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

A. Brandão and D.S. Butterworth

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

ABSTRACT

Three Operating Models (OMs) reflecting an "Optimistic", "Intermediate" 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. This MP provides encouraging performance over the wide range of scenarios considered, increasing catches substantially if the resource is above MSYL, while increasing more slowly if the resource is heavily depleted while nevertheless securing stock increase with high probability.

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 have been 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 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.

Brandão and Butterworth (2006a) considered stochastic projections under the "Optimistic" and "Pessimistic" scenarios to investigate the performance of a simple control rule for computing future TACs. However, the OMs they considered did not take the pot fishery into account and treated pot catches as if they had the same selectivity as the longline fishery. In this paper, OMs are developed that take into account data from both the past longline and pot fisheries, and in which different scenarios for the current status of the toothfish fishery are reflected. These OMs are used to generate future data to test a candidate MP that takes 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 TAC recommendations for the toothfish resource in the Prince Edward Islands vicinity.

OPERATING MODELS AND PROJECTIONS

Assessment component

Three Operating Models (OMs) reflecting an "Optimistic", an "Intermediate" 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 candidate MPs. These OMs are derived 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. A further OM ("Basecase") in which all the CPUE and length data are considered in the population model fitting process, is also utilised. This OM reflects the population assessment model of Brandão and Butterworth (2006b) used for management advise at present, with the exception that a relative weight (w_{len}) of 0.186 (instead of 1.0 as in Brandão and Butterworth (2006b)) has been applied to the catch-at-length contribution to the log-likelihood. This value of w_{len} is given by 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. The OMs developed are Age-Structure 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 OMs differentiate the selectivities for the longline and pot fisheries.

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, in this paper 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 $\omega_{y'}$ factors distributed N(0, σ_R^2), where $\sigma_R = 0.6$. 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. Thus, for ages 1–7, the numbers-at-age are given by $N_{y',a}e^{\left(\omega_{y'}-\sigma_R^2/2\right)}$. The catches-at-age ($C_{y'-1,a}$) are obtained from equation (A1.4). 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 (A1.34), which allows for fluctuations about this relationship. These fluctuations are computed for each future year simulated by generating $\zeta_{y'}$ factors also distributed N(0, σ_R^2), where $\sigma_R = 0.6$.
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 (A1.24); then a 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 (equation (A1.26)), as is q (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 are used to compute future TACs ($TAC_{y'+1}$) from the TACs for the current year ($TAC_{y'}$) as described in the next section.
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 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:
$$\bar{\ell}_{y'} = \frac{\sum_{\ell} \ell C_{y',\ell}}{\sum_{\ell} C_{y',\ell}} = \frac{\sum_{\ell} \ell \left(\sum_a C_{y',a} A_{a,\ell}\right)}{\sum_{\ell} C_{y',\ell}},$$
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'*, and

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).

For these initial evaluations, the future observed $\bar{\ell}_{y'}$ values have been taken to equal the model values exactly (i.e. no observation error is considered for these data).

6. Steps (2)–(5) are repeated for each future year considered.
7. This projection procedure is replicated 100 times, to reflect the probability distributions for projection results arising from uncertainties in future recruitment and observation errors for CPUE.

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 to have catches increase even though the biomass drops to some extent). The mean length of catches is used 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 increase). If the CPUE is decreasing and the mean length is below ℓ *, then the TAC decreases (again using both values to set 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 value of the mean length) but only if the CPUE trend is increasing.

Figure 2 shows typical deterministic projections for CPUE, CPUE slope and the mean length of the catch for the four operating models obtained under one particular control rule. These behave as anticipated under the reasoning described above. Thus the candidate MP investigated in this paper is one where the TAC is modified in synchrony with the trend in the CPUE abundance index and the value of the mean length of the longline catches, given by:

$$TAC_{y+1} = TAC_y \left[1 + \Psi\right] \tag{1}$$

where:

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

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 *mean*ℓ is the average of mean length ($\bar{\ell}_{y'}$) over the last 5 years. The λ, μ and ℓ * are control parameters.

RESULTS

Experimentation with different values of the three control parameters led to the selections $\lambda = 1$, $\mu = 3$ and $\ell^* = 80$ for the MP of equation (1). Testing this MP for the four scenarios yields the results shown in Figure 3, some of which are listed in Table 1b. 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 desirably low probability of any further decline.

Robustness tests

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. Two robustness tests were therefore considered in which future selectivity changes were examined. 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 targeted more smaller fish to a greater extent. Figure 4 and Table 1a show the performance of the MP under the different OMs. The second robustness test, considered the opposite scenario in which the fishery targeted more bigger fish and the age at 50% selectivity was set at 7.5 years from 2010. The results are shown in Figure 5 and Table 1c. 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 taking the change into account when future catch-at-length data were generated.

A change in selectivity to smaller fish decreases the catches under the "Optimistic" scenario. Under the "pessimistic" scenario, a change in selectivity to larger fish lowers the recovery rate of the stock; however, the lower 5 percentile for depletion at the end of twenty years remains higher than the depletion at present.

CONCLUDING REMARKS

Clearly more extensive robustness testing is required before the MP of equation (1) could be applied in practice to provide TAC recommendations. Nevertheless it is encouraging that the relatively simple approach considered is able to provide sensible performance over a wide range of scenarios, increasing catches substantially if the resource is above MSYL, while increasing more slowly if the resource is heavily depleted while nevertheless securing stock increase with high probability.

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REFERENCES

Brandão, A., Watkins, B.P., Butterworth, D.S. and Miller, D.G.M. 2002a. A first attempt at an assessment of the Patagonian toothfish (*Dissostichus eleginoides*) resource in the Prince Edward Islands EEZ. *CCAMLR Science* 9: 11-32.

Brandão, A. and Butterworth, D.S. 2002b. An updated assessment of the toothfish (*Dissostichus eleginoides*) resource in the Prince Edward Islands vicinity and extensions taking commercial catch-at-length data into account. Commission for the Conservation of Antarctic Marine Living Resources Document: WG-FSA-02/76.

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

Brandão, A. and Butterworth, D.S. 2004a. Variants of the ASPM assessment of the toothfish (*Dissostichus eleginoides*) resource in the the Prince Edward Islands vicinity which attempt to reconcile CPUE and catch-at-length. Commission for the Conservation of Antarctic Marine Living Resources Subgroup on Assessment Methods Document: WG-FSA-SAM-04/12.

Brandão, A. and Butterworth, D.S. 2004b. Updated ASPM of the toothfish (*Dissostichus eleginoides*) resource in the Prince Edward Islands vicinity. Commission for the Conservation of Antarctic Marine Living Resources Document: WG-FSA-04/37.

Brandão, A. and Butterworth, D.S. 2005a. Initial development of Operating Models for testing Management Procedures for the toothfish (*Dissostichus eleginoides*) resource in the Prince Edward Islands vicinity. Commission for the Conservation of Antarctic Marine Living Resources Subgroup on Assessment Methods Document: WG-FSA-SAM-05/15.

Brandão, A. and Butterworth, D.S. 2005b. A two-fleet ASPM assessment of the toothfish (*Dissostichus eleginoides*) resource in the Prince Edward Islands vicinity. Commission for the Conservation of Antarctic Marine Living Resources Document: WG-FSA-05/58.

Brandão, A. and Butterworth, D.S. 2006a. An update on the development of a management procedure for the toothfish (*Dissostichus eleginoides*) resource in the Prince Edward Islands vicinity. Commission for the Conservation of Antarctic Marine Living Resources Subgroup on Assessment Methods Document: WG-FSA-SAM-06/12.

Brandão, A. and Butterworth, D.S. 2006b. 2006 assessment of the toothfish (*Dissostichus eleginoides*) resource in the Prince Edward Islands vicinity. Commission for the Conservation of Antarctic Marine Living Resources Document: WG-FSA-05/58.

CCSBT (Commission for the Conservation of the Southern Bluefin Tuna). 2003. Report of the Second Meeting of the Management Procedure Workshop. Queenstown, New Zealand, March 2003.

Table 1. Projected median average annual legal (longline) catches of toothfish (in tonnes) for the period 2007 to 2026 and the median exploitable biomass depletion of at the start of the year 2026 under the MP considered (equation (1)). The 90% percentiles are also shown. These results assume illegal (longline) catches will continue in future at a constant rate of 150 tonnes per year.

a) Age at 50% selectivity changed to 5.5 years from 2010.

	"Optimistic"	**"Intermediate"**	**"Pessimistic"**	**"Basecase"**
$\bar{C}_{2007-2026}$	587 (461; 745)	515 (426; 649)	499 (420; 631)	537 (437; 677)
B^{exp}_{2026}/K^{exp}	0.737 (0.570; 0.985) [2006 value: 0.618]	0.572 (0.436; 0.770) [2006 value: 0.306]	0.299 (0.195; 0.511) [2006 value: 0.079]	0.752 (0.568; 0.951) [2006 value: 0.490]

b) Age at 50% selectivity estimated (in the region of 6.5 years).

	"Optimistic"	**"Intermediate"**	**"Pessimistic"**	**"Basecase"**
$\bar{C}_{2007-2026}$	1 034 (755; 1 198)	718 (571; 878)	552 (443; 744)	859 (670; 1 041)
B^{exp}_{2026}/K^{exp}	0.727 (0.556; 0.976) [2006 value: 0.618]	0.550 (0.405; 0.752) [2006 value: 0.306]	0.282 (0.188; 0.451) [2006 value: 0.079]	0.704 (0.498; 0.916) [2006 value: 0.490]

c) Age at 50% selectivity changed to 7.5 years from 2010.

	"Optimistic"	**"Intermediate"**	**"Pessimistic"**	**"Basecase"**
$\bar{C}_{2007-2026}$	1 311 (1 140; 1 377)	1 141 (896; 1 291)	736 (584; 1 000)	1 264 (1 071; 1 370)
B^{exp}_{2026}/K^{exp}	0.722 (0.553; 0.970) [2006 value: 0.618]	0.505 (0.361; 0.728) [2006 value: 0.306]	0.231 (0.107; 0.362) [2006 value: 0.079]	0.649 (0.457; 0.839) [2006 value: 0.490]

s_{CPUE}

+ λs_{CPUE}	+ $\lambda s_{CPUE} + \mu((mean\,\ell - \ell^*)/\ell^*)$
- $\lambda s_{CPUE} + \mu((mean\,\ell - \ell^*)/\ell^*)$	+ $\mu((mean\,\ell - \ell^*)/\ell^*)$

0 $mean\,\ell - \ell^*$

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 is above or below ℓ^*. The formula of the control rule to be applied is also shown in each quadrant.

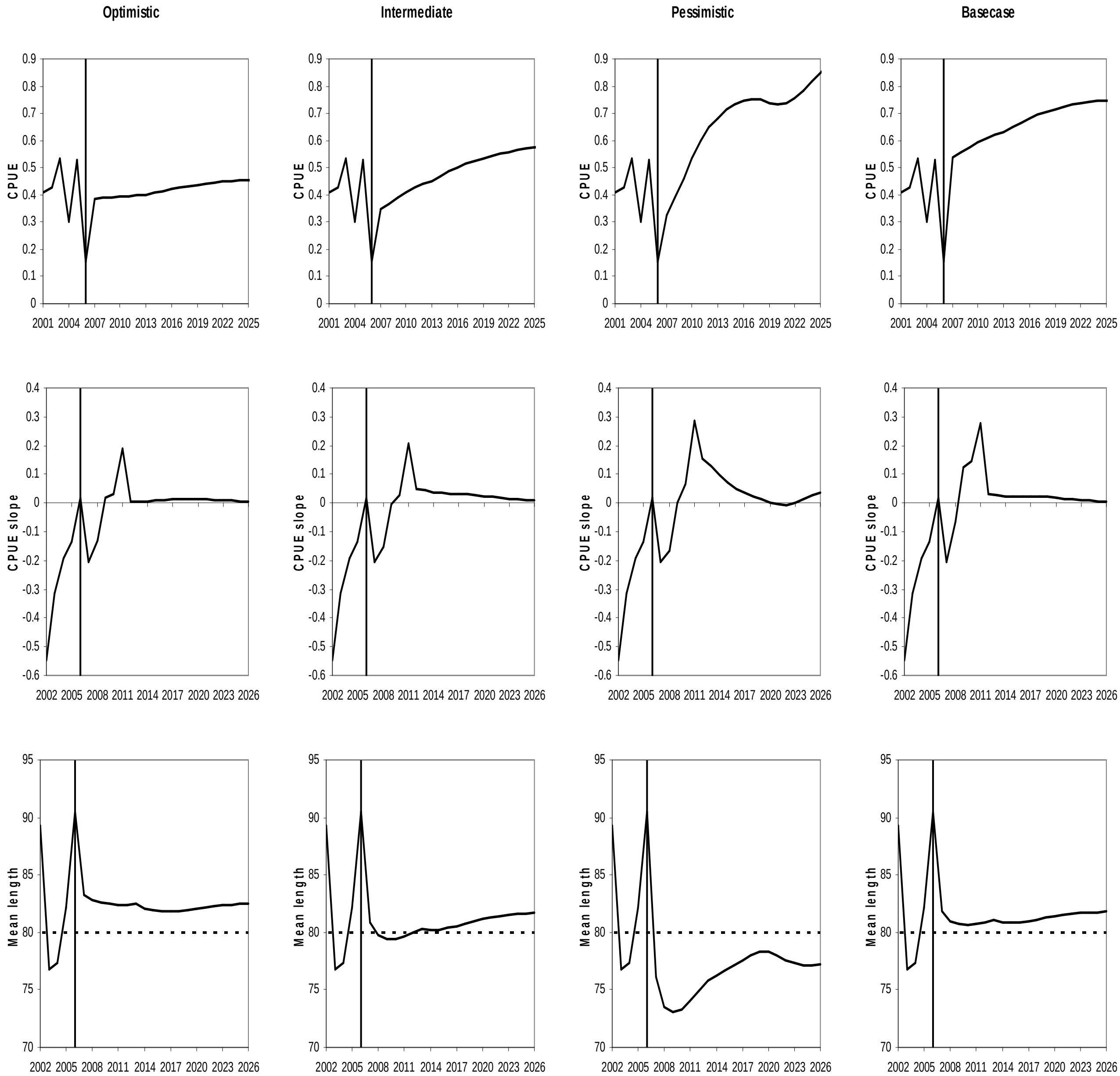

Figure 2. Deterministic projections of CPUE, CPUE slope (s_{CPUE}) and mean length trends under the "Optimistic", "Intermediate", "Pessimistic" and "Basecase" operating models (shown to the right of the vertical line). The values to the left of this line reflect past data from longline operations. The horizontal dashed line in the lowest set of plots show the value of ℓ * = 80 selected for the MP control rule.

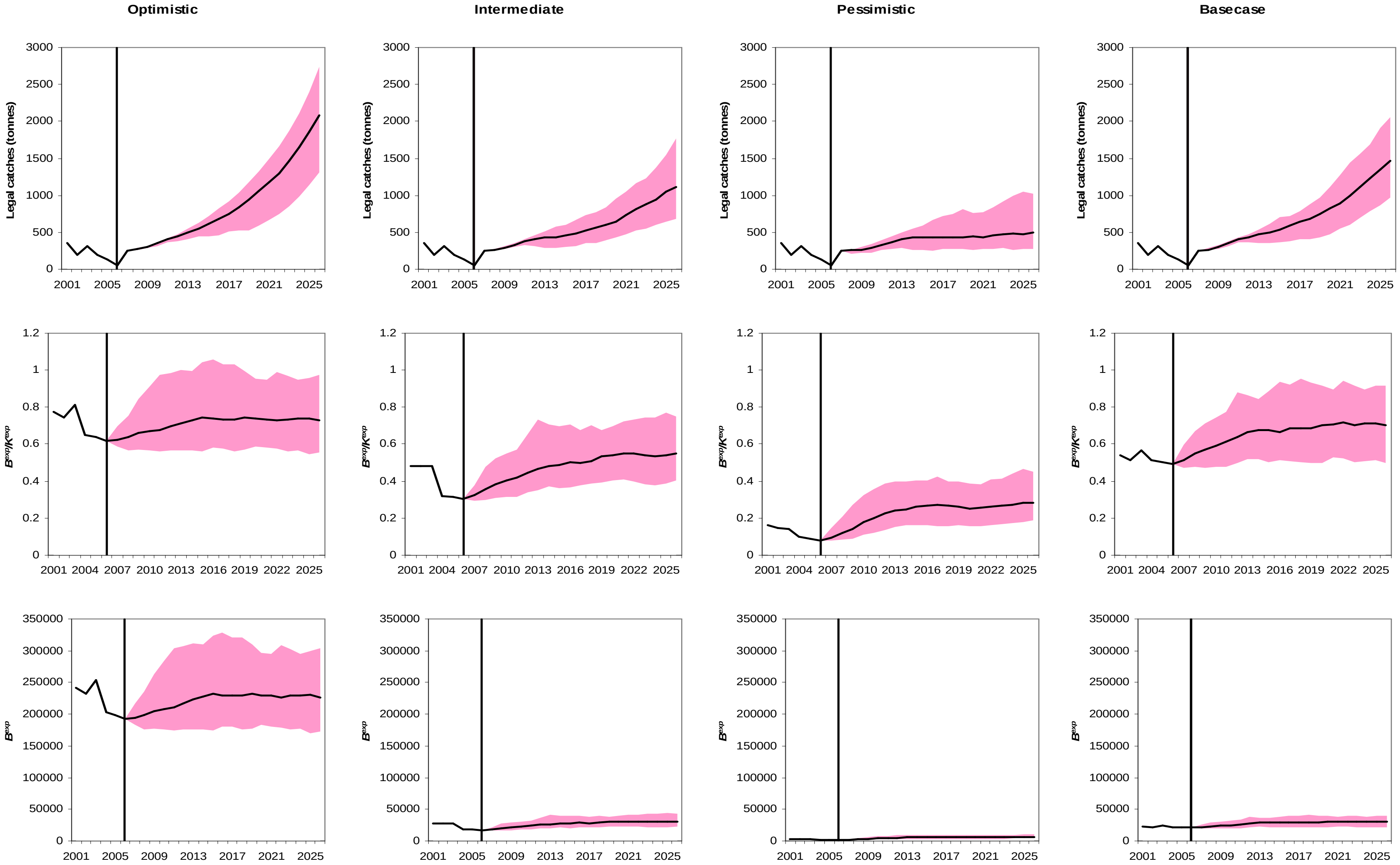

Figure 3. Median trajectories of legal annual catches by longliners (in tonnes), exploitable biomass and exploitable biomass depletion under the candidate empirical MP for the "Optimistic", "Intermediate", "Pessimistic" and "Basecase" Operating Models (OMs). Projections (medians) commence to the right 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. The age at 50% selectivity is estimated for each of the OMs (and is in the region of 6.5 years).

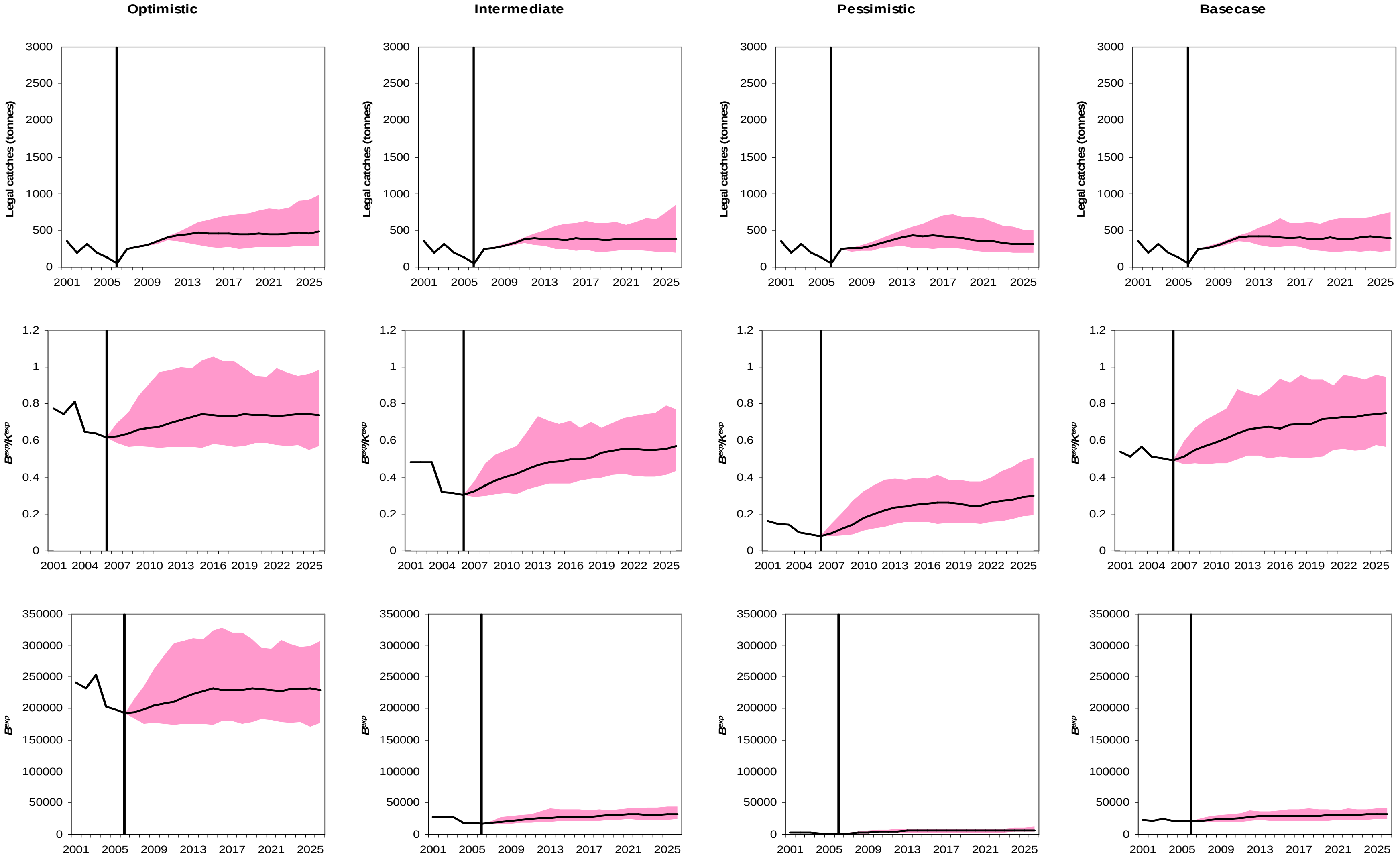

Figure 4. Median trajectories of legal annual catches by longliners (in tonnes), exploitable biomass and exploitable biomass depletion under the candidate empirical MP for the “Optimistic”, “Intermediate”, “Pessimistic” and “Basecase” Operating Models (OMs). Projections (medians) commence to the right 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. The age at 50% selectivity is fixed to be 5.5 years from the year 2010.

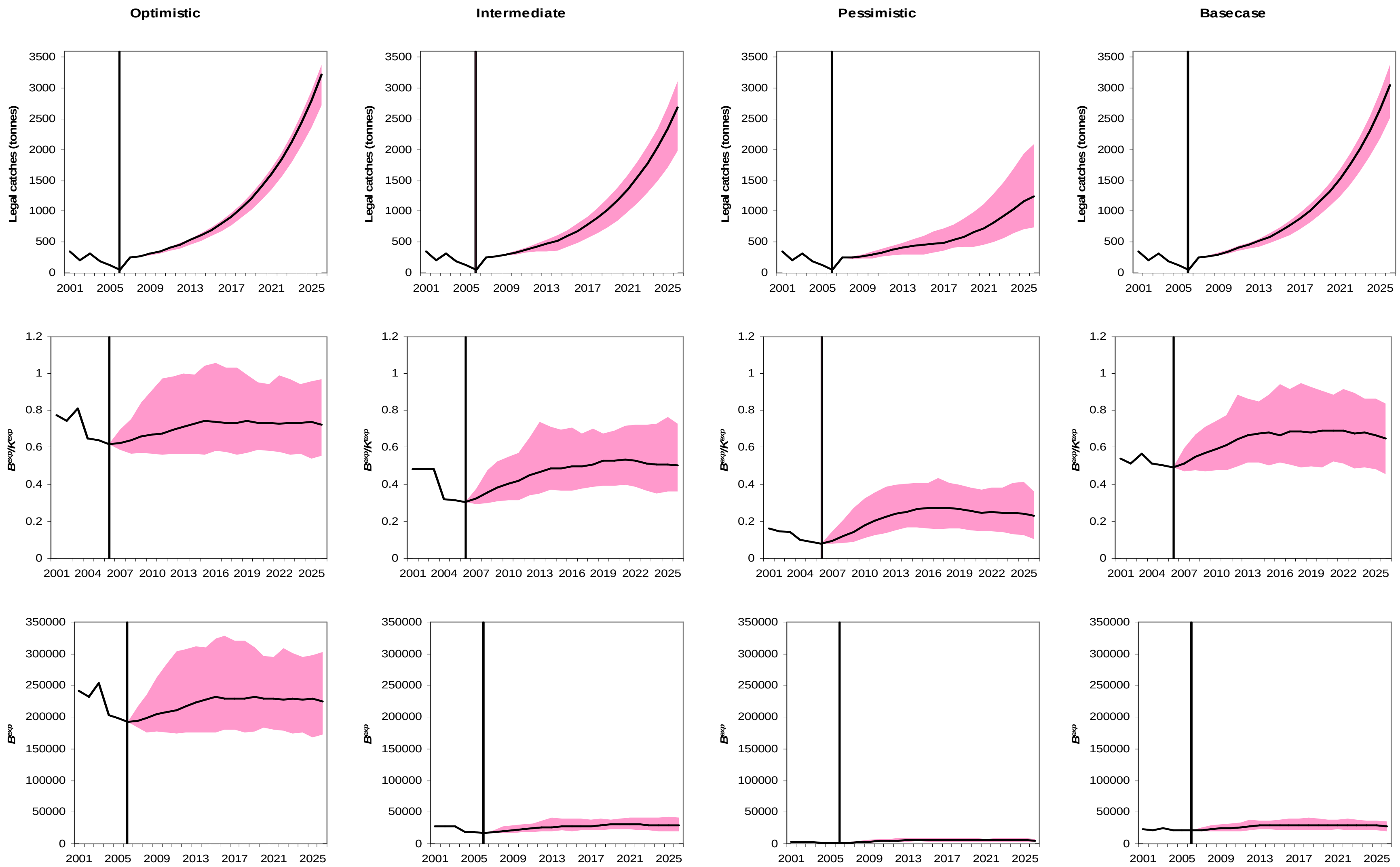

Figure 5. Median trajectories of legal annual catches by longliners (in tonnes), exploitable biomass and exploitable biomass depletion under the candidate empirical MP for the “Optimistic”, “Intermediate”, “Pessimistic” and “Basecase” Operating Models (OMs). Projections (medians) commence to the right 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. The age at 50% selectivity is fixed to be 7.5 years from the year 2010.

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. The first three are fitted to subsets of the data and reflect “Optimistic”, “Intermediate” and “Pessimistic” scenarios with the first and last corresponding to a resource respectively well above and well below MSYL. The final “Basecase” model reflects a fit to all the available CPUE and catch-at-length distribution data.

METHODOLOGY

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

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

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

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

where:

- $N_{y,a}$ is the number of toothfish of age *a* at the start of year *y*,
- $C_{y,a}$ is the number of toothfish of age *a* taken by the fishery in year *y*,
- $R(B^{sp})$ is the Beverton-Holt stock-recruitment relationship described by equation (A1.10) below,
- B^{sp} is the spawning biomass at the start of year *y*,
- M is the natural mortality rate of fish (assumed to be independent of age), and
- m is the maximum age considered (i.e. the “plus group”).

Note that in the interests of simplicity this approximates the fishery as a pulse fishery at the start of the year. Given that toothfish are relatively long-lived with low natural mortality, such an approximation would seem adequate.

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

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

where:

$$C^f_{y,a} = N_{y,a} S^f_{y,a} F^f_y \tag{A1.5}$$

and:

- F^f_y is the proportion of the resource above age *a* harvested in year *y* by fleet *f*, and
- $S^f_{y,a}$ is the commercial selectivity at age *a* in year *y* for fleet *f*.

The mass-at-age is given by the combination of a von Bertalanffy growth equation $\ell(a)$ defined by constants ℓ_∞, κ and t_0 and a relationship relating length to mass. Note that ℓ refers to standard length.

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

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

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,

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

ω^y defines the steepness of the descending section of the selectivity curve for fish older than age a_c for year y (for all the results reported in this paper, a_c is fixed at 8 yrs).

In cases where equation (A1.9) yields a value of F_y^f > 1 for a future year, i.e. the available biomass is less than the proposed catch for that year, F_y^f is restricted to 0.9, and the actual catch considered to be taken will be less than the proposed catch. This procedure makes no adjustment to the exploitation rate ($S^f_{y,a}\ F^f_y$) 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^f_y, is computed as usual using equation (A1.9). If $F^f_y \leq 0.9$ no change is made to the computation of the total catch, C^f_y, given by equation (A1.8). If F^f_y > 0.9, compute the total catch from:

$$C^f_y = \sum_{a=0}^{m} w_a g(S^f_{y,a} F^f_y) N_{y,a} \,. \tag{A1.11}$$

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

$$S^{f*}_{y,a} = \frac{g(S^f_{y,a} F^f_y)}{F^f_y}\,, \tag{A1.12}$$

so that $C^f_y = \sum_{a=0}^{m} w_a S^{f*}_{y,a} F^f_y N_{y,a}$, 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^f_y is not bounded at one, but $g\left(S^f_{y,a} F^f_y\right) \leq 1$ hence $C^f_{y,a} = g(S^f_{y,a} F^f_y) N_{y,a} \leq N_{y,a}$ as required.

STOCK-RECRUITMENT RELATIONSHIP

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

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

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^{sp}_y, by a Beverton-Holt stock-recruitment relationship (assuming deterministic recruitment):

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

The values of the parameters α and β can be calculated given the unexploited equilibrium (pristine) spawning biomass K^{sp} and the steepness of the curve *h*, using equations (A1.15)–(A1.19) below.

If the pristine recruitment is $R_0 = R(K^{sp})$, then steepness is the recruitment (as a fraction of R_0) that results when spawning biomass is 20% of its pristine level, i.e.:

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

from which it can be shown that:

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

Rearranging equation (A1.16) gives:

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

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

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

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

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

where:

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

Past Stock Trajectory and Future Projections

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

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

which can be solved for R_0.

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

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

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

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

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

THE LIKELIHOOD FUNCTION

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

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

where

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

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

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

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

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

where:

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

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

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

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

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

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

EXTENSION TO INCORPORATE CATCH-AT-LENGTH INFORMATION

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

$$p^f_{y,a} = C^f_{y,a} \Big/ \sum_{a'} C^f_{y,a'} \,. \tag{A1.28}$$

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

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

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

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

The *A* matrix has been calculated here under the assumption that length-at-age is normally distributed about a mean given by the von Bertalanffy equation, i.e.:

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

where

N* is a normal distribution truncated at ± 3 standard deviations (to avoid negative values), and

$\theta^f(a)$ is the standard deviation of length-at-age *a* for fleet *f*, which is modelled here to be proportional to the expected length at age *a*, i.e.:

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

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

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

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

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

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 (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 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:

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

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

DATA and IMPLEMENTATION

Three OMs (one reflecting an "Optimistic", one an "Intermediate" and one a "Pessimistic" current status for the toothfish resource) have been developed and are described in the main paper. A further OM ("Basecase") which includes all available CPUE indices and length data in the population model fitting process is also utilised. 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 predation. 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. To include the CPUE for the first part year 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 3 months of the latter analysis was then used to obtain an estimated CPUE index for 2006 from the 1997–2005 standardised indices.

The values in both Table A.1 and Table A.2 make no 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 until March 2006. Table A.3 shows the basic biological updated parameter values which have been used for the latest assessment (Brandão and Butterworth, 2006b).

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 0.5.

A relative weight (w_{len}) of 0.186 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 give 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. The "Pessimistic" OM omits the catch-at-length distributions for the initial years (i.e. for 1997–2002) but includes all the CPUE indices. The "Basecase" OM is fitted to all available CPUE indices and length data.

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.

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 catches for 2006 are based upon data for part of a year only.

Year	***Legal***		***Illegal***	***Total***
	Longline fishery	**Pot fishery**		
1997	2 921.2	—	21 350	24 271.2
1998	1 010.9	—	1 808	2 818.9
1999	956.4	—	1 014	1 970.4
2000	1 561.6	—	1 210	2 771.6
2001	351.9	—	352	703.9
2002	200.2	—	306	506.2
2003	312.9	—	256	568.9
2004	194.9	72.6	156	423.6
2005	128.5	103.5	156	388.0
2006	46.6	—	156	202.6
1997–2006 total	7 685.1	176.2	26 764	34 625.3

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. The indices for 2006 are based upon data for part of a year only.

Year	**Longline fishery *CPUE***
1997	4.597
1998	1.265
1999	1.108
2000	0.676
2001	0.410
2002	0.427
2003	0.532
2004	0.302
2005	0.529
2006	0.153

Table A.3. Biological parameter values assumed for the assessments conducted, based upon the recently updated values for Subarea 48.3. Note that for simplicity, maturity is assumed to be knife-edge in age.

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

Table A.4. Estimates for a two fleet (longline and pot) model that assumes possibly different logistic commercial selectivities, 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" and "Basecase" scenarios, both these functions are estimated; for the "Pessimistic" and "Intermediate" cases, only the 2003–2006 catch-at-length data are fitted, and the associated estimated 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}^{2006}/K_{sp}) and the exploitable biomass ($B_{\exp}^{2006}$) 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 factor discussed in the text).

Parameter estimates		Model: "Optimistic" scenario (97-98 CPUE omitted; only 01-06 length data fitted)	Model: "Intermediate" scenario (97-98 CPUE omitted; only 03-06 length data fitted)	Model: "Pessimistic" scenario (all CPUE fitted; only 03-06 length data fitted)	Model: "Basecase" scenario (all CPUE and length data fitted)
K_{sp} (tonnes)		363 907	56 007	26 555	54 696
B_{sp}^{2006}/K_{sp}		0.791	0.468	0.096	0.534
$B_{\exp}^{2007}$ (tonnes)	Longline	193 051	56 590	22 591	42 753
	Pot	385 418	72 812	34 473	70 629
B_{sp}^{1997}/K_{sp}		0.985	0.926	0.914	1.012
σ_{CPUE}	Longline	0.472	0.407	0.309	0.663
σ_R		0.500††	0.500††	0.500††	0.500††
a_{50}^{97-02} (yr)		6.536	—	—	6.519
δ^{97-02} (yr^{-1})		0.028	—	—	0.027
ω^{97-02} (yr^{-1})		0.056	—	—	0.069
a_{50}^{03-06} (yr)	Longline	6.452	6.518	6.545	6.502
	Pot	8.304	8.210	8.238	8.333
δ^{03-06} (yr^{-1})	Longline	0.031	0.028	0.028	0.029
	Pot	0.598	0.460	0.472	0.569
ω^{03-06} (yr^{-1})	Longline	0.094	0.089	0.077	0.087
	Pot	0.000	0.000	0.000	0.000
β		0.130	0.130	0.126	0.127
σ_{len}	Longline	0.038	0.042	0.042	0.040
	Pot	0.035	0.032	0.034	0.033
-ln *L*: Length		-49.41	-35.36	-34.48	-72.39
-ln *L*: CPUE		-2.012	-3.188	-6.752	0.892
-ln *L*: Recruitment		-27.41	-28.72	-24.20	-21.53
-ln *L*: Total		-78.84	-67.27	-65.44	-93.02
MSY (tonnes)	Longline	14 612†	1 873	903	2 187†
	Pot	16 210	2 494	1 183	2 439

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

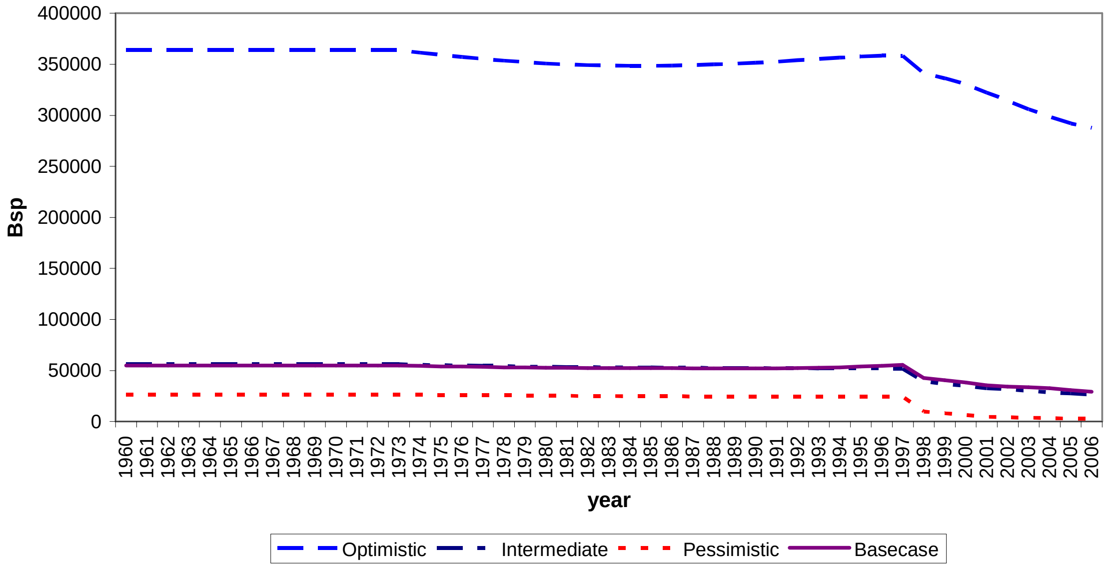

Figure A.1. Spawning biomass estimates when recruitment variability is allowed. Estimates are given for four scenarios: the "Optimistic" scenario when the 1997-98 CPUE indices are omitted and only the 2001-06 length data are fitted, the "Intermediate" scenario when the 1997-98 CPUE indices are omitted and only the 2003-06 length data are fitted, the "Pessimistic" scenario when all the CPUE but only the last four years of length data are fitted, and the "Basecase" scenario when all CPUE indices and all length data are considered in the population model fitting process.

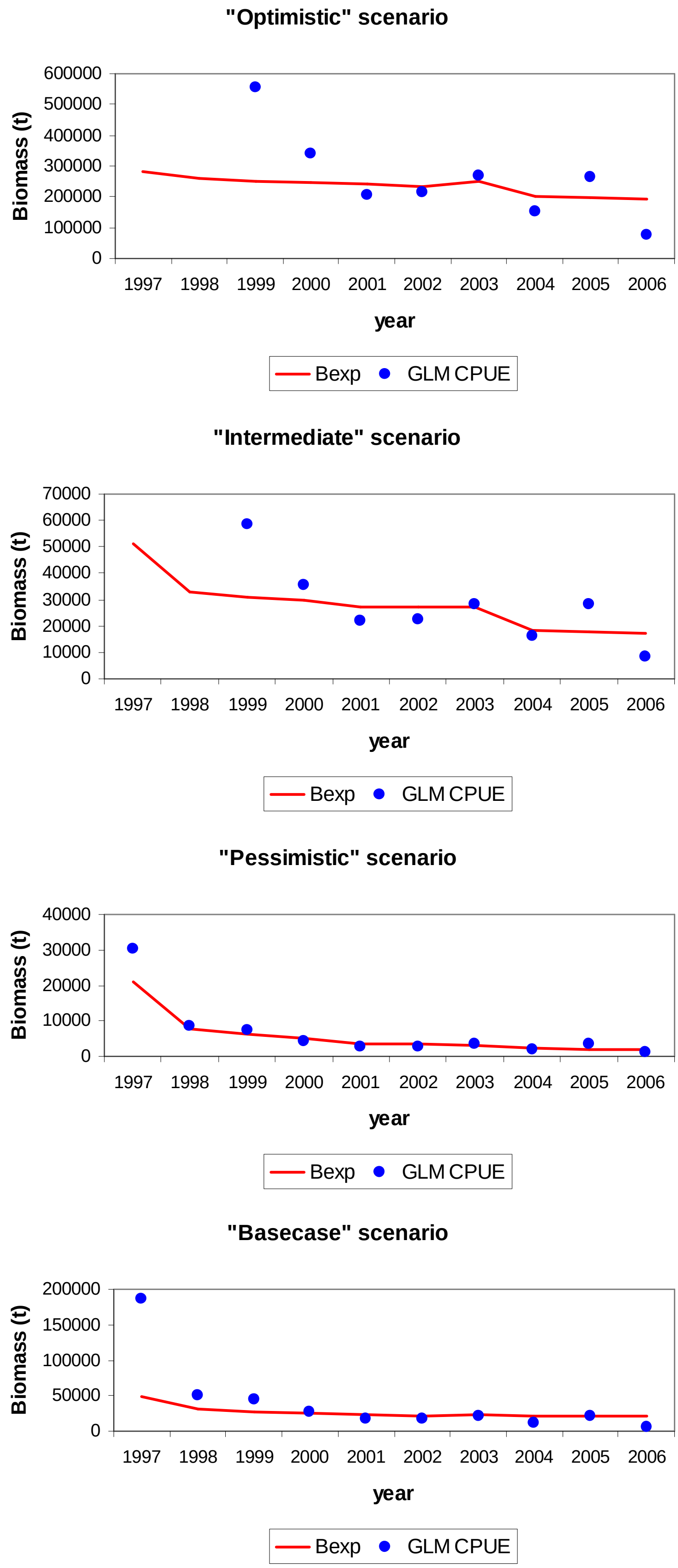

Figure A.2. Longline fishery exploitable biomass and the GLM-standardised CPUE indices to which the population model is fit (divided by the estimated catchability *q* to express them in biomass units) for the “Optimistic”, “Intermediate”, “Pessimistic”, and “Basecase” scenarios. Note the different biomass scales for the four plots, and that only the CPUE indices fitted for the scenario in question are shown.