An holistic approach to determining stock structure of orange roughy on the Chatham Rise

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EXECUTIVE SUMMARY

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The stock structure of orange roughy on the Chatham Rise has been uncertain, and previous assessments have assumed between one and five separate management stocks. This report describes the development of a revised hypothesis of stock structure. The hypothesis was formulated using an holistic approach, where multiple observational data sets were analysed in order to maximise the likelihood of correctly defining stocks, given that no single data set would provide complete and unequivocal information.

The observational data that were summarised and/or analysed included catch distribution, catch-per-unit-effort (CPUE) trends, the location of spawning and nursery grounds, inferred migrations, differences in life history characteristics including patterns in length frequencies, length at maturity, and fish condition, genetic studies using allozymes or mitochondrial DNA, and habitat structure and natural boundaries.

No individual data set provided complete information on stock structure for the Chatham Rise, and no two individual data sets seemed to completely agree on stock numbers and boundaries. However, the holistic analysis favoured the assumption of two stocks on the Chatham Rise:

1. The northwest Chatham Rise. Having a western boundary at the Mernoo Gap and eastern boundary at 178° W.

2. The east and south Chatham Rise. Having the western boundary on the north Rise at 178° W, and including all of the east and south Chatham Rise.

These stocks were assumed to be bounded by relatively shallow water along the centre of the Chatham Rise, and by deeper water to the north, south, and east of the Chatham Rise.

This work was carried out under Ministry of Fisheries project ORH2007/05: Objective 1, "*To review, collate and where necessary analyse data to develop hypotheses of stock structure and migrations of orange roughy on the Chatham Rise.*"

1. INTRODUCTION

The orange roughy (*Hoplostethus atlanticus*) fishery on the Chatham Rise has been the largest and most persistent in the world (Branch 2001, Ministry of Fisheries 2009). The Chatham Rise is the north-eastern region of quota management area ORH 3B, the other regions being the Arrow Plateau, Sub-Antarctic, and Puysegur (Figure 1).

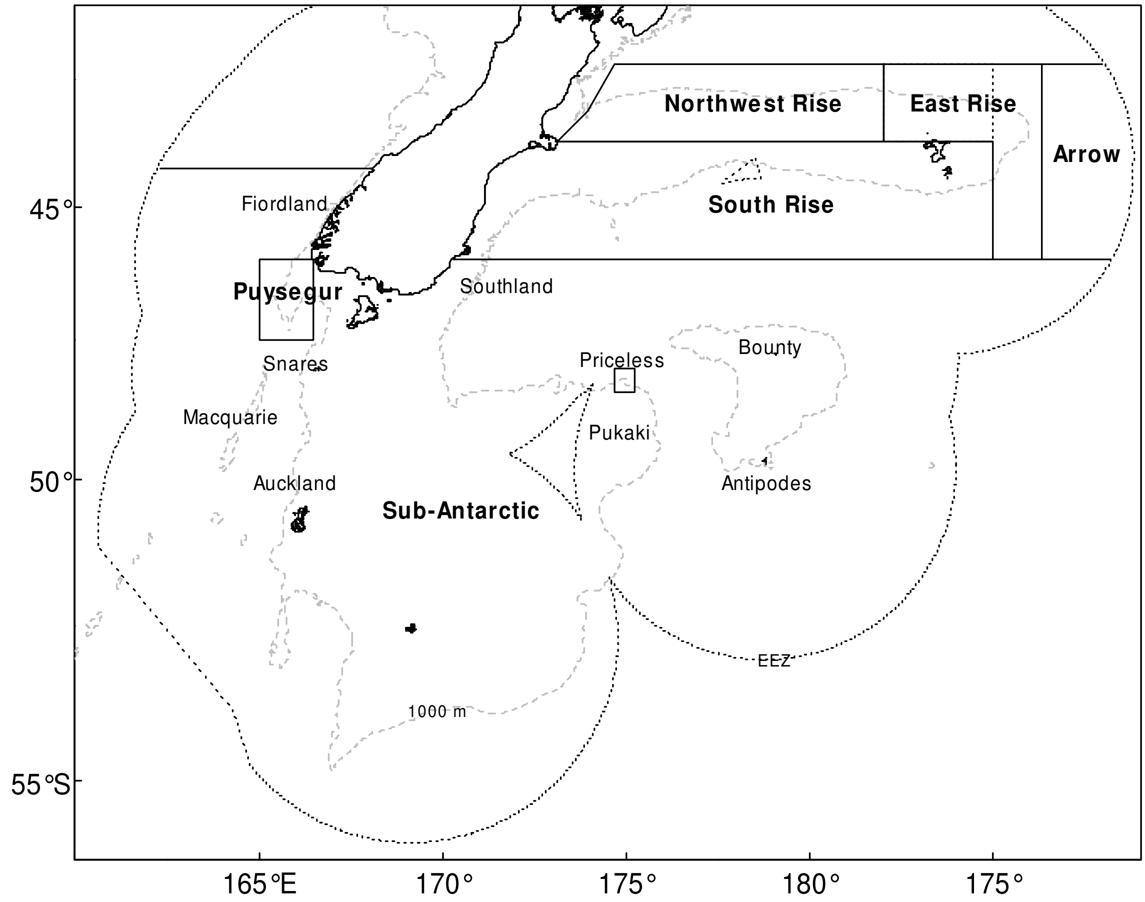


Figure 1: The ORH 3B designated subarea boundaries (drawn and labelled in bold font), and the approximate position of other named fisheries outside of the Chatham Rise (labelled in normal font). The Spawning Box is the western part of the area East Rise (to the west of the vertical broken line at 175° W). The Sub-Antarctic is all areas below 46° S on the east coast, and 44°16' S on the west coast, except Puysegur.

In this report, the term 'stock' has a different meaning from 'population', and follows the Harden-Jones (1968) definition:

"*Management stocks are considered to respond largely independently to the effects of exploitation, because recruitment, growth and mortality within the stock are of more significance than emigration or immigration to the stock*".

Different stocks might be expected to have, for example, separate spawning and nursery grounds, independent migrations, different biological characteristics, discrete fisheries, and different biomass trends.

Between 1983–84 and 1993–94, the stock assessments for the Chatham Rise assumed a single stock, with the fishery focused in the Spawning Box (Francis et al. 1993, Sissenwine & Mace 2007). Following the discovery of several other spawning aggregations on hill complexes outside of the

Spawning Box in the late 1980s and early 1990s, Punt (1993) considered multiple stock hypotheses for the Chatham Rise and conducted quantitative Bayesian assessments with between one and four separate stocks, albeit with few observational data (commercial catch-per-unit-effort (CPUE) indices were not used because CPUE were "no longer considered to be a reliable index of orange roughy abundance"). Probably as a result of the limited data, the resulting estimates of virgin biomass (B0) were almost completely determined by the virgin biomass priors. However, Punt found that for a given total stock biomass, assuming more than one stock, and/or less mixing into the Spawning Box, resulted in an overall stock complex with a higher virgin biomass and lower level of depletion.

The next stock assessment, in 1994–95, assumed three stocks: the Northwest, the East (referred to as "Northeast" in previous reports), and the South Chatham Rise (Francis et al. 1995, Figure 1). The East and Northwest were assumed to contain separate stocks because spawning occurred almost simultaneously in each area, and because the post-spawning migration out of the Spawning Box in the East was away from the assumed boundary between the two north Rise areas (Annala & Sullivan 1997). However, Annala & Sullivan (1997) reported that there might be more than one spawning stock on the East Rise, and that there was no clear boundary between the East and the South Rise, which might or might not contain a separate stock.

The three-stock assumption was maintained for stock assessments in 1998, 2001, and 2002 (Sissenwine & Mace 2007), but was modified during the 2005 assessment (Dunn 2006, 2007a, Ministry of Fisheries 2007). In this assessment, the Chatham Rise was effectively split into five stocks; the Northwest Rise, then the Spawning Box and Northeast Flats, Northeast Hills, and Andes (these three substocks together formed the East Rise), and then the South Rise (Figure 2).

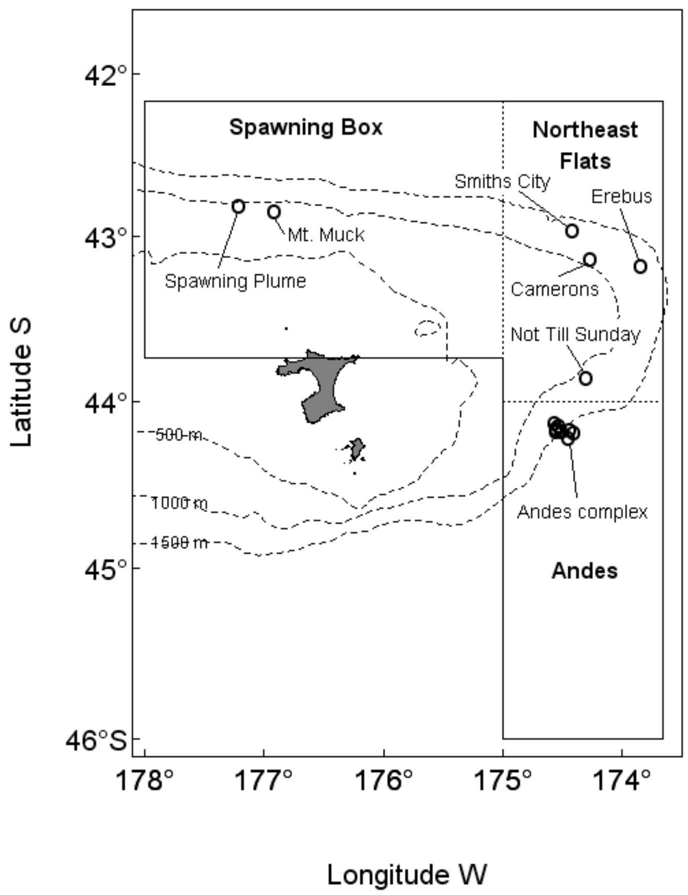


Figure 2: The east Chatham Rise area (solid box), showing the boundaries between the Spawning Box and Northeast Flats, and Northeast Flats and Andes (dotted lines), the position of the main features (circles), including the approximate position of the seasonal Spawning Plume. Mt Muck is also known as the "Crack". The Northeast Hills includes Smiths City, Erebus, Camerons, and Not till Sunday.

The main reason why the East Rise was split into three substocks was to allow all of the CPUE indices to be used, as they could not be reasonably combined within a single model because there was a conflict between a predicted biomass rebuild for any stock which contained the Spawning Box fishery, and declining CPUE for the hill complexes (Dunn 2006). It was not considered likely that the groups of hills contained populations actually separate from the surrounding area, but rather that they might be substocks (Ministry of Fisheries 2007). In addition, management on a finer spatial scale might prevent serial depletion of hills (Clark 1999).

In 2008, stock assessment models were not used. This was because in the previous assessment of the Spawning Box and Eastern Flat substock all of the model runs predicted that the biomass had been rebuilding since catches were substantially reduced in the early 1990s, but this rebuild was insensitive to the recent observational data: when all of the data after 1994 were excluded the model gave an almost identical result to when they were included (Dunn 2007a, 2007b). From this, it became clear that the rebuild was being driven largely by model assumptions concerning productivity, rather than actual data. The previous stock assessment of the South Chatham Rise, which provided a poor fit to the observational data, assumed similar productivity, and also predicted a biomass rebuild which was not seen in the biomass indices (Anderson 2005). Therefore in 2008, rather than repeat the stock assessment models requiring a productivity assumption, a model-free "evaluation" of stock status was made (Dunn et al. 2008, Ministry of Fisheries 2008). In association with this, in 2008 the stock structure assumption was revisited, and the East Rise and South Rise subareas were combined and assumed to contain a single stock. As a result, at the end of 2008 the Chatham Rise was assumed to consist of 2 stocks, the Northwest Rise, and the East and South Rise (Ministry of Fisheries 2008).

This document describes the rationale for the combination of the East and South Rise into a single stock. The work was carried out under Ministry of Fisheries project ORH2007/05: Objective 1, "*To review, collate and where necessary analyse data to develop hypotheses of stock structure and migrations of orange roughy on the Chatham Rise.*"

2. METHODS

2.1 General approach

The testing of stock structure hypotheses followed an holistic approach, where all available and relevant observational data were used (Pawson & Jennings 1996, Begg & Waldman 1999). The observational data considered included:

- Distribution of catches (Ministry of Fisheries Science Group 2008).
- Historical CPUE trends (Dunn 2006).
- Location and timing of spawning (Smith et al. 2002, Ministry of Fisheries Science Group 2008).
- Location of nursery grounds.
- Ontogenetic patterns in length frequencies (to establish connectivity).
- Analysis of length frequency (Smith et al. 2002).
- Migrations inferred from CPUE analyses (Taylor 1993, Coburn & Doonan 1994, 1997, Doonan & Coombs 2004).
- Migrations inferred from length at maturity (Francis & Clark 1998).
- Habitat structure and natural boundaries.
- Genetics using allozymes (Elliott & Ward 1992, Smith & Benson 1997, Smith et al. 1997).
- Genetics using mitochondrial or nuclear DNA (Elliot et al. 1992, Smolenski et al. 1993, Smith et al. 1996, 1997, 2002).
- Age or length at maturity (Horn et al. 1998, Smith et al. 2002).
- Trends in fish condition.
- Morphometrics (Elliot et al. 1995, Haddon & Willis 1995, Gauldie & Jones 2000, Smith et al. 2002).

- Growth rates (Gauldie & Jones 2000).
- Natural tags, i.e., parasites (Lester et al. 1988, Gauldie & Jones 2000).
- Otolith microchemistry (Edmonds et al. 1991, Thresher & Proctor 2007).
- Artificial tags.

The citations above all refer to studies on orange roughy, but many of these were not done on the Chatham Rise: no citation above means the data had not been analysed for stock structure in orange roughy (to the best of our knowledge).

The observational data summarised and reviewed in this study included catch distribution, CPUE trends, spawning and nursery grounds, inferred migrations, differences in life history characteristics (from patterns from length frequencies, length at maturity, and fish condition), genetics (allozymes and mitochondrial DNA), and habitat structure and natural boundaries.

2.2 Catch and effort data

The groomed estimated catch and effort data for orange roughy fisheries on the Chatham Rise used in this analysis were described in detail by Anderson & Dunn (2008). More than 90% of the orange roughy catches on the Chatham Rise since 1993–94 were recorded on detailed (tow-by-tow) trawl catch effort processing return (TCEPR) forms. Catch distribution was analysed by allocating catches and effort to the nearest point on an axis which ran around the Chatham Rise, from northwest around to southwest (Figure 3).

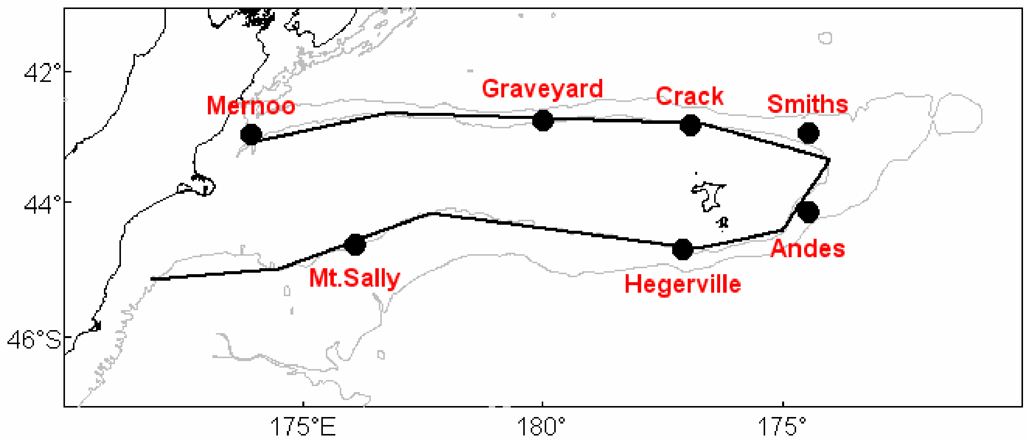


Figure 3: Distribution of the axis running around the Chatham Rise, and the location of hill features as labelled on subsequent figures. The features labelled are Mernoo Hill, the Graveyard Hills complex, the Crack, Smiths City, the Andes complex, Hegerville, and Mt Sally.

2.3 CPUE trends

The trends in standardised CPUE by year were all obtained from Mormede (2009).

2.4 Spawning and nursery grounds

The main spawning grounds on the Chatham Rise have been comprehensively described from commercial and research trawls and acoustic surveys (Clark et al. 2000, Dunn et al. 2008). In this study the occurrence of all observed spawning grounds was estimated using catch rates of ripe and running-ripe orange roughy sampled on board scientific research trawls, or by Ministry of Fisheries observers on board commercial trawlers. The proportion of female orange roughy by maturity stage sampled from each tow was obtained, along with tow details, from Ministry of Fisheries databases. The data were not groomed. The location of nursery grounds for orange roughy on the Chatham Rise was obtained from Dunn et al. (2009).

2.5 Inferred migrations

Migrations of orange roughy on the Chatham Rise have previously been inferred from CPUE data by Taylor (1993), Coburn & Doonan (1994, 1997), Doonan & Coombs (2004), and from maturity at length data by Francis & Clark (1998). In this analysis we also infer migrations from the seasonal effects estimated in published standardised CPUE analyses (McKenzie 2003, Dunn 2006, 2007a, Mormede 2009), and from published analyses of seasonal changes in length frequency (Francis 2006).

2.6 Ontogenetic shifts in distribution

Orange roughy length samples were sampled on board scientific research trawls, or by Ministry of Fisheries observers on board commercial trawlers. Data describing the length sample from each tow, and the tow details, were obtained from Ministry of Fisheries databases. The data set selected covered the period October 1979 to September 2007, and consisted of 7867 tows and 846 102 fish measured (Table 1).

Table 1: Number of tows sampled by source and fishing year. Fishing years run from 1 October to 30 September.

Fishing year	Research	Observer	Fishing year	Research	Observer
1978–79	35	0	1993–94	485	167
1979–80	50	0	1994–95	284	123
1980–81	1	0	1995–96	223	46
1981–82	244	0	1996–97	27	92
1982–83	3	0	1997–98	116	115
1983–84	137	0	1998–99	170	61
1984–85	125	0	1999–2000	72	129
1985–86	161	0	2000–01	40	230
1986–87	360	25	2001–02	318	193
1987–88	389	1	2002–03	3	269
1988–89	301	209	2003–04	127	113
1989–90	327	142	2004–05	114	300
1990–91	62	123	2005–06	79	229
1991–92	443	168	2006–07	81	142
1992–93	121	92	Total	4 898	2 969

Optimal stratification for the length frequency data was developed using a tree-based regression model described by Dunn (2008). The final regression trees were estimated using 10-fold cross-validation, and pruned back to the smallest sized tree within 1 standard deviation of the minimum of the cost-complexity measure. The analysis was completed by sex, using only tows where 20 or more fish were measured. Model runs used the median fish length or length range from each tow as the response variable. Final model runs were completed using a variety of environmental variables as potential predictors, including continuous variables describing the distance of the mid-point of the tow from the summit of the nearest known hill or seamount, the tow start longitude and latitude, time of day, tow depth, number of fish measured in the sample, the elevation, depth of the summit and base, mean depth of the nearest hill, and position on an axis running clockwise around the Chatham Rise roughly following the 1000 m isobath (similar to that shown in Figure 3), and categorical variables describing the year, month, season (June & July, May & August, and September to April), origin (MFish observer or research vessel), and distance to the nearest hill (in 2 km bins to 10 km, after which tows were allocated to an >10 km bin).

2.7 Length at maturity

Orange roughy catches from research survey data from the Chatham Rise were partitioned into one of 14 subareas: Eastern flats, South Rise, Northwest flats, Spawning Box, Graveyard hills, Andes hills, ORH 3A, Arrow Plateau, Hegerville and surrounds, Big Chief and neighbouring hills, Smiths City and neighbouring hills, The Hole, and the aggregated East Rise and Spawning box, and East hills (Andes, Smith City, and Big Chief) (Figure 4). Length, weight, and maturity status were collected on 70 research trips between 1980 and 2007. Orange roughy with macroscopic gonad stage 3 (ripe) or greater were considered mature (Clark et al. 2000).

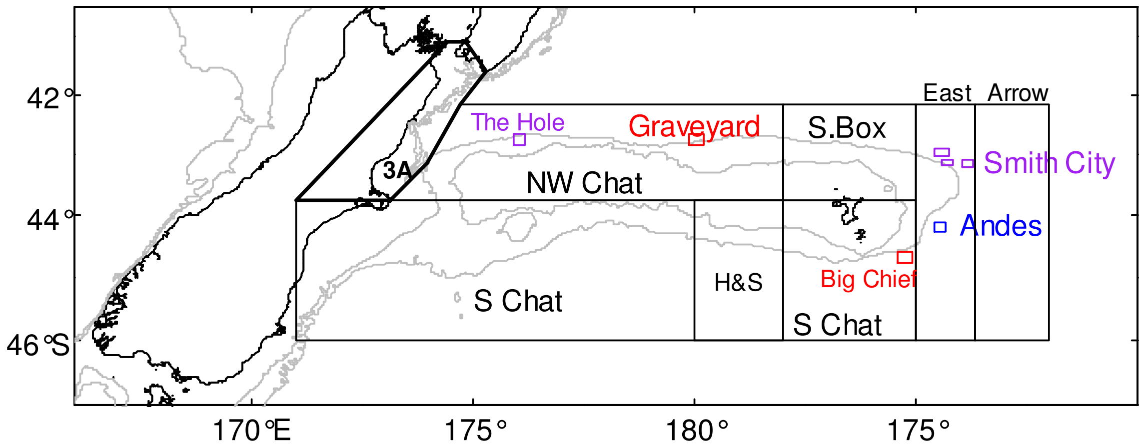


Figure 4. Location of the 12 orange roughy Chatham Rise subareas/stocks used in the length-at-maturity and condition analyses. S. Box, spawning box; H&S, Hegerville and surrounds; Arrow, Arrow Plateau.

Scaled numbers-at-length of immature and mature fish by trip were estimated for each sex and subarea using the NIWA catch-at-age software (Bull & Dunn 2002), implemented in R. The median month was chosen to represent sampling from the trip. Fish length records were resampled within each trip with replacement and the bootstrap length-frequency distributions were computed. Length frequency distributions were scaled to the catch using a length-weight relationship: for both sexes from the South Chatham Rise and Hegerville and surrounds this was $weight = 0.000921*length^{2.71}$; for both sexes from all other subareas this was $weight = 0.0008*length^{2.75}$ (Ministry of Fisheries 2008).

For each sex, subarea, and trip, median length at maturity was estimated using a generalised linear model (GLM) with a binomial error distribution and a logit link function. Trips were excluded where the number of mature or immature fish over all length classes was zero, or where too few fish of one maturation stage were measured to estimate the GLM (i.e., the length range of mature fish was much less than the length range of immature fish or vice versa). If in doubt, data were initially retained, and then excluded if the GLM failed to converge. Data were also excluded where estimates of median length-at-maturity were greater than 40 cm or less than 20 cm.

The effect of year on median length-at maturity for each sex and subarea was examined for data from spawning months only (June and July) using a GLM with a Gaussian error distribution and an identity link function. The base model was an intercept-only model. The model was then given the categorical predictor *year* to fit in a stepwise procedure. *Year* was retained in the model if the amount of deviance explained increased by at least 2%. The year effects in length at maturity were analysed for common trends in different regions. Length at maturity may decrease in four ways: (1) because of migration, where relatively more mature fish move into an area (Francis & Clark 1998); (2) because of a change in life history, including faster growth and/or earlier maturity; (3) because of a change in relative abundance, such as a decrease in recruitment; (4) because of changes in fishing selectivity or timing of fishing trips. Whilst an attempt was made to control for these factors using spatial and temporal data restrictions, further analyses would be necessary to prove the most likely causative factor.

2.8 Fish condition

Condition was described using Fulton's K and the relative condition factor. Fulton's K (Fulton 1904) is a measure of somatic condition and was estimated as:

$$K = \left(total\_body\_weight / gonad\_weight\right) \big/ L^3 \times 10^3$$

where L is fish length (cm) and weight is in grams. Fulton's K assumes that heavier fish for a given length are in better condition. Fulton's K has been shown to be related to lipid density, which is typically used as a measure of energetic state as lipids are the main energy source used during periods of reproduction, maturation, and starvation (Pangle & Sutton 2005). Fulton's K is useful to compare fish, irrespective of the value of the growth exponent (b) (Ricker 1975).

A relative condition factor, which relates actual weight (including gonads) to the estimated average weight of a fish in the population, was estimated as:

$$CF = observed\ weight / expected\ weight$$

where expected weight was estimated from the length-weight parameters given in Section 2.6.

The potential predictors *year*, *month*, *sex*, *maturity* (mature or immature), and fish *length* were offered to a GLM with fish condition as the response variable. The GLM used a Gaussian error distribution and an identity link function. The continuous variables were offered as 2nd, 3rd, 4th, or 5th degree polynomials. Interaction terms were tested. Predictors were selected using a forward and backwards stepwise procedure, where terms were added to the base (intercept only) model in order of decreasing deviance explained. Predictors were included in the final model only of they explained at least 2% of the residual deviance.

2.9 Genetics

Information on stock boundaries inferred from genetics studies was obtained from Smith & Benson (1997) and Smith et al. (1996).

2.10 Habitat structure and natural boundaries

The association of orange roughy with seamounts, hills, and other underwater topographic features has been well described (Tracey & Fenaughty 1997, Clark 1999, Dunn 2008). The distribution of seamount and hill habitat on the Chatham Rise was obtained from the *Seamounts* database (A. Rowden, NIWA, pers.comm.), and compared with catch distributions. Information on ocean currents and bottom water temperatures on the Chatham Rise was obtained from Dunn et al. (2009).

3. RESULTS

3.1 Distribution of catches

During the spawning season, the largest catches have come from the Spawning Box, with smaller catches from the hill complexes either side, specifically the Graveyard Hills and Northeast Hills, and to a lesser extent the Big Chief area, and near Mt Kiso (Figure 5).

Outside the spawning season, catches started on the northwest Chatham Rise, near The Hole, and on the south Chatham Rise in the Mt Kiso area (Figure 6). The centre of the catches on the south Rise then progressed eastwards towards the Andes from the late 1980s (Clark 1999), with the development of the "middle ground" fishery (located between the Big Chief and Andes areas) since 2000–01, and 'Kenwood' fishery (just north of the Andes) since 2005–06, continuing this trend (Anderson & Dunn 2008).

The catch distribution is equivocal about stock structure. It could support a single stock, with the Spawning Box being the centre of the spawning distribution, and the Andes the centre of the non-spawning distribution. The non-spawning catches could support two stocks, one on the north Rise from The Hole to the Spawning Box, and the other from the Northeast Hills clockwise to Mt Kiso. It could also support three stocks: the Graveyard Hills and surrounding area (as far as The Hole), the Spawning Box clockwise to the Big Chief area, and then Hegerville and the surrounding area. Finally, it could support perhaps six stocks, focused around the Graveyard Hills, Spawning Box, Northeast Hills, Andes, Big Chief area, and Hegerville area.

3.2 CPUE trends

The use of standardised CPUE as a valid index of orange roughy vulnerable biomass has frequently been questioned. Nevertheless, standardised CPUE has routinely been used in stock assessments, usually because there is no other biomass index available (Ministry of Fisheries 2008). Of particular interest to stock structure is the identification of common CPUE trends in different areas, suggesting at least common fishery trends, if not common biomass trends.

The CPUE indices derived from the Spawning Box fishery are likely to be biased, since the fishery targets large and predictable spawning aggregations (Punt 1993, Coburn & Doonan 1994, 1997). Nevertheless, to be comprehensive, and because the indices have been used in some stock assessments, they are included here.

All of the CPUE indices have declined, and over the past decade all have been declining except that for Hegerville, and possibly the Spawning Box (Figures 7 & 8). The timing and extent of the initial steep decline in CPUE varied. For the hill fisheries, after the initial decline there was no substantial difference in the CPUE trend between the Northeast Hills, Andes, and Big Chief and neighbours. These areas all show a decrease in CPUE in 1997–98, then an increase in 1999–2000 to 2001–02, followed by a decline: the index for the Eastern Flats is similar. In a broad sense the Graveyard CPUE index is similar, in that it declines to 1997–98, but the increase around 1999–2000 to 2001–02 is less pronounced. If the 1995 observation for the Spawning Box was discounted, the gradient from the Spawning Box CPUE would also be broadly similar.

Only the Hegerville index showed a markedly different trend (Figures 7 & 8). The linear rate of decline of the untransformed CPUE index between 1997–98 and 2006–07 was negative all areas (Graveyard -0.10; Northeast Hills -0.04; Andes -0.10; Big Chief and neighbours -0.09; Spawning Box (excluding 1994–95) -0.10), except Hegerville (0.05). The Spawning Box trawl survey, Spawning Box CPUE, and eastern flats CPUE, had a similar trend during the 1980s and early 1990s to the Hegerville CPUE, although Hegerville may show a steeper decline. The early Graveyard CPUE index is broadly similar, but perhaps less steep than the other indices through the 1980s.

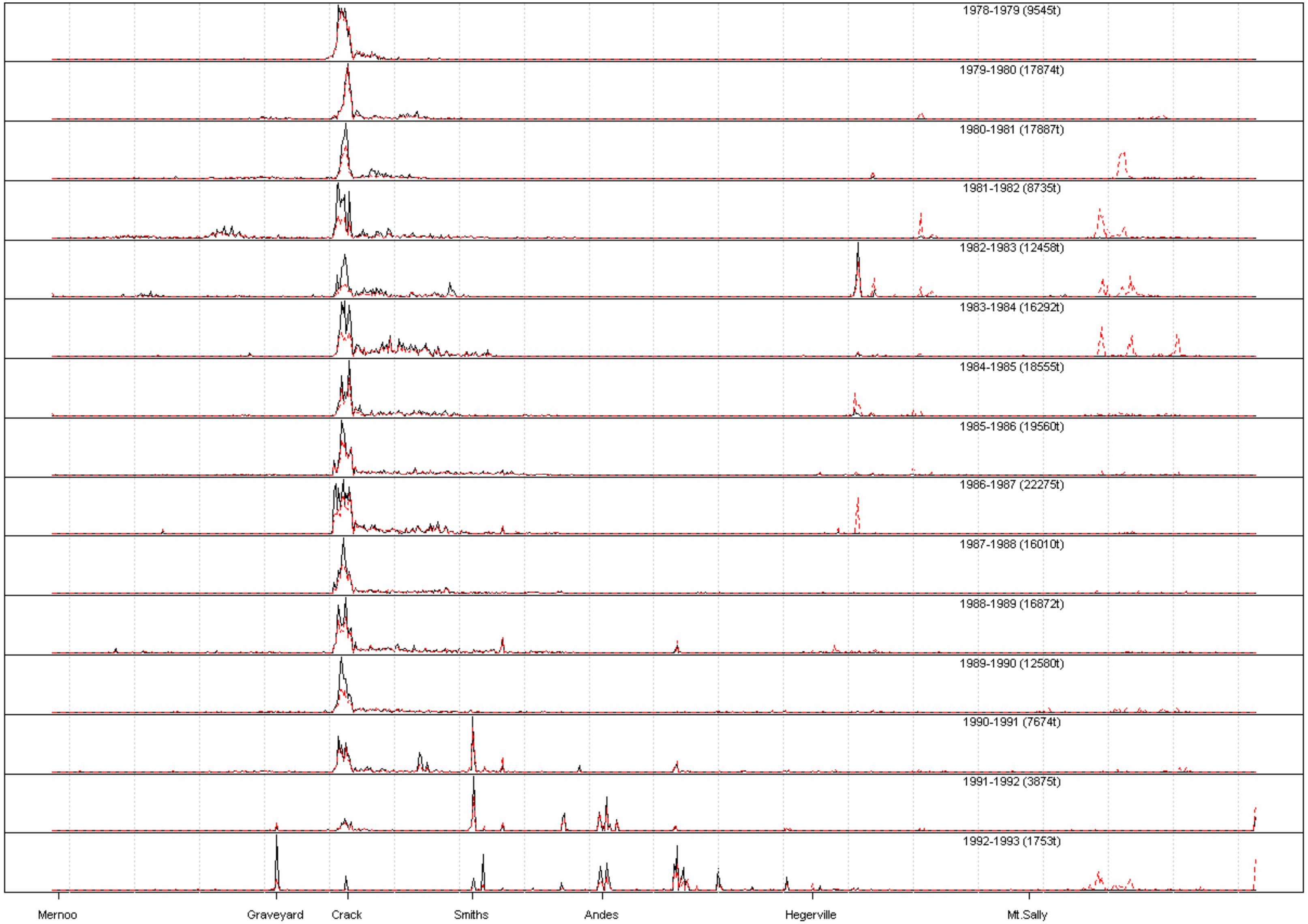


Figure 5: Distribution of estimated orange roughy catch (solid line) and number of tows (broken line) on the Chatham Rise axis (Figure 3) during the spawning season (June–August) by fishing year. Catches and effort have been normalised for each year: estimated catch for each year is shown in parentheses.

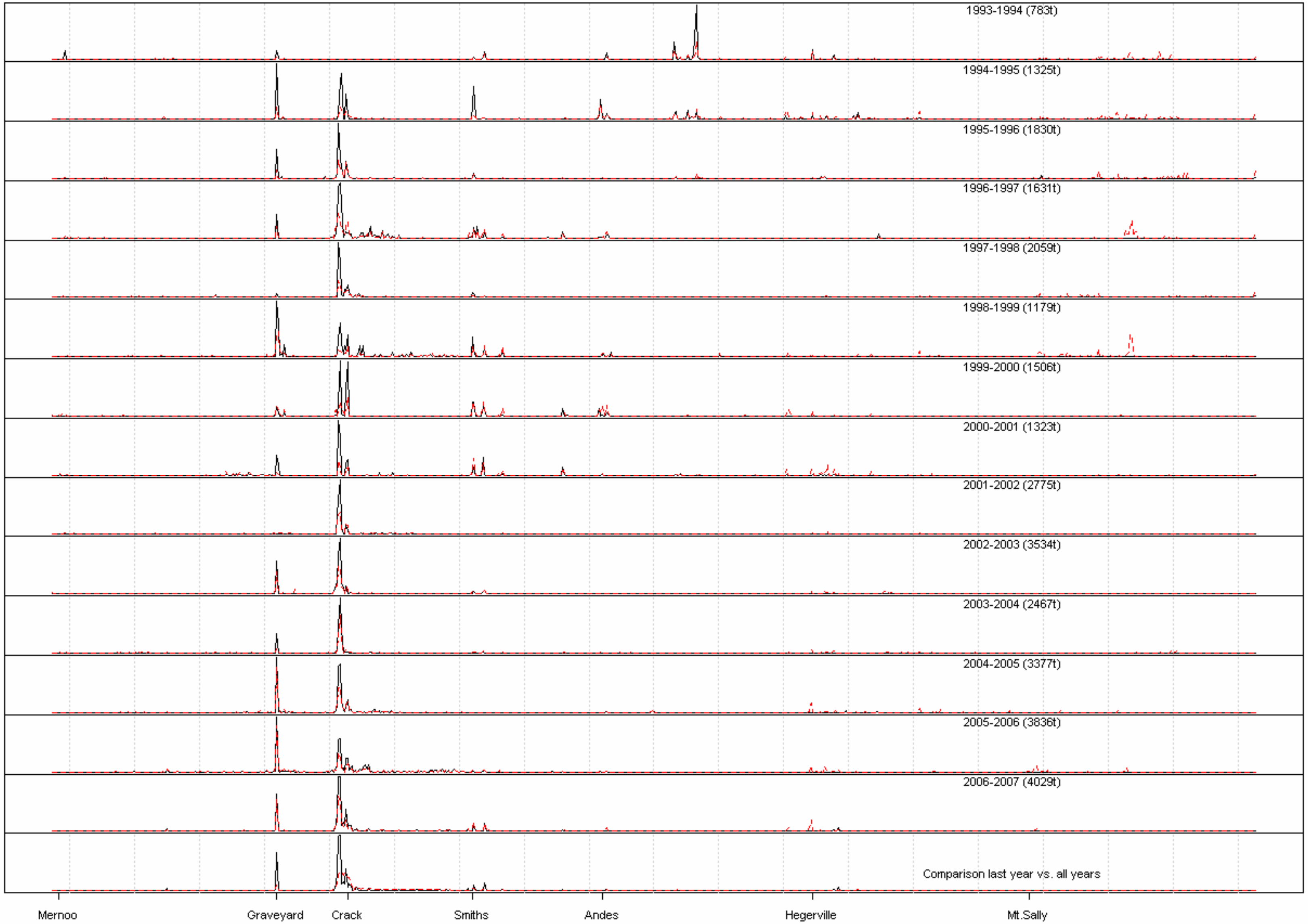


Figure 5 (cont.): Distribution of estimated orange roughy catch (solid line) and number of tows (broken line) on the Chatham Rise axis (Figure 3) during the spawning season (June–August) by fishing year. Catches and effort have been normalised for each year: estimated catch for each year is shown in parentheses.

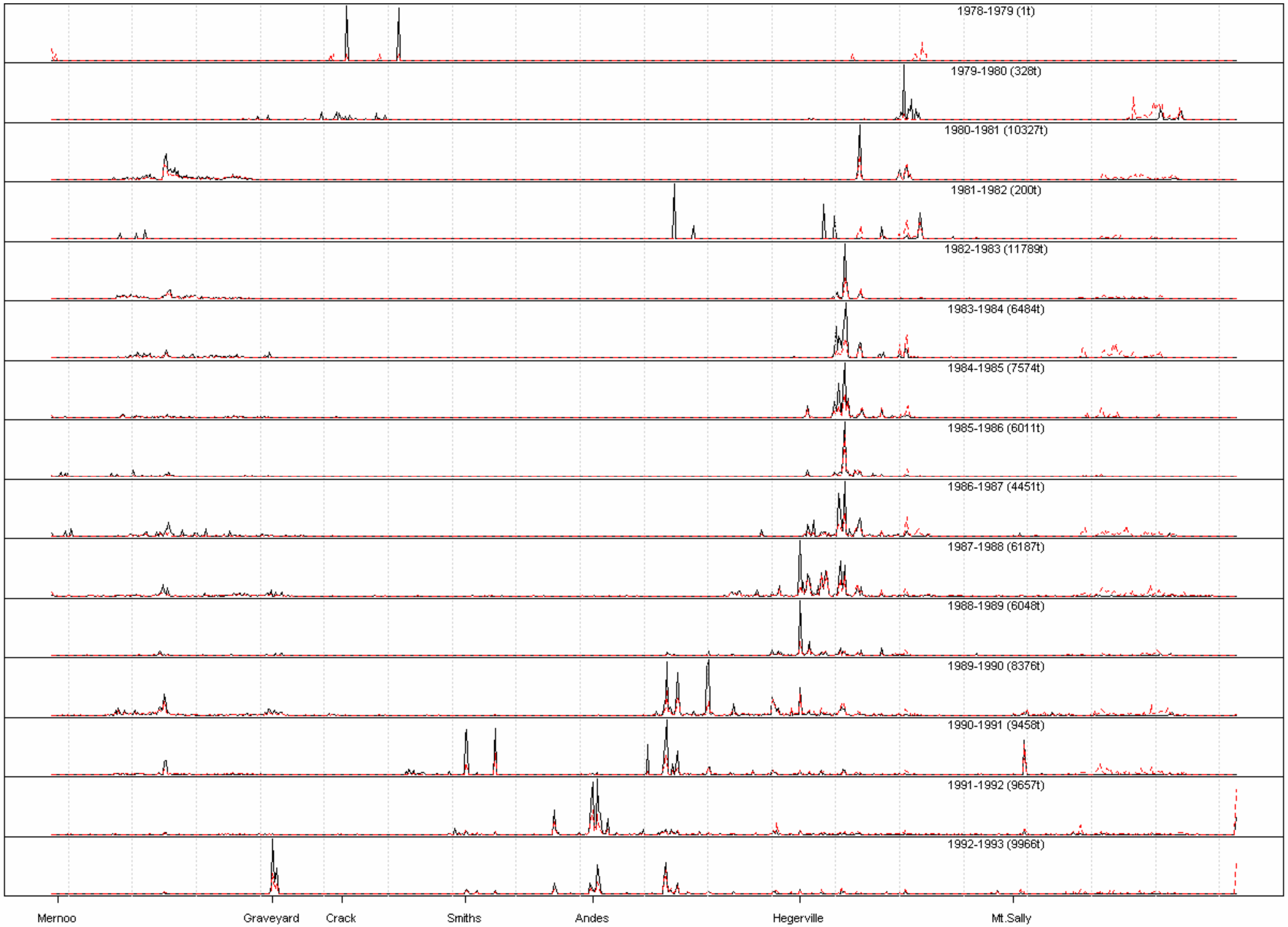


Figure 6: Distribution of estimated orange roughy catch (solid line) and number of tows (broken line) on the Chatham Rise axis (Figure 3) during the non-spawning season (September–May) by fishing year. Catches and effort have been normalised for each year: estimated catch for each year is shown in parentheses.

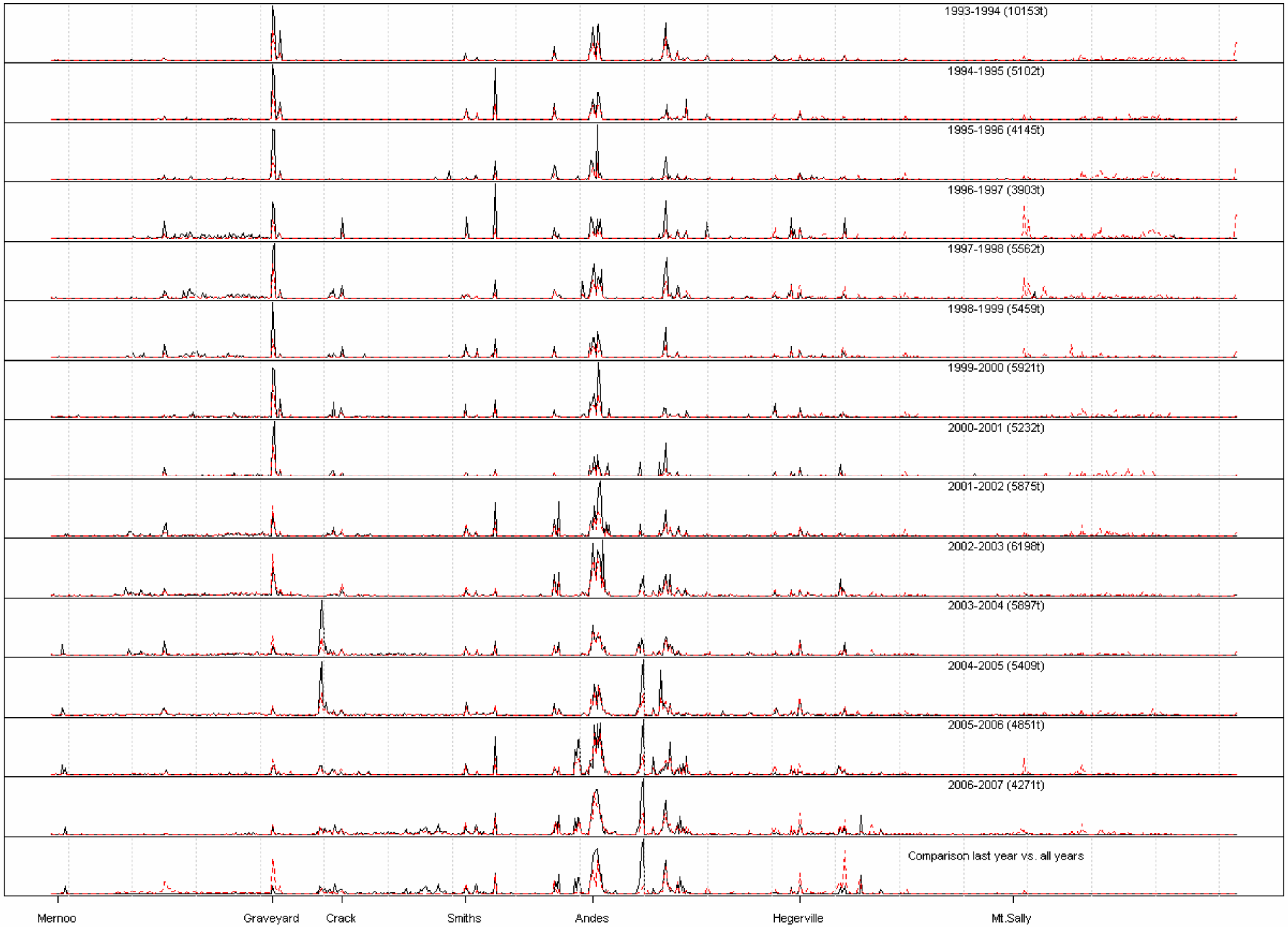


Figure 6 (cont.): Distribution of estimated orange roughy catch (solid line) and number of tows (broken line) on the Chatham Rise axis (Figure 3) during the non-spawning season (September–May) by fishing year. Catches and effort have been normalised for each year: estimated catch for each year is shown in parentheses.

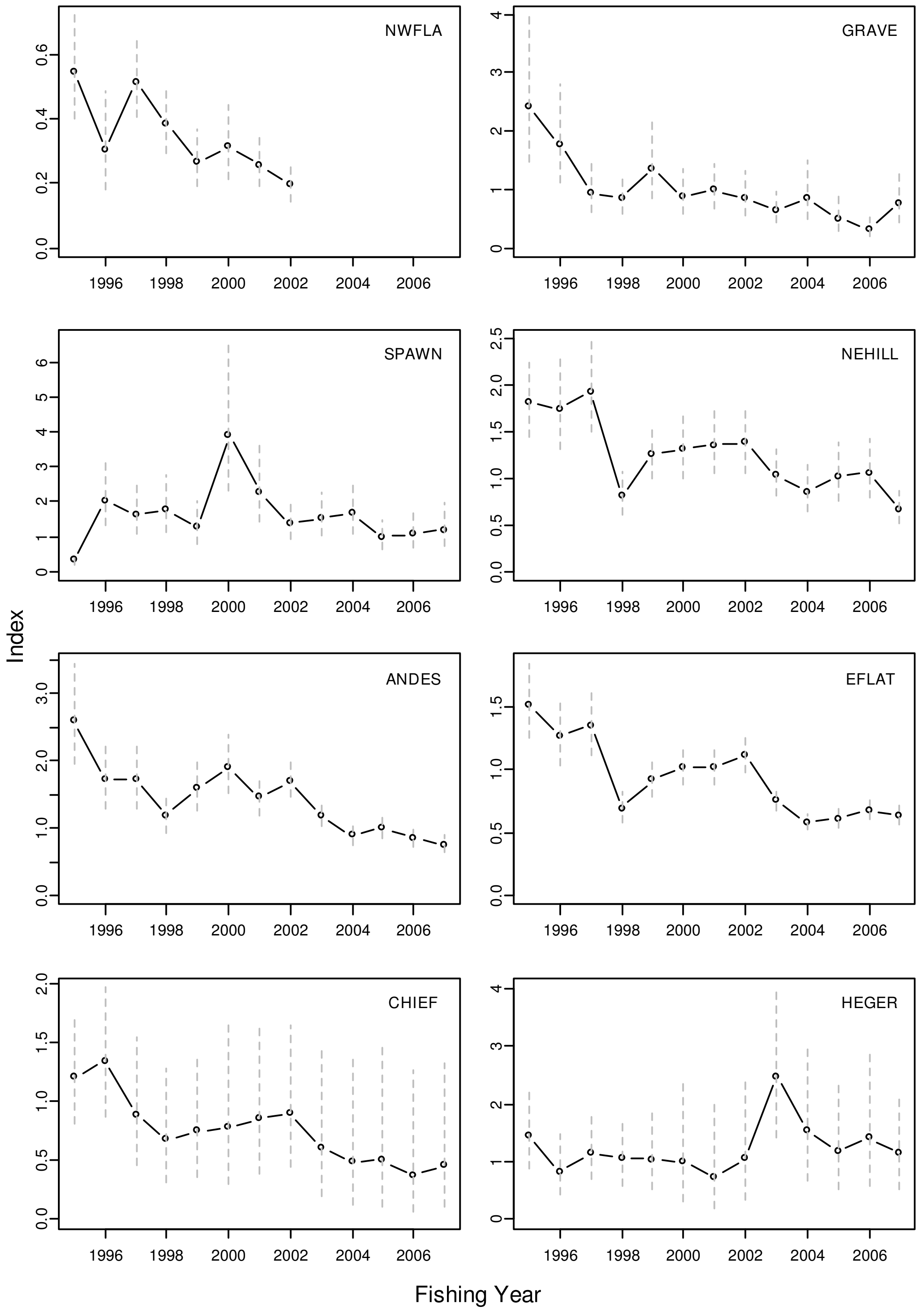


Figure 7: Standardised CPUE indices for areas of the Chatham Rise over the last 10 years (from Mormede 2009). NWFLA, Northwest Flats; GRAVE, Graveyard Hills; SPAWN, Spawning Box; NEHILL, Northeast Hills; ANDES, Andes complex; EFLAT, Northeast Flats; CHIEF, Big Chief and neighbours; HEGER, Hegerville. Fishing years are labelled by the year ending, i.e., 1994–95 is labelled as 1995. Vertical broken lines indicate the 95% confidence intervals.

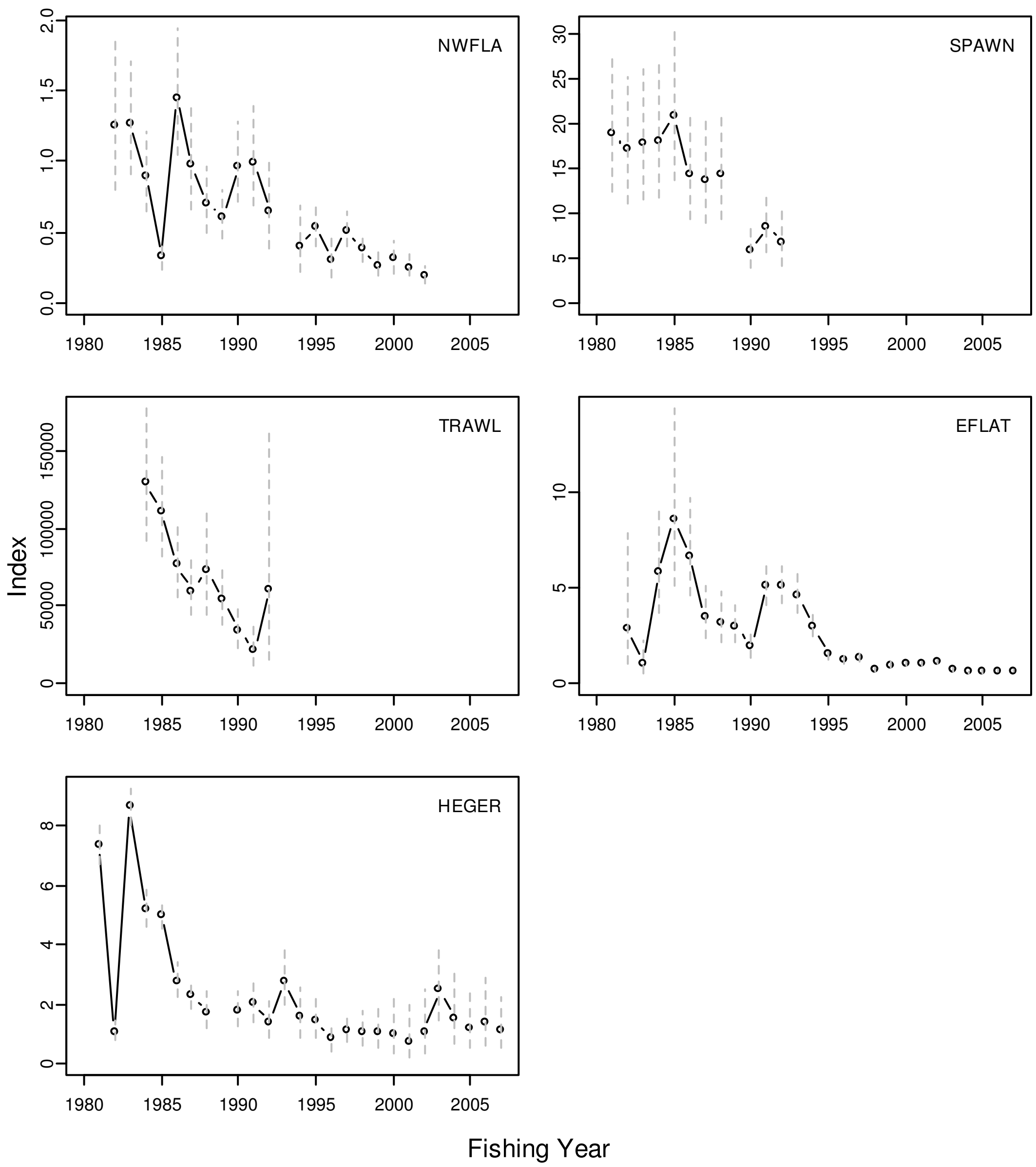


Figure 8: Standardised CPUE indices for areas of the Chatham Rise which included the 1980s (from Dunn et al. 2008 and Mormede 2009). NWFLA, Northwest Flats; SPAWN, Spawning Box; TRAWL, Spawning Box research trawl index; EFLAT, Northeast Flats; HEGER, Hegerville. Fishing years are labelled by the year ending, i.e., 1994–95 is labelled as 1995. Vertical broken lines indicate the 95% confidence intervals.

The CPUE indices contain some potentially strong signals about stock structure. The similarity of the Northeast Hills, Andes, Big Chief and neighbours, and Northeast Flats seems marked given their spatial separation, and may indicate a single stock in these areas. A link between these areas and the Spawning Box is not supported. However, the Spawning Box index was derived from tows made on orange roughy aggregations, and as a result the index is unlikely to index abundance. Nevertheless, the Spawning Box research trawl survey index shares a steep overall decline during the 1980s with the Northeast Flats and Spawning Box CPUE.

Hegerville could be considered separate as the CPUE was unique in being flat or increasing in recent years, and the Graveyard may be separate as there was a shallower decline in early years and a subtly different trend in recent years. CPUE for the Spawning Box is likely to be misleading, and is therefore considered equivocal about stock structure.

3.3 Location of spawning and nursery grounds

The largest spawning aggregations (plumes) have been found on flat grounds in the Spawning Box, with smaller aggregations on various hills, including the Graveyard, the Crack, the Northeast Hills, Not Till Sunday, the Andes, and Big Chief (Dunn et al. 2009). In general, the spawning aggregations appeared to get smaller either side of the Spawning Box (Figure 9). The data indicate little or no spawning on much of the south or northwest Chatham Rise.

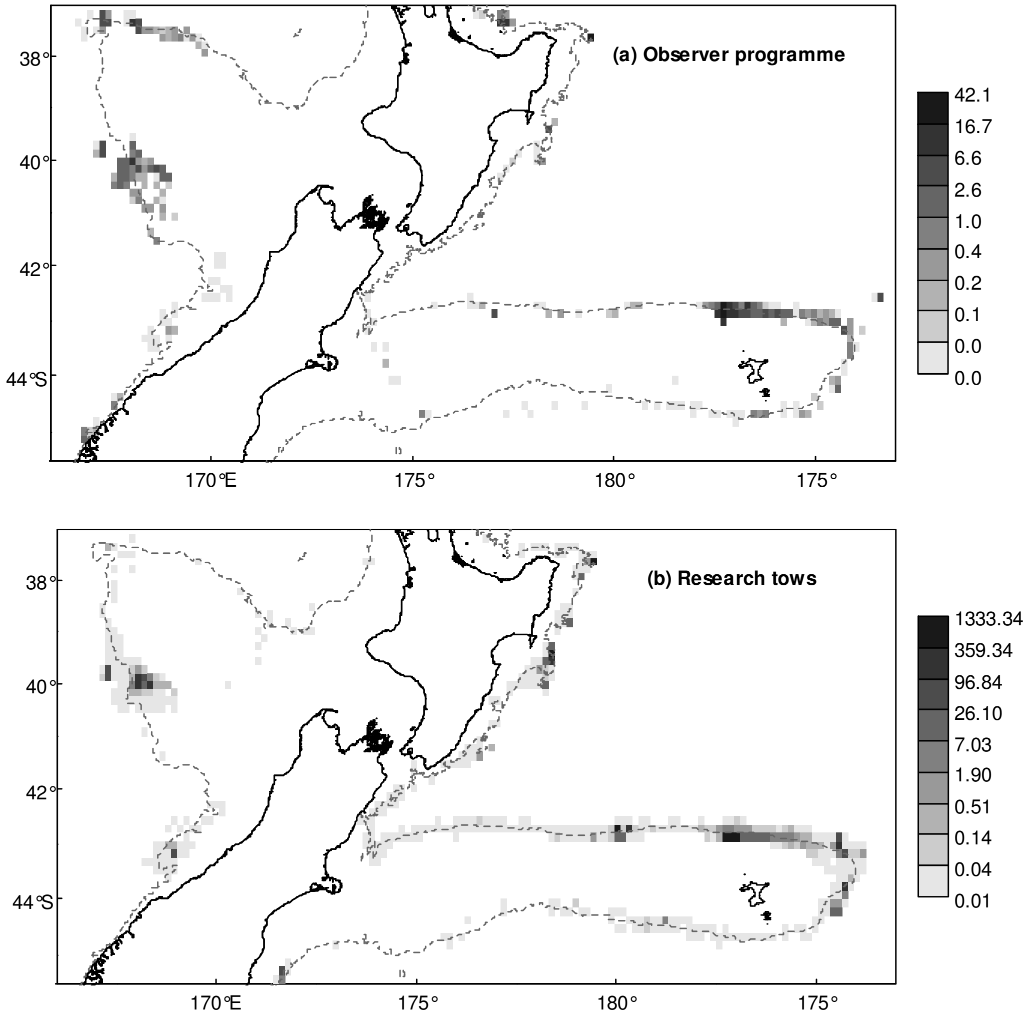


Figure 9: Density plot showing the maximum catch rate of ripe and running female orange roughy observed by 0.15° latitude and longitude cells, from (a) t/tow from commercial trawls as sampled by the MFish observer programme, and (b) t/nautical mile from research trawls. In order to plot the data using a log scale 0.01 kg was added to all catch weights. The lowest catch category in both plots indicates the area was sampled but no ripe and running female orange roughy were caught.

The hypothesised nursery grounds for orange roughy on the Chatham Rise were described by Dunn et al. (2009). Juveniles were initially caught on the bottom, and towards the shallower end of the species' depth distribution, in highest densities at 850–900 m. They were not caught in midwater, nor in the shallower or deeper bottom tows. As juveniles got larger, the spatial and depth distribution expanded, into both shallower and deeper water, with a skew towards deeper water, such that by the onset of maturation they occurred at relatively high densities from 850 to 1300 m.

Orange roughy are believed to settle on the bottom relatively quickly, after about 10 days (Zeldis et al. 1995). The smallest juveniles were caught near known spawning grounds, from the Spawning Box to the Northeast Hills with scattered occurrence around to the Andes and Big Chief on the east Chatham Rise, and on the northwest Chatham Rise to the west of the Graveyard hills (Dunn et al. 2009, Figures 10a & 10b).

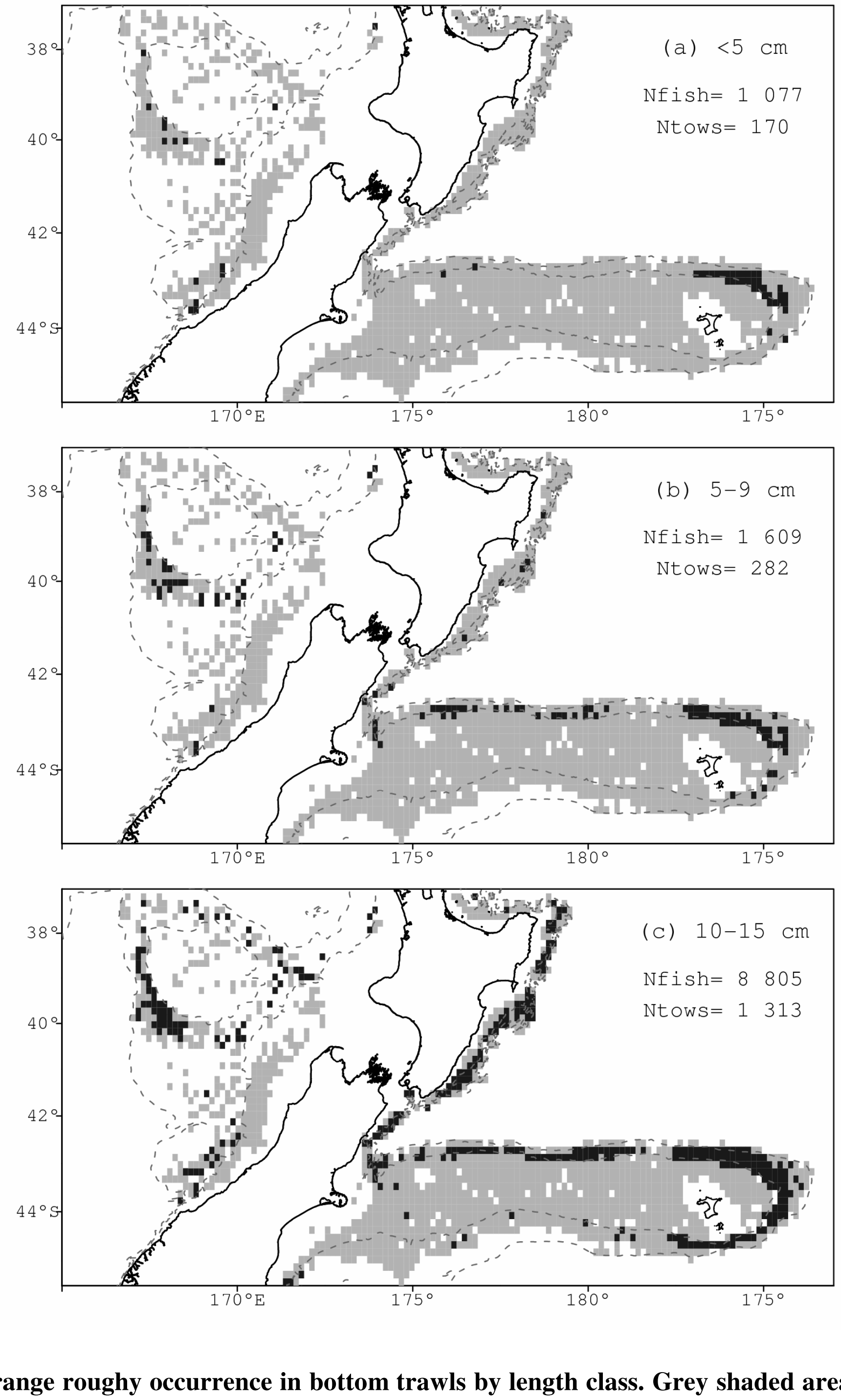


Figure 10: Orange roughy occurrence in bottom trawls by length class. Grey shaded areas were sampled, black shaded areas show where orange roughy were caught. The broken lines indicate the 750 m and 1500 m isobaths. Nfish, number of orange roughy caught; Ntows, number of tows in which orange roughy were caught (out of a total of 12 541 tows). Figure reproduced from Dunn et al. (2009).

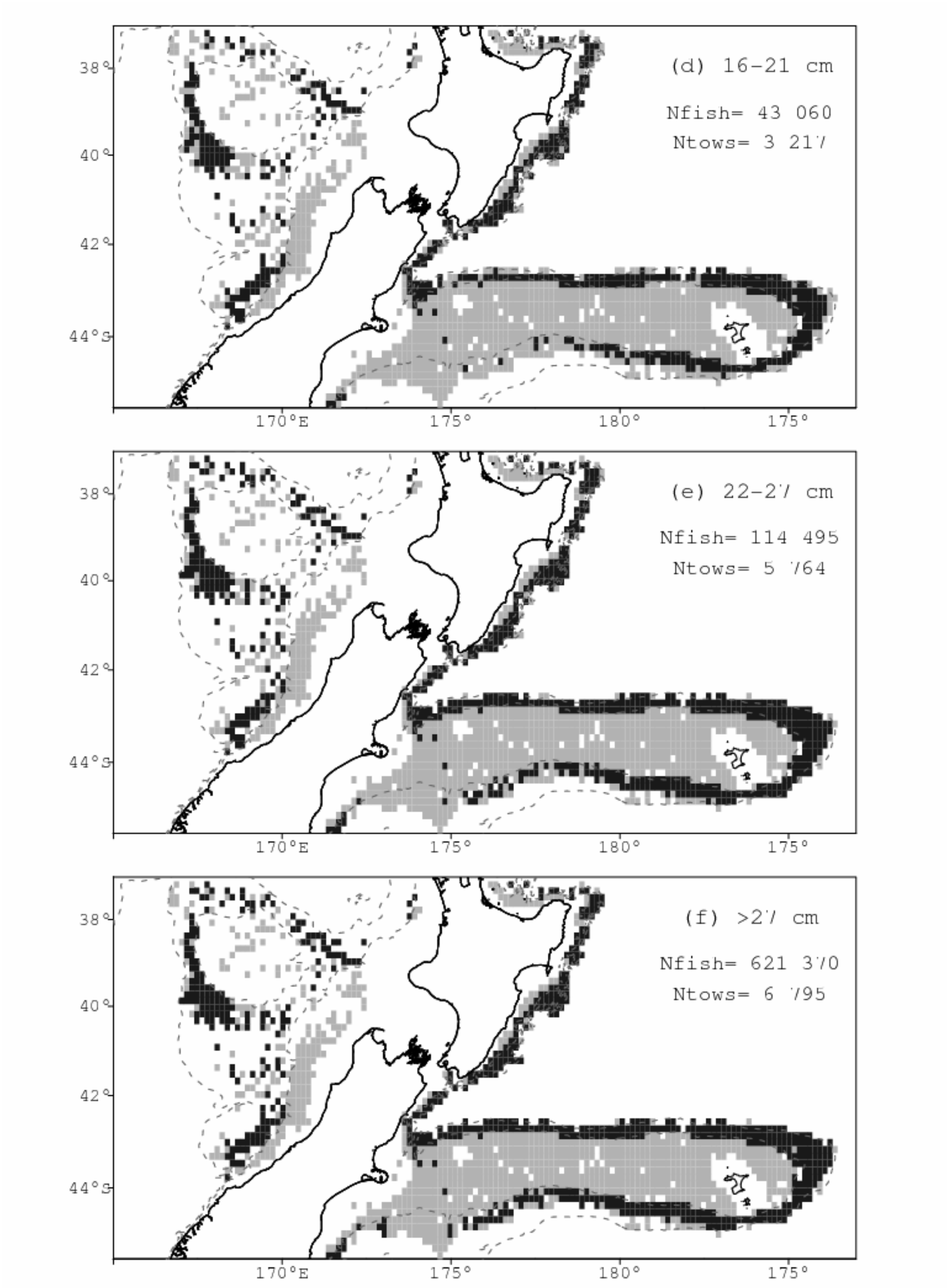


Figure 10 (cont.): Orange roughy occurrence in bottom trawls by length class. Grey shaded areas were sampled, black shaded areas show where orange roughy were caught. The broken lines indicate the 750 m and 1500 m isobaths. Nfish, number of orange roughy caught; Ntows, number of tows in which orange roughy were caught (out of a total of 12 541 tows). Figure reproduced from Dunn et al. (2009).

The association of initial nursery grounds with spawning grounds, and then the increase in spatial extent with increasing fish length, both suggest connectivity. The depth range was initially relatively shallow, and then expanded with increasing length (Dunn et al. 2009), again suggesting connectivity. The rarity of smaller juveniles (<16 cm) on the South Rise (west of Hegerville) is consistent with there being no substantial spawning in that area. Once the orange roughy had reached adolescence (over 21 cm SL) the distribution of pre-recruit fish was almost continuous around the Chatham Rise.

Based on the spawning locations and gaps in the occurrence for juveniles (under 16 cm SL, Dunn et al. 2009) before they start to spread into deeper water, boundaries between stocks might occur on the south Chatham Rise at about 179–177.5°W, and on the north Chatham Rise at about 175° E and 177° W.

3.4 Inferred migrations

Francis & Clark (1998) used the estimated mean length of maturity (L50) from samples of orange roughy between May and August to infer a spawning migration to the Spawning Box from areas as far away as the south Chatham Rise.

Coburn & Doonan (1994, 1997) used commercial CPUE to infer a post-spawning easterly migration from the plumes in the Spawning Box, to the Northeast Flats as far as the eastern edge of the Chatham Rise. The analysis is not especially convincing, because of the limited amount of fishing in low CPUE areas and times, and many areas and times not fished (Figures 11 & 12). The area of peak catch rates moved eastwards at a rate of about 10 km/day. The analysis also suggested some mature fish may have moved into the Spawning Box from the west.

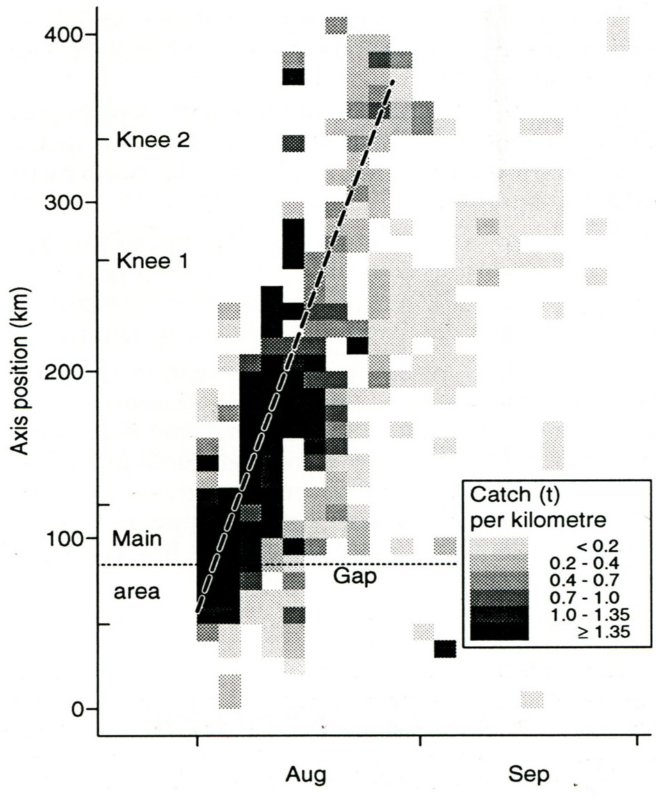


Figure 11: Median catch per kilometre during the postspawning period (Aug–Sep) for all commercial and research tows during 1979–99. Median catch per kilometre is calculated and shown by cells of 10 km axis position and 3 days. Cells are shown if there were at least two tows. The axis position is shown in Figure 12. Figure reproduced from Coburn & Doonan (1994).

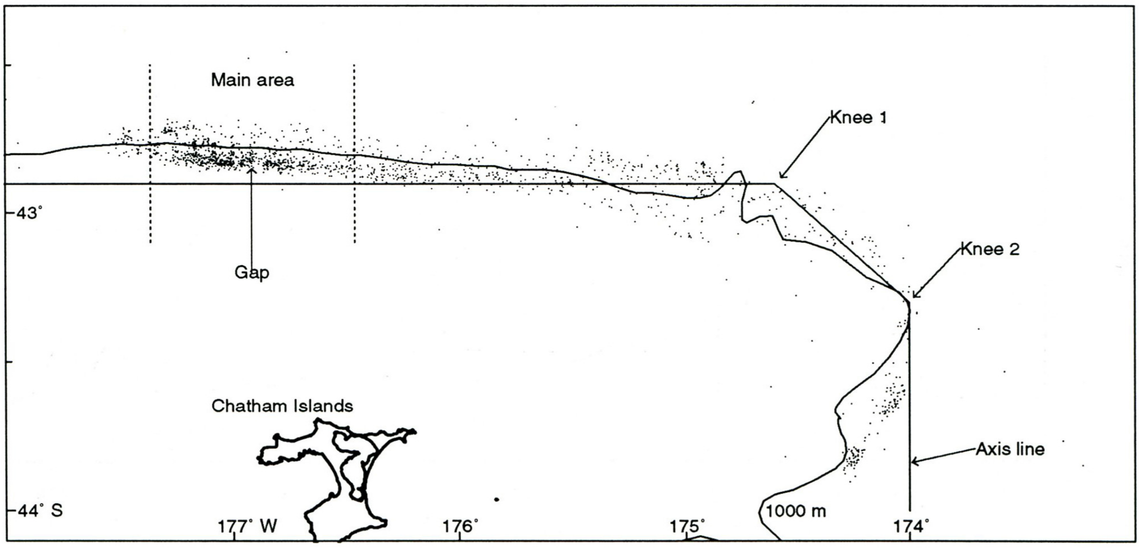


Figure 12: The start position of tows that caught or targeted orange roughy on the northeast Chatham Rise in 1988 (knee 1 is at 42.8° S 174.6° W, knee 2 is at 43.3°S, 174.0° W). Figure reproduced from Coburn & Doonan (1994).

Taylor (1993) used commercial CPUE to infer a westerly post-spawning migration from the Graveyard Hills, although the results were less clear than those for the East Rise by Coburn & Doonan (1994, 1997). Doonan & Coombs (2004) used research trawl survey data to infer a westerly post-spawning migration from the Graveyard Hills (Figure 13). The trawl survey covered the flat grounds from mid-spawning to the end of spawning. Migrating and spent fish were found out to 40 km to the west of the graveyard, at densities about five times higher than that of the surrounding area. No high densities were found to the east of the Graveyard, and the authors suggested the post-spawning migration was almost entirely to the west. The estimated migration rate was similar to the Spawning Box, at about 10 km/day.

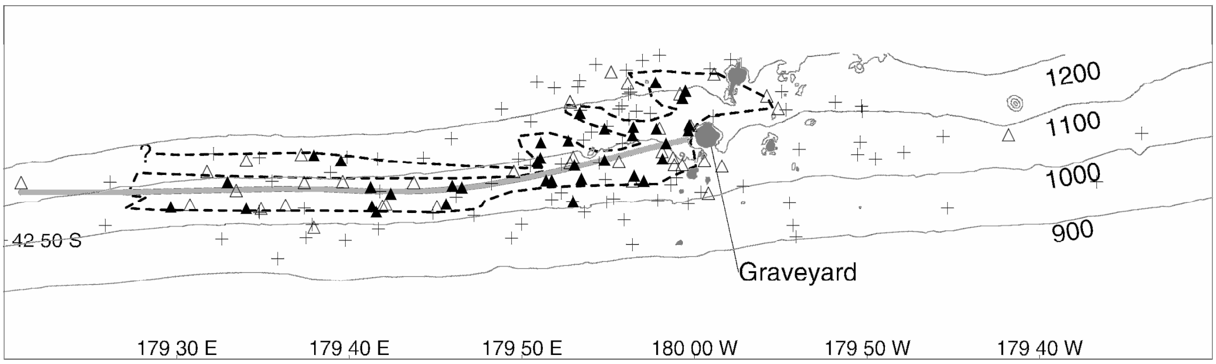


Figure 13: Distribution of migrating fish on the flat. Catches over 55 kg (filled triangles), catches below 55 kg (triangles), and zero catch (cross). The wide faded line running east-west between the 1000 and 1100 m contours is the axis of migration. The dotted lines immediately above and below delimit the north-south spread of migrants. The second dotted line north of the axis (ending with "?") is an alternative northern boundary. Bases of hills are shaded areas. Figure reproduced from Doonan & Coombs (2004).

Seasonal changes in CPUE have been estimated in several standardised (GLM) analyses. An increase in CPUE during the spawning season (June–July) has been estimated for the Spawning Box, the Graveyard hills, and the Northeast Flats (Figure 14).

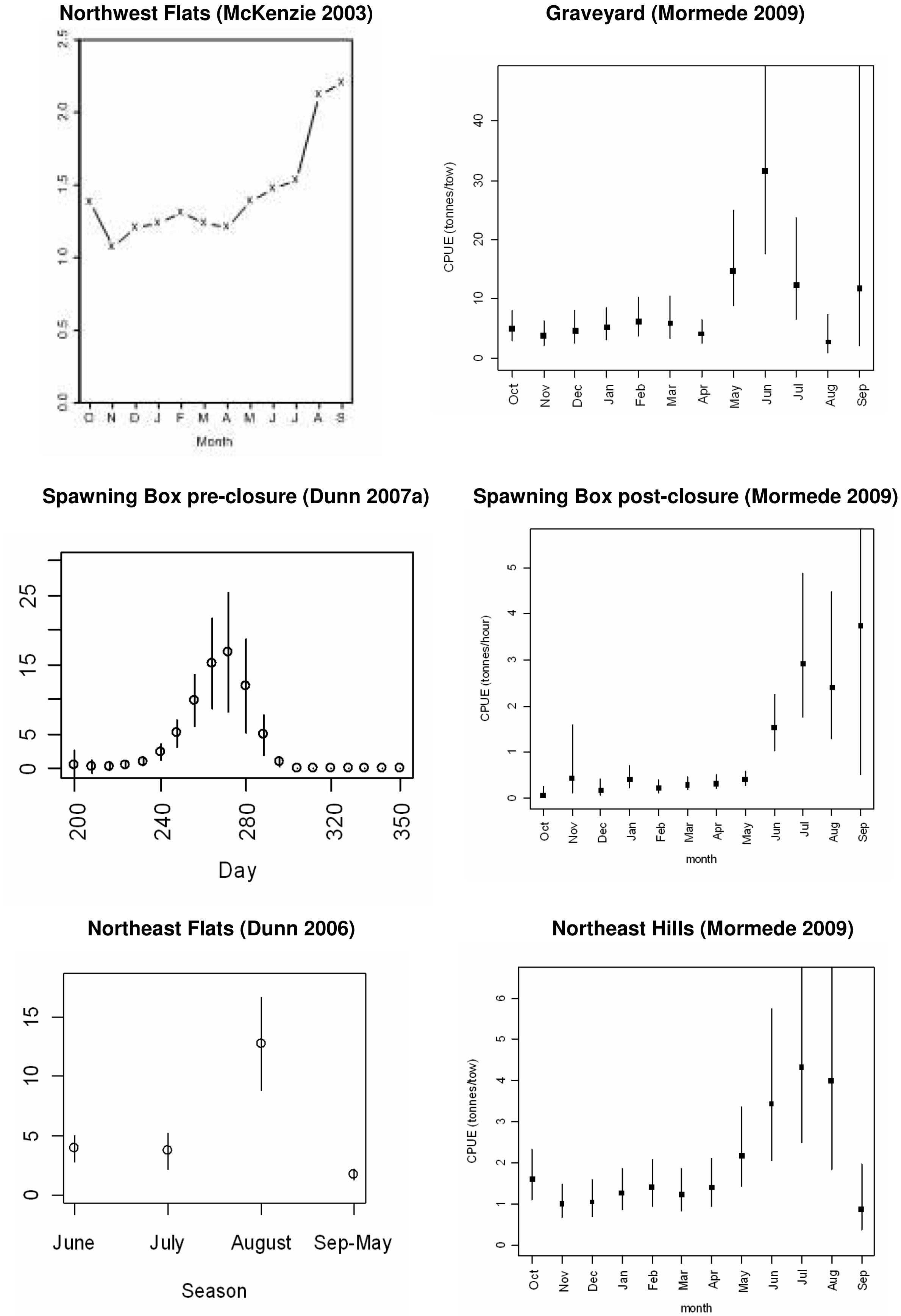
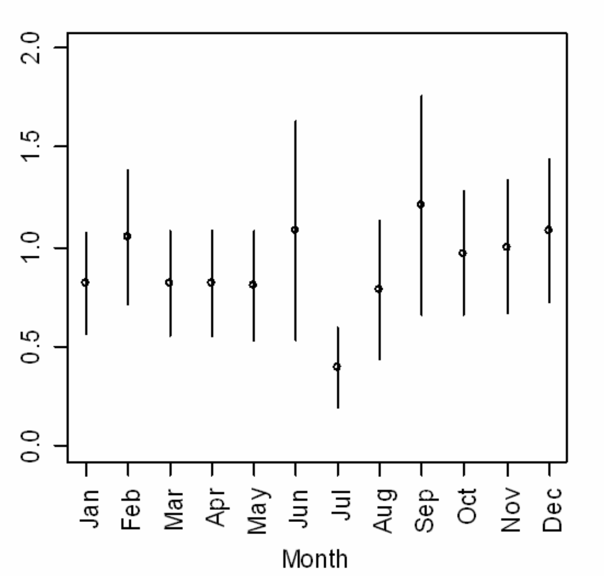


Figure 14: Seasonal changes in CPUE estimated from standardised CPUE analyses for subareas of the Chatham Rise. The title of each figure indicates the area, with the source of the figure in parentheses. Vertical bars indicate 95% confidence intervals.

Andes (Dunn 2007a)



Hegerville (Mormede 2009)

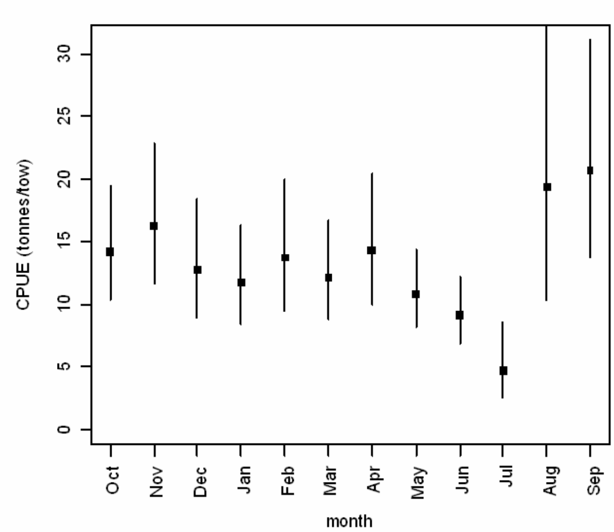
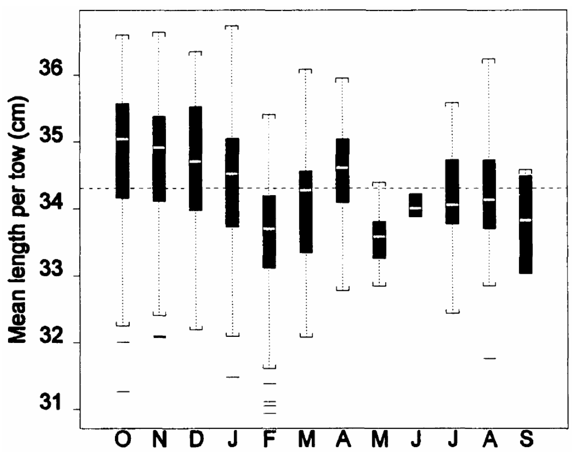


Figure 14 (cont.): Seasonal changes in CPUE estimated from standardised CPUE analyses for subareas of the Chatham Rise. The title of each figure indicates the area, with the source of the figure in parentheses. Vertical bars indicate 95% confidence intervals.

An increase in CPUE immediately post-spawning (August) has been estimated for the Northeast Flats. A decrease in CPUE around the time of spawning has been estimated for the Andes and Hegerville. We can infer from this that mature orange roughy leave certain hill areas of the south Chatham Rise during the spawning season, arrive at the Graveyard, Spawning Box, and Northeast Hills, and pass through the Northeast Flats in August. Analyses of CPUE for Big Chief and surrounding area have not estimated a seasonal effect. There is no obvious interpretation for the increase in CPUE for the northwest flats during August and September.

Length frequency data show an increase in mean length on the Northeast Hills during spawning, and an increase during October–December on the Andes (Figure 15). This would be consistent with the arrival of larger mature fish on the Northeast Hills for spawning, and the Andes three months after spawning.



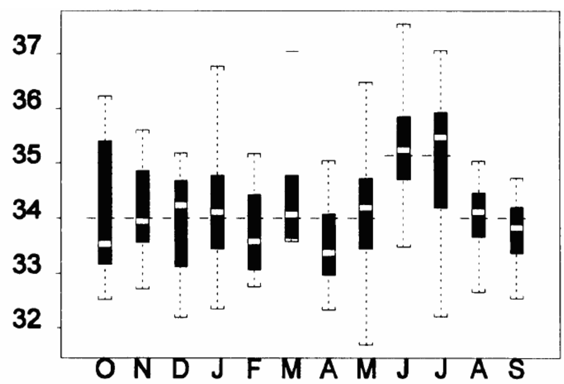


Figure 15: Seasonal changes in length frequency distribution on the Andes (left panel) and the Northeast Hills (right panel). Both figures reproduced from Francis (2006).

We can infer that there is a spawning migration into the Spawning Box, which peaks in July, followed by an easterly post-spawning migration, with abundance on the Northeast Flats peaking a month after spawning, in August. Mature orange roughy also move onto the Graveyard Hills and Northeast Hills for spawning. The length frequency data suggest these are primarily larger (i.e., mature) fish. There is a westerly post-spawning migration from the Graveyard Hills, and an easterly migration from the Spawning Box. Although Coburn & Doonan (1994) found some evidence for fish arriving in the Spawning Box from the west, overall this would support the separation of the Graveyard and the Spawning Box.

Orange roughy may move away from hill areas of the south Chatham Rise during the spawning season, specifically from Hegerville, and possibly also from the Andes. The decrease in CPUE on the Andes and Hegerville (1–2 months) may be too short to allow for a migration to the Spawning Box, given the migration rate estimated by Coburn & Doonan (1994) and Doonan & Coombs (2004). This hypothesis also assumes that the fish were not replaced during their absence, i.e., the increase in CPUE in August was caused by post-spawning fish returning to the area, not by other local (e.g., non-hill) fish taking the place of the absent spawners. With a migration rate of 10 km/day, a trip from Hegerville to the Spawning Box following the 1000 m contour around the east Chatham Rise would take about 2 months (a distance of about 600 km), and therefore CPUE would be expected to decrease over at least a four month period.

3.5 Ontogenetic patterns in length frequencies

The predictors of mean length for male orange roughy were sampling source (research vessel or Ministry of Fisheries observer on board a commercial vessel), season, distance from the nearest hill, depth, and spatial (axis position). The first split was between research and MFish observer samples, with research samples having a smaller mean length than samples from commercial trawlers (Figure 16). There were no further splits for observer samples. For research samples, the next effect was seasonal, with mean length being smaller outside of the spawning season, and smaller away from hills; during spawning the fish were again smaller away from the hills, where they were smaller in shallow water; away from the hills and in deeper water the fish were smaller on the north Chatham Rise west of 178.08° W (between the Spawning Box and the Graveyard).

The predictor analysis was repeated for the research vessel non-spawning data, and the Ministry of Fisheries Scientific Observer Programme data, after reducing the minimum number of tows per terminal node from 100 to 50. This potentially allows further splits in the data. The research non-spawning tows away from the hills were split further, with smaller fish shallower than large fish (Figure 17). The Ministry of Fisheries observer tows were split into five groups, the first of which was a year split, with fish during the early years, 1986–1992, being larger (Figure 18). In more recent years (1993–2007), larger fish were found close to the hills, and of these larger fish were found on the north Chatham Rise clockwise around to 175.4° W (just to the west of the Andes). Away from the hills, larger fish were found on the south Chatham Rise and north Chatham Rise east of 177.9° W (the western end of the Spawning Box).

The length range of male orange roughy was greater in the research tows than the commercial tows sampled by the Ministry of Fisheries observers (Figure 19). Within the observer tows, the length range was smaller on the north Chatham Rise west of 179.94° E (the area east of the Graveyard hills). Within the research tows, the length range was lowest between 179.94° E and 176.6° W, equivalent to the spawning grounds at the western end of the Spawning Box west to the Graveyard hills. The length range was also relatively low on the east and south Chatham Rise since 1993. The length range was highest on the east and south Chatham Rise before 1993, and the northwest Chatham Rise west of the Graveyard hills.

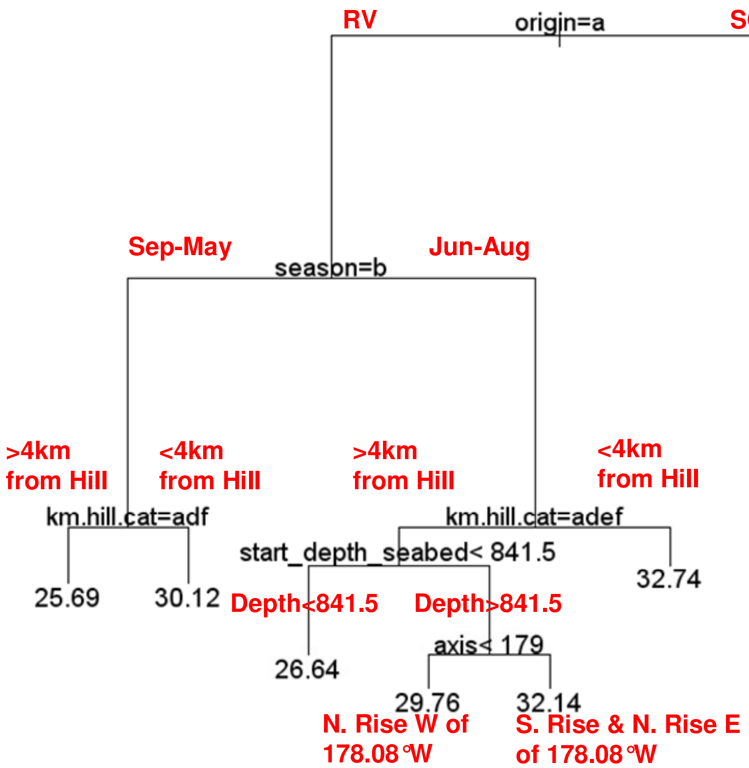


Figure 16: Regression tree analysis on median length (cm SL) for male orange roughy. The model explained 36.4% of the deviance. No. tows = 3974. The text at each split is the model split criteria ('yes' goes left, 'no' goes right), therefore an explanation of the split is also given above each limb. RV, research vessel; SOP, Ministry of Fisheries Scientific Observer Programme. The average median length is shown at the end of each terminal group.

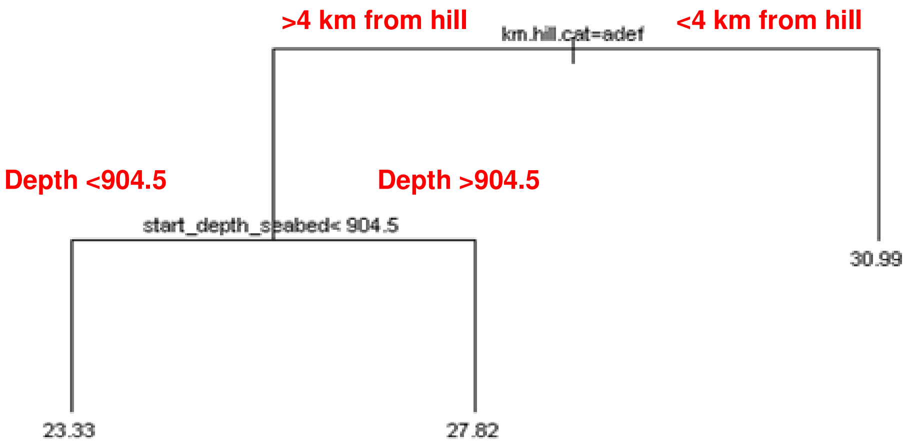


Figure 17: Regression tree analysis on median length (cm SL) for male orange roughy sampled by research trawls during September to May. No. tows = 452. The text at each split is the model split criteria ('yes' goes left, 'no' goes right), therefore an explanation of the split is also given above each limb. The average median length is shown at the end of each terminal group.

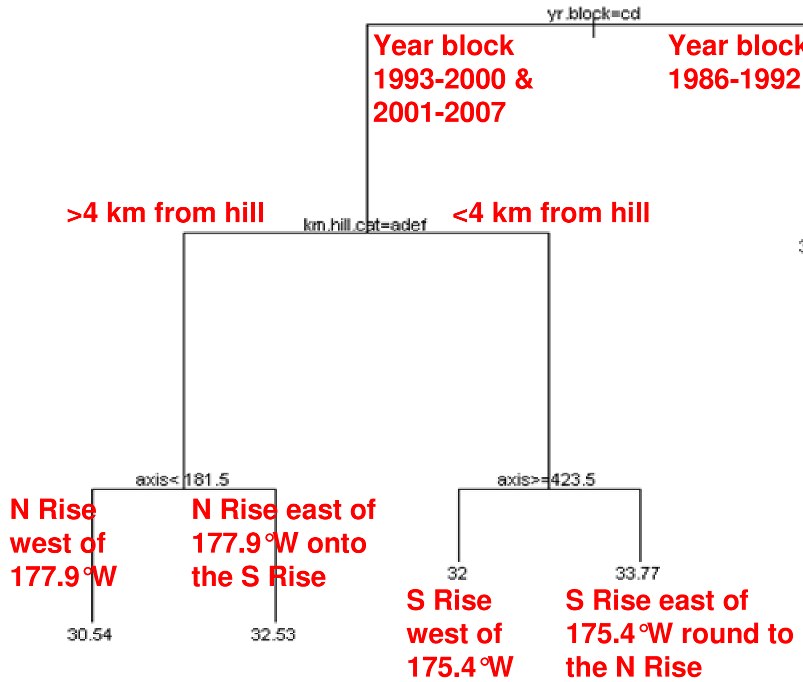


Figure 18: Regression tree analysis on median length (cm SL) for male orange roughy sampled by Ministry of Fisheries observers on board commercial trawlers. The model explained 30.9% of the deviance. No. tows = 2340. The text at each split is the model split criteria ('yes' goes left, 'no' goes right), therefore an explanation of the split is also given above each limb. The average median length is shown at the end of each terminal group.

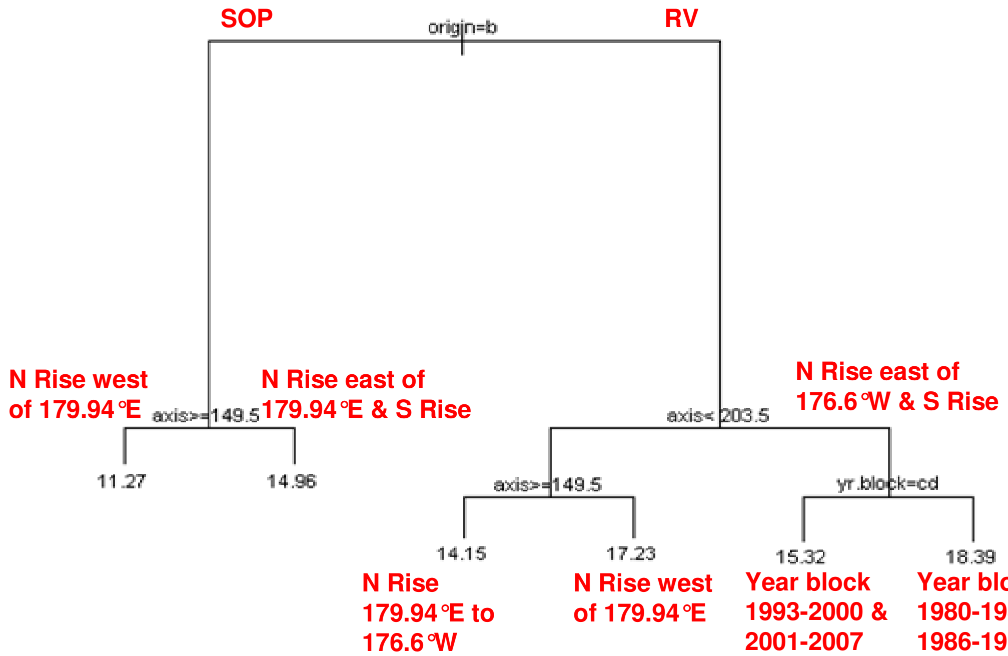


Figure 19: Regression tree analysis on length range (cm SL) for male orange roughy. The text at each split is the model split criteria ('yes' goes left, 'no' goes right), therefore an explanation of the split is also given above each limb. RV, research vessel; SOP, Ministry of Fisheries Scientific Observer Programme. The average length range is shown at the end of each terminal group.

The predictors of mean length for female orange roughy were similar to those for males, with sampling source, season, spatial location (axis position), distance from the nearest hill, and depth (Figure 20). The largest females were sampled from commercial vessels. For research trawls, outside of the spawning season females were larger on the south Chatham Rise west of 177.28° W (between Hegerville and Big Chief), and on the north and east Chatham Rise females were larger were close to the hills. During the spawning season the largest females were found between 176.4° and 177.5° W (the western end of the Spawning Box), and the next largest between 179.5° E and 177.5° W (the area including the Graveyard Hills). On the remainder of the east and south Chatham Rise the females were smaller in shallower water, where they were a similar size to the females on the northwest Chatham Rise.

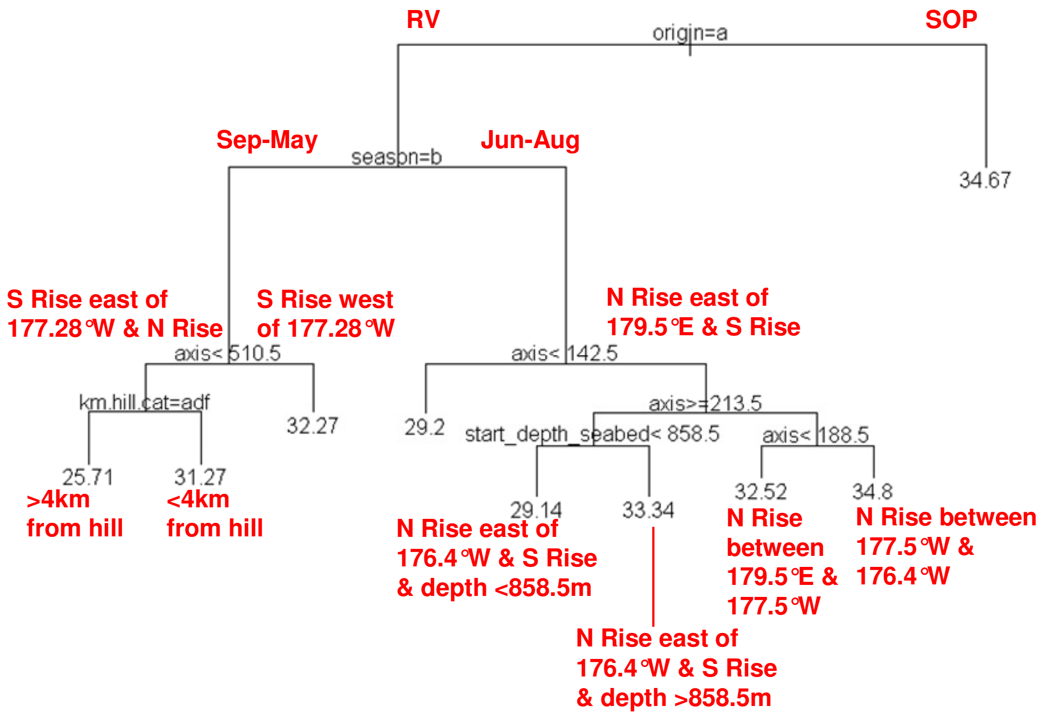


Figure 20: Regression tree analysis on median length (cm SL) for female orange roughy. The model explained 35.7% of the deviance. No. tows = 5367. The text at each split is the model split criteria ('yes' goes left, 'no' goes right), therefore an explanation of the split is also given above each limb. RV, research vessel; SOP, Ministry of Fisheries Scientific Observer Programme. The average median length is shown at the end of each terminal group.

The analysis after reducing the minimum number of tows per terminal node from 100 to 50 had a similar result for females as males, with the research tows away from the hills split further by depth (Figure 21). The further analysis of Ministry of Fisheries observer tows gave six groups, the first of which was a year split, with fish during the early years, 1986–1992, being larger (Figure 22). In more recent years (1993–2007), larger fish were found from the Graveyard Hills clockwise around onto the south Chatham Rise, and within this the largest fish were found on hills on the north Chatham Rise and south Chatham Rise east of 175.77° W (The Crack around to Big Chief), followed by hills on the south Chatham Rise (west of 175.77° W), followed by those away from the hills. On the northwest Chatham Rise west of the Graveyard Hills the female fish were larger in deeper water.

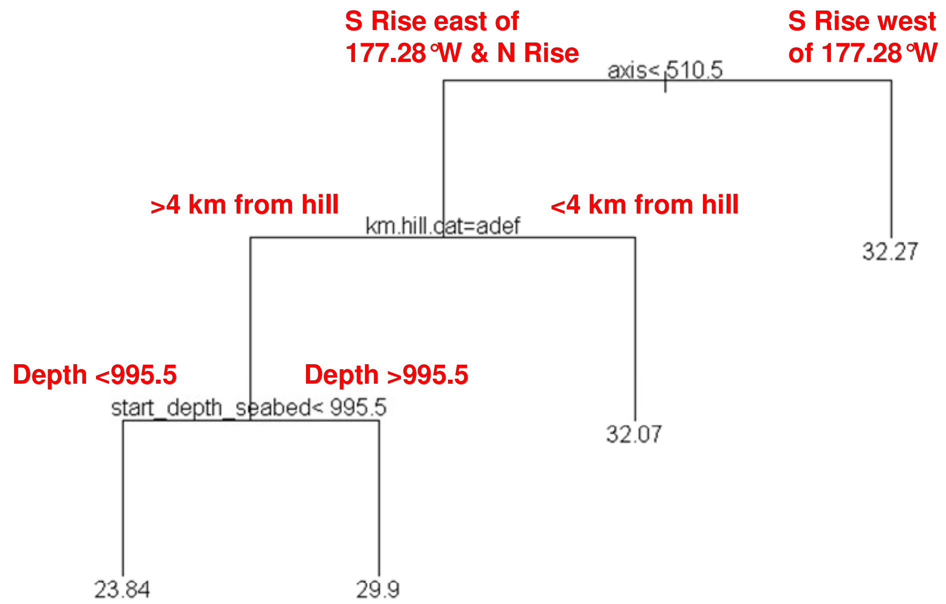


Figure 21: Regression tree analysis on median length (cm SL) for female orange roughy sampled by research trawls during September to May. No. tows = 510. The text at each split is the model split criteria (‘yes’ goes left, ‘no’ goes right), therefore an explanation of the split is also given above each limb. The average median length is shown at the end of each terminal group.

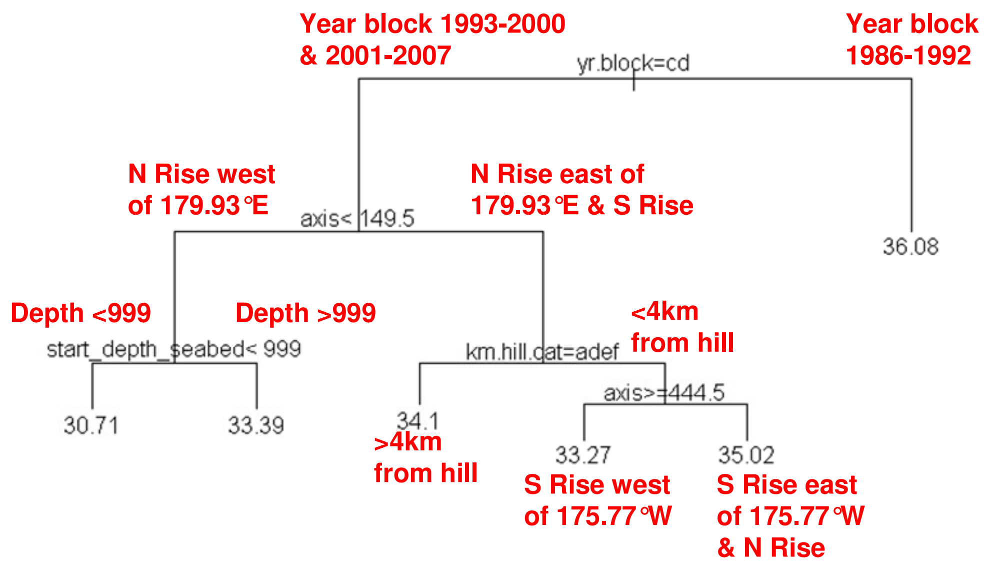


Figure 22: Regression tree analysis on median length (cm SL) for female orange roughy sampled by Ministry of Fisheries observers on board commercial trawlers. The model explained 27.6% of the deviance. No. tows = 2362. The text at each split is the model split criteria (‘yes’ goes left, ‘no’ goes right), therefore an explanation of the split is also given above each limb. The average median length is shown at the end of each terminal group.

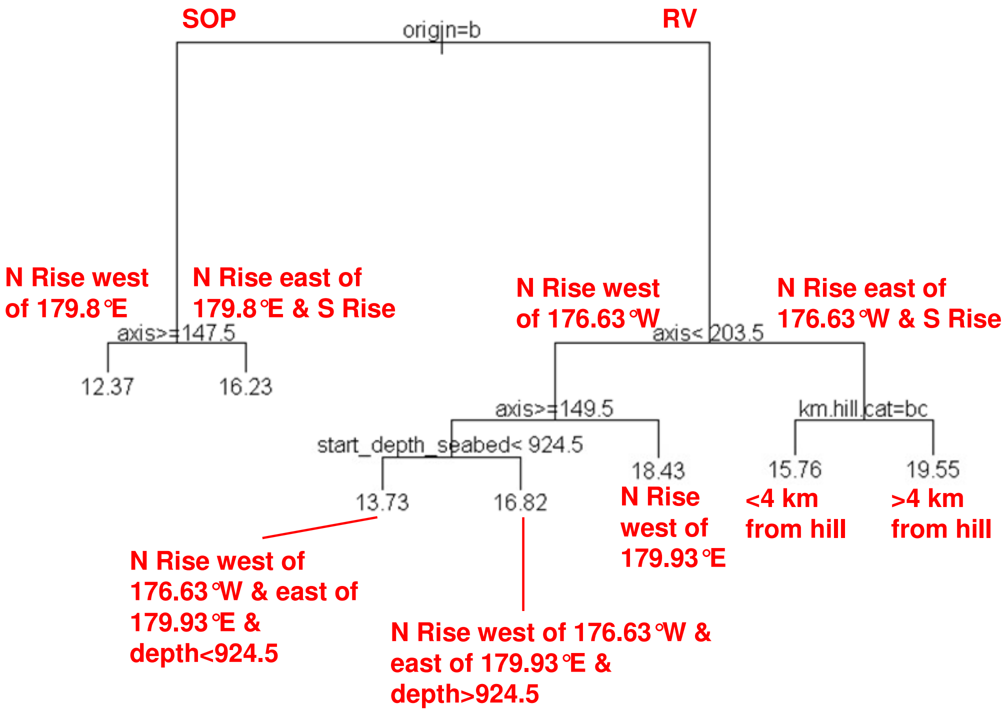


Figure 23: Regression tree analysis on length range (cm SL) for female orange roughy. The text at each split is the model split criteria ('yes' goes left, 'no' goes right), therefore an explanation of the split is also given above each limb. RV, research vessel; SOP, Ministry of Fisheries Scientific Observer Programme. The average length range is shown at the end of each terminal group.

The length range of female orange roughy was greater in the research tows than in the commercial tows sampled by the Ministry of Fisheries observers (Figure 23). Within the observer tows, the length range was smaller on the north Chatham Rise west of 179.8° E (the area east of the Graveyard hills). Within the research tows, the length range was lowest between 179.93° E and 176.63° W and relatively shallow depths, equivalent to the spawning grounds at the western end of the Spawning Box west to the Graveyard Hills. The length range was greater in relatively deep water in this area. The length range was relatively high close to hills on the east and south Chatham Rise and northwest Chatham Rise (in contrast to the observer samples), and relatively low close to hills on the east and south Chatham Rise.

The regression models were similar for males and females. In general, during the non-spawning season, larger fish were found on the hills, and when away from the hills in deeper water (stratum boundaries varied from 905 to 999 m). During the spawning season, the largest fish were found at the western end of the Spawning Box, with slightly smaller fish on the Graveyard Hills. Fish were relatively large near hills, and in samples from commercial trawlers were relatively small on flat areas of the northwest Chatham Rise. The relative size of fish on the south Chatham Rise west of the Andes and Big Chief area depended on the sampling method (research suggested relatively large, commercial relatively small). The only temporal effect estimated was from samples from commercial trawls, where fish were larger before 1993. The length range was lower where the median length was higher, suggesting where large fish were dominant, small fish were rare.

We can use the analyses of length frequency data to infer stock boundaries provided we assume that there is an ontogenetic shift in depth with increasing fish length on flat areas (Dunn et al. 2009), and larger fish are dominant on hills, perhaps because this is a preferred habitat or one where predation on smaller fish is relatively high. Given these assumptions, the analyses indicate that a stock boundary might occur between the east and south Chatham Rise and the northwest Chatham Rise, with the boundary being just to the west (non-spawning) or east (spawning) of the Graveyard Hills. The northwest Chatham Rise is an area where fish of a smaller median length were usually caught. A second boundary may occur on the south Chatham Rise, in the area between 177.28° W and 175.4° W, which is roughly the area between Hegerville and Big Chief. To the west of this area relatively large fish were usually caught by research trawls and relatively small fish by commercial trawls.

3.6 Length at maturity

In total, 213 071 orange roughy were measured during research surveys between 1980 and 2007, of which 199 132 were staged for maturity (Table 2).

Table 2: The number of immature and mature orange roughy measured by sex and subarea 1980–2007.

	Number of females		Number of males	
Subarea	Mature	Immature	Mature	Immature
3A	281	4 769	51	3 107
Andes	577	1 911	1 499	1 572
Arrow Plateau	4	–	–	–
Big Chief & neighbours	192	490	90	419
East Chatham Rise	3 431	3 499	2 974	3 271
Graveyard	11 227	2 978	18 412	4 269
Hegerville & Surrounds	519	1 869	188	1 418
NW Chatham Rise	6 907	11 136	5 547	10 417
South Chatham Rise	1 116	5 002	449	4 171
Smith City & neighbours	2 453	955	4 177	831
Spawning Box	33 282	9 820	23 179	10 535
The Hole	33	89	19	85

Most of the data covered spawning months (Figures 24 & 25). A year effect was estimated for only a few of the subareas (Figure 26). The estimated median length-at-maturity declined for both males and females from the Graveyard Hills, and for males at Smith City & neighbours and the east hills (Smith City, Big Chief, and Andes), but there was no obvious trend for the northeast Chatham Rise flats (Figure 26). On the northwest Chatham Rise, the estimated length at maturity for males increased from 1989 to 1990 and then declined, and for females increased from 1982 to 1992 and then declined (Figure 26). The decline in length at maturity observed for the Graveyard was also estimated for the flat areas of the northwest Chatham Rise. The hills on the east Chatham Rise showed a similar trend, but this was different from the pattern on the surrounding northeast flats. The apparent decline in length at maturity after the mid 1990s for the Spawning Box was not significant in this analysis. The analysis of estimated length at maturity did not provide much insight on stock structure, but supported splitting the east hills from the surrounding area.

3.7 Fish condition

There was no year effect estimated for Fulton’s K and the subareas ORH 3A, the Andes, and The Hole, nor for condition factor (CF) and the subareas ORH 3A and the Andes. The variables that best explained condition were year, month, sex, and fish length (Appendix 1). Fulton’s K tended to decline overall in the Spawning Box, east Chatham Rise flats, and south Chatham Rise (Figure 26); the trend was not clear for Smiths City, Hegerville, Big Chief, Graveyard, and northwest Chatham Rise flats (Figure 27). The relatively high Fulton’s K in 2005 for the Graveyard was also apparent in the Hegerville and south Chatham Rise subareas. A similar general pattern was seen in CF, with an initial increase in CF to about 1985 and then a decline in the Spawning Box, northwest Chatham Rise, and east Chatham Rise flats, an overall decline for the south Chatham Rise, and no clear trend for other subareas (Figure 28).

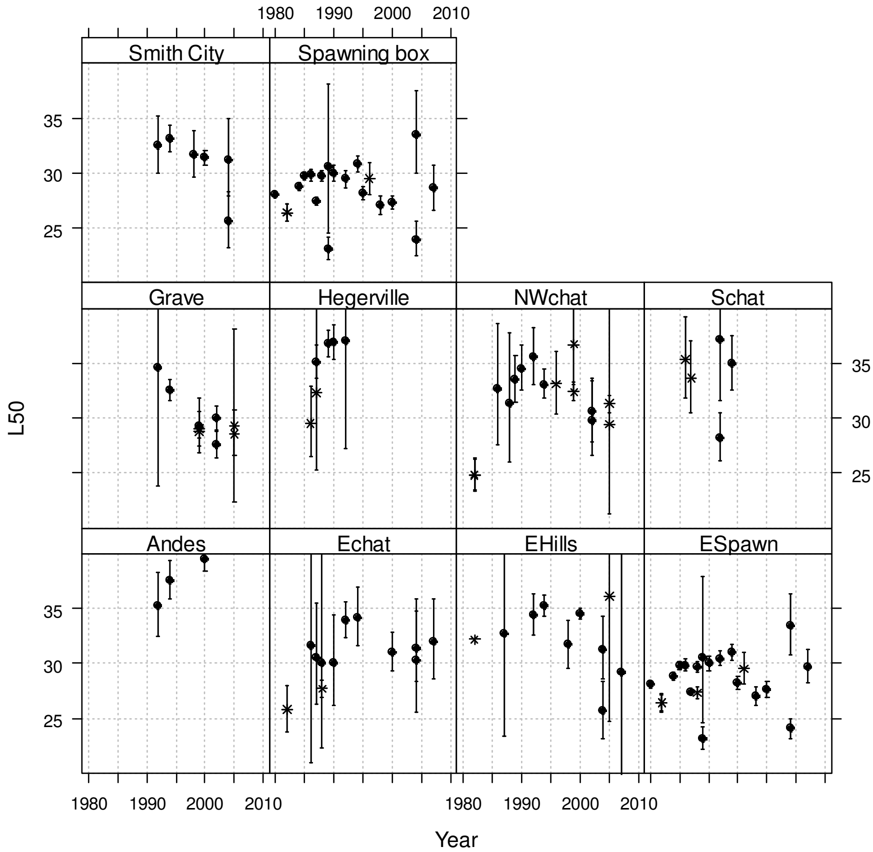


Figure 24: Estimated median length-at-maturity by trip for female orange roughy by year and subarea. Black squares, spawning months; stars, non-spawning months.

4

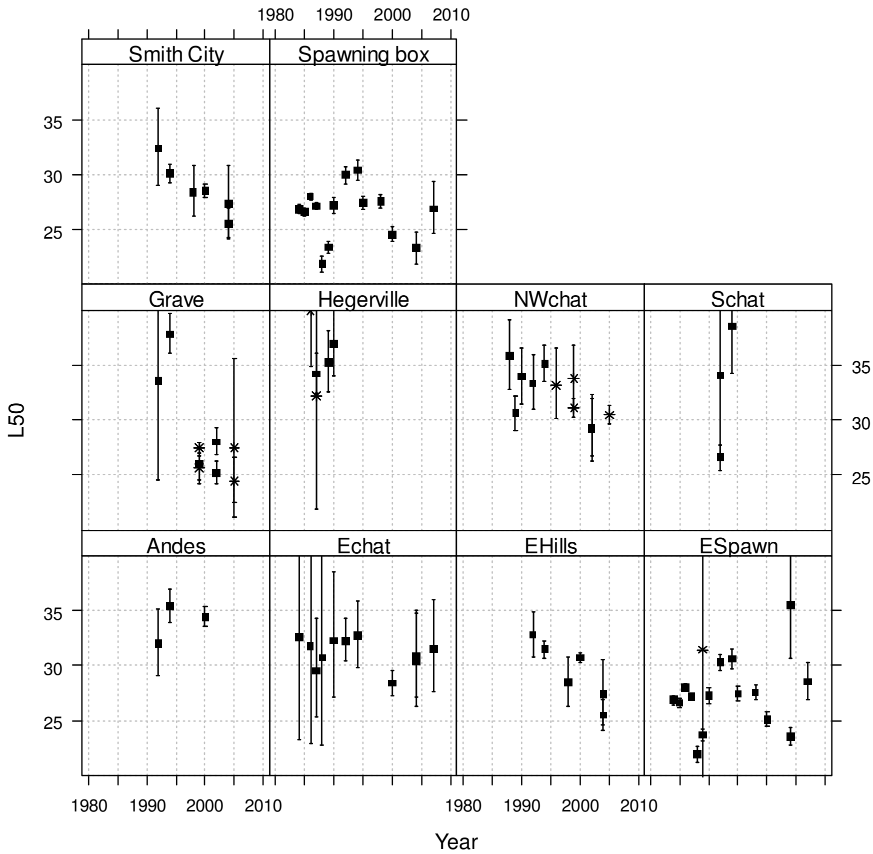


Figure 25: Estimated median length-at-maturity by trip for male orange roughy by year and subarea. Black squares, spawning months; stars, non-spawning months.

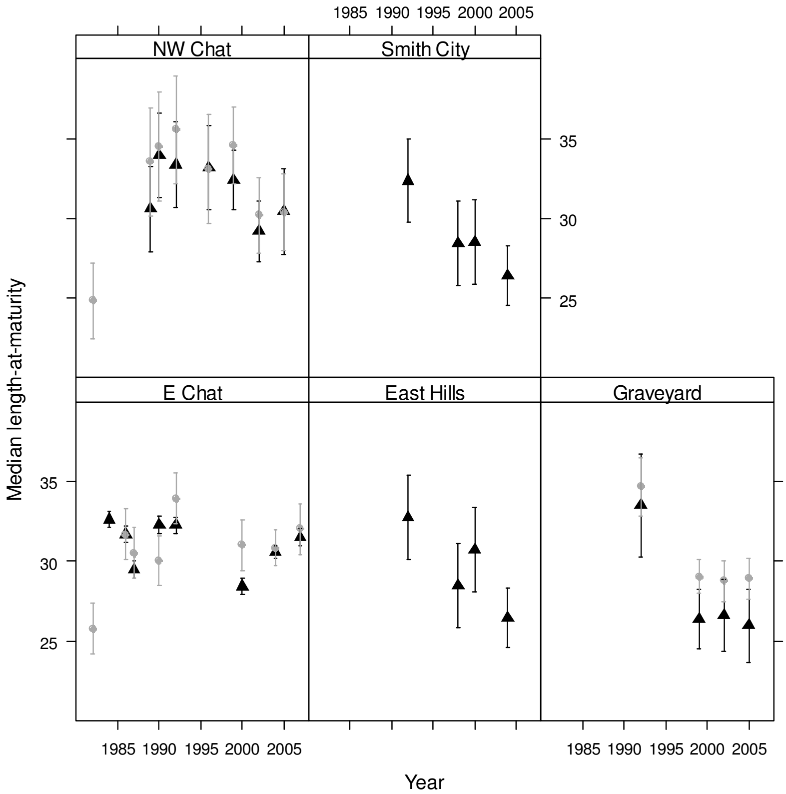


Figure 26: Median length-at-maturity where year explained 2% or more of the residual deviance for male (black triangles) and female (grey circles) orange roughy on the Chatham Rise.

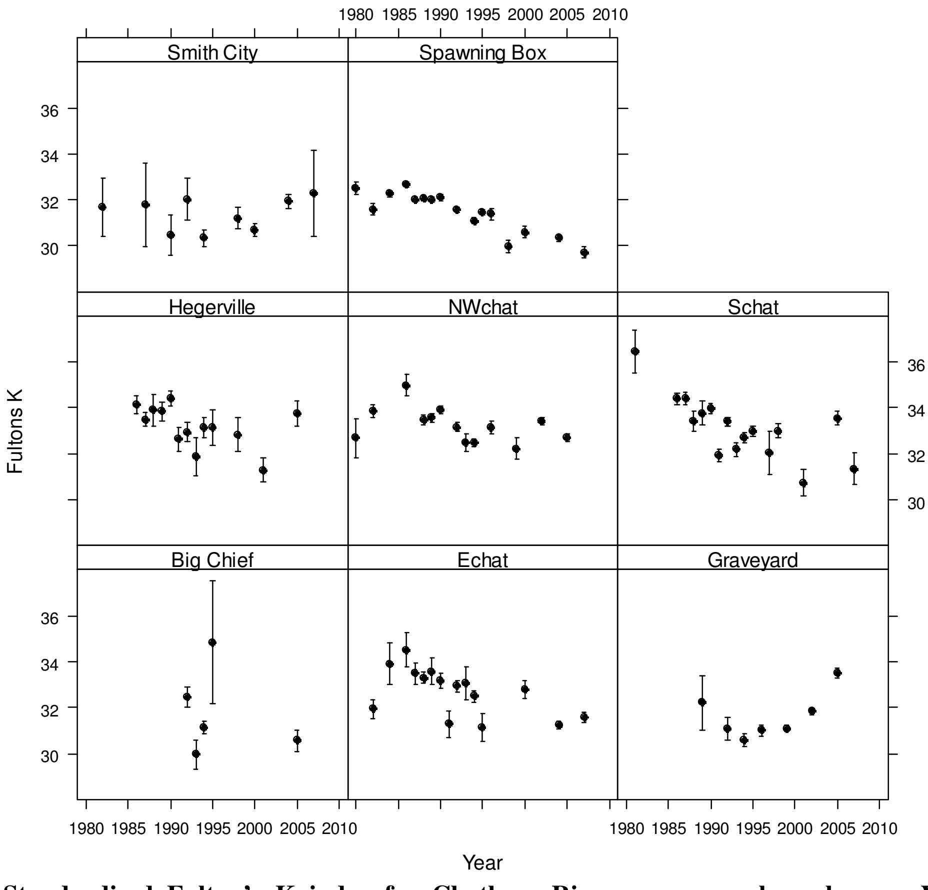


Figure 27. Standardised Fulton's K index for Chatham Rise orange roughy subareas. Vertical lines indicate the estimated 95% confidence intervals.

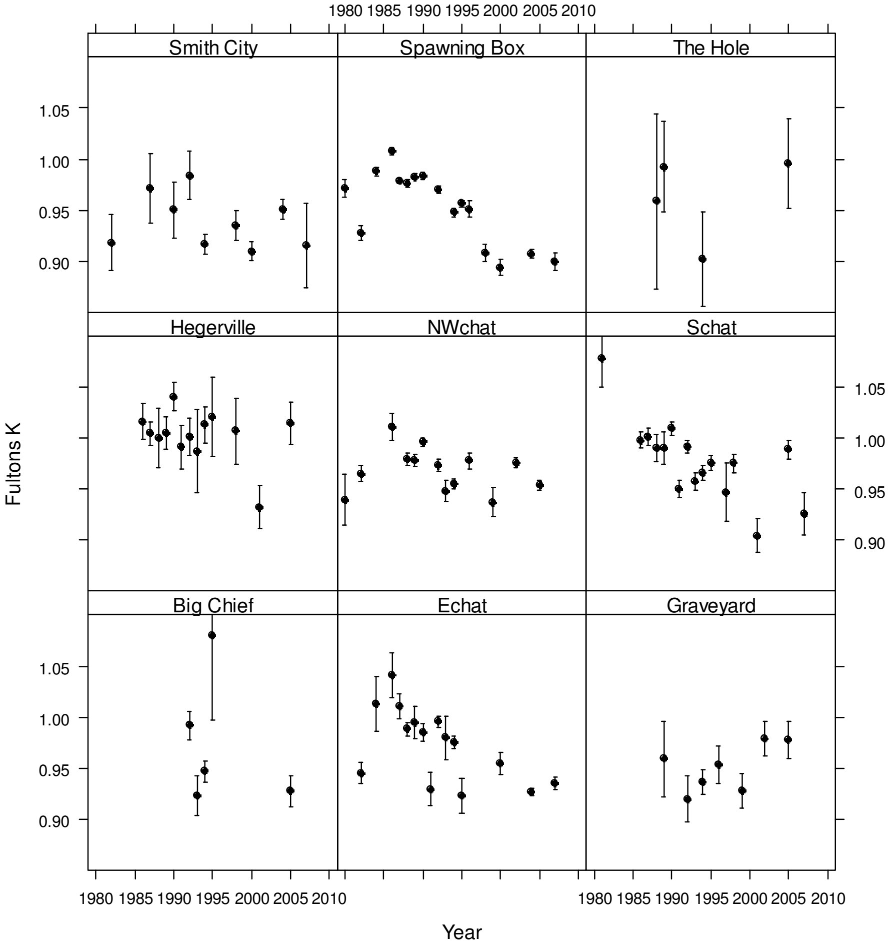


Figure 28. Standardised condition index for Chatham Rise orange roughy subareas with high value (1.2) from The Hole in 1982 omitted. Vertical lines indicate the estimated 95% confidence intervals.

The results indicated that fish on the hills of the east and south Chatham Rise could be a different stock from those on the surrounding flats. Fulton's K suggested the northwest Chatham Rise was different from the east and south Chatham Rise flats, but the CF suggested the Spawning Box and northwest Chatham Rise were similar. The pattern of CF was similar for the northwest Chatham Rise and the Graveyard Hills. The similar general decline in condition was estimated for the south and east Chatham Rise, suggesting they may contain the same stock. There were too few data to evaluate Big Chief and The Hole in relation to other subareas.

3.8 Genetics

Smith & Benson (1997) used frequencies of 11 allozyme loci to evaluate orange roughy stock structure on the east coast of New Zealand including the Chatham Rise. Allozymes are variations in a protein which are coded for by different alleles at the same locus. However, allozyme frequencies may also be influenced by time and selection pressure, and so may reflect local differences in selection pressure rather separate populations (Smith et al. 1997). Nevertheless, local differences in selection pressure could be considered adequate rationale for separate stocks. Smith & Benson (1996) concluded that the genetic heterogeneity on the Chatham Rise implied that there was more than one stock unit. Specifically, there was a significant difference between The Hole and the Morgue (Graveyard Hills), and between the Morgue and Smiths City. There were no other genetic-stock boundaries, rather there was evidence for isolation by distancing. This result was consistent with a common stock on the east and south Chatham Rise, two further stocks on the northwest Chatham Rise, and some degree of philopatry. The Smith & Benson (1996) study didn't sample fish from the spawning plumes in the Spawning Box because the fishery was closed at the time.

Smith et al. (1996) measured polymorphism in mitochondrial DNA to examine the stock structure of orange roughy around New Zealand, and found significant differences between fish from the Ritchie Bank (east coast North Island) and the Spawning Box, and between the Spawning Box and Waitaki (east coast South Island). Mitochondrial DNA may also be influenced by local selection, but is believed to be less influenced than allozymes (e.g., Smith et al. 1997, Stewart Grant et al. 2006).

Genetics provide evidence for stock separation between the east coast of the North Island and the Chatham Rise. There was also evidence from allozyme studies of two stocks on the northwest Chatham Rise, and a single stock on the east and south Chatham Rise, within which there was evidence for isolation by distancing. However, at Mount Kiso on the south Chatham Rise the temporal heterogeneity in allozyme frequency was greater than the spatial heterogeneity, casting doubt on stock structure conclusions, at least at that location.

3.9 Habitat structure and natural boundaries

By 1995–96, about 65% of the Chatham Rise orange roughy catch was taken on hills, and by 1999, this had increased to about 70% (Clark, 1999). The association of orange roughy with underwater features such as hills is widely known (e.g., Tracey & Fenaughty 1997), and there are reasonable hypotheses why the fish might favour these habitats (e.g., Fock et al. 2002). On the Chatham Rise, hills and other features are concentrated on the south–east Chatham Rise, and the commercial catches have been clearly associated with this area and with specific features (Figure 29). The hill habitat on the southeast Chatham Rise is largely uninterrupted, with no clear natural breaks. Most commercial catches outside the spawning season have been taken in the southeast corner of the Chatham Rise (Clark et al. 2000).

The deep sea currents result in a front on the southeast Chatham Rise, where warmer water from the north meets colder water from the west and south (Figure 30). The distribution of juvenile orange roughy is consistent with them being found primarily in the warm water around the north and east Chatham Rise, and avoiding the cold water west of the front (Dunn et al. 2009). A gyre to the north of the Graveyard could help to retain eggs and larvae from the spawning on the Graveyard, and prevent their eastward drift, resulting in a separation between the northwest and east Chatham Rise. An extension of subantarctic water through the Mernoo Gap at the western end of the Chatham Rise (Heath 1985) could contribute to a westerly limit of orange roughy distribution on the north Chatham Rise. This analysis supports a split or limit on the south Chatham Rise to the west of Hegerville, and possibly a split on the north Chatham Rise at around the Graveyard Hills.

3.10 Stock structure hypotheses

Four key questions were addressed.

(1) Is the northwest Chatham Rise a separate stock?
The analyses which tended to support the hypothesis of a separate stock were CPUE trends, spawning locations, nursery grounds, inferred migrations, length frequency analyses, genetics, and possibly habitat and natural boundaries. The analyses which tended to reject the hypothesis were the observation that some spawning fish may have come to the Spawning Box plumes from the west (Coburn & Doonan 1994), and possibly the analysis of length at maturity. The analyses which were equivocal were catch history and condition factor. On balance it seems most likely that a separate stock can be assumed for the northwest Chatham Rise, which includes the major spawning ground at the Graveyard Hills. Therefore the existing split between the northwest and east Chatham Rise, at 178° W, seems appropriate.

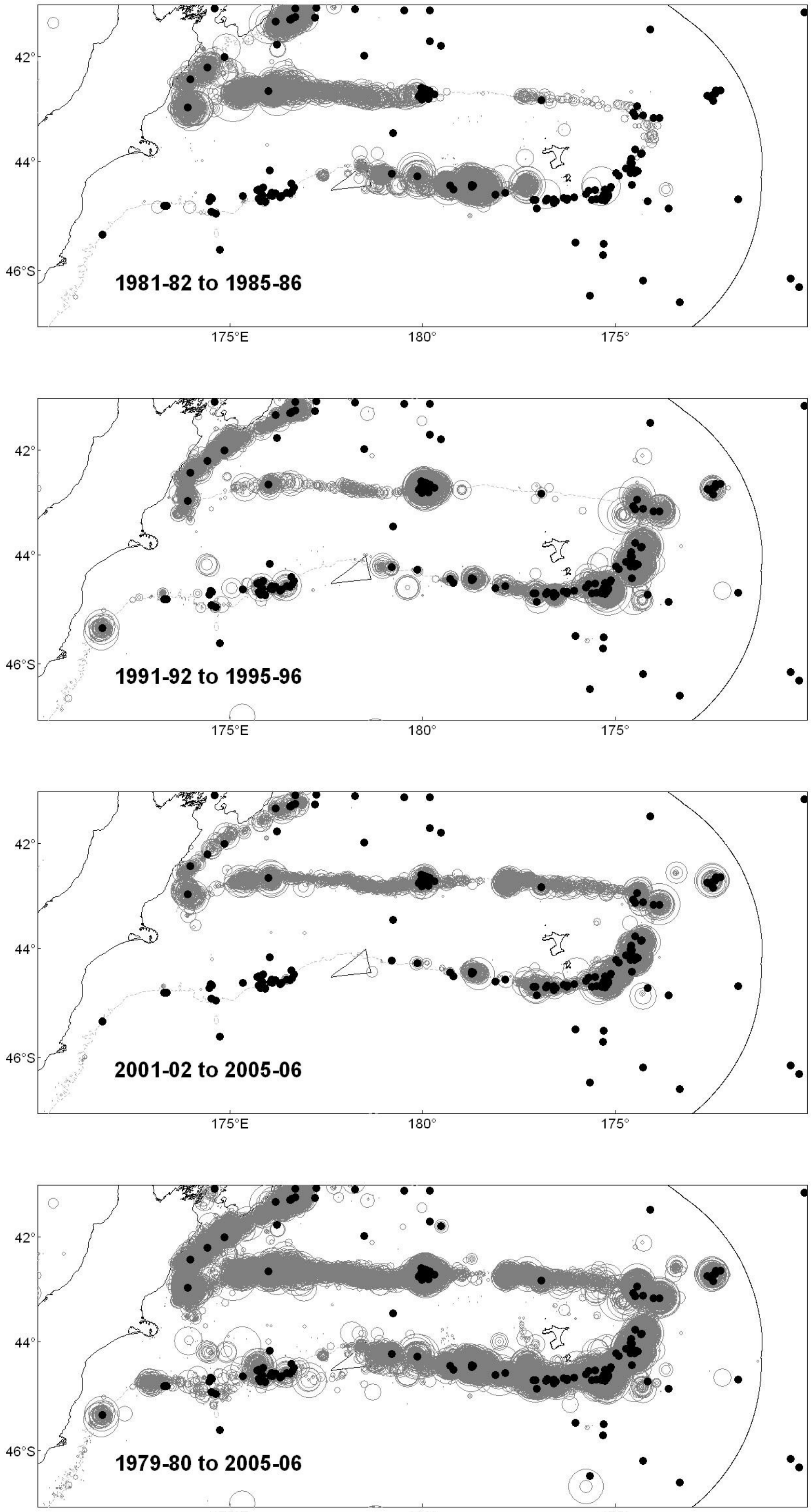


Figure 29: Commercial estimated catches of orange roughy (expanding circles) during October to April by fishing year. Catches are proportional to circle size, with the maximum catch rate (t/tow), from top to bottom, of 77 t, 85 t, 85 t and 85 t. The location of known seamount, hill or pinnacle features is shown as solid points. The Hole on the NW Chatham Rise has also been marked, although it is a canyon area rather than a hill.

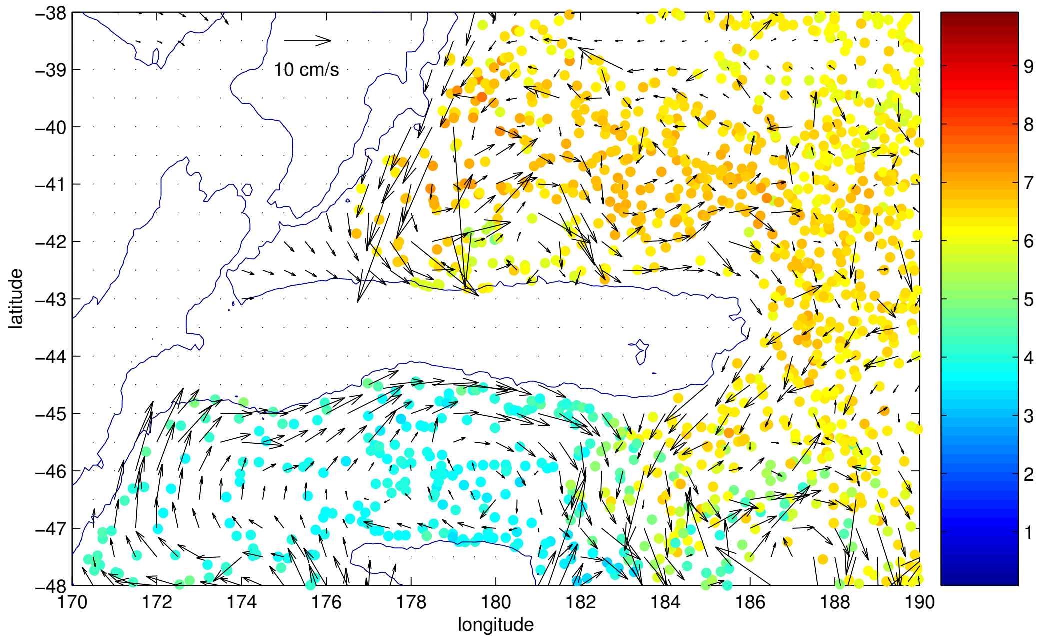


Figure 30: Temperature (°C) measured at 900 m from Argo profiles, with estimates of the velocity at 900 m overlaid. The velocity vectors have been averaged in 0.5° latitude and longitude bins. Figure reproduced from Dunn et al. (2009).

The genetics study suggested there may have been two stocks on the northwest Chatham Rise, but this was not strongly supported by other studies, therefore a single stock seems the sensible assumption at present. The area including The Hole was frequently fished through the 1980s and 1990s, but has been rarely fished in recent years (Anderson & Dunn 2008). Therefore if a substantial stock did exist in this area, it seems that it has now been substantially declined, or it no longer exists.

(2) Are the eastern hills (northeast hills and the Andes) separate from each other and from the Spawning Box and Northeast Flats?

The analyses which tended to support the hypothesis of a separate stock on the eastern hills were spawning locations, fish condition, and length at maturity. The analyses which tended to reject the hypothesis were CPUE, nursery grounds, inferred migrations, and also habitat and length frequency analyses (if we assume an ontogenetic shift in distribution takes place). The analyses which were equivocal were catch history and genetics. On balance it seems most likely that the eastern hills do not contain a separate stock.

It seems somewhat unreasonable that the spatially distinct hills, which support high densities of predominantly large fish, are distinct from the surrounding area, which contained both small and large fish. We do not believe that assuming the hills are part of a wider east Chatham Rise stock precludes a degree of site fidelity to specific locations or hills, but it would preclude widespread natal philopatry: the presence of multiple spawning locations would, in this case, require the assumption that orange roughy on the east Chatham Rise form a metapopulation.

(3) Is the eastern part of the south Chatham Rise (Big Chief and surrounding area) part of the east Chatham Rise?

The analyses which tended to support the hypothesis of the Big Chief and surrounding area being continuous with the east Chatham Rise were catch history, CPUE trends, spawning grounds (or a lack of substantial spawning ground in the Big Chief area), nursery grounds, length frequency analyses, genetics, and habitat and natural boundaries. No analyses tended to reject the hypothesis. The analyses of fish condition were equivocal, and analyses of inferred migrations and length at maturity provided no information. On balance it seems likely that the Big Chief and surrounding area are continuous with the east Chatham Rise, and part of the same stock.

(4) Is the area of the south Chatham Rise to the west of the Big Chief, which includes Hegerville and the surrounding area, continuous with the east Chatham Rise?
The analyses which tended to support the hypothesis of the Hegerville and surrounding area being continuous with the east Chatham Rise were spawning locations, nursery grounds, inferred migrations, fish condition, and genetics. The analyses which tended to reject the hypothesis were CPUE, length frequency analyses, and habitat and natural boundaries. The analyses of catch history and length at maturity were equivocal. On balance it seems likely that the south Chatham Rise area that includes Hegerville is part of the same stock as the eastern (Big Chief) area of the south Chatham Rise and the east Chatham Rise.

The absence of a known substantial spawning ground on the south Chatham Rise seems a reasonable argument that this area does not contain a separate stock, and is consistent with infrequent occurrence of juveniles. However, the spawning migration to the Spawning Box was estimated to take about two months in each direction, which would be a substantial and prolonged migration. It is possible that the central and western areas of the south Chatham Rise are comparatively marginal habitat, especially for juveniles, being colder than the eastern and northern areas. This would explain the contraction of the stock to the eastern and northern areas following exploitation, and the described "serial depletion" of the south Chatham Rise (Clark 1999).

3.11 Overall conclusion

No individual analysis provided complete information on stock structure, and no two individual analyses seemed to completely agree. The holistic analysis used suggested two stocks should be assumed for the Chatham Rise:

- The northwest Chatham Rise. Having a western boundary at the Mernoo Gap and eastern boundary at 178° W.

- The east and south Chatham Rise. Having the western boundary on the north Rise at 178° W, and including all of the east and south Chatham Rise.

These stocks are assumed to be bounded by the relatively shallow water (less than 600 m) along the centre of the Chatham Rise, and by the deeper water (over 2000 m) to the north, south and east of the Chatham Rise: it is implicitly assumed orange roughy do not extend or move through these waters, and to date there is no information to suggest that they do.

This stock structure hypothesis assumes that orange roughy stocks may act as metapopulations. Under this hypothesis, there may be groups of fish that exist as largely independent units (substocks), having separate spawning grounds and behaving as if they were 'local resident' stocks (for example, on hill complexes). However, we assume that the fish recruit from a common nursery ground, not from within the substock, such that local depletion of a substock can be followed by recolonisation. This assumption allows for multiple spawning grounds within a single stock, and complex and subtly different dynamics within different parts of the distribution.

4. DISCUSSION

4.1 Other arguments

Stock assessments have indicated that the virgin biomass of mature orange roughy on the northeast Chatham Rise was probably 300 000–450 000 t (Ministry of Fisheries 2009). The simple question is where would this very large biomass exist outside of the spawning season? It seems unlikely that the few Northeast hills, the Andes, and the northeast flat areas would support such a large biomass. It seems more sensible to assume that the south Chatham Rise was part of the same stock range, thereby providing the extra habitat. We could then assume the southeast corner of the Chatham Rise provides the most favourable habitat as the fishery has remained centered in that area. The southeast Chatham Rise would therefore be the centre of the stock distribution outside of spawning, and the Spawning Box the main spawning location.

Pelagic residence times of orange roughy eggs and larvae are believed to be short (about 10 days, Zeldis et al. 1995), and would therefore allow only limited dispersal, and could result in localised populations. The main dispersal stage in marine fishes is usually thought to be egg and larval drift in ocean currents, but adolescents of some fish species have also been found to undertake extensive dispersal movements (Pawson et al. 1987, Dunn & Pawson 2002). There is some evidence in this study that adolescent or mature orange roughy may undertake extensive dispersal movements. It is therefore possible that mixing might occur over the whole Chatham Rise at a level sufficient to result in a single genetic population; it may, however, be spatially or temporally low enough that we should still assume multiple management stocks.

4.2 Changes in length at maturity and fish condition

A decline in length at maturity could have been caused by several factors, but rapid changes would not be expected in a long-lived fish like orange roughy (Clark et al. 2000). The most likely causes are trends in the selectivity of the fishery, trends in the timing of spawning migrations, or a decline in recruitment. A recruitment level lower than expected (the long-term average) was estimated from trawl surveys of the east and south Chatham Rise in 2004 and 2007 by Doonan & Dunn (unpublished results).

A decline in condition can be a response to many factors, including environmental conditions and stock density (e.g., Dutil et al. 1999, Ratz & Lloret 2003). Fish in poor condition before stressful periods, such as spawning, migration, or over-wintering, are more likely to have higher mortality rates (Lambert & Dutil 1997 and references therein, Carscadden & Frank 2002), lower fecundity (Koops et al. 2004), and may skip spawning or have less viable gametes (Marteinsdottir & Begg 2002). Declining condition is therefore likely to result in declining stock productivity. A decline in fish condition also results in an increasing amount of individual fish caught per tonne. This is equivalent to an increase in fishing mortality rate under a constant catch scenario. Changes in fish condition seem to be rarely measured during stock assessments, which may fail to identify changes in fishing mortality as a result.

4.3 Future research

No single analysis method provided enough information on its own to determine stock structure, and there was disagreement on potential stock boundaries from the different analyses. As a result, the hypothesis of stock structure presented here should be experimentally tested. The best methods to achieve this are probably further genetic studies, or tagging experiments.

6. ACKNOWLEDGMENTS

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APPENDIX 1

Results of the generalized linear models testing the effect of year, month, fish length, and interactions on the two measures of fish condition for orange roughy.

Table A1: Spawning Box. Predictors by order of selection and the percentage of deviance explained (r^2) for the model for Fulton's K and relative condition factor.

Fultons K	r^2
Length (5th)	0.41
Year	0.44
Condition factor	
Year	0.07
Sex	0.09

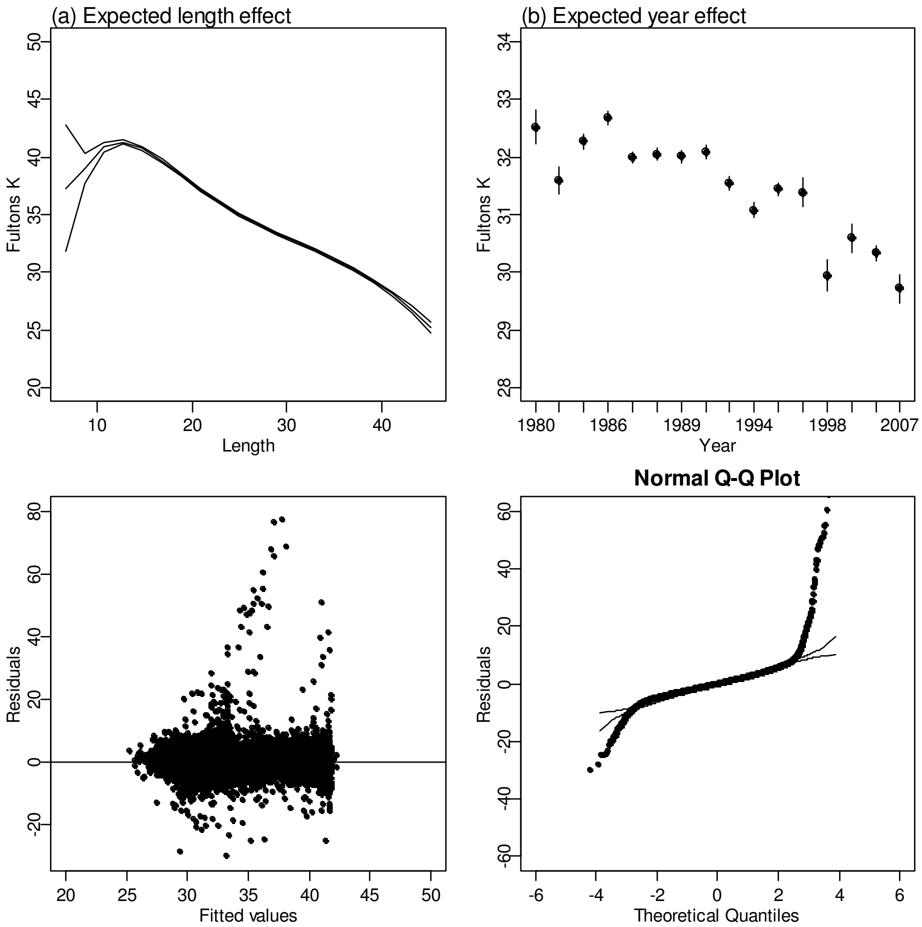

Figure A1: Spawning Box. Predicted effects of the selected variables in the binomial model for Fulton's K (a,b), and model diagnostic plots (c,d). The upper and lower lines in panel (a), and vertical bars in panel (b), indicate the 95% confidence intervals.

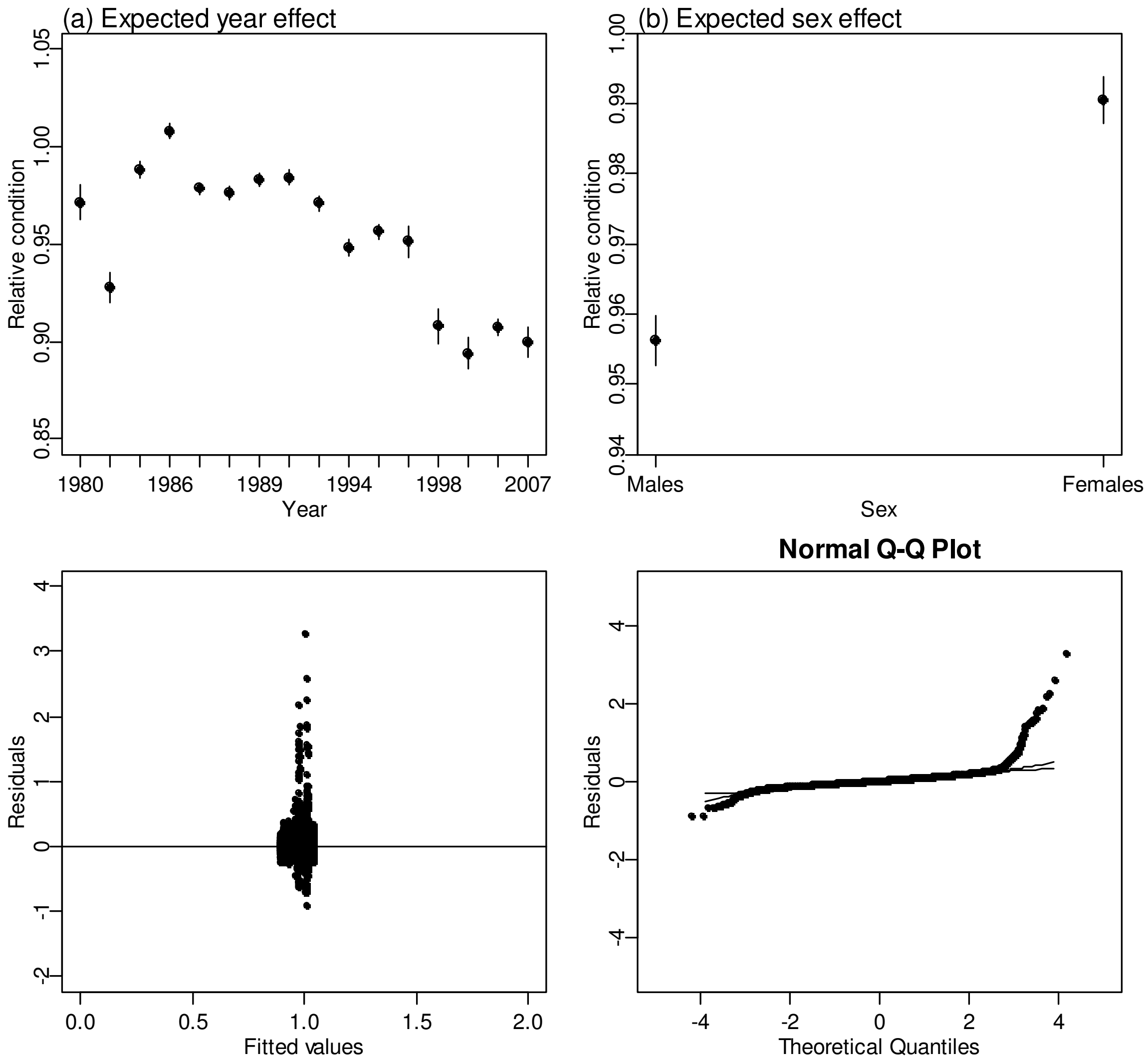

Figure A2: Spawning Box. Predicted effects of the selected variables in the binomial model for CF (a,b), and model diagnostic plots (c,d). The upper and lower lines in panel (a), and vertical bars in panel (b), indicate the 95% confidence intervals.

Table A2: Graveyard Hills: Predictors by order of selection and the percentage of deviance explained (r^2) for the model for Fulton's K and relative condition factor.

Fultons K	r^2
Length (4^{th})	0.19
Year	0.25
Condition factor	
Year	0.08
Sex	0.12
Month	0.15

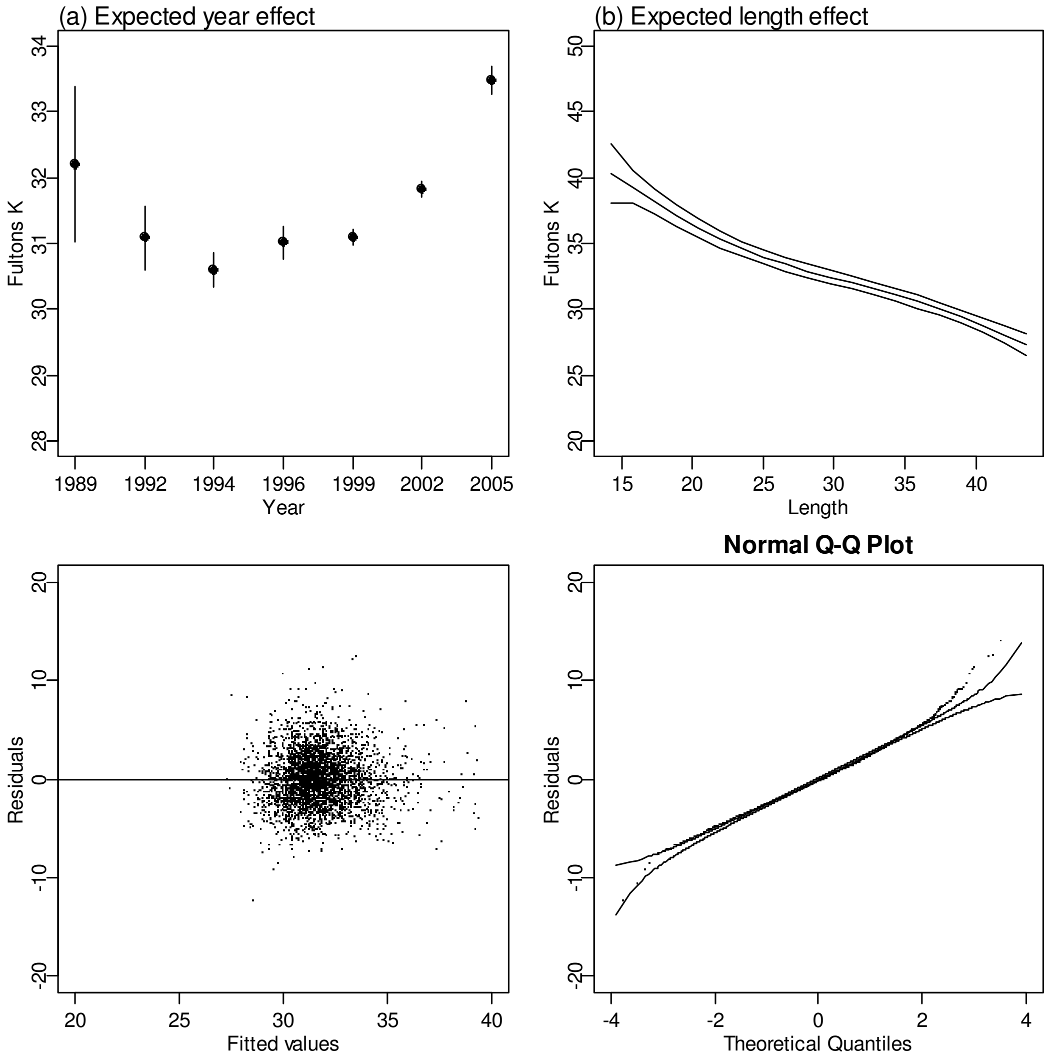

Figure A3: Graveyard Hills. Predicted effects of the selected variables in the binomial model for Fulton's K (a,b), and model diagnostic plots (c,d). The upper and lower lines in panel (a), and vertical bars in panel (b), indicate the 95% confidence intervals.

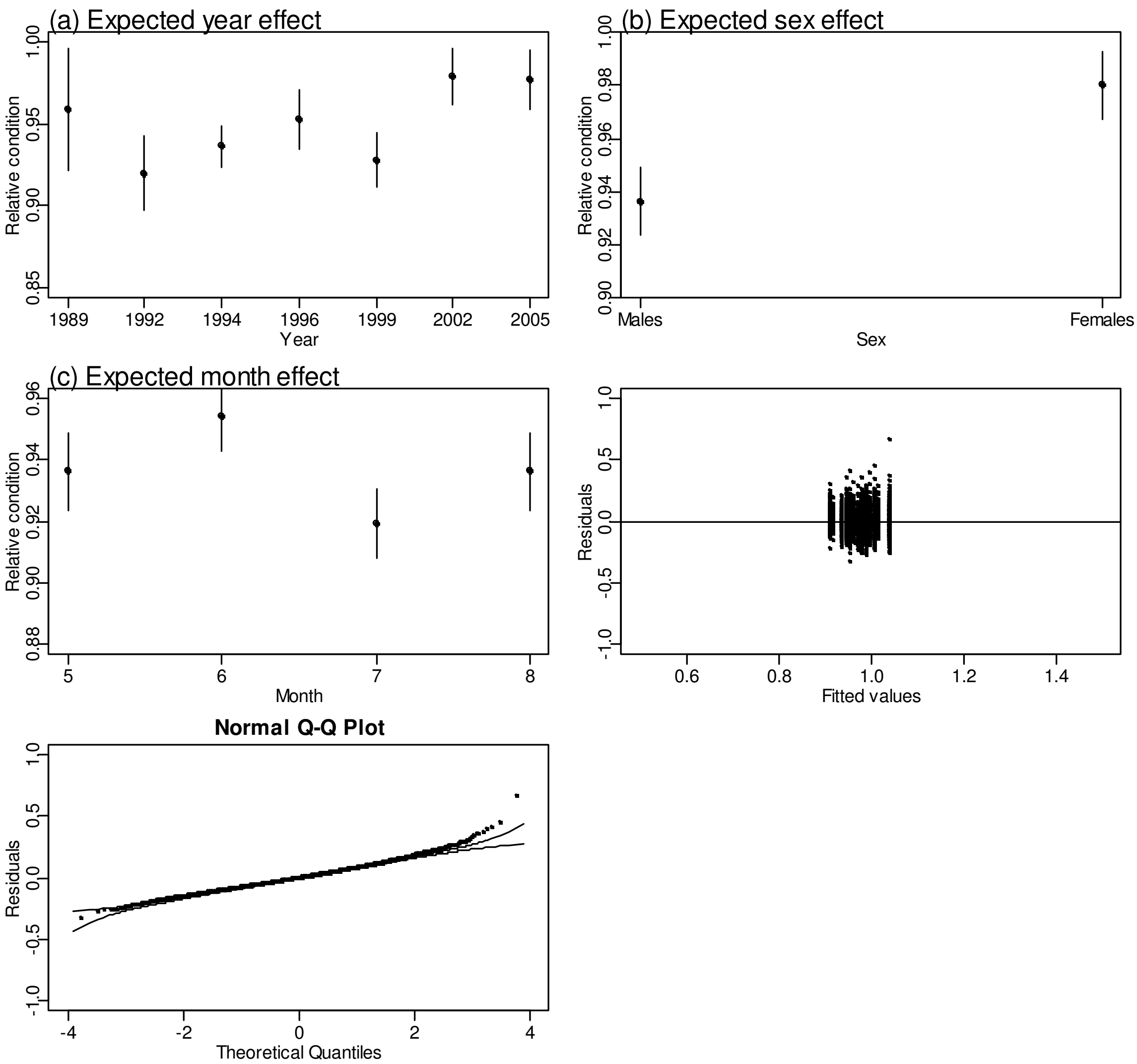

Figure A4: Graveyard Hills. Predicted effects of the selected variables in the binomial model for CF (a,b,c), and model diagnostic plots (c,d). The upper and lower lines in panel (a), and vertical bars in panels (b) and (c), indicate the 95% confidence intervals.

Table A3: Smith City & neighbours: Predictors by order of selection and the percentage of deviance explained (r^2) for the model for Fulton's K and relative condition factor.

Fultons K	r^2
Length (2nd)	0.17
Year	0.22
Year:Length (2nd)	0.30
Condition factor	
Year	0.07
Sex	0.11

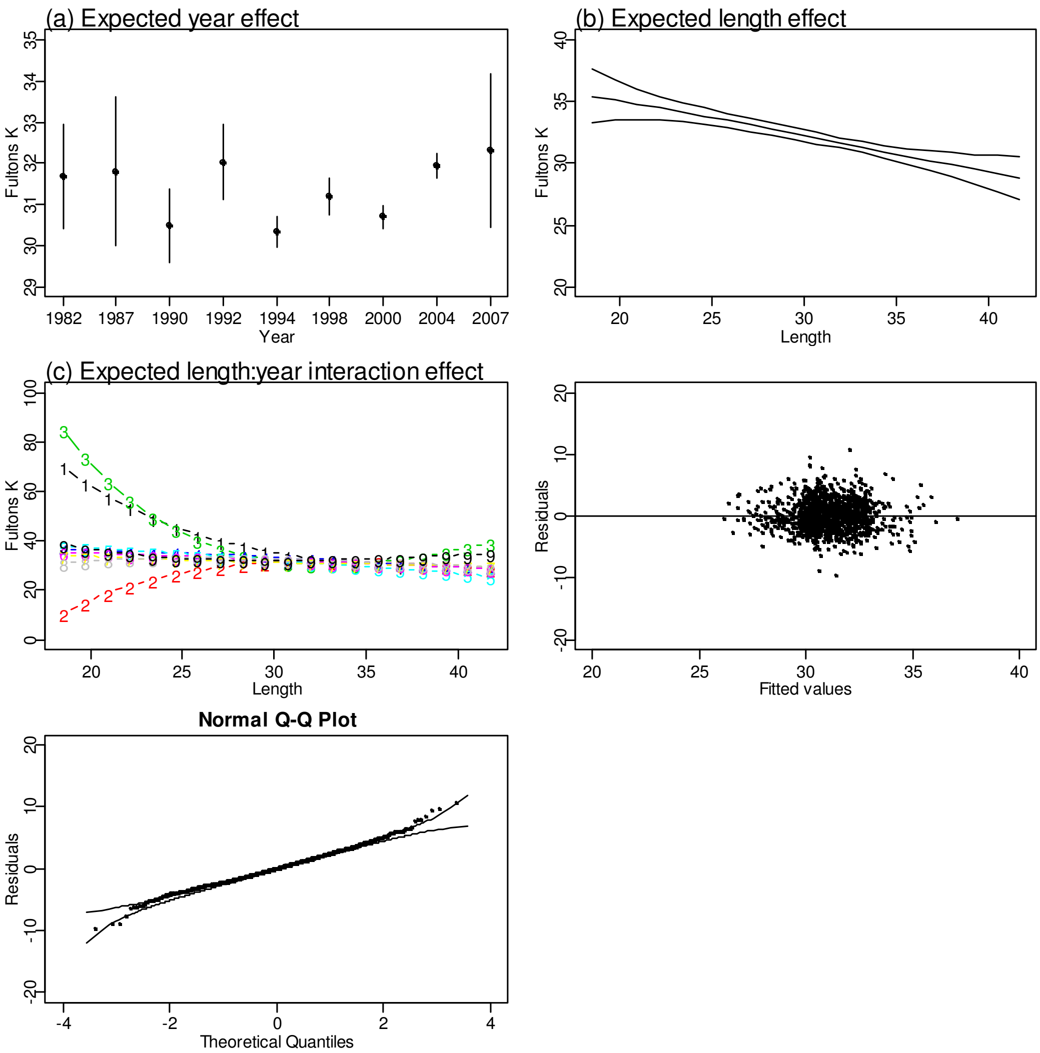

Figure A5: Smith City & neighbours. Predicted effects of the selected variables in the binomial model for Fulton's K (a,b,c), and model diagnostic plots (d,e). The vertical bars in panel (a), and upper and lower lines in panel (b), indicate the 95% confidence intervals.

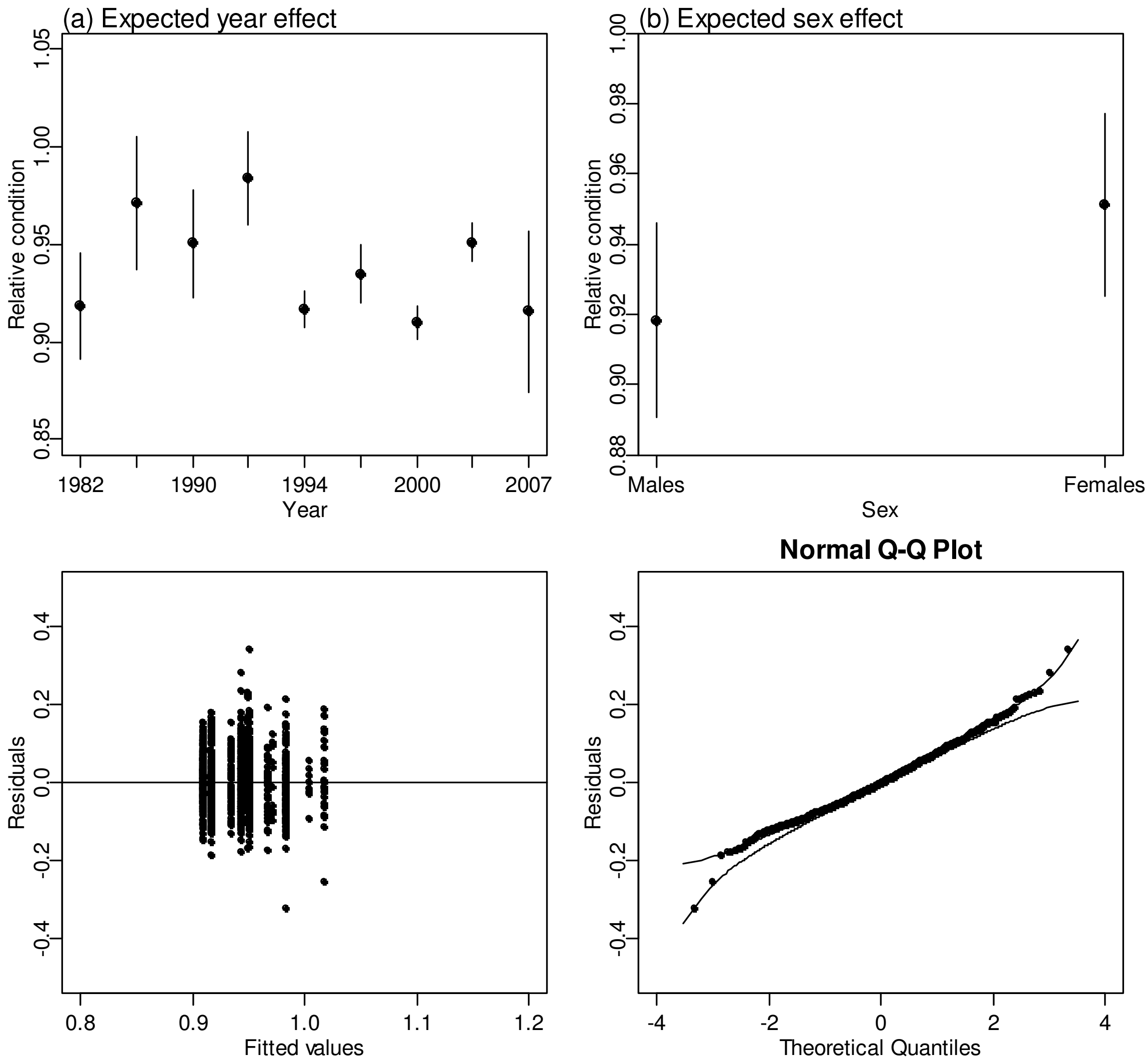

Figure A6: Smith City & neighbours. Predicted effects of the selected variables in the binomial model for CF (a,b), and model diagnostic plots (c,d). The vertical bars in panels (a) and (b) indicate the 95% confidence intervals.

Table A4: Big Chief & neighbours: Predictors by order of selection and the percentage of deviance explained (r^2) for the model for Fulton's K and relative condition factor.

Fultons K	r^2
Length (2nd)	0.17
Year	0.25
Condition factor	
Year	0.10
Maturity	0.15
Length (2nd)	0.19

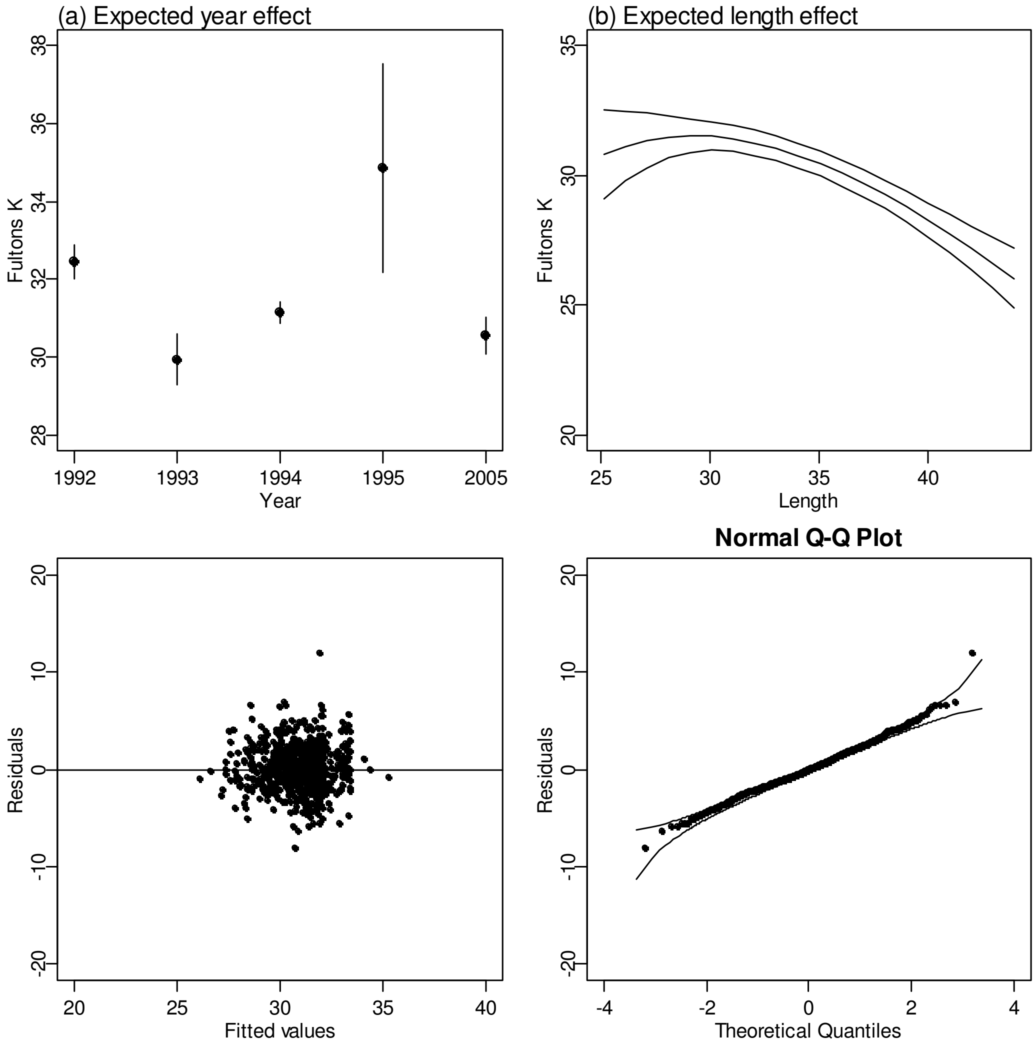

Figure A7: Big Chief & neighbours: Predicted effects of the selected variables in the binomial model for Fulton's K (a,b), and model diagnostic plots (c,d). The vertical bars in panel (a), and upper and lower lines in panel (b), indicate the 95% confidence intervals.

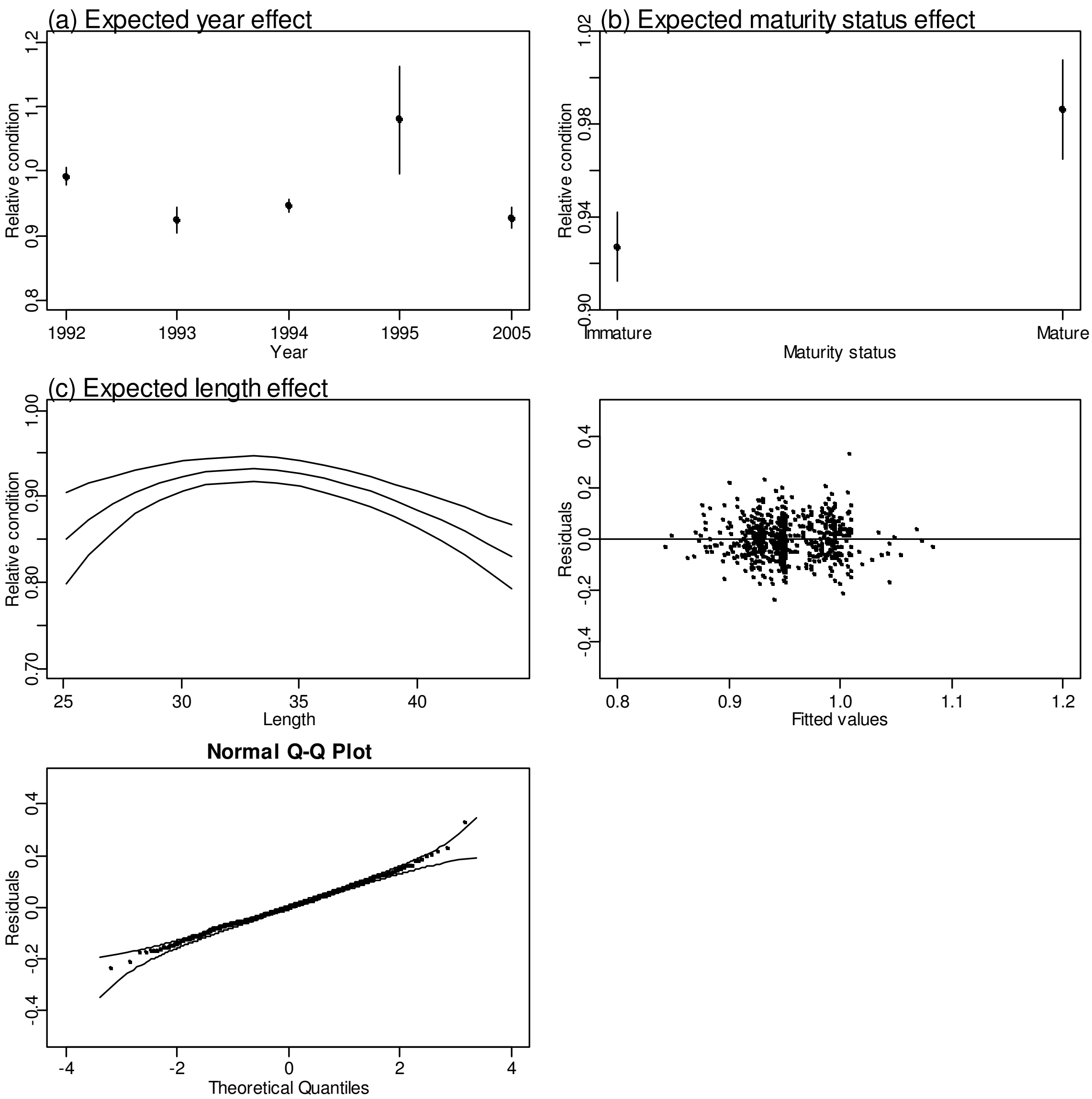

Figure A8: Big Chief & neighbours: Predicted effects of the selected variables in the binomial model for CF (a,b,c), and model diagnostic plots (d,e). The vertical bars in panels (a) and (b), and upper and lower lines in panel (c), indicate the 95% confidence intervals.

Table A5: ORH 3A: Predictors by order of selection and the percentage of deviance explained (r^2) for the model for Fulton's K and relative condition factor.

Fultons K	r^2
Length (5th)	0.25
Month	0.32
Condition factor	
Month	0.08

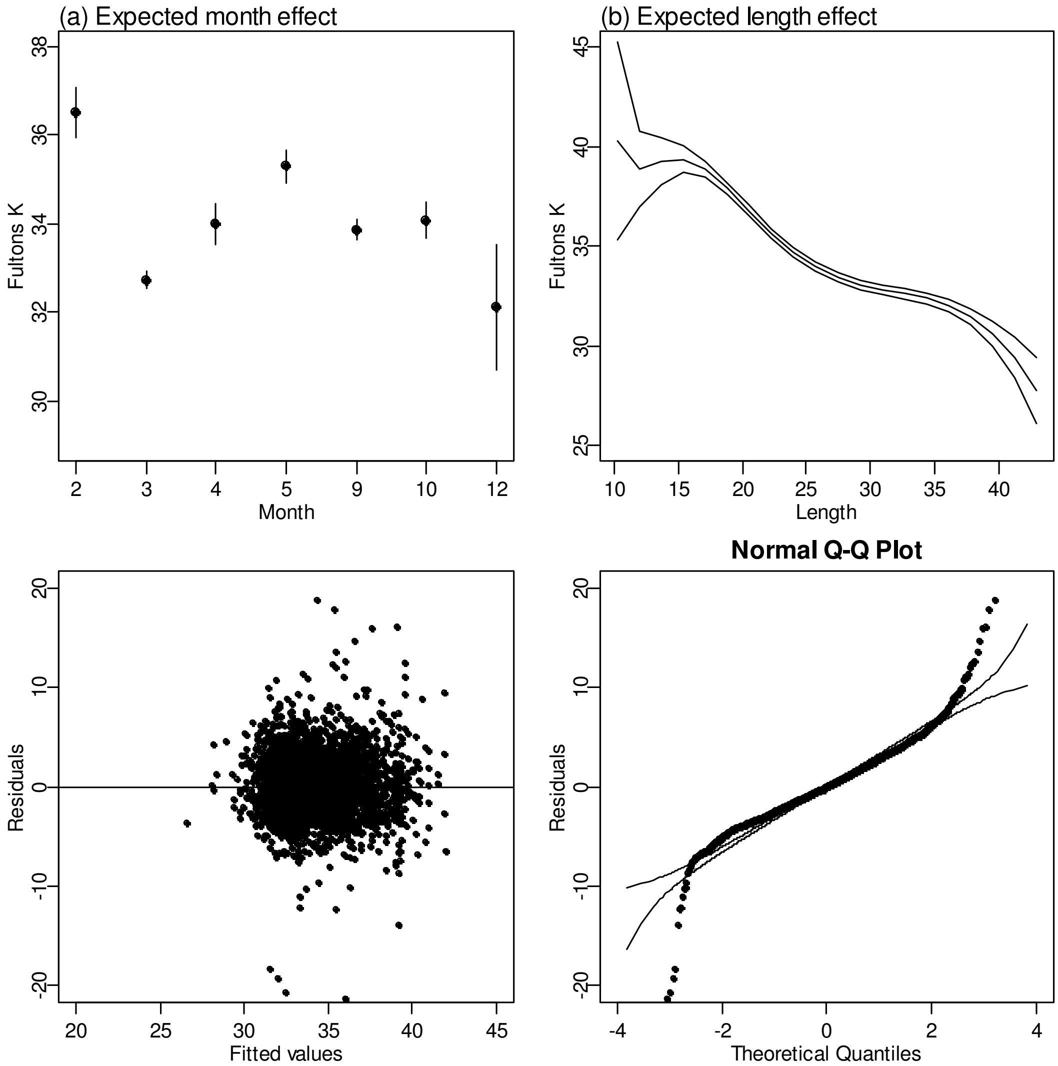

Figure A9. ORH 3A: Predicted effects of the selected variables in the binomial model for Fulton's K (a,b), and model diagnostic plots (c,d). The vertical bars in panel (a), and upper and lower lines in panel (b), indicate the 95% confidence intervals.

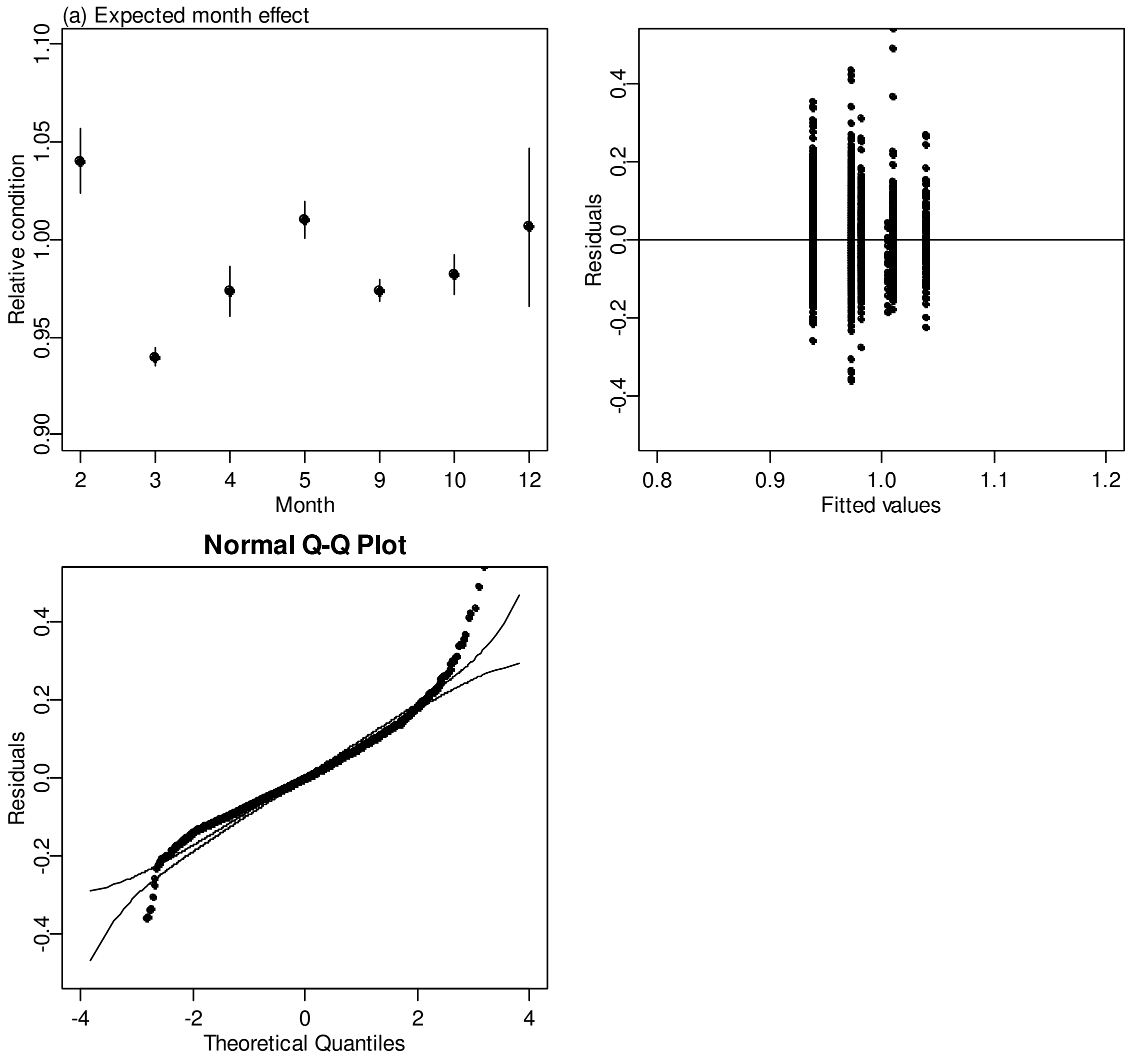

Figure A10: ORH 3A: Predicted effects of the selected variables in the binomial model for CF (a), and model diagnostic plots (b,c). The vertical bars in panel (a) indicate the 95% confidence intervals.

Table A6: Andes: Predictors by order of selection and the percentage of deviance explained (r^2) for the model for Fulton's K and relative condition factor.

Fultons K	r^2
Length (5^{th})	0.11
Month	0.14
Condition factor	
Month	0.04
Maturity	0.06
Sex	0.09

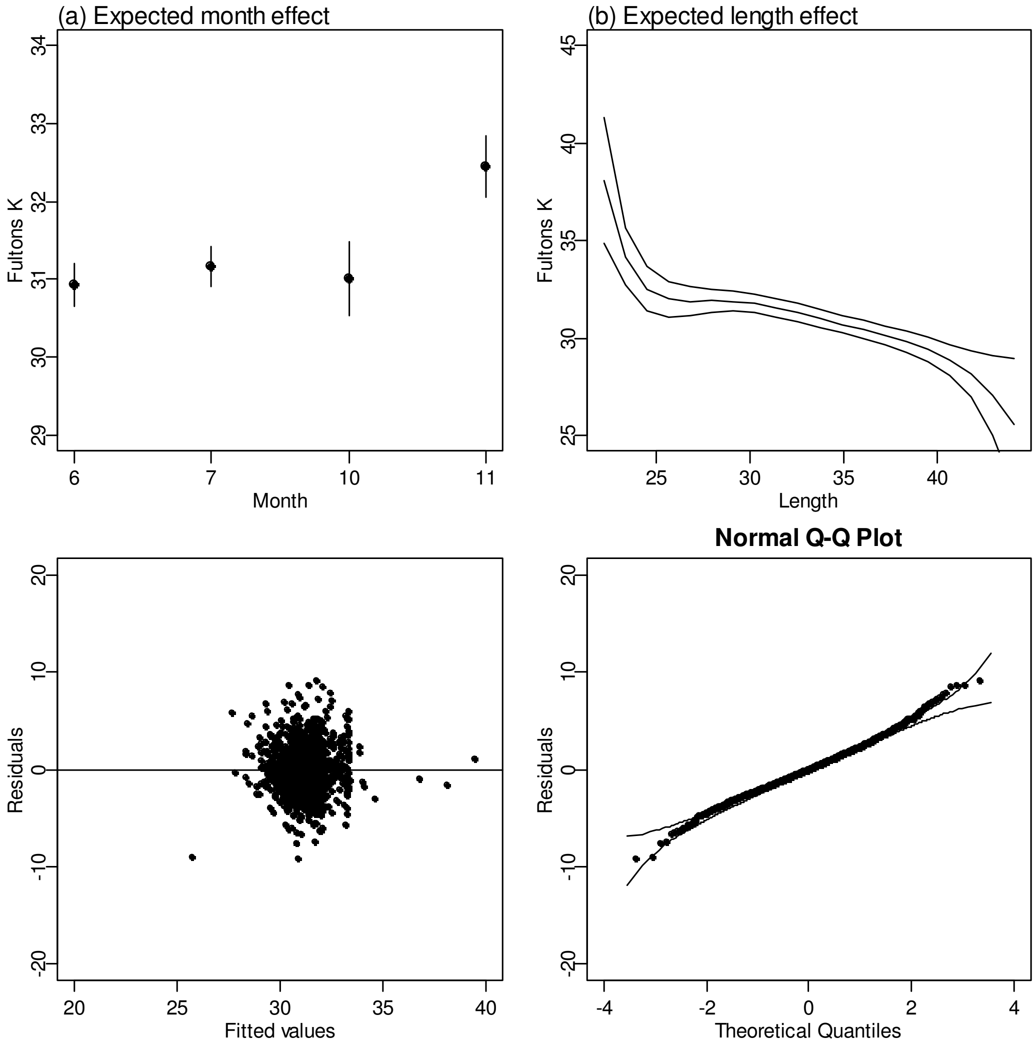

Figure A11: Andes: Predicted effects of the selected variables in the binomial model for Fulton's K (a,b), and model diagnostic plots (c,d). The vertical bars in panel (a), and upper and lower lines in panel (b), indicate the 95% confidence intervals.

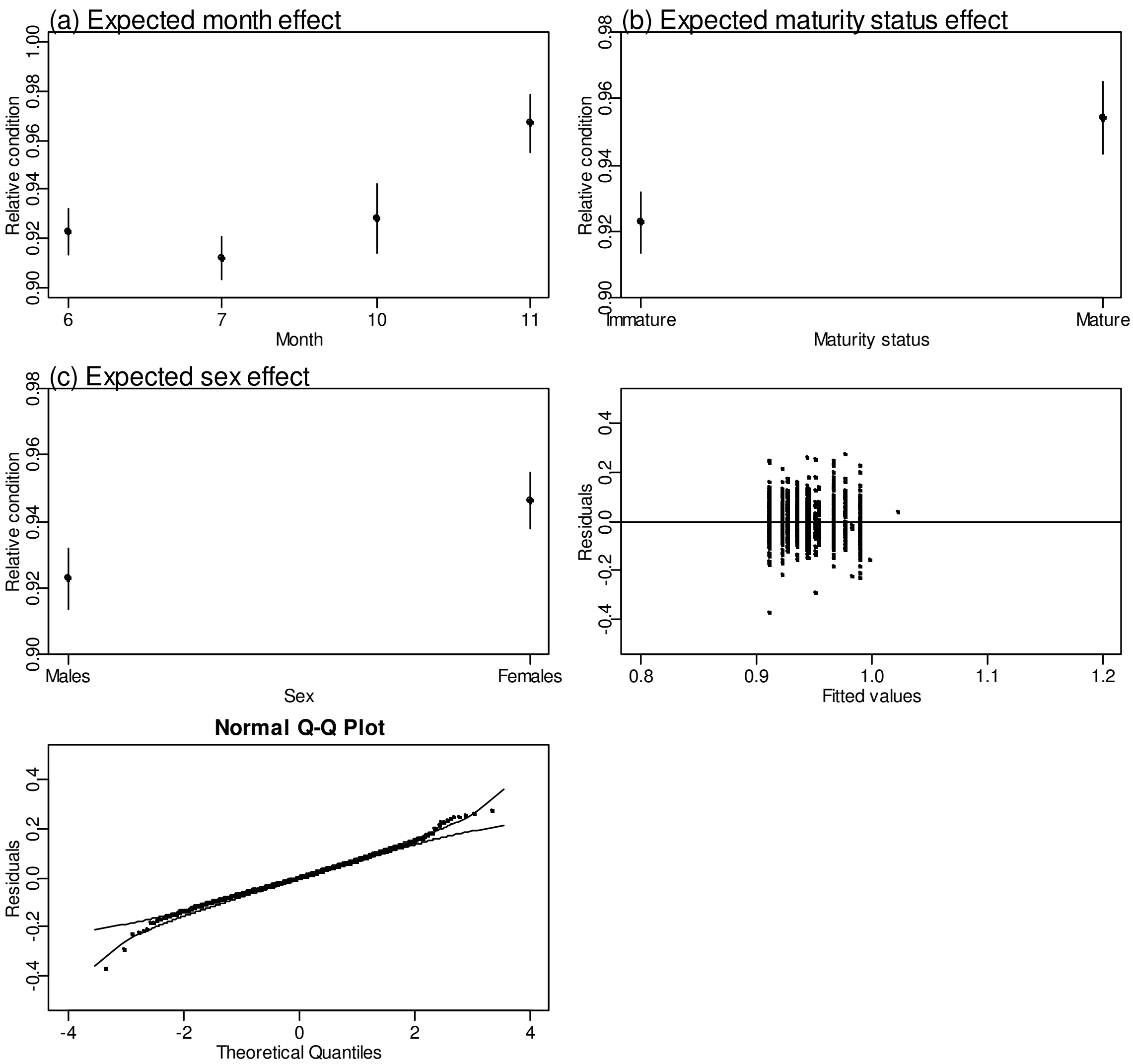

Figure A12: Andes: Predicted effects of the selected variables in the binomial model for CF (a,b,c), and model diagnostic plots (d,e). The vertical bars in panels (a) to (c) indicate the 95% confidence intervals.

Table A7: Hegerville & Surrounds: Predictors by order of selection and the percentage of deviance explained (r^2) for the model for Fulton's K and relative condition factor. An interaction between length and year for Fulton's K was excluded because it didn't appear to be credible.

Fultons K	r^2
Length (3^rd^)	0.13
Year	0.17
Condition factor	
Year	0.06
Length (3^rd^)	0.08
Year:Length (3^rd^)	0.12

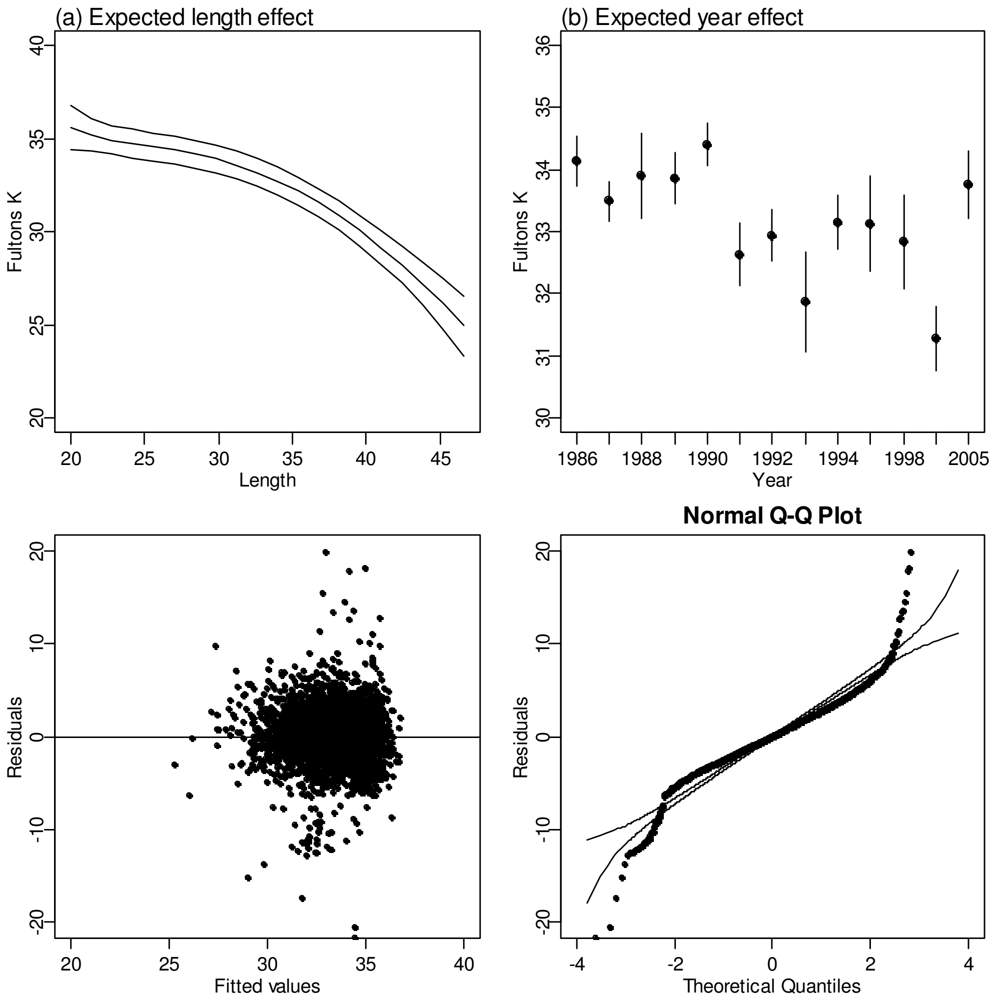

Figure A13: Hegerville & Surrounds: Predicted effects of the selected variables in the binomial model for Fulton's K (a,b), and model diagnostic plots (c,d). The upper and lower lines in panel (a), and vertical bars in panel (b), indicate the 95% confidence intervals.

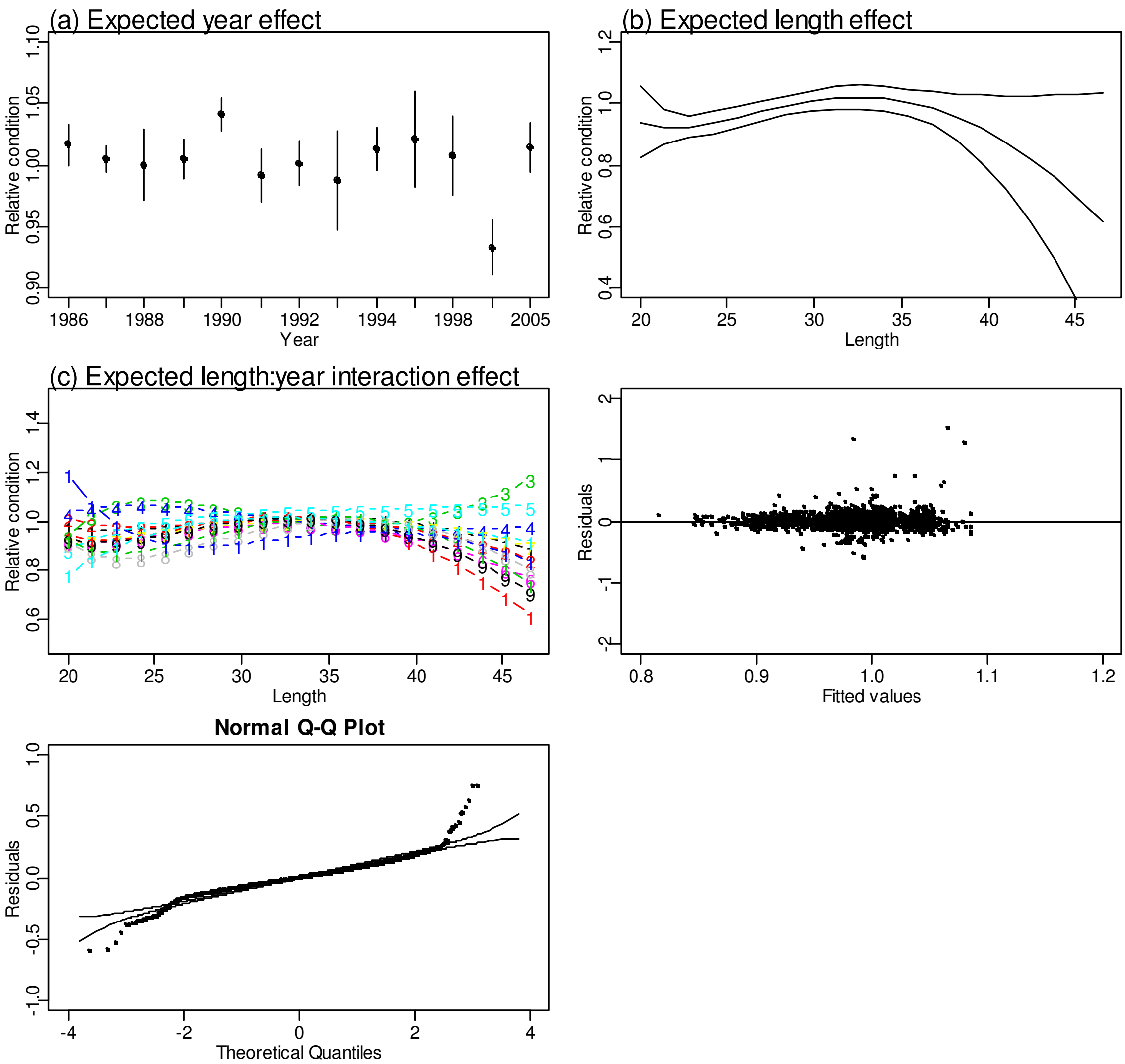

Figure A14: Hegerville & Surrounds: Predicted effects of the selected variables in the binomial model for CF (a,b,c), and model diagnostic plots (d,e). The vertical bars in panel (a), and upper and lower lines in panel (b), indicate the 95% confidence intervals.

Table A8: East Chatham Rise: Predictors by order of selection and the percentage of deviance explained (r^2) for the model for Fulton's K and relative condition factor.

Fulton's K	r^2
Length (5th)	0.32
Year	0.37
Condition factor	
Year	0.12

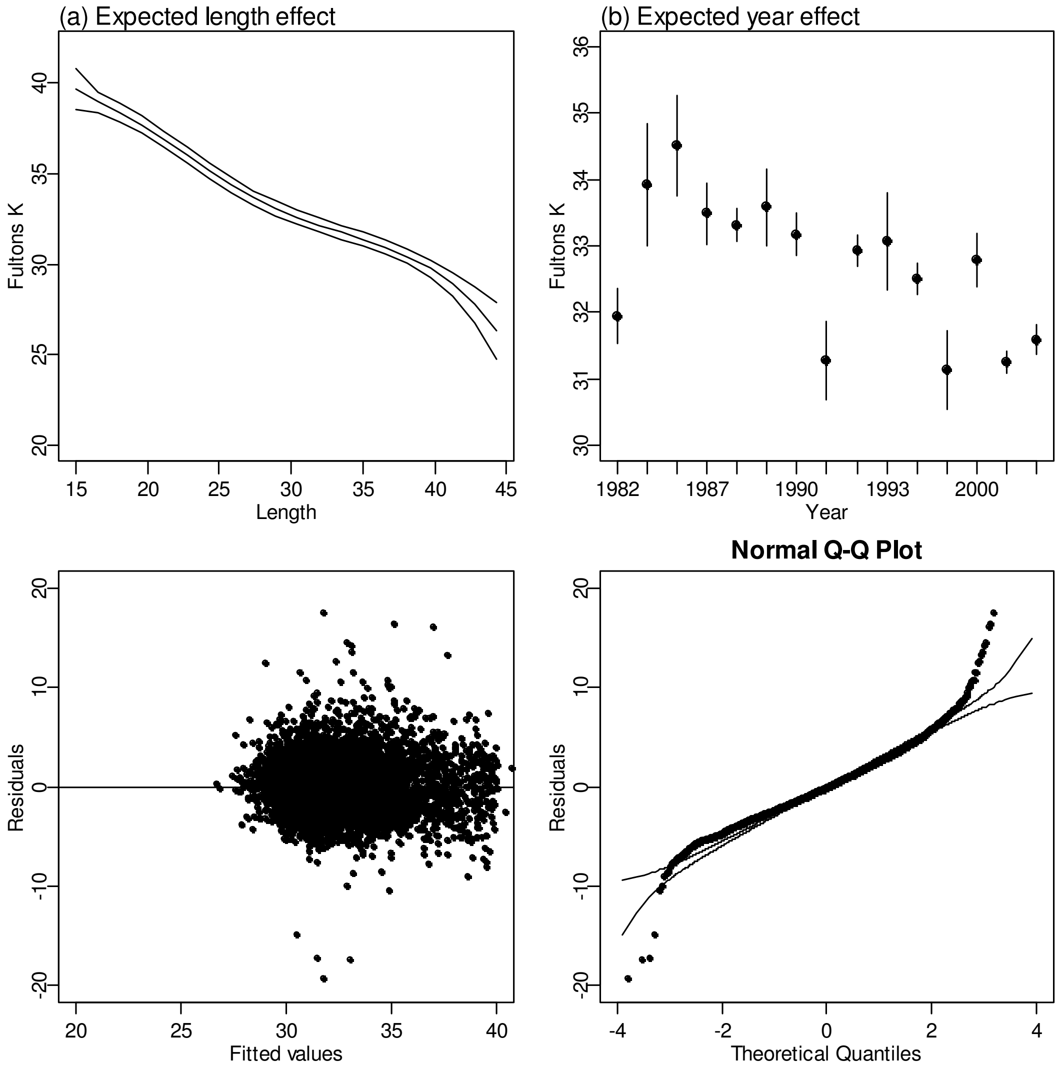

Figure A15: East Chatham Rise: Predicted effects of the selected variables in the binomial model for Fulton's K (a,b), and model diagnostic plots (c,d). The upper and lower lines in panel (a), and vertical bars in panel (b), indicate the 95% confidence intervals.

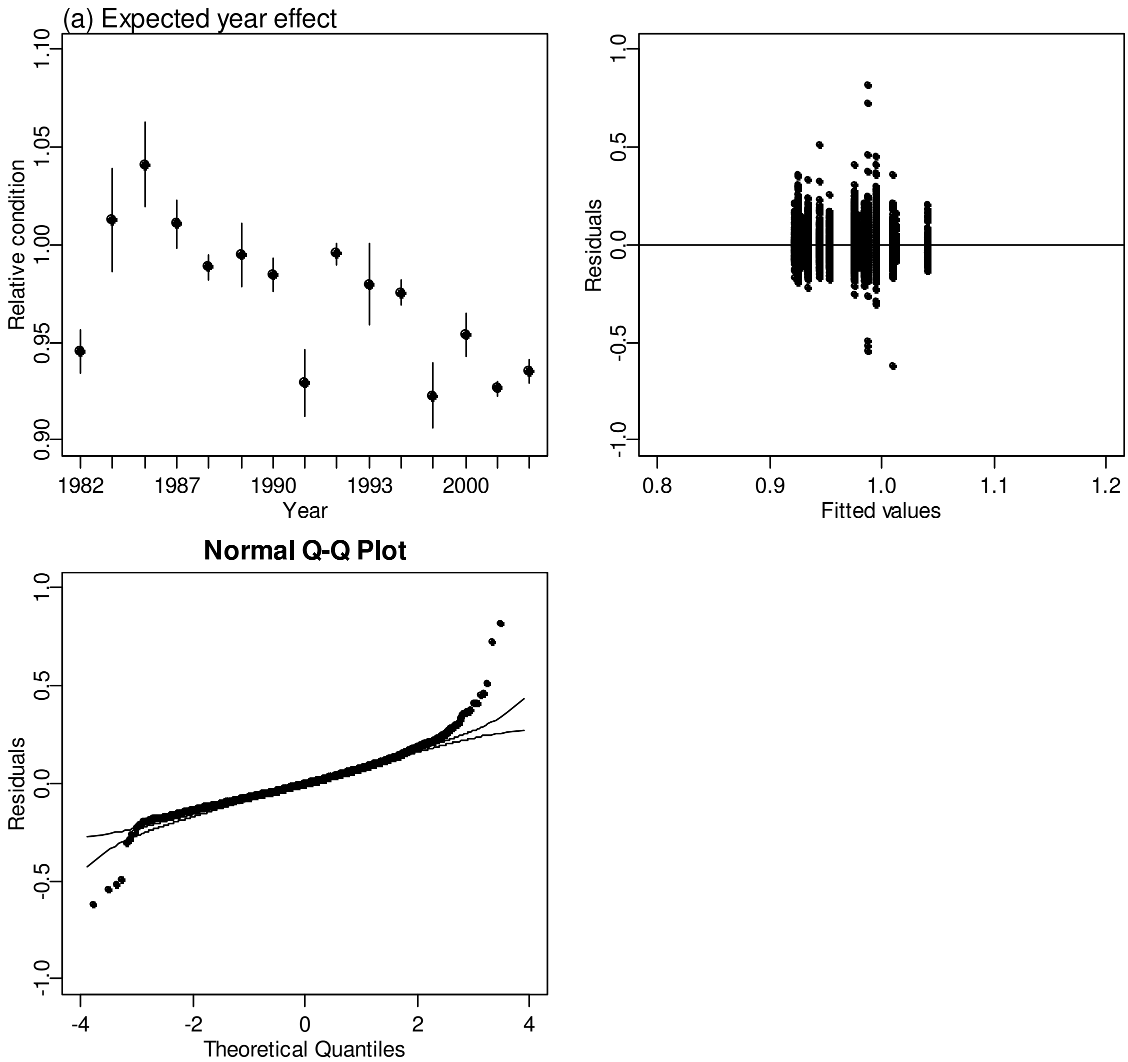

Figure A16: East Chatham Rise: Predicted effects of the selected variables in the binomial model for CF (a), and model diagnostic plots (b,c). The vertical bars in panel (a) indicate the 95% confidence intervals.

Table A9: South Chatham Rise: Predictors by order of selection and the percentage of deviance explained (r^2) for the model for Fulton's K and relative condition factor. An interaction between length and year for Fulton's K was excluded because it didn't appear credible.

Fultons K	r^2
Length (5th)	0.25
Year	0.30
Condition factor	
Maturity	0.08
Year	0.12
Length (5th)	0.16

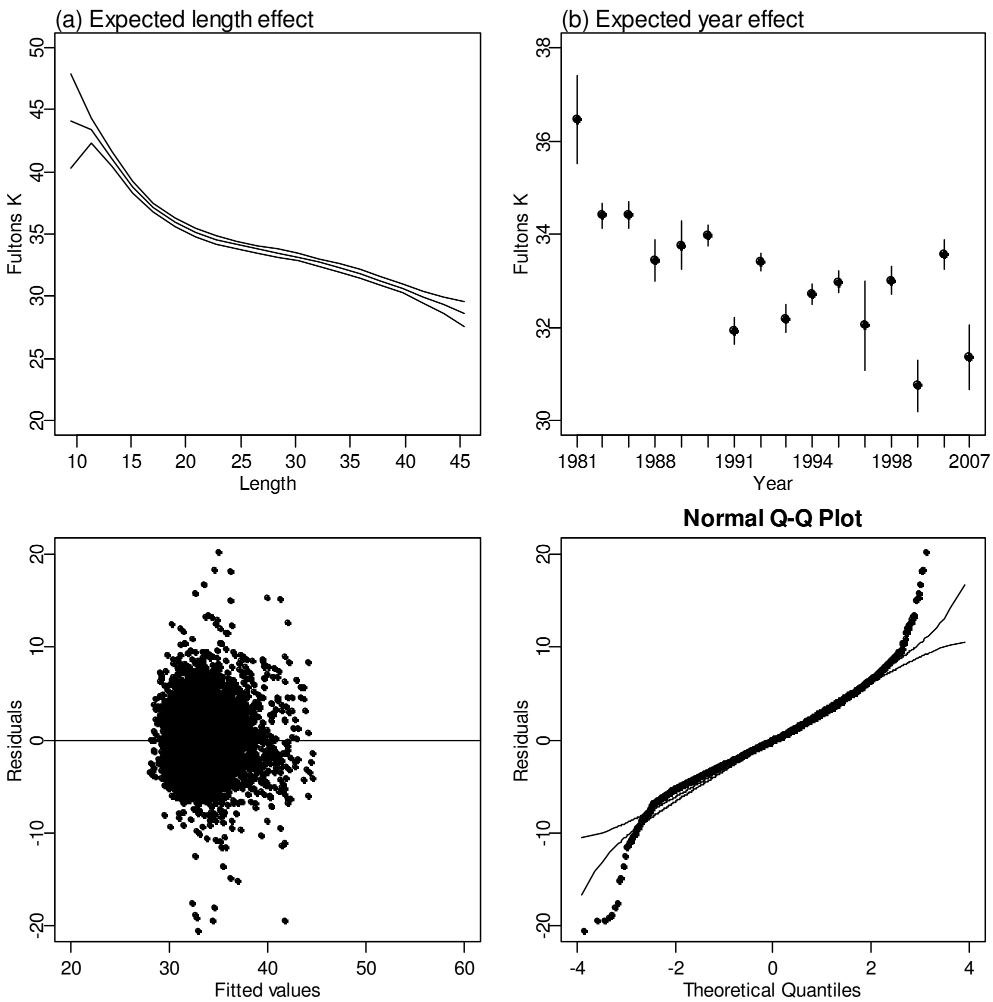

Figure A17: South Chatham Rise: Predicted effects of the selected variables in the binomial model for Fulton's K (a,b), and model diagnostic plots (c,d). The upper and lower lines in panel (a), and vertical bars in panel (b), indicate the 95% confidence intervals.

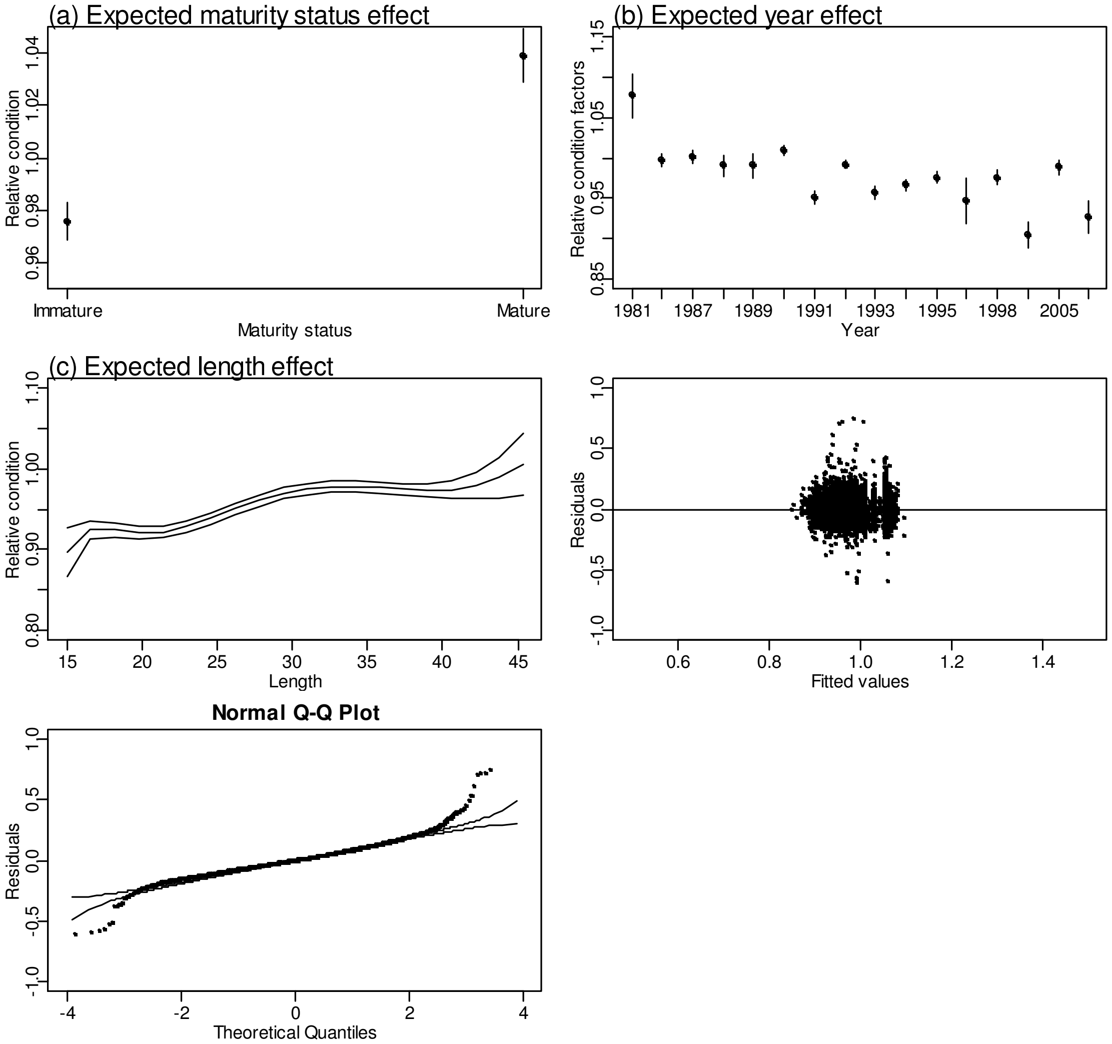

Figure A18: South Chatham Rise: Predicted effects of the selected variables in the binomial model for CF (a,b,c), and model diagnostic plots (d,e). The vertical bars in panels (a) and (b), and upper and lower lines in panel (c), indicate the 95% confidence intervals.

Table A10: Northwest Chatham Rise: Predictors by order of selection and the percentage of deviance explained (r^2) for the model for Fulton's K and relative condition factor.

Fultons K	r^2
Length (4th)	0.19
Year	0.21
Condition factor	
Maturity	0.04
Year	0.07

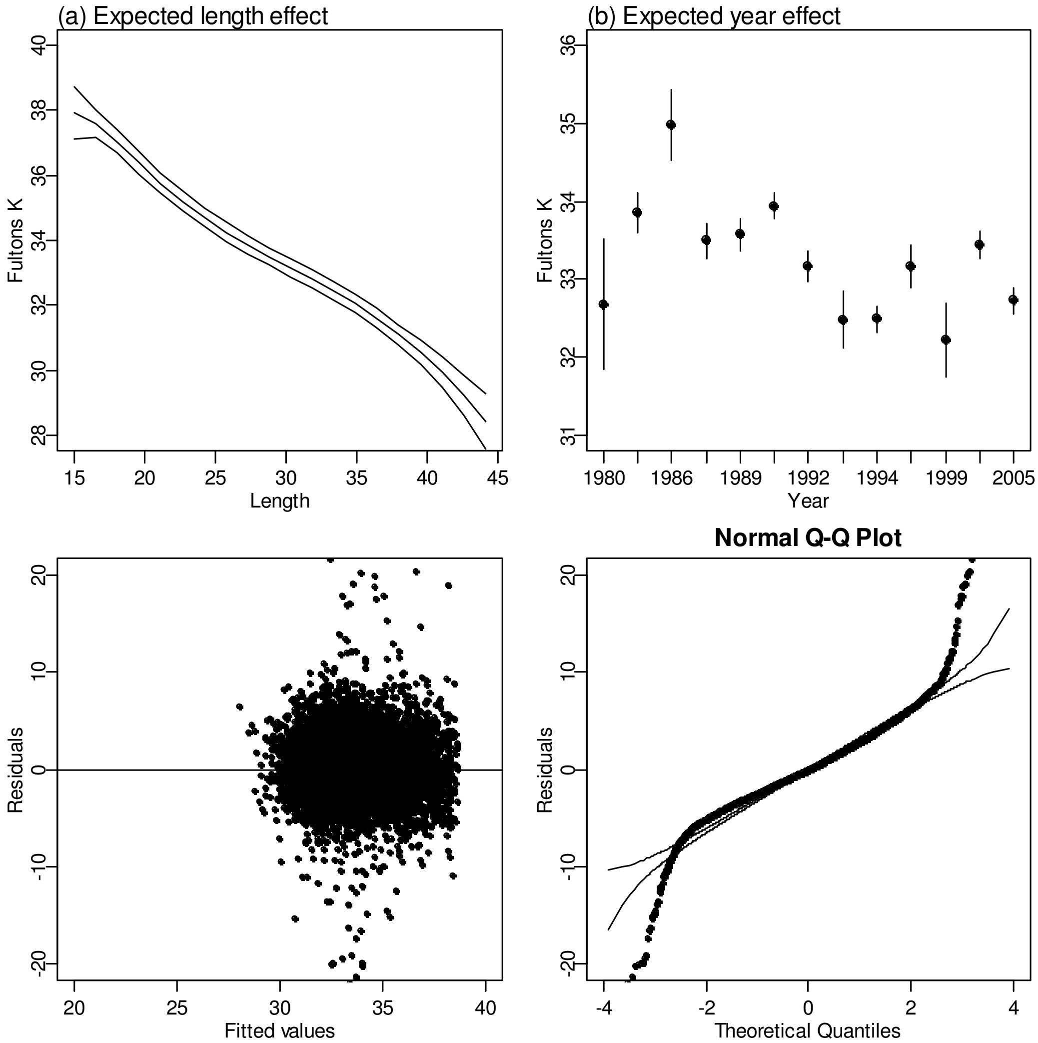

Figure A19: Northwest Chatham Rise: Predicted effects of the selected variables in the binomial model for Fulton's K (a,b), and model diagnostic plots (c,d). The upper and lower lines in panel (a), and vertical bars in panel (b), indicate the 95% confidence intervals.

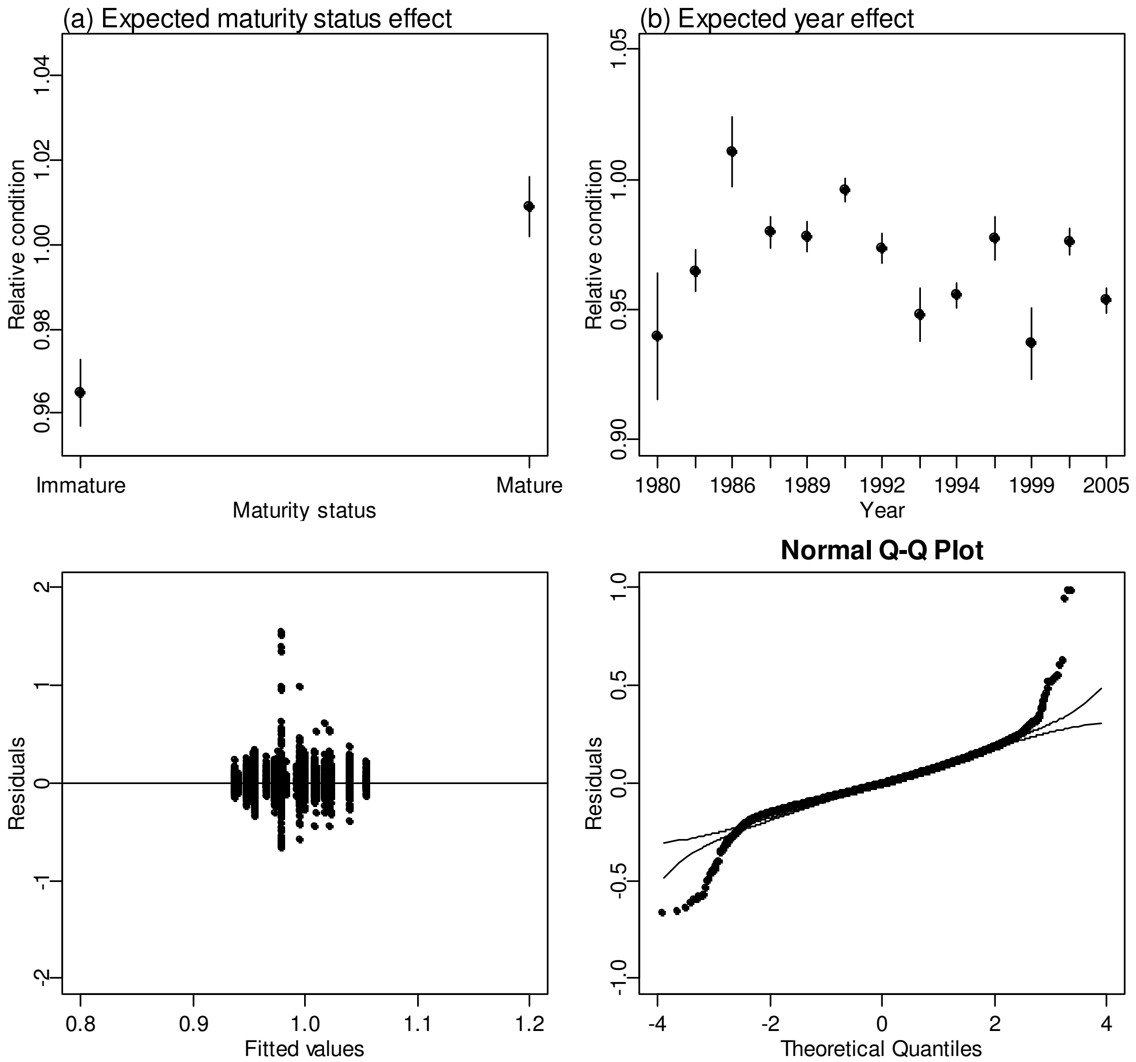

Figure A20: Northwest Chatham Rise: Predicted effects of the selected variables in the binomial model for CF (a,b), and model diagnostic plots (c,d). The vertical bars in panels (a) and (b) indicate the 95% confidence intervals.

Table A11: The Hole: Predictors by order of selection and the percentage of deviance explained (r^2) for the model for Fulton's K and relative condition factor.

Fultons K	r^2
Month	0.44
Length (5^{th})	0.64
Maturity	0.66
Condition factor	
Year	0.48
Length (5^{th})	0.58
Year:Length (5^{th})	0.76

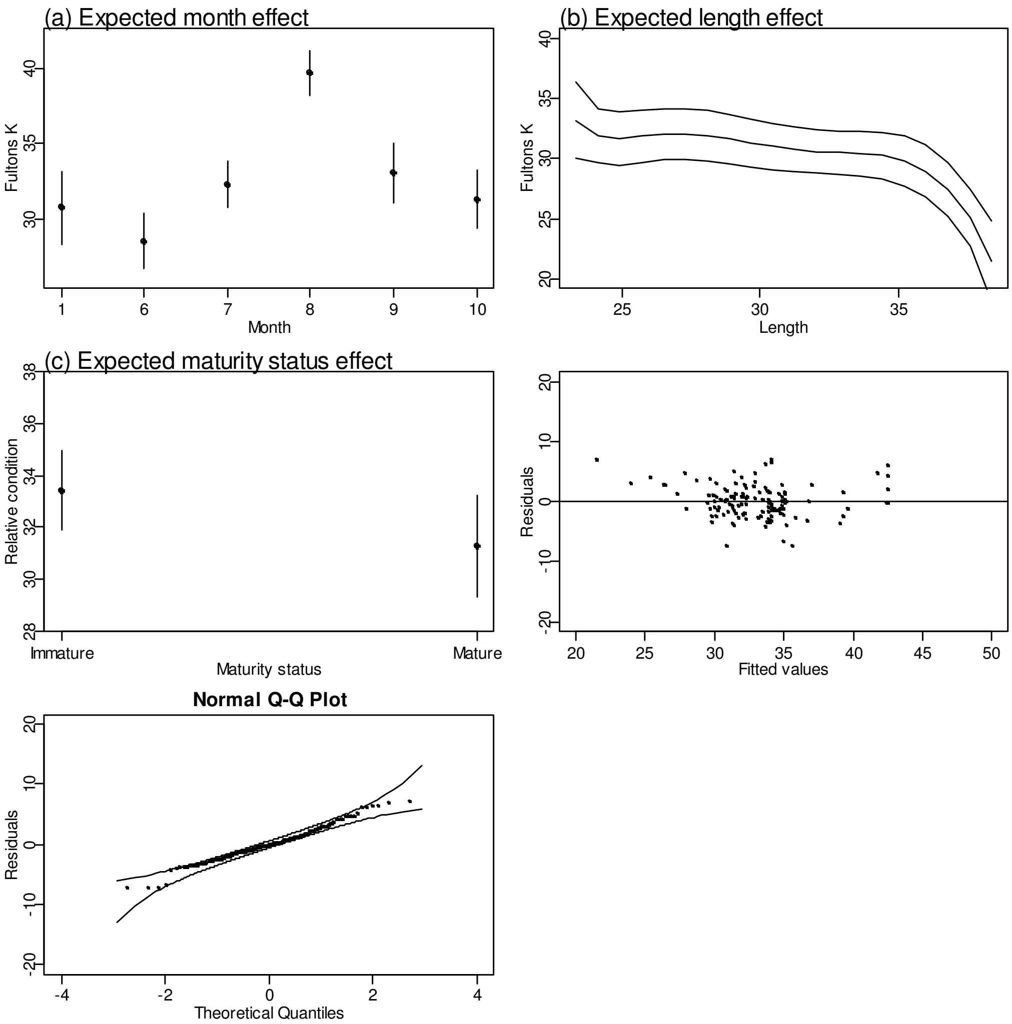

Figure A21: The Hole: Predicted effects of the selected variables in the binomial model for Fulton's K (a,b,c), and model diagnostic plots (d,e). The vertical bars in panels (a) and (c), and upper and lower lines in panel (b), indicate the 95% confidence intervals.

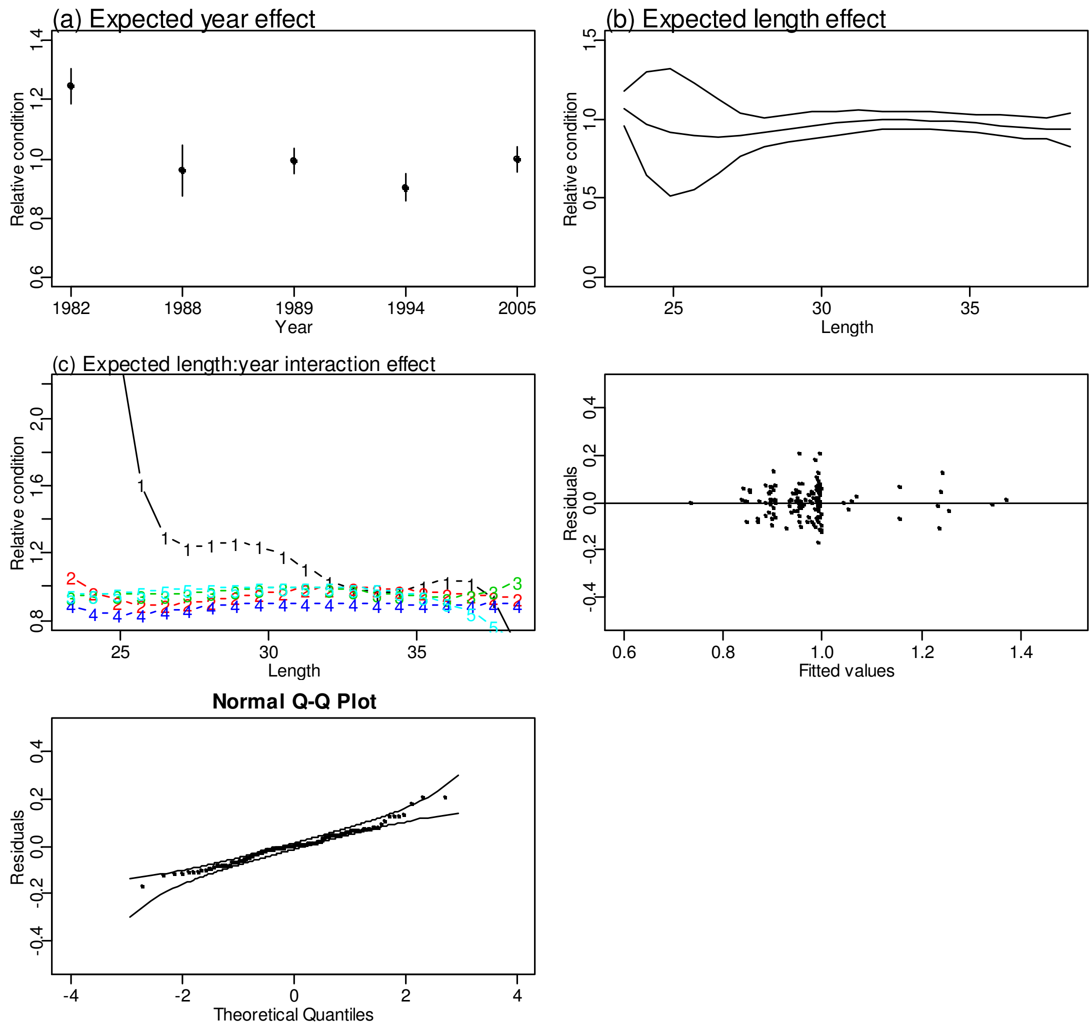

Figure A22: The Hole: Predicted effects of the selected variables in the binomial model for CF (a,b,c), and model diagnostic plots (d,e). The vertical bars in panel (a), and upper and lower lines in panel (b), indicate the 95% confidence intervals.