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Fisheries Research 45 (2000) 217–238

FISHERIES RESEARCH

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The effects of commercial exploitation on orange roughy (*Hoplostethus atlanticus*) from the continental slope of the Chatham Rise, New Zealand, from 1979 to 1997

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Received 16 March 1999; received in revised form 18 October 1999; accepted 4 November 1999

Abstract

Orange roughy (*Hoplostethus atlanticus*) is a recently exploited species, fished by trawling at depths of 700–1200 m on the continental slope around New Zealand. In this paper, changes in the major New Zealand orange roughy fishery on the Chatham Rise during a 19-year period are examined. Data from research trawl surveys and commercial fishing returns from 1979 to 1997 were analysed, and changes in the population described. The distribution of orange roughy showed a marked contraction, and aggregations became largely centred around seamounts or very localised areas of the slope. The biomass of orange roughy, measured by trawl survey and commercial catch-per-unit-effort indices, declined substantially, and in 1997 was estimated to be about 20% of virgin levels. Most bycatch species also declined in abundance, with no indication of species replacement. Size structure of the population did not change markedly over the period. Timing of spawning in July, and the pattern of gonad development, were also consistent over the years. There was no change in size or age at maturity. Prey composition remained similar. Biological changes may not have been apparent because orange roughy is a long-lived, slow-growing species, with low productivity. There could be a long response time of the population to fishing pressure.

Keywords: Orange roughy; New Zealand; Commercial fishing; Exploitation; *Hoplostethus atlanticus*

1. Introduction

Orange roughy (*Hoplostethus atlanticus* Collet) has a worldwide distribution (Kotylar, 1996) on the continental slope at depths of 700–1500 m. It frequently forms dense aggregations for spawning or feeding, and these aggregations provide the basis for major commercial fisheries. It has been fished commercially off New Zealand (Clark, 1995), Australia (Kailola et al., 1993), parts of the North Atlantic Ocean west of the United Kingdom-Faroes Islands (Chareau et al., 1995), and off Namibia (Clark et al., 1997). The New Zealand fishery is the most established having started in 1978, while the others date from 1988, 1991, and 1995, respectively. It is one of the most valuable commercial species in New Zealand waters, with annual reported landings of up to 60 000 t and export earnings of NZ $100–150 million (Clark, 1995).

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0165-7836/00/$ – see front matter
PII: S0165-7836(99)00121-6

Orange roughy is long-lived and slow-growing. Studies based on otolith zone counts (e.g. Mace et al., 1990; Smith et al., 1995; Tracey and Horn, 1999) and radio-isotope ratios (e.g. Fenton et al., 1991; Fenton and Short, 1992; Francis, 1995) indicate that it may live for more than 100 years. Recent estimates of age at maturity are around 30 years (Smith et al., 1995; Francis and Horn, 1997; Horn et al., 1998), with rates of natural mortality of 0.04–0.05 per year (Francis, 1992; Doonan, 1994). Together with low and perhaps variable recruitment (Francis, 1992), and relatively low fecundity (Clark et al., 1994; Koslow et al., 1995) these characteristics make orange roughy a relatively unproductive species. Sustainable yields are low, estimated at between 1 and 2% of the virgin biomass level per year (Annala et al., 1998). Local populations are vulnerable to overexploitation because of their tendency to form dense spawning or feeding aggregations which are predictable in time and space (Clark, 1996), and because of low productivity recovery of the population may take many years.

Well-documented effects of exploitation of fish populations include:

- Contraction of the species' geographical range and a reduction in the size of high density areas;
- Decline in abundance;
- Change in population age or size structure;
- Increase in individual growth rate;
- Change in body condition;
- Lower age or size at maturity;
- Change in species composition.

Examples come from lake ecosystems (e.g. Regier and Loftus, 1972; Spangler et al., 1977), coral reef fisheries (e.g. Russ and Alcala, 1989), and relatively shallow-water marine environments (e.g. Hempel, 1978; Borisov, 1979; Pauly, 1979; Grosslein et al., 1980). There have been relatively few studies on deep-water, long-lived, species such as orange roughy.

Clark and Tracey (1994) examined a 7-year time series from research trawl surveys and commercial catch-effort data for orange roughy fished on the Challenger Plateau to the west of New Zealand. They observed a decline in biomass, and a contraction in the area of high-density aggregations. No shift in relative species composition was observed, nor were changes in size structure, reproductive development, or feeding noted. There was also no change in fecundity of orange roughy between 1987 and 1990 (Clark et al., 1994), although an increase in fecundity of orange roughy off Tasmania was reported in association with a decrease in population size (Koslow et al., 1995). Clark (1995) gave general accounts of New Zealand fisheries on the Challenger Plateau and Chatham Rise, and summarised changes in distribution, abundance, and biological characteristics.

Pacific Ocean Perch (*Sebastes alutus*), which occurs at depths to 600 m in the North Pacific and North Atlantic Oceans, has some similarities to orange roughy, in that it grows slowly, reaches maturity around 25 years, and has a maximum age of 90 years (e.g. Gunderson, 1977; Leaman, 1991). Some of the changes related to commercial exploitation and reductions in stock size off the west coast of Canada were a shift in age structure to younger individuals, increased growth rates, and slightly earlier age at maturation (Leaman, 1991).

In this paper, we examine available data on distribution, abundance, and biology of orange roughy on the Chatham Rise, over the period 1979–1997. The Chatham Rise fishery is situated off the east coast of

Table 1
Annual reported catches (rounded to nearest 100 t) and total allowable catch (TAC) of orange roughy from the Chatham Rise[a]

Year	Catch (t)	TAC (t)
1978–1979	11 800	–
1979–1980	31 100	–
1980–1981	28 200	23 000
1981–1982	24 900	23 000
1982–1983	15 400	23 000
1983–1984	24 900	30 000
1984–1985	29 300	30 000
1985–1986	30 100	29 865
1986–1987	30 100	38 065
1987–1988	24 200	38 065
1988–1989	32 800	38 300
1989–1990	31 500	32 787
1990–1991	20 600	23 787
1991–1992	15 500	18 787
1992–1993	13 700	14 000
1993–1994	14 000	14 000
1994–1995	8000	8000
1995–1996	7900	7200
1996–1997	7300	7200

[a] Catches are for an October–September fishing year, but prior to 1983–1984 TACs were set for April–March year. Figures in early years are underestimates due to unreported mortality (data are derived from Annala et al., 1998).

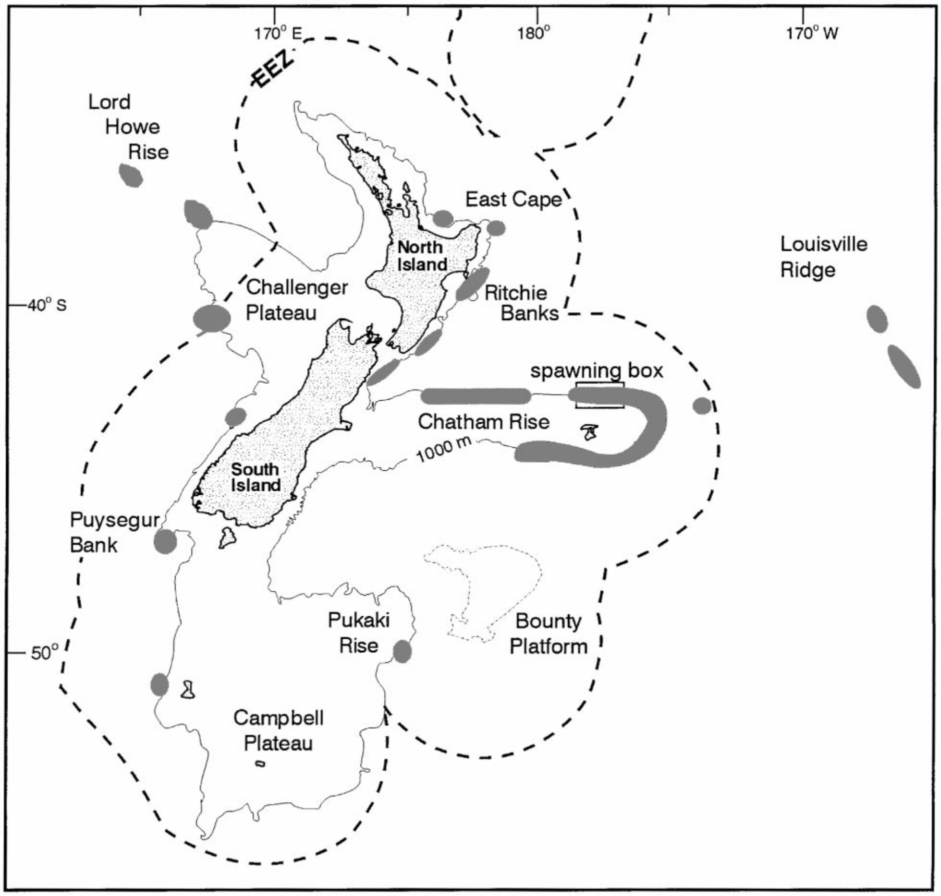

Fig. 1. The New Zealand region, showing location of main fishing grounds for orange roughy (shaded), the Chatham Rise, the "Spawning Box", and other locations referred to in this paper.

the South Island (Fig. 1), and has historically been the largest in New Zealand, with annual reported catches of 20 000–30 000 t for most of the 1980s (Annala et al., 1998). In recent years catch reductions to levels of <10 000 t per year have occurred (Table 1), but the fishery still remains one of the most important in New Zealand. The period examined here covers the early years of the developing fishery, to maximum levels of exploitation, and subsequent decline of the population. The fishery has been extensively studied, and with trawl surveys carried out in most years from 1984 to 1995, has a relatively long time series of comparable data with which to describe and assess changes. These data span a much longer time (19 years) than other studies on orange roughy on the Challenger Plateau (Clark and Tracey, 1994) or off Tasmania (Koslow et al., 1997) (7 and 5 years, respectively), and so may give a more reliable insight into population responses to the fishing of a long-lived deepwater species.

2. Methods

The main source of data for this study was a series of research trawl surveys. Details of these, and data collected, are given below.

2.1. Research survey design

Comparable stratified random trawl surveys have been carried out on the Chatham Rise during the spawning season (July) each year from 1984 to 1990 and also in 1992 and 1994. The area covered

Table 2
Summary of trawl surveys carried out on the Chatham Rise in winter (July) for orange roughy

Vessel	Year	Survey area (km^2)	Number of research trawls	Number of trawls in Spawning Box
Otago Buccaneer	1984	5000 (Spawning Box)	115	115
Otago Buccaneer	1985	5000 (Spawning Box)	115	115
Otago Buccaneer	1986	5000 (Spawning Box)	122	122
Otago Buccaneer	1987	5000 (Spawning Box, east Rise, south Rise)	246	219
Cordella	1988	5000 (Spawning Box)	126	126
Cordella	1989	25 500 (Spawning Box, north Rise, south Rise)	198	113
Cordella	1990	38 600 (Spawning Box, north, east, and south Rise)	280	142
Tangaroa	1992	26 333 (Spawning Box, north, east, and south Rise)	281	127
Tangaroa	1994	35 108 (Spawning Box, north, east, and south Rise)	416	120
Tangaroa	1995	1322 (main strata of Spawning Box)	132	132

and vessel used differed between years (Table 2), but the surveys always included the main spawning area known as the "Spawning Box" (see Fig. 1) for which the same basic survey design was applied. A survey in 1995 covered only the central part of the Spawning Box, and so is not included in analyses of distribution or abundance, but some biological data are used. The surveys followed a two-phase design (Francis, 1984). The survey area was divided into strata according to depth and longitude, and covered a depth range of 750–1500 m (Fig. 2). Individual surveys were described in detail by Anderson and Fenaughty (1996), and Tracey and Fenaughty (1997).

Catch rate data were contoured using the PC software "Surfer" (Golden Software, 1995). Null catch data were added along the 700 m depth line to restrain

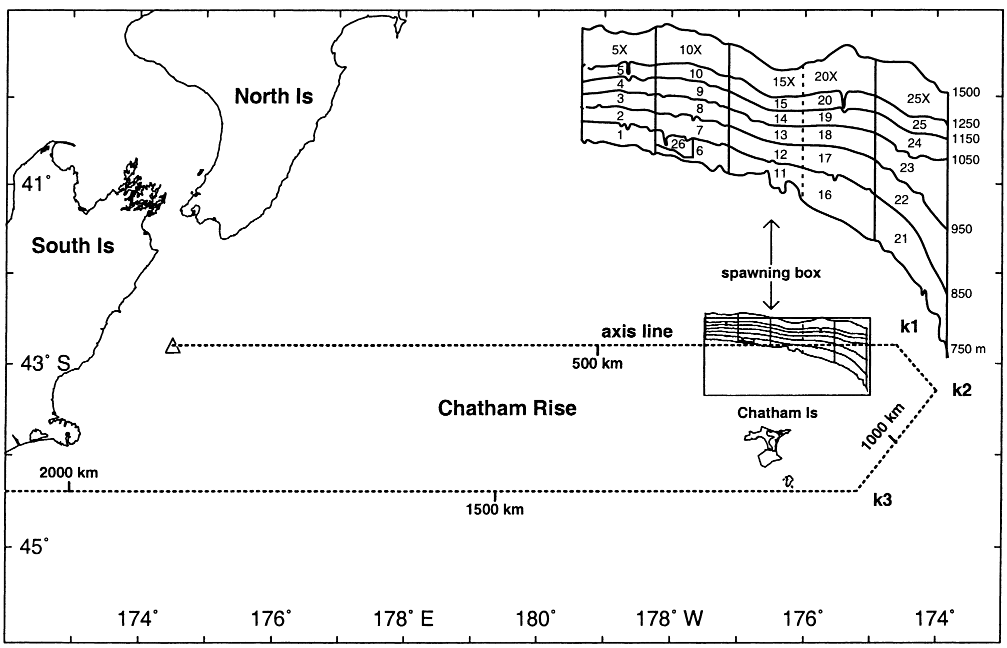

Fig. 2. The Chatham Rise, showing the "axis-line" used to describe changes in distribution of commercial fishing effort and catch over time. The points k1, k2, and k3 are turning points and labelled for reference in Fig. 5, as are distance markers along the axis-line. Inset: the Spawning Box area of the trawl survey series, showing strata and depth divisions referred to in Table 3.

the contouring to the known shallow limit of the depth range of orange roughy.

2.2. Relative abundance estimation

From the trawl surveys, biomass indices were calculated for orange roughy using the area-swept method. Biomass B (t) and standard error S_B (t) were calculated using the following formulae:

$$B = \frac{\mathrm{S}\,(X_i a_i)}{b}$$

and

$$S_B = \left(\frac{S s_i^2 a_i^2}{b^2}\right)^{0.5}$$

where X_i and s_i are the mean and standard deviation of catch rate (kg km^{-1}) in stratum i, a_i is the area of stratum i (km^2), b is the width swept by the gear (defined as wingspread (m) = 26.0 m).

It is assumed that the following three quantities do not vary from year to year: vulnerability (the proportion of fish in the path of the net that get caught); vertical availability (the proportion of fish in the water column above the area swept that are in the path of the net); areal availability (the proportion of the population sampled that is within the survey area at the time of the survey).

The coefficient of variation of the biomass estimate was calculated by

$$\mathrm{CV} = 100 \times \frac{S_B}{B}$$

Relative indices of abundance were also calculated in this manner for 17 non-target fish species regularly caught in orange roughy trawls.

2.3. Stock reduction analysis

A stock-reduction technique was used to estimate virgin biomass based on an extension of the maximum likelihood method of Francis (1992) to allow stochastic recruitment. This used a complete catch history for the stock, a time series of mean length and abundance indices from the 1984–1994 trawl surveys, and life history parameters used in an age-structured population model (Francis et al., 1995). Biological parameters were the von Bertalanffy growth parameters (for males and female, respectively: $L_\infty = 36.4$ and 38.0 cm; $k = 0.070$ and 0.061 per year, $t_0 = -0.4$ and -0.6 year), natural mortality = 0.045 per year, weight–length parameters ($a = 0.0921$, $b = 2.71$), age at maturity (30 years), age at entry to the fishery (30 years), recruitment variability of 1.1, and Beverton–Holt recruitment steepness of 0.75 (Annala et al., 1998).

2.4. Size structure

Length frequency distributions were calculated from sample data scaled to the population biomass. Distributions were calculated for sexes separately as well as combined, and examined graphically for patterns of change over time. Mean lengths of adult fish (>25 cm which is the beginning of the maturity/recruitment ogive, sexes combined) were calculated from the population size distributions, and a bootstrapping technique used for estimating variance (Francis et al., 1993). To test for patterns in the frequency of the largest orange roughy (which could be expected to change with heavy fishing pressure on older, larger fish), we examined data for fish over 39 cm from surveys between 1984 and 1995. Three overlapping groups were examined (>39, >40 and >41 cm). However, as results were similar for these, only one (>39 cm for male, >41 cm for female, with the least interannual variance) is described in this paper. The left-hand limb of the length frequency (fish <30 cm) was also examined in greater detail for indications of recruitment.

2.5. Age structure

Smith et al. (1995) have shown a strong linear relationship between fish age (from otolith ring counts) and otolith weight. Otolith weight has been examined here as a proxy for age. Between 500 and 1000 otoliths were taken at random from samples collected each year during trawl surveys between 1984 and 1992. The left sagittal otolith was air-dried for 12 h, and weighed to the nearest 10 mg.

2.6. Condition factor

The mean gonad-free weight (fish weight less gonad weight) was calculated for three size groups of fish covering the range of mature fish; 32.0–32.9, 35.0–35.9 and 38.0–38.9 cm.

Length–weight regression relationships were calculated for each year from the trawl survey data. These were plotted for evidence of any trend, and analysis of covariance carried out after checking for homogeneity of slopes (Systat, 1997).

A gonadosomatic index (GSI) was calculated for female fish between 32.0 and 38.9 cm. Gonad weight increases with advancement in gonad stage through to spawning when eggs are released, and so data from fish in the maturing and ripe stage of vitellogenesis (stages 3 and 4) were used, and analysed separately. Data were initially examined to check that there was no relationship between fish length and GSI. The GSI was calculated using the formula;

$$\mathrm{GSI} = \frac{(100 \times \text{gonad weight})}{(\text{fish weight} - \text{gonad weight})}$$

2.7. Spawning time

Data on reproductive state (stages after Pankhurst et al., 1987 with an additional partially spent stage) were used to examine the relative timing of spawning between years. Data from trawl surveys were used for all years except 1991 for which data were collected by scientific observers on commercial vessels. The percentage of fish in each of the mature macroscopic stages was plotted and a smoothed line drawn through them using a distance-weighted least squares procedure (Systat, 1997). Spawning time has been defined as the date when the proportion of spent fish increased to represent 20% of all mature fish. Peak spawning, when the fraction of running-ripe fish reaches a maximum, would be a better measure, but with orange roughy this is often not well defined (fish may move off the bottom to spawn and become less available to trawl gear) and the 20% spent mark has been used as a substitute (after Pankhurst, 1988; Clark and Tracey, 1994).

2.8. Size at maturity

Size at maturity was determined using a probit analysis (after Finney, 1971) available in the Systat statistical software package (Systat, 1997). This analysis calculates maximum likelihood estimates of the parameters of the probit general linear model. Females only were analysed, as macroscopic gonad staging is much clearer and more reliable than for males. Fish with a gonad stage of 3 or greater were assigned mature, although it was recognised this would not include some mature fish which are not spawning in a given year.

Further information on size and age at maturity was available from two years, 1984 and 1990, for which counts were made of the number of zones from the primordium to the transition zone of the otolith, which is a region associated with the onset of maturity (Francis and Horn, 1997).

2.9. Feeding

Examination of the diet was done using the frequency of occurrence of five broad prey categories: natant decapods, euphausids/mysids, crustacean remains/other groups, squid, and teleosts. The frequency of occurrence of an item was taken as the fraction of stomachs in which a prey category was found over all non-empty orange roughy stomachs.

2.10. Commercial catch-effort data

Since the beginning of the fishery there has been a requirement for all fishing vessels to keep detailed records of each trawl made. Some 60 000 trawls which targeted or caught orange roughy between 1979 and 1997, with information on position, depth and catches of commercial species, were available for analysis.

To examine changes in the distribution of effort and catch of orange roughy over the whole Chatham Rise, commercial tow-by-tow data were plotted along a continuous axis-line extending from a point at the north-west limit of the fishery (174°30′E) along the north Rise, through the east Rise and back along the south Rise (Fig. 2). All tow positions were assigned a distance along this line based on their longitude and the shortest distance to the axis. This simplified trawl locations to a single dimension. Numbers of tows which targeted or caught orange roughy, and total catches, were summed over intervals of 2 km along this line.

Results of catch per unit of effort (CPUE) analyses of the north Chatham Rise fishery between 1979 and

1992 are also presented here based on earlier work by Doonan (1991) and Francis et al. (1995). Some of their results were summarised by Clark (1996) in a review of techniques for estimating stock size of orange roughy in New Zealand, but it is appropriate that the data are considered here more fully in the context of changes in the Chatham Rise fishery. Doonan (1991) carried out a standardised CPUE analysis, using a stepwise fitting procedure regressing catch rate (tonnes per kilometre towed) against variables of season, year, time of month, and nationality of vessel. A wide area from 42°30′ to 43°30′S and 178° to 173°50′W was analysed, as well as the smaller region of the Spawning Box. Annual indices of abundance were produced. Analyses of unstandardised catch and effort were also carried out by Francis et al. (1995) for the Chatham Rise fishery as a whole. Results of both these sets of analyses are summarised here.

3. Results

3.1. Distribution and abundance

3.1.1. Research trawl survey

The distribution of orange roughy in the survey area changed substantially over time (Fig. 3). In 1984 and 1985 catch rates in excess of 1 t km^{-1} were observed across a wide area between 177°30′ and 176°30′W. There were also several smaller aggregations further east. These areas of moderate density began to contract after 1986 and 1987. The broad region of high catch rates (>5 t km^{-1}) centred around 177°W during 1984–1988 began to break up, and by 1990 was small and localised. There were no high catch rates in the eastern part of the area. In 1992, there was a single aggregation only, covering a small area. In 1994, the situation seemed to improve with both higher catch

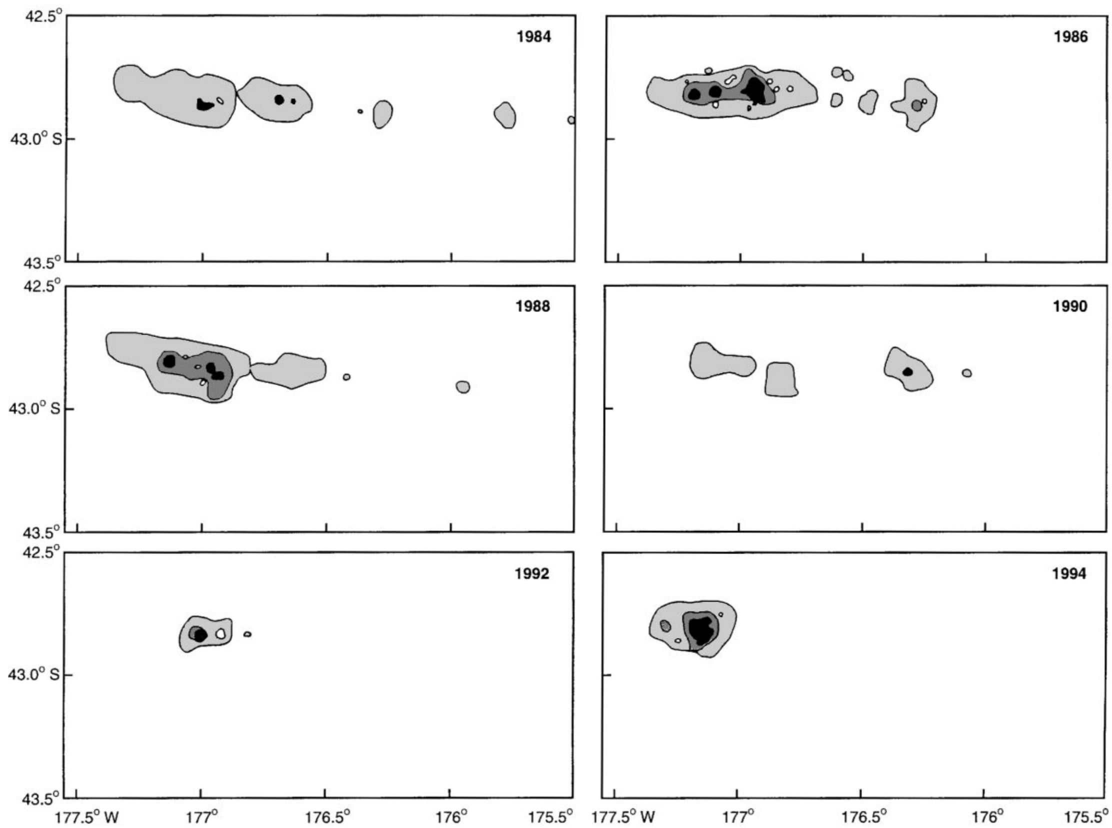

Fig. 3. Contours of trawl survey catch rates (kg km^{-1}) of orange roughy in the Spawning Box from 1984 to 1994. Only surveys every second year are shown. Light grey = 1000–4999 kg km^{-1}, dark grey = 5000–9999 kg km^{-1}, black = >10 000 kg km^{-1}.

Table 3
Relative biomass estimates ('000 t) of orange roughy from the Chatham Rise Spawning Box from trawl surveys 1984–1994, and the contribution by stratum (rounded to nearest percent) (see Fig. 2 for stratum boundaries)

Year	1984	1985	1986	1987	1988	1989	1990	1992	1994
Biomass	130	111	77	60	73	54	34	22	61
c.v. (%)	17	15	16	15	25	18	19	34	67
Stratum									
1	12	0	5	1	0	0	0	1	0
2	17	14	14	15	34	20	14	49	94
3	3	13	3	10	16	11	6	5	0
4	3	5	1	2	1	2	7	3	0
7	18	15	17	12	22	8	7	16	1
8	3	3	2	3	1	2	4	1	0
9	1	3	7	6	1	1	3	1	0
12	12	11	15	16	1	18	28	1	1
17	5	14	6	9	5	2	2	1	1
26	15	6	4	6	6	11	20	5	0
Total contribution(%)	90	85	75	80	88	75	90	81	98

rates, and a larger area of distribution. However, the extent of the aggregation was still extremely limited compared with the early years of the fishery.

Biomass indices from trawl surveys between 1984 and 1994 in the Spawning Box are given in Table 3. These show a clearly declining trend. The biomass index decreased each year from 1984 to 1987. Different vessels were used between 1988 and 1990, and then again in 1992–1994. No attempt has been made to adjust for possible differences in fishing power of the vessels or gear, as this would be arbitrary. The main point is that despite changes in vessels, an overall decline in abundance is marked. The variance of the biomass index was consistent until 1992, when it started to increase, and was very high for the 1994 result.

There were also changes in the distribution of biomass between strata. Table 3 includes the percentage contribution to the overall biomass index by the main strata (stratum boundaries are shown in Fig. 2). Although only 10 strata are included out of 26 assigned during the surveys, these accounted for >75% of the biomass in each year. Many of the areas show varying importance between surveys with no marked trend, although some of the outer regions (e.g. 12, 17) show a decrease. The most substantial change over time is in stratum 2, which dominated biomass from 1992. This is the core of the aggregation area.

Trawl surveys in 1992 and 1994 also covered areas of slope on northwest and northeast parts of the Chatham Rise. Relative biomass indices from these regions are given in Table 4.

Recent stock assessment treats the northeastern part of the Rise as a separate unit (including the Spawning Box, NE seamounts, and E seamounts), and uses the time series of trawl survey indices as a measure of relative biomass (Annala et al., 1998). Stock reduction analysis of the northeastern part of the Chatham Rise gives an estimate of virgin biomass of around 300 000 t, and estimates that the biomass declined by about 20 000 t per year during the 1980s (Fig. 4). Biomass at the maximum sustainable yield level is 90 000 t, with a biomass in 1997 of about 60 000 t which is 20% of virgin biomass. Population decline in the model runs stopped in 1992, and the biomass is expected to increase slowly with catches around the 1996−1997 level of 7000 t.

Table 4
Relative biomass estimates (t) of orange roughy for northwest and northeast areas of the Chatham Rise (percentage c.v's in parentheses; from Tracey and Fenaughty, 1997)

Area	1992	1994
Northwest	6400 (26)	4900 (17)
Northeast	8100 (29)	2400 (27)

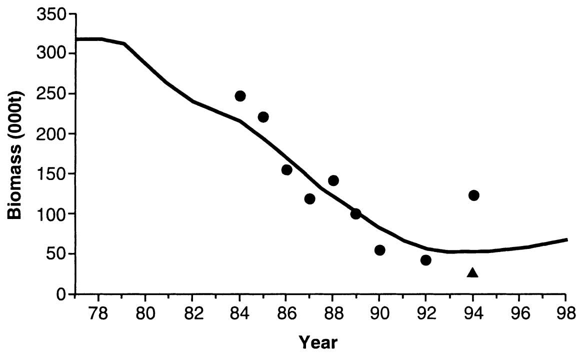

Fig. 4. Estimated population biomass trajectory (solid line) from stock reduction analysis and scaled trawl survey abundance indices (dots) for the northeast Chatham Rise orange roughy stock (the year 1978 refers to the 1977–1978 fishing year; the triangle in 1994 shows an alternative biomass estimate from the survey that year with the removal of a single large catch).

3.2. Changes in abundance of bycatch

Abundance indices for 17 bycatch species in the Spawning Box generally showed a decreasing trend over the 10 years examined. The 1994 biomass, presented as a fraction of the 1984 biomass, ranged from a large decline to 0.06 for Plunket's shark (*Centroscymnus plunketi*) and black cardinalfish (*Epigonus telescopus*) to a marked increase of 3.6 for longnose velvet dogfish (*Centroscymnus crepidater*) (Table 5), with a median value of 0.5. Thirteen of the seventeen species recorded lower biomass indices in 1994, but for many species catch rates were generally low with large variations in the indices, and little weight can be placed on each result individually. Nine species showed a declining trend as assessed by linear regression. However for two of the species most commonly landed in orange roughy trawls, a strong trend was uncovered (Fig. 5) with evidence of substantial reductions in biomass. The estimated biomass for basketwork eels (*Diastobranchus capensis*) dropped from 1280 t in 1984 to 170 t in 1994. Similarly white rattail (*Trachyrincus aphyodes*) biomass estimates fell from 650 t in 1984 to 140 t by 1994. One species of deepwater dogfish (longnose velvet dogfish, *Centroscymnus crepidater*) showed an increase in relative abundance.

3.3. Commercial fishery

The distribution of orange roughy catch on the Chatham Rise has changed substantially over the

Table 5
Change in relative biomass of the main bycatch species in the orange roughy trawl surveys, as a proportion of their abundance in 1984 (1984 biomass rounded to nearest 10 t; trend direction assessed by linear regression, $p < 0.1$)

Species	Biomass 1984 (t)	Fraction of 1984 biomass								
		1985	1986	1987	1988	1989	1990	1992	1994	Trend
Orange roughy *Hoplostethus atlanticus*	130 570	0.88	0.59	0.46	0.56	0.42	0.26	0.28	0.47	↘
Basketwork eel *Diastobranchus capensis*	1280	0.72	0.39	0.35	0.18	0.16	0.18	0.19	0.13	↘
Baxter's dogfish *Etmopterus baxteri*	770	0.45	0.64	0.71	0.51	0.16	0.49	0.43	0.26	↘
White rattail *Trachyrincus aphyodes*	650	0.71	0.70	0.79	0.63	0.28	0.53	0.41	0.21	↘
Ribaldo *Mora moro*	650	1.37	1.08	1.03	0.50	0.35	0.36	0.55	0.37	↘
Pale ghost shark *Hydrolagus* sp. B2	470	0.81	0.63	0.76	0.76	0.26	0.49	0.43	0.16	↘
Johnson's cod *Halargyreus johnsonii*	470	0.95	0.83	0.74	0.57	0.39	1.04	0.37	0.42	↘
Hake *Merluccius australis*	340	0.53	0.86	0.74	0.41	0.35	0.83	0.26	0.38	↘
Black cardinalfish *Epigonus telescopus*	20	0.94	1.97	0.76	0.33	0.70	0.36	0.42	0.06	↘
Ling *Genypterus blacodes*	20	3.71	3.41	3.39	2.28	1.87	0.59	0.45	0.58	↘
Pacific spookfish *Rhinochimaera pacifica*	360	0.91	0.86	0.58	1.23	0.45	0.95	0.64	0.50	→
Four-rayed rattail *Coryphaenoides subserrulatus*	160	0.13	2.57	1.40	1.55	0.49	0.98	1.81	0.67	→
Bigscaled brown slickhead *Alepocephalus australis*	510	0.56	0.39	0.37	0.40	0.11	0.29	0.49	0.63	→
Smallscaled brown slickhead *Alepocephalus antipodianus*	10	0.05	1.19	5.56	0.21	14.80	0.29	1.24	2.07	→
Plunket's shark *Centroscymnus plunketi*	50	0.16	0.15	0.53	0.36	0.31	0.10	0.32	0.06	→
Shovelnose dogfish *Deania calcea*	1520	0.60	1.54	1.83	1.94	0.91	2.07	1.78	1.14	→
Owston's dogfish *Centroscymnus owstoni*	250	1.11	2.37	2.92	1.68	1.05	0.99	2.82	1.95	→
Longnose velvet dogfish *Centroscymnus crepidater*	370	0.76	1.49	1.59	5.34	3.03	4.70	4.33	3.65	↗

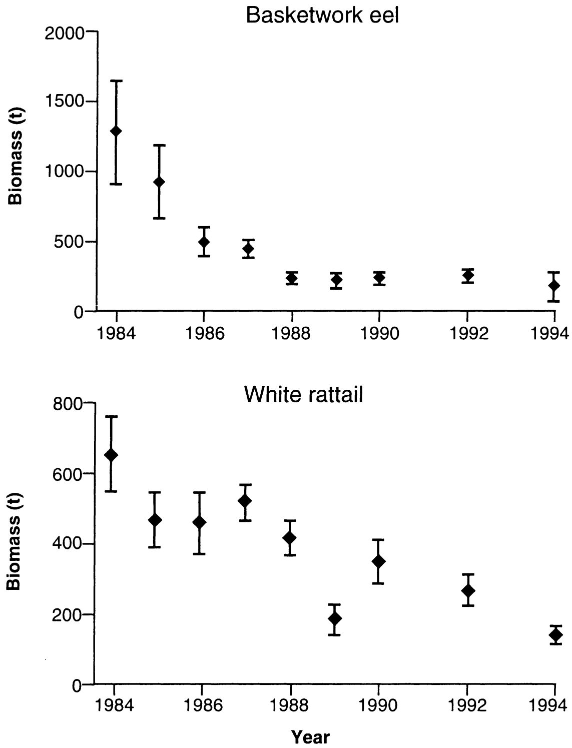

Fig. 5. Biomass estimates from trawl surveys for basketwork eel (top) and white rattail (bottom) in the Spawning Box from 1984 to 1994. Error bars are 95% confidence interval.

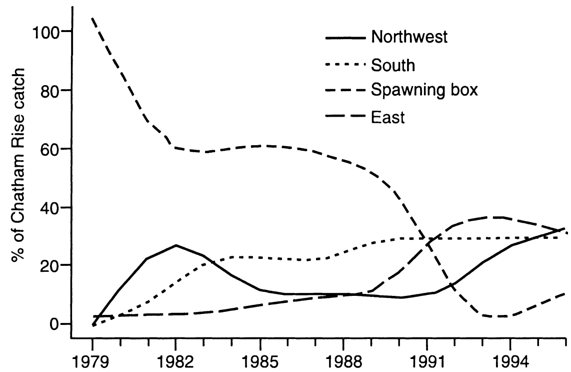

Fig. 6. Distribution of reported orange roughy catch from four sub-areas of the Chatham Rise (data from Annala et al., 1998).

period of the fishery (Fig. 6). Most of the catch was reported from the Spawning Box until 1990. Since then, other regions of the Chatham Rise have provided the majority of catch, although this has been partly driven by changes in quota levels and the distribution of fishing effort.

A more detailed analysis of these changes is given in Fig. 7. Fishing effort was concentrated in the Spawning Box in the early years of the fishery, with areas of the northwest and southwest slope being targeted later in this period. Through the 1980s the Spawning Box remained the most important part of the fishery with catches from that area remaining consistently high. Effort over the whole Chatham Rise, however, almost doubled between 1979–1981 and 1988–1990 with much of this increased effort taking place on seamount complexes in southern and eastern regions of the Rise. The increased spikiness in the plots towards the end of the 1980s reflects a change from a fishery based on a population spread over broad areas of slope to a fishery focused on aggregations near bathymetric features such as seamounts, ridges and drop-offs. Each of the clear spikes outside of the Spawning Box in the plots is associated with a known seamount or seamount complex. Also evident from 1979 through 1993 is a strong trend in the eastwards movement of the fishery as vessels discovered new seamounts and gained experience in fishing on difficult terrain. Serial depletion of seamount populations occurred along western parts of the south Chatham Rise, where catch levels declined dramatically.

Unstandardised catch rates for the Chatham Rise as a whole (summarised as total catch divided by number of trawls) were about 7–9 t per tow for most of the 1980s, but started to decline to 5–7 t per tow in the late 1980s, and further in the mid-1990s to 2–4 t per tow (Table 6). Catch rates by area showed more variation. The Spawning Box maintained high levels to 1991, and in the following year the area was voluntarily closed to commercial fishing. On the South Chatham Rise, effort and catch levels peaked in the early 1980s. Most of the fishery has focused on seamounts, and these have seen a steady decline in catch rates over the period of the fishery, from around 4 t per tow to <1 t per tow. Most fishing on the south Rise occurs on a seamount complex in the southeast (SE seamounts), where catch per tow values were historically 5–7 t per tow, and by 1996 were about 3–4 t per tow. Seamounts on the eastern margin of the Chatham Rise yielded catch rates of 8–10 t per tow when first fished in the early 1990s, but typical catch rates in the mid-1990s were around 3 t per tow.

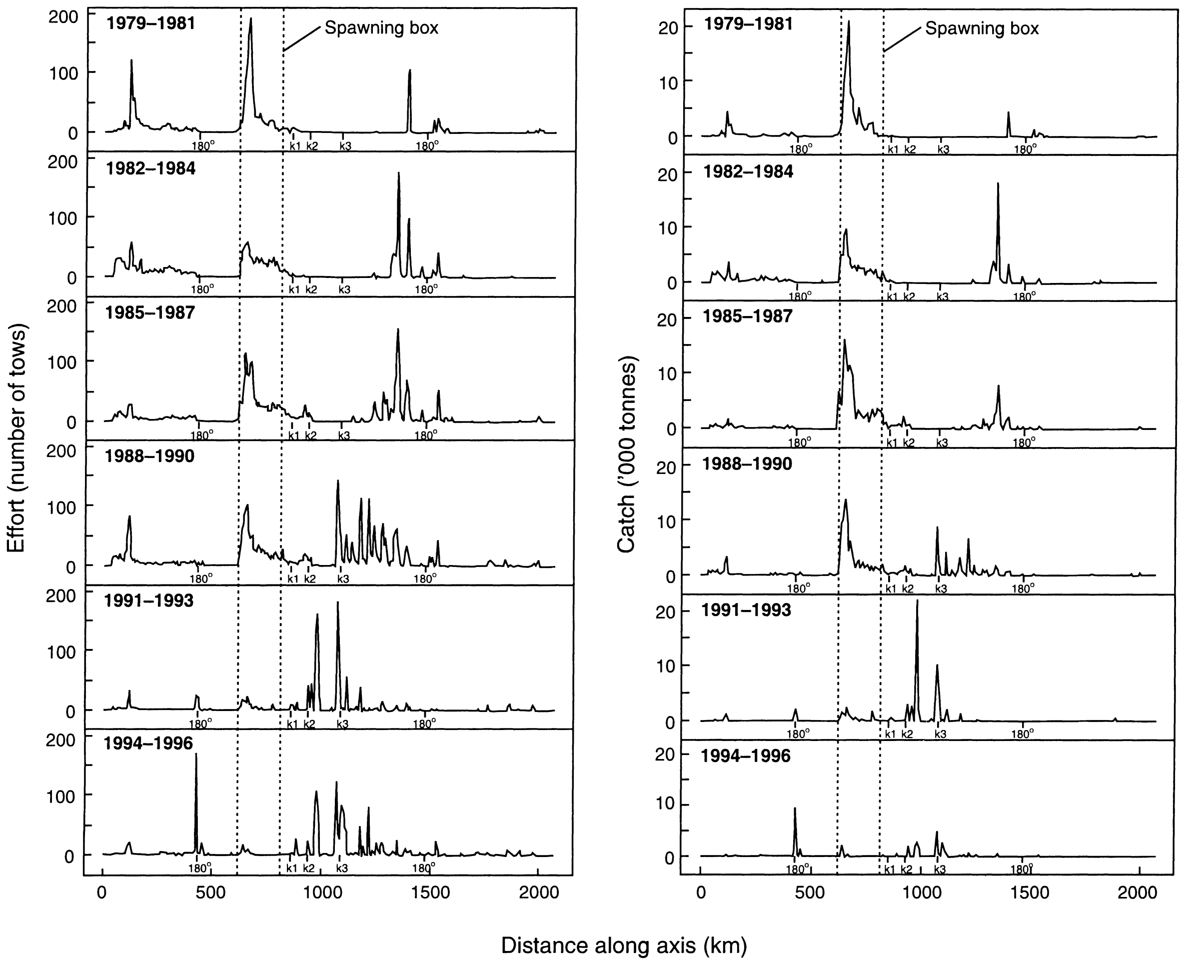

Fig. 7. Distribution of commercial effort (left panel, relative number of trawls) and commercial catch (right panel, tonnes) directed at orange roughy along the axis-line in three-yearly blocks (1979–1981 = the fishing years 1978–1979, 1979–1980, and 1980–1981; 180°, k1, k2, and k3 refer to points on the axis-line in Fig. 2; distance along the axis-line is in km).

Table 6
Summary of commercial catch rates (unstandardised, t per tow) for the Chatham Rise orange roughy fisheries (year 1979 refers to the fishing year 1978–1979; (–) indicates zero catch)

Area	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997
Entire Rise	15.1	8.9	7.2	7.5	8.2	8.7	9.6	7.9	8.0	6.2	5.2	6.1	7.1	7.2	6.2	3.8	2.4	3.2	3.5
Spawn Box	15.2	9.8	12.8	8.6	12.9	12.5	13.9	10.7	12.2	10.3	9.7	11.7	12.6	6.7	–	–	–	9.5	6.9
NE seamounts													7.8	5.8	7.5	5.1	3.4	2.7	4.5
E seamounts														9.8	8.6	5.6	2.9	2.6	2.9
SE seamounts											5.1	5.3	6.9	6.0	4.7	3.3	2.1	3.8	3.2
S seamounts						3.9	3.9	3.0	2.5	2.7	2.4	1.3	1.2	0.7	2.2	1.5	0.5	0.8	1.2
NW seamounts															11.0	6.1	4.2	5.0	3.6

Table 7
Abundance indices derived from standardised CPUE analysis of the Chatham Rise orange roughy fishery (from Francis et al., 1992; Clark, 1995)

	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991
Full year	1.0	0.58	0.67	0.27	0.29	0.26	0.27	0.17	0.13	0.13	0.05	0.11	0.08
Winter Spawning Box		1.0	0.93	1.57	0.89	0.83	0.98	0.96	0.78	0.52	0.20	0.47	0.26

Abundance indices from standardised CPUE analysis for the Chatham Rise orange roughy fishery are summarised in Table 7. The full year indices declined rapidly up to 1982 followed by a much more gradual decline. In contrast, the spawning data-set indices did not change substantially over the period from 1980 through to 1986, but then declined quite rapidly. The contrasting pattern of change in these indices, together with very sudden and substantial changes between years, indicates they might not track abundance accurately, or the relationship between CPUE and abundance is non-linear. Nevertheless CPUE changes are regarded as giving a good idea of general trends in stock size.

3.4. Biological changes

3.4.1. Size structure

Size distributions of orange roughy in the Spawning Box remained consistently unimodal over the 10-year period covered and there has been no apparent shift in the position of the mode (Fig. 8). The length frequencies generally show only small fluctuations around the overall shape. Smaller fish pushing out the left-hand limb of the distribution were apparent in 1994 and 1995 data sets, and these distributions are identified separately. The 1994 distribution for males is based on a small sample size, and may not be representative.

Both limbs of the size distributions were examined to determine if more subtle changes were occurring in size composition over time (Table 8). Results are presented by sex because of a change in sex ratio in post-1990 surveys. Females on average were larger than males, and so considering combined data could bias results in recent years.

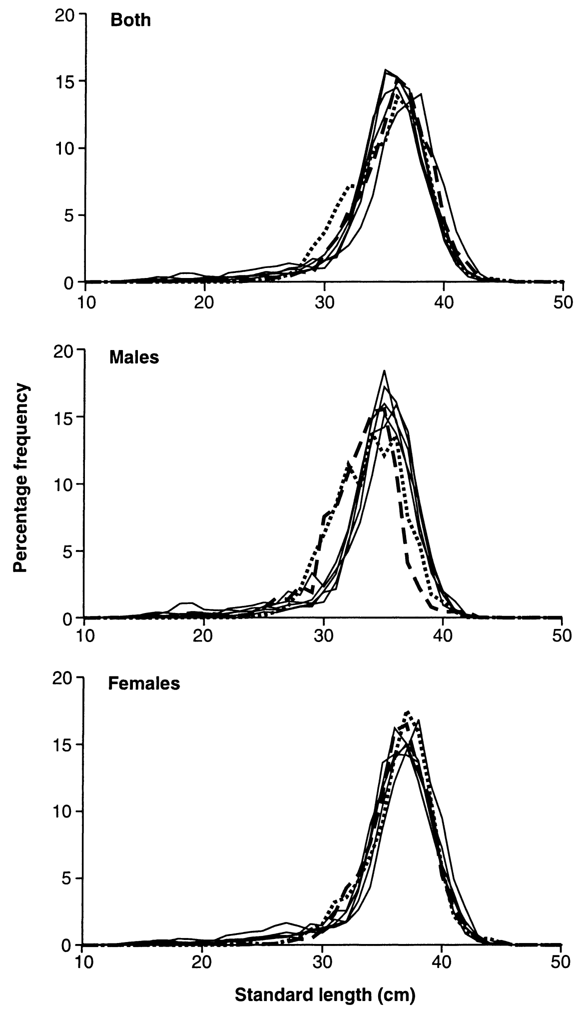

Fig. 8. Length frequency distributions of orange roughy, 1984–1995 (every second year is plotted, dashed line = 1994 survey, dotted line = 1995 survey). Distributions are scaled to represent the total population, and plotted as a percentage of the total.

The proportion of large fish in the length distribution varied between years, with no strong or consistent trend. The proportion of small males increased markedly in 1990–1992, and has stayed at relatively high levels through to 1995. The percentage of large females also increased in 1990, but has since decreased.

Table 8
Changes in proportion of the population size structure consisting of "large" (>39 cm SL for males, 41 cm for females) and "small" (<30 cm SL) over time

Year	1984	1985	1986	1987	1988	1989	1990	1992	1994	1995
Male										
Large (%)	2.6	3.3	2.9	4.5	2.3	2.9	1.4	3.4	1.3	1.6
Small (%)	6.7	6.8	11.4	6.8	6.7	5.3	10.7	17.3	17.4	14.4
Female										
Large (%)	5.8	7.0	5.3	6.6	5.8	5.3	3.6	8.6	4.9	2.2
Small (%)	6.4	5.0	11.8	4.2	6.6	3.8	9.5	7.6	2.8	3.8

Mean lengths calculated from each survey (Fig. 9) varied between years, but there has not been a strong or consistent trend. The length of females has fluctuated around 35.5 cm. The mean length of male fish decreased between 1992 and 1994 (from around 33.8 to 32.3 cm), but this may not be representative because biomass in 1994 was dominated by a single large catch (see Fig. 6).

The sex ratio of orange roughy remained constant at close to 1:1 for the trawl surveys between 1984 and 1990. However, after 1990 it skewed in favour of females. The percentage of male fish dropped to 28% in the 1992 survey, and to 14% in the following survey (Table 9).

3.5. Age structure

The mean weight of otoliths showed no significant change over the period from 1984 to 1992 (Table 10), suggesting that there had been no major change in age structure of the recruited population. However, the proportion of small-sized otoliths present in the random samples declined.

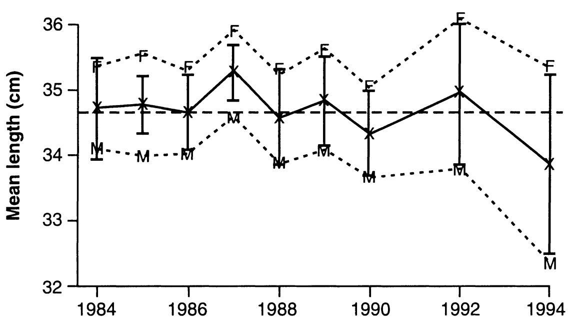

Fig. 9. Mean length (cm) of orange roughy from trawl surveys in the Spawning Box (f = female, m = male, x = average of male and female means; dashed horizontal line is the average of the combined means from all years).

Table 9
Sex ratio of orange roughy (% male by biomass) in trawl surveys from 1984 to 1994 (from Francis, 1996)

Year	1984	1985	1986	1987	1988	1989	1990	1992	1994
Male (%)	51	50	54	52	57	49	54	28	14

3.6. Condition factor

Mean gonad-free weight from 1984 to 1996 for fish of three size groups were examined, but all showed a similar pattern. Therefore, only results from 35 to 35.9 cm fish are given here, as this group had the largest sample size (Fig. 10a). The mean weights were variable between years, with peaks evident in 1984–1986 and 1989–1990, but a general decline since

Table 10
Changes in mean otolith weight (g) and proportion of small-sized otoliths (<0.15 g) from samples 1984 to 1992 (–, no data)

Year	n	Mean weight	Proportion small
1984	904	0.217	0.264
1985	842	0.213	0.258
1986	894	0.232	0.214
1987	916	0.219	0.243
1988	928	0.219	0.239
1989	933	0.224	0.203
1990	894	0.216	0.224
1991	–	–	–
1992	861	0.225	0.154

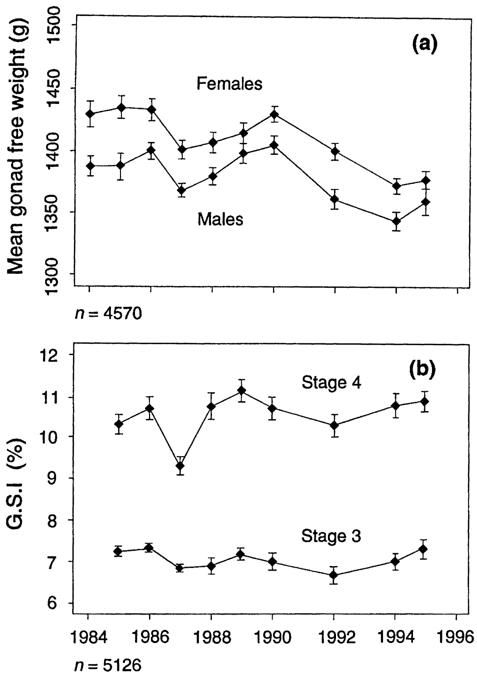

Fig. 10. (a) Mean gonad-free weights (g) of orange roughy between 35.0 and 35.9 cm (inclusive) from the Spawning Box during winter trawl surveys (error bars are one standard error); (b) gonadosomatic indices for stage 3 and 4 female orange roughy between 32.0 and 38.9 cm (inclusive) from the Spawning Box (error bars are one standard error).

1990. Overall there was a significant linear regression (with negative slope) between gonad-free weight and year with females, but not males.

Length–weight relationships showed no consistent change over time. Analysis of covariance indicated there were significant differences between years (ANCOVA, $p < 0.05$), but this result was primarily due to the years 1992 and 1994 where fish were lighter for a given length than previously. Between 1984 and 1990 the relationship was variable with no pattern.

Mean GSI indices were plotted by year for maturing and ripe females (Fig. 10b). Results from 1984 were excluded, as a different and perhaps confusing staging interpretation was applied. Mean values for the percentage gonad weight varied little from year to year, and no clear trends were apparent. Values ranged from 6.7 to 7.3% for maturing (stage 3, exogenous vitellogenesis) females, and 9.3 to 11.1% for ripe (stage 4, hydrating) females.

3.7. Reproduction

The Spawning Box historically was recognised as the main site of spawning on the Chatham Rise. Spawning occurs elsewhere on the Rise on seamounts of the northwest Chatham Rise, and around the eastern margin (Fig. 11), but these sites are generally small and spawning appears localised. There is little evidence of major spawning on the south Chatham Rise. This was also found by Francis and Clark (1998) who examined spawning ogives and concluded the western part of the Spawning Box was the main focus of spawning on the Chatham Rise.

The time of spawning was found to be very consistent between years in the Spawning Box (Table 11). The date at which the fraction of spent fish reached 20% each winter fell within a two week period between 14 and 28 July. There was no discernible pattern to the variation in the timing of spawning.

3.8. Size at maturity

Probit analysis of length and maturity data indicated that size at maturity varied considerably between years (Fig. 12), with no significant trend over time.

Mean age at maturity was not significantly different (t-test, $p > 0.01$) between the two years examined (29.0 and 29.2 in 1984 and 1990, respectively), although the decrease from 32.2 to 30.4 cm in mean

Table 11
Dates of mid-spawning period (defined as 20% spent stages) of orange roughy in July in the Spawning Box (1984–1996) (no data available for 1993, no gonad stage data for males in 1991)

Date in July		
Year	Males	Females
1984	20–21	20–21
1985	20	25
1986	20	28
1987	20	22
1988	24	26–27
1989	23–24	23–24
1990	24	18
1991	–	23
1992	18	14
1993	–	–
1994	23	23
1995	14	17
1996	17–18	17–18

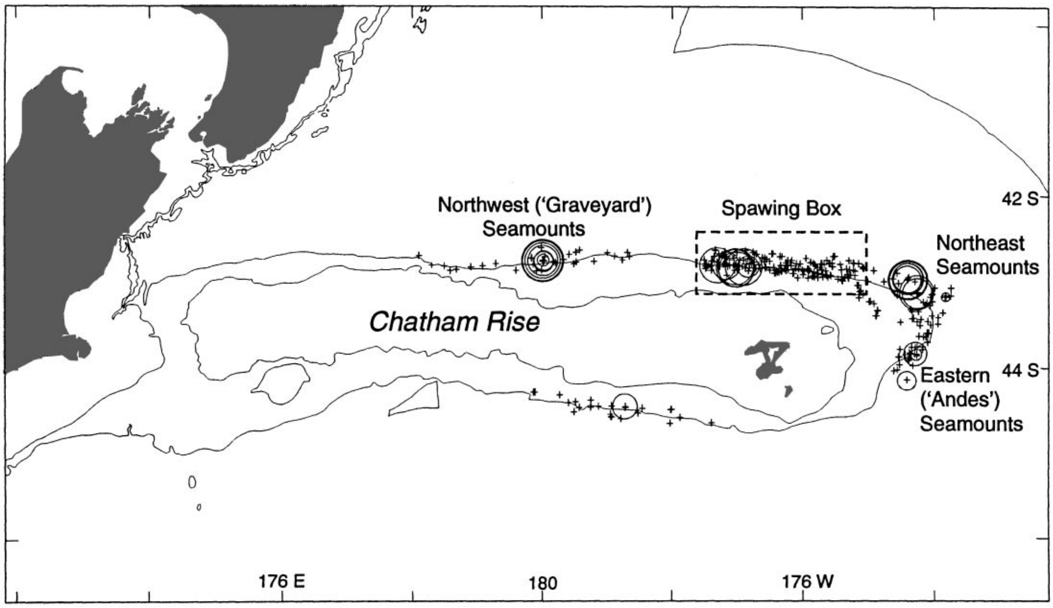

Fig. 11. Distribution of spawning orange roughy (ripe and running ripe female stages) in July on the Chatham Rise from research surveys 1990–1994 (where catch rates $\geq$1000 kg km^{-1}; (+) position of trawls in July that caught orange roughy; each circle represents the percentage of spawning fish in each tow, largest circle size = 100%).

length at maturity derived from these samples was significantly different (t-test, $p < 0.01$).

3.9. Feeding

The majority of the stomachs examined (85%) were either empty or had only a trace of food. The frequencies of occurrence of the major prey groups identified from orange roughy stomachs classified as part-full or greater are presented in Table 12. Crustaceans, fish (primarily mesopelagic species) and small squid made up the bulk of the diet of orange roughy in each year. There were no apparent trends which could indicate a shift in diet.

3.10. Environment

Reliable data on temperature and salinity at orange roughy depths from CTD (conductivity–temperature–depth) casts are available for a number of years in the 1980s, and more frequently in the 1990s (Fig. 13). These show differences in winter month temperatures of about 0.5°C between years at 800–1000 m depths. Salinity has also been relatively constant at around 34.5 ppt. These values are consistent with the presence of the Antarctic Intermediate Water mass (e.g. Piola and Georgi, 1982).

4. Discussion

The Chatham Rise orange roughy fishery has shown marked changes over the 19 years since its development. In early years the fishery was focused on the

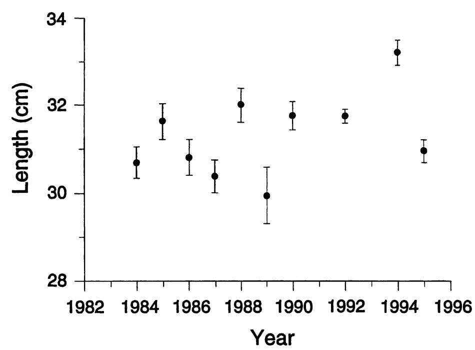

Fig. 12. Mean length at maturity for female orange roughy, and 95% confidence intervals, from probit analyses.

Table 12
Frequency of occurrence of major prey groups of orange roughy sampled in research surveys between 1984 and 1996 (–, not recorded)

	1984	1985	1986	1987	1988	1989	1990	1992	1994	1995	1996
All Crustacea	44	55	38	46	18	37	42	58	53	75	55
Decapoda Natantia	–	53	33	26	17	30	32	0.4	30	62	42
Euphausiacea/Mysidacea	0.8	0.3	4	5	2	5	3	0	6	3	4
Crustacean remains/other groups	43	2	0	15	0	2	7	58	17	9	9
Mollusca											
Cephalopoda Coleoidea	21	12	14	18	4	11	7	6	9	9	11
Teleostei	48	37	38	42	26	60	55	38	45	24	38
Thaliacea											
Salpidae	0.6	0.6	0.6	0.1	0	0.4	0.2	0.6	1.0	0.5	0

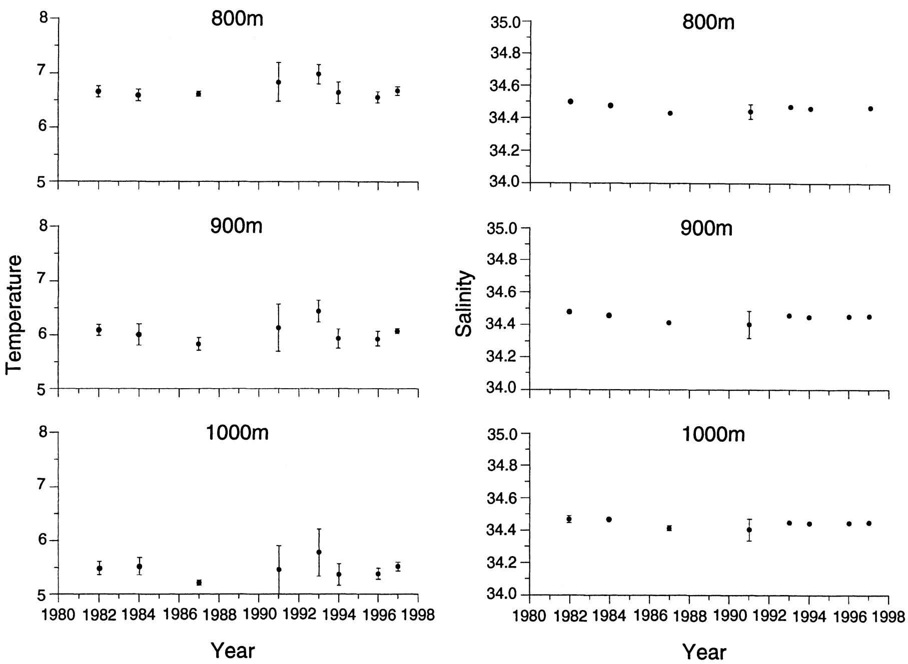

Fig. 13. Mean temperature (°C, left panel) and mean salinity (ppt, right panel) at depths of 800, 900, and 1000 m on the North Chatham Rise from 1982 to 1997 (data from CTD casts, error bars are 2 standard errors).

Spawning Box, but then started to spread over a larger area, as well as throughout the year, as new grounds were opened up, and areas found where orange roughy formed aggregations outside the winter spawning period. The 1990s saw a reduction in the area of fishing, a decline in catch rates, and decreases in the TAC and catch levels.

The orange roughy stock in the region of the Spawning Box was overexploited in the late 1980s. This is evident from the present study with strong contractions in the high density areas, a progressive decline in abundance estimated from trawl surveys, and decreases in commercial catch rates. Coburn and Doonan (1994, 1997) noted in the Spawning Box a progressive decrease in both the duration and the magnitude of high commercial catch rates. The stock in 1997 was estimated to be about 20% of virgin biomass present in the 1970s (Annala et al., 1998).

Other fishing grounds on the Chatham Rise have also shown signs of overexploitation. Trawl survey results from areas of slope in northwest and northeast regions of the Chatham Rise indicated a decrease in abundance. Catch rates on seamounts in these areas have declined in recent years (Annala et al., 1998; Clark, 1999). The health of the northwestern stock is uncertain, although available data from an egg production survey indicate that the stock is much smaller than that of the Spawning Box region (Francis et al., 1997). The south Rise region was also fished heavily in the 1980s, and catches and catch rates were maintained only by the discovery of new seamounts. A marked eastwards progression of effort and catch occurred through the mid-late 1980s, as serial depletion of aggregations on seamounts occurred (Francis et al., 1995; Clark, 1999).

Contractions in distribution and decreased abundance, are typical of exploited populations, and have been observed with orange roughy fisheries on the Challenger Plateau (Clark and Tracey, 1994), and off Tasmania (Koslow et al., 1997).

Most other bycatch species in the trawl surveys also declined in abundance. Biomass levels relative to 1984 have varied between years, but 9 of the 18 species examined show a strong decreasing trend, and longnose velvet dogfish was the only species to increase in abundance. However, it must be remembered that the trawl surveys were designed specifically to measure abundance of orange roughy. Area covered, stratification, depth range, and trawl intensity and distribution might not be appropriate for representing the true abundance of other species. Nevertheless, assuming relative comparability between years, the trawl fishery for orange roughy appears to have caused a general decline in abundance of other demersal fish and shark species. There are no indications of any major shift in relative abundance with other species replacing orange roughy. Similar results were found on the Challenger Plateau (Clark and Tracey, 1994). The time period for such shifts in deepwater assemblages might be longer than in more dynamic shallow environments, but changes in species composition, distribution, and abundance in shelf and upper slope fisheries can occur over periods of 10 years or less (e.g. Grosslein et al., 1980; Brown et al., 1983; Overholtz and Tyler, 1985; Gomes et al., 1995).

It has been assumed that the observed changes in the orange roughy stocks are attributable to the effects of the commercial fishery. In common with many fisheries worldwide, there are no data from the Chatham Rise on stock size and its natural variability prior to the onset of fishing. Although the Chatham Rise has been studied for more years than any other orange roughy fishery, this research started several years after the development of the fishery. Therefore, the level of any natural fluctuations in population size and distribution is unknown. The extreme longevity of orange roughy means that natural oscillations in population size may occur over a relatively long time period (Leaman and Beamish, 1984), and hence it seems likely that the marked and rapid changes observed on the Chatham Rise can be attributed to fishing.

Changes in the location of water masses favoured by fish can affect their distribution or availability to trawl gear, and thereby influence whether abundance results from a trawl survey are representative (e.g. Pinhorn and Halliday, 1985; Smith et al., 1991; Swain and Kramer, 1995). Environmental indicators of temperature and salinity have been relatively constant over the period of the fishery. The northern side of the Rise receives older (and more mixed) Antarctic Intermediate Water than the southern flanks of the Rise, which is derived from a major eddy off the east coast of the North Island. This eddy picks up water deflected east along the southern side of the Chatham Rise and then northwards at its eastern end (Piola and Georgi, 1982; Hamilton, 1990; Chiswell and Sutton, 1998). It is not known what level of variation in temperature or salinity could be important for orange roughy, or whether other factors not measured here could be influential. However, the high degree of consistency between years, with no trend in the data, suggests that hydrological conditions have not influenced the distribution or abundance of orange roughy.

It is unknown whether changes in fish availability may have occurred. Trawl surveys were effective at measuring distribution and abundance of orange roughy in the Spawning Box during the 1980s. The time series was discontinued in 1995 when the variance of the abundance index increased due to the localised and dense aggregations of fish. It is possible that reduced trawling pressure following closure of the Spawning Box to commercial fishing between 1992 and 1996 may have allowed the fish to form spawning aggregations more effectively in the absence of disruption by the fishing fleet (as suggested by Clark and Tracey (1991) on the Challenger Plateau). Fish availability may vary seasonally. Clark and Tracey (1994) postulated for the Challenger Plateau fishery that there are both resident and migratory components to a spawning orange roughy stock. The Chatham Rise Spawning Box fishery is highly seasonal, and depends upon fish moving in from surrounding areas, particularly from the east, and migrating back to the east after spawning (Robertson et al., 1984; Coburn and Doonan, 1994). If the proportion of the population which migrates to spawn varies from year to year, this could affect how well trawl survey or CPUE data in the Spawning Box can monitor true biomass. However, the trend in abundance indices has been relatively consistent, which suggests that a change in fish availability has not been a significant factor causing bias in abundance estimates.

Reproductive parameters can be indicators of changes in abundance, even with long-lived species. Leaman (1991) reported accelerated growth and earlier maturation in heavily exploited stocks of Pacific Ocean perch (*Sebastes alutus*). However, orange roughy has a much greater age at maturity than *Sebastes* spp., between 22 and 35 years from different parts of the world (Horn et al., 1998). Late maturity is often associated with environments at high latitudes with longer-term environmental variation and low temperatures, which do not require a high compensatory response (Garrod and Horwood, 1984). Our results suggest that over the period of the fishery neither age nor size at maturity have changed. The slow growth rate of orange roughy means that size is unlikely to be sensitive to changes in the rate of maturation. Pitt (1975) and Leaman (1991) noted there was no shift in size despite a reduction in age at maturity with plaice and rockfish respectively, both of which are relatively long-lived fish. Although early maturation is recognised as a "standard" population response to exploitation, it is considered unlikely that this would happen within the 20-year duration of the orange roughy fishery, with no input from fishery-affected recruitment, which with orange roughy would not occur until 25–30 years after its commencement.

The time of spawning has been consistent between years in the Spawning Box, ranging from 14 July to 28 July. Dates presented here differ slightly from those of Pankhurst (1988) who examined average daily data over the period 1984–1986 rather than our approach of using data from each trawl and a smoothing function. Coburn and Doonan (1997) noted the time of peak running-ripe fish varied only by about a week. Similar consistency was also observed by Clark and Tracey (1994) on the Challenger Plateau.

Changes in fecundity of a fish species have been associated with exploitation. Koslow et al. (1995) reported a 20% increase in fecundity over a 3-year period from 1990 to 1992 with Tasmanian fish, and postulated the increase was due to a density-dependant increase in food per female as stock size declined. Orange roughy on the Challenger Plateau showed no change in fecundity between 1987 and 1990 (Clark et al., 1994). Fecundity of orange roughy in the Spawning Box showed a decrease between 1990 and 1994 from 31 500 eggs kg^{-1} body weight to 25 000 eggs (authors' unpublished data), although with only two years data it is uncertain whether this was a real and permanent change, or just natural variation between years. Leaman (1991) recorded a decrease in fecundity with exploitation of *Sebastes alutus*. If increased fecundity was a result of an increase in food availability (Giesel, 1976; Koslow et al., 1995), this could be reflected in improved condition of the fish. Our study showed no continuous trend in condition factor, expressed as mean weight of fish for a given length range. A decrease in female body weight since 1990 was significant, but its meaning is unclear. There was no indication of any increase in available food energy being transferred to reproductive output, as measured by relative GSI. Tasmanian fish showed a marked increase in GSI associated with the higher levels of fecundity (Koslow et al., 1995). It therefore appears that on the Chatham Rise there has been no reproductive compensation for decreasing stock size.

The observed shift in sex ratio based on the trawl survey results was unexpected. It was relatively stable around 50% in surveys from 1984 to 1990, before changing to strong predominance of females in 1992. The surveys in 1992 and 1994 had relatively high variance of catch rates, and this means the sex ratio estimate was less precise. A survey in 1995 addressed these problems and found that females predominated over most of the survey area (Francis, 1996; Tracey et al., 1997). Midwater trawling, and fishing in small localities previously not covered by the standard surveys, did not locate concentrations of males, and Francis (1996) concluded that the dominance of females in the spawning population appeared to be real. Data on sex ratios of the commercial catch from Scientific Observers provided no direct evidence that fishing caused the change in sex ratio. Recent Observer sex-ratio data are nearly 1:1 (Anderson et al., 1998). However, the observed change in sex ratio occurred just after the first exploitation of a number of seamounts to the east of the Spawning Box. Initial catches on these features are often dominated by males (Francis, 1996), and part of this could be the tendency for males to occur at lesser depths than females which are found further down the sides of seamounts (e.g. Clark and Field, 1998).

Age structure has not been examined in detail in this study. The large number of otolith zone counts involved with ageing of adult orange roughy means that estimates of age structure have a high variance, which is probably too great to allow reliable determination of small shifts in age composition. There was no trend or significant change in average otolith weight between 1984 and 1992, which suggests there has been no major shift in age structure. Adult orange roughy grow very slowly, and so an increase in age structure (and hence otolith weight) would be very small between years. However, the pattern should be more affected by new recruits entering the exploited population. The proportion of smaller otoliths showed a decline over the years and this may be due to low or declining levels of recruitment through the 1980s and 1990s. Smith et al. (1998) noted a 10–20 year shift downwards in age structure (based on otolith zone counts) in orange roughy off Tasmania between 1992 and 1995, and suggested this may be due to either an increase in recruitment, or earlier maturation and hence earlier recruitment to the adult spawning fishery.

There has been little change in the general size structure of orange roughy in the Spawning Box. Length frequency distributions, and mean lengths of fish, have been relatively constant between years. With heavy exploitation a truncation of the distribution at the upper end, and a reduction in mean size, would have been expected in this population (Francis and Smith, 1995). The detailed examination of both limbs of the size distribution showed no evidence of any selective removal of larger-sized fish. There may be indications of an increase in the relative proportions of small male fish, but this is not seen with females. Fishing mortality appears to have occurred evenly across all sizes. Otolith and length-frequency data together imply that recruitment levels have been low for some time. Mean recruitment is likely to have been above average in the 1970s, but below through the 1980s by on average 25% (Francis et al., 1992). The stochastic stock reduction analysis interprets these changes as caused by low recruitment, but it is possible that other unknown factors could be involved. A low frequency of strong year classes has been correlated with longevity of a fish species (Leaman and Beamish, 1984) and the extent of depletion of a population (Brown et al., 1983).

Similar stability of size structure despite substantial decreases in stock size have been reported for other orange roughy populations in New Zealand (Clark and Tracey, 1994; Field et al., 1994) as well as Australia (Bax, 1997). It has also been noted with pelagic armourhead (*Pseudopentaceros wheeleri*) on seamounts of the North Pacific Ocean, where it is thought that somatic growth ceases after recruitment to a seamount (Humphreys and Tagami, 1986).

The orange roughy populations on the Chatham Rise have shown a number of changes with exploitation during the 1980s and 1990s. There have been the "usual" contractions in distribution, and declines in abundance, of both orange roughy, and a range of associated species. However, there have been few obvious changes in biological parameters, and indicators of stock productivity. The important issue for the future of this fishery, and for its management, is how resilient the orange roughy population is to exploitation. The TAC has been reduced several times since 1990−1991, and from 1994−1995 was thought to be at a level that would allow rebuilding of the stock in the northeast Chatham Rise towards its optimal size (Francis et al., 1995). Stochastic modelling of the population predicted an increase in population size after 1992. The 1994 and 1995 trawl survey results on distribution, together with a levelling off of commercial catch rates in many areas, suggest the stocks might have stabilised, but it is perhaps too early yet to evaluate whether this is happening or if rebuilding is occurring. The rate of rebuilding, given the biological parameter values used in the stock assessment, is slow at about 2.5% of virgin biomass per year (Francis et al., 1995), and this level of increase would be difficult to recognise given the variance of estimates of abundance indices (especially CPUE). With a high age at maturity and recruitment to the adult fished population, any change in levels of recruitment induced by fishing down the stock will not enter the fishery for another 5–10 years. Coupled with indications that recruitment may be infrequent, or at low levels for extended periods, this poses major concerns for management (Clark, 1995). Lack of adequate knowledge of recruitment, or sporadic and unpredictable recruitment, can clearly lead to increased risk of overexploitation, or even stock collapse (e.g. Mayo, 1986; Hutchings and Myers, 1994). Although mean size has been consistent over most of the period of the fishery, there are indications from 1994 and 1995 of a higher proportion of small-sized fish in the population. It is uncertain whether this might represent some resilience in the stock with lessening of fishing pressure, and emphasises the need to monitor closely such fisheries for an extended period when the history of exploitation is relatively short.

Acknowledgements

Many people have contributed to research on Chatham Rise orange roughy over the years (too numerous to name individually) so a collective thanks to a range of staff from NIWA (formerly MAF Fisheries Research). The input to the research programme from Dr. Don Robertson (NIWA) and Jack Fenaughty (Sanford Ltd.) is acknowledged. Thanks to Ralph Coburn and Ian Doonan (both NIWA) for making results of unpublished catch-effort work available, and to Steve Chiswell (NIWA) for providing some of the hydrographic data. Peter McMillan and Don Robertson (NIWA) reviewed and made constructive comments on an early draft of the manuscript. Journal referees also made very useful suggestions. This work was in part funded by the Ministry of Fisheries (project DEOR02) during 1997.

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