CCAMLR Science, Vol. 9 (2002): 11–32

A FIRST ATTEMPT AT AN ASSESSMENT OF THE PATAGONIAN TOOTHFISH (*DISSOSTICHUS ELEGINOIDES*) RESOURCE IN THE PRINCE EDWARD ISLANDS EEZ

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Abstract

The history of the fishery for Patagonian toothfish (*Dissostichus eleginoides*) in the Prince Edward Islands Exclusive Economic Zone (EEZ) is reviewed briefly. It is characterised by very large illegal catches and a sharply declining longline catch-per-unit-effort (CPUE) trend. Application of a simple age-structured production model (ASPM) provides a robust indication that the spawning biomass has been depleted to, at most, a few percent only of its pre-exploitation level. Projections suggest that the annual catch limit should be reduced to a maximum of about 400 tonnes. Implications for surveillance are discussed.

Résumé

L’historique de la pêcherie de la légine australe (*Dissostichus eleginoides*) dans la Zone économique exclusive (ZEE) des îles du Prince Édouard fait l’objet d’un bref examen. Cette pêcherie se distingue par des captures illicites très importantes et une tendance nettement à la baisse de la capture par unité d’effort (CPUE) de pêche à la palangre. L’application d’un modèle de production simple reposant sur la structure des âges (ASPM) indique clairement que la biomasse reproductrice a été surexploitée au point qu’il ne reste tout au plus qu’un pourcentage infime de son niveau de pré-exploitation. Les projections suggèrent de réduire la limite annuelle de capture à 400 tonnes au maximum. Les implications que cela aurait pour la surveillance sont discutées.

Резюме

Дается краткий обзор истории промысла патагонского клыкача (*Dissostichus eleginoides*) в Исключительной экономической зоне (ИЭЗ) о-вов Принс-Эдуард. Можно отметить очень большой объем незаконных уловов и тенденцию к быстрому сокращению вылова на единицу усилия (CPUE) для ярусного промысла. Применение простой модели повозрастной продуктивности (ASPM) ясно свидетельствует о том, что нерестовая биомасса была истощена, в лучшем случае, до всего нескольких процентов от ее предэксплуатационного уровня. Прогнозные оценки говорят о том, что годовое ограничение на вылов должно быть сокращено до примерно 400 т максимум. Обсуждаются последствия для наблюдения.

Resumen

Se resume la historia de la pesquería del bacalao de profundidad (*Dissostichus eleginoides*) en la zona económica exclusiva (ZEE) de las islas Príncipe Eduardo. Esta pesquería se caracteriza por un alto nivel de capturas ilegales y una marcada tendencia a la disminución de la captura por unidad de esfuerzo (CPUE) con palangres. La aplicación de un modelo de producción simple basado en la estructura por edades (ASPM) proporciona una buena indicación de que la biomasa del stock en desove ha disminuido a un nivel que, cuando mucho, corresponde a un porcentaje mínimo de su nivel antes de la explotación. Las estimaciones indican que se debe reducir el límite de captura a unas 400 toneladas. Se discuten las repercusiones para la vigilancia.

Keywords: CPUE, IUU fishing, maximum likelihood, Prince Edward Islands, production model, steepness, surveillance, toothfish, CCAMLR

INTRODUCTION

There is serious concern about the status of the Patagonian toothfish (*Dissostichus eleginoides*) resource in the Prince Edward Islands Exclusive Economic Zone (EEZ) because of the high level of illegal catches that have been taken from this region, and because of a large drop in longline catch-per-unit-effort (CPUE).

This paper presents a first attempt at a quantitative assessment of the resource, by applying a simple age-structured production model (ASPM). First a brief history of the fishery is given, followed by descriptions of the data available and the methodology applied. Results are considered for a base case assessment, as well as for a number of evaluations of sensitivity, and include projections under different levels of constant future catches. The implications of these results for the catch limit and for surveillance are discussed.

HISTORY OF THE FISHERY

The Fishery

In early 1996, the then South African Sea Fisheries Research Institute received applications from three operators wishing to initiate a toothfish fishery in the South African EEZ around the Prince Edward Islands. Anticipating this development, notification of the impending fishery had already been forwarded to CCAMLR in November 1995, as part of the Prince Edward Islands EEZ falls within the CCAMLR Convention Area. This notification followed the format of CCAMLR Conservation Measure 31/X. In keeping with the precautionary approach which has come to characterise most international fisheries agreements, Conservation Measure 31/X strives to ensure that fishery development does not outpace the flow of information necessary to manage the target resource in a sustainable manner.

Concomitant with the above developments, the clauses on access and access rights were being negotiated by the South African Fisheries Policy Development Committee for incorporation into the Marine Fisheries Policy for South Africa and the Marine Living Resources Act (Act 18 of 1998). Given the prevailing uncertainty as to the final policy on access rights, there was a delay of some five months in the processing of the above applications and before experimental permits to fish for toothfish in the Prince Edward Islands EEZ were granted.

In October 1996, five experimental permits were issued for harvesting of toothfish in the Prince Edward Islands EEZ. A catch level of 2 500 tonnes (i.e. 500 tonnes/operator) was set for the 1996/97 season, which was limited to the period from 30 October 1996 to 31 August 1997.

Fishery Development

The Prince Edward Islands EEZ fishery for toothfish by South African operators developed in the face of unprecedented levels of illegal fishing within the EEZ, along with unregulated fishing in the adjacent CCAMLR Convention Area and on the high seas (see below). For various reasons, it has not been possible to eliminate illegal fishing by vigorous patrolling of the remote Prince Edward Islands EEZ. However, a number of measures have been adopted to protect this toothfish resource. Such measures were 'precautionary' in nature and a major element of control rested on independent verification of fishing location and the carrying of scientific observers.

Nevertheless, despite some positive signs that South African ports are now seldom (if ever) being used for the discharge of illegally caught toothfish, illegal exploitation of the Prince Edward Islands EEZ continues. Intelligence reports and information from the neighbouring French and Australian EEZs have indicated that vessels conducting illegal fishing enter the Prince Edward Islands EEZ in greater numbers when no legitimate South African vessels are present in the area. There are also indications that such illegal vessels enter South African waters when the French authorities are patrolling their EEZ. In the interests of providing some protection for the resource, this forced South Africa in late 1997 to break with CCAMLR's closed season for the fishery (31 August 1997 to 1 April 1998) and from 31 August 1998 onwards to provide for year-round access.

The granting of year-round access to the five permit holders necessitated a reappraisal of the catch allocated to the operators concerned. A catch allocation of 600 tonnes was granted, and to achieve a year-round presence this was divided into quarterly allocations of 150 tonnes per operator. The setting of these catch allocations attempted to balance estimates of sustainable yield with the economic returns necessary to maintain a year-round fishing presence. This policy was implemented from December 1997 to November 1998, when the catch allocated to each operator was reduced to 550 tonnes since resource indicators suggested that potential sustainable harvest levels were likely to have been greatly reduced as a result of illegal catch levels. The catch limit for the 2000/01 season was 450 tonnes for each of the five operators. These resource indicators comprised longline CPUE levels recorded by the fishery, in the absence of direct scientific surveys of stock abundance.

The CPUE has dropped dramatically since the inception of the fishery, as detailed below. This is probably primarily due to the illegal fishery, though there is a more recent concern that appreciable amounts of the catch were being lost to killer whales (*Orcinus orca)* and sperm whales (*Physeter catodon)*. Two of the vessels have experimented with pot fishing to try to evade this toothed cetacean problem, but with limited success only. Improvements in pot design may help to alleviate this problem.

DATA

In the interests of simplicity, this initial analysis has ignored the split-year nature of the fishing season for toothfish. Thus catches in the 1998/99 season, for example, are denoted as taken in 1999. Furthermore, the limited data available for 1996 have been pooled with the data for 1997.

Catches

Illegal, unregulated and unreported (IUU) catches constitute the bulk of the toothfish removals from the Prince Edward Islands EEZ. Estimates of this take, and the basis/reference for their computation, are given in Table 1.

Table 2 combines these IUU catch estimates with legal catches (for calendar years) by South African operators.

CPUE

Appendix 1 details a Generalised Linear Model (GLM) standardisation of the longline CPUE data for the legal component of the toothfish fishery in the Prince Edward Islands EEZ. The results are reported in Table 3. While there are concerns as to whether longline CPUE is proportional to fish density, the values in Table 3 are assumed to be proportional to abundance in the analyses that follow, given the absence of any other data related to abundance trends.

Surveys

An exploratory scientific bottom trawl survey of the Prince Edward Islands EEZ was conducted by the commercial trawler *Iris* during April 2001. A crude analysis of the resulting data, based on swept-area methodology (with distance between wings taken to be the distance swept), suggested a biomass estimate of 1 168 tonnes, with a large associated CV of 213%. Some further details of the survey and the biomass estimation procedure used may be found in Leslie and Watkins (2001).

ASSESSMENT METHODOLOGY

This initial assessment for toothfish in the Prince Edward Islands EEZ applies a deterministic ASPM. ASPMs are now used widely in the assessment of marine resources, for example for whales (see de la Mare, 1989 and Punt, 1999, for methodology), for tuna (e.g. Punt et. al., 1995) and for orange roughy (e.g. Francis, 1992). The first application to toothfish (in Subarea 48.3) was undertaken by Gasiukov and Dorovskikh (2000). Details of the method as applied in this instance are given in Appendix 2. In the interests of simplicity, a pulse fishing approximation is used, which is sufficiently accurate for the purposes of an initial analysis such as this. ASPMs have an advantage over age-aggregated (or biomass-based) production models in that they allow for the delay between reduction in spawning biomass and hence year-class strength as a result of fishing, and the impact that this has on the exploitable biomass component of the resource because of the time taken for fish to reach the age of recruitment to the fishery. The use of a deterministic model assumes that the resource was at its average pre-exploitation level at the time

Table 1: Estimates of IUU fishing in the Prince Edward Islands EEZ from July 1996 to June 2001. The data from 1996/97 to 1999/2000 are from CCAMLR WG-FSA reports. The figures for 2000/01 were calculated as 2 fishing vessels x 40 fishing days x 2 fishing trips/year x 1.1 tonnes nominal catch/day. To determine the amount of toothfish taken from Subarea 58.6 within the Prince Edward Islands EEZ, a somewhat arbitrary proportion of 50% was taken of the estimated catch from the whole subarea, the majority of which lies outside the Prince Edward Islands EEZ.

Split-year	Year (as defined in this paper)	Subarea 58.7 (tonnes)	Subarea 58.6 (tonnes)	50% of Subarea 58.6 (tonnes)	EEZ (58.7 and 50% 58.6)
1996/97	1997	11 900	18 900	9 450	21 350
1997/98	1998	925	1 765	883	1 808
1998/99	1999	140	1 748	874	1 014
1999/00	2000	220	1 980	990	1 210
2000/01	2001	176	No data	(assumed) 176	352
Total		13 361		12 373	25 734

Table 2: Yearly catches of toothfish (in tonnes) estimated to have been taken from Prince Edward Islands EEZ for the analyses conducted in this paper. The legal catch indicated for 2001 is an estimate.

Year	Legal	Illegal	Total
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	1 558.7	1 210	2 768.7
2001	600.0	352	952.0
Total	7 047.2	25 734	32 781.2

Table 3: Relative abundance index (normalised to its mean) for toothfish provided by the standardised commercial CPUE series for the Prince Edward Islands EEZ.

Year	CPUE
1997	2.601
1998	0.938
1999	0.842
2000	0.455
2001	0.164

exploitation commenced. This might not be the case if recruitment fluctuates considerably about the stock-recruitment curve assumed, but there are insufficient data available in this instance to allow the model to be extended to estimate such an effect.

The model fitting process involved estimating a single parameter only (the pre-exploitation spawning biomass, K^{sp}) by maximising the likelihood of the fit of the GLM standardised CPUE of Table 3 to the trend in the exploitable component of biomass as predicted by the population model. All other parameters are specified on input. There is insufficient information in these few CPUE data points to attempt to estimate further parameters. This necessitates pre-fixing the stockrecruitment function steepness parameter h, which relates to the productivity of the resource (for a fixed natural mortality M, greater steepness corresponds to

Table 4: Biological and technological parameter values assumed for the assessments conducted, based on the values given in Table 34 of the WG-FSA-2000 report (SC-CAMLR, 2000 and A. Constable, pers. comm.). The base case analyses use the parameters for Subarea 48.3; those for Division 58.5.2 are used only for one sensitivity test. Note that for simplicity, both maturity and fishing selectivity are assumed to be knife-edge in age for the base case; for the sensitivity test for Division 58.5.2 the functional forms given in Table 34 of SC-CAMLR (2000) are used, except that the selectivity-at-age is modified as described in the text following equation A2.4.

Parameter	Subarea 48.3	Division 58.5.2
Natural mortality M (yr^{-1})	0.165	0.105
von Bertalanffy growth		
ℓ_∞ (cm)	194.6	194.6
κ (yr^{-1})	0.066	0.04114
t_0 (yr)	-0.21	-1.8
Weight–length relationship		
a	25×10^{-6}	25.9×10^{-6}
b	2.8	3.2064
Age-at-maturity (yr)	10	see Table 34
Age-at-first capture (yr)	6	see Table 34

greater sustainable yields). The value adopted for the base case fit of the model is $h = 0.6$. This is likely to be a little on the conservative side in comparison to teleosts generally. Sensitivity is shown to alternative choices of $h = 0.35$ and $h = 0.9$. It should be noted, however, that the model fits themselves are independent of the value of h assumed. This is because the age-at-recruitment assumed for the longline fishery (6 years) is greater than the duration of the fishery (only 5 years), so that the consequences of a drop in recruitment resulting from a reduction in spawning biomass through fishing have yet to impact on the exploitable component of the toothfish resource. Different values of h do, however, affect projections, which are shown for a range of future annual catch levels of 0, 400 and 800 tonnes.

The biological and technological parameter values assumed for the assessment are listed in Table 4. These are based on values adopted by the CCAMLR Working Group on Fish Stock Assessment (WG-FSA) for toothfish in Subarea 48.3 (see SC-CAMLR, 2000, Table 34). For this initial analysis, values corresponding to the central values for ranges given in Table 34 have been used. Given the dominant influence of the CPUE and catch data on the analyses that follow, neglecting the uncertainty in the values for these parameters is not an immediate major concern.

Sensitivity Tests

A number of sensitivity tests are conducted in addition to the base case assessment above, in the light of the considerable uncertainty associated with various model assumptions and inputs. In addition to variants of the $h = 0.6$ base case selection for steepness, the following are the tests run and their underlying rationale.

(i) Lower 2001 legal catch
The 600 tonne estimate for the 2001 legal catch (see Table 2) may not be reached. A 400 tonne figure is substituted.

(ii) Higher 2000 + 2001 catches and CPUEs
Total catches and CPUEs for these two years (Tables 2 and 3) are doubled to reflect the effects of predation of toothfish caught on the longlines by whales (see above). This is almost certainly too extreme an adjustment for this effect, but is considered here in the sense of 'bounding' any possible consequences.

(iii) Alternative IUU catches
Given the uncertainty about the levels of these catches (Table 1), they are first all doubled, and then all halved.

(iv) Alternative natural mortality values
Resource productivity is strongly dependent on the value of natural mortality. Here both ends of the range for Subarea 48.3 specified in Table 34 of WG-FSA's 2000 report (SC-CAMLR, 2000), 0.13 and 0.2, are considered.

(v) Alter CPUE trend
Given concerns that longline CPUE may not be proportional to local density (and hence abundance), the trend indicated by the standardised CPUE series of Table 3 is assumed to be biased either up or down by 10% per year.

(vi) Use of 2001 survey biomass results
The *Iris* trawl survey results are very imprecise, but two representative values are chosen (1 200 and 2 500 tonnes), and the model estimate of exploitable biomass for 2001 is forced to equal these values, in turn. Note that this extra datum serves to define K^{sp} uniquely, so that the CPUE data do not affect this fit.

(vii) Alternative biological and technological parameters
Values for the slower-growing and longer-lived toothfish resource in Division 58.5.2 (also taken from SC-CAMLR, 2000, Table 34 and A. Constable, pers. comm.) are used in place of these for Subarea 48.3.

RESULTS AND DISCUSSION

Results for the base case fit of the model and the sensitivity tests are shown in Table 5, together with those for projections to 2010 and to 2020 under a future constant annual catch of 400 tonnes. The statistics reported are detailed in the table caption.

Figure 1 shows the base case fit and projections in terms of both the spawning and exploitable components of the biomass. Figure 2 shows variants of this base case for steepness h = 0.35 and 0.9, in terms of the exploitable biomass. Figure 3 shows results for exploitable biomass for the four other sensitivity tests which show the greatest differences from the base case in terms of projections.

One feature of these plots that needs explanation is the projected 'bump' some 5–10 years into the future. This arises because of time-lags in the model. The high age-at-recruitment coupled to an even higher age-at-maturity mean that initially the fishery benefits from strong recruiting year classes spawned before or only shortly after the onset of fishing. However, in time, the negative consequences of reduced recruitment because of the fall in spawning biomass as a result of fishing, become evident.

All analyses assume that the fishery exploits a single isolated stock. However, sensitivity tests which vary historic catch levels do serve as a surrogate for alternative assumptions concerning stock boundaries, and in fact make little difference to qualitative conclusions concerning stock status.

Note that the negative log likelihood values for the sensitivity tests that fit to representative biomass estimates from the *Iris* swept-area survey differ by less than 2 from those for the base case. This indicates that the survey estimates are compatible with the catch and CPUE history of the fishery. Notable improvements to the fit to the CPUE series are achieved by reducing the IUU catch estimate, lowering natural mortality, or making (large) allowance for whale predation over the last two years.

Overall, however, the broad results of the analyses are clear across all cases considered in Table 5: a spawning biomass now reduced to, at most, a few percent of its pre-exploitation level. Clearly the large catch taken in 1997 (Table 2) together with the large fall in CPUE from 1997 to 1998 (Table 3) are particularly influential in leading to this conclusion. Figure 4 plots the nominal CPUE by month over this two-year period, and confirms a systematic pattern of decline as these large removals were made during 1997. Improvements on the initial and somewhat simple nature of these analyses would not seem likely to lead to any substantial change to this conclusion. For this result to change appreciably would require one or more major changes in the current consideration of likely past levels of illegal fishing, the relationship between longline CPUE and abundance, and absolute abundance estimates from scientific surveys.

CONCLUDING REMARKS

Projections shown in Figures 1 to 3 suggest that, at the very least, annual catches need to be reduced to 400 tonnes per year if the toothfish resource in the Prince Edward Islands EEZ is to have any hope of some recovery.

Clearly, appreciable levels of IUU fishing in the future will render such recovery impossible. Surveillance is essential. To date two aerial and one sea reconnaissance trips have been undertaken by South Africa, the last one as recent as 24 August 2001. On the first aerial survey in September 1996, illegal operators were photographed in the Prince Edward Islands EEZ. No illegal operators were sighted during the at-sea reconnaissance in 2000. No prosecutions have as yet been instigated by South Africa on any illegal activities in the Prince Edward Islands EEZ.

Table 5: Estimates for both the base case and sensitivity tests obtained when the population model is fitted to the CPUE data for toothfish from the Prince Edward Islands EEZ. The estimates shown are for the pre-exploitation spawning toothfish abundance (K^{sp}), the pre-exploitation exploitable toothfish abundance (K^{exp}), the spawning stock depletion $\left(B^{sp}_{2002}/K^{sp}\right)$ and the exploitable stock depletion $\left(B^{exp}_{2002}/K^{exp}\right)$ at the beginning of the year 2002, and the projected exploitable stock depletion at the beginning of the years 2010 $\left(B^{exp}_{2010}/K^{exp}\right)$ and 2020 $\left(B^{exp}_{2020}/K^{exp}\right)$ under a future annual catch of 400 tonnes. The 95% confidence interval is given for K^{sp}, evaluated using the likelihood profile method. MSYL is the exploitable biomass yielding MSY expressed as a fraction of K^{exp}. Biomass-related units are tonnes.

Model	Parameter Estimates (95% confidence interval)								
	K^{sp}	K^{exp}	-ln L	MSY	MSYL	B^{sp}_{2002}/K^{sp}	B^{exp}_{2002}/K^{exp}	B^{exp}_{2010}/K^{exp}	B^{exp}_{2020}/K^{exp}
Base case h = 0.6	15 153 (14 002; 28 382)	18 758	-4.015	529	0.392	0.010	0.116	0.162	0.156
Changed steepness									
h = 0.35	15 153 (14 002; 28 382)	18 758	-4.105	261	0.448	0.010	0.116	0.105	0.000
h = 0.9	15 153 (14 002; 28 382)	18 758	-4.105	792	0.302	0.010	0.116	0.313	0.471
Lower 2001 legal catch	15 153 (14 002; 28 382)	18 758	-4.015	529	0.392	0.012	0.128	0.178	0.183
Higher 2000 and 2001 catch and CPUE (whale predation)	26 341 (24 180; 31 825)	32 609	-5.948	919	0.392	0.043	0.132	0.235	0.339
Double IUU catch	41 642 (38 036; 49 431)	51 552	-1.861	1 454	0.392	0.001	0.063	0.117	0.212
Half IUU catch	14 192 (13 193; 15 245)	17 569	-5.509	495	0.392	0.003	0.056	0.006	0.000
Lower M (0.13)	15 973 (15 241; 25 840)	18 457	-6.539	423	0.382	0.008	0.074	0.079	0.000
Higher M (0.2)	15 440 (13 667; 49 330)	20 686	-1.946	693	0.403	0.014	0.166	0.217	0.318
Increase in CPUE trend	24 297 (20 201; 34 543)	30 079	-2.936	848	0.392	0.022	0.108	0.169	0.243
Decrease in CPUE trend	17 296 (13 543; 123 045)	21 412	1.201	604	0.392	0.006	0.093	0.126	0.119
Fit 2001 survey biomass = 1 200	23 142	28 649	-3.343	808	0.392	0.0003	0.049	0.056	0.007
Fit 2001 survey biomass = 2 500	24 044	29 765	-2.688	839	0.392	0.016	0.096	0.147	0.207
Division 58.5.2 biological parameters	24 502 (23 691; 26 462)	31 780	-5.308	499	0.338	0.013	0.035	0.000	0.000

Because of the expense, such State surveillance can at best be infrequent, and reliance still needs to be placed on the deterrent effect of having a year-round legal fishing presence. This, however, will be difficult to achieve given the level of catch limit reduction that appears necessary.

ACKNOWLEDGEMENTS

We wish to thank Linda Staverees and Jan Wissema for data extraction, scientific observers for collection of fishery data and officers and crew on the fishing vessels for their assistance. Stuart Hanchet and Geoff Kirkwood are thanked for their comments on an earlier version of the paper. Financial support from the South African National Antarctic Programme is also gratefully acknowledged.

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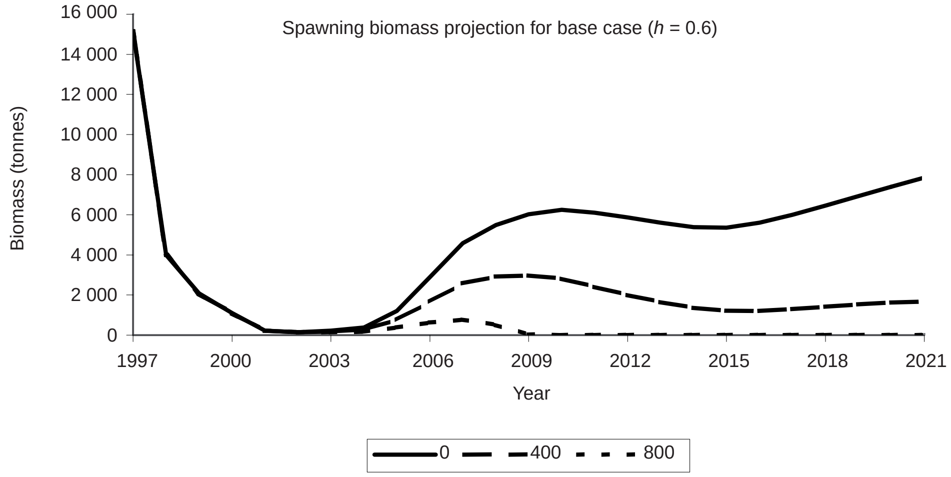


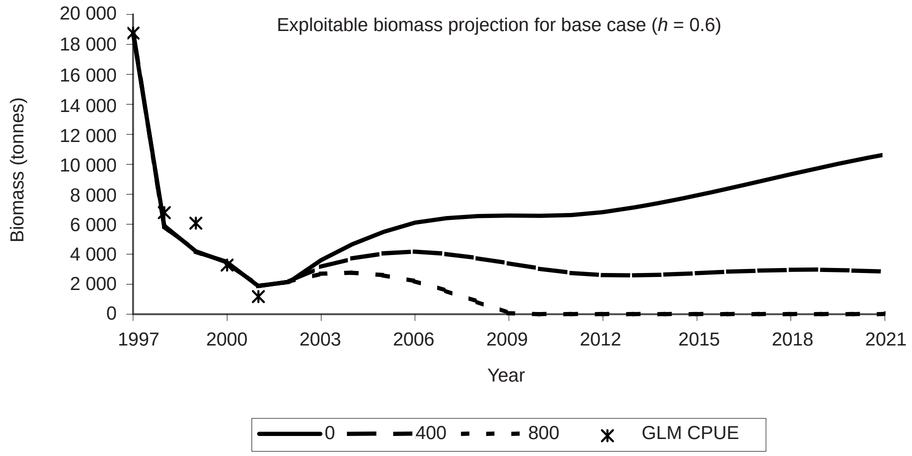
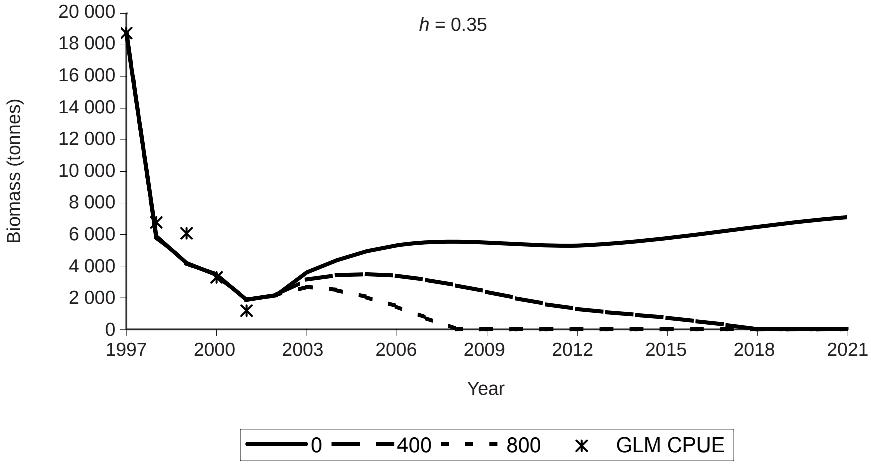


Figure 1: Population model fits and 20-year projections in terms of both the spawning and exploitable components of biomass of the toothfish stock of the Prince Edward Islands EEZ under the scenario of the base case model with the steepness parameter h = 0.6. Projections are shown for various levels of constant annual future catch in tonnes. The GLM standardised CPUE values (divided by the estimated catchability coefficient q) to which the population model is fitted are also shown.



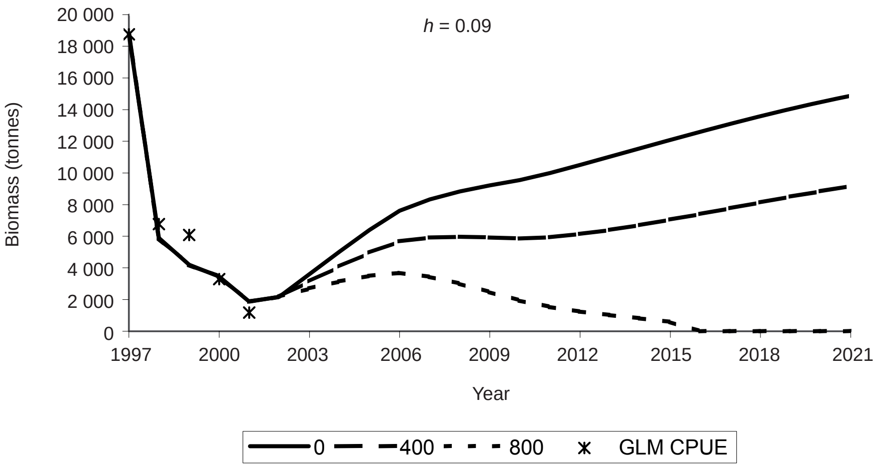


Figure 2: Population model fits and 20-year projections in terms of the exploitable component of biomass of the toothfish stock of the Prince Edward Islands EEZ under the scenario of the base case model with the steepness parameter h = 0.35 and h = 0.9. Projections are shown for various levels of constant annual future catch (in tonnes). The GLM standardised CPUE values (divided by the estimated catchability coefficient q) to which the population model is fitted are also shown.

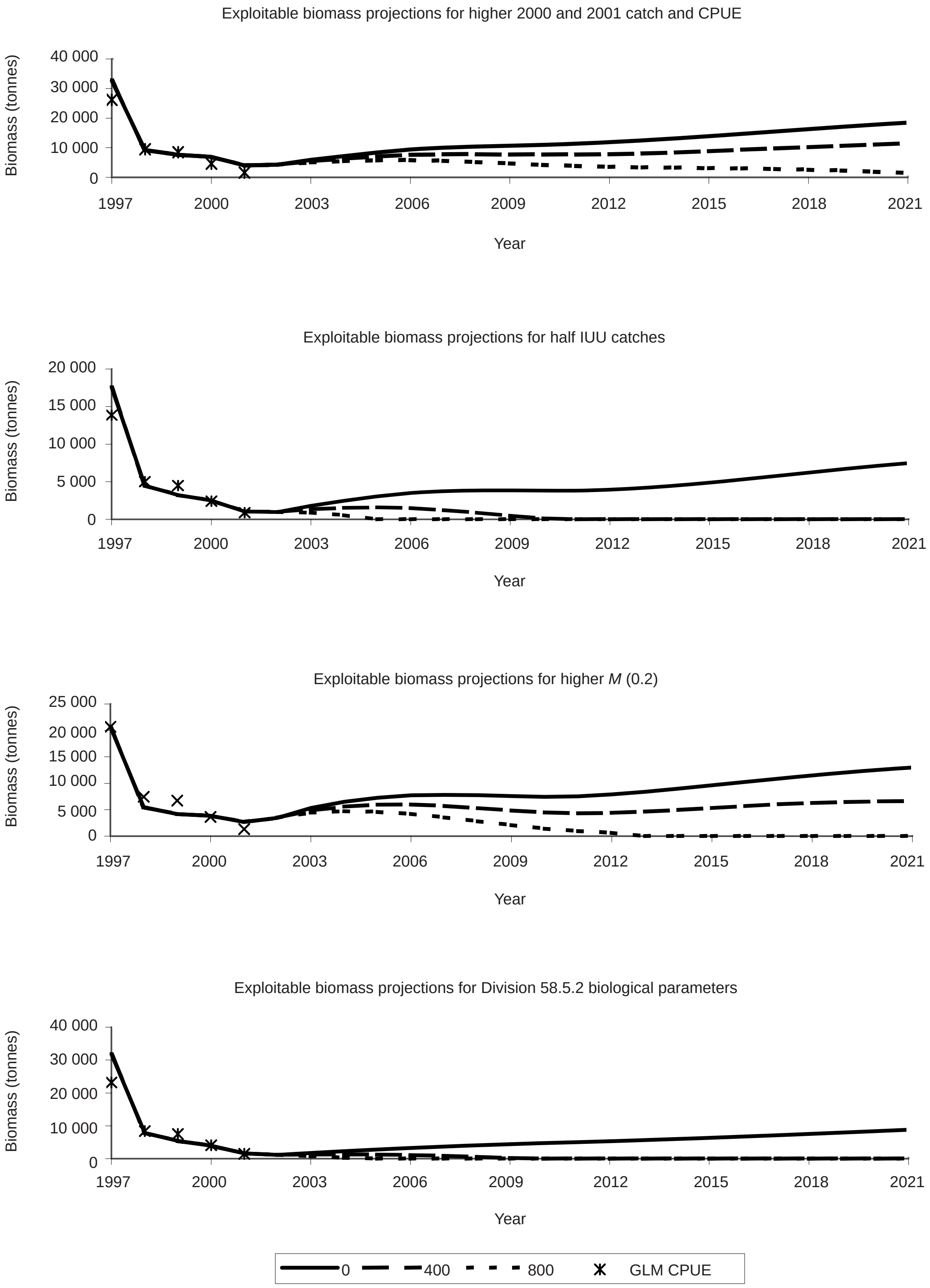


Figure 3: Population model fits and 20-year projections in terms of the exploitable component of biomass of the toothfish stock of the Prince Edward Islands EEZ under the different scenarios of the four of the sensitivity tests performed which show the largest differences from the base case in terms of projections. Projections are shown for various levels of constant annual future catch (in tonnes). The GLM standardised CPUE values (divided by the estimated catchability coefficient q) to which the population model is fitted are also shown.

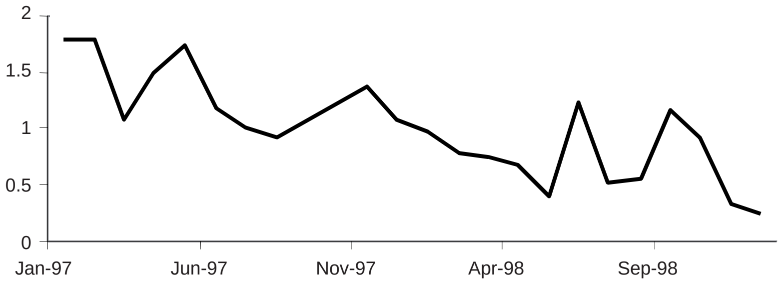


Figure 4: Nominal CPUE series by month for the first two years of the fishery (normalised to the mean for these two years).

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APPENDIX 1

GLM STANDARDISATION OF LONGLINE CPUE DATA

MODEL TO STANDARDISE THE CPUE

Two GLMs have been applied to the CPUE data for toothfish in the Prince Edward Islands EEZ. The initial model, referred to as the 'base case model', includes the main effects of all the explanatory variables considered (excluding depth), as well as some interactions, but no interaction between year and vessel. The second model, referred to as the 'full model', includes the interaction between year and vessel. This model was fitted to the data to investigate vessel–year interactions. The standardised CPUE indices of abundance for the base case model are then used as an input to a population model to assess the state of the stock.

The Base Case Model

The base case model considered in this paper is given by:

$$\ln(CPUE + \delta) = \mu + \alpha_{vessel} + \beta_{year} + \gamma_{month} + \lambda_{area} + \eta_{year \text{x} area} + \theta_{year \text{x} month} + \varphi_{month \text{x} area} + \varepsilon \qquad \text{(A1.1)}$$

where:

CPUE is catch rate measured in kg/hook;

μ is the intercept;

vessel is a factor with five levels associated with each of the vessels that have operated in the fishery (to an appreciable extent – see below for further details):

Aquatic Pioneer
Arctic Fox
Eldfisk
Isla Graciosa
Koryo Maru II;

year is a factor with four levels associated with the years 1997–2000;

month is a factor with 12 levels (January–December);

area is a factor with four levels associated with the four spatially distinct fishing areas:

A: 43–48°S latitude and 32–37°E longitude
B: 43–45.3°S latitude and 37–40.3°E longitude
C: 45.3–48°S latitude and 37–40.3°E longitude
D: 43–48°S latitude and 40.3–43.3°E longitude;

*year*x*area* is the interaction between year and area (this allows for the possibility of different trends over time for the different areas);

*year*x*month* is the interaction between year and month;

*month*x*area* is the interaction between month and area;

δ is a small constant added to the toothfish CPUE to allow for the occurrence of zero CPUE values; and

ε is an error term assumed to be normally distributed.

Table A1.1: Estimated area (n miles²) for the Prince Edward Islands EEZ.

Area	Area Size (n miles²)
A: 43–48°S latitude and 32–37°E longitude	895.85
B: 43–45.3°S latitude and 37–40.3°E longitude	1 091.62
C: 45.3–48°S latitude and 37–40.3°E longitude	1 621.81
D: 43–48°S latitude and 40.3–43.3°E longitude	2 931.40

The Full Model

The full model is given by:

$$\ln(\text{CPUE} + \delta) = \mu + \alpha_{vessel} + \beta_{year} + \gamma_{month} + \lambda_{area} + \eta_{yearxarea} + \theta_{yearxmonth} + \varphi_{monthxarea} + \varpi_{yearxvessel} + \varepsilon \quad \text{(A1.2)}$$

where *yearxvessel* is the interaction between year and vessel.

Variants of this model omitting the interaction term and incorporating the main effects only, as well as single factor models, are also considered. The value of δ was taken to be 10% of the average toothfish CPUE.

The standardised CPUE for the base case model is calculated by summing over the four areas within a year and month, weighting by the total area, and then averaging over the months:

$$CPUE_y = \sum_{month}\left[\sum_{area}\left\{\exp\begin{bmatrix}\mu + \overline{\alpha} + \beta_{year} + \gamma_{month} + \lambda_{area} + \eta_{year\times area} \\ + \theta_{year\times month} + \varphi_{month\times area}\end{bmatrix} - \delta\right\} * A_{area}\right]\Big/ 12 \quad \text{(A1.3)}$$

where $\overline{\alpha}$ is the median vessel factor estimate and A_{area} is the size of the respective area.

In some instances there were insufficient data to estimate all the interaction terms. Such missing values were then computed by linear interpolation from adjacent values. Table A1.1 gives the breakdown of the size of each area (A_{area}).

MODEL IMPLEMENTATION AND RESULTS

Commercial longline CPUE data for the Prince Edward Islands EEZ for the years 1997 to July 2001 have been used. Data are available for 1996, but only for the latter months and therefore the final analyses did not include CPUE data from this year. To include the CPUE for the first part of 2001, two analyses were performed: one including CPUE data from 1997 to 2000 and the other from 1997 to 2001. The trend in the standardised CPUE indices for the first six months of each year of the latter analysis were then used to obtain an estimated CPUE index for 2001 comparable to the 1997–2000 standardised indices based on data for all months. Because of the interactions present in the GLM between vessel and other factors, especially with year, and because of the sparseness of CPUE data for some vessels, the analyses were also restricted to the CPUE data from vessels that had more than 20 records. A total of 458 records was available for the 1997–2000 CPUE data, with the value of δ equal to 0.0167. When the 2001 CPUE data were included in the analyses, 522 records were available.

To determine the importance of each of the explanatory variables in the model, each individual variable was fitted to the CPUE data time series. The percentage of the total variation of toothfish CPUE accounted for by each individual model is shown in Table A1.2. The explanatory variables that account for most of the total variance in the CPUE time series for the single-parameter models are vessel and year: 14% and 13% respectively. The base case model accounts for 49.2% of the total variation in the CPUE series. Table 3 and Figure A1.1 show the standardised CPUE series. When year–vessel interactions are taken into account, separate standardised CPUE trends have to be computed for each vessel. Although these interactions have a large effect (note increase in r^2_{adj} in Table A1.2) on the GLM fit, the standardised CPUE trends for each (apart for last year of *Aquatic Pioneer*) show a downward trend as do the standardised CPUE indices of the base case GLM (Figures A1.1 and A1.2), so results are appreciably affected.

Table A1.2: The percentage of the total variation (adjusted by a degrees of freedom correction factor) of the CPUE time series of toothfish in the Prince Edward Islands EEZ accounted for by various GLMs. Results shown are for the GLMs applied to the 1997–2000 CPUE data.

Model	r^2_{adj}
$\mu + \alpha_{vessel}$	0.140
$\mu + \beta_{year}$	0.131
$\mu + \gamma_{month}$	0.024
$\mu + \lambda_{area}$	0.028
$\mu + \phi_{depth}$	0.002
$\mu + \alpha_{vessel} + \beta_{year} + \lambda_{area} + \gamma_{month}$	0.329
$\mu + \alpha_{vessel} + \beta_{year} + \lambda_{area} + \gamma_{month} + \eta_{yearxarea} + \theta_{yearxmonth} + \varphi_{monthxarea}$ (Base case)	0.492
$\mu + \alpha_{vessel} + \beta_{year} + \lambda_{area} + \gamma_{month} + \eta_{yearxarea} + \theta_{yearxmonth} + \varphi_{monthxarea} + \omega_{yearxvessel}$ (Full model)	0.593

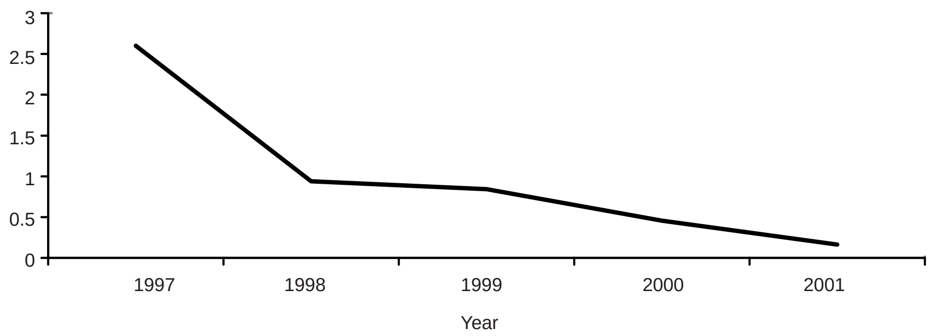

Figure A1.1: Standardised CPUE series (normalised to its mean) obtained when the base case GLM is fitted to the CPUE data.

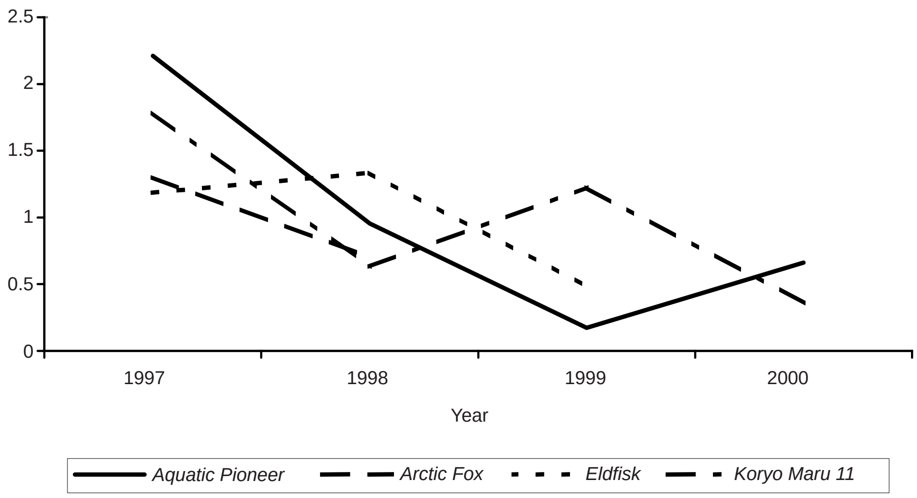

Figure A1.2: Standardised CPUE series (each normalised to its mean) for each vessel obtained when the full GLM is fitted to the CPUE data. The *Isla Graciosa* is not shown because it fished in 2000 only.

APPENDIX 2

THE AGE-STRUCTURED PRODUCTION MODEL (ASPM) ASSESSMENT METHODOLOGY

THE BASIC DYNAMICS

The toothfish population dynamics are given by the equations:

$$N_{y+1,0} = R(B^{sp}_{y+1}) \qquad \text{(A2.1)}$$

$$N_{y+1,a+1} = (N_{y,a} - C_{y,a})e^{-M} \qquad 0 \le a \le m-2 \qquad \text{(A2.2)}$$

$$N_{y+1,m} = (N_{y,m} - C_{y,m})e^{-M} + (N_{y,m-1} - C_{y,m-1})e^{-M} \qquad \text{(A2.3)}$$

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 (A2.10) 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') (m = 35 was used).

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:

$$C_{y,a} = S_a F_y N_{y,a} \qquad \text{(A2.4)}$$

where:

F_y is the proportion of the resource above age a_r harvested in year y; and

S_a is the commercial selectivity at age a; this is assumed to be knife-edged for the base case, so that $S_a = 0$ for $a < a_r$ and $S_a = 1$ for $a \ge a_r$; for the sensitivity test for Division 58.5.2 values, the form specified in Table 34 of SC-CAMLR (2000) is used. A problem does, however, arise if the values in Table 34 are used exactly as specified. This occurs because this paper uses a pulse fishing model (equations A2.2 and A2.3) in contrast to the continuous model used to derive the selectivity estimates in Table 34. While the models are near equivalent for low levels of fishing mortality, they differ for the very high levels that occur for the fishery under examination here. To better mimic the Division 58.5.2 assumptions in these circumstances, selectivity S_a is set to 1 at all ages $a \ge 7$, and the Table 34 values for $a \le 6$ are scaled appropriately.

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

$$\ell(a) = \ell_\infty[1 - e^{-\kappa(a-t_0)}] \qquad \text{(A2.5)}$$

$$w_a = c\ell(a)^d \qquad \text{(A2.6)}$$

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

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

$$C_y = \sum_{a=0}^{m} w_a C_{y,a} = \sum_{a=0}^{m} w_a S_a F_y N_{y,a} \qquad \text{(A2.7)}$$

which can be re-written as:

$$F_y = \frac{C_y}{\sum_{a=0}^{m} w_a S_a N_{y,a}} \,. \qquad \text{(A2.8)}$$

STOCK–RECRUITMENT RELATIONSHIP

The spawning biomass in year y is given by:

$$B_y^{sp} = \sum_{a=1}^{m} w_a f_a N_{y,a} \qquad \text{(A2.9)}$$

where f_a is the proportion of fish of age a that are mature; this is assumed to be knife-edged for the base case, so that $f_a = 0$ for $a < a_m$ and $f_a = 1$ for $a \geq a_m$; for the sensitivity test for Division 58.5.2 values, the form specified in Table 34 of SC-CAMLR (2000) is used.

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

$$R(B_y^{sp}) = \frac{\alpha B_y^{sp}}{\beta + B_y^{sp}} \,. \qquad \text{(A2.10)}$$

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 (A2.11)–(A2.15) below. If the initial (pristine) recruitment is $R_0 = R(K^{sp})$, then steepness is the recruitment (as a fraction of R_0) that results when spawning biomass is 20% of its pristine level, i.e.:

$$hR_0 = R(0.2K^{sp}) \qquad \text{(A2.11)}$$

from which it can be shown that:

$$h = \frac{0.2(\beta + K^{sp})}{\beta + 0.2K^{sp}} \,. \qquad \text{(A2.12)}$$

Rearranging equation (A2.12) gives:

$$\beta = \frac{0.2K^{sp}(1-h)}{h-0.2} \qquad \text{(A2.13)}$$

and solving equation (A2.10) 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:

$$\gamma K^{sp} = R_0 = \frac{\alpha K^{sp}}{\beta + K^{sp}} \tag{A2.14}$$

where:

$$\gamma = \left\{ \sum_{a=1}^{m-1} w_a f_a e^{-Ma} + \frac{w_m f_m e^{-Mm}}{1-e^{-M}} \right\}^{-1} . \tag{A2.15}$$

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:

$$K^{sp} = R_0 \left(\sum_{a=1}^{m-1} w_a f_a e^{-Ma} + \frac{w_m f_m e^{-Mm}}{1-e^{-M}} \right) \tag{A2.16}$$

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:

$$N_{0,a} = \begin{cases} R_0 e^{-Ma} & 0 \le a \le m-1 \\ \dfrac{R_0 e^{-Ma}}{1-e^{-M}} & a = m \end{cases} . \tag{A2.17}$$

Numbers-at-age for subsequent years are then computed by means of equations (A2.1)–(A2.4) and (A2.7)–(A2.10) under the series of annual catches given. In cases where equation (A2.8) 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.

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

$$B_y^{\exp} = \sum_{a=0}^{m} w_a S_a N_{y,a} = \sum_{a=a_r}^{m} w_a N_{y,a} . \tag{A2.18}$$

THE LIKELIHOOD FUNCTION

The 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:

$$I_y = \hat{I}_y e^{\varepsilon_y} \text{ or } \varepsilon_y = \ln(I_y) - \ln(\hat{I}_y) \tag{A2.19}$$

where:

I_y is the standardised CPUE series index for year y;

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

$\hat{B}_y^{\exp}$ 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:

$$\ln \hat{q} = \frac{1}{n} \sum_y \left(\ln I_y - \ln \hat{B}_y^{\exp} \right) \tag{A2.20}$$

where:

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

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

$$\hat{\sigma} = \sqrt{\frac{1}{n} \sum_y \left(\ln I_y - \ln \hat{q} \hat{B}_y^{\exp} \right)^2} \tag{A2.21}$$

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

$$-\ln L = \sum_y \left[\frac{1}{2\sigma^2} \left(\ln I_y - \ln \left(q B_y^{\exp} \right) \right)^2 \right] + n (\ln \sigma) \tag{A2.22}$$

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

Confidence intervals for some of the parameters estimated have been evaluated using the likelihood profile method.