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Documentation of the separable Sequential Population Analysis used in the assessments of southern blue whiting, and a comparison with other models

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This series documents the scientific basis for stock assessments and fisheries management advice in New Zealand. It addresses the issues of the day in the current legislative context and in the time frames required. The documents it contains are not intended as definitive statements on the subjects addressed but rather as progress reports on ongoing investigations.

Documentation of the separable Sequential Population Analysis used in the assessments of southern blue whiting, and a comparison with other models

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1. EXECUTIVE SUMMARY

This paper documents recent developments of the separable Sequential Population Analysis (sSPA) model used to assess southern blue whiting, and compares the results of the sSPA with other models.

The sSPA model used in previous assessments has been improved to take into account concerns raised at stock assessment meetings. Weight-at-age has been calculated for each year where catch-at-age data are available, and the variable weight-at-age matrix is now used in the model rather than the constant weight-at-age used in the past. An extra term has been added to the objective function so that recruitment indices can be fitted in the model. The 1997 Campbell Island assessment was not particularly sensitive to either of these changes.

A new equilibrium version of the model is documented which allows the estimation of year class strength and historical biomass for years before catch-at-age data are available. The model suggested strong recruitment and a very large increase in the biomass of the Campbell Island stock during the late 1960s and early 1970s. Independent supporting evidence for this comes from the slow growth rates of the strong year classes.

Three other catch-at-age models were evaluated for estimating biomass of southern blue whiting on the Campbell Island Rise. These were a catch-at-age model used for estimating snapper biomass, the least squares estimation procedure from the hoki MIAEL model, and a Laurec-Shepherd tuned VPA. All four models were run over the period 1979 to 1995, essentially using the same input data and biological parameters. The patterns of year class strength were very similar between the models with all models identifying the strong 1979, 1980, and 1991 year classes. The biomass trajectories for the models were also reasonably similar since about 1983, with a decline to 1993 followed by an increase to 1995. However, the results from the models diverge strongly before 1983. The sSPA and snapper models had a similar trajectory back to 1979. The hoki model estimated a lower initial biomass with stronger early year class strengths, and the VPA estimated a higher initial biomass with weaker early year class strengths, compared to the other models.

It is recommended that studies should be carried out using simulated data to determine which models and/or estimation procedures are most appropriate for modelling southern blue whiting populations.

2. INTRODUCTION

The southern blue whiting (*Micromesistius australis* Norman) fishery is one of the largest fisheries in New Zealand waters. It was developed in the early 1970s by the Soviet fleet and since then landings have fluctuated considerably averaging about 20 000 t, and peaking at over 75 000 t in 1992 (Figure 1). The fishery targets southern blue whiting as they aggregate to spawn on the Bounty Platform, Pukaki Rise, Auckland Islands Shelf, and the Campbell Island Rise. Fish from these four grounds appear to form separate stocks (Hanchet 1998), and have been treated separately for stock assessment purposes (Hanchet 1998). Before 1993, there were no catch or effort restrictions in the fishery. In 1993, a total catch limit of 32 000 t was introduced with an area limit of 11 000 t on the Campbell Island Rise, 15 000 t on the Bounty Platform, and 6000 t on the Pukaki Rise. Historically, most fishing has been on the Campbell Island Rise (*see* Figure 1). This paper deals primarily with that stock.

The first quantitative assessment of the Campbell Island stock was carried out in 1991 using an age-structured stock reduction analysis following the method of Francis (1990). The model was fitted to CPUE data and estimates of Z from catch curve analysis, and assumed deterministic recruitment (Hanchet 1991a). The following year a time series of catch-at-age data extending back to 1982 was developed which allowed the use of catch-at-age models for the first time (Hanchet 1992). Virtual Population Analysis, tuned using the Laurec-Shepherd method (Laurec & Shepherd 1983), was carried out using the Lowestoft suite of programs (Darby & Flatman 1994). However, the CPUE data used to tune the VPA were noisy, and the diagnostics from the tuning indicated that the terminal fishing mortalities on each age were poorly estimated with *c.v.* s ranging from 0.2 to 0.9 (Hanchet 1993). Several limitations of the model were identified: (i) there was likely to be error in the catch-at-age, CPUE, and landings data, (ii) a time series of biomass estimates from acoustic surveys was being developed, which could not be fitted in the model, (iii) confidence intervals had not been estimated. A separable Sequential Population Analysis was developed in 1994 to address these issues and to integrate all the available data in one stock assessment (Hanchet & Haist 1994, Hanchet *et al.* in press).

The current work was carried out to meet objective 6 in the Ministry of Fisheries Contract SBW9701:

“To evaluate alternative catch-at-age models for estimation of biomass and yields”.

This involved two aspects.

Firstly, to carry out further developments to the sSPA model in response to some concerns raised by the working group. These included modifications to allow annual variations in weight at age, and to allow for inclusion of indices of 1 and 2 year olds in the fitting procedure. Additionally, an “initial equilibrium” model was developed to allow estimation of fishing mortality and biomass for years before catch-at-age data are available.

Secondly, to compare the results of the sSPA model with those of other models which have been used in New Zealand stock assessments. Because of the time taken to make the above changes to the existing model there was not a great deal of time to evaluate or develop alternative catch-at-age models. Furthermore, earlier assessments of southern blue whiting

used stock reduction analysis (Hanchet 1991a, 1992) and Virtual Population Analysis (Hanchet 1992, 1993, Punt 1994) and these "packaged" models have since been dropped in favour of the more integrated approach of the sSPA.

The three models finally chosen for comparison with the sSPA were an Excel spreadsheet model which has been used in the assessment of snapper (e.g., Maunder & Starr 1998), a Laurec-Shepherd tuned VPA, which was used in earlier assessments of southern blue whiting (Hanchet 1993, Punt 1994), and the least squares fits from the hoki MIAEL model (Cordue 1993).

3. METHODS

3.1 Changes to the sSPA model

The sSPA model used for the 1996 assessment of the Campbell Island stock (Hanchet & Ingerson 1996) was fully documented by Hanchet *et al.* (in press), and the catch equations and details of the model are repeated here in Appendix 1.

A number of small changes were made to the fitting procedure for the 1997 assessment of the Campbell Island stock. These included fitting the adult acoustic indices as absolute indices of abundance and the exclusion of the effort data from the fitting procedure (Hanchet 1997). During the 1997 working group meetings a number of improvements were suggested, including the use of variable (as opposed to constant) annual weight at age, and fitting to recruitment indices (numbers of 1 and 2 year olds) from the acoustic surveys, and fitting the annual catch in terms of weight rather than numbers. The sensitivity of the 1997 assessment to these changes was examined and the changes to the programme are documented in Appendix 2. The input parameters are shown in Table 1.

In previous assessments biomass has been estimated only for those years where catch-at-age data have been available. Under this scenario the numbers in the initial population and the subsequent recruitment were estimated (*see* Appendix 1). To extend the assessment back to B_0 the initial population age structure must be assumed to be at equilibrium (otherwise the model becomes over-parameterised). Recruitment between the year of the start of the model and the year before the catch-at-age data are available can be derived from virgin recruitment (either deterministically or stochastically) or estimated from the catch-at-age data. The sensitivity of historical biomass to the number of year class strengths being estimated was investigated by estimating 0, 5, and 9 of these earlier year class strengths. Details of the "equilibrium" model are summarised in Appendix 2.

3.2 Changes to the input data sets

Landings data

Landings for the period 1971 to 1995–96 are shown in Figure 1. To allow the estimation of historical biomass before 1978 it is necessary to have estimates of the annual catches for the Campbell Island stock from 1971 to 1977. Hanchet (1997) reviewed the early Soviet literature and concluded that fishing probably took place on spawning and/or feeding aggregations of all four stocks throughout the Campbell Plateau and Bounty Platform, but that the proportion

in each stock could not be determined. There have been major changes in the fishery since 1977 with the advent of larger nets, new fish finding technology such as sonar and colour sounders, the arrival of the Japanese fleet (after 1986), the development of other commercial fisheries, and more recently the introduction of catch limits, so the pattern of recent catches could be quite different from those before 1978. However, there are no other data available and so for the purposes of modelling it has been assumed that the proportion of the catch on the Campbell Island ground is the same as that from the period of the fishery from 1978 to 1995–96. The proportion of the catch from the Campbell Island stock for this period was 0.61 (for comparison the proportion for the period 1978 to 1986 was 0.71). The catch history used for the modelling is shown in Table 2. The catches for the years 1995 and 1996 are slightly different from those given in Hanchet (1998) because they refer to the fishing season (including catches in October) rather than the fishing year.

Catch-at-age data

Commercial length frequency data and otoliths are available from 1979 to 1996. The length frequency data were scaled up to the commercial catch which was then converted to catch-at-age data by application of a year specific age-length key (*see* Hanchet 1997). Between-reader ageing variability increased after age 10 and so for most of the model runs ages 2 to 10 were used with a plus group at age 11 (Table 3).

Acoustic data

Southern blue whiting were surveyed acoustically in the spawning season in 1993, 1994, and 1995 (Ingerson & Hanchet 1996). Although primarily designed as a survey of spawning biomass, transects were extended inshore to cover the principal nursery grounds so that both adult and pre-recruit biomass estimates were obtained. The biomass estimates from the surveys are shown in Table 4.

CPUE data

Individual tow by tow data were analysed for the Campbell Island fishery from 1986 to 1995 using a generalised linear model (Hanchet & Ingerson 1996). Because of the large number of zero tows (ranging from 2 to 20% per year), a gamma error distribution with a log-link function was used to model CPUE. Annual catch per unit effort indices were obtained after standardising for the effects of vessel length, depth fished, time of day, tow position, season, and headline height. The resulting CPUE indices were converted to estimates of total annual effort by dividing them into the annual landings (Table 5).

Weight at age and M

In previous assessments of southern blue whiting, weight-at-age was calculated from the weight-length relationship and von Bertalanffy growth coefficients given in Hanchet (1991a) and assumed to be constant for each year. However, there is considerable inter-annual variability in growth, and so the weight-at-age for each year was calculated by transforming the individual length-age data to weight-age using the weight-length relationship and then calculating the mean weight at age for each year (Table 6). Weights-at-age in years before the catch-at-age data are available were assumed to be the mean of the period 1979 to 1986.

Natural mortality (M) was assumed to be 0.2 (Hanchet 1991a).

3.3 Comparison of sSPA with other models

Three other catch-at-age models were evaluated for estimating biomass of southern blue whiting on the Campbell Island Rise. All four models (including the sSPA) were run over the period 1979 to 1995, and the input parameters shown in Table 7. They all used the same catch data, catch-at-age data, CPUE indices, constant weight at age vector, and M of 0.2. In addition to the fitting approach there were some other differences between the models. The sSPA, hoki, and snapper models all fitted the adult acoustic biomass estimates as relative indices of abundance. The VPA was not fitted to the acoustic indices. Further details of the models are given below and summarised in Table 7.

A catch-at-age model used for estimating snapper biomass (Maunder & Starr 1998) was modified for use in the southern blue whiting fishery. The main modification was a change in the catch equations, so that fishing mortality was assumed to occur in a short period at the end of the season after natural mortality. The selectivity ogive for ages 2, 3, and 4 estimated by the sSPA model was used as input to this model. Estimation was carried out using the non linear solver function in Excel. Preliminary model runs using a *c.v.* of 0.2 gave too much weight to the catch at age data and resulted in unrealistic exploitation rates, and so an arbitrary *c.v.* of 2.0 was used.

The least squares estimation procedure from the MIAEL model, used for estimating year class strength in the hoki assessment (Cordue 1993), was the second approach used in the current study. This model is similar to the sSPA equilibrium model discussed above. However, the population in the initial year (in this case 1979) is assumed to have an equilibrium age structure, and the year class strengths since then are estimated using least squares. The input parameters, catch equations, and data sets used in the model were the same as for the sSPA model, and, as in the sSPA model, the catch-at-age data are assumed to follow a multinomial distribution. Because the model is a two-sex model the biological parameters and proportion at age data were input separately for each sex. As with the sSPA model selectivity was assumed to be complete by age 5 and the selectivity of ages 2, 3, and 4 were estimated by the model.

A Laurec-Shepherd tuned VPA was the third approach used to model biomass. This approach was used by Hanchet (1993) and Punt (1994) for assessing the southern blue whiting stocks. The current analysis used the Lowestoft suite of programs (Darby & Flatman 1994). This package requires age-structured tuning data (proportion-at-age data) which were not available for the southern blue whiting acoustic data, so the fitting was confined to the standardised CPUE indices. This model differs in a number of respects from the three statistical catch-at-age models. It assumes no error on the catch-at-age or CPUE data and fits the terminal fishing mortality exactly to the final year of the CPUE tuning data. The fishing mortality on the final age in each year is assumed equal to the mean of the three younger ages in the same year. Once the fishing mortalities in the final year have been estimated, the remaining age and year specific fishing mortalities and population numbers are calculated using the Baranov catch equations given in Darby & Flatman (1994).

4. RESULTS AND DISCUSSION

4.1 Variable weight-at-age

The sensitivity of the results to the incorporation of variable weight-at-age is shown in Figure 2. Use of the annual weight-at-age resulted in a 10% reduction of historic biomass and a 5% reduction in current biomass (Table 8). The changes appear to be a result of the relatively light weight-at-age of the dominant plus group in 1979 and 1980, and the relatively light weight-at-age of the dominant 1991 year class more recently (*see* Table 6). Future assessments will incorporate annual weight at age for each stock.

4.2 Inclusion of the recruitment indices

The sensitivity of the results to the inclusion of the 2 year old acoustic index is also shown in Figure 2 and Table 8. This resulted in a slight increase to historical biomass but a 10% increase in current biomass. This is probably because of the large numbers of 2 year olds in each of the acoustic surveys. Indices of recruitment from the acoustic surveys will be used in future assessments of all southern blue whiting stocks.

4.3 “Equilibrium” model

The biomass trajectory from the non-equilibrium (base case) model is compared to the equilibrium model in Figure 3. Historical biomass is considerably lower in the equilibrium model but current biomass is substantially higher. However, the fit to the large observed plus group in 1979 in the equilibrium model (not shown) was particularly poor.

To try and address the problem of the poor fit to the large plus group the model was taken back to 1970. The biomass trajectory from the equilibrium and non-equilibrium models are similar from 1979 to 1996 (Figure 4). However, the trajectory before 1979 is very sensitive to the number of extra year classes being estimated. When no additional year classes were estimated the biomass increased gradually to about 200 000 t by 1970. When five year classes were estimated the biomass increased steeply to 350 000 t in 1970. When all nine year classes were estimated the biomass increased back to 1972, and then dropped sharply to 100 000 t. The reason for this behaviour is the large plus group in the catch-at-age data in 1979. When no extra year classes are being estimated, the model provides a poor fit to this plus group. When five extra year classes are estimated their year class strength is low because the fish are present in only small numbers in the catch-at-age, so the virgin recruitment must be increased and the earlier biomass is correspondingly higher (Figure 5). When nine year classes are estimated, the model estimates the first (1968) year class to be extremely high so that it fits the observed size of the plus group in the catch-at-age data much better. This results in a large increase in biomass as this year class recruits into the fishery, followed by a decline as it is fished out and subsequent recruitment is low.

An additional model run was made using a plus group at age 20 (*see* Figures 4 and 5). This smoothes out the effect of the sudden increase in biomass by spreading the recruitment over a number of year classes (from 1965 to 1968). However, it still builds up the early 1970s biomass to a very large value. To determine whether this was a result of the assumed large catches taken during the 1970s the analysis was rerun assuming that the Campbell catch was only 25% of the total. The resulting biomass trajectory was essentially the same.

There is also uncertainty over the catch-at-age data. Between 1979 and 1985 samples were small and came from a single vessel each year (Hanchet *et al.* in press) and may not be representative of the commercial catch. However, the trends appeared to be consistent throughout that time period and the size distribution for 1986 was very similar between the single vessel which had been the source of the data between 1981 and 1985 (*Shinkai Maru*) and the other observer data (Hanchet 1991a). Furthermore, research trawls carried out on the Campbell Plateau by the *Kaiyo Maru* in December 1970/January 1971 caught southern blue whiting with a strongly unimodal size distribution with a peak at 39–40 cm (Hanchet, 1991a). Ageing suggested these fish were mainly age 4 and 5 (Anon. 1972), which corresponds to the 1965 and 1966 year classes. This is consistent with the strong 1963–66 year classes estimated in the equilibrium model (*see* Figure 5). The slow growth of this year class can also be tracked from 1975 to 1978 in length frequency figures from Japanese surveys (Hanchet 1991b, Anon. 1978), and is consistent with the small mean weight (and length) at age in the older fish during the early 1980s (*see* Table 6). Given the slow growth rate observed in the strong 1991 year class, it is likely that these year classes were exceptionally strong. The question is, how strong?

Unfortunately no reliable data are available on the relative abundance of southern blue whiting during the 1970s. Shpak (1978) gave estimates of stock size ranging from 111 000 t – 1 240 000 t between 1972 and 1976. His estimates appeared to be based on scaling up catch per unit effort data and some acoustic surveys, although the details are not given. Francis & Fisher (1979) analysed the results of several exploratory fishing cruises made by *Shinkai Maru* between 1975 and 1977. Mean catch rates were calculated by $\frac{1}{2}^\circ$ square of latitude and longitude, and 200 m depth range, standardised to the commercial fleet, and then scaled up to the total area. Wingspread biomass estimates of southern blue whiting were 808 000 t. However, as the authors note, the fishing by *Shinkai Maru* was not carried out in a random or systematic manner, and so the resulting estimates could be biased upwards. Trawl surveys by *Shinkai Maru* in 1982 and 1983 used a stratified random survey design (van den Broek *et al.* 1984, Hatanaka *et al.* 1989), and are therefore not comparable.

Although uncertainty remains over the precise strength of the early strong year classes, the results of the equilibrium model are useful in providing a stock trajectory for the early part of the fishery

4.4 Comparison of models

The biomass trajectories and recruitment estimates for the sSPA, snapper, and hoki models and the Laurec-Shepherd tuned VPA are shown in Figures 6 and 7. The patterns of year class strength are very similar between the models with all models identifying the strong 1979, 1980, and 1991 year classes (Figure 7). The biomass trajectories for the models since 1983 are also reasonably consistent, with a decline to 1993 followed by an increase to 1995. However, the models diverge strongly before 1983. The sSPA and snapper models have a similar trajectory back to 1979. The hoki model estimated a lower initial biomass with stronger early year class strengths, whilst the VPA estimated a higher initial biomass with weaker early year class strengths, compared to the other models.

The sSPA and snapper models are very similar, both using maximum likelihood to estimate the initial population numbers and subsequent recruitment, so it is not surprising that they give similar biomass trajectories and estimates of year class strength. The slight differences in results can probably be attributed to the way the catch-at-age data are treated (they are fitted as a multinomial distribution in the sSPA), and the estimation of annual deviations in selectivity (for ages 2 and 3) in the sSPA model. These features have been used in the sSPA model because of the operation of the fishery and the nature of the catch-at-age data.

The VPA estimated a higher initial biomass but a lower current biomass than the other models. However, this model was tuned only to the CPUE data, and so did not incorporate the large increase in relative abundance shown by the acoustic indices. When the acoustic data were omitted from the snapper model the current biomass dropped to about 80 000 t. The main limitations of the “packaged” version of the VPA continues to be those identified by Hanchet *et al.* (in press); (i) there are likely to be errors in the catch-at-age, CPUE, and landings data, (ii) the time series of adult and pre-recruit biomass estimates from acoustic surveys cannot be used, and (iii) confidence intervals cannot be estimated. Nevertheless, the general agreement in biomass and year class strength between the VPA and sSPA is encouraging.

The divergence between the sSPA and hoki models in the initial biomass can be partly explained by the way the initial population is estimated by the two models. The hoki model assumes that the initial population is at equilibrium whereas the sSPA estimates the numbers at age in the initial population. It was seen in Section 4.3 that the use of the sSPA equilibrium model resulted in a 20% reduction in initial biomass, and using the current data set the resulting initial biomass was 104 000 t. However, this value is still over double that estimated by the hoki model. Another difference between the models is the use of the least squares in the estimation procedure. Cordue (1998) carried out simulation studies to evaluate alternative stock reduction estimators in the west coast hoki stock. He concluded that the maximum likelihood estimator often performed better when estimating year class strengths, but its performance was worse at higher levels of virgin biomass. The least squares estimator had a more consistent performance, being better than the maximum likelihood estimator for virgin biomass and not much worse for year class strength. Without carrying out studies using simulated southern blue whiting data it is difficult to know how his findings relate to the current study.

In summary, whilst the convergence of the biomass trajectories in all the models since 1984 is encouraging, the divergence of biomass trajectories before then is somewhat disturbing. The reason for this divergence is unclear but indicates there is a great deal of uncertainty about historic biomass. This uncertainty is not reflected in recent assessments of the southern blue whiting stock (e.g., Hanchet & Ingerson 1996, Hanchet 1997) where the confidence bounds on historic biomass have been unrealistically tight. Clearly the catch-at-age data by themselves provide little information without an abundance index and the uncertainty in the initial biomass is ultimately due to the lack of tuning data before 1986. It is important to carry out simulation studies (such as those by Patterson & Kirkwood 1995, Cordue 1998), with known statistical assumptions about the observations, to determine which models and/or estimators are most appropriate for modelling southern blue whiting stocks.,

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Table 1: sSPA model input parameters and sensitivity tests

Parameter	Base case	Sensitivity
M	0.2	–
Acoustic adult index	absolute	–
Acoustic <i>c.v.</i>	0.3	–
Catch-at-age sample sizes	100	–
Catch-at-age data	1979–96	–
Ages for which selectivity allowed to vary annually	2, 3	–
CPUE data	NF	–
Weight at age	constant	variable
Acoustic 2+ index	NF	fitted
Acoustic 2+ <i>c.v.</i>	–	0.5
sSPA model used	non-equilibrium	equilibrium

Table 2: The catch history of the Campbell Island stock used in the modelling

Season	Catch (t)
1971	6 373
1972	15 810
1973	29 720
1974	25 859
1975	1 457
1976	10 466
1977	16 199
1978	6 403
1979	25 305
1980	12 828
1981	5 989
1982	7 915
1983	12 803
1984	10 777
1985	7 490
1986	15 252
1987	12 804
1988	17 422
1989	26 611
1990	16 542
1991	21 314
1992	14 208
1993	9 316
1994	11 668
1995	10 436
1996	16 504

Table 3: Catch-at-age (years) matrix for the Campbell Island Rise (in '000s) from 1979 to 1996, with a plus group at age 20. Also given is the numbers at age for a plus group at age 11

	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996
2	389	43	1 508	1 940	934	45	296	813	689	2 617	192	838	150	2 558	577	1 363	135	301
3	979	247	91	7 599	10 626	1 113	130	2 975	4 342	5 238	10 340	4 649	30 548	506	6 616	33 854	3 098	2 391
4	9 497	584	205	1 153	7 713	5 262	1 604	1 381	4 563	5 226	6 093	14 870	6 983	13 262	761	2 671	23 791	6 419
5	3 036	1 367	177	479	330	6 188	3 739	1 642	589	4 118	5 078	2 630	6 353	3 997	5 327	176	1 266	25 792
6	711	183	565	256	428	780	3 037	6 035	1 218	118	5 027	1 934	1 709	3 936	1 336	1 496	66	484
7	418	612	248	1 231	336	554	186	5 887	4 293	1 596	391	1 779	1 132	440	1 866	277	927	115
8	3 241	460	116	197	1 154	471	103	775	3 454	6 059	2 224	278	556	485	260	632	148	534
9	391	721	434	169	268	1 143	181	438	390	3 012	6 446	527	244	338	219	57	471	113
10	949	91	403	401	0	365	395	635	299	187	4 316	1 383	432	59	131	30	33	130
11	1 969	680	120	513	596	106	195	676	287	436	1 333	1 188	704	202	58	15	28	52
12	3 582	1 366	363	224	429	149	108	215	388	174	239	248	440	133	36	0	16	17
13	3 577	1 408	606	134	0	557	498	337	157	440	564	51	200	155	172	0	5	21
14	5 770	2 459	643	274	136	210	361	354	262	172	321	243	92	97	54	59	6	1
15	7 422	4 188	996	422	472	263	283	479	275	357	350	229	58	0	19	14	54	16
16	2 008	2 436	1085	206	448	198	132	284	224	435	56	32	95	0	6	9	5	22
17	538	2 039	1 146	1 126	572	191	267	314	144	232	370	0	34	45	5	5	0	18
18	0	748	723	1 228	1 808	267	24	200	112	57	291	145	64	28	20	0	0	0
19	0	0	133	450	710	687	192	687	77	26	1	64	55	0	1	0	0	0
20+	0	0	83	177	454	1 068	548	1 682	994	426	129	127	19	0	39	0	11	0
11+	24 869	15 326	5 898	4 754	5 626	3 696	2 608	5 228	2 920	2 755	3 654	2 327	1 761	664	410	107	128	150

Table 4: Biomass (t) and c.v. (%) of adult and pre-recruit and numbers of pre-recruit ('000s) southern blue whiting from acoustic surveys of the spawning and nursery grounds on the Campbell Island Rise

	Adult		Pre-recruit		
	Biomass	cv	Biomass	cv	Numbers
1993	18 500	21	89 600	23	465 000
1994	161 400	36	22 400	38	126 000
1995	121 100	30	20 000	25	104 000

Table 5: Results of standardised CPUE analysis for the Campbell Island Rise

Year	Number of tows	Percentage zero tows	Relative year effect	Standard error	Landings (t)	Relative effort
1986	893	4.6	1.00	—	15 252	15 252
1987	637	5.3	0.68	0.06	12 804	18 829
1988	843	7.1	0.52	0.04	17 422	33 504
1989	1008	4.7	0.53	0.04	26 611	50 209
1990	994	7.8	0.46	0.04	16 652	35 883
1991	1057	3.7	0.35	0.03	21 314	61 072
1992	1091	18.7	0.23	0.02	14 208	62 044
1993	411	10.7	0.61	0.06	9 316	15 272
1994	384	6.8	0.53	0.07	11 290	21 302
1995	170	2.4	0.88	0.13	9 750	11 080

Table 6: Weight at age matrix (kg) for the Campbell Island Rise stock of southern blue whiting used in the modelling

	2	3	4	5	6	7	8	9	10	11
pre 1979	0.205	0.332	0.467	0.538	0.604	0.636	0.692	0.711	0.747	0.768
1979	0.244	0.316	0.446	0.528	0.613	0.593	0.655	0.654	0.616	0.636
1980	0.193	0.325	0.457	0.503	0.544	0.606	0.690	0.622	0.812	0.773
1981	0.208	0.276	0.537	0.512	0.623	0.625	0.721	0.696	0.683	0.744
1982	0.193	0.285	0.446	0.599	0.634	0.652	0.714	0.740	0.771	0.832
1983	0.207	0.314	0.391	0.543	0.576	0.660	0.680	0.755	0.785	0.799
1984	0.193	0.386	0.454	0.531	0.617	0.619	0.694	0.710	0.747	0.756
1985	0.211	0.399	0.480	0.547	0.622	0.679	0.669	0.726	0.759	0.796
1986	0.193	0.356	0.522	0.543	0.599	0.656	0.712	0.786	0.802	0.810
1987	0.212	0.343	0.465	0.568	0.651	0.715	0.763	0.799	0.826	0.845
1988	0.196	0.348	0.488	0.543	0.517	0.702	0.720	0.755	0.954	0.950
1989	0.186	0.342	0.475	0.560	0.673	0.773	0.759	0.783	0.813	0.862
1990	0.144	0.339	0.472	0.580	0.646	0.709	0.788	0.812	0.825	0.858
1991	0.134	0.302	0.490	0.596	0.727	0.784	0.787	0.909	0.899	0.966
1992	0.254	0.351	0.469	0.632	0.717	0.777	0.791	0.831	0.960	0.961
1993	0.150	0.378	0.506	0.582	0.745	0.790	0.863	0.905	0.867	1.001
1994	0.146	0.223	0.515	0.610	0.667	0.804	0.854	0.934	0.939	1.150
1995	0.228	0.278	0.324	0.562	0.620	0.704	0.876	0.822	0.963	0.993
1996	0.219	0.279	0.350	0.407	0.743	0.779	0.811	0.883	0.904	0.977

Table 7: Values for the input parameters to the separable Sequential Population Analysis and other models used in this study. *, both models fitted catch-at-age data assuming a multinomial distribution with a sample size of 100, which equates to a c.v. of about 0.2

Parameter	sSPA	Hoki	Snapper	VPA
M	0.2	0.2	0.2	0.2
Acoustic index	relative	relative	relative	NF
Acoustic c.v.	0.3	0.3	0.3	NF
CPUE c.v.	0.5	0.5	0.5	—
Catch-at-age c.v.	0.2*	0.2*	2.0	—
Selectivity of ages 2, 3, 4	estimated	estimated	0.15, 0.6, 0.95	estimated
Years of catch-at-age data	1979-95	1979-95	1979-95	1979-95
Annual weight at age	constant	constant	constant	constant

Table 8: Relative changes (expressed as percentages) of selected parameter estimates as a result of alternative model assumptions for the Campbell Island stock. B, mid-season spawning stock biomass; $N_{2,1993}$ size of the 1991 year class; GMR, geometric mean of the recruitment of 2 year olds omitting the last three years

Model	B_{1979}	B_{1993}	B_{1996}	$N_{2,1993}$	GMR
Variable wt at age	-15.1	19.5	-4.1	23.9	1.4
Acoustic 2+ index	6.1	0.3	19.5	13.4	2.5
Equilibrium model	-20.6	20.6	16.3	41.4	4.0

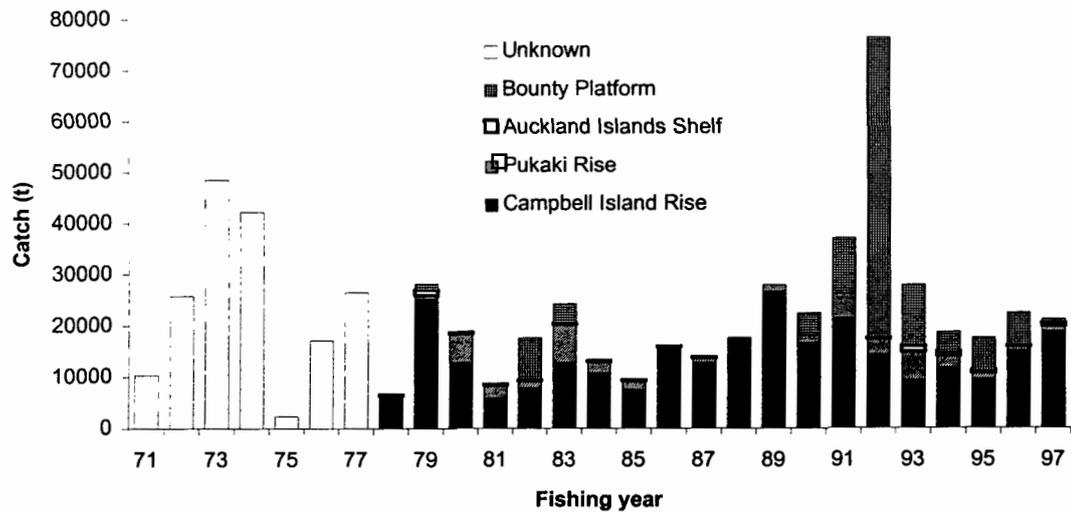


Figure 1: Annual landings of southern blue whiting (t) by the split October-September fishing year. (Note: 95, refers to the 1994–95 fishing year).

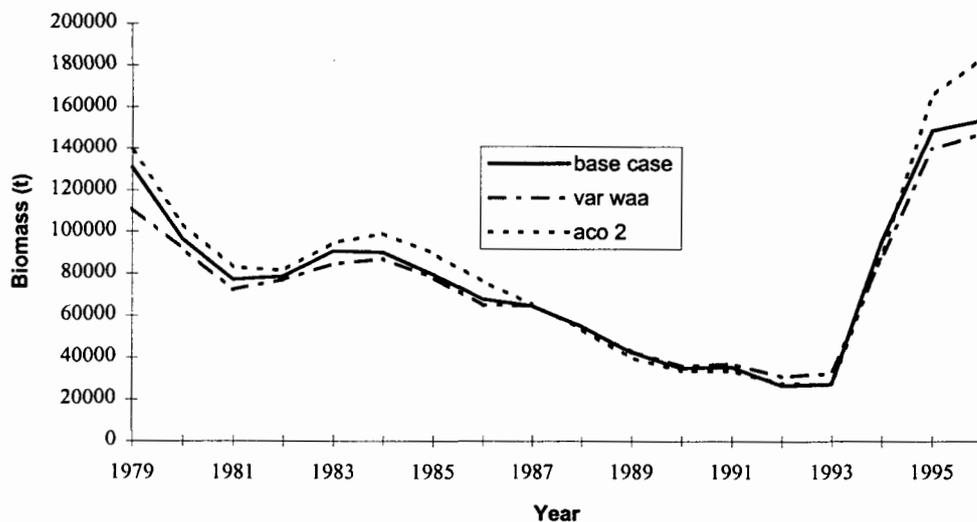


Figure 2: Sensitivity of the Campbell Island spawning stock biomass to the use of variable weight at age (var waa) and the inclusion of 2 year old acoustic index (aco 2) in the sSPA model.

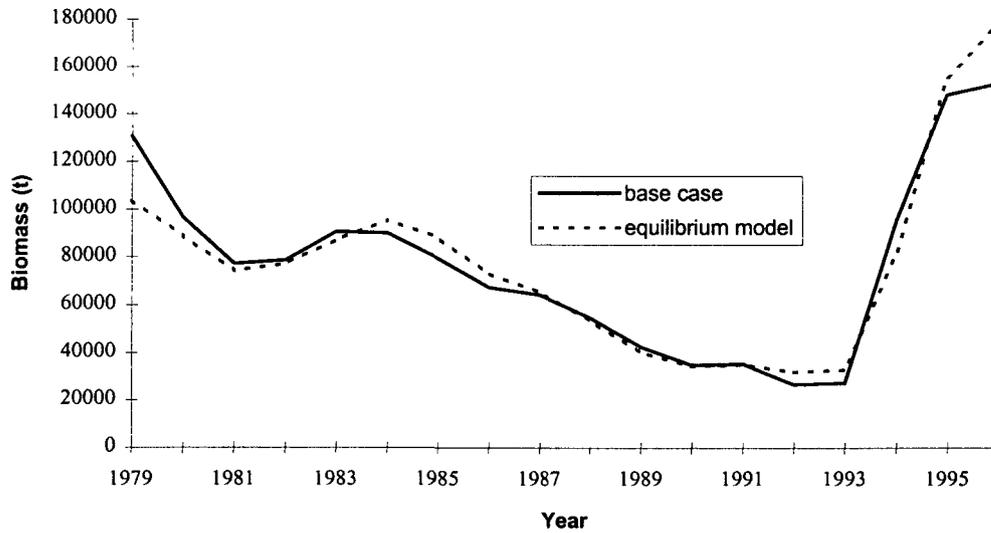


Figure 3: Sensitivity of the Campbell Island spawning stock biomass to the type of sSPA model used.

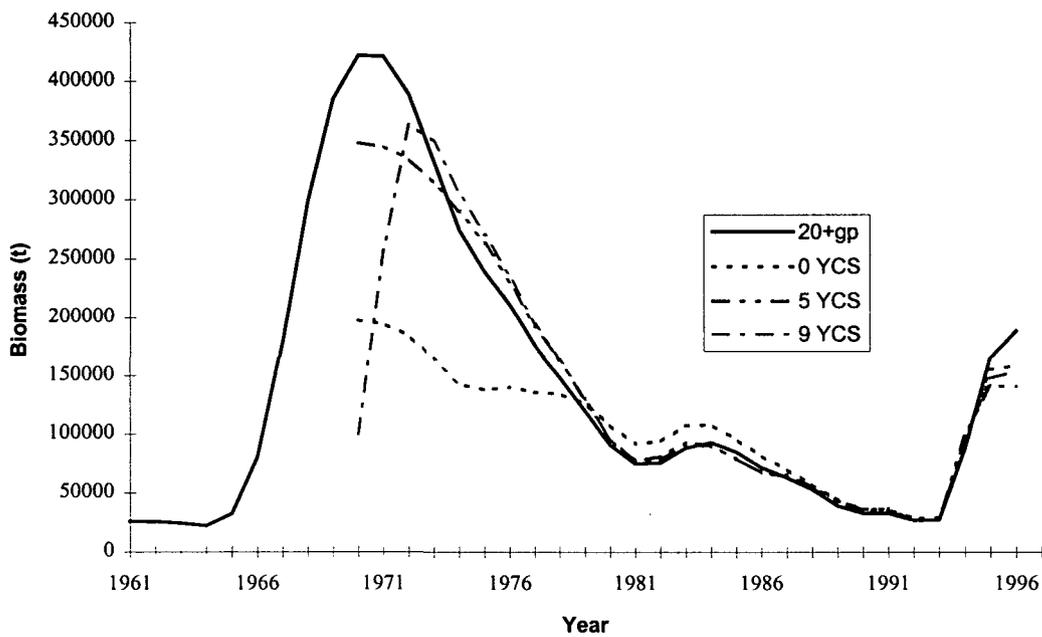


Figure 4: Spawning stock biomass estimates for equilibrium sSPA models with 0, 5, and 9 extra year classes being estimated using a plus group at age 11, and with 19 extra year classes being estimated with a plus group at age 20. Note catch at age data available only for 1979–1996

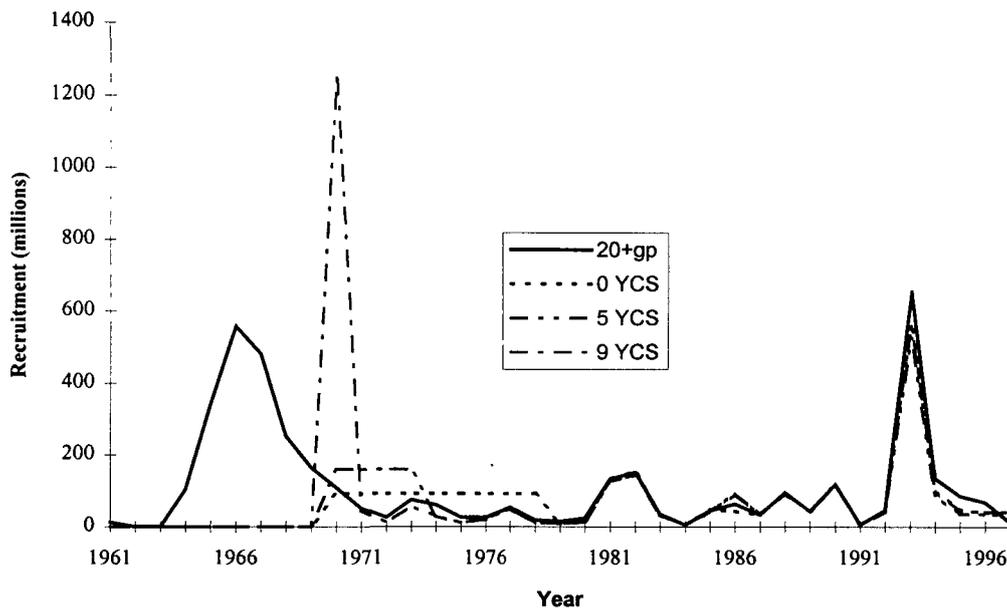


Figure 5: Campbell Island recruitment strengths (number of 2 year olds) for equilibrium sSPA models with 0, 5, and 9 extra year classes being estimated using a plus group at age 11, and with 19 extra year classes being estimated with a plus group at age 20. Note catch at age data available only for 1979–1996.

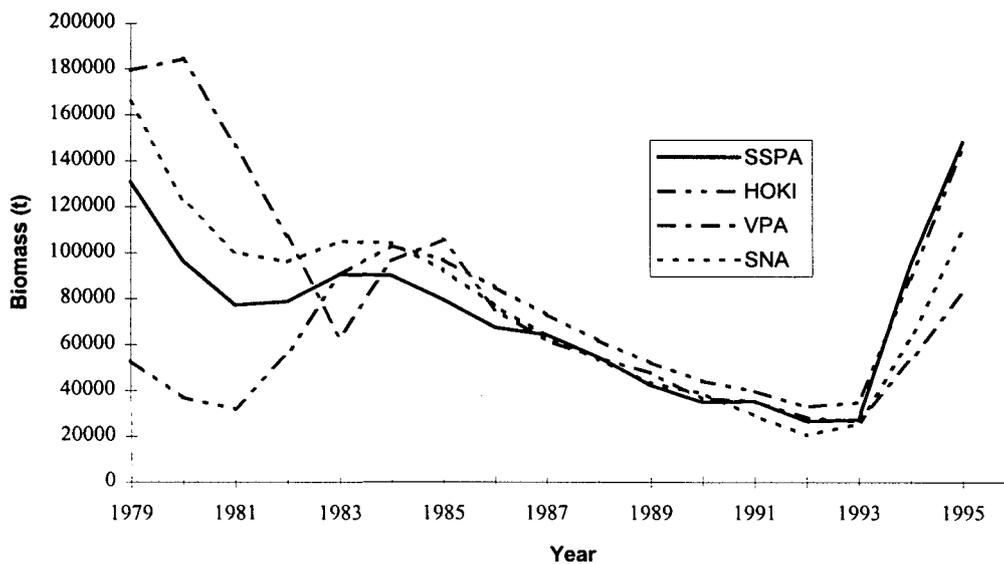


Figure 6: Comparison of Campbell Island spawning stock biomass trajectories between the non-equilibrium sSPA, snapper, and hoki models and the Laurec-Shepherd tuned VPA.

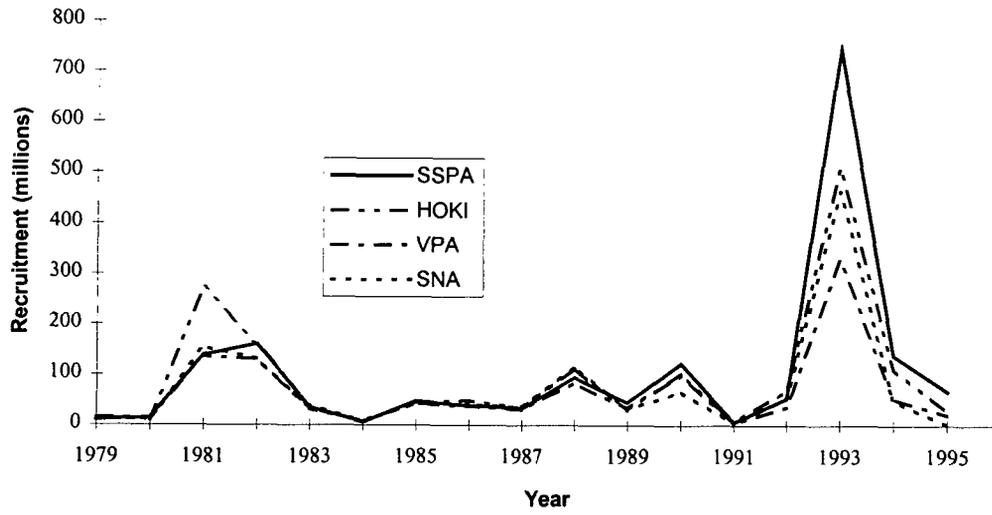


Figure 7: Comparison of Campbell Island recruitment strengths (number of 2 year olds) between the non-equilibrium sSPA, snapper, and hoki models and the Laurec-Shepherd tuned VPA.

Appendix 1: Documentation of the separable Sequential Population Analysis

Model specification

The model developed to analyse the fishery is an extension of the approach outlined by Fournier & Archibald (1982). Errors associated with the observed catch, the proportion-at-age, fishing effort, and the acoustic biomass indices are all explicitly considered in the model. The fit to the total catch and the catch-at-age data are kept separate following Fournier & Archibald (1982), which has allowed incorporation of variability into the age determination process. Because fishing takes place during a very short 2–3 week season in September, at the end of the fishing year, the catch equations assume that 95% of M occurs before fishing starts and the remaining 5% of M occurs during fishing.

The form of the catch equations used in the model is given by the following relationships.

$$C_{ij} = \frac{F_{ij}}{Z_{ij}} [1 - \exp(-Z_{ij})] N'_{ij}$$

$$C_i = \sum_j C_{ij}$$

$$Z_{ij} = F_{ij} + 0.05 M$$

$$N'_{ij} = \exp(-0.95 M) N_{ij}$$

$$N_{i+1,j+1} = \exp(-Z_{ij}) N'_{ij}$$

$$N_{i+1,a} = \exp(-Z_{i,a-1}) N'_{i,a-1} + \exp(-Z_{ia}) N'_{ia}$$

where,

- i indexes year,
- j indexes age class,
- a is the number of age classes,
- C_{ij} is the catch (in numbers) of age class j fish in year i ,
- C_i is the total catch (in numbers) in year i ,
- F_{ij} is the instantaneous fishing mortality rate for age class j in year i ,
- M is the instantaneous natural mortality,
- Z_{ij} is the instantaneous total mortality rate for age class j during the fishing period in year i ,
- N_{ij} is the number of age class j fish in the population at the beginning of year i ,
- N'_{ij} is the number of age class j fish in the population at the beginning of the fishing period in year i ,

Fishing mortality is treated as a function of the observed fishing effort (\tilde{E}_i), catchability (q), and age-specific selectivity (s_{ij}). Preliminary analysis suggested asymptotic selectivity, completed by age 5, so selectivity of age 5 and older was assumed to be 1.0. Because of the potential for targeting new recruits, time dependent changes in age-selectivity were also estimated for ages 2 and 3. A single selectivity parameter is estimated for age 4 fish. The relationships describing observed fishing effort, expected fishing effort (E_i), and fishing mortality are:

$$E_i = \tilde{E}_i \exp(d_i^E)$$

and

$$F_{ij} = q s_{ij} \tilde{E}_i \exp(d_i^E)$$

where,

$$s_{ij} = \exp(l_j + d_{ij}^s)$$

the d_{ij}^s represent deviations from average selectivity at age for $j = 2$ and 3 , and 0 for $j > 3$.

$$l_j = 0 \quad \text{for } 4 < j \leq a$$

and the d_i^E represent deviations in the effort-fishing mortality relationship.

Following Fournier & Archibald (1982) we assume that the age-composition samples adhere to a multinomial sampling distribution and that annual total catch estimates are independent and log-normally distributed. The negative of the log-likelihood function for the catch-at-age model is then

$$-n_i \tilde{p}_{ij} \ln p_{ij} + \sigma_C \sum_i (\ln(\tilde{C}_i) - \ln(C_i))^2 + \sigma_E \sum_i (d_i^E)^2$$

where n_i is the sample size, \tilde{p}_{ij} and p_{ij} are the observed and predicted proportion of fish of age j in year i respectively. \tilde{C}_i is the observed catch in year i , and σ_C and σ_E are standard deviations for catch and effort which are described below. An additional component is added to the negative of the log-likelihood function to tune the model to the acoustic survey biomass estimates. These surveys are conducted during the spawning season and the model is fit to the estimates of adult abundance. The model estimates of spawning stock biomass (B_i) are

$$B_i = \sum_j l_j w_j \exp(-0.5 Z_{ij}) N_{ij}'$$

where w_j is the weight of fish in age class j . In this formulation we are assuming that the average selectivity l_j is synonymous with maturity, which is probably valid for this spawning fishery. We assume the survey abundance estimates are relative and they have a log-normal error distribution. The following term is added to the negative of the log-likelihood function.

$$\sigma_B \sum_{i=93}^{i=95} (\ln(\tilde{B}_i) - \ln(r B_i))^2$$

where σ_B is the standard deviation of the biomass described below, \tilde{B}_i is the adult acoustic biomass estimate in year i , and r is the abundance scalar.

The model was implemented using AD Model Builder software (Fournier 1994), which gave simple and ready access to minimisation routines, and provided the ability to estimate the

variance-covariance matrix for all dependent and independent parameters of interest. The parameters being estimated when minimising the negative log-likelihood function are $\ln(N_{11})$, $\ln(N_{1j})$, d_i^E , d_{ij}^S , l_j , q , and r . The first four groups of parameters are estimated in the model as a vector of deviations from a common mean and constrained so that they sum to zero.

Weightings

It was not possible to estimate the various standard deviations so they were fixed at values that represented our levels of confidence in the various data sets. A convenient way to do this was in terms of weights where $w_x = \sigma_x^{-2}$, for each variate x , and the corresponding *c.v.s* are given for each dataset considered. An estimate of the confidence came from a consideration of both the estimated variance and possible bias inherent in the data. Where appropriate, weights were assigned different values between years.

Annual catches appear to be well estimated in this fishery and so a weight equivalent to a *c.v.* of 5% was given to each year's catch.

Weights were assigned to the proportion-at-age based on the sample size in a multinomial distribution. The amount and precision of data collected from this fishery suggests a sample size of about 300 may be warranted (Hanchet & Ingerson 1996). However, the standard multinomial sampling process is not robust to violations of assumptions (Fournier & Archibald 1982). A number of factors including ageing error, sampling bias, and non-conformity with the model assumption of separability would all lead to the sample size being inflated relative to the true deviations of predicted versus observed proportions-at-age. The sample size was therefore reduced to 100 in the model.

The earlier data (pre-1986) are much less reliable than more recent data because only one vessel was sampled each year, and there were fewer length-frequencies taken and otoliths collected and read. Therefore, the sample size was adjusted between years by the proportion of tows made in that year compared to the median number of tows in the series following Cordue (1993):

$$n_i = n(t_i / t_{med})$$

where, n_i is the sample size in year i , n is the sample size, t_i is the number of tows sampled in year i , and t_{med} is the median number of tows in any year in the series.

A weight of 5 (equivalent to a *c.v.* of 30%) was used for each acoustic data point which is consistent with the average of the *c.v.s* from the surveys. There is no reason to believe that the biomass was better estimated in any of the years, since each estimate was based on two surveys, so the indices were given equal weighting for each year.

The standard errors of the CPUE indices estimated by the general linear model were quite low, suggesting a high weighting (*see* Table 2). However, because of the highly aggregated nature of the fishery, it was considered that the CPUE series may not be accurately monitoring abundance and that it should have a lower weighting than the acoustic indices. Therefore, the weight for the effort data was assigned a value of 2, which is equivalent to a *c.v.* of 50%.

Appendix 2: Changes to the sSPA

Catch in weight and variable weight at age

Catch was calculated in terms of weight rather than numbers, so the catch equation becomes:

$$C_{ij} = \frac{F_{ij}}{Z_{ij}} \left[1 - \exp(-Z_{ij}) \right] N'_{ij} w_{ij}$$

and the model estimate of biomass becomes:

$$B_i = \sum_j l_j w_{ij} \exp(-0.5 Z_{ij}) N'_{ij}$$

Inclusion of recruitment indices

The following term was added to the objective function:

$$\sigma_R \sum_{i=93}^{i=95} \left(\ln(\tilde{N}_{ij}) - \ln(s N_{ij}) \right)^2 \quad \text{for } j = \text{age 2}$$

where, σ_R is the standard deviation of the recruitment index, \tilde{N}_{ij} is the recruitment index in year i , and s is the abundance scalar.

The equilibrium model

The initial age structure is assumed to be:

$$N_{0j} = R_0 \exp^{-M(j-1)} \quad \text{for } 1 \leq j \leq a-1$$

and for the plus group

$$N_{0j} = R_0 \exp^{-M(a-1)} / (1 - \exp^{-M}) \quad \text{for } j = a$$

where,

$$R_0 = R \cdot \bar{N}_{i1}$$

where, $\log R$ is a scalar estimated by the model,

$$\log \bar{N}_{i1} = \frac{\sum_{i=Ryrs}^{i=nyrs-3} \log N_{i1}}{(nyrs - 3 - Ryrs + 1)}$$

where, $Ryrs$ is the first year where year class strength is estimated, and $nyrs$ is the number of years in the model.