UPDATED ASSESSMENT OF THE SOUTH AFRICAN KINGKLIP RESOURCE INCLUDING AN INITIAL ATTEMPT AT INCLUDING CATCH-AT-LENGTH DATA

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November 2008

ABSTRACT

This paper updates the kingklip assessment by Brandão and Butterworth presented earlier this year by taking further data into account. Further, the analysis which treats the resource on both West and South coasts as a single stock is extended to take catch-at-length data into account. If the resource is treated as two separate stocks, current (2008) depletion of spawning biomass on the West and South coasts is estimated at 0,50 and 0.12 respectively. A more optimistic picture is obtained with the resource treated as a single stock, which yields a current depletion estimate of 0.36, which increases to 0.52 if the catch-at-length data are incorporated. Projections indicate that if the South coast component of the resource is a separate stock, then catches would need to be reduced to below 1 000 tons at least for sustainability. However if the two coasts combined are treated as a single stock, projections under current catch levels suggest a slight decrease for the assessment excluding catch-at-length data, which changes to a slight increase when those catch-at-length data are also taken into account..

INTRODUCTION

South African kingklip landings currently constitute a proportion of the by-catch from hake-directed trawls off the West and South coasts. A directed longline fishery for this species had existed since 1983, before it was terminated in 1990. Since that date longline catches have been restricted to by-catch from hake-directed longlining. A concern for this resource is the continued high kingklip by-catch in the hake-directed trawl fishery, particularly on the South coast, though this has reduced somewhat over recent years.

This paper updates the assessment of the kingklip resource for the South and West coasts separately that was presented by Brandão and Butterworth (2008). Further data inputs available are taken into account. All available indices of abundance are taken into account, and deterministic projections under various levels of constant catch are reported. The two stock hypothesis model is also updated; in particular, all survey abundance indices are fitted in the model instead of adding those for the same year together as in the previous analyses.

Catch-at-length data from surveys and from the commercial fishery are also taken into account in one of the assessment models in this paper, but for the one stock hypothesis only.

DATA

Catch Data

Total annual catches of kingklip for the West and South coasts from hake-directed trawls over the period 1932–2007 and from hake-directed longliners for the periods 1983–2007 are shown in Table 1 and Figure 1. The total annual catches for 2008 were not available for the present analysis; however, to be able to include the information from surveys for 2008, the assumption was made to set the total annual catches for 2008 to change from the 2007 catches to the same proportion by which the catch for *M. paradoxus* for both coast combined changes. The proportion for the trawl catches was calculated using data from the offshore hake catches.

Survey abundance data

Survey abundance data for each of the West and South coasts from 1986–2008 obtained from Marine and Coastal Management are used (Table 2). Previously no distinction had been made between surveys that surveyed the coast up to 200m and those that surveyed the coast up to 500m. The choice made here between using abundance indices for the 200 or 500m coastal area was based on selecting the longest series. Thus, for the South coast surveys conducted in May/June (autumn) a 500m coastal area was selected, while for those in Sept/Oct (spring) a 200m coastal area was chosen.

CPUE data

CPUE abundance data for the years 1983 to 1991 for the trawl and longline fisheries from Punt and Japp (1994) are used (see Table 3). There have been recent attempts to develop CPUE index for kingklip from trawl fishery data but for the moment this is not ready to be used in the assessment model.

Catch-at-length data

Survey catch-at-length data for each coast are available for most years in which a survey was carried out. Observer commercial catch-at-length data disaggregated by coast and fishery are available in the main from 2000 to 2008.

THE MODEL

The Age-Structured Production Model (ASPM) used to model a one or a two stock hypothesis, without including any catch-at-length data, is as in Mori and Butterworth (2002), which is similar to the model used by Punt and Japp (1994). Detailed specification of the model is given in the Appendix. In contrast to adding data from surveys on the two coasts as done in Brandão and Butterworth (2008) for the one stock hypothesis, in this paper data from the surveys are treated separately in the model. The ASPM model is also extended to include catch-at-length data (see Appendix for details).

The biological parameters used in the assessment are those used by Punt and Japp (1994). These values, including those for selectivity (when no catch-at-length data are used in the modelling procedure, are listed in Table 4.

As in Brandão and Butterworth (2008), the different gear types (old or new) and the vessels (the *Africana* or the *Nansen*) used during the surveys are differentiated.

Deterministic projections for various catch scenarios have been conducted. The longline catch is fixed at its average value over 2003–2007, and projections consider different levels of trawl-caught kingklip.

RESULTS

The updated analyses conducted in this paper of the two stock hypothesis show the same pattern as observed by Mori and Butterworth (2002) and Brandão and Butterworth (2008) (Table 5). The current assessment estimates the depletion (B_{sp}/K_{sp}) at the beginning of 2008 for the South coast at 12% of the pre-exploitation abundance. For the West coast, this depletion is estimated at 50%. The *q* estimates for the surveys are all less than 1 (except that for the autumn *Nansen q*, but this estimate is based on only one value), suggesting considerable underestimation of biomass in absolute terms by the swept-area method.

The fits of the model to the various abundance indices available are shown in Figures 2a–b for the West and South coasts. The current assessment shows that all of the abundance indices for the West coast suggest a slight recovery (Figure 2a). On the other hand, for the South coast while the abundance indices show a recovery from 1991 to 1994, probably because of the termination of longline fishery, since 1995, the abundance indices fall substantially due to the increased trawl by-catch in recent years (Figure 2b).

The one stock hypothesis (with and without catch-at-length data) results in a more optimistic status estimated for the kingklip resource (Table 5) in contrast to the two stock hypothesis. However, peculiar result (a higher depletion for the one stock than for a separate West coast stock alone) obtained in Brandão and Butterworth (2008) is no longer evident, with the depletion of the single coast-combined stock estimated at 36%. If catch-at-length data are incorporated in the model, a more optimistic status is estimated with depletion estimated to be at 52% at the beginning of 2008.

Figures 3a–b show the fits of the one stock model to the various abundance indices available for the West and South coasts when catch-at-length data are not included, and Figures 4a–b show these fits when catch-at-length data are incorporated in the model fitting procedure.

The trajectories with 95% confidence intervals for depletion (B_{sp}/K_{sp}) and the spawning biomass (B_{sp}) for the base case (h = 0.5) are shown for both assessments in Figures 5a–b for both the one and the two stock hypothesis models as well as when catch-at-length data are included in the model.

Projections under various constant trawl catch scenarios for the two stock hypothesis are shown in Figure 6a. Future constant catch levels for the longline fishery have been kept at the average of the past five years (2003–2007). These average longline catches are 200 tons for the West coast and 120 tons for the South coast. Projections with 95% confidence intervals are also shown for future constant catches for the trawl fishery set at the annual average for the past five years (1 300 tons for the West coast and 2 300 tons for the South coast). A constant future catch at this level for the West coast shows a slight increase in abundance. However, for the South coast, when considered to be an isolated stock, downward trends continue even for catches reduced to 1 000 tons. This assessment scenario indicates that the recent average trawl catch level of 2 300 tons on the South coast is considerably above a sustainable level.

Similar projections under the one stock hypothesis are shown in Figure 6b. If no catch-at-length data are used, future constant catches for the trawl fishery set at the annual average for the past five years result in a slight decline in abundance. If the trawl catches are reduced to 1 100 and 2 000 tons for the West and South coasts respectively, there is a very slight increase in abundance. If catch-at-length data are incorporated in the model, under this average catch level continued in the future, there is a slight increase in abundance.

Figure 7 the estimated selectivity curves for the survey and the commercial fishery. Fits to the averaged catch-at-length distributions for the surveys and the commercial fishery are shown in Figure 8.

Further work might consider:

a) allowing for variation about the deterministic stock-recruitment relationship assumed;
b) an evaluation of sensitivities to variation in some of the choices for values for certain parameters;
c) incorporating catch-at-length data in the assessments for the West and South coasts separately; and
d) a box-type model which explicitly models movement between coasts rather than representing this implicitly through selectivity.

ACKNOWLEDGEMENTS

Dr. Rob Leslie is acknowledged for kindly providing the catch and abundance survey data. Dave Japp is acknowledged for kindly providing observer catch-at-length data.

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Table 1. Yearly catches (in tons) of kingklip taken by the trawl and longline fisheries on the West and South coasts of South Africa (R. Leslie, pers. commn).

Year	West coast		South coast		Year	West coast		South coast	
	Trawl	Longline	Trawl	Longline		Trawl	Longline	Trawl	Longline
1932	480	0	120	0	**1971**	2 940	0	1 960	0
1933	320	0	80	0	**1972**	3 120	0	2 080	0
1934	320	0	80	0	**1973**	3 480	0	2 320	0
1935	560	0	140	0	**1974**	2 093	0	1 395	0
1936	560	0	140	0	**1975**	2 149	0	1 433	0
1937	560	0	140	0	**1976**	1 520	0	1 951	0
1938	560	0	140	0	**1977**	1 690	0	1 000	0
1939	560	0	140	0	**1978**	2 030	0	2 280	0
1940	560	0	140	0	**1979**	2 369	0	2 243	0
1941	480	0	120	0	**1980**	3 147	0	2 146	0
1942	480	0	120	0	**1981**	2 621	0	1 491	0
1943	480	0	120	0	**1982**	2 000	0	1 131	0
1944	480	0	120	0	**1983**	1 983	842	1 432	200
1945	1 040	0	260	0	**1984**	2 159	1 881	1 433	1 159
1946	800	0	200	0	**1985**	1 400	1 314	2 000	5 656
1947	880	0	220	0	**1986**	1 709	1 231	977	7 453
1948	1 200	0	300	0	**1987**	1 676	1 948	799	4 504
1949	1 260	0	540	0	**1988**	1 264	2 091	663	3 311
1950	1 330	0	570	0	**1989**	1 144	1 607	486	2 209
1951	1 680	0	720	0	**1990**	740	557	528	708
1952	1 960	0	840	0	**1991**	973	0	978	0
1953	1 890	0	810	0	**1992**	1 517	0	1 043	0
1954	1 400	0	600	0	**1993**	1 947	0	1 144	0
1955	1 610	0	690	0	**1994**	1 183	92	1 822	48
1956	1 400	0	600	0	**1995**	1 480	65	1 658	48
1957	1 050	0	450	0	**1996**	1 191	170	2 386	60
1958	1 190	0	510	0	**1997**	1 465	155	2 635	120
1959	1 400	0	600	0	**1998**	1 387	53	1 611	87
1960	1 050	0	450	0	**1999**	1 352	141	2 489	171
1961	1 470	0	630	0	**2000**	1 507	199	2 142	103
1962	1 190	0	510	0	**2001**	1 747	183	3 166	57
1963	1 260	0	540	0	**2002**	1 586	312	3 440	202
1964	980	0	420	0	**2003**	1 267	317	3 162	160
1965	1 750	0	750	0	**2004**	1 473	266	2 889	141
1966	2 220	0	1 480	0	**2005**	1 561	255	2 086	121
1967	1 920	0	1 280	0	**2006**	1 131	81	1 660	103
1968	1 740	0	1 160	0	**2007**	942	81	1 484	95
1969	1 740	0	1 160	0	**2008**	870†	75†	1 371†	88†
1970	1 740	0	1 160	0					

† Catch data for 2008 assumed to change from 2007 in the same proportion as the catch for *M. paradoxus* for both coast combined. The proportion for the trawl catches is calculated using data from the offshore hake catches.

Table 2. Abundance indices of kingklip in tons together with CVs obtained from surveys (separated by season) for the West and South coasts of South Africa. Values in bold denote abundance estimates obtained using the new rather than the old gear on *Africana*, while italicised values denote abundance estimates obtained from surveys carried out on the *Nansen*.

Year	**West coast**				**South coast**			
	Jan/Feb (summer)		**Jul/Aug (winter)**		**Sep/Oct (spring) (0 – 200 m)**		**May/Jun (autumn) (0 – 500 m)**	
	Index	**CV**	**Index**	**CV**	**Index**	**CV**	**Index**	**CV**
1986	3 749	0.159	2 917	0.156	4 800	0.229	—	—
1987	2 883	0.184	5 800	0.250	3 551	0.172	—	—
1988	6 154	0.199	1 651	0.266	—	—	6 373	0.450
1989	—	—	997	0.324	—	—	—	—
1990	3 885	0.258	1 443	0.397	1 258	0.357	—	—
1991	3 468	0.306	—	—	1 992	0.248	8 140	0.148
1992	8 731	0.190	—	—	2 001	0.217	4 415	0.372
1993	10 155	0.180	—	—	1 210	0.205	10 047	0.392
1994	8 208	0.183	—	—	1 319	0.276	30 494	0.596
1995	7 642	0.256	—	—	1 290	0.434	19 606	0.408
1996	12 724	0.282	—	—	—	—	3 714	0.176
1997	7 023	0.218	—	—	—	—	5 077	0.257
1998	—	—	—	—	—	—	—	—
1999	14 242	0.288	—	—	—	—	11 479	0.604
2000	*14 983*	*0.415*	—	—	—	—	*12 807*	*0.256*
2001	*8 780*	*0.264*	—	—	1 581	0.198	—	—
2002	12 763	0.159	—	—	—	—	—	—
2003	14 363	0.249	—	—	**1 735**	**0.352**	6 256	0.523
2004	**7 460**	**0.180**	—	—	**530**	**0.334**	**3 598**	**0.555**
2005	**5 699**	**0.156**	—	—	—	—	**4 133**	**0.759**
2006	9 485	0.359	—	—	1 966	0.433	2 213	0.378
2007	**5 604**	**0.224**	—	—	**729**	**0.298**	**4 118**	**0.391**
2008	**5 429**	**0.121**					**3 395**	**0.211**

Table 3. Standardised commercial CPUE indices of relative abundance for kingklip for the trawl and longline fishery for the South and West coasts of South Africa. These data have been obtained from Punt and Japp (1994).

Year	West coast		South coast	
	Trawl	Longline	Trawl	Longline
1983	1.786		1.294	
1984	2.147	2.253	1.230	2.276
1985	2.193	1.302	1.250	3.082
1986	1.829	1.394	1.190	3.113
1987	1.530	1.300	0.906	2.397
1988	1.420	1.294	0.826	2.202
1989	0.897	1.234	0.763	1.551
1990	0.720	1.000	0.520	1.000
1991	1.000		1.000	

Table 4. Biological parameters values for kingklip for the West and South coasts of South Africa. Parameter values assumed for the trawl and the longline selectivity functions are also given. Note that for simplicity, maturity is assumed to be knife-edge in age. These values are as used by Punt and Japp (1994).

Parameter	West coast	South coast	Coasts combined (without length data)
Natural mortality M (yr^{-1})	0.2	0.2	0.2
von Bertalanffy growth			
L_∞ (cm)	129.2	136.0	132.6
κ (yr^{-1})	0.141	0.142	0.142
t_0 (yr)	-0.32	0.22	0.05
Weight (in gm) length relationship			
e ($g.cm^{-1}$)	0.00083	0.00162	0.00132
f	3.41	3.26	3.31
Age of "plus group" (yr)	30	30	30
Age at maturity (yr)	5	5	5
Steepness parameter (h)	0.5	0.5	0.5
Selectivity parameters			
a_{50}^{L} (years)	5.5	5.5	5.5
a_{50}^{T} (years)	2.5	2.5	2.5
δ^{L} (years)	0.333	0.333	0.333
δ^{T} (years)	0.167	0.167	0.167
γ ($year^{-1}$)	0.07	0.07	0.07

Table 5. Estimated model parameters for the base case model (h = 0.5) as well as for several sensitivity tests. The "current" year refers to the most recent year of the assessment (i.e. 2008). 95% confidence intervals calculated from the Hessian matrix are shown for some parameters.

Parameter estimates	West coast	South coast	Coasts combined	Coasts combined (with length)
-ln L: Total	2.512	-14.24	-0.185	500.2
-ln L: Survey (summer)	11.94	—	19.48	10.15
-ln L: Survey (spring)	—	3.094	4.418	5.449
-ln L: Survey (winter)	5.067	—	4.561	4.184
-ln L: Survey (autumn)	—	0.443	3.414	5.175
-ln L: CPUE (trawl) WC/SC	-5.383	-12.03	-6.700 / -10.07	-4.758 / -11.497
-ln L: CPUE (longline) WC/SC	-9.115	-5.746	-9.780 / -5.511	-8.221 / -3.749
-ln L: Survey length (summer)	—	—	—	64.81
-ln L: Survey length (spring)	—	—	—	55.99
-ln L: Survey length (winter)	—	—	—	20.41
-ln L: Survey length (autumn)	—	—	—	164.0
-ln L: trawl length WC/SC	—	—	—	48.44 / 68.45
-ln L: longline length WC/SC	—	—	—	59.46 / 21.92
K^{sp}	67 326 (55 888; 78 764)	57 639 (55 122; 60 156)	128 142 (113 004; 143 280)	153 752 (120 591; 186 913)
$B^{sp}_{current}$	33 346 (16 925; 49 767)	7 138 (2 024; 12 253)	46 689 (23 610; 69 768)	80 513 (42 848; 118 178)
$B^{sp}_{current}/K^{sp}$	0.495 (0.336; 0.655)	0.124 (0.041; 0.207)	0.364 (0.227; 0.501)	0.524 (0.391; 0.657)
$K^{trawl}_{exp}\,(WC)$	41 187	—	77 074	6 310
$K^{trawl}_{exp}\,(SC)$	—	34 377	77 074	22 604
$B^{\exp,trawl}_{current}\,(WC/SC)$	23 601	5 891	33 832	4 756 / 13 939
$B^{\exp,trawl}_{current}/K^{\exp}\,(WC/SC)$	0.573	0.171	0.439	0.754 / 0.617
q^{summer}_{survey} (old gear)	0.347	—	0.197	0.204
q^{spring}_{survey} (old gear)	—	0.148	0.057	0.052
q^{summer}_{survey} (new gear)	0.264	—	0.184	0.161
q^{spring}_{survey} (new gear)	—	0.119	0.026	0.021
q^{summer}_{survey} (Nansen)	0.166	—	0.289	0.286
q^{winter}_{survey} (old gear)	0.121	—	0.065	0.045
q^{autumn}_{survey} (old gear)	—	0.440	0.165	0.219
q^{autumn}_{survey} (new gear)	—	0.578	0.107	0.121
q^{autumn}_{survey} (*Nansen*)	—	1.011	0.341	0.433
$\sigma^{trawl}_{CPUE}\,(WC)$	0.334	—	0.288	0.357
$\sigma^{trawl}_{CPUE}\,(SC)$	—	0.159	0.198	0.169
$\sigma^{longline}_{CPUE}\,(WC)$	0.165	—	0.150	0.187
$\sigma^{longline}_{CPUE}\,(SC)$	—	0.267	0.276	0.355
B^{sp}_{MSY}	29 254	25 394	56 273	66 828
MSYL/K^{sp}	0.435	0.441	0.439	0.435

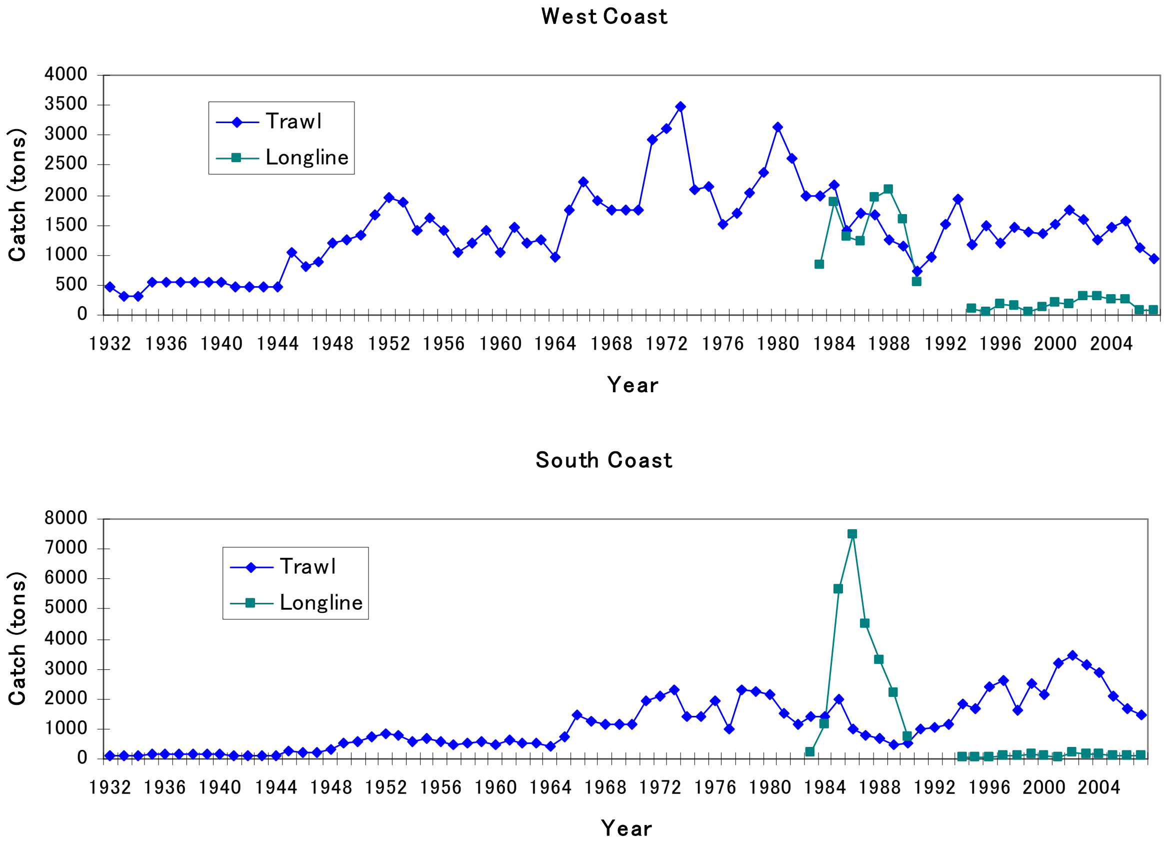


Figure 1. Historical catches of kingklip in the West and South coasts of South Africa separated by gear type (i.e. trawl or longline).

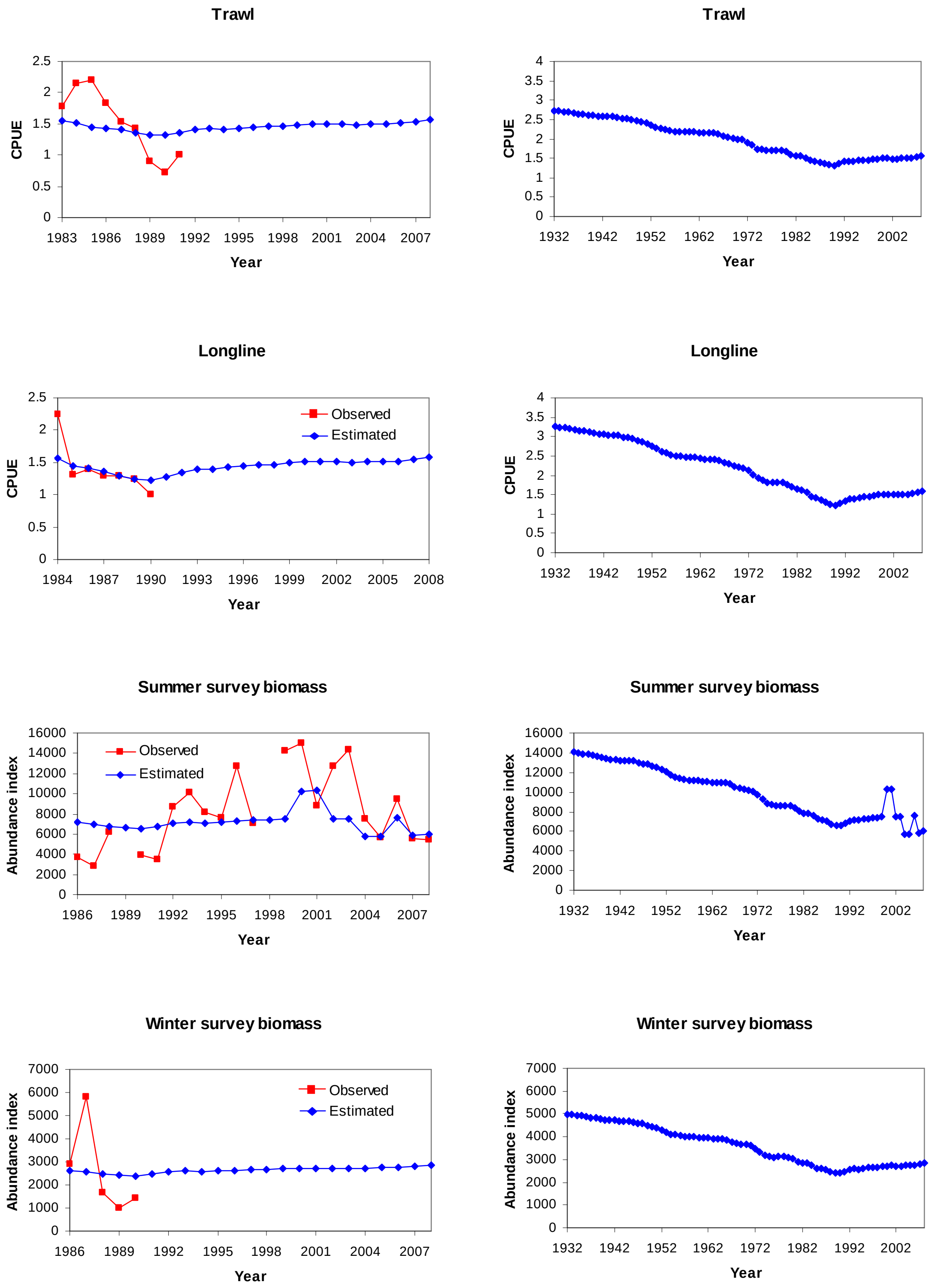


Figure 2a. Observed and estimated trend of abundance indices for the two stock hypothesis model (h = 0.5) fitted to data up to 2008 for the West coast of South Africa. Fluctuations shown for the estimated summer survey biomass are a consequence of differing q's for the different vessels/gears used from year to year (the default is the old gear).

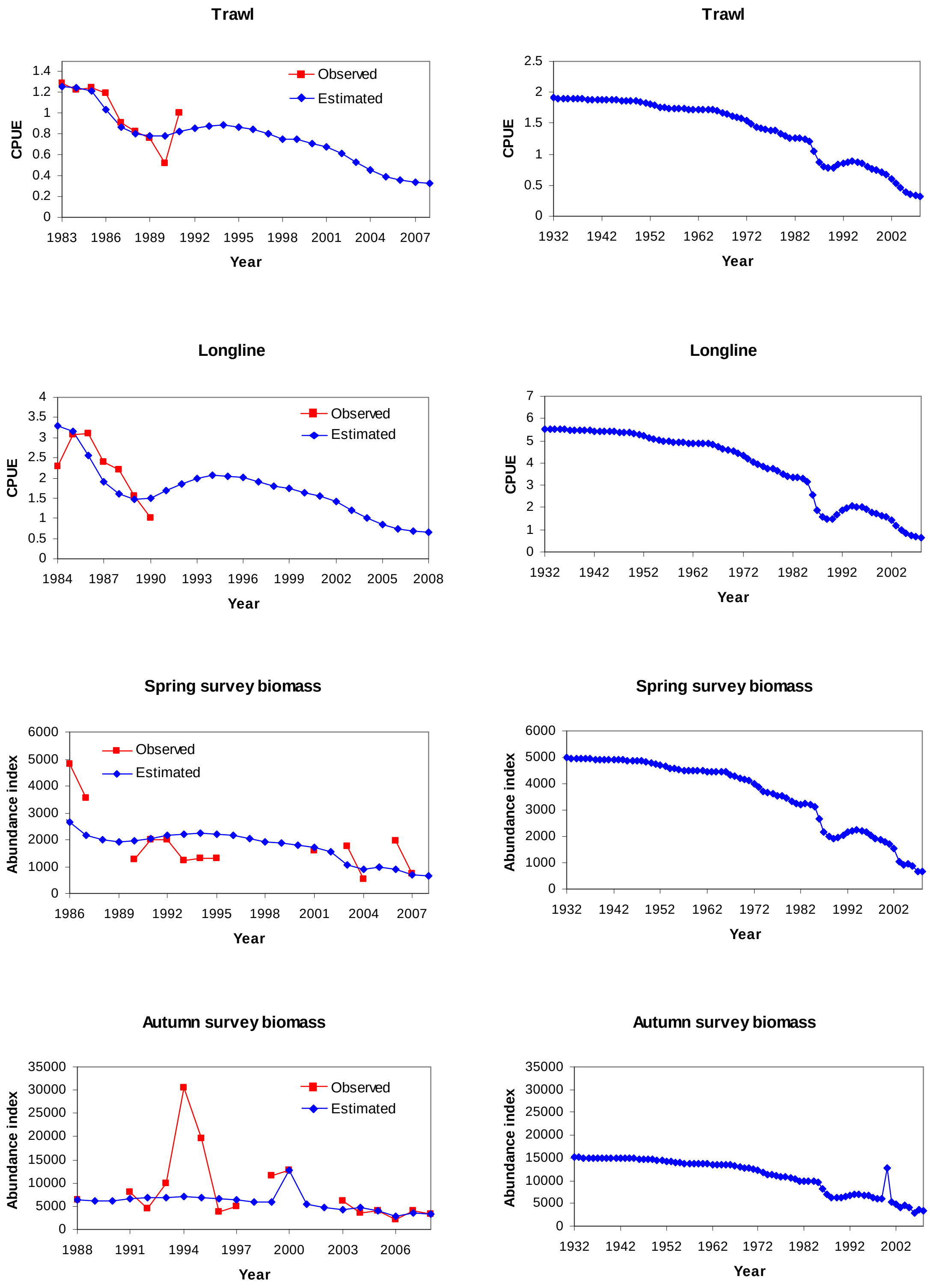


Figure 2b. Observed and estimated trend of abundance indices for the two stock hypothesis model (*h* = 0.5) fitted to data up to 2008 for the South coast of South Africa. Fluctuations shown for the estimated autumn survey biomass are a consequence of differing *q*'s for the different vessels/gears used from year to year (the default is the old gear).

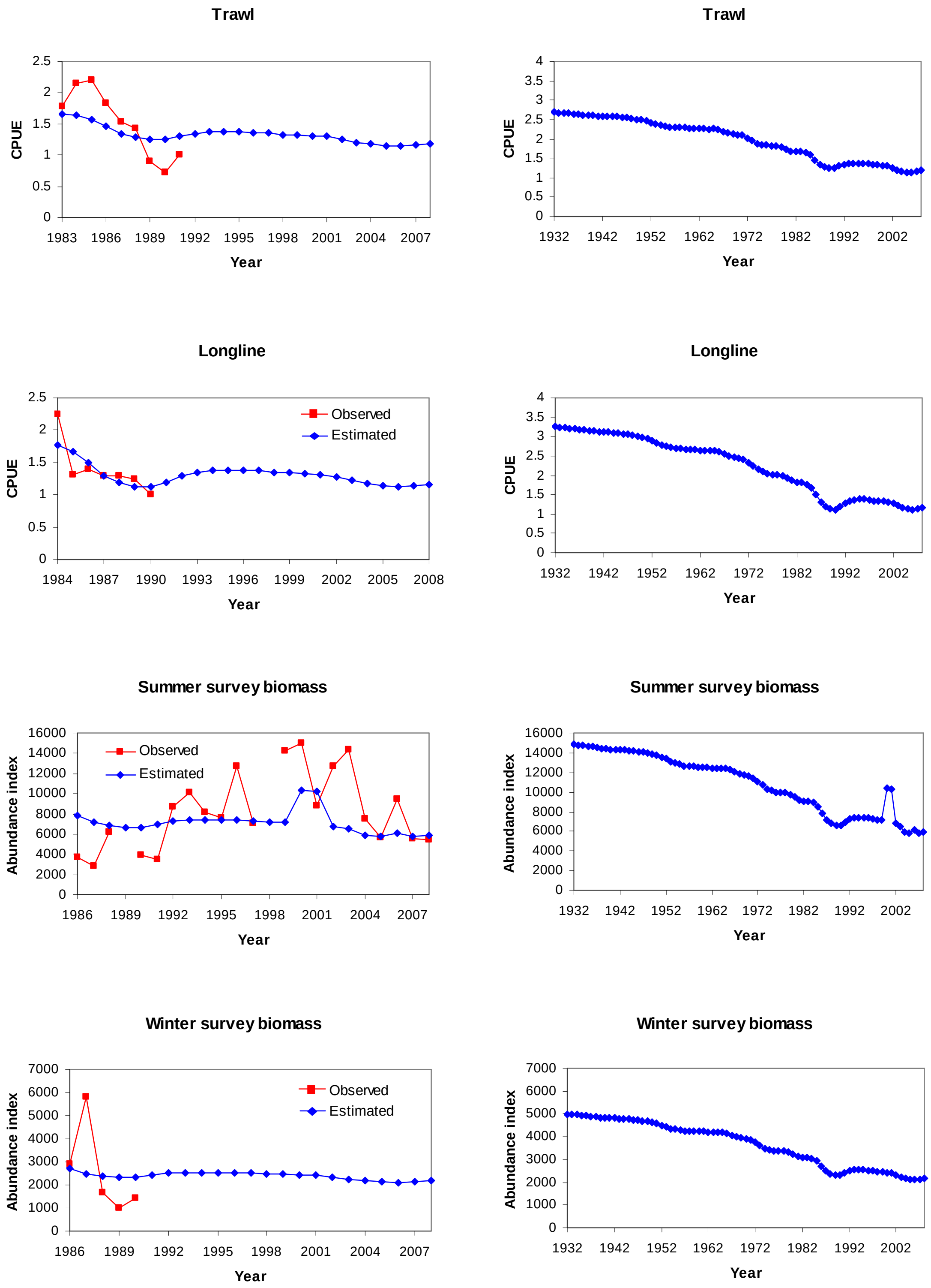


Figure 3a. Observed and estimated trend of abundance indices for the one stock model (h = 0.5) fitted to data up to 2008 for the West coast of South Africa. Fluctuations shown for the estimated summer survey biomass are a consequence of differing q's for the different vessels/gears used from year to year (the default is the old gear).

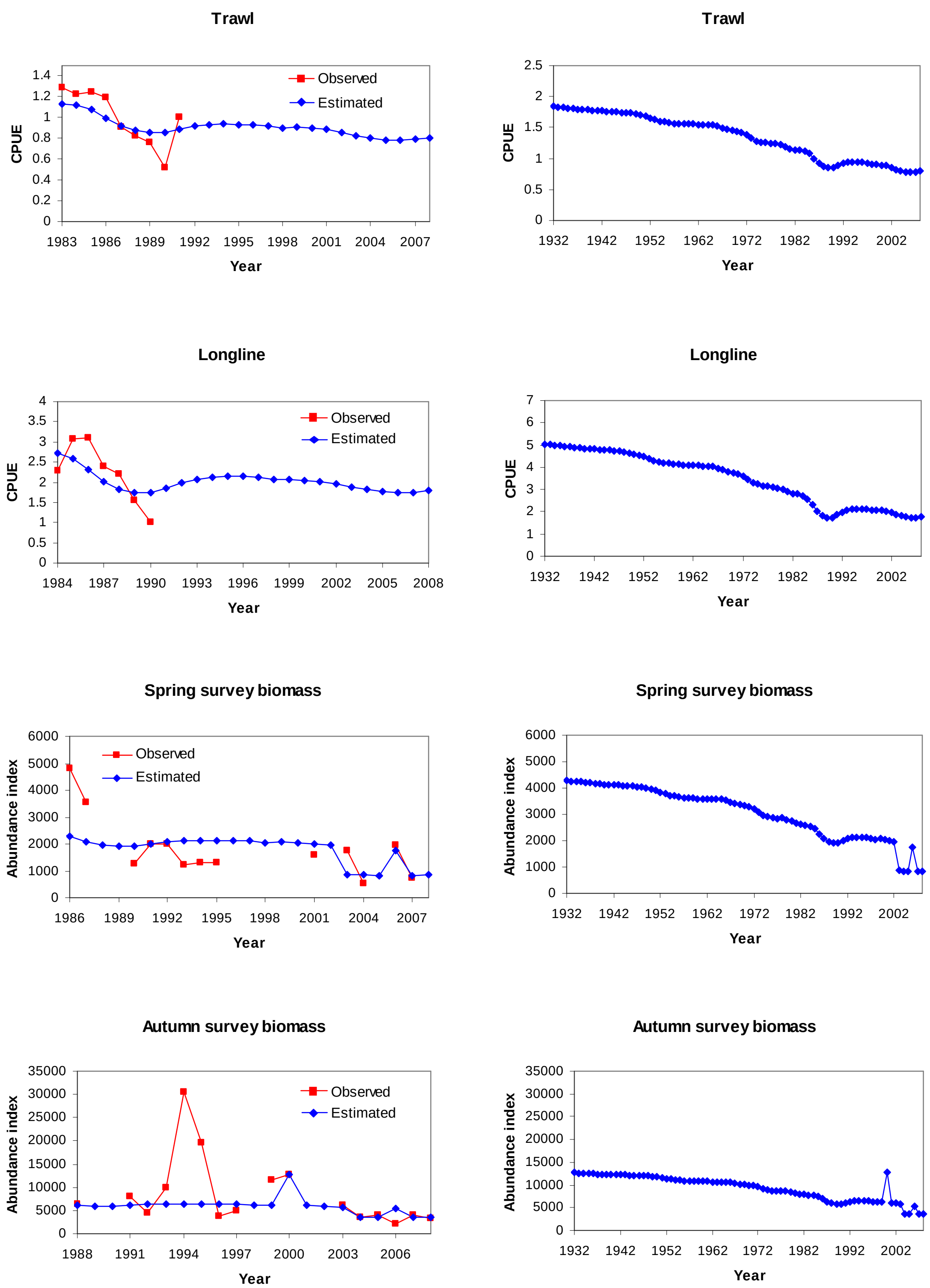


Figure 3b. Observed and estimated trend of abundance indices for the one stock model (h = 0.5) fitted to data up to 2008 for the South coast of South Africa. Fluctuations shown for the estimated spring and autumn survey biomass are a consequence of differing q's for the different vessels/gears used from year to year (the default is the old gear).

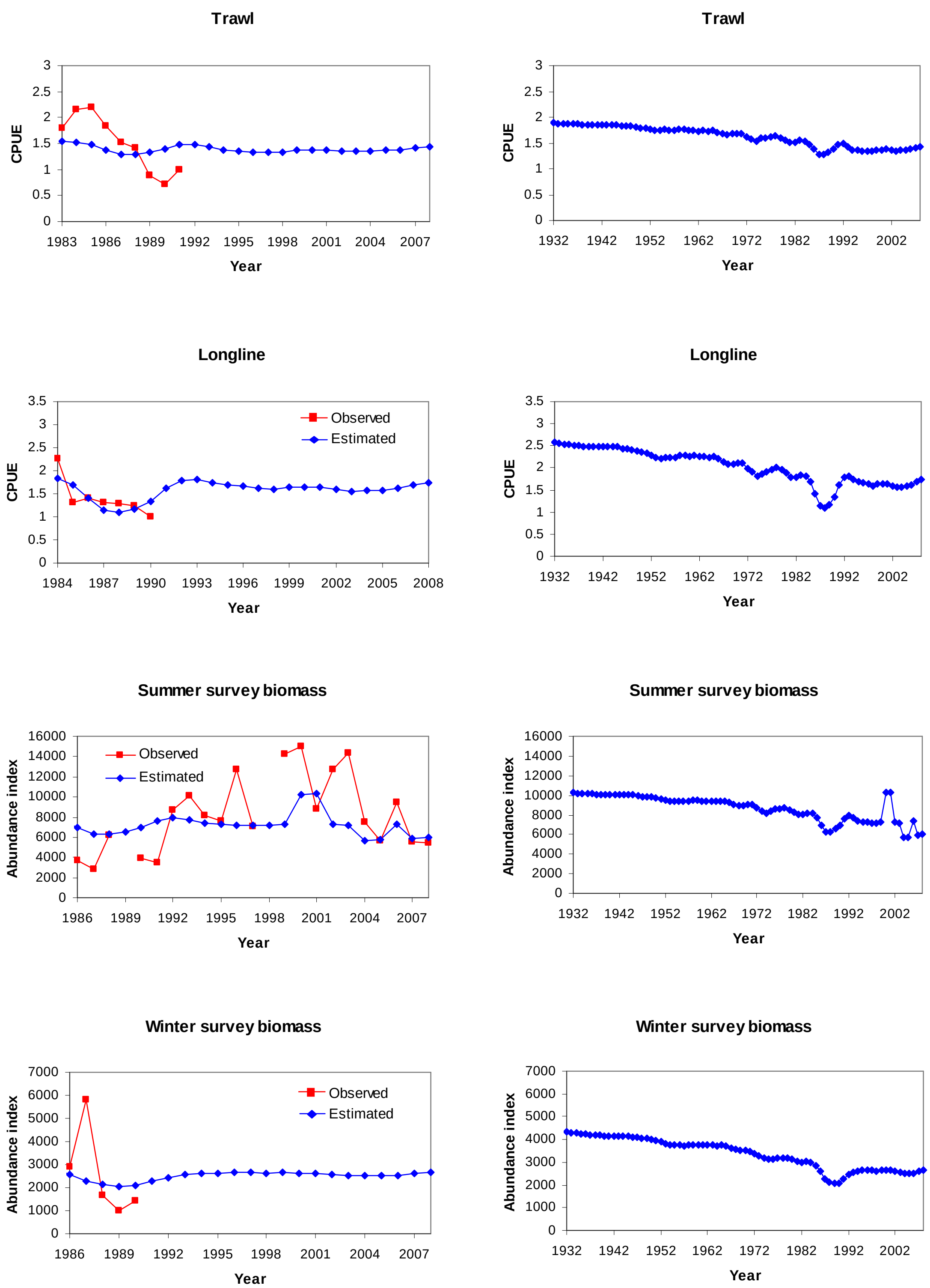


Figure 4a. Observed and estimated trend of abundance indices for the one stock model (h = 0.5) including catch-at-length data fitted to data up to 2008 for the West coast of South Africa. Fluctuations shown for the estimated summer survey biomass are a consequence of differing q's for the different vessels/gears used from year to year (the default is the old gear).

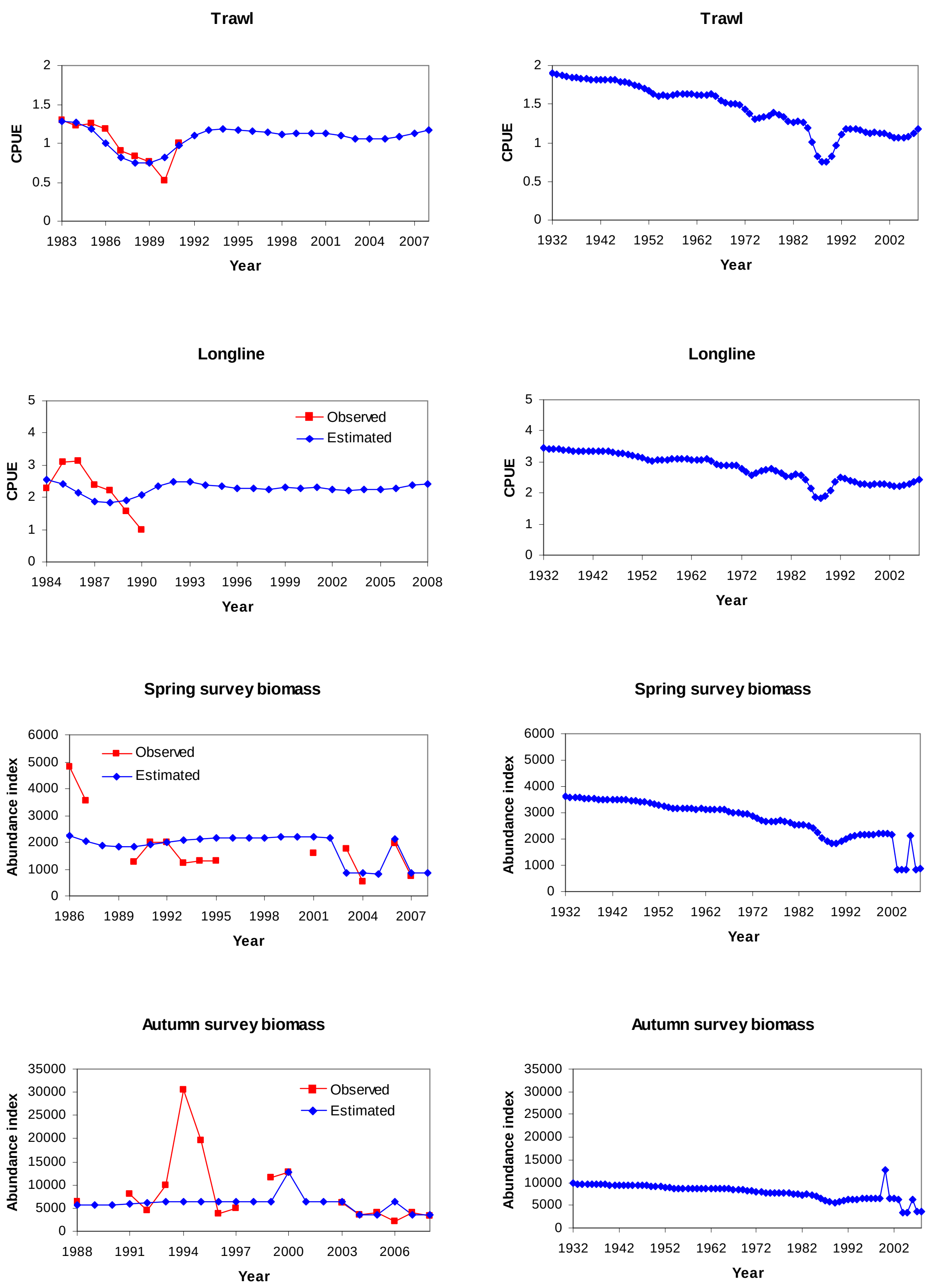


Figure 4b. Observed and estimated trend of abundance indices for the one stock model (h = 0.5) including catch-at-length data fitted to data up to 2008 for the South coast of South Africa. Fluctuations shown for the estimated spring and autumn survey biomass are a consequence of differing q's for the different vessels/gears used from year to year (the default is the old gear).

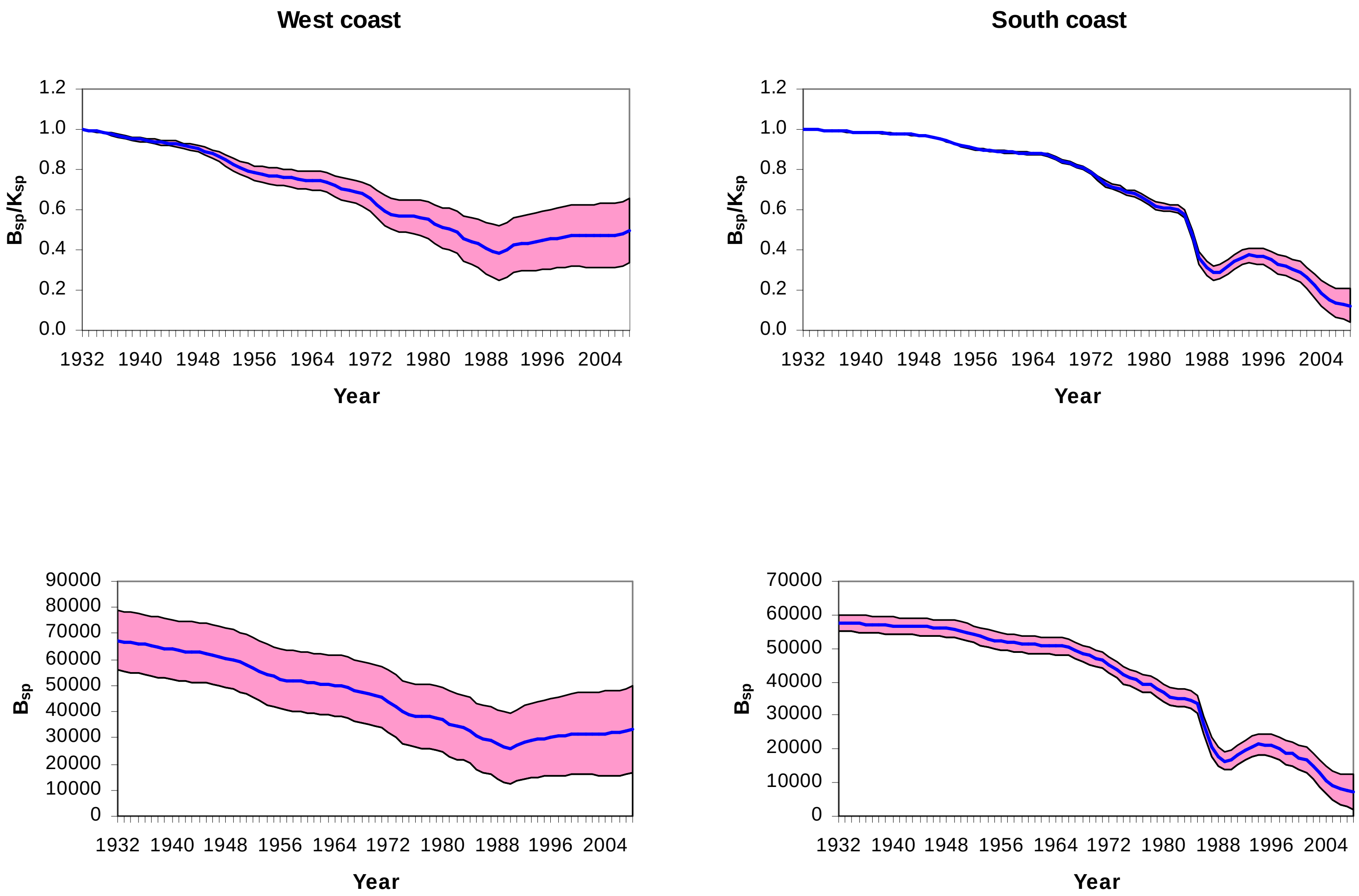


Figure 5a. Trajectories of spawning stock depletion (B_{sp}/K_{sp}) and spawning biomass (B_{sp}) estimates for kingklip for the West and South coast of South Africa for the separate coast model (h = 0.5). The shaded area represents the 95% confidence intervals calculated from the Hessian matrix.

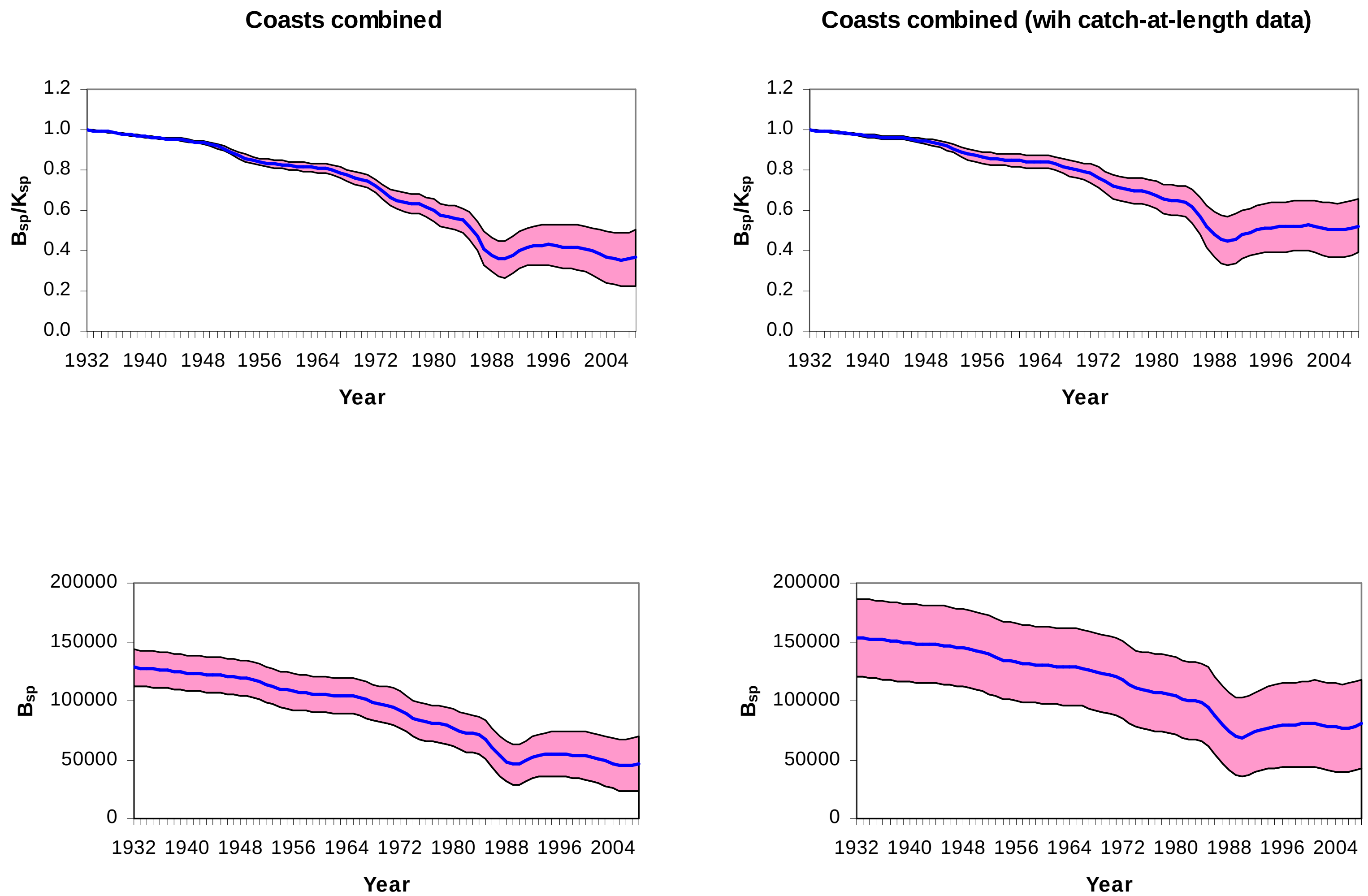


Figure 5b. Trajectories of spawning stock depletion (B_{sp}/K_{sp}) and spawning biomass (B_{sp}) estimates for kingklip of South Africa for the combined coast model (left hand side) and when the model is fitted to the combined coasts and catch-at-length data are included (right hand side). The shaded area represents the 95% confidence intervals calculated from the Hessian matrix.

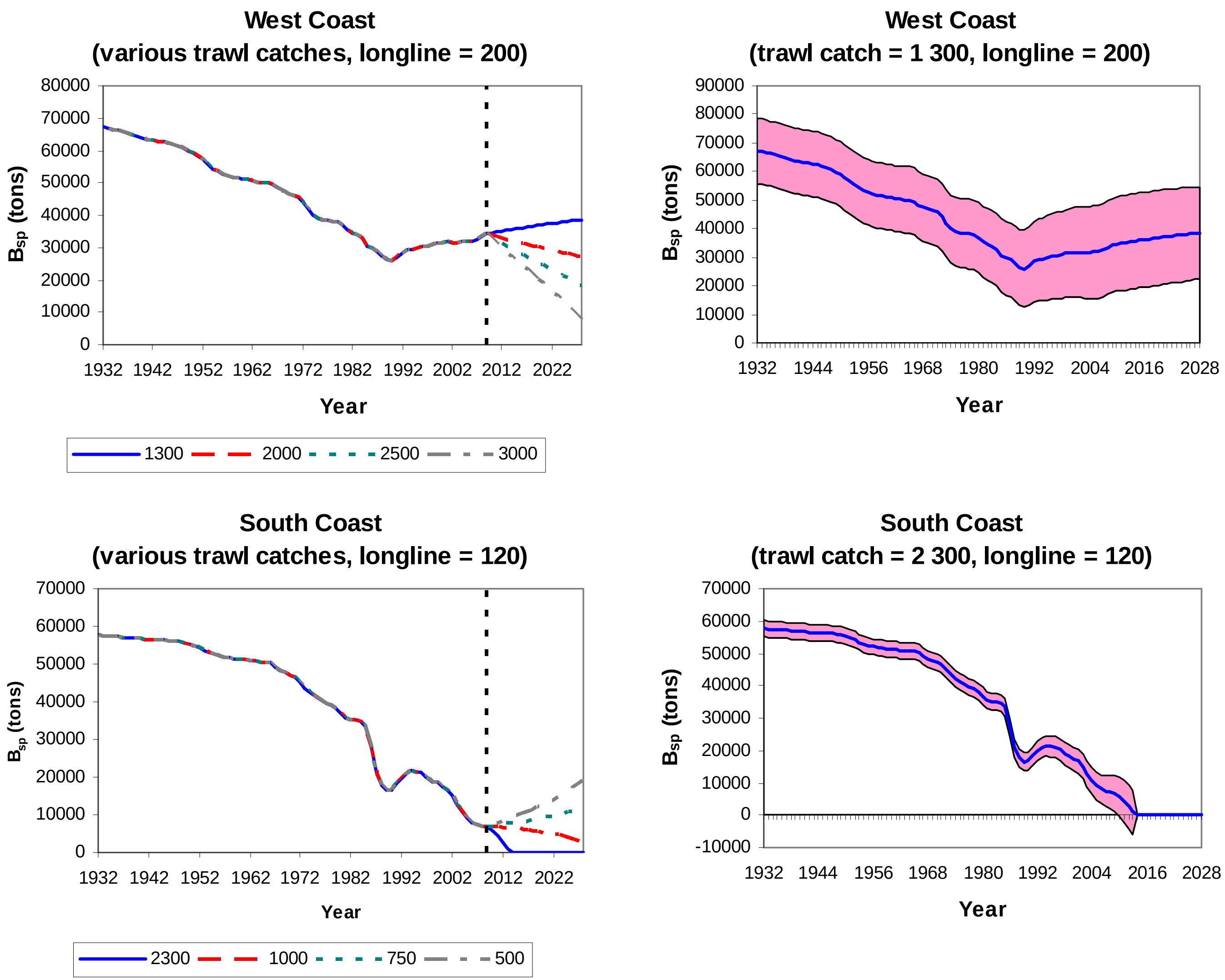
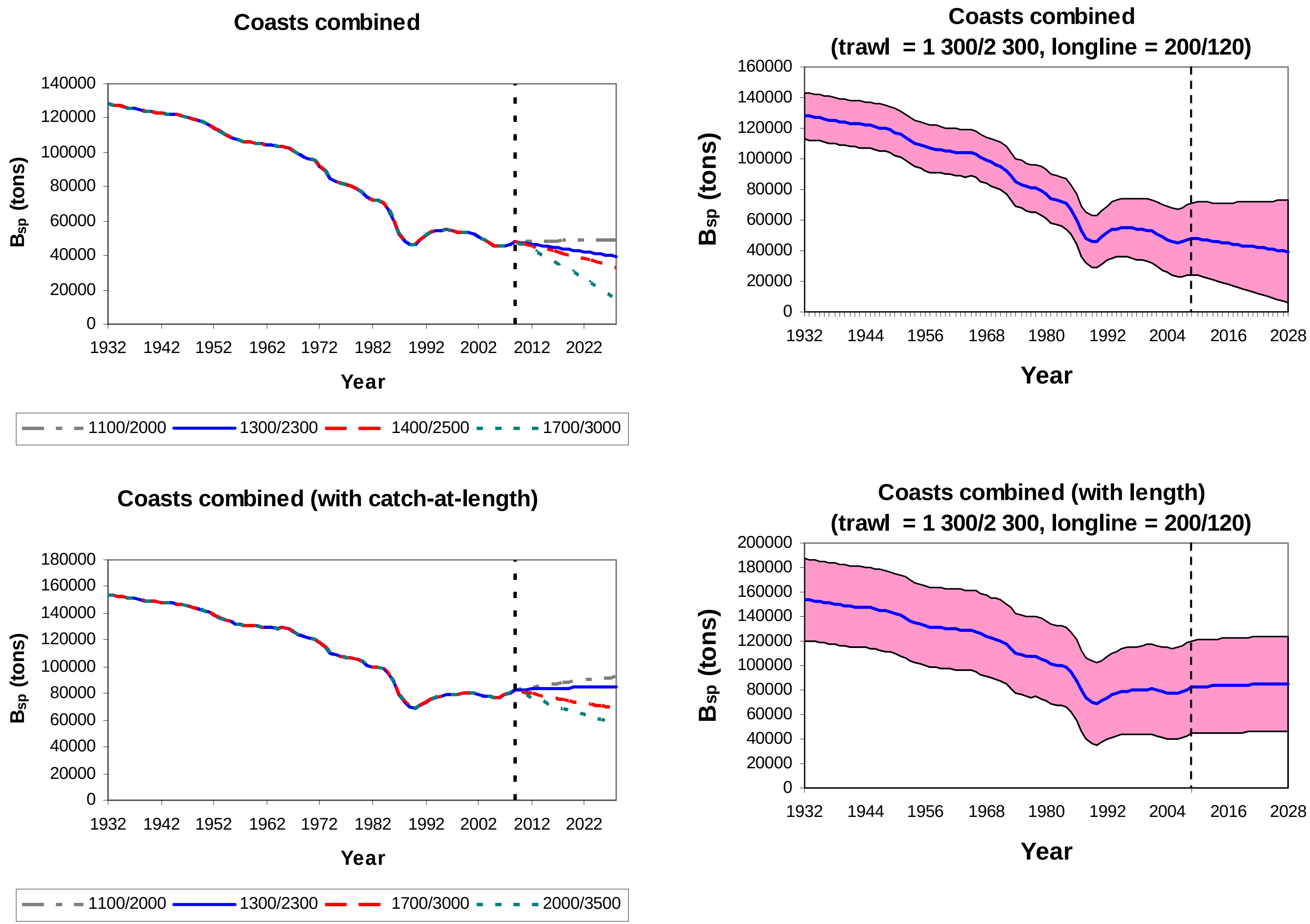


Figure 6a. Twenty year projections for kingklip for the West and the South coasts of South Africa for the separate coast model (*h* = 0.5). Results for various levels of future constant catches for the trawl fishery are shown on the left hand side. Plots on the right hand side give the projections when future constant catches for each coast are set to be the average of the past five years (2003–2007) of each fishry, together with 95% CIs.



igure 6b. Twenty year projections for kingklip for the West and the South coasts of South Africa for the combined coast model (top) and the combined coast model with catch-at-length data (bottom). Results for various levels of future constant catches for the trawl fishery are shown on the left hand side (WC/SC catch is given in the legends). Plots on the right hand side give the projections when future constant catches for each coast are set to be the average of the past five years (2003–2007) of each fishery, together with 95% CIs.

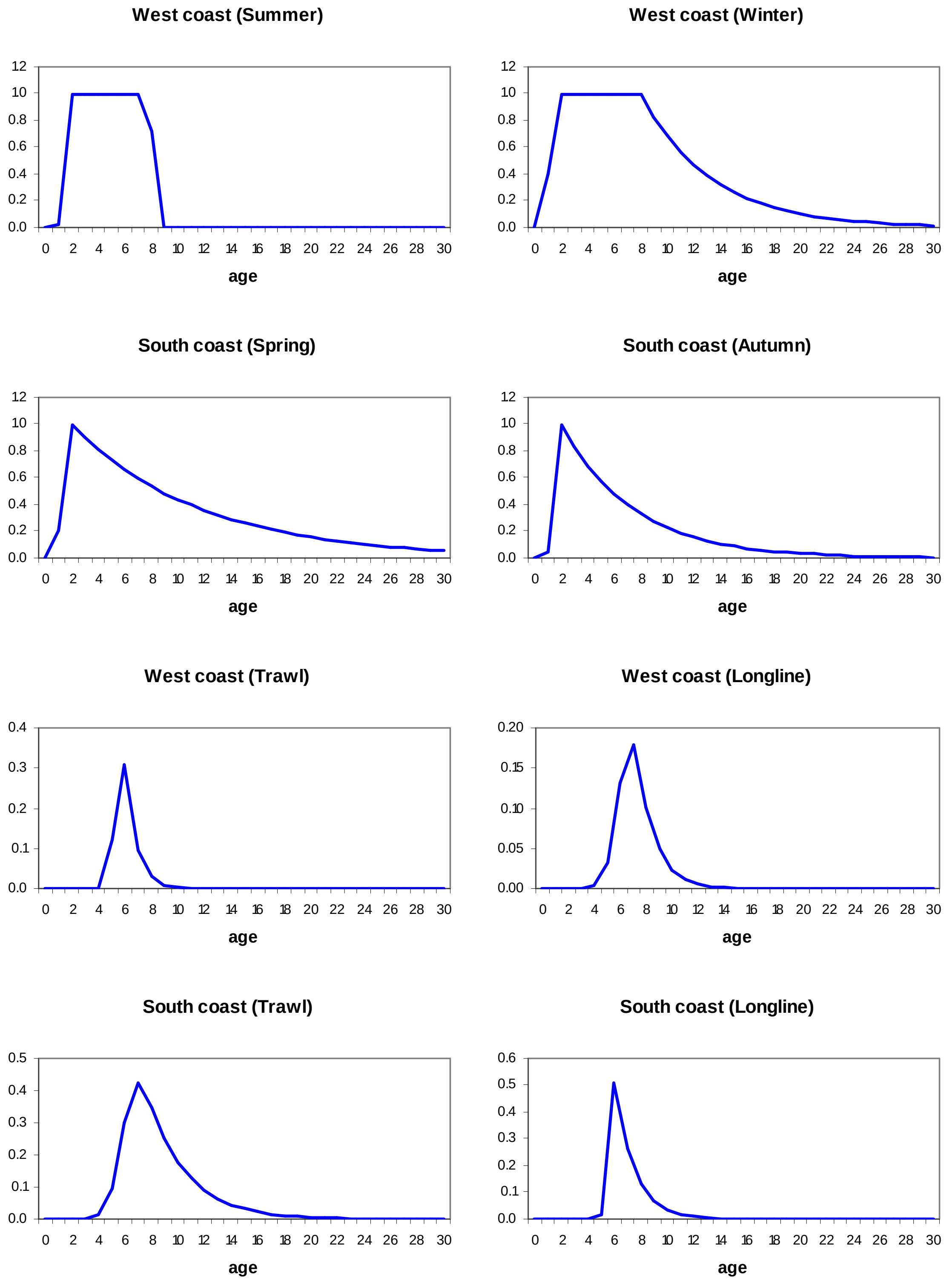


Figure 7. Estimated selectivity curves for West and South coast surveys (top four plots) and for the trawl and longline fishery (bottom four plots) for the combined coast model with catch-at-length data.

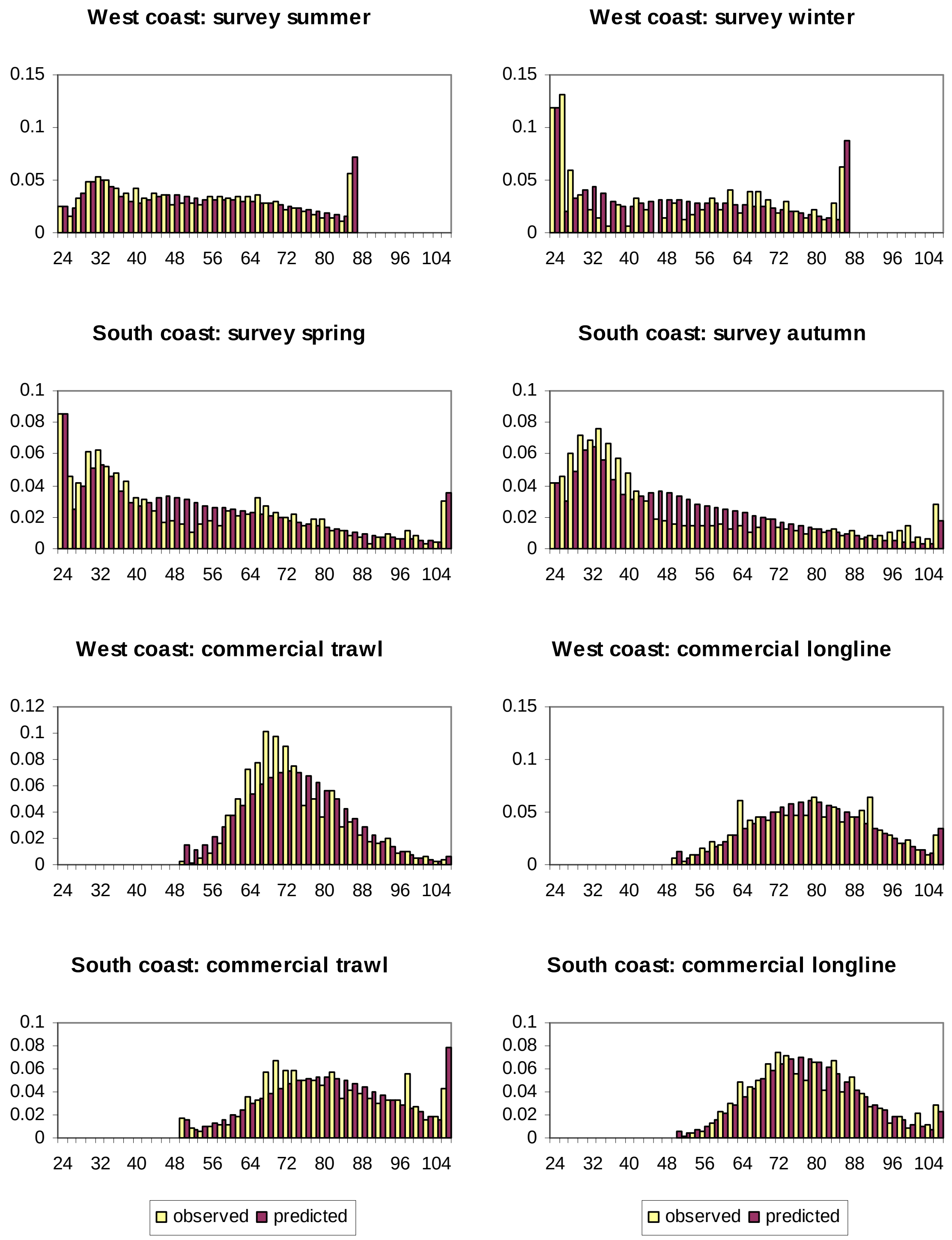


Figure 8. Observed and assessment predictions for the average catch-at-length proportions in the West and South coast research surveys (top four plots) and in the trawl and longline fishery (bottom four plots). Note that lengths below 24 and above 86 cm are combined into minus- and plus-groups for the West coast surveys, lengths below 24 and above 106 cm for the South coast surveys and lengths below 50 and above 106 cm for the West and South coast commercial fishery.

APPENDIX

THE AGE-STRUCTURED PRODUCTION MODEL FOR KINGKLIP

THE POPULATION DYNAMICS

The kingklip population dynamics are represented by:

$$\begin{aligned} N_{y+1,a} &= R_{y+1} && \text{if } a=0 \\ N_{y+1,a} &= (N_{y,a-1}e^{-\frac{M_{a-1}}{2}} - C_{y,a-1})e^{-\frac{M_{a-1}}{2}} && \text{if } 1 \le a < x \\ N_{y+1,a} &= (N_{y,a}e^{-\frac{M_a}{2}} - C_{y,a})e^{-\frac{M_a}{2}} + (N_{y,a-1}e^{-\frac{M_{a-1}}{2}} - C_{y,a-1})e^{-\frac{M_{a-1}}{2}} && \text{if } a=m \end{aligned} \quad \text{(A.1)}$$

where:

- $N_{y,a}$ is the number of kingklip of age *a* at the start of year *y*,
- $C_{y,a}$ is the number of kingklip of age *a* taken by the fishery (both longline and trawl) in year *y*,
- R_y is the number of 0 year olds at the start of year *y*,
- M_a is the instantaneous rate of natural mortality of kingklip of age *a* (assumed to be age invariant with a value of 0.2 yr^{-1}), and
- *m* is the largest age considered (i.e. the “plus group”, taken to be 30 years).

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

For a two-coast (West and South) and a two-gear (or “fleet”, trawl and longline) fishery, the total predicted number of fish of age *a* caught in year *y* is given by:

$$C_{y,a} = \sum_{c=1}^{2}\sum_{f=1}^{2} C_{y,a}^{c,f}, \quad \text{(A.2)}$$

where:

$$C_{y,a}^{c,f} = N_{y,a}e^{-\frac{M_a}{2}} S_a^{com,c,f} F_y^{c,f} \quad \text{(A.3)}$$

and:

- $F_y^{c,f}$ is the proportion of the resource above age *a* harvested in coast *c*, in year *y* by fleet *f*, and
- $S_a^{com,c,f}$ is the commercial fishing selectivity at age *a* for fleet *f* and coast *c*.

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.

$$\ell(a) = \ell_\infty[1 - e^{-\kappa(a-t_0)}] \quad \text{(A.4)}$$

$$w_a = c[\ell(a)]^d \quad \text{(A.5)}$$

where:

w_a is the mass of a fish at age a, and

c, d are the mass-length relationship parameters.

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

$$C_y^{c,f} = \sum_{a=0}^{m} w_{a+0.5} C_{y,a}^{c,f} = \sum_{a=0}^{m} w_{a+0.5} S_a^{com,c,f} F_y^{c,f} N_{y,a} e^{-\frac{M_a}{2}} \tag{A.6}$$

which can be re-written as:

$$F_y^{c,f} = \frac{C_y^{c,f}}{\sum_{a=0}^{m} w_{a+0.5} S_{y,a}^{com,c,f} N_{y,a} e^{-\frac{M_a}{2}}} = \frac{C_y^{c,f}}{B_{y,mid}^{\exp,c,f}}, \tag{A.7}$$

where

$B_{y,mid}^{\exp,c,f}$ is the mid-year coast and fleet-specific exploitable component of the biomass, and

$w_{a+0.5}$ is the mid-year mass of fish of age a assumed to be the same for each coast.

FISHING SELECTIVITY

When no catch-at-length data is used in the model fitting procedure, the coast and fleet-specific commercial fishing selectivity, $S_a^{c,f}$, is assumed to be of the same form as in Punt and Japp (1994). In this instance, the fishing selectivities are assumed to be the same for the West and the South coasts. For the longline this is given by:

$$S_a^{com,c,L} = \left\{1 + \exp\left[-\left(a - a_{50}^L\right)/\delta^L\right]\right\}^{-1} \tag{A.8}$$

and for the trawl fishery by:

$$S_a^{com,c,T} = \begin{cases} \left\{1 + \exp\left[-\left(a - a_{50}^T\right)/\delta^T\right]\right\}^{-1} & \text{if } a \le a_{50}^T \\ \dfrac{\exp\left[-\gamma\left(a - a_{50}^T\right)\right]}{\left\{1 + \exp\left[-\left(a - a_{50}^T\right)/\delta^T\right]\right\}^{-1}} & \text{if } a > a_{50}^T \end{cases} \tag{A.9}$$

where:

$a_{50}^{L/T}$ is the age-at-50% selectivity for the longline/trawl fishery,

$\delta^{L/T}$ is the parameter which determines the width of the age-specific selectivity function for the longline/trawl fishery, and

γ is (approximately) the negative of the slope of the selectivity function for large ages.

For the model that includes both commercial and survey catch-at-length data, the coast and fleet-specific commercial selectivity, $S_a^{com,c,f}$, and the coast and survey-specific selectivity,

$S_a^{surv,c,s}$, are assumed to be described by a logistic curve, modified by a decreasing selectivity for fish older than age $a_{ch}^{surv/com,c}$. The commercial selectivity is given by:

$$S_a^{com,c,f} = \begin{cases} \left[1+e^{-\left(a-a_{50}^{com,c,f}\right)/\delta^{com,c,f}}\right]^{-1} & \text{for } a \leq a_{ch}^{com,c} \\ \left[1+e^{-\left(a-a_{50}^{com,c,f}\right)/\delta^{com,c,f}}\right]^{-1} e^{-\omega^{com,c,f}\left(a-a_{ch}^{com,c}\right)} & \text{for } a > a_{ch}^{com,c} \end{cases} \tag{A.10}$$

where:

$a_{50}^{com,c,f}$ is the age-at-50% selectivity (in years) for the commercial fishery *f* and coast *c*,

$\delta^{com,c,f}$ relates to the steepness of the ascending section of the commercial selectivity curve (in years^{-1}) for fishery *f* and coast *c*, and

$\omega^{com,c,f}$ specifies the steepness of the descending section of the commercial selectivity curve for fish older than age $a_{ch}^{com,c}$ for fishery *f* and coast *c* (for all the results reported in this paper, $a_{ch}^{com,c}$ for the commercial selectivities is fixed at 5 yrs).

The survey selectivity is of the same form as the commercial selectivity given by equation (A.10), however the age at which the selectivity function decreases for older fish is fixed at $a_{ch}^{surv,WC} = 7.97$ and $a_{ch}^{surv,SC} = 2$ for the West and South coasts respectively. These values as well as the value for $a_{ch}^{com,c}$ were chosen from the best attempt at estimating them. However, convergence problems were encountered and therefore the values were fixed in further analyses.

STOCK-RECRUITMENT RELATIONSHIP

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

$$B_y^{sp} = \sum_{a=1}^{m} w_a f_a N_{y,a} = \sum_{a=a_m}^{m} w_a N_{y,a} \tag{A.11}$$

where:

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

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

$$R(B_y^{sp}) = \frac{B_y^{sp}}{\alpha + \beta\, B_y^{sp}}. \tag{A.12}$$

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

(A.13)–(A.14) 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.:

$$hR_0 = R(0.2K^{sp}) \tag{A.13}$$

from which it can be shown that:

$$h = \frac{0.2(\alpha + \beta K^{sp})}{\alpha + \beta 0.2K^{sp}} \tag{A.14}$$

and hence:

$$\begin{aligned} \alpha &= K^{sp}(1-h)\big/(4hR_0) \\ \beta &= (5h-1)\big/(4hR_0) \end{aligned} \tag{A.15}$$

The model estimate of the mid-year exploitable component of the biomass for each fleet is given by:

$$B_{y,mid}^{\exp,c,f} = \sum_{a=0}^{m} w_{a+0.5} S_a^{com,c,f} N_{y,a} e^{-M/2}, \tag{A.16}$$

where:

$w_{a+0.5}$ is the mid-year weight of kingklip of age *a*.

The model estimate of the start of the year exploitable component of the biomass for each coast and each fleet is given by:

$$B_{y,st}^{\exp,c,f} = \sum_{a=0}^{m} w_a S_a^{com,c,f} N_{y,a} \tag{A.17}$$

The model estimate of the survey biomass at the start of the year for each coast is given by:

$$B_{y,st}^{surv,c} = \sum_{a=0}^{m} w_a S_a^{surv,c,s} N_{y,a} \tag{A.18}$$

where:

$S_a^{surv,c,s}$ is the survey selectivity at age *a* for survey *s* and coast *c*,

and the model estimate of the survey biomass at mid-year is given by:

$$B_{y,mid}^{surv,c} = \sum_{a=0}^{m} w_{a+0.5} S_a^{surv,c,s} N_{y,a} e^{-M/2}. \tag{A.19}$$

PAST STOCK TRAJECTORY AND FUTURE PROJECTIONS

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

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

which can be solved for R_0.

The resource is assumed at its unexploited equilibrium when catches start in 1932 for the West and South coasts. The initial numbers at each age *a* for the trajectory calculations, corresponding to the deterministic equilibrium, are given by:

$$N_{1932,a} = R_0 n_a \,, \qquad \text{(A.21)}$$

where:

$$n_a = \begin{cases} 1 & \text{if } a = 0 \\ \exp\left(-\sum_{a'=0}^{a-1} M_{a'}\right) & \text{if } 1 \le a < m \\ \exp\left(-\sum_{a'=0}^{m-1} M_{a'}\right) \Big/ \left(1-\exp\left(-M_m\right)\right) & \text{if } a = m \end{cases} \qquad \text{(A.22)}$$

Numbers-at-age for subsequent years are then computed by means of equations (A1.1)-(A1.3) and (A1.6)-(A1.11) under the series of annual catches given.

THE LIKELIHOOD FUNCTION

The age-structured production model (ASPM) is fitted to the coast and fleet-specific CPUE data and to the coast and season-specific (i.e. summer or winter) survey abundance series.

CPUE abundance data

The likelihood is calculated assuming that the observed abundance indices are lognormally distributed about their expected values:

$$I_y^{c,i} = \hat{I}_y^{c,i} e^{\varepsilon_y^{c,i}} \qquad \text{or} \qquad \varepsilon_y^{c,i} = \ln\left(I_y^{c,i}\right) - \ln\left(\hat{I}_y^{c,i}\right) \qquad \text{(A.23)}$$

where:

$I_y^{c,i}$ is the abundance index of type *i* for year *y* and coast *c*, where for example, *i* = $CPUE_{trawl}$, when dealing with the CPUE index for the trawl fishery,

$\hat{I}_y^{c,i} = \hat{q}_i^c \hat{B}_{y,t}^{\exp,c,f}$ is the corresponding model estimated value, where $B_{y,t}^{\exp,c,f}$ is the model value for exploitable resource biomass for coast *c* (*c* = *WC* for the West coast or *c* = *SC* for the South coast), for fishery *f* (*f* = *T* for trawl or *f* = *L* for longline fishery) and time of the year *t* (*t* = *mid* for mid-year or *t* = *st* for the start of year),

$\hat{q}_i^c$ is a constant of proportionality for abundance index *i* and coast *c*, and

$\varepsilon_y^{c,i}$ is normally distributed with mean zero and standard deviation $\sigma_y^{c,i}$.

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

$$-\ln L_{CPUE} = \sum_c \sum_i \sum_y \left[\ln \sigma_y^{c,i} + \left(\varepsilon_y^{c,i}\right)^2 \Big/ 2\left(\sigma_y^{c,i}\right)^2 \right], \qquad \text{(A.24)}$$

where the model estimate of exploitable resource biomass is given by equation (A.16) and homoscedasticity of residuals is assumed, so that $\sigma_y^{c,i} = \sigma^{c,i}$ and this is estimated by its maximum likelihood value:

$$\hat{\sigma}^{c,i} = \sqrt{\frac{1}{n_{c,i}} \sum_y \left(\ln I_y^{c,i} - \ln \hat{q}_i^c \hat{B}_{y,mid}^{\exp,c,f} \right)^2} ,$$

where:

$n_{c,i}$ is the number of data points for the abundance series *i* and coast *c*,

and the maximum likelihood estimate of q_i^c is given by:

$$\ln \hat{q}_i^c = \frac{1}{n_{c,i}} \sum_y \left\{ \ln I_y^{c,i} - \ln \hat{B}_{y,mid}^{\exp,c,T} \right\}.$$

Survey abundance data

Survey abundance indices are treated in a similar way to the CPUE series, where abundance index of type *i* now represent those from the research surveys, for example $i = Survey_{summer}$ when dealing with the abundance index from the summer survey, and so on. The West coast winter survey and the South coast autumn survey were taken to correspond to the middle of the year, while the West coast summer survey and the South coast spring survey were taken to correspond to the beginning of the year. Some survey abundance indices were obtained using either the old or the new gear on the *Africana*, and sometimes the *Africana* or the *Nansen* was used for the survey. To differentiate between gear type and between vessels, the term $\varepsilon_y^{c,i}$ in Equation (A.23) is modified to:

$$\varepsilon_y^{c,i} = \ln\left(I_y^{c,i}\right) - \ln\left(\hat{q}_i^{*c} \hat{B}_{y,t}^{\exp,c,T}\right)$$

where:

$\hat{q}_i^{*c}$ is a constant of proportionality for abundance index *i*, where

$$\hat{q}_i^{*c} = \begin{cases} \hat{q}_i^{old,c} & \text{if index } i \text{ in year } y \text{ is from } Africana \text{ with old gear} \\ \hat{q}_i^{old,c} \hat{q}_i^{d,c} & \text{if index } i \text{ in year } y \text{ is from } Africana \text{ with new gear} \\ \hat{q}_i^{old,c} \hat{q}_i^{d2,c} & \text{if index } i \text{ in year } y \text{ is from } Nansen \end{cases}$$

When survey catch-at-length data are not used in the model fitting procedure, the surveys are assumed to have the same selectivity as the trawl fishery, and the time of year when the survey took place is taken into account. Thus, for the summer survey, the corresponding model estimated exploitable resource biomass is given by equation (A.17) and for the winter survey, $B_{y,t}^{\exp,c,f}$ is given by equation (A.16), with the corresponding selectivity function being that for the trawl fishery and the specific coast being considered.

When survey catch-at-length data are used in the model fitting procedure, survey specific selectivity functions can be estimated and thus the survey model estimated biomass $B_{y,t}^{surv,c}$ given by equation (A.18) or equation (A.19) is used in this case.

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

$$-\ln L_{survey} = \sum_{c}\sum_{i}\sum_{y}\left[\ln\sigma_y^{c,i} + \left(\varepsilon_y^{c,i}\right)^2 \Big/ 2\left(\sigma_y^{c,i}\right)^2\right] \qquad \text{(A.25)}$$

where:

$\sigma_y^{c,i}$ are given by $\ln\left(1+\left(CV_y^{c,i}\right)^2\right)$, where the $CV_y^{c,i}$ are the coefficients of variation of the resource abundance estimate for coast *c* and index *i* for year *y*. These CVs are input and are given in Table 2.

The catchability coefficient $q_i^{old,c}$ for the survey abundance index *i* and coast *c* is estimated by its maximum likelihood value and is given by:

$$\ln\hat{q}_i^{old,c} = \frac{\sum_y X_y^{c,i}\left(1\Big/\left(\sigma_y^{c,i}\right)^2\right)}{\sum_y 1\Big/\left(\sigma_y^{c,i}\right)^2}, \qquad \text{(A.26)}$$

where:

$$X_y^{c,i} = \begin{cases} \ln I_y^{c,i} - \ln\hat{B}_{y,t}^{\exp,c,T} & \text{if index } i \text{ in year } y \text{ is from } Africana \text{ with old gear} \\ \ln I_y^{c,i} - \ln\left(\hat{q}_i^{d,c}\hat{B}_{y,t}^{\exp,c,T}\right) & \text{if index } i \text{ in year } y \text{ is from } Africana \text{ with new gear} \\ \ln I_y^{c,i} - \ln\left(\hat{q}_i^{d2,c}\hat{B}_{y,t}^{\exp,c,T}\right) & \text{if index } i \text{ in year } y \text{ is from } Nansen \end{cases}$$

and $q_i^{d,c}$ and $q_i^{d2,c}$ are estimated in the non-linear search.

In the case when survey catch-at-length data are included in the model fit, $\hat{B}_{y,t}^{\exp,c,T}$ in equation (A.26) is replaced by $\hat{B}_{y,t}^{surv,c}$.

EXTENSION TO INCORPORATE CATCH-AT-LENGTH INFORMATION

The model above provides estimates of the commercial catch-at-age ($C_{y,a}^{c,f}$) by number made by the each fleet in the fishery each year from equation (A.3). These in turn can be converted into proportions of the catch of age *a*:

$$p_{y,a}^{c,f} = C_{y,a}^{c,f} \Big/ \sum_{a'} C_{y,a'}^{c,f}\ . \qquad \text{(A.27)}$$

Using the von Bertalanffy growth equation (A.4), these proportions-at-age can be converted to proportions-at-length – here under the assumption that the distribution of length-at-age remains constant over time:

$$p_{y,\ell}^{c,f} = \sum_a p_{y,a}^{c,f} A_{a,\ell}^{c,f} \tag{A.28}$$

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

$$\sum_\ell A_{a,\ell}^{c,f} = 1 \qquad \text{for all ages } a. \tag{A.29}$$

The *A* matrix has been calculated here under the assumption that length-at-age is normally distributed about a mean given by the von Bertalanffy equation, i.e.:

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

where:

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

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

$$\theta(\text{a}) \ = \ \upsilon\ell_\infty\left\{1-e^{-\kappa(a-t_0)}\right\} \tag{A.31}$$

with υ 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 υ and hence the $\theta(a)$'s estimated will reflect not only the real variability of length-at-age, but also the "spread" that arises from the fact that fish in the same annual cohort are not all spawned at exactly the same time, and that catching takes place throughout the year so that there are differences in the age (in terms of fractions of a year) of fish allocated to the same cohort.

Similarly, the proportion of fish of age *a* for the surveys in the beginning of year *y* and coast *c* are given by:

$$p_{y,a}^{surv,c,s} = C_{y,a}^{surv,c,s} \Big/ \sum_{a'} C_{y,a'}^{surv,c,s} = S_a^{surv,c,s} N_{y,a} \Big/ \sum_{a'} S_{a'}^{surv,c,s} N_{y,a'} \tag{A.32}$$

and for those at mid year by:

$$p_{y,a}^{surv,c,s} = C_{y,a}^{surv,c,s} \Big/ \sum_{a'} C_{y,a'}^{surv,c,s} = S_a^{surv,c,s} N_{y,a} e^{-M_a/2} \Big/ \sum_{a'} S_{a'}^{surv,c,s} N_{y,a'} e^{-M_a/2} \tag{A.33}$$

These survey proportions-at-age can be converted to proportions-at-length using the same procedure as for the commercial proportions-at-age.

The observed commercial and survey proportions-at-length are assumed to follow a multinomial distribution, and so the contribution of the survey catch-at-length data to the negative log-likelihood function is given by:

$$-\ln L_{len}^{surv} = -N \sum_{c,s,y,\ell} \left\{ p_{y,\ell}^{surv,c,s} \ln\left(\hat{p}_{y,\ell}^{surv,c,s}\right)\right\} + K \tag{A.34}$$

where:

$p_{y,\ell}^{surv,c,s}$ is the observed proportion by number of the catch for coast *c* in year *y* in length group *ℓ* for survey *s*,

$\hat{p}_{y,\ell}^{surv,c,s}$ is the model predicted proportion by number of the catch for coast *c* in year *y* in length group ℓ for survey s,

N is the effective sample size, assumed to be 25 in this application, and

K is a constant used to keep the value of –ln L to a manageable number of digits. It measures the value that would be attained if the data fit would be exactly the model's expectation, that is:

$$K = N \sum_{c,s,y,\ell} \left\{ p_{y,\ell}^{surv,c,s} \ln \left(p_{y,\ell}^{surv,c,s} \right) \right\}$$

and the contribution of the survey catch-at-length data to the negative log-likelihood function is given by:

$$-\ln L_{len}^{com} = -N \sum_{c,f,y,\ell} \left\{ p_{y,\ell}^{c,f} \ln \left(\hat{p}_{y,\ell}^{c,f} \right) \right\} + K \qquad \text{(A.35)}$$

In the practical application of equations (A.34) and (A.35), length observations were grouped by 2 cm intervals, with minus- and plus-groups specified below 24 and above 86 cm for the West coast surveys, lengths below 24 and above 106 cm for the South coast surveys and lengths below 50 and above 106 cm for the West and South coast commercial fishery.