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EXECUTIVE SUMMARY

Smith, A.D.M.; Punt, A.E.; Wayte, S.E.; Starr, P.J.; Francis, R.I.C.C.; Stokes, T.K.; Hilborn, R.; Langley, A. (2002). Stock assessment of the northeast Chatham Rise orange roughy for 2001.

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This report provides assessment results for the orange roughy stock on the northeast Chatham Rise, including the major spawning grounds to the north of the Chatham Rise and other grounds at the eastern end of the Rise. The assessment estimates the parameters of the growth curve within the assessment. It also uses new data on age-frequency, length-at-age, and trends in catch-rates, as well as revised acoustic estimates. The catches, trawl survey indices, acoustic estimates, and catch rates used in this assessment are the same as those used by Francis (2001). However, Francis (2001) does not use the age-frequency or the length-at-age data directly, and uses mean lengths rather than survey and observer length-frequencies.

The base-case assessment fits all the data sets reasonably well, with no evidence for major model mis-specification. The results show that the age-at-50%-recruitment is larger than the age-at-50%-maturity. Mature biomass slightly exceeds recruited biomass, but there is no evidence for a large pool of mature but unrecruited animals.

The base-case results are broadly similar to those of Francis (2001). Both assessments show similar trends in abundance, and both estimate the stock to be currently above B_{MSY} with high probability. The estimates of MCY and MAY are also similar between the two assessments, but the estimates of CAY are higher in this assessment than in Francis (2001), and results from catch projections are much more optimistic.

The results are sensitive to some of the assumptions and data set choices. In particular, the estimates of current depletion and of yields based on catch projections are considerably more optimistic when all of the data are used and growth is estimated within the assessment. However, the general conclusion that the stock is currently above target reference levels is robust across data set choices and assumptions, a result also found by Francis (2001).

This document represents the final report for a project funded by the Orange Roughy Management Company.

Reference

Francis, R.I.C.C. (2001). *New Zealand Fisheries Assessment Report 2001/41.* 32 p.

1. INTRODUCTION

The northeast Chatham Rise orange roughy stock is found in an area that includes a major spawning area to the north of the Chatham islands (the spawning box) and a series of pinnacles to the east (Figure 1). Orange roughy on the Chatham Rise was assessed and managed as a single stock before 1997, but since then the spawning box and northeast hills area has been treated as a separate stock. Francis (2001a) described the development of the fishery since 1978–79.

The assessments for this stock (along with those for most stocks of orange roughy in New Zealand) have been conducted primarily using the stock reduction method of Francis et al. (1992). For the spawning box/northeast hills area, this approach involved fitting an age-structured population dynamics model to a data set consisting of time series of catches, trawl survey indices, and the mean length of fish sampled during the surveys (Francis 1999). An important and necessary assumption of this approach was that recruitment to the fishery corresponded to the onset of maturity, with the recruitment/maturity ogive estimated from data independently of the assessment. This approach also implied that the recruited biomass and the spawning biomass were identical.

Hilborn et al. (2000) introduced two significant modifications to the assessment method: fitting to the entire length-frequency distributions rather than to mean length, and estimating the recruitment ogive along with the other model parameters rather than assuming it is identical to the maturity ogive. This approach resulted in estimates of the age-at-50%-recruitment substantially in excess of the (assumed) age-at-50%-maturity, implying a large pool of mature but unrecruited fish. These results were regarded as "interesting", but were not used as the basis for setting TACCs in 2000.

Towards the end of 2000, the Orange Roughy Management Company initiated a project to pursue the approach of Hilborn et al. (2000) further. The work was undertaken as a collaborative project by scientists from CSIRO Marine Research, the University of Washington, NIWA, and SeaFIC. This report describes the outcomes of that project. Results are compared with the assessment of the same stock by Francis (2001a) and Hilborn et al. (2000). The results reported in this document are not *identical to those reported in the May 2001 assessment plenary report (Annala et. al. (2001)). This is* because the Bayesian analyses were repeated following the assessment plenary based on a much larger number of MCMC cycles.

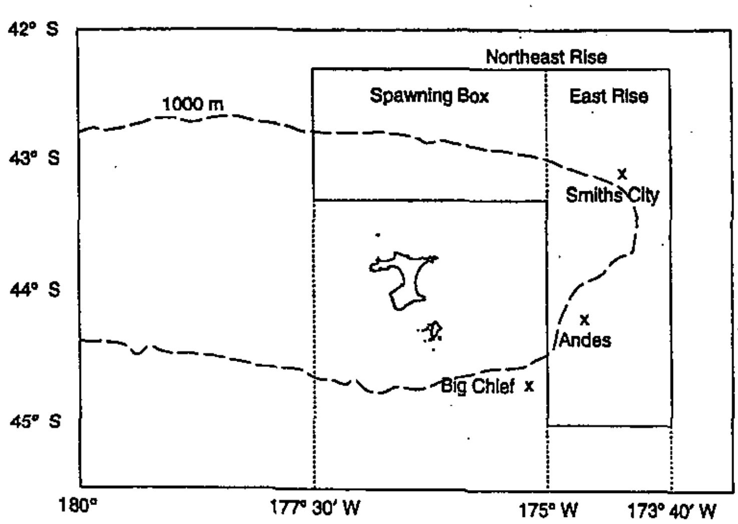

Figure 1: The Chatham Rise, showing the areas considered for the assessments of this report.

2. DATA SOURCES AND METHODS

2.1 Data sources

Several sources of data (catches, catch-rates, trawl survey indices of relative abundance, an estimate of acoustic biomass, length-frequency, age-composition, and length-at-age data) are available for assessment purposes. The catch data (corrected for over-runs due to lost fish and discards, and discrepancies in tray weights and conversion factors) for the spawning box and the northeast hills area of the Chatham Rise are shown in Table 1.

Table 1: Catch history for the spawning box and east hills. All years are from 1 October – 30 September .

Year	Reported catch (t)	Overrun (%)	Total catch (t)
1978-79	11 800	30	15 340
1979–80	29 100	30	37 830
1980–81	16 100	30	20 930
1981–82	17 400	30	22 620
1982–83	5 200	30	6 760
1983–84	16 500	30	21 450
1984–85	19 500	30	25 350
1985–86	21 100	28	27 008
1986–87	22 600	26	28 476
1987–88	15 800	24	19 592
1988–89	19 800	22	24 156
1989–90	17 300	20	20 760
1990–91	12 200	15	14 030
1991–92	13 000	10	14 300
1992–93	4 800	10	5 280
1993–94	4 900	10	5 390
1994–95	4 000	5	4 200
1995–96	3 800	5	3 990
1996–97	3 600	5	3 780
1997–98	4 600	5	4 830
1998–99	3 600	5	3 780
1999–2000	4 600	5	4 830

Two sources of information on relative abundance are available (trawl survey indices and catch-rates): the two relative abundance series with their associated sampling coefficients of variation (c.v.s) are given in Table 2. The trawl survey indices are the standard series used in past assessments (Francis 1999), while the catch-rate series represents the results of the application of Generalised Linear Modelling techniques to the orange roughy catch and effort data for the spawning box (Langley 2001). Sensitivity is explored to splitting the catch-rate series into two series (1983–92 and 1996–99), as in recent years there has been a considerable change in the configuration of the fleet, the operation of the fishery, and the intensity of fishing effort (Langley 2001). The higher trawl survey index (61 000 t) for 1994 is used for the bulk of the analyses.

The squared c.v.s used in the analyses are based on inflating the squares of the c.v.s in Table 2 by 0.2^2 and 0.17^2 (trawl surveys and catch-rates respectively) to account for additional uncertainty associated with use of the data in Table 2 as indices of relative abundance (Francis et al. 2001, Francis 2001b).

Table 2: The two relative abundance series and the time series of mean lengths with their associated 'sampling' coefficients of variation (c.v.).

Year	Trawl survey	c.v.	CPUE	c.v.	Mean length	c.v.
1983			1.000	0.10		
1984	130 000	0.17	1.018	0.10	34.72	0.0077
1985	111 000	0.15	1.087	0.10	34.78	0.0044
1986	77 000	0.16	0.749	0.10	34.65	0.0059
1987	60 000	0.15	0.713	0.09	35.27	0.0042
1988	73 000	0.25	0.665	0.10	34.59	0.0073
1989	54 000	0.18			34.84	0.0068
1990	34 000	0.19	0.423	0.10	34.35	0.0063
1991			0.445	0.10		
1992	22 000	0.34	0.392	0.12	34.95	0.0107
1993						
1994	61 000 or 21 000	0.67			33.87	0.0137
1995						
1996			0.777	0.13		
1997			0.904	0.13		
1998			0.609	0.14		
1999			0.436	0.16		

Acoustic estimates of biomass can be derived from two surveys conducted during 1998 and one survey during 2000. These surveys covered different areas but have been combined to produce four estimates (which are assumed to apply to 1999) based on different assumptions regarding target strength and background density (Doonan & Bull 2001). For the bulk of the analyses of this report, the highest and lowest estimates were averaged to produce a single value (142 000 t), although sensitivity is explored to instead basing the assessment on the highest and lowest estimates (123 000 t and 161 000 t respectively). The c.v. for these estimates (0.16) seems unrealistically low given the assumptions underlying the method of estimation. Therefore, the c.v. assumed for the acoustic estimates of biomass is (arbitrarily) set equal to 0.4.

Length-frequency data for orange roughy in the spawning box are available from nine research surveys and from observer data in the MFish Scientific Observer database (see Table 2 for the mean lengths from these surveys). Hilborn et al. (2000) detailed the approach used to obtain the observer length-frequency distributions used for the analyses of this report. *Inter alia*, this involved restricting the data to those from the spawning box and excluding the data for 1992–93 (considered atypical, possibly reflecting the low numbers of tows sampled in that year – Hilborn et al. (2000)). Information on length-at-age is available from the 1984 and 1990 surveys.

Age-composition data by sex are available from the 1984 *Otago Buccaneer* survey of the spawning box. Fish over 24 cm long are the only ones used in this calculation because the otolith sample was restricted to fish of this length. The estimated number of fish of age a and sex s in the survey area, N_a^s, is estimated by:

$$N_a^s = \sum_j \sum_{i \in S_j} W_i n_{a,i}^s \tag{1}$$

where W_i is the weight assigned to survey station i (which is in survey stratum j):

$$W_i = A_j c_i / (m_j w_i) \tag{2}$$

$n_{a,i}^s$ is the number of aged fish from station i that are of sex s and age a,

A_j is the area of stratum j,

c_i is the catch-rate (kg.km^{-2}) for station i (based on fish of length $\geq$ 24 cm),

m_j is the number of stations in stratum j,

S_j is the set of stations in stratum j,

w_i is the weight (kg) of aged fish from station i (calculated from the lengths of the aged fish and the length-weight regression $W(\text{kg}) = 9.63 \times 10^{-5} L(\text{cm})^{2.68}$).

The effective sample sizes for the survey length-frequency data (Table 3) are determined using the approach outlined by Francis et al. (1992, 1993), and the sample sizes for the observer length-frequencies are based on the sample sizes in table 7 of Hilborn et al. (2000). For the years for which there are both survey and observer length-frequency data, the effective sample sizes for the latter are calculated by multiplying the actual sample sizes for the observer length-frequency data by the ratio of the effective to the actual sample sizes for the survey length-frequency data. The effective sample sizes for the observer length-frequency data for the remaining years are calculated by multiplying the actual sample sizes by 0.01 (the average of the ratios of effective to actual sample sizes for the survey length-frequency data for the years in which there are both survey and observer length-frequency data). The effective sample sizes for the age-composition data based on the algorithm used to determine the effective sample sizes for the survey length-frequency data are 34 and 24 (males and females) respectively. However, these samples sizes are multiplied by 10 to increase the emphasis placed on these data. Sensitivity tests examine the implications of not increasing the effective sample size for the age-composition data.

Table 3: Effective sample sizes for the length-frequency data.

Year	Survey length-frequency data		Observer length-frequency data	
	Males	Females	Males	Females
1984	68	47	-	-
1985	182	154	-	-
1986	100	95	-	-
1987	167	199	21	28
1988	51	65	-	-
1989	46	80	30	33
1990	87	80	44	40
1991	-	-	26	26
1992	34	32	-	-
1993	-	-	-	-
1994	28	12	-	-
1995	-	-	-	-
1996	-	-	34	26
1997	-	-	8	7
1998	-	-	19	18

The weight applied to each length-at-age data point is given by W_i (see Equation 2).

2.2 The population dynamics model and the likelihood function

The population dynamics model (Appendix A) is virtually identical to that used for previous assessments of Chatham Rise orange roughy (Francis et al. 1995, Francis 1999). The key difference, in common with the model used by Hilborn et al. (2000), is that the age-specific probabilities of being recruited to the fishery, and of being selected during the trawl surveys, are not forced to be the same as those of being mature. Instead, the parameters of logistic functions that define the probability of being recruited to the fishery and to the trawl survey are estimated as free parameters of the model.

The abundance indices are assumed to be independently and identically distributed about the corresponding model quantities (see Section 1 of Appendix B) while the mean length data are assumed to be relative indices of the model-predicted mean length of the catch. The length-frequency and age-composition data are included in the likelihood function based on the robust likelihood formulation of Fournier et al. (1998). This formulation is modified so that the variance depends on the observed rather than the predicted proportions because this leads to less biased estimates (M. Maunder, IATTC, pers. commn)

Length-at-age is assumed to be log-normally distributed about the von Bertalanffy growth equation (see Section 5 of Appendix B).

2.3 Parameter estimation

Results are summarised by the mode of the posterior density function (the MPD estimates) and by full Bayesian posterior distributions. Table 4 lists the parameters for the base-case analysis. The value for the parameter that defines the width of the recruitment ogive, S_r, was fixed at 5 for the calculations in which the age-composition or the length-frequency data are included in the analyses based on preliminary fits of the model. The width of the survey selectivity ogive (see Equation B.5) has also been fixed at 5 for these analyses.

Including the catchability coefficients (nuisance parameters for which closed form solutions exist – Walters & Ludwig (1994)), there are 90 estimable parameters (two selectivity parameters, 79 recruitment deviations, 6 growth parameters, 2 catchability coefficients, and B_0). The performance of the MCMC algorithm used in the Bayesian analyses is improved if the parameters are uncorrelated. The estimates of the growth parameters L_∞^k and K^k (see Equation A.6) were found to be quite highly correlated. The growth curve was therefore reparameterised in terms of length at ages 30 and 60 (L_{30}^k and L_{60}^k). Convergence statistics (not shown, but see below) were substantially improved by this reparameterisation.

The recruitment deviations are bias-corrected when conducting the Bayesian analyses (see Equations A.7 and A.10). However, the bias-correction factors are not applied when conducting the MPD analyses. The rationale for this is that if there were no data (and the historical catches were all zero), the MPD estimate of current biomass should be B_0 rather than $B_0\, e^{-\sigma_R^2}$ which it would be if the bias-correction factors were included in the MPD analyses.

Table 4: The parameters for the base-case analyses. - indicates that the parameter concerned is not included in the model. Priors are provided for the estimated parameters.

Parameter	Symbol	Male	Female	Both sexes	Prior	Source
Natural mortality	M	-	-	0.045 yr^{-1}		
Age-at-50%-recruitment	A_r	-	-	Estimated	U[A_m,100 yr]	
Gradual recruitment	S_r	-	-	5 yr		
Age-at-50%-survey-recruitment	A_s	-	-	Estimated	U[A_m,100 yr]	
Age-at-50%-maturity	A_m	-	-	29 yr		Horn et al. (1998)
Gradual maturity	S_m	-	-	3 yr		Horn et al. (1998)
von Bertalanffy parameters	L^k_{30}	Estimtd	Estimtd	-	U[25, 40 cm]	
	L^k_{60}	Estimtd	Estimtd	-	U[30, 45 cm]	
	t^k_0	0[1]	0[1]	-		
	σ^k	Estimtd	Estimtd	-	U[0, 1]	
Length-weight parameters	a	-	-	0.0000921 kg/cm^3		Francis et al. (1993)
	b	-	-	2.71		
Recruitment variability	σ_R	-	-	1.1		Francis & Robertson (1990); Punt (unpublished data)
Recruitment steepness	d	-	-	0.75		Assumed
Plus-group age	z	-	-	80 yr		
Virgin biomass	B_0	-	-	Estimated	U[0, 2,000,000t]	
Recruitment deviations $\{a=1,2,..,z-1\}$	ε_a	-	-	Estimated	N(0; σ_R^2)	
Catchability coefficients (trawl survey and catch-rate)	q	-	-	Estimated	$\ell n\, q \sim U[-\infty,\infty]$	

The base-case analysis (abbreviation TCA_SOLA[2]) estimates all 90 parameters and uses all of the available data. Sensitivity tests involve modifying the data set choices. Some of these sensitivity tests involve not fitting to the length-frequency, age-composition, or length-at-age data. For these sensitivity tests the parameters that determine the recruitment ogives and the growth curve have to be pre-specified (Table 5).

Table 5: The pre-specified values for the recruitment and growth parameters.

Parameter	Symbol	Male	Female	Both sexes
Age-at-50%-recruitment	A_r	-	-	29 yr
Gradual recruitment	S_r	-	-	3 yr
Age-at-50%-survey-recruitment	A_s	-	-	29 yr
von Bertalanffy parameters	L^k_∞	36.4 cm	38.0 cm	-
	K^k	0.070 yr^{-1}	0.061 yr^{-1}	-
	t_0	-0.4 yr	-0.6 yr	-

The posterior distributions for the quantities of interest to management (and those upon which the projections were based) were determined using the Markov Chain Monte Carlo (MCMC) algorithm (Hastings 1970, Gelman et al. 1995). This method is preferred to the Sample-Importance-Resample (SIR) algorithm (Rubin 1987) as it performs better for assessments based on age- and size-composition data (Punt & Hilborn 1997). The MCMC method is easy to apply but suffers from the

[1] t_0^k was fixed at 0 because otherwise unrealistically large negative values were estimated due to the lack of data at the younger ages.

[2] Indicates that the Trawl survey, Catch rate, Acoustic estimate, Survey length-frequency, Observer length-frequency, Length-at-age, and Age-frequency data are included in the analysis.

problem that it is not possible to prove that it has been run for a sufficiently long period to ensure that it has converged to the posterior distribution. A variety of diagnostic statistics (see Geweke (1992), Raftery & Lewis (1992), and Heidelberger & Welch (1983) for details) and plots (e.g., traces and the correlation between adjacent values in the chain) were used to assess whether convergence had taken place. It should be noted that these statistics and plots only detect failure to achieve convergence, they cannot indicate that convergence has, in fact, occurred.

The Bayesian results are based on 1 400 000 cycles of the MCMC algorithm, the first 400 000 of which were discarded as a 'burn in' period. The remaining 1 000 000 cycles were sampled every 400 cycles to produce 2500 draws from the posterior.

3. RESULTS AND DISCUSSION

3.1 Fits to the data (base-case analysis)

The base-case analysis (abbreviation TCA_SOLA) includes all of the data and estimates all 90 free parameters. Figure 2 shows the fits to the two relative abundance indices and to the acoustic estimate of biomass. The model does not replicate the drop in the trawl survey index from 1984 to 1986 and it also does not match the acoustic estimate of biomass particularly well. The poor fit to the acoustic estimate of biomass is, however, probably a consequence of the high c.v. (0.4) assumed for this data point. The inability to fit the early trawl survey indices is probably a result of different trends over the years 1983 to 1986 for the trawl and catch-rate indices, with the catch-rate indices being given greater weight when fitting the model than the trawl indices owing to their lower (assumed) c.v.s (Table 2, Figure 2).

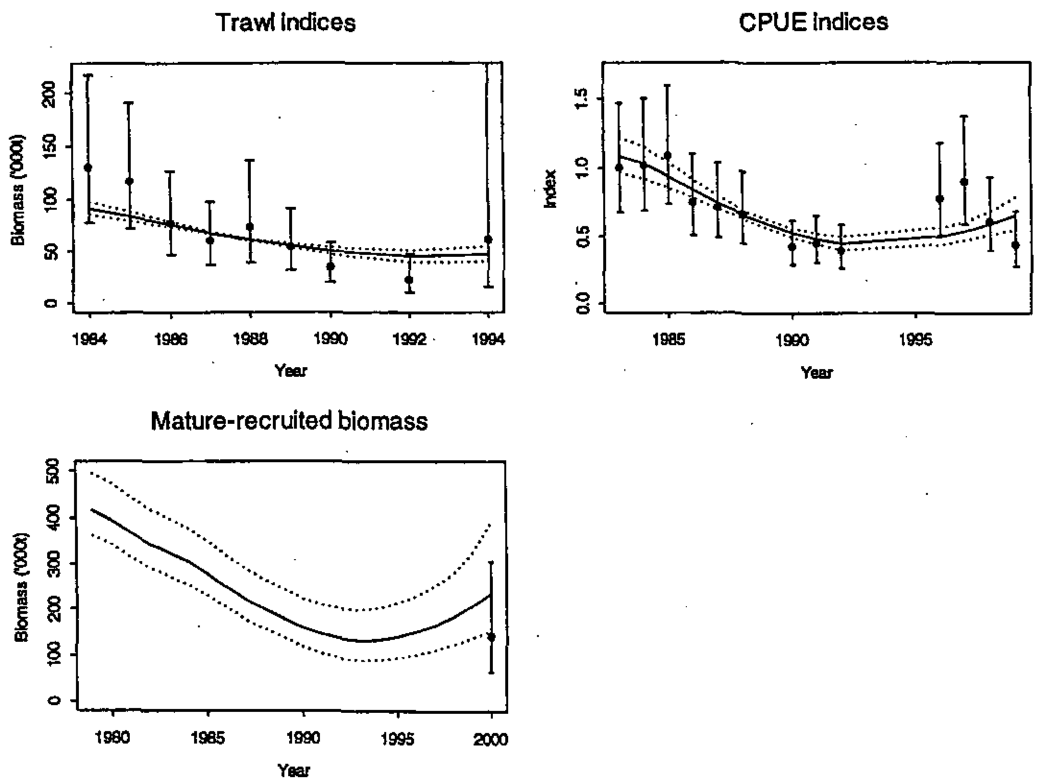

Figure 2: The base-case fits to the trawl and catch-rate indices and to the acoustic estimate of biomass. The solid lines are posterior medians and the dotted lines 90% probability intervals. The whiskers about the data points (solid dots) represent 95% confidence intervals.

The base-case MPD fits to the age-composition and the length-frequency data are shown in Figures 3 and 4 (the full posteriors are not shown as they lead to rather cluttered graphs). The fits to the age-composition data are relatively poor. This is due to inconsistency between the data for the two sexes regarding which are strong and weak year-classes, whilst the model nevertheless assumes a 50:50 sex-ratio at birth. There is no evidence for substantial model mis-specification effects from the fits to the length-frequency data (Figure 4). However, there is a tendency for the model to under-predict the catch of 20–30 cm animals. As expected from the low effective sample sizes for the 1992 and 1994 survey length-frequency data (see Table 3), the fits for these years are relatively poorer than for the remaining years.

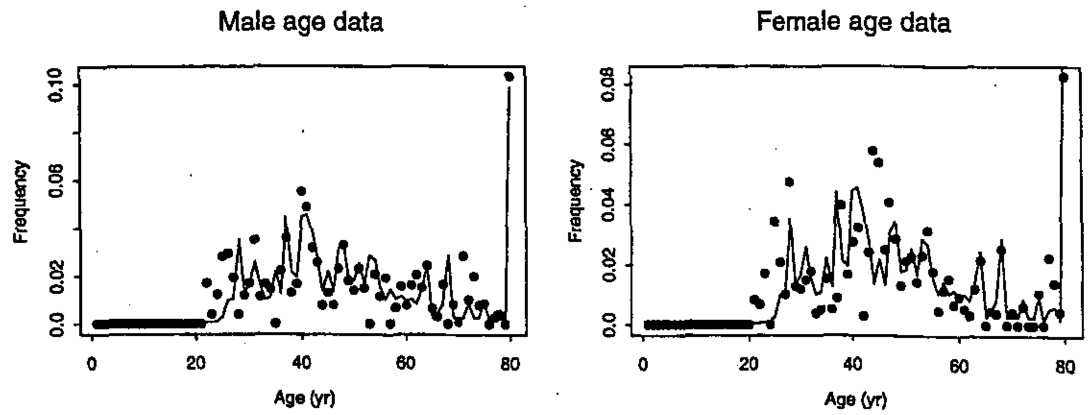

Figure 3: MPD fits (solid lines) to the age-composition data (solid dots) for the base-case analysis.

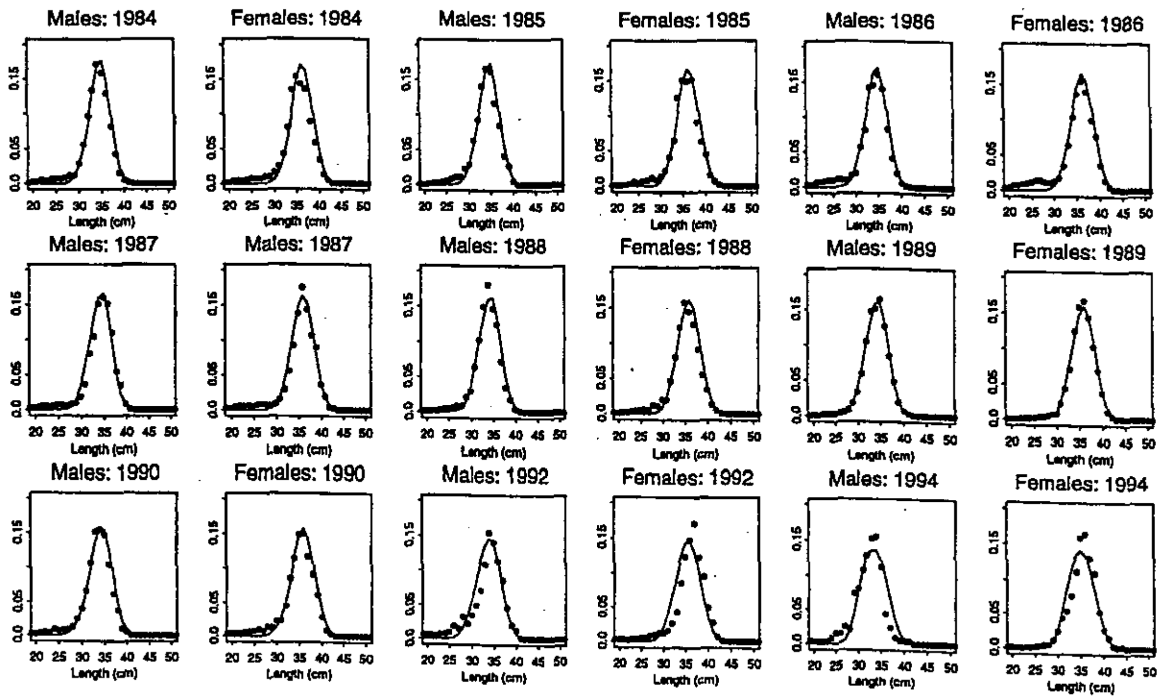

Figure 4(a): Base-case MPD fits (solid lines) to the survey length-frequency data (solid dots).

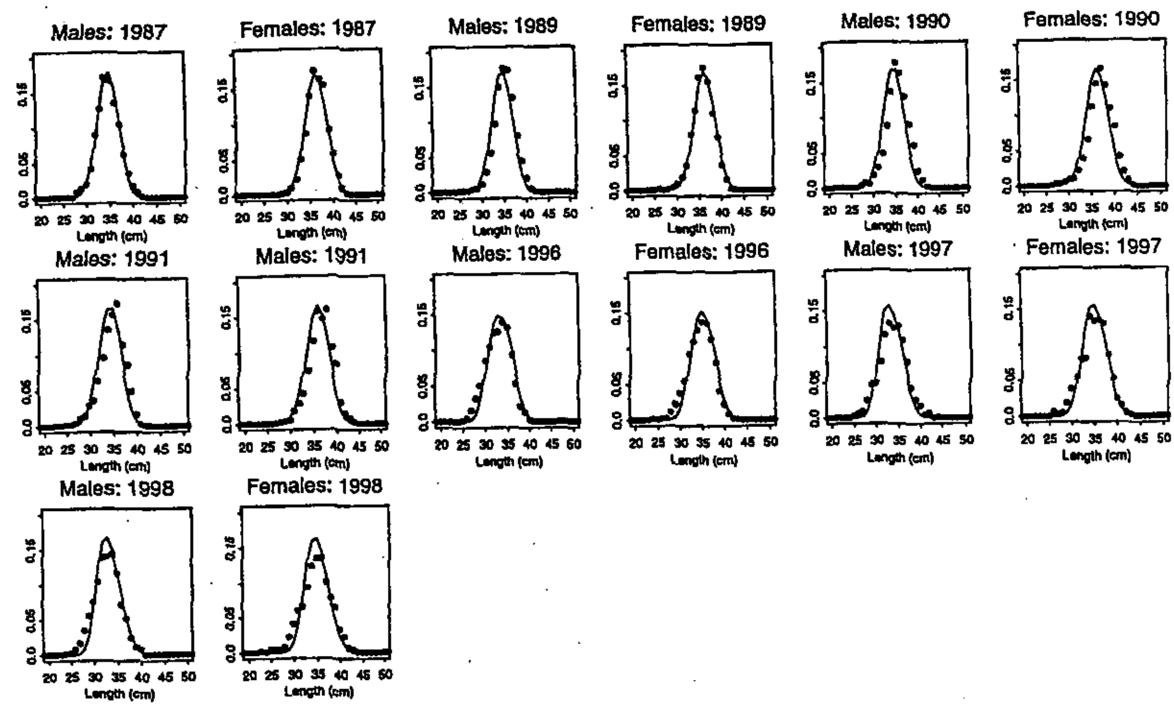

Figure 4(b): Base-case MPD fits (solid lines) to the observer length-frequency data (solid dots).

Figure 5 shows the posterior median and 90% probability intervals for the estimated growth curve (mean length-at-age and individual length-at-age) and the fit to the length-at-age data. For fish aged less than 25 years, the effective sample size is small, and the model fits are poor. For animals larger than 30 cm, the 90% probability intervals for individual length-at-age well represent the length-at-age data.

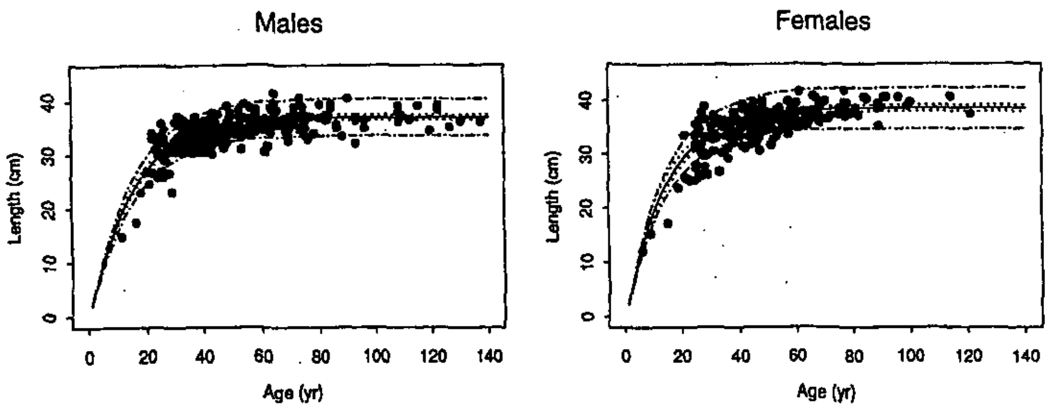

Figure 5: Base-case posterior medians and 90% probability intervals of mean length-at-age (dotted lines) and individual length-at-age (dot-dashed lines), and the length-at-age data used for estimation purposes (solid dots).

3.2 MPD sensitivity tests

Tables 6 and 7 show results for sensitivity tests that involve modifying the choice of data sets included in the analysis. The results in Table 6 are for analyses including at least two of the age-composition, length-frequency, or length-at-age data sets; they therefore include estimates of the parameters of the growth curves and recruitment ogives. The values for parameters of the growth curves are shown in terms of L_∞ and K rather than as the lengths at ages 30 and 60 to ease comparison with the fixed values reported in Table 5. The results shown in Table 7 (except those for the base-case analysis) are for analyses in which the growth and recruitment parameters are fixed (see Table 5). The results reported for each analysis are the estimates of the growth and recruitment parameters; the pre-exploitation, 1978–79, and 1999–2000 biomasses; and the ratios of the 1999–2000 biomass to the pre-exploitation equilibrium and 1978–79 biomasses. Results are shown for both mid-season recruited biomass (Equation B.4c) and mid-season mature biomass (both sexes combined). Also indicated is the contribution of each data source to the negative of the logarithm of the mode of the posterior density function. The results in Table 7 should be interpreted with some caution because the number of data points for the analyses that fix the growth and recruitment parameters is small compared with the number of estimable parameters.

The analyses display a number of general features. All analyses that use the length-frequency data (i.e., all the analyses in Table 6 except for TCA_AL) indicate that the 1978–79 biomass was larger (by between 10 and 16%) than the pre-exploitation equilibrium biomass, B_0. This is because these analyses all suggest that some very strong year-classes (recruitment deviations greater than 1) were present in the population in 1978–79. Such year-classes appear to be needed to retain consistency with the length-frequency information (but not necessarily the mean length data – see analysis TCAM[3] in Table 7). Except for TCA_AL, TA_SOLA, and the analysis in which the catch-rate series is split into two (TC2A_SOLA), the analyses in Table 6 all indicate the recruited biomass in 1999–2000 to be close to or larger than half of the 1978–79 recruited biomass and to be in excess of half of B_0. In contrast, TCA_AL, TA_SOLA, TC2A_SOLA and the analyses that fix the growth and recruitment parameters indicate the recruited biomass in 1999–2000 to be between 36 and 45% of B_0.

Ignoring the length-at-age data has little impact on the results (contrast TCA_SOLA with TCA_SOA in Table 6). Ignoring the age-composition data (analysis TCA_SOL) leads to slightly larger initial biomasses but to essentially unchanged estimates of current biomass. In contrast to the virtual lack of sensitivity to ignoring the length-at-age and age-composition data, ignoring the length-frequency data (analysis TCA_AL) leads to much less optimistic results (lower initial and current biomasses and lower current depletions). A feature of this sensitivity test is the much poorer fit to the acoustic estimate of biomass (a model-estimate of 57 000 t compared to a model-estimate of 123 000 t for TCA_SOLA and the actual estimate of acoustic biomass of 142 000 t). The results for the analyses in which the survey and observer length-frequency data are omitted in turn are intermediate between those for TCA_SOLA and TCA_AL.

Ignoring the catch-rate data (analysis TA_SOLA) leads to less optimistic results and ignoring the trawl survey data (analysis CA_SOLA) leads to more optimistic results. This result is not unexpected given the fits to these data for the base-case analysis (see Figure 2). An analysis (TloCA_SOLA) that replaces the 1994 trawl survey index of 61 000 t by an alternative estimate (21 000 t, c.v. = 0.34) shows little impact on the results. Reducing the effective sample size assumed for the age-composition by a factor of 10 (i.e., assuming effective sample sizes of 34 and 24 for males and females respectively; analysis TCA_SOLA10) leads to a more depleted population. Splitting the catch-rate series into two series (1983–92 and 1996–99) (analysis TC2A_SOLA) leads to the most pessimistic of the results in Table 6 in terms of the depletion of the recruited component of the population, while ignoring length-frequency data (analysis TCA_AL) is most pessimistic in terms of the depletion of the mature component of the population.

Fixing the values for the growth and recruitment parameters (Table 7) leads, in general, to less optimistic results. The depletion levels relative to 1978–79 are in the range 0.37 to 0.50, and 0.38 to 0.57 relative to B_0.

The estimate of the age-at-50%-survey-selectivity is always equal to its lower bound of 29 years (the assumed age-at-50%-maturity). Furthermore, if either the survey length-frequency data or the

[3] Indicates that the Trawl survey, Catch rate, Acoustic estimate, and Mean length data are included in the analysis.

observer length-frequency data are ignored (analyses TCA_OLA and TCA_SLA), the estimate of the age-at-50%-selectivity for the commercial fishery is equal to its lower limit of 29 years.

Table 6: Specifications and results for the sensitivity tests that involve modifying the base-case analysis (TCA_SOLA). Reported biomasses are mid-season values. Biomass units are '000 t.

	Analysis acronym				
	TCA_SOLA	TCA_SOA	TCA_SOL	TCA_AL	TA_SOLA
Data					
Trawl survey indices	yes	yes	yes	yes	yes
CPUE indices	yes	yes	yes	yes	no
Acoustic estimate	142	142	142	142	142
Survey LFs	yes	yes	yes	no	yes
Observer LFs	yes	yes	yes	no	yes
Length-at-age	yes	no	yes	yes	yes
Age frequency	yes	yes	no	yes	yes
Mean length	no	no	no	no	no
Parameters					
A_f, A_s	(30.5, 29.0)	(30.5, 29.0)	(30.6, 29.0)	(29.0, 29.0)	(31.1,29.0)
L_∞^k (m,f)	(36.6, 38.0)	(36.7, 38.0)	(37.0, 38.4)	(36.6, 39.2)	(36.7, 38.1)
K^k (m,f)	(0.072, 0.077)	(0.072, 0.078)	(0.067, 0.070)	(0.069, 0.056)	(0.071, 0.075)
σ^k (m,f)	(0.05, 0.053)	(0.05, 0.053)	(0.048, 0.051)	(0.059, 0.066)	(0.049, 0.052)
Derived parameters					
Recruited : B_0	359	355	390	242	331
Recruited : B_{79}	415	409	430	254	389
Recruited : B_{00}	207	205	207	91	152
Recruited : B_{00}/B_0	0.58	0.58	0.53	0.38	0.46
Recruited : B_{00}/B_{79}	0.50	0.50	0.48	0.36	0.39
Mature : B_0	378	374	412	241	356
Mature : B_{79}	429	423	458	254	408
Mature : B_{00}	251	249	250	93	226
Mature : B_{00}/B_0	0.66	0.67	0.61	0.39	0.64
Mature : B_{00}/B_{79}	0.59	0.59	0.55	0.37	0.56
Likelihood components					
Trawl survey indices	4.45	4.43	4.33	4.01	3.44
CPUE indices	8.53	8.48	8.76	5.53	-
Acoustic estimate	0.35	0.32	0.35	0.95	0.00
Survey LFs	-2976	-2976	-2980	-	-2977
Observer LFs	-2060	-2060	-2064	-	-2062
Length-at-age	12.49	-	12.36	11.55	12.42
Age frequency	-615	-615	-	-633	-613
Mean length	-	-	-	-	-
Rec devs	10.17	10.15	3.82	9.85	11.30
Total	*-5616*	*-5629*	*-5014*	*-601.2*	*-5626*

Table 6 (continued)

	Analysis acronym				
	TCA_SOLA	CA_SOLA	TCAlo_SOLA	TCAhi_SOLA	TCA_OLA
Data					
Trawl survey indices	yes	no	yes	yes	yes
CPUE indices	yes	yes	yes	yes	yes
Acoustic estimate	142	142	123	161	142
Survey LFs	yes	yes	yes	yes	no
Observer LFs	yes	yes	yes	yes	yes
Length-at-age	yes	yes	yes	yes	yes
Age frequency	yes	yes	yes	yes	yes
Mean length	no	no	no	no	no
Parameters					
A_r , A_s	(30.5, 29.0)	(30.7, 29.0)	(30.4, 29.0)	(30.6, 29.0)	(29.0, 29.0)
L_∞^k (m,f)	(36.6, 38.0)	(36.7, 38.1)	(36.6, 38.0)	(36.6, 38.0)	(37.5, 38.6)
K^k (m,f)	(0.072, 0.077)	(0.072, 0.076)	(0.072, 0.077)	(0.072, 0.077)	(0.078, 0.084)
σ^k (m,f)	(0.05, 0.053)	(0.049, 0.053)	(0.05, 0.053)	(0.05, 0.053)	(0.055, 0.057)
Derived parameters					
Recruited : B_0	359	377	357	361	274
Recruited : B_{79}	415	436	410	419	291
Recruited : B_{00}	207	233	198	214	139
Recruited : B_{00}/B_0	0.58	0.62	0.56	0.59	0.51
Recruited : B_{00}/B_{79}	0.50	0.53	0.48	0.51	0.48
Mature : B_0	378	401	374	382	273
Mature : B_{79}	429	453	424	434	291
Mature : B_{00}	251	289	238	263	146
Mature : B_{00}/B_0	0.66	0.72	0.63	0.69	0.53
Mature : B_{00}/B_{79}	0.59	0.64	0.56	0.61	0.50
Likelihood components					
Trawl survey indices	4.45	-	4.33	4.56	3.34
CPUE indices	8.53	8.51	8.50	8.56	7.46
Acoustic estimate	0.35	0.74	0.54	0.20	0.20
Survey LFs	-2976	-2977	-2976	-2976	-
Observer LFs	-2060	-2061	-2060	-2060	-2060
Length-at-age	12.49	12.47	12.50	12.48	14.04
Age frequency	-615	-616	-615	-615	-629
Mean length	-	-	-	-	-
Rec devs	10.17	10.05	10.09	10.24	10.28
Total	*-5616*	*-5621*	*-5616*	*-5616*	*-2643*

Table 6 (continued)

	Analysis acronym				
	TCA_SOLA	TCA_SLA	TloCA_SOLA	TC2A_SOLA	TCA_SOLA10
Data					
Trawl survey indices	yes	yes	yes (low value in 1994)	yes	yes
CPUE indices	yes	yes	yes	2 series	yes
Acoustic estimate	142	142	142	142	142
Survey LFs	yes	yes	yes	yes	yes
Observer LFs	yes	no	yes	yes	yes
Length-at-age	yes	yes	yes	yes	yes
Age frequency	yes	yes	yes	yes	lower effective sample size
Mean length	no	no	no	no	no
Parameters					
A_r, A_s	(30.5, 29.0)	(29.0, 29.0)	(30.3, 29.0)	(31.0, 29.0)	(30.6, 29.0)
L_∞^k (m,f)	(36.6, 38.0)	(36.4, 37.4)	(36.6, 38.0)	(36.7, 38.1)	(36.7, 38.1)
K^k (m,f)	(0.072,0.077)	(0.082, 0.098)	(0.072, 0.077)	(0.07, 0.074)	(0.067, 0.071)
σ^k (m,f)	(0.05, 0.053)	(0.052, 0.060)	(0.05, 0.053)	(0.049, 0.052)	(0.05, 0.052)
Derived parameters					
Recruited : B_0	359	287	354	336	399
Recruited : B_{79}	415	309	409	403	473
Recruited : B_{00}	207	142	198	134	214
Recruited : B_{00}/B_0	0.58	0.50	0.56	0.40	0.54
Recruited : B_{00}/B_{79}	0.50	0.46	0.48	0.33	0.45
Mature : B_0	378	286	371	360	421
Mature : B_{79}	429	309	422	422	490
Mature : B_{00}	251	146	237	175	255
Mature : B_{00}/B_0	0.66	0.51	0.64	0.49	0.60
Mature : B_{00}/B_{79}	0.59	0.47	0.56	0.42	0.52
Likelihood components					
Trawl survey indices	4.45	3.83	5.31	3.54	4.46
CPUE indices	8.53	6.20	8.64	(0.89, 5.01)	8.90
Acoustic estimate	0.35	0.07	0.22	0.01	0.44
Survey LFs	-2976	-2969	-2977	-2977	-2980
Observer LFs	-2060	-	-2060	-2062	-2063
Length-at-age	12.49	13.24	12.49	12.34	12.16
Age frequency	-615	-627	-615	-612	-510
Mean length	-	-	-	-	-
Rec devs	10.17	9.26	10.20	9.89	7.57
Total	*-5616*	*-3563*	*-5615*	*-5620*	*-5521*

Table 7: Specifications and results for the sensitivity tests that involve fixing the values (indicated by asterisks) for the growth and recruitment parameters. Reported biomasses are mid-season values. Biomass units are '000 t.

	Analysis acronym				
	TCA_SOLA	TA	TCA	TCAM	CA
Data					
Trawl survey indices	yes	yes	yes	yes	no
CPUE indices	yes	no	yes	yes	yes
Acoustic estimate	142	142	142	142	142
Survey LFs	yes	no	no	no	no
Observer LFs	yes	no	no	no	no
Length-at-age	yes	no	no	no	no
Age frequency	yes	no	no	no	no
Mean length	no	no	no	yes	no
Parameters					
A_r, A_s	(30.5, 29.0)	(29, 29)*	(29, 29)*	(29, 29)*	(29, 29)*
L_∞^k (m,f)	(36.6, 38.0)	(36.4, 38.0)*	(36.4, 38.0)*	(36.4, 38.0)*	(36.4, 38.0)*
K^k (m,f)	(0.072, 0.077)	(0.070,0.061)*	(0.070,0.061)*	(0.070,0.061)*	(0.070,0.061)*
Derived parameters					
Recruited : B_0	359	290	302	312	313
Recruited : B_{79}	415	272	291	317	299
Recruited : B_{00}	207	111	125	118	134
Recruited : B_{00}/B_0	0.58	0.38	0.41	0.38	0.43
Recruited : B_{00}/B_{79}	0.50	0.41	0.43	0.37	0.45
Mature : B_0	378	290	302	312	313
Mature : B_{79}	429	272	291	317	299
Mature : B_{00}	251	112	125	119	134
Mature : B_{00}/B_0	0.66	0.39	0.42	0.38	0.43
Mature : B_{00}/B_{79}	0.59	0.41	0.43	0.37	0.45
Likelihood Components					
Trawl survey indices	4.45	1.56	2.66	2.69	-
CPUE indices	8.53	-	4.69	-	4.65
Acoustic estimate	0.35	0.50	0.13	0.34	0.06
Survey LFs	-2976	-	-	-	-
Observer LFs	-2060	-	-	-	-
Length-at-age	12.49	-	-	-	-
Age frequency	-615	-	-	-	-
Mean length	-	-	-	7.28	-
Rec devs	10.17	0.79	1.01	0.896	0.81
Total	*-5616*	*2.85*	*8.49*	*11.2*	*5.52*

3.3 Bayesian results

Bayesian posterior distributions were computed for five of the analyses in Tables 6 and 7 (the base-case analysis TCA_SOLA, and the four analyses in which the growth and recruitment parameters are pre-specified rather than estimated). The emphasis for the Bayesian analyses has been placed on those analyses that ignore the length-frequency and age-composition data and instead pre-specify the values for the parameters that define growth and selectivity, primarily because of the focus on these analyses by the 2001 Assessment Plenary. TCA_SOLA was chosen for consideration in this and the following sections because it includes all of the data (except, of course, for the information on the mean length of the survey catches). The use of the convergence statistics and plots (see, for example, Figure 6 for the traces for the log-posterior density, B_0, the age-at-50%-recruitment, and the six growth parameters for TCA_SOLA) indicated no evidence that the MCMC algorithm failed to converge for the parameters in Figure 6 and the mid-season biomasses.

However, the Geweke (1992) statistic indicated a lack of convergence for some of the recruitment deviations. This is perhaps expected given the very large number (79) of these parameters and the nature of the Geweke (1992) statistic which is based on conducting z-tests between the mean value of a quantity over the first 10% of the MCMC chain and the last 50% of this chain. The 'single chain Gelman' statistic which involves comparing the variability of the means in 10 segments of the chain with the variability within each such segment did not provide evidence for a lack of convergence for any of the parameters or the derived quantities.

The posterior distributions for the Bayesian analyses based on fixed values for the recruitment and growth parameters were determined by two separately developed computer programs as an additional test of the numerical methods used to sample parameter vectors from the posterior distributions.

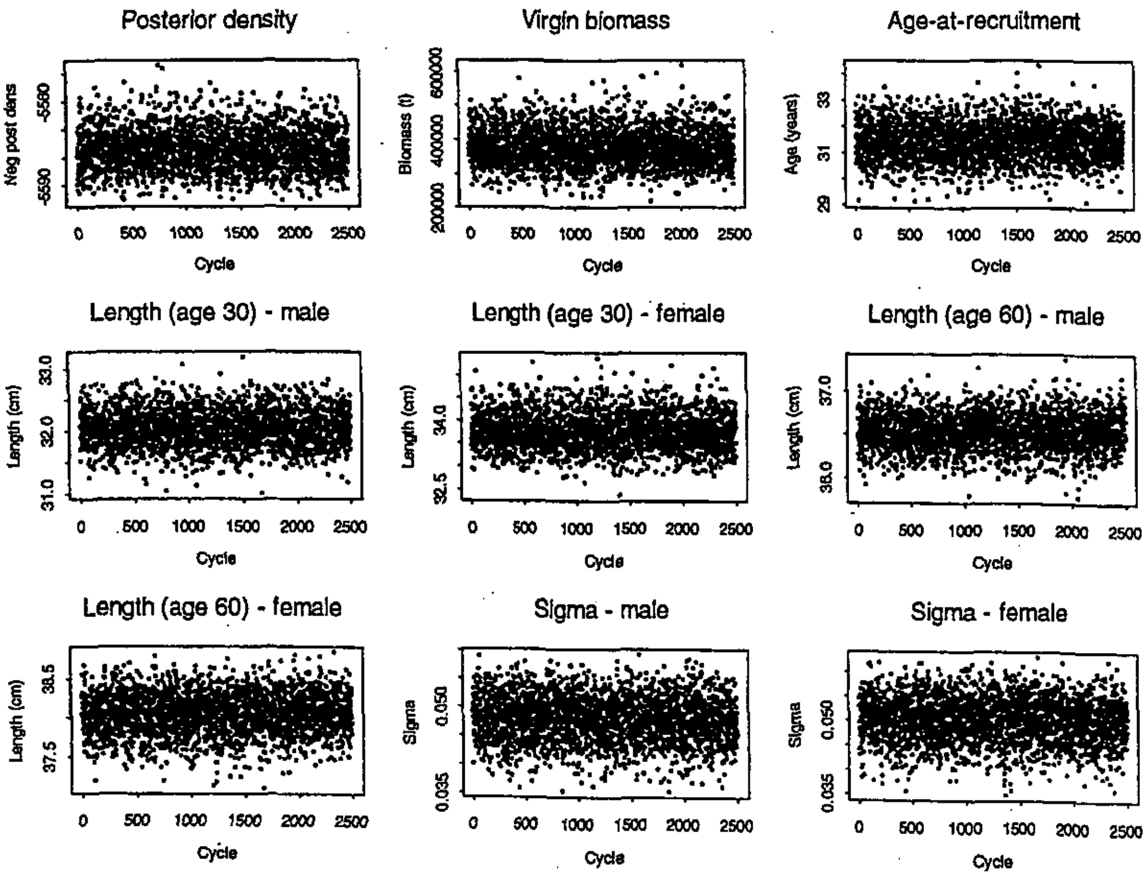

Figure 6: Traces for the negative of the logarithm of the posterior density and eight key parameters for the base-case (TCA_SOLA) analysis.

Table 8 lists posterior medians and 90% probability intervals for B_0, $B_{1978\text{-}79}$, $B_{1999\text{-}00}$ and $B_{1999\text{-}00}/B_0$ (in terms of the recruited component of the population) and the probability that $B_{1999\text{-}00}$ exceeds $0.2B_0$ and B_{MSY}[4] for the five Bayesian analyses. Figure 7 shows the medians and 90% probability intervals for the time-trajectories of mid-season recruited biomass for these analyses. The recruited biomass in 1999–2000 is estimated to be considerably in excess of both $0.2B_0$ and B_{MSY} (even though the estimates of absolute biomass differ markedly among the five analyses). Figure 8 explores the results for analysis TCA_SOLA further by means of the posteriors (summarised by their medians and 90% probability intervals) for mid-season recruited biomass, mid-season recruited biomass expressed as a percentage of B_0, and the recruitment deviations.

Table 8: Posterior medians and 90% probability intervals for the quantities B_0, $B_{1978\text{-}79}$, $B_{1999\text{-}00}$ and $B_{1999\text{-}00}/B_0$ (recruited component, biomass units '000 t) and the probability that $B_{1999\text{-}00}$ exceeds $0.2B_0$ and B_{MSY}.

Run	B_0	$B_{1978\text{-}79}$	$B_{1999\text{-}00}$	$B_{1999\text{-}00}/B_0$	$P(B_{1999\text{-}00}>0.2B_0)$	$P(B_{1999\text{-}00}>B_{MSY})$
TCA_SOLA	374	382	211	0.56	1.00	1.00
	[294, 473]	[333, 448]	[153, 294]	[0.42, 0.78]		
TCA	321	325	142	0.44	1.00	0.93
	[223, 444]	[243, 418]	[96, 208]	[0.31, 0.66]		
CA	336	342	157	0.46	1.00	0.95
	[234, 492]	[252, 472]	[103, 246]	[0.32, 0.70]		
TCAM	336	352	162	0.48	1.00	0.98
	[230, 484]	[242, 460]	[114, 232]	[0.34, 0.70]		
TA	316	326	133	0.42	0.99	0.81
	[220, 463]	[235, 463]	[76, 232]	[0.24, 0.73]		

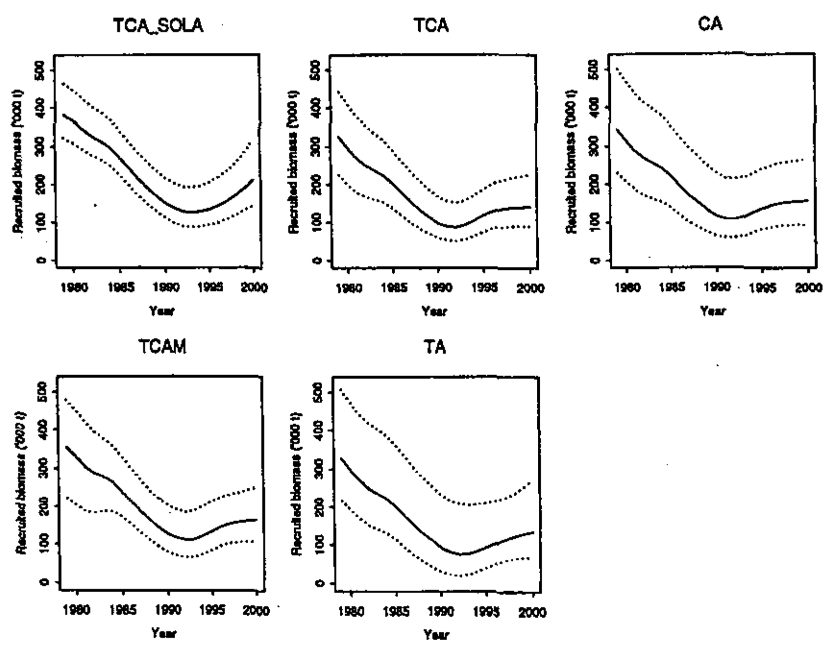

Figure 7: Posterior medians (solid lines) and 90% probability intervals (dotted lines) for the time-trajectory of mid-season recruited biomass for the five Bayesian analyses.

The posterior medians in Table 8 can be compared with the MPD estimates in Tables 6 and 7 (with some care, given the treatment of the bias-correction factors – see Section 3.3). This comparison, and

[4] The yield (MCY, CAY, and MAY) estimates, and consequently the estimates of B_{MSY}, were obtained using a method analogous to that described by Francis (1992), with the main difference being that yields were calculated as a percentage of the recruited biomass rather than the mature biomass, and, for the TCA_SOLA analysis, account was taken that recruitment to the fishery is not the same as maturation.

the upper left panel of Figure 8, confirm that, although there are differences between the MPD estimates and the posterior medians (and means), there are no undesirable results (e.g., the MPD estimate lying outside the 90% probability intervals). Figures 9 and 10 illustrate this further by displaying the marginal posteriors for B_0, $B_{1999\text{-}00}$ and $B_{1999\text{-}00}/B_0$ (recruited component of the population) for the TCA_SOLA and TCAM analyses indicating the MPD estimates by arrows. Although the MPD estimates for the TCA_SOLA analysis are close to the modes of the marginal posterior distributions, this is not the case for the TCAM analysis.

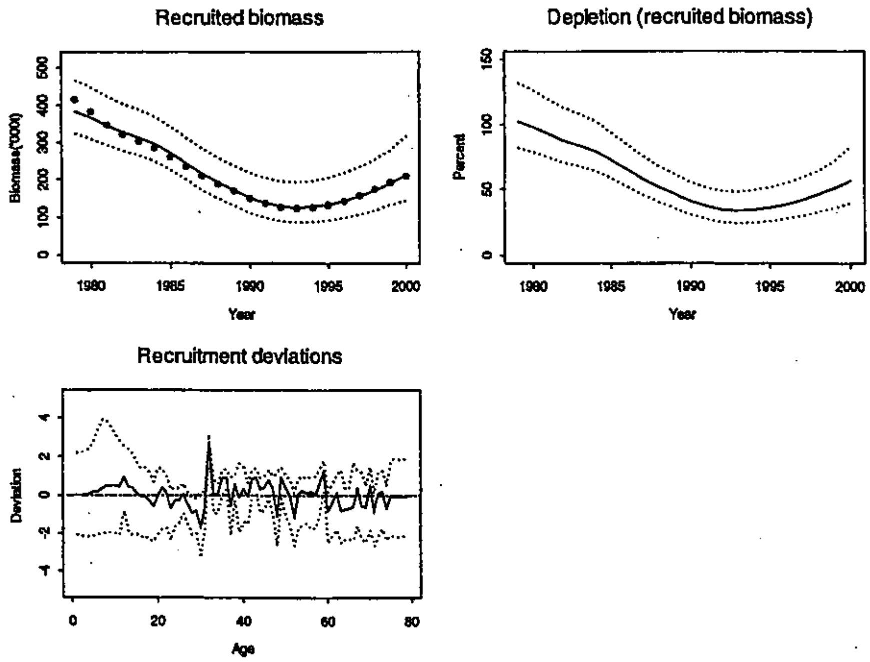

Figure 8: Posterior distributions (medians and 90% probability intervals) for the TCA_SOLA analysis of the time-trajectories of recruited biomass, recruited biomass expressed as a percentage of B_0, and the recruitment deviations. The dots in the upper left panel represent the MPD point estimates of recruited biomass.

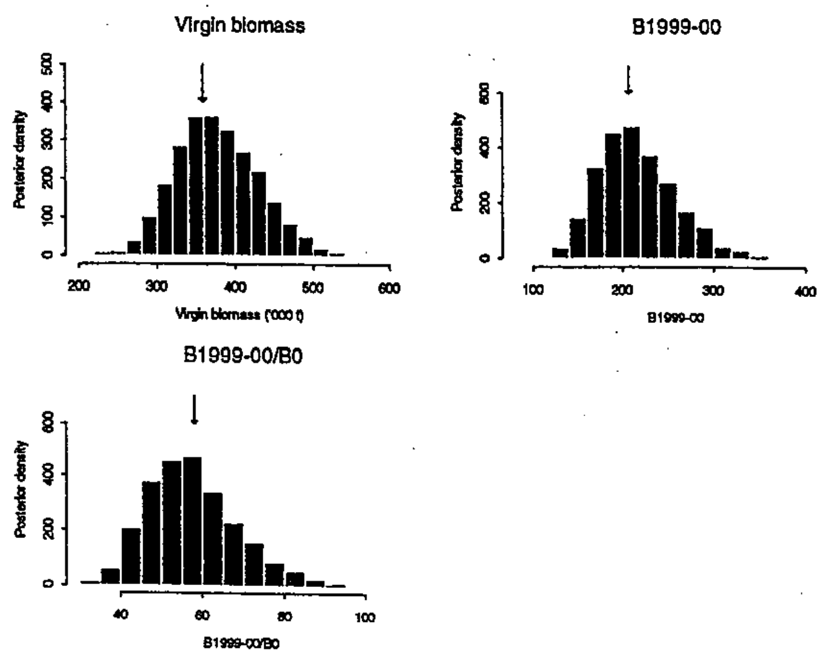

Figure 9 : Marginal posterior distributions for the TCA_SOLA analysis for the virgin recruited biomass, B_0, the recruited biomass in 1999–2000, and the ratio $B_{1999\text{-}00}/B_0$. The arrows indicate the MPD estimates from Table 6.

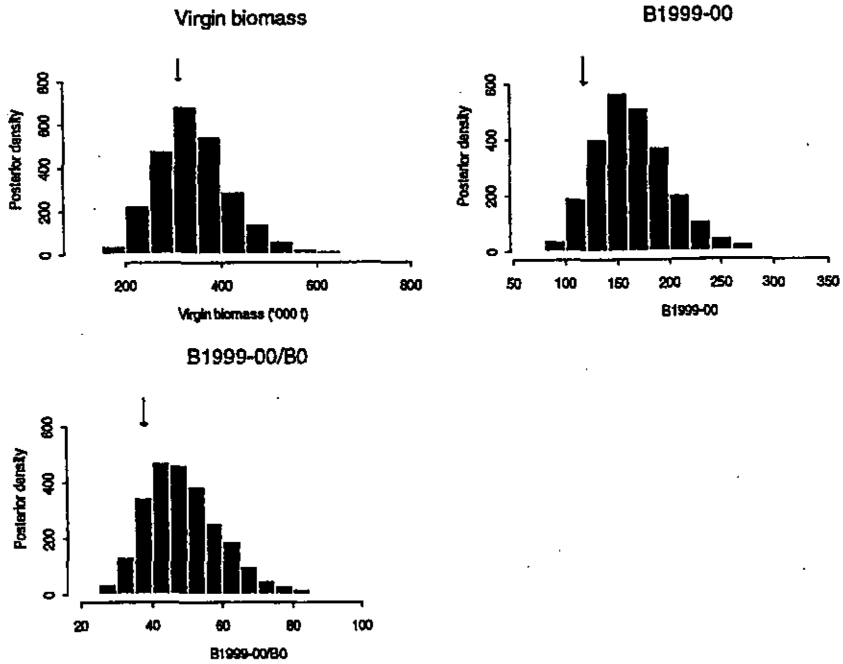

Figure 10: Marginal posterior distributions for the TCAM analysis for the virgin recruited biomass, B_0, the recruited biomass in 1999–2000, and the ratio $B_{1999\text{-}00}/B_0$. The arrows indicate the MPD estimates from Table 7.

3.4 Estimation of yields

Table 9 lists the posterior medians and 90% probability intervals for the estimates of maximum constant yield (MCY), current annual yield (CAY) and maximum average yield (MAY) (Francis (1992)) for the five Bayesian analyses.

Table 9 : Estimates of equilibrium percentages and the associated yields (*t*, corrected for an assumed overrun of 5%) based on the posterior medians and 90% probability intervals for the five Bayesian analyses.

Run	MCY (%)	CAY (%)	MAY (%)	MCY (*t*)	CAY (*t*)	MAY (*t*)
TCA_SOLA	1.62	8.56	2.33	5 800	17 200	8 300
	[1.50, 1.75]	[7.67, 9.79]	[2.23, 2.46]	[4 400, 6 700]	[12 300, 25 100]	[6 500, 10 500]
TCA	1.43	6.68	2.11	4 400	9 000	6 400
	[1.43, 1.43]	[6.68, 6.68]	[2.11, 2.11]	[3 000, 6 000]	[6 100, 13 300]	[4 500, 8 900]
CA	1.43	6.68	2.11	4 600	10 000	6 800
	[1.43, 1.43]	[6.68, 6.68]	[2.11, 2.11]	[3 200, 6 700]	[6 500, 15 700]	[4 700, 9 900]
TCAM	1.43	6.68	2.11	4 600	10 300	6 700
	[1.43, 1.43]	[6.68, 6.68]	[2.11, 2.11]	[3 100, 6 600]	[7 200, 14 700]	[4 600, 9 700]
TA	1.43	6.68	2.11	4 300	8 500	6 400
	[1.43, 1.43]	[6.68, 6.68]	[2.11, 2.11]	[3 000, 6 300]	[4 800, 14 800]	[4 400, 9 300]

3.5 Forward projections

Forward projections were carried out for the five Bayesian assessments for a 10-year period with the catch held constant at a range of levels. The results from these five projections were then used to calculate the catch levels that would be required to meet each of the following three criteria (see also Francis (2001a)), which are defined in terms of the recruited biomass in the last year of the projection (B_{LAST} - $B_{2009\text{-}10}$ given a 10-year projection period):

- *safety criterion*: the probability that B_{LAST} exceeds 20% B_0 should be at least 0.9 (this criterion is consistent with the definition of safety that is used in the calculation of MCY and CAY),
- *target criterion*: the probability that B_{LAST} exceeds B_{MSY} should be at least 0.5 (this relates to the Fisheries Act requirement that a stock should be at or above the level that sustains *MSY*), and
- *moving towards B_{MSY} criterion*: B_{LAST} should be less than $B_{1999\text{-}00}$ (since $B_{1999\text{-}00}$ is greater than B_{MSY}, the stock will move towards B_{MSY} only if B_{LAST} is less than $B_{1999\text{-}00}$).

Table 10 lists the values for the annual constant catches that satisfy each of these criteria for the five Bayesian assessments.

Table 10: Annual constant catches (unadjusted for the 5% over-run) required to satisfy the three criteria in 2009–10 for the five Bayesian analyses.

	Maximum catch (t)		Minimum catch (t)
Run	'Safety' criterion	'Target' criterion	'Moving to B_{MSY}' criterion
TCA_SOLA	21 200	31 500	18 200
TCA	9 900	11 600	6 400
CA	10 700	12 600	6 200
TCAM	9 900	11 600	6 400
TA	9 000	11 600	7 100

4. CONCLUSIONS

The method used in this paper to assess the northeastern Chatham Rise stock of orange roughy extends that of Hilborn et al. (2000) by estimating the parameters of the growth curve within the assessment. It also uses new data on age-frequency, length-at-age, and trends in catch-rates, as well as revised acoustic estimates. The catches, trawl survey indices, acoustic estimates and catch rates used in this assessment are the same as those used by Francis (2001a). However, Francis (2001a) did not use the age-frequency or the length-at-age data directly, and used mean lengths rather than length-frequencies.

The base-case assessment (TCA_SOLA) is fitted to all the data sets that were considered suitable and representative for this stock – catches, catch-rates, trawl survey indices, acoustic estimates, observer and survey length-frequencies, the 1984 survey age-frequency distribution, and the length-at-age data from the surveys in 1984 and 1990. In general, the model fits these data sets reasonably well (Figures 2–5), with no evidence for major model mis-specification.

The results of the base-case assessment show that the age-at-50%-recruitment to the commercial fishery is larger than the age-at-50%-maturity, but not to the extent found by Hilborn et al. (2000). Mature biomass slightly exceeds recruited biomass, but there is no evidence for a large pool of mature but unrecruited animals as implied by Hilborn et al. (2000). This change appears to be due to fitting the growth curve to the length-at-age data within the assessment, rather than before the assessment. For example, K (females) changes from 0.061 year^{-1} (assumed in previous assessments) to 0.077 year^{-1} (estimated in this assessment). The model fit to the length-at-age data for females is somewhat worse than to the data for males (see Figure 5). The present assessment estimates the age-at-50%-recruitment to the commercial fishery and the age-at-50%-survey-recruitment. However, this assessment is based on a pre-specified value for the age-at-50%-maturity (which is the lower bound for the estimates of the age-at-50%-recruitment to the commercial fishery and the age-at-50%-survey-recruitment), even though there is clearly uncertainty regarding the size of this parameter.

The base-case results are broadly similar to those of Francis (2001a). Both assessments show similar trends in abundance, and both estimate the stock to be presently above B_{MSY} with high probability. The estimates of MCY and MAY are also similar between the two assessments, although the estimates of CAY are higher in this assessment than in Francis (2001a), and results from catch projections are much more optimistic (Table 10). Scenario TCAM in Tables 8 and 9 corresponds most closely to the assumptions and data used by Francis (2001a). The results for this scenario match quite closely (estimates of current biomass and depletion are very similar, and there is little discrepancy in estimates of CAY or in results from catch projections). However, it should be noted that the method of Francis (2001a) is based on the SIR algorithm. Attempts to use this algorithm failed, in the sense that the sample from the posterior was dominated by a small number of parameter vectors, even for the analyses which fixed the growth and recruitment parameters. This is probably because the data set upon which the present analyses are based is substantially larger than earlier data sets. This suggests that additional testing of the method of Francis (2001a) may be warranted.

The results are sensitive to some of the assumptions and data set choices. In particular, the results in Tables 8–10 show that the estimates of current depletion and of yields based on catch projections are considerably more optimistic when all of the data are used and growth is estimated within the assessment. However, the general conclusion, that the stock is presently above target reference levels, is robust across choice of data sets and assumptions, a result also found by Francis (2001a).

5. ACKNOWLEDGMENTS

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Appendix A : The Population Dynamics Model

A.1. Resource Dynamics

The dynamics of fish aged 2 and older are described by the following equations:

$$N^k_{y+1,a} = \begin{cases} e^{-M}\left\{N^k_{y,a-1}e^{-F_y} + U^k_{y,a-1}Q_a\right\} & \text{if } 2 \le a < z \\ (N^k_{y,z} + N^k_{y,z-1})e^{-F_y - M} & \text{if } a = z \end{cases} \qquad \text{(A.1a)}$$

$$U^k_{y+1,a} = e^{-M}U^k_{y,a-1}(1 - Q_a) \qquad \text{if } 2 \le a < z \qquad \text{(A.1b)}$$

where $N^k_{y,a}$ is the number of recruited fish of age a and sex k at start of year y,

$U^k_{y,a}$ is the number of unrecruited fish of age a and sex k at start of year y,

Q_a is the proportion of unrecruited fish of age a-1 which recruit at age a:

$$Q_a = \begin{cases} 0 & \text{if } a = 1 \\ (P_a - P_{a-1})/(1 - P_{a-1}) & \text{otherwise} \end{cases} \qquad \text{(A.2)}$$

P_a is the proportion of fish of age a which would be recruited at deterministic equilibrium:

$$P_a = \begin{cases} 0 & \text{if } a = 1 \\ (1 + e^{-\ln(19)(a - A_r)/S_r})^{-1} & \text{otherwise} \end{cases} \qquad \text{(A.3)}$$

z is the maximum (lumped) age class,

A_r is the age at which 50% of fish would be recruited at deterministic equilibrium,

S_r is the parameter that determines the extent of gradual recruitment,

M is the instantaneous rate of natural mortality, and

F_y is the instantaneous rate of fishing mortality during year y.

Note that, unlike previous assessments of Chatham Rise orange roughy, Equation (A.3) does not implement the assumption that selectivity is 0 below age $A_r - S_r$ and 1 above age $A_r + S_r$. This change is needed to ensure that the likelihood function is differentiable with respect to the model parameters.

The biomass of recruited fish at the start of year y is given by:

$$B_y = \sum_k \sum_{a=1}^{z} N^k_{y,a} w^k_a \qquad \text{(A.4)}$$

and the biomass of recruited fish in the middle of year y is given by :

$$\hat{B}_y = \sum_k \sum_{a=1}^{z} N^k_{y,a} w^k_a e^{-0.5(F_y + M)} \qquad \text{(A.5)}$$

where w_a^k is the mass (in tonnes) of a fish age a and sex k, given here by the von Bertalanffy growth equation and the allometric length-weight relationship:

$$\begin{aligned} L_a^k &= L_\infty^k(1-\exp(-K^k(a-t_0^k))) \\ w_a^k &= a^k(L_a^k)^{b^k}/1000 \end{aligned} \qquad \text{(A.6)}$$

L_∞^k, K^k, t_0^k are the parameters of the von Bertalanffy growth equation for sex k,

a^k is the constant of the length-weight relationship (length in cm and weight in kg) for sex k, and

b^k is the power coefficient of the length-weight relationship for sex k.

The growth curve is parameterised in terms of L_{30}^k, L_{60}^k and t_0^k for improved numerical stability when conducting the Bayesian analyses (see Section 3.3).

A.2. Births

$$N_{y,1}^k = 0 \qquad\qquad U_{y,1}^k = \frac{0.5\hat{B}_{y-1}^f}{(\alpha+\beta\hat{B}_{y-1}^f)}e^{\varepsilon_y-\sigma_R^2/2} \qquad \text{(A.7)}$$

where σ_R is the standard deviation of the natural logarithm of the multiplicative fluctuations in births,

ε_y is a random variable from $N(0;\sigma_R^2)$,

$\hat{B}_y^f$ is biomass of mature females in the middle of year y:

$$\hat{B}_y^f = \sum_{a=1}^{z}(N_{y,a}^f e^{-0.5F_y} + U_{y,a}^f)w_a^f\Omega_a e^{-0.5M} \qquad \text{(A.8)}$$

Ω_a is the fraction of females of age a that are mature:

$$\Omega_a = (1+e^{-\ln(19)(a-A_m)/S_m})^{-1} \qquad \text{(A.9)}$$

A_m is the age at which 50% of females would be mature,

S_m is the parameter that determines the extent of gradual maturity of females, and

α, β are the parameters of the stock-recruitment relationship (see Section A.3)

A.3. Initial conditions

The initial (year $y = y_1$) numbers-at-age are given by the equations:

$$N_{y_1,a}^k = \begin{cases} 0.5R_1 e^{-M(a-1)}P_a e^{\varepsilon_a-\sigma_R^2/2} & \text{if } 1 \le a < z \\ 0.5R_1 e^{-M(z-1)}/(1-e^{-M}) & \text{if } a = z \end{cases} \qquad \text{(A.10a)}$$

$$U_{y_1,a}^k = 0.5R_1 e^{-M(a-1)}(1-P_a)e^{\varepsilon_a-\sigma_R^2/2} \qquad \text{if } 1 \le a < z \qquad \text{(A.10b)}$$

where ε_a is a random variable from $N(0;\sigma_R^2)$,

R_1 is the number of 1-year-olds at deterministic equilibrium:

$$R_1 = 2B_0 \Big/ \left\{ \sum_k e^{-0.5M} \left[\sum_{a=1}^{z-1} P_a w_a^k e^{-M(a-1)} + w_z^k e^{-M(z-1)} \big/ (1-e^{-M}) \right] \right\} \tag{A.11}$$

B_0 is the unexploited equilibrium recruited biomass at mid-season.

Recruitment variability is not added to the plus-group because this group comprises a large number of age-classes which will largely damp out this effect.

The stock-recruitment parameters α and β are calculated from $\hat{B}_{y_1}^f$, mid-season spawning biomass at deterministic equilibrium, and R_1:

$$\hat{B}_{y_1}^f = \sum_{a=1}^{z} (N_{y_1,a}^{\prime f} + U_{y_1,a}^{\prime f}) w_a^f \Omega_a e^{-0.5M} \tag{A.12}$$

where $N_{y_1,j}^{\prime f}$ and $U_{y_1,j}^{\prime f}$ are given by Equation (A.10) when $\varepsilon_a = 0$ and $\sigma_R = 0$.

$$\alpha = \left(\frac{1-d}{4d} \right) \frac{\hat{B}_{y_1}^f}{R_1} \qquad \beta = \frac{5d-1}{4d\,R_1} \tag{A.13}$$

where d is the steepness parameter.

A.4. Catches

F_y, the instantaneous rate of fishing mortality during year y, is calculated using equation:

$$F_y = -\ell n(1 - C_y / (B_y e^{-0.5M})) \tag{A.14}$$

where C_y is catch in year y.

The assumption of a discrete fishery occurring instantaneously in the middle of the year is made primarily for computational convenience but also because most of the catch has (historically) been taken during the spawning season (assumed to be the middle of the year).

Appendix B : The contributions to the likelihood function

B.1. Relative abundance indices

The observed biomass indices, O_i, are assumed to be independently and log-normally distributed with means $\ell n(qE_i)$ and standard deviations c_i. The c_i are assumed to be known, and q is estimated using maximum likelihood. The likelihood of observing the biomass indices, O_i, is given by:

$$L=\prod_{i=1}^{n}\frac{1}{\sqrt{2\pi}\,c_i\,O_i}\exp\left(-\frac{\{\ell n(O_i)-\ell n(qE_i)\}^2}{2c_i^2}\right) \qquad \text{(B.1)}$$

where E_i is the expected biomass,

q is the catchability coefficient,

c_i is the standard deviation of $\ell n(O_i)$, and

n is the number of data points.

The log-likelihood is therefore:

$$\ell n\,L=-0.5n\ell n(2\pi)-\sum_{i=1}^{n}\ell n(c_i\,O_i)-0.5\sum_{i=1}^{n}\frac{\{\ell n(O_i/E_i)-\ell n(q)\}^2}{c_i^2} \qquad \text{(B.2)}$$

Differentiating Equation (B.2) with respect to q and solving the resultant equation provides the maximum likelihood estimate of q:

$$\hat{q}=\exp\left(\sum_{i=1}^{n}\frac{\ell n(O_i/E_i)}{c_i^2}\Big/\sum_{i=1}^{n}\frac{1}{c_i^2}\right) \qquad \text{(B.3)}$$

The biomass available to the trawl surveys, $\hat{B}_y^S$, is defined by a 'survey selectivity' (which may differ from the maturity ogive), the acoustic estimates are assumed to relate to the mature component of the biomass available to the trawl surveys, $\hat{B}_y^A$, and catch-rate indices are assumed to be proportional to the mid-season recruited biomass, $\hat{B}_y$, i.e.:

$$\hat{B}_y^S=\sum_k\sum_{a=1}^{z}w_a^k(N_{y,a}^k e^{-(M+F_y)/2}+U_{y,a}^k e^{-M/2})P_a^S \qquad \text{(B.4a)}$$

$$\hat{B}_y^A=\sum_k\sum_{a=1}^{z}w_a^k(N_{y,a}^k e^{-(M+F_y)/2}+U_{y,a}^k e^{-M/2})P_a^S\,\Omega_a \qquad \text{(B.4b)}$$

$$\hat{B}_y=\sum_k\sum_{a=1}^{z}w_a^k N_{y,a}^k e^{-(M+F_y)/2} \qquad \text{(B.4c)}$$

where P_a^S is the proportion of fish of age a that are recruited to the trawl survey gear:

$$P_a^S=\begin{cases}0 & \text{if } a=1\\ (1+e^{-\ell n(19)(a-A_s)/S_r})^{-1} & \text{otherwise}\end{cases} \qquad \text{(B.5)}$$

where A_s is the age-at-50%-survey-recruitment.

B.2. Absolute abundance indices

The observed biomass indices, $\tilde{O}_i$, are assumed to be independently and log-normally distributed with means $\ell n(E_i)$ and (known) standard deviations c_i. The likelihood of observing the biomass indices, $\tilde{O}_i$, is given by:

$$L = \prod_{i=1}^{n} \frac{1}{\sqrt{2\pi}\, c_i \tilde{O}_i} \exp\left(-\frac{\{\ell n(\tilde{O}_i) - \ell n(E_i)\}^2}{2c_i^2} \right) \qquad \text{(B.6)}$$

The log-likelihood is thus:

$$\ell n L = -0.5 n \ell n(2\pi) - \sum_{i=1}^{n} \ell n(c_i \tilde{O}_i) - 0.5 \sum_{i=1}^{n} \frac{\{\ell n(\tilde{O}_i) - \ell n(E_i)\}^2}{c_i^2} \qquad \text{(B.7)}$$

B.3. Age-composition data

The contribution by the age frequency data to the logarithm of the likelihood function is:

$$\ln L = -\tfrac{1}{2} \sum_{\alpha=1}^{N_A} \sum_{i=1}^{N_I} \ln[2\pi(\xi'_{i\alpha} + \tfrac{0.1}{N_I})\tau_\alpha^2] + \sum_{\alpha=1}^{N_A} \sum_{i=1}^{N_I} \ln\left[\exp\left\{ \frac{-\left(Q_{i\alpha} - \hat{Q}_{i\alpha}\right)^2}{2(\xi'_{i\alpha} + \frac{0.1}{N_I})\tau_\alpha^2} \right\} + 0.01 \right] \qquad \text{(B.8)}$$

where $Q_{i,p}$ is the observed proportion of fish in age frequency sample p having an age lying in age interval i,

$\hat{Q}_{i,p}$ is the model-predicted value of $Q_{i,p}$:

$$\hat{Q}_{i,p} = N_{y,a}^k / \sum_{a''} N_{y,a''}^k$$

$\xi_{i\alpha} = (1 - \hat{Q}_{i\alpha})\hat{Q}_{i\alpha}$

N_A is the number of years of age frequency data,

N_I is the number of age intervals in the age frequency for each year,

$\tau_p^2 = \min(S_p, 1000)^{-1}$, and

S_p is the effective sample size for age frequency sample p.

B.4. Size-composition data

The approach used to include the length-frequency data in the likelihood function follows Equation (B.8) except that the expected value is given by:

$$\hat{Q}_{i,p} = \sum_a \lambda_{1,a}^k N_{y,a}^k / \sum_{a''} N_{y,a''}^k \qquad \text{(B.9)}$$

where $\lambda_{1,a}^k$ is the proportion for sex k of animals of age a that are in (1cm) length-class l:

$$\lambda_{l,a}^{k} = \int_{\bar{L}_l-\Delta L}^{\bar{L}_l+\Delta L} \frac{1}{\sqrt{2\pi}\,\sigma^k L} e^{-\frac{1}{2(\sigma^k)^2}[\ell n L - \ell n L_a^k]^2}\, dL \tag{B.10}$$

σ^k is the coefficient of variation in length-at-age for sex k (assumed to be independent of age),

$\bar{L}_l$ is the mid-point of length-class l, and

ΔL is the half the width of each length-class.

B.5. Length-at-age data

The contribution of the length-at-age data to the logarithm of the likelihood function is based on the assumption that length-at-age is log-normally distributed:

$$\ell n L = \sum_i \left\{ -\ell n(\sqrt{2\pi}\,\sigma^i L_i) - \frac{1}{2(\sigma^i)^2}\left(\ell n L_i - \ell n \hat{L}_i\right)^2 \right\} \tag{B.11}$$

where L_i is the length of the ith fish for which age and length is available,

$\hat{L}_i$ is the model-estimate of the mean length of a fish with age equal to that of the ith fish for which age and length is available (see Equation A.6), and

σ^i is the coefficient of variation in length-at-age that corresponds to the sex of the ith fish for which age and length is available.