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Review and stock assessment of black cardinalfish (*Epigonus telescopus*) on the east coast North Island, New Zealand

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EXECUTIVE SUMMARY

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This stock assessment report reviews and analyses data on black cardinalfish spawning locations and times, location of nursery grounds, catch history and unreported catch, growth, natural mortality, maturity, length frequency distributions, and catch-per-unit-effort indices. A quantitative stock assessment is described for Quota Management Areas CDL 2, CDL 3, and CDL 4 (east coast North Island and Chatham Rise), which were assumed to contain a single stock.

All model runs indicated a continued decline in stock biomass since the fishery began. The CDL 2–4 stock was estimated to be substantially depleted, with biomass in 2008–09 at 12–24% of the virgin biomass level. Sensitivity runs were completed to allow for a number of different assumptions. The model was found to be most sensitive to the assumed natural mortality rate, and to assumptions about vulnerability in relation to maturity. Assuming constant recruitment, the stock biomass was estimated to rebuild at catch levels of about 530–1200 t. This is substantially less than the 2008–09 total allowable catch limit (2490 t).

The model results were highly uncertain. The wide confidence intervals reflected the uncertainty in fitting a model only to relative biomass indices, which themselves had relatively high uncertainty. Other key uncertainties in the assessment concerned recruitment, the level of historical unreported catch, whether all mature biomass was vulnerable to the fishery, and stock structure.

This document is a final report on work carried out as part of the Ministry of Fisheries project CDL2008/01. It covers Objective 2: “To carry out a stock assessment, including estimating biomass and sustainable yields, for black cardinalfish in CDL2.”

1. INTRODUCTION

Black cardinalfish (*Epigonus telescopus*, Risso 1810) is the only commercially exploited species of cardinalfish in New Zealand waters (Ministry of Fisheries Science Group 2008). There are several species of cardinalfish in New Zealand waters, but commercial catches of other species are very rare (Dunn 2007). The biology and ecology of black cardinalfish is poorly known. They are described as benthopelagic or mesobenthopelagic, where they form dense and mobile schools, which often result in large individual trawl catches (over 50 t) (Field et al. 1997, Hareide & Garnes 2001, Dunn & Bian in press).

Black cardinalfish fisheries occur in the north Atlantic on the Mid-Atlantic Ridge (Vinnichenko 1997, Kukuev 2004), where they are a dominant species in the warmer sub tropical waters (south of 48º N, Hareide & Garnes 2001). ICES fishing statistics show that black cardinalfish are primarily a bycatch in trawl fisheries targeting blue ling (*Molva dypterygia*), argentine (*Argentina silus*), redfish (*Sebastes* spp), and occasionally orange roughy (*Hoplostethus atlanticus*), but ICES provide no specific management advice on black cardinalfish. Catches of black cardinalfish reported by ICES have been greatest in the areas to the west of the British Isles (ICES areas VI and VII), averaging 635 t per year during 2003–07, although declining substantially over that period. Catches in other ICES areas have not exceeded 25 t per year. Black cardinalfish on the Mid-Atlantic Ridge have been caught in bottom trawls but not on longlines, at depths between 500 and 900 m, and in greatest abundance at depths around 800 m (Hareide & Garnes 2001). Black cardinalfish in the North Atlantic grow up to about 85 cm TL (Vinnichenko 1997).

Fisheries for black cardinalfish have also occurred in the Indian Ocean, where catches reported by South Africa exceeded 200 t in 2000, and 450 t in 2001, and Soviet/Ukrainian vessels caught black cardinalfish intermittently between 1980 and 2001, up to 80 t per year (FAO 2002).

The New Zealand fisheries have reported a black cardinalfish catch of about 54 000 t between 1980–81 and 2007–08, with catches occasionally over 4000 t per year (Ministry of Fisheries Science Group 2008). The exploitation of black cardinalfish within the New Zealand EEZ started as a bycatch in the early 1980s, with a targeted fishery developing from the mid 1990s, and the species entering the Quota Management System (QMS) on 1 October 1998 (Field et al. 1997, Dunn 2005, 2007). The focus of fishing effort for black cardinalfish has been on or near hills and other underwater features, with about 80% of the catch in 2004–05 taken on or near features (Dunn 2007). The largest black cardinalfish fisheries have been to the east of the North Island, in Quota Management Area CDL 2 (Figure 1).

Black cardinalfish flesh has been found to contain high levels of mercury, equivalent to that expected for high trophic level predators, and it has been suggested this may be because they are long-lived, or because they occur around hydrothermal vents where mercury is in relatively high concentrations (Tracey 1993, Martins et al. 2006). Black cardinalfish feed primarily on a wide variety of crustaceans, in particular natant decapods, and also various fish, chaetognaths, mysids, and occasional cephalopods (Du Buit 1978, Mauchline & Gordon 1984). Smaller fish (8–19.4 cm SL) predate more on copepods, and larger fish (19.5–34 cm SL) more on mysids and decapods (Mauchline & Gordon 1984).

The first quantitative stock assessment for black cardinalfish in New Zealand was attempted for the fishery in CDL 2 by Field & Clark (2001). The assessment used standardised catch per unit effort (CPUE) as an index of abundance, but the stock assessment was rejected by the Ministry of Fisheries Deepwater Fisheries Assessment Working Group because the model biomass trajectory did not fit the CPUE index well. Specifically, the CPUE index declined more rapidly than the model biomass trajectory (Field & Clark 2001).

The work described in this report was carried out under Ministry of Fisheries (MFish) project CDL200801 objective 2: "To carry out a stock assessment, including estimating biomass and sustainable yields, for black cardinalfish in CDL2." It includes a review of stock structure, catches, growth, longevity and natural mortality, maturity, recruitment and vulnerability, and then the results of stock assessment modelling. A more detailed description of the fishery, and derivation of the standardised catch per unit effort (CPUE) indices, are given by Dunn & Bian (in press).

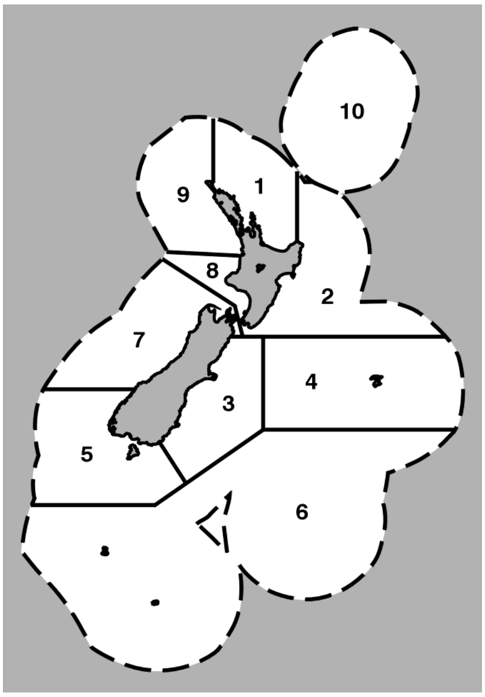

Figure 1: Location of Quota Management Areas (QMAs) for black cardinalfish within the New Zealand EEZ.

2. MODEL ASSUMPTIONS AND INPUTS

2.1 Stock structure

There have been no previous studies of the stock structure of black cardinalfish. Potential methods to study stock structure include tagging exercises, genetics, parasite occurrence, otolith microchemistry, morphometrics, and growth and maturity comparisons. This study examines the length and maturity samples taken during research trawl surveys and commercial fishing, in order to determine the location and timing of spawning and the possible location of nursery grounds.

In samples from both research surveys and commercial catches (by MFish observers) it is possible that juveniles of black cardinalfish may have been confused with adults of other cardinalfish, specifically *Epigonus lenimen* and *E. robustus*, both of which reach a maximum size of about 18 cm, and are superficially similar to juvenile black cardinlfish. An identification guide for these species was published in 2002 (Ministry of Fisheries Observer Programme Biological Data Collection Manual, 2002). The improvement in resolution of cardinalfish species associated with the publication of this guide would explain why few juvenile black cardinalfish were identified before 2002 (85 fish from 1981–2001, compared to 243 fish from 2002–2007).

Black cardinalfish were reported as spawning (macroscopic stage "ripe and running") in eight research trawl tows, and biological samples of black cardinalfish completed in 52 tows (total of 775 fish sampled) (Figure 2). These sparse data indicate spawning took place on the southern Challenger Plateau, in the northern Bay of Plenty, and on the east coast North Island in the Ritchie Bank and Rockgarden area, and Tuaheni and Tolaga Knoll area (Dunn & Bian in press). Ripe and running females were reported on the east coast of the North Island in February 1985 (trip code JCO8503), March 1993 and 1994 (TAN9303 & TAN9403), April 1986 (WNK8604), and June 2001 (TVI0101). This suggests a prolonged or variable spawning period. Ripe and running females were also found on the Challenger Plateau in June 2006 (THH0601). The observation on the Chatham Rise was a single ripe and running male.

Female black cardinalfish were reported as spawning (macroscopic stages "ripening" and "ripe and running") in 72 commercial catches, and samples completed in 488 tows (total of 4946 female fish sampled) (Figure 3). These samples indicate spawning took place in numerous locations around the North Island. Spawning females were sampled from 3 tows in CDL 2 (median catch 20 t), 29 tows in CDL 1 (median 0.7 t), and 39 tows on the west coast and Challenger Plateau (CDL 7–9 and ET), Lord Howe Rise and West Norfolk Ridge (ET) (median catch 0.4 t). The observation of spawning on the Chatham Rise was a single ripening female. Spawning was sampled in CDL 2 on Tuaheni in April 1990, and Ritchie Bank and the Rockgarden in May 2000. Spawning in CDL 1 was reported in November (1 tow), March (12 tows), April (7 tows), May (3 tows) and June (6 tows). To the west and northwest of New Zealand, spawning was reported in November (1 tow), January (1 tow), February (3 tows), March (12 tows), April (4 tows), May (10 tows), June (4 tows), and July (4 tows).

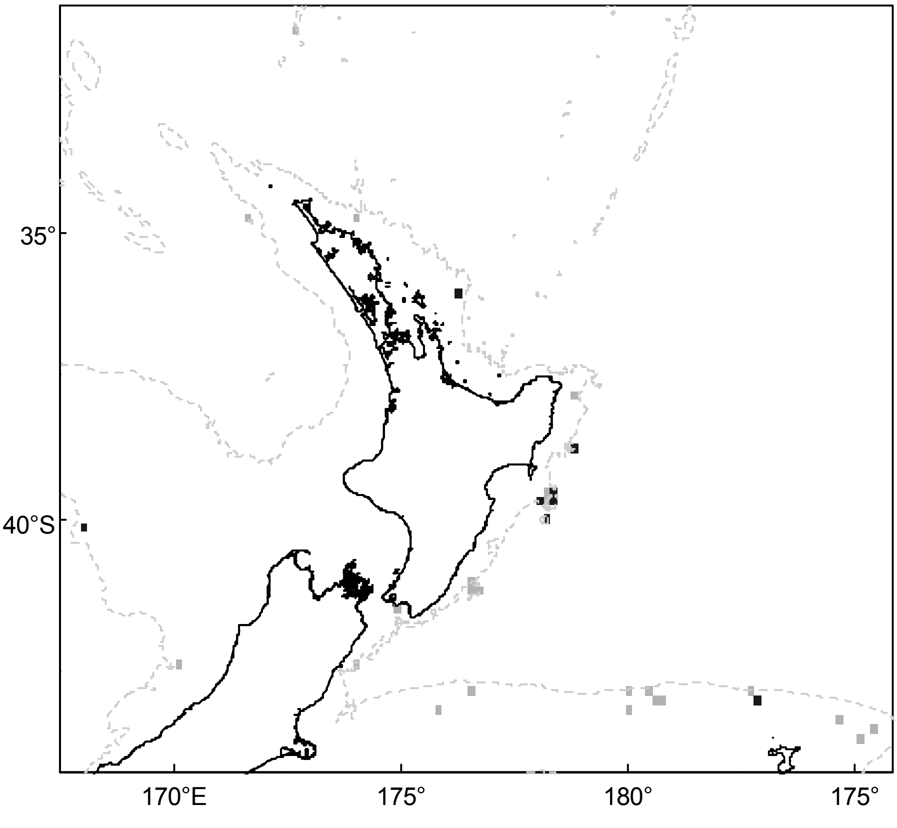

Figure 2: Location of research trawl biological samples (grey areas), and occurrence of ripe and running black cardinalfish (black squares). Tows were grouped into 0.15° longitude and latitude bins, roughly equivalent to 6.7 nautical miles longitude by 9 n. miles latitude. Broken grey line indicates the 1000 m isobath.

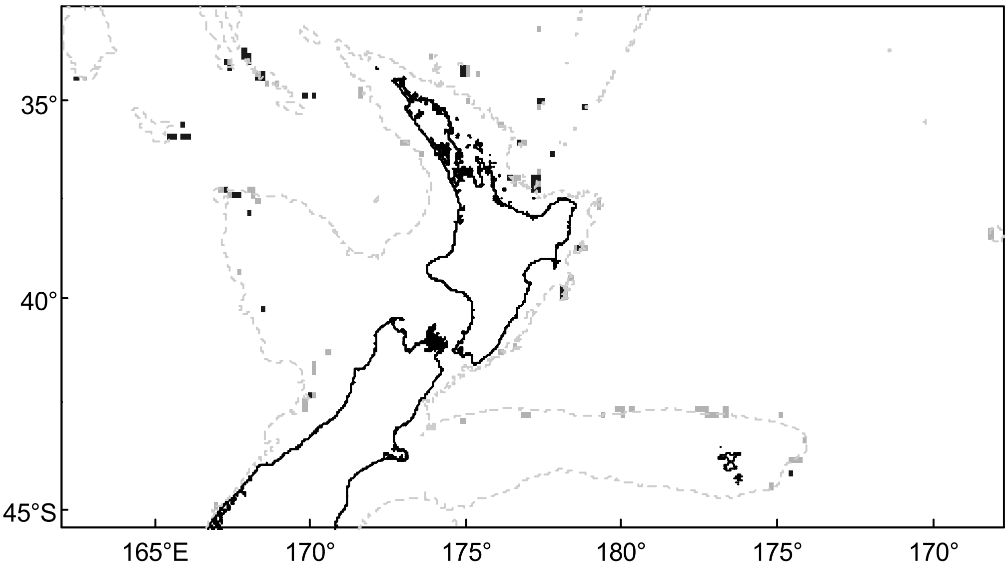

Figure 3: Location of MFish observer biological samples from commercial trawl tows (grey areas), and occurrence of ripe and running black cardinalfish (black squares). Tows were grouped into 0.15° longitude and latitude bins, roughly equivalent to 6.7 n. miles longitude by 9 n. miles latitude. Broken grey line indicates the 1000 m isobath.

Conclusions about the location and timing of spawning are limited by the sparse data. Within CDL 2, spawning has been found only in the Tuaheni and Ritchie Bank and Rockgarden areas, and between February and June. This suggests an extended spawning period for black cardinalfish. Little or no spawning has been reported on the Chatham Rise. Spawning was more frequently found around northern New Zealand, over a wide area, and between November and July. Most of the black cardinalfish measured in samples from research vessel bottom trawl catches were between 40 and 75 cm fork length (FL (Figure 4).

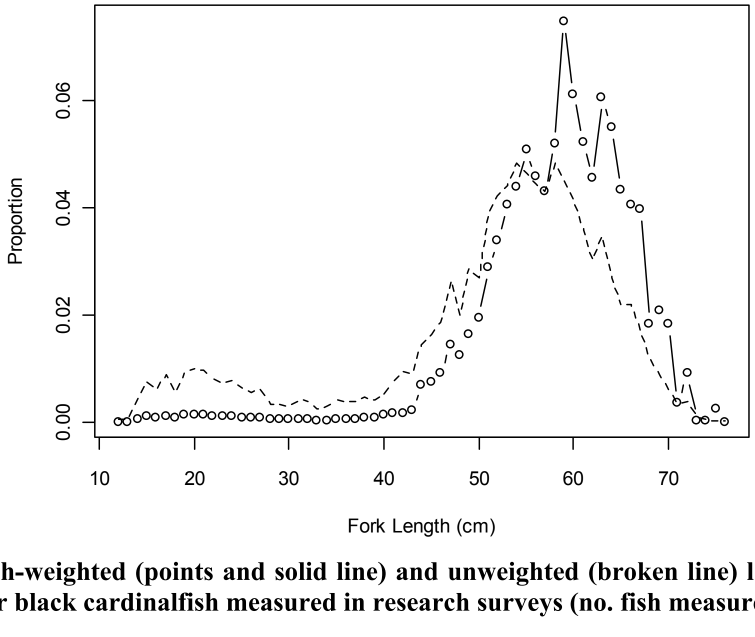

Figure 4: Catch-weighted (points and solid line) and unweighted (broken line) length frequency distribution for black cardinalfish measured in research surveys (no. fish measured = 5771).

Although relatively rare, black cardinalfish as small as 12 cm FL were measured. Most of the small (less than 30 cm) black cardinalfish were sampled during the Chatham Rise middle-depths trawl surveys (61% of 643 fish). For subsequent analyses, the fish were classified into three length groups: less than 30 cm FL, 30 cm to 54 cm FL (the mean length of first maturity, see Section 2.5), and over 54 cm FL.

Small black cardinalfish (less than 30 cm FL) occurred most frequently on the northern flanks of the Chatham Rise, with one occurrence at East Cape, one off Wairarapa, some on the west coast of the South Island, and some in the subantarctic, notably the Puysegur area (Figure 5). Small fish were rarely sampled on the east coast of the North Island (CDL 2), and were not sampled on the south Chatham Rise, despite extensive sampling in this area (Dunn et al. in press). On the Chatham Rise, small fish appeared to be more widespread in the northwest.

Medium sized black cardinalfish (30–54 cm FL) were also found along much of the northern Chatham Rise, although more focused around the Graveyard (180) hills, were less widespread in the northwest, and extended onto the east and southeast Chatham Rise (Figure 6). Fish were also found on the east coast North Island, notably close to the Tuaheni, East Cape, Ritchie Bank, and Rockgarden hills, with a single occurrence in Kaikoura, and at scattered locations through the Bay of Plenty, west coast of New Zealand, and in the Puysegur area.

Large black cardinalfish (over 54 cm FL) on the Chatham Rise occurred largely around the Graveyard hills, the hill known as the Crack, and were relatively scarce elsewhere (Figure 7). On the east coast of the North Island, the fish occurred off Wairarapa, and in association with hill areas off Castlepoint, at Ritchie Bank and Rockgarden, Tuaheni, and East Cape. Fish were relatively scarce off the west coast of the South Island, and in Puysegur they were found only to the south (an area of hills).

Black cardinalfish were sampled from research vessel bottom trawl survey tows between 401 m and 1232 m (Figure 8). The small (less than 30 cm FL) black cardinalfish were most abundant from roughly 400–700 m, medium sized fish (30–54 cm FL) from roughly 700 to 1000 m, and large fish (over 54 cm FL) from roughly 800 to 1000 m.

The black cardinalfish measured in samples from catches of commercial trawls by MFish observers were between 30 cm and 79 cm FL. Medium sized black cardinalfish (30–54 cm FL) occurred in scattered locations on the east coast North Island and Chatham Rise, associated with hills Tuaheni, Ritchie Bank and Rockgarden, Graveyard, and the Crack (Figure 9). The fish also occurred in the Bay of Plenty, and around northern New Zealand, including notably the West Norfolk Ridge, and northern Challenger Plateau and Lord Howe Rise. The only area where any gap (given the limited coverage) appears in the distribution was the eastern Chatham Rise. Large black cardinalfish (>54 cm FL) had a very similar distribution, and were found at almost all sites sampled (Figure 10).

Black cardinalfish occurred in research and commercial trawl tows over a more limited area than other commercial deepwater fishes, such as orange roughy (Anderson & Dunn 2008), and this may indicate that they are relatively uncommon.

Spawning grounds have been found on Tuaheni, Ritchie Bank, and Rockgarden, and although adults occurred on the Chatham Rise, little or no spawning was reported there. The nearest spawning ground to the north was a substantial distance away, in the Bay of Plenty. An apparently extended spawning season made it difficult to determine separate and simultaneous spawning grounds.

The juveniles of less than 30 cm FL occurred near East Cape and off Wairarapa, but otherwise appeared to be absent on the east coast North Island (CDL 2), although few trawl tows have been completed at 400–700 m in this area (N=254). Juveniles were relatively common on the northern flanks of the Chatham Rise however.

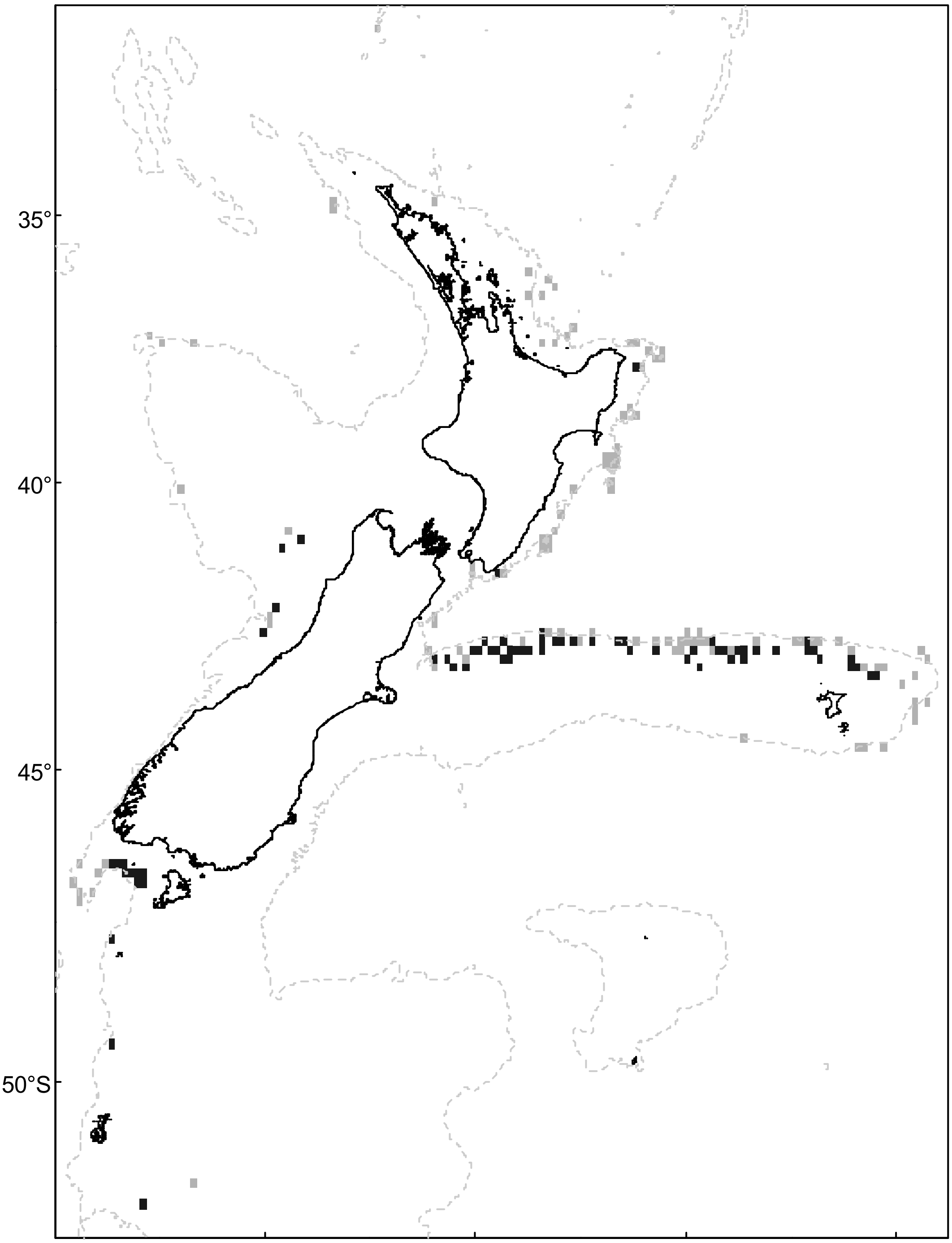

Figure 5: Location of research trawl biological samples (grey areas), and occurrence of black cardinalfish <30 cm FL (black squares). Tows were grouped into 0.15° longitude and latitude bins, roughly equivalent to 6.7 n. miles longitude by 9 n. miles latitude. Broken grey line indicates the 1000 m isobath.

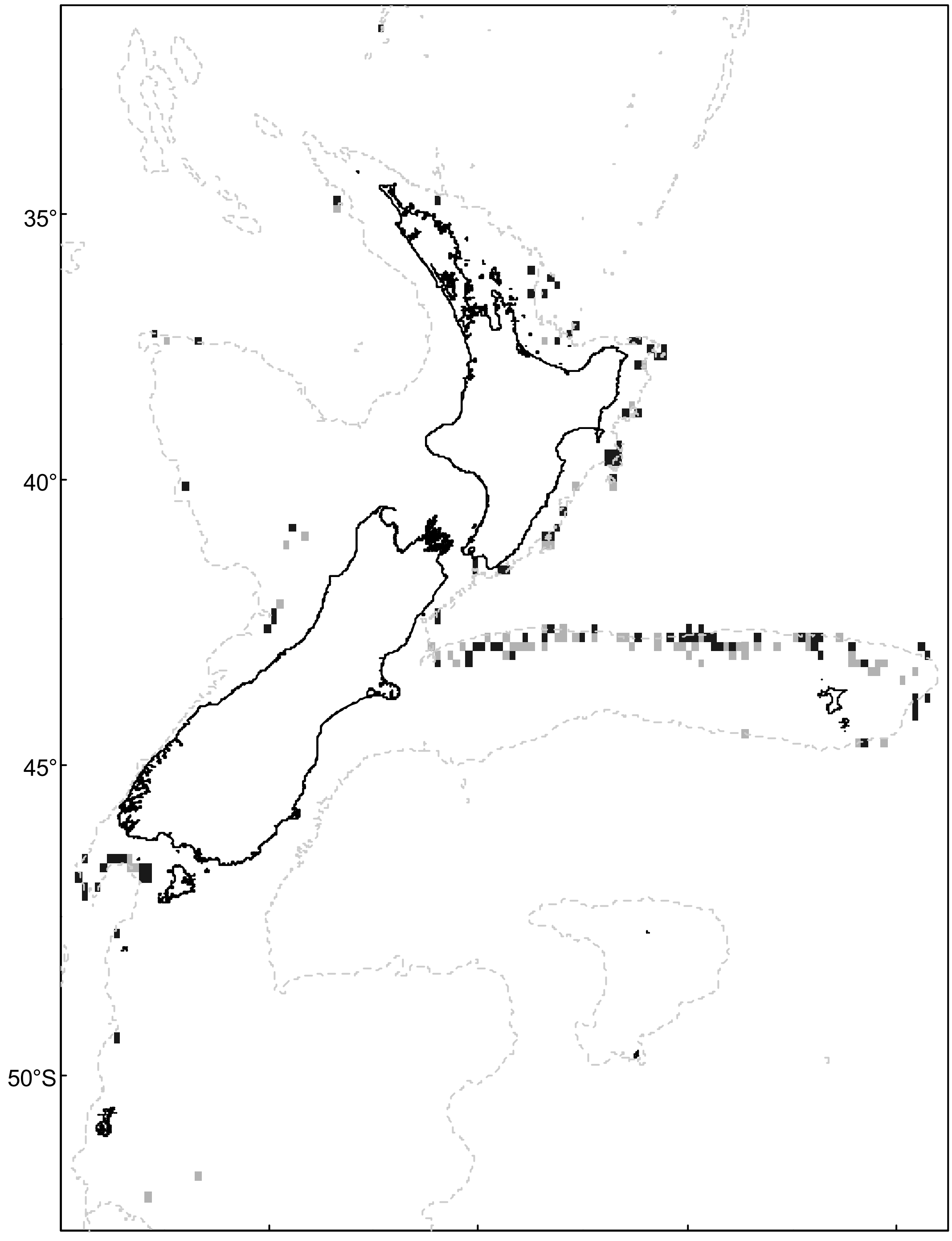

Figure 6: Location of research trawl biological samples (grey areas), and occurrence of black cardinalfish 30–54 cm FL (black squares). Tows were grouped into 0.15° longitude and latitude bins, roughly equivalent to 6.7 n. miles longitude by 9 n. miles latitude. Broken grey line indicates the 1000 m isobath.

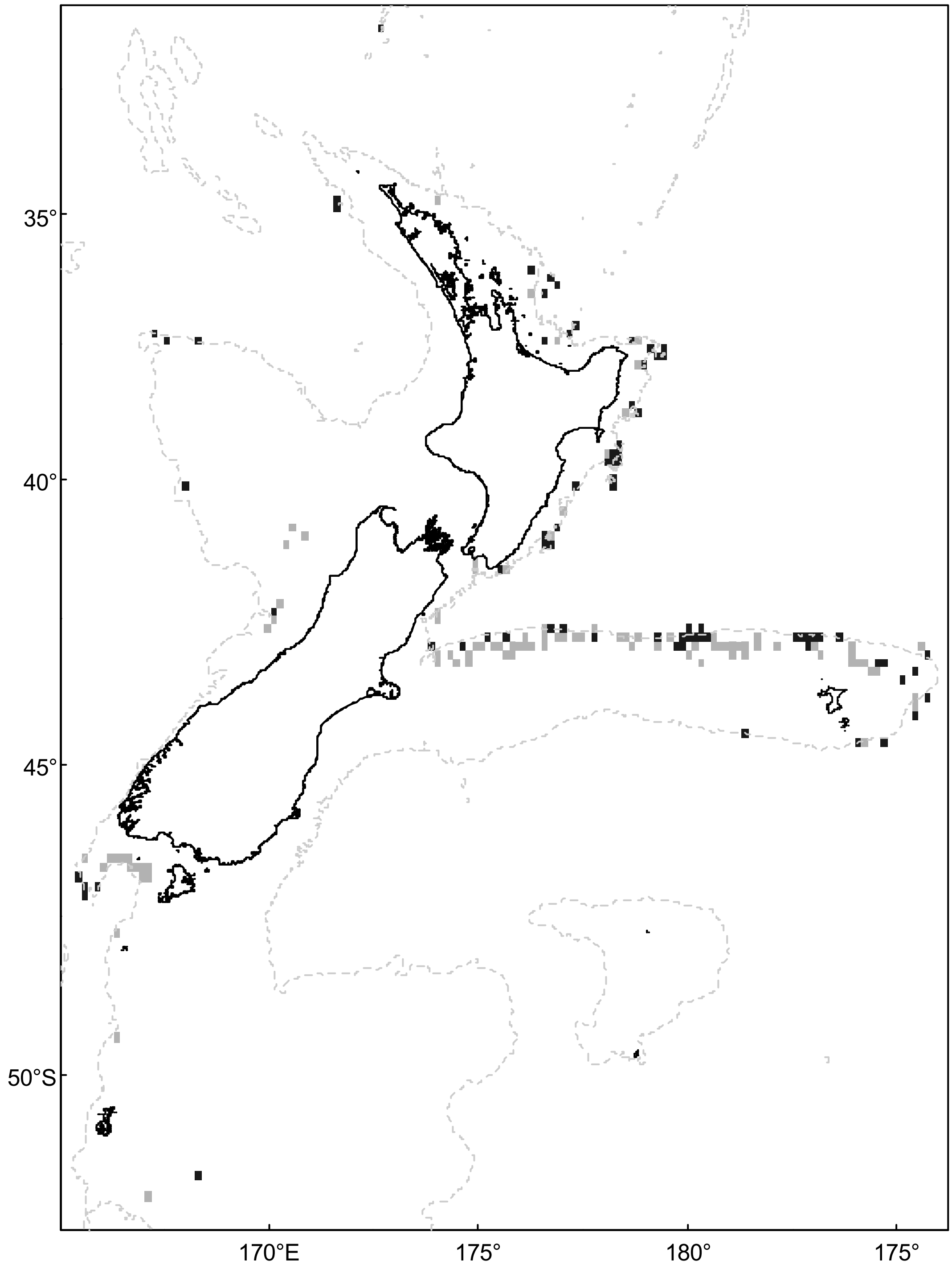

Figure 7: Location of research trawl biological samples (grey areas), and occurrence of black cardinalfish >54 cm FL (black squares). Tows were grouped into 0.15° longitude and latitude bins, roughly equivalent to 6.7 n. miles longitude by 9 n. miles latitude. Broken grey line indicates the 1000 m isobath.

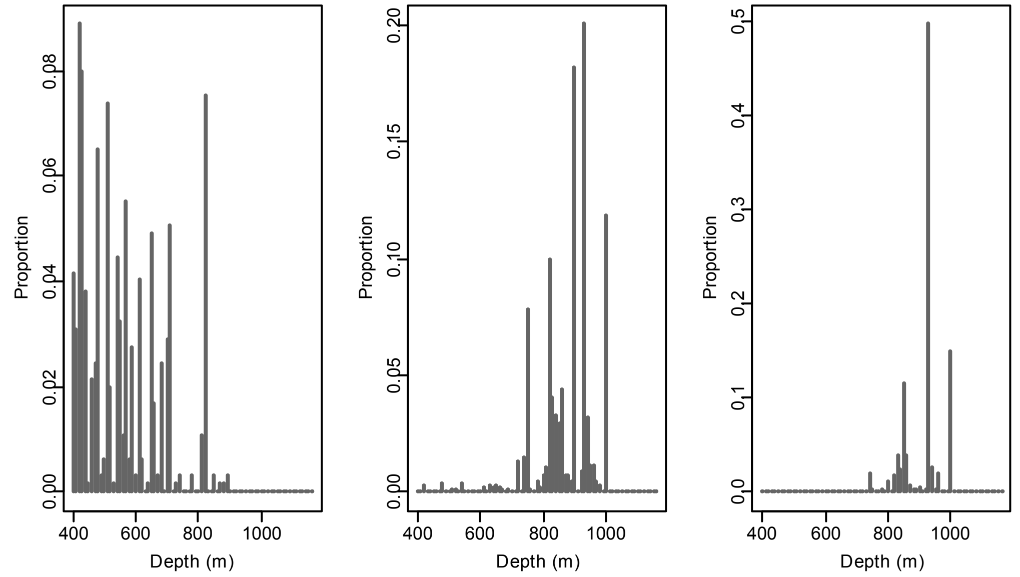

Figure 8: Proportion of black cardinalfish of <30 cm FL (left panel), 30–54 cm FL (middle panel), and >54 cm (right panel) at depth from research vessel bottom trawl surveys (weighted only by catch).

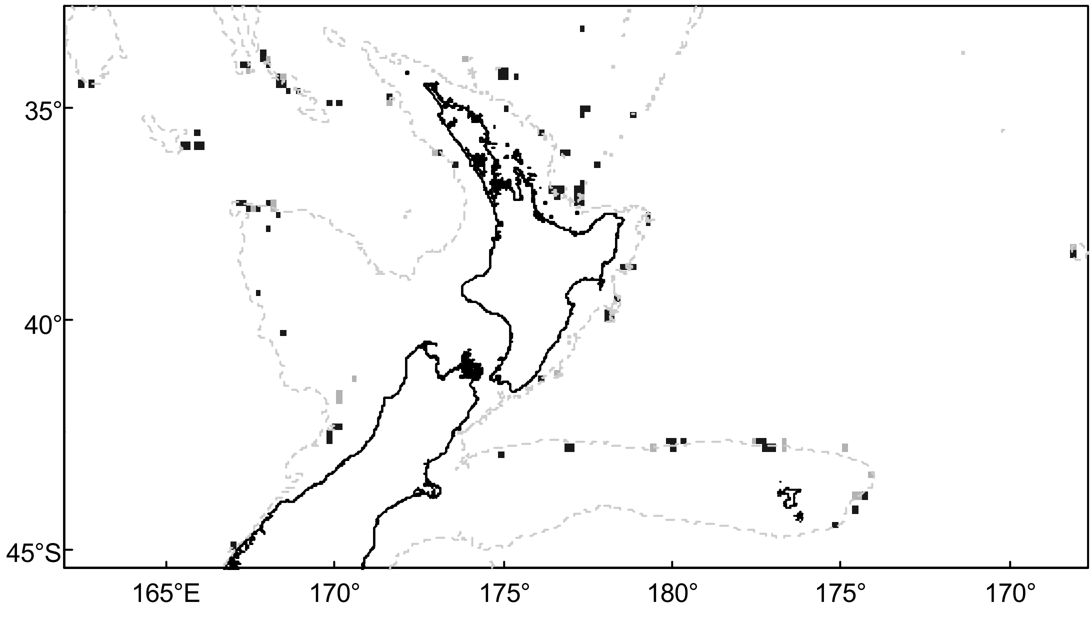

Figure 9: Location of MFish biological samples from commercial trawls (grey areas), and occurrence of black cardinalfish 30–54 cm FL (black squares). Tows were grouped into 0.15° longitude and latitude bins, roughly equivalent to 6.7 n. miles longitude by 9 n. miles latitude. Broken grey line indicates the 1000 m isobath.

The absence of a substantial spawning ground on the Chatham Rise is a good argument against this area containing a discrete stock. There have been extensive fisheries (e.g., Anderson & Dunn 2008) and research trawl surveys (Dunn et al. 2009) on the Chatham Rise, so it seems likely that a spawning ground would have been recorded at some stage if one existed.

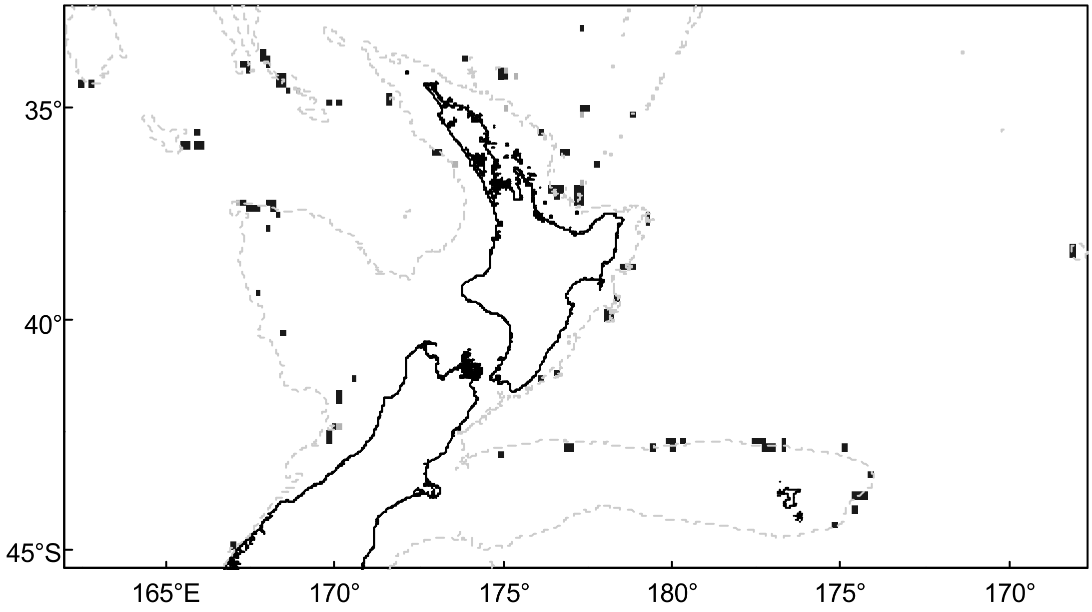

Figure 10: Location of MFish biological samples from commercial trawls (grey areas), and occurrence of black cardinalfish >54 cm FL (black squares). Tows were grouped into 0.15° longitude and latitude bins, roughly equivalent to 6.7 n. miles longitude by 9 n. miles latitude. Broken grey line indicates the 1000 m isobath.

As there were both juveniles and adults on the Chatham Rise (particularly the middle to eastern end), it is nevertheless possible that the Chatham Rise might support a stock. However, the very small commercial catches from the Chatham Rise (Table 1), despite extensive deepwater fisheries (Anderson & Dunn 2008), would suggest such a stock was small, and so it might not be responsible for the relatively frequent occurrence of juveniles in the area.

The rare occurrence of juveniles in CDL 2 is an argument, albeit weak, against CDL 2 being a discrete stock. From the available data, it makes sense to link the spawning areas of east coast North Island with the more apparent "nursery grounds" on the north Chatham Rise. This would be consistent with a downstream dispersal, perhaps in an extended pelagic phase as proposed by Neil et al. (2008), followed by settlement at fish lengths of over 12 cm FL and depths of 400–700 m on the north Chatham Rise. However, most research surveys of the east coast North Island took place during the 1980s and 1990s, before the identification guide for cardinalfish (Ministry of Fisheries Observer Programme Biological Data Collection Manual, 2002) was published, and so the apparent rarity of juvenile black cardinalfish in CDL 2 may simply be an artefact caused by poor species identification. The continuous habitat of flat grounds and hills and other features, at depths of over 400 m, on both the east coast North Island and north Chatham Rise would make it likely that juveniles occur in both areas.

As black cardinalfish get larger they appear to shift towards deeper water, and become infrequent on the northwest Chatham Rise. If the east coast North Island and the Chatham Rise were assumed to contain a continuous stock, then adults from the Chatham Rise would be assumed to return to the east coast to spawn, which would be a substantial migration (several hundred kilometres). The southern limit of black cardinalfish on the Chatham Rise appeared to be the southeast corner, consistent with the fish preferring warmer temperatures

(Dunn et al. 2009). This would also explain the occurrence of black cardinalfish largely to the north of New Zealand, and present in Puysegur but not other areas of the subantarctic (the subtropical convergence runs around the South Island and through Puysegur). Black cardinalfish seemed to be found to the north of Puysegur as juveniles, and the hill area to the south as adults.

The research survey data suggested black cardinalfish were found over a smaller spatial area as they got larger, and became focused on and around hill areas, consistent with the commercial fishery (Dunn & Bian in press). The MFish observer data did not indicate any clear ontogenetic changes in distribution. Therefore this conclusion might be incorrect because larger black cardinalfish become hard to capture in research bottom trawls outside hill areas.

Inferring stock structure for the east coast North Island with such limited information will always be prone to error. Inferring stock structure for other areas would be similarly difficult. The west coast South Island and Puysegur might be argued to contain separate stocks as both juveniles and adults were found in these areas. Parts of CDL 1, and the west Norfolk Ridge and northern Challenger Plateau and Lord Howe, might be argued to contain separate stocks on the grounds of their spatial separation, and because spawning fish were found in each of these areas.

From this analysis, and for this stock assessment, the black cardinalfish stock on the east coast North Island (CDL 2) has been treated as continuous with the northern Chatham Rise (CDL 3 and CDL 4), with the adult stock being predominantly in CDL 2.

2.2 Catch history

The reported catches for CDL 2, CDL 3, and CDL 4 are shown in Table 1. About 90% of the reported catch from these three areas combined came from CDL 2.

A known source of mortality for black cardinalfish has been the discarding at sea of this species while target fishing for higher value species. The following general description was derived from interviews with several skippers and fleet operators, and the quantitative information obtained was used to derive the catch over-run estimates shown in Table 1.

During the early to mid 1980s, there was little market for black cardinalfish. Whilst some vessels did land black cardinalfish, many catches were discarded at sea, sometimes including entire large catches. Black cardinalfish had little or no commercial value at the time, and there was no legal requirement to report the catches. Some catches were landed and reported, but some of these were ultimately not processed because they could not be sold, and were discarded on land. As a result, attempts were made to avoid catching black cardinalfish.

In the mid 1980s the orange roughy fishery on the east coast North Island started to develop, and then peaked between the late 1980s and mid 1990s (Anderson & Dunn 2008). Black cardinalfish were a bycatch in this fishery, but the market was still relatively poor, the target species was specifically the higher value orange roughy, and because the potentially large catches of black cardinalfish could rapidly fill the hold, efforts continued to be made to either dump, or preferably avoid catching, black cardinalfish.

The orange roughy fishery declined from the mid 1990s. After this time, and since the introduction of the TACC in 1998–99, there has been an overall reduction in fishing effort, most of which was targeting orange roughy, and an improved market for black cardinalfish (largely domestic), resulting in occasional targeting of black cardinalfish. Black cardinalfish marks (schools) seem to be relatively dense, and it was common to get “stuck in the mark”, meaning relatively large catches often resulted. When these catches got hauled, the expanding swimbladder of the fish increased pressure within the net and this, combined with the large catch (sometimes over 100 t), often caused the net to burst, losing part or most of the catch. This problem of burst bags has occurred throughout the duration of the fishery, although was more frequent during the early years.

Black cardinalfish has remained effectively a bycatch species. Black cardinalfish marks have often been seen in midwater, and have been found to be elusive, with fishers also often having to wait for midwater marks to get closer to the seabed, where they would then become available to the bottom trawls. Fishing for the species could be hit or miss, with the marks hard to predict, and often disappearing, making it a potentially frustrating and unpredictable species to target. As a result, fishing for black cardinalfish alone has been too uncertain to be commercially viable, and other species, particularly orange roughy, have been the primary target species for a given trip.

It is therefore appropriate to add an “over-run” to the reported catches (Table 1). This allows for any fish caught, but not reported (i.e., dumped), and fish lost through burst nets. Non-reporting of bycatch (before the introduction of the TACC) was not illegal. For comparison, the assumed catch over-runs for the associated orange roughy fishery were 30–50% between 1981–82 and 1987–88, 15–30% between 1988–89 and 1990–91, 10% from 1991–92 to 1993–94, and 5% subsequently. The assessment by Field & Clark (2001) did not include an allowance for catch over-runs.

Table 1: Reported catches (to the nearest tonne) of black cardinalfish for CDL 2, CDL 3, and CDL 4 (reproduced from MFish Science Group 2008).

	Reported catch (t)				Assumed over-run (%)	Total including over-run (t)
Fishing year	CDL 2	CDL 3	CDL 4	Total		
1982–83	76	<1	<1	76	100	152
1983–84	212	7	<1	219	100	438
1984–85	189	341	<1	530	100	1 060
1985–86	238	50	3	291	100	582
1986–87	1 738	72	2	1 812	50	2 718
1987–88	1 556	28	1	1 585	50	2 378
1988–89	1 434	57	4	1 495	50	2 243
1989–90	1 718	20	18	1 756	50	2 634
1990–91	3 473	598	1	4 072	50	6 108
1991–92	1 652	146	3	1 801	30	2 341
1992–93	1 550	519	2	2 071	30	2 692
1993–94	2 310	277	10	2 597	30	3 376
1994–95	2 207	51	7	2 265	20	2 718
1995–96	2 621	57	4	2 682	20	3 218
1996–97	1 910	100	7	2 017	20	2 420
1997–98	1 176	40	351	1 567	20	1 880
1998–99	1 268	181	41	1 490	10	1 639
1999–00	2 158	215	36	2 409	10	2 650
2000–01	1 135	99	35	1 269	10	1 396
2001–02	1 693	146	29	1 868	10	2 055
2002–03	1 845	172	80	2 097	10	2 307
2003–04	966	96	148	1 210	10	1 331
2004–05	1 102	43	49	1 194	10	1 313
2005–06	2 153	50	53	2 256	10	2 482
2006–07	1 692	66	31	1 789	10	1 968
2007–08	861	7	23	891	10	980

2.3 Growth

Growth parameters for CDL 2 were estimated by Tracey et al. (2000) after ageing 722 black cardinalfish otoliths using zone counts of transverse sections. A sub-sample of these otoliths was aged twice, and showed no sign of between reader bias, and a moderate variability in zone counts (coefficient of variation of 16.7%). Tracey et al. (2000) reported that the otoliths were difficult to read, especially towards the outer edge of the otolith in larger (assumed older) individuals. The fit of the estimated von Bertalanffy growth curve to their length at age data appeared good, and the data and fitted model indicated very slow growth after about 60 years of age. No further age data were available, and therefore the Tracey et al. (2000) parameter estimates were used for this stock assessment (Table 2).

Table 2: Parameters of the Von Bertalanffy growth curve for black cardinalfish in CDL 2 (from Tracey et al. 2000). L_∞ is fork length (cm).

Parameter	Both sexes	Female	Male
K	0.034	0.038	0.034
L_∞	70.8	70.9	67.8
t_0	-6.32	-4.62	-8.39

The interpretation of zone counts on otoliths as age estimates has been validated using lead-radium dating (Andrews & Tracey 2007) and the bomb chronometer method (Neil et al. 2008). Tracey et al. (2000) attempted marginal increment analysis, but this method failed because they couldn't determine the state of the outer edge of the otolith. The lead-radium dating method provided good agreement to zone count estimates of age for fish up to about 60 years, but beyond this the zone counts underestimated age, by perhaps 30% (Andrews & Tracey 2007). Given the aged data set, this would indicate a maximum age for black cardinalfish of at least 104 years. There was an apparent time lag between the known start of the bomb-carbon signal and the occurrence of $\delta^{13}C$ in the black cardinalfish otoliths, based on the inferred ages, and this method supported otolith zone counts as uncertain but unbiased estimates of age to about 90 years (Neil et al. 2008).

The parameters of the length-weight relationship, weight (g) = a * FL^b (where FL is the fork length), were estimated for black cardinalfish samples taken during research surveys in CDL 2, CDL3, and CDL4 combined (Figure 11, Table 3). The resulting length-weight relationship was different from that estimated by Doonan et al. (1999) for the Chatham Rise (Figure 11, Table 3), with the Doonan et al. curve giving a better visual fit to the smaller fish (less than 45 cm FL), and the curve estimated in this study a better visual fit to the larger fish (over 45 cm FL). However, neither curve seems to fit the data especially well. The length weight curve estimated in this study gave the best visual fit to the data for CDL 2, where almost all of the catch has been taken, so was more appropriate for use in the stock assessment model.

The data suggest that larger fish (over 50 cm FL), which would be largely mature fish, may be heavier at length in CDL 3 and CDL 4 than in CDL 2. This might be a sampling bias, or perhaps related to fish condition, where fish were in better condition on the Chatham Rise, perhaps where they were resting from spawning, or more actively feeding.

The length-weight relationship will be used in the stock assessment model to convert catches at length to total catch weight, and it is therefore important to have the best length-weight relationship over the recruited length range. As all black cardinalfish in samples of commercial catches were over 25 cm FL, and mean lengths were usually over 50 cm FL (see Section 2.6), the length-weight relationship estimated in this study has been used in the stock assessment model.

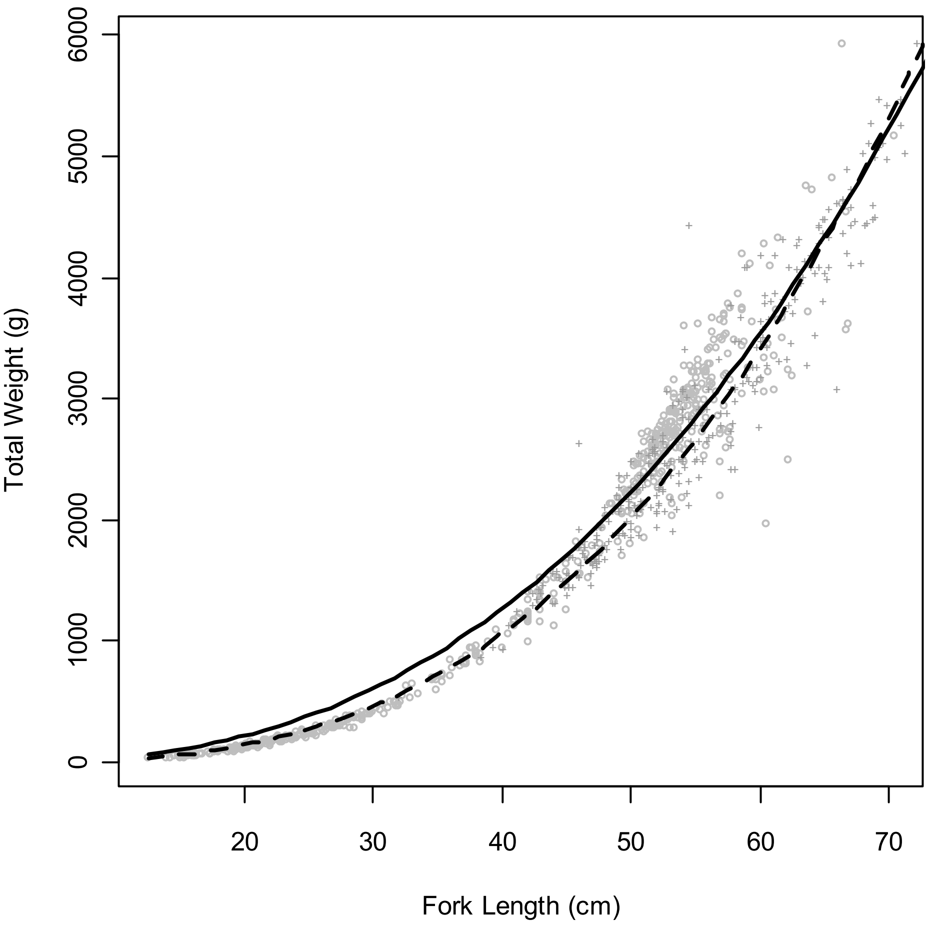

Figure 11: Length-weight relationship for black cardinalfish from CDL 2 ("+"), and CDL 3 and CDL 4 ("o") (N=676), showing the least-squares fitted regression line (solid line) and the regression line from Doonan et al. (1999) (broken line).

Table 3: Length-weight parameters for black cardinalfish estimated for the Chatham Rise (Doonan et al. 1999, cited in Tracey et al. 2000 and MFish Science Group 2008), and estimated for CDL 2, CDL 3, and CDL 4 combined (this study, with standard errors shown in parentheses).

Parameter	Doonan et al. 1999	This study (CDL 2)	This study (CDL 2–4)
a	0.0269	0.0788 (0.015)	0.1134 (0.015)
b	2.87	2.610 (0.047)	2.528 (0.033)

The stock assessment requires a measure of the variability of length around mean length at age, specifically the coefficient of variation (c.v.) of sizes at age around the mean. The CASAL model assumes a linear relationship between the c.v. at the first and last ages in the partition. The c.v.s for black cardinalfish were estimated from the CDL 2 aged data set (Tracey et al. 2000), which had between 2 and 32 length observation per age for ages between 3 and 89. The c.v.s decreased significantly ($p<0.001$) with increasing age (Figure 12), being 0.091 at age 1 and 0.036 at age 90, with a median of 0.061.

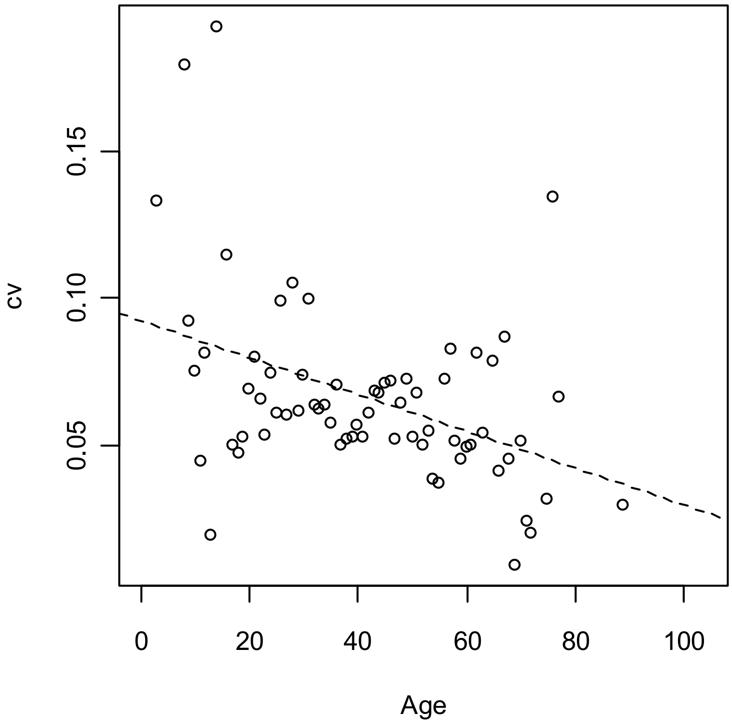

Figure 12: Coefficient of variation of length at age around the mean length for black cardinalfish sampled in CDL 2. The broken line shows the fitted linear regression.

2.4 Longevity and natural mortality (*M*)

Tracey et al. (2000) counted between 3 and 104 growth zones on black cardinalfish otoliths. A high longevity was validated by Andrews & Tracey (2007) and Neil et al. (2008). Total mortality (*Z*) was estimated by Tracey et al. (2000) using the aged CDL 2 data set and the Chapman & Robson (1960) estimator, after assuming full recruitment at age 45, at 0.034 yr^{-1}. The samples used were obtained between November 1998 and December 1999, and after roughly 24 000 t of reported catch had been made by the fishery. Tracey et al. (2000) were able to assume that Z=M because the ages over which *Z* was estimated were fully recruited before the fishery began, and so their relative abundance was not affected by fishing mortality (when assuming a flat selectivity at age after full recruitment). Tracey et al. (2000) also found a slow increase in the *Z* estimate with increasing age at full recruitment, with *Z* slowly increasing and approaching 0.05 yr^{-1}, and so suggested *Z* (*M*) might increase with age. The subsequent age validation studies indicated that ages greater than about 60 years were probably underestimated, by up to 30% (Section 2.3). This would result in a bias in the *M* estimate, where *M* was probably overestimated. Estimates of *M* for other long-lived deep sea species have been about 0.045 yr^{-1} for orange roughy, 0.044 $yr^{-1}$for black oreo, and 0.063 yr^{-1} for smooth oreo (Ministry of Fisheries Science Group 2008). In the last stock assessment, Field & Clark (2001) assumed an ‘arbitrary’ *M* of 0.05. FAO (2002) report an *M* for black cardinalfish of 0.3–0.4, but do not specify the source of this estimate; an *M* of 0.3-0.4 would be inconsistent with the validated high longevity. This was presumably argued from the maximum *M* found by Tracey et al. (2000), and from parity with the available estimates for other deep water fishes.

2.5 Maturity

Field & Clark (2001) performed stock assessment model runs assuming maturity was equal to age of recruitment (assumed to be 45 years, following Tracey et al. (2000), or alternatively assuming maturity was equal to 35 years (from the authors' unpublished data and analysis). The most likely source of data for the Field & Clark unpublished estimate was some length and maturity samples taken from black cardinalfish landings on the east coast North Island in 1999 and 2000. The age from 50% to 95% (Ato95) was also reported by Field & Clark as 13 years, presumably also estimated from the unpublished analysis. Tracey et al. (2000) reported mean age at first maturity as 36.4 years for females and 34.5 years for males, but the source of these estimates was not reported. Neil et al. (2008) reported a major change in δ^{13}C between ages of 26 and 44 years (mean 33 years), which would imply that maturity took place between these ages.

Most of black cardinalfish biological samples from research trawls have been classified as maturing (Table 4). The most recent samples have been taken during orange roughy surveys of the east coast North Island in 2001 and 2003, in which 73.2% were at least macroscopic stage 3 (mature through to spent), and 41.4% were actively spawning (Table 4). According to this maturity stage key, immature (non spawning) would be stages 1 and 2, and mature stage 3 to 8. Stage 2 means "maturing", but at spawning time "maturing" would effectively mean "not spawning".

Table 4: Number of black cardinalfish sampled during all research trawl surveys, and the two orange roughy surveys in June–July 2001 and 2003, by macrosopic maturity stage (1, immature; 2, maturing; 3, mature; 4, ripe in females and ripe and running in males; 5, ripe and running in females and spent in males; 6, spent in females; 7, atretic; 8, partially spent).

	1	2	3	4	5	6	7	8
All	38	536	167	68	36	62	4	12
2001 & 2003	8	67	36	56	29	45	0	11

A research trawl survey of the east coast North Island in June 1993 (TAN9306) measured 182 black cardinalfish for length and maturity, and found almost all (71.4%) were "maturing" (macroscopic stage 2). Only a single fish fish, a female at 50 cm FL, was classified as immature. Most of the rest of the sample were at stage 3 "mature" (23.1%), with only 1 fish spawning and 8 spent.

Logistic curves fitted to the proportion mature at length indicate black cardinalfish started to mature at about 25 cm FL, and 50% were mature (L50) at 52.4 cm FL in males, and 56.0 cm in females (Figure 13). Using the growth parameters estimated by Tracey et al. (2000), 25 cm FL would be equivalent to an age of about 6 years, and the maturity L50 for 2001 and 2003 combined would be equivalent to an age of first maturity (A50) of about 35.8 years for males, 36.6 years for females, and 36.7 years for males and females combined.

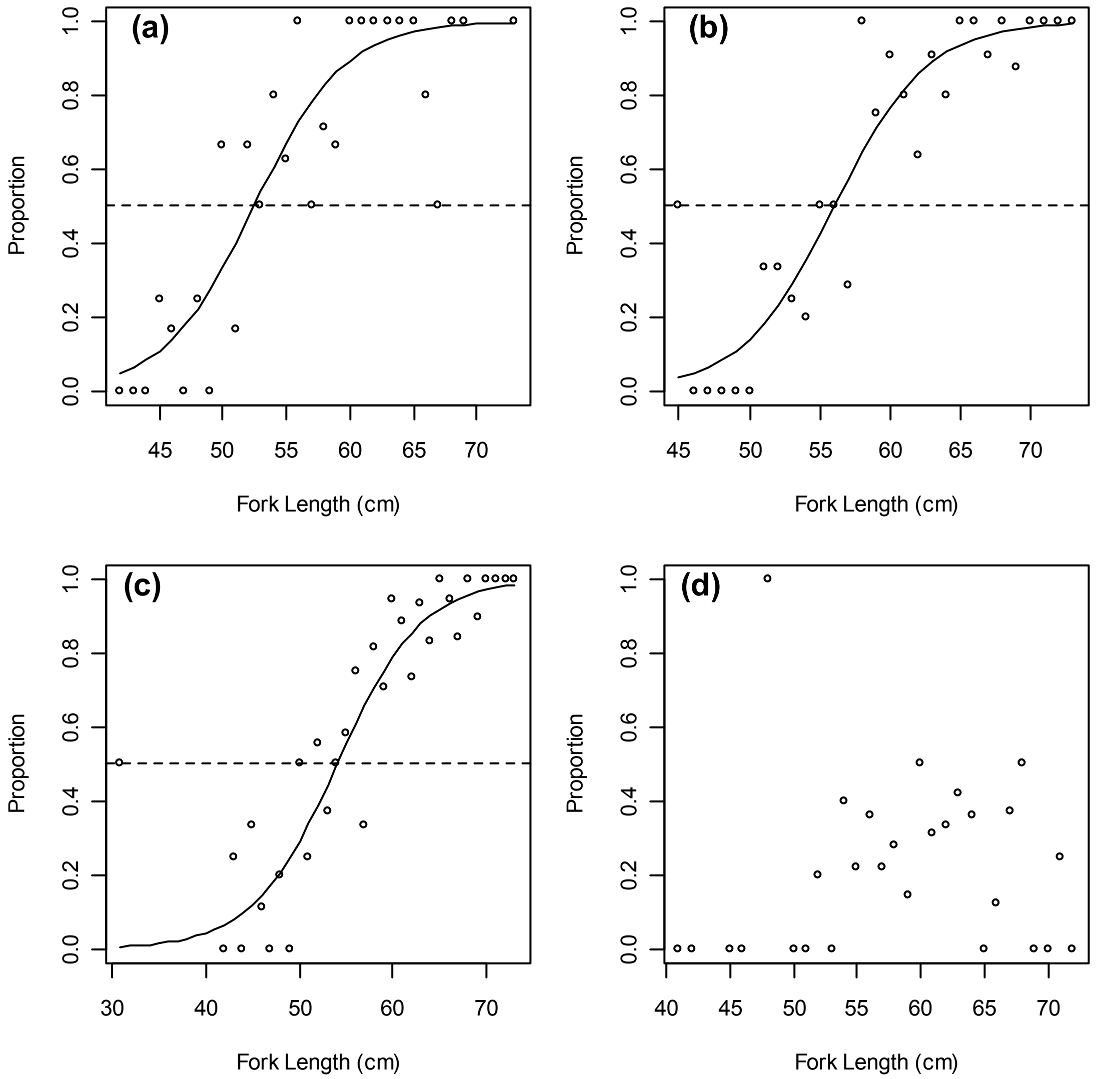

Figure 13: Estimated proportion of black cardinalfish mature at length from trawl surveys of CDL 2 in June and July for (a) 2001 & 2003 male (N=114, L50 52.4 cm FL); (b) 2001 & 2003 female (N=164, L50 56.0 cm); (c) 2001 & 2003 both sexes (N=280, L50 54.0 cm); (d) 1993 both sexes (N=182). The solid line is the fitted logistic curve. The horizontal broken line indicates 50% mature.

The conversion of length to age, using the parameters estimated by Tracey et al. (2000) in the von Bertalanffy growth equation (in the form $\mathrm{Age}_t = t_0 + \ln(1 - \mathrm{Length}_t / L_\infty)/(-K)$), will be biased because of the distribution of lengths at age (the mean age at length will change depending on the underlying age structure; also the parameters were estimated from a regression of length against age, rather than age against length). It is possible that the age at maturity estimates from Field & Clark (2001) were calculated in a similar way, and therefore may also be biased. To avoid this problem, and the calculations necessary to compensate for this bias, the maturity was simply estimated in the stock assessment model, using the proportions mature at length from the 2001 and 2003 data (Figure 13c).

The sample from June 1993 included almost all mature fish (Figure 13d), but only one of which was actively spawning. This could be because most of the fish were spawning at other times of year, consistent with an extended spawning season. However, it could also indicate that not all mature fish were spawning in any one year, and that there was a non-spawning (resting) component of the mature stock. A substantial proportion of resting adults has previously been reported for orange roughy (Bell et al. 1992).

2.6 Recruitment and vulnerability

Based on an age frequency distribution, Tracey et al. (2000) estimated most of the black cardinalfish catch sampled in CDL 2 in 1999–2000 to be 35–55 years old, with full recruitment at 45 years (equivalent to a length of about 58 cm FL).

Black cardinalfish length frequencies in commercial catches were collected by Ministry of Fisheries observers at sea, and by market sampling of landed catches (data held in the 'market' database). The observer samples have been sporadic (Table 5), and measured between 1 and 121 fish per tow, with a median of 5 fish per tow. Black cardinalfish were measured between 36 and 73 cm FL, and all length frequency distributions were unimodal. There were only 23 tows where 20 or more fish were measured (Table 5).

Table 5: Number of tows by QMA and fishing year where black cardinalfish length frequency samples were collected by Mninstry of Fisheries observers. The number of tows where 20 or more fish were measured is shown in parentheses.

Fishing year	FMA2	FMA3	FMA4
1989–90	1 (1)	–	–
1990–91	2 (2)	–	–
1964–95	1 (1)	–	–
1996–97	–	–	2
1997–98	–	–	3
1998–99	3 (1)	–	–
1999–2000	5 (4)	–	–
2000–01	2 (1)	1	1
2001–02	–	–	7 (2)
2002–03	–	–	30 (3)
2003–04	–	–	8 (1)
2004–05	1	–	11 (2)
2005–06	–	–	7
2006–07	–	–	19
2007–08	6 (5)	–	2
2008–09	–	–	1

The mean lengths from observer samples were analysed using a regression tree method (Dunn 2008), and indicated that the black cardinalfish mean length was greater in samples from the east coast North Island, specifically the hills at Ritchie Bank and Rockgarden, Tuaheni and Tolaga, and East Cape, compared to the Chatham Rise (Figure 14). This would be consistent with the smaller fish being found on the Chatham Rise, as indicated by research vessel samples (Section 2.1).

The market samples were collected in 1991 (N=7), 1999 (N=11), and 2000 (N=6). Of the 24 catches sampled, 1 came from outside the EEZ (ET), 22 from the east coast North Island (CDL 2), and 1 from the east coast South Island (CDL 3). A total of 13 582 fish were measured, between 178 and 720 fish per landing, at lengths between 25 and 76 cm FL, and all length frequency distributions were unimodal.

The observer samples suggested no trend in mean length between 1990 and 2008 for the east coast North Island (Figure 15). Three of the market samples measured landings of relatively small fish in 1999 and 2000, with mean lengths of less than 45 cm FL (Figure 15). Overall, black cardinalfish seemed to be smaller on the Chatham Rise (CDL 3 and CDL 4), and there was no clear trend in mean length over time. The samples were too few to determine whether the smaller mean lengths obtained in 1999 and 2000 were representative, a consequence of greater sampling effort in those years (small fish are infrequent, and so only seen when sampling effort is higher), or ‘unusual’.

Catch-weighted length frequency distributions for the Ministry of Fisheries observer and market sampling data combined are shown in Figure 16. If the position of the left hand side of the length frequency distribution, to the first plateau or mode, is indicative of the length of vulnerability to the fishery, then vulnerability would be at a mean length of about 44 cm FL in CDL 2, and 25 cm FL in CDL 3 and CDL 4. Vulnerability at about 44 cm FL would be equivalent to about 22 years of age, and younger than the mean age at first maturity. The length frequency distribution for the whole area closely resembles that for CDL 2 (Figure 16). The highly skewed length frequency distribution for CDL 3 and CDL 4 may indicate different catchabilities for smaller (less than 50 cm FL) and larger fish, possibly related to ontogenetic spatial shifts in distribution.

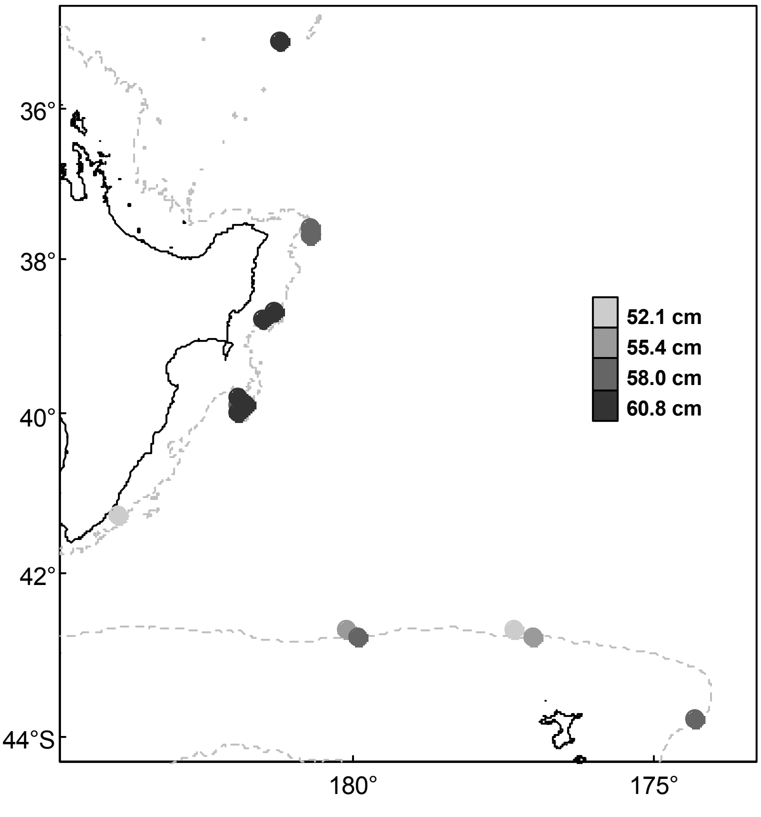

Figure 14: Black cardinalfish mean FL by location from the ‘spot’ regression model using Ministry of Fisheries observer samples.

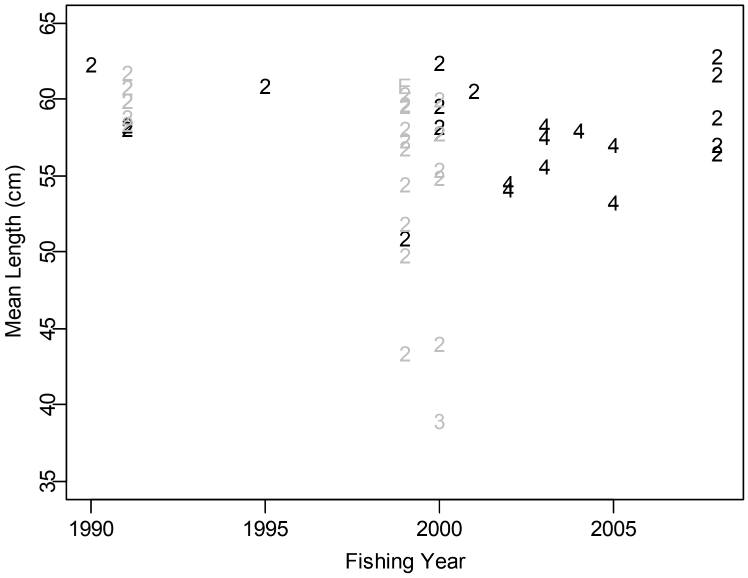

Figure 15: Black cardinalfish mean FL by tow or landing by year from the Ministry of Fisheries observer programme (black text; 2, CDL 2; 4, CDL 4), and market sampling programme (grey text; 2, CDL 2; 3, CDL 3; E, ET).

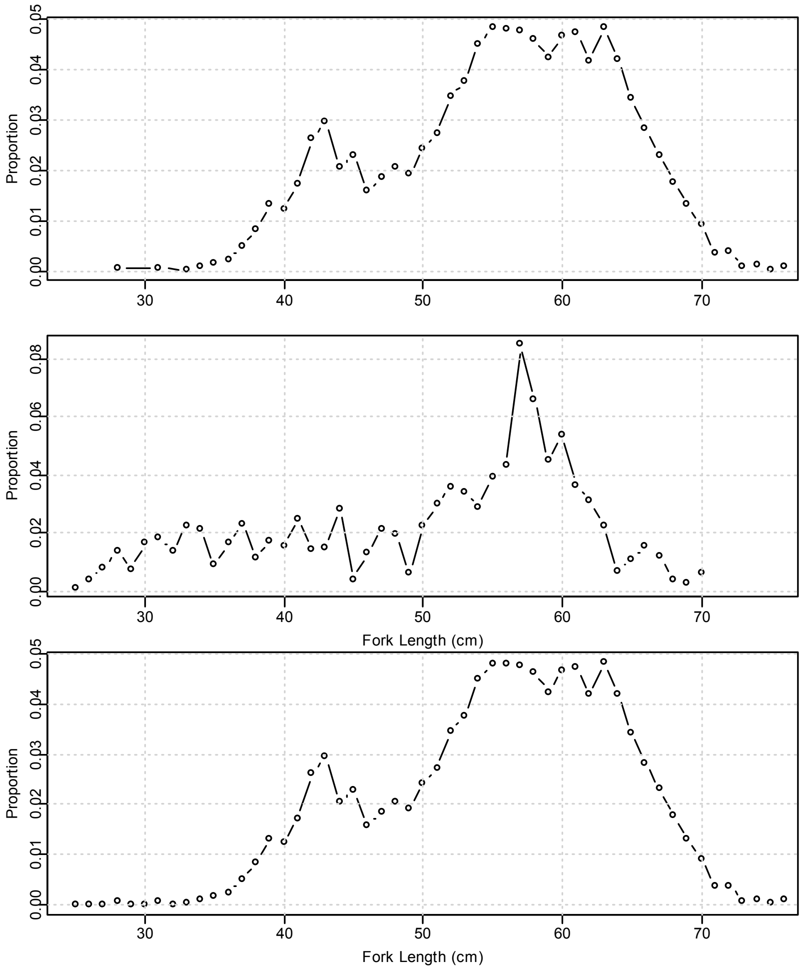

Figure 16: Catch-weighted length frequency distributions for black cardinalfish sampled by the Ministry of Fisheries observer programme and the shed sampling programme. Upper panel, CDL 2; middle panel, CDL3, and CDL 4; lower panel, all areas combined.

The first mode in the overall length frequency distribution, at about 44 cm FL, might be a result of vulnerability, recruitment variability (a period of relatively good recruitment), or a sampling error. The fishery in CDL 3 and CDL 4 has been small compared to the CDL 2 fishery (Section 2.2). As a result, ignoring the lower age of vulnerability in the former areas, and just assuming the CDL 2 vulnerability, would probably not introduce a substantial bias in a stock assessment. Therefore, for simplicity in the initial stock assessment models, it seemed sensible to estimate vulnerability for a single fishery.

The catch-weighted length frequency distributions for combined CDL 2–4 varied substantially between years (Figure 17). For stock assessment modelling, the distributions were assumed to have a multinomial error, with effective sample sizes estimated from the intercept of the linear regression of log(c.v.) versus log(proportion) (Figure 18, Table 6). Most of the samples fitted the expected slope of the multinomial distribution, with deviations for 1999–2000 and 2000–01, where, respectively, small fish were sampled, and the length distribution was irregular. This lack of fit for these years was not seen as a major problem, as the purpose of this analysis was only to estimate the relative effective sample sizes, which seemed sensible for these years given the number of samples and fish measured (Table 6).

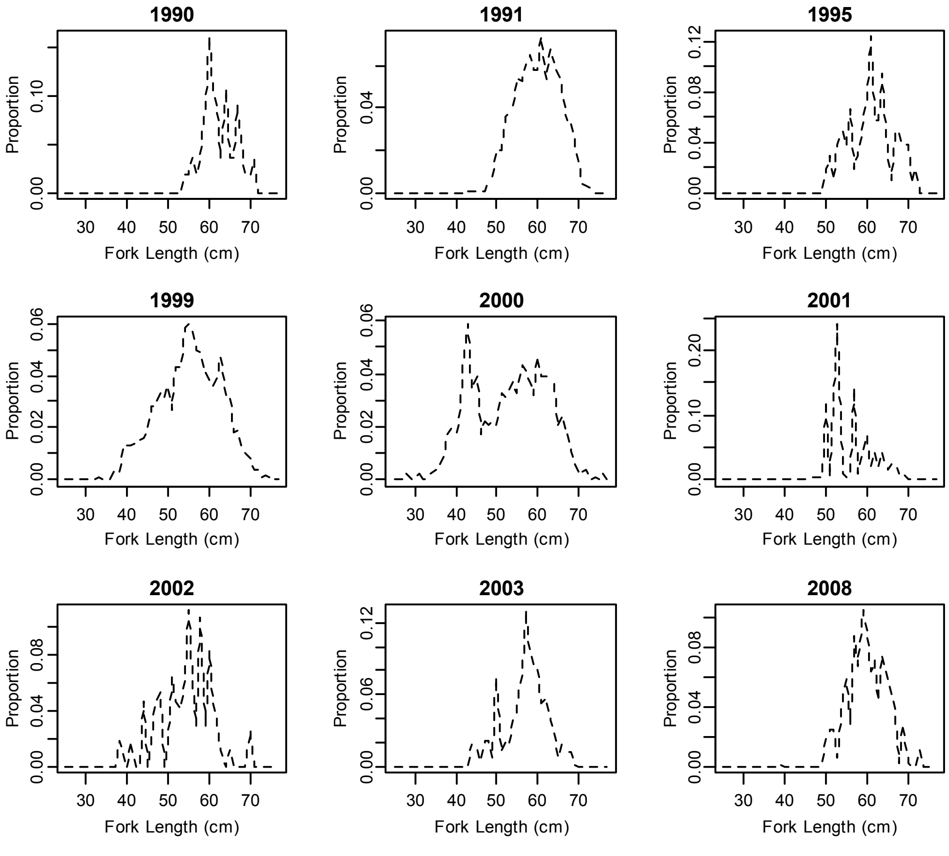

Figure 17: Black cardinalfish catch-weighted length frequency distributions for CDL 2–4 combined, where at least 50 fish were measured per year. The c.v.s were estimated from 300 bootstraps using the NIWA catchatage software (implemented in R).

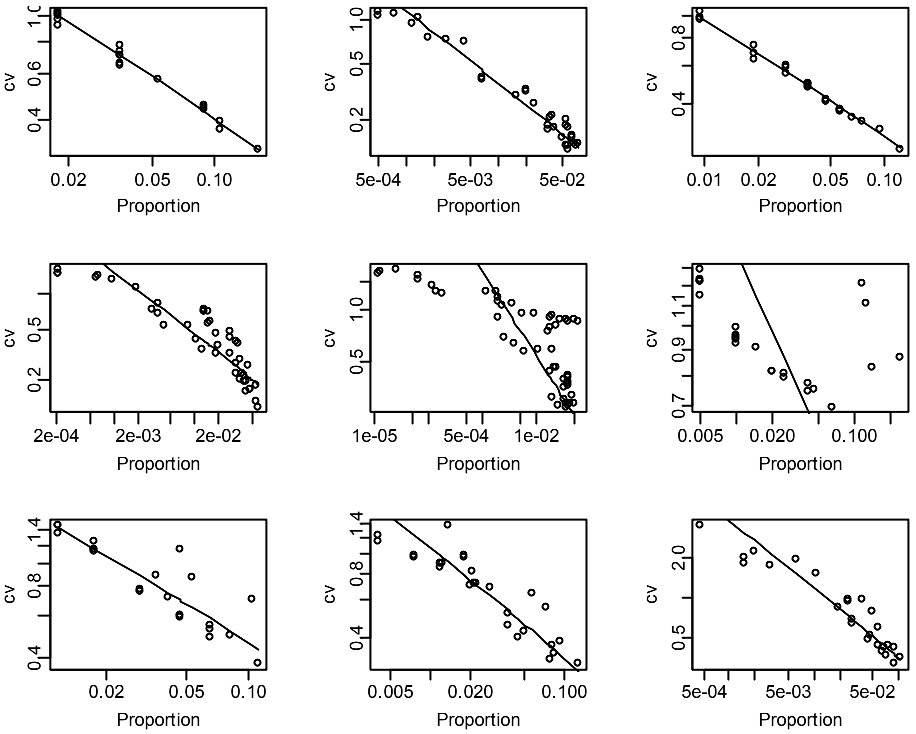

Figure 18: Log(proportion and log(c.v.) for the length frequency distributions as shown in Figure 17.

Table 6: Length frequency samples for black cardinalfish in CDL 2–4, where there were at least 20 fish measured in any one sample, and at least 50 fish were measured in any one year.

Fishing year	No. tows or landings measured	No. fish measured	Effective sample size	Mean length (cm)
1989–90	1	56	56	62.4
1990–91	9	1 877	682	60.0
1994–95	1	105	102	61.0
1998–99	11	2 200	424	55.3
1999–2000	10	1 629	329	53.0
2000–01	1	81	42	56.2
2001–02	2	64	42	54.3
2002–03	3	173	80	56.9
2007–08	5	190	77	60.0

The previous stock assessment (Field & Clark 2001) assumed either maturity was equal to vulnerability (set at 45 years), or that vulnerability was equal to maturity (35 years). Field & Clark (2001) assumed a recruitment variability (σ^R) of 1.2, and steepness of 0.75. There have been no studies of potential recruitment variability in black cardinalfish, but high longevity has been argued to be an adaptive advantage where there are extended periods between good recruitment episodes (Longhurst 2002). As a result, it is possible that black cardinalfish might encounter highly variable recruitment levels over a short time period, where 'short' will be measured in relation to the species longevity, and so for black cardinalfish might be several decades. However, in the absence of information to the contrary, initial stock assessment models runs assumed deterministic (constant) recruitment.

2.7 Standardised CPUE indices

The standardised CPUE indices used in this assessment were described by Dunn & Bian (in press). The indices covered two time periods: (1) 1990–91 to 1997–98, and (2) 1998–99 to 2007–08.

The Ministry of Fisheries Deepwater Working Group specified the use of non-zero catch (normal) models as the "base case". For 1998–99 to 2007–08, the index using *target species* as a predictor was treated as the base case. The rationale behind the preference for non-zero catch models was that combined models, which included a binomial model to describe catch success, were more likely to be biased. This was because catch success was considered more likely to reflect other factors, such as reporting trends, rather than abundance.

The data set used for standardised CPUE analyses included a relatively large proportion of the fishery (65–77% of the total estimated catch), but covered a relatively small spatial area (Figure 19). The only areas of the black cardinalfish fishery not covered by the data set were relatively small fisheries, off the Wairarapa coast south of the Castlepoint Hills, and an area to the south and west of the Rockgarden (Dunn & Bian in press). Because the fisheries are so spatially distinct, the indices may well describe local vulnerable biomass, but it is less certain that they describe total abundance.

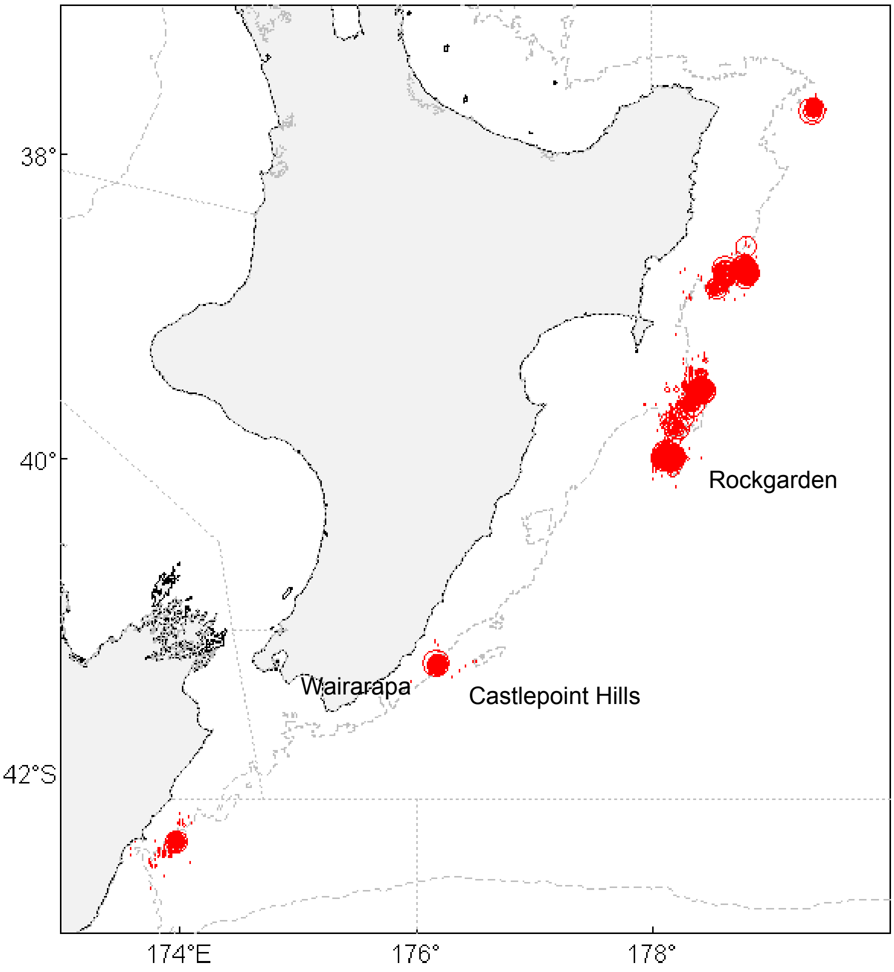

Figure 19: Unstandardised catch per tow of black cardinalfish as used in the standardised CPUE index (1990–91 to 2007–08). Circle proportional to catch rate (max 77 t per tow). The dotted grey line indicates the QMA boundaries (see Figure 1). The broken grey line indicates the 1000 m isobath.

3. STOCK ASSESSMENT

The observational data were incorporated into a Bayesian stock assessment, using the program CASAL (Bull et al. 2005). The stock was partitioned by age, with age groups 1–90 years and a plus group at 90+. There was no partition by sex or maturity. The stock was assumed to reside in a single area, with a single time step, in which the order of processes was ageing, recruitment, growth, and mortality.

Growth was modelled using the von Bertalanffy growth curve (assumed constant), and vulnerability and maturity using logistic curves (both initially estimated). Variability of length around mean length at age was assumed to be normally distributed, with a c.v. of 0.091 at age 1 (*cv1*) and 0.036 at age 90 (*cv90*), and a linear interpolation (as a function of age) assumed between the two. In the absence of information to the contrary, recruits were assumed to be 50% male. The catch equation used was the instantaneous mortality equation from Bull et al. (2005), whereby half the natural mortality was applied, followed by the fishing mortality from the fishery, then the remaining natural mortality. In preliminary runs, natural mortality (*M*) was assumed to be constant at 0.034 yr^{-1}.

Lognormal errors, with known (sampling error) c.v.s were assumed for the CPUE, and because the c.v.s were relatively high no additional process error was included. Multinomial errors (see Bull et al. 2005) were assumed for the proportions at length data, and binomial errors for the proportion mature at length. A process error for the proportions at length data was estimated in preliminary runs and then fixed. A penalty function was added to discourage the model from allowing the stock biomass to drop below a level at which the historical catch could not have been taken. Recruitment was assumed to be deterministic, and the model assumed a linear relationship between CPUE and abundance.

The priors for catchability (*q*) and virgin biomass (B_0) estimates were assumed to be uniform-log (uniform in log space). The upper bound for the B_0 parameter was set at 120 000 t. This was roughly equivalent to the virgin biomass estimated for the two overlapping orange roughy stocks (East Cape and Mid-East Coast) (Ministry of Fisheries Science Group 2008). Expert opinion suggested that the black cardinalfish biomass in the area was smaller than that of orange roughy. Priors on the vulnerability and maturity parameters (A_{50} and A_{to95}) were assumed to be uniform (in normal space).

Maximum posterior density (MPD) estimates were found for the free parameters during preliminary runs of the model. For final model runs, including those specified by the Ministry of Fisheries Deepwater Working Group, the uncertainty in the estimates was also evaluated by using the Markov Chain Monte Carlo (MCMC) technique (Bull et al. 2005).

3.1 Preliminary model runs

The biomass showed a continuous decline in all model runs (Figure 20, Table 7). The fits to the proportions mature at length were similar in all model runs, with the mean age at first maturity varying between 37.2 and 39.9 years (Figure 21). The model fits to the left hand side of the length frequency distributions, determined by the estimated age of vulnerability, were variable, but the observations were inconsistent, with 2000 including more smaller fish, and 2008 consisting of only relatively large fish (Figures 22–25). The model fits to the right hand side of the length frequency distribution were equally variable, with typically more large fish expected than observed, notably for 1999 and 2000.

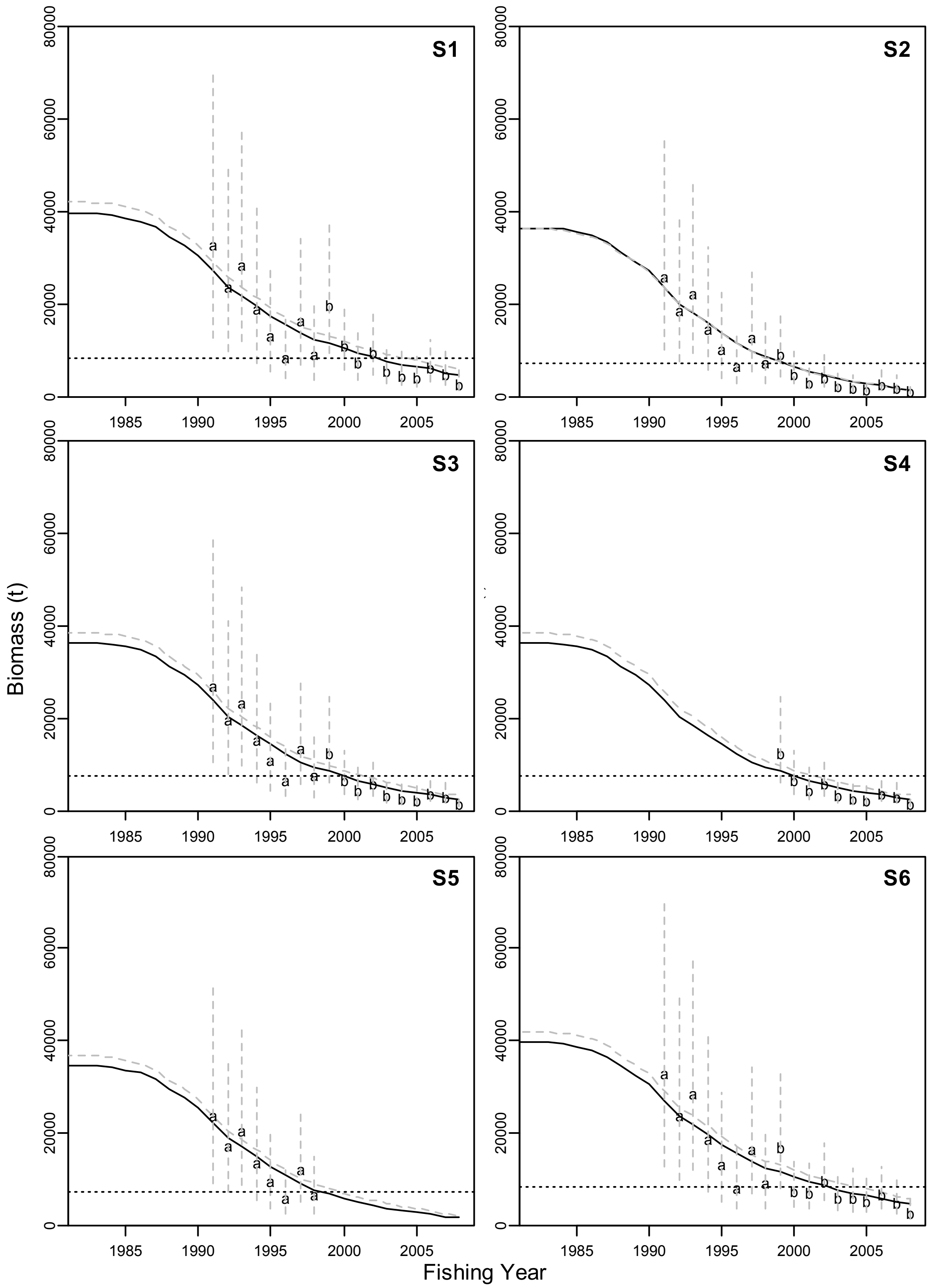

Figure 20: MPD estimated fits of the vulnerable biomass (solid line) and mature biomass (broken grey line) to the early (a) and late (b) CPUE indices for sensitivity runs (labelled S1–S12, see Table 7). Vertical broken lines indicate the 95% confidence intervals for the CPUE indices. The horizontal dotted line is for reference, and indicates 20% B_0.

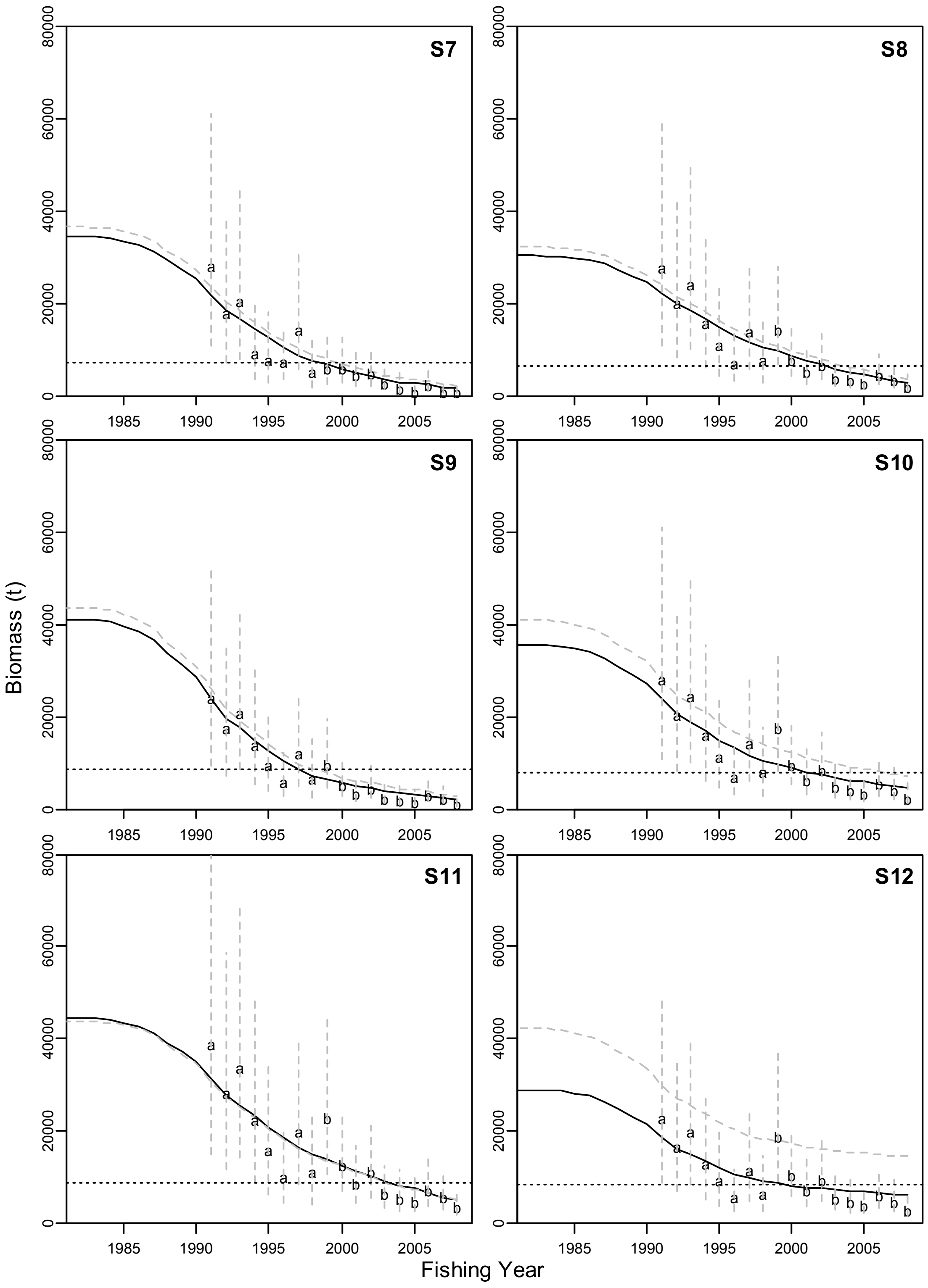

Figure 20 (cont.): MPD estimated fits of the vulnerable biomass (solid line) and mature biomass (broken grey line) to the early (a) and late (b) CPUE indices for sensitivity runs (labelled S1–S12, see Table 7). Vertical broken lines indicate the 95% confidence intervals for the CPUE indices. The horizontal dotted line is for reference, and indicates 20% B_0.

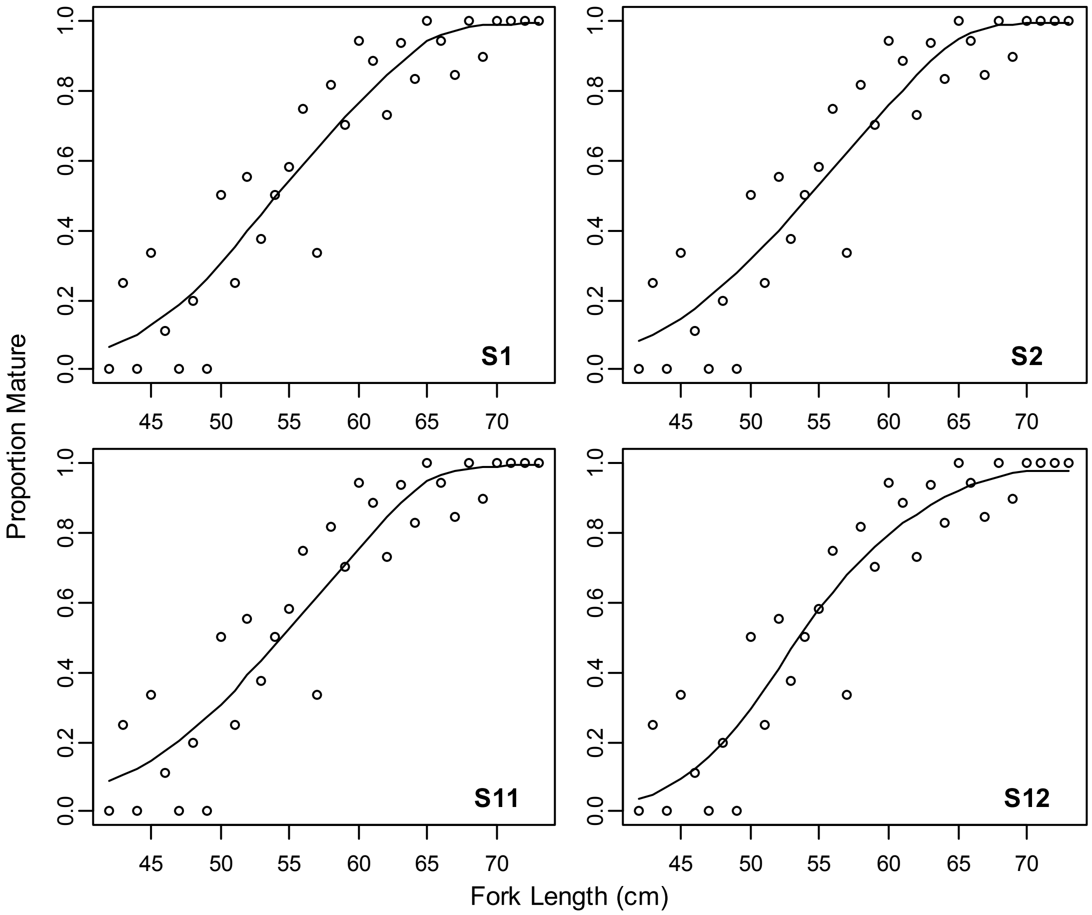

Figure 21: MPD estimated fits (lines) of the proportion mature at length (points), for selected sensitivity runs (labelled S1–S12, see Table 7).

There was little visual difference in the fits to the various CPUE indices. The fit to the early CPUE was relatively poor in all runs, with the CPUE index indicating a steeper decline in biomass than estimated by the model. Compared to the 'base' CPUE run (S3), the run using only the late CPUE index estimated a similar biomass and level of depletion (S4), and the run using only the early index estimated a smaller biomass and greater level of depletion ((Table 7). The run where the late CPUE index excluded the *target species* predictor estimated a larger and less depleted biomass (S6). The combined CPUE indices, and the early CPUE index alone, both exhibited a steeper decline, and the model runs estimated a smaller and more depleted stock (S7 and S5 respectively).

The run where no catch over-runs were added estimated a smaller and less depleted biomass (S8), and the run where the pre-TACC over-runs were double estimated a larger and more depleted biomass (S9).

The most obvious difference in results occurred when *M* was varied. The sensitivities to *M* showed that the biomass decreased and became less depleted when *M* was increased to 0.04 or 0.06. This was due, in part, to an increase in 'cryptic' mature biomass. This occurred when the estimated vulnerability curve was displaced to the right of the maturity curve, resulting in a proportion of the spawning stock which was not available to the fishery. At *M*=0.027 all of the mature biomass was vulnerable, but the vulnerable biomass in 2009 decreased to 77%, 65% and 44% of the mature biomass as *M* was increased to 0.034, 0.04 and 0.06 respectively.

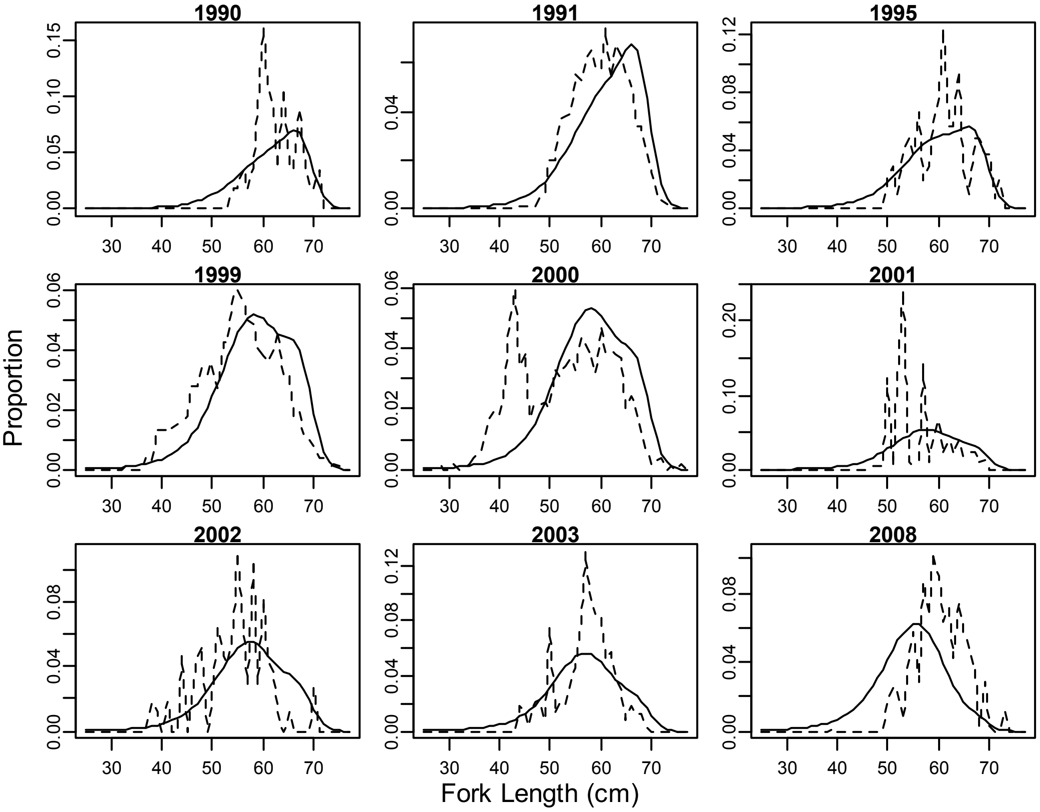

Figure 22: MPD estimated fits (solid line) of the proportion at length (broken line), for sensitivity run S1 (see Table 7).

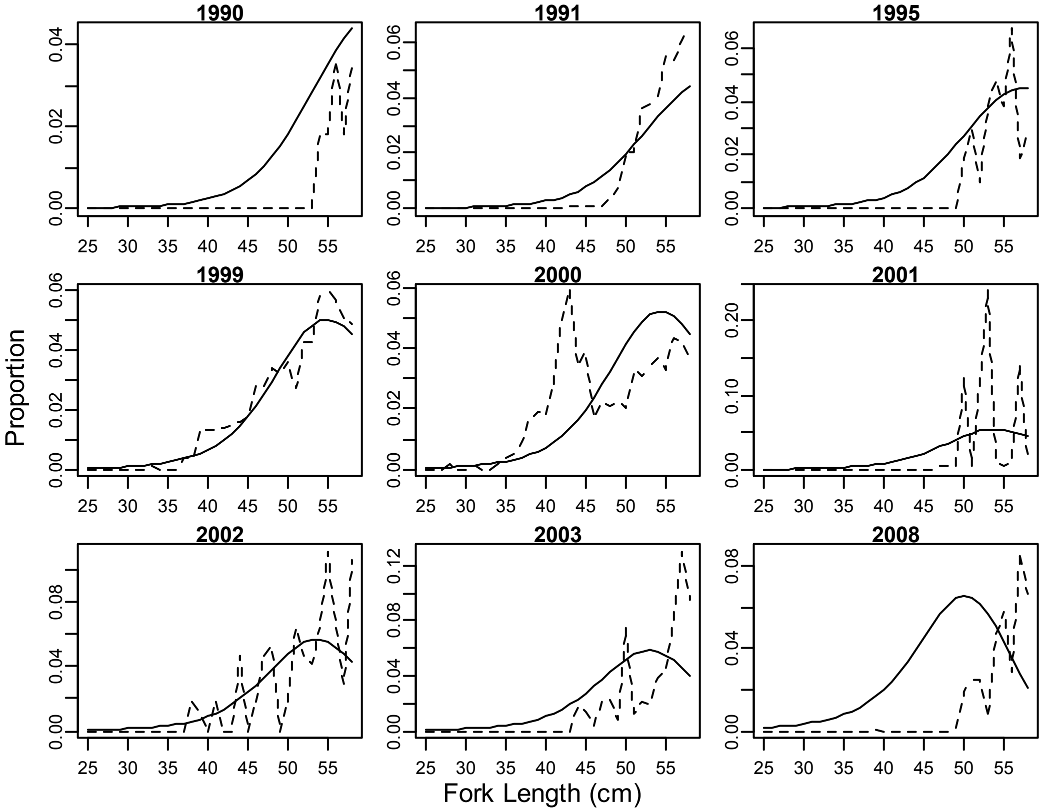

Figure 23: MPD estimated fits (solid line) of the proportion at length (broken line), for sensitivity run S2 (see Table 7).

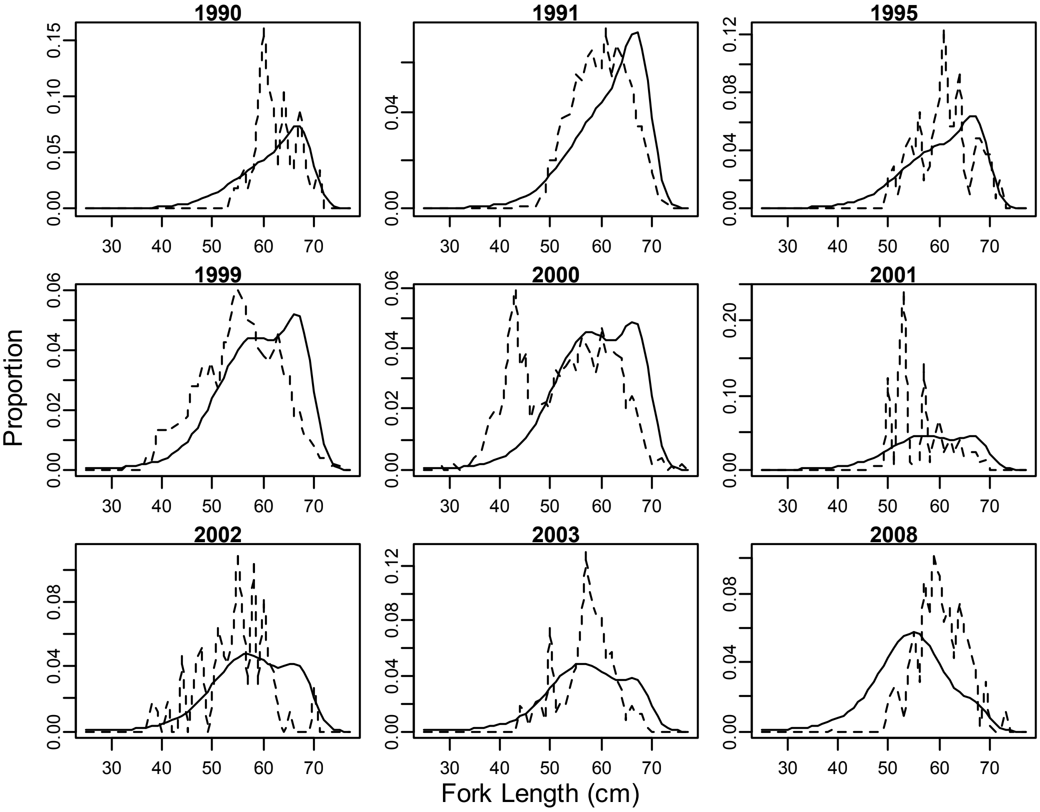

Figure 24: MPD estimated fits (solid line) of the proportion at length (broken line), for sensitivity run S11 (see Table 7).

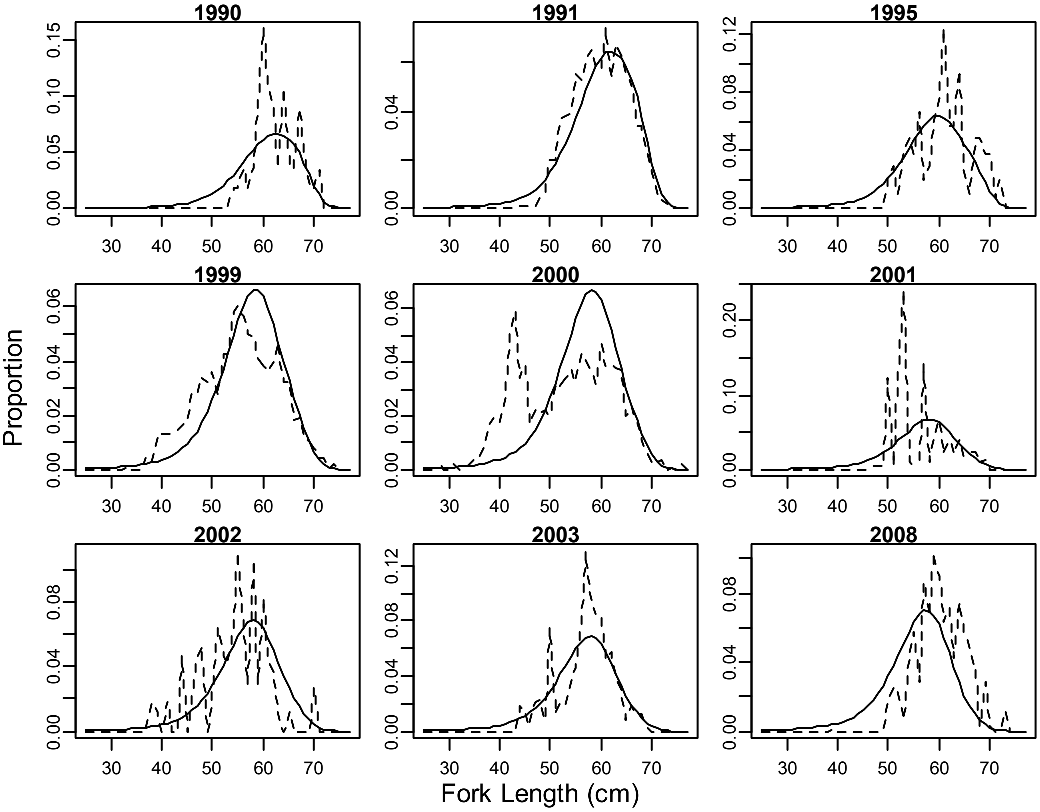

Figure 25: MPD estimated fits (solid line) of the proportion at length (broken line), for sensitivity run S12 (see Table 7).

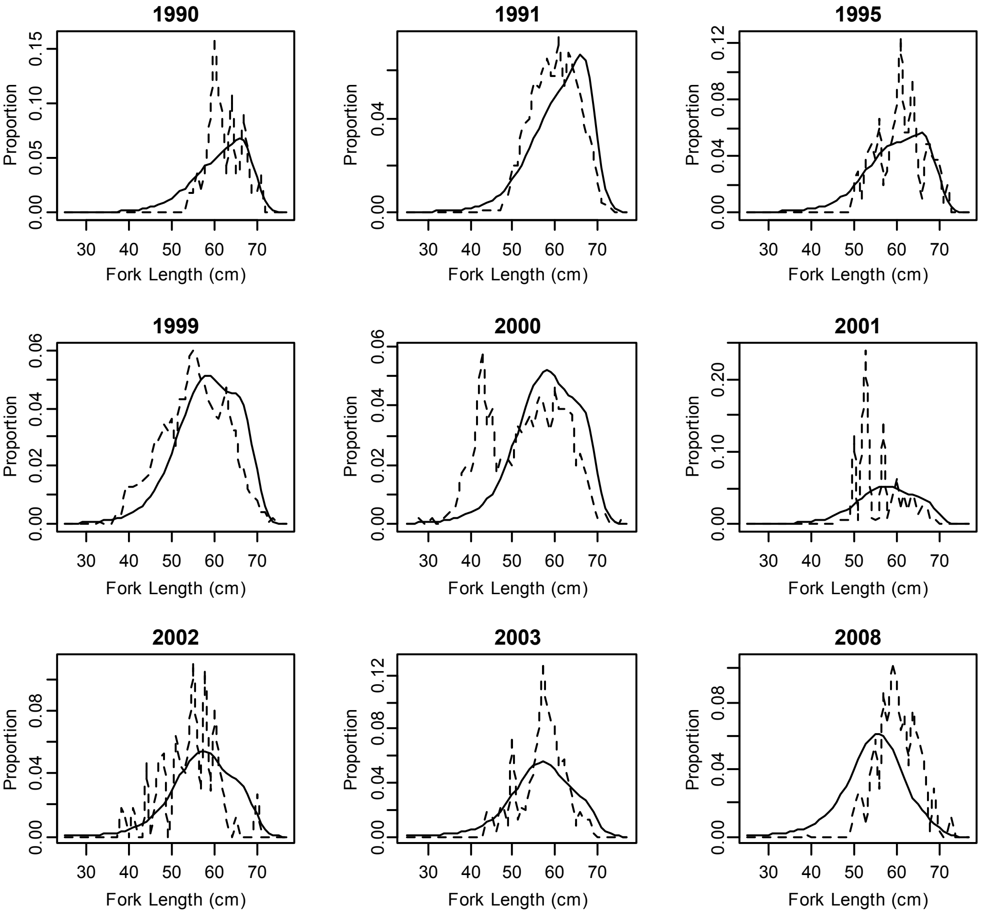

Figure 26: MPD estimated fits (solid line) of the proportion at length (broken line), for sensitivity run S13 (see Table 7).

The fit to the length frequency data improved as *M* increased, improving by about 17 likelihood units between M=0.027 and M=0.06, with a visible improvement in fits (Figures 24 and 25).

For run S2 the length frequency distribution was truncated at 58 cm, so that the vulnerability would be estimated, but the right hand side of the length frequency distribution would not be fitted. This prevented any biomass depletion signal being obtained from the length frequency data. The fits to the CPUE improved (marginally), and the mean age of vulnerability was estimated to be earlier than in any other run, at 37 years. The stock was estimated to be very highly depleted (4% B_0). The age at maturity was also estimated to be relatively low (37.2 years), presumably because of the depleted age structure in the years when the maturity at length observations were input (2002).

The run where the CPUE indices were excluded and only the length frequency observations were fitted (S13) indicated a similar and slightly less depleted biomass compared to the ‘base’ case (S1). There was little visible difference in the fit to the length frequency observations (Figures 22 & 26). The length frequency observations therefore indicate a less depleted stock than the CPUE indices, but the conflict is not large.

Table 7: Sensitivity run data inputs, with MPD estimates of likelihoods, parameter estimates, and derived quantities. The prefix *B* refers to mature biomass, and *V* to vulnerably biomass. * indicates a fixed parameter. *M* was fixed in all runs.

	S1	S2	S3	S4	S5
Data inputs					
Catches + over-runs	x	x	x	x	x
Catches + no over-runs	-	-	-	-	-
Catches + double over-runs	-	-	-	-	-
CPUE early	x	x	x	-	x
CPUE late target	x	x	x	x	-
CPUE late non-target	-	-	-	-	-
CPUE combined models	-	-	-	-	-
LFs	x	-	-	-	-
LFs truncated at 58cm	-	x	-	-	-
Props. Mature	x	x	-	-	-
M*	0.034	0.034	0.034	0.034	0.034
Likelihoods					
Total	255.83	-78.83	-22.65	-7.23	-4.89
CPUE early	-4.96	-5.28	-5.20	-	-5.31
CPUE late	-7.60	-7.84	-8.31	-8.31	-
Commercial LFs	236.06	-100.06	-	-	-
Maturity Props	42.02	43.22	-	-	-
Prior on B_0	10.65	10.50	10.56	10.57	10.51
Prior on selectivity	0	0	-	-	-
Prior on maturity	0	0	-	-	-
prior on q Early	-10.41	-10.17	-10.22	-	-10.09
prior on q Late	-9.92	-9.19	-9.48	-9.49	-
Catch penalty	0	1.25E-08	0	0	0
Estimable parameters					
B_0	42 136	36 399	38 751	38 773	36 855
Vulnerability A_{50}	42.1	37.0	42.1*	42.1*	42.1*
Vulnerability A_{to95}	16.0	14.2	16.0*	16.0*	16.0*
Maturity A_{50}	39.6	37.2	39.6*	39.6*	39.6*
Maturity A_{to95}	15.4	14.4	15.4*	15.4*	15.4*
q CPUE early	3.02E-05	3.84E-05	3.65E-05	-	4.14E-05
q CPUE late	4.92E-05	1.02E-04	7.60E-05	7.58E-05	-
Derived parameters					
B_{2009}	6 001	1 512	3 480	3 495	2 332
$\%B_0$	14.2	4.2	9.0	9.0	6.3
V_0	39 708	36 596	36 517	36 536	34 730
V_{2009}	4 835	1 543	2 672	2 685	1 740
V_{2009}/B_{2009}	0.81	1.02	0.77	0.77	0.75
$\%V_0$	12.2	4.2	7.3	7.3	5.0

Table 7 (cont.): Sensitivity run data inputs, with MPD estimates of likelihoods, parameter estimates, and derived quantities. The prefix *B* refers to mature biomass, and *V* to vulnerably biomass. * indicates a fixed parameter. *M* was fixed in all runs.

	S6	S7	S8	S9	S10
Data inputs					
Catches + over-runs	x	x	-	-	x
Catches + no over-runs	-	-	x	-	-
Catches + double over-runs	-	-	-	x	-
CPUE early	x	-	x	x	x
CPUE late target	-	-	x	x	x
CPUE late non-target	x	-	-	-	-
CPUE combined models	-	x	-	-	-
LFs	-	-	-	-	x
LFs truncated at 58cm	-	-	-	-	-
Props. Mature	-	-	-	-	-
*M**	0.034	0.034	0.034	0.034	0.04
Likelihoods					
Total	-23.49	-19.99	-22.56	-22.31	251.85
CPUE early	-4.96	-4.19	-4.89	-5.39	-5.04
CPUE late	-8.98	-7.28	-8.21	-8.26	-7.13
Commercial LFs	-	-	-	-	232.14
Maturity Props	-	-	-	-	41.32
Prior on B_0	10.65	10.51	10.38	10.69	10.62
Prior on selectivity	-	-	-	-	0
Prior on maturity	-	-	-	-	0
prior on *q* Early	-10.41	-10.26	-10.24	-10.1	-10.26
prior on *q* Late	-9.78	-8.78	-9.6	-9.25	-9.81
Catch penalty	0	0	0	0	0
Estimable parameters					
B_0	42 112	36 661	32 284	43 699	41 197
Vulnerability A_{50}	42.1*	42.1*	42.1*	42.1*	44.6
Vulnerability A_{to95}	16.0*	16.0*	16.0*	16.0*	16.3
Maturity A_{50}	39.6*	39.6*	39.6*	39.6*	39.6
Maturity A_{to95}	15.4*	15.4*	15.4*	15.4*	14.1
q CPUE early	3.02E-05	3.51E-05	3.58E-05	4.12E-05	3.49E-05
q CPUE late	5.64E-05	1.54E-04	6.74E-05	9.60E-05	5.48E-05
Derived parameters					
B_{2009}	5 980	2 228	3 652	3 157	7 362
$\%B_0$	14.2	6.1	11.3	7.2	17.9
V_0	39 684	34 547	30 423	41 179	35 855
V_{2009}	4 816	1 657	2 877	2 376	4 806
V_{2009}/B_{2009}	0.81	0.74	0.79	0.75	0.65
$\%V_0$	12.1	4.8	9.5	5.8	13.4

Table 7 (cont.): Sensitivity run data inputs, with MPD estimates of likelihoods, parameter estimates, and derived quantities. The prefix *B* refers to mature biomass, and *V* to vulnerably biomass. * indicates a fixed parameter. *M* was fixed in all runs.

	S11	S12	S13
Data inputs			
Catches + over-runs	x	x	x
Catches + no over-runs	-	-	-
Catches + double over-runs	-	-	-
CPUE early	x	x	-
CPUE late target	x	x	-
CPUE late non-target	-	-	-
CPUE combined models	-	-	-
LFs	x	x	x
LFs truncated at 58cm	-	-	-
Props. Mature	-	-	-
*M**	0.027	0.06	0.034
Likelihoods			
Total	264.41	249.77	288.65
CPUE early	-4.87	-4.91	-
CPUE late	-7.89	-4.37	-
Commercial LFs	244.05	227.82	235.89
Maturity Props	43.05	40.51	42.10
Prior on B_0	10.69	10.65	10.66
Prior on selectivity	0	0	0
Prior on maturity	0	0	0
prior on q Early	-10.57	-10.04	-
prior on q Late	-10.05	-9.88	-
Catch penalty	0	0	0
Estimable parameters			
B_0	43 915	42 221	42 750
Vulnerability A_{50}	38.7	48.6	41.6
Vulnerability A_{to95}	15.4	15.7	16.0
Maturity A_{50}	39.5	39.9	39.6
Maturity A_{to95}	17.6	12.4	15.8
q CPUE early	2.56E-05	4.35E-05	-
q CPUE late	4.30E-05	5.12E-05	-
Derived parameters			
B_{2009}	4 834	14 893	6 587
$\%B_0$	11.0	35.3	15.4
V_0	44 576	28 987	40 772
V_{2009}	4 878	6 566	5 562
V_{2009}/B_{2009}	1.01	0.44	0.84
$\%V_0$	10.9	22.7	13.6

3.2 Final model runs

The key rationale behind the choice of final model runs by the Ministry of Fisheries Deepwater Fisheries Assessment Working Group was as follows:

- Whilst the length frequency distributions could contain a biomass signal (through depletion of the right hand side), the primary biomass information was provided by the CPUE indices. A two-step approach was used to ensure that the biomass signal from the CPUE was not dominated by that from the length frequency data, which might be biased through uncertainties in growth, vulnerability, and sampling. In the first step, all observation data were included in the model and vulnerability and maturity estimated from MCMC runs. In the second step, these estimates of maturity and vulnerability were fixed, and the length frequency and maturity observations discarded, so that the final model runs used CPUE as the only biomass index.

- The preliminary runs were sensitive to the assumed value of *M*. The available estimate of *M* was considered uncertain as it was likely to be biased because of the bias in ageing (Section 2.3). The Deepwater Fisheries Assessment Working Group therefore agreed to a base case having *M* set at 0.04, and sensitivity runs with *M* set one and a half times greater (0.06) and lower (0.027) than this value. The sensitivity of the model to assumed growth parameters, which would also be influenced by the bias in ageing, was not investigated. This was because the ageing bias was only for ages over 60 years, and at these ages fish length was close to the asymptotic length: fish length at 60 years was about 90% of the asymptotic length. Therefore the bias in growth parameter estimate caused by the ageing bias would be relatively low.

- For runs assuming an *M* of 0.04 and 0.06 the vulnerability ogive was set to be the same as the maturity ogive, because independently estimating maturity and vulnerability ogives resulted in cryptic biomass. The Deepwater Fisheries Assessment Working Group considered that it was not likely that the vulnerable biomass was much less than the mature biomass, and agreed that the age of vulnerability should be fixed to the age at maturity. Assuming cryptic biomass without clear evidence would also not be consistent with the precautionary approach. A precedent for this vulnerability to maturity assumption was set in previous orange roughy and oreo stock assessments (Ministry of Fisheries Science Group 2008). The issue of cryptic biomass is considered further in the discussion of this report (Section 4). Because of the limited spatial extent of the fisheries the possibility of cryptic biomass could not be entirely discounted, therefore in order to illustrate the result a final model run was included for *M*=0.04 where maturity and vulnerability were estimated separately.

Four final model runs were therefore presented in the Ministry of Fisheries Working Group Report, two with vulnerability assumed to be the same as maturity and *M* assumed to be either 0.06 or 0.04, and two with vulnerability and maturity fitted as separate ogives and *M* assumed to be 0.04 or 0.027 (Table 8). The two-step approach meant that 8 model runs were actually completed (Table 9).

Table 8: Final model runs accepted for the Ministry of Fisheries Working Group Report.

Run name	*M*	Vulnerability
M0.04	0.04	Equal to maturity
M0.04 vul&mat	0.04	Separate
M0.027	0.027	Separate
M0.06	0.06	Equal to maturity

Table 9: MPD and MCMC estimates for the final model runs. Model runs presented in the Deepwater Fisheries Assessment Working Group Report are indicated in bold (see Table 6). The prefix *B* refers to mature biomass, and *V* to vulnerably biomass. * indicates a fixed parameter. *M* was fixed in all runs.

	M0.06 base			M0.06 vul&mat		
	MPD	MCMC		MPD	MCMC	
Data inputs						
Catches + over-runs	x	x		x	x	
Catches + no over-runs	–	–		–	–	
Catches + double over-runs	–	–		–	–	
CPUE early	x	x		x	x	
CPUE late target	x	x		x	x	
LFs	x	x		–	–	
Props. Mature	x	x		–	–	
M	0.06*	0.06*		0.06*	0.06*	
Likelihoods						
Total	249.77	–		-18.92	–	
CPUE early	-4.91	–		-5.40	–	
CPUE late	-4.37	–		-5.18	–	
Commercial LFs	227.82	–		–	–	
Maturity Props	40.51	–		–	–	
Prior on B_0	10.65	–		10.45	–	
Prior on selectivity	0	–		–	–	
Prior on maturity	0	–		–	–	
prior on q Early	-10.04	–		-9.58	–	
prior on q Late	-9.88	–		-9.21	–	
Catch penalty	0	–		0	–	
Estimable parameters						
B_0	42 221	44 921	(37 529 – 60 930)	34 380	47471	(32 326 – 114 482)
Vulnerability A_{50}	48.6	48.1	(41.0 - 54.3)	48.1*	48.1*	
Vulnerability A_{to95}	15.7	15.9	(12.6 - 19.2)	15.9*	15.9*	
Maturity A_{50}	39.9	39.8	(37.4 - 42.0)	39.8*	39.8*	
Maturity A_{to95}	12.4	13.9	(8.4 - 20.9)	13.9*	13.9*	
q CPUE early	4.35E-05	–		6.93E-05	–	
q CPUE late	5.12E-05	–		1.00E-04	–	
Derived parameters						
B_{2009}	14 893	17 660	(10 309 – 33 834)	8 433	20 042	(6 847 – 86 151)
%B_0	35.3	39.6	(27.4 - 55.8)	24.5	42.2	(21.2 - 75.3)
V_0	28 987	31 013	(23651 - 51512)	23 813	32 880	(22 390 – 79 295)
V_{2009}	6 566	8 113	(3 903 – 24 882)	3 245	9 625	(2 523 – 53 782)
V_{2009}/B_{2009}	0.44	0.47	0.24 - 0.87)	0.38	0.48	(0.37 - 0.62)
%V_0	22.7	26.2	(16.0 - 48.5)	13.6	29.3	(11.3 - 67.8)

Table 9 (cont.): MPD and MCMC estimates for the final model runs. Model runs presented in the Deepwater Fisheries Assessment Working Group Report are indicated in bold (see Table 6). The prefix *B* refers to mature biomass, and *V* to vulnerably biomass. * indicates a fixed parameter. *M* was fixed in all runs.

	M0.06			M0.04 base		
	MPD	MCMC		MPD	MCMC	
Data inputs						
Catches + over-runs	x	x		x	x	
Catches + no over-runs	–	–		–	–	
Catches + double over-runs	–	–		–	–	
CPUE early	x	x		x	x	
CPUE late target	x	x		x	x	
LFs	–	–		x	x	
Props. Mature	–	–		x	x	
M	0.06*	0.06*		0.04*	0.04*	
Likelihoods						
Total	-20.43	–		251.85	–	
CPUE early	-5.45	–		-5.04	–	
CPUE late	-6.58	–		-7.13	–	
Commercial LFs	–	–		232.14	–	
Maturity Props	–	–		41.32	–	
Prior on B_0	10.14	–		10.63	–	
Prior on selectivity	–	–		0	–	
Prior on maturity	–	–		0	–	
prior on q Early	-9.57	–		-10.26	–	
prior on q Late	-8.98	–		-9.81	–	
Catch penalty	0	–		0	–	
Estimable parameters						
B_0	25 313	33 828	(25 468 – 110 650)	41 197	42 348	(38 534 – 49 908)
Vulnerability A_{50}	39.8*	39.8*		44.6	44.6	(38.0 - 52.4)
Vulnerability A_{to95}	13.9*	13.9*		16.3	16.7	(12.0 - 21.8)
Maturity A_{50}	39.8*	39.8*		39.6	39.5	(37.1 - 41.7)
Maturity A_{to95}	13.9*	13.9*		14.1	15.6	(9.7 - 23.4)
q CPUE early	7.01E-05	–		3.49E-05	–	
q CPUE late	1.26E-04	–		5.48E-05	–	
Derived parameters						
B_{2009}	2 362	8 197	(2 440 – 82 843)	7 362	8 673	(5 149 – 15 913)
$\%B_0$	9.3	24.2	(9.6 - 74.9)	17.9	20.4	(13.2 - 31.7)
V_0	–	–		35 855	36 549	(29 006 – 47 623)
V_{2009}	–	–		4 806	5 380	(2 454 – 14 106)
V_{2009}/B_{2009}	–	–		0.65	0.64	(0.32 - 1.09)
$\%V_0$	–	–		13.4	14.7	(8.1 - 29.2)

Table 9 (cont.): MPD and MCMC estimates for the final model runs. Model runs presented in the Deepwater Fisheries Assessment Working Group Report are indicated in bold (see Table 6). The prefix *B* refers to mature biomass, and *V* to vulnerably biomass. * indicates a fixed parameter. *M* was fixed in all runs.

			M0.04			**M0.04 vul2mat**
	MPD	MCMC		MPD	MCMC	
Data inputs						
Catches + over-runs	x	x		x	x	
Catches + no over-runs	–	–		–	–	
Catches + double over-runs	–	–		–	–	
CPUE early	x	x		x	x	
CPUE late target	x	x		x	x	
LFs	–	–		–	–	
Props. Mature	–	–		–	–	
M	0.04*	0.04*		0.04*	0.04*	
Likelihoods						
Total	-22.26	–		-22.60	–	
CPUE early	-5.37	–		-5.31	–	
CPUE late	-8.37	–		-8.4	–	
Commercial LFs	–	–		–	–	
Maturity Props	–	–		–	–	
Prior on B_0	10.49	–		10.42	–	
Prior on selectivity	–	–		–	–	
Prior on maturity	–	–		–	–	
prior on q Early	-9.91	–		-10.05	–	
prior on q Late	-9.10	–		-9.26	–	
Catch penalty	0	–		0	–	
Estimable parameters						
B_0	35 786	40 782	(35 613 – 96 673)	33 400	36 817	(32 786 – 95 424)
Vulnerability A_{50}	44.6*	44.6*		39.5*	39.5*	
Vulnerability A_{to95}	16.7*	16.7*		15.6*	15.6*	
Maturity A_{50}	39.5*	39.5*		39.5*	39.5*	
Maturity A_{to95}	15.6*	15.6*		15.6*	15.6*	
q CPUE early	4.96E-05	–		4.32E-05	–	
q CPUE late	1.12E-04	–		9.54E-05	–	
Derived parameters						
B_{2009}	3 621	7 266	(3 514 – 61 346)	2 234	4 369	(1 928 – 60 361)
$\%B_0$	10.1	17.8	(9.9 - 63.5)	6.7	11.9	(5.9 - 63.3)
V_0	30 970	35 294	(30 820 – 83 663)	–	–	
V_{2009}	2 026	4 531	(1 959 – 49 903)	–	–	
V_{2009}/B_{2009}	0.56	0.62	(0.56 - 0.81)	–	–	
$\%V_0$	6.5	12.8	(6.4 - 59.6)	–	–	

Table 9 (cont.): MPD and MCMC estimates for the final model runs. Model runs presented in the Deepwater Fisheries Assessment Working Group Report are indicated in bold (see Table 6). The prefix *B* refers to mature biomass, and *V* to vulnerably biomass. * indicates a fixed parameter. *M* was fixed in all runs.

	M0.027 base			**M0.027**		
	MPD	MCMC		MPD	MCMC	
Data inputs						
Catches + over-runs	x	x		x	x	
Catches + no over-runs	–	–		–	–	
Catches + double over-runs	–	–		–	–	
CPUE early	x	x		x	x	
CPUE late target	x	x		x	x	
LFs	x	x		–	–	
Props. Mature	x	x		–	–	
M	0.027*	0.027*		0.027*	0.027*	
Likelihoods						
Total	264.41	–		-22.80	–	
CPUE early	-4.87	–		-4.97	–	
CPUE late	-7.89	–		-8.10	–	
Commercial LFs	244.05	–		–	–	
Maturity Props	43.05	–		–	–	
Prior on B_0	10.69	–		10.65	–	
Prior on selectivity	0	–		–	–	
Prior on maturity	0	–		–	–	
prior on q Early	-10.57	–		-10.50	–	
prior on q Late	-10.05	–		-9.89	–	
Catch penalty	0	–		0	–	
Estimable parameters						
B_0	43 915	44 597	(41 619 – 51 008)	42 260	45 141	(39 491 – 93 451)
Vulnerability A_{50}	38.7	38.4	(32.2 - 45.8)	38.4*	38.4*	
Vulnerability A_{to95}	15.4	15.7	(10.4 - 22.2)	15.7*	15.7*	
Maturity A_{50}	39.5	39.5	(26.5 - 42.0)	39.5*	39.5*	
Maturity A_{to95}	17.6	19.6	(13.2 - 29.7)	19.6*	19.6*	
q CPUE early	2.56E-05	–		2.74E-05	–	
q CPUE late	4.30E-05	–		5.09E-05	–	
Derived parameters						
B_{2009}	4 834	5 754	(3 314 – 11 633)	3 820	6 133	(1 996 – 52 932)
%B_0	11.0	12.8	(7.9 - 22.9)	9.0	13.6	(5.0 - 56.6)
V_0	44 576	45 296	(39 252 – 55 569)	43 114	46 053	(40 289 – 95 340)
V_{2009}	4 878	5 487	(2 836 – 13 730)	3 726	6 130	(1 827 – 54 113)
V_{2009}/B_{2009}	1.01	0.99	(0.60 - 1.36)	0.98	1	(0.92 - 1.02)
%V_0	10.9	12.2	(7.0 - 24.4)	8.6	13.3	(4.5 - 56.8)

Diagnostic checks indicated that all MCMC traces had converged. The MCMC biomass estimates had a skew towards higher values, with a low probability of a high biomass, and as a result the median estimates were higher than the MPD estimates (Appendix 1).When biomass was large the level of depletion was low. A high uncertainty in biomass estimates reflects the use of only relative biomass indices, with relatively high c.v.s; it is possible to put a straight line through the 95% confidence intervals of the early CPUE index, and very nearly a straight line through the late index. However, the fit to the CPUE indices when biomass was large resulted in strong trends in the CPUE residuals: there was no penalty in CASAL against these trends, although visually they indicated a poor fit.

The mean age at first maturity from the MCMC runs was similar to the MPDs, at 39.5–39.8 years. The mean age of vulnerability increased with increasing *M*, from 38.4 years at *M*=0.027 to 48.1 years at *M*=0.06. There was little visible difference in the fits of the vulnerable biomass to the CPUE indices (Figure 26).

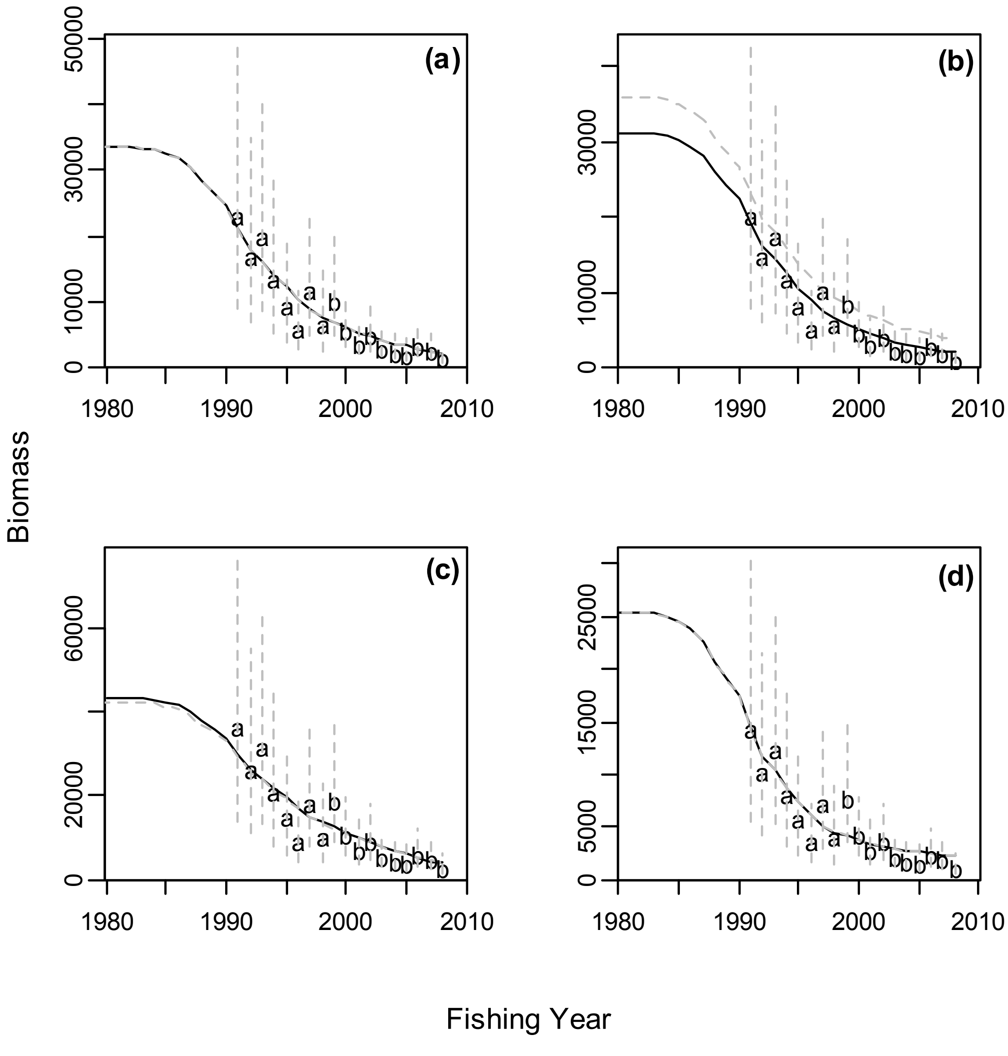

Figure 26: MPD fits of the vulnerable biomass (solid line) and mature biomass (broken grey line) to the early (a) and late (b) CPUE indices for final runs (a) M0.04, (b) M0.04 vul&mat, (c) M0.027, (d) M0.06. Vertical broken lines indicate the 95% confidence intervals for the CPUE indices.

The length frequency distributions were not fitted in the final model runs, but the predicted fit was used as a diagnostic. The fits of the M0.04 and M0.04 vul&mat runs to the observations were similar (Figures 27 and 28). Therefore, compared to the *M*=0.04 mat&sel run, the sel2mat run did not seem to be inconsistent with the length frequencies. The M0.027 and M0.06 runs gave a worse fit to the observations (Figures 29 and 30). For the M0.027 run the predicted fit tended to be to the right of the observations, and for the M0.06 run the predicted fit was to the left of the observations.

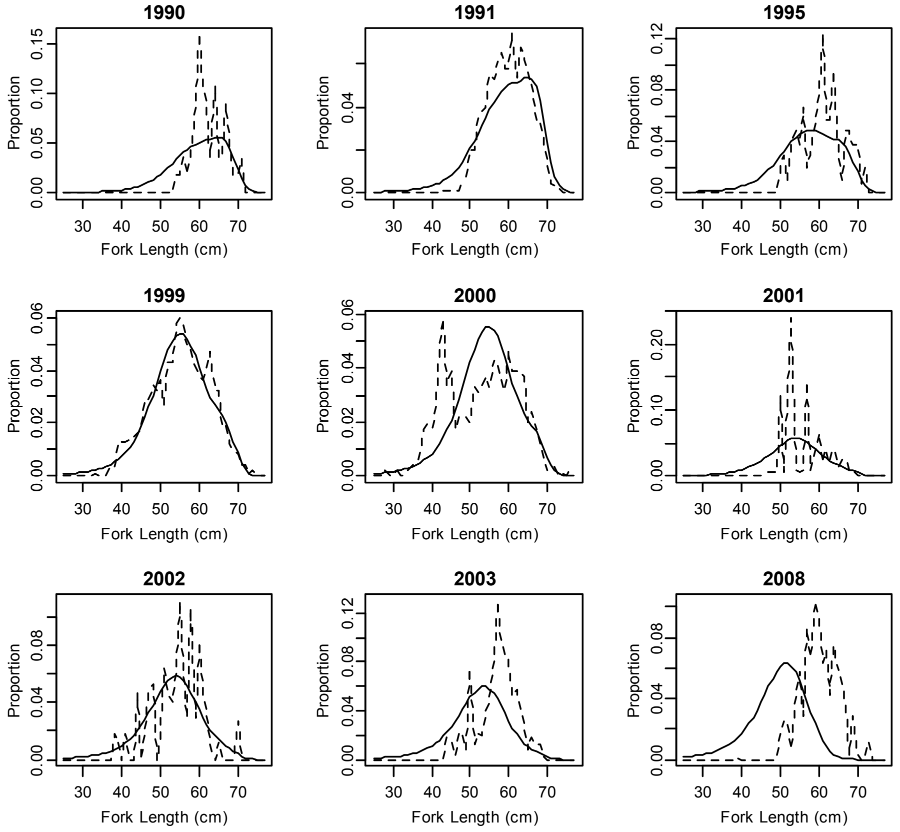

Figure 27: Comparison of the length frequency distribution from the model run M0.04 (solid line) and the estimated length frequency distributions from the fishery (broken lines, see Section 2.6).

The biomass estimates depended on the assumed *M*, with the M0.027 run resulting in a larger and less productive stock, and the M0.06 run in a smaller and more productive stock (Table 10, Figure 31). Estimates of current biomass were lowest in the 'base' M0.04 run. The M0.04 vul&mat run estimated cryptic spawning stock biomass such that only 86% and 62% of the mature biomass was vulnerable to the fishery at the virgin and 2009 biomass levels respectively. It is unclear whether cryptic biomass could occur for black cardinalfish, and it is possible that this result is an artefact caused by the model. Cryptic biomass was not estimated when maturity and selectivity were estimated separately and *M* was assumed to be 0.027, and in sensitivity runs the level of cryptic biomass was found to increase as *M* increased. The wide confidence intervals reflect the uncertainty in fitting the model only to relative biomass indices having relatively high c.v.s (Table 8).

Table 10: Summary of biomass estimates (medians rounded to the nearest 100 t, with 95% confidence intervals in parentheses) for the four model runs. p(B_{2009} >0.1 B_0 is the probability of the mature biomass in 2009 being greater than 10% of the virgin mature biomass (B_0) (and p(B_{2009} >0.2 B_0) greater than 20% B_0).

Run	B_0 (t)	%B_0	p(B_{2009} >0.2 B_0)	p(B_{2009} >0.1 B_0)
M0.04	36 800 (32 800 – 95 400)	11.9 (5.9 – 63.3)	0.30	0.59
M0.04 vul&mat	40 800 (35 600 – 96 700)	17.8 (9.9 – 63.5)	0.44	0.87
M0.027	45 100 (39 500 – 93 500)	13.6 (5.0 – 56.6)	0.31	0.68
M0.06	33 800 (25 500 – 110 700)	24.2 (9.6 – 74.9)	0.57	0.84

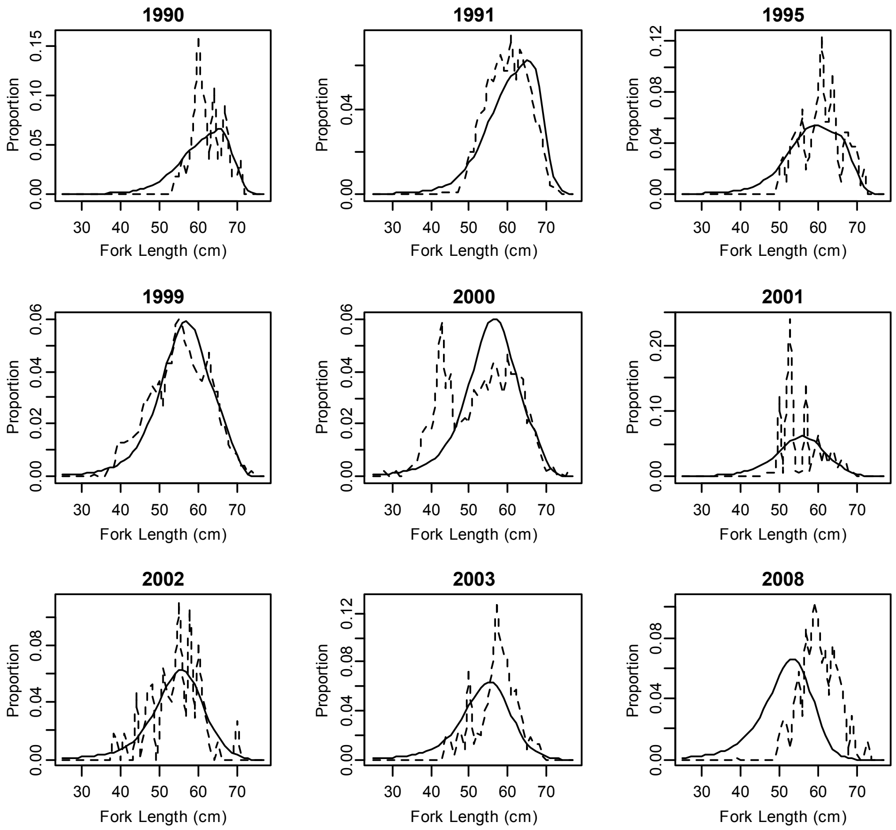

Figure 28: Comparison of the length frequency distribution from the model run M0.04 vul&mat (solid line) and the estimated length frequency distributions from the fishery (broken lines, see Section 2.6).

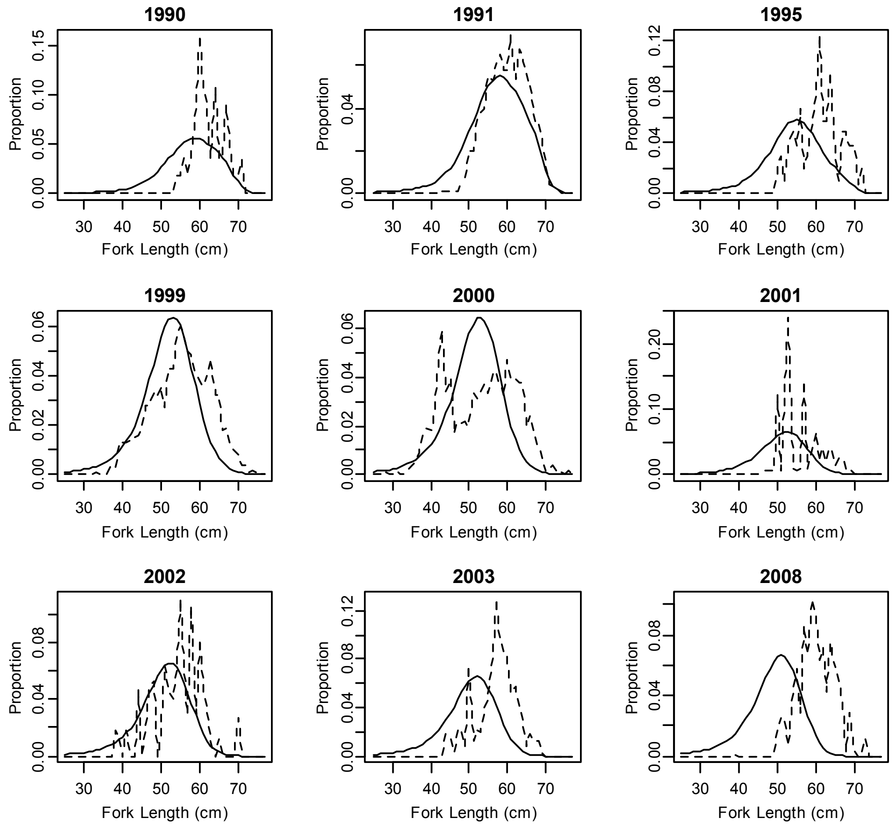

Figure 29: Comparison of the length frequency distribution from the model run M0.06 (solid line) and the estimated length frequency distributions from the fishery (broken lines, see Section 2.6).

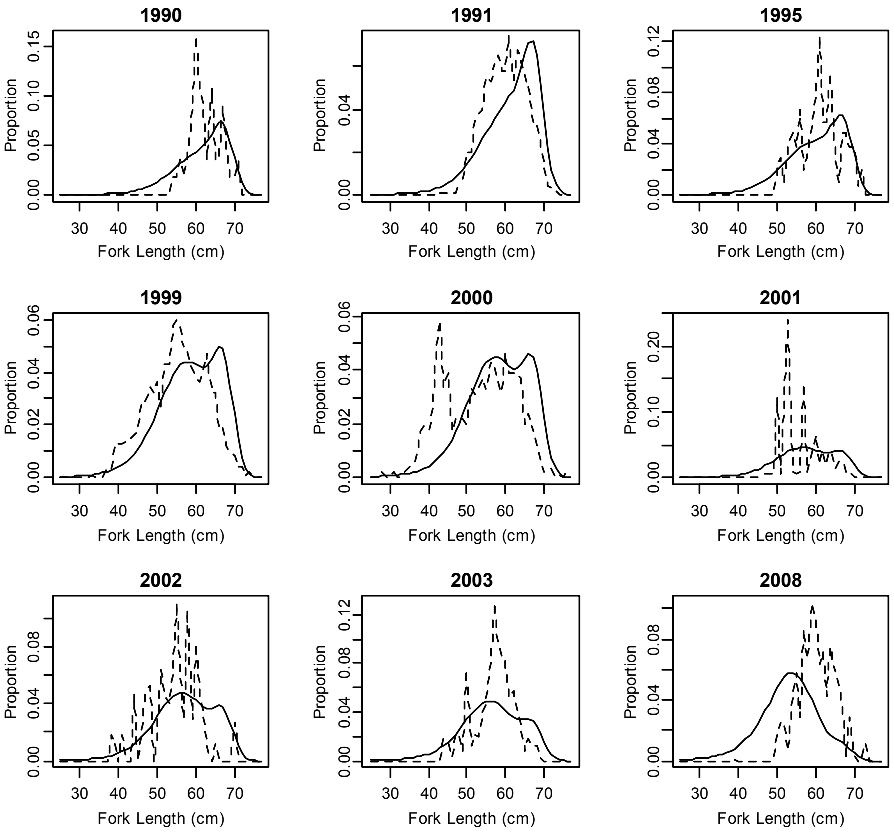

Figure 30: Comparison of the length frequency distribution from the model run M0.027 (solid line) and the estimated length frequency distributions from the fishery (broken lines, see Section 2.6).

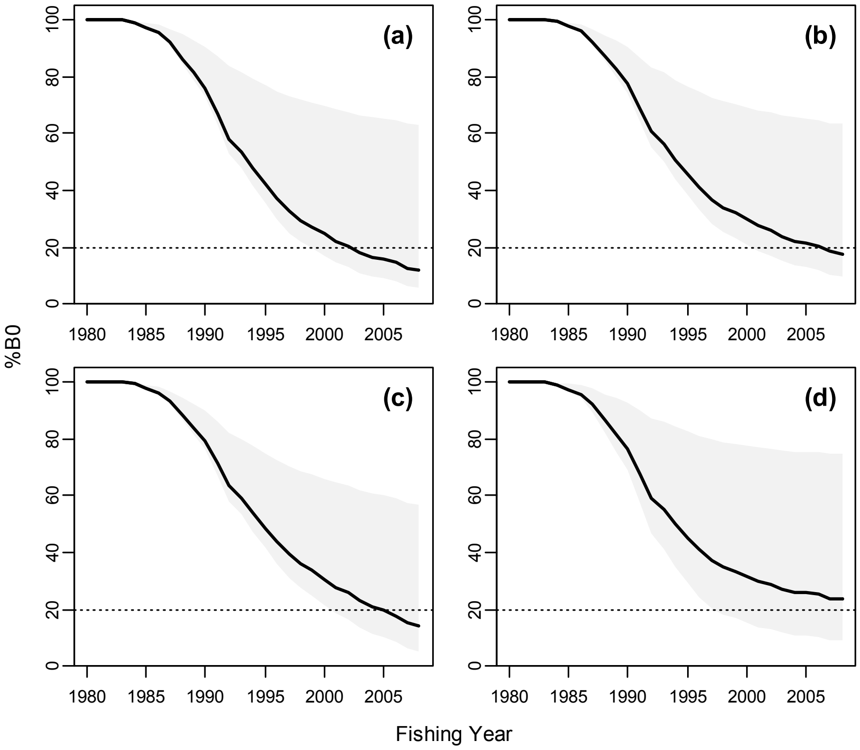

Figure 31: Estimated stock status (%B_0) trajectories (solid line) and 95% confidence intervals (shaded area) for the model runs (a) M0.04, (b) M0.04 vul&mat, (c) M0.027, (d) M0.06. The horizontal broken line indicates 20% B_0.

MCMCs were completed for the sensitivity runs to the assumed catch over-runs (Table 11). When over-runs were either assumed to be zero, or were doubled for the period before 1998–99 (before the TACC was introduced), the mature stock in 2009 was estimated to be slightly less depleted compared to the M0.04 run, at 13.5% (5.9 – 67.0%) B_0, and 12.2% (5.5 – 58.3%) B_0 respectively.

Table 11: MPD and MCMC estimates for the final model sensitivity runs. The prefix *B* refers to mature biomass, and *V* to vulnerably biomass. * indicates a fixed parameter. *M* was fixed in all runs. These runs are sensitivities of the run M0.04 (Table 7).

	M0.04 no over-runs			M0.04 double over-runs		
	MPD	MCMC		MPD	MCMC	
Data inputs						
Catches + over-runs	–	–		–	–	
Catches + no over-runs	x	x		–	–	
Catches + double over-runs	–	–		x	x	
CPUE early	x	x		x	x	
CPUE late target	x	x		x	x	
LFs	–	–		–	–	
Props. Mature	–	–		–	–	
M	0.04*	0.04*		0.04*	0.04*	
Likelihoods						
Total	-21.60	–		-21.83	–	
CPUE early	-5.01	–		-5.40	–	
CPUE late	-8.30	–		-7.89	–	
Commercial LFs	–	–		–	–	
Maturity Props	–	–		–	–	
Prior on B_0	10.24	–		10.55	–	
Prior on selectivity	–	–		–	–	
Prior on maturity	–	–		–	–	
prior on q Early	-10.11	–		-9.96	–	
prior on q Late	-9.42	–		-9.34	–	
Catch penalty	0	–		0	–	
Estimable parameters						
B_0	28 015	30 392	(26 352 – 85 635)	38 320	43 022	(37 790 – 97 228)
Vulnerability A_{50}	39.6*	39.6*		39.6*	39.6*	
Vulnerability A_{to95}	15.4*	15.4*		15.4*	15.4*	
Maturity A_{50}	39.6*	39.6*		39.6*	39.6*	
Maturity A_{to95}	15.4*	15.4*		15.4*	15.4*	
q CPUE early	4.08E-05	–		4.78E-05	–	
q CPUE late	8.08E-05	–		1.07E-04	–	
Derived parameters						
B_{2009}	2 467	4 114	(1 556 – 57 384)	2 340	5 243	(2 086 – 56 655)
$\%B_0$	8.8	13.5	(5.9 – 67.0)	6.1	12.2	(5.5 – 58.3)
V_0	–	–		–	–	
V_{2009}	–	–		–	–	
V_{2009}/B_{2009}	–	–		–	–	
$\%V_0$	–	–		–	–	

3.3 Model projections

Forward projections were carried out over a 5-year period using a range of constant-catch options. For each catch option, three measures of fishery performance were calculated. The first one, %B_0, is the median biomass in 2009 as a percentage of B_0. The second one, $P_{0.1}$, is the probability that the biomass at the end of the 5-year period is greater than 10% B_0. The third, $P_{0.2}$, is the probability that the biomass at the end of the 5-year period is greater than 20% B_0. At high future catches the biomass may be reduced to such a low level that the catch could not be taken (assumed to occur when the exploitation rate exceeds 0.9). This is indicated as P(no catch), the probability that the catch could not be taken.

All projections indicate that the biomass would increase for all catch levels at or below the 2008–09 catch (890 t), and would continue to decline at catch levels of 1200 t in all runs except *M*=0.06, where it would remain about the same (Table 12). In all runs the biomass would decline at catch levels equal to the current TACC (2 490 t), and there was a 38–71% probability the biomass would decline to a level where the catch could not be taken.

Table 12: Results from forward projections to 2013 for the model runs. Performance measures are as described above. Current (2007–08) values of %B_0 are shown for each run in parentheses next to the measure. 95% confidence intervals are shown for the %B_0 estimates in 2013. A catch of 180 t is roughly *F=M* for current biomass in the M0.04 run; 890 t is the 2007–08 catch; 2490 t is the 2008–09 TACC.

		Future catch (t)					
Run	Measure	0	180	530	890	1200	2490
M0.04	%B_0 (11.9)	17.6	16.5	14.3	12.6	10.2	5.2
		(8.5 – 67.4)	(7.0 – 65.0)	(5.3 – 63.9)	(3.6 – 62.7)	(2.9 – 62.6)	(2.7 – 56.2)
	$P_{0.1}$	0.89	0.81	0.70	0.60	0.51	0.30
	$P_{0.2}$	0.43	0.40	0.35	0.29	0.26	0.17
	P(no catch)	0	0	0	0	0	0.38
M0.04	%B_0 (17.8)	24.5	23.6	20.4	18.6	16.2	9.5
vul2mat		(14.1 – 68.8)	(12.9 – 67.8)	(10.2 – 65.5)	(8.0 – 63.4)	(6.5 – 61.7)	(5.5 – 57.8)
	$P_{0.1}$	1.00	1.00	0.94	0.86	0.78	0.47
	$P_{0.2}$	0.65	0.62	0.51	0.45	0.39	0.25
	P(no catch)	0	0	0	0	0	0.42
M0.027	%B_0 (13.6)	17.9	16.7	14.3	12.0	10.0	4.3
		(7.1 – 59.4)	(6.2 – 59.1)	(4.5 – 56.7)	(2.9 – 56.5)	(2.2 – 55.0)	(2.0 – 50.1)
	$P_{0.1}$	0.86	0.81	0.72	0.60	0.51	0.29
	$P_{0.2}$	0.43	0.40	0.33	0.29	0.25	0.16
	P(no catch)	0	0	0	0	0	0.41
M0.06	%B_0 (24.2)	33.6	31.4	29.8	26.3	24.6	17.4
		(13.0 – 80.2)	(12.5 – 79.2)	(10.6 – 77.5)	(8.3 – 77.2)	(6.7 – 75.7)	(4.8 – 71.2)
	$P_{0.1}$	0.98	0.67	0.93	0.85	0.83	0.65
	$P_{0.2}$	0.73	0.71	0.65	0.6	0.58	0.46
	P(no catch)	0	0	0	0	0	0.71

4. DISCUSSION

4.1 Stock status

This is the first time that a stock assessment for black cardinalfish had been attempted since 2000 (Field & Clark 2001). The main reason for the delay was the absence of an accepted biomass index. Black cardinalfish fisheries have not been valuable enough to support directed fishery independent biomass surveys, and the time series of better quality CPUE, after the entry of black cardinalfish into the QMS, was previously considered too short or unreliable to attempt an assessment.

All model runs indicated a substantially depleted stock, which was probably just above the current Ministry of Fisheries ‘hard’ limit of 10% B_0, and close to or below the ‘soft limit’ of 20% B_0. These limits are essentially arbitrary in relation to black cardinalfish, and it is not clear how they relate to the sustainability (or not) of the stock and catches.

The model was highly uncertain, for many reasons, but the results were nevertheless consistent with expectations of risk for this species. Black cardinalfish have been validated as long lived, slow growing, and late maturing, with a very low productivity. The CDL 2–4 stock has a distribution and depth overlap with the larger fisheries for orange roughy, alfonsino, and hoki, and black cardinalfish consequently have a history as a low value or unwanted bycatch in these fisheries. Since the introduction of the TACC in 1998–99, reported catches of black cardinalfish in CDL 2 have been 71% of those for the overlapping orange roughy stocks (CDL 2: 14 873 t; orange roughy East Cape and Mid-East Coast stocks combined: 20 873 t), with the black cardinalfish catches exceeding the orange roughy catches in 3 years (2001–02, 2002–03, and 2005–06) (Ministry of Fisheries Science Group 2008). The TACC for black cardinalfish has rarely, if ever, been restrictive, and in 2008–09 was about 50% higher than the TACC estimated to be sustainable for the Mid-East Coast orange roughy stock. Expert opinion suggested the black cardinalfish biomass on the east coast North Island was never as large as that of orange roughy. Based on this productivity and fishery information, we might classify black cardinalfish *a priori* as a species with a current high risk of over-exploitation.

4.2 Main uncertainties

Stock structure remains unknown for black cardinalfish. The proposed link between the east coast North Island and Chatham Rise seems sensible at present. A similar southerly ocean current links the Bay of Plenty (CDL 1) and the east coast North Island, so these areas could also be linked to some degree: the extended mesopelagic phase makes it unlikely that these areas have entirely closed populations. Phillips (2002) reported steep declines in commercial and research trawl CPUE from CDL 1, where the TACC was not being taken (only 25% caught), and concluded that “this fishery should be monitored carefully”. The degree of site fidelity of black cardinalfish is unknown, but the reports of highly mobile schools suggest a reasonable degree of mixing could take place. In the CDL 2–4 assessment, the commercial catches from CDL 3 and 4 were very small (1990–91 to 2007–08: 432 t for CDL 4; 2854 t for CDL 3; compared to 27 683 t for CDL 2), therefore the bias that an incorrect stock structure could introduce in this case is likely to be small.

The CPUE indices were spatially distinct, and whilst they covered a substantial proportion of the fishery catch, they covered only a small set of features, and a small proportion of the potential stock range. The CPUE may be an unbiased index of stock abundance if adult black cardinalfish live predominantly on and around these features, but if they exist outside these areas, then a bias may occur, and there is also a potential for the existence of spatially related cryptic biomass.

CPUE indices have been found to decline steeply in many deepwater trawl fisheries focused on features, and cryptic biomass has often been estimated by the stock assessment models (Ministry of Fisheries Science Group 2008). Catches are constant, so in order to fit a steep biomass decline the vulnerable biomass must be of a given size. If the vulnerable biomass is too small the decline is too fast, and vice versa. In the model, the size of the vulnerable biomass is determined by the age of vulnerability, and the virgin biomass and mean recruitment (determined by M). For a given virgin biomass, catch history, and vulnerability, and higher M increases the recruiting biomass (productivity), so increasing the vulnerable biomass, and decreasing the rate of biomass decline. In order to improve the fit to a steeply declining CPUE index, the model can then either modify (reduce in this case) the virgin biomass, or increase the age of vulnerability, both of which will serve to reduce the size of the vulnerable biomass. The correlation between the estimates of virgin biomass, *M*, and vulnerability was not fully investigated in this study, but the estimation of cryptic biomass for more productive stocks (in this case *M* of 0.034 or higher) suggested that the fit to the CPUE was best if both the virgin biomass was reduced *and* the age of vulnerability increased. One hypothesis is that there could be some real cryptic biomass for black cardinalfish, although it might not necessarily be related to age of vulnerability (e.g., it could be spatial); age of vulnerability is changed because the model has no other option. The estimation of cryptic biomass is problematic for fisheries management, and has been "solved" by fixing maturity to vulnerability (or vice versa), or by estimating a non-linear relationship between CPUE and abundance, or by excluding CPUE data points (Ministry of Fisheries Science Group 2008). Cryptic biomass might just be a model artefact, but it might be related to spatial patterns in the fishery and stock (Dunn 2008). Steep CPUE declines are common in deepwater fisheries, and need to be better understood.

Recruitment was assumed to be constant in the model, simply because there were no available observations to the contrary. Given the short duration of the fishery compared to fish longevity, the fishery could occur in a period of continued average, high, or low recruitment (Longhurst 2002). The catch projections must be considered especially uncertain as they are entirely dependent on the level of recruitment.

4.3 Suggested future research

- Consider developing fishery independent indices of biomass, or making absolute biomass estimates. The former might be derived from trawl surveys (albeit with potentially low catchability depending on their design), and the latter from acoustic surveys (which might be conducted from research and/or industry vessels).

- Estimate recruitment. Recruitment variability could be estimated from age frequency distributions. This would require work to improve the ageing, specifically to reduce the potential under-ageing older fish.

- Investigate stock status in the next largest fishery (CDL 1). Black cardinalfish are likely to be a high risk species in most areas (where orange roughy are almost always the preferred target species). Concerns about stock status in CDL 1 have already been raised (Philips 2002).

- Improve the estimates of catch over-runs. This might be achieved through an analysis of historical Ministry of Fisheries observer reports. Catch over-runs might also be scaled using effort rather than catch.

- Further evaluate the hypothesis of cryptic biomass. More extensive collection of length frequency data from research and commercial fishing would allow ontogenetic patterns in distribution, in relation to the fishery, to be investigated. Specifically, are there mature fish outside the fishery area?

- Improve knowledge of stock structure. Successful tagging exercises seem extremely unlikely for black cardinalfish. Analysis of otolith chemistry might reveal different chemical signatures from different areas, and be used to determine stock boundaries and mixing.

- CASAL might be modified to allow trends in residuals to be penalised. This could result in smaller (more realistic?) estimates of uncertainty from the MCMC runs.

5. ACKNOWLEDGMENTS

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APPENDIX 1

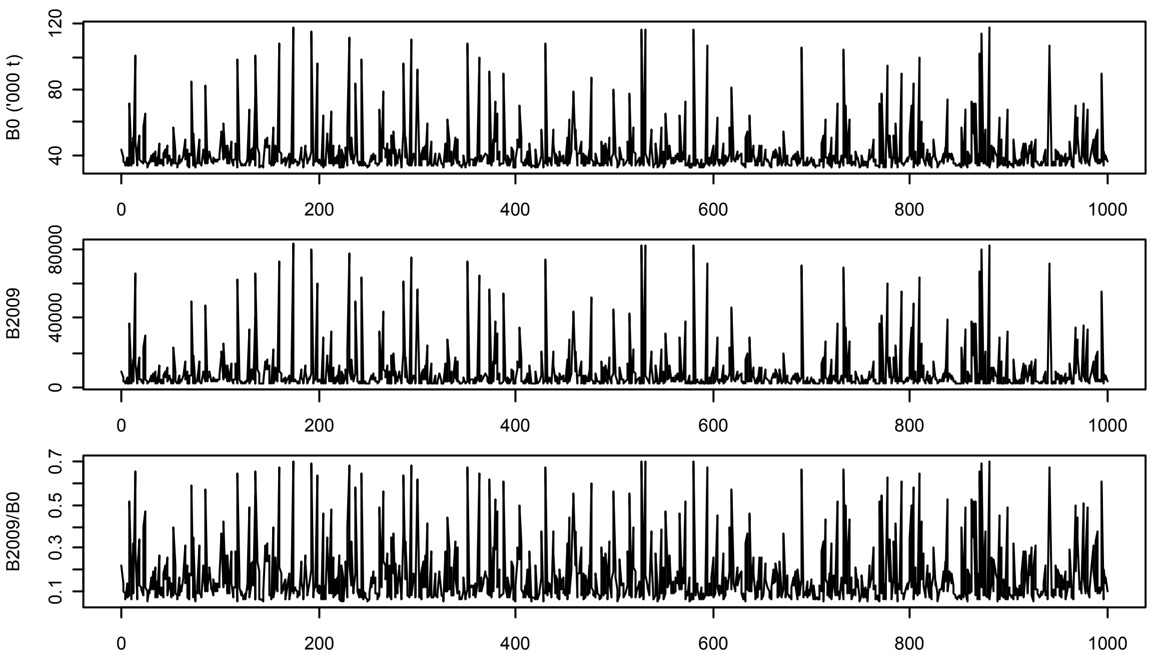

Figure A1: MCMC traces for the model run M0.04.

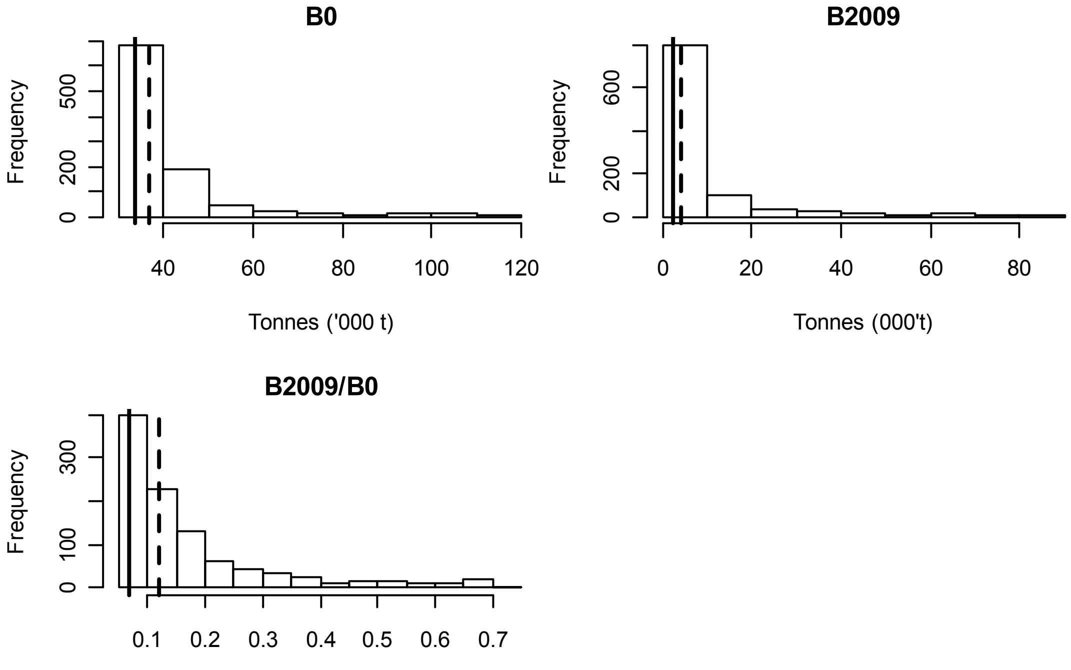

Figure A2: Estimated posterior distributions for parameters and derived quantities for the run M0.04, with the median shown as the broken vertical line, and the MPD estimate as the solid vertical line.

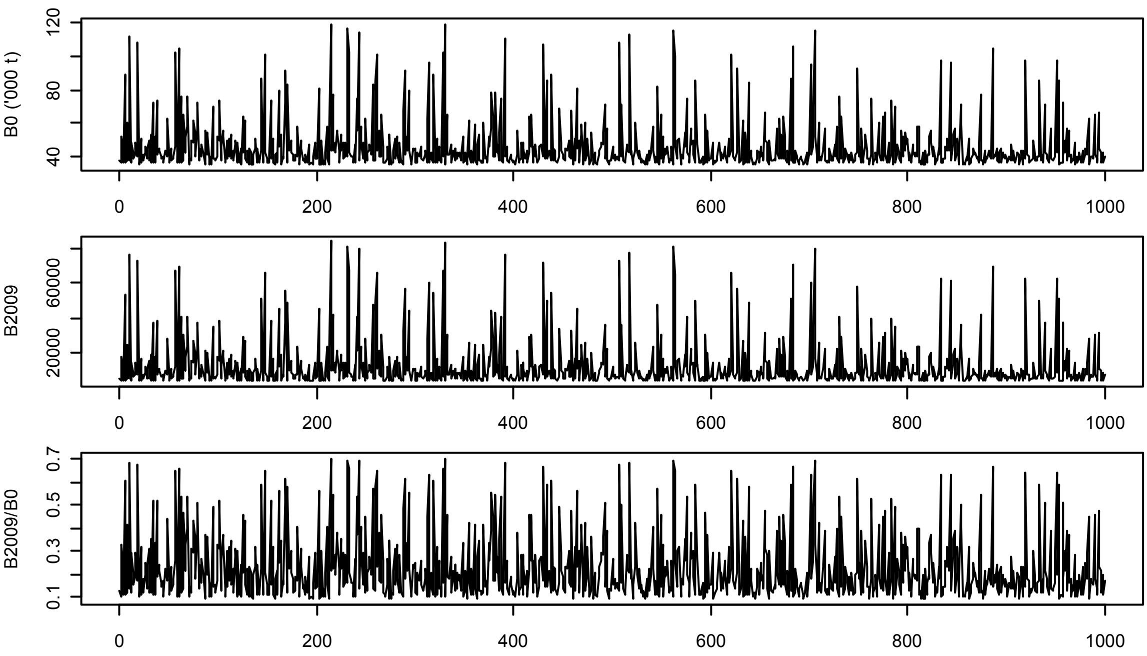

Figure A3: MCMC traces for the model run M0.04 vul&mat.

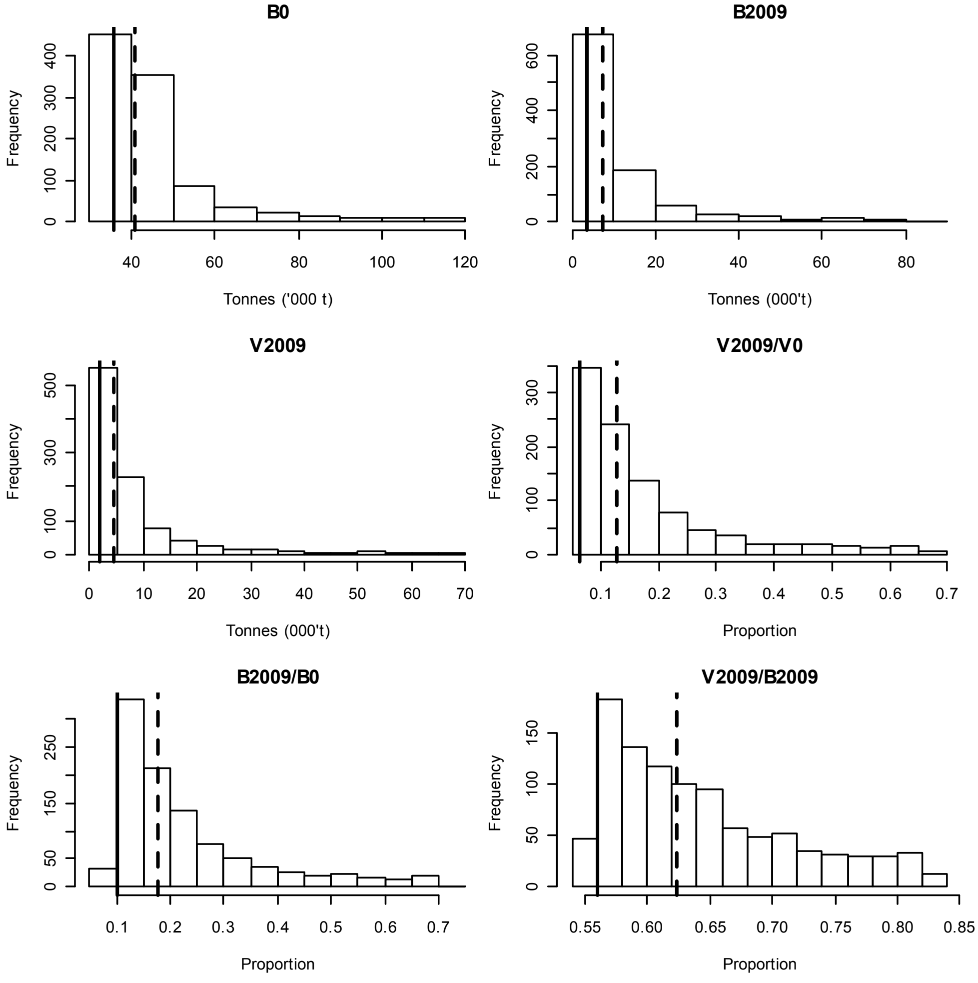

Figure A4: Estimated posterior distributions for parameters and derived quantities for the run M0.04 vul&mat, with the median shown as the broken vertical line, and the MPD estimate as the solid vertical line.

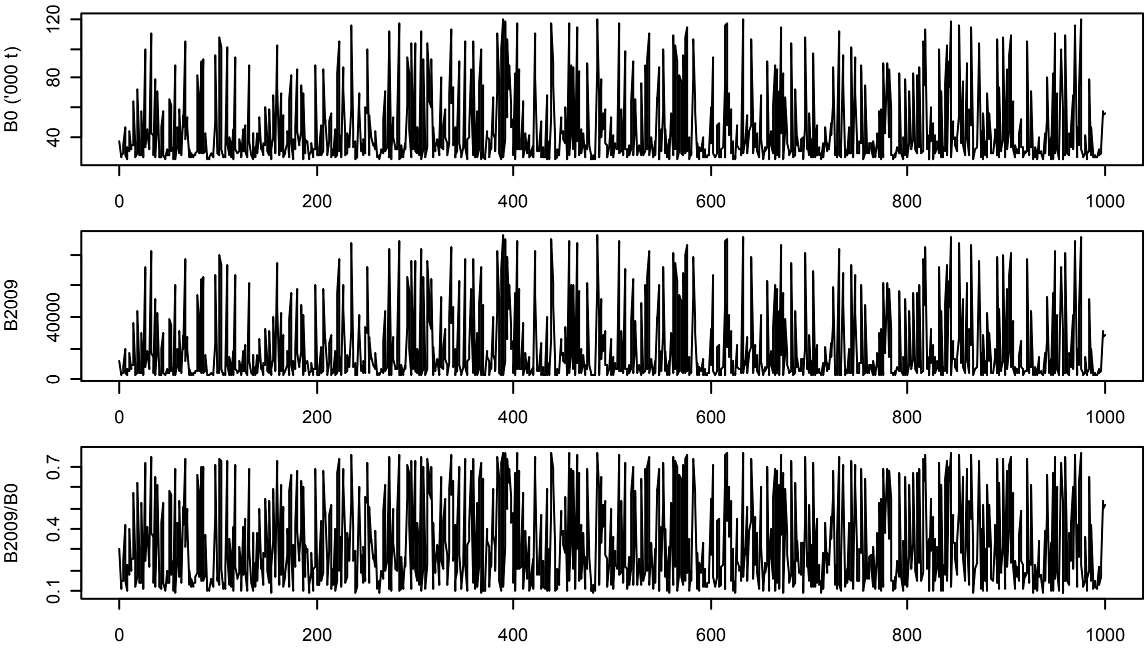

Figure A5: MCMC traces for the model run M0.06.

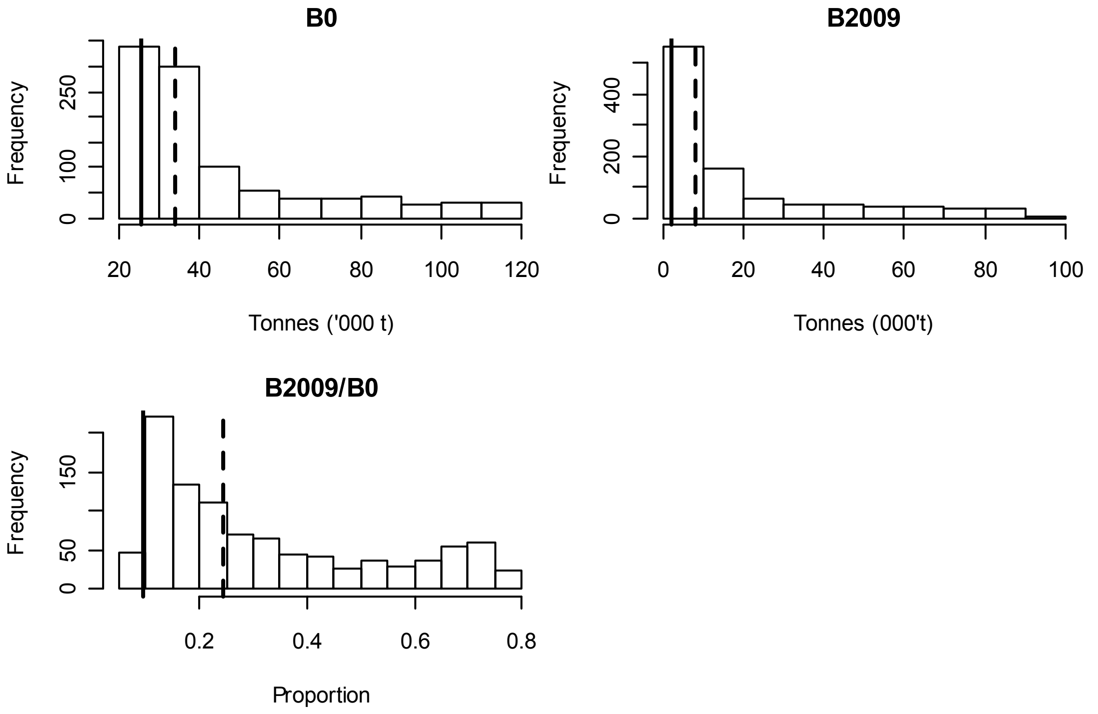

Figure A6: Estimated posterior distributions for parameters and derived quantities for the run M0.06, with the median shown as the broken vertical line, and the MPD estimate as the solid vertical line.

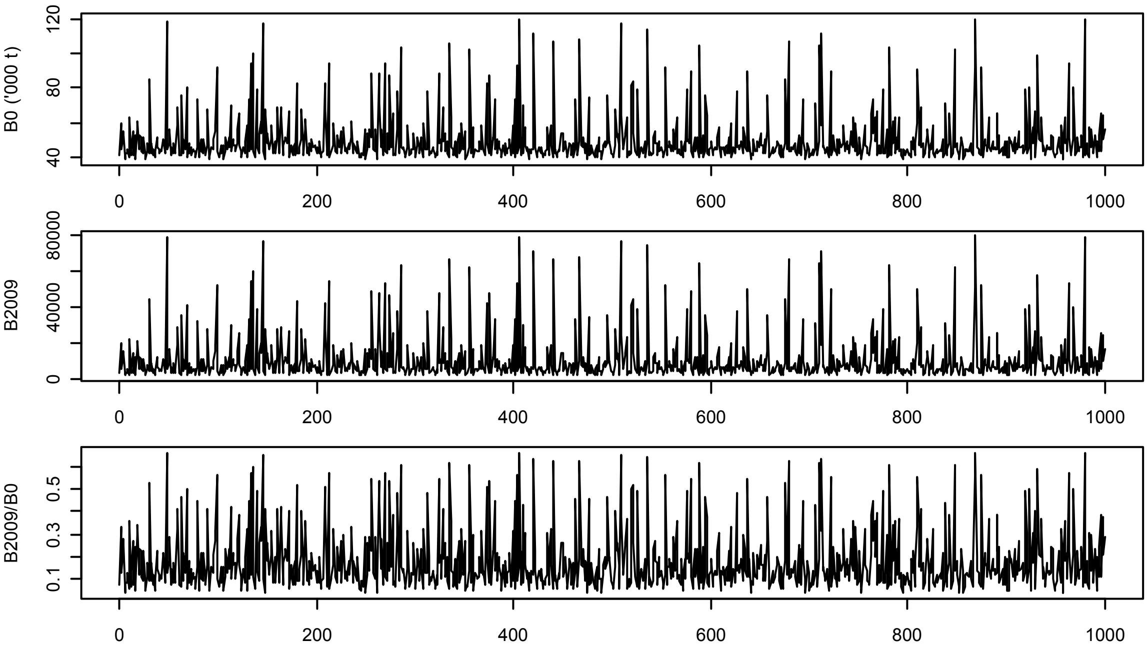

Figure A7: MCMC traces for the model run M0.027.

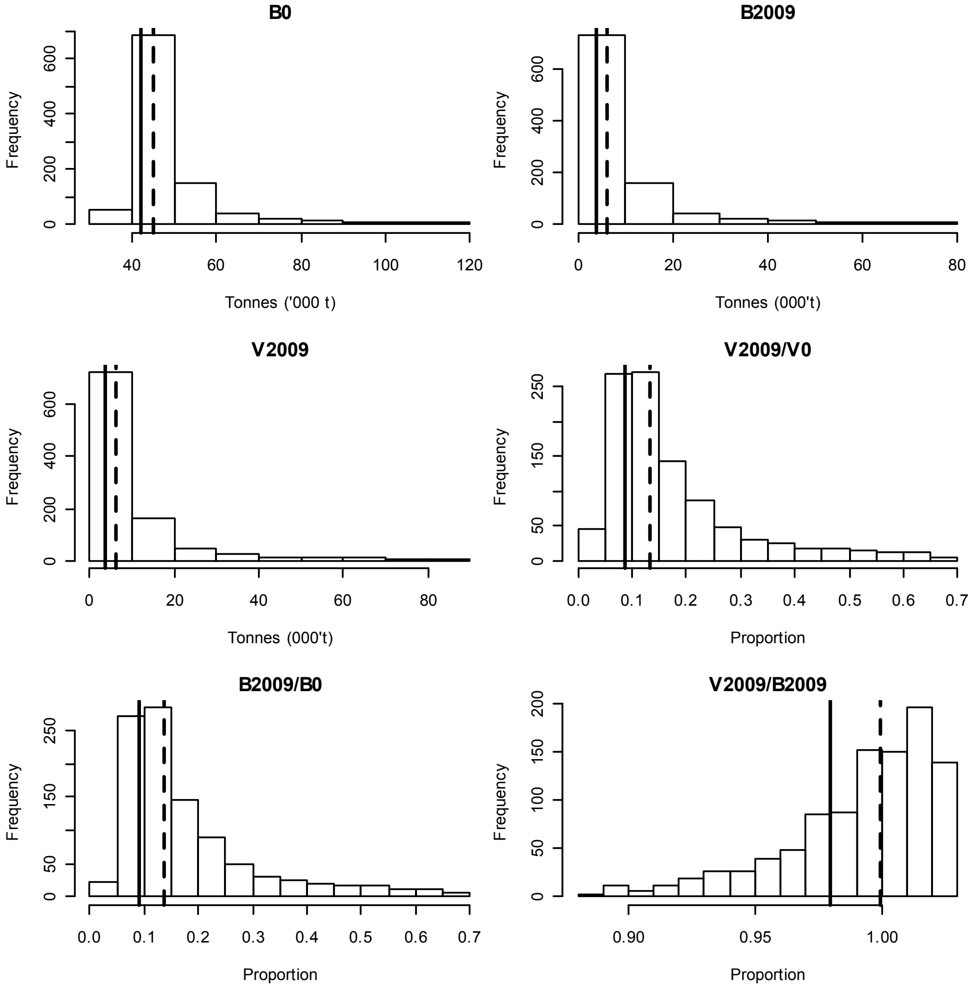

Figure A8: Estimated posterior distributions for parameters and derived quantities for the run M0.027, with the median shown as the broken vertical line, and the MPD estimate as the solid vertical line.