Development of estimates of biomass and sustainable catches for orange roughy fisheries in the New Zealand region outside the EEZ: CPUE analyses, and application of the “seamount meta-analysis” approach

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EXECUTIVE SUMMARY

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This report describes two approaches to estimate sustainable catch limits for orange roughy fisheries, and seamount features, for areas outside the New Zealand EEZ on the West Norfolk Ridge, Lord Howe Rise, Northwest Challenger Plateau, and Louisville Ridge.

Standardised catch per unit effort (CPUE) analyses were carried out using tow by tow data between 1992–93 and 2006–07. The analyses fitted a generalised linear model to CPUE, using a step-wise multiple regression technique. Two sets of analyses were carried out: one on the combined dataset, where fishing ground was a variable within the model; and secondly a series of sensitivity analyses on more selective data from each fishing ground separately.

Trends differed between areas. The South Tasman Rise showed a sharp decline over three years; there was an initial steep decline in CPUE for the West Norfolk Ridge, followed by five years of stable or perhaps increasing CPUE. The CPUE declined for Louisville Central and Louisville North to about one-quarter and one-third respectively of the initial levels. The CPUE for the Northwest Challenger subarea was variable, with perhaps a slow increase overall, a peak in 2001–02, and little change since 2002–03. There was no clear trend for Louisville South, nor for Lord Howe Rise,

It is concluded that standardised CPUE indices of orange roughy from New Zealand fisheries on the High Seas are dubious as indices of stock abundance. The CPUE data for all subareas showed evidence of sequential fishing of locations, suggesting the overall CPUE may be biased upwards over time, with high catch rates being maintained by sequential movement to new fishing areas. Some CPUE trends were also sensitive to the data selection criteria such as fishery spatial extent, length of tow, or vessel selection criteria. Trends in biomass from sensitivity analyses of data subsets differed from those estimated from the overall analysis for some areas, possibly because the application of data selection criteria resulted in a smaller data set with more intermittent catches and effort, and describing less of the catch.

A second, very different, approach was attempted, whereby the regression formulae derived from an earlier "Seamounts Meta-analysis" that related unexploited orange roughy biomass to physical characteristics of a seamount, were applied to seamount data. In the present study a total of 59 seamounts were analysed. The physical variables used in the analysis were latitude, geological association, depth at summit, and estimated slope.

The total estimated virgin biomass predicted by the model for these seamounts was about 84 000 t. Seamounts with the highest predicted biomass were on the Louisville Ridge, with lower biomass in other areas. For the West Norfolk Ridge and two regions within the Louisville, seamounts were included which may be outside the geographical area where orange roughy occur in high densities. Excluding these seamounts reduced the estimated biomass to 70 000 t. The estimated Region Effect has a major influence on results from the meta-analysis approach, and uncertainties of the estimates are discussed. An updated analysis using more seamounts with a longer catch history could improve the reliability of the method.

Indicative levels of long-term sustainable yields (MCY and MAY) for the areas are given based on the virgin biomass estimates

1. INTRODUCTION

1.1 General overview

Orange roughy fisheries in the New Zealand region outside the EEZ developed in the mid 1980s on the southwest Challenger Plateau as an extension of the fishery within the EEZ on the Challenger Plateau and extended further in the late 1980s early 1990s to the Lord Howe Rise, Northwest Challenger Plateau, and the Louisville Ridge. In the late 1990s, areas on the South Tasman Rise and West Norfolk Ridge were fished. Further afield, New Zealand vessels in the past have also been involved in fishing for orange roughy in the mid Pacific, southern Atlantic, and southern Indian Oceans (Clark 2008).

Many of these fishing grounds are in an area which is covered by the proposed convention area of the developing South Pacific Regional Fisheries Management Organisation (SPRFMO). A number of meetings have been held to establish SPRFMO and its fisheries management policies and measures. Interim bottom fishing conservation and management measures adopted at the 3rd negotiation meeting on the establishment of SPRFMO, held in Chile, in April-May 2007 require participants in bottom fisheries in the SPRFMO area to:

- "Limit bottom fishing effort or catch in the Area to existing levels in terms of the number of fishing vessels and other parameters that reflect the level of catch, fishing effort, and fishing capacity", and further to implement measures to:
- "...establish conservation and management measures to prevent significant adverse impacts ... the long-term sustainability of deep sea fish stocks".

NIWA and MFish have jointly undertaken descriptions of New Zealand catch and effort in fisheries within the SPRFMO area (Penney et al. 2007). Currently, to meet the first interim obligation, New Zealand is considering options for implementing interim limits on catch of the main target species, based on average catch over the defined window period from which to estimate past performance, 2002–06. Given the low productivity of orange roughy stocks and the past history of rapid decline of many orange roughy fisheries, it is uncertain whether catch limits at recent historic average levels will be sustainable. This is particularly the case in areas only recently fished, and so, to meet the longer term obligation of ensuring sustainability of deep sea fish stocks, these interim limits may have to be set at relatively low levels, below historical maximum annual catches, to ensure sustainability of the stocks. Such limits will also need to be internationally agreed to and implemented across all participants to ensure that overall TACs are not exceeded. New Zealand agencies therefore need to work towards developing principles upon which to base such limits, to support development of catch limit proposals for tabling and implementation by the future SPRFMO process. Initially, emphasis is being placed on the bottom trawl fishery for orange roughy, which has contributed 75% of the total New Zealand bottom trawl catch in the SPRFMO area over this period.

Exploratory fishing for deepwater commercial species around New Zealand is to a large extent focused on seamounts and other seabed topographic features, where orange roughy (*Hoplostethus atlanticus*) and oreos (black oreo, *Allocyttus niger*, and smooth oreo, *Pseudocyttus maculatus*) often aggregate. It is estimated that over 60% of orange roughy catch, and 50% of oreo catch, has been taken off seamount features (Clark & O'Driscoll 2003, O'Driscoll & Clark 2005). However, in some areas the stocks, especially those which originally had dense aggregations, have been rapidly depleted and most orange roughy fisheries have declined (Clark 1999, Francis & Clark 2005). Seamounts are also widely regarded as being fragile habitat (Rogers 1994, Clark et al. 2010), and susceptible to both overfishing and benthic habitat damage, requiring careful management in the initial stages of fishery development to reduce the risks of uncontrolled spread of effort and possible overexploitation of low productivity resources. Designing and carrying out appropriate abundance surveys on seamounts can be lengthy, expensive, and complicated. However, fish stocks on such features may be small and localised and such research surveys are typically not cost-effective. Catch per unit effort analyses can be useful, but may also be limited or biased if orange roughy aggregations are variable (e.g., Clark 2006). For these reasons trends in existing and historical seamount fisheries around New Zealand, together with information on their physical characteristics to support habitat classification and biomass prediction models, may provide the most cost-effective way of estimating initial precautionary sustainable catch levels until more is known about the nature of each specific fishery and seamount stock.

1.2 Objectives

The specific objectives of this work carried out under the Ministry of Fisheries research project IFA2008-05 were two-fold.

1. To analyse historic catch and effort data for New Zealand bottom trawl catches of orange roughy in the high-seas Challenger Plateau, Lord Howe Rise (North and South areas), West Norfolk Ridge, Three Kings Ridge, and Louisville Ridge (North, Central and South areas), to develop estimates of likely annual sustainable orange catches in these respective fishing areas.
2. To use seabed bathymetry and information on the capacity of specific seabed features, groups of features or sub-areas to sustain particular biomasses of orange roughy, to develop recommendations on appropriate limits for features or specific defined sub-areas, that will contribute to prevention of over-fishing of the above fishing areas.

This report addresses estimation of sustainable catch limits in two ways: firstly, standardised catch per unit effort analyses are carried out where data were suitable. The methods and results of this work are presented in Section 2. Secondly, information on the physical characteristics of seamount features (defined here as topographically distinct seafloor features with an elevation of 100 m or more (after Pitcher et al. 2007)) were used to predict potential orange roughy stock size. This work is presented separately, in Section 3.

2. ANALYSES OF CATCH PER UNIT EFFORT

2.1 The interpretation of catch–per–unit–effort (CPUE) for orange roughy

The use of CPUE as an index of vulnerable biomass has been considered undesirable for orange roughy, but has nevertheless continued to be used (Ministry of Fisheries 2009). CPUE has been used where other information on biomass trends is unreliable or unavailable. Using CPUE as a biomass index for orange roughy is undesirable for several reasons, including the following.

1. Orange roughy form predictable aggregations, for both spawning and feeding. The fishery prefers to target these aggregations, where large catches can be taken in a short time. When fishing on large spawning plumes, gear saturation may take place, or fisher behaviour may deliberately modify (limit) the catches, for example to avoid net damage. The catch rates from a large aggregation can be maintained, even though the overall size of the aggregation may be declining. Under these circumstances, catch rates will be biased, and not related to biomass. Nevertheless, commercial catch rates of orange roughy in the spawning plumes in the Chatham Rise Spawning Box did (eventually) decline substantially as the resource was fished down (Figure 1).

2. In an attempt to maintain profitable catch rates, areas have been fished and apparently depleted sequentially (Clark 1999, Anderson & Dunn 2008). In this way, catch rates are maintained by movement from one area to another, giving the overall appearance of a stable

catch rate. When this takes place, neither local nor overall catch rates are likely to be proportional to total stock biomass (Walters 2003). In an attempt to reduce this potential bias, and where there are sufficient data, some previous analyses of orange roughy CPUE have selected data to include only consistently fished locations (e.g., Mormede 2009).

3. The performance of fishing gear will be spatially and temporally inconsistent, varying for example with bottom type, fishing technique, the fishing crew, and fishing gear development. On hills, trawls may bounce or temporarily come fast; this may vary with tow location and skipper ability, and will influence catch rates. Few analyses to date have accounted for fishing gear development, and this so called 'technology creep' could introduce a substantial bias in CPUE (Marchal et al. 2007). Doonan et al. (2009) did account for the increase in black oreo catch rates associated with the advent of GPS by splitting the CPUE into pre- and post-GPS indices.

It may be that CPUE indices reflect trends in local biomass, but it is less certain that they index total biomass. The initial steep declines in CPUE seen in many fisheries (see Figure 1) are too rapid to be indexing total stock abundance (Dunn 2006, 2007a). This problem is not unique to orange roughy, but has also been encountered in other deep sea fisheries, targeting black cardinalfish (e.g., Dunn 2009), black oreo (e.g., Doonan et al. 2009), and smooth oreo (e.g., McKenzie & Coburn 2009).

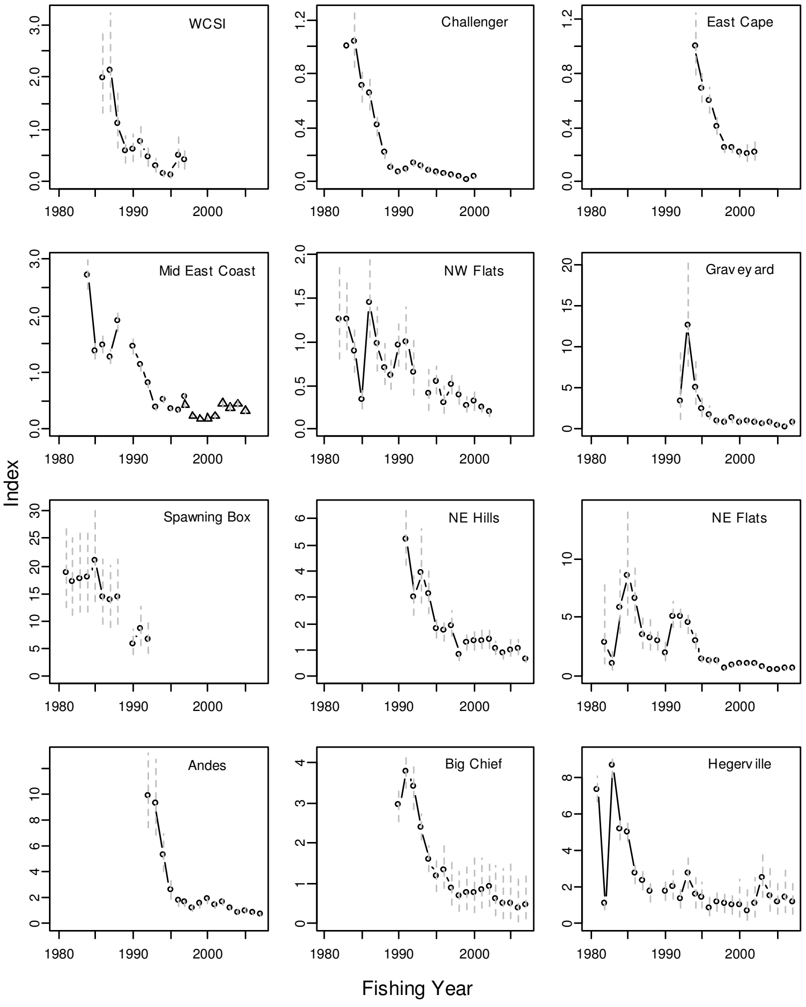

Figure 1: Orange roughy standardised CPUE indices (circles with vertical lines showing 95% confidence intervals) from the commercial fisheries at various locations within the New Zealand EEZ (indices from Mormede (2009) and Ministry of Fisheries (2009)).

Although CPUE is generally considered unreliable, and the initial declines are not proportional to total stock abundance, the CPUE indices for the main non-spawning fisheries on the east and south Chatham Rise have been remarkably similar since the mid 1990s (Figure 2, Table 1), despite their geographic separation. The correlations between the indices (Table 1) suggest they are measuring a similar thing. If they are measuring vulnerable biomass, then we would conclude that these local areas must all be indexing the same wider stock (NIWA, unpublished results). Similarly, the common observation of a rapid initial decline in CPUE across many different fisheries (see Figure 1) suggests a common process is taking place, where CPUE is presumably declining in response to a decline in the amount of vulnerable biomass.

Orange roughy CPUE patterns do therefore appear to be related to biomass in some way, and so may contain valuable biomass signals. However, they may not be proportional to overall stock biomass, and therefore must be interpreted with care.

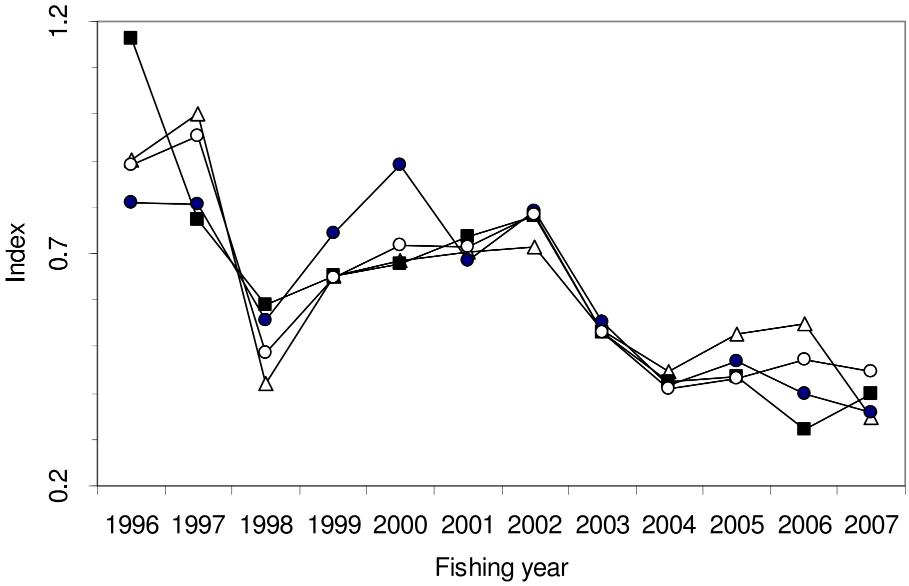

Figure 2: Orange roughy standardised CPUE indices from the commercial fisheries on the East and South Chatham Rise (see Table A1.1). Indices have been scaled to the mean (indices from Mormede (2009)). ■, Chiefs; △, NE hills; •, Andes; ○, NE flats.

Table 1: Pearson's product-moment coefficient estimated for standardised CPUE indices for subareas of the east and south Chatham Rise, for 1995–96 to 2005–07 (indices from Mormede 2009).

	NE Hills	NE Flats	Andes	Chiefs
NE Hills	–	–	–	–
NE Flats	0.93	–	–	–
Andes	0.91	1	–	–
Chiefs	0.86	0.97	0.96	–

2.2 Data sources and grooming

The data set used in CPUE analyses was groomed bottom trawl catch and effort data covering 1980–81 to 2007–08. Data for 1980–81 to 2004–05 were groomed under previous MFish contracts, including project IFA2007-02 (Development of a Draft SPRFMO Benthic Assessment Standard). Data for 2005–06 to 2007–08 were obtained from MFish databases and groomed during this project. The data were from the "high seas" versions of the Catch Effort and Landings Return forms, which provide tow-by-tow information, with location and estimated catch for each trawl. In addition, details of the corresponding vessel specifications were provided by MFish, and included a time series of records of vessel length, engine-power, and tonnage.

Error checks were performed for the following data fields:

- Bottom depth (where more than 1300 m or less than 500 m)
- Fishing effort depth (in comparison with *bottom depth*)
- Position (for large differences between start and finish position, and for estimated steaming speed between tow locations)
- Trawl speed (where more than 5 kt or less than 1.5 kt)
- Tow duration (where more than 10 hours)
- Tow distance (where more than 30 nautical miles)
- Target species (where not a deepwater bottom trawl target species)
- Vessel nationality (NZ vessels only. If none recorded then assumed to be domestic)
- Time of day

Missing or erroneous values were replaced, where possible, with imputed average values. For example, (1) where depth was missing it was replaced with the mean depth from all other tows recorded within 1 n.mile of that tow position; (2) where tow length calculated using given positions was greater than 30 n.mile, and speed calculated from distance and duration was greater than 5 knots, the tow positions were replaced with the median values for that vessel and day (this would allocate the vessel to roughly the right area); (3) where tow speed appeared to be an error, it was replaced with the median tow speed for that vessel on that day. Records containing errors that could not be corrected in this way were excluded from further analyses. Data fields were edited for less than 1% of the records.

2.3 Definition of fishery areas

The areas used to subset analyses were those defined by Clark (2008). The Northwest Challenger Plateau core area included only the northern flank of the Challenger Plateau (166–170°E and 36.8–38°S). The West Norfolk Ridge fishery straddled the EEZ, as presumably does the orange roughy stock fished by that fishery, so the fishery inside the EEZ was also included in this area. The area was defined by a polygon, having longitudes (°E) of 170.547, 170.547, 168.767, 167.051, 165.716, 165.526, 168.513, 168.704, 168.767, 169.721, and 170.483, paired with latitude (°S) of 34.852, 35.940, 35.631, 34.381, 32.890, 30.849, 30.958, 32.472, 33.644, 34.224, 34.852, and 34.852.

2.4 Analyses

In order to examine spatial and temporal patterns in the fishery, each tow was first allocated to an area of 1/10th degree longitude and latitude. The total catch in each area and year was then summed. The y-axis (area) of a plot of catch by year and area was ordered by the arithmetic mean year for each area. When plotted in this way, sequential fishing of areas produces a diagonal band across the plot. Similar plots were completed for nominal effort (number of tows), and unstandardised CPUE (tonnes per tow).

Standardised CPUE analyses used only tows where orange roughy catch was greater than zero. It was therefore assumed that zero catch tows did not contain any information about abundance (they might reflect catch reporting behaviour instead). Fishing years before 1992–93 were excluded from the analyses because there were insufficient data. Records were also excluded if potential CPUE predictor fields used in the standardisation were not available.

Continuity rules were applied to the data selection in order to adequately estimate categorical predictor effects over time in the model. The only categorical predictor accepted into the models was *vessel*. The vessel continuity rule used specified that, to be included in the data set, there must have been at least three years with 10 or more non-zero catch tows per year for each *vessel*. This criterion was relaxed to two years of five or more tows for a sensitivity run for Lord Howe Rise.

The standardised CPUE analyses were carried out by fitting a generalised linear model to CPUE, using the stepwise multiple regression technique described by Francis (2001). The units of CPUE used were tonnes per tow (t/tow), and the dependent variable was log(t/tow). The GLM assumed a normal error distribution and identity link function. The predictor variable *fishing year* was forced into the model, and other potential predictors tested for inclusion, including interactions between predictors (Table 2). A stepwise forward procedure was used to select predictors, and they were entered into the model in the order which gave the maximum decrease in the Akaike Information Criterion (AIC). Predictors were also only accepted into the final model if they explained at least 1% of the deviance and their predicted effects were sensible (i.e., the effect of the variable on CPUE was in the direction expected).

Table 2: Potential predictor variables included in the standardised CPUE analysis.

Variable	Type	Comment	Variable	Type	Comment
Fishing year	Categorical	Forced into the model	Tow distance	3rd or 4th order polynomial	–
Vessel	Categorical	Vessel key	Tonnage	3rd or 4th order polynomial	Gross tonnage of vessel
Month	Categorical	–	Tow type	Categorical	Duration <30 minutes (short) or long. May alias for tows on the hill or flat.
Fishing day	3rd or 4th order polynomial	Day of the fishing year	Bottom depth	3rd or 4th order polynomial	–
Time	3rd order polynomial	Time of day tow was shot	Longitude	3rd order polynomial	Start longitude
Tow speed	3rd order polynomial	–	Subarea	Categorical	Areas defined by Clark (2008)
Latitude	3rd order polynomial	Start latitude	Subarea.2	Categorical	Areas as Clark (2008) except all Louisville a single area
Tow duration	3rd or 4th order polynomial	–			

2.5 Results

2.5.1 CPUE indices

The estimated orange roughy catches in the data set were compared against those in Ministry of Fisheries (2009). The data set catches were similar for most years, but were relatively low before 1992–93, in 1997–98, and 1999–2000 when a number of non-New Zealand registered vessels made large catches which are not included in the New Zealand catch and effort database. It is uncertain why they were also low in 2007–08, and relatively high in 1998–99 (Table 3). In the subsequent analyses the years before 1992–93, and 2007–08, were excluded because they were relatively incomplete. The data selection criteria for the CPUE analyses did not reduce the data set much, except for 1992–93, 1995–96, and 2004–05 (Table 3).

Table 3: Estimated catches from Ministry of Fisheries (2009) (a) compared to the estimated catches in this data set (b), and in the data set used for standardised CPUE analyses (c). Fishing years run from 1 October to 30 September, and are indicated by the year ending (e.g., 1999 means the 1998–99 fishing year). "–", zero tows.

Fishing year	(a) Estimated catches	(b) This data set	(b) / (a)	(c) CPUE analysis data set	(c) / (b)
1981	–	19	–	–	–
1982	–	50	–	–	–
1983	–	70	–	–	–
1984	–	14	–	–	–
1985	–	–	–	–	–
1986	–	4	–	–	–
1987	–	3	–	–	–
1988	4 005	4	0.00	–	–
1989	2 727	1 036	0.38	–	–
1990	1 352	148	0.11	–	–
1991	405	53	0.13	–	–
1992	1 479	711	0.48	–	–
1993	4 763	3 825	0.80	1 359	0.36
1994	3 260	2 459	0.75	1 710	0.70
1995	15 151	12 109	0.80	10 250	0.85
1996	9 321	9 022	0.97	3 966	0.44
1997	3 685	3 590	0.97	2 486	0.69
1998	5 757	2 532	0.44	2 311	0.91
1999	5 270	5 435	1.03	4 054	0.75
2000	6 004	1 834	0.31	1 559	0.85
2001	4 094	2 731	0.67	2 593	0.95
2002	3 729	3 284	0.88	3 146	0.96
2003	2 782	2 446	0.88	2 331	0.95
2004	2 490	2 133	0.86	2 117	0.99
2005	2 736	2 300	0.84	1 479	0.64
2006	1 855	1 151	0.62	1 030	0.90
2007	1 011	708	0.70	708	1.00
2008	858	252	0.29	–	–

There was intermittent fishing over a relatively wide high seas area before 1992–93 (Figure 3). After 1992–93 there was a sequential fishing of areas. There were a number of areas fished where catches of orange roughy were not taken (areas above about 760 in Figure 3). There were a few areas where relatively large catches were taken for more than three years, although these years were not always consecutive. The spatial progression was less pronounced in effort than catch, and there was relatively high effort continuing for several years in many areas, without a similar continuation in orange roughy catches.

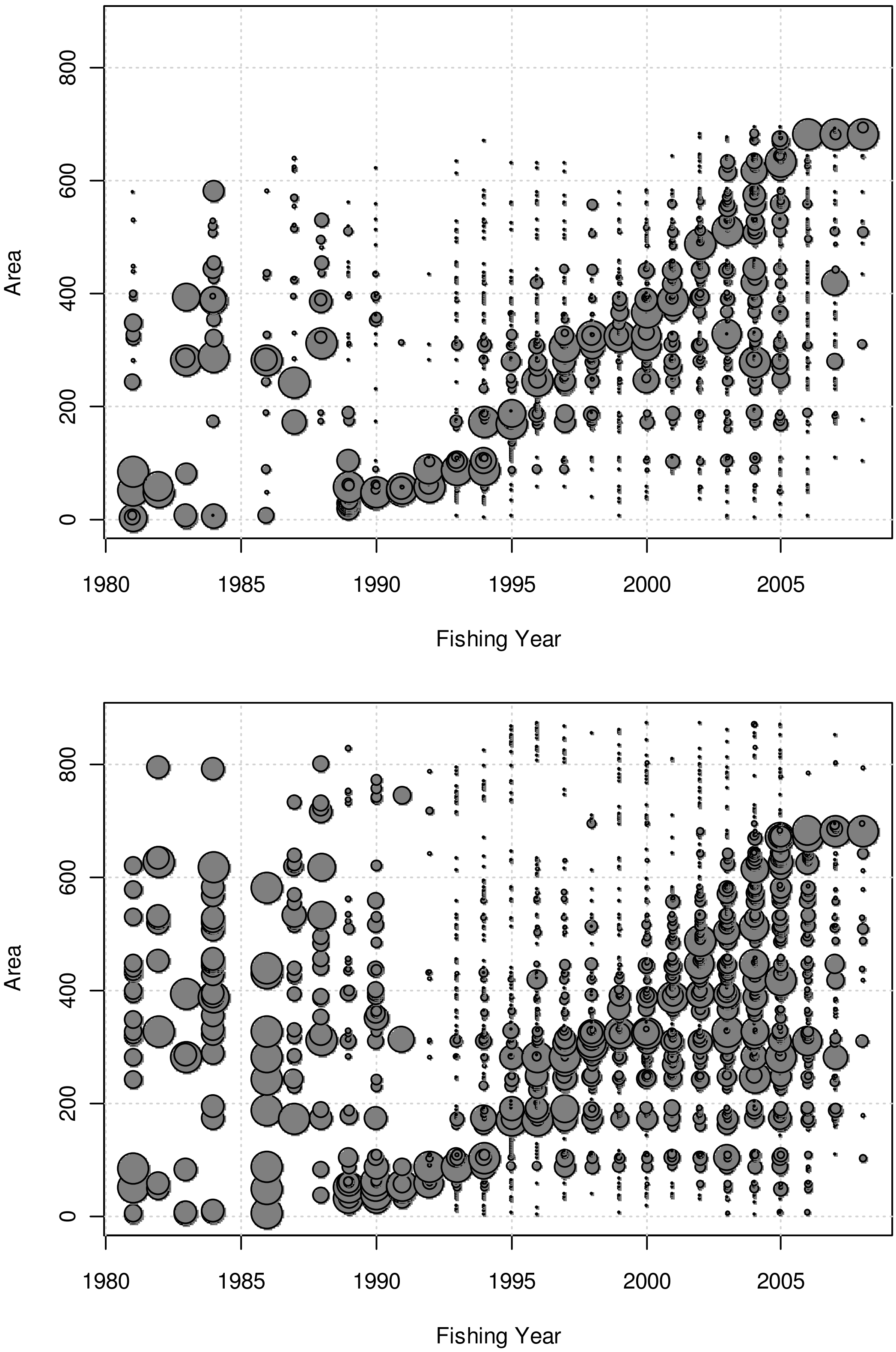

Figure 3: The distribution of orange roughy estimated catch (top panel) and effort (number of tows, bottom panel) by fishing year and area (where area is a square of 1/10th of a degree latitude and longitude) for the total High Seas fishery. Catch and effort are proportional to circle size; each year sums to 1. Areas were ordered, in both plots, by the mean year in which the catch was taken.

The serial spatial progression of the fishery was highly pronounced for unstandardised catch rate, particularly after about 1990, and areas with peak catch rates were rarely the same for more than two consecutive years (Figure 4).

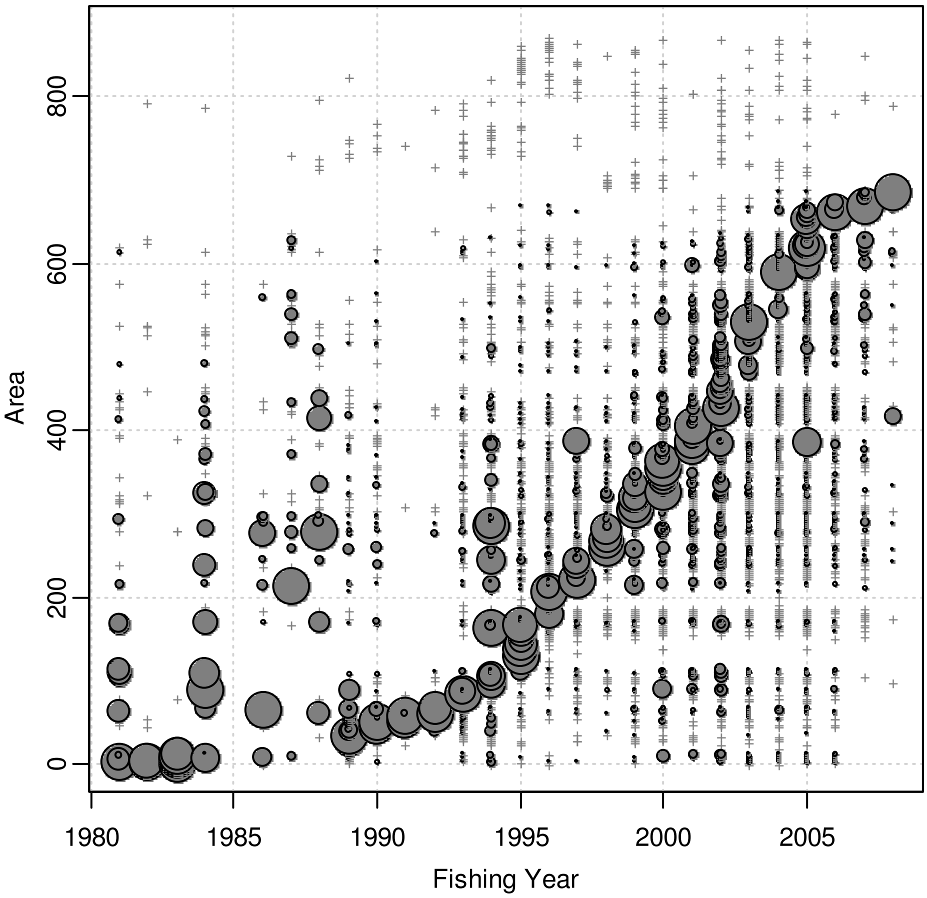

Figure 4: The distribution of orange roughy unstandardised median catch rate (t/tow) by fishing year and area (where area is a square of 1/10th of a degree latitude and longitude) for the total High Seas fishery. Catch rates are proportional to circle size; each year sums to 1. Crosses indicate areas where effort took place but no catch was taken. Areas were ordered by mean year in which the catch was taken (see Figure 3).

After data grooming and applying the data selection criteria, the initial data set of 24 077 tow records was reduced to 20 517 records (85.8%), and the estimated catch reduced from 49 008 t to 41 099 t (85.2%). Thirty-six vessels were included in the data set, with good inter-annual overlap between vessels (Table 4). Data also covered the seven subareas with good overlap (Table 5).

Preliminary runs showed that if the vessel selection criteria were made more stringent, for example 5 years of 10 or more tows per vessel per year, the predictors selected in the final model, and their order, did not change. The percentage of data included in the model decreased with increasingly stringent vessel selection criteria, to 77.2% of catch and 73.6% of the number of tows, when using 5 years of 10 or more tows per year. However, the different vessel selection criteria made virtually no difference to the CPUE trend, or to the percentage of the deviance explained by the model. As a result, the 3 years and 10 or more tows per year criterion was kept as it retained more of the data.

The number of vessels and fishing effort (number of tows) peaked in early 2000s, and were lowest in 2006–07 (Table 6). The greatest catch and catch rates were earlier, in 1994–95. Median tow duration was typically short (less than 1 h) except between 2000–01 and 2005–06 with median tow duration reaching 3.3 h in 2005–06. The median catch high-seas rates of less than 0.5 t/tow were low compared with established fisheries inside the zone, which were typically greater than 1 t/tow or 1.5 t/h (Anderson & Dunn 2008). Most of the catch was taken between June and August, which would be consistent with a spawning fishery, provided spawning had the same timing in these areas as found inside the EEZ. The focus of fishing effort around the expected spawning times was most pronounced in 1992–93, 1996–97, 1998–99, and 2003–04 to 2006–07 (Figure 5).

Table 4: Tows by vessel key and fishing year as used for the orange roughy standardised CPUE index, after application of the data selection criteria. Fishing years run from 1 October to 30 September, and are indicated by the year ending (e.g., 1999 means the 1998–99 fishing year). "–", zero tows.

Vessel key	1993	1994	1995	1996	1997	1998	1999	2000
10223	118	479	116	10	-	-	-	-
10142	74	104	375	-	-	-	-	-
10244	-	33	152	1	65	-	-	-
10235	-	352	185	232	243	115	-	-
10221	108	13	148	170	1	31	87	-
10173	49	33	104	2	8	18	57	5
10238	-	16	140	-	104	-	-	-
10232	-	12	250	343	99	25	53	-
10250	-	-	13	78	14	-	6	-
10024	-	-	82	277	99	69	146	164
10234	-	141	114	59	101	35	38	30
10121	-	-	288	80	-	1	41	33
9913	-	-	-	94	77	19	95	48
10245	-	34	95	-	20	-	43	93
10083	-	-	97	24	7	111	11	-
12095	-	-	-	-	-	1	106	38
10236	-	125	290	81	141	122	143	273
10020	125	-	115	-	-	82	-	-
8804	-	-	-	77	78	-	39	144
10237	-	-	42	37	-	23	117	-
13106	-	-	-	-	-	12	21	66
10067	-	-	-	-	-	-	-	-
10021	-	-	49	-	-	-	-	-
9259	-	-	-	-	-	-	62	-
15180	-	-	-	-	-	-	-	-
10208	26	4	10	-	-	-	68	85
6618	-	-	-	-	-	-	-	52
10231	24	-	-	-	-	-	-	-
6473	-	-	-	-	1	-	-	-
15561	-	-	-	-	-	-	-	-
10260	-	-	-	-	-	-	-	-
10241	-	-	-	-	-	-	-	-
10155	-	-	-	-	-	-	-	-
10135	-	-	-	-	-	-	1	-
7002	-	-	-	-	-	-	-	-
10256	-	-	-	-	-	-	9	-

Table 4 (cont.): Tows by vessel key and fishing year as used for the orange roughy standardised CPUE index, after application of the data selection criteria. Fishing years run from 1 October to 30 September, and are indicated by the year ending (e.g., 1999 means the 1998–99 fishing year). "–", zero tows.

Vessel key	2001	2002	2003	2004	2005	2006	2007
10223	-	-	-	-	-	-	-
10142	-	39	-	-	-	-	-
10244	-	-	-	-	-	-	-
10235	-	-	-	-	-	-	-
10221	-	-	-	-	-	-	-
10173	-	-	-	-	-	-	-
10238	-	-	-	-	-	-	-
10232	-	-	-	-	-	-	-
10250	-	-	-	-	-	-	-
10024	-	-	-	-	-	-	-
10234	74	172	33	45	-	-	-
10121	128	180	56	43	-	-	-
9913	39	94	8	-	-	-	-
10245	-	-	9	92	-	-	-
10083	-	-	176	-	-	-	-
12095	30	-	-	-	-	-	-
10236	181	189	257	149	169	-	-
10020	-	-	-	217	98	-	63
8804	319	325	258	-	5	-	-
10237	114	37	67	29	81	35	-
13106	113	125	29	14	56	-	-
10067	61	151	64	-	-	-	-
10021	32	166	174	165	-	-	-
9259	27	118	108	72	32	-	-
15180	67	85	79	77	15	-	-
10208	27	164	45	139	131	119	36
6618	-	111	90	84	47	-	-
10231	-	-	53	-	11	-	57
6473	31	88	137	76	68	-	-
15561	-	37	312	128	197	43	-
10260	-	54	26	-	54	1	22
10241	48	151	93	94	130	152	18
10155	-	-	136	49	120	-	1
10135	67	105	-	93	-	84	94
7002	-	78	71	82	105	94	-
10256	-	150	77	98	123	96	83

Table 5: Tows by subarea and fishing year as used for the orange roughy standardised CPUE index, after application of the data selection criteria. Fishing years are indicated by the year ending (e.g., 1999 means the 1998–99 fishing year). "–", zero tows.

Fishing year	Lord Howe Rise	Louisville Central	South Tasman Rise	Louisville North	Core Northwest Challenger	Louisville South	West Norfolk Ridge
1993	332	–	–	–	192	–	–
1994	700	47	–	5	594	–	–
1995	17	2 118	–	24	500	6	–
1996	10	678	–	588	187	102	–
1997	66	490	–	192	229	81	–
1998	33	229	155	80	148	19	–
1999	30	443	231	42	368	29	–
2000	42	278	155	208	328	20	–
2001	73	201	–	226	815	42	1
2002	132	115	–	360	1 753	46	213
2003	180	173	–	302	1 611	29	63
2004	132	261	–	439	704	130	80
2005	102	211	–	76	755	108	190
2006	5	62	–	50	315	7	185
2007	19	83	–	44	27	30	171

Table 6: Summary statistics for the data set used for the orange roughy standardised CPUE index, after application of the data selection criteria. Fishing years are indicated by the year ending (e.g., 1999 means the 1998–99 fishing year). Peak month is the month in which the largest catch of orange roughy was taken.

Fishing year	% tows non-zero catch	No. Vessels	No. Tows	Estimated Catch (t)	Peak month	Mean duration	Median t/tow	Median t/hr
1993	73.4	7	524	1 359	Jun	1.2	0.5	0.7
1994	55.2	12	1 346	1 710	Jul	0.9	0.1	0.3
1995	64.0	19	2 665	10 250	Jun	0.6	1.0	2.0
1996	62.8	15	1 565	3 966	Jun	0.6	0.5	1.4
1997	60.0	15	1 058	2 486	Jun	0.6	0.5	1.2
1998	50.6	14	664	2 311	Jun	0.4	0.5	2.0
1999	63.8	19	1 143	4 054	Jul	0.6	0.5	1.3
2000	66.4	12	1 031	1 559	Jun	0.6	0.2	0.6
2001	75.4	16	1 358	2 593	Jun	1.8	0.5	0.4
2002	81.7	21	2 619	3 146	Jun	2.7	0.5	0.2
2003	81.0	23	2 358	2 331	Jun	2.9	0.3	0.1
2004	74.9	19	1 746	2 117	Jun	1.7	0.3	0.3
2005	78.3	17	1 442	1 479	Jun	2.7	0.3	0.1
2006	86.1	8	624	1 030	Jun	2.9	0.3	0.1
2007	73.2	8	374	708	Jun	0.7	0.2	0.7

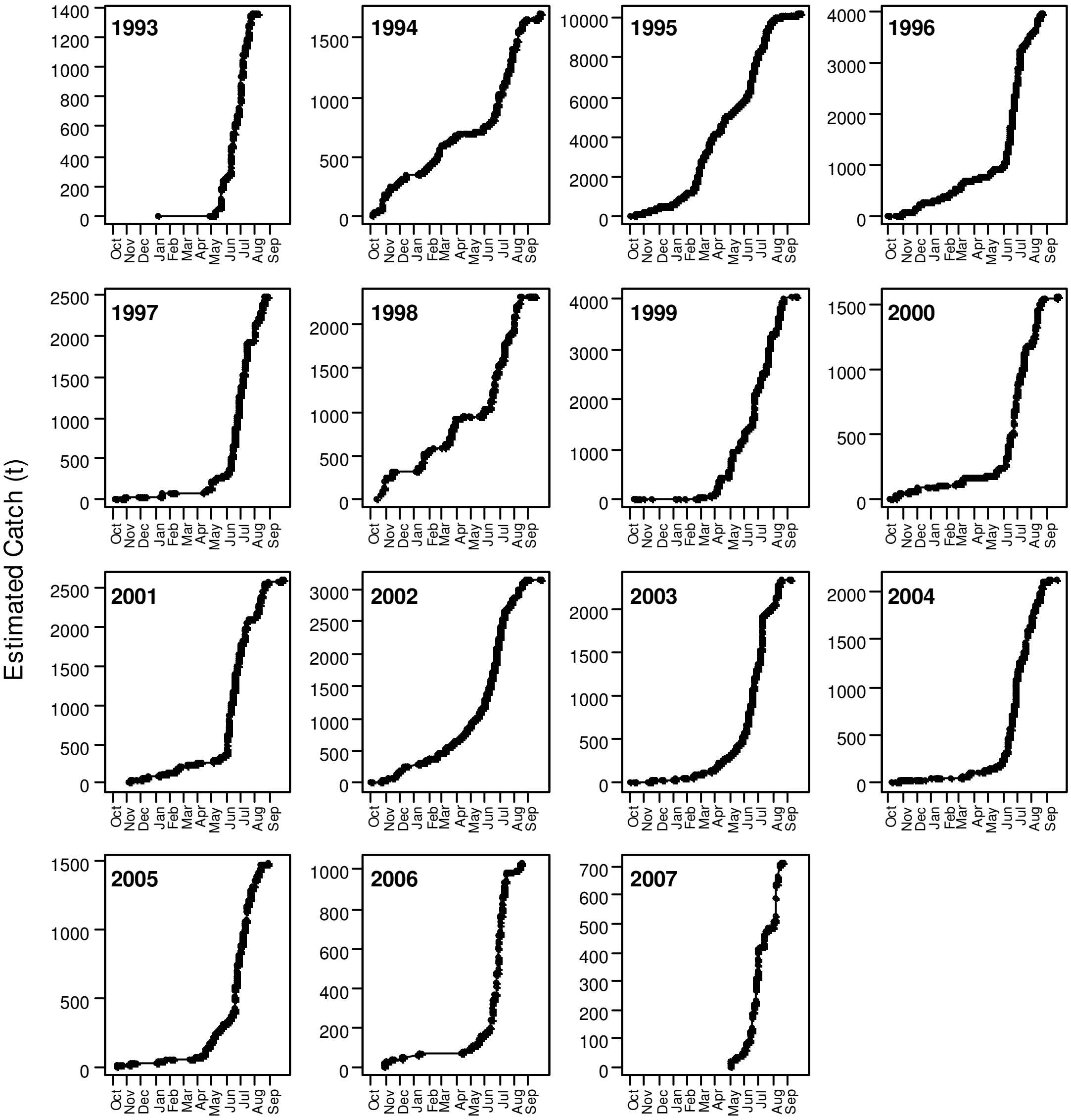

Figure 5: Cumulative annual plots of orange roughy catch by the end of each tow (black dots) for the high seas fisheries by fishing year showing seasonality of the fisheries. Fishing years are indicated by the year ending (e.g., 1999 means the 1998–99 fishing year).

Only two vessels fished in all six areas, and two in only one area (Table 7). There was a temporal trend in the proportion of tows which caught orange roughy, with a greater proportion of non-zero tows in later years (Table 6). An increase in the proportion of non-zero tows was also evident for some individual vessels (Table 8). Some vessels (e.g., 10260) reported nearly always catching orange roughy, whereas others (e.g., 10221) reported orange roughy catch in less than half of the tows, and some (e.g., 10121) showed high temporal variability (Table 8).

Table 7: Tows by vessel key and subarea as used for the orange roughy standardised CPUE index, after application of the data selection criteria. "–", zero tows.

Vessel key	Core Northwest Challenger	Lord Howe Rise	Louisville Central	Louisville North	Louisville South	South Tasman Rise	West Norfolk Ridge
10020	92	33	278	144	122	31	-
10021	496	23	44	1	22	-	-
10024	172	64	139	230	42	190	-
10067	276	-	-	-	-	-	-
10083	142	106	121	-	-	57	-
10121	296	1	428	92	-	33	-
10135	-	-	158	284	2	-	-
10142	345	89	156	2	-	-	-
10155	303	2	-	-	-	-	1
10173	38	64	150	13	11	-	-
10208	184	78	17	11	14	34	516
10221	95	38	257	130	38	-	-
10223	231	385	107	-	-	-	-
10231	41	32	-	-	-	-	72
10232	13	9	683	66	11	-	-
10234	442	127	135	116	19	3	-
10235	87	249	452	255	77	7	-
10236	1072	132	494	365	31	26	-
10237	181	29	154	111	27	80	-
10238	16	-	241	3	-	-	-
10241	686	-	-	-	-	-	-
10244	28	5	197	19	2	-	-
10245	51	11	246	41	37	-	-
10250	-	-	96	13	2	-	-
10256	307	128	24	18	27	-	132
10260	135	7	-	-	-	-	15
12095	95	9	34	-	8	29	-
13106	130	22	85	14	14	12	159
15180	279	41	-	-	-	-	3
15561	713	4	-	-	-	-	-
6473	1	-	240	148	12	-	-
6618	-	-	122	246	16	-	-
7002	430	-	-	-	-	-	-
8804	825	88	115	127	53	37	-
9259	216	82	2	75	39	-	5
9913	108	15	214	112	23	2	-

The dependent variable in the GLM was log(t/tow), and the final non-zero catch (normal) model explained 17.8% of the deviance (Table 9). The final model included interactions between *fishing year* and *subarea*, and *subarea* and *fishing day*. The fit of the model was very good, with departures in the quantile plot only outside of the 3rd quantile, indicating the model failed to describe only the extremes of the catch rate (Figure 6).

Table 8: Proportion of tows with a non-zero orange roughy catch, by vessel key and fishing year. "–", zero tows. Fishing years are indicated by the year ending (e.g., 1999 means the 1998–99 fishing year).

Vessel	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007
6473	-	-	-	0	0.33	-	-	-	0.6	0.73	0.9	0.92	0.69	-	-
6618	-	-	-	-	-	-	-	0.55	-	0.74	0.45	0.7	0.58	-	-
7002	-	-	-	-	-	-	-	-	-	1	1	1	0.98	1	-
8804	-	-	-	0.89	0.44	-	0.89	0.7	0.77	0.82	0.77	-	0.7	-	-
9259	-	-	-	-	-	-	0.74	-	0.38	0.69	0.84	0.69	0.73	-	-
9913	-	-	-	0.58	0.52	0.56	0.74	0.96	0.98	0.75	1	-	-	-	-
10020	0.44	-	0.89	-	-	0.4	-	-	-	-	-	0.55	0.45	-	0.66
10021	-	-	0.61	-	-	-	-	-	0.97	0.99	0.9	0.65	-	-	-
10024	-	-	0.63	0.63	0.54	0.79	0.79	0.8	-	-	-	-	-	-	-
10067	-	-	-	-	-	-	-	-	0.87	0.97	1	-	-	-	-
10083	-	-	0.54	0.86	0.36	0.56	0.92	-	-	-	0.65	-	-	-	-
10121	-	-	0.57	0.82	-	0.04	0.62	0.4	0.74	0.76	0.93	0.49	-	-	-
10135	-	-	-	-	-	-	0.17	-	0.82	0.81	-	0.78	-	0.63	0.55
10142	0.83	0.74	0.75	-	-	-	-	-	-	0.93	-	-	-	-	-
10155	-	-	-	-	-	-	-	-	-	-	0.93	1	0.99	-	0.5
10173	0.56	0.41	0.71	0.17	0.29	0.6	0.71	0.5	-	-	-	-	-	-	-
10208	0.64	0.5	0.56	-	-	-	0.76	0.75	1	0.93	0.83	0.95	0.94	0.89	0.95
10221	0.65	0.41	0.61	0.41	0.25	0.3	0.47	-	-	-	-	-	-	-	-
10223	0.91	0.64	0.79	0.67	-	-	-	-	-	-	-	-	-	-	-
10231	0.67	-	-	-	-	-	-	-	-	-	0.87	-	0.73	-	0.81
10232	-	0.41	0.76	0.74	1	0.37	0.48	-	-	-	-	-	-	-	-
10234	-	0.64	0.72	0.46	0.56	0.53	0.66	0.82	0.67	0.79	0.53	0.73	-	-	-
10235	-	0.56	0.74	0.82	0.54	0.44	-	-	-	-	-	-	-	-	-
10236	-	0.49	0.49	0.63	0.67	0.71	0.65	0.7	0.72	0.7	0.82	0.89	0.8	-	-
10237	-	-	0.78	0.69	-	0.45	0.83	-	0.75	0.73	0.84	0.53	0.54	0.92	-
10238	-	0.36	0.74	-	0.57	-	-	-	-	-	-	-	-	-	-
10241	-	-	-	-	-	-	-	-	0.98	0.99	1	1	0.99	0.95	0.95
10244	-	0.35	0.56	1	0.47	-	-	-	-	-	-	-	-	-	-
10245	-	0.47	0.63	-	0.38	-	0.41	0.49	-	-	0.48	0.5	-	-	-
10250	-	-	0.32	0.67	0.88	-	0.24	-	-	-	-	-	-	-	-
10256	-	-	-	0.5	-	-	0.82	-	-	0.94	0.93	1	0.81	0.79	0.89
10260	-	-	-	-	-	-	-	-	-	1	1	-	1	1	0.96
12095	-	-	-	-	-	1	0.72	0.41	0.79	-	-	-	-	-	-
13106	-	-	-	-	-	1	0.75	0.77	0.9	0.59	0.57	0.7	0.88	-	-
15180	-	-	-	-	-	-	-	-	0.58	0.92	0.91	0.98	1	-	-
15561	-	-	-	-	-	-	-	-	-	0.97	0.9	0.91	0.88	0.98	-

Table 9: Predictors and percentage of deviance explained for the final normal model fit for orange roughy CPUE outside the EEZ. Df, degrees of freedom; AIC, Akaike Information Criterion; % dev. expl., % of deviance explained; Add % dev. expl., additional % deviance explained. Predictors which explained less than 1% of additional deviance were excluded from the final model.

Predictor	Step	Df	AIC	% dev. expl.	Add % dev. expl.
Fishing year	1	13	85 514	4.5	4.5
Vessel	2	35	82 386	9.9	5.5
Subarea	3	6	82 066	11.3	1.4
*Fishing year * Subarea*	4	60	81 590	13.9	2.5
Fishing day (4^{th} order poly)	5	4	81 332	15.0	1.1
*Subarea * Fishing day*	6	24	81 015	16.5	1.5

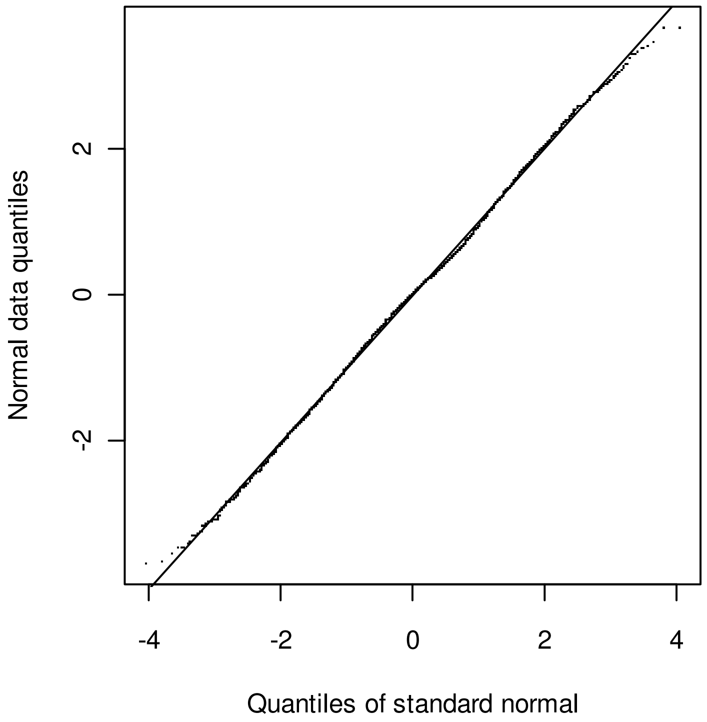

Figure 6: Normal quantile plot for the fit of the normal model for orange roughy CPUE outside of the EEZ.

The model predicted strong seasonal effects on CPUE, which varied between subareas. A peak in CPUE was predicted for all subareas around days 250–300 (June–July), probably associated with fishing on spawning aggregations (Figure 7). A second peak in CPUE between days 0 and 100 (October–December) was predicted for all areas except Louisville Central and the South Tasman Rise, being most pronounced relative to the June–July peak in the core Northwest Challenger and Lord Howe Rise subareas. A peak in CPUE towards the start of the year could be a result of fishing on re-forming fish aggregations, following resting of the grounds between the post-spawning period and the start of the next fishing year.

The predicted effect of vessel on CPUE was substantial, with the best vessel having a CPUE about 10-fold better than worst, and the CPUE of most of the vessels varying about three-fold between vessels (Figure 7).

The predicted year effect (standardised CPUE trends) for the South Tasman Rise showed a sharp decline (Figure 8; Table 10). There was an initial steep decline in CPUE for the West Norfolk Ridge, followed by five years of stable or perhaps increasing CPUE. The CPUE declined for Louisville Central and Louisville North to about one-quarter and one-third respectively of the initial levels. The CPUE for the core Northwest Challenger subarea was variable, with perhaps a slow increase overall, a peak in CPUE in 2001–02, and little change since 2002–03. There was no clear trend for Louisville South, where there were some peaks in CPUE but with large confidence intervals, nor for Lord Howe Rise, where CPUE was relatively high in 1992–93.

Table 10: Estimated year effects and standard errors (s.e.s) for the interaction model fitted to New Zealand High Seas orange roughy fishery data (see Figure 8). Years labelled as year ending (i.e., 1993 means 1992–93).

	Core NW Challenger		Lord Howe Rise		Louisville Central		Louisville North	
	Index	s.e.	Index	s.e.	Index	s.e.	Index	s.e.
1993	0.31	0.05	0.85	0.12	–	–	–	–
1994	0.18	0.02	0.14	0.02	1.20	0.36	0.31	0.26
1995	0.38	0.05	0.02	0.01	1.38	0.13	0.13	0.05
1996	0.33	0.05	0.31	0.18	0.81	0.10	0.85	0.11
1997	0.22	0.03	0.18	0.05	0.66	0.08	0.31	0.05
1998	0.36	0.06	0.27	0.09	0.69	0.10	0.63	0.14
1999	0.25	0.03	0.06	0.02	0.57	0.07	0.56	0.16
2000	0.27	0.03	0.09	0.03	0.35	0.05	0.24	0.04
2001	0.47	0.05	0.24	0.05	0.58	0.09	0.53	0.08
2002	0.50	0.04	0.14	0.03	0.29	0.06	0.29	0.04
2003	0.35	0.03	0.19	0.03	0.34	0.06	0.32	0.04
2004	0.39	0.04	0.21	0.04	0.24	0.03	0.15	0.02
2005	0.34	0.04	0.28	0.05	0.25	0.04	0.18	0.04
2006	0.36	0.05	0.03	0.02	0.47	0.12	0.28	0.08
2007	0.42	0.15	0.12	0.05	0.20	0.04	0.13	0.04

	Louisville South		South Tasman Rise		West Norfolk Ridge	
	Index	s.e.	Index	s.e.	Index	s.e.
1993	–	–	–	–	–	–
1994	–	–	–	–	–	–
1995	0.38	0.33	–	–	–	–
1996	0.55	0.27	–	–	–	–
1997	0.25	0.12	–	–	–	–
1998	0.44	0.27	23.94	9.54	–	–
1999	0.36	0.18	6.60	1.60	–	–
2000	0.36	0.21	0.36	0.08	–	–
2001	0.31	0.17	–	–	0.32	0.56
2002	0.25	0.14	–	–	1.19	0.22
2003	0.93	0.51	–	–	0.29	0.07
2004	0.22	0.11	–	–	0.67	0.18
2005	0.12	0.05	–	–	0.60	0.10
2006	0.28	0.22	–	–	0.61	0.11
2007	0.23	0.13	–	–	0.82	0.14

There was a pattern of sequential fishing within all subareas, being least pronounced for the Core Northwest Challenger between 1999–2000 and 2005–06, Louisville North between 1998–99 and 2006–07, and Lord Howe Rise between 1993–94 and 1999–2000 (Figure 9). Sequential fishing is a problem because catch rates may be maintained through serial depletion of specific locations, which will result in CPUE being a positively biased index of biomass. Nevertheless, standardised CPUE for Louisville Central and North suggested vulnerable biomass (fishable aggregations available to the vessels involved at the specific times and sites fished) has decreased, and for the core Northwest Challenger subarea CPUE suggests vulnerable biomass may have increased.

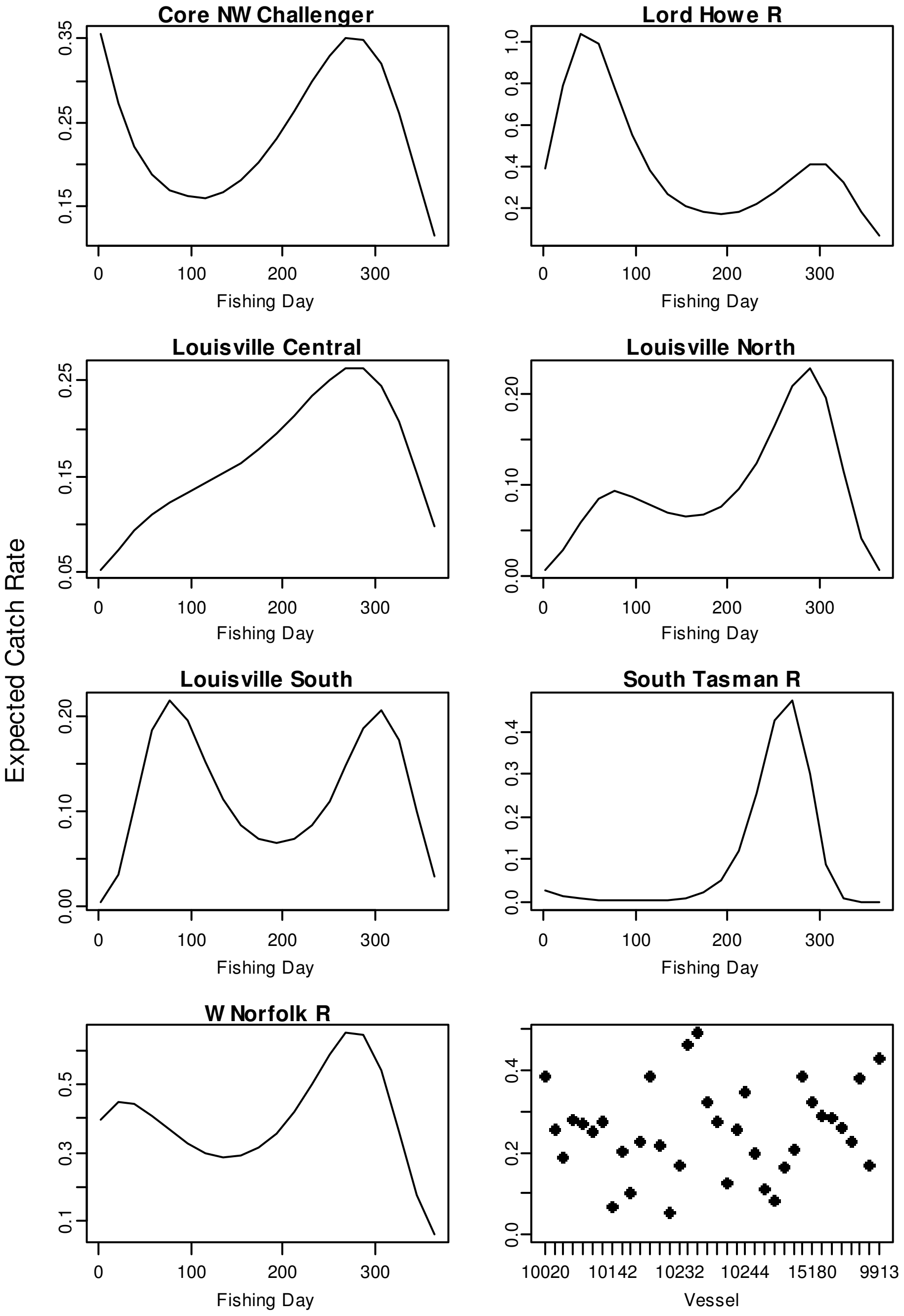

Figure 7: Model predictions of expected seasonal catch rates (t/tow) by fishing area (top 7 plots), and of vessel effects (all areas combined, lower right plot), for the normal model for orange roughy CPUE outside the EEZ, made with all other predictors set to the median (fixed) values.

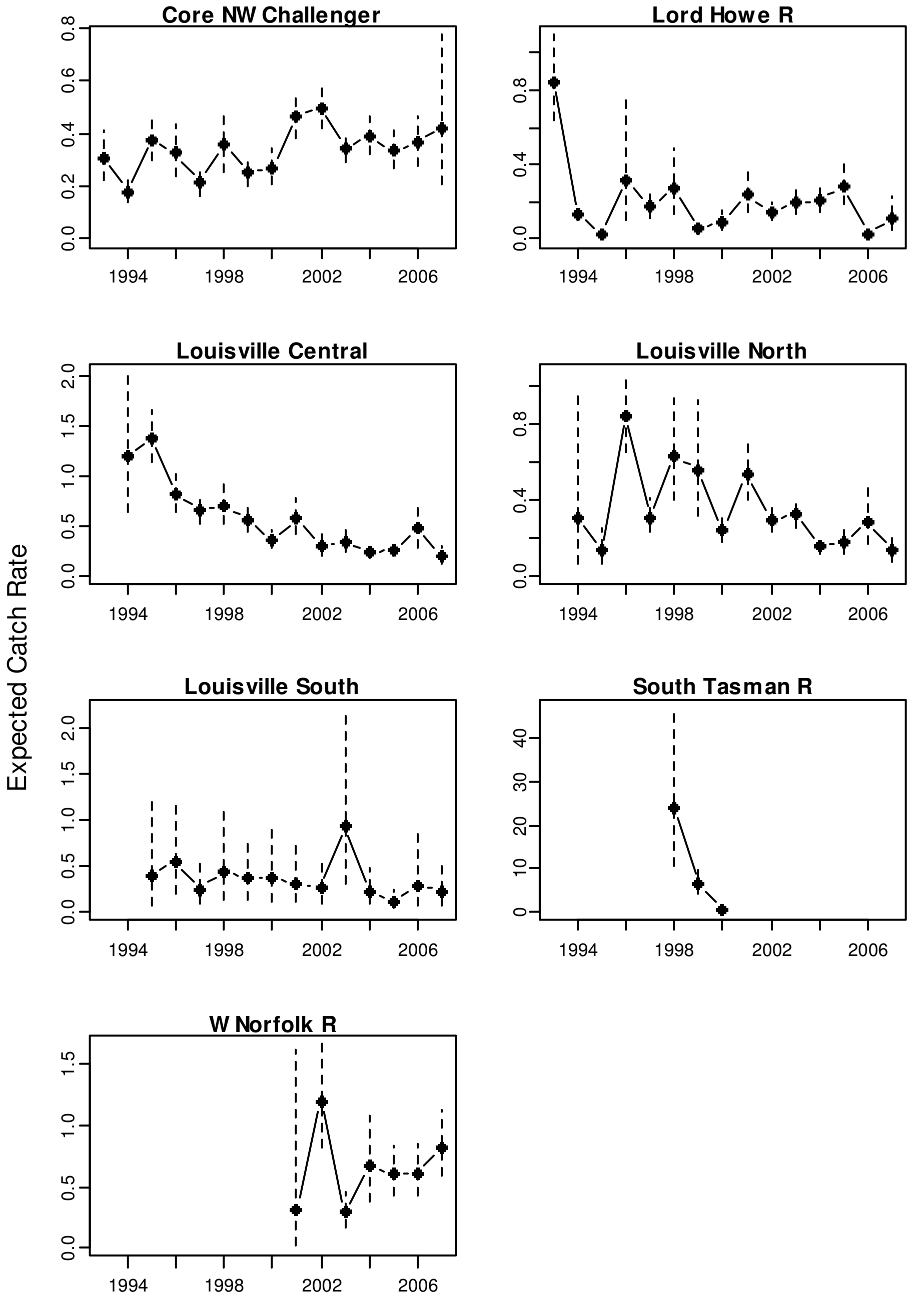

Figure 8: Model predictions for the fishing year effect of the normal model for orange roughy CPUE by fishing area outside the EEZ, made with all other predictors set to the median (fixed) values.

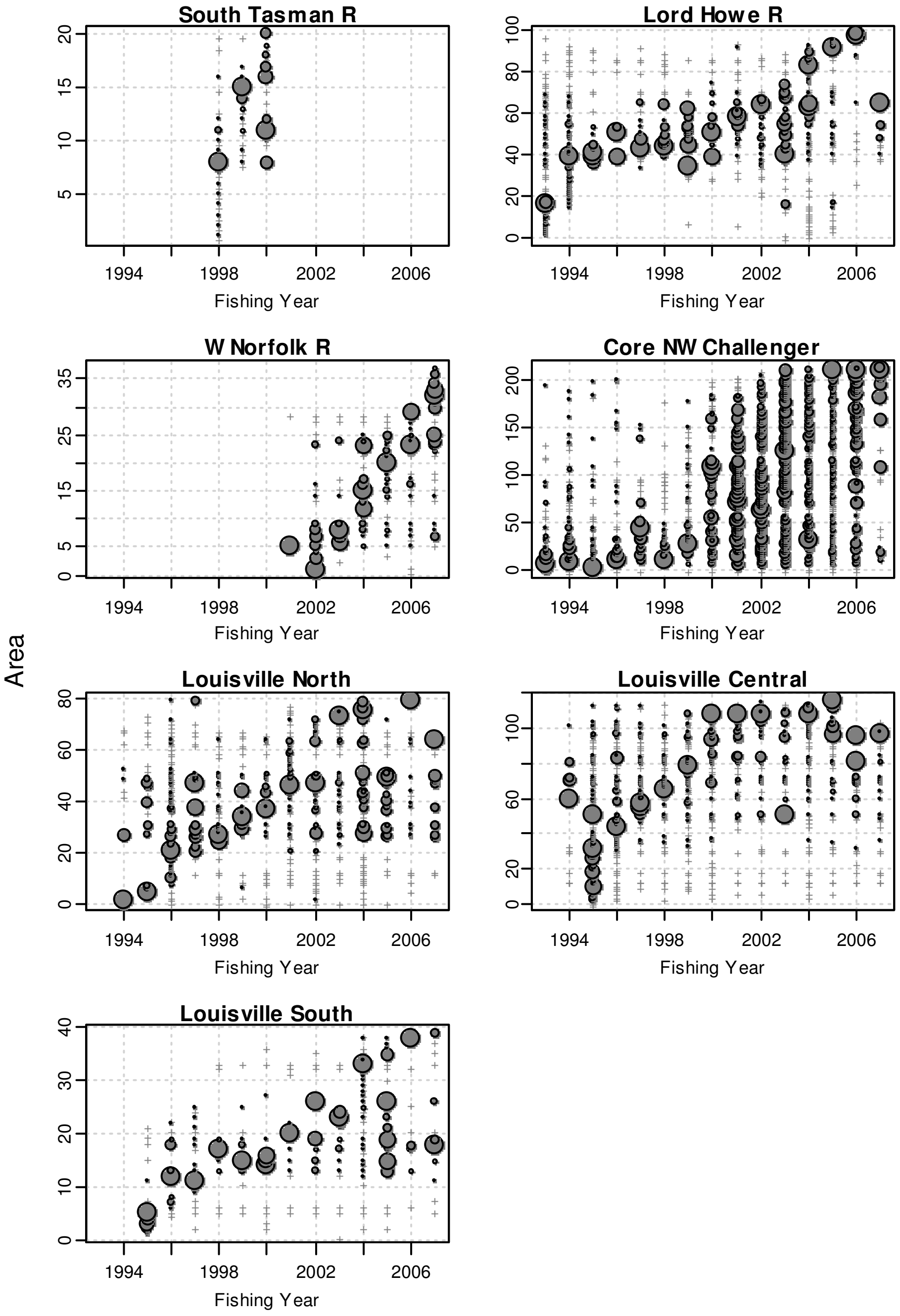

Figure 9: The distribution of orange roughy unstandardised median catch rate (t/tow) by fishing year and area (where area is a square of 1/10th of a degree latitude and longitude) for subareas of the High Seas fishery. Catch rates are proportional to circle size; each year sums to 1. Crosses indicate areas where effort took place but no catch was taken. Areas were ordered by mean year in which the catch was taken.

2.5.2 Sensitivity analysis

Analyses were also completed for individual subareas, using data selection criteria that attempted to provide as much consistency as possible within each subarea (Table 11, Figure 10). These analyses provide a measure of the sensitivity of the estimated CPUE trends to the data selection.

Table 11: Summary of standardised CPUE models for subareas of the High Seas orange roughy fishery. The vessel selection criteria were three years with 10 or more tows per year, unless stated otherwise. The predictors shown are those selected by the final model in addition to the *Fishing Year* predictor. The last column shows the catch in the CPUE index as a percentage of the total catch from the data set for each subarea, and gives an indication of how representative the CPUE index may be of each specific fishery.

Data set	Additional predictors	% deviance explained	% of catch in index
1. NW Challenger 2000–01 to 2005–06	*Duration* + *Vessel* + *Fishing Day*	14.9	88.9
2. NW Challenger short tows (30 minutes or less)	*Vessel* + *Fishing Day* + *Duration*	19.1	40.4
3. NW Challenger long tows (over 1.5 hours)	*Vessel* + *Duration*	13.8	72.9
4. Louisville North 1998–99 to 2006–07	*Vessel* + *Tonnage* + *Fishing Day* + *Duration*	21.3	80.0
5. Louisville North 1998–99 to 2006–07 excluding vessel key 8804	*Tonnage* + *Fishing Day* + *Vessel* + *Duration* + *Depth*	15.5	74.7
6. Lord Howe Rise 1994–95 to 1999–2000, vessel criteria 2 years of 5 or more tows	*Vessel* + *Duration*	29.7	31.4
7. Louisville Central 1994–95 to 2006–07, vessel criteria 4 years of 10 or more tows	*Vessel* + *Fishing Day* + *Duration* + *Depth*	15.9	46.3
8. Louisville Central short tows (1 hour or less)	*Vessel* + *Fishing Day* + *Duration*	19.5	67.8

When the Northwest Challenger data set was restricted to the period when the fishery was spread over a wide area (2000–01 to 2005–06) and consisted primarily of longer tows (data set 1 in Table 11), the CPUE trend was broadly similar to that estimated from the overall analysis (compare Figure 10 top panel, with Figure 8 top left panel from 2000–01 to 2005–06). When only short hill tows were used (data set 2), CPUE was high in 1994–95, 1995–96, and 2005–06, but otherwise showed no clear trend (Figure 10). When only longer tows were used (data set 3), there was a decline in CPUE from 1995–96 to a low in 1998–99, and then an increase back to mid-1990s levels, followed by a slow decline from 2001–02 to 2005–06 and an increase (with high uncertainty) back to 2001 levels in 2006-07. The increase in the middle of this CPUE index (1999–2000) coincides with the spatial expansion of the fishery. None of these subsets of data showed the slow overall increase in CPUE which was estimated from the overall analysis for the core Northwest Challenger area.

When the Louisville North data set was restricted to the period when the spatial extent of the fishery was relatively consistent (1998–99 to 2006–07, although sequential fishing did take place within this subset, see Figure 9), the confidence intervals were wide and no CPUE trend was apparent (data set 4). Vessel 8804 had a mean catch rate (*vessel* effect) estimated to be about four times greater than any other vessel in this area, and so was excluded from the next data set (data set 5). In this model, the CPUE trend was similar to the CPUE trend from the overall analysis for Louisville North, but with much tighter confidence intervals. Although the index for 1998–99 was estimated to be relatively low, this estimate is highly uncertain and there are indications of a decline in CPUE over this time series from 2000–01 onwards. The Lord Howe Rise data set could not be used with the vessel selection criteria of three years and 10 or more tows per year because no vessel had achieved this. A less stringent criterion of two years of five or more tows was therefore used (data set 6) over the period 1994–95 to 1999–2000 during which the spatial extent of the fishery was relatively constant (see Figure 9). The resultant CPUE shows no clear trend, although 1998–99 was estimated to be relatively low. The Louisville Central data set was restricted to 1995–96 to 2006–07 when the spatial extent of the fishery was more consistent, although sequential fishing did take place during this period (see Figure 9). The overall analysis for this area suggested a steady decline in CPUE. However, when the vessel criterion was made more stringent (data set 7) the resultant CPUE index was virtually flat between 1998–99 and 2004–05. When only short (hill) tows were used, the CPUE for this area index broadly declined between 1995–96 and 2001–02, but then increased steadily back to 1997-98 levels by 2006-07.

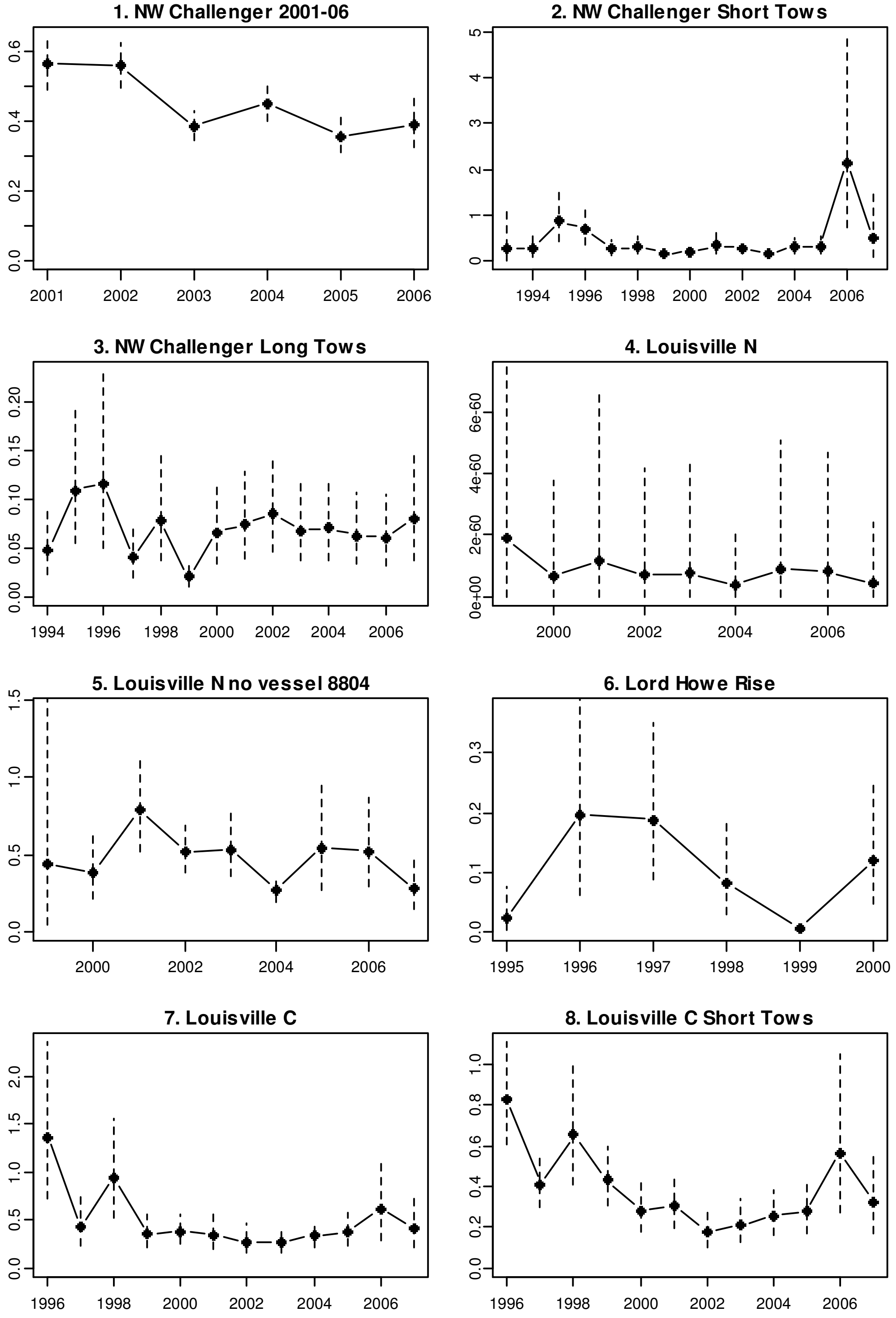

Figure 10: Model predictions for the fishing year effect of the normal model for orange roughy CPUE in subareas outside the EEZ, made with all other predictors set to the median (fixed) values. The model numbers refer to those in Table 11, where details of each model and data set are given.

The CPUE indices estimated for the Challenger Plateau were either flat, or increased between 1992–93 and 2006–07, and as a result did not conform to expectations from descriptive analyses of the fishery, which suggested the availability of orange roughy had substantially declined (Clark 2008). A decrease in the incidence of large catches (over 5 t) on the Challenger Plateau supports a decline in biomass (Figure 11). The incidence of large catches can be used as a basic measure of fishery performance, and suggests biomass declines in Louisville North and the Challenger Plateau, a rapid depletion of biomass on Lord Howe Rise, and an increase on West Norfolk Ridge (Figure 11).

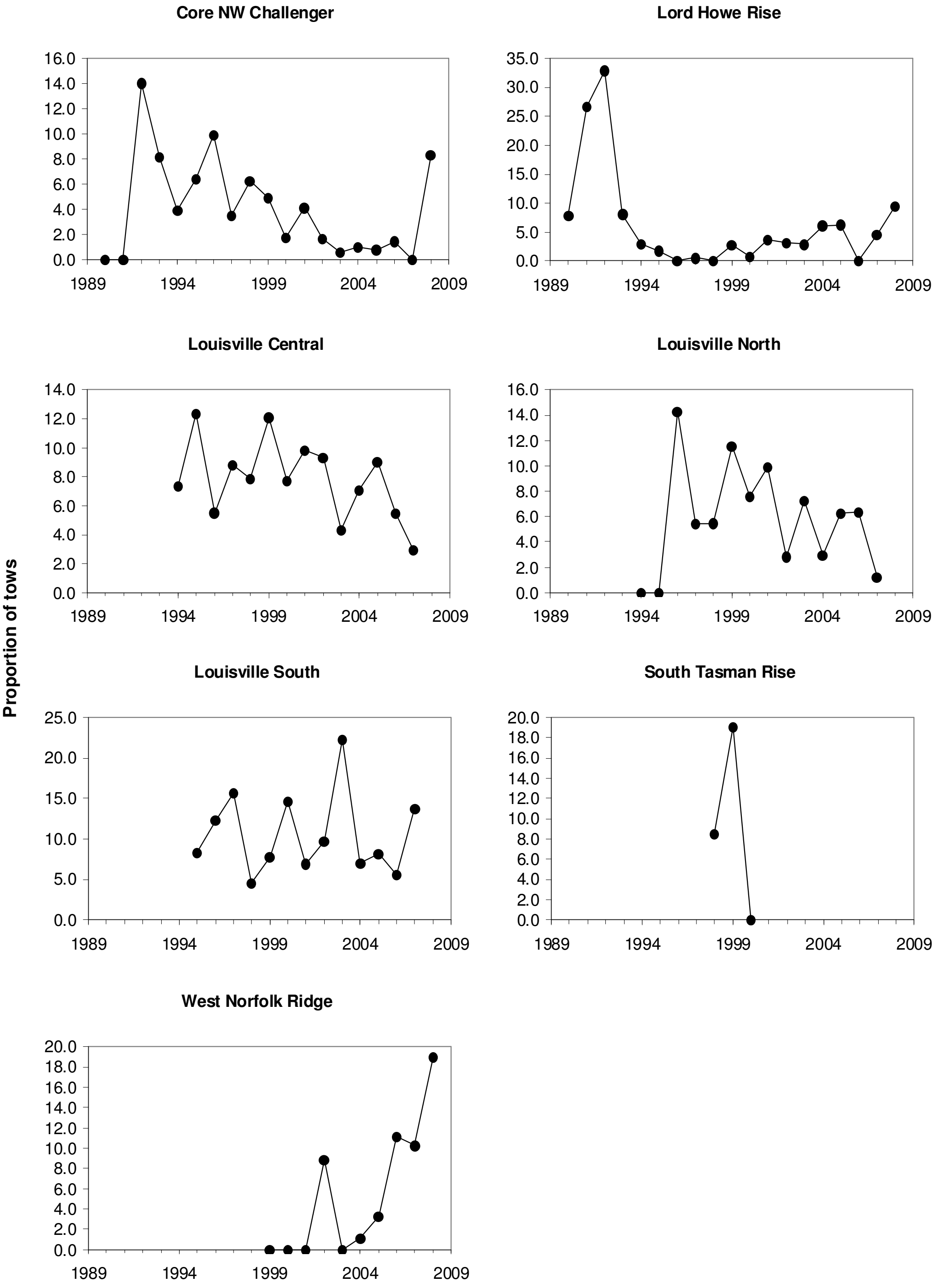

Figure 11: The proportion of tows where more than 5 t of orange roughy were caught, by area and fishing year.

2.6 Discussion of the CPUE analyses

Standardised CPUE indices of orange roughy from New Zealand fisheries on the High Seas are highly dubious as indices of stock abundance.

The CPUE data for all subareas showed evidence of sequential fishing of locations, suggesting the overall CPUE may be biased upwards over time, with high catch rates being maintained by sequential movement to new fishing areas. Some CPUE trends were also sensitive to the data selection criteria such as fishery spatial extent, length of tow, or vessel selection criteria.

The conclusions about trends in biomass drawn from sensitivity analyses of data subsets differed from those estimated from the overall analysis for some areas, perhaps the best example being for Louisville Central. This highlighted the sensitivity of these CPUE indices to some of the predictors and the uncertainty in using CPUE as a biomass index. Taking an areal or temporal subset of the data might, in some cases, provide a more uncertain estimate of CPUE trends. This is because the application of data selection criteria results in a smaller data set with more intermittent catches and effort, and one which describes less of the catch. The best example of this is for Lord Howe Rise.

A substantial proportion of the tows did not record orange roughy as a catch, but this varied with year and vessel. Whilst in principle the incidence of zero-catch tows could tell us something about orange roughy abundance, in reality there have been discrepancies in the recording of zero catch tows (which are also evident in this data set), meaning zero-tows are unlikely to contain unbiased information about orange roughy abundance.

Although CPUE is likely to be related to vulnerable biomass in some way, the behaviour of the fisheries means the indices estimated are unlikely to reflect overall subarea stock biomass.

Orange roughy on the northwest Challenger Plateau (ET) and southwest Challenger Plateau (inside the EEZ except for the Westpac Bank) have been assumed to be separate stocks (Clark 1990, Smith et al. 2002). However, observational evidence for the separation of the northwest and southwest Challenger is largely equivocal, and it remains possible that the Challenger supports just one stock. Catches from the southwest Challenger were substantially reduced in the late 1980s, to levels that should have allowed the rebuilding of the stock. However, the predicted stock recovery was not observed in southwest Challenger CPUE indices, and the fishery was effectively closed in 2001 (Ministry of Fisheries 2009). The CPUE index for the northwest Challenger did show a slow biomass increase between 1993 and 2007, which would be consistent with the rebuild predicted from the southwest Challenger, provided the two areas were linked. Stock structure is poorly known, and the CPUE sensitivities showed the northwest Challenger CPUE trend to be highly uncertain, so this hypothesis remains highly speculative.

Additional future analyses might consider measures of fishing disturbance as a potential predictor (e.g., Dunn 2007b), and effort measures might try to incorporate the time spent searching for aggregations (if any).

Methods which account for serial depletion, following Walters (2003), have been applied successfully for orange roughy on the south and east Chatham Rise (Doonan & Dunn, unpublished data) and may also be useful, but there are currently insufficient data to use this approach for the high seas fisheries.

3. APPLICATION OF SEAMOUNT META-ANALYSIS

3.1 Background to the Seamount Meta-Analysis approach

Seamount physical data have in the past been analysed to determine if geo-morphological characteristics could be useful in predicting orange roughy biomass on seamounts. Clark et al. (2001) compiled physical attributes and catch data of deepwater fisheries for 77 seamounts in the New Zealand region. Characteristics of location, depth, size, elevation above the seafloor, age, continental association, geological origin, distance offshore, distance from surrounding seamounts, and degree of spawning were defined for each seamount. These data were then regressed as independent variables against the minimum orange roughy population size estimated from the historical level of catch taken from seamounts to investigate whether they could be useful predictors of likely safe catch from newly found seamounts.

Multiple regression procedures were used to model the effects of the physical variables on orange roughy stock size. There were two stages in the analysis. First, biomass was modelled on individual seamounts grouped in regions (as a categorical variable) and including predictors specific to individual seamounts. This analysis showed region, depth of the peak, and slope of the seamount to be significant. A second analysis was carried out where the region effects derived from the initial regression were modelled, using predictors related to entire regions. This showed latitude and association (continental/oceanic) to be important. The predictive power of the models was tested by cross validation, and compared with simpler models to assess their informative value. The method was applied to a section of the Louisville Ridge in Ministry of Fisheries project ORH2002/03 (Clark 2003).

Region effects, taken either from values supplied by Clark et al. (2001) or for new regions estimated using the region effects model, were used to predict biomass for seamounts on the Lord Howe Rise, Northwest Challenger Plateau, West Norfolk Ridge, and Louisville Ridge.

3.2 Methods

3.2.1 Fishing areas

The following coordinates were used to define fishing areas for analysis (after Clark 2008):

a) **Lord Howe Rise:** The main region of the fishery is 35°00’ S – 36°45’ S and 164°00’ E – 167°00’ E

b) **Northwest Challenger Plateau:** The main target fishery (referred to as the “Core Area”), is on the northern slopes of the Plateau, between 36°50’ S – 38°00’ S, and 166°00’ E – 170°00’ E.

c) **West Norfolk Ridge:** 32°30’ S – 34°30’ S, 166°30’ E – 168°10’ E.

d) **Louisville Ridge:** There are three general areas:
   - North: 35°00’ S – 39°54’ S, 165°00’W – 172°00’ W.
   - Central: 40°00’ S – 44°54’ S, 157°00’ W – 167°00’ W.
   - South: 45°00’ S – 50°00’ S, 148°00’ W – 159°00’ W.

3.2.2 Seabed bathymetry

A number of sources of seabed bathymetry data were examined to compile a listing of major topographic features in the area that may be appropriate for estimating orange roughy biomass, focussing on identification of seamount and ridge features. Data sources included:

a) Kitchingman & Lai (2004) predicted position and depth of over 14 000 large seamounts globally from satellite altimetry data.
b) NIWA seamounts database (Rowden et al. 2008) comprising 1200 features in the New Zealand region.
c) A central-western Pacific regional seamount data compilation (Allain et al. 2008) which combines a number of datasets.
d) A new edition of GEBCO data (known as GEBCO II).
e) NIWA general Pacific bathymetry (ETOPO2 bathymetry).
f) Published data records (Lonsdale 1988) for the Louisville Ridge.
g) Multibeam data from research surveys of the area (e.g., *Sonne* 2002, *Atalante* “Tasmante” voyage, *Rig Seismic* “Resolution Ridge” voyage, *Tangaroa* voyages in 2004, 2007).
h) Seamount compilations from previous studies (Clark et al. 2001, Clark 2003)

Seamounts were also evaluated by their summit and base depths, with seamounts excluded if their summits were deeper than 1500 m, or if their base depth was less than 600 m. Seamounts beyond the latitudinal range of 30°–60° (beyond which orange roughy are known not to occur) were also excluded. This resulted in a dataset of 59 seamounts.

3.2.3 Physical variables

Values of six key physical variables (as per Clark et al. 2001) were estimated for each seamount or peak.

1) Latitude of the seamount (based on location of the summit (to nearest 100 m))
2) Depth at summit (i.e., minimum depth of seamount).
3) Elevation – defined as the depth range between the summit and base of the seamount. The base depth is determined by the deepest depth contour which completely encircles the seamount. The summit is the shallowest point. A seamount was defined as a discrete feature rising at least 100 m from the surrounding slope.
4) Area – calculated as the area of the seamount base, only in the horizontal plane within the base depth contour defined above.
5) Slope index – approximated as $\text{Elevation}\big/\sqrt{\text{Area}}$. This represents the average steepness of the flanks of the seamount.
6) Association – defined as either continental or oceanic. Continental classification indicates the seamounts are close to the continental shelf around New Zealand or its associated rises and plateau; an oceanic association means a seamount is more isolated from continental margins.

3.2.4 Meta-analysis formulae

The predictors of region effects used were latitude and association. The formula given by Clark et al. (2001) is:

Predicted region effect = exp(intercept + latitude effect + association effect)

where the intercept is 0.73 and the region, depth of top, and slope effects are given below.

Latitude	Effect
north of 37° S	–0.45
39° S – 37° S	–0.01
42° S – 39° S	0.33
44° S – 42° S	0.39
45° S – 44° S	0.23
49° S – 45° S	–0.30
South of 49° S	–0.77

Association	Effect
Continental	0.00
Oceanic	–1.00

All Louisville and West Norfolk Ridge seamounts are oceanic, Lord Howe and Northwest Challenger Plateau are continental.

Region effects were taken from Clark et al. (2001) where they had already been calculated using the seamounts in that study. For areas that were not estimated in the 2001 study, the above formula was applied. As a sensitivity, estimates of total biomass by region were also produced using only region effects calculated from the formula.

The predictors of orange roughy biomass on individual seamounts were region, depth of top, and slope. The approximating formula (Clark et al. 2001) is:

Predicted biomass = exp(intercept + region effect + depth of top effect + slope effect)

where the intercept is 6.89 and the region, depth of top, and slope effects are given below.

Region	Effect	Source
Louisville northern North	-0.72	Formula
Louisville North	-0.35	Clark et al. (2001)
Louisville Central	0.83	Clark et al. (2001)
Louisville South (and further south)	-0.57	Formula
Northwest Challenger	-0.88	Clark et al. (2001)
Lord Howe Rise	0.28	Formula
West Norfolk Ridge	-0.72	Formula

Depth of top (m)	Effect
<600	0.95
600–649	0.76
650–699	0.65
700–749	0.39
750–799	0.19
800–849	0.02
850–899	–0.19
900–949	–0.41
950+	–0.64

Slope	Effect
<0.1	0.46
0.1–0.2	0.08
0.2–0.25	–0.22
0.25–0.3	–0.41
0.3–0.4	–0.62
0.4–0.5	–0.84
0.5+	–1.00

3.2.5 Commercial catch and effort data

For several checks and analyses, commercial catch and effort data were extracted from the Ministry of Fisheries database *snapper*. Tow by tow data covered the period 1981 to 2008. The data were groomed as per Objective 1 of this project (see Section 2.2).

3.2.6 Estimation of yield

Yield estimates were calculated from relationships between virgin biomass and yield given in the Fisheries Assessment Plenary report for 2009 (Ministry of Fisheries 2009). Maximum Constant Yield (MCY) is approximated as 1.51% of B_0, and Maximum Average Yield (MAY) as 1.99% of B_0 (based on Chatham Rise values).

3.3 Results

3.3.1 Seamount physical characteristics

The location of seamounts selected for inclusion in this study, is shown in Figure 12.

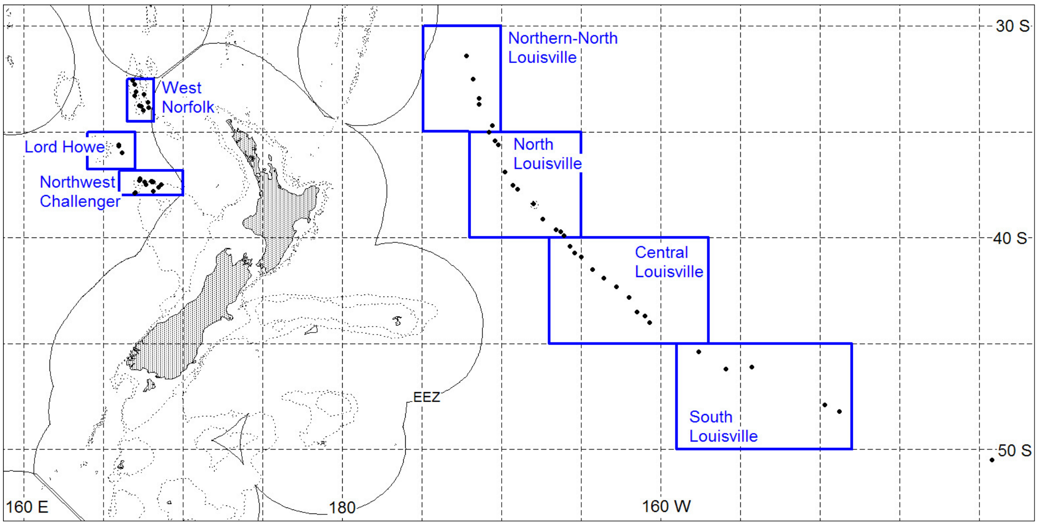

Figure 12: The New Zealand region, showing location of the 59 seamounts used in the study.

The seamounts extend from 30° S to over 50° S, between longitudes 165° E and 148° W. Most are along the Louisville Ridge (Table 12)

Table 12: Summary of seamount numbers by region.

Region	Sub-region	No. seamounts
Louisville Ridge	northern North	5
	North	11
	Central	10
	South	5 (+1)
Northwest Challenger		14
Lord Howe Rise		3
West Norfolk Ridge		10

The physical characteristics of the 59 seamounts included in the study are summarised in Appendix 1.

3.3.2 Seamount model biomass estimates

The total estimated biomass of orange roughy for all the above seamounts was 83 800 t (Table 13). The regional totals were:

West Norfolk	14 520 t
Northwest Challenger	8 800 t
Lord Howe	4 130 t
Louisville	56 340 t

The biomass estimate for the West Norfolk Ridge is reasonably evenly spread between 6 of the 10 seamounts which are estimated to host about 2000 t each, with between 400 t and 1300 t on each of the remaining four. Five seamounts on the Northwest Challenger Plateau had similar estimated biomass of 850–1150 t, with the remainder in the region predicted to have around 500 t or less of orange roughy. The three seamounts on the Lord Howe Rise had predicted biomass levels between 1000 t and 1700 t. On the Louisville Ridge, most of the estimated biomass occurs on seamounts in the central region which generally had estimates over 1000 t of orange roughy (see Figure 13), with lower biomass to the southeast, and low predicted orange roughy abundance on the northern Louisville seamounts.

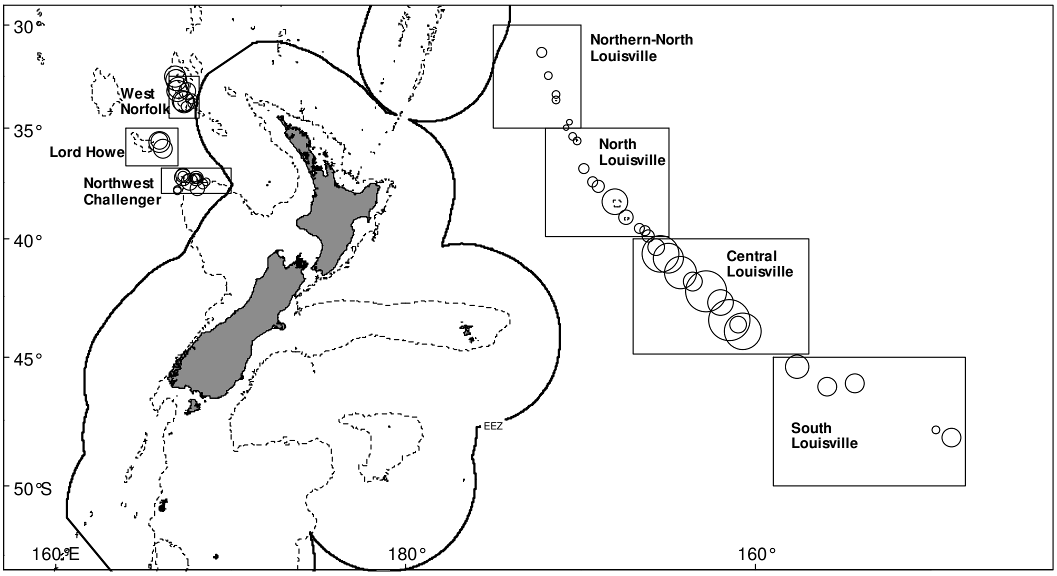

Figure 13: Distribution of predicted biomass of orange roughy on individual seamounts. The area of the circle is proportional to biomass, with a maximum at 6 850 t.

Many of the seamounts included in this study have been fished, and catches have been estimated from TCEPR/HSCER logbooks for individual features over the history of the fishery. The assignment of catches to seamounts was based on tows of less than 30 minutes duration, within 10 km of the summit peak position (after O'Driscoll & Clark 2005) for seamounts of the West Norfolk Ridge, Lord Howe Rise, and Northwest Challenger Plateau. On the Louisville Ridge, there is no adjacent slope or non-seamount habitat, and because the seamounts are all large, no length or distance criteria were applied. The plot of predicted biomass against historical catch shows a positive relationship (Figure 14). There are notable outliers on the Louisville Ridge (seamounts 34, 36, 38), but in general there is a good correspondence between high predicted biomass and large catches.

Table 13: Summary of effect values and estimated biomass (t) of orange roughy for the seamounts. Region, summit depth and slope effects are those values used in the Individual Seamount model, while the latitude effect is used to estimate a region effect.

IFA_no	Region	LAT_effect	ASSOC_effect	REGION_effect	DEPTH_effect	SLOPE_effect	Biomass
1	WestNorfolk	-0.45	-1	-0.72	-0.41	0.46	503
2	WestNorfolk	-0.45	-1	-0.72	0.02	0.08	528
3	WestNorfolk	-0.45	-1	-0.72	-0.64	0.46	399
4	WestNorfolk	-0.45	-1	-0.72	0.95	0.08	1339
5	WestNorfolk	-0.45	-1	-0.72	0.95	0.46	1959
6	WestNorfolk	-0.45	-1	-0.72	0.95	0.46	1959
7	WestNorfolk	-0.45	-1	-0.72	0.95	0.46	1959
8	WestNorfolk	-0.45	-1	-0.72	0.95	0.46	1959
9	WestNorfolk	-0.45	-1	-0.72	0.95	0.46	1959
10	WestNorfolk	-0.45	-1	-0.72	0.95	0.46	1959
11	NWChallenger	-0.01	0	-0.88	0.65	0.08	846
12	NWChallenger	-0.01	0	-0.88	0.95	0.08	1141
13	NWChallenger	-0.01	0	-0.88	-0.19	0.08	365
14	NWChallenger	-0.01	0	-0.88	0.76	0.08	944
15	NWChallenger	-0.01	0	-0.88	0.76	0.08	944
16	NWChallenger	-0.01	0	-0.88	0.02	0.08	450
17	NWChallenger	-0.01	0	-0.88	0.95	0.08	1141
18	NWChallenger	-0.01	0	-0.88	-0.19	0.08	365
19	NWChallenger	-0.01	0	-0.88	0.19	0.08	534
20	NWChallenger	-0.01	0	-0.88	-0.64	0.46	340
21	NWChallenger	-0.01	0	-0.88	-0.64	0.46	340
22	NWChallenger	-0.01	0	-0.88	-0.41	0.46	428
23	NWChallenger	-0.01	0	-0.88	-0.19	0.46	534
24	NWChallenger	-0.01	0	-0.88	-0.41	0.46	428
25	Lord Howe	-0.45	0	0.28	0.19	0.08	1703
26	Lord Howe	-0.45	0	0.28	0.02	-0.22	1064
27	Lord Howe	-0.45	0	0.28	-0.41	0.46	1366
28	Louisville (SS)	-0.77	-1	-0.57	0.95	0.08	1556
29	Louisville (S)	-0.3	-1	-0.57	0.95	0.08	1556
30	Louisville (S)	-0.3	-1	-0.57	-0.64	0.08	317
31	Louisville (S)	-0.3	-1	-0.57	0.95	0.08	1556
32	Louisville (S)	-0.3	-1	-0.57	0.95	0.08	1556
33	Louisville (S)	-0.3	-1	-0.57	0.95	0.46	2276
34	Louisville (C)	0.39	-1	0.83	0.39	0.46	5271
35	Louisville (C)	0.39	-1	0.83	-0.64	0.08	1287
36	Louisville (C)	0.39	-1	0.83	0.65	0.46	6836
37	Louisville (C)	0.39	-1	0.83	0.02	0.08	2490
38	Louisville (C)	0.39	-1	0.83	0.65	0.46	6836
39	Louisville (C)	0.33	-1	0.83	-0.41	0.08	1620
40	Louisville (C)	0.33	-1	0.83	0.19	0.46	4316
41	Louisville (C)	0.33	-1	0.83	0.65	-0.22	3463
42	Louisville (C)	0.33	-1	0.83	0.76	0.08	5219
43	Louisville (C)	0.33	-1	0.83	-0.64	0.08	1287
44	Louisville (N)	0.33	-1	-0.35	-0.64	0.46	578
45	Louisville (N)	0.33	-1	-0.35	-0.64	0.08	395
46	Louisville (N)	0.33	-1	-0.35	-0.64	0.08	395
47	Louisville (N)	0.33	-1	-0.35	-0.19	0.46	907
48	Louisville (N)	-0.01	-1	-0.35	0.95	0.46	2836
49	Louisville (N)	-0.01	-1	-0.35	-0.64	0.46	578
50	Louisville (N)	-0.01	-1	-0.35	-0.64	0.08	395
51	Louisville (N)	-0.45	-1	-0.35	-0.64	0.08	395
52	Louisville (N)	-0.45	-1	-0.35	-0.64	0.08	395
53	Louisville (N)	-0.45	-1	-0.35	-0.64	0.08	395
54	Louisville(N)	-0.45	-1	-0.35	-0.64	-0.41	242
55	Louisville(NN)	-0.45	-1	-0.72	-0.64	-0.41	167
56	Louisville(NN)	-0.45	-1	-0.72	-0.64	0.08	273
57	Louisville(NN)	-0.45	-1	-0.72	-0.64	0.08	273
58	Louisville(NN)	-0.45	-1	-0.72	-0.64	0.08	273
59	Louisville(NN)	-0.45	-1	-0.72	-0.64	0.46	399

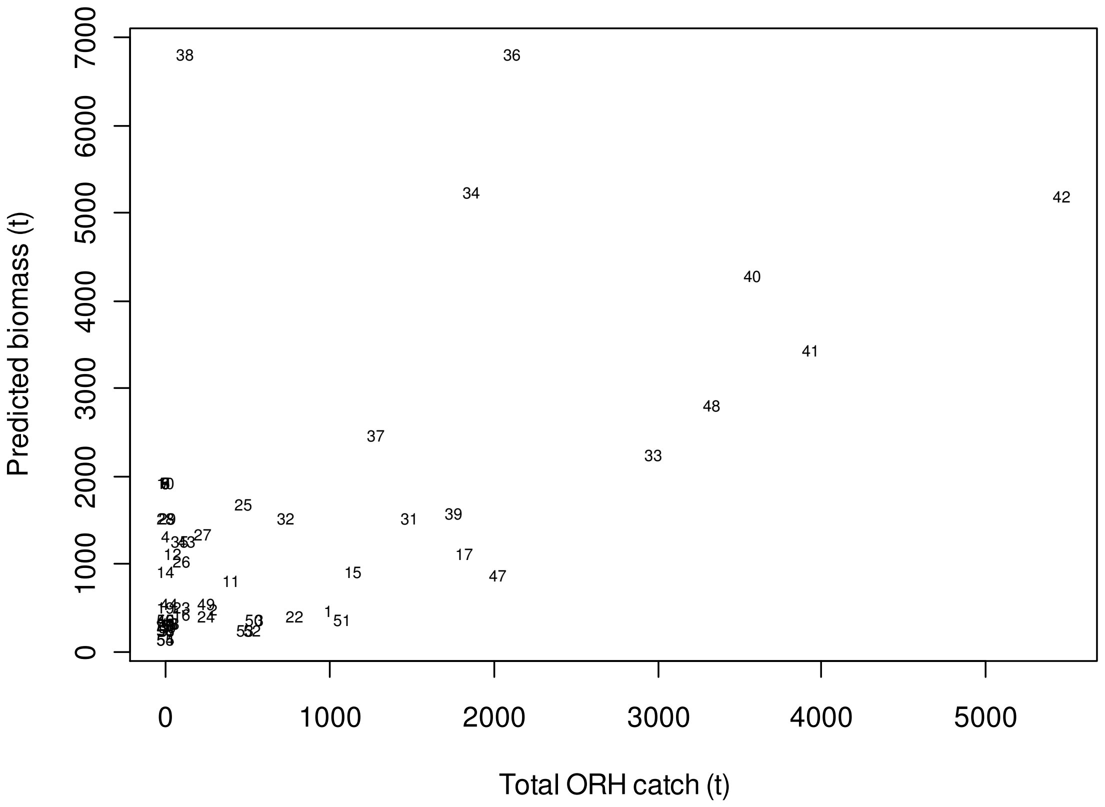

Figure 14: Predicted biomass plotted against the total recorded estimated catch for each of the 59 seamounts in the study. The plotting symbols represent the IFA_no for each seamount (see Appendix 1)

The geographical distribution of predicted biomass compared with reported catch is shown for all the seamounts in the study in Figure 15. Although there is a general correspondence between predicted biomass and historical catch, the pattern is variable between seamounts. On the West Norfolk Ridge the northern seamounts have relatively high levels of predicted biomass, yet little catch. The shallower seamounts on the Northwest Challenger Plateau similarly have low catch levels relative to their predicted biomass. Northernmost seamounts on the Louisville Ridge have low predicted biomass and low catch. In the southern part of North Louisville Ridge both predicted biomass and catch increase, and this continues into the central region. This is where seamounts 34, 36, and 38 are anomalous, with high predicted biomass yet low catches. This may simply reflect variability in the size of fish populations on seamounts, or could be due to the model averaging environmental factors over a wide range that may not adequately represent some of the small-scale features of seamounts, or not picking up the main drivers of orange roughy distribution in some cases, or it could be explained by the seamounts being difficult to fish if the seafloor is too steep or rough. These seamounts also have summit depths less than 750 m, whereas the main fished seamounts are typically deeper than this, and so there may be a depth effect which is not being captured well in the model.

Several of these areas outside the EEZ are approaching the "edges" of known orange roughy distribution. Orange roughy rarely occur north of 30° S, and the aggregations fished on the southern section of the West Norfolk Ridge are the most northerly known in the region. Similarly, orange roughy on the Louisville Ridge extend towards the northern, eastern, and southern limits of orange roughy distribution in the New Zealand area. In such situations, extrapolating biomass predictions beyond the known distribution of orange roughy aggregations may overestimate the biomass and be a bias in the method. As a check on this, plots were made of the known distribution of fishing activity in relation to the seamount location (Figures 16 to 21).

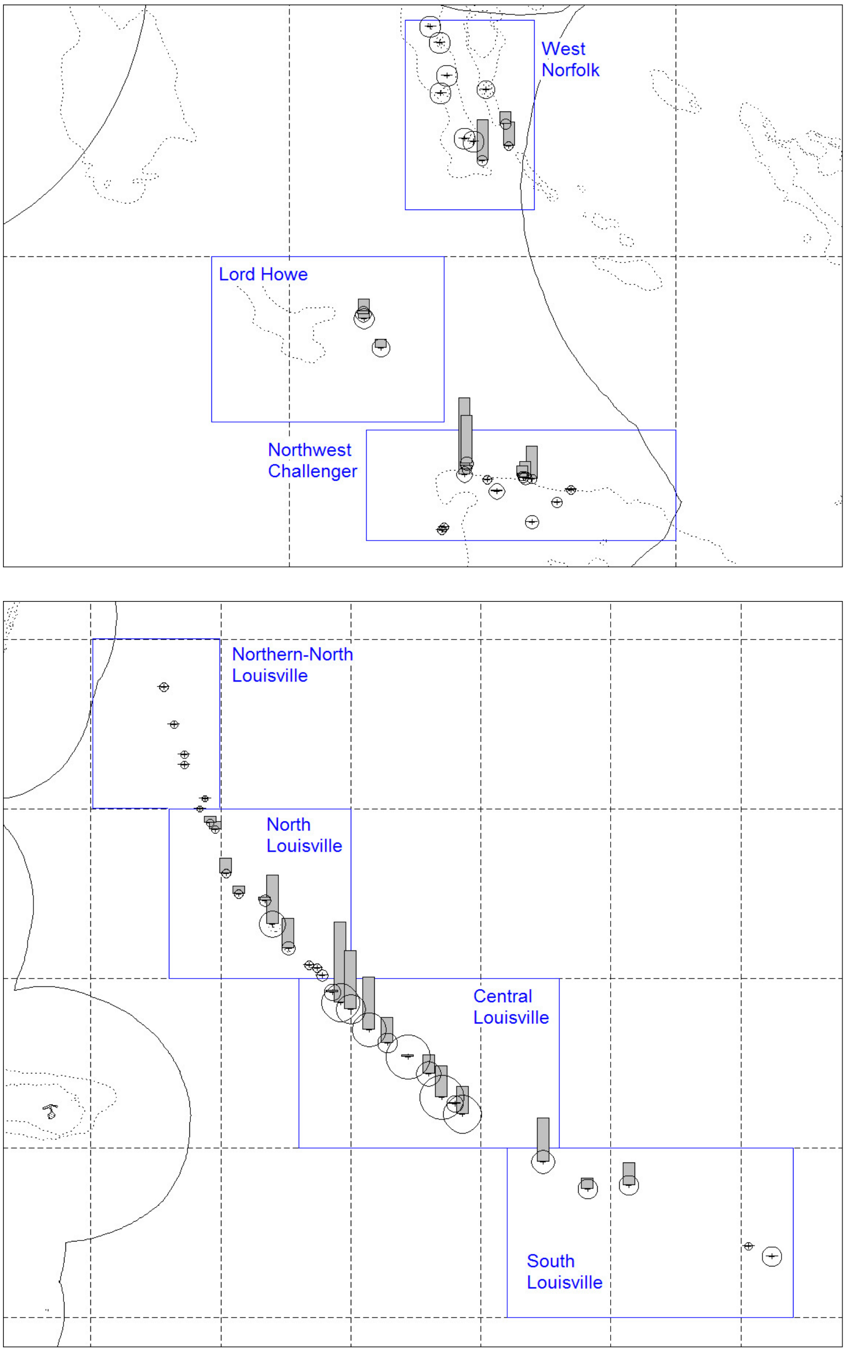

Figure 15: Predicted orange roughy biomass (open circles), and distribution of catch (bars) on seamounts outside the EEZ (top panel: Lord Howe Rise, NW Challenger, West Norfolk: maximum biomass=2000 t, catch=1800 t): bottom panel Louisville Ridge: maximum biomass=6850 t, catch=5500 t)

The West Norfolk seamounts included in this study were mainly new ones identified during this study, and not included in the previous work by Clark et al. (2001). These are also the most recently fished seamounts and so opportunities for comparison between reported catch and estimated biomass are limited. However, most catch on the ridge is known to come from small seamount features separated from the main ridge, and not from the general ridge area. Commercial tows have been made north of the area of high catch rates (Figure 16) with little success, and trawls done during the NORFANZ research survey in 2003 on this bank and further north also caught only low numbers of orange roughy. The northernmost five seamounts in this area have no recorded catch, and may be beyond the limit of high densities of orange roughy. Hence predicted biomass is likely to be too high, and it may be more realistic to exclude these seamounts in the total regional biomass estimate.

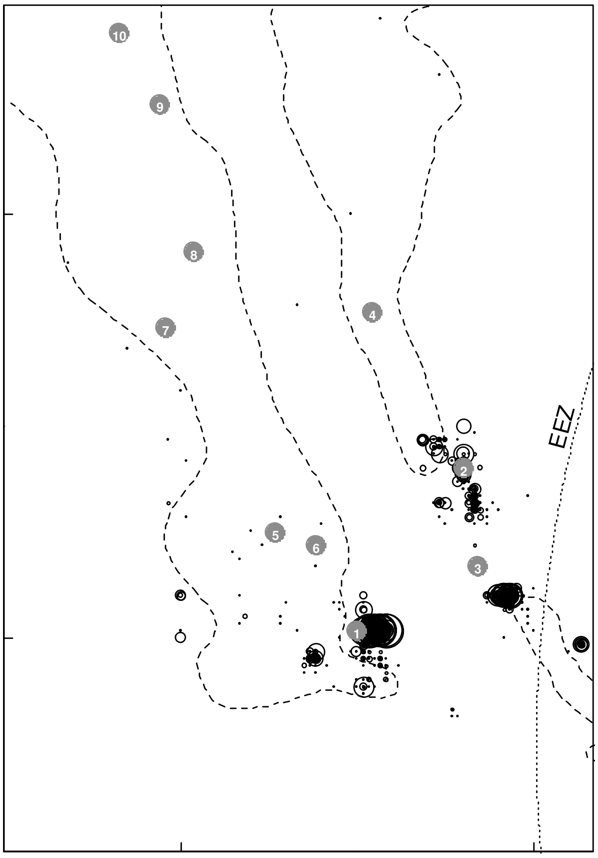

Figure 16: The West Norfolk Ridge, showing location of the seamounts in this study (grey dots) and catch per tow of orange roughy from 1981 to 2008 (open circles). The area of the circles is proportional to catch, with a maximum of 36 t. The dashed line shows the 1000 m depth contour.

The distribution of high catch rates in areas of the Lord Howe Rise (Figure 17) and Northwest Challenger Plateau (Figure 18) show no equivalent decrease or cut-off. All seamounts had reported catch. Orange roughy are known to occur throughout these areas, and although several of the seamounts in the latter region have low catches, this is unlikely to be due to a major distributional change, as orange roughy fisheries occur further south on the Challenger Plateau, and there is a continual distribution along the western margin of the Plateau (see Clark 2008).

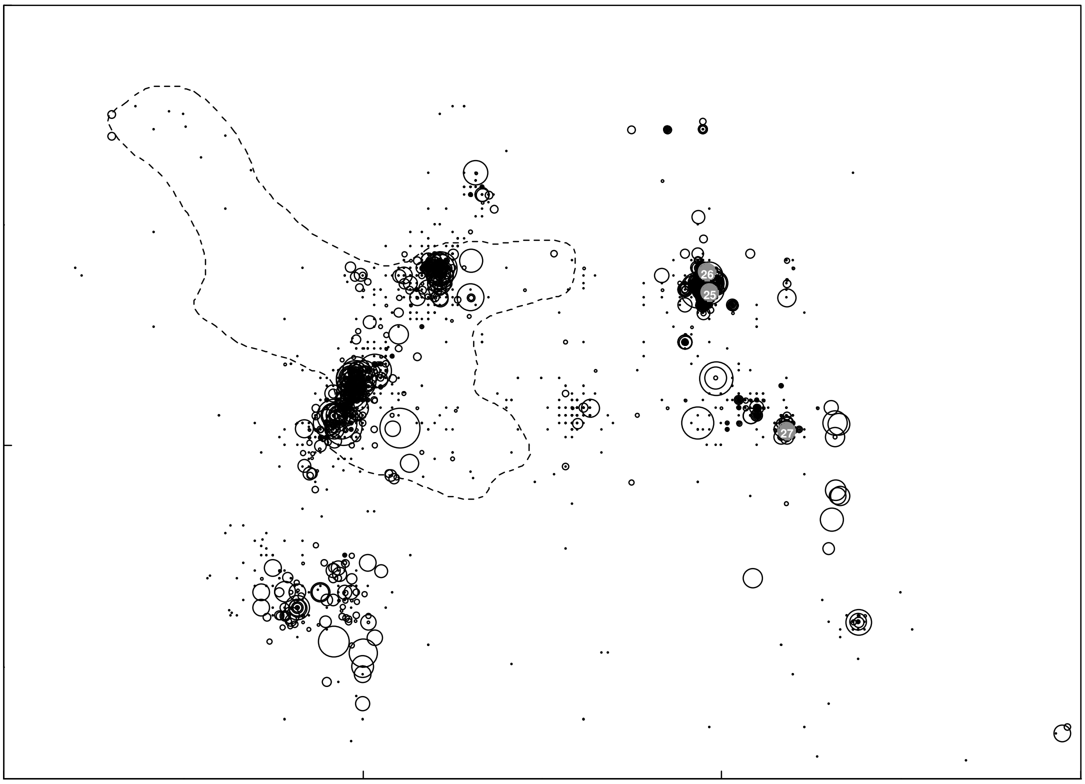

Figure 17: The Lord Howe Rise, showing location of the seamounts in this study (grey dots) and catch per tow of orange roughy from 1981 to 2008 (open circles). The area of the circles is proportional to catch, with a maximum of 60 t. The dashed line shows the 1000 m depth contour.

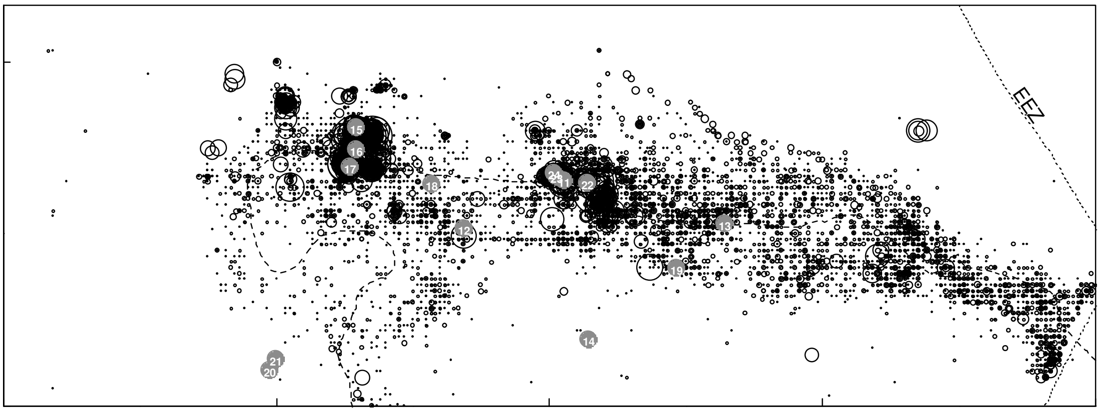

Figure 18: The Northwest Challenger Plateau, showing location of the seamounts in this study (grey dots) and catch per tow of orange roughy from 1981 to 2008 (open circles). The area of the circles is proportional to catch, with a maximum of 70 t. The dashed line shows the 1000 m depth contour.

The five seamounts in the northern North Louisville region (Figure 19) have low predicted biomass, and very little fishing has occurred there. All but one seamount has no reported catch, and seamount 57 has less than 50 kg reported. Seamounts in the North Louisville region have been fished extensively (only three have no catch), and there is a good match between the seamounts in the area and fishing activity. All the known seamounts in the central region of the Louisville Ridge (Figure 20) have been fished, and there is no distributional effect likely on the seamounts where catches or catch rates have been low.

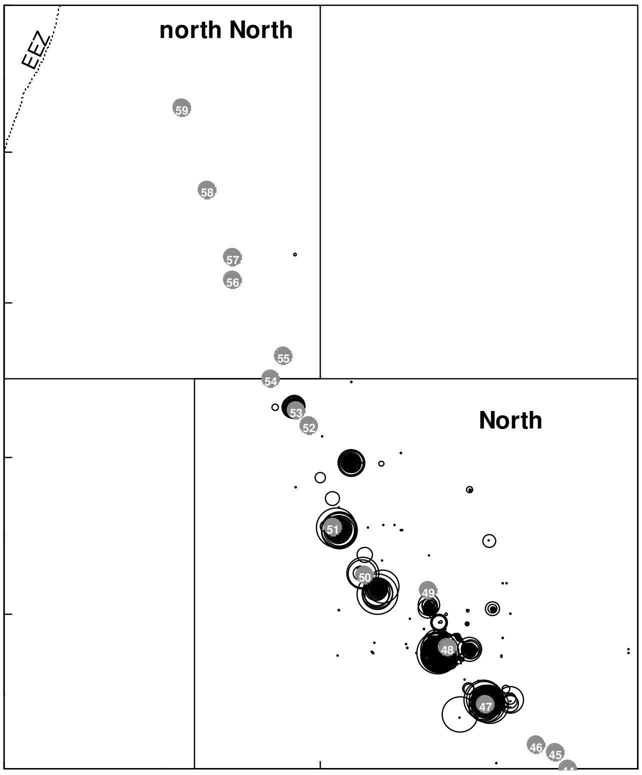

Figure 19: The Louisville Ridge (northern regions), showing location of the seamounts in this study (grey dots) and catch per tow of orange roughy from 1981 to 2008 (open circles). The area of the circles is proportional to catch, with a maximum of 70 t.

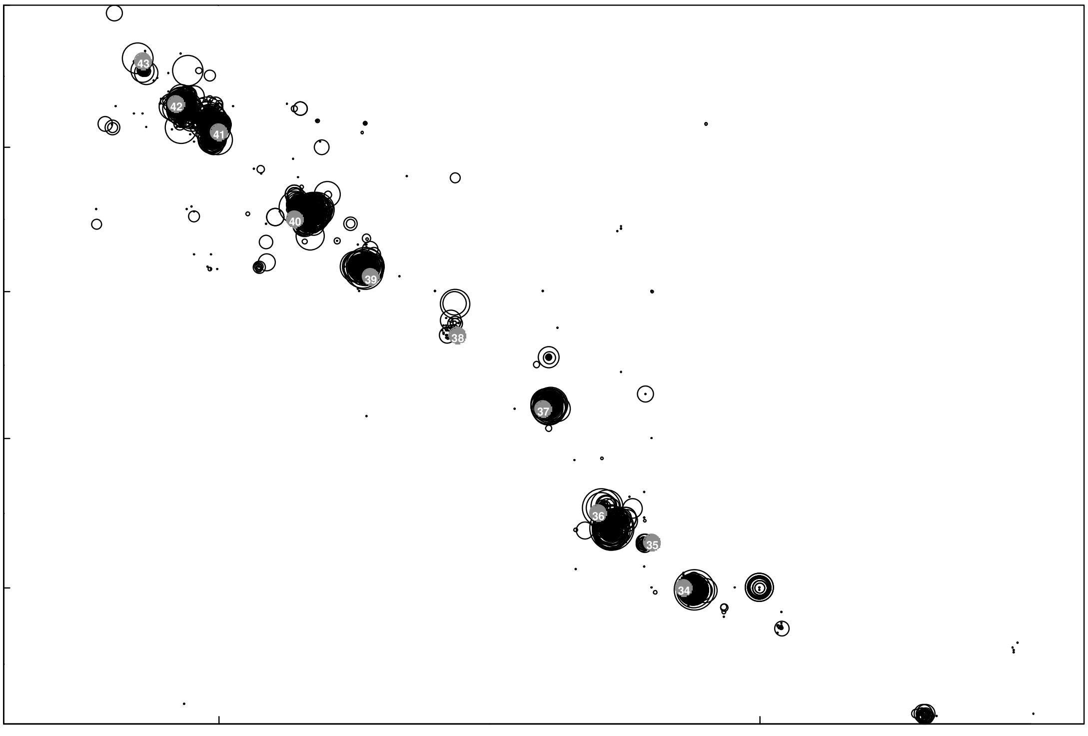

Figure 20: The Louisville Ridge (central region), showing location of the seamounts in this study (grey dots) and catch per tow of orange roughy from 1981 to 2008 (open circles). The area of the circles is proportional to catch, with a maximum of 80 t.

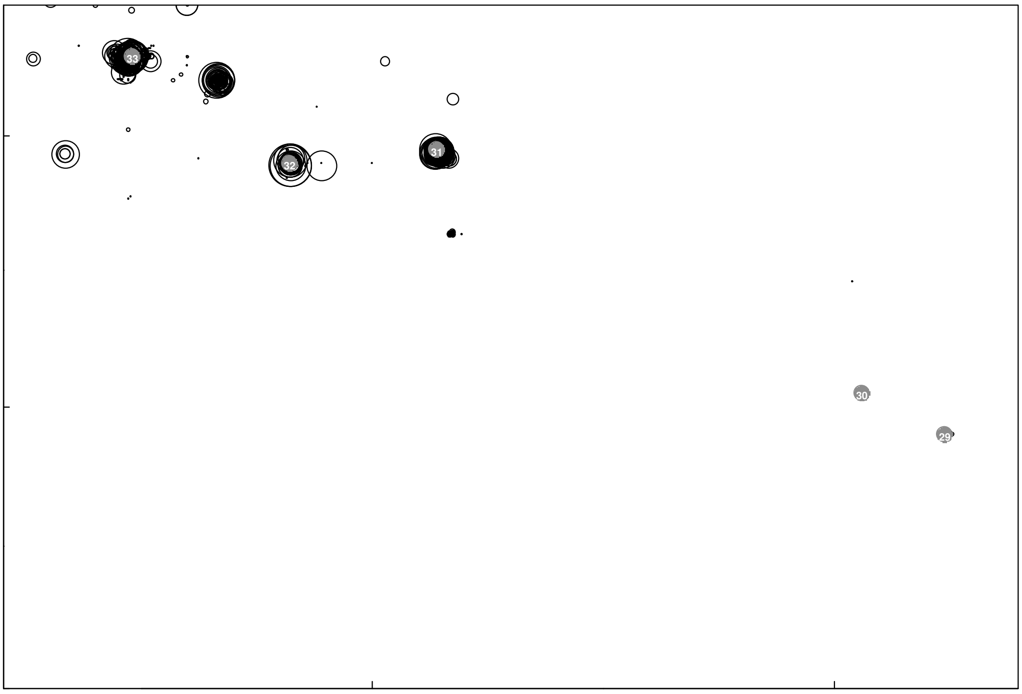

Figure 21: The Louisville Ridge (southern region), showing location of the seamounts in this study (grey dots) and catch per tow of orange roughy from 1981 to 2008 (open circles). The area of the circles is proportional to catch, with a maximum of 88 t.

All the seamounts in the southern Louisville Ridge area have been fished (Figure 21), although seamounts 29 and 30 to the east have reported catches less than 50 kg. Seamount 28 further southeast again (and not plotted) had no recorded effort or catch of orange roughy. The seamounts towards the eastern extent of the area examined here may also be beyond the limits of high density orange roughy distribution.

The removal of predicted biomass attributed to seamounts that are likely to extend beyond the distributional range of high-density orange roughy reduces the biomass estimates for West Norfolk, North North Louisville, and South Louisville (Table 14). Regions of the Lord Howe Rise, Northwest Challenger Plateau, North and Central Louisville are unaltered.

Table 14: Comparison of predicted biomass by region, total reported orange roughy catch, and estimated yields per region (values in parentheses are yields based on the adjusted biomass values).

Region	No. seamounts	Total Predicted biomass (t)	Adjusted Predicted biomass (t)	Reported catch (t)	MCY (t)	MAY (t)
West Norfolk	10	14 520	5 350[a]	1 838	220 (80)	290 (110)
Lord Howe	3	4 130	4 130	786	60	80
NW Challenger	14	8 800	8 800	4 646	130	170
North North Louisville	5	1 390	170[b]	1	20 (3)	30 (3)
North Louisville	11	7 510	7 510	8 214	110	150
Central Louisville	10	38 620	38 620	20 307	580	770
South Louisville	6	8 820	5 200[c]	5 176	130 (80)	170 (100)

[a] removal of seamounts 4, 7, 8, 9, 10.

[b] removal of seamounts 56, 57, 58, 59

[c] removal of seamounts 28, 29, 30

3.4.3 Sensitivity analysis

Although model cross validation showed that the region effects calculated from the individual seamount model of Clark et al. (2001) provided considerably more predictive power than a simple model lacking individual seamount physical variables, overall regional biomass was recalculated using only the region effects derived from the region effects model, as a sensitivity. Regional effects were available from the individual seamount model for three regions: Northwest Challenger, North Louisville, and Central Louisville.

For the North Louisville region, the region effect was very similar for the two models and the alternative biomass estimates were within 7% of each other (Table 15). In the other two regions the alternative estimates differed considerably, the region effects model estimate of biomass for Northwest Challenger being nearly five times, and for Central Louisville about half, that of the base case.

Table 15: Comparison of region effects from the individual seamount model and region effects model of Clark et al. (2001) and resultant regional biomass estimates, for the three regions for which comparisons are possible.

	Region effect		Biomass	
Region	Clark et al. (2001)	Model	Base Case	Alternative (model region effects)
NW Challenger	-0.88	0.72	8800	43590
North Louisville	-0.35	-0.28	7510	8060
Central Louisville	0.83	0.12	38620	18990

3.4.4 Yield estimation

Estimates of MCY and MAY are given in Table 14. These are based on a fixed percentage of virgin biomass (Ministry of Fisheries 2009). It is assumed that the predicted minimum biomass estimates from the seamount model approximate virgin biomass on the seamounts. It is also assumed the seamounts are independent, as biomass estimates are summed for each region before applying the percentage calculation.

The MCY estimates for Lord Howe Rise, Northwest Challenger, and West Norfolk Ridge range from 60 t to 220 t, depending on the assumptions made about seamount location and orange roughy distribution. The highest estimated yield is for the Louisville Ridge, with the combined regional total being 800–850 t.

These estimates are generally less than historical reported catch (Table 16), but for Lord Howe Rise, Northwest Challenger and Louisville Ridge not markedly different from the levels in recent years.

Table 16: Estimated catches (t) of orange roughy for ET fisheries from 1987–88 to 2006–07. Source, Ministry of Fisheries (2009).

Fishing year	Lord Howe	NW Challenger	Louisville	West Norfolk
1987–88	4 000	5	0	0
1988–89	2 430	297	0	0
1989–90	927	425	0	0
1990–01	282	123	0	0
1991–02	859	620	0	0
1992–03	2 300	2 463	0	0
1993–04	840	1 731	689	0
1994–05	761	1 138	13 252	0
1995–06	5	500	8 816	0
1996–07	139	332	3 209	0
1997–08	26	397	1 404	0
1998–09	440	961	3 164	0
1999–00	52	473	1 369	0
2000–01	428	1 228	1 598	10
2001–02	120	2 075	1 004	649
2002–03	272	1 010	1 296	94
2003–04	324	654	1 419	90
2004–05	430	464	1 510	277
2005–06	240	201	675	727
2006–07	40	96	323	552

3.4 Discussion of the seamount meta-analysis

Orange roughy fisheries typically occur on small seamount features which may be only a few square kilometres in size, and have an elevation of a few hundred metres. Although the general bathymetry is well known in the New Zealand region, as one goes further offshore the availability of bathymetric data for such small features becomes limiting. As part of this study, multibeam sonar lines were examined, and new features added to the New Zealand seamount database on the Northwest Challenger Plateau (7 new hills, although 2 were too shallow at the base to support orange roughy and hence excluded) and West Norfolk Ridge (5 new hills). However, it is likely there are further seamount features in the areas that are unknown to us, and that the true number of seamount features is higher than used here.

The variables included in the model (depth, latitude, oceanic association, and slope) all appear biologically meaningful (Clark et al. 2001). However, the original data used in the study did not enable the full relationship for some to be well described. For example, the depth effect modelled a maximum effect at 600 m, with a decline as summit depth increased. There were few data from shallow seamounts, and so the expected decline with shallow depth was not captured by the modelling. Depth can alias many biological processes, and care is needed interpreting the relative effects of this variable. Adult orange roughy typically occur in Antarctic Intermediate Water in the New Zealand region, and this typically has its core (defined by a salinity minimum) at depths around 800–1000 m. The modelled peak at 600 m may be too shallow.

The effect of slope in the model decreases with increasing steepness. Seamounts with a gentle slope are predicted to have more orange roughy than steep-sided seamounts (all else being equal). This appears sensible, as a seamount with a gradual slope will have a larger area at any given depth, and therefore more suitable habitat for orange roughy. However, seamounts with areas of steep slope can be difficult to trawl successfully, and hence catch records used in the initial analysis may reflect available biomass rather than total biomass. Almost 90% of the seamounts used by Clark et al. (2001) had a slope index of less than 0.3, which equates to about 18°. The average slope on most of these seamounts would therefore be trawlable, although there could be parts of the seamounts that are too steep, or too rough, for trawling. As many of the seamounts in this study were relatively shallow (a quarter are less than 600 m deep at the summit), and slope is not well known unless there is detailed bathymetry, one needs to be careful when interpreting the accuracy of the predictions.

The region effect is very important, and small variations in the value used in the model make a relatively large difference to the predicted biomass. Although the 2001 work established a relationship and formula for estimating the regional effect, there was high variability in the comparison of actual versus predicted values (Clark et al. 2001). Hence we used the actual values for regions where they were available from the 2001 study, and used the formula to estimate regional effects only for new regions (Louisville northern North, Louisville South, West Norfolk Ridge, and Lord Howe). We also looked at the trend in the effect with region, in particular ensuring that trends in the relative effect values seemed sensible given our knowledge of orange roughy distribution and abundance in the New Zealand region. For example, the latitude effect has a strong bearing on the region effect value. This showed a decreasing trend either side of 41–43° S, which is supported by the distribution of major fisheries over time. Nevertheless, the sensitivity runs highlighted the large discrepancies in estimates of biomass between the formula-derived and calculated region effect values. The estimates from North Louisville were similar, but Northwest Challenger and Central Louisville values differed by 2–4 times. This emphasises the caution that needs to be exercised when interpreting the predicted biomass estimates.

There are no estimates of error or variance associated with the predicted values of catch for a new seamount. Normally a bootstrapping procedure would have been applied, but this was not possible given the two-stage approach taken in the meta-analysis study. However, plots of predicted versus actual biomass (figures 14 and 17 in Clark et al. (2001)) show there can be considerable variability in biomass estimates.

The extent of residency of orange roughy on seamounts in not well known. There appear to be several uses of seamount habitat, for feeding and spawning, at various time of the year. Migration on and off seamounts occurs, and this does not necessarily follow a consistent pattern between areas or years. The initial method of calculating biomass included all known catch from a seamount. This would therefore give high biomass estimates for seamounts where aggregations for spawning occurred, with fish migrating in from a wider area during the spawning months. Percent spawning was included in the original analysis, but was not significant. Nevertheless, if migration does occur, the prediction based on catch history could overestimate the biomass that is resident on the seamount. If little fishing occurred on the population outside the spawning season on the slope or other seamounts not covered in the study (as seems likely for the Louisville Ridge and West Norfolk areas), this might not be a significant error. However, if the population was being exploited on non-seamount habitat (as occurs in the Challenger and Lord Howe Rise areas), then catch limits based on this analysis could be too high.

Estimates of original (minimum) biomass derived in the initial analyses by Clark et al. (2001) were based on a deterministic age-structured model used extensively at that time for orange roughy stock assessment (Francis 1992). This model back-calculated the original biomass required to support the catch history. Long-term average recruitment was assumed, and this may not necessarily be appropriate, as recent research suggests orange roughy recruitment may be variable, and low for extended periods (e.g., Francis & Clark 2005). If assumed annual recruitment over the period of the fishery on the seamount was too high, then the estimated biomass would be too high.

The method applied here has many uncertainties, in addition to the qualifications above about the within-model variables. Predicted biomass could be overestimated if seamounts are included which are beyond the appropriate distribution of orange roughy (or the appropriate region effect), if assumed productivity in the orange roughy model used to estimate B_{min} was too high, or if catches used in the catch history are a combination of resident seamount fish and those from a wider stock/population that visit from adjacent slope areas. Conversely, predicted biomass could be too low if bathymetry is poorly known, and more seamounts exist in the region, if the reported catch history was insufficient to represent the fully developed fishery, if catches were low because the seamount was too rough or steep, or if much of the population in an area is on the adjacent slopes, and not on seamounts. Nevertheless, results of this study are generally consistent with the catch history, and with knowledge and experience from other fisheries inside the EEZ. Long-term yield estimates for each area are in the order of hundreds of tonnes, not thousands, and highlight that careful management is required to ensure these fisheries are sustainable.

The method could be enhanced in future by using the more extensive data on orange roughy seamount catch that exists now compared with the 2001 study. Longer catch histories for more seamounts are available, and this would improve the reliability of the regression formulae. The region effect in particular could be more tightly defined, and more seamounts close to the limits of orange roughy fishery distribution (e.g., Macquarie Ridge, Louisville Ridge, outer Bay of Plenty) would reduce the uncertainty of the "edge" effect.

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Appendix 1: Physical characteristics of seamounts included in this study.

IFA_no	Region	Latitude	Longitude	Summit(m)	Elevation(m)	Area (km2)
1	WestNorfolk	-33.98	167.50	915	335	15.0
2	WestNorfolk	-33.60	167.80	830	370	4.9
3	WestNorfolk	-33.83	167.84	966	534	40.0
4	WestNorfolk	-33.23	167.54	450	1050	50.0
5	WestNorfolk	-33.75	167.27	250	450	50.0
6	WestNorfolk	-33.78	167.38	480	270	10.0
7	WestNorfolk	-33.27	166.96	540	210	7.5
8	WestNorfolk	-33.09	167.04	450	250	25.0
9	WestNorfolk	-32.74	166.94	230	470	55.0
10	WestNorfolk	-32.57	166.83	480	270	27.0
11	NW Challenger	-37.34	168.05	695	255	4.2
12	NW Challenger	-37.48	167.68	595	365	4.0
13	NW Challenger	-37.47	168.64	899	101	1.0
14	NW Challenger	-37.81	168.14	609	191	1.0
15	NW Challenger	-37.19	167.23	606	394	4.0
16	NW Challenger	-37.25	167.29	822	178	1.5
17	NW Challenger	-37.31	167.27	578	322	4.0
18	NW Challenger	-37.36	167.57	874	126	1.0
19	NW Challenger	-37.60	168.47	752	148	1.5
20	NW Challenger	-37.89	166.97	1187	163	16.0
21	NW Challenger	-37.86	166.99	1242	108	1.5
22	NW Challenger	-37.35	168.14	940	80	1.3
23	NW Challenger	-37.33	168.02	898	77	1.1
24	NW Challenger	-37.32	168.01	923	52	0.6
25	Lord Howe	-35.65	165.97	772	428	5.0
26	Lord Howe	-35.61	165.96	807	393	3.0
27	Lord Howe	-35.97	166.18	920	280	11.8
28	Louisville (S.S)	-50.50	220.80	540	3660	1331.5
29	Louisville (S)	-48.20	211.20	490	4310	1739.1
30	Louisville (S)	-47.90	210.30	1090	3710	550.3
31	Louisville (S)	-46.10	205.70	590	4110	1148.1
32	Louisville (S)	-46.20	204.10	590	4210	1739.1
33	Louisville (S)	-45.40	202.40	540	3860	2201.0
34	Louisville (C)	-44.00	199.30	740	3260	1148.1
35	Louisville (C)	-43.70	199.00	1010	2690	434.8
36	Louisville (C)	-43.50	198.50	690	3310	1331.5
37	Louisville (C)	-42.80	198.00	810	3690	679.3
38	Louisville (C)	-42.30	197.20	655	3845	2717.3
39	Louisville (C)	-41.90	196.40	918	3082	679.3
40	Louisville (C)	-41.50	195.70	785	3216	3912.9
41	Louisville (C)	-40.90	195.00	662	3338	244.6
42	Louisville (C)	-40.70	194.60	620	3380	332.9
43	Louisville (C)	-40.40	194.30	1070	3080	332.9
44	Louisville (N)	-39.90	193.90	1410	2580	679.3
45	Louisville (N)	-39.70	193.70	1375	1625	169.8
46	Louisville (N)	-39.60	193.40	1385	2415	332.9
47	Louisville (N)	-39.10	192.60	880	3652	2717.3
48	Louisville (N)	-38.40	192.00	274	4507	3288.0
49	Louisville (N)	-37.70	191.00	1085	-1085	434.8
50	Louisville (N)	-37.50	190.70	1035	3613	332.9
51	Louisville (N)	-36.90	190.20	955	3868	1148.1
52	Louisville (N)	-35.60	189.80	1210	4076	434.8
53	Louisville (N)	-35.40	189.60	980	3920	679.3
54	Louisville (N)	-35.00	189.20	1390	4052	244.6
55	Louisville (N.N)	-34.70	189.40	1150	3950	244.6
56	Louisville (N.N)	-33.70	188.60	1250	5070	978.2
57	Louisville (N.N)	-33.40	188.60	1430	3670	550.3
58	Louisville (N.N)	-32.50	188.20	1490	3500	679.3
59	Louisville (N.N)	-31.40	187.80	1135	4390	3912.9