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

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ABSTRACT

Two Operating Models (OMs) reflecting an “Optimistic” and a “Pessimistic” current status for the toothfish resource in the Prince Edward Islands region that were developed last year are updated given further data. These models are for use for initial trials of candidate Management Procedures (MPs) which could provide future TAC recommendations for this resource. Deterministic projections under a constant future catch suggest that the two scenarios will only be qualitatively distinguished in the short-term by an increase in the mean length of longline-caught toothfish over the next five years for the “Pessimistic”, but not the “Optimistic” case. Accordingly the performance of a simple MP control rule based upon recent trends in both CPUE and this mean length is investigated. This MP is able to secure a faster increase in the TAC for the “Optimistic” case, and some recovery in abundance for the “Pessimistic” scenario, but neither is as appreciable as one might wish. Suggestions for future work are made.

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.

In this paper, the "Optimistic" and "Pessimistic" OMs developed by Brandão and Butterworth (2005a) are first updated by refitting them given the further resource monitoring data now available for 2004 and 2005. The deterministic trends in CPUE and mean length of the catch suggested by projections of these two operating models under constant future catches are then used to motivate a simple form of control rule for computing future TACs. Stochastic projections under this rule, which take account of future fluctuations in recruitment and observation error in future CPUE data, are then used to preliminarily investigate whether such an approach can generate increasing catches for the "Optimistic" scenario, while at the same time ensuring some recovery in abundance for the "Pessimistic" scenario.

OPERATING MODELS AND PROJECTIONS

Assessment component

Two Operating Models (OMs) developed by Brandão and Butterworth (2005a), one reflecting an "Optimistic" and the other 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. The OMs developed are Age-Structure Production Models (ASPM) and the methodology applied to fit ("condition") these models to updated data together with the associated results are given in Appendix 1.

Projections component

The MP investigated here assumes that commercial longline CPUE and catch-at-length data will continue to be available annually. The evaluation of the MP requires the simulation of such future 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' = 2006) are estimated by applying equations (A1.1)–(A1.3). 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 (see Figure 1). 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 distributed N(0, σ_R^2), where $\sigma_R = 0.6$.

2. Future spawning and exploitable biomasses are calculated using equations (A1.13) and (A1.22). Given the exploitable biomass, the expected CPUE abundance index $I_{y'}^{CPUE}$ is first generated using equation (A1.23); 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 by the operating model (equation A1.25) as is q (equation A1.24).

3. The TAC for the starting year 2006 (TAC_{2006}) is set to be 250 tonnes. For future years (i.e. 2007, 2008, etc. for year y'), the generated CPUE abundance indices and the mean length ($\bar{\ell}_y$ described below) 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 $C_{y',a}$, the mean length ($\bar{\ell}_{y'}$) of toothfish for year y' 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)),

$C_{y',\ell}$ is the catch-at-length, and

ℓ is the length class (where the minus group is 54 cm and the plus group is 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 considered).

6. Steps (2)–(5) are repeated for each future year required.
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.

RESULTS AND DISCUSSION

Figure 2 shows deterministic projections for CPUE and the mean length of the catch for both "Optimistic" and "Pessimistic" operating models for the case of a fixed future annual catch of 250 tonnes. An immediate difficulty in formulating an MP which is evident from these plots is the small upward trend in CPUE for the "Optimistic" scenario, which hence seems unlikely to provide any signal of the much larger yields possible in this case. The mean length projections seem more promising as a basis to discriminate between the two scenarios, as the "Pessimistic" case shows an appreciable upward trend for the next five years which is not evident for the "Optimistic" operating model.

Normally a first candidate investigated for a simple MP is one where the TAC is modified in synchrony with the trend in a resource abundance index (such as CPUE), e.g.:

$$TAC_{y+1} = TAC_y \left[1 + \lambda s_{CPUE}\right] \tag{1}$$

where s_{CPUE} is the slope of a log-linear regression of the abundance index against time for the last (say) 5 years and λ is a control parameter. However the observations above suggest that this alone would provide inadequate differentiation between the scenarios to secure a reasonable increase in catch over time for the "Optimistic" scenario. Equation (1) was therefore modified as follows:

$$TAC_{y+1} = TAC_y \left[1 + \lambda s_{CPUE} - \mu\left(\left(s_{mean\ell} - s^*\right)/0.1\right)\right] \tag{2}$$

where $s_{mean\ell}$ is the slope of a log-linear regression of mean length against time for the last 5 years, except that after 2010 this estimate is not updated. The μ and s^* are additional control parameters. The motivation for the additional term is to give rise to an increasing TAC trend for the "Optimistic" case for which $s_{mean\ell}$ is expected to be small so that the TAC is increased by a proportional amount of about μs^* each year. For the "Pessimistic" case, however, the positive value for $s_{mean\ell}$ counterbalances this effect, so that changes in the TAC are smaller and hence the risk of further resource depletion is reduced.

Experimentation with different values of the three control parameters led to the selections λ = 0.5, μ = 3 and s^* = 0.01 for the simple MP of equation (2). Testing this MP for the two scenarios yields the results shown in Figure 3, some of which are listed in Table 1. 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.

Viewed in more detail however, these results are not as positive as one would wish: ideally a faster TAC increase rate for the "Optimistic" scenario would be sought, but also a lower rate for the "Pessimistic" case to allow more recovery. A further complication arises if illegal catches continue at their current estimated levels of some 150 tonnes per year (see Figure 4 and Table 2). This would make very little difference to results for the "Optimistic" scenario, but in the "Pessimistic" case recovery is very slight in median terms, and there is some probability of further resource decline.

FUTURE WORK

Clearly the results above are very preliminary. MP testing needs to be conducted across a much wider range of scenarios for the current status of the population and other aspects of its dynamics. The OMs need to be updated to take account of data available for the pot fishery (Brandão and Butterworth 2005a), and also of estimation error when fitted to the data ("conditioned") under various assumptions.

It would be surprising if the simple empirical approach for an MP of equation (2) stands scrutiny under more thorough testing – its primary intent here was to serve an illustrative purpose. However, it is not immediately obvious that an MP based on fitting a population model to the available data is going to perform much better, given the lack of contrast evident in the projections for CPUE and mean length for the extremes of the "Optimistic" and "Pessimistic" scenarios, as shown in Figure 2. The core distinction between these two scenarios is the order of magnitude difference in current absolute abundance that they represent; any initiative that could improve current knowledge about the absolute scale of this abundance would clearly also be able to enhance the performance of any MP.

ACKNOWLEDGEMENTS

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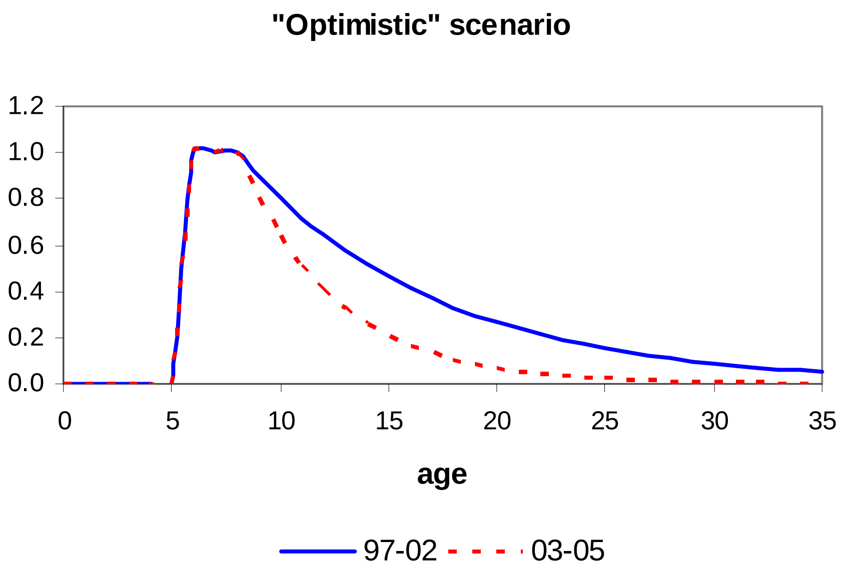
Table 1. Projected median average annual legal catches of toothfish (in tonnes) for the period 2006 to 2025 and the median exploitable biomass depletion of at the start of the year 2025 under the simple MP considered (equation (2)). The 90% percentiles are also shown. These results assume no illegal catches in future.

	"Optimistic"	**"Pessimistic"**
$\bar{C}_{2006-2025}$	403 (367, 448)	297 (276; 327)
B^{exp}_{2025}/K^{exp}	0.652 (0.463; 0.930) [2005 value: 0.510]	0.231 (0.165; 0.317) [2005 value: 0.091]

Table 2. Projection results as for Table 1, but here for the case where illegal catches continue at a constant rate of 150 tonnes per year.

	"Optimistic"	**"Pessimistic"**
$\bar{C}_{2006-2025}$	403 (366, 448)	275 (249; 311)
B^{exp}_{2025}/K^{exp}	0.644 (0.457; 0.921) [2005 value: 0.510]	0.114 (0.057; 0.178) [2005 value: 0.091]



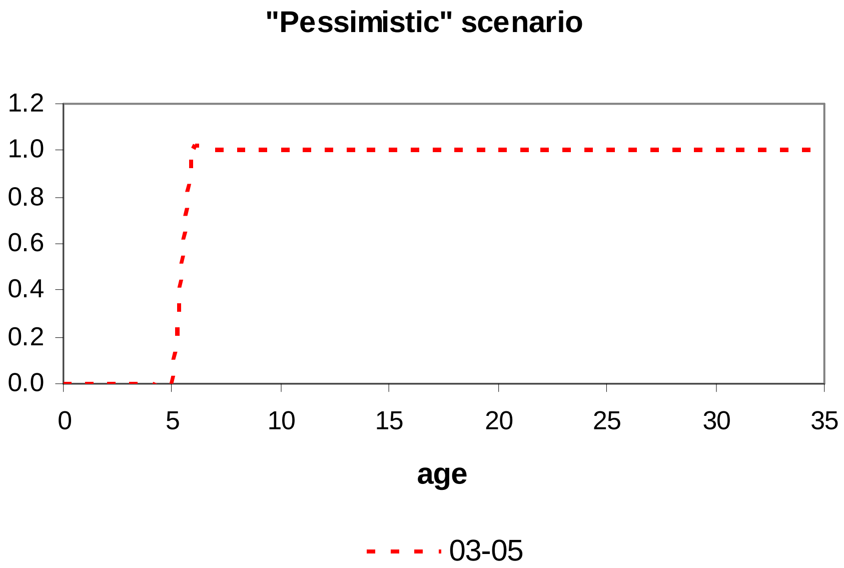


Figure 1. Estimated longline selectivity curves for the periods 1997–2002 and 2003–2005 for the "Optimistic" scenario when only the 1997 CPUE index is omitted, and the "Pessimistic" scenario when all the CPUE but only the last two years of length data are considered in the model fitting process. These selectivity curves are taken to apply in the future for the projections (the 03–05 curve in the case of the "Optimistic" scenario).

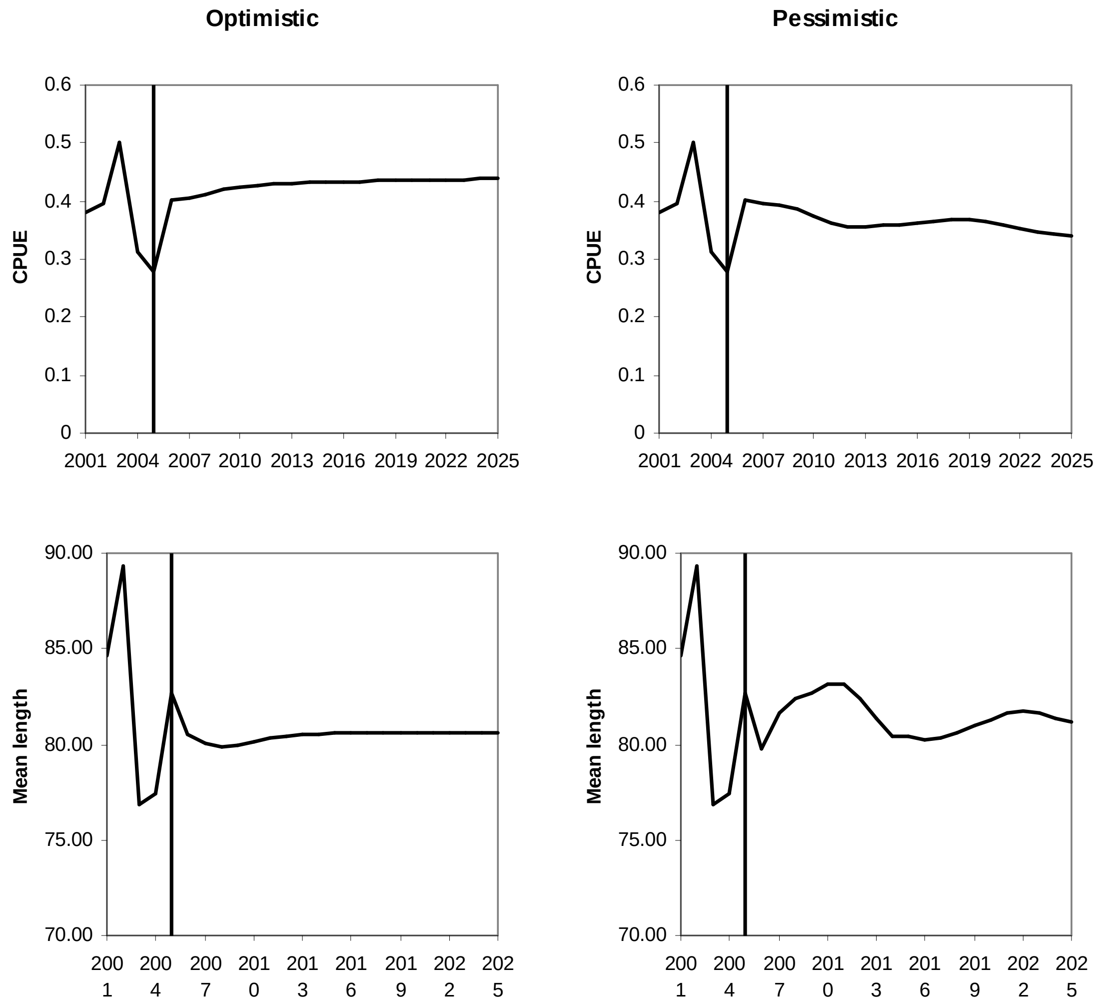


Figure 2. Deterministic projections of CPUE and mean length trends under the “Optimistic” and “Pessimistic” operating models (shown to the right of the vertical line) which assume a continuation of a fixed total catch of 250 tonnes per year. The values to the left of this line reflect past data from longline operations.

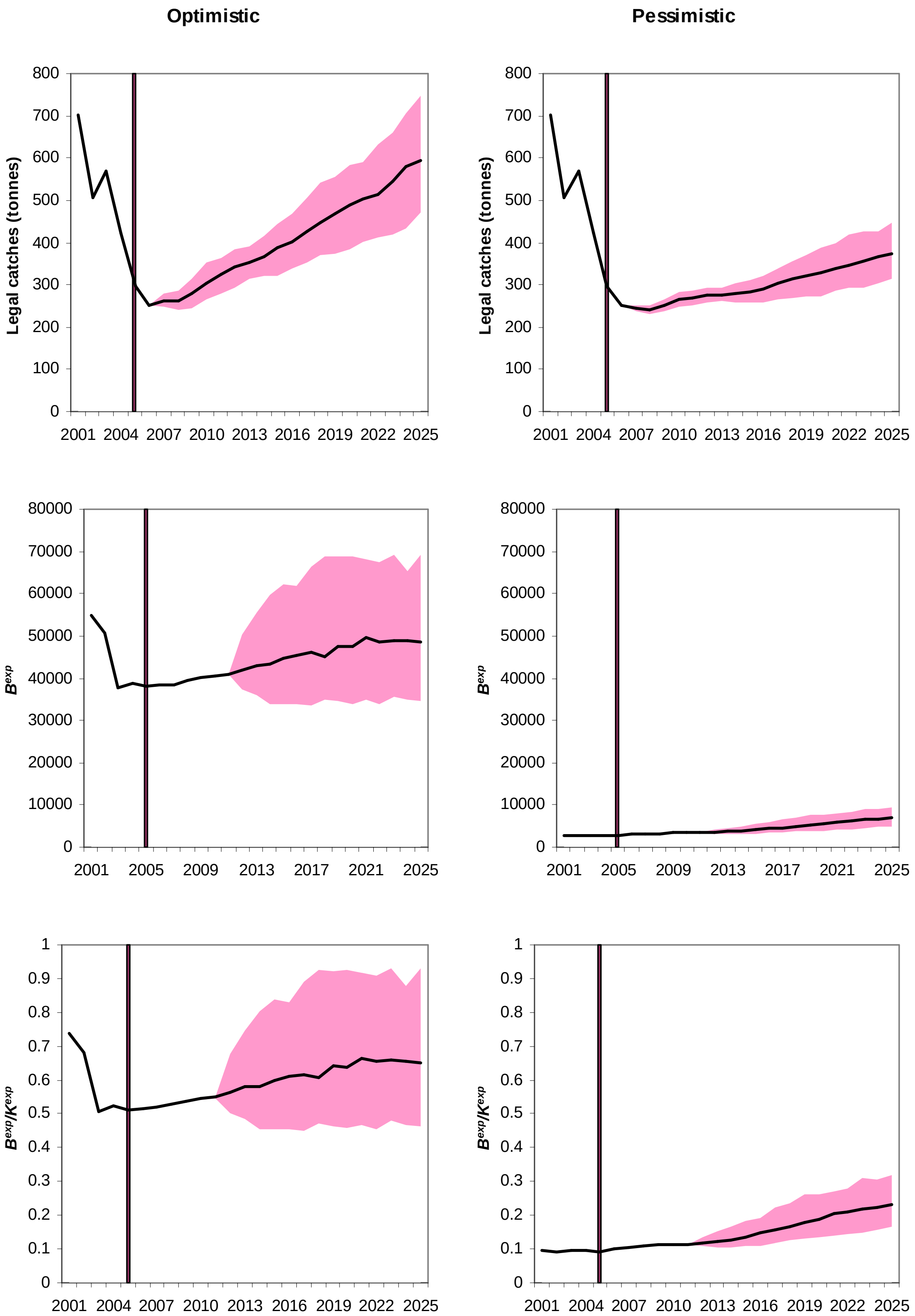


Figure 3. Median trajectories of legal annual catches (in tonnes), exploitable biomass and exploitable biomass depletion under the candidate empirical OMP for the "Optimistic" and "Pessimistic" Operating Models. Projections commence to the right of the vertical lines and the shaded areas represent 90% probability envelopes. (The reason biomass projections initially show no variation is that the two operating models are deterministic "best fits"; stochastic effects enter later only through variability in future recruitment which takes a period to propagate through to the exploitable component of the biomass shown.) These results assume no illegal catches in future.

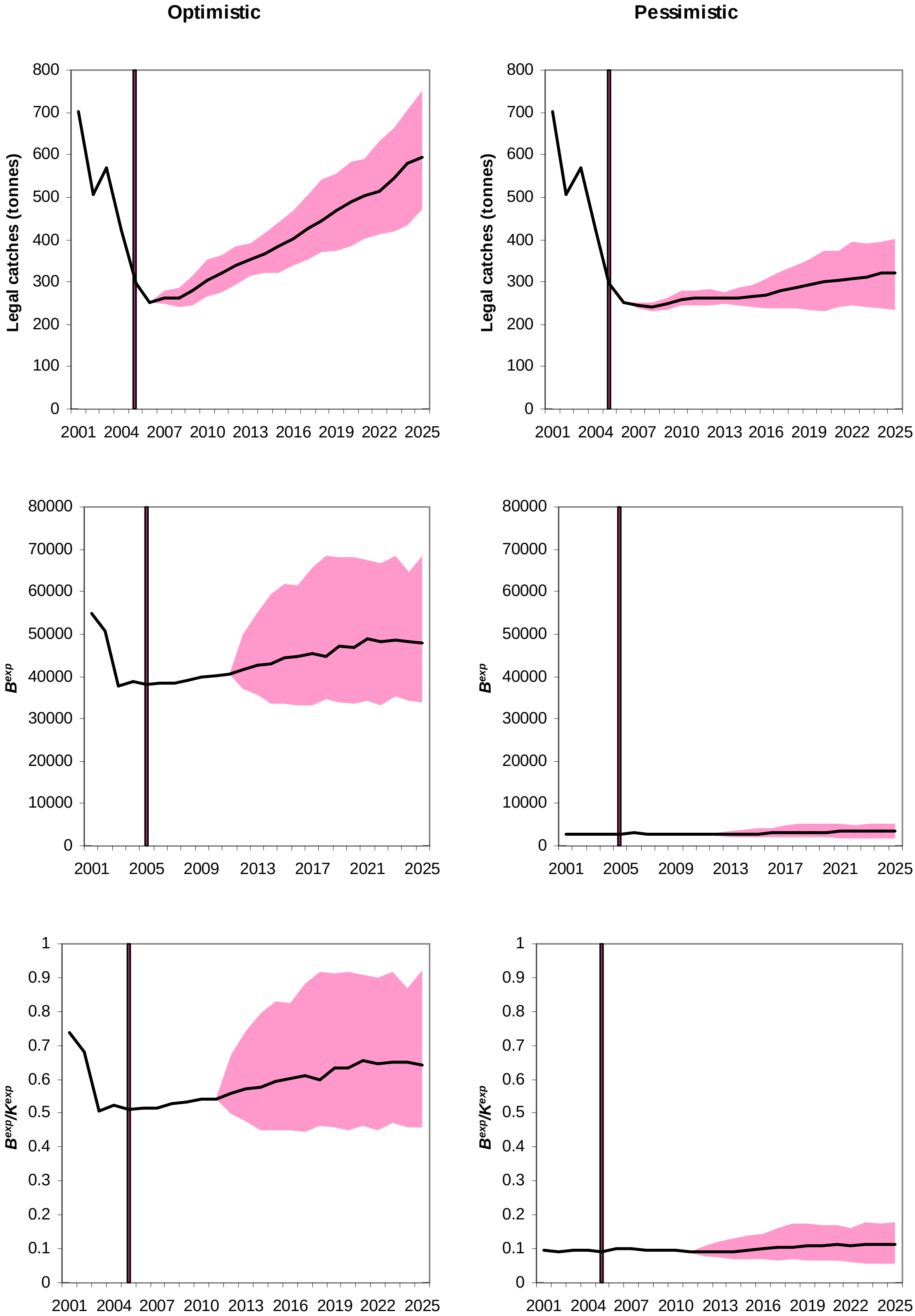


Figure 4. Projection results as for Figure 1, but here for the case where illegal catches continue at a constant rate of 150 tonnes per year.

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, only two of these OMs are considered: the "Optimistic" case which reflects the toothfish resource to be above MSYL at present, and the "Pessimistic" case reflecting a resource that is currently highly depleted.

METHODOLOGY

THE BASIC DYNAMICS

The toothfish population dynamics are given by the equations:

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

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

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

where:

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

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

The number of fish of age *a* caught in year *y* is given by:

$$C_{y,a} = N_{y,a} S_a F_y \tag{A1.4}$$

where:

- F_y is the proportion of the resource above age *a* harvested in year *y*, and
- S_a is the commercial selectivity at age *a*.

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.

$$\ell(a) = \ell_{\infty}[1 - e^{-\kappa(a-t_0)}] \tag{A1.5}$$

$$w_a = c\ell(a)^d \tag{A1.6}$$

where:

w_a is the mass of a fish at age a.

The total catch by mass in year y is given by:

$$C_y = \sum_{a=0}^{m} w_a C_{y,a} = \sum_{a=0}^{m} w_a S_a F_y N_{y,a} \tag{A1.7}$$

which can be re-written as:

$$F_y = \frac{C_y}{\sum_{a=0}^{m} w_a S_a N_{y,a}} \tag{A1.8}$$

Fishing Selectivity

The commercial fishing selectivity, S_a, 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:

$$S_a = \begin{cases} \left[1 + e^{-(a-a_{50})/\delta}\right]^{-1} & \text{for } a \le a_c \\ \left[1 + e^{-(a-a_{50})/\delta}\right]^{-1} e^{-\omega(a-a_c)} & \text{for } a > a_c \end{cases} \tag{A1.9}$$

where

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

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

ω defines the steepness of the descending section of the selectivity curve for fish older than age a_c.

In cases where equation (A1.8) yields a value of $F_y > 1$ for a future year, i.e. the available biomass is less than the proposed catch for that year, F_y 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 ($S_a F_y$) 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_y, is computed as usual using equation (A1.8). If $F_y \le 0.9$ no change is made to the computation of the total catch, C_y, given by equation (A1.7). If $F_y > 0.9$, compute the total catch by:

$$C_y = \sum_{a=0}^{m} w_a g(S_a F_y) N_{y,a} \,. \tag{A1.10}$$

Denote the modified selectivity by S_a^*, where:

$$S_a^* = \frac{g(S_a F_y)}{F_y}\,, \tag{A1.11}$$

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

$$g(x) = \begin{cases} x & x \le 0.9 \\ 0.9 + 0.1\left[1 - e^{(-10(x-0.9))}\right] & 0.9 < x \le \infty \end{cases}. \tag{A.1.12}$$

Now F_y is not bounded at one, but g(S_aF_y) ≤ 1 hence $C_{y,a} = g(S_a F_y) N_{y,a} \le N_{y,a}$ as required.

STOCK-RECRUITMENT RELATIONSHIP

The spawning biomass in year y is given by:

$$B_y^{sp} = \sum_{a=1}^{m} w_a f_a N_{y,a} = \sum_{a=a_m}^{m} w_a N_{y,a} \tag{A1.13}$$

where

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

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

$$R(B_y^{sp}) = \frac{\alpha B_y^{sp}}{\beta + B_y^{sp}}\,. \tag{A1.14}$$

The values of the parameters α and β can be calculated given the initial spawning biomass K^{sp} and the steepness of the curve h, using equations (A1.14)–(A1.18) below. If the initial (and 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.:

$$hR_0 = R(0.2K^{sp}) \tag{A1.15}$$

from which it can be shown that:

$$h = \frac{0.2(\beta + K^{sp})}{\beta + 0.2K^{sp}}\,. \tag{A1.16}$$

Rearranging equation (A1.15) gives:

$$\beta = \frac{0.2K^{sp}(1-h)}{h-0.2} \tag{A1.17}$$

and solving equation (A1.13) 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:

$$\gamma K^{sp} = R_0 = \frac{\alpha K^{sp}}{\beta + K^{sp}} \tag{A1.18}$$

where:

$$\gamma = \left\{ \sum_{a=1}^{m-1} w_a f_a e^{-Ma} + \frac{w_m f_m e^{-Mm}}{1-e^{-M}} \right\}^{-1}. \tag{A1.19}$$

PAST STOCK TRAJECTORY AND FUTURE PROJECTIONS

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

$$K^{sp} = R_0 \left(\sum_{a=1}^{m-1} w_a f_a e^{-Ma} + \frac{w_m f_m e^{-Mm}}{1-e^{-M}} \right) \tag{A1.20}$$

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:

$$N_{0,a} = \begin{cases} R_0 e^{-Ma} & 0 \le a \le m-1 \\ \dfrac{R_0 e^{-Ma}}{1-e^{-M}} & a = m \end{cases} \tag{A1.21}$$

Numbers-at-age for subsequent years are then computed by means of equations (A1.1)-(A1.4) and (A1.7)-(A1.13) under the series of annual catches given.

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

$$B_y^{\exp} = \sum_{a=0}^{m} w_a S_a N_{y,a} \tag{A1.22}$$

THE LIKELIHOOD FUNCTION

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

$$I_y = \widehat{I}_y e^{\varepsilon_y} \text{ or } \varepsilon_y = \ln(I_y) - \ln(\widehat{I}_y), \qquad \text{(A1.23)}$$

where

I_y is the standardised CPUE series index for year y,

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

$\widehat{B}_y^{\exp}$ is the model estimate of exploitable biomass of the resource for year y, and

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

$$\ln \hat{q} = \frac{1}{n}\sum_y \left(\ln I_y - \ln \hat{B}_y^{\exp}\right), \qquad \text{(A1.24)}$$

where

n is the number of data points in the standardised CPUE abundance series, and

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

$$\hat{\sigma} = \sqrt{\frac{1}{n}\sum_y \left(\ln I_y - \ln \hat{q}\hat{B}_y^{\exp}\right)^2} \; . \qquad \text{(A1.25)}$$

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

$$-\ln L = \sum_y \left[\frac{1}{2(\sigma)^2} \left(\ln I_y - \ln\left(q\, B_y^{\exp}\right)\right)^2 \right] + n\left(\ln \sigma\right). \qquad \text{(A1.26)}$$

The estimable parameters of this model are q, K^{sp}, and σ, 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 ($C_{y,a}$) by number made by the fishery each year from equation (A1.4). These in turn can be converted into proportions of the catch of age a:

$$p_{y,a} = C_{y,a} \Big/ \sum_{a'} C_{y,a'} \; . \qquad \text{(A1.27)}$$

Using the von Bertalanffy growth equation (A1.5), these proportions-at-age can be converted to proportions-at-length – here under the assumption that the distribution of length-at-age remains constant over time:

$$p_{y,\ell} = \sum_a p_{y,a} A_{a,\ell} \qquad \text{(A1.28)}$$

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

$$\sum_\ell A_{a,\ell} = 1 \quad \text{for all ages } a. \qquad \text{(A1.29)}$$

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.:

$$\ell(a) \sim \mathrm{N}^*\left[\ell_\infty\left\{1 - e^{-\kappa(a-t_0)}\right\}; \theta(a)^2\right] \qquad \text{(A1.30)}$$

where

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

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

$$\theta(\mathrm{a}) = \beta\ell_{\infty}\left\{1 - e^{-\kappa(a-t_0)}\right\} \tag{A1.31}$$

with β 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 and hence the $\theta(a)$'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 (A1.26):

$$-\ln L_{len} = w_{len}\sum_{y,\ell}\left\{\ln\left[\sigma_{len}\Big/\sqrt{p_{y,\ell}}\right] + \left(p_{y,\ell}\Big/\left(2\sigma_{len}^2\right)\right)\left[\ln p_{y,\ell}^{obs} - \ln p_{y,\ell}\right]^2\right\} \tag{A1.32}$$

where

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

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

$$\hat{\sigma}_{len}^2 = \sum_{y,\ell} p_{y,\ell}\left[\ln p_{y,\ell}^{obs} - \ln p_{y,\ell}\right]^2 \Big/ \sum_{y,\ell} 1. \tag{A1.33}$$

Equation (A1.32) makes the assumption that proportions-at-length data are log-normally distributed about their model-predicted values. The associated variance is taken to be inversely proportional to $p_{y,\ell}$ 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 (see Figure 1), subsequent refinements of this approach may need to adjust the variance assumed for equation (A1.32) 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 (A1.26). The reason that this factor is introduced is that the $p_{y,\ell}^{obs}$ data for a given year frequently show evidence of strong positive correlation, and so are not as informative as the independence assumption underlying the form of equation (A1.32) would otherwise suggest.

In the practical application of equation (A1.32), length observations were grouped by 2 cm intervals, with minus- and plus-groups specified below 54 and above 138 cm respectively, to ensure $p_{y,\ell}^{obs}$ 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 (A1.14) is replaced by:

$$R(B_y^{sp}) = \frac{\alpha B_y^{sp}}{\beta + B_y^{sp}} e^{\left(\zeta_y - \sigma_R^2/2\right)}, \tag{A1.34}$$

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:

$$-\ln L_{rec} = \sum_{y=1961} \left\{ \ln \sigma_R + \zeta_y^2 \big/ \left(2\sigma_R^2 \right) \right\}, \qquad \text{(A1.35)}$$

which is added to the negative log-likelihood of equation (A1.26) 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 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).

DATA and IMPLEMENTATION

Two of the OMs described in Brandão and Butterworth (2005a) (one reflecting an "Optimistic" and one a "Pessimistic" current status for the toothfish resource) have been updated to incorporate further data available from November 2004 to April 2005. 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. In the interest of simplicity, however, the OMs considered in this paper do not take this new "fleet" into account and treat pot catches as if they had the same selectivity as the longliners over 2003–2005. 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) for a description of the basis for the estimates of illegal catches for 2004 and 2005).

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 2005, two analyses were performed: one including CPUE data from 1997 to 2004 and another from 1997 to 2005. 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 2005 from the 1997–2004 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 extra data now available for 2004 and 2005. Table A.3 shows the basic biological parameter values which have been maintained unchanged from those used for previous assessments.

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 0.6.

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 catch-at-length data but omits the initial CPUE index (1997), whereas the “Pessimistic” OM omits the catch-at-length distributions for the initial years (i.e for 1997–2002) but includes all the CPUE indices.

RESULTS

Table A.4 reports the results for the two scenarios considered. The first scenario, in which only the first year’s CPUE data are omitted, reflects an “Optimistic” status (possibly unrealistically so) for the current abundance of the toothfish stock. This case is referred to as the “Optimistic” scenario in this paper. The second scenario (termed “Pessimistic”) refers to the variant when all the CPUE but only the last three years (2003 to 2005) of catch-at-length data are 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 and 2005 are detailed in Brandão and Butterworth (2005b).

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	423.5
2005	37.6	103.5	156	297.1
1997–2005 total	7 547.6	176.2	26 608	34 331.7

Table A.2. Relative abundance indices (normalised to their mean over 1997-2004) for toothfish provided by the standardised commercial CPUE series for the Prince Edward Islands EEZ for the longline fishery. For comparison, indices from the previous analysis (Brandão and Butterworth 2005b) are also shown, as are the CPUE indices adjusted to take cetacean predation into account. The indices for 2005 are based upon data for part of a year only.

Year	**Longline fishery**	
	CPUE **(previous analysis)**	***CPUE*** **(present analysis)**
1997	3.908	3.914
1998	1.059	1.083
1999	0.959	0.962
2000	0.571	0.581
2001	0.359	0.350
2002	0.365	0.364
2003	0.467	0.459
2004	0.310	0.287
2005	—	0.257

Table A.3. Biological parameter values assumed for the assessments conducted, based upon the values for Subarea 48.3 given in Table 34 of the 2000 WG–FSA report (CCAMLR, 2000). The value of M, however, is set to the highest value considered plausible by the August 2003 meeting of the Subgroup on Assessment Methods (CCAMLR, 2003). Note that for simplicity, maturity is assumed to be knife-edge in age.

Parameter	**Value**
Natural mortality M (yr^{-1})	0.2
von Bertalanffy growth	
ℓ_∞ (cm)	194.6
κ (yr^{-1})	0.066
t_0 (yr)	-0.21
Weight length relationship	
c	25×10^{-6}
d	2.8
Age at maturity (yr)	10

Table A.4. Estimates for a model that assumes possibly different logistic commercial selectivities, one for the years 1997 and 2002 and another for 2003 to 2005, when fitted to the CPUE and catch-at-length data for toothfish from the Prince Edward Islands EEZ. For the "Optimistic" scenario, both these functions are estimated; for the "Pessimistic" case, only the 2003 – 2005 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 2006 (assuming the same selectivity as for 2005). 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 CPUE omitted; all length data fitted)	**"Pessimistic" scenario (all CPUE fitted; only 03-05 length data fitted)**
K_{sp} (tonnes)	96 049	22 324
B_{sp}^{2006}/K_{sp}	0.677	0.056
$B_{\exp}^{2006}$ (tonnes)	38 347	2 999
B_{sp}^{1997}/K_{sp}	0.920	0.938
σ_{CPUE}	0.356	0.162
σ_R	0.600††	0.600††
a_{50}^{97-02} (yr)	5.520	—
δ^{97-02} (yr^{-1})	0.026	—
ω^{97-02} (yr^{-1})	0.110	—
a_{50}^{03-05} (yr)	5.479	5.509
δ^{03-05} (yr^{-1})	0.028	0.027
ω^{03-05} (yr^{-1})	0.223	0.000
β	0. 121	0.124
σ_{len}	0.033	0.027
-ln L: Length	-64.18	-23.78
-ln L: CPUE	-4.262	-11.89
-ln L: Recruitment	-16.51	-14.32
-ln L: Total	-84.95	-49.99
MSY (tonnes)	3 837†	1 001

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

†† Input parameter.

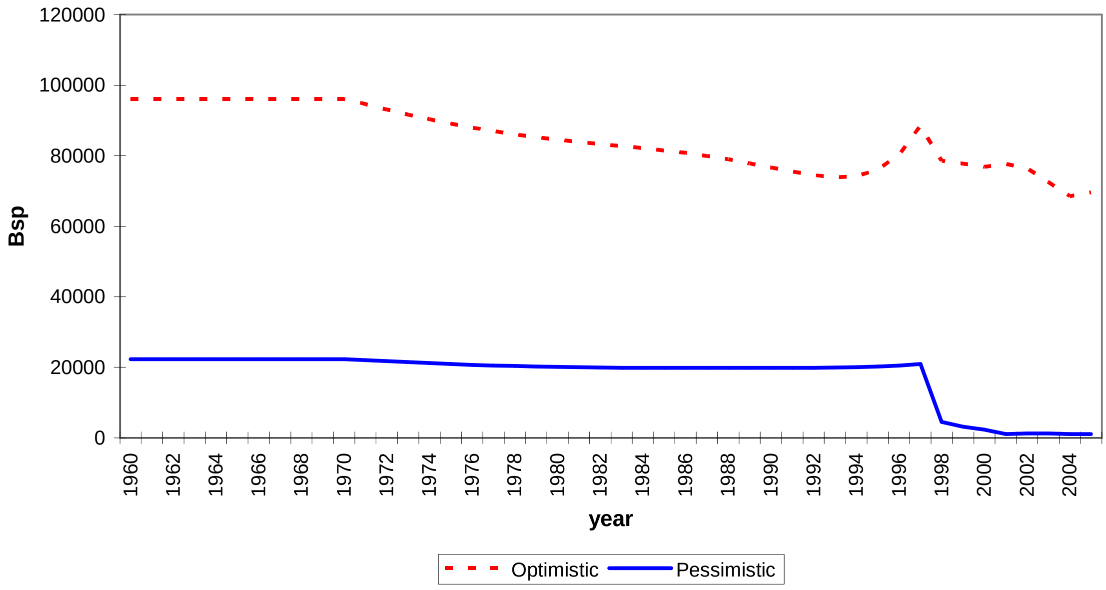


Figure A.1. Spawning biomass estimates when recruitment variability is allowed. Estimates are given for two scenarios: the “Optimistic” scenario when only the 1997 CPUE index is omitted and the “Pessimistic” scenario when all the CPUE but only the last three years of length data are considered in the population model fitting process.

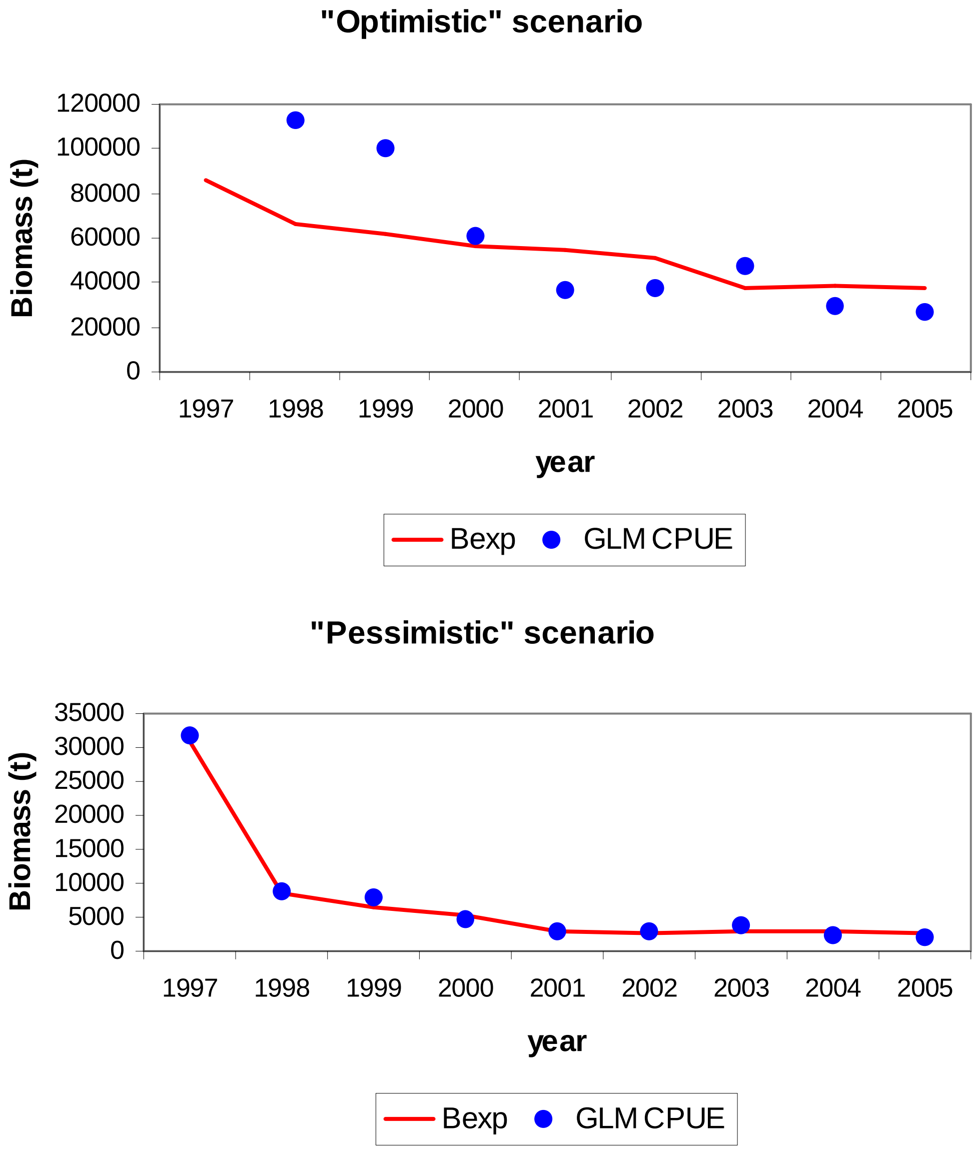


Figure A.2. Exploitable biomass and the GLM-standardised CPUE indices to which the population model is fit (divided by the estimated catchability *q* to express them in biomass units) for the "Optimistic" and "Pessimistic" scenarios. Note the different biomass scales for the two plots.