03-06 length data fitted;** w_{len} = 0.165**)**	**"Pessimistic" scenario (all CPUE fitted; only 03-06 length data fitted;** w_{len} = 0.1**)**
K^{sp} (tonnes)		138 499	88 205	45 703	29 723
B_{2007}^{sp}/K^{sp}		0.677	0.572	0.374	0.149
B_{2007}^{exp} (tonnes)	Longline	74 231	41 375	18 185	10 505
	Pot	129 883	71 131	24 433	5 218
B_{1997}^{sp}/K^{sp}		0.978	0.968	0.955	0.960
σ_{CPUE}	Longline	0.208	0.227	0.355	0.236
σ_R		0.500††	0.500††	0.500††	0.500††
a_{50}^{97-02} (yr)		6.536	—	—	—
δ^{97-02} (yr^{-1})		0.028	—	—	—
ω^{97-02} (yr^{-1})		0.055	—	—	—
a_{50}^{03-06} (yr)	Longline	6.513	6.519	6.532	6.551
	Pot	8.713	8.787	9.395	12.261
δ^{03-06} (yr^{-1})	Longline	0.028	0.028	0.029	0.031
	Pot	0.788	0.772	0.897	1.342
ω^{03-06} (yr^{-1})	Longline	0.082	0.080	0.061	0.010
	Pot	0.000	0.000	0.000	0.000
υ		0.121	0.124	0.123	0.125
σ_{len}	Longline	0.035	0.039	0.040	0.043
	Pot	0.035	0.034	0.036	0.043
-ln L: Length		-55.85	-37.90	-29.72	-13.85
-ln L: CPUE		-8.577	-7.872	-5.344	-9.427
-ln L: Recruitment		-26.45	-27.70	-27.74	-29.61
-ln L: Total		-90.87	-73.47	-62.80	-52.89
MSY (tonnes)	Longline	5 585†	3 519	1 852	1 261
	Pot	6 204	3 958	2 072	1 407
MSYL	Longline	0.244	0.242	0.244	0.252

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

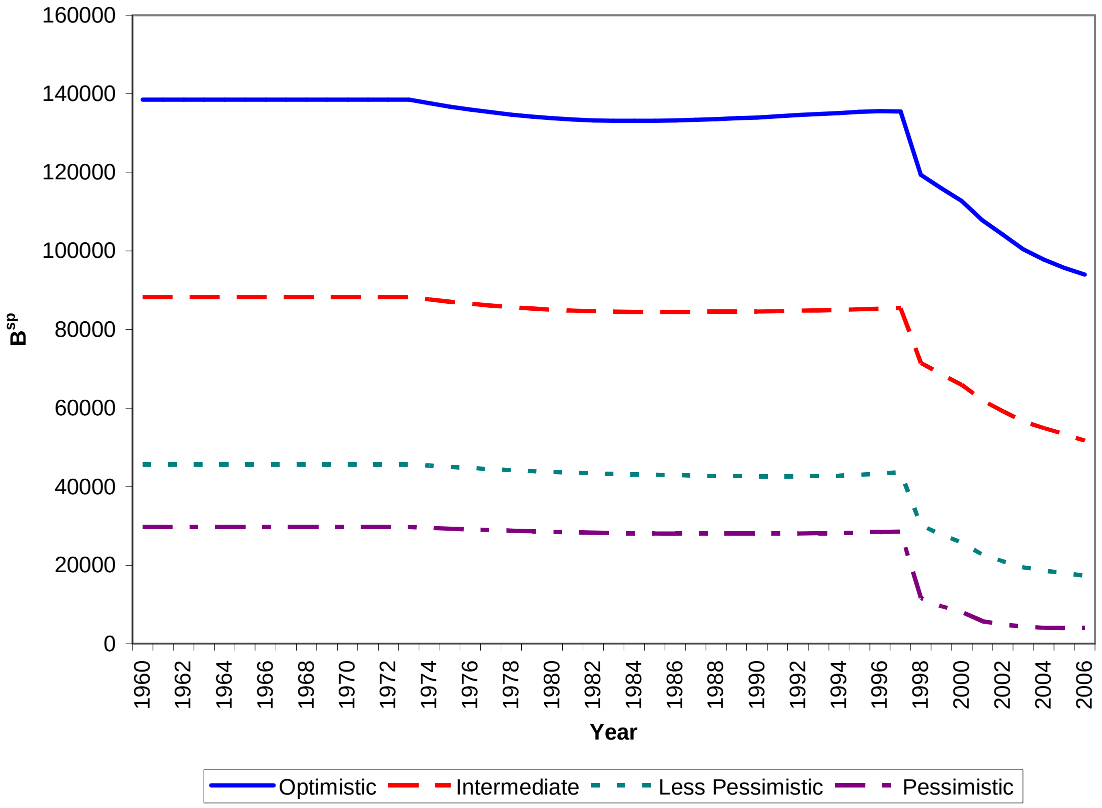

Figure A.1. Spawning biomass estimates when recruitment variability is allowed. Estimates are given for four scenarios: the “Optimistic” scenario when the 1997-98 CPUE indices are omitted, only the 2001-06 length data are fitted and a relative weight of 0.2 is applied to the catch-at-length data; the “Intermediate” scenario when the 1997-98 CPUE indices are omitted, only the 2003-06 length data are fitted and a relative weight of 0.2 is applied to the catch-at-length data; the “Less Pessimistic” scenario when all the CPUE but only the last four years of length data are fitted and a relative weight of 0.165 is applied to the catch-at-length data; and the “Pessimistic” scenario when the same data as for the “Less Pessimistic” scenario are considered in the population model fitting process, but a relative weight of 0.1 is applied to the catch-at-length data. All results shown assume a cetacean depredation factor z = 1, i.e. recent loses to cetacean depredation are equal to the landed longline catch.

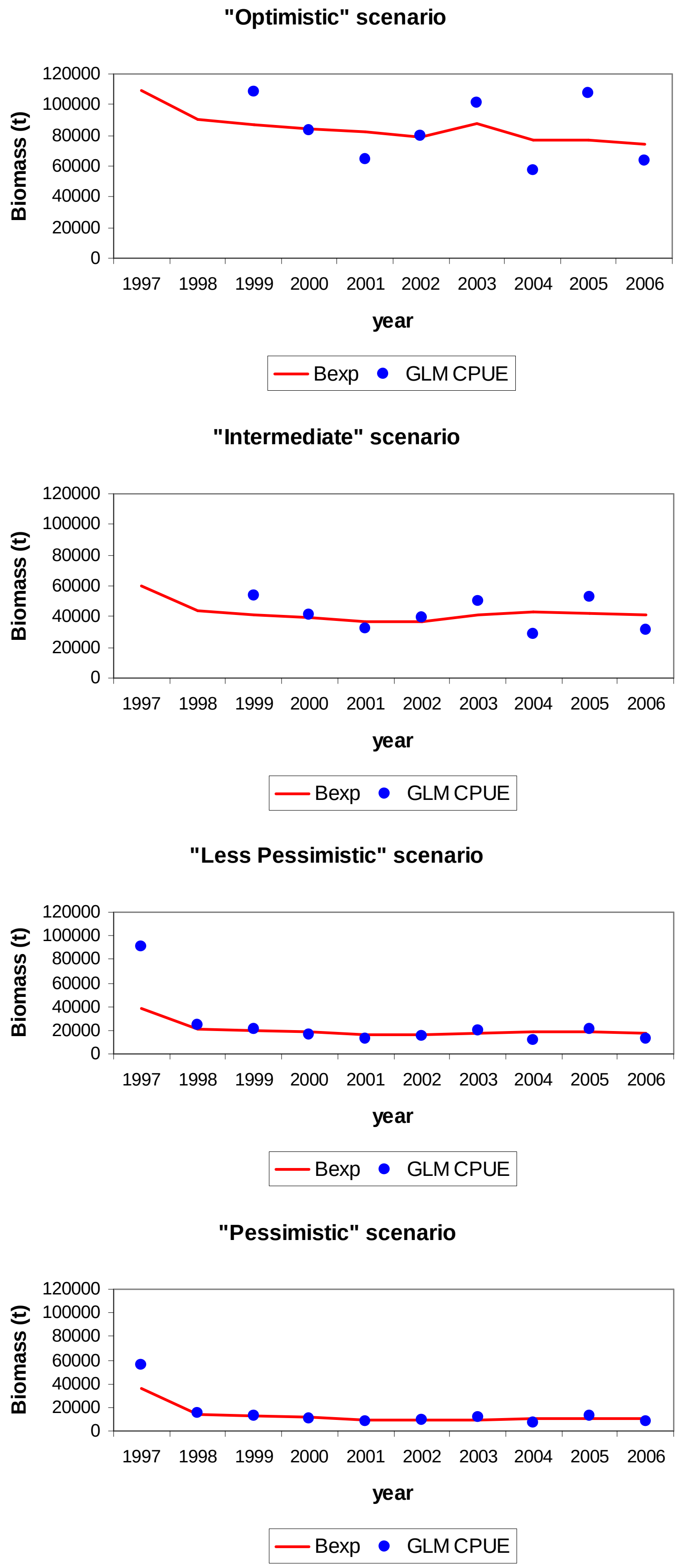

Figure A.2. Longline fishery exploitable biomass and the GLM-standardised CPUE indices to which the population model is fit (divided by the estimated catchability *q* to express them in biomass units) for the "Optimistic", "Intermediate", "Less Pessimistic" and "Pessimistic" scenarios. All results shown assume a cetacean depredation factor z = 1, i.e. recent loses to cetacean depredation are equal to the landed longline catch. Note that only the CPUE indices fitted for the scenario in question are shown.

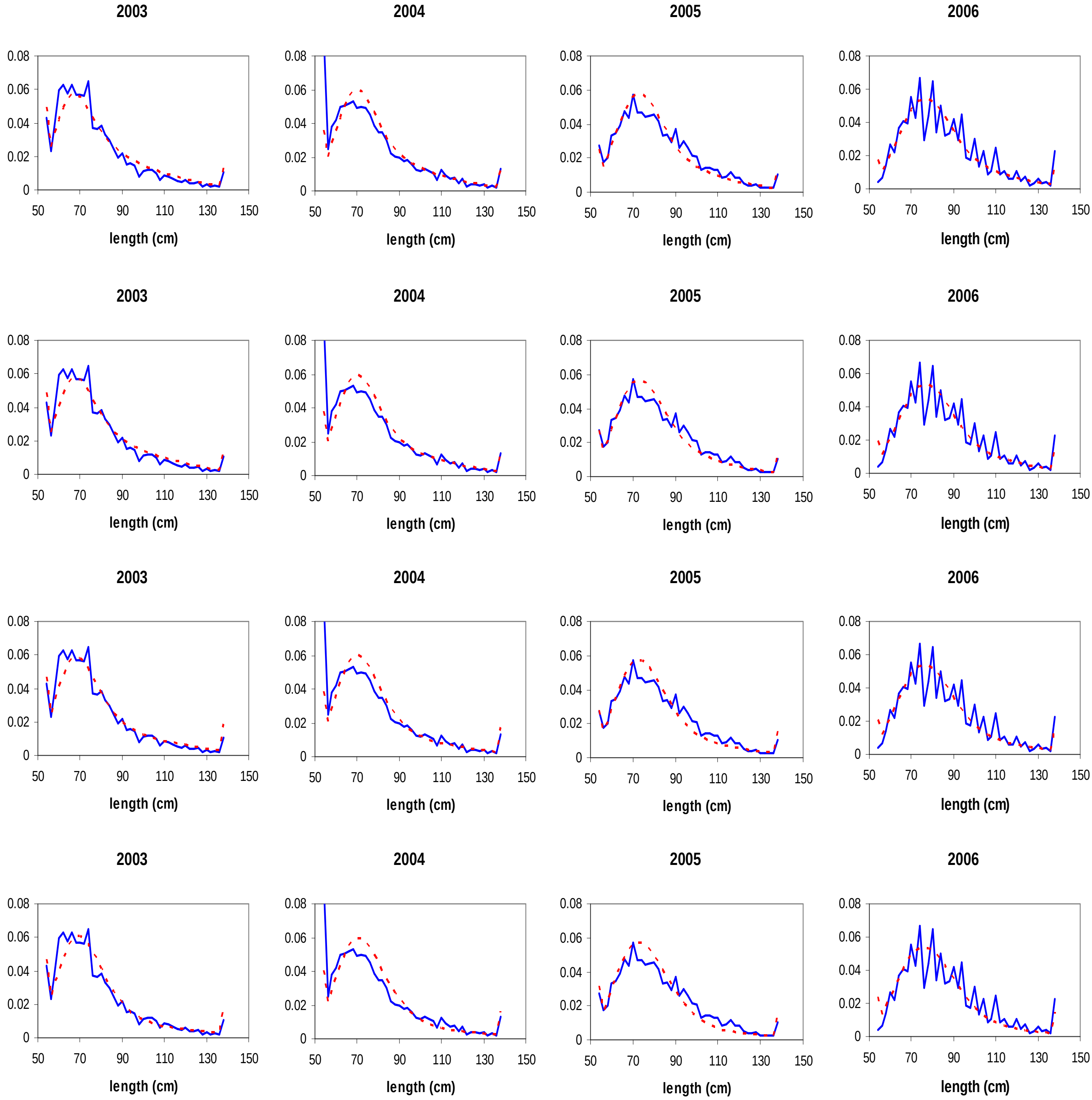

Figure A.3. Observed (line) and assessment predictions for the annual catch-at-length proportions in the longline fishery for the years 2003 to 2006 for the “Optimistic” (top), “Intermediate” (second row), “Less Pessimistic” (third row) and “Pessimistic” (bottom) scenarios. Note that lengths below 54 and above 138 cm are combined into minus- and plus-groups. All results shown assume a cetacean depredation factor z = 1, i.e. recent loses to cetacean depredation are equal to the landed longline catch.

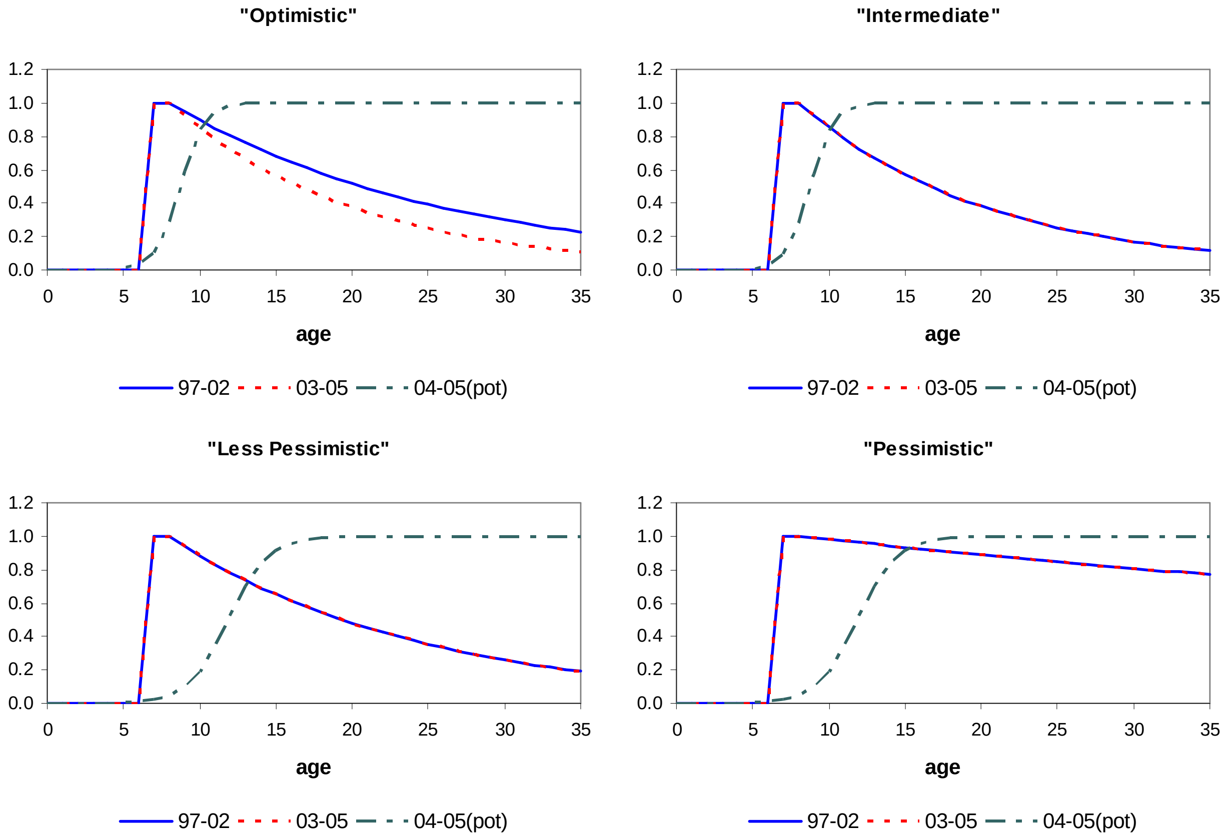

Figure A.4. Estimated selectivity curves for the periods 1997–2002 and 2003–2006 for the longline fishery, and for the period 2004-2005 for the pot fishery (note that the nearly flat selectivity at large ages for this fishery is as estimated; it is not an input assumption). Curves are shown for the “Optimistic”, “Intermediate”, “Less Pessimistic” and “Pessimistic” scenarios.