ISSN 1175-1584

MINISTRY OF FISHERIES
Te Tautiaki i nga tini a Tangaroa

CPUE analysis and stock assessment of the South Chatham Rise orange roughy fishery for 2003–04

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New Zealand Fisheries Assessment Report 2005/7
February 2005

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Published by Ministry of Fisheries
Wellington
2005

ISSN 1175-1584

Citation:
Anderson, O.F. (2005).
CPUE analysis and stock assessment of the South Chatham Rise orange roughy fishery
for 2003–04.
New Zealand Fisheries Assessment Report 2005/7. 33 p.

This series continues the informal
New Zealand Fisheries Assessment Research Document series
which ceased at the end of 1999.

EXECUTIVE SUMMARY

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The South Chatham Rise orange roughy fishery developed in the early 1980s, with annual catches rapidly increasing to between 5000 and 11 000 t and remaining at this level until the early 1990s. Annual catches fell rapidly at this point and since 1995 have stabilised at about 1100–1700 t. In the early stages of the fishery much of the catch came from fishing flat grounds over a wide region of the South Rise. In recent years the fishery has contracted into the eastern end of the South Rise and become more concentrated on hill features.

The only previous assessment for this fishery, in 2001, estimated the stock size to be about 24% of the virgin size. The fishery was thought to be sustainable at the current level of fishing. This report describes an update of that assessment, with the addition of three years of catch data. These catches, along with biological parameters and catch per unit effort (CPUE), are the only inputs into the assessment.

CPUE indices are calculated for three separate sectors of the fishery (all flat areas and all hill areas divided into two sub-areas) and the assessment treats these areas as separate stocks with separate catch histories. Model outputs for each area are summed to provide biomass estimates for the fishery as a whole.

This assessment estimates the current stock size to be at either 29% or 41% of B_0 (depending on the choice of two alternative assessments made) where B_0 is either 95 000 t or 113 000 t. Although this lack of agreement between assessments undermines confidence in forward projections of fishery performance, the current level of fishing is expected to be sustainable. The more conservative of the two alternative assessments estimates that there would be insufficient biomass available in the main fishery area to sustain a 50% increase in the overall catch for the next 5 years. Both assessments indicate a recent rebuilding of biomass in two of the three areas, but this is not supported by trends in the CPUE series which are flat in recent years in all areas.

1. INTRODUCTION

The South Chatham Rise is one of three separately managed fishstocks on the Chatham Rise part of the Quota Management Area (QMA) ORH 3B (Figure 1). Before 1997, this fishery was assessed as part of a single Chatham Rise stock (see Francis et al. 1995), and was assessed separately for the first time in 2001 (Francis 2001b) using a stock reduction analysis on four separate sectors of the fishery. This split was required because analysis of CPUE revealed strong trends in fishing location and methods, making it impossible to derive a single, representative set of CPUE indices. This is the first update of that assessment.

This report addresses the parts of objectives 2 and 4 of the Ministry of Fisheries project ORH2003/02 that deal with the South Chatham Rise orange roughy fishery:

"*To update the unstandardised and standardised catch per unit effort analyses with the inclusion of data up to the end of the 2002/03 fishing year ...*" and "*To update the stock assessment, including estimating biomass and sustainable yields...*"

The analysis of catch per unit effort (CPUE) follows closely the methods of Francis (2001a), particularly in the procedures used to stratify the fishery by combinations of tow type and area, with the addition of three years of catch effort data. The stock assessment differs from that used in the previous assessment (Francis 2001b) in that the fishery is treated as three instead of four sub-stocks, and uses Bayesian estimation methods as implemented by CASAL stock assessment software (Bull et al. 2003).

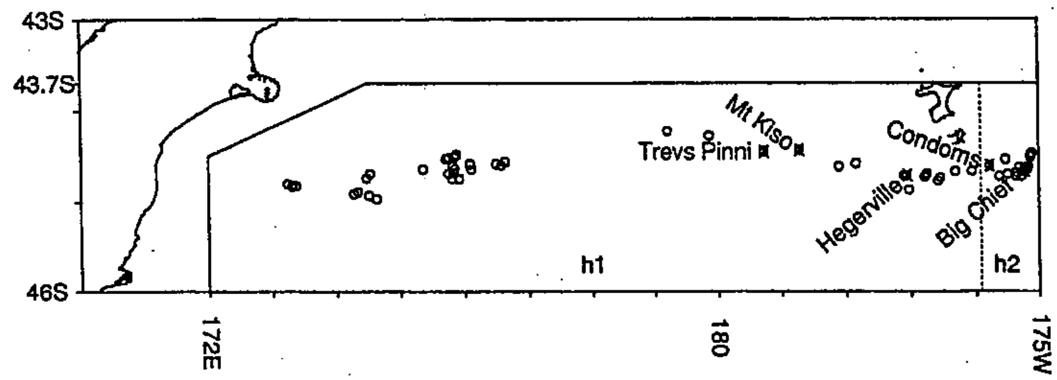


Figure 1: The South Chatham Rise, showing the boundaries of the orange roughy fishstock, circles of 5 km radius centred on each of 86 known hills, the location of the 5 major hills referred to in the report (crosses), and the boundary between the two hill strata, h1 and h2 (vertical dotted line).

2. STOCK STRUCTURE

The separation of the Chatham Rise into three orange roughy stocks is primarily for management rather than biological reasons. Although there is some evidence that Chatham Rise orange roughy are genetically distinct from those in other areas (Annala et al. 1998), there is no strong evidence for stock boundaries within the Chatham Rise itself (Francis et al. 1995, Smith & Benson 1997). No major spawning aggregations have been reported on the South Rise, and it has been postulated that fish migrate from this area, probably in an anticlockwise direction around the Rise, to known spawning locations in the northeast Rise (Francis 2001b).

3. THE FISHERY

Only a brief review of the South Chatham Rise orange roughy fishery is given here. A more detailed description of this fishery, along with other New Zealand orange roughy fisheries, is presented in Dunn et al. (in press.).

The South Rise fishery developed in the early 1980s, with annual catches rapidly increasing to between 5000 and 11 000 t and remaining at this level until the early 1990s (Table 1). Annual catches fell, in line with declining TACCs, and since 1995 have stabilised at about 1100–1700 t. Effort on the flat grounds rose rapidly from the early 1980s, peaking at about 1800 tows in 1989, and then dropped sharply in the early 1990s as the practice of fishing on hills became more predominant. Since 1995, there has been a decline in both hill and flat fishing effort. Catch rates for tows on the flat peaked at about 6 t/h in 1983, declined slowly over the following 15 years to about 1 t/h, then increased to a level of about 3 t/h in 2000 and have remained at this level over the last 3 years. Catch rates for hill tows followed a similar pattern to those of flat tows, with a decrease from a peak of about 6 t/tow in 1991 to a low of just under 2 t/tow in 1995, followed by an increase to about 3 t/tow over the last 4 years.

There have been a significant, but annually variable, number of tows which caught orange roughy when targeting other species (mostly oreos). There were more such tows in the 1980s than in the 1990s, and over the last 10 years they have fluctuated between 100 and 200 tows per year. Oreos are an important bycatch of orange roughy target fishing in this fishery, particularly in the west. They constitute about 80% of the total catch from orange roughy target trawls in the west (172° E to 178° W), dropping to about 50% in the east (178° W to 175° W).

Table 1: South Rise orange roughy reported catches (excludes overruns from lost fish, discards, and conversion factor anomalies), to the nearest 100 t, percentage (to the nearest percent) of the total ORH 3B catch, and catch limits (from Annala et al. 2004).

Year	ORH catch (t)	%	Catch limit (t)
1979–80	800	3	–
1980–81	3 700	13	–
1981–82	500	2	*
1982–83	4 800	31	*
1983–84	5 100	21	*
1984–85	7 900	27	*
1985–86	5 300	18	*
1986–87	4 900	16	*
1987–88	6 800	28	*
1988–89	9 200	28	*
1989–90	11 000	35	*
1990–91	6 900	32	*
1991–92	2 200	9	*
1992–93	5 400	27	6 300
1993–94	5 100	30	6 300
1994–95	1 600	13	2 000
1995–96	1 300	10	*
1996–97	1 400	15	*
1997–98	1 700	17	*
1998–99	1 200	13	*
1999–00	1 100	13	*
2000–01	1 700	18	*
2001–02	1 100	10	1 400
2002–03	1 500	12	1 400

– No catch limit

* Catch limit spread over multiple sub-areas of ORH 3B

Fishing effort and catches have focused on five main hill features in recent years; all are located in the eastern half of the South Rise (Figure 2). Large catches of orange roughy (up to 40 t in the most recent year) have frequently been made, particularly in the vicinity of the Big Chief hill complex. Very little fishing for orange roughy now occurs west of about 180° on the South Rise.

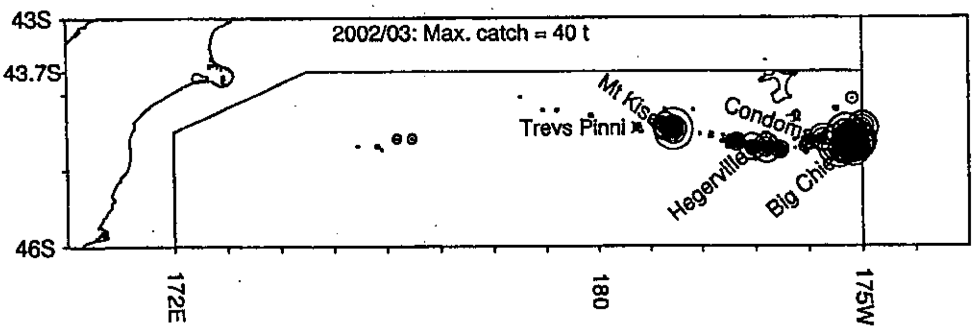


Figure 2: Catch (t) per tow of orange roughy in the South Rise for the 2002–03 fishing year. Circle area is proportional to catch.

4. MODEL INPUTS

The three main inputs to the stock assessment model were biological parameters, relative biomass estimates (annual CPUE indices), and annual catches.

4.1 Biological parameters

Separate estimates of biological parameters are not available for the South Rise. Where parameter estimates are available for the Northeast Rise fishery these values are used, otherwise default values for all other orange roughy stocks (as reported by Annala et al. 2004) are used (Table 2). New estimates for age at maturity (A_m), gradual maturity (S_m), and the von Bertalanffy parameters L_∞ and K are available from recent analysis of otolith ring count and transition zone data from Northeast Rise Rise orange roughy (Allan Hicks, SeaFIC, unpublished data), and these were used in the model.

Table 2: Orange roughy biological parameters for the Chatham Rise. Age at maturity, gradual maturity, and the von Bertalanffy parameters L_∞ and K are new estimates (Allan Hicks, SeaFIC, unpublished data), old values are shown in parentheses.

Parameter	Symbol	Male	Female	Both sexes
Natural mortality	M	–	–	0.045 yr^{-1}
Age at recruitment	A_r	–	–	$=A_m$
Gradual recruitment	S_r	–	–	$=S_m$
Age at maturity	A_m	–	–	28.8 yr (29)
Gradual maturity	S_m	–	–	6.5 yr (3)
Von Bertalanffy parameters	L_∞	34.94 cm (36.4)	37.6 cm (38.0)	–
	K	0.083 yr^{-1} (0.070)	0.073 yr^{-1} (0.061)	–
	t_0	-0.4 yr	-0.6 yr	–
Length-weight parameters	a	–	–	0.0921
[W(g)=aL(cm)^b]	b	–	–	2.71
Recruitment variability	σ_R	–	–	1.1
Recruitment steepness		–	–	0.75

4.2 Catch per unit effort (CPUE) analysis

There were six main steps in this analysis.

1. Trimming of catch-effort data to remove less useful records
2. Creation of a tow-type factor to differentiate between flat and hill fishing
3. Selection of initial GLM model predictors
4. Re-stratification by new area/tow type factor
5. Selection of final predictors
6. Calculation of c.v.s for the year effects.

1. Records for tows that targeted species other than orange roughy were excluded (about 17% of the total catch). Data from vessels with fewer than 30 target tows in each of 3 fishing years were excluded to eliminate data from inexperienced fishing operations and reduce the number of parameters to be fitted. This reduced the number of vessels from 92 to 17, while still covering 85% of the catch and 88% of the tows. There was a good overlap of vessels over time, so that in each year in the time series (after 1983) the fleet included several vessels (range 4 to 10) that had been operating in the previous year.

2. The descriptive analyses (Francis 2001a, Dunn et al. in press) showed that there have clearly been two methods of fishing on the South Rise: longer tows on relatively flat ground, and shorter tows on hills. Not only are catch rates very different between the two methods, but there is also a lack of overlap in time between them, due to an abrupt change from flat to hill fishing in about 1990. It did not seem appropriate either to combine records of both methods, or to ignore one method and produce a CPUE index based on only the other; therefore, tows were categorised as 'flat' or 'hill' (measuring CPUE as t/tow for hill tows and t/h for flat tows) and tow-type was included as a factor in the regressions.

The categorisation of all tows into flat and hill was based on an examination of tow duration over time between regions within the South Rise and near the five main hills. This showed that the best definition of a hill tow was one that was less than 30 minutes long and which began at a point within a 5-n.mile radius of a known hill (see Figure 1). The classification used for the descriptive analysis (based solely on tow duration) proved to be inadequate as catch rates of a relatively few tows near hills which were longer than 30 minutes had a strong influence in initial regression models (Francis 2001a).

3. The fraction of target tows on the South Rise that recorded no catch of orange roughy is high (31% over all years), and shows considerable variation over time and space. For these reasons it was necessary to incorporate a *binomial* model into the CPUE analyses, to estimate the probability of a non-zero catch. The other component of the 2-part model was a *normal* model, which estimates transformed catch rates of non-zero tows only. Usually, a log(CPUE) transformation is applied to catch rates to approximate a normal distribution, but in this case Kolmogorov-Smirnov tests, comparing transformed catch rate distributions to the normal distribution, showed that a better fit could be obtained by using a $(\text{CPUE})^{0.1}$ transformation. This was found to make little difference to the order of variable selection or to the amount of deviance explained by each variable, but it improved the model diagnostics. The two models together form a *combined* model, which estimates catch rates from all tows by combining results from the *binomial* and *normal* models in a manner similar to that of Vignaux (1994) as modified by Francis (2001a).

A forward stepwise procedure using the predictor variables listed in Table 3 was run, allowing an interaction between year and tow type, forcing year and tow type into the normal model, and year into the binomial model. The predictor at each step was selected according to the Akaike Information Criterion (AIC; Akaike 1973), which takes into account the degrees of freedom of each predictor. Predictors were included in the model only if they increased the percentage deviance explained by at least 0.5%.

Table 3: Summary of variables tested in the models selecting initial predictors (number of categories in parenthesis).

Variable name	Variable type	Description
Year (23)	factor	fishing year
Vessel (17)	factor	vessel code (A–Q, see Appendix 1)
Tow type (2)	factor	flat or hill
Month (12)	factor	month in which tow occurred
Depth	continuous (cubic polynomial)	depth (m) of groundrope at start of tow
Vessel tonnage	continuous (cubic polynomial)	gross tonnage of vessel
Vessel power	continuous (cubic polynomial)	vessel power (kW)

In the normal model, year and tow type explained most of the total percentage deviance explained and vessel was the first additional predictor selected, providing an additional 5.7% (Table 4). The year:tow type interaction term was accepted into the model, as was depth. The additional deviance explained by the month variable was below the 0.5% threshold.

Only three variables were accepted into the binomial model, with vessel providing most of the explanatory power, followed by year and then depth. The year:tow type interaction term was not accepted, but otherwise these were the same variables as included in the normal model.

Table 4: Initial predictor selection. Model fits for the normal and binomial models in the stepwise order determined by AIC. Predictors in parentheses not accepted. Df, degrees of freedom.

Normal model (predictand=$CPUE^{0.1}$)

	Df	AIC	Percentage deviance explained	Additional deviance explained
year+tow type	23	351.30	10.97	10.97
vessel	16	329.73	16.68	5.71
year: tow type	21	326.31	17.85	1.17
depth	3	323.60	18.58	0.73
(month)	11	323.24	18.83	0.25

Binomial model

	Df	AIC	Percentage deviance explained	Additional deviance explained
year	22	21747.21	3.45	3.45
vessel	16	20134.20	10.77	7.32
depth	3	19951.18	11.61	0.84
(tow type)	1	19914.02	11.78	0.17
(month)	11	19883.06	12.02	0.24
(year:tow type)	21	19851.67	12.34	0.33

The model predictions showed a wide variation in catch rates among vessels (Figure 3, top), with a ratio of best to worst of 17.1 for the combined model. The degree of this variability and the magnitude of the ratio were influenced strongly by two of the four vessels added to the analysis since that of Francis (2001a), vessels M and Q. These vessels are relative newcomers to the fishery, having first fished in 1997 and 2001 respectively (see Appendix 1). The ratio of best to worst vessel catch rate, ignoring these vessels, reduces to 12.1. Also of interest is the comparatively low probability of a successful trawl for many vessels, with 6 of the 17 vessels failing to catch any orange roughy in more than half of the trawls they carried out.

Catch rates and the probability of a nonzero catch increased with depth to a maximum at about 750–800 m, then declined to minimum levels at about 1200 m. The peaks do not align exactly with the peak of the distribution of tow depths (Figure 3, middle), with most trawls occurring deeper than the depth of maximum catch rates and probabilities. The rapid rise in expected catch rates for depths greater than 1200 m is a typical outcome of the fitting requirements of the polynomial function and can generally be disregarded as this part of the curve is based on very few data points.

The binomial model has relatively little influence on the catch rates by year in the combined model, although there has been a strong trend in increasing probability of a nonzero catch since the low in 1995 (Figure 3, bottom). Expected catch rates for flat tows show a rapid decline between 1980 and 1990 and are low but variable up until the last estimated value in 1996. Similarly, expected catch rates for hill tows declined rapidly up until 1995 and have remained relatively constant since.

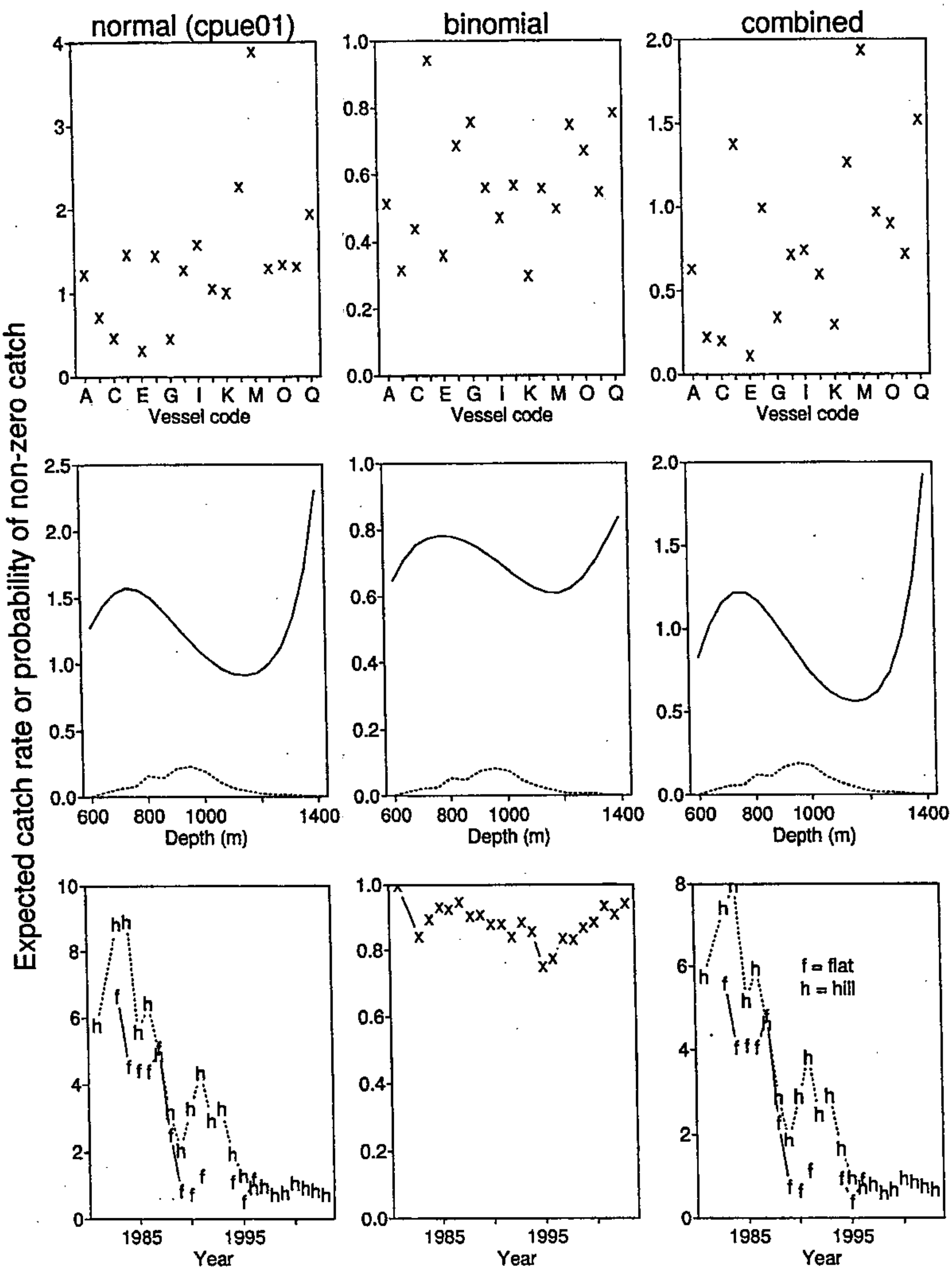


Figure 3: Model predictions by vessel (top), depth (middle), and year (bottom) for the initial normal (left), binomial (middle), and combined (right) models of Table 4. The variable coefficients upon which these plots are based were calculated by rerunning the models using the accepted predictors only. Unless specified, predictions are for hill tows by vessel N at depth 900 m in 1995. Dashed lines in the middle row show the overall distribution of tow depths. Predicted values in the bottom row are shown only where the number of observations is 50 or more.

Model diagnostics show that the binomial model fits well to the observed data. The means of expected proportions in intervals of 0.05 match closely the means of the equivalent observed values over most of the range of expected proportions (Figure 4, left). The other two plots in Figure 4 show how the $CPUE^{0.1}$ transformation is an improvement over log(CPUE), with the distribution of residuals from the $CPUE^{0.1}$ model closer to normal over the upper range of residual values than that from the log(CPUE) model. Although the $CPUE^{0.1}$ transformation under-compensates for the skewness in catch rates at the lower end of the range, this appears at least no worse than the overcompensation produced by the log(CPUE) transformation.

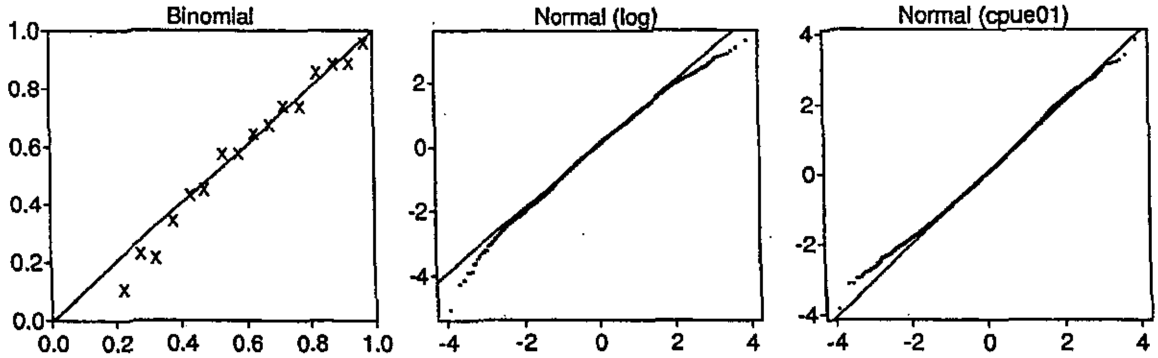


Figure 4: Model diagnostics for the binomial and normal models of Table 4, and for the normal model using a log(CPUE) transformation of catch rates. Accepted predictors only.

4. Because of the strong trends in the spatial distribution of the fishery over time and the link between tow type and location, it was necessary to test whether an area factor should be introduced into the models, and what areas to define for each tow type. Three potential dividing points were considered (north–south at 175.9° W, 178.2° W, and 179.1° W), based on the distribution of cumulative catches over time and the positions of the main hills, producing four potential sub-areas. These were the same as considered by Francis (2001a).

A stepwise regression procedure was followed, based on the normal model of Table 4 using the accepted predictors only, but with the 'tow type' factor converted into a 'stratum' factor with the levels being combinations of tow type and area. Each potential dividing point was tested in turn for each tow type at each step, with the best tow type/area split going forward to the next step and the process repeated until all eight levels of the stratum factor had been created, i.e., flat1, flat2, flat3, flat4, hill1, hill2, hill3, hill4. As in the initial model, only splits that explained at least an additional 0.5% deviance were accepted. Only one split was accepted by the model, a hill tow split at longitude 175.9° W (Table 5). Two further splits were very close to the 0.5% deviance increase threshold for inclusion; a further hill tow split at 178.2° W and a flat tow split at the same longitude as the accepted hill tow split (175.9° W). The first of these splits was accepted into the equivalent model in the previous analysis (Francis 2001a), providing an additional stratum (and therefore an additional CPUE series) for his final models. This is the main difference between this analysis and that of Francis (2001a), and leads to the South Rise orange roughy fishery being modelled as three separate stocks instead of four.

Table 5: Model results for stepwise selection of boundaries for the stratum factor (a combination of tow type and area).

	Tow type to split	Dividing Point	Percentage deviance explained	Additional deviance explained
Initial model			18.58	18.58
	hill	175.9° W	20.66	2.08
	hill	178.2° W	21.14	0.49
	flat	175.9° W	21.57	0.42
	flat	178.2° W	21.97	0.40
	hill	179.1° W	22.27	0.30
	flat	179.1° W	22.52	0.25

5. Having created the new factor 'stratum', the models were rerun to test that an interaction between stratum and year was acceptable, to retest all predictors with this new factor to produce a final set of predictors, and to determine final year effect indices. A stepwise procedure was again used in two model types, normal and binomial (Table 6). For both final models, the accepted predictors were the same as those selected in the initial models (with stratum replacing tow type) except for the addition of stratum and an interaction between year and stratum in the binomial model. The final models also explain slightly more variance than the equivalent initial models.

Table 6: Final predictor selection. Model fits for the normal and binomial models in the stepwise order determined by AIC. Predictors in parentheses not accepted.

Normal model

	Df	AIC	Percentage deviance explained	Additional deviance explained
year+stratum	24	346.75	12.13	12.13
vessel	16	324.31	18.06	5.93
year:stratum	36	319.70	19.74	1.68
depth	3	316.27	20.66	0.92
(month)	11	316.02	20.87	0.22

Binomial model

	Df	AIC	Percentage deviance explained	Additional deviance explained
year	22	21747.21	3.45	3.45
vessel	16	20134.20	10.77	7.32
stratum	2	19861.58	12.00	1.23
year:stratum	36	19693.10	13.07	1.07
depth	3	19586.12	13.57	0.50
(month)	11	19561.00	13.78	0.21

Estimated catch rates by year and stratum for the combined final model are shown in Figure 5. For the flat1 stratum catch rates are very similar to those shown in Figure 3. The two hill strata (hill1, 172° E–175.9° W; hill2, 175.9° W–175° W, see Figure 1) show a different pattern of catch rates over time, particularly for the early part of their period of overlap, but both show an initial increase in catch rates followed by a steady decline and a levelling off in more recent years.

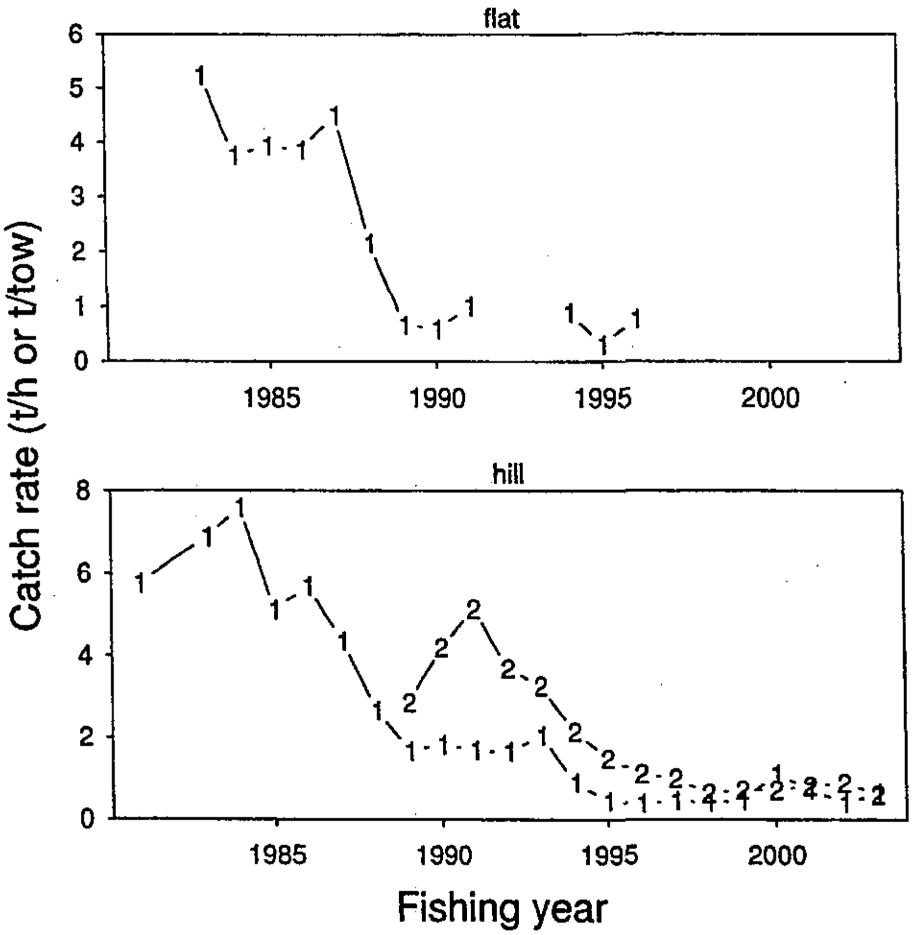


Figure 5: Expected catch rates by year for the single flat and two hill strata in the final combined model described in Table 6. Values are not plotted for year stratum combinations based on less than 50 observations.

6. Sampling error c.v.s were calculated for the final year indices using a bootstrap procedure as follows (after Francis 2001a). The model data were resampled to create 500 simulated data sets from which the normal and binomial models (Table 6) were fitted and expected catch rates were derived. The catch rates were converted to their canonical form (by dividing by the series mean) to remove the influence of the reference year, producing the three sets of standardised cpue indices used in the assessment model. Coefficients of variation were then calculated for each year/stratum represented by more than 50 tows, from the 500 canonical catch rate estimates. These are shown in Table 7.

Table 7: Estimated catch rates (t/tow for hill tows, t/h for flat tows), c.v.s, and numbers of non-zero tows (n) based on vessel N fishing at depth 900 m in July, by year and stratum for the final combined normal/binomial model described in Table 6. No estimates were made where n<50.

	flat1			hill1			hill2		
	Catch rate	c.v.	n	Catch rate	c.v.	n	Catch rate	c.v.	n
1981	-	-	10	5.76	0.10	78	-	-	0
1983	5.23	0.12	79	6.90	0.14	62	-	-	0
1984	3.76	0.09	188	7.60	0.09	118	-	-	0
1985	3.93	0.06	367	5.11	0.09	169	-	-	0
1986	3.86	0.08	314	5.69	0.09	245	-	-	0
1987	4.51	0.08	334	4.36	0.09	246	-	-	0
1988	2.14	0.07	569	2.67	0.07	482	-	-	2
1989	0.67	0.08	710	1.67	0.07	856	2.86	0.11	185
1990	0.58	0.11	212	1.84	0.07	550	4.21	0.07	566
1991	0.99	0.17	84	1.69	0.11	178	5.12	0.07	457
1992	-	-	19	1.65	0.12	138	3.69	0.11	143
1993	-	-	17	2.05	0.11	185	3.26	0.06	603
1994	0.88	0.15	79	0.89	0.08	337	2.14	0.07	631
1995	0.31	0.20	57	0.43	0.12	183	1.48	0.09	349
1996	0.77	0.21	57	0.38	0.16	129	1.11	0.13	168
1997	-	-	34	0.45	0.17	116	0.99	0.14	174
1998	-	-	38	0.42	0.14	178	0.63	0.12	257
1999	-	-	32	0.45	0.17	110	0.71	0.12	174
2000	-	-	5	1.10	0.24	70	0.71	0.21	107
2001	-	-	7	0.75	0.18	126	0.81	0.17	219
2002	-	-	5	0.39	0.22	100	0.88	0.14	241
2003	-	-	13	0.64	0.17	101	0.60	0.15	304

4.3 Catches and catch overruns

Annual catches used in the assessment model were derived from official catches for ORH 3B and estimated (TCEPR) catches for the South Rise following the methods described in the previous assessment (Francis 2001b) (Table 8). Briefly, this involved multiplying TCEPR catches for each area by the annual ratio of official catches to TCEPR catches for all of ORH 3B. This process was necessary to scale estimated (TCEPR) catches, which could be summed separately for each Chatham Rise fishery and the subareas used in this assessment, to match the official totals, which could not.

There has been a history of catch overruns (additional catch or fishing mortality unaccounted for in reported landings) on the Chatham Rise due to fish losses through gear damage, discarding, and discrepancies in tray weights and conversion factors (Annala and Sullivan 1997). Total removals were assumed to exceed reported catches by the overrun percentages in Table 8.

Table 8: Estimated catches used in the model, and the overrun percentages used to calculated them.

	Catch (t)				Overruns
Year	flat1	hill1	hill2	All	(%)
1979	22	0	0	22	30
1980	676	113	0	789	30
1981	1 599	4 731	0	6 330	30
1982	386	43	0	429	30
1983	5 051	5 584	0	10 634	30
1984	4 104	3 704	0	7 808	30
1985	6 624	3 773	0	10 396	30
1986	3 505	3 354	0	6 858	28
1987	3 740	2 205	0	5 945	26
1988	3 554	4 804	73	8 431	24
1989	3 217	6 329	1 651	11 197	22
1990	992	4 373	7 787	13 152	20
1991	515	2 316	5 093	7 925	15
1992	198	1 014	1 075	2 287	10
1993	131	1 307	4 534	5 972	10
1994	268	1 147	4 093	5 509	10
1995	98	462	1 113	1 673	5
1996	212	407	741	1 361	5
1997	107	542	834	1 483	5
1998	82	464	1 093	1 639	5
1999	143	459	684	1 285	5
2000	89	591	537	1 217	5
2001	64	554	1 170	1 788	5
2002	17	340	815	1 172	5
2003	62	399	1 119	1 580	5
2004	62	399	1 119	1 580	5

5. STOCK ASSESSMENT

5.1 Model description and assumptions

An age-based model was fitted using Bayesian estimation in the CASAL stock assessment program (Bull et al. 2003) to recreate the history of the stock from the beginning of the fishery. The model assumed the fishery comprised three separate stocks; f1, fish residing in area flat1 (less than 5 km from the peak of any known hill); h1, fish residing in area hill1 (less than or equal to 5km from the peak of any hill between 172° E and 175.9° W); and h2, fish residing in area hill2 (less than or equal to 5km from the peak of any hill between 175.9° W to 175° W). Model outputs for each stock were summed to produce biomass estimates for the fishery as a whole. It was assumed that no net migration took place between the three stocks.

The South Rise stock population was partitioned in the model into age-groups 1–70, with a plus group, 70+. The population was also partitioned by sex, with the sex ratio of recruits assumed to be 50:50, and by maturity (the fishery was assumed to act on mature fish only). The model applied a single maturation episode, with maturation modelled by a logistic producing ogive (Bull et al. 2003) in which 50% of fish of both sexes were mature at age 28.8 and 95% at age 35.3. Age at recruitment was equal to age at maturity in the model, and annual recruitment was assumed to be constant.

Annual catches and a separate CPUE time series (with assumed lognormal errors) were supplied for each stock. The c.v.s for the CPUE indices were derived by adding a process-error c.v. of 0.16 to the sampling error (after Francis 2001b, Francis et al. 2001). An attempt to estimate the process-error c.v. within the stock-assessment model produced an implausibly high value of 0.60.

The instantaneous mortality catch equation was used. This first applies half the natural mortality, followed by all of the fishing mortality, and then the remaining natural mortality. Growth was modelled using the von Bertalanffy Growth formula, with parameters K=0.083 (m) and 0.073 (f), L_∞=34.9 (m) and 37.6 (f), t_0=-0.4 (m) and -0.6 (f) (Table 2).

The annual cycle of model processes took place in the following order:

- ageing
- recruitment
- maturation
- migration (where modelled)
- mortality (natural and fishing)

In sensitivity runs, a curvature parameter (β) was estimated for CPUE. This allows the relationship between biomass and CPUE to be non-linear (see Annala et al. (2004), p. 324 for more information on the use of this parameter in orange roughy assessments). In addition, an attempt to model migration between areas was made. In this case β was not estimated and the fishery was modelled as a single stock with movement of fish between areas allowed.

The model estimated virgin biomass (B_0) and catchability (q) parameters for each stock (a total of six parameters). When β was also estimated, the number of parameters increased to between seven and nine. A penalty function was incorporated into the estimation procedure to discourage the model from allowing the stock biomass to drop below a level at which the historical catch could not have been taken. Parameters and their uncertainty, and forward projections, were evaluated using Markov Chain Monte Carlo (MCMC) techniques using 1000 samples from a chain of length 1 million.

5.2 Sensitivity runs

A number of alternative model runs were considered to determine the sensitivity of biomass estimates to the model assumptions. The two models considered by the Deepwater Fisheries Assessment Working Group and reported in the Plenary Report (Annala et al. 2004) were:

1. *Beta1*: Initial model with β set to 1 for each stock.
2. *EstBeta*: Initial model with 2 separate estimates of β, one for stock f1 and one for stocks h1 and h2 combined.

A third model, testing the effect of an assumed migration pathway was also trialled.

3. *Migr*: Initial model with the fishery treated as a single stock, but allowing an annual cycle of movement of fish between areas in the following steps.

    1) 50% of mature fish migrate from each area to distant spawning grounds
    2) Following spawning (and recruitment) all fish migrate from the spawning grounds to area flat1
    3) A density-dependent migration takes place from flat1 to hill2
    4) A density-dependent migration takes place from flat1 to hill1

The magnitude of the migrations in steps 3 and 4 was determined by a 3-parameter density dependence function as described by Bull et al. (2003). The parameter P relates to the fraction of fish migrating from the source area, parameter S is a measure of the density-dependent pressure to migrate from the source area, and parameter D is a measure of the density-dependent pressure to migrate into the source area.

5.3 Model results

For the *Beta1* assessment, B_0 was estimated to be 94 900 t (Table 9). The biomass was estimated to have reached a minimum of 15 100 t (16% B_0) in 1995, and to have subsequently rebuilt to 27 900 t (29% B_0) in 2003–04. This model showed that most of the depletion occurred in hill2, where biomass declined to the current level of 12% B_0, whereas current biomass in the other two areas is estimated to be 30–40% of B_0.

For the *EstBeta* assessment, the estimates of the curvature parameter (β) were slightly less than 1 for flat1 (0.96, implying that biomass declines slightly faster than CPUE), and considerably greater than 1 for the two combined hill areas (1.64, implying that biomass declines more slowly than CPUE). The estimate of B_0 was almost 20% greater than for *Beta1* (112 900 t) (Table 9) with a minimum biomass of 32 400 t (29% B_0) in 1995, followed by a rebuild to 46 300 t (41% B_0) in 2003–04. In this model, depletion was more even among areas (35–43% B_0) with the strong hyperdepletion (β greater than 1) modelled for the two hill areas producing a much more optimistic assessment. This assessment fitted the data only slightly better than *Beta1* (the objective function decreased by 2 for an additional two parameters), (Table 10).

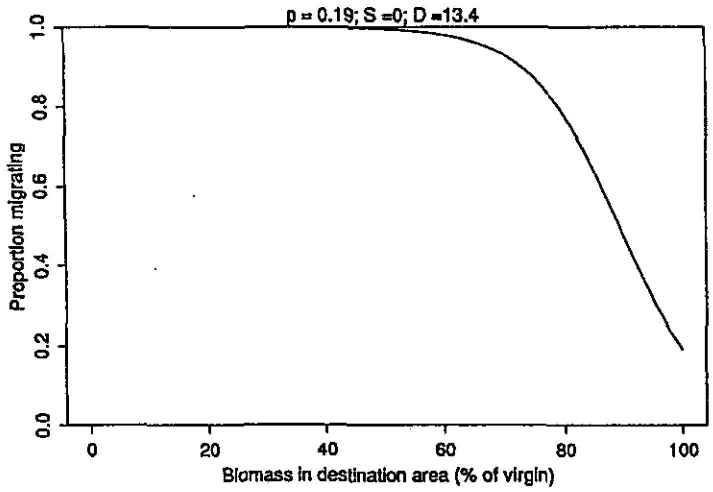
The objective function was much lower in the *Migr* model than in the *Beta1* and *EstBeta* assessments, with the objective function 30 units less for the same number of estimated parameters. Although much of this was due to treating the fishery as a single stock, considerable improvement in the fit to the CPUE indices was achieved, especially in area hill1. This model was the least optimistic of the three, with the overall current biomass ($B_{current}$) estimated to be 25% of B_0 (virgin biomass was not calculated for each area separately). In initial model runs, the estimation of parameters S in the flat1→hill2 migration and D in the flat1→hill1 migration was constrained by their upper (S) and lower (D) allowable limits (both 0), and the parameters were subsequently fixed at that value (Table 10). The model predicted that in years when biomass in hill2 was less than about 50% of virgin, the flat1→hill2 migration (driven solely by fish density in hill2) comprised virtually all fish (Figure 6). The fraction of fish migrating decreased rapidly for increasing relative biomass in hill2. In contrast, the fraction of fish subsequently migrating from flat1→hill1 (driven solely by fish density in flat1) was constant at all levels of relative biomass in hill1, at about 60%.

Table 9: Estimates of biomass (MCMC sample medians) for the South Rise, for each of three alternative models (95% confidence intervals are shown in parentheses for all areas combined for the two models considered by the Deepwater Fisheries Assessment Working Group). $B_{current}$ is the mid-year biomass in 2003–04; –, not calculated.

				Area
	flat1	hill1	hill2	All
B_0 (t)				
Beta1	30 400	38 700	25 600	94 900 (93 300–96 800)
EstBeta	30 900	46 600	34 300	112 900 (99 600–156 400)
Migr	–	–	–	90 200
$B_{current}$ (t)				
Beta1	12 800	11 800	3 200	27 900 (26 200–29 900)
EstBeta	13 300	20 000	12 000	46 300 (32 700–90 000)
Migr	–	–	–	22 584
$B_{current}$ (% B_0)				
Beta1	42	30	12	29 (28–31)
EstBeta	43	43	35	41 (33–57)
Migr	–	–	–	25

Table 10: Summary of non-biomass model results, objective function components and parameter estimates (MCMC sample medians). Values marked * were fixed at that value.

Model run	Base	EstB	Migr
OBJF components			
CPUE f1	20.0	20.0	24.5
CPUE h1	87.8	77.2	67.5
CPUE h2	0.8	8.6	5.0
All CPUE	108.6	105.7	96.9
B_0	31.0	31.4	10.7
Penalties	0	0	0.02
Sum	145	143	113
Parameters			
β (f1)	1*	0.96	1*
β (h1)	1*	1.64	1*
β (h2)	1*	1.64	1*
P (flat1→hill2)	—	—	0.19
S (flat1→hill2)	—	—	0*
D (flat1→hill2)	—	—	13.4
P (flat1→hill1)	—	—	0.64
S (flat1→hill1)	—	—	-0.19
D (flat1→hill1)	—	—	0*



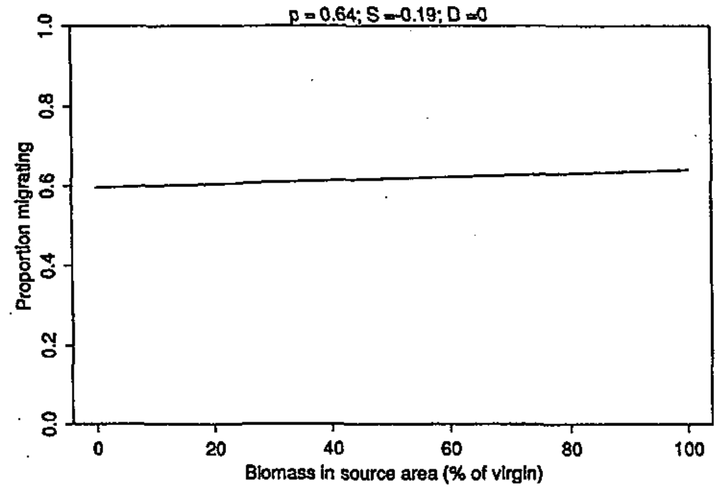


Figure 6: *Migr* model. Proportion of fish migrating from flat1 to hill2 at different levels of depletion in hill2 (top) and proportion of fish subsequently migrating from flat1 to hill 1 at different levels of depletion in flat1 (bottom).

A feature common to both the *Beta1* and *EstBeta* models is the contradiction between the CPUE indices and the biomass trajectories in the flat1 and hill1 areas. Whereas the CPUE indices in these areas show no trend in the final several years of each series, the models predict increasing biomass (Figure 7). This is due to a combination of the assumption of constant (virgin fishery level) recruitment in each area, and low recent catches (the fishery is now strongly focussed in area hill2). The biomass trajectory matches the trend in CPUE indices much better for the currently most important hill2 area. The biomass trajectory matches CPUE in hill1 much better in the *Migr* model than in *Beta1* and *EstBeta*, but there is no obvious improvement in the fit for the other two areas.

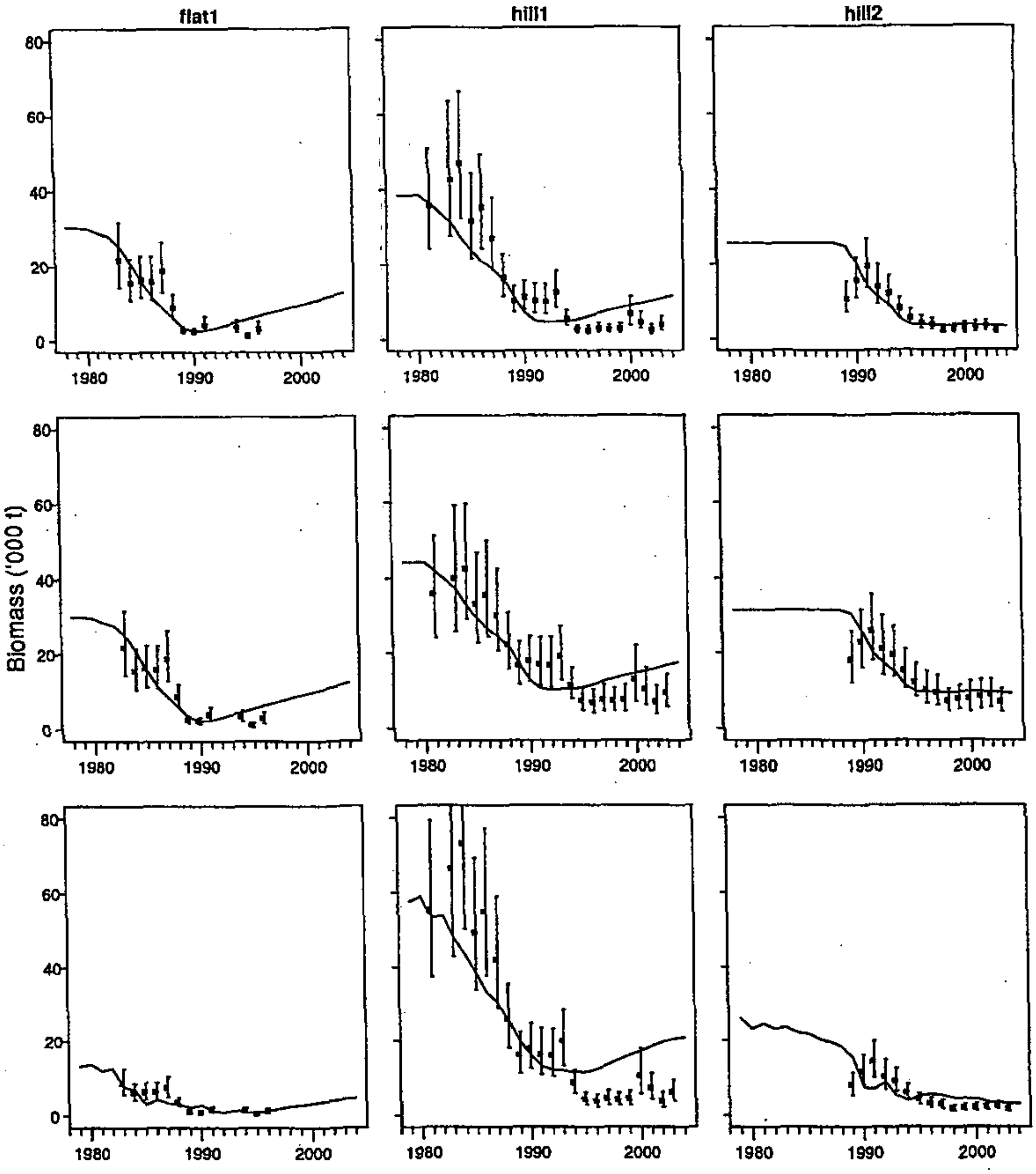


Figure 7: Estimated biomass trajectories (maximum posterior density (MPD) estimates) for each area of the South Rise fishery, from the *Beta1* (top), *EstBeta* (middle), and *Migr* (bottom) model runs. CPUE indices (scaled to the biomass) are shown along with 95% confidence intervals.

5.4 Forward projections

Forward projections were calculated for only the two alternative model runs considered by the Deepwater Fisheries Assessment Working Group (*Beta1* and *EstBeta*). Projections were carried out over a 5-year period (to 2008–09) using a range of constant-catch options with the catch for the current year (2003–04) set equal to the 2002–03 catch. Three constant-catch options were used: the current catch limit (1400 t); 1.5 times this limit (2100 t); and twice the limit (2800 t). The catch in each year was split amongst the three areas in the same proportion as the average for the three most recent completed fishing years. Mid-year biomass is expected to exceed 30% B_0 at all levels of projected annual catch in the *EstBeta* assessment, but only at a level of 1400 t in the *Beta1* assessment (Table 11). In the *Beta1* assessment, catches of 2100 t were unable to be taken from the hill2 sector in more than 5% of the simulations (and catches of 2800 t in none of the simulations) because of the low current biomass (see Table 9), and dependence of the fishery (see Table 8), in this sector.

Table 11: Probability of the mid-year spawning biomass in 2008–09 exceeding 20% B_0 ($P_{0.2}$) and 30% B_0 ($P_{0.3}$), and the median biomass in 2008–09 as a percentage of B_0 (Bmed) for the South Rise stock for each of the Beta1 and Estbeta assessments and three constant catch options. The current biomass, $B_{2003-04}/B_0$ (%), is given in parentheses next to the assessment name for Bmed. Performance measures are shown only for assessment /annual catch combinations in which there was sufficient biomass in each sector for the catch to able to be taken in 90% or more of the simulations.

		Annual catch (t, over 5-year period)		
Performance measure	Assessment	1400*	2100	2800
$P_{0.2}$	Beta1	1.000	–	–
$P_{0.2}$	EstBeta	1.000	1.000	1.000
$P_{0.3}$	Beta1	1.000	–	–
$P_{0.3}$	EstBeta	1.000	1.000	1.000
Bmed	Beta1 (29)	35.1	–	–
Bmed	EstBeta (41)	46.0	43.3	40.5

* current catch limit

6. DISCUSSION

As reported by Annala et al. (2004), the limited information available for this fishery makes the current status of this stock uncertain. Changes in the fishing patterns throughout the history of the fishery necessitated the production of separate CPUE indices for three sectors of the fishery, but no information is available about the movement of fish between these sectors. The lack of agreement between the assessment results, which indicate rebuilding over the past 15 years to levels of between 29% and 41% B_0, and the CPUE data, undermines confidence in the yield estimates (not presented) and forward projections.

One of the central assumptions in the two assessments considered by the Deepwater Fisheries Assessment Working Group (*Beta1* and *EstBeta*) is that there is no net migration of fish between the three stocks modelled. Although this assumption does not appear realistic, and attempts to model migration within this fishery were able to produce a better fit to the available data, it was accepted because of uncertainty about the migration pathways proposed in the *Migr* model. Further modelling of migration in this fishery, using alternative pathways or migration formulae, or incorporating knowledge of real migration pathways from direct research, is required to ultimately complete the 3-area approach to stock assessment in this fishery, an approach which is likely to remain necessary as long as CPUE indices are the only abundance estimates available. The Deepwater Fisheries Assessment Working Group has recommended that examination of alternative migration models be incorporated into future stock assessment research for this stock.

7. ACKNOWLEDGMENTS

This work was funded by the Ministry of Fisheries (Project ORH2003/02). Thanks to Chris Francis, Matthew Dunn, and Andy McKenzie (all NIWA) for their assistance and advice. Andy also provided a useful review of a draft of this report. Thanks also to Allan Hicks for providing updated growth and maturity parameters.

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Appendix 1: Number of tows by fishing vessel and fishing year for vessels used in the CPUE standardisation. The vessel codes, A–Q, are derived from vessel ID codes on the catch-effort database and are ordered according to the mean fishing year from all records for each vessel.

	Vessel code																
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
1981	89	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1982	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1983	19	88	97	38	0	0	0	0	0	0	0	0	0	0	0	0	0
1984	36	155	121	112	0	0	9	0	0	0	0	0	0	0	0	0	0
1985	183	231	107	72	11	0	96	0	0	0	0	0	0	0	0	0	0
1986	0	361	197	58	11	0	156	0	0	0	0	0	0	0	0	0	0
1987	0	211	125	17	105	0	153	0	129	0	0	0	0	0	0	0	0
1988	0	195	100	173	143	0	204	282	308	35	0	0	0	0	0	0	0
1989	0	412	251	238	52	115	270	518	340	179	31	0	0	0	0	0	0
1990	0	120	3	86	43	145	320	541	414	64	127	0	0	0	0	0	0
1991	0	2	130	0	21	73	249	225	93	98	120	0	0	0	0	0	0
1992	0	0	0	0	0	0	60	144	102	62	125	0	0	0	0	0	0
1993	0	0	0	0	0	0	88	449	63	212	369	0	0	0	0	0	0
1994	0	0	0	0	0	0	171	456	407	258	328	0	0	0	0	0	0
1995	0	0	0	0	0	0	224	174	322	232	141	49	0	0	0	0	0
1996	0	0	0	0	0	0	0	212	269	20	164	19	0	58	0	0	0
1997	0	0	0	0	0	0	0	0	111	32	177	106	9	120	0	0	0
1998	0	0	0	0	0	0	0	0	114	133	195	50	100	123	61	0	0
1999	0	0	0	0	0	0	0	0	117	118	0	65	84	14	46	0	0
2000	0	0	0	0	0	0	0	0	44	0	0	35	0	18	5	138	0
2001	0	0	0	0	0	0	0	0	48	0	0	0	39	50	49	159	63
2002	0	0	0	0	0	0	0	0	25	0	0	0	0	94	39	201	51
2003	0	0	0	0	0	0	0	0	33	0	0	22	0	137	9	186	77

Appendix 2: CASAL input files

```
################################################################################
#POPULATION FILE (Beta1 and EstBeta case)
################################################################################

#INITIALISATION
@initialization f1
B0 3e4
@initialization h1
B0 4e4
@initialization h2
B0 3e4

#PARTITION
@size_based F
@min_age 1
@max_age 70
@plus_group T
@sex_partition T
@mature_partition T
@n_areas 3
@area_names flat1 hill1 hill2
@n_stocks 3
@stock_names f1 h1 h2

#EXCLUSIONS
@exclusions_char1 stock stock stock stock stock stock
@exclusions_val1 f1 f1 h1 h1 h2 h2
@exclusions_char2 area area area area area area
@exclusions_val2 hill1 hill2 flat1 hill2 flat1 hill1

#TIME SEQUENCE
@initial 1979
@current 2004
```

```
@final 2009
@annual_cycle
time_steps 1
recruitment_time 1
recruitment_areas flat1 hill1 hill2
aging_time 1
n_migrations 0
M_props 1
fishery_names f1fishery h1fishery h2fishery
fishery_areas flat1 hill1 hill2
fishery_times 1 1 1
n_maturations 1
maturation_times 1
spawning_time 1
spawning_areas flat1 hill1 hill2
spawning_p 1
spawning_part_mort 0.5
baranov F

#RECRUITMENT
@y_enter 1
@recruitment f1
YCS_years 1978 1979 1980 1981 1982 1983 1984 1985 1986 1987 1988 1989 1990 1991 1992 1993 1994
1995 1996 1997 1998 1999 2000 2001 2002 2003
YCS          1    1    1    1    1    1    1    1    1    1    1    1    1    1    1    1    1
1    1    1    1    1    1    1    1    1
n_rinitial 0
SR none
p_male 0.5
sigma_r 1.1
@recruitment h1
YCS_years 1978 1979 1980 1981 1982 1983 1984 1985 1986 1987 1988 1989 1990 1991 1992 1993 1994
1995 1996 1997 1998 1999 2000 2001 2002 2003
YCS          1    1    1    1    1    1    1    1    1    1    1    1    1    1    1    1    1
1    1    1    1    1    1    1    1    1
n_rinitial 0
SR none
p_male 0.5
sigma_r 1.1
@recruitment h2
YCS_years 1978 1979 1980 1981 1982 1983 1984 1985 1986 1987 1988 1989 1990 1991 1992 1993 1994
1995 1996 1997 1998 1999 2000 2001 2002 2003
YCS          1    1    1    1    1    1    1    1    1    1    1    1    1    1    1    1    1
1    1    1    1    1    1    1    1    1
n_rinitial 0
SR none
p_male 0.5
sigma_r 1.1

#RECRUITMENT VARIABILITY
@randomisation_method lognormal

#NATURAL MORTALITY
@natural_mortality
male    0.045
female  0.045

#FISHING
@fishery f1fishery
years   1979 1980 1981 1982 1983 1984 1985 1986 1987 1988 1989 1990 1991 1992 1993 1994 1995
1996 1997 1998 1999 2000 2001 2002 2003 2004
catches  22 676 1599 386 5051 4104 6624 3505 3740 3554 3217 992 515 198 131 268 98 212 107 82
143 89 64 17 62 62
selectivity sel_spawn
U_max 0.67
@fishery h1fishery
years   1979 1980 1981 1982 1983 1984 1985 1986 1987 1988 1989 1990 1991 1992 1993 1994 1995
1996 1997 1998 1999 2000 2001 2002 2003 2004
catches  0 113 4731 43 5584 3704 3773 3354 2205 4804 6329 4373 2316 1014 1307 1147 462 407 542
464 459 591 554 340 399 399
selectivity sel_spawn
U_max 0.67
@fishery h2fishery
years   1979 1980 1981 1982 1983 1984 1985 1986 1987 1988 1989 1990 1991 1992 1993 1994 1995
1996 1997 1998 1999 2000 2001 2002 2003 2004
catches    0    0    0    0    0    0    0    0    0   73 1651 7787 5093 1075 4534 4093 1113
741  834 1093  684  537 1170  815 1119 1119
```

```
selectivity sel_spawn
U_max 0.67

#SELECTIVITIES
@selectivity_names sel_spawn
@selectivity sel_spawn
mature constant 1
immature constant 0

#SIZE AT AGE
@size_at_age_type von_Bert
@size_at_age
k_male 0.083
t0_male -0.4
Linf_male 34.9
k_female 0.073
t0_female -0.6
Linf_female 37.6

#MATURATION
@maturation
rates_all   logistic_producing 22 36   28.8 6.5

#SIZE WEIGHT
@size_weight
a 9.21e-08
b 2.71


################################################################################
#ESTIMATION FILE (Beta1 cases)
################################################################################

#ESTIMATION
@estimator Bayes
@max_iters 300
@max_evals 1000

#OBSERVATIONS
@relative_abundance cpuef1
curvature T    #but fixed at 1
biomass T
q qcpuef1
years 1983 1984 1985 1986 1987 1988 1989 1990 1991 1994 1995 1996
step 1
proportion_mortality 0.5
area flat1
ogive sel_spawn
1983 5.23
1984 3.76
1985 3.93
1986 3.86
1987 4.51
1988 2.14
1989 0.67
1990 0.58
1991 0.99
1994 0.88
1995 0.31
1996 0.77
dist lognormal
cv_1983 0.20
cv_1984 0.18
cv_1985 0.17
cv_1986 0.18
cv_1987 0.18
cv_1988 0.17
cv_1989 0.18
cv_1990 0.19
cv_1991 0.23
cv_1994 0.22
cv_1995 0.26
cv_1996 0.26
@relative_abundance cpueh1
curvature T
biomass T
```

```
q qcpueh1
years 1981 1983 1984 1985 1986 1987 1988 1989 1990 1991 1992 1993 1994 1995 1996 1997 1998
1999 2000 2001 2002 2003
step 1
proportion_mortality 0.5
area hill1
ogive sel_spawn
1981 5.76
1983 6.90
1984 7.60
1985 5.11
1986 5.69
1987 4.36
1988 2.67
1989 1.67
1990 1.84
1991 1.69
1992 1.65
1993 2.05
1994 0.89
1995 0.43
1996 0.38
1997 0.45
1998 0.42
1999 0.45
2000 1.10
2001 0.75
2002 0.39
2003 0.64
dist lognormal
cv_1981 0.19
cv_1983 0.21
cv_1984 0.18
cv_1985 0.18
cv_1986 0.18
cv_1987 0.18
cv_1988 0.17
cv_1989 0.17
cv_1990 0.17
cv_1991 0.19
cv_1992 0.20
cv_1993 0.19
cv_1994 0.18
cv_1995 0.20
cv_1996 0.23
cv_1997 0.23
cv_1998 0.21
cv_1999 0.23
cv_2000 0.29
cv_2001 0.24
cv_2002 0.27
cv_2003 0.23
@relative_abundance cpueh2
curvature T
biomass T
q qcpueh2
years 1989 1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003
step 1
proportion_mortality 0.5
area hill2
ogive sel_spawn
1989 2.86
1990 4.21
1991 5.12
1992 3.69
1993 3.26
1994 2.14
1995 1.48
1996 1.11
1997 0.99
1998 0.63
1999 0.71
2000 0.71
2001 0.81
2002 0.88
2003 0.60
dist lognormal
```

```
cv_1989 0.19
cv_1990 0.17
cv_1991 0.17
cv_1992 0.19
cv_1993 0.17
cv_1994 0.17
cv_1995 0.18
cv_1996 0.21
cv_1997 0.21
cv_1998 0.20
cv_1999 0.20
cv_2000 0.26
cv_2001 0.23
cv_2002 0.21
cv_2003 0.22

#RELATIVITY CONSTANTS
@q_method free
@q qcpuef1
q  1
b  1
@q qcpueh1
q  1
b  1
@q qcpueh2
q  1
b  1
@estimate
parameter q[qcpuef1].b
same q[qcpueh1].b q[qcpueh2].b
lower_bound 1
upper_bound 1
prior lognormal
mu 0.85
cv 1.41

#FREE PARAMETERS
@estimate
parameter q[qcpuef1].q
lower_bound 1e-6
upper_bound 20
prior uniform-log
@estimate
parameter q[qcpueh1].q
lower_bound 1e-6
upper_bound 20
prior uniform-log
@estimate
parameter q[qcpueh2].q
lower_bound 1e-6
upper_bound 20
prior uniform-log
@estimate
parameter initialization[f1].B0
lower_bound 3e3
upper_bound 3e5
prior uniform-log
@estimate
parameter initialization[h1].B0
lower_bound 4e3
upper_bound 4e5
prior uniform-log
@estimate
parameter initialization[h2].B0
lower_bound 3e3
upper_bound 3e5
prior uniform-log

#PENALTIES
@catch_limit_penalty
label f1fisheryCatchMustBeTaken
fishery f1fishery
log_scale T
multiplier 1000
@catch_limit_penalty
label h1fisheryCatchMustBeTaken
```

```
fishery h1fishery
log_scale T
multiplier 1000
@catch_limit_penalty
label h2fisheryCatchMustBeTaken
fishery h2fishery
log_scale T
multiplier 1000


##############################################################################
#ESTIMATION FILE (EstBeta case)
##############################################################################

#ESTIMATION
@estimator Bayes
@max_iters 300
@max_evals 1000

#OBSERVATIONS
@relative_abundance cpuef1
curvature T
biomass T
q qcpuef1
years 1983 1984 1985 1986 1987 1988 1989 1990 1991 1994 1995 1996
step 1
proportion_mortality 0.5
area flat1
ogive sel_spawn
1983 5.23
1984 3.76
1985 3.93
1986 3.86
1987 4.51
1988 2.14
1989 0.67
1990 0.58
1991 0.99
1994 0.88
1995 0.31
1996 0.77
dist lognormal
cv_1983 0.20
cv_1984 0.18
cv_1985 0.17
cv_1986 0.18
cv_1987 0.18
cv_1988 0.17
cv_1989 0.18
cv_1990 0.19
cv_1991 0.23
cv_1994 0.22
cv_1995 0.26
cv_1996 0.26
@relative_abundance cpueh1
curvature T
biomass T
q qcpueh1
years 1981 1983 1984 1985 1986 1987 1988 1989 1990 1991 1992 1993 1994 1995 1996 1997 1998
1999 2000 2001 2002 2003
step 1
proportion_mortality 0.5
area hill1
ogive sel_spawn
1981 5.76
1983 6.90
1984 7.60
1985 5.11
1986 5.69
1987 4.36
1988 2.67
1989 1.67
1990 1.84
1991 1.69
1992 1.65
1993 2.05
1994 0.89
```

```
1995 0.43
1996 0.38
1997 0.45
1998 0.42
1999 0.45
2000 1.10
2001 0.75
2002 0.39
2003 0.64
dist lognormal
cv_1981 0.19
cv_1983 0.21
cv_1984 0.18
cv_1985 0.18
cv_1986 0.18
cv_1987 0.18
cv_1988 0.17
cv_1989 0.17
cv_1990 0.17
cv_1991 0.19
cv_1992 0.20
cv_1993 0.19
cv_1994 0.18
cv_1995 0.20
cv_1996 0.23
cv_1997 0.23
cv_1998 0.21
cv_1999 0.23
cv_2000 0.29
cv_2001 0.24
cv_2002 0.27
cv_2003 0.23
@relative_abundance cpueh2
curvature T
biomass T
q qcpueh2
years 1989 1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003
step 1
proportion_mortality 0.5
area hill2
ogive sel_spawn
1989 2.86
1990 4.21
1991 5.12
1992 3.69
1993 3.26
1994 2.14
1995 1.48
1996 1.11
1997 0.99
1998 0.63
1999 0.71
2000 0.71
2001 0.81
2002 0.88
2003 0.60
dist lognormal
cv_1989 0.19
cv_1990 0.17
cv_1991 0.17
cv_1992 0.19
cv_1993 0.17
cv_1994 0.17
cv_1995 0.18
cv_1996 0.21
cv_1997 0.21
cv_1998 0.20
cv_1999 0.20
cv_2000 0.26
cv_2001 0.23
cv_2002 0.21
cv_2003 0.22

#RELATIVITY CONSTANTS
@q_method free
@q qcpuef1
q  1
```

```
b 1
@q qcpueh1
q 1
b 1
@q qcpueh2
q 1
b 1

#FREE PARAMETERS
@estimate
parameter q[qcpuef1].b
lower_bound 0.01
upper_bound 5
prior lognormal
mu 0.85
cv 1.41
@estimate
parameter q[qcpueh1].b
same q[qcpueh2].b
lower_bound 0.01
upper_bound 5
prior lognormal
mu 0.85
cv 1.41
@estimate
parameter q[qcpuef1].q
lower_bound 1e-6
upper_bound 20
prior uniform-log
@estimate
parameter q[qcpueh1].q
lower_bound 1e-6
upper_bound 20
prior uniform-log
@estimate
parameter q[qcpueh2].q
lower_bound 1e-6
upper_bound 20
prior uniform-log
@estimate
parameter initialization[f1].B0
lower_bound 3e3
upper_bound 3e5
prior uniform-log
@estimate
parameter initialization[h1].B0
lower_bound 4e3
upper_bound 4e5
prior uniform-log
@estimate
parameter initialization[h2].B0
lower_bound 3e3
upper_bound 3e5
prior uniform-log

#PENALTIES
@catch_limit_penalty
label f1fisheryCatchMustBeTaken
fishery f1fishery
log_scale T
multiplier 1000
@catch_limit_penalty
label h1fisheryCatchMustBeTaken
fishery h1fishery
log_scale T
multiplier 1000
@catch_limit_penalty
label h2fisheryCatchMustBeTaken
fishery h2fishery
log_scale T
multiplier 1000
```

Appendix 3: MCMC traces

Figure A3–1. ***Beta1*** **case. Sample values are plotted for the relativity constants (q, left column) and virgin biomass (B_0 right column) for each stock.**

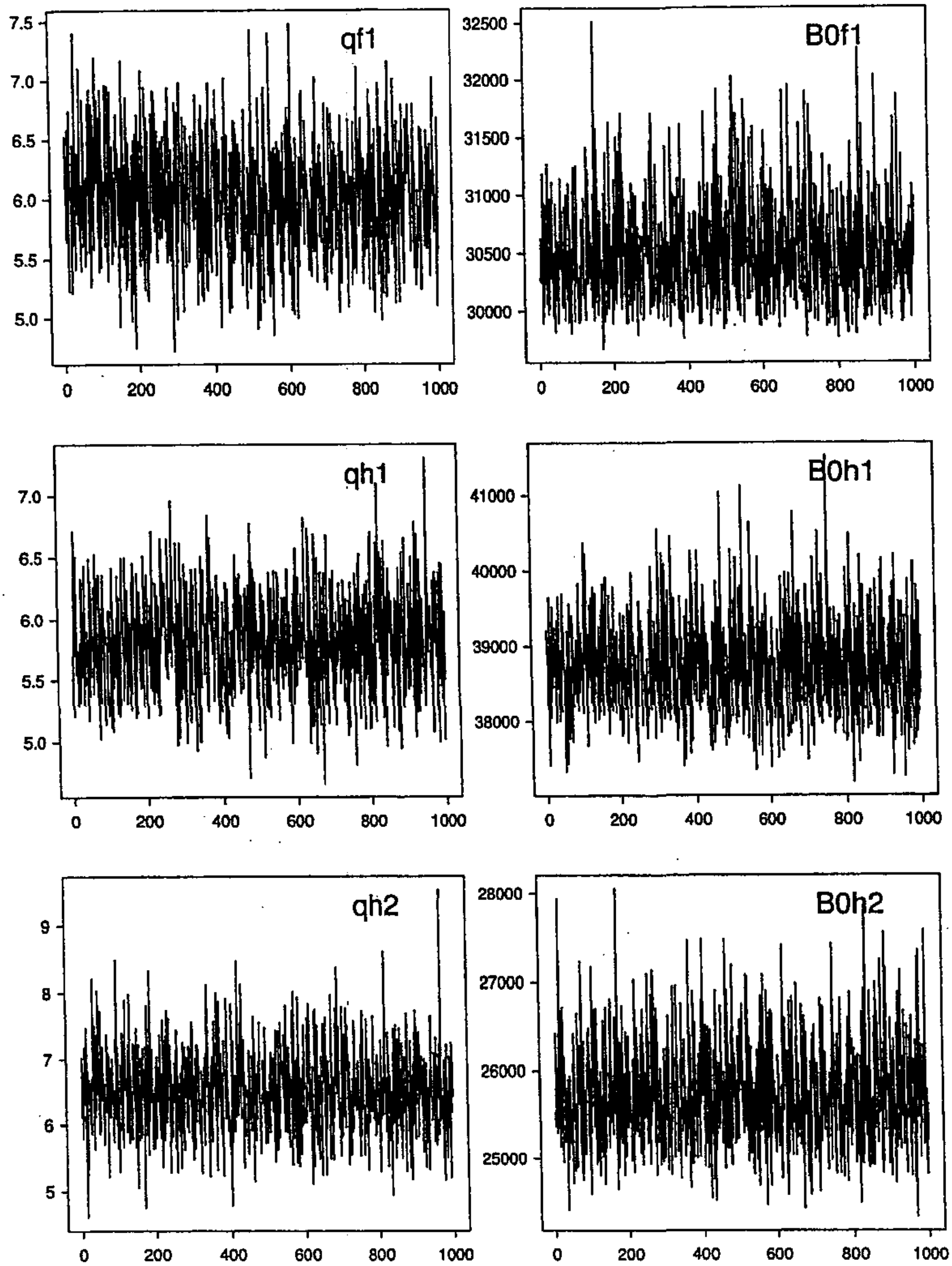

Figure A3–2: ***EstBeta*** **case. Sample values are plotted for the relativity constants (*q*, left column) and virgin biomass (*B_0* right column) for each stock.**

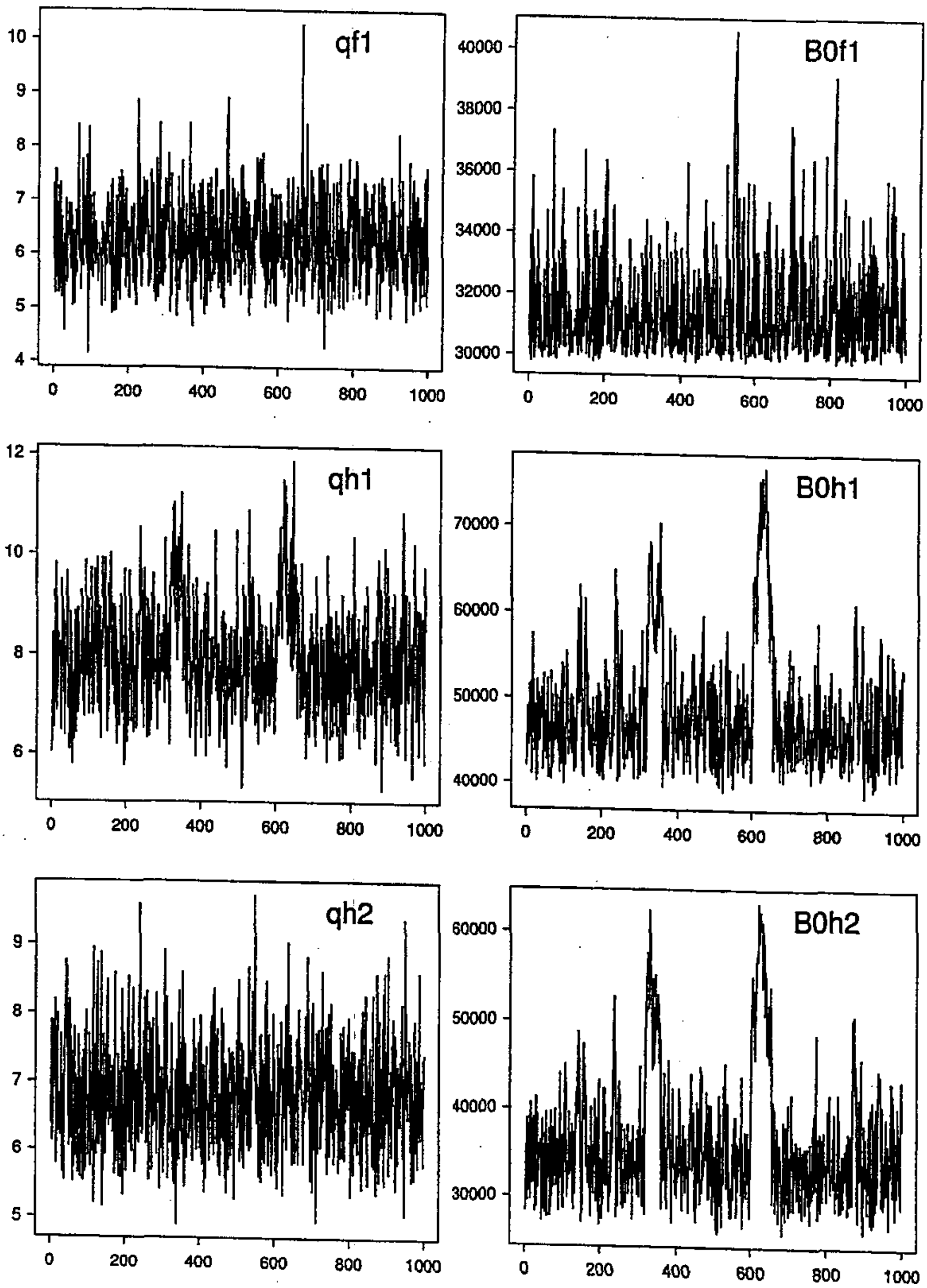

Figure A3–3: ***EstBeta* case (continued). Sample values are plotted for b (=1/ β) for the flat (left) and hill (right) stocks.**