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

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Abstract

The status of the toothfish resource in the Prince Edward Islands region is unclear because CPUE data suggest considerable depletion, whereas catch-at-length information indicates that past catches have had relatively little impact on abundance. A Management Procedure (MP) approach is proposed to provide a sound scientific basis to recommend future TACs in the face of this appreciable uncertainty. Four Operating Models (OMs) reflecting 'Optimistic', 'Intermediate', 'Less Pessimistic' and a 'Pessimistic' current status for the resource are developed which take account of the different selectivities of past longline and pot fisheries. These OMs are used for trials of a candidate generic 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. An MP with control parameter values specified is proposed for implementation based on 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, although it does deteriorate in conservation terms if the stock-recruitment curve 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.

Résumé

Il est difficile d'évaluer l'état de la ressource de légine dans la région des îles du Prince Édouard, car les données de CPUE suggèrent un épuisement considérable, alors que les informations sur la capture selon la longueur indiquent que, par le passé, les captures n'ont eu que relativement peu d'impact sur l'abondance. L'approche proposée consiste en une procédure de gestion qui fournira une base scientifique solide pour recommander les futurs TAC face à cette incertitude appréciable. Les quatre modèles opérationnels – « Optimiste », « Intermédiaire », « Moins Pessimiste » et « Pessimiste » –développés pour refléter l'état actuel de la ressource tiennent compte des différences de sélectivité des anciennes pêcheries à la palangre et aux casiers. Ces modèles sont utilisés pour tester la procédure générique de gestion proposée qui permettrait de recommander à l'avenir des TAC applicables à cette ressource. La procédure de gestion est fondée sur deux sources de données : la tendance récente de la CPUE des palangriers et la longueur moyenne des poissons capturés. Compte tenu des résultats des essais, il est proposé de mettre en œuvre une procédure de gestion dont les valeurs des paramètres de contrôle sont spécifiées. Étant donné l'importance d'un taux de capture adéquat pour la viabilité économique de la pêcherie, le choix des valeurs des paramètres de contrôle repose principalement sur la probabilité raisonnable d'obtenir une augmentation du taux de capture, quel que soit l'état actuel de la ressource. La procédure de gestion donne des résultats assez robustes pour toute une série de tests de sensibilité, mais qui se détériorent en termes de conservation si la pente h de la courbe stock-recrutement est faible. Ces tests indiquent également qu'un suivi des informations sur la capture selon la longueur serait nécessaire à l'avenir pour veiller à ce qu'il ne se produise pas de changement de sélectivité favorisant la capture des poissons les plus âgés.

Резюме

Состояние ресурсов клыкача в районе о-вов Принс-Эдуард неясно, поскольку данные CPUE свидетельствуют о значительном истощении, тогда как информация о размерном составе уловов показывает, что прошлые уловы оказали относительно небольшое воздействие на численность. Предлагается подход «Процедура управления» (ПУ), чтобы предоставить надежную научную основу для рекомендаций о будущих ОДУ с учетом этой значительной неопределенности. Разработаны четыре операционных модели (ОМ), отражающих «оптимистичное», «переходное», «менее пессимистичное» и «пессимистичное» текущее состояние этого запаса, которые учитывают различную селективность прошлого ярусного и ловушечного промыслов. Эти ОМ используются для испытаний вариантов типовой ПУ, которые могут предоставить рекомендации о будущих ОДУ для этого запаса. ПУ использует два источника данных: недавние тенденции изменения CPUE ярусного промысла и среднюю длину полученных уловов. На основе результатов этих испытаний предлагается выполнять ПУ с установленными значениями контрольных параметров. Учитывая важность адекватного коэффициента вылова для экономической целесообразности этого промысла, выбор значений контрольных параметров фокусируется преимущественно на удовлетворительной вероятности того, что будет обеспечен рост коэффициента вылова, каким бы ни было текущее состояние запаса. Результаты ПУ довольно устойчивы для ряда испытаний на чувствительность, хотя и ухудшаются в природоохранном плане, если крутизна (h) кривой запас–пополнение небольшая. Эти испытания также показывают, что потребуется мониторинг информации о размерном составе уловов в будущем, чтобы предотвратить изменение селективности в направлении увеличения вылова более старшей рыбы.

Resumen

El estado de los stocks de austromerluza en la región de las Islas Príncipe Eduardo no se conoce bien porque los datos de la CPUE apuntan a una reducción considerable, mientras que los datos de captura por tallas indican que las capturas anteriores han tenido un efecto relativamente pequeño en la abundancia. Se propone un enfoque para una estrategia de ordenación (MP) con el fin de proporcionar una base científica sólida para recomendar la captura total permisible (TAC) en el futuro, habida cuenta de esta considerable incertidumbre. Se desarrollaron cuatro modelos operacionales (OM) que representan cuatro estados hipotéticos del stock del recurso: 'Optimista', 'Moderadamente optimista', 'Moderadamente pesimista' y 'Pesimista', que toman en cuenta la distinta selectividad de la pesca de palangre y con nasas efectuada en el pasado. Estos modelos operacionales se utilizan para probar una posible estrategia genérica de ordenación que podría servir para recomendar la captura total permisible (TAC) de este recurso en el futuro. La MP emplea dos fuentes de datos: la tendencia reciente en la CPUE de la pesca de palangre y la talla promedio de las capturas efectuadas. Se propone la implementación de una MP con valores especificados para los parámetros de control en base a los resultados de las pruebas. Dada la importancia de una tasa de captura adecuada para la viabilidad económica de la pesquería, la elección de los valores de los parámetros de control se concentró ante todo en la probabilidad razonable de asegurar el aumento de la tasa de captura, cualquiera que sea el estado actual del stock. Los resultados de la MP son razonablemente robustos según una gama de pruebas de sensibilidad, si bien empeoran en términos de la conservación si la pendiente h de la curva de reclutamiento del stock es baja. Estas pruebas indican también que el seguimiento futuro de los datos de la captura por tallas sería necesario, para prevenir un cambio de la selectividad que resultara en mayores capturas de peces de mayor edad.

Keywords: Patagonian toothfish, *Dissostichus eleginoides*, management, management procedure, MP, Prince Edward Islands, CCAMLR

Introduction

Fisheries for deep-water toothfish (*Dissostichus* spp.) populations have developed in the higher latitudes of the southern hemisphere over the last two decades, marked by a disconcertingly high level of IUU fishing, particularly in their early stages. The CCAMLR Working Group on Fish Stock Assessment regularly reviews assessments of these fisheries and develops scientific management advice (e.g. SC-CAMLR, 2006). These reviews include commentary on the fishery for toothfish (*Dissostichus eleginoides*) that takes place in the waters surrounding the Prince Edward Islands (see Figure 1). However, since these islands fall under the jurisdiction of the Republic of South Africa, and the fishery takes place within the South Africa EEZ around these islands, management decisions rest with South Africa, which sets an annual TAC. Brandão et al. (2002a) provide a brief account of the history of this fishery's development, which was marked by extremely high levels of IUU fishing immediately before legal catches commenced in the mid-1990s.

The first attempt at an assessment of the toothfish resource in the Prince Edward Islands region through the use of an Age-Structured Production Model (ASPM) is detailed in Brandão et al. (2002a). This assessment, based on CPUE and catch data only, indicated that the spawning biomass had been depleted to a few percent of its pre-exploitation level. Brandão et al. (2002b) extended the ASPM to incorporate catch-at-length data. The results showed the CPUE data and catch-at-length data to be inconsistent within the modelling framework considered. The former suggested the resource to be heavily depleted, whereas the latter suggested quite the reverse. Since then, several variants of the ASPM have been considered in an attempt to reconcile the CPUE and catch-at-length data, but these have yielded wide-ranging results (Brandão and Butterworth, 2003; 2004a, 2004b; 2005a; 2006; 2007a). 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 the 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. This approach to fisheries management is described in many references (e.g. Butterworth and Punt, 1999; Cooke, 1999), and is alternatively known as Management Strategy Evaluation (MSE) (e.g. Smith et al., 1999). The case to be considered here does, however, differ from many other applications of the approach because not only is the fishery what might be termed 'data-poor', but also these limited data are in conflict. The fundamental rationale underlying application of the approach to this toothfish resource 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 a 'Pessimistic' assessment is correct, while allowing catches to be increased if future data indicate support for a 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 which are compatible with past data. These generated future data are then used by the algorithms within a candidate generic MP to compute projected future catch limits for the candidate under examination. 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 (2005b) 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 (2005b) 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 (2007b) considered stochastic projections under such Optimistic, 'Intermediate' and Pessimistic scenarios that took into account data from both the past longline and pot fisheries, although 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 the level yielding Maximum Sustainable Yield (MSY) – MSYL) to provide future TACs.

In this paper, these OMs are further updated to include recent 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.

Methods

Operating models and projections

Assessment component

A reference set of four OMs reflecting an Optimistic, Intermediate, Less Pessimistic and Pessimistic current status for the toothfish resource in the Prince Edward Islands region is used to generate future data to test a candidate generic MP. The OMs developed are ASPMs, and the methodology applied to fit ('condition') these models to updated data, together with the associated results, are provided in Appendix 1. These four OMs reflect the spawning biomass depletion at the start of 2007 to be at 68, 57, 37 and 15% respectively.

All four reference set OMs take the pot 'fleet' into account and differentiate the selectivities for the longline and pot fisheries, as well as taking account of the impact of cetacean depredation. 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 on board the vessel *South Princess* (T. Reddell, pers. comm.) suggested that two of every three toothfish caught on longlines were lost to 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 (Purves et al., 2004; 2006), 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.

In conditioning the Optimistic and Intermediate OMS on past data, 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) eight age-classes that make substantial contributions to the catches each year and the 43 length classes included in the likelihood, and thus roughly reflects treating the data from each of these eight age-classes as independent. However, to be able to reflect current depletions as low as 37% for the Less Pessimistic and 15% for the Pessimistic scenario, values of w_{len} of 0.165 and 0.1 respectively had to be used, as using the weight of 0.2 as for the first two scenarios produced results that were not too different from the Intermediate scenario.

By further down-weighting the (limited) length distribution data included to provide the Less Pessimistic and Pessimistic OMs, a yet more pessimistic scenario fitting the CPUE data more closely still could be obtained, which gives rise to the question of whether such a 'More Pessimistic' scenario should also have been included in the reference set. However, this must be balanced against considerations of statistical plausibility. Setting $w_{len} = 0.2$, which, as explained above and in Appendix 1, seems reasonable statistically, there is a deterioration of about 1.5 in log-likelihood points in the fitting of the model when moving from the Less Pessimistic to the Pessimistic scenario, so that the latter remains within a statistically plausible range. However, if one takes the length down-weighting as far as it can go to optimise the fit to the CPUE data, this results in a further drop of over 12 log-likelihood points, or in AIC weighting terms a relative plausibility of less than 10^{-5}, when compared to the Pessimistic scenario, as well as a mis-specified fit to the length-distribution data. This was considered to be moving well outside plausible limits, so that a further More Pessimistic scenario was not included in the reference set.

Projections component

The generic 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) to (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 $\sigma_R = 0.5$. Naturally, the value selected for σ_R has important implications for the evaluation of risk. Beddington and Cooke's (1983) analysis of a large number of fish populations suggested 0.4 as reasonably central over the range of values they found, while a more recent Bayesian meta-analysis of 128 stocks by Punt et al. (2005) yielded a posterior median of 0.62. The value of $\sigma_R = 0.5$ used here is roughly intermediate between these two.

2. Future exploitable and spawning biomasses are calculated using equations (A1.10) and (A1.15). Given the exploitable biomass for longliners, the expected (longliner) CPUE abundance index $I_{y'}^{CPUE}$ is first generated using equation (A1.24); 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. These estimates of σ ranged from about 0.2 to 0.35 for the reference set of OMs (see Table A.4).

3. The TAC for the starting year 2007 (TAC_{2007}) is set to be 250 tonnes, reflecting roughly the legal annual catch achieved over recent years. 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 (taken here to be a continuation of the estimated recent level of 150 tonnes annually), together with the assumed level of cetacean depredation which is taken to remain at its current 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 ($\overline{\ell}_{y'}$) of toothfish for year y' caught by longliners is given by:

$$\overline{\ell}_{y'} = \frac{\sum_\ell \ell C_{y',\ell}\left(e^{\eta_{y',\ell}-\sigma_{y',\ell}^2/2}\right)}{\sum_\ell C_{y',\ell}\left(e^{\eta_{y',\ell}-\sigma_{y',\ell}^2/2}\right)} = \frac{\sum_\ell \ell\left(\sum_a C_{y',a}A_{a,\ell}\right)\left(e^{\eta_{y',\ell}-\sigma_{y',\ell}^2/2}\right)}{\sum_\ell C_{y',\ell}\left(e^{\eta_{y',\ell}-\sigma_{y',\ell}^2/2}\right)} \quad (1)$$

where:

$A_{a,\ell}$ is the proportion of fish of age a that fall in length group ℓ (equations (A1.29) and (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 of equation (1) above), and

$\eta_{y',\ell}$ is a factor distributed as N(0, $\sigma^2_{y',\ell}$), where $\sigma_{y',\ell} = \dfrac{\hat{\sigma}_{len}}{\sqrt{\sum_a C_{y',a} A_{a,\ell}}}$, and $\hat{\sigma}_{len}$ is given by equation (A1.34) for the longline fishery.

6. Steps (2) to (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.

The MP considered

A simple generic 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 that catches could be increased, 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 it is acceptable, 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 (coarsely) that biomass is above MSYL, and below this length that biomass is below MSYL. Figure 2 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*. Within each quadrant of the figure, 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.

The generic control rule of the MP is thus:

$$TAC_{y+1} = TAC_y \left[1+\Psi\right] \qquad (2)$$

where:

$$\Psi = \begin{cases} \lambda s_{CPUE} + \mu\left(\left(\ell_{mean} - \ell^*\right)/\ell^*\right) & \text{(i)} \\ \lambda s_{CPUE} & \text{(ii)} \\ \lambda s_{CPUE} + \mu\left(\left(\ell_{mean} - \ell^*\right)/\ell^*\right) & \text{(iii)} \\ \mu\left(\left(\ell_{mean} - \ell^*\right)/\ell^*\right) & \text{(iv)} \end{cases}$$

(i) if $s_{CPUE} \geq 0$ and $\ell_{mean} - \ell^* \geq 0$

(ii) if $s_{CPUE} \geq 0$ and $\ell_{mean} - \ell^* \leq 0$

(iii) if $s_{CPUE} \leq 0$ and $\ell_{mean} - \ell^* \leq 0$

(iv) if $s_{CPUE} \leq 0$ and $\ell_{mean} - \ell^* \geq 0$

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

Figure 3 shows typical deterministic projections for CPUE, CPUE slope and the mean length of the catch for the four OMs of the reference set which are obtained under one particular set of choices of the control parameter values for this generic control rule. These projections behave as anticipated under the reasoning given above.

Summary performance statistics

The performances of different candidate MPs were considered in terms 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:

Catches achieved

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

Risk to resource

Final resource size: $\dfrac{B^{sp(s)}_{2026}}{K^{sp(s)}}$.

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 Operating Models (OMs). The 90% probability intervals are shown in parenthesis. These results assume illegal (longline) catches will continue in the future at a constant rate of 150 tonnes per year. The probability of the CPUE index in 2026 being less than that of the average of the 2004 to 2006 values is also given.

Scenario	Performance statistic				
	$\bar{C}_{2007-2026}$	B^{sp}_{2026}/K^{sp}	AAV	$\dfrac{CPUE_{2026}}{\overline{CPUE}_{04-06}}$	Probability $\dfrac{CPUE_{2026}}{\overline{CPUE}_{04-06}}<1$
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)	0.36
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)	0.14
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)	0.10
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)	0.23

Industrial stability

Average annual catch variation:

$$AAV^s = \frac{1}{20}\sum_{y=2007}^{2026}\frac{\left|C^s_y - C^s_{y-1}\right|}{C^s_{y-1}}.$$

Economic viability

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

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, with the probability that the last of the four is below 1, also reported here).

Results and discussion

Experimentation with different values of the three control parameters led to the selections $\lambda = 1$, $\mu = 1$ and $\ell^* = 81$ cm for the generic MP of equation (2). For economic viability reasons, the major concern of the industry is that the CPUE not decline. Thus, the control parameter values were chosen in consultation with the industry, keeping this concern as a priority.

Testing the MP with these control parameter values specified for the four reference set scenarios yields the results shown in Table 1, and by the left-most entry in Figure 4, where the bars represent the 90th percentiles. Figure 5 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.

The CCAMLR decision rules (SC-CAMLR, 1994, paragraphs 5.18 to 5.26) were considered in evaluating the performance of the MP proposed under the reference set OMs. The probability of B^{sp} falling below 20% of K^{sp} within the 20-year projection period is zero under all OMs except for the Pessimistic one for which it is (self-evident) one because $B^{sp}_{2006} < 0.2K^{sp}$ for that scenario. The probability of the median of B^{sp} over the 20-year projection period falling below 50% of K^{sp} is zero for the Optimistic and the Intermediate OMs, 0.96 for the Less Pessimistic OM and one for the Pessimistic OM. It should be noted that the CCAMLR decision rules were developed primarily in the context of commencing harvesting of an unexploited resource, so that failure to satisfy the associated

Table 2: Reference set and robustness tests carried out to test the performance of the proposed Management Procedure (MP), together with the abbreviations for these used in Figure 4.

Robustness test	Description
Ref set	Reference set (z = 1, a_{50} = 6.5, h = 0.75)
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

criteria in cases where initial abundance is low for a resource which is slow-growing is not necessarily indicative of poor MP performance.

Robustness tests

Table 2 describes the various robustness tests carried out whose results are shown in Figure 4, 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 for both past and projected future catches; earlier discussion and associated references quoted under 'Methods' suggest that this is reasonably reflective of a plausible range. The results of these two robustness tests are shown in Figure 4 for the Intermediate and the Pessimistic OMs. For z = 2, final stock status is better for the Pessimistic scenario compared to the corresponding result within 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 there having been any change in 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 be able 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 4 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) is 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 larger 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 (A1.10, A1.24)), likely resulting in a consequential change in catchability q. To keep computations simple, this factor was ignored by applying equation (A1.10) 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 4). 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 5th 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 4).

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 6 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).

Conclusions

The MP of equation (2), 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, although it does deteriorate in conservation terms if steepness h is appreciably less than the reference set value of 0.75 assumed.

Application of an MP to a fishery under South African jurisdiction would fall under generic 'Procedures for deviating from Operational Management Procedure (OMP) output for the recommendation for a TAC, and for initiating a TAC review' (see Rademeyer et al., 2008, Appendix 2). These specify a default period of four years by the end of which MPs must have been reviewed and possibly consequentially amended. They also specify routine assessments to take place during this period, a particular aim of which is to check whether resource behaviour remains within the range covered by the OMs used to select the MP. This process would provide a basis to check, given future catch-at-length information, whether the appropriateness of the MP had been compromised by a change in selectivity towards greater catches of older fish.

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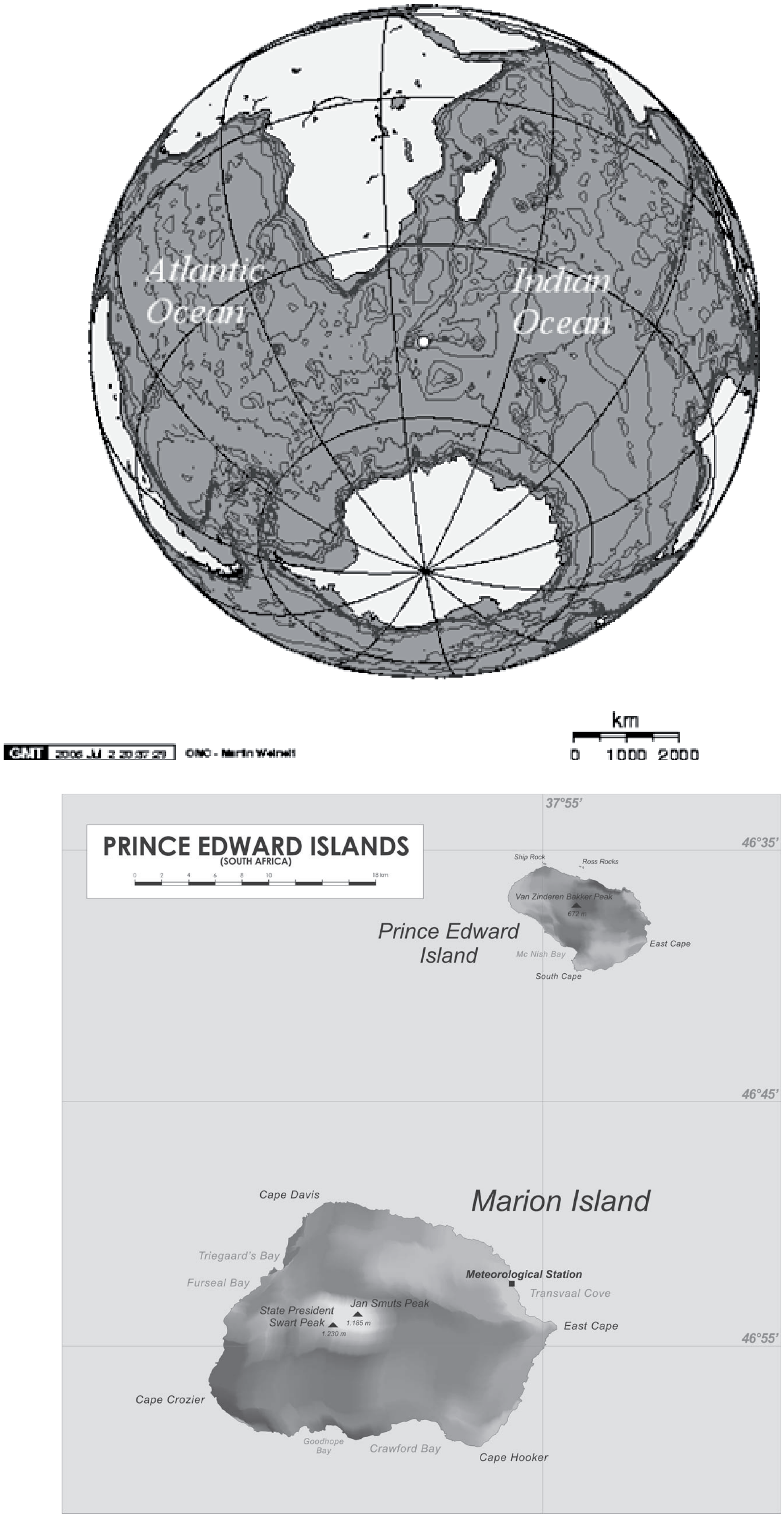

Figure 1: Map of Prince Edward Islands, their position globally (top map) and the two islands, Prince Edward Island and Marion Island (bottom map) that constitute the island group. Pictures obtained from Wikipedia, The Free Encyclopedia (http://en.wikipedia.org/w/index.php?title=Prince_Edward_Islands&oldid=287650440).

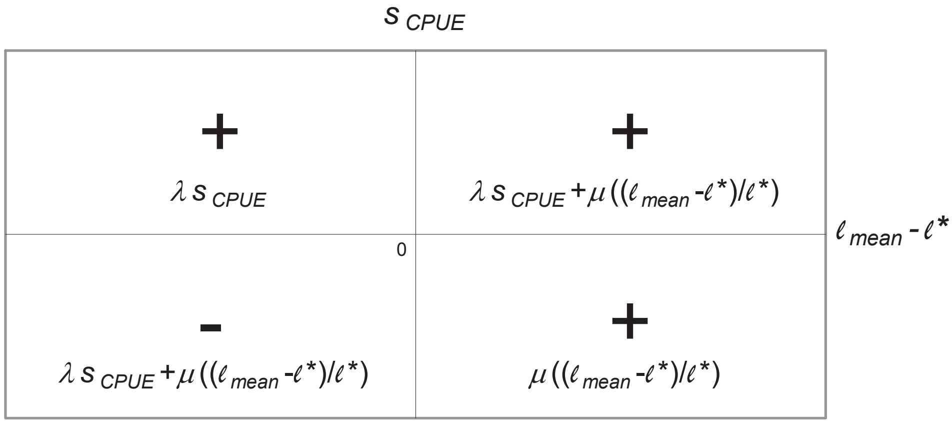

Figure 2: The structure in the formulation of a generic Management Procedure (MP) that takes the trend in CPUE indices into account, but reacts differently to this trend depending on whether biomass is above or below the Maximum Sustainable Yield Level (MSYL) (for which a mean length at capture of ℓ^* 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} (on the vertical axis)) and whether the mean length of catches ℓ_{mean} is above or below ℓ^* (on the horizontal axis). The formula of the generic control rule to be applied is also shown in each quadrant.

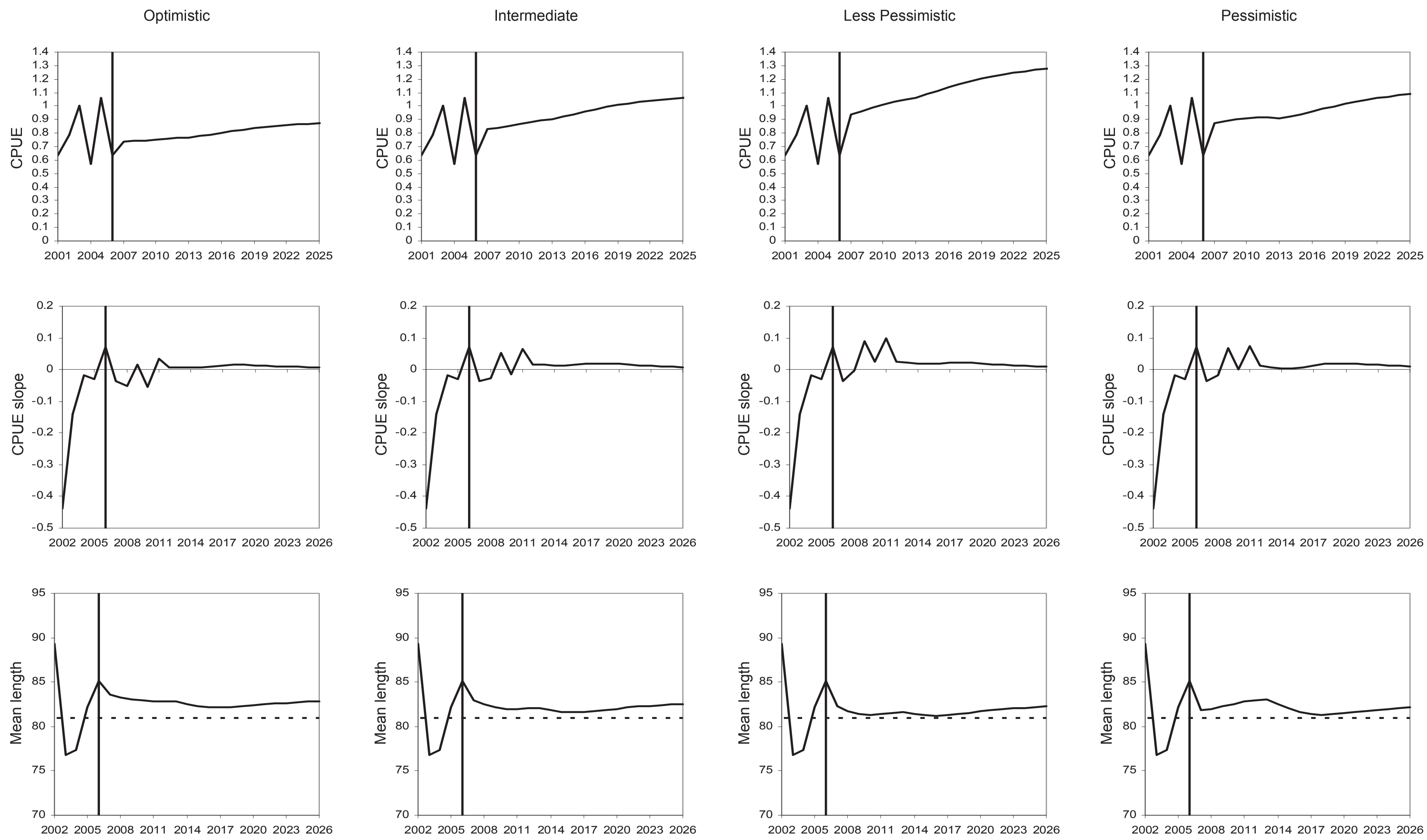

Figure 3: Deterministic projections (shown to the right of the vertical line) of CPUE, CPUE slope (s_{CPUE}) and mean length (in cm) trends under the Optimistic, Intermediate, Less Pessimistic and Pessimistic operating models. The values to the left of the vertical line reflect past data from longline operations. The horizontal dashed line in the lowest set of plots shows the value of $\ell^* = 81$ cm selected for the Management Procedure (MP) control rule.

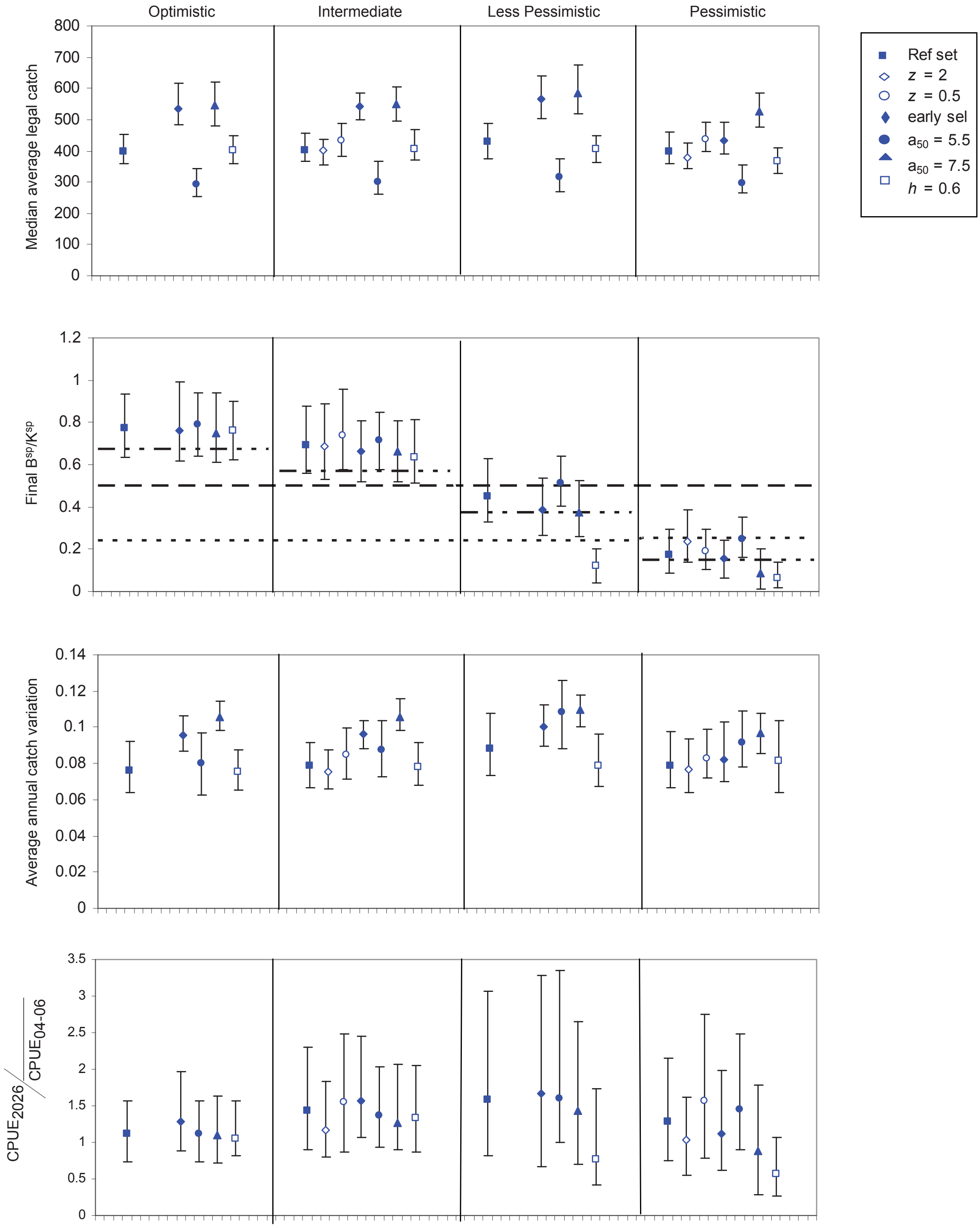

Figure 4: Projected median (and 90% probability intervals) of the average annual legal (longline) catches of toothfish (in tonnes) for the period 2007 to 2026, the spawning biomass depletion at the start of 2026, the average annual variation in catch and the CPUE index in 2026 as a proportion of the average of the 2004 to 2006 CPUE indices for the four Operating Models (OMs) for various robustness tests shown in the following order from left to right: 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 years, and steepness parameter h = 0.6. Note that for the Optimistic and Less Pessimistic OMs, results are not shown for all robustness tests. The horizontal dashed lines on the second row represent the Maximum Sustainable Yield Level (MSYL) (small dashes), the CCAMLR target value (large dashes) and current spawning stock depletion (dash-dot).

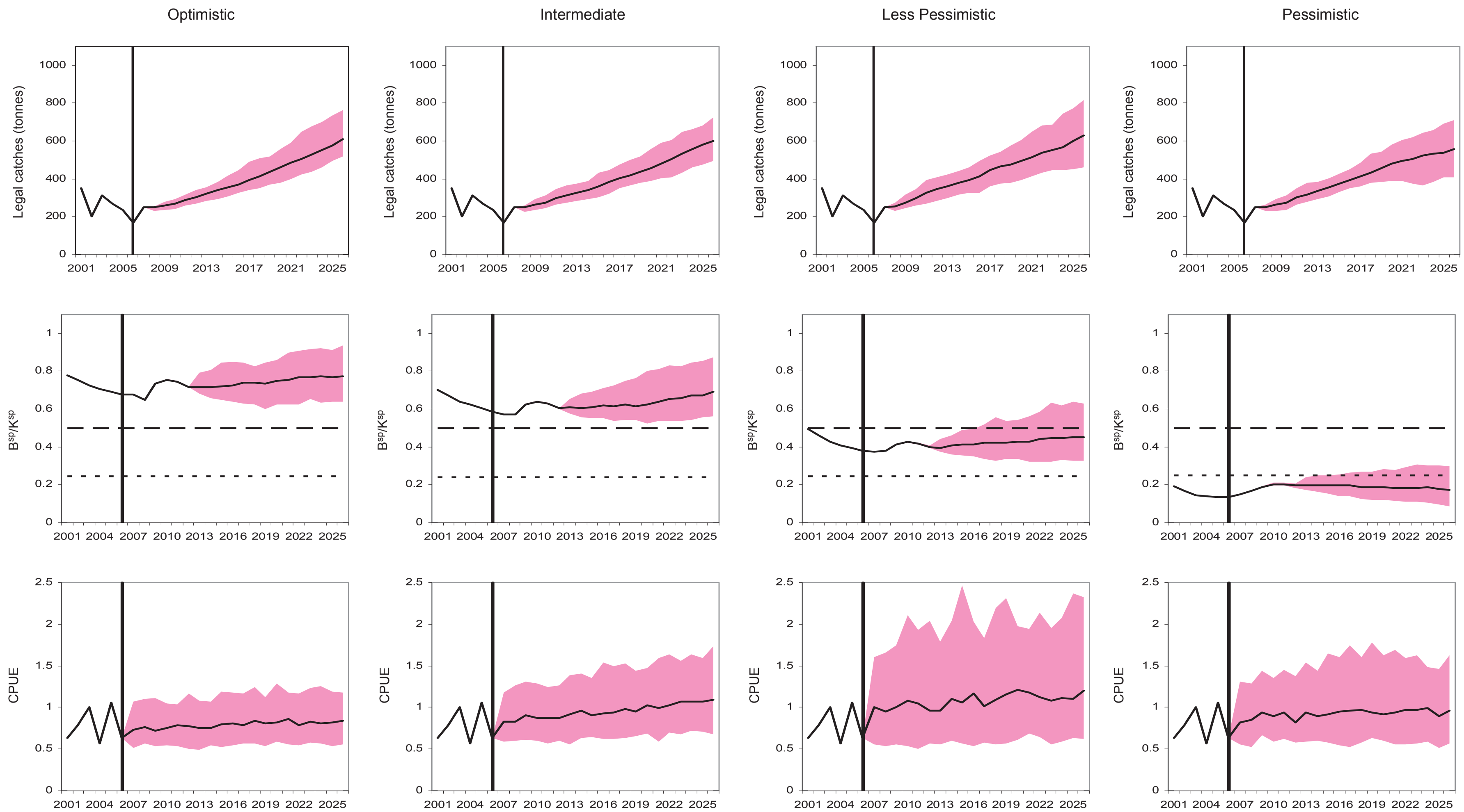

Figure 5: Median trajectories of legal annual catches by longliners (in tonnes), spawning biomass depletion and CPUE trends under the proposed Management Procedure (MP) for the Optimistic, Intermediate, Less Pessimistic and Pessimistic Operating Models (OMs). Projections (medians) commence to the right 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). The horizontal dashed lines on the central panel represent Maximum Sustainable Yield Level (MSYL) (small dashes) and the CCAMLR target value (large dashes).

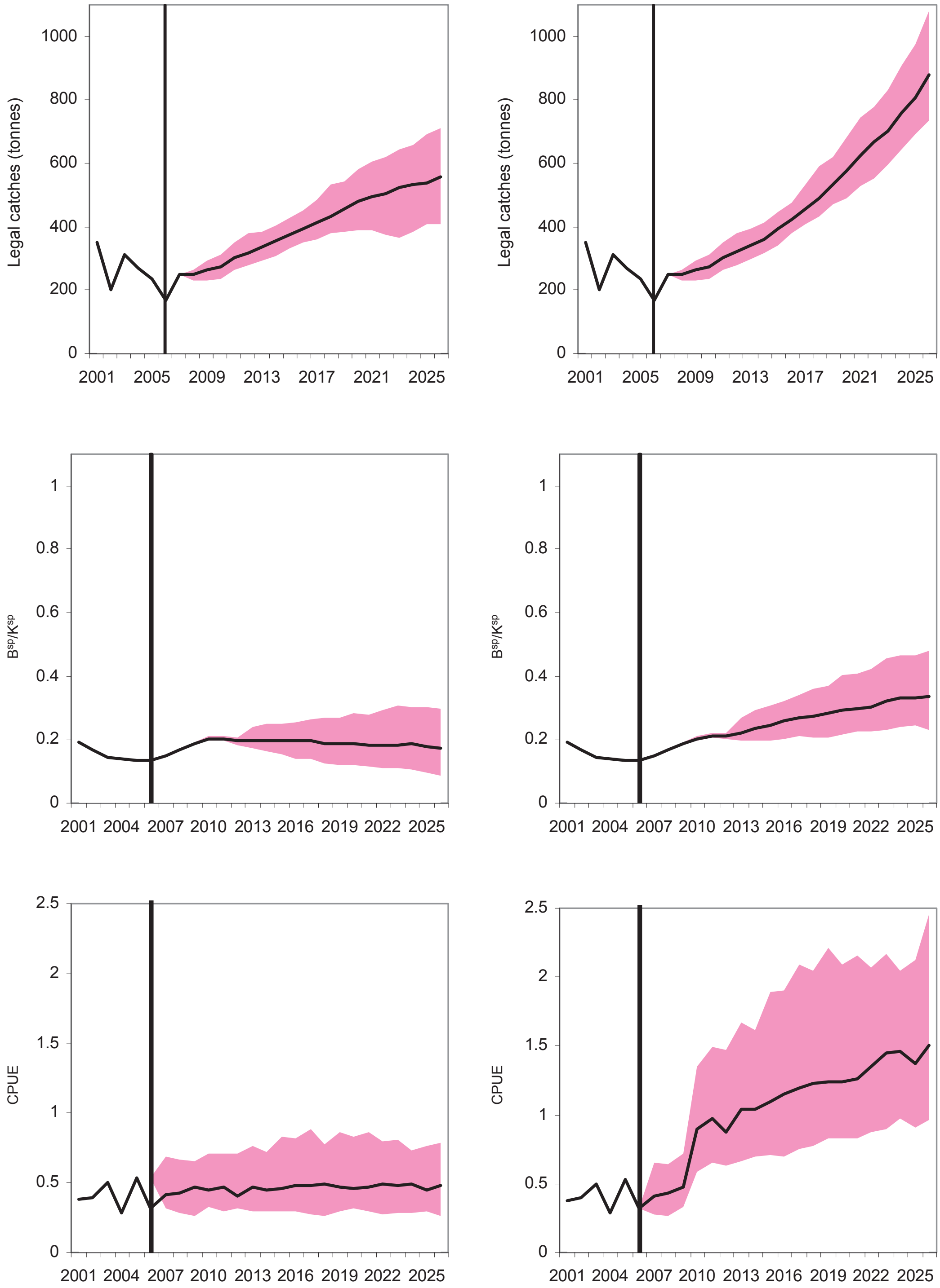

Figure 6: Median trajectories of legal annual catches by longliners (in tonnes), spawning biomass depletion and CPUE trends under the proposed empirical Management Procedure (MP) for the Pessimistic Operating Model (OM) for the robustness test that assumes that cetacean depredation will cease from 2010 (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 losses to depredation as in Table A.2)

Liste des tableaux

Liste des figures

Figure 3: Projections déterministes (indiquées à droite de la ligne verticale) des tendances de la CPUE, de la pente de la CPUE (s_{CPUE}) et de la longueur moyenne (en cm) dans le cadre des modèles opérationnels Optimiste, Intermédiaire, Moins Pessimiste et Pessimiste. Les valeurs situées à gauche de la ligne verticale reflètent d'anciennes données d'opérations palangrières. La ligne horizontale discontinue sur les graphes de la dernière rangée indique la valeur de $\ell^* = 81$ cm retenue pour la règle de contrôle de la procédure de gestion.

Figure 4: Médiane projetée (et intervalles de probabilités à 90%) des captures (à la palangre) moyennes annuelles licites de légine (en tonnes) pour la période de 2007 à 2026, épuisement de la biomasse reproductrice au début de 2026, variation annuelle moyenne de la capture et indice de CPUE en 2026 par rapport aux indices moyens de CPUE de 2004 à 2006 des quatre modèles opérationnels pour divers tests de robustesse indiqués dans l'ordre suivant de gauche à droite : jeu de référence, déprédation par les cétacés $z = 2$ et $z = 0{,}5$, ancienne sélectivité de la pêche à la palangre appliquée à l'avenir, âge de 5,5 et 7,5 ans à 50% de sélectivité, et paramètre d'inclinaison de la pente $h = 0{,}6$. À noter que les résultats des tests de robustesse ne sont pas tous indiqués pour les modèles Optimiste et Moins Pessimiste. Les traits horizontaux discontinus sur la deuxième ligne représentent le niveau de rendement maximum équilibré (MSYL) (petits tirets), la valeur visée par la CCAMLR (grands tirets) et l'épuisement actuel du stock reproducteur (tiret-point).

Figure 5: Trajectoires médianes des captures annuelles licites des palangriers (en tonnes), épuisement de la biomasse reproductrice et tendances de la CPUE dans le cadre de la procédure de gestion proposée de modèles opérationnels Optimiste, Intermédiaire, Moins Pessimiste et Pessimiste. Les projections (médianes) commencent à droite des lignes verticales et les zones foncées représentent les enveloppes de probabilité de 90%. Ces résultats présument des captures illicites continues à un taux constant de 150 tonnes par an et une déprédation par les cétacés à l'avenir au même taux que celui du passé récent ($z = 1$, c.-à-d. égal à la capture à la palangre débarquée). Les lignes horizontales discontinues sur le panneau central représentent le niveau de production maximale équilibrée (MSYL) (petits tirets) et la valeur visée par la CCAMLR (grands tirets).

Figure 6: Trajectoires médianes des captures annuelles licites des palangriers (en tonnes), épuisement de la biomasse reproductrice et tendances de la CPUE dans le cadre de la procédure de gestion empirique proposée du modèle opérationnel Pessimiste pour le test de robustesse qui présume que la déprédation par les cétacés s'arrêtera à partir de 2010 (à droite). Les trajectoires du jeu de référence correspondant sont également indiquées (à gauche) à titre de comparaison. Les projections (médianes) commencent à droite des lignes verticales et les zones foncées représentent les enveloppes de probabilité de 90%. Ces résultats présument des captures illicites continues à un taux constant de 150 tonnes par an. À noter que la CPUE, telle qu'indiquée ici, est celle qui a été réalisée par les navires (c.-à-d. qu'elle n'a pas été ajustée pour incorporer les pertes dues à la déprédation comme dans le tableau A.2).

Figure A.1: Estimations de la biomasse reproductrice (à noter que le recrutement peut varier avant le début de la pêche). Des estimations sont données pour les scénarios Optimiste, Intermédiaire, Moins Pessimiste et Pessimiste (le conditionnement de ces scénarios aux données est expliqué dans le texte ; voir également la légende du tableau A.4). Tous les résultats indiqués présument un facteur de déprédation par les cétacés $z = 1$, c.-à-d. que les pertes récentes dues à la déprédation par les cétacés sont égales à la capture à la palangre débarquée.

Figure A.2: Biomasse exploitable de la pêcherie à la palangre et indices de CPUE normalisée par le modèle linéaire généralisé (GLM) auxquels est ajusté le modèle de population (divisés par la capturabilité estimée q pour les exprimer en unités de biomasse) pour les scénarios Optimiste, Intermédiaire, Moins Pessimiste et Pessimiste. Tous les résultats indiqués présument un facteur de déprédation par les cétacés $z = 1$, c.-à-d. que les pertes récentes dues à la déprédation par les cétacés sont égales à la capture à la palangre débarquée. À noter que les indices de CPUE ajustés pour le scénario en question sont indiqués.

Figure A.3: Prédictions des proportions de la capture annuelle selon la longueur d'après l'observation (trait) et l'évaluation de la pêcherie à la palangre des années 2003 à 2006 pour les scénarios Optimiste (première ligne), Intermédiaire (deuxième ligne), Moins Pessimiste (troisième ligne) et Pessimiste (dernière ligne). À noter que les longueurs inférieures à 54 cm et supérieures à 138 cm sont combinées en groupes « moins » et « plus ». Tous les résultats indiqués présument un facteur de déprédation par les cétacés $z = 1$, c.-à-d. que les pertes récentes dues à la déprédation par les cétacés sont égales à la capture à la palangre débarquée.

Figure A.4: Courbes de sélectivité estimées pour les périodes 1997–2002 et 2003–2006 de la pêcherie à la palangre, et pour la période 2004–2005 de la pêcherie au casier (à noter que la courbe pratiquement plate de la sélectivité des plus âgés dans cette pêcherie est telle qu'estimée ; il ne s'agit pas d'une hypothèse d'entrée). Les courbes correspondent aux scénarios Optimiste, Intermédiaire, Moins Pessimiste et Pessimiste.

Список таблиц

Список рисунков

требуется ли увеличение или сокращение уловов в зависимости от тенденции изменения CPUE (что показано угловым коэффициентом s_{CPUE} (по вертикальной оси)) и находится ли средняя длина уловов ℓ_{mean} выше или ниже ℓ^* (по горизонтальной оси). В каждой клетке также показана формула применяемого стандартного правила управления.

Рис. 3: Детерминистические прогнозы CPUE (показаны справа от вертикальной линии), угловой коэффициент CPUE (s_{CPUE}) и тенденции изменения средней длины (в см) в рамках «Оптимистичной», «Переходной», «Менее пессимистичной» и «Пессимистичной» операционных моделей. Значения слева от вертикальной линии отражают прошлые данные по операциям ярусного промысла. Горизонтальной пунктирной линией на нижних графиках показано значение $\ell^* = 81$ см, выбранное для правила контроля Процедуры управления (ПУ).

Рис. 4: Прогнозируемая медиана (и 90% вероятностные интервалы) средних годовых законных уловов (при ярусном промысле) клыкача (в т) за период 2007–2026 гг., истощение медианной нерестовой биомассы в начале 2026 г., средняя годовая изменчивость уловов и индекс CPUE в 2026 г. как доля от среднего значения индексов CPUE 2004–2006 гг. для четырех операционных моделей (ОМ) в случае различных испытаний на устойчивость, показанных в следующем порядке, слева направо: базовый набор, хищничество китов $z = 2$ и $z = 0.5$, прежняя селективность ярусов применяется и в будущем, возраст при 50% селективности составляет 5.5 и 7.5 лет, и параметр крутизны $h = 0.6$. Следует отметить, что в случае «Оптимистичной» и «Менее пессимистичной» ОМ результаты не показаны для всех испытаний на устойчивость. Горизонтальными пунктирными линиями во втором ряду показаны: уровень максимального устойчивого вылова (УМУВ) (мелкий пунктир); целевые значения АНТКОМ (крупный пунктир) и существующее истощение нерестового запаса (точки-тире).

Рис. 5: Медианные траектории законных годовых уловов, полученных ярусоловами (в т), истощение нерестовой биомассы и тенденции изменения CPUE в рамках предлагаемой Процедуры управления (ПУ) для «Оптимистичной», «Переходной», «Менее пессимистичной» и «Пессимистичной» операционных моделей (ОМ). Прогнозы (медианы) начинаются справа от вертикальных линий, а заштрихованные участки представляют 90% доверительные вероятности. Эти результаты допускают, что незаконные уловы останутся в будущем на постоянном уровне 150 т в год и что хищничество китов будет продолжаться в будущем в том же объеме, что и в недавнем прошлом ($z = 1$, т. е. равно выгруженному улову ярусного промысла). Горизонтальными пунктирными линиями в среднем ряду показан устойчивый максимальный уровень вылова (УМУВ) (мелкий пунктир) и целевые значения АНТКОМ (крупный пунктир).

Рис. 6: Медианные траектории законных годовых уловов, полученных ярусоловами (в т), истощение нерестовой биомассы и тенденции изменения CPUE в рамках предлагаемой эмпирической Процедуры управления (ПУ) для «Пессимистичной» операционной модели (ОМ) в случае испытания на устойчивость, в котором принято, что хищничество китов прекратится начиная с 2010 г. (справа). Для сравнения также показаны соответствующие траектории базового набора (слева). Прогнозы (медианы) начинаются справа от вертикальных линий, а заштрихованные участки представляют 90% доверительные вероятности. Эти результаты допускают, что незаконные уловы останутся в будущем на постоянном уровне 150 т в год. Следует отметить, что показанный здесь CPUE – это CPUE, реализованный судами (т. е. он не пересчитан с целью включения потерь в результате хищничества, как в табл. A.2).

Рис. A.1: Оценки нерестовой биомассы (следует учитывать, что пополнение может меняться до начала промысла). Оценки даются для «оптимистичного», «переходного», «менее пессимистичного» и «пессимистичного» сценариев (подробности согласования этих сценариев с данными приводятся в тексте; см. также подпись к табл. A.4). Во всех показанных результатах принят коэффициент хищничества китов $z = 1$, т. е. недавние потери в связи с хищничеством китов равны выгруженному улову ярусного промысла.

Рис. A.2: Пригодная для ярусного промысла биомасса и стандартизованные по Обобщенной линейной модели (GL-модели) индексы CPUE, к которым подобрана модель популяции (разделенные на оценочную уловистость q, чтобы выразить их в единицах биомассы) для «оптимистичного», «переходного», «менее пессимистичного» и «пессимистичного» сценариев. Во всех показанных результатах принят коэффициент хищничества китов $z = 1$, т. е. недавние потери в связи с хищничеством китов равны выгруженному улову ярусного промысла. Следует учитывать, что показаны только индексы CPUE, соответствующие рассматриваемому сценарию.

Рис. A.3: Наблюдаемые (линия) и расчетные прогнозы процентного распределения ежегодных уловов по длине для ярусного промысла за 2003–2006 гг. в случае «оптимистичного» (вверху), «переходного» (второй ряд), «менее пессимистичного» (третий ряд) и «пессимистичного» (внизу) сценариев. Следует учитывать, что длины меньше 54 см и больше 138 см объединены в минус- и плюс-группы. Во всех показанных результатах принят коэффициент хищничества китов $z = 1$, т. е. недавние потери в связи с хищничеством китов равны выгруженному улову ярусного промысла.

Lista de las tablas

Lista de las figuras

estimada q para expresarlos en unidades de biomasa) para los modelos Optimista, Moderadamente optimista, Moderadamente pesimista y Pesimista. Todos los resultados mostrados suponen un factor de depredación por cetáceos $z = 1$, es decir, las pérdidas recientes por la depredación de cetáceos son iguales a la captura de los palangres subida a bordo. Nótese que solamente se muestran los índices de la CPUE ajustados a los modelos mencionados.

Figura A.3: Composición por talla de la captura anual observada (línea) y pronosticada por la evaluación en la pesquería de palangre desde 2003 hasta 2006 para los modelos Optimista (hilera superior), Moderadamente optimista (segunda hilera), Moderadamente pesimista (tercera hilera) y Pesimista (hilera inferior). Nótese que las tallas menores que 54 cm y mayores que 138 cm han sido combinadas en los grupos 'menos ' y 'más'. Todos los resultados mostrados suponen un factor de depredación por cetáceos $z = 1$, es decir, las pérdidas recientes por la depredación de cetáceos son iguales a la captura de los palangres subida a bordo.

Figura A.4: Curvas de la selectividad de la pesquería de palangre estimadas para los períodos 1997–2002 y 2003–2006, y para el período de 2004–2005 para la pesquería con nasas (nótese que la selectividad casi plana de las edades mayores para esta pesquería corresponde a la selectividad estimada, y no la supuesta como parámetro de entrada). Se muestran las curvas para los modelos Optimista, Moderadamente optimista, Moderadamente pesimista y Pesimista.

APPENDIX 1

The Age-Structured Production Model (ASPM) methodology underlying the Operating Models

Four Operating Models (OMs) provide a reference set 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. These are fitted to different subsets of the data and apply different relative weights to the catch-at-length data so as 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 described by the equations:

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

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

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

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 these equations approximate 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:

$$C_{y,a} = \sum_{f=1}^{2} C^f_{y,a} \qquad \text{(A1.4)}$$

where:

$$C^f_{y,a} = N_{y,a} S^f_{y,a} F^f_y \qquad \text{(A1.5)}$$

and:

F^f_y	is the proportion of a fully selected age group that is 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 (normalised to 1 for an age which is fully selected).

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.

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

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

where w_a is the mass of a fish at age a.

The fleet-specific total catch by mass in year y is given by:

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

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

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

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

$$B_y^{\exp}(f) = \sum_{a=0}^{m} w_a S_{y,a}^f N_{y,a}. \tag{A1.10}$$

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:

$$S_{y,a}^f = \begin{cases} \left[1 + e^{-\left(a - a_{50}^y\right)/\delta^y}\right]^{-1} & \text{for } a \le a_c \\ \left[1 + e^{-\left(a - a_{50}^y\right)/\delta^y}\right]^{-1} e^{-\omega^y (a - a_c)} & \text{for } a > a_c \end{cases} \tag{A1.11}$$

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 years).

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 ($S^f_{y,a}F^f_y$) 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 $F^f_y > 0.9$, however, the total catch is computed from:

$$C^f_y = \sum_{a=0}^{m} w_a g(S^f_{y,a}F^f_y)N_{y,a} \quad \text{(A1.12)}$$

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

$$S^{f*}_{y,a} = \frac{g(S^f_{y,a}F^f_y)}{F^f_y}, \quad \text{(A1.13)}$$

so that $C^f_y = \sum_{a=0}^{m} w_a S^{f*}_{y,a} F^f_y N_{y,a}$, where:

$$g(x) = \begin{cases} x & x \leq 0.9 \\ 0.9 + 0.1\left[1 - e^{(-10(x-0.9))}\right] & 0.9 < x \leq \infty \end{cases} \quad \text{(A1.14)}$$

Now F^f_y is no longer bounded above by 1, 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:

$$B^{sp}_y = \sum_{a=a_m}^{m} w_a N_{y,a} \quad \text{(A1.15)}$$

where f_a is 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):

$$R(B^{sp}_y) = \frac{\alpha\, B^{sp}_y}{\beta + B^{sp}_y}. \quad \text{(A1.16)}$$

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) to (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.:

$$hR_0 = R(0.2K^{sp}) \quad \text{(A1.17)}$$

from which it can be shown that:

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

Rearranging equation (A1.18) gives:

$$\beta = \frac{0.2K^{sp}(1-h)}{h-0.2} \tag{A1.19}$$

and solving equation (A1.16) 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:

$$\gamma K^{sp} = R_0 = \frac{\alpha K^{sp}}{\beta + K^{sp}} \tag{A1.20}$$

where:

$$\gamma = \left\{ \sum_{a=1}^{m-1} w_a f_a e^{-Ma} + \frac{w_m f_m e^{-Mm}}{1-e^{-M}} \right\}^{-1} \quad . \tag{A1.21}$$

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:

$$K^{sp} = R_0 \left(\sum_{a=1}^{m-1} w_a f_a e^{-Ma} + \frac{w_m f_m e^{-Mm}}{1-e^{-M}} \right) \tag{A1.22}$$

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:

$$N_{0,a} = \begin{cases} R_0 e^{-Ma} & 0 \le a \le m-1 \\ \dfrac{R_0 e^{-Ma}}{1-e^{-M}} & a = m \end{cases} \quad . \tag{A1.23}$$

Numbers-at-age for subsequent years are then computed by means of equations (A1.1) to (A1.5) and (A1.8) to (A1.16) under the series of annual catches given.

The likelihood function

The ASPM is fitted to the fleet-specific generalised linear model (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:

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

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 at this stage 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 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*:

$$p_{y,a}^f = C_{y,a}^f \Big/ \sum_{a'} C_{y,a'}^f. \tag{A1.28}$$

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:

$$p_{y,\ell}^f = \sum_a p_{y,a}^f A_{a,\ell}^f \tag{A1.29}$$

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:

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

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 on 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 down-weight 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 down-weight 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 (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 $p_{y,\ell}^{obs}(f)$ values in excess of about 2% for these cells.

Adjustment to incorporate recruitment variability

To allow for stochastic recruitment, the number of recruits at the start of year y given by equation (A1.16) is replaced by:

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

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

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

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

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, and to allow for that computationally the resource is assumed to be 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 as described in the main paper. Commencing in 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. The basis for estimating IUU catches prior to 2002 is described in Brandão et al. (2002b). The illegal catch estimates for 2002 to 2004 are based on the number of illegal vessels as well as the duration of fishing activity estimated from the number of illegal vessels known to have operated in the South African EEZ. The estimated average tonnage of green weight is obtained from the performance achieved in that year by one of the vessels fishing legally. From 2005, there have been no reports of illegal vessels. However, these reports cover only times when the legal vessels were operating, and it is not obvious that the same situation can be assumed during periods when no monitoring was possible. Therefore, the same amount of illegal take is assumed for the years since 2005 as for 2004.

The CPUE GLM standardisation procedure described in Appendix 1 of Brandão et al. (2002b) has been reapplied to the commercial longline 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 (primarily killer and sperm whales) taking fish from lines as they are hauled (depredation).

Catch-at-length data sampled from commercial operations, grouped in 2 cm intervals, are available since the inception of the legal fishery. The samples contributing to these distributions have been weighted by the size of the catch for the areas from which they were taken. Table A.3 shows the basic biological parameter values for toothfish in Subarea 48.3 (Agnew et al., 2006), which are assumed to apply to the Prince Edward Islands toothfish as well.

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 2 cm width only and number 43 in total, and amounts to over-weighting such data. Inspection of the selectivity curves suggests that (for most fits considered) effectively only about eight age-classes contribute to the catches each year. The somewhat coarse 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 reference set 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 are detailed in the text of this appendix. 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	24 271.2	24 271.2	24 271.2	24 271.2
1998	2 818.9	2 818.9	2 818.9	2 818.9
1999	1 970.4	1 970.4	1 970.4	1 970.4
2000	2 771.6	3 233.5	3 695.5	4 619.3
2001	703.9	938.5	1 173.2	1 642.4
2002	506.2	759.3	1 012.4	1 518.5
2003	568.9	853.3	1 137.8	1 706.7
2004	423.6	635.4	847.2	1 270.8
2005	390.7	586.1	781.5	1 172.2
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)	152.0
κ (yr^{-1})	0.067
t_0 (yr)	-1.49
Weight (in gm) length (in cm) relationship	
c	25.4×10^{-6}
D	2.8
Age at maturity (yr)	13
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 factor discussed in the text). The results shown assume a cetacean depredation factor z = 1, i.e. recent losses to cetacean depredation are equal to the landed longline catch. Note that as the models are fitted to datasets or with weights that differ, the likelihoods are not comparable.

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^{sp}_{2007}/K^{sp}		0.677	0.572	0.374	0.149
$B^{\exp}_{2007}$ (tonnes)	Longline	74 231	41 375	18 185	10 505
	Pot	129 883	71 131	24 433	5 218
B^{sp}_{1997}/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 on the average of the two selectivity functions estimated.
†† Input parameter

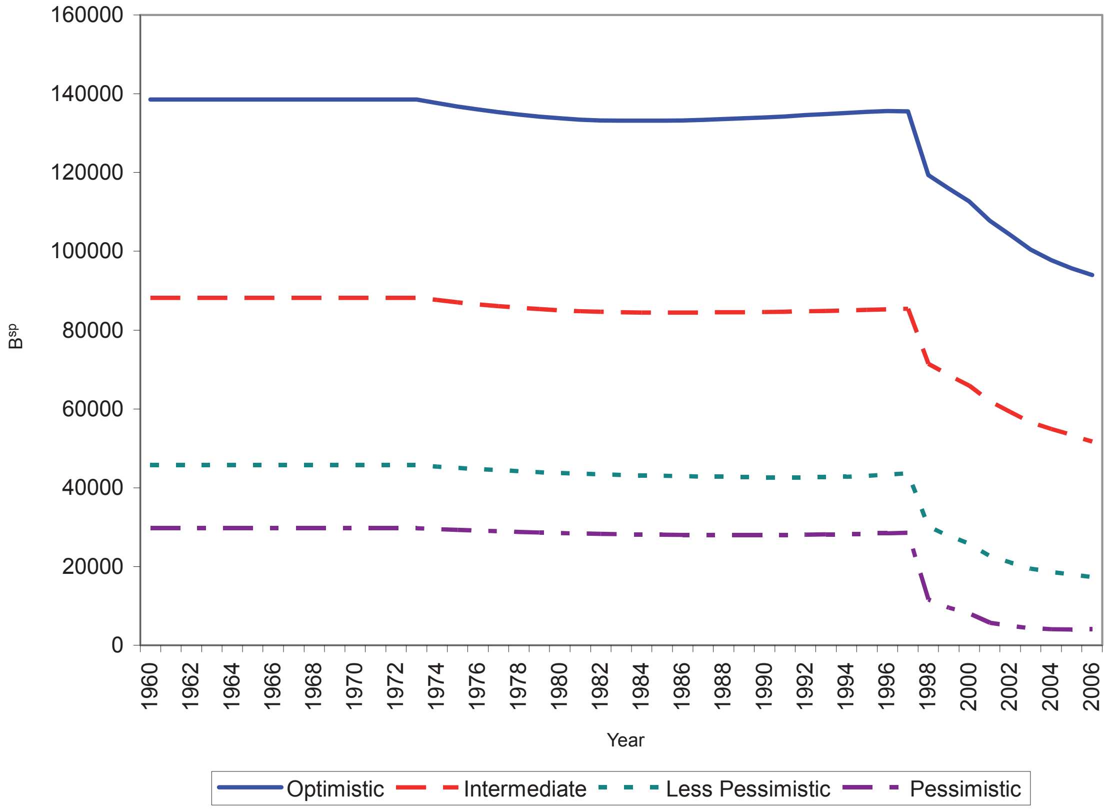

Figure A.1: Spawning biomass estimates (note that recruitment can vary prior to the onset of harvesting). Estimates are given for the Optimistic, Intermediate, Less Pessimistic and Pessimistic scenarios (details of the conditioning of these scenarios to the data are provided in the text; see also the caption to Table A.4). All results shown assume a cetacean depredation factor $z = 1$, i.e. recent losses to cetacean depredation are equal to the landed longline catch.

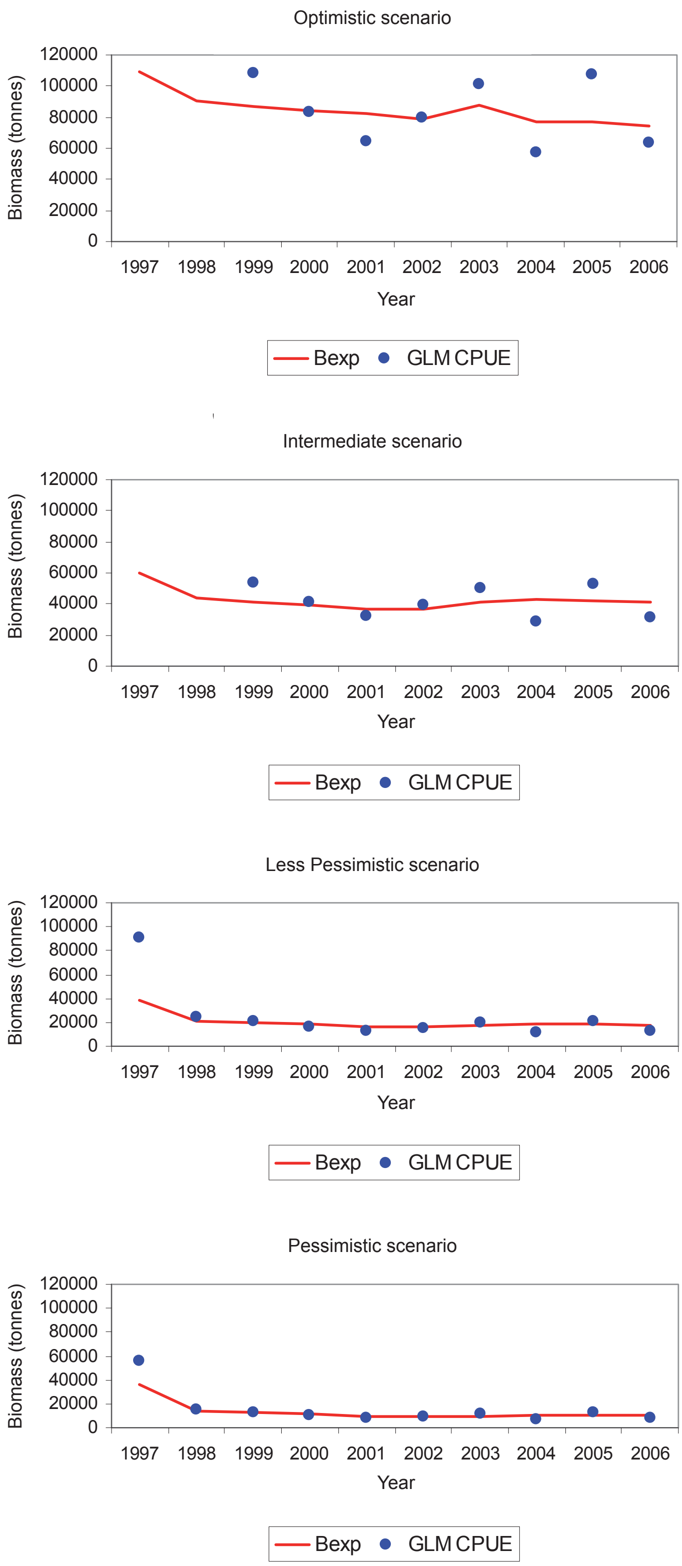

Figure A.2: Longline fishery exploitable biomass and the Generalised Linear Model (GLM)-standardised CPUE indices to which the population model is fit (divided by the estimated catchability q to express them in biomass units) for the Optimistic, Intermediate, Less Pessimistic and Pessimistic scenarios.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

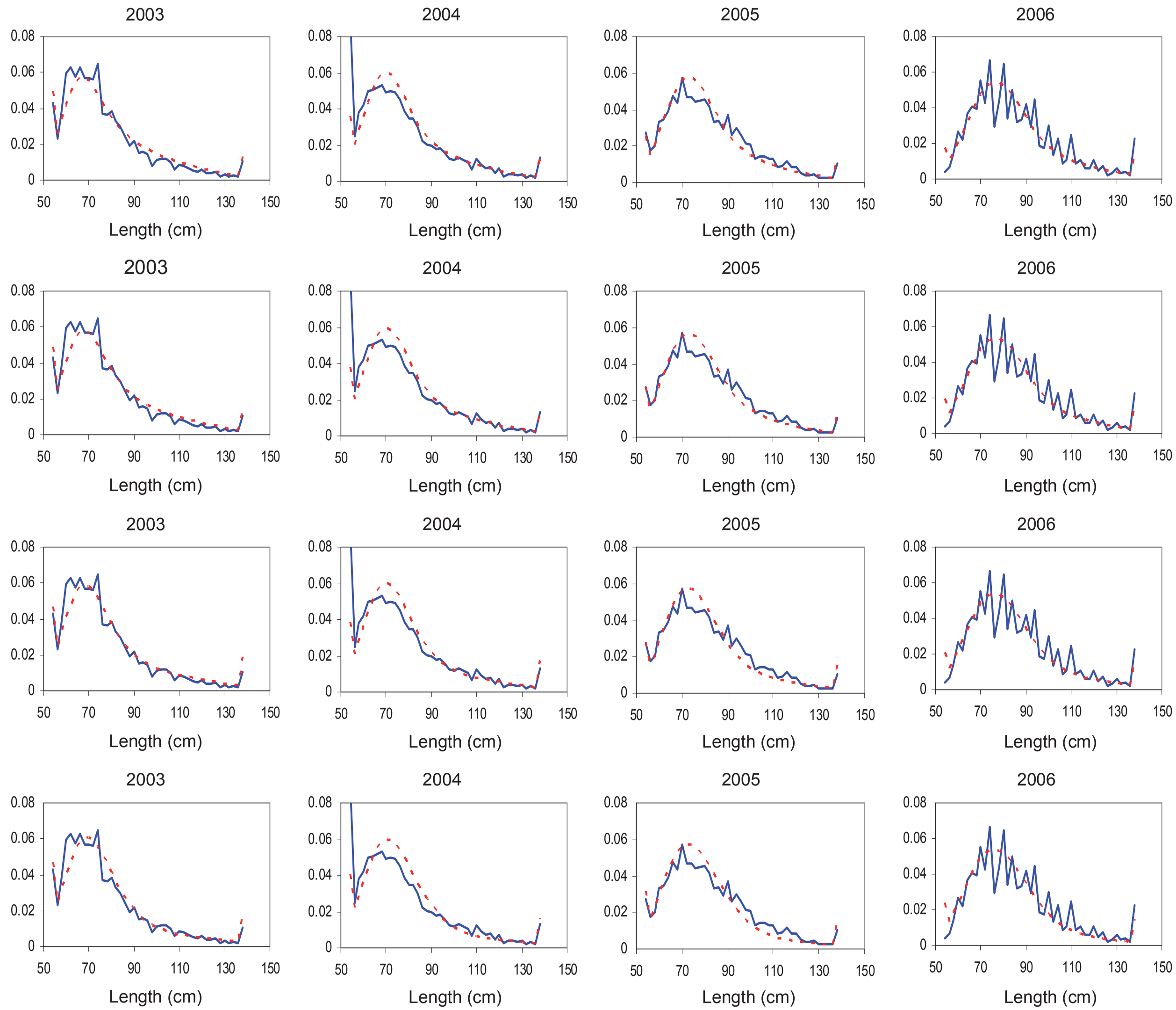

Figure A.3: Observed (line) and assessment predictions for the annual catch-at-length proportions in the longline fishery for the years 2003 to 2006 for the Optimistic (top), Intermediate (second row), Less Pessimistic (third row) and Pessimistic (bottom) scenarios. Note that lengths below 54 and above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

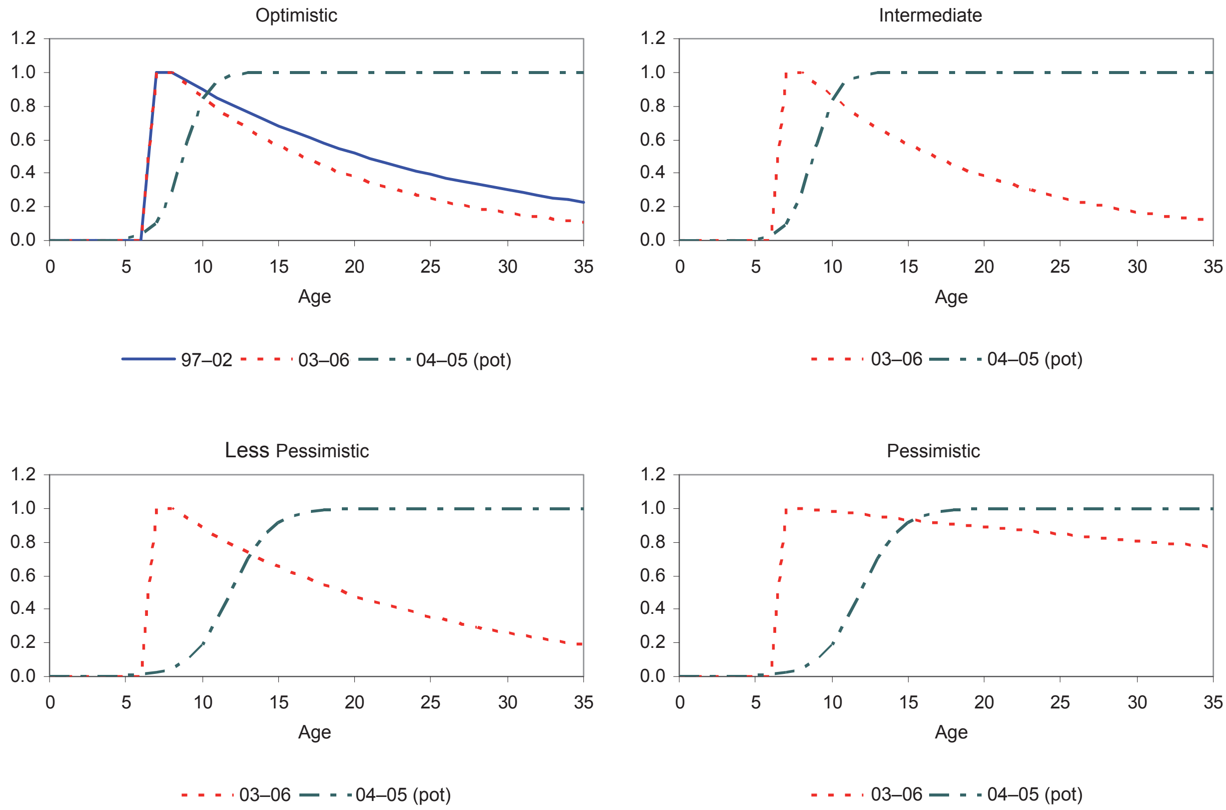

Figure A.4: Estimated selectivity curves for the periods 1997–2002 and 2003–2006 for the longline fishery, and for the period 2004–2005 for the pot fishery (note that the nearly flat selectivity at large ages for this fishery is as estimated; it is not an input assumption). Curves are shown for the Optimistic,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