New Zealand Fisheries Assessment Research Document 95/4

Assessment of the ORH 3B orange roughy fishery for the 1994–95 fishing year

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February 1995

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N.Z. Fisheries Assessment Research Document 95/4. 43 p.

1 Executive Summary

Orange roughy in ORH 3B are assumed to come from four stocks. These are associated with the Chatham Rise, the Waitaki area, the area just south of Puysegur, and the Macquarie Ridge.

1.1 Chatham Rise

The current status and virgin biomass of the Chatham Rise stock are estimated using stock reduction analysis. The main inputs to this analysis are the history of catches from the Chatham Rise, and estimates of biomass and mean length from a series of eight trawl surveys in the main spawning area.

It is possible that there is more than one stock on the Chatham Rise because there are significant differences between genetic samples taken from different locations. However, similar differences have been found between samples taken from the same location at different times, so there are no clear stock boundaries within the Rise. There is no reason to believe that the existence of more than one stock in this area would imply either a more optimistic or more pessimistic picture than the current assessment.

Two changes in life history parameters (a change in the maturity ogive and an increase in natural mortality) result in substantial increases in the estimated productivity of orange roughy. However, there remains considerable uncertainty about the true values of these parameters because of uncertainty about age estimates.

The biomass index from the 1994 spawning ground (Box) survey is highly uncertain because 95% of the biomass is associated with one stratum, and 66% is associated with a single catch, and there is a strong imbalance in the sex ratio (86% of the estimated biomass is female). Consequently, the analysis was carried out with four alternative assumptions concerning the survey data.

For all four assumptions the stock is estimated to be below the level that will support the MSY. The estimated mid-season biomass for 1993–94 is 10–17% B_0, although the biomass required to support the MSY, B_{MSY}, is 29% B_0 (the long-term average biomass using a CAY strategy).

The current TACC and recent catches are at levels that are unlikely to allow the stock to move toward a level that will support the MSY. For there to be a more than 50% chance that the biomass will rebuild, the 1994–95 reported catch would need to be no more than 7600 – 12 500 t.

Rebuilding of the stock is likely to be slow. Even with no fishing, it is estimated that it will take until somewhere between 2000–01 and 2002–03 (depending on which data assumption is used) before there is more than a 50% chance that the biomass is greater than B_{MSY}.

The best estimates of long-term yield for the Chatham Rise are that (after rebuilding) it could sustain annual removals of about 6300 t under an MCY policy, or average removals of about 8000 t under a CAY policy. These estimates are uncertain because of uncertainties in life history parameters.

1.2 Puysegur

There is limited information available to assess the state of the Puysegur Bank orange roughy stock. The virgin biomass, and current stock size, cannot be estimated. However, commercial catch and effort data show a marked decline in most months over the period from 1991–92 to 1993–94. These data suggest strongly that the Puysegur stock has been substantially reduced by the fishery in recent years, and the 1993–94 catch level of 5000 t is probably not sustainable.

1.3 Waitaki

There is currently insufficient information available to assess the state of the Waitaki orange roughy stock. Results of a trawl survey in 1992 indicate it is a small and localised spawning area, with limited commercial potential for orange roughy. Catches in recent years have been small, and principally a bycatch of fishing for oreos in the region.

1.4 Macquarie

There is insufficient information available to assess the state of the Macquarie Ridge orange roughy stock(s). Spawning is known to occur on two hill complexes, off the Snares and Auckland Islands, but commercial catches and catch rates have been relatively low.

2 Introduction

2.1 Overview

This document updates the stock assessment of orange roughy in Quota Management Area 3B (ORH 3B) and provides yield estimates for the Chatham Rise fishery for the 1994–95 fishing year.

This assessment incorporates new genetic data on stock structure, analyses of catch and effort (on the south and east Chatham Rise, and for the Puysegur fishery), and new survey data from the Chatham Rise.

Biomass and yield estimates for the Chatham Rise fishery are calculated using stock reduction analysis, and the likely effect of various alternative management actions is assessed using forward projections. A qualitative assessment of the Puysegur fishery is made using catch per unit effort data.

2.2 Description of the Fishery

Orange roughy are found in waters deeper than 750 m throughout Quota Management Area 3B. Before 1991, the main fishery was concentrated along the northern, eastern, and southeastern slopes of the Chatham Rise with more than half the catch being taken between mid June and mid August. This is the period immediately before, during, and after the spawning aggregations appear at depths of 800 – 1000 m in an arc from about 70 miles north around to east of the Chatham Islands.

Since 1991 the pattern of fishing on the Chatham Rise has changed markedly (*see* Sections 3.2 and 4.3.1) and fisheries have developed in the Puysegur and Waitaki areas.

Some orange roughy are caught below 1250 m, the lower depth limit for the biomass indices used in the stock assessments. However, during the period of the survey, catches below this depth are only a small percentage of the total catch, and there is evidence that, at this time, fish migrate into shallower water to spawn (Coburn & Doonan 1994).

The fishery for orange roughy on the Puysegur Bank developed from 1991. Most fishing takes place in a small area on the western side of the Bank comprising several hills and an area of undulating slope. Catches in the region are generally mixed, with black oreo and smooth oreo as well as orange roughy. Orange roughy spawn there in winter, but to date the bulk of the fishery has taken place in the spring-summer period.

Small fisheries have also recently developed in areas near the Waitaki Canyon (1992) and south of Puysegur on the Macquarie Ridge and near the Auckland Islands (1993). Catches in these fisheries have been small.

2.3 Literature Review

Published material relevant to this assessment is discussed in stock assessment reports over recent years (Robertson & Mace 1988, Robertson 1989, Francis & Robertson 1990, 1991, Francis *et al.* 1992, Francis *et al.* 1993). Other relevant papers include an analysis of CPUE (Doonan 1991), studies on ageing (Mace *et al.* 1990, Fenton *et al.* 1991, Smith *et al.* in press, Francis 1995a), a description of the Chatham Rise commercial fishery (Coburn & Doonan 1994), two FARDs on the estimation of life history parameters (Doonan 1993, 1994), and papers on the risk analysis techniques used in this assessment (Francis 1992b, Cordue & Francis 1994).

Other recent New Zealand studies include papers on recent trawl surveys (Clark & Tracey 1993a, 1993b; McMillan & Hart 1994a, 1994 b, 1994c, Clark & Thomas 1994), fecundity (Clark *et al.* 1994), the development of the Challenger fishery (Clark & Tracey 1994), and indicators of biomass depletion (Francis 1995b).

Other recent Australian studies include papers on orange roughy genetics (Ward & Elliot 1993, Smolenski *et al.* 1993, Elliot *et al.* 1994), acoustic surveys (Elliot & Kloser 1993), modelling (Campbell *et al.* 1993, Smith 1993), and larval development (Jordan & Bruce 1993).

3 Review of the Fishery

3.1 TACCs and Catches

Annual orange roughy catches in area 3B averaged just over 30 000 t throughout the 1980s, and then dropped to just over 20 000 t because of a substantial quota cut for 1990–91, and a smaller cut for 1992–93 (Table 1).

In recent years catches have been limited by subarea by agreement between industry and the Minister. In 1991–92, after the discovery of the Puysegur fishery, it was agreed that the catch south of 46° S would be at least 5000 t. In the following year (1992–93) seven subareas were defined (Francis *et al.* 1993, figure 0) with the following catch limits:

North western Chatham Rise	3500 t
Survey Box	0 t
East Chatham Rise	4500 t
South Chatham Rise	6000 t
Waitaki	300 t
Puysegur	5000 t
Exploratory area	2000 t

These subareas are of administrative rather than scientific significance. In particular they should not be thought of as defining stocks. For example, the eastern boundary of the Waitaki subarea passes through the middle of the Waitaki fishing ground and there is solid evidence against considering the survey box and east Chatham Rise as separate (Coburn & Doonan 1994).

In 1993, these catch limits were extended to the 1993–94 fishing year, but the Minister warned of the likelihood of further catch reductions "in the absence of a dramatic improvement in the conclusions of the stock assessment over the next year" (Anon. 1993).

Table 1: Annual reported catches and TACs of orange roughy from ORH 3B. (Catches from 1978–79 to 1985–86 are from Robertson & Mace (1988) and from 1986–87 to 1992–93 from Fisheries Statistics Unit and Quota Monitoring System data). –, no TAC

Fishing year	Reported catch (t)	TAC (t)
1979–80†	11 800	–
1980–81†	31 100	–
1981–82†	28 200	23 000
1982–83*	32 605	23 000
1983–84*	32 525	30 000
1984–85‡	29 340	30 000
1985–86‡	30 075	29 865
1986–87‡	30 689	38 065
1987–88‡	24 214	38 065
1988–89‡	32 785	38 300
1989–90‡	31 669	32 787
1990–91‡	21 521	23 787
1991–92‡	23 269	23 787
1992–93‡	20 077	21 300

(† Catches for 1979–80 to 1981–82 are for a April-March fishing year.
* Catches for 1982–83 and 1983–84 are 15 month totals to accommodate the change over from an April-March fishing year to an October-September fishing year. The TAC for the interim season, March to September 1983, was 16 125 t.
‡ Catches from 1984–85 onwards are for a October-September fishing year.)

3.2 Recent Changes in the Fishery

Substantial changes in the geographical distribution of the ORH 3B fishery from 1990-91 were documented by Francis *et al.* (1993, section 3.2.2) and are partly seen in Tables 2 and 3. The major feature of these changes was a shift of catch and effort from the Box to hills on the east Rise, and to other areas ouside the Chatham Rise. In the last two years (1991–92 and 1992–93) changes have been constrained by the subdivision of the area (*see* Section 3.1).

Table 2: ORH 3B catches by area from 1978–79 to 1992–93, by tonnage (to the nearest 100 t) and by percentage (to the nearest percent) of the total ORH 3B catch. All years are from 1 October-30 September

Year	Northwest		South		Spawning box		East		Non-Chatham	
	t	%	t	%	t	%	t	%	t	%
1978–79	0	0	0	0	11 500	98	300	2	0	0
1979–80	1 200	4	800	3	27 900	90	1 200	4	0	0
1980–81	8 400	30	3 700	13	16 000	57	100	0	0	0
1981–82	7 000	28	500	2	16 600	67	800	3	0	0
1982–83	5 400	35	4 800	31	4 600	30	600	4	0	0
1983–84	3 300	13	5 100	21	15 000	61	1 500	6	0	0
1984–85	1 800	6	7 900	27	18 400	63	1 100	4	0	0
1985–86	3 700	12	5 300	18	17 000	56	4 100	13	0	0
1986–87	3 200	10	4 900	16	20 200	66	2 400	8	0	0
1987–88	1 600	7	6 800	28	13 500	56	2 300	10	0	0
1988–89	3 800	12	9 200	28	16 700	51	3 100	9	0	0
1989–90	3 300	10	11 000	35	16 200	51	1 100	3	200	1
1990–91	1 500	7	6 900	32	6 100	28	6 100	29	900	4
1991–92	300	1	2 200	9	1 000	4	12 000	52	7 800	34
1992–93	4 100	20	5 200	26	100	0	4 400	22	6 300	32

Table 3: ORH 3B catches outside the Chatham Rise, by tonnage (nearest 50 t) and by percentage (nearest 1%) of the total ORH 3B catch. For this table the areas were defined by the following rectangles: Puysegur — 46–47.5 °S, 165–166.5 °E; Waitaki — 45–45.5 °S, 171–172 °E; Macquarie - 47.5–52 °S, 163–167 °E. All years are from 1 October to 30 September

	Puysegur		Waitaki		Macquarie	
Season	t	%	t	%	t	%
1989–90	150	0	0	0	0	0
1990–91	850	4	0	0	50	0
1991–92	6900	30	650	3	0	0
1992–93	5450	27	50	0	750	4

In 1992–93, 77% of the Chatham Rise catch was taken from three hill complexes – one in each of the three subareas where fishing was allowed: Big Chief in the South, Andes in the East, and Graveyard in the Northwest (Figure 1). Catch rates and bycatch fraction varied markedly amongst these hills, with catch rates highest (and bycatch lowest) at Graveyard, and lowest (with highest bycatch) at Big Chief (Table 4). The bycatch fraction at Big Chief has risen steadily over the five years it has been fished (Table 4). In the South, catches from the other main hills were only 1–200 t, with the oreo bycatch often being as much or more (Figure 1).

Table 4. Orange roughy catches and catch rates, and oreo bycatch fractions, for the three hill complexes that provided 77% of the 1992–93 Chatham Rise orange roughy catch (shown for all years that these hills have supported significant catches). All are calculated using only those tows where orange roughy was targeted; catch rate is total tonnage divided by number of tows; bycatch fraction is oreo catch divided by orange roughy catch

Area	Year	Catch (t)	Catch rate (t per tow)	Bycatch fraction
Graveyard (42°50'S – 42°40'S, 179°53'W – 179°48'W)				
	1991-92	100	2.7	0.35
	1992-93	3300	11.0	0.11
Andes (44°15'S – 44°06'S, 174°35'W – 174°20'W)				
	1991-92	7000	9.7	0.34
	1992-93	2600	8.5	0.25
Big Chief (44 °5 ' – 44°35'S, 175°25'W – 175°05'W)				
	1988-89	1000	5.1	0.12
	1989-90	2800	5.3	0.16
	1990-91	3100	6.9	0.20
	1991-92	800	6.0	0.43
	1992-93	3000	4.7	0.64

The Chatham Rise catch was almost entirely (96%) taken by five domestic vessels (in contrast to 1989–90 where 18 vessels, including 10 foreign chartered vessels, took 91%).

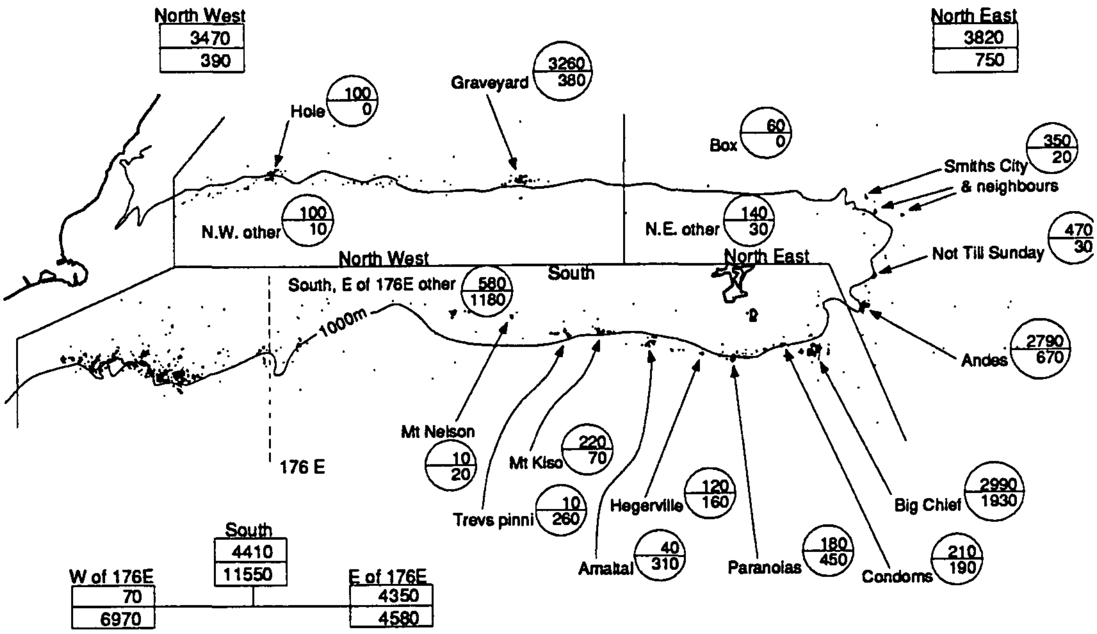

Figure 1. Tow positions, and catches of orange roughy and oreos by area, for the deepwater Chatham Rise fishery in 1992–93. Each dot represents a tow position where orange roughy or oreos were targeted or caught (no attempt has been made to remove obvious errors in tow positions). Within each circle or box, the upper figure is the orange roughy catch and the lower figure is the oreo catch (both in tonnes, as reported in tow-by-tow data).

3.3 Maori and Recreational Fishing

There is no known non-commercial catch of orange roughy in ORH 3B.

4 Research

4.1 Stock Structure

Allozyme data for 21 samples from 14 locations on the Chatham Rise and east coast of New Zealand (Figure 2, Table 5) were analysed to determine stock strucure for Chatham Rise orange roughy.

Table 5. Genetic data sample sizes (numbers of fish with allele frequencies) by area, sampling time, and genetic locus. The 1982 and 1988 samples are as reported in Smith *et al.* (1991). Where no month is specified samples were collected during the spawning period. Data from some loci for samples before 12/93 have been excluded because they are not comparable with the later data (different gels were used). Small numbers for some areas for EST-1 and IDH-1 are because processing was not complete at the time of this analysis

Area (abbreviation)	Date	Locus										
		CCK-1	EST-1	GPI-1	GPI-2	IDH-1	IDH-2	LDH-1	LDH-2	MDH-1	MPI-1	PGM-2
Ritchie (Rch)	3/94	90		99	99		96	99	96	96	94	99
Wairarapa (War)	4/94	93		96	96		95	85	96	96	94	96
Kaikoura (Kai)	3/94	87		96	96		94	96	92	94	92	96
Hole (Hol)	1/94	85	87	95	95	87	95	95	96	96	96	95
Graveyard (Grv)	1993					49		49	49	49		
Graveyard (Grv)	1/94	87	99	92	92	99	95	92	97	97	95	92
Box (Box)	1982			90	106							100
Box (Box)	1988			48	48							48
Box (Box)	1993					46		47	47	47		
Smiths City (Smt)	1993						48		48	48	48	
Smiths City (Smt)	12/93	78	8	93	93	8	92	93	92	92	92	93
Colliery (Col)	12/93	40	97	97	40	96	97	97	97	97	97	
Possum (Pos)	1993						47		47	47	47	
Possum (Pos)	12/93	75	12	87	87	12	93	87	95	95	95	87
Big Chief (BCh)	1993						49		49	49	49	
Big Chief (BCh)	12/93	76		93	93		91	93	93	93	93	93
Hegerville (Heg)	1/94	84	98	94	94	98	88	94	91	90	91	94
Kiso (Kis)	1/94	70	73	70	70	73	71	70	71	71	71	70
Kiso (Kis)	3/94	27	13	27	27	13	26	27	24	25	24	27
SWMemoo (SWM)	3/94	51	55	51	52	55	54	52	53	52	53	52
Waitaki (Wai)	3/94	47	47	48	48	47	47	47	47	47	48	47

A chi-square test on the 1993 and 1994 samples showed strong heterogeneity with most of the heterogeneity arising from two loci, IDH-2 and MDH-1; this was also true when the test was restricted to the Chatham Rise samples (Table 6). (Alleles that were too rare to use in chi-square tests were lumped with adjacent alleles; this made 4 loci monomorphic – GPI-2, IDH-1, LDH-1, and LDH-2.)

Table 6. Results of chi-square tests for heterogeneity amongst the 1993 and 1994 samples: presented by individual locus and for all loci combined.

Locus	Chatham Rise samples			All samples		
	chisq	dof	P	chisq	dof	P
CCK-1	6.4	9	0.701	22.2	13	0.053
EST-1	17.0	16	0.384	29.7	18	0.041
GPI-1	14.3	18	0.708	28.5	26	0.335
IDH-2	93.8	14	0.000	123.9	18	0.000
MDH-1	37.2	14	0.001	156.2	18	0.000
MPI-1	13.4	14	0.494	16.8	18	0.539
PGM-2	9.0	9	0.438	11.5	13	0.573
Combined	191.1	94	0.000	388.6	124	0.000

To determine possible stock boundaries, a series of heterogeneity tests were done to see which groups of contiguous locations could be considered genetically homogeneous (or, rather, not significantly heterogeneous). These tests identified four possible stock boundaries: Kaikoura/Hole, Hole/Graveyard, Kiso/SWMernoo, and SWMernoo/Waitaki (Figure 3).

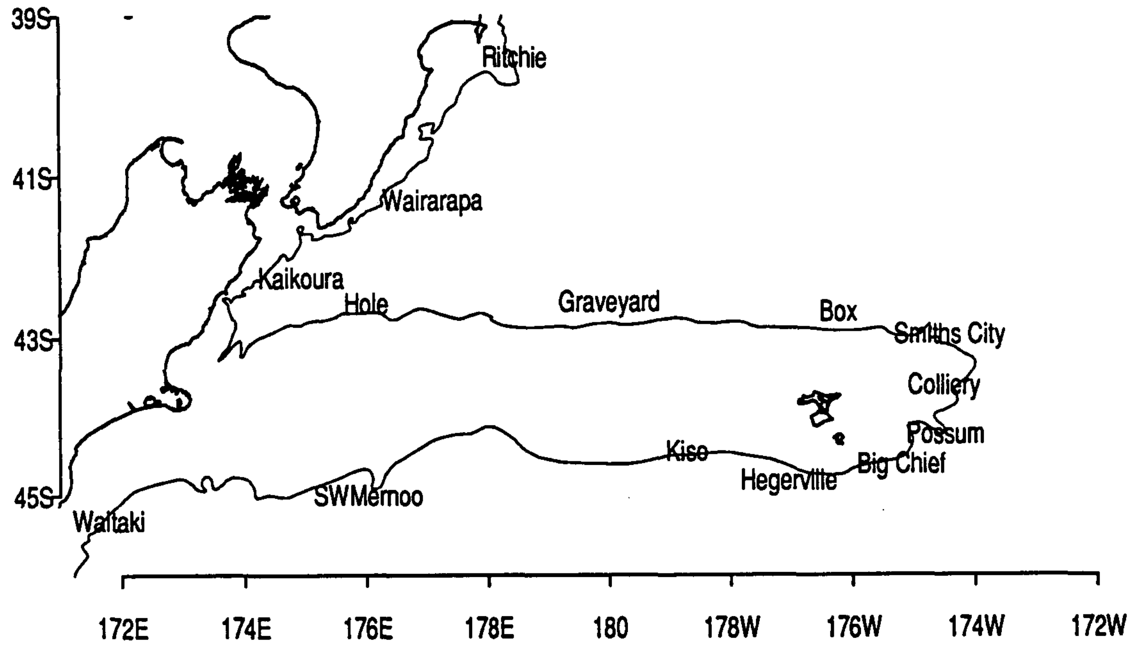

Figure 2. Approximate positions of 14 locations from which genetic samples were taken (*see* Table 5).

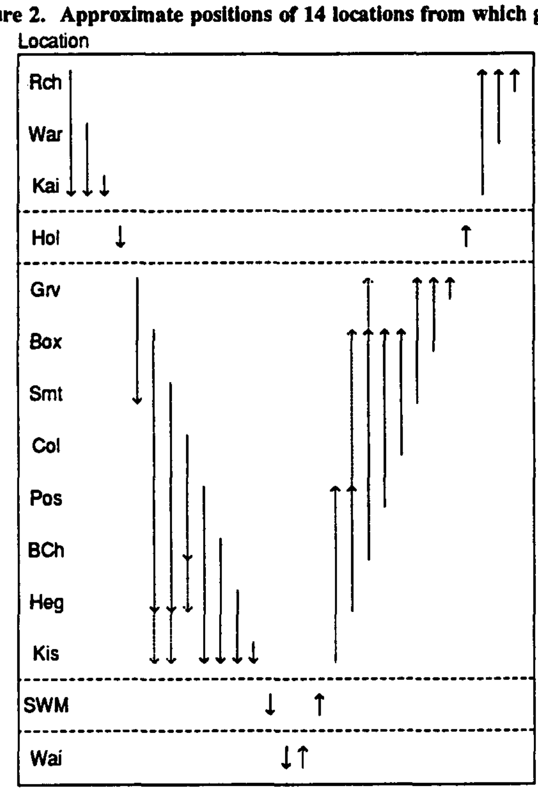

Figure 3. Schematic diagram illustrating the extent of genetic homogeneity between contiguous sampling locations. Vertical arrows show how far it is possible to move from the stock at the tail of the arrow before significant heterogeneity is found (solid line, P > 0.1; broken lines, P > 0.05). Horizontal lines identify possible stock boundaries suggested by these test results. Location abbreviations are given in Table 5.

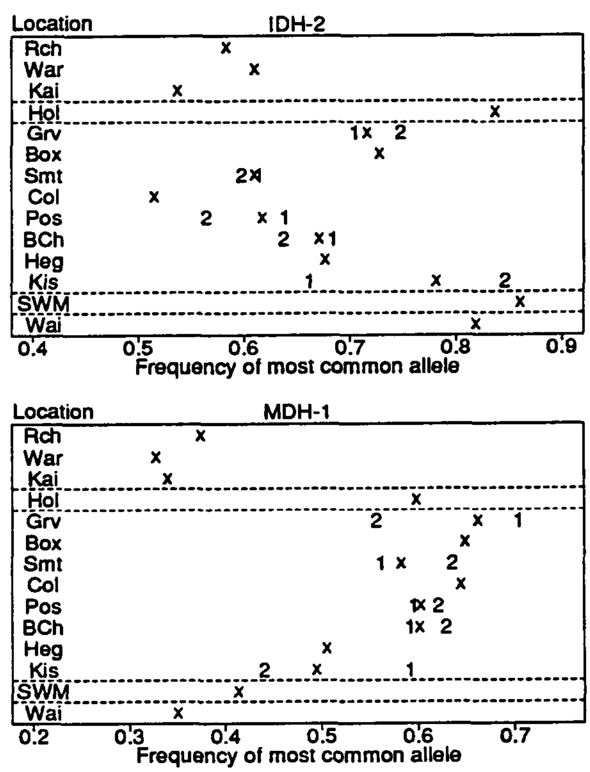

Figure 4. Frequency of the most common allele at the IDH-2 and MDH-1 loci plotted by sample location (there were only two non-rare alleles at each of these loci). Where repeat samples were available, frequencies for individual samples are plotted as '1' and '2'; horizontal lines are as in Figure 3. Location abbreviations are given in Table 5.

However, an examination of repeat samples at Graveyard and Kiso casts doubt on three of these possible stock boundaries. The 1993 Graveyard sample is genetically closer to that from Hole than to the 1994 sample from Graveyard, and the March 1994 sample from Kiso was closer to both SWMernoo and Waitaki than to the January Kiso sample (Table 7). This suggests that gene frequencies at a given location can vary over time to an extent that is comparable to the between-location variation that generated some of the possible boundaries in Figure 3. Chi-square tests showed marginally significant differences between repeat samples at Graveyard and at Kiso but no significant difference overall (Table 8).

Table 7: Genetic distance matrices (Nei's distance (Nei 1975) multiplied by 10 000) for two groups of samples near possible boundaries in Figure 3

	Graveyard 1993	Graveyard 1994
Hole	24	92
Graveyard 1993	-	80

	Kiso 3/94	SWMernoo	Waitaki
Kiso 1/94	91	118	131
Kiso 3/94	-	27	47
SWMernoo	-	-	73

Table 8. Results of chi-square tests for differences between repeat samples at the same location: presented by individual locus and for all loci combined

Area	chisq	dof	P
Graveyard	7.2	3	0.064
Smiths City	3.1	3	0.378
Possum	2.0	3	0.573
Big Chief	1.1	4	0.893
Kiso	14.9	9	0.095
Combined	28.3	22	0.166

The reason that stock boundaries at Hole/Graveyard, Kiso/SWMernoo, and SWMernoo/Waitaki are inferred when repeat samples are lumped (Figure 3), but rejected when they are not, is illustrated in gene frequency plots (Figure 4). These plots also show a reasonably clear Kaikoura/Hole boundary. However, it would seem prudent to collect repeat samples on either side of this boundary to confirm it.

The 1982 and 1988 Box sample data were excluded from the above analyses because they were for only three loci (Table 5), and no significant heterogeneity was found at these loci in the later samples (Table 6). However, there was significant heterogeneity between the two early samples at two of these three loci (Table 9) and allele frequency differences between these samples (at the same location) were of the same degree as between-location differences in the 1993 and 1994 samples (Figure 5).

Table 9. Results of chi-square tests for differences between the 1982 and 1988 Box samples: presented by individual locus and for all loci combined.

Locus	chisq	dof	P
GPI-1	7.30	2	0.026
PGM-1	4.63	1	0.032
Combined	11.92	3	0.008

Two further sources of information are relevant to the question of stock structure for ORH 3B: mitochondrial DNA analyses and fish distribution patterns.

Mitochondrial DNA analyses found no differences between the north Chatham Rise, Ritchie Bank, and Cook Canyon spawning populations. Samples from the Waitaki and Puysegur fisheries were similar to each other but different from the Chatham Rise/Ritchie/Cook samples (P.J. Smith, MAF Fisheries Greta Point, pers. comm.).

More or less simultaneous spawning has been observed at Puysegur, Cook Canyon, Waitaki, and Ritchie, and at a number of locations on the Chatham Rise – in the Box, and on hill complexes in the northwest, northeast, southeast, and southwest. The Macquarie Ridge orange roughy fishing ground is well separated from other orange roughy grounds.

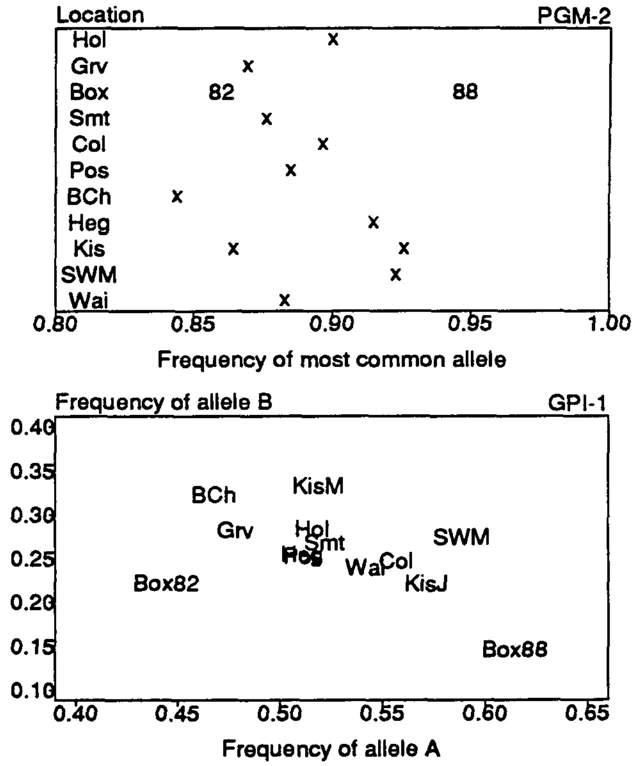

Figure 5. Gene frequencies, showing sample location, for the two loci (PGM-2 and GPI-1) at which there was significant heterogeneity between the 1982 and 1988 Box samples (Table 9). PGM-2 had only two non-rare alleles; GPI-1 had three. Location abbreviations are given in Table 5.

The abundance of orange roughy in the spawning box is low outside the spawning season, and there is uncertainty as to the origin of the fish that spawn there. However, there is evidence from analysis of commercial catch-effort data from 1979 to 1988 that fish move into and out of the spawning box from the northeast and east, and there is an indication that there may be movement from the west. This suggests that, if there is more than one stock, there could be substantial mixing between those spawning in the box and fish in the east.

On the basis of the above information it was decided to treat ORH 3B as consisting of four stocks – Chatham Rise, Waitaki, Puysegur, and Macquarie Ridge – which are separate from stocks in other QMAs.

Although there is substantial genetic heterogeneity within the Chatham Rise, there are no clear stock boundaries. The continuous distribution of orange roughy around most of the Rise, the existence of genetic differences between samples from the same location at different times, and known migration patterns within the Rise, all suggest that it will be difficult to clearly define more than one stock on the Chatham Rise. Allozyme and DNA work is continuing in an attempt to define stock relationships for orange roughy in and adjacent to ORH 3B.

4.2 Resource Surveys

Surveys that have been conducted in ORH 3B are shown in Table 10.

Table 10: Major research surveys for orange roughy in ORH 3B since 1982. Surveys were of two types: those aimed at estimating biomass or at locating and sampling juveniles. (N, S, and E refer to the north, south, and east Chatham Rise, respectively.)

Date month/year	Area (km^2)	Survey Type	Vessel	Survey area	Species
8–9/1982	25 000	biomass	*Kaltan*	N	ORH
7/1984	5 000	biomass	*Otago Buccaneer*	N	ORH
7/1985	5 000	biomass	*Otago Buccaneer*	N	ORH
7/1986	5 000	biomass	*Otago Buccaneer*	N	ORH
11/1986	47 100	biomass	*Arrow*	S	Oreos/ORH
7/1987	5 000	biomass	*Otago Buccaneer*	N & S	ORH
11/1987	47 500	biomass	*Amaltal Explorer*	S	Oreos/ORH
2/1988	na	juvenile	*James Cook*	N	ORH
5–6/1988	na	juvenile	*James Cook*	N	ORH
7/1988	5 000	biomass	*Cordella*	N	ORH
9/1988	na	juvenile	*James Cook*	N	ORH
9/1988	72 000	biomass	*Cordella*	N & S	ORH/Oreos
1/1989	na	juvenile	*James Cook*	N	ORH
4/1989	na	juvenile	*James Cook*	N	ORH
7/1989	25 500	biomass	*Cordella*	N & S	ORH
8/1989	na	juvenile	*James Cook*	N	ORH
10/1989	na	juvenile	*James Cook*	N	ORH
12/1989	na	juvenile	*James Cook*	N	ORH
6–8/1990	38 600	biomass	*Cordella*	N & S & E	ORH
11/1990	56 800	biomass	*Cordella*	S & E	Oreos/ORH
7/1991	850	biomass	*Will Watch*	Puysegur	ORH/Oreos
10/1991	56 800	biomass	*Tangaroa*	S & E	Oreos/ORH
6–7/1992	26 333	biomass	*Tangaroa*	N & S & E	ORH
7/1992	850	biomass	*Giljanes*	Puysegur	ORH/Oreos
7/1992	645	biomass	*Giljanes*	Waitaki	ORH
8–9/1992	6 180	biomass	*Tangaroa*	Puysegur	ORH/Oreos
10–11/1992	60 500	biomass	*Tangaroa*	S & E	Oreos/ORH
10–11/1993	60 500	biomass	*Tangaroa*	S & E	Oreos/ORH
5–7/1994	35 108	biomass	*Tangaroa*	N & S & E	ORH

A stratified random trawl survey was completed during May to July 1994. This continued coverage of the Box in July (the second survey using *Tangaroa*) and included most other areas of the Chatham Rise as well. Some of these had been covered in previous surveys to various degrees, but the 1994 survey involved much more rigorous sampling of several areas consisting of hill and drop-off features. These areas included both known commercial features and 'new' ones identified during bathymetric survey work carried out by the fishing industry. Hence, for those parts of the 1994 survey area outside the Box, biomass indices cannot be used until further surveys are carried out.

The 1994 survey of the Box is the ninth in a series of biomass surveys (Table 11). It was carried out following the same design as for the 1992 survey (which differed from that from previous surveys in the order of occupation of the 26 strata that make up the survey area). The biomass index from this survey is highly uncertain because:

- the coefficient of variation (*c.v.*) for the index is very high,
- 95% of the survey biomass is associated with just one stratum (stratum 2),

- the biomass index is reduced by 66% if a single catch (from station 399) is omitted from the biomass calculation, and
- there is a strong imbalance in the sex ratio (Table 11).

Table 11: Spawning box survey biomass indices (t) for both sexes combined (with *c.v.*) and by sex, percentage male (by biomass) and mean length for both sexes combined. The effect of removing one high catch rate station (station 399) from the 1994 survey is also presented. –, not estimated

Year	Combined	*c.v.* (%)	Male	Female	% male	Mean length (cm)
1984	164 073	17	83 952	80 120	51	34.72
1985	147 093	15	73 744	73 329	50	34.78
1986	103 367	16	55 481	47 873	54	34.65
1987	79 388	15	41 216	38 155	52	35.27
1988	94 583	25	53 730	40 798	57	34.59
1989	66 955	18	32 799	34 040	49	34.84
1990	37 780	19	20 269	17 492	54	34.35
1992	29 011	34	8 170	20 611	28	34.95
1994	83 169	67	11 401	71 523	14	33.87
1994 (no stn 399)	28 263	45	4 828	23 435	17	–

The most likely explanation for the sex ratio imbalance is that it is an artefact caused by the change in survey design and the way that this relates to the (unknown) pattern of movements and catchability of male and female fish over the spawning period. There was a similar (though less extreme) imbalance in the 1992 index, when 28% of the biomass was from males. In both surveys the imbalance was observed in many catches, both small and large (Figure 6). This is in strong contrast to the earlier surveys (1984 to 1990) in which the percentage of males in the biomass ranged from 49% to 57%. However, it is unlikely that the imbalance in the survey sex ratio is representative of a shift in the population sex ratio. In order for such a shift to occur from fishing, there would have had to be strong imbalances in the sex ratio of the catches over the last four years, together with a very high exploitation rate, to cause this degree of change in the sex ratio of the population spawning in the survey area. There is no evidence for an imbalance in the sex ratios of the catch in the admittedly sketchy observer database (*see* Section 4.3.4).

In the time series of Box surveys there is a pattern which is continued by the last two surveys. The area in which moderate to large catch rates (greater than 1 t.n.mile^{-1}) were obtained has progressively shrunk (Figure 7, Table 12). In 1994 this area was confined to one stratum, which contributed 95% of the biomass index. However, the number of large catch rates (greater than 10 t.n.mile^{-1}) has not shown a similar trend. Therefore, it is not possible to say whether mean fish densities within the high catch rate area have decreased or not.

Table 12: Incidence of orange roughy catch rates exceeding 1 t.n.mile^{-1} in each of the nine Box surveys. The 'No. strata' columns indicate the number of strata (of 26) which contained <u>at least</u> one tow in the indicated range of catch rates. The 'percentage' columns indicate the proportion of tows which were contained in the indicated range of catch rates

	(1 – 10 t.n.mile^{-1})		(> 10 t.n.mile^{-1})	
Year	No. strata	Percentage	No. strata	Percentage
1984	9	20	2	4
1985	11	25	4	5
1986	14	25	3	3
1987	8	20	0	0
1988	7	12	3	5
1989	9	17	1	2
1990	6	13	2	2
1992	3	6	1	2
1994	0	0	1	4

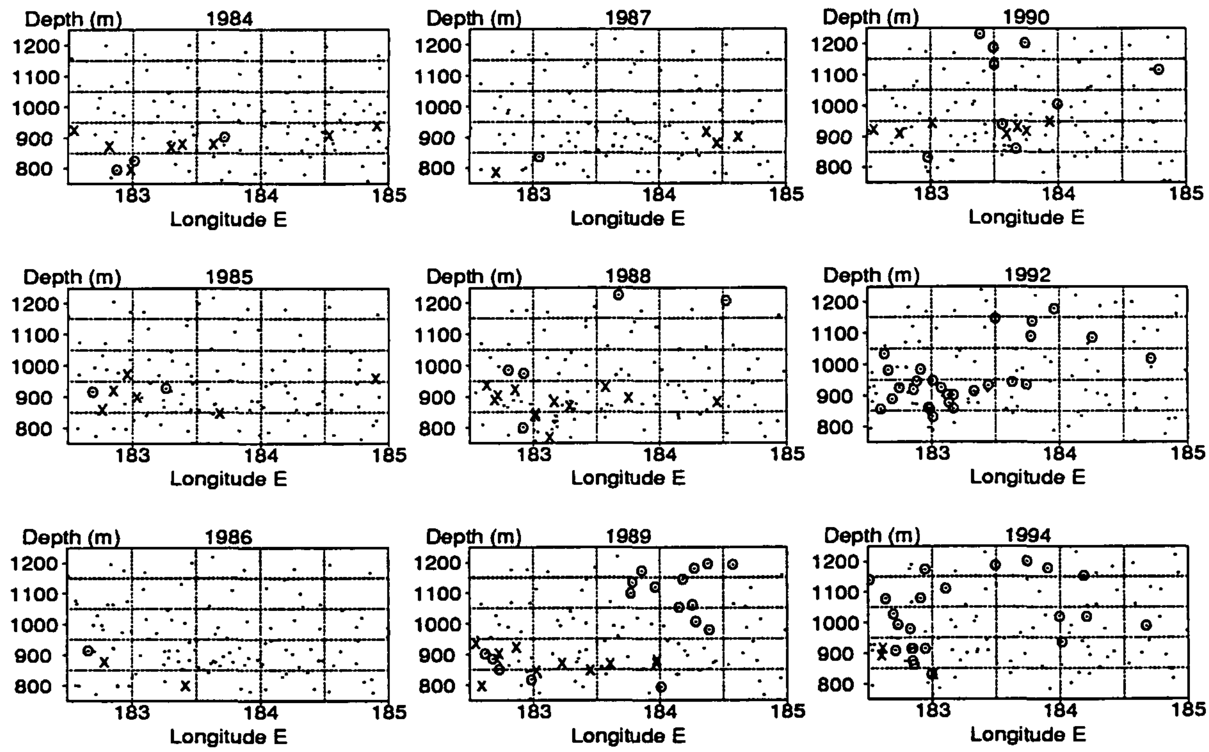

Figure 6. Positions of stations with extreme sex ratios: 'o' – more than ¾ female; 'x' – more than ¾ male (others stations shown as '.'). Dotted lines indicate stratum boundaries.

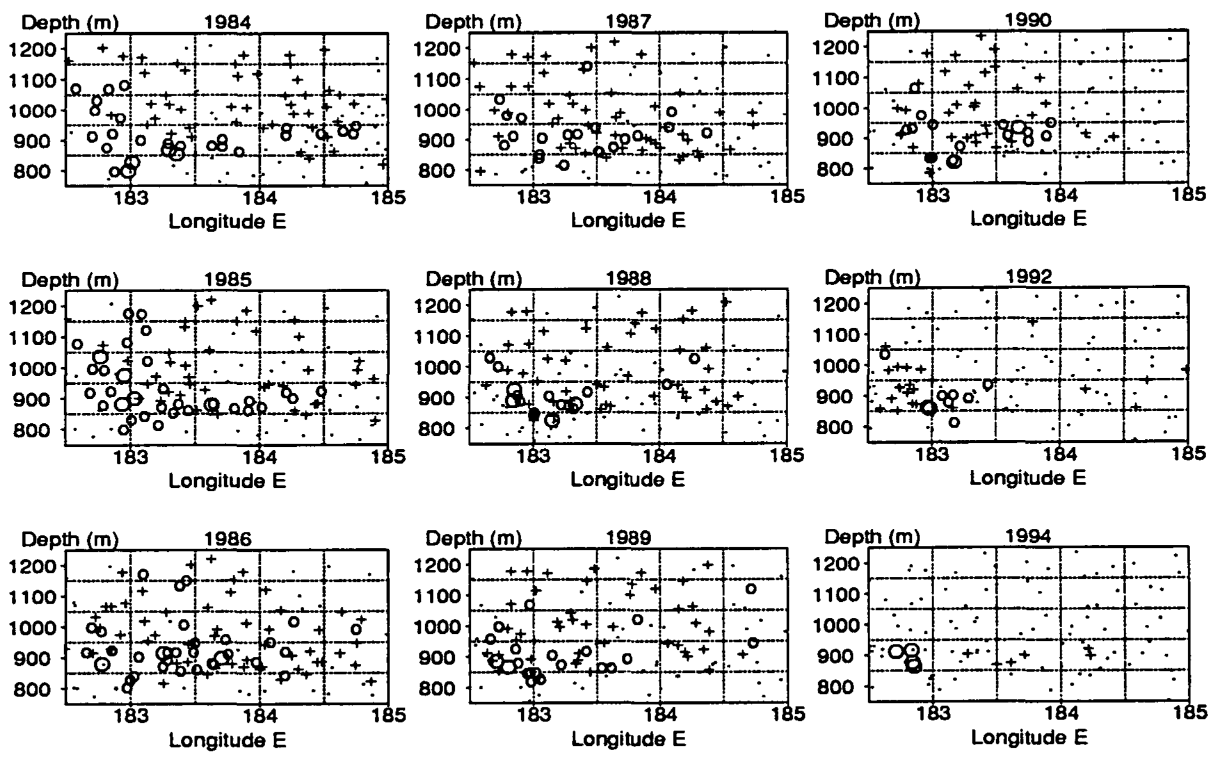

Figure 7. Positions of stations, with catch rate identified by plotting symbol: '.' – <= 0.1 t.n.mile^{-1}; '+' – 0.1 to 1 t.n.mile^{-1}; 'o' – 1 to 10 t.n.mile^{-1}; 'O' – > 10 t.n.mile^{-1}. Dotted lines indicate stratum boundaries.

The pattern of decrease in the moderate catch rates is consistent with a steady decrease in overall biomass, with a large proportion of the biomass located in an ever-shrinking area of high fish density. Thus it is reasonable to conclude that the biomass decline indicated by the survey indices up to 1992 is continuing, and that the 1994 biomass index is unrepresentative because of one station which by chance had a high catch rate. This pattern also explains the observation of increasing *c.v.* that has recently become apparent (Table 11). As the area of high fish density shrinks, the number of tows with moderate and high catch rates should fall, and the estimate of mean density in this area becomes less precise. If this hypothesis is true, the time sequence of male biomass estimates may be more representative of the trend in total biomass than the female biomass (Table 11) because the male biomass estimates do not show such a strong increase in 1994.

4.3 Other Studies

4.3.1 Catch and Effort in the South and East Chatham Rise

Catch and effort data for the south and east Chatham Rise between 1978 and 1993 (inclusive) were analysed to determine major trends in the fishery in these areas. This work extends earlier analyses for the south Rise (Francis & Robertson 1991, Francis *et al.* 1992).

The area covered by these analyses is that south of 43.3° S or east of 175° W (Figure 8). The boundary at 175° W defines the eastern end of the survey box and has been used since October 1992 in restricting catches (*see* Section 3.1). However, there appears to be no natural boundary for orange roughy near this line. Catches and catch rates of orange roughy decline smoothly from west to east in this area.

In the south and east rise between 1978 and 1993 (inclusive) there were 50 000 tows where either orange roughy or oreos were targeted or caught. Of these tows only 18 500 targeted orange roughy but, except in the early years (before 1983), target tows accounted for most (87%) of the orange roughy catch (Figure 9B). The number of target tows increased steadily to a peak of 2600 in 1988 and has declined steadily since (Figure 9A). Trends in orange roughy catch rates and oreo bycatches are shown in Figure 9C–F; these trends are discussed in the context of three subfisheries that are defined below.

In Figure 9, and throughout this section, catch rates are calculated as t per tow (total tonnage divided by number of tows); oreo bycatch is calculated only for tows that targeted orange roughy; and percentage oreo bycatch is calculated as 100 times the total oreo catch divided by the sum of orange roughy and oreo catches (using only those tows that targeted orange roughy). All references to years refer to calender, rather than fishing, years.

To simplify the graphical presentation of the data a "longitude" was defined for each tow on the south and east Rise as follows. The tows in this area lie along a long thin strip that runs roughly eastward from 172° E to 175° W, then approximately northeast to 174° W, and finally approximately northwest to the edge of the "Box" (Figure 8). The "longitude" for each tow describes how far it is along this strip. Specifically, each tow was projected onto the fine dotted line marked in Figure 8, and the "longitude" of each tow was set equal to the distance along this line, where the unit of distance is about 80.2 km, so that, in the horizontal portion of the line, "longitude" is the same as longitude.

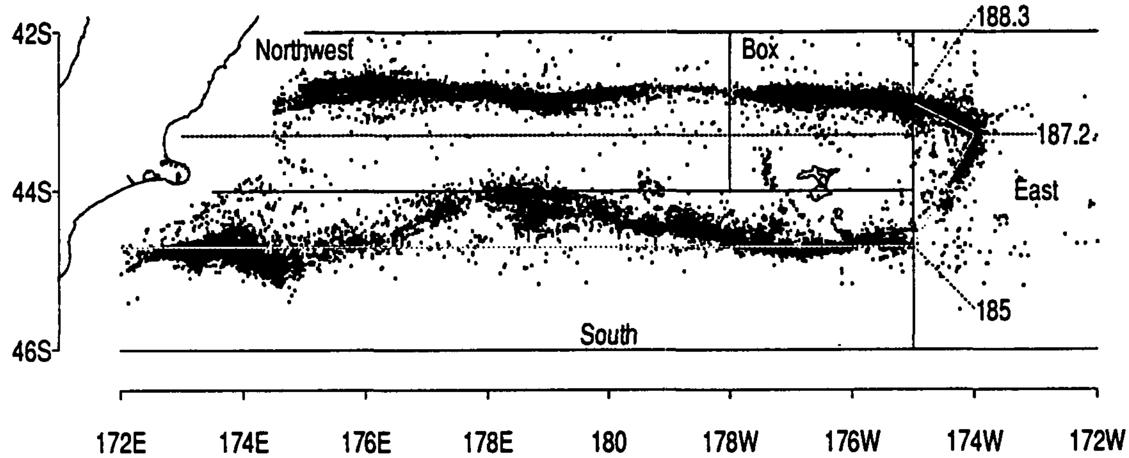

Figure 8. Positions of all tows that targeted or caught either orange roughy or oreos, 1978–1993. The solid lines define the areas (Northwest, Box, East, South) to which catch restrictions have applied from October 1992. The analysis of catch and effort data described in the text for the south and east Rise covers the area which is either south of 43.3° S or east of 175° W. The fine dotted line is the axis for "longitude" (*see* text for details); the "longitudes" of "corners" in this axis are marked ("185","187.2","188.3"). No attempt has been made to remove obvious errors in tow positions.

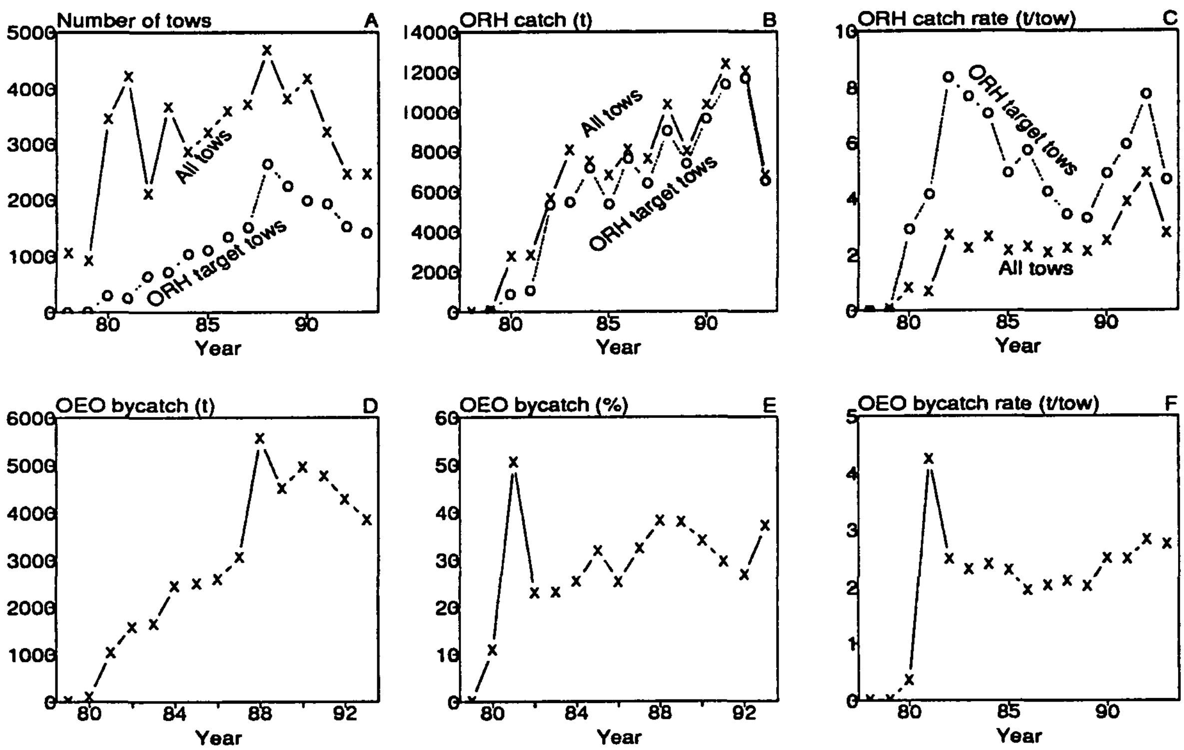

Figure 9. Analysis by calender year of tows in the south and east Rise (south of 43.3° S or east of 175° W) that caught or targeted orange roughy (ORH) or oreos (OEO).

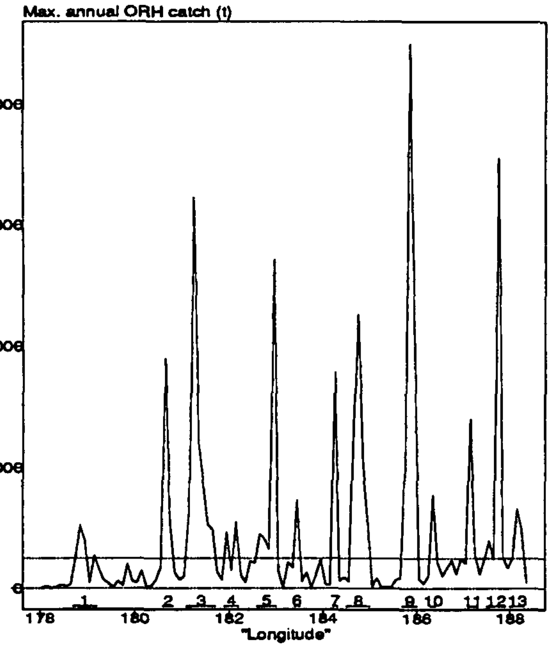

Figure 10. Maximum annual orange roughy catch by 0.1 degree "longitude" steps, with 13 areas of high catch identified (*see* text for definition of "longitude").

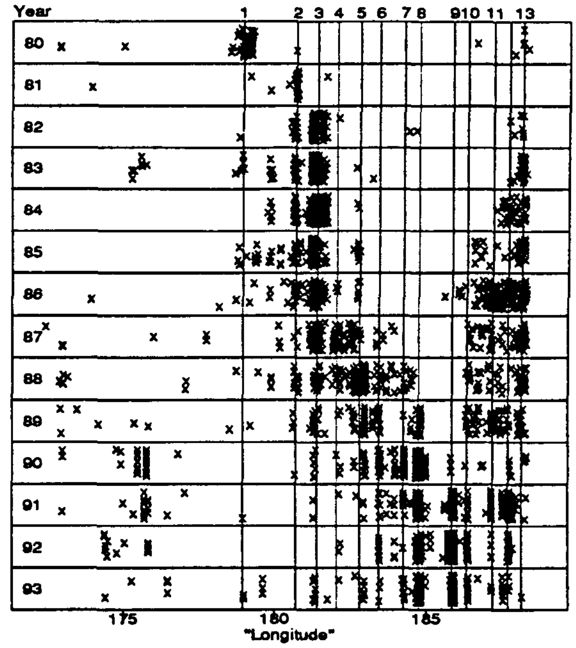

Figure 11. "Longitudes" by year for tows on the south and east Rise where more than 10 t of orange roughy was caught (*see* text for definition of "longitude"). Vertical lines show the centres of the 13 areas of Figure 10.

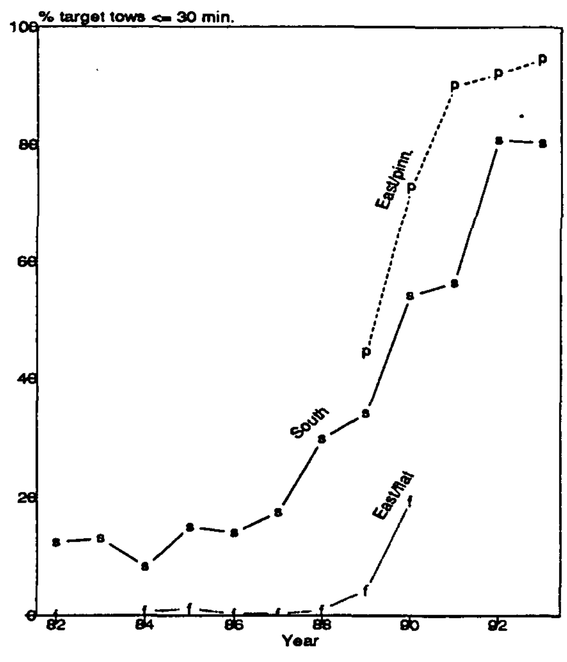

Figure 12. Percentage by year of orange roughy target tows that are ≤ 30 min. in duration for each of three sub-fisheries: *south, east/flat,* and *east/pinn.*

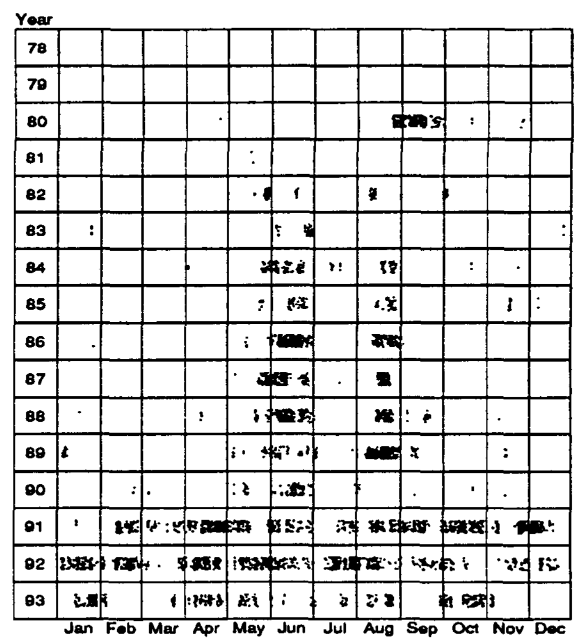

Figure 13. Dates of orange roughy target tows east of 175°W (= "longitude" 185). Each dot represents a tow.

84 % of the total orange roughy catch from the south and east rise was caught from the 13 areas defined in Figure 10 (Table 13). Note that these areas are all east of 178° E; the western part of the south rise (west of 178° E) is primarily an oreo fishery – it accounts for only 3% of this total catch.

Table 13: Catch information for, and named features associated with, the 13 areas of high catch identified in Figure 10. Letters in parentheses, and Hills 1 to 3, refer to the features described in figure 2 of Francis *et al.* (1992). Percentages are calculated relative to the total south and east Rise catches

Area	Max. ann. catch (t)	% of total catch	% of catch in 1992 and 1993	Named features
1	1512	2.5	0.4	
2	2456	5.8	0.1	Trevs pinni (d)
3	5613	22.9	1.3	Mt. Kiso, The Busby (f,g)
4	1111	2.1	0.5	Amaltal pinni
5	3633	6.2	1.0	Hegerville (m)
6	732	1.9	2.3	Paranoias
7	1785	2.3	1.3	Condoms
8	4947	11.5	21.1	Cooks, Big Chief
9	7587	10.8	50.8	Andes, Cotopaxi, Possum
10	771	1.9	7.1	Not 'til Sunday
11	1405	2.7	1.0	(Hill 2)
12	4132	7.9	8.2	Smiths City (Hills 1,3)
13	861	4.8	0.1	
Total		83.5	95.1	

The south and east Rise orange roughy fishery may be divided into three subfisheries:

south – west of 175.5° W
east/flat – primarily on the flat, east of 175° W and before 1991
east/pinn. – primarily on pinnacles, east of 175.5° W from 1991 (with some fishing in area 8 in 1989 and 1990) (Figure 11)

The eastward trend in the the south fishery (noted by Francis & Robertson (1991)) is clearly seen in Figure 11 (also, compare columns 3 and 4 of Table 13). Another trend in this fishery is the gradual reduction in average tow duration as the ability to tow on pinnacles increased over time (Figure 12).

The contrast between the east/flat and east/pinn. fisheries is apparent in three ways. First, tows east of "longitude" 185 were not clustered around a few "longitudes" before 1991, as they were subsequently (Figure 11). Second, tows on the flat are typically longer than those on pinnacles (Figure 12). Third, the east/flat fishery was predominantly a pre- and post-spawning fishery in June and August, whereas the east/pinn. fishery is prosecuted throughout the year (Figure 13).

The evolution of the three subfisheries is shown in Figure 14. For south, effort rose rapidly up to 1988 and then both catch and effort fell sharply (Figure 14A,B); catch rates peaked in 1982 at 9.2 t per tow, gradually declined through to 1989, and have been stable at about 2.6 t per tow since (Figure 14C); percentage oreo bycatch has risen consistently and is now very high, at around 60% (Figure 14E).

In the east/flat fishery, effort has been relatively low (Figure 14A), but catch rates have been high, declining from a peak of 20 t per tow in 1983 (with little effort) to 5 t per tow in 1990 (Figure 14C); oreo bycatch has been uniformly low (Figure 14D–F).

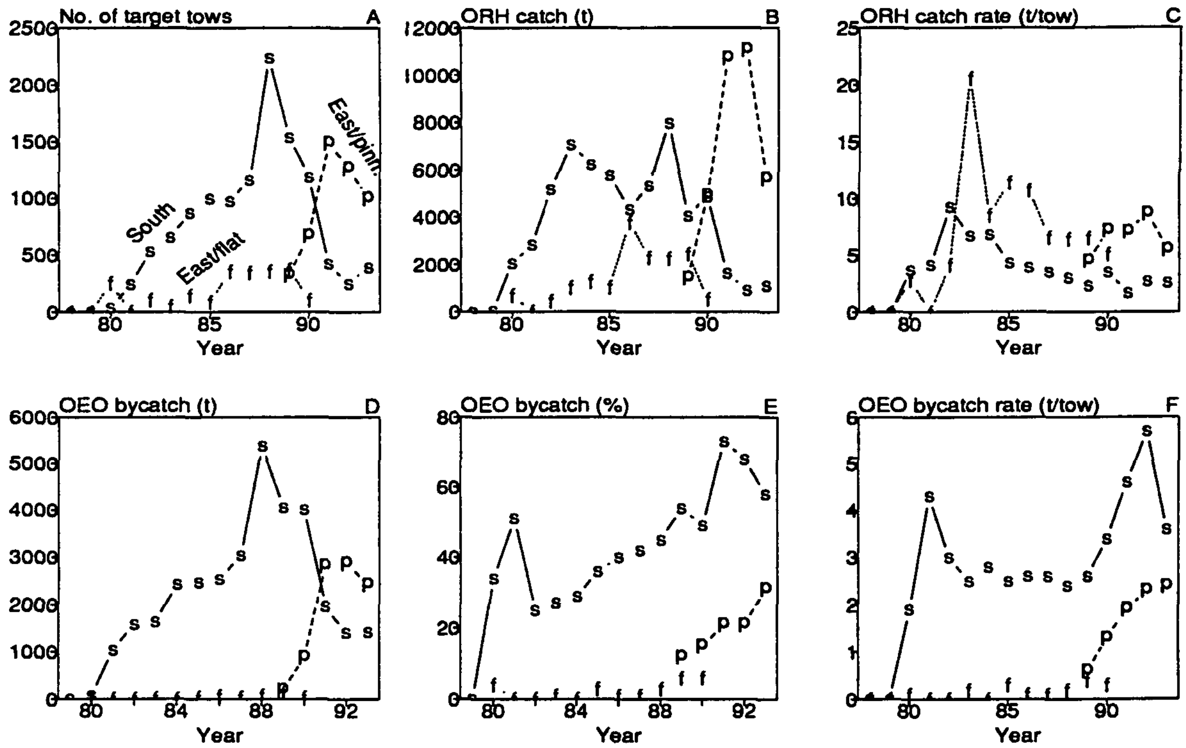

Figure 14. Analysis by calender year and subfishery of tows that caught or targeted orange roughy or oreos on the south and east Rise (south of 43.3° S or east of 175° W). The three subfisheries are identified in the plots by the plotting symbols 's', 'f', and 'p' (as indicated in panel A). Catch rates in panel C are for orange roughy target tows only.

Both effort and catch rose rapidly in the first three years of the east/pinn. fishery (Figure 14A,B); catch rates fluctuated about 6.6 t per tow (Figure 14C); oreo bycatch (in terms of percentage and t per tow) is not as high as in the south fishery, but has risen continuously (Figure 14E,F).

4.3.2 Puysegur Catch per Unit Effort

Catch and effort data from 1991–92 to 1993–94 (to June) from the central part of the Puysegur Bank fishery area have been examined. Data have been analysed by month, for two vessel categories: trawlers less than 50 m (mainly fresh fish vessels between 20 and 40 m), and vessels greater than 50 m (mainly factory freezer trawlers of 60 – 70 m). Months where less than 20 tows were carried out have been excluded. The average monthly catch per unit effort (total catch divided by number of tows) is shown in Table 14.

Table 14: Unstandardised CPUE (catch (t) per tow) for Puysegur Bank orange roughy, based on two size classes of vessel. -, insufficient data.

	< 50 m			> 50 m		
	91–92	92–93	93–94	91–92	92–93	93–94
Oct	-	3.8	1.3	-	5.9	2.8
Nov	9.2	5.4	1.0	11.7	2.0	1.8
Dec	5.1	6.7	-	19.4	7.6	2.1
Jan	8.6	-	-	15.8	8.1	3.9
Feb	10.9	-	-	10.0	9.6	1.3
Mar	-	-	-	-	9.5	1.0
Apr	-	1.7	-	-	7.5	0.8
May	-	-	-	-	-	2.1
Jun	-	-	-	6.2	-	3.8
Jul	-	-	-	8.0	-	-
Aug	-	-	-	5.5	7.5	-
Sep	-	-	-	5.0	4.0	-

CPUE generally has shown a decline between years in all months for both vessel categories. This trend is most obvious with larger vessels, which have a more complete coverage of months, and experienced crews who have worked the grounds from the start of the fishery. CPUE over the period November – February shows a decrease from general levels of 10–20 t per tow in 1991–92, to 5–10 t per tow in 1992–93, to less than 5 t per tow in 1993–94.

4.3.3 Egg Surveys

In July 1994, eight vertical-haul plankton tows were carried out in the 'spawning box' to obtain fresh orange roughy eggs for use in trials of a new egg ageing technique. The method relies on being able to accurately measure the amount of DNA in each egg as an index of age. The tows targeted areas where the highest egg densities were expected. Samples between 850 m and the surface were taken using a 2 m^2 ring net with 0.7 mm mesh.

Catch rates for orange roughy eggs were two orders of magnitude lower than they were in the same area 10 years earlier: maximum and mean catch rates were 0.65 and 0.33 eggs per cubic metre, compared to 57 and 15 in 1984. (These catch rates assume 100% filtration and an effective net mouth of 2 m^2 for both nets; in 1984 there were 15 double oblique tows using a 2 x 2 m plankton net with a 1.0 mm mesh). The comparable tows in 1992 (three oblique tows from the surface to about 780 m using multiple opening and closing nets) yielded catch rates of 0.27, 0.39, and 0.44 eggs per cubic metre – of the same order of magnitude, as the 1994 data.

The 1994 tows were notable for the number of orange roughy yolk-sac larvae caught (195 in total, and a maximum of 88 per tow). These appeared to be recently hatched as they were completely unpigmented, indicating that the eggs were hatching before they sank right to the bottom. That no larvae were found in 1984 may be because the tows were too shallow (all were shallower than 500 m) or the mesh size of 1 mm was too large to catch yolk-sac larvae. No later stage larvae were caught in either year. No larvae were caught in 1992, even though the mesh size and depths sampled were suitable.

4.3.4 Sex Ratios

Chatham Rise orange roughy sex ratio data in the scientific observer database were examined to see if the sex ratio imbalance observed in the last two biomass surveys (*see* Section 4.2) could have been caused by fishing. Samples were taken from 843 tows between 24.11.86 and 2.5.94, with the number of tows sampled from each area varying substantially from year to year (Table 15).

Table 15: Number of tows sampled for sex ratio by area and year

Year	Northwest	Box	East	South	Total
1986–87	0	19	0	1	20
1987–88	0	0	0	1	1
1988–89	23	107	30	13	173
1989–90	2	108	8	24	142
1990–91	32	57	18	16	123
1991–92	6	0	146	14	166
1992–93	4	2	39	40	85
1993–94	17	0	80	36	133

Unweighted sex ratios show that, since 1992, samples on the northwest Rise have contained mostly male fish, and that on the south Rise female fish have always dominated the samples. In the "box" and on the east Rise sex ratios have been highly variable, but approximately balanced between the sexes.

However, when the samples are weighted by catch, and the percentage of the reported catch that was sampled is taken into account, the sampling of the catch appears to have been too patchy to allow any firm conclusions to be drawn from these data.

For commercial fishing to significantly reduce the proportion of males in the population, there would have to be *substantial* catches of predominantly male fish. All years and areas which were well sampled *and* had reasonably high catches had sex ratios of about 50:50 (underlined numbers in Table 16).

Table 16: Mean percentage male (weighted by catch) by area and year (with percentage of reported catch sampled in parentheses). Underlined figures are those where catches were reasonably high and well sampled. -, no sample

Year	Northwest		Box		East		South		Total	
1986–87	-	(0)	50	(4)	-	(0)	33	(<1)	50	(2)
1987–88	-	(0)	-	(0)	-	(0)	43	(<1)	43	(<1)
1988–89	44	(5)	62	(14)	53	(14)	40	(2)	58	(10)
1989–90	54	(<1)	53	(12)	47	(4)	42	(<1)	52	(6)
1990–91	48	(22)	48	(22)	48	(4)	38	(2)	47	(10)
1991–92	70	(10)	-	(0)	41	(18)	42	(7)	42	(15)
1992–93	76	(1)	18	(54)	53	(16)	47	(6)	51	(8)
1993–94	64	*	-	*	51	*	45	*	51	*

* reported catch not available for 1993–94

4.4 Biomass Estimates

4.4.1 Life History Parameters

Life history parameters for Chatham Rise orange roughy have been revised since the previous assessment (Table 17) on the basis of otolith ring counts from fish sampled during a survey in 1984 (Doonan 1994).

Table 17. Revised life history parameters as used in this assessment. The parameters used in the 1993 assessment are given (under 'Old') for comparison. –, not estimated

Parameter	Symbol	New			Old
		Male	Female	Both sexes	Both sexes
Natural mortality	M	–	–	0.045yr^{-1}	0.04 yr^{-1}
Age of recruitment	A_r	33 yr	34 yr	–	22.2 yr
Gradual recruitment	S_r	9 yr	8 yr	–	6.6 yr
Age at maturity	A_m	33 yr	34 yr	–	22.2 yr
Gradual maturity	S_m	9 yr	8 yr	–	6.6 yr
von Bertalanffy parameters	L_∞	36.4 cm	38.0 cm	–	37.3 cm
	k	0.070 yr^{-1}	0.061 yr^{-1}	–	0.07 yr^{-1}
	t_0	–0.4 yr	–0.6 yr	–	–0.3 yr
Length-weight parameters	a	–	–	0.0921	0.0921
	b	–	–	2.71	2.71
Recruitment variability	σ_R	–	–	1.1	1.2
Recruitment steepness		–	–	0.75	0.75

Parameter estimates and results from ageing studies are similar to those obtained by Australian researchers working on Tasmanian stocks of orange roughy. A re-examination of the radiometric data used by Fenton *et al.* (1991) to age orange roughy incorporated more robust methods of analysis, but supported the conclusion that ages approaching, or exceeding, 100 years can be attained (Francis 1995a).

The new life history parameters result in a large increase in yield estimates (*see* Section 4.5). The reason for this can be seen by examining the effect of these changes on the dynamics of a model of a virgin population. The significant change is a substantial increase in recruitment, caused partly by the increase in A_r and A_m and partly by the increase in M, with the former change being more influential (Table 18).

Table 18: The three components of change in recruited biomass (growth, recruitment, and natural mortality – all expressed as percentages of mean recruited biomass) in a virgin orange roughy population, calculated for various sets of life history parameter values

Life history parameters	Growth (% B_0)	Recruitment (% B_0)	Natural mortality (% B_0)
1993 parameters	+1.41	+2.63	-4.08
1994 parameters	+0.82	+3.77	-4.60
1993 parameters with M as in 1994	+1.54	+3.02	-4.60
1993 parameters with A_m and A_r as in 1994	+0.65	+3.39	-4.08
1993 parameters with S_m and S_r as in 1994	+1.45	+2.59	-4.08
1993 parameters with σ_R as in 1994	+1.41	+2.64	-4.08
1993 parameters with L_∞, k, and t_0 as in 1994	+1.50	+2.53	-4.08

Recruitment is important as a determinant of yield because, as a population biomass is reduced by fishing, the growth and natural mortality terms of Table 18 are reduced proportionately, but the recruitment term does not reduce at all for the first A_m years of the fishery, and then reduces only slowly, because of the steepness of the stock-recruit relationship.

4.4.2 Input Data for Biomass Estimation

The input data for the stock reduction analysis used in estimating biomass are given in Tables 11 and 19.

Table 19: Catch and overrun values used in the stock reduction analyses (a 10% overrun for 1993–94 is consistent with the assumptions made in the 1993 assessment, but these assumptions were not reviwed this year)

Year	Catch (t)	Overrun (%)
1978–79	11 800	30
1979–80	31 100	30
1980–81	28 200	30
1981–82	24 888	30
1982–83	15 434	30
1983–84	24 818	30
1984–85	29 340	30
1985–86	30 075	28
1986–87	30 689	26
1987–88	24 214	24
1988–89	32 785	22
1989–90	31 444	20
1990–91	20 640	15
1991–92	15 529	10
1992–93	14 000	10
1993–94	14 000*	10

* projected

Because of uncertainties concerning the survey data (*see* Section 4.2), four alternative sets of data assumptions were used in estimating biomass (Table 20). The first assumption ignores the uncertainties and takes the biomass index as calculated from the entire data set. In the second assumption, the effect of removing a single very high catch rate is evaluated. Thirdly, the entire series of mean length indices was omitted because of uncertainty as to whether this contained information about recruitment. Fourthly, all data from the last two surveys (which estimated extreme sex ratios) were omitted. The first two assumptions are most comparable with the 'length, biomass' assumption in the 1993 assessment; the fourth is most comparable with the 'none' assumption.

Table 20. Four sets of data assumptions used in the stock reduction analyses. (83 169 is the 1994 survey biomass estimate using the entire data set; 28 263 is the same estimate when one very high catch rate is omitted)

Data assumption	Biomass indices	Mean length indices	1994 biomass index (*c.v.*, %)
1	all	all	83 169 (67)
2	all	all	28 263 (45)
3	all	none	28 263 (45)
4	up to 1990	up to 1990	-

4.4.3 Chatham Rise Biomass Estimates

Biomass was estimated using the enhanced stock reduction analysis used in the 1993 assessment (Francis *et al.* 1993) with two modifications (*see* Appendix for full details). First, the *c.v.* for each biomass index was taken as the value estimated in the associated survey, rather than the median value for all indices. This was done because of the trend of increasing *c.v.* in these surveys (Table 11). Second, errors in the biomass indices were assumed to be lognormally, rather than normally, distributed (for an index that must be positive, normal errors are inconsistent with high *c.v.*s).

The effect of these changes was evaluated by repeating the 1993 analysis (for assumption 'length, biomass') with the new model assumptions. This resulted in only slight changes in the estimated biomass (Table 21).

Table 21: The effect on the 1993 stock-reduction estimates of biomass of modifications to the model assumptions (*see* text)

Parameter values	Model assumptions	B_0 ('000 t)	B_{1978} ('000 t)	B_{1992} ('000 t)	B_{1992} (% B_0)
As in 1993	as in 1993	411	466	83	21
As in 1993	revised	405	453	78	20

The 1994 assessment results are consistent with those from 1993. Estimates of B_0 are similar to those in the 1993 assessment (Table 22). Estimates of "current" biomass from the 1994 assessment (10 – 17% B_0 for B_{1994}) were slightly lower than from the 1993 assessment (14 – 21% B_0 for 1992). This decline was predicted in the 1993 assessment. (The results from the 'length only' analysis from the 1993 assessment are not included in this comparison because they were not repeated in 1994.) The value of B_{1994} estimated (under the 'length, biomass' assumption) in the 1993 assessment (64 000 t, 16% B_0) is intermediate between the most comparable estimates (data assumptions 1 and 2) in the current assessment. The difference between the data assumptions has more influence on estimates of current biomass than on B_0 (Table 22, Figure 15).

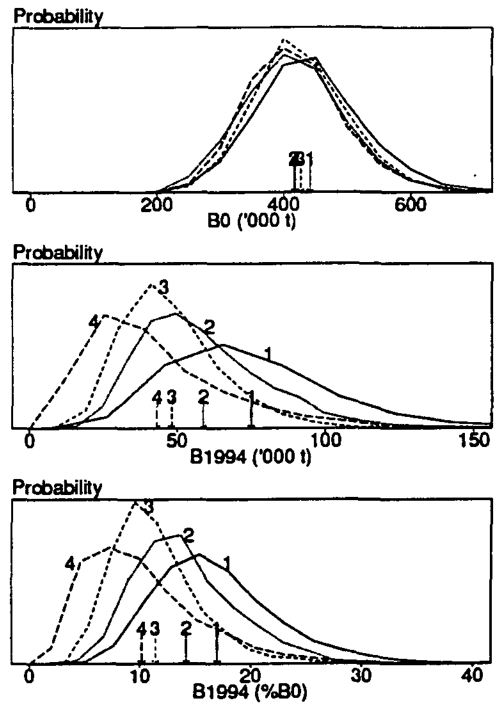

Figure 15. Results from the stock reduction analysis with the four alternative data assumptions of Table 20. Arrows indicate biomass estimates; lines represent the uncertainty about these estimates.

Table 22: Stock-reduction biomass estimates under four data assumptions (Table 20)

Data assumption	B_0 ('000 t)	B_{1978} ('000 t)	B_{1994} ('000 t)	B_{1994} (% B_0)
1	442	462	75	17
2	416	445	59	14
3	427	403	48	11
4	418	424	43	10

4.4.4 Biomass Estimates for Puysegur, Waitaki, and Macquarie areas

Reliable biomass estimates cannot be derived for the Puysegur stock. Trawl surveys in 1991 and 1992 were carried out with different vessels, and the time series started in 1992 with *Tangaroa* has not yet developed.

Similarly, trawl survey data from the Waitaki and Macquarie areas are insufficient at this stage to estimate biomass.

4.5 Yield Estimates

4.5.1 Estimation of Maximum Constant Yield (MCY)

Using the method of Francis (1992a) the maximum constant catch that can be taken indefinitely (without reducing the population below 20% B_0 more than 10% of the time) from a population with life history parameters as in Table 17 is 1.62% B_0. This is markedly higher than last year's figure of 1.20% B_0 (Francis *et al.* 1993) because of the revised parameter values (specifically, changes in A_r, A_m, and M – *see* Section 4.4.1). Under continued fishing at this level the mean biomass is 50% B_0.

The sensitivity of the MCY estimate to variations in M and steepness is shown in Table 23.

Table 23: Maximum constant catch (as a percentage of B_0) that can be taken indefinitely (without reducing the population below 20% B_0 more than 10% of the time) from an orange roughy population, calculated for different values of M and steepness. –, not calculated

			Steepness
M	0.50	0.75	0.95
0.03	–	1.06	–
0.045	1.16	1.62	1.93
0.06	–	2.02	–

MCYs for the Chatham Rise (Table 24) were calculated following Francis (1992a). It is not yet possible to estimate MCY for the Puysegur or Waitaki populations.

Table 24. Estimates of 1994–95 beginning-of-season biomass, MCY, CAY, and MAY for the Chatham Rise population under various data assumptions (Table 20). The long-term MCY is the MCY when the biomass is greater than 20% B_0; the MAY is the long-term average CAY. All yields are corrected for an assumed overrun of 10%. All values in t

Data assumption	$B_{1994-95}$	$MCY_{1994-95}$	$MCY_{long-term}$	$CAY_{1994-95}$	MAY
1	80 000	5900	6500	4800	8300
2	62 000	4600	6100	3700	7800
3	57 000	4300	6300	3400	8000
4	49 000	3500	6200	2900	7900

4.5.2 Estimation of Current Annual Yield (CAY)

Using the method of Francis (1992a), E_{CAY}, the exploitation rate producing maximum average yield (without reducing the population below 20% B_0 more than 10% of the time) for a population with life history parameters as in Table 17 is 0.069. This is markedly higher than last year's figure of 0.054 (Francis *et al.* 1993) because of the revised parameter values (specifically, changes in A_r, A_m, and M – *see* Section 4.4.1). The mean catch when fishing at $E = 0.069$ is 2.07% B_0 and the mean biomass is 29% B_0.

CAY estimates for the Chatham Rise are shown in Table 24. The sensitivity of the estimates of E_{CAY} to variations in M and steepness is shown in Table 25.

Table 25: The exploitation rate, E_{CAY}, for an orange roughy population, calculated for different values of M and steepness. –, not calculated

		Steepness	
M	0.50	0.75	0.95
0.03	–	0.049	–
0.045	0.037	0.069	0.086
0.06	–	0.088	–

It is not yet possible to estimate CAY for the Puysegur or Waitaki populations.

4.5.3 Sensitivity of yields to life history parameters

The effects on the estimated biomass and yield levels of changes in M and the maturity/recruitment ogive are shown in Table 26. This shows that uncertainty in yields is much greater than indicated by the range of yields in Table 24. This is particularly so for the long-term yields, $MCY_{long\text{-}term}$ and MAY.

Table 26: Sensitivity of estimates of 1994–95 beginning-of-season biomass, MCY, CAY, and MAY for the Chatham Rise population to changes in M and the parameters that determine the maturity/recruitment ogive (A_m, A_r, S_m, S_r). The long-term MCY is the MCY when the biomass is greater than 20% B_0; the MAY is the long-term average CAY. All yields are corrected for an assumed overrun of 10%

Data assumption	M	Maturity ogive	$B_{1994-95}$	$MCY_{1994-95}$	$MCY_{long\text{-}term}$	$CAY_{1994-95}$	MAY
2	0.045	1994 version	62 000	4600	6100	3700	7800
	0.03	1994 version	59 000	2800	4300	2500	5700
	0.06	1994 version	64 000	5900	7100	4800	9600
	0.045	1993 version	71 000	4300	5100	3600	7200
3	0.045	1994 version	57 000	4300	6300	3400	8000
	0.03	1994 version	54 000	2600	4400	2300	5800
	0.06	1994 version	60 000	5600	7400	4500	10100
	0.045	1993 version	58 000	3500	5500	3000	7700

4.6 Decision Analysis for the Chatham Rise Fishery

Forward simulations were carried over the period 1994–95 to 2001–02 for the constant-catch options shown in Table 27. The time period and catch options were chosen so that the results of the simulations should be as comparable as possible with those from the 1993 assessment. Option 6, an immediate cessation of fishing, is included to illustrate how the population might behave in the absence of fishing.

Table 27: Annual Chatham Rise catches (t) for six constant-catch options used in forward simulations over the period 1994–95 to 2001–02, inclusive. (In the forward simulations, actual catches were assumed to be 10% higher than the values below)

Option	1	2	3	4	5	6
Catch (t)	9000	7500	6000	5000	4000	0

For each catch-reduction option, four measures of fishery performance were calculated (Table 28). All four measures relate to the mid-year biomass in 2001–02: thus P(Improve by 2002) is the probability that this is *either* greater than the "current" mid-year biomass *or* greater than 30% B_0; and P(B_{2002} > 20% B_0) and P(B_{2002} > 30% B_0) are the probabilities that it exceeds 20% B_0 and 30% B_0, respectively. To enhance comparability with the 1993 assessment, two versions of P(Improve by 2002) were calculated. These are distinguished by the subscripts "93" and "94", which denote the year which is treated as "current" in the definition just given. The measure P(No collapse) is not presented because its estimated values were uniformly high and so show very little contrast between the catch options and/or data assumptions. The measures P_{93}(Improve by 2002) and P(B_{2002} > 20% B_0) are directly comparable with the similarly named measures in the 1993 assessment (after allowance for differences in the total catches over the 1993–94 to 2001–02 period). Note that, in terms of these fishery performance indicators, only the total catch over the period considered is important; the sequence of individual catches has little effect.

Table 28: Estimates of fishery performance for six catch options (Table 27), calculated for four alternative data assumptions (*see* Table 20)

Data assumption	Performance measure	Option 1	2	3	4	5	6
1	P_{94}(Improve by 2002)	0.49	0.71	0.89	0.96	0.99	1.00
	P_{93}(Improve by 2002)	0.39	0.57	0.78	0.88	0.95	1.00
	P(B_{2002} > 20% B_0)	0.34	0.45	0.58	0.67	0.76	0.97
	P(B_{2002} > 30% B_0)	0.09	0.12	0.18	0.23	0.28	0.60
2	P_{94}(Improve by 2002)	0.38	0.61	0.85	0.94	0.98	1.00
	P_{93}(Improve by 2002)	0.28	0.45	0.69	0.83	0.92	1.00
	P(B_{2002} > 20% B_0)	0.16	0.26	0.38	0.48	0.59	0.93
	P(B_{2002} > 30% B_0)	0.03	0.05	0.07	0.10	0.15	0.43
3	P_{94}(Improve by 2002)	0.82	0.92	0.98	0.99	1.00	1.00
	P_{93}(Improve by 2002)	0.77	0.88	0.95	0.98	0.99	1.00
	P(B_{2002} > 20% B_0)	0.37	0.49	0.62	0.70	0.78	0.98
	P(B_{2002} > 30% B_0)	0.10	0.14	0.20	0.25	0.32	0.64
4	P_{94}(Improve by 2002)	0.67	0.83	0.95	0.99	1.00	1.00
	P_{93}(Improve by 2002)	0.58	0.75	0.89	0.95	0.98	1.00
	P(B_{2002} > 20% B_0)	0.21	0.29	0.40	0.48	0.57	0.89
	P(B_{2002} > 30% B_0)	0.06	0.09	0.11	0.15	0.19	0.44

Estimates of P_{93}(Improve by 2002) and P(B_{2002} > 20% B_0) are markedly greater than the comparable values in the 1993 assessment (Figure 16). Two factors are responsible for this increase. The first is the increase in estimated productivity of orange roughy caused by the revised values of the biological parameters A_r, A_m, and M (*see* Section 4.4.1). The second reason applies mainly to data assumption 3 (and to a lesser extent to assumption 4). When mean length data are not used in the assessment, estimates of recent recruitment are higher, which leads to predictions of faster rebuilding.

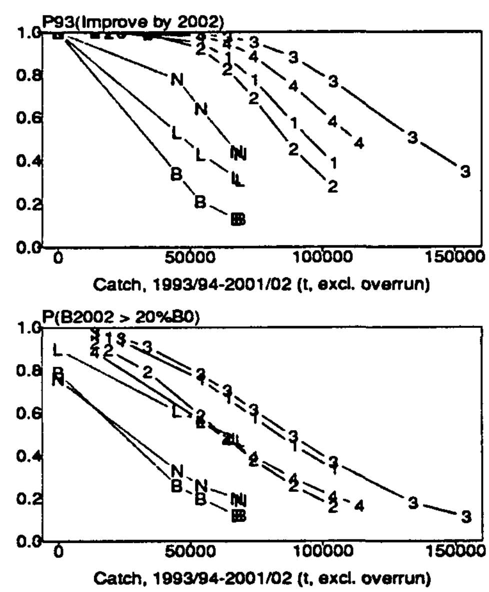

Figure 16. Comparison of the 1993 and 1994 estimates of the performance measures P_{93}(Improve by 2002) (upper panel) and P(B_{2002} > 20% B_0) (lower panel). Plotting symbols '1', '2', '3', '4' correspond to data assumptions 1 to 4 in the current assessment (Table 20); symbols 'B', 'N', and 'L' correspond to the 'Length, biomass', 'None', and 'Length' data assumptions of the 1993 assessment.

That estimates of P_{94}(Improve by 2002) are always higher than P_{93}(Improve by 2002) shows that, for all data assumptions, the current assessment indicates a drop in biomass between 1992–93 and 1993–94. This means that current catch exceeds estimated surplus production (otherwise the biomass would have increased).

Two performance criteria that are suggested by the performance measures given here are:

'safety' criterion: $P(B_{2002} > 20\% B_0) > 0.9$
'target' criterion: $P(B_{2002} > 30\% B_0) > 0.5$

These are analogous to the criteria used in the 1994 ORH 2A, 2B, 3A assessment (Field *et al.* 1994).

None of the non-zero catch options of Table 27 meets both criteria (using any of the four data assumptions). Estimates of the maximum total catch (excluding overrun) over the 8 year period 1994–95 to 2001–02 that would meet both criteria range from 0 to 14 000 t (Table 29). Even with no fishing, neither of these criteria is expected to be met before 2000–01 (Table 30)

Table 29: Maximum total catch (t, excluding overrun), over the eight year period 1994–95 to 2001–02, that would meet the 'safety' or 'target' performance criteria (or both), for each of the data assumptions of Table 20

Data			Performance criterion
assumption	'safety'	'target'	'safety' + 'target'
1	13 000	9 000	9 000
2	4 000	0	0
3	17 000	14 000	14 000
4	0	0	0

Table 30: Estimates of the fishing year in which the 'safety' and 'target' performance criteria are first expected to be met, assuming no fishing in the future (calculated for each of the data assumptions of Table 20)

Data			Performance criterion
assumption	'safety'	'target'	'safety' + 'target'
1	2000–01	2001–02	2001–02
2	2001–02	2002–03	2002–03
3	2000–01	2000–01	2000–01
4	2002–03	2002–03	2002–03

Estimates of the total catch which can be taken in the eight year period 1994–95 to 2001–02, and which will result in a 50% probability that the stock size in 2001–02 will be an 'improvement' on that in 1992–93, range from 58 000 to 96 000 t (Table 31). The 1993–94 catch of 14 000 t must be added to these figures to make them comparable to the value resulting from the 1993 stock assessment (about 45 000 t). The increase in these catch levels is caused mainly by the increase in the estimated productivity of orange roughy (*see* Section 4.4.1.

Table 31. Estimates of total catch (excluding overrun) for the eight year period 1994–95 to 2001–02 for which P_{93}(Improve by 2002) equals 50%

Data Assumption	Total Catch (t)
1	65 000
2	58 000
3	96 000
4	78 000

4.7 Effect of 1994–95 catch

The effect of the 1994–95 catch may be summarised by the probability that this catch will allow the biomass to 'rebuild'. In this context the term 'rebuild' means that EITHER the 1994–95 end-of-year biomass was greater than that for 1993–94 OR the 1994–95 mid-season biomass was greater than 20% B_0. The maximum 1994–95 catch that allows at least a 50% chance that the biomass will rebuild, ranges from 7600 to 12 500 t, according to the assumptions made (Table 32). These 50% rebuild catches are substantially higher than those estimated for 1993–94 in the 1993 stock assessment. The increase in these catch levels is caused mainly by the increase in the estimated productivity of orange roughy (*see* Section 4.1.1).

Table 32: The probability that the biomass will rebuild with various 1994–95 catch levels, and the catch that allows a 50% chance of rebuilding, calculated for four alternative data assumptions (Table 20). (10% catch overrun was assumed for 1994–95). -, not estimated

Data						1994–95 catch (t)	50% rebuild
assumption	12000	9000	7500	6000	5000	4000	catch (t)
1	-	0.36	0.64	0.89	0.97	0.99	8 300
2	-	0.24	0.52	0.83	0.95	0.99	7 600
3	0.55	0.85	0.94	0.98	1.00	1.00	12 500
4	-	0.62	0.84	0.96	0.99	1.00	9 700

4.8 Sensitivity to Life History Parameters

Estimates of the performance measures of Table 28, and the 50% rebuild catches of Table 32, are rather sensitive to changes in key life history parameters (Tables 33 and 34). Thus the degree of uncertainty in these estimates is substantially greater than shown in Tables 28 and 32 (and, by implication, Table 31).

Table 33: Sensitivity of estimates of fishery performance for catch option 2 (Table 27) to changes in *M* and the parameters that determine the maturity/recruitment ogive (A_m, A_r, S_m, S_r), calculated for two alternative data assumptions (Table 20)

Data assumption	*M*	Maturity ogive	P_{94}(Improve by 2002)	P_{93}(Improve by 2002)	P(B_{2002}>20% B_0)	P(B_{2002}>20% B_0)
2	0.045	1994 version	0.61	0.45	0.26	0.05
	0.03	1994 version	0.25	0.13	0.07	0.01
	0.06	1994 version	0.82	0.71	0.46	0.13
	0.045	1993 version	0.19	0.11	0.17	0.03
3	0.045	1994 version	0.92	0.88	0.49	0.14
	0.03	1994 version	0.68	0.58	0.19	0.04
	0.06	1994 version	0.98	0.97	0.71	0.30
	0.045	1993 version	0.81	0.74	0.34	0.11

Table 34: Sensitivity of estimates of the 1994–95 '50% rebuild' catch to changes in M and the parameters that determine the maturity/recruitment ogive (A_m, A_r, S_m, S_r), calculated for two alternative data assumptions (Table 20)

Data assumption	M	Maturity ogive	50% rebuild catch (t)
2	0.045	1994 version	7 600
	0.03	1994 version	5 900
	0.06	1994 version	9 000
	0.045	1993 version	4 500
3	0.045	1994 version	12 500
	0.03	1994 version	9 700
	0.06	1994 version	14 300
	0.045	1993 version	11 000

5 Management Implications

5.1 Chatham Rise Fishery

This stock assessment is based on the results of applying the stock reduction model using the following assumptions: a) there is a single stock for the entire Chatham Rise; b) the stock is accurately indexed by the time series of surveys in the Box; and c) the ranges used for the biological parameters encompass their true values. This leads to the following five conclusions:

- The mid-season 1993–94 biomass estimates ranged from 10 to 17% B_0. These estimates are substantially less than B_{MSY} (29% B_0).

- In terms of long-term yield and rebuilding potential, the results of this assessment are more optimistic than those of last year. This is primarily because revised values of some biological parameters (A_m, A_r, M) have caused an increase in the estimated productivity of orange roughy. However, current catch levels are about twice the estimated long-term yields ($MCY_{long\text{-}term}$ and MAY – *see* Table 24). There is no significant change in the estimated size of the virgin stock (B_0).

- The estimated biomass continues to decline. This indicates that the current catch exceeds estimated surplus production.

- Current estimates of the catch that will result in *either* the 1994–95 end-of-year biomass being greater than that for 1993–94 *or* the 1994–95 mid-season biomass being greater than 20% B_0 range from 7600 to 12 500 t (excluding overrun) for 1994–95. Estimates of the maximum total catch (excluding overrun) over the period 1994–95 to 2001–02 (inclusive) that will allow a 50% chance that the biomass in 2001–02 will be an 'improvement' on that in 1992–93, range from 58 000 to 96 000 t. Note that catch levels that allow only a 50% probability of rebuilding are, in effect, "status quo" catches in that there are equal probabilities that the stock will rebuild or be depleted as a result of these catches.

- The low productivity of orange roughy makes rebuilding rates slow. To achieve rebuilding to B_{MSY} by 2001–02 would require a substantial reduction in catch, and might not be possible even if fishing ceased (*see* Table 29).

This section concludes with a discussion of the main sources of uncertainty associated with this assessment (life history parameters, stock definition, interpretation of the 1992 and 1994 survey results, recruitment, and representativeness of the survey indices). The first two are the most important. None of these sources of uncertainty give reason to believe that the status of Chatham Rise orange roughy is likely to be either more pessimistic or more optimistic than indicated by the current assessment.

- Life history parameters

  The main uncertainties concerning the biological parameters are age estimation and the steepness of the stock-recruit relationship. The former is fundamental to the determination of the productivity of orange roughy (through parameters like M, A_m, and A_r). Although current estimates of these parameters are more consistent than those used in 1993 with the data now available, they are still highly uncertain. This leads to similar uncertainty in estimates of yield, rebuilding catches, and fishery performance. The steepness parameter is an important component in determining long-term productivity. No data are available to check the assumed value of this parameter.

- Stock definition

  Recent genetic data suggest that Wairarapa and Kaikoura fish are separate from those on the Chatham Rise, but have not resolved the issue of stock structure within the Rise. Heterogeneity within the data suggests more than one stock (as may the widespread spawning activity outside the Box), but there are no clear stock boundaries. If there is more than one stock, then (a) the size of the stock indexed by the Box surveys has been substantially reduced, but the exact level of depletion is unknown, and (b) the status of the stock(s) not indexed by the Box surveys is unknown.

- Survey results

  High coefficients of variation (*c.v.*s) and an imbalance in the sex ratios make interpretation of the 1992 and 1994 survey results difficult and uncertain. However, all four data assumptions (*see* Table 20) considered in this assessment lead to the conclusion that the biomass of this stock has continued to decline since the last assessment. The effect on yield estimates of this uncertainty is less than that from the life history parameters.

- Recruitment

  Uncertainty with regard to recruitment centres on the interpretation of the lack of consistent change in mean length, combined with a strong decline in the biomass index. The traditional interpretation is that recent recruitment has been poor. However, the observation that mean length has not changed in other orange roughy populations casts doubt on this interpretation, so recent recruitment may be higher than estimated for data assumptions 1 and 2 (*see* Table 20). The uncertainty with regard to recruitment is responsible for the differences in the assessment results based on data assumptions 1 and 2 compared to those based on assumptions 3 and 4.

- Representativeness of survey indices

  Another uncertainty is that of representativeness, i.e., the assumption that the survey data index the biomass and mean length of a single recruited Chatham Rise population of orange roughy. The main argument in favour of this assumption is that the Box covers what appears to have been, for at least most of the history of the fishery, the major orange roughy spawning ground on the Chatham Rise. A possible alternative hypothesis is that the proportion of Chatham Rise orange roughy that spawn in the Box has declined over the years. This would produce a more optimistic assessment. However, to make a major difference to the assessment the decline in the proportion spawning would need to have been considerable before the 1991 season (because the analysis with data assumption 4 uses only survey data from before 1991).

5.2 Puysegur Fishery

There is little information available to assess the state of the Puysegur Bank orange roughy stock. CPUE data suggest strongly that the Puysegur stock has been reduced by the fishery in the last two years. The current catch level of 5000 t is probably not sustainable. For it to be sustainable, a virgin biomass of around 300 000 t (about 70% of the size estimated from the Box surveys on the north Chatham Rise) would be required. To reduce risks to the fishery, lower catch levels are required.

An additional research survey of the Puysegur stock was carried out in September–October 1994, after this assessment.

5.3 Waitaki Fishery

There has been only one research survey in this area. Results had a low level of precision, and are of limited use in assessing the state of the stock. However, the patchiness of the distribution of orange roughy was more extreme than in the other spawning grounds in New Zealand, and the very low 'background' catch rates in surrounding strata were also unusual in comparison with other fishing areas. Survey results indicated a small and localised spawning area, with limited potential to support a major target fishery for orange roughy.

5.4 Macquarie Ridge Fishery

Two hill complexes fished commercially in 1993 may have some potential. Spawning occurs in both areas in July. There are no quantitative data on abundance, but indications are that the distribution of orange roughy is very localised on these features.

Acknowledgments

We are indebted to Jack Fenaughty for running the Chatham Rise surveys and managing the associated data sets, and to other Working Group members for many helpful comments and insights.

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Appendix: Stock Reduction and Decision Analysis

This appendix describes the versions of stock reduction and decision analysis used in this assessment. The techniques are similar in principle to those described by Francis (1990, 1992b), but have been modified in a number of ways (including the addition of stochastic recruitment, recruitment/maturity ogives, importance sampling, and lognormal error structures).

Overview

I first give an overview of the two techniques. Details of the methods are given in subsequent sections.

The aim of stock reduction analysis is to estimate past and present biomass for a fishery. Three types of input data are required: biological parameters, abundance (and possibly mean length) indices, and a complete catch history (Table A1). For decision analysis, we extend the catch history into the future by adding proposed future catch levels, and evaluate the likely response of the fishery to these catch levels by estimating various measures of risk or fishery performance.

Table A1. Data required, and corresponding model notation, for stock reduction and decision analyses

Parameter	Description
Subscripts	
s	sex (1 = male, 2 = female)
y	year
j	indexes the jth series of biomass (or mean length) indices
Biological parameters	
M_s	instantaneous natural mortality (y^{-1})
A_{rs}	age at 50% recruitment (y)
S_{rs}	recruitment ogive width parameter (y)
A_{ms}*	age at 50% maturity (y)
S_{ms}*	maturity ogive width parameter (y)
$L_{\infty s}$	von Bertalanffy parameters (cm)
k_s	von Bertalanffy parameters (y^{-1})
t_{0s}	von Bertalanffy parameters (y)
a_s	length-weight parameters [$W = aL^b$, L in cm, W in g]
b_s	length-weight parameters [$W = aL^b$, L in cm, W in g]
σ_R	recruitment variability
h	stock-recruit steepness
A_{max}	maximum age in model (y) (there is a plus group at this age)
F_{max}	maximum possible exploitation rate
Biomass and/or mean length indices	
O_{yj}	value of jth index in year y
c_{yj}	coefficient of variation of O_{yj}
Catch history	
C_y	catch (historical or projected) in year y

* For orange roughy, it is assumed that recruitment to the fishery occurs at maturity, so that $A_{rs} = A_{ms}$ and $S_{rs} = S_{ms}$.

To run the population model underlying these analyses we need values for the biological parameters in Table A1, and for B_0 (mean virgin biomass). In addition, the model generates a vector, ε, of recruitment deviates, which, together with a stock-recruit relationship, allows it to calculate the number of fish at age 1 in any year (see below).

The model is used for stock reduction and decision analyses in the following way.

1. Choose a trial B_0 value.

2. Generate a vector, ε, of recruitment deviates.

3. Run the population model to calculate the biomass and mean length in each year (together with any other quantities needed for performance or risk measures – e.g., whether it would be possible to catch the projected catches).

4. Calculate the likelihood associated with (B_0,ε) and the indices, O_{yj} (see below).

5. Repeat steps 2 – 4 with a large number (20 000 in this assessment) of different recruitment deviate vectors.

6. Repeat steps 1 – 5 with an equally spaced sequence of trial B_0 values, using the same set of recruitment deviate vectors for each trial B_0.

7. From the resulting set of model runs (in this assessment there were 380 000 runs: 19 trial B_0 values times 20 000 recruitment deviate vectors) select a sample of size 5000, with replacement, with the probability of selection for any one run being proportional to the likelihood. This is called an importance sample.

8. Calculate mean biomass (or length) for any year as the mean of the biomass values calculated at step 3, where the mean is taken over all runs in the importance sample (with each run having equal weight). Use a similar procedure to calculate risk/performance measures (see below).

The importance sample is used to cut down the computation time. This is possible because the likelihood associated with each model run depends only on the *historical* catches, but decision analyses are typically carried out for a series of catch "histories" that are identical for the historical catches but contain different future catch levels (associated with alternative management strategies). Thus, while 380 000 model runs are required for one catch history, only 5000 model runs are required for subsequent catch histories. (In fact fewer than 5000 runs are required because the importance sample is selected with replacement, so that some runs will be selected many times).

For each trial B_0 value we can calculate the sum of the associated 20 000 likelihoods. The range of trial B_0 values selected at step 6 must be wide enough so that the value of this sum for the maximum and minimum B_0 values is a small fraction (< 1%, say) of the maximum value of this sum.

The Population Model

Given input data (Table A1) and a value for B_0, the population model first calculates values for the derived parameters (Table A2) as follows.

$$(A1) \qquad A_{r,lo} = int(A_{rs} - S_{rs})$$

$$(A2) \qquad A_{r,hi} = int(A_{rs} + S_{rs} + 0.999)$$

(where *int(x)* returns the greatest integer less than or equal to *x*)

$$(A3) \qquad r_{is} = \begin{cases} 0 & 1 \le i < A_{r,lo} \\ 1/[1 + 19^{(A_{rs} - i)/S_{rs}}] & A_{r,lo} \le i \le A_{r,hi} \\ 1 & A_{r,hi} < i \le A_{max} \end{cases}$$

$$(A4) \qquad p_{is} = \frac{1 - r_{is}}{1 - r_{i-1,s}}$$

$$(A5) \qquad L_{is} = L_{\infty s}[1 - e^{k_s(i - t_{0s})}]$$

$$(A6) \qquad w_{is} = 10^6 a_s L_{is}^{b_s}$$

$$(A7) \qquad \theta_s = \Sigma_i r_{is} w_{is} e^{-M_s i} + \frac{r_{A_{max}s} w_{A_{max}s} e^{-M_s(A_{max}+1)}}{1 - e^{-M_s}}$$

$$(A8) \qquad \overline{R_0} = \frac{2B_0}{\Sigma_s \theta_s}$$

$$(A9) \qquad \alpha = 0.5\theta_2\left(1 - \frac{h-0.2}{0.8h}\right)$$

$$(A10) \qquad \beta = \frac{h-0.2}{0.8h\bar{R}_0}$$

Note the distinction between two uses of "recruitment": recruitment to the fishery, which happens at maturity (and involves parameters A_{rs}, S_{rs}, N^r_{yis}, r_{is}, p_{is}, $A_{r,lo}$, $A_{r,hi}$), and recruitment to the population, which happens at age 1 (and involves parameters σ_R, h, $\bar{R}_y$, R_y, ε_y).

Table A2. Description and notation for model parameters and variables (in addition to those in Table A1). These are given in the order in which they are introduced in the text.

Parameter	Description
Subscripts	
s	sex (1 = male, 2 = female)
i	age (y)
y	year
j	indexes the *j*th series of biomass (or mean length) indices
Derived parameters	
$A_{r,lo}$	range of ages for which there is
$A_{r,hi}$	partial recruitment/maturity
r_{is}	proportion of fish (of age i and sex s) that are recruited (= mature) in the virgin population
p_{is}	proportion (of fish of age i-1 and sex s that were unrecruited in one year) that will still be unrecruited in the next year
L_{is}	mean length of fish of age i and sex s
w_{is}	mean weight of fish of age i and sex s
θ_s	constant used in calculating $\bar{R}_0$
$\bar{R}_0$	mean virgin recruitment (at age 1)
α	Beverton & Holt stock-recruit
β	relationship parameters
Variables calculated at each model iteration	
$\bar{R}_y$	expected recruitment (at age 1) in year y
N_{yis}	number of fish (age = i, sex = s) in year y
ε_y	recruitment deviate for cohort that recruits (at age 1) in year y
R_y	actual recruitment (at age 1) in year y
N^r_{yis}	number of recruited fish (age = i, sex = s) in year y
N^u_{yis}	number of unrecruited fish (age = i, sex = s) in year y
B^1_{ys}	begining-of-year biomass for sex s in year y
B^2_{ys}	pre-fishing biomass for sex s in year y
B^3_{ys}	mid-year biomass for sex s in year y
B^4_{ys}	end-of-year biomass for sex s in year y
F_y	exploitation rate in year y
$\bar{L}_y$	mean length in year y

The model then initialises the population structure by generating a vector of standard normal variates $\{\varepsilon_{1-i}: 1 \le i \le A_{max}\}$ and calculating numbers at age as follows.

$$(A11) \qquad R_{1-i} = \overline{R_0} e^{\epsilon_{1-i}\sigma_R - 0.5\sigma_R^2} \qquad for\, 1 \le i \le A_{max}$$

$$(A12) \qquad N_{0is} = \begin{cases} 0.5 R_{1-i} e^{-M_s(i-1)} & 1 \le i < A_{max} \\ 0.5 \overline{R_0} \dfrac{e^{-M_s(A_{max}-1)}}{1-e^{-M_s}} & i = A_{max} \end{cases}$$

$$(A13) \qquad N_{0is}^{r} = N_{0is} r_{is}$$

$$(A14) \qquad N_{0is}^{u} = N_{0is}(1 - r_{is})$$

An iterative procedure is used to calculate numbers at age for each successive year. At each step, a standard normal variate, ϵ_y, is generated, and the following equations are evaluated.

$$(A15) \qquad \overline{R_y} = \frac{B_{y-1,2}^{3}}{\alpha + \beta B_{y-1,2}^{3}}$$

$$(A16) \qquad R_y = \overline{R_y} e^{\epsilon_y \sigma_R - 0.5\sigma_R^2}$$

$$(A17) \qquad N_{yis}^{u} = \begin{cases} 0.5 R_y & i = 1 \\ N_{y-1,i-1,s}^{u} e^{-M_s} & 2 \le i < A_{r,lo} \\ N_{y-1,i-1,s}^{u} p_{is} e^{-M_s} & A_{r,lo} \le i \le A_{r,hi} \\ 0 & A_{r,hi} < i \le A_{max} \end{cases}$$

$$(A18) \qquad N^r_{yis} = \begin{cases} 0 & 1 \le i < A_{r,lo} \\ N^r_{y-1,i-1,s} e^{-M_s}(1 - F_{y-1}) + N^u_{y-1,i-1,s} e^{-M_s}(1 - p_{is}) & A_{r,lo} \le i \le A_{r,hi} + 1 \\ N^r_{y-1,i-1,s} e^{-M_s}(1 - F_{y-1}) & A_{r,hi} + 1 \le i < A_{max} \\ (N^r_{y-1,i-1,s} + N^r_{y-1,i,s}) e^{-M_s}(1 - F_{y-1}) & i = A_{max} \end{cases}$$

The biomasses, exploitation rate, and mean length associated with each year are calculated using the following equations.

$$(A19) \qquad B^1_{ys} = \Sigma_i N^r_{yis} w_{is}$$

$$(A20) \qquad B^2_{ys} = B^1_{ys} e^{-M_s}$$

$$(A21) \qquad B^3_{ys} = B^2_{ys}(1 - 0.5F_y)$$

$$(A22) \qquad B^4_{ys} = B^2_{ys}(1 - F_y)$$

$$(A23) \qquad F_y = \begin{cases} \dfrac{C_y}{\Sigma_s B^2_{ys}} & \text{if } \dfrac{C_y}{\Sigma_s B^2_{ys}} < F_{max} \\ F_{max} & \text{otherwise} \end{cases}$$

$$(A24) \qquad \overline{L_y} = \frac{\Sigma_{is} N^r_{yis} L_{is}}{\Sigma_{is} N^r_{yis}}$$

Calculation of Likelihood

In this section I show how the likelihood associated with (B_0,ε) and the indices O_{yj} is calculated.

For all indices, it is assumed that O_{yj} is either normally (for mean length) or lognormally (for biomass) distributed with mean q_jE_{yj} and coefficient of variation c_{yj}. The c_{yj} are assumed known, the q_j is to be estimated, and the E_{yj} are calculated from the population model – either as mid-season biomass $(B^3_{y1} + B^3_{y2})$ or as $\bar{L}_y$. (Note that, because we are more interested in the trend in observed mean lengths than their absolute values, and because the $L_{\infty s}$ are not well determined, observed mean lengths are treated as relative, rather than absolute, indices.)

If the recruitment deviates, ε, are such that the historical catches could not have been caught, the likelihood, L, is set to zero. Otherwise, it is calculated as

$$(A25) \qquad L = e^{\Sigma_j \lambda_j}$$

where the value of λ_j, the log-likelihood associated with the O_{yj}, depends on whether the O_{yj} are assumed to be normally or lognormally distributed.

When the O_{yj} are normally distributed

$$(A26) \qquad \lambda_j = -m_j \ln q_j - \Sigma_y \ln E_{yj} - 0.5\Sigma_y c_{yj}^{-2} - \Sigma_y \ln c_{yj} + \frac{0.5 S_1}{q_j}$$

where

$$(A27) \qquad q_j = \frac{(S_1^2 + 4m_j S_2)^{0.5} - S_1}{2m_j}$$

$$(A28) \qquad S_1 = \sum_y \left(\frac{O_{yj}}{E_{yj}c_{yj}} \right)$$

$$(A29) \qquad S_2 = \sum_y \left(\frac{O_{yj}}{E_{yj}c_{yj}} \right)^2$$

and m_j is the number of years for which there is an observation in the jth series of biomass indices (throughout this section all sums over the index y are assumed to cover only these years).

When the O_{yj} are lognormally distributed

$$(A30) \qquad \lambda_j = 0.5m_j - \Sigma_j \ln(O_{jy}s_{yj}) - \sum_y \frac{0.5}{s_{yj}^2}\left[\ln\left(\frac{O_{yj}}{q_j E_{yj}}\right) + 0.5s_{yj}^2\right]^2$$

where

$$(A31) \qquad q_j = e^{(S_1 + 0.5m_j)/\Sigma_y s_{yj}^{-2}}$$

$$(A32) \qquad S_1 = \sum_y \left[s_{yj}^{-2} \ln\left(\frac{O_{yj}}{E_{yj}}\right)\right]$$

and

$$(A33) \qquad s_{yj} = \left[\ln\left(1 + c_{yj}^2\right)\right]^{0.5}$$

Fishery Performance Measures

All performance measures are expressed as probabilities (*see* Tables 28 and 32) and calculated as proportions. Thus, for example, P(B_{2002} > 20% B_0) is calculated as the proportion of runs in the importance sample in which the mid-year biomass in 2002 exceeded 20% of the B_0 for the run.