A TWO-FLEET ASPM ASSESSMENT OF THE TOOTHFISH (*Dissostichus eleginoides*) RESOURCE IN THE PRINCE EDWARD ISLANDS VICINITY

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ABSTRACT

The ASPM assessment of the Prince Edward Islands toothfish resource by Brandão and Butterworth (2004) that permitted annual fluctuations about a deterministic stock-recruitment relationship is updated to take account of further catch, GLM standardised CPUE and catch-at-length information that has become available for the years 2004 and 2005. The assessment is also generalised to allow for a second fleet to accommodate data from a pot fishery that has been in operation since November 2004. Results obtained show a much greater selectivity for larger toothfish for the pot than for the longline fishery – a feature which has important implications for the status of the population. The possible extent of cetacean predation and its consequences are also investigated. Twenty year biomass projections under the assumption of various constant annual catches for the two-fleet model are computed. Although higher sustainable yields may be possible, it is suggested that a prudent management approach at this stage would be for the annual legal catch not to exceed 500 tonnes for the time being, together with encouragement that this be taken more by pots than by longline to reduce the impact of cetacean predation. Industry observations of the extent of cetacean predation for the longline fishery have proved helpful, and should be extended to a more formal data recording basis in the future.

INTRODUCTION

An updated and extended Age-Structured Production Model (ASPM) assessment of the Prince Edward Islands (PEI) toothfish (*Dissostichus eleginoides*) resource is presented in this paper. Compared to the previous assessment of Brandão and Butterworth (2004), further data inputs available for the last few months in 2004 and data until April 2005 are now also taken into account. From November 2004 one vessel in the fishery adopted a pot fishing strategy in an attempt to minimise the extent of cetacean predation occurring during fishing operations. To take this into account, the ASPM presented by Brandão and Butterworth (2004) (in which annual fluctuations about a deterministic stock-recruitment relationship were included) is generalised to allow for two fleets in the fishery. Details of the methodology are given in Appendix 1.

Several sensitivities tests of the basecase model are performed to investigate the implications for the status of the resource if certain assumptions are modified.

DATA UPDATES

Further data available from November 2004 to April 2005, which were not available for previous assessments of toothfish in the Prince Edward Islands vicinity, have been incorporated in the present analyses. The estimate of the illegal catch for 2004 has been left unchanged from that used by Brandão and Butterworth (2004), which assumes three vessels fishing illegally, each making a trip of 40 days duration and landing an average of 1.3 tonnes green weight per day. The number of illegal vessels as well as the duration of fishing activity assumed is estimated from the number of illegal vessels known to have operated in the South African EEZ: three were seen in 2004, and intelligence from neighbouring nations suggests a somewhat higher number in the preceding year so that four was assumed. The estimated average tonnage of green weight is obtained from the performance achieved in that year by one of the vessels fishing legally. There have been no reports of illegal vessels seen in 2005. 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 2005 as for 2004. A sensitivity test is conducted assuming zero illegal catches in 2005.

The theft by toothed cetaceans of toothfish from longlines particularly as they are hauled (“cetacean predation”) has escalated over recent years. T. Reddell (pers. commn) considers that by 2002 this had reached saturation. During the last season he had a member of the crew of the *South Princess* carry out regular observations throughout a period of about two weeks of the number of hooks on which only some remains of a toothfish were evident, with results that suggests that cetaceans consume two of every three toothfish caught on longlines. A sensitivity test has thus been conducted assuming that the extent of toothfish predation by cetaceans from longlines increased linearly from 2000 to saturate at the level suggested by these observations from 2002 onwards. Table 1 shows the catch figures with and without this assumed cetacean predation. This basis for inflating the catch figures to account for predation was also applied to the illegal vessels as it seems likely that these vessels are also longliners and would therefore have the same problems with cetacean predation as the legal longline fishery.

Since November 2004 one vessel in the toothfish fishery has changed its fishing operations in that it began to use pots in an attempt to overcome the problem with cetacean predation. There have been no indications of toothfish lost to cetaceans in this pot fishery. Pot data from this vessel are separated from the data obtained from the commercial longline fishery and analysed as a second fleet. The CPUE GLM standardisation procedure described in Appendix 1 of Brandão and Butterworth (2003) (see also Appendix 2 of this paper) has been reapplied to the longline commercial data, resulting in the revised series of relative abundance indices listed in Table 2. To include the CPUE for the first part year of 2005, two analyses were performed: one including CPUE data from 1997 to 2004 and another from 1997 to 2005. The trend in the standardised CPUE indices for the first 3 months of the latter analysis was then used to obtain an estimated CPUE index for 2005 from the 1997–2004 standardised indices. Note that for the sensitivity test including cetacean predation, the longline CPUE indices are inflated by the same proportions as the longline catch. Although the pot fishery has operated in two years (over November 2004 to April 2005), the lack of replicate months precludes a GLM standardisation distinguishing month and year effects, so that incorporation of these CPUE data in assessments must await further pot fishing.

Catch-at-length information for the longline fishery has also been updated to include the data available for the whole of 2004 and to April 2005. Catch-at-length data for the pot fishery for November 2004 to April 2005 are also included in the present assessment.

ASSESSMENT METHODOLOGY

The fundamental ASPM methodology applied to the one-fleet assessment (i.e. excluding all the information from the pot fishery) is as in Brandão and Butterworth (2004). This methodology has been generalised to incorporate two fleets so that the information from the pot fishery can be incorporated in the ASPM assessment. Appendix 1 describes the ASPM methodology for a multiple fleet fishery. The basic biological parameter values have been maintained unchanged from those used for previous assessments (see Table 3).

The variant that allows for annual recruitment to vary about the prediction of the Beverton-Holt stock-recruitment function, where these annual variations ("residuals", each treated as an estimable parameter) are assumed to be log-normally distributed with a CV set in this application to 0.5, has been fitted to the updated data of the toothfish off the Prince Edward Islands. Brandão and Butterworth (2005) suggested a more appropriate break in the selectivity function for the longline fishery to be between the periods 1997–2002 and 2003 onwards in contrast to the previous selectivity break between 1997–1998 and 1999 onwards. This new break has been adopted for all assessments carried out in this paper. A sensitivity test was carried out to with the break in the selectivity function before 2002 rather than 2003, but this resulted in a poorer fit to the abundance indices. The model that allows for stochastic recruitment and assumes the new selectivity break before 2003 is referred to as the "basecase" model (for both one-fleet or two-fleet assessments). The relative weight accorded to the catch-at-length contribution to the log-likelihood in all computations reported is w_{len} = 1.0.

In addition to the sensitivity tests already mentioned above, several other sensitivity tests were carried out, mainly for the two-fleet model:

- Taking into account cetacean predation (carried out for both one-fleet and two-fleet assessments).
- Omitting the 1997 CPUE index, because it appears potentially highly influential.
- Lowering the input value of natural mortality from 0.2 to 0.165 yr^{-1} (the value used for assessments of toothfish in other areas).
- Fixing selectivity to be flat for older fish for the pot fishery.

RESULTS AND DISCUSSION

Results for the basecase model for the longline fleet only are reported in Table 4 (this single fleet approach treats pot catches as if they had the same selectivity as the longliners had over 2003–2005). A sensitivity test to allow for cetacean predation was also conducted (Table 4). The stock depletion at the beginning of the year 2006 is estimated at 53% of the pre-exploitation equilibrium spawning biomass when the basecase model is fitted, and at 59% if cetacean predation is taken into account.

Table 5 shows the results for a two-fleet assessment of the toothfish resource, including those for the basecase model as well as for a number of the sensitivity tests performed. These suggest the status of the resource to be good (64%–71% of pre-exploitation equilibrium biomass). Figure 1 shows estimated spawning biomass and recruitment trends for the basecase model and the sensitivity test that takes cetacean predation into account. Both models estimate a large peak in recruitment in 1987 in response to the large estimated illegal catch taken in 1997, so as to better fit the trend in the CPUE abundance indices. Fits to the CPUE data are shown in Figure 2 for these two assessments. Both models fail to fit the comparatively very high 1997 CPUE index.

Fits of the basecase model to the catch-at-length distributions of the longline and the pot fisheries are shown in Figure 3. The selectivity functions estimated for the basecase model and the sensitivity that allows for cetacean predation are shown in Figure 4.

Figure 5 shows both the spawning and the longline exploitable components of the biomass, together with twenty year projections under different constant future annual catches for the basecase model. Projections assuming the longline fishery selectivity into the future are shown in Figures 5a–b, while those assuming the pot fishery selectivity in the future are shown in Figures 5 c–d. Figure 6 provides similar results to Figure 5, but for the sensitivity test that takes cetacean predation into account. Here the future catches for the case that assumes a longline selectivity in the future have been inflated by multiplying by three to account for future cetacean predation. Table 6 shows some summary statistics for these projections.

The sensitivity tests in Table 5 which omit the 1997 CPUE data point, or assume pot selectivity to be flat for older ages, reflect little differences in results compared to the basecase. If natural mortality M is reduced to 0.165 yr^{-1}, K_{sp} increases but productivity estimates (see MSY values) decrease, and the pot selectivity falls off much faster for older fish. The methodology to incorporate catch-at-length information (see Appendix 1, equation (A1.32)) allows for fleet-specific dependence in the variance of length at age (the β^f parameter) as this is, in part, also surrogating operational effects. However, the inter-fleet differences in β^f for the basecase seem larger than reasonably attributed to such effects. A sensitivity test was therefore conducted with a single fleet-independent β parameter, but the results shown in Table 5 indicate that this makes little difference. A sensitivity test assuming zero illegal catch in 2005 had minimal effects on basecase results.

The estimated selectivity curves in Figure 4 are of particular interest. The larger fish taken by pots (and the associated near flat selectivity at older ages for the basecase) serve to confirm impressions gained from earlier assessments that the rapid fall-off in longline catches at greater lengths reflects non-availability of such fish to the longline gear for some reason, rather than their already having been virtually fished out. A possible reason for the drop in longline selectivity for larger fish in more recent years is movement of these vessels to shallower waters (with fewer large fish) in an attempt to reduce hauling times and consequently the extent of cetacean predation.

While the relatively good fits of the two-fleet model to available data is encouraging, the results obtained should nevertheless be considered with circumspection until the collection of further data may place them on a firmer footing. A particular immediate concern is that these fits appear not to be particularly stable to variations in the relative weight (w_{len}) given to the catch-at-length data compared to other contributions to the likelihood, and the w_{len} = 1 choice for the results presented may be overweighting these particular data because of correlation effects.

CONCLUSIONS

The two-fleet model that takes the information available from the pot fishery into account estimates the status of the toothfish population to be better than when only the longline fishery information is analysed. The greater selectivity for larger toothfish in the pot fishery has important implications to the status of the toothfish population in the Prince Edward Islands vicinity, and perhaps also for other toothfish populations. Taking the possible extent of cetacean predation of toothfish into account further improves the estimated current status of the population.

On the basis of the MSY estimates in Table 5 together with the projections in Figures 5 and 6 (see also Table 6), it seems that a future total annual catch of some 1 000 tonnes would be sustainable, unless taken entirely by longlining (which would increase the effective catch to 3 000 tonnes as a result of cetacean predation – see Figures 6a–b). However, given that standardised longline CPUEs over the last two years (see Table 2) are the lowest on record, the lack of stability of the assessment to alternative weighting of the catch-at-length information, the coarse nature of the available estimate of the extent of cetacean predation, and the relatively unknown extent of possible continuing IUU fishing, it seems prudent for the annual legal catch not to exceed 500 tonnes for the time being, together with encouragement being provided that this be taken more by pots than by longlines.

Information provided by industry on the impact of cetacean predation, while coarse, is very valuable, and efforts should be made to extend such observations in the future on a more formal data recording basis.

ACKNOWLEDGEMENTS

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Table 1. Yearly catches of toothfish (in tonnes) estimated to have been taken from the Prince Edward Islands EEZ for the analyses conducted in this paper. The bases for the estimates of the illegal catches for 2004 and 2005 are detailed in the text. Catches from the longline fisheries ("legal" and "illegal") modified to include cetacean predation (see text for basis) are also given.

Year	***Legal***		***Illegal***	***Total***	
	Longline fishery	**Pot fishery**		**Without predation**	**With predation on longline fishery**
1997	2 921.2	—	21 350	24 271.2	24 271.2
1998	1 010.9	—	1 808	2 818.9	2 818.9
1999	956.4	—	1 014	1 970.4	1 970.4
2000	1 561.6	—	1 210	2 771.6	4 619.4
2001	351.9	—	352	703.9	1 642.4
2002	200.2	—	306	506.2	1 518.5
2003	312.9	—	256	568.9	1 706.7
2004	194.9	72.6	156	423.6	1 052.8
2005	37.6	103.5	156	297.2	580.9
1997–2005 total	7 547.6	176.2	26 608	34 331.8	40 181.2

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

Year	**Longline fishery**		
	***CPUE* (previous analysis)**	***CPUE* (present analysis)**	***CPUE* including predation**
1997	3.908	3.914	3.914
1998	1.059	1.083	1.083
1999	0.959	0.962	0.962
2000	0.571	0.581	0.968
2001	0.359	0.350	0.817
2002	0.365	0.364	1.091
2003	0.467	0.459	1.378
2004	0.310	0.287	0.861
2005	—	0.257	0.770

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

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

Table 4. Estimates for a model that assumes different commercial selectivities, one for the years 1997 and 2002 and another for 2003 to 2005, when fitted to the CPUE data and catch-at-length data for toothfish from the Prince Edward Islands EEZ from the longline fleet only. The estimates shown are for the pre-exploitation toothfish spawning biomass (K_{sp}), the current spawning stock depletion (B_{sp}^{2006}/K_{sp}) and the (longline) exploitable biomass ($B_{\exp}^{2006}$) at the beginning of the year 2006 (assuming the same selectivity as for 2005). Estimates of parameters pertinent to fitting the catch-at-length information are also shown, together with contributions to the (negative of the) log-likelihood.

Parameter estimates	Model	
	Basecase	**Including predation**
K_{sp} (tonnes)	28 952	42 486
B_{sp}^{2006}/K_{sp}	0.525	0.594
$B_{\exp}^{2006}$ (tonnes)	10 224	17 719
B_{sp}^{1997}/K_{sp}	1.240	1.106
σ_{CPUE}	0.424	0.342
σ_R	0.500††	0.500††
a_{50}^{97-02} (yr)	5.518	5.518
δ^{97-02} (yr^{-1})	0.024	0.024
ω^{97-02} (yr^{-1})	0.091	0.081
a_{50}^{03-05} (yr)	5.498	5.499
δ^{03-05} (yr^{-1})	0.026	0.026
ω^{03-05} (yr^{-1})	0.202	0.192
β	0. 123	0.123
σ_{len}	0.031	0.031
-ln *L*: Length	-370.4	-364.3
-ln *L*: CPUE	-3.218	-5.149
-ln *L*: Recruitment	-6.881	-11.67
-ln *L*: Total	-380.4	-381.1
MSY (tonnes)	1 171†	1 730†

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

Table 5. Estimates for a two fleet (longline and pot) model that assumes different commercial selectivities for the two gears, and also a change for the longliners between 2002 and 2003, when fitted to the CPUE data and catch-at-length data for toothfish from the Prince Edward Islands EEZ. The estimates shown are for the pre-exploitation toothfish spawning biomass (K_{sp}), the current spawning stock depletion (B_{sp}^{2006}/K_{sp}) and the (longline) exploitable biomass (B_{exp}^{2006}) at the beginning of the year 2006 (assuming the same selectivity as for 2005). Estimates of parameters pertinent to fitting the catch-at-length information are also shown, together with contributions to the (negative of the) log-likelihood.

Parameter estimates		Model					
		Basecase	**Model with predation**	**Omit 1997 CPUE**	**M = 0.165**	**Flat selectivity of older fish for pot fleet**	**Single β parameter**
K_{sp} (tonnes)		32 913	45 273	35 618	41 113	32 901	31 855
B_{sp}^{2006}/K_{sp}		0.666	0.708	0.687	0.681	0.698	0.635
B_{exp}^{2006} (tonnes)	Longline	13 659	20 830	14 943	12 202	15 320	12 363
	Pot	26 473	40 433	24 452	22 146	30 897	22 527
B_{sp}^{1997}/K_{sp}		1.290	1.183	1.267	1.195	1.276	1.293
σ_{CPUE}	Longline	0.486	0.304	0.309	0.477	0.511	0.465
σ_R		0.500††	0.500††	0.500††	0.500††	0.500††	0.500††
a_{50}^{97-02} (yr)		5.514	5.515	5.514	5.513	5.514	5.510
δ^{97-02} (yr^{-1})		0.024	0.024	0.024	0.024	0.026	0.024
ω^{97-02} (yr^{-1})		0.095	0.085	0.097	0.135	0.084	0.098
a_{50}^{03-05} (yr)	Longline	5.502	5.504	5.501	5.499	5.393	5.494
	Pot	7.167	7.171	7.143	7.319	7.115	7.192
δ^{03-05} (yr^{-1})	Longline	0.026	0.026	0.026	0.026	0.021	0.026
	Pot	0.616	0.619	0.610	0.680	0.616	0.517
ω^{03-05} (yr^{-1})	Longline	0.208	0.200	0.212	0.242	0.200	0.211
	Pot	0.013	0.008	0.013	0.055	0.000††	0.024
β	Longline	0.125	0.125	0.125	0.125	0.125	0.123
	Pot	0.105	0.106	0.105	0.104	0.104	
σ_{len}	Longline	0.031	0.032	0.031	0.031	0.031	0.031
	Pot	0.033	0.032	0.033	0.033	0.033	0.034
-ln L: Length		-454.6	-451.3	-453.9	-453.1	-454.8	-451.3
-ln L: CPUE		-5.006	-9.263	-8.405	-5.174	-4.497	-5.394
-ln L: Recruitment		-6.662	-9.543	-7.607	-5.091	-6.616	-6.751
-ln L: Total		-466.3	-470.1	-469.9	-463.3	-465.9	-463.4
MSY (tonnes)	Longline	1 327†	1 837†	1 434†	1 185†	1 336†	1 282†
	Pot	1 551	2 141	1 677	1 458	1 561	1 494

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

Table 6. Some summary statistics of the 20–year spawning biomass projections.

a) Basecase two-fleet model: $\frac{B_{sp}^{2006}}{K_{sp}} = 0.666$

	$\frac{B_{sp}^{2025}}{K_{sp}}$		
Future catch (tonnes)	**0**	**400**	**1000**
Longline selectivity	0.877	0.749	0.552
Pot selectivity	0.877	0.773	0.611

b) Including cetacean predation: $\frac{B_{sp}^{2006}}{K_{sp}} = 0.708$

	$\frac{B_{sp}^{2025}}{K_{sp}}$		
Future catch (tonnes)	**0**	**400**	**1000**
Longline selectivity	0.895	0.617	0.170
Pot selectivity	0.895	0.822	0.708

FIGURE CAPTIONS

Figure 1a–b: Spawning biomass estimates and estimated recruitment for the two-fleet model for a) the basecase model and b) the sensitivity test that takes cetacean predation into account.

Figure 2a–b: Exploitable biomass and the GLM-standardised CPUE indices to which the model is fit (divided by the estimated catchability *q* to express them in biomass units) for a) the basecase model and b) the sensitivity test that takes cetacean predation into account.

Figure 3 a–b: ASPM assessment predictions for the annual catch-at-length proportions in the a) longline and b) pot fisheries for the basecase model. Note that lengths below 54 and above 138 cm are combined into minus- and plus-groups respectively for the longline fishery, while for the pot fishery lengths above 176 cm are combined into a plus-group.

Figure 4a-b: Estimated selectivity curves for the periods 1997–2002 and 2003–2005 for the longline fishery, and for the period 2004-2005 for the pot fishery. Estimated selectivities are shown for a) the basecase model and b) the sensitivity test that takes cetacean predation into account.

Figure 5a-d: ASPM assessment results for the basecase model together with projections under future annual catches of 0, 400 and 1 000 tonnes. The top panels are for spawning biomass, while the bottom panels show exploitable biomass for the longline fishery and the GLM-standardised CPUE indices to which the model is fit (divided by the estimated catchability *q* to express them in biomass units). Panels a–b on the left assume the current longline selectivity applies in the future, while panels c–d on the right assume the pot fishery selectivity applies in the future.

Figure 6a-d: ASPM assessment results for the sensitivity test that takes cetacean predation into account together with projections under future annual catches of 0, 400 and 1 000 tonnes. The top panels are for spawning biomass, while the bottom panels show exploitable biomass for the longline fishery and the GLM-standardised CPUE indices to which the model is fit (divided by the estimated catchability *q* to express them in biomass units). Panels a–b on the left assume the current longline selectivity applies in the future, while panels c–d on the right assume the pot fishery selectivity applies in the future.

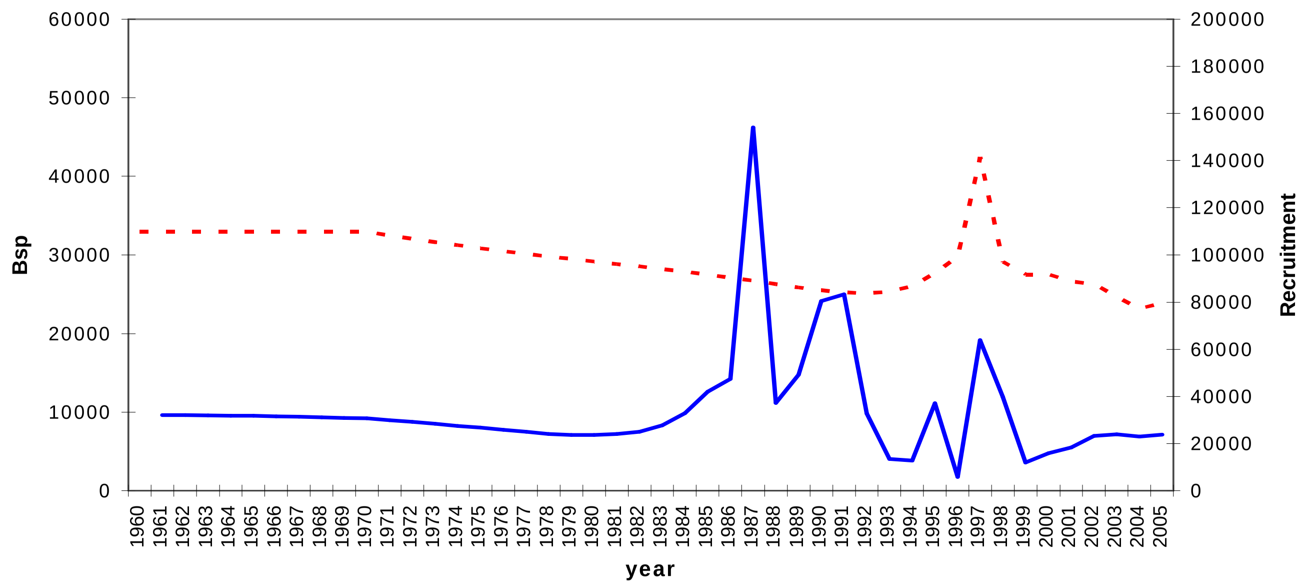

Figure 1a. Basecase two-fleet model.

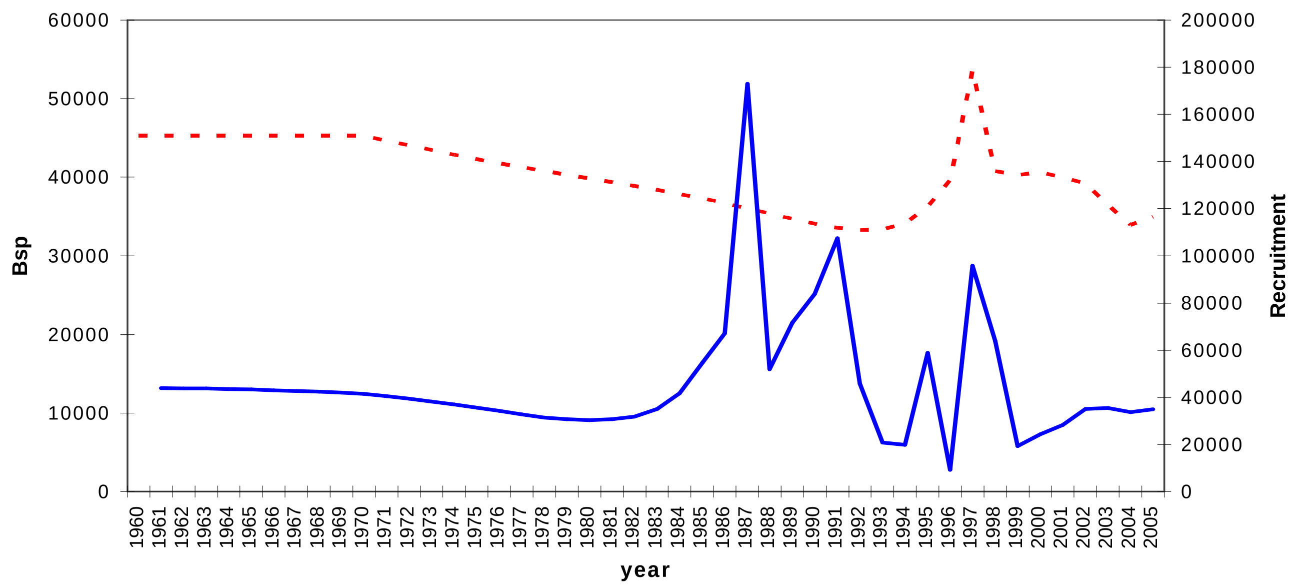

Figure 1b. Including cetacean predation.

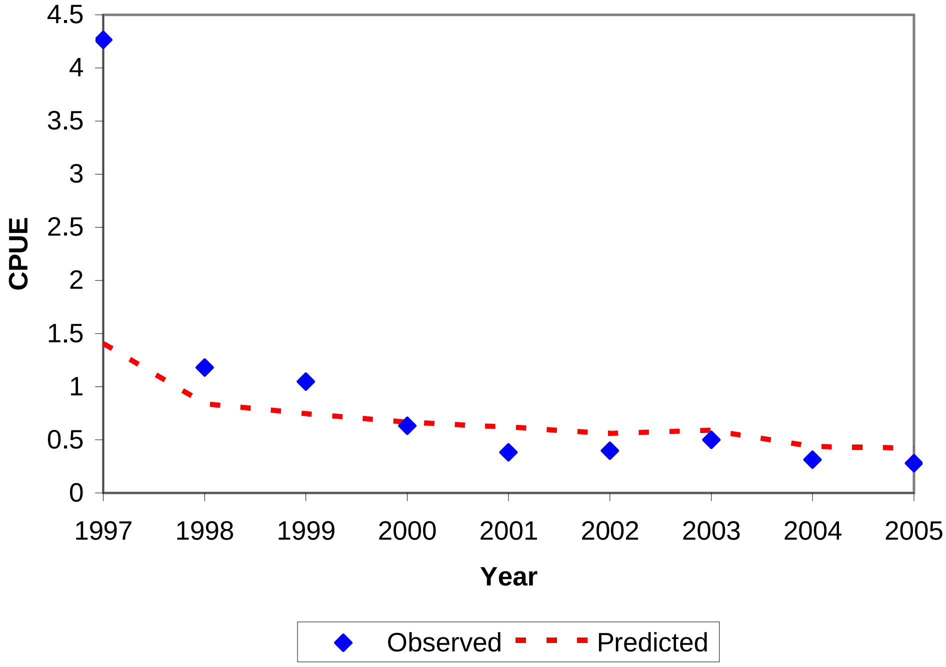

Figure 2a. Basecase two-fleet model.

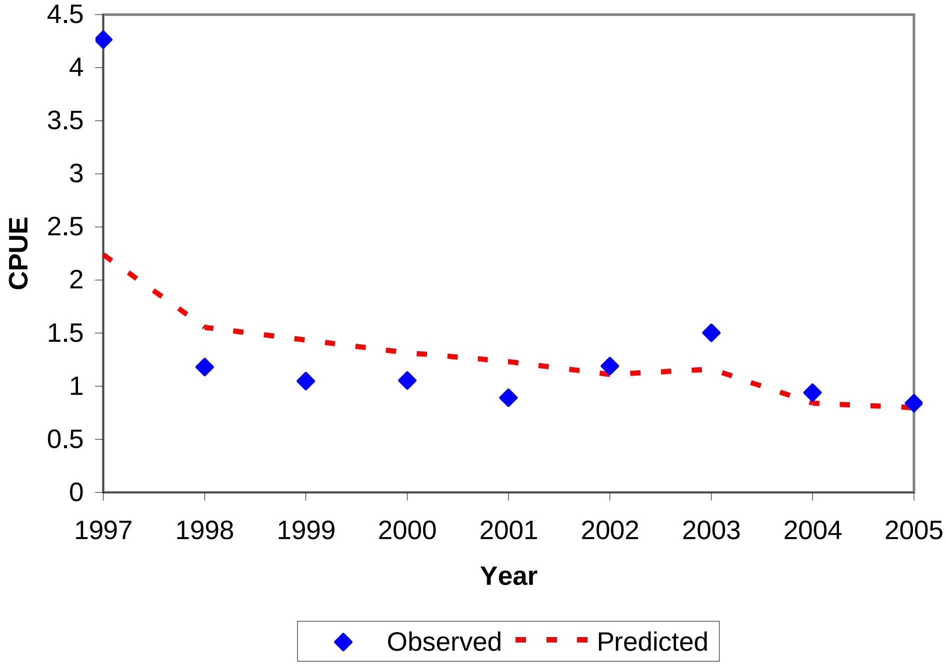

Figure 2b. Including cetacean predation.

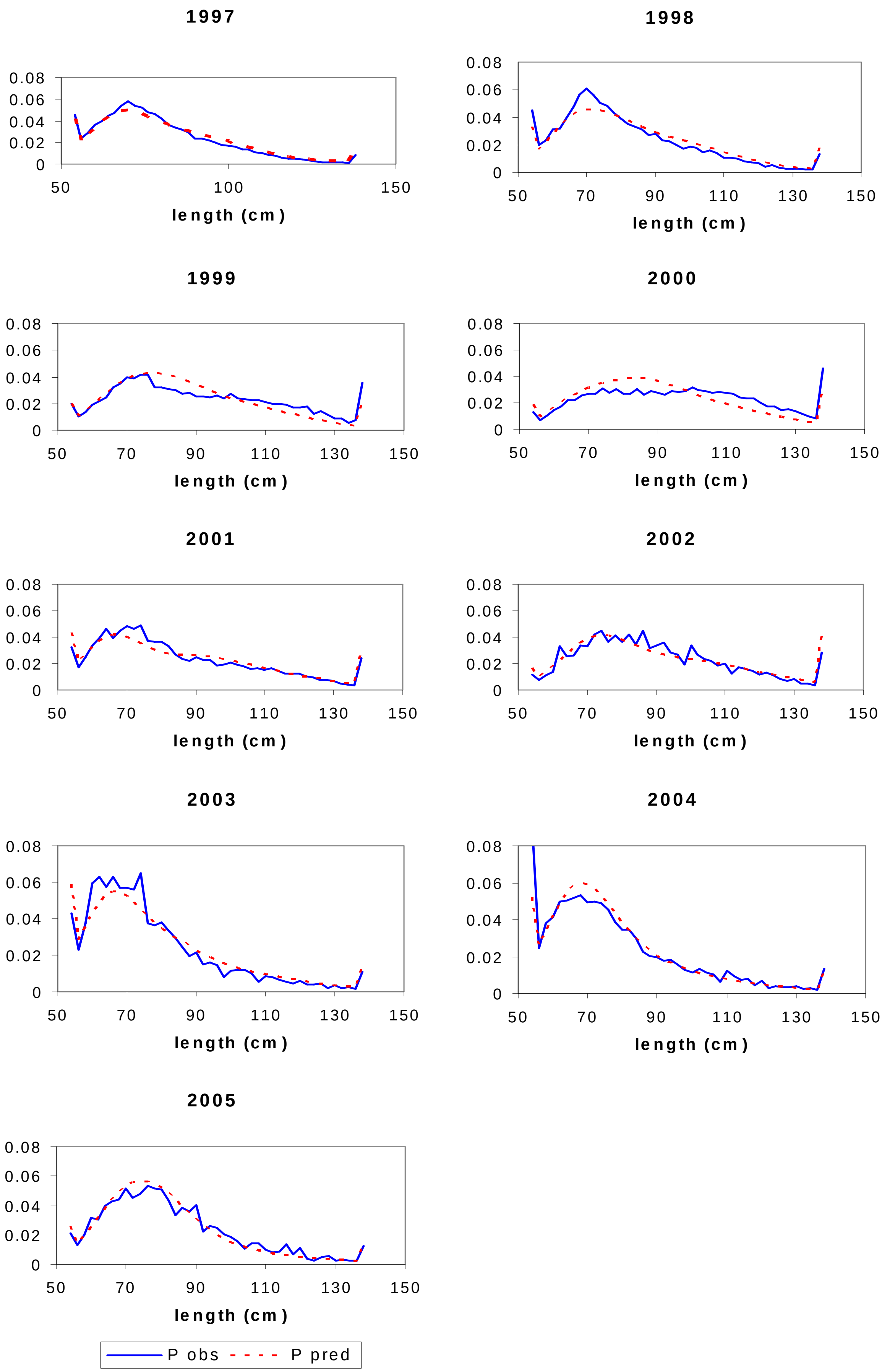

Figure 3a. Basecase longline catch-at-length.

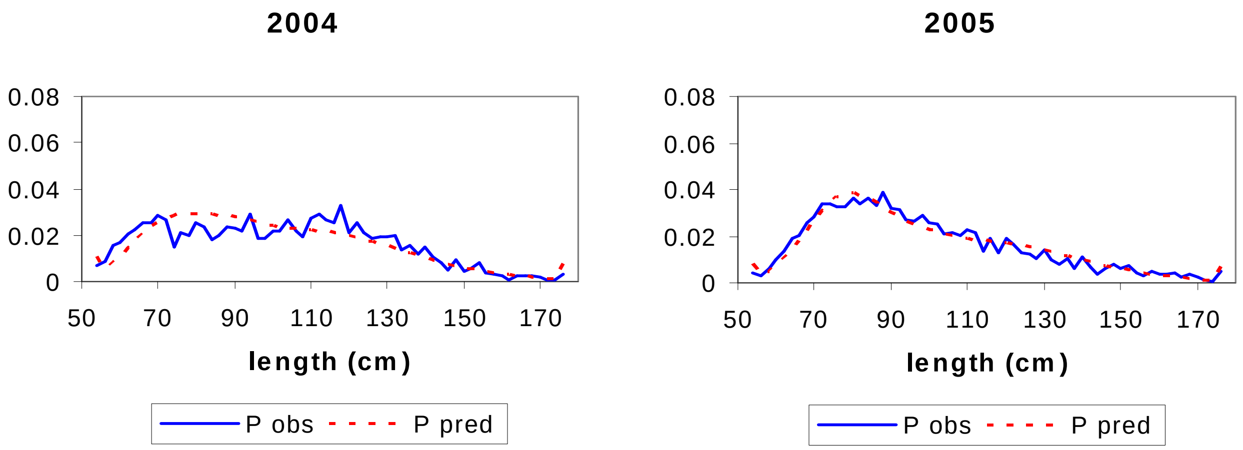

Figure 3b. Basecase pot catch-at-length.

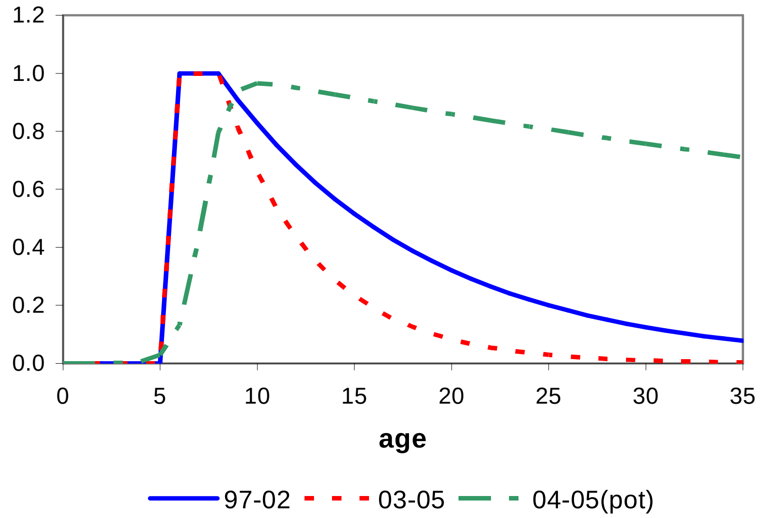

Figure 4a. Basecase selectivity

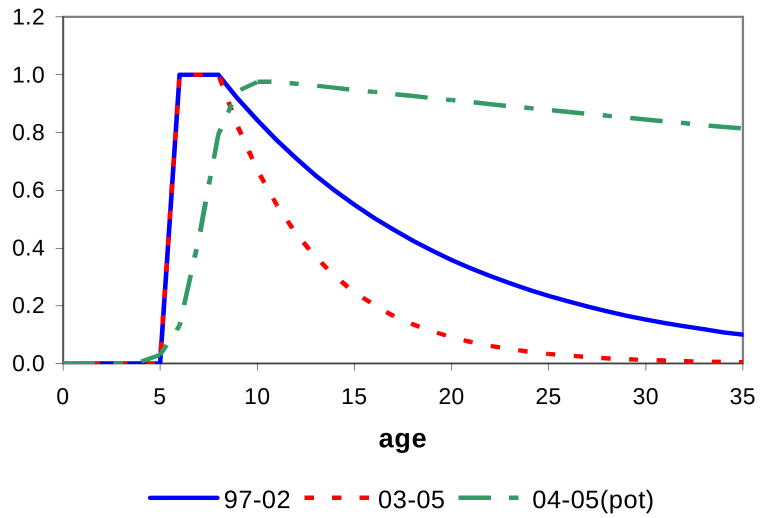

Figure 4b. Selectivity when including cetacean predation.

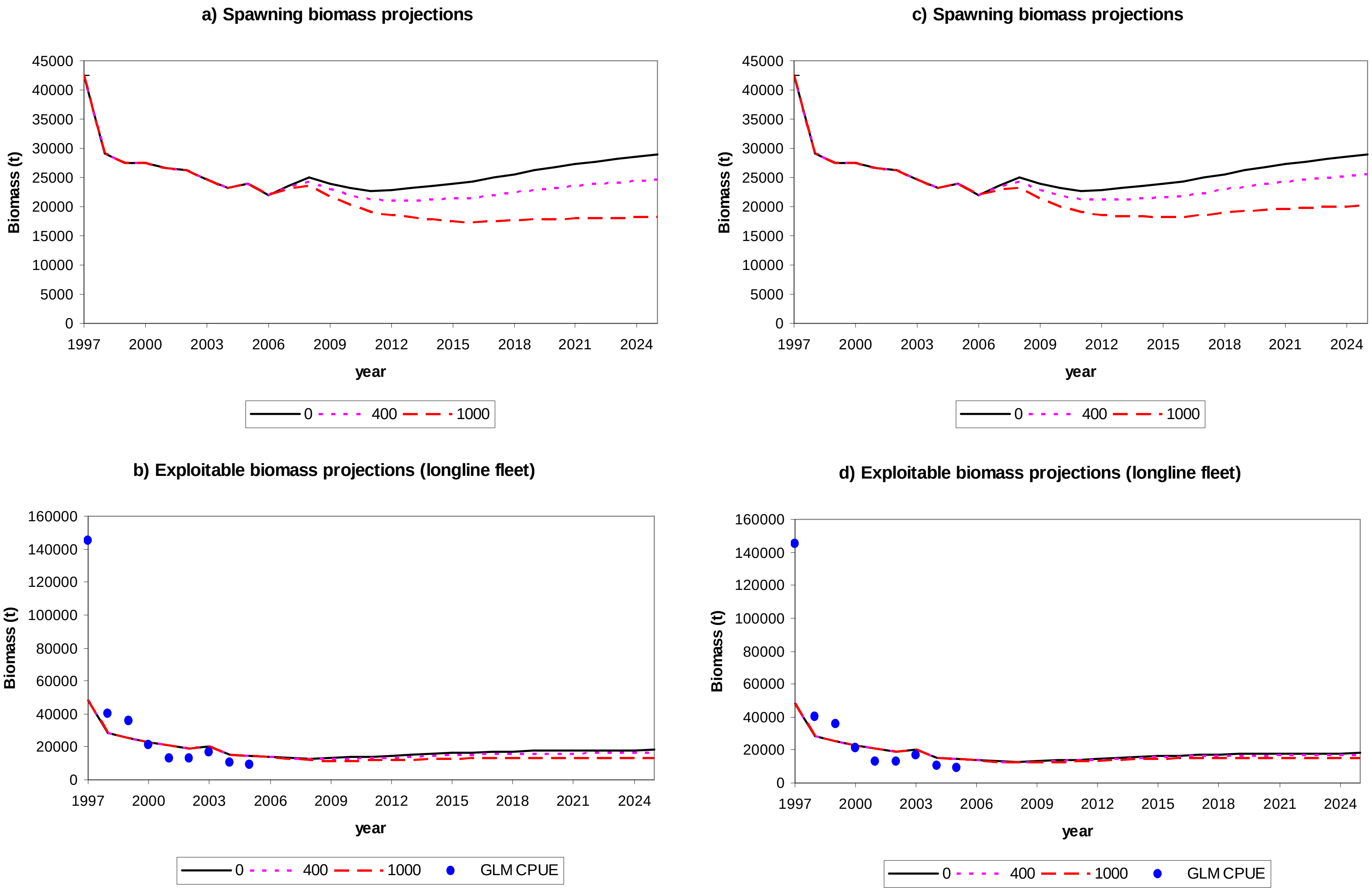

Figure 5. Basecase two-fleet model: a)–b) longline selectivity in the future; c)–d) pot selectivity in the future.

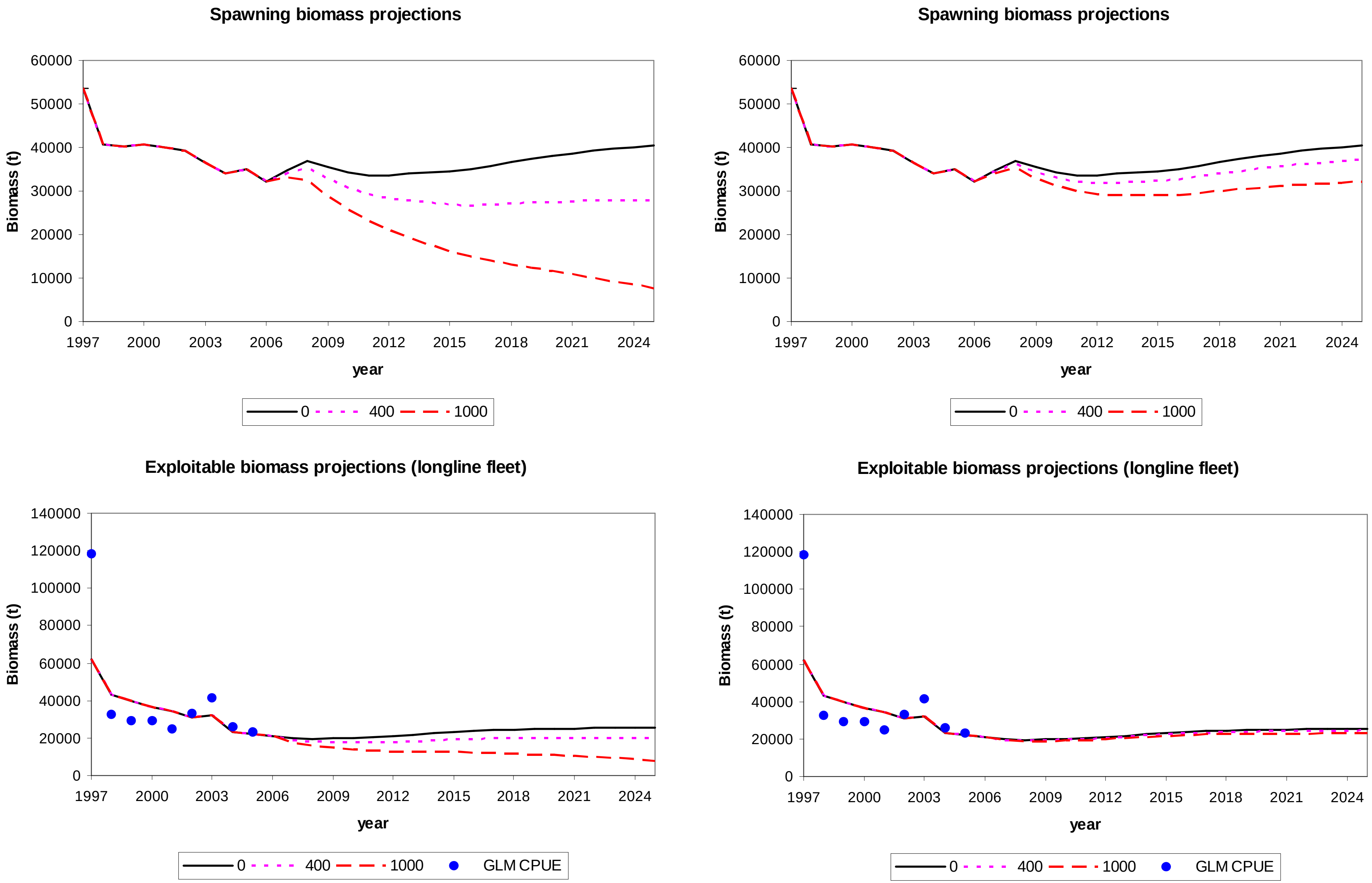

Figure 6. Including cetacean predation: a)–b) longline selectivity in the future; c)–d) pot selectivity in the future.

APPENDIX 1

THE AGE STRUCTURED PRODUCTION MODEL (ASPM) ASSESSMENT METHODOLOGY

THE BASIC DYNAMICS

The toothfish population dynamics are given by the equations:

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

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

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

where:

$N_{y,a}$ is the number of toothfish of age *a* at the start of year *y*,

$C_{y,a}$ is the number of toothfish of age *a* taken by the fishery in year *y*,

$R(B^{sp})$ is the Beverton-Holt stock-recruitment relationship described by equation (A1.10) below,

B^{sp} is the spawning biomass at the start of year *y*,

M is the natural mortality rate of fish (assumed to be independent of age), and

m is the maximum age considered (i.e. the "plus group").

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

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

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

where:

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

and:

F^f_y is the proportion of the resource above age *a* harvested in year *y* by fleet *f*, and

$S^f_{y,a}$ is the commercial selectivity at age *a* in year *y* for fleet *f*.

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

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

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

where:

w_a is the mass of a fish at age a.

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

$$C^f_y = \sum_{a=0}^{m} w_a C^f_{y,a} = \sum_{a=0}^{m} w_a S^f_{y,a} F^f_y N_{y,a} \tag{A1.8}$$

which can be re-written as:

$$F^f_y = \frac{C^f_y}{\sum_{a=0}^{m} w_a S^f_{y,a} N_{y,a}} \tag{A1.9}$$

FISHING SELECTIVITY

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

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

where

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

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

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

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

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

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

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

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

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

Now F_y^f is not bounded at one, but $g\left(S_{y,a}^f F_y^f\right) \leq 1$ hence $C_{y,a}^f = g(S_{y,a}^f F_y^f) N_{y,a} \leq N_{y,a}$ as required.

STOCK-RECRUITMENT RELATIONSHIP

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

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

where:

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

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

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

The values of the parameters α and β can be calculated given the unexploited equilibrium (pristine) spawning biomass K^{sp} and the steepness of the curve *h*, using equations (A1.15)–(A1.19) below. If the pristine recruitment is $R_0 = R(K^{sp})$, then steepness is the recruitment (as a fraction of R_0) that results when spawning biomass is 20% of its pristine level, i.e.:

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

from which it can be shown that:

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

Rearranging equation (A1.16) gives:

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

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

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

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

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

where:

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

PAST STOCK TRAJECTORY AND FUTURE PROJECTIONS

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

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

which can be solved for R_0.

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

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

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

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

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

THE LIKELIHOOD FUNCTION

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

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

where

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

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

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

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

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

where:

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

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

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

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

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

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

EXTENSION TO INCORPORATE CATCH-AT-LENGTH INFORMATION

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

$$p^f_{y,a} = C^f_{y,a} \Big/ \sum_{a'} C^f_{y,a'} \ . \qquad \text{(A1.28)}$$

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

$$p^f_{y,\ell} = \sum_a p^f_{y,a} A^f_{a,\ell} \qquad \text{(A1.29)}$$

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

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

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.:

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

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.:

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

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

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

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

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

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:

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

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

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

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

ADJUSTMENT TO INCORPORATE RECRUITMENT VARIABILIITY

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

$$R(B_y^{sp}) = \frac{\alpha B_y^{sp}}{\beta + B_y^{sp}} e^{(\zeta_y - \sigma_{R/2}^2)}, \tag{A1.35}$$

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

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

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

which is added to the negative log-likelihood of equation (A1.27) as a penalty (the frequentist equivalent of a Bayesian prior for these parameters). In the present application, it is assumed that the resource is not at equilibrium at the start of the fishery, but rather that the resource was at deterministic equilibrium in 1960 with zero catches taken until the start of the fishery in 1997 (by which time virtually all “memory” of the original equilibrium has been lost because of subsequent recruitment variability).

APPENDIX 2

GLM STANDARDISATION OF LONGLINE CPUE DATA

MODEL TO STANDARDISE THE CPUE

The "base case" General Linear Model (GLM) of Brandão *et al.* (2002) has been applied to standardise the longline CPUE data for toothfish in Prince Edward Islands EEZ. This model includes the main effects of all the explanatory variables for which data are available (excluding depth since its effect on the GLM fit was not significant), as well as some interactions.

The base case model

The base case model considered for the longline CPUE data is given by:

$$\ln(CPUE + \delta) = \mu + \alpha_{vessel} + \beta_{year} + \gamma_{month} + \lambda_{area} + \eta_{year\times area} + \theta_{year\times month} + \varphi_{month\times area} + \varepsilon \quad \text{(A2.1)}$$

where:

CPUE is the longline catch per unit effort in kg per hook,

μ is the intercept,

vessel is a factor with 7 levels associated with each of the vessels that have operated in the fishery (to an appreciable extent):

Aquatic Pioneer
Arctic Fox
Eldfisk
Isla Graciosa
Koryo Maru
South Princess
Suidor One

year is a factor with 9 levels associated with the years 1997–2005,

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

area is a factor with 4 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×*area* is the interaction between year and area (this allows for the possibility of different trends for the different areas),

year×*month* is the interaction between year and month,

month×*area* is the interaction between month and area,

δ is a small constant (0.022) 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.

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:

$$CPUE_y = \sum_{month}\left[\sum_{area}\left\{\exp\begin{bmatrix}\mu + \overline{\alpha} + \beta_{year} + \gamma_{month} + \lambda_{area} + \eta_{year\times agg} \\ + \theta_{year\times month} + \varphi_{month\times area}\end{bmatrix} - \delta\right\} * A_{area}\right] \Big/ 12 \quad \text{(A2.2)}$$

where

$\overline{\alpha}$ is the median vessel estimate, and

A_{area} is the size of the respective area (values for the size of each area (A_{area}) are given in Appendix 1 of Brandão *et al*. (2002)).

Thus equation (A2.2) is taking CPUE to provide an index of local density and effectively integrating over area to obtain an index of overall abundance. 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.