Results for the Reference-case abalone spatial- and age-structured assessment model for Zones A, B, C and D in 2009

A. Brandão and D.S. Butterworth
Marine Resource Assessment & Management Group (MARAM)
Department of Mathematics and Applied Mathematics

University of Cape Town

Rondebosch 7701, Cape Town

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SUMMARY

A summary is presented of the results obtained from the Reference-case model described by Plagányi (2008) that was fit to Zones A, B, CNP, CP and D in combination (hereafter referred to as the "combined ABCD model"). The full details of the spatial- and age-structured production model (ASPM) are provided in Appendices 1 and 2.

The Reference-case model (when the updated and extrapolated "old" CPUE series is used in the model fitting procedure) estimates a pristine spawning biomass, B_0^{sp} (in tonnes) with 90% Hessian-based confidence intervals shown in brackets, of 9 876 (5 985; 13 767), 5 902 (5 449; 6 355), 7 462 (7 177; 7 747) and 10 439 (6 562; 14 316) for Zones A, B, C and D respectively. The 2010 (inshore+offshore) spawning biomasses (and associated 90% confidence intervals) of abalone in Zones A, B, C and D are estimated at ca. 29 % (23%; 35%), 26 % (19%; 32%), 6% (3%; 9%) and 11 % (8%; 14%) respectively of their pre-exploitation levels. The "nonpoached" CNP and "poached" CP areas of Zone C are estimated at ca. 11 % and 6 % respectively with the inshore region particularly depleted: the model predicts almost no remaining abalone in the inshore area of Zone D. Equivalent estimates for Zones A and B are 15% and 19%. The model estimate of the proportion poached from Zone A is 0.68 (90% Hessian-based confidence interval 0.58 – 0.77). Natural mortality is reasonably estimated (e.g. 0.32 yr^{-1} for age 0 and 0.13 yr^{-1} for age 15+) and in Zones C and D, the additional mortality estimated for 0-yr old abalone (due to the ecosystem-change effect) corresponds to near zero current annual survival rates. Poaching is severely impacting the resource, with Zone A particularly impacted in recent years. The combined Zones A-D model-predicted 2009 poaching estimate is 939 MT and corresponds to the assumption that, on average, 14% of all poached abalone are confiscated.

BACKGROUND

This document provides **selected** results from fitting the abalone spatial- and age-structured production model (ASPM) to Zones/Subareas A, B, CNP, CP and D in combination (hereafter referred to as the "combined ABCD model") using updated 2008 and new 2009 data for some of the model inputs. The full details of the spatial- and age-structured production model are provided in Appendices 1 and 2. A summary defining the model parameters is given in Table 1.

Concern was expressed by the AWG that the CPUPE trend for Zone B declines too steeply in recent years. This may be attributable to an incorrect partitioning of confiscated abalone between Zones A and B. Rather than estimating the amount poached in Zone B in recent years, this model combines the estimates of the amount poached from Zones A and B and then estimates a parameter that describes the proportion of this total that is taken from Zone A compared to Zone B from 2000 onwards. This is the Reference-case model described by Plagányi (2008).

Updated data for 2008 and new data for 2009 for some of the model inputs have been used in this paper. Specifically, GLM standardised commercial catch-per-unit-effort indices extended to include data for Model years 2007 and 2008 have become available, referred to as the "new" CPUE series in this paper. The following data set versions have been used as inputs to the Reference-case model:

a) new data updates but the same CPUE series as in Plagányi (2008) is used (referred to as the "old" CPUE series). In this data set version, the "old" CPUE series has been updated to include a missing value for 2006 in Zone CNP and the series for Zone B has been extended from 2006 to 2008 using the same scaling as evident for the "new" CPUE series,
b) new data updates but the "old" CPUE series is used,
c) new data updates and the "new" CPUE series is used.

This paper focuses on presenting results for the Reference-case model (when the updated and extrapolated "old" CPUE series is used in the model fitting procedure, i.e. version a)) only, with some selected results shown for other scenarios. The reason that the presentation of results is not concentrated on version c), i.e. with the "new" CPUE series is because the model run for this version did not converge. Again, due to model run convergence problems and a lack of time, results in this paper only reflect the base-case (Marcel Kroese) policing efficiency option.

Parameters

The Reference-case ABCD model estimates the following 32 parameters:

1) B_0^{sp} for Zones A, B, CNP, CP and D [5 parameters];
2) Inshore-offshore migration parameter ρ (CP) [1 parameter];
3) Poaching estimate for yr with assumed highest level of poaching: $CP_{\max}$ estimated for A, B, C (combined), and D [4 parameters];
4) $\boldsymbol{p}_{\mathbf{poach}}$ [1 parameter] – equates roughly to old assumption that 10% of the Zone C poaching take is from CNP;
5) ***Cmult*** – historic catch multiplier for Zone A;
6) $M_a : \mu$ $(\lambda = 0.2)$ where the formulation to model age-dependent mortality rates is $M_a = \mu + \dfrac{\lambda}{a+1}$. Natural mortality parameter assumed common to all Zones [1 parameter];
7) Two "recruitment failure" effect parameters common to CNP, CP and D: a steepness of recruitment failure parameter ν and a maximum increase in mortality parameter M_{max} [2 parameters];
8) Three parameters for each of five selectivity functions (assumed common to all Zones) [15 parameters];
9) One parameter that determines the proportion of the combined Zones A and B poaching that is taken from Zone A; and
10) Additional variance parameter, assumed common to all Zones [1 parameter].

RESULTS

A summary of results is provided in Table 2 and model parameter estimates as well as log-likelihood contributions for the Reference-case combined ABCD model and some sensitivities are given in Table 3. The model selectivity functions and fits to the abundance indices are presented in Figures 1 to 12. A number of additional diagnostics results are presented for purposes of indepth analysis of model results.

Parameter estimates

Model results estimates a pristine spawning biomass, B_0^{sp} (in tonnes), of 9 876 (5 985; 13 767), 5 902 (5 449; 6 355), 7 462 (7 177; 7 747) and 10 439 (6 562; 14 316) for Zones A, B, C and D respectively. The 2010 (inshore + offshore) spawning biomasses (and associated 90% confidence intervals) of abalone in Zones A, B, C and D are estimated at ca. 29 % (23%; 35%), 26 % (19%; 32%), 6% (3%; 9%) and 11 % (8%; 14%) respectively of their pre-exploitation levels. The “nonpoached” CNP and “poached” CP areas of Zone C are estimated at ca. 11 % and 6 % respectively with the inshore region particularly depleted: the model predicts almost no abalone in the inshore area of Zone D.

Natural mortality is reasonably estimated (e.g. 0.32 (0.30; 0.34) yr^{-1} for age 0 and 0.13 (0.11; 0.15) yr^{-1} for age 15+) and in Zones C and D, the additional mortality estimated for 0-yr old abalone (due to the ecosystem-change effect) corresponds to near zero current annual survival rates (Table 3). The estimated additional variance parameter σ_{Add} is 0.17 with 90% confidence interval (normal approximation) of (0.07; 0.26).

The Reference-case selectivity estimates are illustrated in Figure 1a. The estimated commercial and recreational selectivity functions reflect the fact that the minimum legal size corresponds to an age of approximately 9 years, whereas the estimated poaching selectivity function reflects the fact that sub-legal-size animals are caught. The minimum size of animals caught has been set at 3. The estimated FIAS selectivity function reflects the fact that the FIAS transects are situated inshore where smaller animals occur (Figure 1a).

Figure 1b shows the estimated selectivity trends when the “new” CPUE series is used in the model (version c)). The model estimates a slight decline in selectivity with age for the poaching sector when the “new” CPUE series is used in the model (Figure 1b).

Fits to data

The Reference-case model fits to the CPUE and FIAS data are shown in Figures 2-6. The model fits to the “new” CPUE series (version c)) are shown in Figure 7.

Biomass trajectories and projections

Figure 8 shows the combined Zones A-D commercially exploitable biomass trajectory compared to historic data. Overall, the resource is estimated to now be at 17% of the pre-exploitation spawning biomass level.

Figure 9 shows the Reference-case (when the updated and extrapolated “old” CPUE series is used in the model fitting procedure) total (inshore + offshore) spawning biomass trajectories for Zones A to D. Note that the 20-yr projections shown (indicated by vertical bar) represent scenarios under which future poaching levels are assumed to remain at the current estimated level (average of 2008 and 2009) and future commercial catches are set to zero.

Figure 10 shows the inshore and offshore spawning biomass components separately. Figure 11 shows the model estimates of the numbers of abalone available to the FIAS sector in each Zone. Figure 12a includes confidence intervals associated with the model estimates of spawning biomass as a proportion of the pre-exploitable level. Figure 12b compares the model estimated spawning biomass as a proportion of the pre-exploitable level when version a) and version c) data sets are input into the model fitting procedure.

Poaching estimates

Poaching is severely impacting the resource, with Zone A particularly impacted in recent years. The combined Zones A-D model-predicted 2009 poaching estimate from the Reference-case model (when the updated and extrapolated “old” CPUE series is used in the model fitting procedure) is 939 MT and corresponds to the assumption that, on average, 14% of all poached abalone are confiscated. Figures 13 to 15 show the model estimates of the numbers and corresponding biomass of abalone that is assumed poached.

Density estimates

Reference-case model (when the updated and extrapolated “old” CPUE series is used in the model fitting procedure) estimated abalone density per Zones A-D is shown in Figure 16. Density is computed as the total number of abalone (inshore and offshore combined) divided by the habitat area, which is measured either as a) kelp area multiplied by a scaling factor of 1.5 or b) kelp area. Given difficulties in accurately computing abalone habitat area, it is difficult to compare model density estimates with observed estimates. Maharaj *et al.* (2008) note that the abalone density in Betty’s Bay (a relatively pristine region) measured by FIAS during 1995-1999 was 2.7 (range: 0.9-5.5) abalone per square metre. Depending on the habitat area estimate as described above, the model-estimated pristine density estimates for Zones A and B are 1.8-2.7 and 1.4-2.0 per square metre. As these represent the average density throughout the model area, the inshore densities are likely to be higher than the offshore densities (but it is not possible to split the inshore/offshore habitat estimates). The model is thus not inconsistent with the possibility that pristine densities were appreciably higher than the current values.

CONCLUSIONS

Model results suggest that the abalone resource has been heavily impacted by poaching and is currently declining in all Zones.

REFERENCES

Maharaj, G., Mackenzie, A. and Tarr, R. 2008. The present status of the abalone resource in Zone B: Is the model estimate a realistic reflection? Marine and Coastal Management document: MCM/2008/NOV/SWG-AB/14.

Plagányi, É. 2008. Reference-case 2008 assessment model for abalone in Zones A, B, C and D. Marine and Coastal Management document: MCM/2008/NOV/SWG-AB/21.

Table 1. Summary description of model parameters and definitions of other abbreviated terms utilised in the text.

Parameter	Description	Units
$B_0^{sp} = K$	Pre-exploitation (assumed to be 1951) spawning biomass	MT
$B^{sp}, B_{insh}^{sp}, B_{offsh}^{sp}$	Spawning biomass (total per zone), Inshore spawning biomass, Offshore spawning biomass	MT
ρ	Rate at which inshore animals move offshore at the start of each Model year	yr^{-1}
r_I	Proportion of the recruits which settle inshore	-
$CP_{\max}$ (number) (zone)	The total number of abalone poached in the year corresponding to the poaching maximum for the zone under consideration	no.
$CP_{\max}$ (MT) (zone)	The poaching maximum in terms of mass	MT
C_{mult}	Historic catch multiplier for Zone A	-
p_{poach}	Parameter that specifies the relative exploitation rate effected by poachers in subareas CP and CNP	-
$M_a : \mu$ $(\lambda = 0.2)$ $\left(M_a = \mu + \frac{\lambda}{a+1}\right)$	Age-dependent mortality rate parameters; M_0 is the mortality rate of 0-yr old animals; M_{15} is the plus group mortality rate etc.	yr^{-1}
υ	Parameter that controls the steepness of the function describing an increase in 0-yr old mortality due to the ecosystem-change effect	-
$M_{\max}$	Maximum increase in 0-yr old mortality rate due to the ecosystem-change effect	yr^{-1}
$\hat{a}$ (sector)	Selectivity parameter for sector as indicated; shifts the selectivity function to the left or right	-
μ (sector)	Selectivity parameter that controls the slope of the right hand limb of the function	-
δ (sector)	Selectivity parameter that controls the steepness of the ascending left hand limb of the selectivity function.	-
<u>Other definitions</u>		
Zone	Fishery area / management unit: Zones A-G	
CNP, CP	Two subareas comprising Zone C, with CNP subject to less poaching historically than CP	
FIAS	Fishery Independent Abalone Survey	
FIAS N_{2006}/N_{1951}	FIAS depletion statistics expressing depletion in terms of *number* rather than mass	
CS	Commercial sector	
RS	Recreational sector	
PS	Poaching sector (corresponding to illegal catches)	
FS	Parameters pertaining to FIAS	
OS	Parameters pertaining to the Old Surveys conducted during the 1980's	
IS	Industry/MCM joint full population surveys conducted in 2002	
Co/Po_{yr}	Confiscations (i.t.o. number) as a proportion of the	

	model-estimated number of animals poached in year *yr*.
CI	Confidence Interval (typically 95% CI) determined by likelihood profile method
MSY	Maximum Sustainable Yield
MSYL	Maximum Sustainable Yield Level
TAC	Total Allowable Catch (annual catch allocation)

Table 2. Indication of the precision (Hessian-based) associated with key model results when using the Reference-case assessment model when the updated and extrapolated "old" CPUE is used in the model fitting procedure.

Parameter	Value	90% Confidence Interval	
$B(2010)^{sp}/B(0)^{sp}$*(Zone A)*	0.290	0.227	0.354
$B(2010)^{sp}/B(0)^{sp}$*(Zone B)*	0.258	0.194	0.321
$B(2010)^{sp}/B(0)^{sp}$*(Zone C)*	0.059	0.031	0.087
$B(2010)^{sp}/B(0)^{sp}$*(Zone D)*	0.113	0.085	0.140
$B(0)^{sp}$*(Zone A)*	9 876	5985	13767
$B(0)^{sp}$*(Zone B)*	5 902	5449	6355
$B(0)^{sp}$*(Zone C)*	7 462	7177	7747
$B(0)^{sp}$*(Zone D)*	10 439	6562	14316
$B(current)^{sp}$*(Zone A)*	3 036	1459	4613
$B(current)^{sp}$*(Zone B)*	1 534	1235	1834
$B(current)^{sp}$*(Zone C)*	634	452	816
$B(current)^{sp}$*(Zone D)*	1 317	570	2064

Table 3. Best fit estimates of the pre-exploitation spawning biomass B_0^{sp} (or *K*) for the "poached" CP and "nonpoached" CNP areas of Zone C, and for each of Zones A, B and D, the estimated natural mortality estimates M_a, the inshore-offshore migration parameters ρ (yr^{-1}), the proportions of recruitment in each subarea that occur inshore versus offshore r_I, and the poaching maximum CP_{max} (i.t.o. NUMBERS). The CP_{max} estimates are also shown in terms of biomass and the years to which these estimates apply are given in the row below. Minimum values of the negative of the log-likelihood function are also shown. The estimated selectivity parameters are shown for the commercial sector (CS), recreational sector (RS), poaching sector (PS), FIAS (FS) and the old 1980's survey (OS). Note that for the 2002 industry survey (IS), $S_a^{IS}=1$. Note also that all -*ln*L contributions from catch-at-age data have been multiplied by 0.1 as an *ad hoc* adjustment to compensate for likely positive correlation in these data.

Model	a) Ref case - Updated and scaled Old CPUE series					b) Ref case - Old CPUE series					c) Ref case - New CPUE series				
No. parameters			32					32					32		
Zone	A	B	CNP	CP	D	A	B	CNP	CP	D	A	B	CNP	CP	D
Ave confiscation %	15%	29%	9%		4%	16%	27%	9%		4%	17%	29%	8%		6%
$B(0)^{sp}$	9876	5902	2981	4481	10439	9544	5854	2981	4481	9953	10275	5802	2982	4560	9602
ρ	0.033	0.033	0.033	0.016	0.033	0.030	0.030	0.030	0.015	0.030	0.037	0.037	0.037	0.018	0.037
r^I	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
Cpmax (no.)	2044360	690877		512237	1110930	2054130	710725		509501	1061640	2135710	588192		540571	724036
Cpmax (MT)	757	343		262	611	717	354		261	584	576	289		272	393
Cpmax (YEAR)	2006	2002		1995	2002	2006	2002		1995	2002	2006	2002		1995	2002
CP(2009) (MT)	530	263		142	5	512	266		142	5	502	246		131	234
Cmult (Zone A)	2.602					2.572					2.905				
Ppoach			0.900					0.900					0.900		
M_0			0.320					0.319					0.316		
M_1			0.220					0.219					0.216		
M_2			0.187					0.186					0.182		
M_3			0.170					0.169					0.166		
M_4			0.160					0.159					0.156		
M_5			0.153					0.152					0.149		
M_6			0.149					0.147					0.144		
M_7			0.145					0.144					0.141		
M_8			0.142					0.141					0.138		
M_9			0.140					0.139					0.136		
M_{10}			0.138					0.137					0.134		
M_{11}			0.137					0.136					0.132		
M_{12}			0.135					0.134					0.131		
M_{13}			0.134					0.133					0.130		
M_{14}			0.133					0.132					0.129		
M_{15}			0.132					0.131					0.128		
n (steepness of recruitment failure)			0.198					0.197					0.190		
Mmax (Recruitment failure scale parameter|)			13.95					13.95					13.95		
h	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
$\alpha(CS)$			8.999					8.999					8.999		
$\alpha(RS)$			8.996					8.998					8.997		
$\alpha(PS)$			4.904					4.904					4.904		
$\alpha(FS)$			6.559					6.554					6.581		
$\alpha(OS)$			4.563					4.419					4.480		
$\alpha(IS)$			-					-					-		
μ(CS)			0.000					0.000					0.000		
μ(RS)			0.001					0.001					0.001		
μ(PS)			0.000					0.000					0.000		
μ(FS)			0.001637					0.001655					0.002		
μ(OS)			0.000					0.000					0.000		
μ(IS)			-					-					-		
δ(CS)			901.2					896.3					900.2		
δ(RS)			72.90					116.7					104.9		
δ(PS)			306.2					306.2					306.2		
δ(FS)			0.781					0.794					0.777		
δ(OS)			0.681					0.692					0.687		
δ(IS)			-					-					-		

Table 3 continued.

Model	a) Ref case - Updated and scaled Old CPUE series					b) Ref case - Old CPUE series					c) Ref case - New CPUE series				
Zone	**A**	**B**	**CNP**	**CP**	**D**	**A**	**B**	**CNP**	**CP**	**D**	**A**	**B**	**CNP**	**CP**	**D**
-*ln* L CPUE	-50.27	-52.97	-28.00	-43.82	-33.32	-49.96	-49.90	-29.29	-43.97	-33.64	-52.17	-53.60	-37.20	-40.96	-34.39
-*ln* L FIAS	-0.950	-2.541	-4.454	6.233	-3.883	-0.856	-3.091	-4.547	6.178	-3.936	-0.405	-2.559	-4.192	5.944	-3.195
-*ln* L age CS	-15.74	-19.82	-7.135	-7.586	-12.13	-15.75	-19.63	-7.248	-7.648	-12.14	-15.19	-18.87	-6.221	-8.176	-12.17
-*ln* L age RS	-1.642	-7.996	-6.932	0.008	-8.558	-1.643	-7.969	-6.867	0.009	-8.537	-1.642	-7.927	-6.635	-0.046	-8.657
-*ln* L age PS	-4.213	-5.484		-2.565	-3.188	-4.103	-5.463		-2.581	-3.218	-3.586	-4.842		-2.556	-2.526
-*ln* L age FIAS	-3.117	-10.46	-3.629	-0.303	-5.162	-2.967	-10.30	-3.639	-0.314	-5.198	-2.129	-10.66	-3.396	-0.247	-5.266
-*ln* L age OS inshore	-3.420	-1.036		-1.248	-0.872	-3.408	-1.027		-1.226	-0.852	-3.398	-1.087		-1.203	-0.931
-*ln* Lage OS offsh.	-3.650	-1.759		-1.269	-2.194	-3.687	-1.808		-1.236	-2.140	-3.589	-1.654		-1.344	-2.187
-*ln* L age IS insh+offsh.		-0.854	-0.300				-0.879	-0.289				-0.756	-0.238		
-*ln* L zone subtotal	-83.00	-102.9	-101.0		-69.30	-82.37	-100.1	-102.7		-69.66	-82.11	-102.0	-106.5		-69.32
-*ln* L TOTAL & AIC			-356.2	**-648.5**				-354.8	**-645.5**				**-359.9**	-655.7	
s CPUE	0.096	0.099	0.207	0.068	0.180	0.097	0.097	0.192	0.067	0.178	0.089	0.097	0.145	0.078	0.173
s age CS	0.085	0.074	0.125	0.116	0.095	0.085	0.074	0.124	0.116	0.095	0.088	0.077	0.132	0.111	0.095
s age RS	0.114	0.058	0.060	0.205	0.062	0.114	0.058	0.061	0.206	0.062	0.114	0.058	0.063	0.190	0.061
s age PS	0.105	0.108		0.136	0.109	0.106	0.108		0.136	0.108	0.113	0.115		0.136	0.123
s age FIAS	0.115	0.071	0.098	0.134	0.089	0.117	0.072	0.098	0.133	0.089	0.132	0.070	0.102	0.136	0.088
s OS insh.	0.037	0.065		0.054	0.078	0.037	0.065		0.055	0.080	0.038	0.062		0.056	0.074
s OS offsh.	0.038	0.041		0.058	0.027	0.037	0.039		0.059	0.028	0.039	0.044		0.055	0.027
s IS		0.043	0.123				0.042	0.124				0.049	0.132		
Additional variance	0.409					0.400					0.433				
q CPUE	0.00026	0.00063	0.00270	0.00096	0.00023	0.00027	0.00064	0.00290	0.00096	0.00025	0.00025	0.00069	0.00241	0.00095	0.00025
Confiscation percentage			**Zone C**					**Zone C**					**Zone C**		
$\%Co/Po_{1997}$		0.239	0.054		0.021		0.258	0.054		0.022		0.539	0.052		0.032
$\%Co/Po_{1998}$		0.293	0.073		0.029		0.317	0.073		0.030		0.661	0.070		0.044
$\%Co/Po_{1999}$		0.063	0.057		0.012		0.068	0.057		0.013		0.142	0.055		0.019
$\%Co/Po_{2000}$	0.073	0.416	0.128		0.040	0.078	0.407	0.128		0.041	0.100	0.514	0.123		0.061
$\%Co/Po_{2001}$	0.034	0.319	0.062		0.022	0.036	0.311	0.062		0.023	0.046	0.390	0.059		0.034
$\%Co/Po_{2002}$	0.086	0.639	0.078		0.037	0.091	0.622	0.078		0.039	0.112	0.751	0.074		0.057
$\%Co/Po_{2003}$	0.077	0.459	0.084		0.053	0.081	0.444	0.084		0.055	0.096	0.515	0.081		0.081
$\%Co/Po_{2004}$	0.091	0.410	0.102		0.026	0.095	0.395	0.102		0.028	0.108	0.441	0.098		0.040
$\%Co/Po_{2005}$	0.084	0.284	0.097		0.042	0.087	0.271	0.097		0.044	0.094	0.287	0.093		0.064
$\%Co/Po_{2006}$	0.153	0.350	0.091		0.051	0.159	0.333	0.091		0.053	0.168	0.345	0.087		0.078
$\%Co/Po_{2007}$	0.264	0.310	0.068		0.036	0.274	0.296	0.068		0.038	0.290	0.307	0.066		0.055
$\%Co/Po_{2008}$	0.172	0.224	0.114		0.040	0.179	0.214	0.114		0.042	0.192	0.226	0.109		0.062
$\%Co/Po_{2009}$	0.099	0.269	0.061		0.029	0.104	0.258	0.061		0.030	0.115	0.281	0.059		0.044
Ave prop over last 5 yrs	**0.154**	**0.287**	**0.086**		**0.040**	**0.161**	**0.275**	**0.086**		**0.041**	**0.172**	**0.289**	**0.083**		**0.061**
Mean CS Fishing mortality	0.055	0.098	0.103	0.149	0.028	0.057	0.101	0.110	0.149	0.030	0.062	0.104	0.092	0.143	0.032
Catches	939.2	0				924.7	0				1113.333	0			
Ccomm(2009)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cpoa(2009)	529.7	262.9	56.63	84.99	5.021	511.5	265.9	57.05	84.90	5.297	502.4	246.4	55.56	75.31	233.6
Catch total (2009) MT	529.7	262.9	56.63	84.99	5.021	511.5	265.9	57.05	84.90	5.297	502.4	246.4	55.56	75.31	233.6
	A	**B**	**CNP**	**CP**	**D**	**A**	**B**	**CNP**	**CP**	**D**	**A**	**B**	**CNP**	**CP**	**D**
Depletion comp. yr	1986/87	1982		1981	1983	1986/87	1982		1981	1983	1986/87	1982		1981	1983
Insh OBS	0.330	0.670		0.330	0.360	0.330	0.670		0.330	0.360	0.330	0.670		0.330	0.360
Insh PRED	0.736	0.524		0.444	0.730	0.720	0.510		0.437	0.711	0.713	0.501		0.443	0.701
Offsh OBS	0.200	0.540		0.240	0.500	0.200	0.540		0.240	0.500	0.200	0.540		0.240	0.500
Offsh PRED	0.574	0.334		0.254	0.614	0.559	0.325		0.252	0.594	0.533	0.301		0.248	0.569

Table 3 continued. Depletion statistics.

Model	a) Ref case - Updated and scaled Old CPUE series					b) Ref case - Old CPUE series					c) Ref case - New CPUE series				
Zone	A	B	CNP	CP	D	A	B	CNP	CP	D	A	B	CNP	CP	D
Depletion statistics															
B^{sp}(2009)/K (Insh. + Offsh)	0.307	0.260	0.109	0.069	0.126	0.299	0.234	0.106	0.069	0.120	0.370	0.252	0.115	0.069	0.181
B^{sp}(2009)/K (Insh.)	0.171	0.197	0.038	0.027	0.001	0.169	0.170	0.041	0.029	0.001	0.244	0.185	0.033	0.023	0.062
B^{sp}(2009)/K (Offsh.)	0.575	0.383	0.248	0.257	0.372	0.569	0.368	0.242	0.258	0.368	0.589	0.369	0.257	0.252	0.386
B^{total}(2009)/K	0.355	0.309	0.099	0.063	0.115	0.346	0.284	0.097	0.063	0.109	0.413	0.300	0.105	0.063	0.166
$B^{commercial}$(2009)/K	0.256	0.186	0.103	0.083	0.148	0.246	0.162	0.097	0.083	0.141	0.320	0.186	0.115	0.082	0.221
FIAS N_{2009}/N_{1951}	0.182	0.248	0.005	0.002	0.000	0.183	0.210	0.007	0.004	0.000	0.274	0.224	0.001	0.001	0.013
Projections	A	B	CNP	CP	D	A	B	CNP	CP	D	A	B	CNP	CP	D
Ccomm(2009)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Cpoa(2009) (NUMBERS)	1391040	669634	71193	112433	412155	1334420	699623	71605	112035	393867	1222920	652730	73877	117588	268617
Cpoa(2009) (MT)	508	259	12.93	10.43	0	491	262	18.62	18.15	0	495	247	3.501	5.140	105
Catch total (2009) MT	508	259	12.93	10.43	0.474	491	262	18.62	18.15	0.489	495	247	3.501	5.140	105
B^{sp}(2014)/K	0.233	0.238	0.048	0.026	0.067	0.225	0.205	0.045	0.025	0.064	0.305	0.228	0.055	0.029	0.084
B^{sp}(2029)/K	0.126	0.156	0.007	0.004	0.009	0.122	0.118	0.007	0.004	0.009	0.171	0.140	0.008	0.004	0.012
B^{sp}(2014)/Bsp(2009)	0.758	0.915	0.442	0.383	0.533	0.754	0.877	0.429	0.369	0.536	0.824	0.906	0.479	0.425	0.463
B^{sp}(2029)/Bsp(2009)	0.410	0.598	0.063	0.054	0.074	0.408	0.505	0.062	0.053	0.076	0.463	0.555	0.072	0.064	0.069

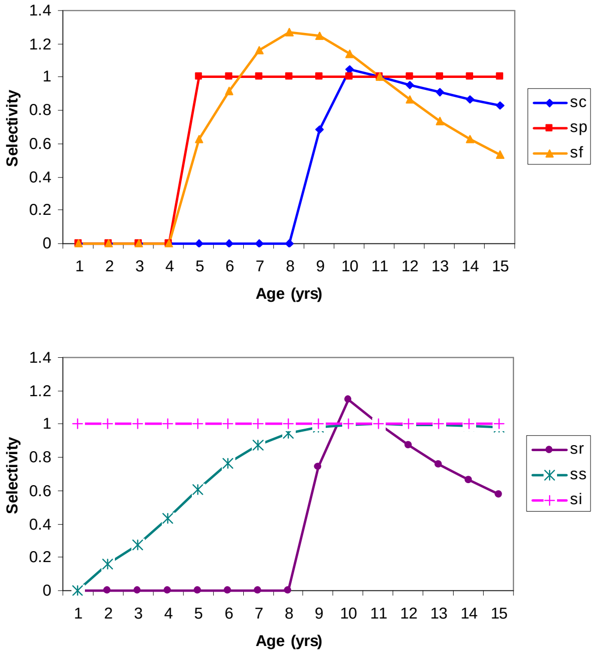


Figure 1a. Plots of the Reference-case combined ABCD model (when the updated and extrapolated "old" CPUE series is used in the model fitting procedure) selectivity functions estimated for the commercial (sc), recreational (sr) and poaching (sp) fishery sectors, and for FIAS (sf) and the old 1980's surveys (ss). A description of the general functional form used is given in Appendix 1 and the fitted parameter values are listed in Table 3. A uniform value is assumed for the industry/MCM survey (si) because of the extractive nature of the sampling methodology used.

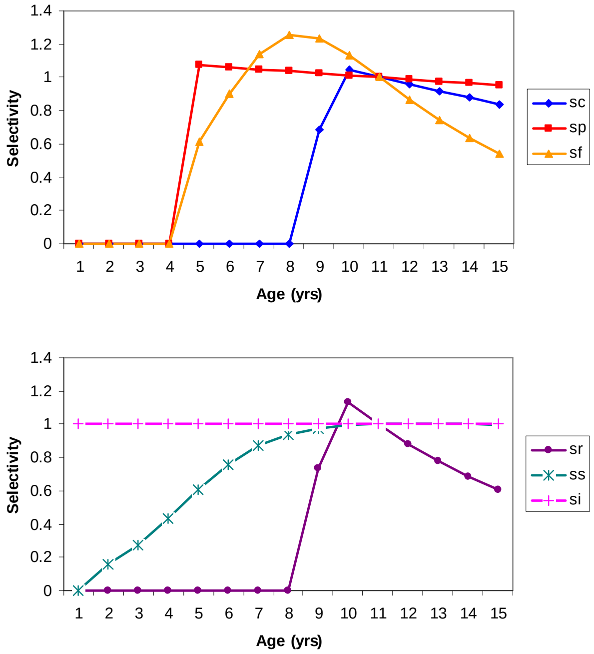


Figure 1b. Plots of the model selectivity functions estimated for version c) in which the "new" CPUE series is used in the model fitting procedure.

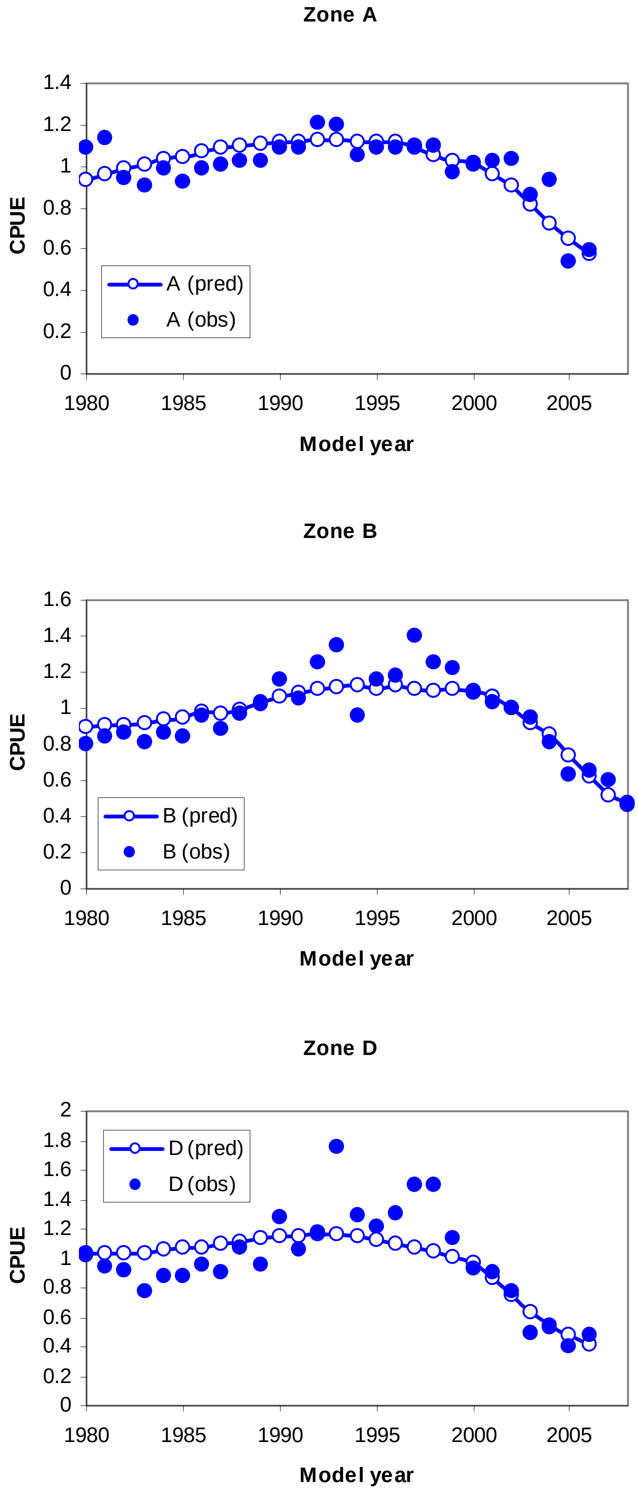


Figure 2. Comparisons between the standardised CPUE and model-predicted CPUE values (for the Reference-case combined ABCD model (when the updated and extrapolated "old" CPUE series is used in the model fitting procedure)) for each of Zones A, B and D.

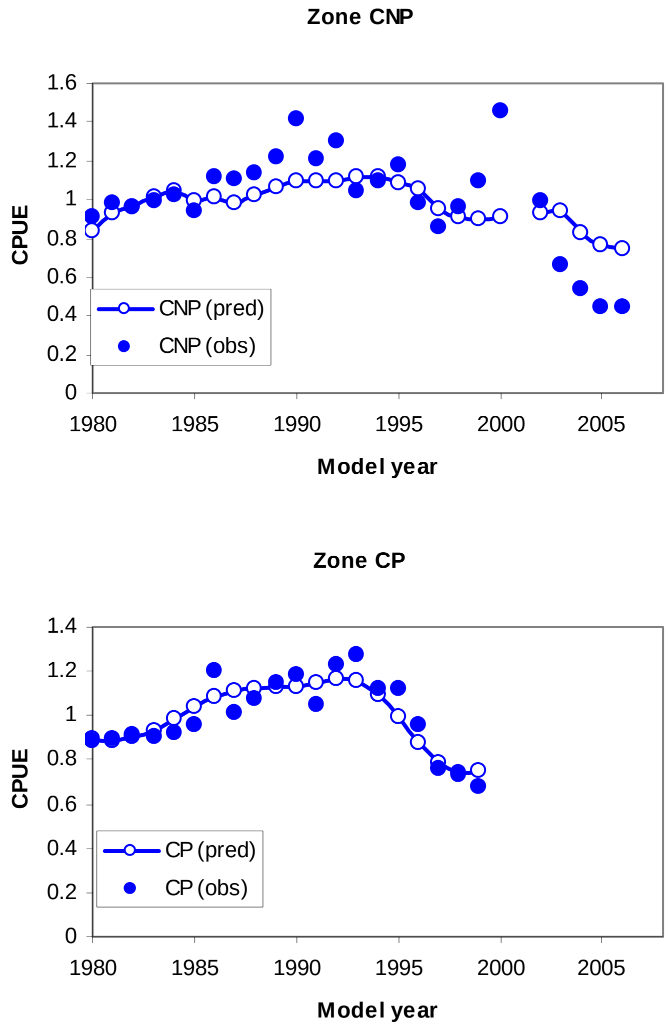
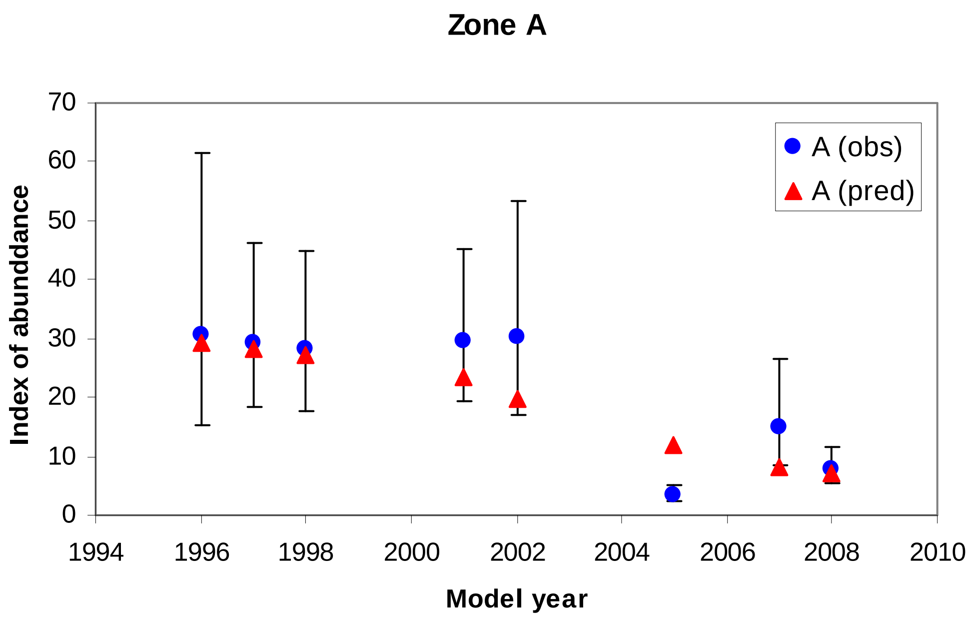


Figure 3. Comparisons between the standardised CPUE and model-predicted CPUE values (for the Reference-case combined ABCD model (when the updated and extrapolated "old" CPUE series is used in the model fitting procedure)) for each of Zones CNP and CP.



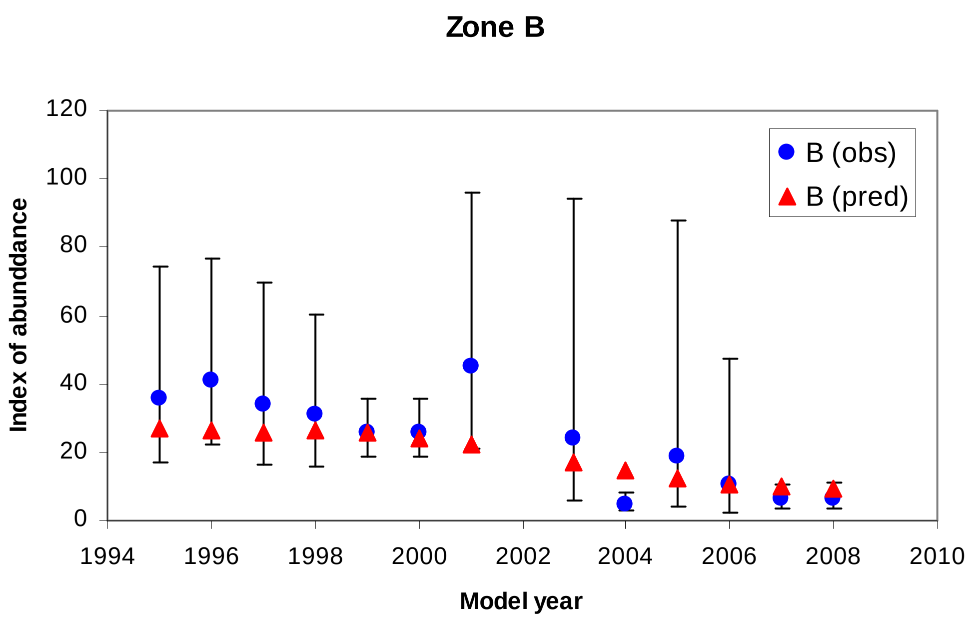
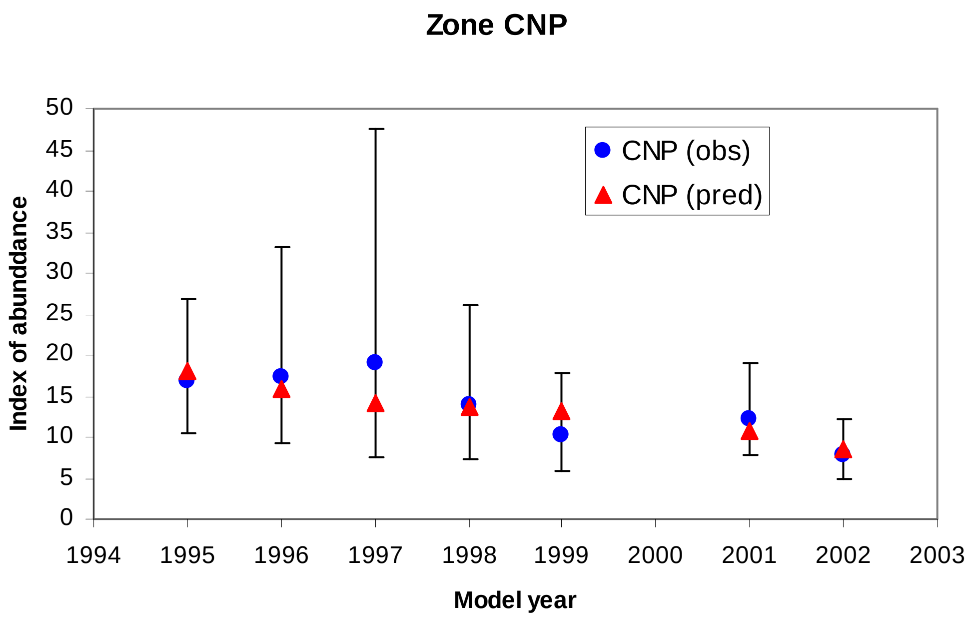


Figure 4. Comparison of model-predicted (Reference-case combined ABCD model (when the updated and extrapolated "old" CPUE series is used in the model fitting procedure)) and observed FIAS trends for each of Zones A and B. Note that 95% confidence intervals have been computed as estimate*exp(±1.96*CV).



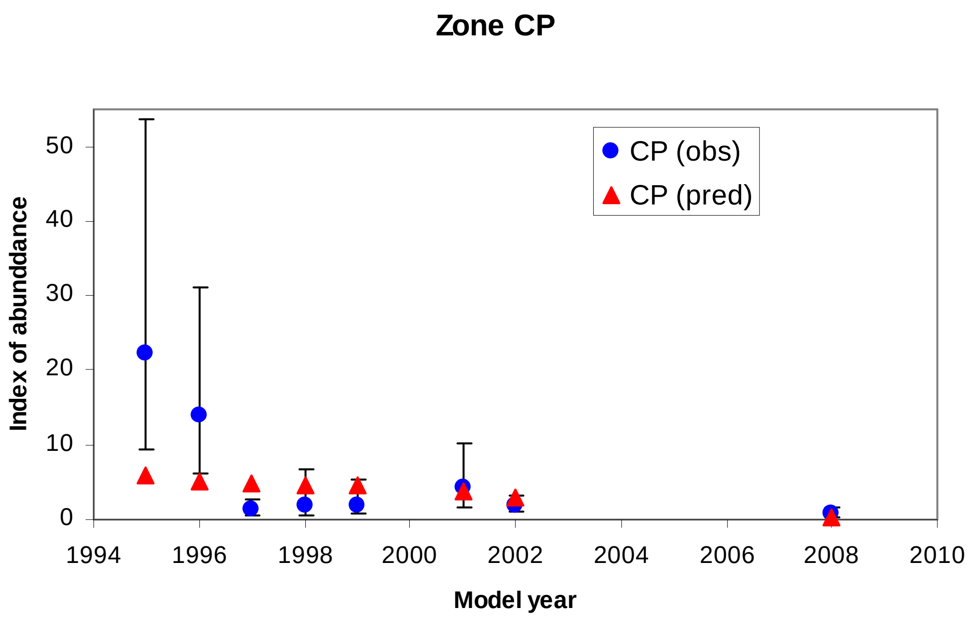


Figure 5. Comparison of model-predicted (Reference-case combined ABCD model (when the updated and extrapolated "old" CPUE series is used in the model fitting procedure)) and observed FIAS trends for each of subareas CNP and CP in Zone C. Note that 95% confidence intervals have been computed as estimate*exp(±1.96*CV).

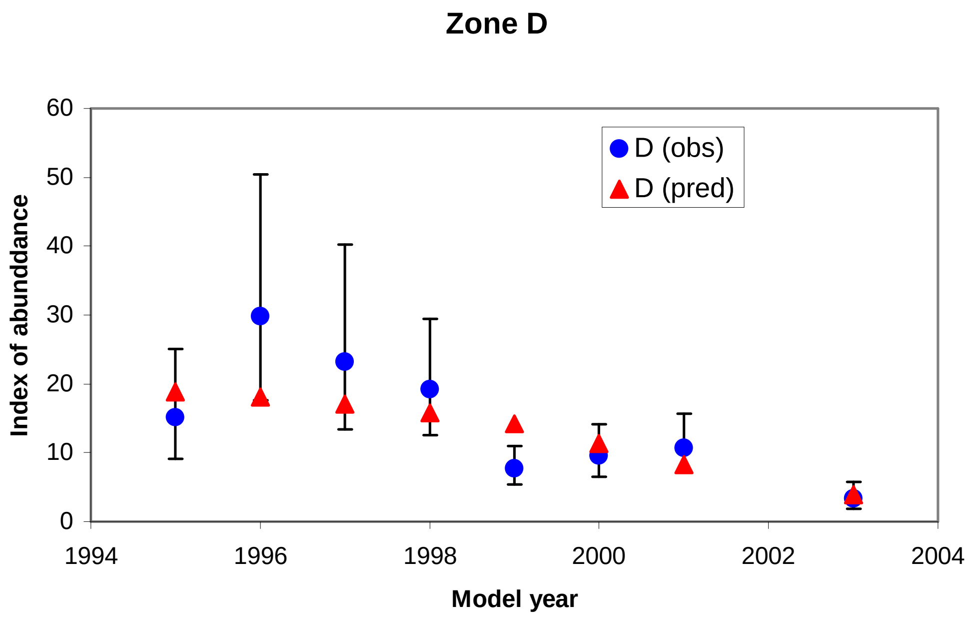
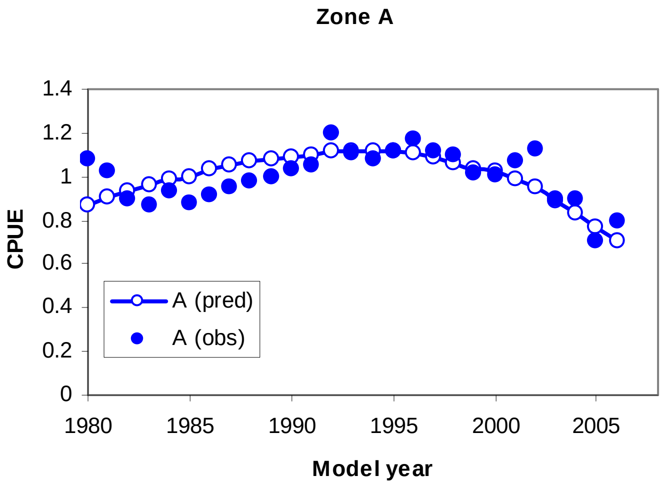
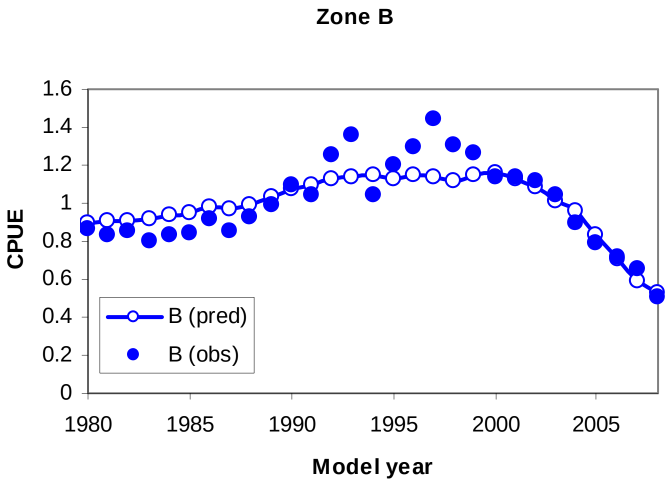


Figure 6. Comparison of model-predicted (Reference-case combined ABCD model (when the updated and extrapolated “old” CPUE series is used in the model fitting procedure)) and observed FIAS trends for each of Zone D. Note that 95% confidence intervals have been computed as estimate*exp(±1.96*CV).





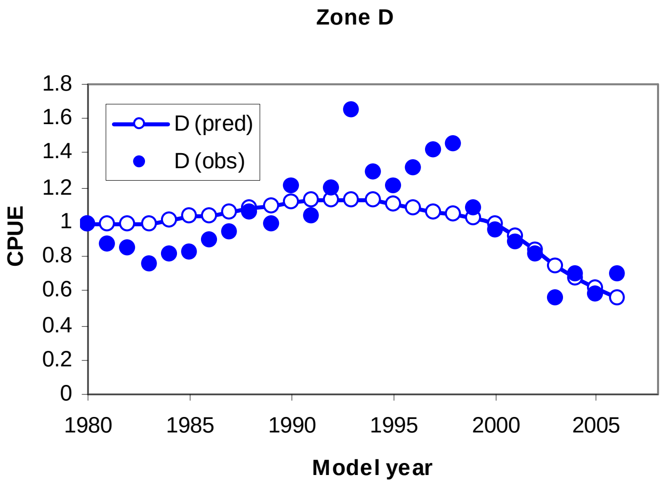
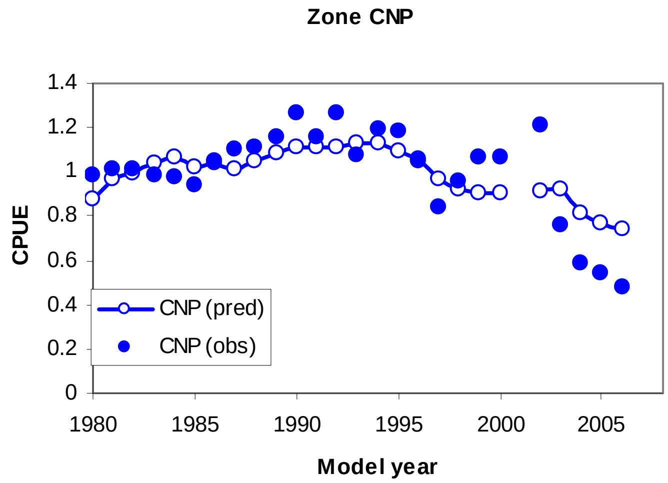


Figure 7. Comparisons between the standardised CPUE and model-predicted CPUE values (for the Reference-case combined ABCD model (when the "new" CPUE series is used in the model fitting procedure)) for each of Zones/suareas A, B, CNP, CP and D.



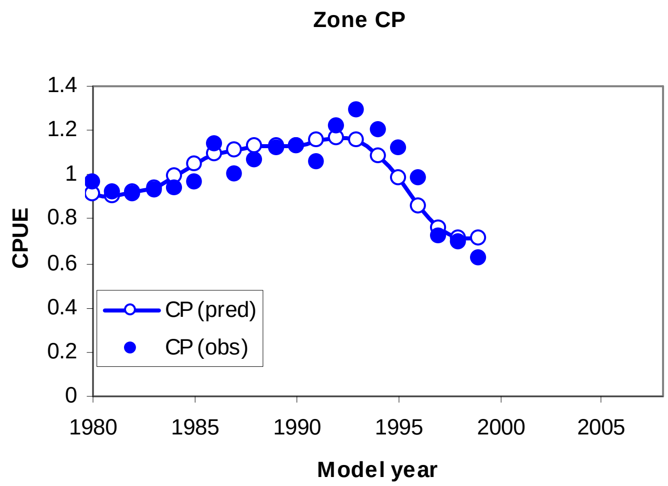


Figure 7 cont. Comparisons between the standardised CPUE and model-predicted CPUE values (for the Reference-case combined ABCD model (when the "new" CPUE series is used in the model fitting procedure)) for each of Zones/suareas A, B, CNP, CP and D.

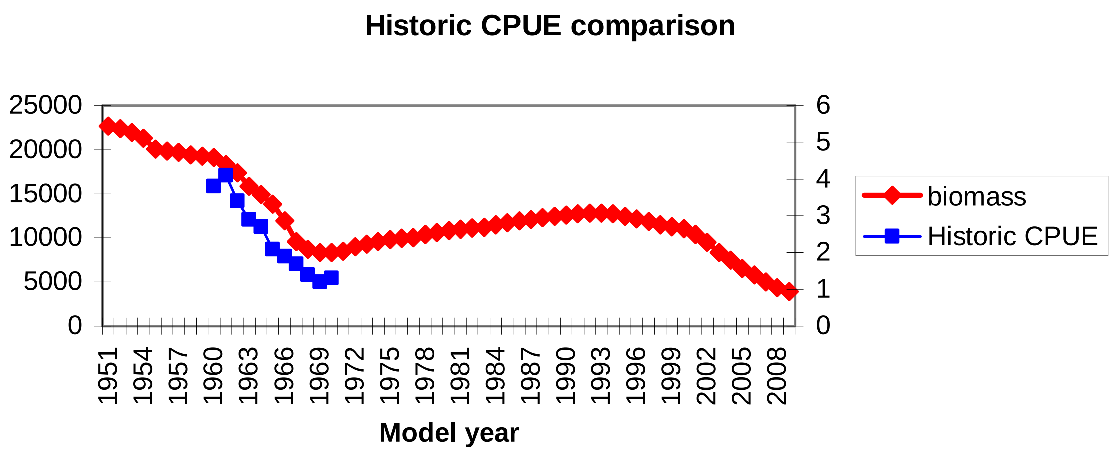


Figure 8. Historic CPUE comparison with Zones A-D combined commercial exploitable biomass trajectory.

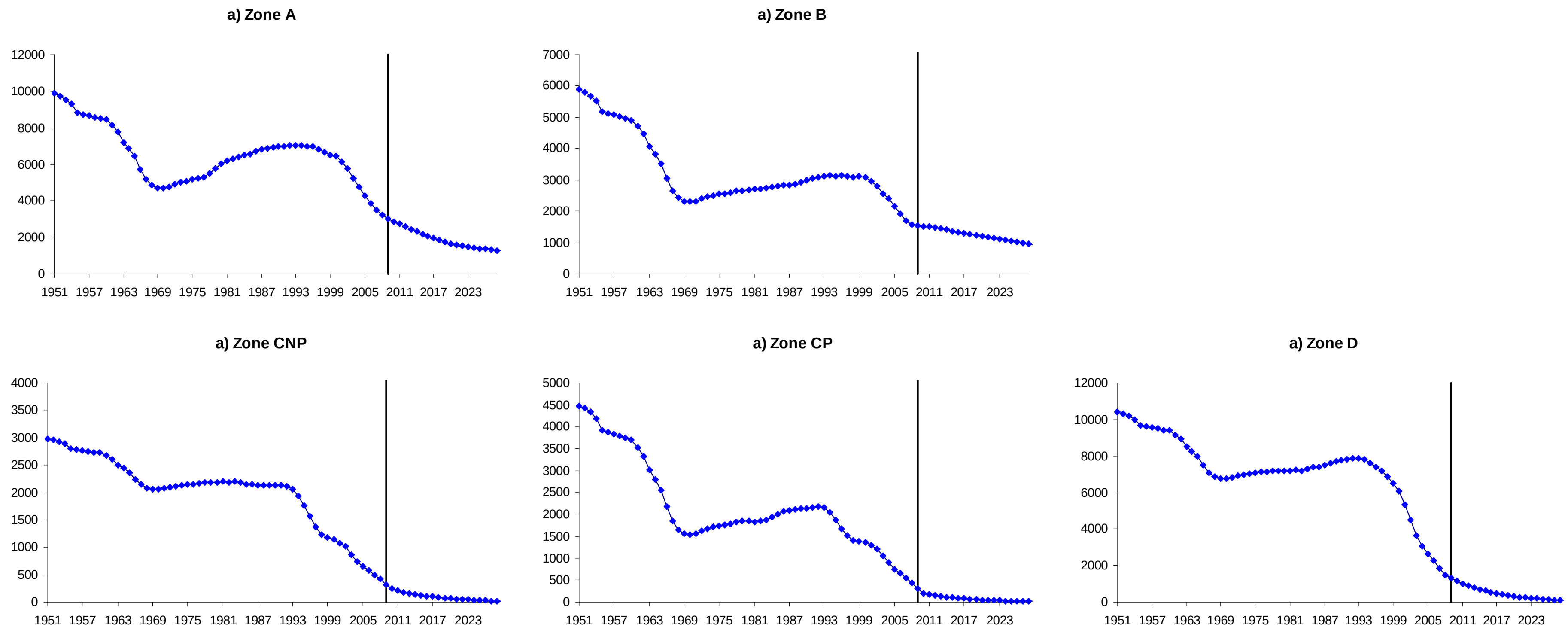


Figure 9. Reference-case combined ABCD model (when the updated and extrapolated "old" CPUE series is used in the model fitting procedure) total (inshore + offshore) spawning biomass trajectories shown for Zones A to D. Note that the 20-yr projections shown (indicated by vertical bar) represent scenarios under which future poaching levels are assumed to remain at the current estimated level (average of 2008 and 2009) and future commercial catches are set to zero.

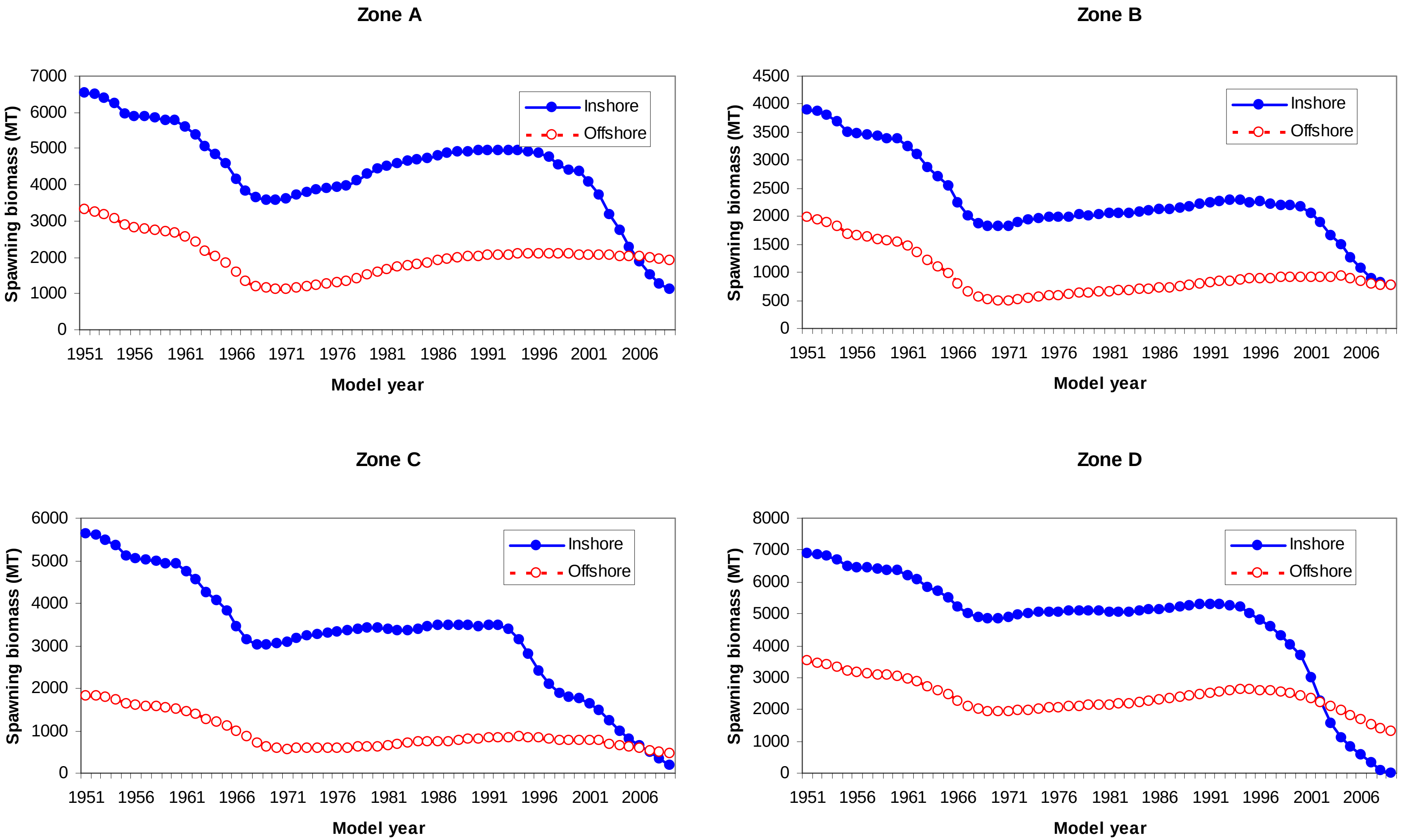
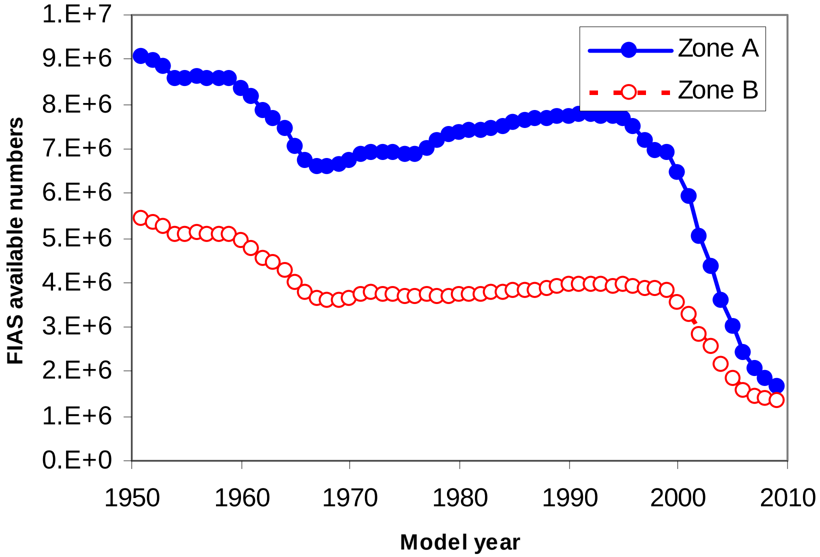


Figure 10. Spawning biomass trajectories for the inshore and offshore components of Zones A, B, C and D from the Reference-case model (when the updated and extrapolated "old" CPUE series is used in the model fitting procedure).



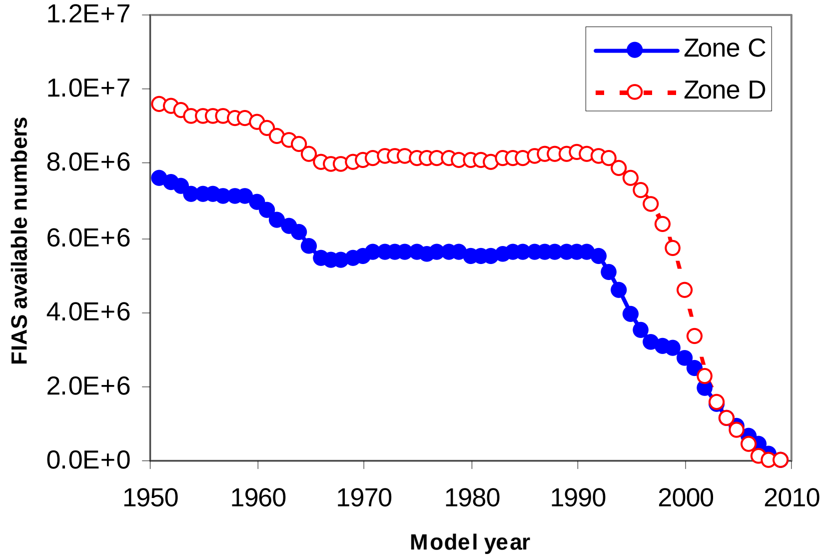


Figure 11. Reference-case model (when the updated and extrapolated "old" CPUE series is used in the model fitting procedure) estimates of the numbers of abalone available to the FIAS sector in Zones A, B, C and D.

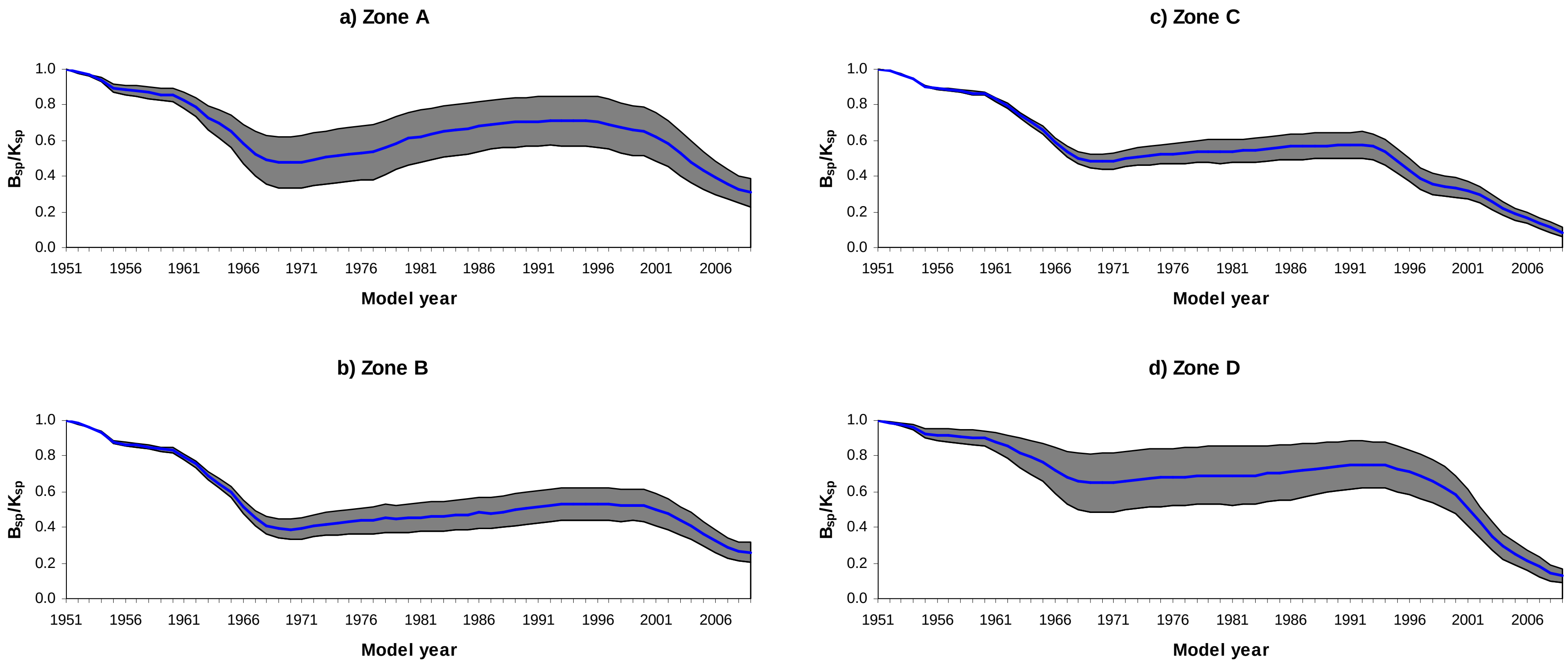


Figure 12a. Total spawning biomass trajectories (inshore and offshore combined shown as a proportion of the pre-exploitation level) for a) Zone A, b) Zone B, c) Zone C and d) Zone D when using the Reference-case model (when the updated and extrapolated "old" CPUE series is used in the model fitting procedure). The shaded areas represent the associated Hessian-based 95% probability intervals.

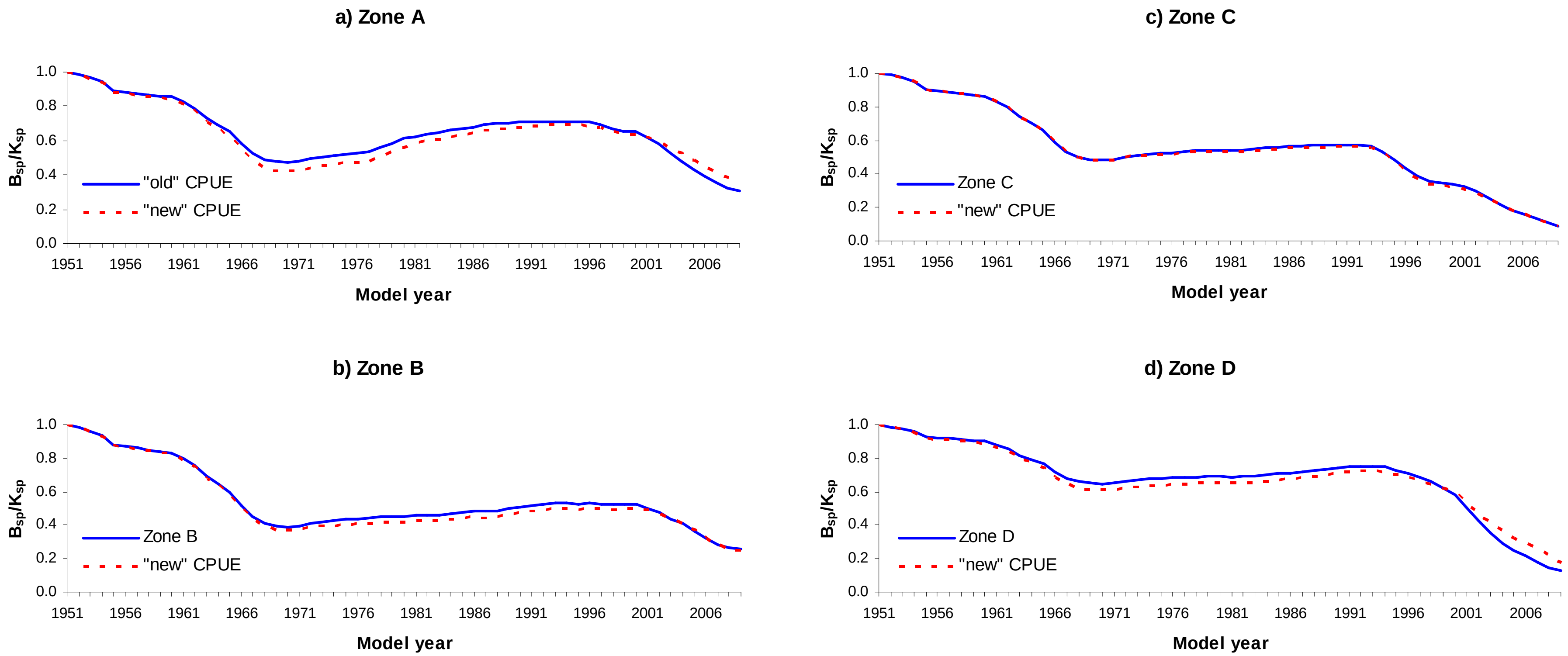


Figure 12b. Comparison of total spawning biomass trajectories (inshore and offshore combined shown as a proportion of the pre-exploitation level) for a) Zone A, b) Zone B, c) Zone C and d) Zone D when using the Reference-case model when the updated and extrapolated "old" CPUE series (version a) and when the "new" CPUE series (version c) is used in the model fitting procedure.

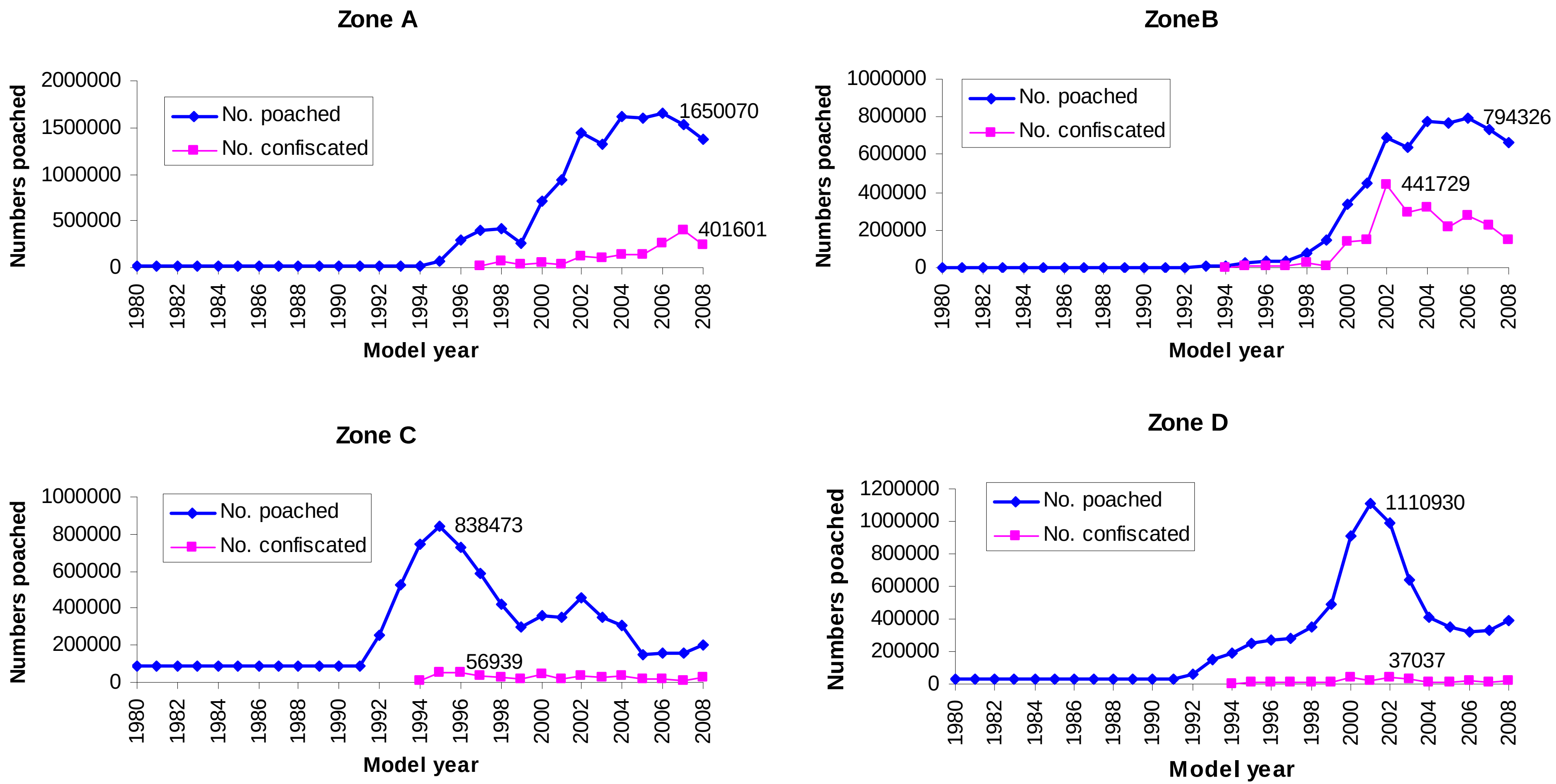


Figure 13. Comparison of model-predicted numbers of abalone poached per Zone with "observed" numbers confiscated (after allocating confiscated abalone from the Unknown category to each of Zones A-D). The numerical value (units are numbers) corresponding to selected points on the graph is given. Results are for the Reference-case model (when the updated and extrapolated "old" CPUE series is used in the model fitting procedure).

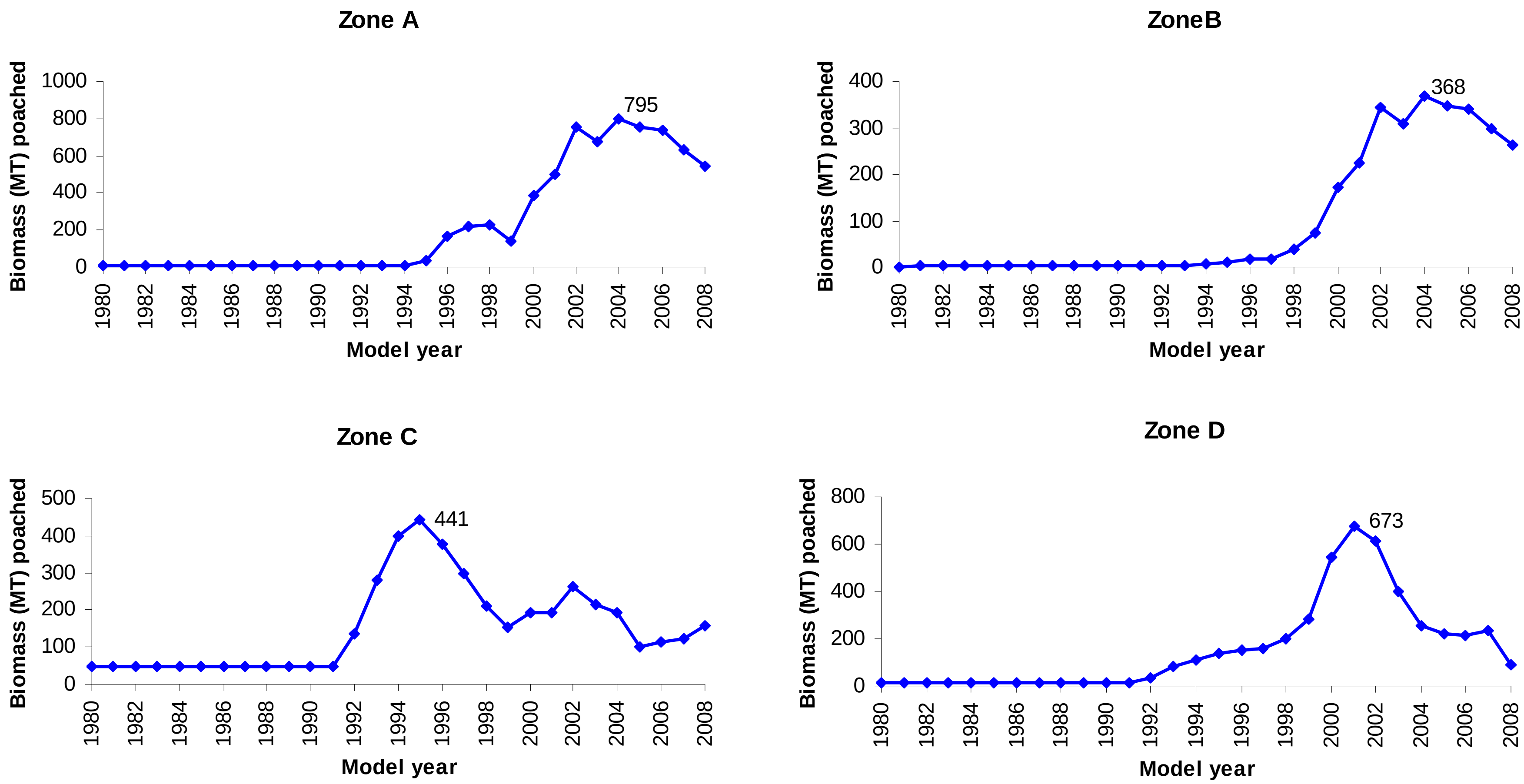


Figure 14. Model-predicted biomass (in MT) of abalone poached per Zones A-D. Results are for the Reference-case model (when the updated and extrapolated “old” CPUE series is used in the model fitting procedure).

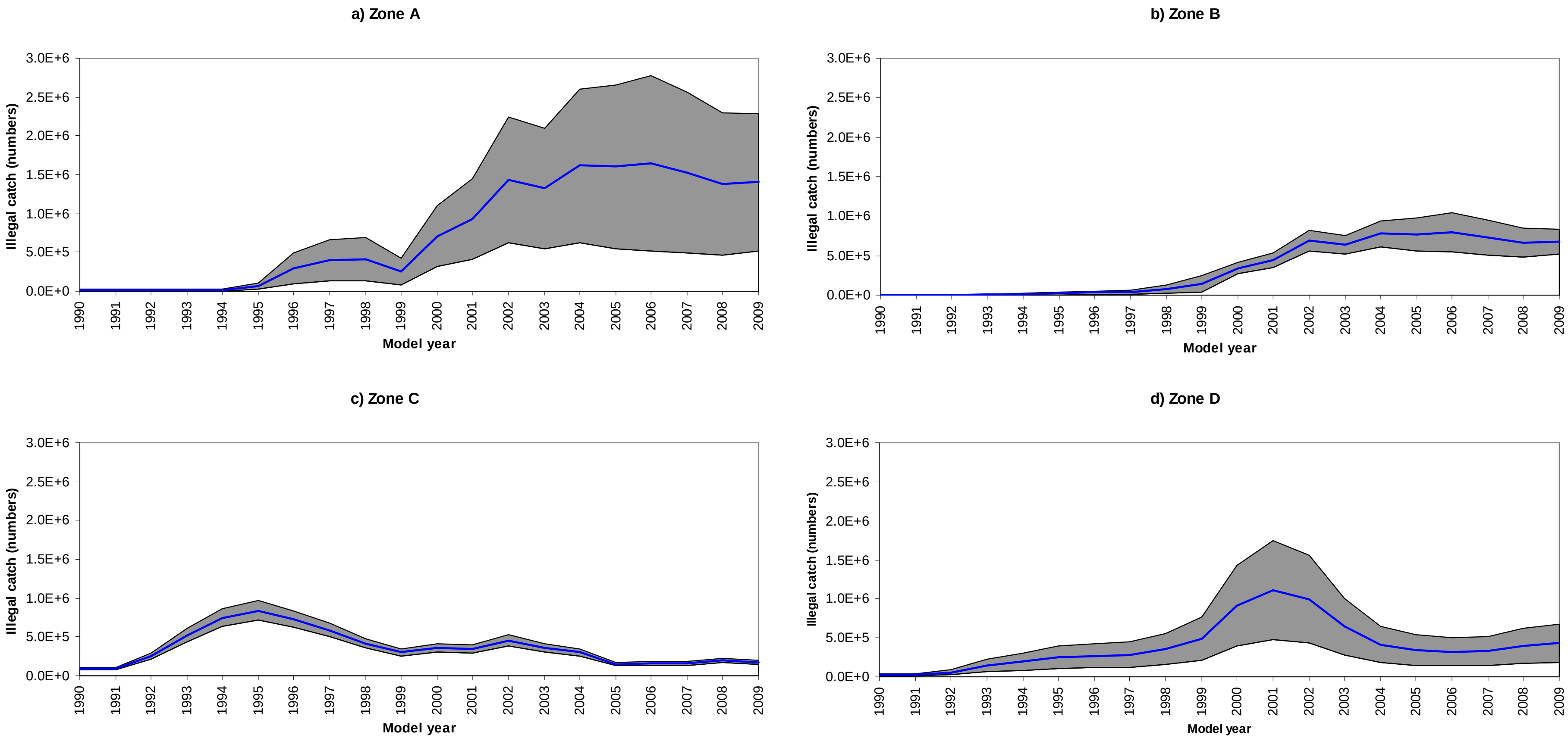


Figure 15. Reference-case model (when the updated and extrapolated "old" CPUE series is used in the model fitting procedure) results showing the uncertainty associated with estimates of the total numbers of abalone poached for years 1990 to present and for a) Zone A, b) Zone B, c) Zone C and d) Zone D. The vertical axis scale is the same in all plots for purposes of comparing amongst Zones. The shaded areas represent the associated Hessian-based 95% probability intervals.

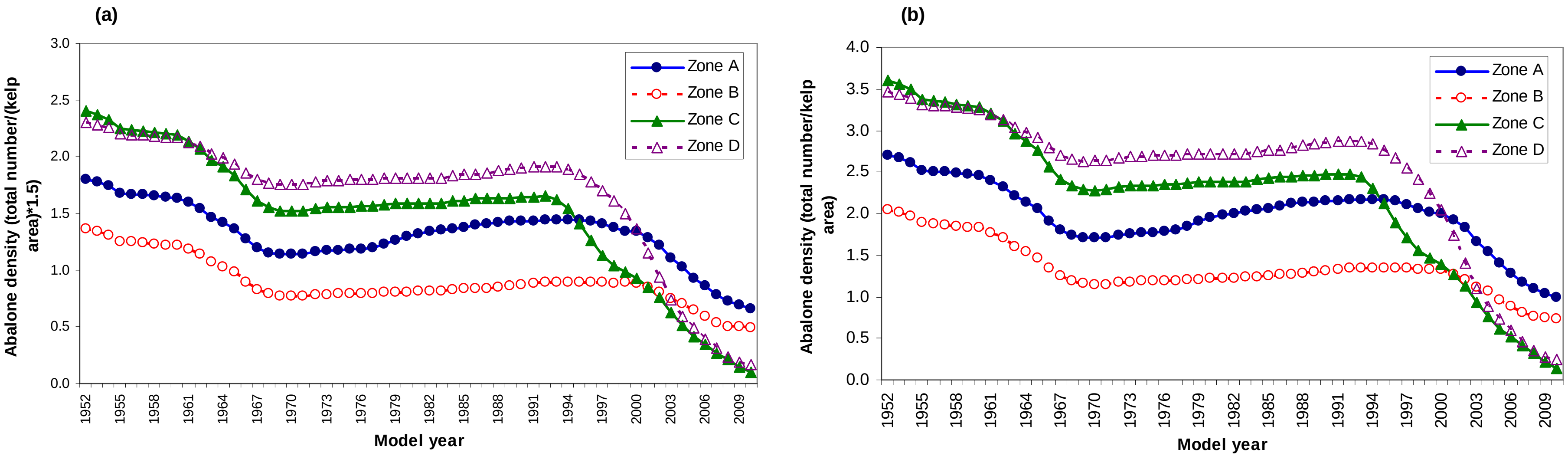


Figure 16. Reference-case model (when the updated and extrapolated "old" CPUE series is used in the model fitting procedure) estimated abalone density per Zones A-D. Density is computed as the total number of abalone (inshore and offshore combined) divided by the habitat area, which is measured either as a) kelp area multiplied by a scaling factor of 1.5 or b) kelp area.

Appendix 1. The base-case inshore/offshore population model used for estimating resource dynamics parameters and projecting biomass trends

The description which follows is for Zone C but the same equations apply to the other Zones.

1 Dynamics

For each subarea, the dynamics of the **inshore** component are given by:

(A1) $N^I_{y+1,0} = r_I \cdot R(B^{sp}_{y+1})$

(A2) $N^I_{y+1,a+1} = \left(N^I_{y,a} e^{-\frac{M_a}{4}} - C^I_{y,a} \right) e^{-\frac{3M_a}{4}}$ $\qquad 0 \le a \le 4$

(A3) $N^I_{y+1,a+1} = \left((1-\rho) \cdot N^I_{y,a} e^{-\frac{M_a}{4}} - C^I_{y,a} \right) e^{-\frac{3M_a}{4}}$ $\qquad 5 \le a \le z\text{-}2$

(A4) $N^I_{y+1,z} = ((1-\rho) \cdot N^I_{y,z} e^{-\frac{M_z}{4}} - C^I_{y,z}) e^{-\frac{3M_z}{4}} + ((1-\rho) \cdot N^I_{y,z-1} e^{-\frac{M_{z-1}}{4}} - C^I_{y,z-1}) e^{-\frac{3M_{z-1}}{4}}$

where $N^I_{y,a}$ is the *inshore* number of abalone of age *a* at the start of Model year *y*,

ρ is the proportion of inshore animals of age *a* ($5 \le a \le z$) that move offshore at the start of Model year *y*,

$C^I_{y,a}$ is the total number of abalone of age *a* taken by recreationals and by poachers in Model year *y*, as well as the *inshore* number of abalone taken by the commercial fishery,

$R(B^{sp})$ is the recruitment vs spawner biomass relationship assumed (see below),

r_I is the proportion of the recruits which settle inshore,

M_a is the (time-invariant) natural mortality rate on abalone of age *a*, and

z is the largest age considered (i.e. corresponding to a "plus group").

Similarly, for each subarea, the dynamics of the **offshore** component are given by:

(A5) $N^O_{y+1,0} = r_O \cdot R(B^{sp}_{y+1})$

(A6) $N^O_{y+1,a+1} = \left(N^O_{y,a} e^{-\frac{M_a}{4}} - C^O_{y,a} \right) e^{-\frac{3M_a}{4}}$ $\qquad 0 \le a \le 4$

(A7) $N^O_{y+1,a+1} = \left((N^O_{y,a} + \rho \cdot N^I_{y,a}) e^{-\frac{M_a}{4}} - C^O_{y,a} \right) e^{-\frac{3M_a}{4}}$ $\qquad 5 \le a \le z\text{-}2$

(A8)

$$N^O_{y+1,z} = ((N^O_{y,z} + \rho \cdot N^I_{y,z})e^{-\frac{M_z}{4}} - C^O_{y,z})\, e^{-\frac{3M_z}{4}} + ((N^O_{y,z-1} + \rho \cdot N^I_{y,z-1})e^{-\frac{M_{z-1}}{4}} - C^O_{y,z-1})\, e^{-\frac{3M_{z-1}}{4}}$$

where $N^O_{y,a}$ is the *offshore* number of abalone of age *a* at the start of Model year *y*,

r_O is the proportion of the recruits which settle offshore (= 1-r_I), and

$C^O_{y,a}$ is the *offshore* number of abalone of age *a* taken by the commercial fishery.

The commercial abalone fishery season currently extends from October to June but several historic changes in the commencement and closure dates for the commercial fishing season are on record. For reasons of internal consistency in the assessment process, a standard Model or fishing year *y* is thus taken to run from October of year *y*-1 to September of year *y*. The population model used here assumes pulse fishing (Pope's approximation – Pope 1984), rather than the more customary Baranov catch equations which assume continuous fishing through the year (Baranov 1918). Pope's approximation has been used in order to simplify computations. As long as mortality rates are not too high, the differences between the Baranov and Pope formulations will be minimal. The approximation of the fishery as a pulse catch at the start of each calendar year is here considered to be of sufficient accuracy given that most of the catch is made over the October-March period, and because the annual catches from this long lived resource are not that large a fraction of the overall biomass. This last reason also constitutes the justification for treating inshore-to-offshore movement as a pulse at the start of the Model year. The equations reflect the fact that catches are subtracted at the end of the first quarter of the Model year (i.e. in the middle of the October-March period of high catches). As the fishery-independent surveys (FIAS) are conducted only towards the end of the second quarter of the Model year, comparisons with the abundance indices obtained from FIAS are made at time $y+\frac{1}{2}$ in terms of the model whereas comparisons with the CPUE data are made at time $y+\frac{1}{4}$ in the model.

Because different sectors of the fishery exhibit different selectivity patterns with age, the following five sectors are explicitly differentiated in the model: the commercial fishery sector (mostly offshore); the recreational sector (mostly inshore); the poaching/illegal sector (mostly inshore), the fishery-independent survey (inshore and offshore) and the "old survey" (inshore and offshore).

The equations given below are applied separately to each of the inshore and offshore components of the two subareas CNP and CP.

The total number of abalone of age *a* caught each year ($C_{y,a}$) is given by:

(A9) $$C_{y,a} = \sum_s C^s_{y,a}$$

where *s* indicates the sector of the fishery (e.g. commercial, recreational, poaching).

The annual catch by mass (C_y^s) for sector *s* is given by:

(A10) $$C_y^s = \sum_{a=3}^{z} w_{y,a+1/4} C_{y,a}^s$$

where $w_{y,a+1/4}$ is the mass of an abalone of age *a* at the end of the first quarter of Model year *y* (note however that only the plus group mass $w_{y,z}$ is year-dependent in the model formulation pursued and that the plus group mass is modelled separately for the inshore and offshore components). The summation is taken from age *a* = 3 as no abalone of a size corresponding to ages below 3 are taken by any of the fishing sectors.

A von Bertalanffy growth equation is used to relate shell length ℓ (mm) to age in years (*t*), and is based on tagging data from Betty's Bay (Tarr 1995):

(A11) $$\ell(t) = \ell_\infty [1 - e^{-\kappa(t-t_0)}]$$

The relationship between *shell length* (mm) and abalone whole wet mass (g) is based on data from the Betty's Bay and Danger Point areas and is determined using the following power relationship:

(A12) $$w_{y,a} = w(y, t = a) = c \cdot (\ell)^d$$

Note that mass-at-age is year-independent for abalone of age *a* < *z* and that $w_{y,a+\frac{1}{4}} = w(y, t = a + \frac{1}{4})$ is computed for use in calculating the sector-specific exploitable biomasses after the first quarter of each year (see below). However, the mass-at-age for the plus group varies over time, depending on the average age of the inshore and offshore plus group components in year *y*, $\bar{z}_y^I$ and $\bar{z}_y^O$ respectively, which are calculated as:

(A13) $$\bar{z}_y^I = \frac{\left(\bar{z}_{y-1}^I + 1\right)\left((1-\rho)N_{y,z}^I - C_{y,z}^I\right)e^{-M_z} + z \cdot \left((1-\rho)N_{y,z-1}^I - C_{y,z-1}^I\right)e^{-M_{z-1}}}{N_{y,z}^I}$$

(A14)
$$\bar{z}_y^O = \frac{\left(\left(\bar{z}_{y-1}^O + 1\right)\left(N_{y,z}^O - C^O{}_{y,z}\right) + \left(\bar{z}_{y-1}^I + 1\right)\rho\, N_{y,z}^I\right)e^{-M_z} + z \cdot \left(N_{y,z-1}^O + \rho\, N_{y,z-1}^I - C_{y,z-1}^O\right)e^{-M_{z-1}}}{N_{y,z}^O}$$

The above is an approximation only (as it ignores, e.g., the fact that catches are subtracted not at the start of the year but at the end of the first quarter of each year) but is considered sufficiently accurate for present purposes.

The recreational catch by mass in year *y* is given by:

(A15) $$C_y^s = \sum_{a=8}^{z-1} w_{a+1/4} N_{y,a}^I (1-\rho) e^{-M_a/4} S_a^s F_y^s + w_{y,\bar{z}_y+1/4}^I N_{y,z}^I (1-\rho) e^{-M_z/4} S_z^s F_y^s$$

and the poaching catch by mass in year *y* by:

(A16) $$C_y^s = w_{4+1/4} N_{y,4}^I e^{-M/4} S_4^s F_y^s + \sum_{a=5}^{z-1} w_{a+1/4} N_{y,a}^I (1-\rho) e^{-M/4} S_a^s F_y^s + w_{y,\bar{z}_y+1/4}^I (1-\rho) N_{y,z}^I e^{-M/4} S_z^s F_y^s$$

where S_a^s is the fishing selectivity-at-age for sector *s* (this pattern is assumed not to change over time), $w_{y,\bar{z}_y+1/4}^I$ is the mean mass of the inshore plus group with average age $\bar{z}_y + 1/4$ after the first quarter of Model year *y*, and F_y^s is the fishing "mortality" (strictly here that proportion of the numbers present after the first quarter of the Model year which are caught) at a reference age, set for these computations to be *a* = 11 for all sectors. Based on an analysis of confiscated abalone samples, the minimum age of animals assumed caught by the poaching sector is 4 years, so that for this sector $S_a^s = 0$ for $a < 4$. Note also (cf. Eqn. A16) that there is no inshore-offshore movement of animals aged four and younger. The commercial and recreational sectors are both assumed not to catch animals below the legal size limit, so that for these sectors $S_a^s = 0$ for $a < 8$.

In the case of the recreational sector (which reports in terms of numbers rather than mass), estimates of the annual catch by mass are computed using equation (A15) but it is necessary to first compute the fishing "mortality" F_y^s, using the following relation for the numbers caught in year *y*:

(A17) $$N_y^s = \sum_{a=8}^{z} N_{y,a}^I (1-\rho) e^{-M_a/4} S_a^s F_y^s$$

The relative proportions of the Zone C recreational catch (i.t.o. numbers) taken from the two subareas CP and CNP is assumed to be proportional to the relative lengths of the coastline (CP:CNP = 1:2).

The amount of poached abalone is estimated in terms of numbers and hence the following relation is used to compute the fishing "mortality" F_y^s for the poaching sector in year *y*:

(A18) $$N_y^s = \sum_{a=5}^{z} N_{y,a}^I (1-\rho) e^{-M_a/4} S_a^s F_y^s + N_{y,4}^I e^{-M_a/4} S_4^s F_y^s$$

Equations (A15) to (A18) assume that poaching and recreational activities occur exclusively in the inshore region. In the case of the commercial sector, the 0-2 m depth range is thought to be the only habitat that is almost never fished by commercial divers encroaching inshore because the shallow depth prevents boats from operating easily in these waters. Inshore encroachment by commercial divers is seen as being particularly common in areas that do not have residential houses along the beachfront. Thus, whereas this is thought to be a relatively minor problem in subarea CNP, inshore encroachment by commercial fishers is considered to have been a problem throughout the history of the fishery in subarea CP (and in all the other zones).

Thus, whereas the commercial catch by mass in year y in subarea CP is given by:

$$\text{(A19)} \quad C_y^s = \sum_{a=8}^{z-1} w_{a+1/4}\left(N_{y,a}^I + N_{y,a}^O\right)e^{-M_a/4} S_a^s F_y^s + \left(w_{y,\bar{z}_y+1/4}^I N_{y,z}^I + w_{y,\bar{z}_y+1/4}^O N_{y,z}^O\right)e^{-M_z/4} S_z^s F_y^s$$

in subarea CNP, the commercial catch by mass in year y is given by equation (A19) above for years prior to 1967, and by equation (20) for years 1967 onwards:

(A20)

$$C_y^s = \sum_{a=8}^{z-1} w_{a+1/4}\left(N_{y,a}^O + \rho\, N_{y,a}^I\right)e^{-M_a/4} S_a^s F_y^s + \left(w_{y,\bar{z}_y+1/4}^O N_{y,z}^O + \rho\, w_{y,\bar{z}_y+1/4}^I N_{y,z}^I\right)e^{-M_z/4} S_z^s F_y^s$$

where $w_{y,\bar{z}_y+1/4}^O$ is the mean mass of the offshore plus group with average age $\bar{z}_y + 1/4$ after the first quarter of Model year y.

The exploitable ("available") components of abundance for the recreational and poaching sectors are both expressed in terms of population numbers and are computed using Eqn. (A21) below for the recreational sector and Eqn. (A22) for the poaching sector:

$$\text{(A21)} \qquad B_y^{exp,s} = \sum_{a=8}^{z} S_a^s (1-\rho) N_{y,a}^I e^{-M_a/4}$$

$$\text{(A22)} \qquad B_y^{exp,s} = \sum_{a=5}^{z} S_a^s (1-\rho) N_{y,a}^I e^{-M_a/4} + S_4^s N_{y,4}^I e^{-M_4/4}$$

On the other hand, the exploitable components of abundance for the commercial sector operating in subareas CP (all years) and CNP (years prior to 1967) are computed as:

$$\text{(A23)} \quad B_y^{exp,s} = \sum_{a=8}^{z-1} S_a^s w_{a+1/4}\left(N_{y,a}^I + N_{y,a}^O\right)e^{-M/4} + S_z^s\left(w_{y,\bar{z}_y+1/4}^I N_{y,z}^I + w_{y,\bar{z}_y+1/4}^O N_{y,z}^O\right)e^{-M/4}$$

and in the case of subarea CNP, exploitable biomass for years from 1967 onwards is computed as:

(A24)

$$B_y^{exp,s} = \sum_{a=8}^{z-1} S_a^s w_{a+1/4}\left(N_{y,a}^O + \rho N_{y,a}^I\right)e^{-M_a/4} + S_z^s\left(w_{y,\bar{z}_y+1/4}^O N_{y,z}^O + \rho\, w_{y,\bar{z}_y+1/4}^I N_{y,z}^I\right)e^{-M_z/4}$$

In the case of FIAS, which for these purposes can be considered as another fishery sector *s,* "available" population numbers are given by:

(A25) $$N_y^{exp,s} = \sum_{a=5}^{z} S_a^s \left((1-\rho) N_{y,a}^I e^{-M_a/4} - C_{y,a}^I \right) e^{-M_a/4}$$

The summation is from age a = 5 as only animals larger than 100mm shell length are recorded so as to reduce uncertainty in the estimates due to the non-emergent/cryptic behaviour of juveniles. This corresponds to a minimum sampling age of approximately 5 years, so that for this sector $S_a^s = 0$ for $a < 5$.

The proportion of the resource harvested each year (F_y^s) by sector s is given by:

(A26) $$F_y^s = C_y^s \ / B_y^{exp,s}$$

so that numbers-at-age removed each year by the poaching and recreational sectors can be computed from:

(A27) $$C_{y,a}^s = S_a^s F_y^s (1-\rho) N_{y,a}^I e^{-\frac{M_a}{4}}$$ for $a \geq 5$ and

(A28) $$C_{y,a}^s = S_a^s F_y^s N_{y,a}^I e^{-\frac{M_a}{4}}$$ for $a = 4$ (poaching catches)

In the case of the commercial sector, the numbers-at-age removed each year from subarea CP is given by:

(A29) $$C_{y,a}^s = S_a^s F_y^s \left(N_{y,a}^I + N_{y,a}^O \right) e^{-M_a/4}$$

The commercial numbers-at-age removed from subarea CNP for each of the years prior to 1967 is given by equation (A29) above, and then by equation (A30) below as from 1967:

(A30) $$C_{y,a}^s = S_a^s F_y^s \left(N_{y,a}^O + \rho \cdot N_{y,a}^I \right) e^{-M_a/4}$$

2 Spawning biomass - recruitment relationship

The spawning biomass for each subarea in year y is given by:

(A31) $$B_y^{sp} = \sum_{a=1}^{z-1} f_a w_a \left(N_{y,a}^I + N_{y,a}^O \right) + f_z \left(w_{y,\bar{z}_y}^I N_{y,z}^I + w_{y,\bar{z}_y}^O N_{y,z}^O \right)$$

where f_a is the proportion of abalone of age a that are mature. Note that this formulation assumes independence of subareas in terms of recruitment, *viz*. the recruitment in one subarea depends only on the spawning biomass in that subarea and not on the biomass in adjoining subareas.

The number of recruits in each of the two subareas at the start of Model year y is related to the spawner stock size by a stock-recruitment relationship. A Beverton-Holt form (Beverton and Holt, 1957) is assumed, i.e. :

(A32) $$R\left(B_y^{sp}\right)=\frac{\alpha\, B_y^{sp}}{\beta+B_y^{sp}}$$

Note from equations (A1) and (A5) that the relative proportion of recruits settling inshore versus offshore in each subarea is determined by parameter r_I.

In order to work with estimable parameters that are more meaningful biologically, the stock-recruit relationship is re-parameterised in terms of the pre-exploitation equilibrium spawning biomass, B_0^{sp}, and the "steepness" of the stock-recruit relationship, where "steepness" is the fraction of pristine recruitment that results when spawning biomass drops to 20% of its pristine level, i.e.

(A33) $$hR_0 = R\left(0.2B_0^{sp}\right)$$

from which it follows that:

(A34) $$h=0.2\left[\beta+B_0^{sp}\right]/\left[\beta+0.2B_0^{sp}\right]$$

and hence:

(A35) $$\alpha=\frac{4hR_0}{5h-1}$$ and:

(A36) $$\beta=\frac{B_0^{sp}(1-h)}{5h-1}$$

3 Starting values for biomass trajectories

The resource is assumed to be at the deterministic equilibrium (corresponding to an absence of harvesting) at the start of 1951, the initial year considered here. Given a value for the pre-exploitation spawning biomass B_0^{sp} of abalone, together with the assumption of an initial equilibrium age structure, it follows that on a subarea basis:

(A37)

$$B_0^{sp}=R_0\cdot\left[\sum_{a=1}^{z-1} f_a w_a \exp\left(-\sum\nolimits_{a'=0}^{a-1} M_{a'}\right)+f_z w_{0,\bar{z}_0}\,\frac{\exp\left(-\sum\nolimits_{a'=0}^{z-1} M_{a'}\right)}{1-\exp\left(-M_z\right)}\right]$$

which can be solved for R_0. Note that here $w_{0,\bar{z}_0}$ means the equilibrium value of this quantity prior to exploitation, computed using the equilibrium plus group mean age $\bar{z}_0$, where:

(A38) $$\bar{z}_0 = z + \frac{e^{-M_{z-1}}}{1-e^{-M_z}}$$

The initial **inshore** numbers at age for the projections, corresponding to the deterministic equilibrium, are:

(A39)
$$N^I_{0,0} = r_I R_0$$
$$N^I_{0,a+1} = N^I_{0,a} e^{-M_a} \qquad 0 \le a \le 4$$
$$N^I_{0,a+1} = N^I_{0,a}(1-\rho)e^{-M_a} \qquad 5 \le a \le z-2$$
$$N^I_{0,z} = \frac{N^I_{z-1}(1-\rho)e^{-M_{z-1}}}{1-(1-\rho)e^{-M_z}}$$

Similarly, the initial **offshore** numbers at age, corresponding to the deterministic equilibrium, are:

(A40)
$$N^O_{0,0} = (1-r_I)R_0$$
$$N^O_{0,a+1} = N^O_{0,a} e^{-M_a} \qquad 0 \le a \le 4$$
$$N^O_{0,a+1} = N^O_{0,a} e^{-M_a} + N^I_{0,a}\rho e^{-M_a} \qquad 5 \le a \le z-2$$
$$N^O_{0,z} = \frac{N^O_{z-1}e^{-M_{z-1}} + \rho\left(N^I_{0,z}e^{-M_z} + N^I_{0,z-1}e^{-M_{z-1}}\right)}{1-e^{-M_z}} \qquad a = z$$

It follows from the steady-state solutions to these equations that the inshore and offshore equilibrium plus group mean ages are as follows:

(A41)
$$\bar{z}^I_0 = z + \frac{(1-\rho)e^{-M_{z-1}}}{1-(1-\rho)e^{-M_z}}$$
$$\bar{z}^O_0 = z + \frac{e^{-M_{z-1}}}{1-e^{-M_z}} + \frac{\rho\, e^{-M_{z-1}}}{\left(1-e^{-M_z}\right)\left(1-(1-\rho)e^{-M_z}\right)} \cdot \frac{N^I_{0,z}}{N^O_{0,z}}$$

Numbers-at-age for subsequent years are then computed by means of equations (A1)-(A36).

4 Parameter Values

Input parameters:
The following fixed parameter values are used in the model. The three von Bertalanffy parameters are from Tarr (1995) and the two mass-length relationship parameters were computed in this study:

ℓ_∞ = 172.76 mm

κ = 0.186 yr^{-1}

t_0 = 0 yr (and is assumed to correspond to October because Tarr (1995) tagged animals *in situ* in October and November)

c = 0.000098 gm/mm$^{3.155}$

d = 3.1549

with the computations assuming a plus group at age z = 15 yrs.

The proportion of abalone of age a that are mature is approximated by f_4 = 0.25, f_5 = 0.5, f_6 = 0.75 and f_a = 1 for $a \geq 7$ (Tarr 1995).

Moreover, the base-case assumes that h = 0.7. The base-case value of the steepness parameter h corresponds roughly to the median (h = 0.74) of a distribution of h values for stock-recruit functions fitted to the fisheries stock recruitment database developed by R.A. Myers and colleagues (Myers *et al*. 1995a).

Estimable parameters:

The sector-specific fishing selectivities S_a^s (including those for FIAS) are assumed to follow the functional form:

(A42) $$S_a^s = \frac{P \cdot e^{-\mu a}}{1 + e^{-\delta(a - \tilde{a})}}$$

where μ, δ and $\tilde{a}$ are three estimable parameters that control the shape of the function and P is simply a scalar fixed at a value such that S_{11}^s = 1.00. In essence, μ controls the slope of the right hand limb of the function, δ controls the steepness of the ascending left hand limb, and $\tilde{a}$ shifts the function to the left or right, all in relation to age a.

The assumption that commercial selectivity parameters are the same for the inshore and offshore compartments might seem severe, given the greatly different age profiles of abalone in the inshore and offshore areas. Note however that only a small component of the commercial fishing takes place in the inshore region (the numbers of commercially exploitable size in that region being small), so that even if the assumption is in error, the impact on results should not be substantial.

Under the assumption that the sampling methodology is the same inshore and offshore, the same selectivity parameters are used for the inshore and offshore FIAS sectors. A separate selectivity function is used to compute model-predicted catch-at-age when fitting to the "old survey" data and it is again assumed that the same parameters apply to the inshore and offshore regions.

5 The likelihood function

The likelihood function which is maximised in the parameter estimation process is based on equations developed by Geromont and Butterworth (1999). The model is fitted to CPUE and FIAS abundance and catch-at-age data from all sectors (commercial, recreational, poaching, old survey and FIAS) and the contributions by each of these to the negative of the log-likelihood (-*ln L*) calculated as described below.

Abundance data:
The likelihood contribution is calculated assuming that the observed abundance index is log-normally distributed about its expected value:

(A43) $$I_y^s = \hat{I}_y^s e^{\varepsilon_y^s} \qquad \text{or} \qquad \varepsilon_y^s = \ln(I_y^s) - \ln(\hat{I}_y^s)$$

where I_y^s is the abundance index for year *y* and sector *s*,

$\hat{I}_y^s = q^s B_y^{exp,s}$ is the corresponding model estimated value, where $B_y^{exp,s}$ is the model value for exploitable resource biomass corresponding to sector *s*, given by equations (A21- A24) (if the index refers to numbers, $B_y^{exp,s}$ is replaced by $N_y^{exp,s}$ - see equation (A25)).

q^s is the constant of proportionality for abundance series corresponding to sector *s*, and

ε_y^s from $N\left(0,\left(\sigma_y^s\right)^2\right)$.

The contribution of the abundance data to the negative of the log-likelihood function (after removal of constants) is given then by:

(A44) $$-\ln L = \sum_s \left[\sum_y \ln \sigma_y^s + \left(\varepsilon_y^s\right)^2 / 2\left(\sigma_y^s\right)^2 \right]$$

Variance unspecified: (CPUE abundance series)

In this case the standard deviation of the residuals for the logarithms of abundance series *s* is assumed to be independent of *y*, and is estimated in the fitting procedure by its maximum likelihood value:

(A45) $$\hat{\sigma}^s = \sqrt{\frac{1}{n_s} \sum_y \left(\ln I_y^s - \ln \hat{I}_y^s\right)^2}$$

where n_s is the number of data points for the abundance series corresponding to sector *s*.

The catchability coefficient q^s for sector *s*'s abundance index is estimated by its maximum likelihood value:

(A46) $$\ln\hat{q}^s = \frac{1}{n_s}\sum_y \left(\ln I_y^s - \ln\hat{B}_y^{exp,s}\right)$$

Variance specified: (FIAS data)

The sampling variance estimates available for FIAS are used as inputs in the model, but these estimates fail to include all sources of variability. To take this into account an additional variance component is added to the variance estimates, with a single additional variance parameter, assumed to be the same for each zone, estimated in the minimisation process. This is effected subject to the constraint that the overall variance must be greater than or the same as its externally input component.

The FIAS catchability coefficient q^s is thus estimated by its maximum likelihood value which, for the case of a log-normal error distribution, is given by:

(A47) $$\ln\hat{q}^s = \frac{\sum_y 1/\left(\sigma_y^s\right)^2\left(\ln I_y^s - \ln\hat{B}_y^{exp,s}\right)}{\sum_y 1/\left(\sigma_y^s\right)^2}$$

where $\left(\sigma_y^{FS}\right)^2 = \left(\sigma_{Add}\right)^2 + \ln\left(1+\left(CV_y\right)^2\right)$ and the coefficient of variation (CV_y) of the resource abundance estimate for year y is input.

Catches-at-age:

The likelihood contribution is calculated assuming a log-normal error distribution and by making an adjustment (suggested by A. Punt, pers. commn) to weight in relation to the observed proportions so that undue importance is not attached to poorly represented age classes:

(A48) $$-\ln L = \sum_s\sum_y\sum_a\left[\ln\left(\sigma_c^s\Big/\sqrt{p_{y,a}^s}\right) + p_{y,a}^s\left(\ln(\delta + p_{y,a}^s) - \ln(\delta + \hat{p}_{y,a}^s)\right)^2\Big/2\left(\sigma_c^s\right)^2\right]$$

where $p_{y,a}^s = C_{y,a}^s\Big/\sum_{a'} C_{y,a'}^s$ is the observed proportion of abalone caught/sampled by sector s in year y that are of age a,

$\delta = 0.05$ is a constant included because not all of the $p_{y,a}^s$ values are nonzero,

σ_c^s is the standard deviation associated with the catch-at-age data for sector s, estimated in the fitting procedure by:

(A49) $$\sigma_c^s = \sqrt{\sum_y\sum_a p_{y,a}^s\left(\ln(\delta + p_{y,a}^s) - \ln(\delta + \hat{p}_{y,a}^s)\right)^2\Big/\sum_y\sum_a 1}$$

and $\hat{p}^s_{y,a} = \hat{C}^s_{y,a} \Big/ \sum_{a'} \hat{C}^s_{y,a'}$ is the model-predicted proportion of abalone caught/sampled by sector *s* in year *y* that are of age *a*.

For subarea CNP, the earliest catch-at-age data are from 1980 and hence correspond to the period during which all commercial catches are assumed taken from the offshore region, so that $\hat{C}^s_{y,a}$ is given by:

(A50) $$\hat{C}^s_{y,a} = \left(N^O_{y,a} + \rho N^I_{y,a}\right) e^{-\frac{M_a}{4}} S^s_a F^s_y$$

whereas for subarea CP, $\hat{C}^s_{y,a}$ is determined as follows:

(A51) $$\hat{C}^s_{y,a} = \left(N^I_{y,a} + N^O_{y,a}\right) e^{-\frac{M_a}{4}} S^s_a F^s_y$$

The model-predicted recreational catch-at-age data is based on abalone assumed caught from both the CNP and CP subareas, such that for this sector:

(A52) $$\hat{C}^s_{y,a} = \left((1-\rho_{CNP}) N^{I_{CNP}}_{y,a} + (1-\rho_{CP}) N^{I_{CP}}_{y,a}\right) e^{-\frac{M_a}{4}} S^s_a F^s_y$$

except in the case of the single year's (1997) recreational catch-at-age data from subarea CP, for which $\hat{C}^s_{y,a}$ is computed as:

(A53) $$\hat{C}^s_{y,a} = (1-\rho) N^{I_{CP}}_{y,a} e^{-\frac{M_a}{4}} S^s_a F^s_y$$

The poached catch is taken primarily from the inshore region of subarea CP and hence Eqn. (A53) above is used to calculate $\hat{C}^s_{y,a}$ for the poaching sector.

The FIAS, "old survey" and industry survey catches-at-age are similarly incorporated into the negative of the log-likelihood, except that comparisons with observed proportions are made at mid-year rather than after the first quarter of each Model year. Data from the inshore FIAS stations is assumed to correspond to the inshore model region whereas data from the deep FIAS stations is assumed to correspond to the offshore model region. The 0-5 m and 5-15 m "old survey" data are assumed to respectively correspond to the inshore and offshore model regions. Thus, for each subarea, the inshore FIAS and inshore "old survey" model-predicted numbers of abalone of age *a* sampled are computed as:

(A54) $$\begin{aligned} \hat{C}^s_{y,a} &= \left(N^I_{y,a} e^{-\frac{M_a}{4}} - C^I_{y,a}\right) e^{-\frac{M_a}{4}} S^s_a F^s_y \qquad & a < 5 \\ \hat{C}^s_{y,a} &= \left((1-\rho) N^I_{y,a} e^{-\frac{M_a}{4}} - C^I_{y,a}\right) e^{-\frac{M_a}{4}} S^s_a F^s_y \qquad & a \geq 5 \end{aligned}$$

and $\hat{C}^s_{y,a}$ for the deep FIAS and offshore "old survey" are given by:

(A55)

$$\hat{C}^s_{y,a} = \left(N^O_{y.a} e^{-\frac{M_a}{4}} - C^O_{y,a} \right) e^{-\frac{M_a}{4}} S^s_a F^s_y \qquad a < 5$$

$$\hat{C}^s_{y,a} = \left(\left(N^O_{y.a} + \rho\, N^I_{y,a} \right) e^{-\frac{M_a}{4}} - C^O_{y,a} \right) e^{-\frac{M_a}{4}} S^s_a F^s_y \qquad a \geq 5$$

Data from the 2002 industry "total population size composition" survey are assumed representative of the entire Zone C area and hence $\hat{C}^s_{y,a}$ for the industry survey is computed by summing over mid-year inshore and offshore regions for both CNP and CP.

Inspection of the various –ln *L* contributions has revealed that the catch-at-age –ln *L* contributions are substantially larger than those for CPUE and the FIAS series, in part because they include many more data points as a result of summation over age as well as year. This is questionable as the $p^s_{y,a}$ values for a given *y* and *s* are not likely to be independent of each other (as implicitly assumed by equation (A48)), because the cohort-slicing method used to provide the catch-at-age information from length composition data likely introduces positive correlation. The catch-at-age –ln *L* contributions are thus downweighted by a multiplicative factor of 0.1, thereby downscaling these contributions to a similar order of magnitude as the CPUE and FIAS contributions.

References

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Appendix 2 – Incorporating the "ecosystem-change"effect

Method for modelling increased juvenile mortality

1. The following formulation was used to model age-dependent natural mortality rates M_a :

$$M_a = \mu + \frac{\lambda}{a+1} \qquad \text{(A2.1)}$$

where parameter μ was estimated in the model-fitting process and λ was either estimated or set equal to a constant (e.g. 0.2 for all cases shown here).

2. The number of new recruits to the population from 1994 onwards is no longer reduced to 10% of the 1993 level as in previous model versions, but is instead

determined in the same way as for the earlier years, i.e. by using the Beverton – Holt stock-recruit function.

3. To model the rate and extent of the "recruitment failure" effect, two new parameters were introduced: a steepness of recruitment failure parameter ν and a maximum increase in mortality parameter M_{max}. An exponential increase in the M_0 mortality rate is assumed to have occurred as from year y, where different values of the starting year y were tried and the rate of increase in M_0 is determined by parameter ν. M_0 is assumed to increase continuously up to a maximum value M_{max} and then remains constant at this value from years y_{Mmax} forwards. For example, Combined B&C Model I in 2002 was as follows: μ = 0.138 (estimated), λ = 0.2 (fixed), first year with increase M_0 is 1990, ν = 0.227 (estimated) and M_{max} = 3.856 (estimated).

   As M values are more easily understandable when converted to survival rates S (= the proportion of that age-class surviving from one year to the next), M_0 values will be discussed in terms of S_0 instead. The above parameter values thus translate into a situation where currently only 2.1% of abalone recruits survive into the second year compared to 71% in the absence of this "recruitment failure" effect.