Changes in a population of orange roughy, *Hoplostethus atlanticus*, with commercial exploitation on the Challenger Plateau, New Zealand

Malcolm R. Clark
Dianne M. Tracey
MAF Fisheries Greta Point, P.O. Box 297
295 Evans Bay Parade, Wellington, New Zealand

Abstract.—The commercial fishery for orange roughy on the Challenger Plateau developed in 1981, increased markedly throughout the mid-1980s, and then declined rapidly by 1990. Data from research trawl surveys and commercial fishing returns over the period are examined, and changes in the population are described.

The distribution of orange roughy changed over the period examined; there was a contraction of the areas of high density and apparent fishing-out of aggregations on relatively flat bottom. Aggregations are now largely confined to pinnacles. Biomass of orange roughy, measured by bottom trawl survey indices and commercial catch per unit of effort, declined substantially and is currently estimated to be about 20% of virgin levels. Most other incidental species in the trawl surveys have also declined in abundance, and there are no indications of 'species replacement.'

Data on size, reproductive stage, size at maturity, and feeding have also been examined. Size structure of the population has not changed over time. Time of spawning (July) and the pattern of gonad development have been consistent over the years. Diet composition has also remained similar; dominant prey groups are natant decapod crustaceans and small fish.

It is suggested that biological changes have not been apparent because orange roughy are a long-lived, slow-growing species, with low productivity. There could be a long response time to fishing pressure, yet orange roughy populations can be quickly reduced to low levels by commercial fishing.

Manuscript accepted 4 November 1993
Fishery Bulletin 92:236–253 (1994)

Orange roughy (*Hoplostethus atlanticus* Collett) has a worldwide distribution on the continental slope at depths of 700 to 1,500 m. However, it is fished commercially only off New Zealand, Australia, and in the northeastern Atlantic Ocean. The New Zealand fishery is the most established, having started in 1978; the others date from 1988 and 1991, respectively. Orange roughy is one of the most valuable commercial species in New Zealand waters, with annual landings of 40–50,000 metric tons (t) and export earnings of NZ $100–150 million (Robertson, 1991).

The New Zealand fishery for orange roughy occurs in a number of areas (Fig. 1), including the Challenger Plateau, a broad submarine plateau off the west coast of New Zealand. The commercial fishery on the Plateau developed in late 1981 and rapidly expanded into one of the most important orange roughy fisheries in New Zealand waters, with annual catches up to approximately 16,000 t (Table 1). The fishery operates primarily during winter (June–August), when the fish form large spawning aggregations at depths of 850–900 m (Clark, 1991a).

The fishery has been managed by a Total Allowable Catch (TAC) system since 1982. Tracey et al. (1990) and Clark (1991a) discussed details of this management regime. Initially, catches were limited to 7,000 t by the TAC for all areas of the New Zealand Exclusive Economic Zone (EEZ), outside the established fishing grounds on the east coast. A TAC of 4,950 t was set for 1983–84 and 1984–85 (October–September fishing year) on the Challenger Plateau and west coast of the South Island. This was raised to 6,190 t specifically for the Challenger fishery in 1985–86 based on biomass estimates from a trawl survey in winter 1984. The quota was raised to 10,000 t in 1986–87, and further to 12,000 t in 1987–88, in order to assess the effects of heavier fishing on the population dynamics of orange roughy ("adaptive management"). In the following fishing year only 8,200 t of quota were allocated, the rest withheld because of signs that the orange roughy population was declining rapidly. During 1989–90 the TAC was reduced to 2,500 t after new stock assessments showed the population was overexploited and had declined to low levels (Clark and Francis, 1990). The TAC was further reduced for 1990–91 to promote rebuilding of the population.

These changes occurred against a background of increasing infor-

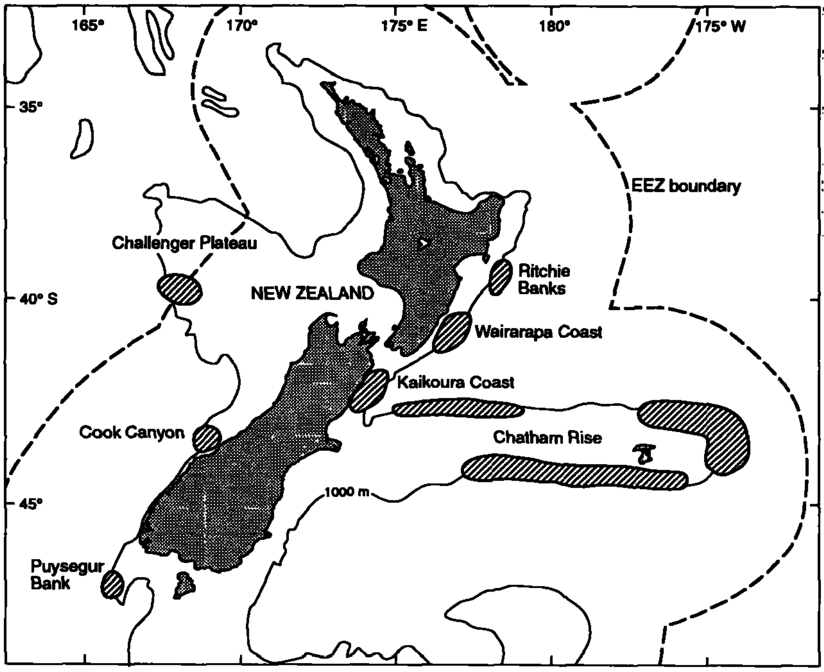

Figure 1

Map of New Zealand and offshore waters of the Exclusive Economic Zone (EEZ), showing the location of the Challenger Plateau and other major fishing areas for orange roughy (*Hoplostethus atlanticus*).

mation on orange roughy. It has only recently been realized that orange roughy is very slow-growing and long-lived. Mace et al. (1990) recorded a growth rate of about three cm per year for the first four years of life (validated ages), and an estimated age at maturity of 24 years and maximum age over 50 years. They estimated natural mortality to be low (less than 0·1 yr^{-1}) and concluded that sustainable yields of orange roughy would be relatively low and show slow recovery from over-fishing. Recent estimates of the maximum age of orange roughy from Australian waters approach 150 years (Fenton et al., 1991).

Quotas for orange roughy harvest from New Zealand have been reduced in recent years on the basis of information which suggests much lower productivity than originally assumed. However, the Challenger Plateau population had already declined markedly and provides some insight into the effects of heavy fishing pressure on orange roughy population dynamics.

There is an extensive literature on general responses of fish populations to exploitation, covering 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; Pauly, 1979; Grosslein et al. 1980). There have been few studies on deep-water or long-lived species such as orange roughy. The closest is probably Pacific ocean perch (*Sebastes alutus*) which is found at depths to 600 m in the North Pacific Ocean and has a maximum age of 90 years (e.g. Gunderson, 1977; Leaman, 1991).

There are a number of general population responses to exploitation, which include

1 Decline in abundance of fished species.
2 Contraction of distribution or areas of high density.
3 Change in age structure or size structure, or both, with fewer old, large fish and the population dominated by new recruits.
4 Increase in growth rate of individuals, with a decrease in age for a given length.
5 Lower age at maturity or size at maturity, or both.

Table 1

Reported catches (t) of orange roughy (*Hoplostethus atlanticus*) from the Challenger Plateau (ORH 7A and outside EEZ) (from Clark 1992; total estimated catch includes allowance for research survey catches and a correction for 15–30% under-estimation of true catch in reported catch figures because of burst trawls, fish discards, and incorrect official conversion factor).

Fishing year (Oct–Sept)	Total reported catch	Total estimated catch	TAC
1980/81	33	43	
1981/82	4,248	5,522	
1982/83	11,839	15,409	
1983/84	9,527	12,514	4,950
1984/85	5,117	6,707	4,950
1985/86	7,753	10,251	6,190
1986/87	11,492	15,750	10,000
1987/88	12,181	15,830	12,000
1988/89	10,241	12,627	12,000[1]
1989/90	4,309	5,171	2,500
1990/91	1,357	1,560	1,900

[1] 8,219 t allocated.

6 Possible change in species composition over time ('species replacement').

Such responses are often observed in short-lived, fast-growing species (e.g. Pauly, 1979; Grosslein et al., 1980). Some have also been noted with *Sebastes alutus* (Gunderson, 1977; Leaman, 1991), but it is not clear whether these changes would occur in such a long-lived species as orange roughy, or over what time period such changes would become apparent. Orange roughy on the Challenger Plateau have been exploited for only 10 years, and hence it seems unlikely that marked changes in biological characteristics could occur over such a relatively short time period in relation to the longevity of the species. Therefore, we might expect to observe changes in biomass and distribution, as well as age and size structure of the population, but not changes in growth rate or reproductive potential.

In this paper, we summarize some of the available data on distribution, abundance, and biology of orange roughy on the Challenger Plateau, primarily over the period 1984–90. This period covers the early years of the developing fishery, to maximum levels of exploitation, and subsequent decline of the population. We describe the reduction in size and distribution of the stock and investigate associated changes in size structure, aspects of reproduction, and feeding.

Methods

Research trawl surveys

Trawl surveys have been carried out in the winter (June–July) of each year from 1984 to 1990. The vessel used, area covered, intensity of trawling, and survey design differed between years, and all are not directly comparable (Table 2). Surveys from 1987 to 1989 were treated as fully comparable, but only selected data have been used from other surveys: distribution from 1984 and 1990, and biology (size, reproductive, and feeding data) from 1984, 1985, 1986, and 1990.

The general survey design was two–phase stratified random (after Francis, 1984). The survey area was divided into a number of strata based on depth and certain bottom features (e.g. pinnacles). General stratification is shown in Figure 2. The depth range covered was 800 to 1,200 m. New, random station positions within strata were selected each year, except in strata 10 and 11 on pinnacles where a random tow direction was adjusted to avoid untrawlable ground, and these trawls were repeated each year. A similar net design and gear set up was used for each survey. Tow length was standardized where possible at 1.5 nautical miles (nmi). Trawling speed was 3.0–3.5 knots.

Biomass indices were calculated by the area swept method as described by Francis (1981). Biomass and its standard error were calculated from the following formulae:

$$B=\sum(X_i a_i)/cb$$

and

$$S_B=\sqrt{\sum s_i^2 a_i^2 / c^2 b^2}\ ,$$

where B is biomass (t), X_i is the mean catch rate ($kg{\cdot}km^{-1}$) in stratum i, a_i is the area of stratum i (km^2), b is the width swept by the gear (defined as doorspread (m) by MAF Fisheries), c is the catchability coefficient (an estimate of the proportion of fish available to be caught by the net), S_B is the standard error of the biomass, s_i is the standard error of X_i.

The catchability coefficient was assigned a value of 0.27, which represents the wingend spread divided by the doorspread, because orange roughy form schools which are not believed to be herded substantially by doors or sweeps.[1]

Approximate 95% confidence limits (CL) were calculated as

$$CL = B \pm 2S_B.$$

[1] Orange Roughy Working Group, MAF Fisheries, Greta Point, P.O. Box 297, Wellington, New Zealand, pers. commun. 1991.

Table 2

Trawl surveys carried out on the Challenger Plateau for orange roughy (*Hoplostethus atlanticus*).

Vessel	Year	Date	Area (km^2)	Number of trawls	Survey design
Arrow	1984	3/7–18/7	11,956	118	2 phase SRTS[1]
Arrow	1985	4/7–20/7	209	16	1 phase SRTS
Arrow	1986	4/7–17/7	94	10	transect grid
Amaltal Explorer	1987	18/6–13/7	8,270	129	2 phase SRTS
Amaltal Explorer	1988	4/7–24/7	8,270	85	2 phase SRTS
Amaltal Explorer	1989	8/7–30/7	8,270	160	2 phase SRTS
Will Watch	1990	7/7–29/7	8,270	141	2 phase SRTS

[1] Stratified random trawl survey.

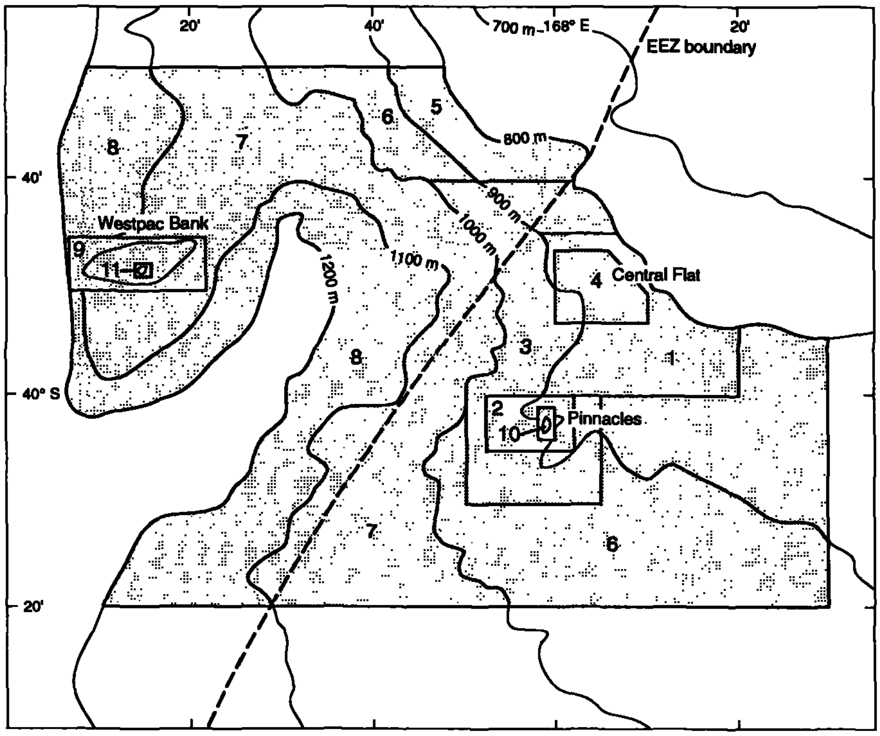

Figure 2
The Challenger Plateau survey area, showing bathymetry (depth contour in m) and details of survey stratification.

The coefficient of variation (CV) is a measure of the precision of the biomass estimate, and was calculated by

$$CV = S_B / B \times 100.$$

Stock reduction analysis

A stock reduction technique was used to estimate virgin biomass based on the method of Francis (1990, 1992). This incorporated a complete catch history for the stock, a time series of abundance indices, and life history parameters used in a deterministic age–structured population model (see Clark, 1992). The latter were the von Bertalanffy growth parameters (L_∞=39.5 cm, k=0.059·yr^{-1}, t_0 = –0.3 yr), natural mortality=0.04·yr^{-1}, weight-length parameters (a=0.0963, b=2.68), age at maturity (24 yr), age at entry to the fishery (24 yr), and Beverton-Holt recruitment steepness of 0.75.

Five sets of abundance indices were used from trawl surveys between 1984 and 1990, and commercial catch per unit of effort (CPUE) data (unstandardized mean catch per tow by monthly groupings):

1 CPUE in winter months (June–September) from 1983 to 1989. This covered the period of development of the fishery through to maximum exploitation. It is felt that the fishery was not constrained much by the TAC over this time.
2 CPUE in winter months from 1983 to 1991. This includes data from 1990 and 1991, following a substantial reduction in TAC and effort.
3 CPUE in non-winter months from 1983 to 1991.
4 Trawl survey indices from 1987 to 1989. These surveys covered the same area, had the same design, and used the same vessel.
5 Trawl survey indices from 1984 and 1987 to 1990. This series incorporated data from a smaller area surveyed in 1984 and from the 1990 survey, both of which used a different vessel from 1987 to 89.

The maximum likelihood method was used to estimate virgin biomass. Ninety-five percent confidence intervals were estimated by using bootstrapping techniques with the coefficient of variation fixed at 20%. The best estimate of virgin biomass was then used in an age-structured model (detailed in Francis, 1992) to estimate current biomass.

Biological data

Standard procedure during trawl surveys was to take a random sample of about 200 fish from each tow. These were measured (standard length rounded down to the nearest whole cm [standard MAF Fisheries procedure]) and sexed. Twenty of these fish were randomly selected, their otoliths extracted, and more detailed data collected: standard length (rounded down to the nearest whole mm), weight (rounded down to the nearest gm), sex, stage of gonad maturity (see below), gonad weight (rounded down to the nearest gm), fullness of stomach, state of digestion of contents, and stomach contents (to species level where possible).

Size Length-frequency distributions have been constructed to represent the total population where possible. In the years 1984 and 1987–90, data have been scaled by percentage sampled to represent each catch and further scaled by stratum biomass to approximate the population. Samples in 1985 and 1986 were scaled to represent solely the catch, as survey design was inadequate for biomass estimation.

Length-frequency data are difficult to compare statistically and, for the purposes of this study, have not been attempted. However, to enable a general comparison, a single distribution was constructed combining length-frequency data from all years weighted by the number of tows each year. This distribution is plotted together with those from each year separately.

Mean size by sex was calculated separately for three main regions of spawning within the survey area (strata 1, 4; 10; 9, 11) as it was unlikely these areas had been fished equally (see later 'Commercial Fishery' section). The sample sizes used in calculating the standard error were number of tows, not number of fish. Orange roughy can associate in size groups; between-tow variance was greater than within-tow variance. Variance is represented by ±2.0 standard errors for all years except 1986, when ±2.2 standard errors was arbitrarily used because there were only 10 trawls.

Reproduction Macroscopic staging of reproductive condition followed Pankhurst et al. (1987):

Stage	Female	Male
1	Immature/resting	Immature/resting
2	Early maturation	Early maturation
3	Maturation	Maturation
4	Ripe	Ripe/running ripe
5	Running ripe	Spent
6	Spent	—

Relative frequency of gonad stages was examined. Analyses were based on the samples taken. They were not scaled in any way, as there were no apparent differences between the length frequencies of the samples and the distribution of the total population. Only data from females are presented, as their macroscopic gonad stages can be determined more accurately than those from males.

Size at maturity was determined from samples taken over the total survey area using a 'probit analysis' approach (after Pearson and Hartley, 1976). It was assumed that length at maturity is normally distributed in the population. The regression part of the analysis was repeated 10 times to ensure convergence of the estimate.[2] A standard linear regression analysis was carried out on results to investigate trends over time by using the SAS statistical package (SAS, 1988).

[2] Francis, C., MAF Fisheries, pers. commun. 1991.

Feeding Data on frequency of occurrence were available from all surveys. Frequency of occurrence was defined as the number of stomachs in which a food item occurs, expressed as a proportion of the total number of stomachs containing food. Only stomachs with part-full or full classifications, and with fresh or partly digested contents, were included in analyses.

Commercial fishing data

Data on the catch and position of each tow and the start and finish times have been collected since 1980. However, catch and effort information is difficult to standardize and interpret for orange roughy. Fish can be highly aggregated at various times of the year, and 'windows' or escape panels in the net are frequently used to reduce catch size and minimise damage to nets. Fishing performance varies with experience of skipper and crew, and technology has advanced considerably in recent years (in particular, development of Global Positioning System navigation, which enabled improved accuracy when fishing pinnacles). Fishing logbooks often do not have accurate information on length of tow on the bottom. Fishing for orange roughy on the Challenger Plateau occurs on a variety of bottom terrain: on flat bottom, in troughs and steep slope, and on the tops and sides of pinnacles. In each case, the effective fishing time and fishing technique differ greatly, and they are almost separate types of fisheries. In order to gain an indication of trends in catch rates, data were examined on the basis of mean catch per tow for two size classes of vessel (20–60 m, generally domestic fresh fish boats; and 60–90 m, domestic factory trawlers). Catch per unit of effort (CPUE) values were similar for both classes, and so data here are combined. Monthly data were amalgamated into two time periods: first, 'winter' (June, July, August) which covers the spawning period; second, 'out of season' (all other months). This division represents two distinct phases of orange roughy distribution, as well as differences in the mode of fishing (Clark, 1992). The former period is characterized by the formation of relatively stable, dense aggregations of fish, whereas in the latter period the orange roughy are more dispersed and widely distributed (Clark, 1991a). Fishing in winter generally involves shorter tows, often with smaller nets, than does out-of-season fishing.

In the following text, three colloquial area names have been used. These are given below with specific strata numbers (see Fig. 2):

Central Flat	strata 1, 4
Pinnacles	stratum 10
Westpac Bank	strata 9, 11

Results

Distribution

Trawl surveys The distribution of orange roughy in the survey area changed substantially between years (Fig. 3). In 1984 high catch rates were observed across much of the Central Flat area. (No trawls were made on the Pinnacles although heavy marks were observed on the echosounder; the survey did not cover the Westpac Bank area.) In 1987 fish were still widely distributed in the Central Flat; there were two main schools and further concentrations around the Pinnacles and the Westpac Bank. In 1988 there was a marked contraction in the area of high catch rates; a single small aggregation was observed on the Central Flat, and by 1989 there were no aggregations in the Central Flat region. High catch rates still occurred on the Pinnacles and Westpac Bank in 1989, and these actually increased in 1990, after the TAC and fishing effort were greatly reduced.

Commercial fishery The commercial fishery has been centered mainly inside the EEZ, targeting aggregations of orange roughy on the Central Flat and Pinnacles. Distribution of effort (number of tows) and catch between these two areas has changed over time (Table 3). In the period 1982–87, over 80% of the catch from the two areas was taken from the Central Flat with over 75% of the number of tows. In 1988 there was a marked increase in the proportion of catch and effort on the Pinnacles, and a corresponding reduction on the Central Flat. This shift continued in 1989 and 1990, during which the Pinnacles accounted for 65–70% of the catch. These changes reflect the change in distribution observed in the research trawl surveys.

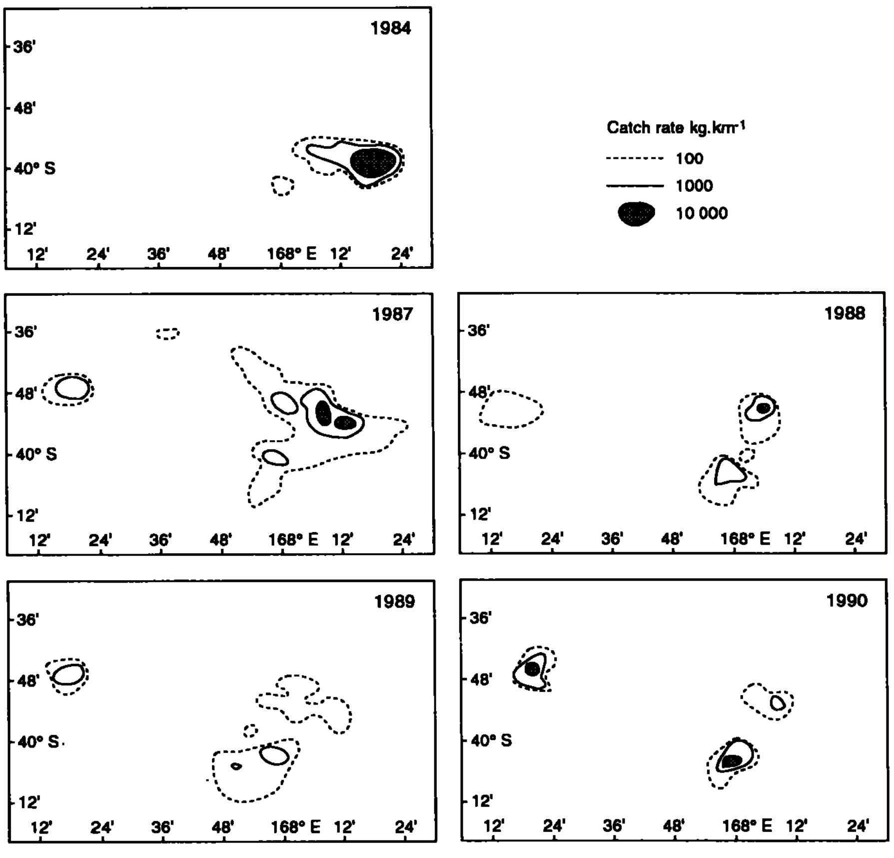

Figure 3

Contours of trawl survey catch rates (kg·km^{-1}) of orange roughy (*Hoplostethus atlanticus*) in 1984 and 1987–90.

Relative abundance

Trawl surveys Biomass indices (estimates of relative biomass) from trawl surveys in 1987, 1988, and 1989 are given in Table 4. The indices indicate a marked decline in biomass over the period. The distribution of biomass among strata changed over the years 1987–90 (Table 5). In 1987 and 1988 over 60% of the biomass was in the Central Flat area, but only 30% in 1989 and 1990. Over this period, there was an increase in the proportion on the Pinnacles, especially between 1989 and 1990. Biomass levels in the surrounding areas have fluctuated but were particularly high in 1989. The proportion of biomass on the Westpac Bank has remained comparatively constant.

Commercial fishery Mean catch per tow for all New Zealand vessels in the fishery from 1983 to 1991 is given in Table 6. Catch rates in winter, when the fish are aggregated for spawning, are generally higher than in other months. Although aggregations occur at other times, presumably for feeding, they are not as large or as stable as in winter. Catch rates in both periods declined steadily from 1983 to 1989 to between about 15% and 20% of original levels. The trend is slightly different in the two periods; winter catch rates declined more sharply to 1988, whereas in the other months the largest decrease was between 1983 and 1984. Catch rates increased in 1990, following a reduction of the TAC, when there were less vessels and fewer trawls on the grounds.

Individual trawl catch rates for orange roughy can be highly variable, consisting of 'hits' and 'misses.' Therefore it is not useful to describe the variance around these mean catch rates, beyond commenting that there is wide variation. It should be stressed that the changes in catch rates presented here may give an indication of changes in stock size but should be treated with caution. Difficulties in interpretation of such data for orange roughy are described in the 'Methods' section, and the form of relationship between mean catch per tow and stock abundance is uncertain.

Stock reduction results

Abundance indices used in, and estimates of virgin biomass from, the stock reduction analyses are given in Table 7. Point estimates of B_0 range from 95,000 t to 278,000 t. The best fits of data to the model (those with the lowest CV) are from the winter CPUE series. Results from trawl survey data have higher CVs but confirm that an estimate of the order of 100,000 t is reasonable.

The 1987–89 trawl survey series gave the lowest virgin biomass estimate. It was not considered reliable because there were only three indices, and high fishing mortality rates were required to support the catch history. A maximum F of 1.0 is regarded as realistic for orange roughy (Francis et al., 1992). This constrains the virgin biomass to a minimum value of 94,000 t.

The estimate from non-winter CPUE is comparatively high. It has a large CV and is based on relatively low numbers of trawls (because most fishing effort is in winter). Such a biomass level would also

Table 3

Distribution of commercial catch (% of total catch taken in the two areas) and effort (% of number of tows) for orange roughy (*Hoplostethus atlanticus*) for the Central Flat and Pinnacles (winter period, June to August).

	Central Flat		Pinnacles	
Year	% catch	% tows	% catch	% tows
1982	97.2	95.6	2.8	4.4
1983	97.0	94.7	3.0	5.3
1984	95.2	93.6	4.8	6.4
1985	87.7	78.0	12.3	22.0
1986	87.3	83.2	12.7	16.8
1987	84.4	77.3	15.6	22.7
1988	52.9	56.0	47.1	44.0
1989	34.0	43.3	66.0	56.7
1990	30.2	45.0	69.8	55.0

Table 4

Biomass indices (t) of orange roughy (*Hoplostethus atlanticus*) from trawl surveys, conducted from 1987 to 1989. (CV = coefficient of variation.)

Year	Biomass (t)	CV
1987	78,661	26
1988	30,946	27
1989	11,746	11

Table 5

Comparison of biomass estimates (t) of orange roughy (*Hoplostethus atlanticus*) by region from 1987 to 1990.

	1987		1988		1989		1990	
Region	Biomass (t)	%	Biomass (t)	%	Biomass (t)	%	Biomass (t)	%
Central Flat	56,636	72.0	21,051	68.0	3,275	27.9	4,228	30.8
Pinnacles	7,794	9.9	5,215	16.9	2,821	24.0	5,508	40.1
Surrounding background	10,717	13.6	2,878	9.3	5,088	43.3	3,208	23.3
Westpac Bank	3,514	4.5	1,802	5.8	563	4.8	794	5.8
Total	78,661	100.0	30,946	100.0	11,747	100.0	13,738	100.0

Table 6

Catch per unit of effort (mean catch (t) per trawl) of orange roughy (*Hoplostethus atlanticus*) for New Zealand fishing vessels.

Calendar year	Winter CPUE	Winter No. trawls	Other months CPUE	Other months No. trawls
1983	16.2	222	9.2	307
1984	15.3	54	5.2	515
1985	13.3	87	4.6	530
1986	10.5	512	3.3	486
1987	10.2	681	2.4	255
1988	5.9	1,269	2.7	99
1989	3.7	1,094	1.3	81
1990	6.6	325	7.3	25
1991	4.1	264	0.1	4

suggest low values of F in recent years, which seems unlikely given the substantial effort in the fishery yet catches being less than the TAC.

There is considerable uncertainty in all the data sets. However, assuming a virgin biomass of 110,000 t (as an approximation of the trawl survey and winter CPUE values), the decline in mid-year biomass of the population was rapid and the level in 1991 was about 20% of the virgin level (Table 8).

Other species

Biomass indices of the 12 main bycatch species caught in the trawl surveys from 1987 to 1989 are presented in Table 9. The coefficients of variation of these mean values range from 11% to 69% and differ between years and species, which limits their comparability.

However, there were no strong indications of increasing abundance of any species relative to abundance in 1987. There was little apparent change in abundance of ribaldo (*Mora moro*), leafscaled gulper shark (*Centrophorus squamosus*), widenosed chimaera (*Rhinochimaera pacifica*), spiky oreo (*Neocyttus rhomboidalis*), Owston's spiny dogfish (*Centroscymnus owstoni*), or white rattail (*Trachyrinchus* sp.). Declining abundance was suggested for big scaled brown slickhead (*Alepocephalus* sp.), basketwork eel (*Diastobranchus capensis*), Johnson's cod (*Halargyreus johnsoni*), smallscaled brown slickhead (*Alepocephalus australis*), shovelnosed spiny dogfish (*Deania calcea*), and seal shark (*Dalatias licha*). The biomass of species relative to orange roughy has generally increased for all species except seal shark. This change is strongest for ribaldo, Owston's dogfish, widenosed chimaera, leafscaled gulper shark, and white rattail.

Size structure

Length-frequency distributions of orange roughy from the entire survey area were similar in all years with no marked differences from the overall weighted length frequency (Fig. 4). There was a strong unimodal distribution with the peak at 32–33 cm standard length. Fish ranged in standard length from 9 cm to 44 cm.

Sex ratios varied between years, but were generally about 1 : 1. However, females always dominated the size distribution above about 35 cm. The mean

Table 7

Summary of biomass indices for orange roughy (*Hoplostethus atlanticus*) used in stock reduction analyses, and estimates of virgin biomass (B_0) (mean and 95% confidence interval), and coefficients of variation (CV).

Year	CPUE (winter)	CPUE (winter)	CPUE (other months)	Trawl survey (full area)	Trawl survey (reduced area)
1983	16.2	16.2	9.2		
1984	15.3	15.3	5.2		143,500
1985	13.3	13.3	4.6		
1986	10.5	10.5	3.3		
1987	10.2	10.2	2.4	78,600	75.000
1988	5.9	5.9	2.7	30.900	28,900
1989	3.7	3.7	1.3	11,700	11,000
1990		6.6	7.3		12,900
1991		4.1	0.1		
Parameter estimates					
B_0 (t)	100,000	122.000	278.000	83,000	95,000
B_0 (95% CI)	94,000–156,000	94,000–224,000	216,000–500,000	94,000–181,000	94,000–194,000
CV (%)	8	22	76	27	37

Table 8

Estimated biomass values by year (mid-year biomass, rounded to nearest 100 t) for orange roughy (*Hoplostethus atlanticus*).

Year	Biomass (t)	Year	Biomass (t)
1980	110,000	1986	67,000
1981	110,000	1987	54,900
1982	107,000	1988	40,500
1983	96,500	1989	28,400
1984	83,200	1990	22,300
1985	74,600	1991	21,400

size of females was significantly greater than that of males (t–test, $P<0.05$). Size data were also examined by the following subareas: Central Flat, Pinnacles, and Westpac Bank. Length frequencies by sex were generally similar to those for the total survey area and are not presented here. However, the distributions were approximately normal in shape and could be described by their means and standard errors to provide a simpler comparison between areas and between years (Fig. 5). There were no apparent differences between years or between areas (t–test, $P<0.05$), and no consistent trend in size over time.

Reproduction

All trawl surveys occurred during the months of June–July. There was considerable variation evident in the overall proportions of fish of different reproductive stage between years and areas (Table 10). To a large extent this reflected the timing of the survey (e.g. 1987 was earlier than the others) and showed a high proportion of maturing fish. However, in all years the majority of fish sampled were mature and were involved in that year's spawning (stages 3–6).

The Central Flat and Pinnacle regions were typically dominated by mature fish in or near spawning condition. In 1987 on the Westpac Bank there was a high proportion of fish that were in very early stages of maturation and hence unlikely to spawn in that year. From 1988 to 1990 the proportion of actively spawning fish increased. However, levels of nonspawning fish have consistently been higher here than in the Central Flat and Pinnacle areas.

Timing of spawning

The progression of gonad stages appeared consistent between years for which data spanning several weeks in July exist (Fig. 6). A pattern of maturing fish declining to low levels was observed early in

Table 9

Biomass (t) of the main bycatch species in the trawl surveys, their proportion of that year's orange roughy (*Hoplostethus atlanticus*) biomass (ref ORH), and their proportion of their biomass in 1987 (ref 1987).

	1987				1988				1989			
	Biomass	(CV)	Ref 1987	Ref ORH	Biomass	(CV)	Ref 1987	Ref ORH	Biomass	(CV)	Ref 1987	Ref ORH
Ribaldo	295	(14)	1.0	0.004	378	(16)	1.3	0.012	317	(11)	1.1	0.027
Owston's dogfish	567	(32)	1.0	0.007	358	(31)	0.6	0.011	400	(20)	0.7	0.034
Leafscaled gulper shark	160	(32)	1.0	0.002	167	(52)	1.0	0.005	208	(40)	1.3	0.018
Spiky oreo	75	(38)	1.0	0.001	156	(36)	2.1	0.005	68	(28)	0.9	0.006
Bigscaled brown slickhead	1,345	(20)	1.0	0.017	486	(21)	0.4	0.016	314	(20)	0.2	0.026
Basketwork eel	332	(19)	1.0	0.004	153	(37)	0.5	0.005	57	(39)	0.2	0.005
Johnson's cod	145	(17)	1.0	0.002	61	(36)	0.4	0.002	44	(16)	0.3	0.004
White rattail	467	(23)	1.0	0.006	345	(29)	0.7	0.011	610	(17)	1.3	0.052
Smallscaled brown slickhead	1,197	(39)	1.0	0.015	285	(22)	0.2	0.009	610	(13)	0.5	0.052
Widenosed chimaera	274	(21)	1.0	0.003	662	(20)	2.4	0.021	283	(16)	1.0	0.024
Shovelnosed dogfish	277	(23)	1.0	0.003	218	(41)	0.8	0.007	73	(31)	0.3	0.006
Seal shark	467	(32)	1.0	0.006	87	(69)	0.2	0.003	47	(39)	0.1	0.004

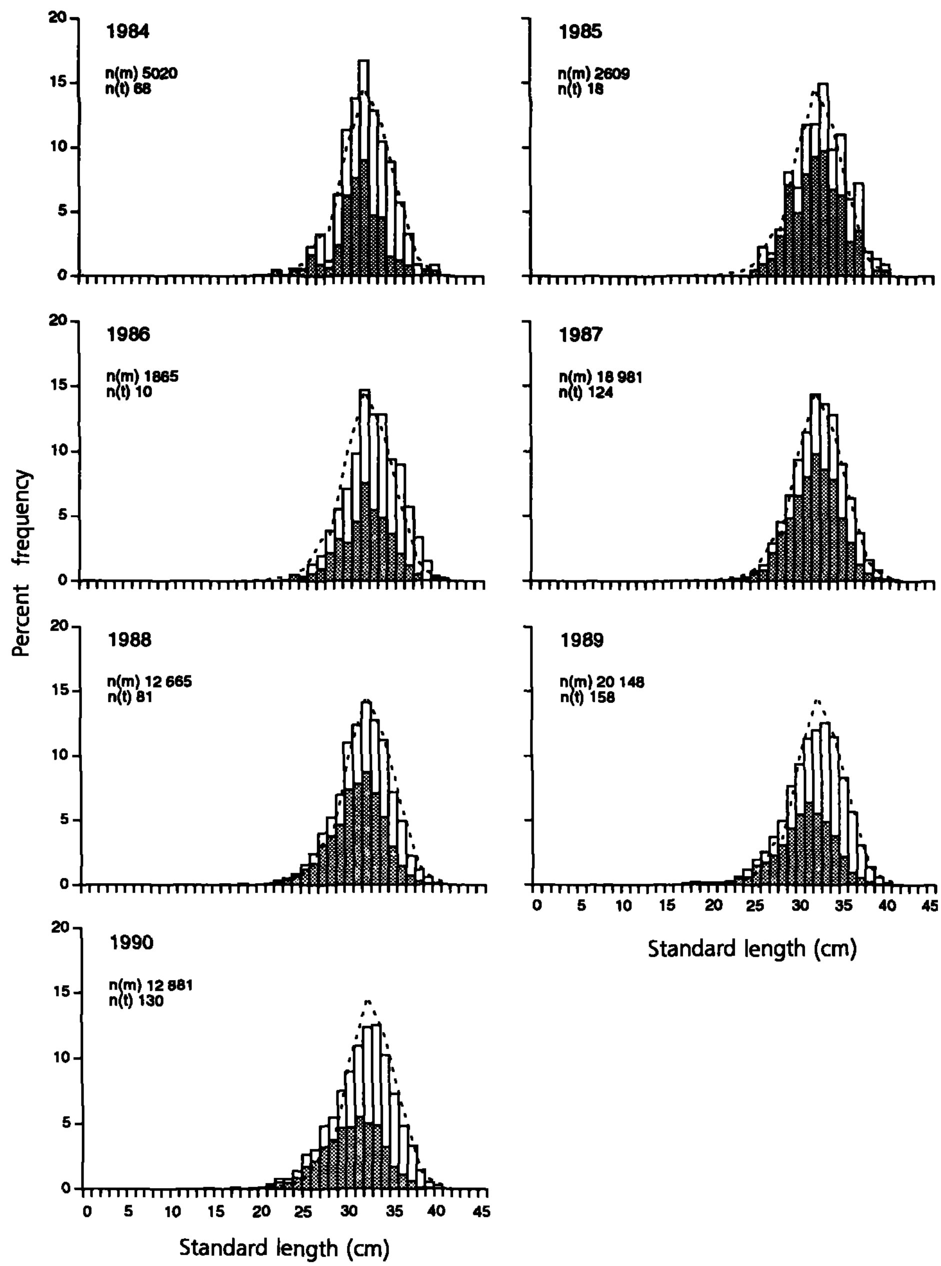

Figure 4

Length-frequency distribution of the orange roughy (*Hoplostethus atlanticus*) population by year (stipple=male, clear=female, dashed line=weighted length frequency for all years combined, $n(m)$=number of fish measured, $n(t)$=number of trawls from which samples were taken, data are scaled by stratum areas to represent total population-size distribution).

July; ripe fish dominated through mid-July; and the proportion of spent fish increased progressively from low levels during the first two weeks in July to peak in the third or fourth week.

Data are insufficient to examine regional variation in this pattern, but there may be some differences between areas; fish appear to spawn slightly later on the Westpac Bank than those on the Central

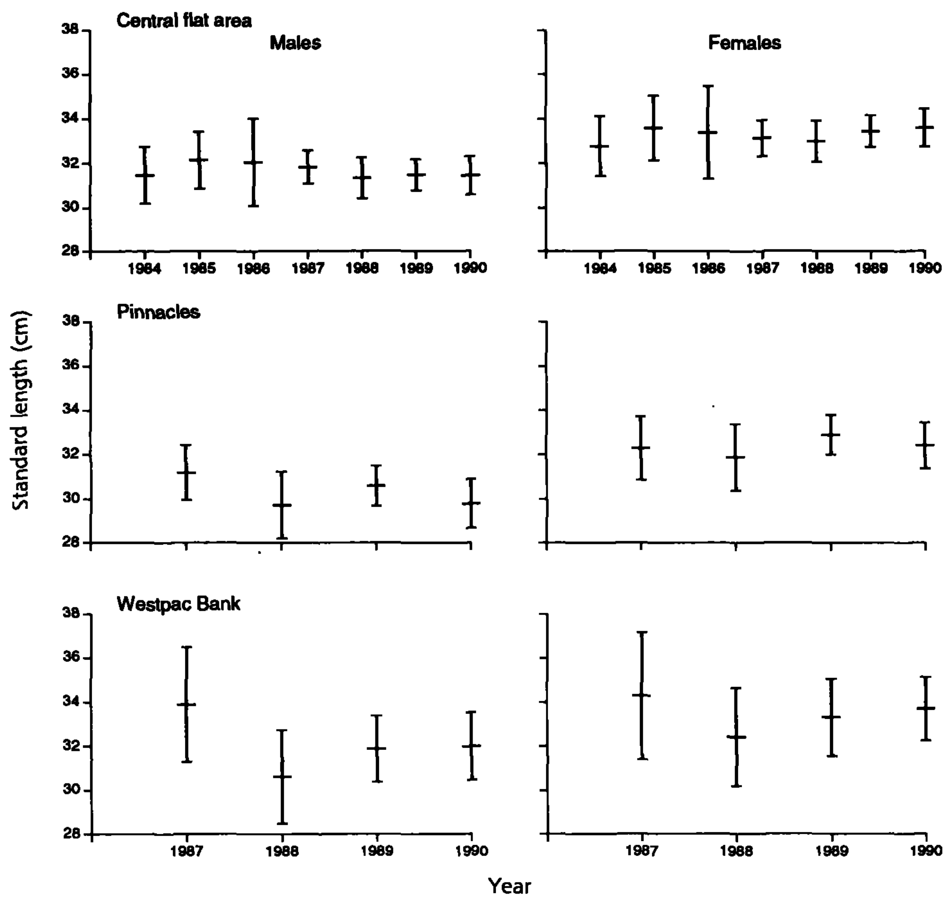

Figure 5
Mean length (±2 standard errors) of orange roughy (*Hoplostethus atlanticus*) by year in the three main spawning areas: Central Flat, Pinnacles, and Westpac Bank.

Flat and Pinnacles. The increase in ripe fish towards the end of the 1990 survey was due largely to sampling the Westpac Bank at this time.

The onset of spawning, defined as the first date on which 20% of fish sampled were spent (after Pankhurst, 1988), has been relatively consistent over the years (Table 11). Actual dates based on females have ranged from 9 July to 16 July.

Size at maturity

Mean lengths at maturity for males and females by year are given in Table 12. There is a significant trend of decreasing mean size for males (linear regression F–test, $P<0.05$), but there is no consistent trend for females.

Feeding

Data on frequency of occurrence of broad taxonomic prey groups from 1984 to 1990 showed the most common prey were natant decapod crustaceans and fish (Table 13).

The main groups that could be identified were macrourids (small species of *Coelorinchus* and *Coryphaenoides*) and myctophids (species of *Lampanyctus* and *Lampanyctodes*). Natant decapod crustacean prey were mainly species in the genera *Pasiphaea*, *Sergestes*, *Oplophorus*, and *Acanthephyra*. Squids and amphipods were also frequent prey.

Discussion

Orange roughy on the Challenger Plateau were overexploited in the late 1980s. Research trawl survey and commercial catch and effort data show similar changes in distribution and abundance. There was a marked contraction in the area of high catch rates,

Table 10

Gonad stage proportions of female orange roughy (*Hoplostethus atlanticus*) by area by year (*n* = sample size; 1 = immature/resting, 2 = early maturation, 3 = maturation, 4 = ripe, 5 = running ripe, 6 = spent).

	Gonad stage						
Area and year	1	2	3	4	5	6	*n*
Central Flat							
1987	0	2.8	81.9	14.7	0	0.6	531
1988	0	1.2	3.4	20.3	17.1	58.0	438
1989	0.3	1.2	20.5	46.5	12.4	19.1	591
1990	0.4	2.0	13.3	41.1	10.0	33.2	460
Pinnacles							
1987	0.4	8.5	74.4	15.9	0	0.8	246
1988	0	5.0	9.9	31.5	14.0	39.6	222
1989	0	1.6	17.6	43.4	7.3	30.1	426
1990	0.3	1.6	10.8	34.9	9.0	43.4	378
Westpac Bank							
1987	0	45.6	50.9	0	0	3.5	57
1988	0	33.7	16.3	32.6	2.3	15.1	86
1989	0	21.4	19.1	35.7	9.5	14.3	84
1990	3.9	15.1	17.5	35.9	8.7	18.9	206

Table 11

Date at which 20% of orange roughy (*Hoplostethus atlanticus*) sampled were spent.

Year	Male	Female
1984	13 July	12 July
1985	8 July	9 July
1986	after 16 July	10 July
1987	before 12 July	10 July
1988	10 July	16 July
1989	20 July	15 July
1990	11 July	9 July

Table 12

Mean length (cm) at maturity and two standard errors (SE), of orange roughy (*Hoplostethus atlanticus*) by sex and year.

	Male		Female	
Year	Length	2 SE	Length	2 SE
1984	27.1	0.54	25.7	0.68
1987	24.4	0.80	24.3	1.02
1988	23.2	1.12	22.7	1.56
1989	23.6	1.16	23.4	1.38
1990	22.3	1.10	24.5	1.00

a reduction in the number of spawning schools, and a marked decline in biomass. Stock reduction analyses have estimated virgin biomass to be about 110,000 t. The stock had declined to about 20% of this by 1991, well below the optimal long-term biomass of 30% of virgin levels predicted by computer modelling under an $F_{0.1}$ fishing strategy (Clark, 1992).

It is clear that the Challenger Plateau spawning population declined rapidly and substantially with commercial fishing in the 1980s. However, it is uncertain exactly how much of the change was directly attributable to the fishery. There are no data on size of the stock prior to its exploitation, so the level of any natural fluctuations in population size and distribution is unknown. It is possible that stock size might have decreased in the absence of any fishing, but it seems very unlikely, given the longevity of orange roughy, that such changes would occur as rapidly as we observed. There could also have been a progressive change in the availability of fish in the area covered by the trawl surveys or bulk of the commercial fleet. Adult orange roughy do not necessarily spawn each year (e.g. Bell et al., 1992; authors' unpubl. data) and hence may not migrate to the general spawning area. In the early years of the fishery, large catches were taken over much of the year, but the period of large catches became progressively reduced to the winter months (Clark, 1991a). This suggests that initially there were resident fish on the grounds, with a migratory component which used the area for spawning only. If this latter group had a variable number of spawners each year, this could have affected how well trawl survey or CPUE data reflected true biomass. However, if this occurred, greater variation in abundance indices between years than observed would be expected. There could also have been other spawning grounds that fish from the 'Challenger stock' used. However, there were no indications of this from either commercial or research survey trawling beyond the main grounds. A further alternative explanation for the observed decline in abundance could be a change in vulnerability to the trawl gear, either by fish residing above the bottom in midwater, or by heavy fishing pressure disrupting existing aggregations or preventing their formation. There is no information on the former (although no fish marks were noted on the echosounder above the bottom during the last two research surveys), but the latter is likely to have occurred (Clark and Tracey, 1991). The effects of fishing on school stability could have resulted in a greater decline in catch rates than true abundance, but reduced stability of schools

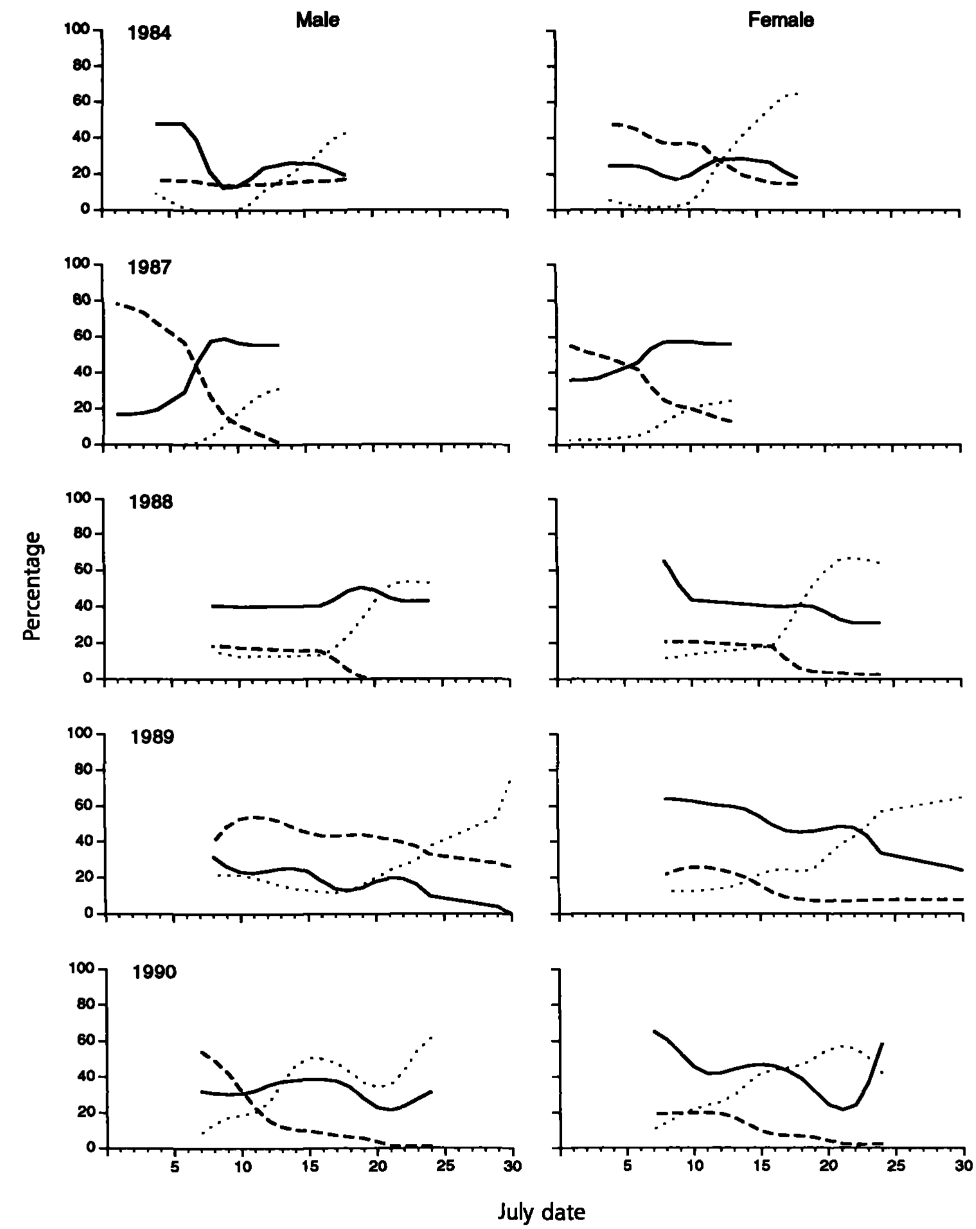

Figure 6
Relative proportions of maturing, ripe, and spent gonads of orange roughy (*Hoplostethus atlanticus*) by day during research surveys in 1984 and 1987–90 (5 day running mean; maturing=dashed line, ripe=solid line, spent=dotted line; maturing=stage-3 male, stage-3 female; ripe=stage-4 male, stages 4 and 5 female; spent=stage-5 male, stage-6 female).

was not observed prior to 1988, and so does not explain the consistent downward trend in CPUE indices. Hence, although alternative hypotheses cannot be discounted, fishing is most likely to have been the major factor in the observed depletion of the stock.

Most other 'bycatch' species also declined in abundance, although changes were relatively minor compared with that of orange roughy. There was no strong indication of any 'species replacement' of orange roughy. The fishery on the Challenger Plateau targets specifically orange roughy, and other species are not caught in large quantities. In the trawl surveys, orange roughy have generally accounted for over 95% of the biomass. The commercial fishery would probably take even less bycatch than the surveys because it focuses on the aggregations which are usually almost exclusively orange roughy. Intuitively, some compensatory increase in other components of the Challenger Plateau community is to be expected because of the extent of orange roughy depletion, but there is no information on biomass, trophic interactions, and productivity of other fish or invertebrate species. In addition, even if most of the other finfish species have higher fecundity and faster growth rates than orange roughy, there could be a relatively long response time to changes in species dominance.

There has been no apparent change in the size structure of the orange roughy population. With heavy exploitation, a truncation of the length frequency distribution and a reduction in the mean size of fish in the population might have been expected, as larger fish were removed and new recruits entered the population. Such changes in size structure of exploited populations are well documented (e.g.

Table 13

Frequency of occurrence of major prey groups of orange roughy (*Hoplostethus atlanticus*) by year.

	1984	1985	1986	1987	1988	1989	1990
Crustacea							
Amphipoda	13.5	7.6	0	6.3	8.0	19.1	5.9
Decapoda/Natantia	53.8	56.1	22.8	44.5	43.0	23.5	34.5
Euphausiacea/Mysidacea	4.3	0.7	13.6	7.7	8.0	2.8	2.3
Crustacean remains/other groups	6.4	5.3	9.1	13.5	9.3	10.0	9.3
Mollusca							
Cephalopoda	14.5	9.1	13.6	10.4	10.6	9.5	7.7
Thaliacea							
Salpidae	—			—	0.3	0.4	0.7
Teleosts	45.7	29.5	40.9	33.1	30.1	36.3	36.6

Smith, 1968; Gulland 1971; Edwards and Bowman, 1979; Grosslein et al., 1980; Rowling, 1990), although none of these studies have dealt with a species as long-lived or slow-growing as orange roughy. The length frequency distribution of spawning orange roughy consists largely of 25–40 cm fish. These sizes are probably fully vulnerable to trawl gear with 100 mm mesh size (legal minimum). Hence, there could be relatively constant fishing mortality across all size groups. There have been no indications of large numbers of new recruits in the length frequency data. This may suggest low levels of recruitment, or at least no entry of any strong year class since 1984 that would reduce mean size.

Interpretation of changes in size structure is also limited by the lack of age data for adult orange roughy. Available ageing data (Mace et al., 1990; MAF Fisheries[3]) for orange roughy suggest a wide range of ages for a given length, and it is possible that age structure may change more rapidly than size structure. Smith et al. (1991) reported a reduction in genetic diversity of orange roughy from several New Zealand areas, including the Challenger Plateau, and suggested this was due to higher mortality of older fish that may remain longer on the spawning grounds than that of younger fish.

Size at maturity showed a significant decline in males, but not in females. It is possible that one sex could be more vulnerable to fishing, but there are no indications of unbalanced sex ratios in commercial catches (authors' unpubl. data). Macroscopic examination of gonads for identification of gonad stage is more reliable in females, where criteria based on colour and size of oocytes are clearer than the presence of milt in male gonads. However, the data may not be representative of true size at maturity in the total population. It is possible that the size at maturity measured here is lower than the true population value because fish that migrate to the spawning grounds are primarily those that are mature, and the relative proportions of immature and mature small fish are not accurately represented.

The apparent lack of change in size at maturity is not surprising in view of the stability of the total population length frequency. An increase in growth rate, with a corresponding reduction in the age at maturity, of individuals in an exploited population is well documented (e.g. Pitt, 1975; Spangler et al., 1977; Borisov, 1978; Hempel, 1978; Leaman, 1991). However, Pitt (plaice, *Hippoglossoides platessoides*, on the Grand Banks) and Leaman (*Sebastes* spp. in the north Pacific Ocean) noted that whereas age at first maturity decreased with exploitation, size at maturity remained the same. Orange roughy are estimated to be about 24 years of age at maturity (Mace et al., 1990), and hence such functional changes in growth rate or maturity may not be obvious after 10 years of fishing, despite a major reduction in population size.

Orange roughy on the Challenger Plateau have consistently spawned in the same general area at the same time of year from 1984 to 1990. The gonad-stage pattern observed in trawl surveys has been similar each year. However, there is evidence of some regional variability in the proportion of fish spawning. The Central Flat and Pinnacles have consistently sustained levels of spawning fish over 90%. On the Westpac Bank this proportion has been lower, and the percentage spawning has progressively increased from 1987 (54%) to 1990 (81%). Reasons for this are not clear. Sample sizes from the Westpac Bank are smaller than those from the other areas but still come from at least six trawls, which should give a representative sample. In 1987 no

[3] MAF Fisheries, unpubl. data, 1993.

actively spawning fish were caught, perhaps because the survey had been taken in June/early July and peak spawning on the Westpac Bank could have occurred slightly later than in the other two areas (Clark, 1991b). Originally it was thought that fish on the Westpac Bank migrated east to the Central Flat and Pinnacles for spawning (Clark and Tracey, 1988). However, in subsequent years ripe and running-ripe fish were found. Nevertheless, in 1987 there was a large proportion of fish that were not spawning that year. It is possible that the Westpac Bank has only developed as a spawning ground since 1987, but if so, whether heavy fishing on the other grounds was a factor is unknown. The biomass index on the Westpac Bank has declined since 1987, so it is unlikely that there has been a major shift of fish from the Central Flat or Pinnacles.

The time of spawning (defined by 20% spent) has consistently been in the second and third weeks of July. Pankhurst (1988) reported that day length was a critical factor in synchronizing the reproductive cycle of orange roughy. The changes in dates of 20% spent between years do not correlate exactly with annual changes in the shortest day, but day length could nevertheless be an important general cue. Gonadal development has remained consistent despite major changes in the size of the population and the spawning school structure. There are indications that heavy fishing pressure may disrupt the stability of schools of orange roughy (Clark and Tracey, 1991). In 1989 when fishing effort was at its peak, a comparatively high proportion of the biomass was in 'background' areas, outside the three main regions of spawning activity. Catch rates in the spawning areas were lower than in other years. It is possible that fishing pressure was affecting the formation of aggregations, but nevertheless reproductive development still occurred normally. However, the success of spawning could have been reduced because the fish were more dispersed.

The diet of orange roughy, and the relative frequency of occurrence of prey groups, were similar over the period examined. Natant decapod crustaceans and fish remains have dominated the diet. This diet composition concurs with other accounts of orange roughy feeding habits in New Zealand waters (e.g. Liwoch and Linkowski 1986; Rosecchi et al., 1988) and is similar to diet composition of orange roughy in the North Atlantic Ocean (e.g. Mauchline and Gordon, 1984; Gordon and Duncan, 1987), Indian Ocean (Kotlyar and Lipskaya, 1981), and off southeastern Australia (Bulman and Koslow, 1992). The trophic effects of the decline in orange roughy biomass are unknown. There is little information on predator–prey relationships within communities containing orange roughy. Published feeding studies and observations from research cruises at different times during the year (authors' unpubl. data) indicate that orange roughy do not prey on eggs or larvae of other fish species. The only published data on predation of orange roughy record them in stomachs of seal shark on the Challenger Plateau (Clark and Tracey, 1988). Sperm whales (*Physeter catodon*) are often observed in orange roughy spawning areas, and although they can dive to depths of over 1000 m. It is uncertain whether they feed on orange roughy.

Orange roughy are slow-growing and long-lived with low productivity, making them highly susceptible to the effects of overfishing. Long-term sustainable yield for the Challenger Plateau stock is estimated at 1.6% of virgin biomass (Clark, 1992). In the early years of a developing fishery catch levels are likely to be high. The schooling behavior of orange roughy for spawning or feeding means that large catches can be taken in a short time, and high catch rates may be maintained despite decreasing biomass. CPUE declined on the Challenger Plateau but not as consistently on the Chatham Rise where the population was also reduced by heavy fishing (Francis et al., 1992), although there was a progressive shortening of the period over which high catch rates occurred (Coburn and Doonan, in press).

In 1986, the TAC on the Challenger Plateau was increased from 6,000 to 10,000 t in order to assess the impact of heavier fishing and to learn more about the productivity of orange roughy. At that stage there was little understanding of stock size, or age and growth characteristics of the species. Hence the intention was to increase catch sufficiently to provide a contrast in abundance indices and give information on the resilience of the stock. However, there were several problems with this 'adaptive management' strategy as applied to Challenger Plateau orange roughy. The first was that it began without good data on the abundance of the stock against which to measure any change. It would have been preferable to have had at least two years of abundance data before increasing fishing pressure. At the time, CPUE had not been examined, and trawl survey results were inadequate to estimate biomass. A new time series of trawl surveys began in 1987, and although the 1988 survey showed a large decrease, with only two survey results we could not be confident about interpreting the differences as a strong decline in stock size. A further difficulty with such management is that with a slow-growing species like orange roughy, potential effects of any changes in spawning stock size on recruitment will not be evident for 20–25 years when the results of that year's spawning recruit to the fishery. Hence, until that time the fishery will be removing only accumulated adult stock and low levels of virgin stock recruitment. A third important feature of adaptive management is the understanding that it can involve high risk to a species like orange roughy. Changes in biomass could occur rapidly and any quota system and industry response must be flexible, so catch levels can be reduced rapidly.

The recovery of orange roughy from heavy fishing may be slow. Their fecundity is low at 20,000–30,000 eggs·kg^{-1} body weight (Pankhurst and Conroy, 1987; Clark and Tracey, 1991). There is no evidence of a marked change in fecundity of Challenger Plateau fish over the period 1987–90 (authors' unpubl. data), but Leaman (1991) reported reduced fecundity in exploited stocks of *Sebastes alutus*, rather than an increase which might have been expected. In addition, Leaman and Beamish (1984) suggested a possible correlation between longevity of a species and the period between strong year classes. Brown et al. (1983) noted that a reduction in population size of several species in the Georges Bank region to low levels (10–20% of peak abundance) was followed by less frequent occurrence of strong year classes.

High vulnerability to fishing and possible slow recovery from over-fishing are important for management of orange roughy fisheries. Data over a comparatively long time period are required to provide a basis for sound management of long-lived species (Leaman, 1991). It is clear with orange roughy on the Challenger Plateau that such species can be overfished in a much shorter time than that required for the desired data collection. Hence, development of an orange roughy fishery needs careful control from the outset. It is important that research occurs in advance of substantial fishing, so that baseline data on distribution, abundance, and biology are collected. The most commonly used techniques for stock assessment of orange roughy (trawl survey, acoustic survey, CPUE analysis) provide relative abundance indices, and therefore require several surveys before absolute biomass can be determined. Results of surveys in other areas, where the relation between survey indices and true biomass has been established, may be useful, but only if gear, bottom type, and fish distribution are similar. Egg production surveys have been carried out in both New Zealand and Australia, and may enable more rapid assessment in some localized areas. 'Adaptive management,' as discussed above, may be appropriate as an aid to estimate biomass by stock reduction methods, but it must be carried out with flexibility in order to change catch levels quickly. If development of the fishery is carefully regulated in the first few years while such data are collected, later management problems such as too many vessels involved in the fishery and the need to quickly and substantially decrease quota levels could be avoided.

Acknowledgments

The authors thank those too numerous to name, who have participated in research cruises over the years which provided the basic data for this study. We also thank Chris Francis and Ian Doonan for statistical advice, Ralph Coburn for some of the commercial data extracts, and Kevin Sullivan and John Annala (all MAF Fisheries) as well as two anonymous journal referees for constructive comments on the manuscript.

Literature cited

Bell, J. D., J. M. Lyle, C. M. Bulman, K. J. Graham, G. M. Newton, and D. C. Smith.
1992. Spatial variation in reproduction, and occurrence of non-reproductive adults, in orange roughy, *Hoplostethus atlanticus* Collett (Trachichthyidae), from southeastern Australia. J. Fish. Biol. 40:107–122.

Borisov, V. M.
1978. The selective effect of fishing on the population structure of species with a long life cycle. J. Ichthyol. 18:896–904.

Brown, B. E., V. C. Anthony, E. D. Anderson, R. C. Hennemuth, and K. Sherman.
1983. The dynamics of pelagic fishery resources off the northeastern coast of the United States under conditions of extreme fishing perturbations. *In* G. D. Sharp and J. Csirke (eds.), Proceedings of the expert consultation to examine changes in abundance and species composition of neritic fish resources. FAO Fish. Rep. 291:465–505.

Bulman, C. M., and J. A. Koslow.
1992. Diet and food composition of a deep-sea fish, orange roughy *Hoplostethus atlanticus* (Pisces: Trachichthyidae), off southeastern Australia. Mar. Ecol. Prog. Ser. 82:115–129.

Clark, M. R.
1991a. Commercial catch statistics for the orange roughy fishery on the Challenger Plateau, 1980–90. N.Z. Fish. Tech. Rep. 27, 11 p.
1991b. Orange roughy fisheries in the mid–Tasman Sea. *In* K. Abel, M. Williams, and P. Smith (eds.), Australian and New Zealand southern trawl fisheries conference. Aust. Bureau of Rural Resources Proc. 10:223–229.

1992. Assessment of the Challenger Plateau (ORH7A) orange roughy fishery for the 1992–93 fishing year. N.Z. Fish. Assess. Res. Doc. 92/6, 13 p. Avail. MAF Fisheries, P.O. Box 297, Wellington, N.Z.

Clark, M. R., and R. I. C. C. Francis.
1990. Revised assessment of the Challenger Plateau (QMA7A) orange roughy fishery for the 1989–90 fishing year. N.Z. Fish. Assess. Res. Doc. 90/1, 17 p. Avail. MAF Fisheries, P.O. Box 297, Wellington, N.Z.

Clark, M. R., and D. M. Tracey.
1988. Report of an orange roughy trawl survey on Challenger Plateau, June–July 1987. N.Z. Fish. Res. Cent. Int. Rep. 86, 87 p. Avail. MAF Fisheries, P.O. Box 297, Wellington, N.Z.
1991. Trawl survey of orange roughy on the Challenger Plateau, July 1990. N.Z. Fish. Tech. Rep. 26, 20 p.

Coburn, R. P., and I. J. Doonan.
In press. Orange roughy fishing on the North East Chatham Rise: a description of the commercial fishery, 1979–1988. N.Z. Fish. Tech. Rep.

Edwards, R. L., and R. E. Bowman.
1979. Food consumed by continental shelf fishes. *In* H. Clepper (ed.), Predator–prey systems in fisheries management, p. 387–405. Sport Fishing Inst., Washington, D.C.

Fenton, G. E., S. A. Short, and D. A. Ritz.
1991. Age determination of orange roughy, *Hoplostethus atlanticus* (Pisces: Trachichthyidae), using 210Pb : 226Ra disequilibria. Mar. Biol. 109:197–202.

Francis, R. I. C. C.
1981. Stratified random trawl surveys of deep-water demersal fish stocks around New Zealand. N.Z. Fish. Res. Div. Occas. Pub. 32, 28 p.
1984. An adaptive strategy for stratified random trawl surveys. N.Z. J. Mar. Freshwater Res. 18:59–71.
1990. A maximum likelihood stock reduction method. N.Z. Fish. Assess. Res. Doc. 90/4, 12 p. Avail. MAF Fisheries, P.O. Box 297, Wellington, N.Z.
1992. Use of risk analysis to assess fishery management strategies: a case study using orange roughy (*Hoplostethus atlanticus*) on the Chatham Rise, New Zealand. Can. J. Fish. Aquat. Sci. 49: 922–930.

Francis, R. I. C. C., D. A. Robertson, M. R. Clark, and R. P. Coburn.
1992. Assessment of the ORH 3B orange roughy fishery for the 1992/93 fishing year. N.Z. Fish. Assess. Res. Doc. 92/4, 45 p. Avail. MAF Fisheries, P.O. Box 297, Wellington, N.Z.

Gordon, J. D. M., and J. A. R. Duncan.
1987. Aspects of the biology of *Hoplostethus atlanticus* and *H. mediterraneus* (Pisces: Berycomorphi) from the slopes of the Rockall Trough and the Porcupine Sea Bight (North-Eastern Atlantic). J. Mar. Biol. Ass. U.K. 67:119–133.

Grosslein, M. D., R. W. Langton, and M. P. Sissenwine.
1980. Recent fluctuations in pelagic fish stocks of the Northwest Atlantic, Georges Bank region, in relation to species interactions. Rapp. P.-v. Réun. Cons. int. Explor. Mer 177:374–404.

Gulland, J. A.
1971. Ecological aspects of fishery research. Adv. Ecol. Res. 7:115–176.

Gunderson, D. R.
1977. Population biology of Pacific ocean perch, *Sebastes alutus*, stocks in the Washington-Queen Charlotte Sound region, and their response to fishing. Fish. Bull. 75:369–403.

Hempel, G.
1978. North Sea fisheries and fish stocks: a review of recent changes. Rapp. P.-v. Réun. Cons. int. Explor. Mer 173:145–167.

Kotlyar, A. N., and N. Y. Lipskaya.
1981. Feeding of *Hoplostethus atlanticus* Collett (Trachichthyidae, Beryciformes). *In* Fishes of the open ocean, p. 89–93. Inst. Oceanology, Academy of Sciences USSR, Moscow.

Leaman, B. M.
1991. Reproductive styles and life history variables relative to exploitation and management of *Sebastes* stocks. Env. Biol. Fish. 30:253–271.

Leaman, B. M., and R. J. Beamish.
1984. Ecological and management implications of longevity in some Northeast Pacific groundfishes. Int. North Pac. Fish. Comm. Bull. 42:85–97.

Liwoch, M., and T. B. Linkowski.
1986. Some biological features of orange roughy *Hoplostethus atlanticus* (Trachichthyidae) from New Zealand waters. Pr. morsk. Inst. ryb. Gdyni 21:27–41.

Mace, P. M., J. M. Fenaughty, R. P. Coburn, and I. J. Doonan.
1990. Growth and productivity of orange roughy (*Hoplostethus atlanticus*) on the north Chatham Rise. N.Z. J. Mar. Freshwater Res. 24:105–119.

Mauchline, J., and J. D. M. Gordon.
1984. Occurrence and feeding of berycomorphid and percomorphid teleost fish in the Rockall Trough. J. Cons. int. Explor. Mer 41:239–247.

Pankhurst, N. W.
1988. Spawning dynamics of orange roughy, *Hoplostethus atlanticus*, in mid-slope waters of New Zealand. Env. Biol. Fish. 21:101–116.

Pankhurst, N. W., and A. M. Conroy.
1987. Size-fecundity relationships in the orange roughy, *Hoplostethus atlanticus*. N.Z. J. Mar. Freshwater Res. 21:295–300.

Pankhurst, N. W., P. J. McMillan, and D. M. Tracey.
1987. Seasonal reproductive cycles in three commercially exploited fishes from the slope waters off New Zealand. J. Fish Biol. 30:193–212.

Pauly, D.
1979. Theory and management of tropical multi-

species stocks. A review, with emphasis on the Southeast Asian demersal fisheries. ICLARM Stud. Rev. 1.

Pearson, E. S., and H. O. Hartley (eds.).
1976. Biometrika tables for statisticians. 2 vols. Cambridge Univ. Press, Cambridge.

Pitt, T. K.
1975. Changes in abundance and certain biological characteriplatessoides.stics of Grand Bank American plaice, *Hippoglossoides platessoides*. J. Fish. Res. Board Can. 32:1383–1398.

Regier, H. A., and K. H. Loftus.
1972. Effects of fisheries exploitation on salmonid communities in oligotrophic lakes. J. Fish. Res. Board Can. 29:959–968.

Robertson, D. A.
1991. The New Zealand orange roughy fishery: an overview. *In* K. Abel, M. Williams, and P. Smith (eds.), Australian and New Zealand southern trawl fisheries conference. Aust. Bureau of Rural Resources Proc. 10:38–48.

Rosecchi, E., D. M. Tracey, and W. R. Webber.
1988. Diet of orange roughy, *Hoplostethus atlanticus* (Pisces: Trachichthyidae) on the Challenger Plateau, New Zealand. Mar. Biol. 99:293–306.

Rowling, K. R.
1990. Changes in the stock composition and abundance of spawning gemfish *Rexea solandri* (Cuvier), Gempylidae, in southeastern Australian waters. Aust. J. Mar. Freshwater Res. 41:145–163.

Russ, G. R., and A. C. Alcala.
1989. Effects of intense fishing pressure on an assemblage of coral reef fishes. Mar. Ecol. Prog. Ser. 56:13–27.

SAS.
1988. SAS/STAT Users Guide, Release 6.03 ed. SAS Institute, Cary, NC.

Smith, P. J., R. I. C. C. Francis, and M. McVeagh.
1991. Loss of genetic diversity due to fishing pressure. Fish. Res. 10:309–316.

Smith, S. H.
1968. Species succession and fishery exploitation in the Great Lakes. J. Fish. Res. Board Can. 25:667–693.

Spangler, G. R., N. R. Payne, J. E. Thorpe, J. M. Byrne, H. A. Regier, and W. J. Christie.
1977. Responses of percids to exploitation. J. Fish. Res. Board Can. 34:1983–1988.

Tracey, D. M., P. J. McMillan, J. H. Armstrong, and D. A. Banks.
1990. Orange roughy trawl survey: Challenger Plateau and west coast South Island, 1983. N.Z. Fish. Tech. Rep. 22, 34 p.