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Stock relationships of tarakihi off the east coast of mainland New Zealand and the feasibility of developing a statistical assessment of the corresponding tarakihi stock(s)

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EXECUTIVE SUMMARY

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A range of data sets were reviewed to develop a number of stock hypotheses for the assessment of tarakihi off the east coast of mainland New Zealand. The available data included historical age frequencies derived from research surveys, recent commercial age compositions, commercial catch and effort data, standardised CPUE indices and length frequency distributions from inshore trawl surveys. The review also summarises previous conclusions regarding the stock structure of tarakihi.

The recent data support the amalgamation of the Bay of Plenty and East Cape–Mahia fishery areas (Statistical Areas 008–013) into a single stock unit. The spatial domain of this stock unit may also extend further south to include the Wairarapa coast, although there is also some suggestion (from catch and CPUE data only) that fish in this area may migrate to spawn in the southern area of TAR 2. The limited data from the East Northland fishery indicate that tarakihi in this area (Statistical Areas 002–004) are relatively distinct from the other fishery areas along the east coast of mainland New Zealand.

Fishery trends in TAR 3 are generally consistent with the observations from the Bay of Plenty/TAR 2 fishery in terms of CPUE and age structure of the catch. These results are also consistent with the northward movement of tagged fish from the Kaikoura coast to the Wairarapa, East Cape and Bay of Plenty. However, comparative data are limited and, while there are strong similarities between TAR 2 and TAR 3, there is insufficient information to conclude that these areas constitute a single stock unit. Thus, the plausible stock hypotheses represent a continuum between two extremes 1) the TAR 2 (plus Bay of Plenty) and TAR 3 fisheries represent discrete stocks and 2) there is substantial mixing (possibly consisting of both northerly and southerly movements) of the fish between the two areas.

The report investigates the feasibility of conducting a robust assessment of the east coast tarakihi stock based on these two main hypotheses. Thus, three models were configured: 1) a *TAR2/BPLE* model encompassing the Statistical Areas 008, 009–016, 2) a *TAR3* model encompassing the Statistical Areas 017, 018, 020, 022 and 024, and 3) a *combined* model encompassing two separate regions equivalent to the *TAR2/BPLE* and *TAR3* model areas and movement between the two areas.

The three models were configured based on the available data specific to the spatial domain of the model. For all models, standardised CPUE indices from 1990–2010 provided the primary relative abundance indices. Recent age frequency data were available from 1–2 years of sampling the commercial catch from the main fisheries. A crucial model assumption was the relative selectivity of the older age classes by the commercial fisheries. For models that assumed full selectivity, the observed age compositions of the commercial catches were incompatible with the CPUE indices, recent catches and key biological parameters (specifically natural mortality). Reasonable fits to the various data sets were attained when the selectivity was parameterised to estimate lower selectivity of the older age classes. However, the resulting estimates of stock biomass were very poorly determined, particularly at the upper bound, suggesting that unrealistically high levels of stock biomass were possible.

Given the uncertainty associated with the key model assumptions, particularly related to fishery selectivity and the stock structure, it was concluded by the NINS WG that the range of models investigated were not suitable for the formulation of management advice for the tarakihi stocks along the east coast of New Zealand. It is considered unlikely that a more definitive stock assessment could be undertaken until a reasonable time-series (5–10 years) of age frequency data was available from the main commercial fisheries. These data would improve the model estimation of fishery selectivity as well as year class strengths. In addition, a range of other analyses and additional data would improve the current models and contribute towards increasing the understanding of tarakihi stock relationships.

A prioritised list of research recommendations to progress the assessment of tarakihi is presented.

1. INTRODUCTION

The distribution of tarakihi is continuous around coastal New Zealand within the 10–200 m depth range (Hurst et al. 2000). However, tarakihi catches are concentrated in seven main areas: i) off the east Northland coast (Statistical Areas 002–004, 6% of the total cumulative tarakihi catch from 1 October 2004 to 30 September 2010), ii) Bay of Plenty (008–010, 13%), iii) around East Cape (Areas 011–013, 23%), iv) Wairarapa and Cook Strait (Areas 014–016), v) off the east coast of the South Island (Areas 017–024, 23%), vi) off the west coast South Island (Areas 033–36, 10%), and vii) off the west coast of the North Island (041, 042, 045–047, 8%).

The stock structure of tarakihi was reviewed by Annala (1988) and Hanchet & Field (2001). Annala (1988) concluded that *"for stock assessment purposes, tarakihi around the North and South Islands can be considered as one stock"*. Limited additional data were available to enable Hanchet & Field (2001) to further investigate stock boundaries. They considered a number of alternative stock hypotheses but concluded that there was insufficient information to adopt a specific stock structure. Nonetheless, Hanchet & Field (2001) recognised that distinct spawning and nursery areas existed around the North and South Islands and that tagging data indicated a *"link between the east coast South Island and the other areas is also consistent with the extensive movements of tagged fish, most of which have been to the north"*. This assertion has been subsequently supported by the Northern Inshore Working Group (NINS WG) which concluded that "*due to close similarity in CPUE trends between the BT(TAR2) and SN(TAR3) indices, results of historical tagging work and industry views on stock structure, all indicate that TAR caught off Kaikoura, north of Point Gibson, are probably related to the TAR 2 stock, and not the TAR 3 stock"* (Ministry of Fisheries 2011).

However, in the absence of sufficient information to resolve tarakihi stock boundaries, Hanchet & Field (2001) recommended that *"assessments of the main Fishstocks (or sub-Fishstocks) is probably the most practical way forward, and is probably the most realistic, on the basis that once tarakihi have recruited to a particular ground they probably remain there*".

On that basis, a stock assessment was developed for TAR 7 (Ministry of Fisheries 2011). Tarakihi are known to spawn off the southern west coast South Island (WCSI) and the results from the time series of inshore trawl surveys indicate that Tasman Bay/Golden Bay represents the primary nursery ground for the stock. For management purposes the TAR 7 fishstock, principally WCSI and Tasman Bay/Golden Bay, represents a relatively discrete stock unit.

Potential stock relationships and stock boundaries are less clear for the other areas of coastal waters around mainland New Zealand. Recent CPUE analyses of the main tarakihi fisheries revealed similar trends in the annual indices from the Bay of Plenty, TAR 2 and TAR 3 (Starr & Kendrick 2012) that may suggest a degree of linkage between the tarakihi fisheries in these areas. Conversely, the CPUE indices derived for the fisheries off the west coast of the North Island (TAR 1W) and east Northland (TAR 1 EN) reveal unique trends in CPUE. On that basis, these areas were considered to be somewhat independent of the east coast tarakihi fisheries.

The primary objective of this study is to further refine the stock boundaries of tarakihi off the east coast of mainland New Zealand through the analysis and review of recent data sets, including:

i. Fishery characterisations - including fine scale spatial information available since the implementation of the new form types by the Ministry of Fisheries) (Starr & Kendrick 2012).
ii. Age composition of tarakihi catches (available for TAR 1, 2, 3).
iii. Size composition (and, where it exists, age structure) and spatial distribution of catches from trawl surveys.
iv. Returns from tarakihi tagged during WCSI trawl surveys.
v. Results from previous studies on the biology and movement of tarakihi.

Characterisations of the relevant tarakihi fisheries are documented in Starr & Kendrick (2012). These analyses form the basis for the CPUE indices derived for the main east coast tarakihi fisheries and include data from 1989/90 to 2010/11.

The primary goal of this project (TAR 2011–02) was to develop a stock assessment model for the tarakihi stock or stocks off the east coast of mainland New Zealand. Thus, conclusions regarding the spatial domain and structure of the stock(s) were intended to inform the configuration of the proposed assessment of the tarakihi stock(s) in the study area. For the purpose of the study, the east coast region was defined to encompass the areas of main tarakihi catch from North Cape to the Otago Peninsula (Statistical Areas 002–004, 008–018, 020, 022 and 024), including the TAR 2 and TAR 3 fishstocks and the eastern component of TAR 1. While tarakihi catches from Statistical Area 017 are predominantly reported under the TAR 7 fishstock, the location of the fishery is distinct from the other TAR 7 fisheries and catches from this area are closely associated with the other eastern fisheries.

This report investigates the feasibility of conducting a robust assessment of the east coast tarakihi stock, including the determination of reference biomass, current stock status and yields. The review examines the utility of the available fishery data sets in a stock assessment framework.

2. STOCK STRUCTURE

The review of the stock structure of tarakihi off the east coast of mainland New Zealand involved an appraisal of a range of alternative stock hypotheses using available fisheries and research data. This review was primarily qualitative in nature, although a modelling approach was investigated to quantitatively evaluate alternative stock hypotheses using key data sets (recent catch and CPUE data).

Initial stock hypotheses were based on the previous review by Hanchet & Field (2001), information regarding the location of tarakihi spawning grounds and the results of the recent tarakihi fishery characterisations (Starr & Kendrick 2012). Most data were available at the spatial resolution of the Ministry of Fisheries General Statistical Areas and the individual stock areas were defined accordingly.

Initially, five alternative stock hypotheses were formulated:

1. Discrete stocks which conform to the main fishery areas along the east coast of mainland New Zealand (east Northland, Bay of Plenty, East Cape, Wairarapa, Pegasus Bay and Canterbury Bight) with corresponding primary spawning areas. Limited movement of tarakihi occurs between adjacent areas.
2. Broader geographic groupings of the distinct tarakihi stocks, each with a primary spawning area and corresponding pre- and post-spawning migrations. Potential groupings include East Northland–Bay of Plenty, Bay of Plenty–East Cape, East Cape–Wairarapa, and Pegasus Bay–Canterbury Bight.
3. Separate stock units off the east coasts of the North Island and South Island. These two stocks share a common nursery ground off the ECSI. At the onset of sexual maturity, a proportion of the fish migrate northward to recruit to the North Island stock unit. The extent of natal fidelity to the two stock units may range from no fidelity (single biological stock) to complete fidelity (two biological stocks).
4. Single stock off the east coasts of North Island and South Island with linkages to other fishery areas around mainland New Zealand (e.g. WCNI). Fish may recruit to these areas from the nursery area off the ECSI. Once recruited, adult fish tend to remain in the fishery areas.
5. Single stock around mainland New Zealand with recruitment to the ECSI area sourced from spawning occurring off the east coasts of the South and North Islands and from other areas (primarily WCSI). Fish that have recruited to the east coast nursery areas may subsequently move to other areas along the east coast of North Island and South Island or to other areas.

The objectives of the current study were primarily focussed on an evaluation of stock hypotheses 1–4. Hypothesis 5 was outside the scope of the project objectives which were confined to the east coasts of the North and South Islands.

The primary data sets available for inclusion in the review included Ministry of Fisheries compulsory catch and effort data, relative abundance and length frequency data from fishery independent trawl surveys, standardised CPUE indices from the main fisheries, historical age frequency data from research trawl surveys and recent age composition data from commercial catches. Details of the individual data sets are described in the following sections.

2.1 Catch distribution

Fishery catch and effort data from the tarakihi fishery were provided by the Ministry for Primary Industries from the *warehou* database (extract 8234; documented in Ministry of Fisheries 2010). The data extract included all fishing activity and associated catch from any fishing trip that reported catching or landing tarakihi and/or targeting tarakihi off the east coast of mainland New Zealand (Statistical Areas 001–018, 020, 022 and 024) during the 1989/90–2009/10 fishing years.

These data were applied to provide a brief description of the key tarakihi fisheries and summarise the spatio-temporal trends in these fisheries. These analyses complement and, to some extent, replicate the analyses presented in the recent fishery characterisations (Starr & Kendrick 2012); however, the characterisation report included more detailed analyses and summaries.

For the purposes of this analysis, the spatial domain of the east coast tarakihi fishery was defined by the area from North Cape to Oamaru (Statistical Areas 001 to 022, excluding 019). The inshore trawl fisheries within this area accounted for approximately 90% of the total annual tarakihi catch from 2004/05 to 2009/10. Of the trawl catch, 80–90% of the tarakihi catch was taken by trawls declared to be targeting tarakihi. The remainder of the tarakihi trawl catch was taken from a range of other target trawl fisheries which varied among the statistical areas (blue warehou, red cod and barracouta in the southern areas; snapper and trevally in the northern areas and red gurnard and gemfish in both areas).

For each statistical area, the monthly tarakihi catch distribution from the target and non-target trawl fisheries was summarised for 1989/90 to 2009/10 (Figure 1 and Figure 2). There are a number of persistent spatio-temporal trends in the distribution of the target trawl catch (Figure 1). Catches off East Cape (Statistical Area 011) and in the Bay of Plenty (008, 009 and 010) peaked during March–May, although there is a tendency for the peak in catch to occur later in the western Bay of Plenty. Target trawl catches in the Bay of Plenty were low during July–September (Figure 1).

Overall, non-target trawl catches in the Bay of Plenty and East Cape were low and do not reveal strong seasonal patterns, with the exception of high catches in the western Bay of Plenty (008 and 009) during May, principally in conjunction with the gemfish target trawl fishery, which has diminished considerably in recent years due to declining gemfish TACCs (Figure 2).

There was a seasonal peak in catch from Statistical Areas 016, 017 and 018 during December–April. In these areas, limited target catches were taken during July–October (Figure 1). In contrast, catches from Statistical Area 020 peaked during April–September. The seasonal trend in target catch from Statistical Areas 016, 017 and 018 was also evident in the non-target fisheries (Figure 2), although there is a different pattern in the catch distribution within Pegasus Bay, with most of the non target catch taken during February–June (Figure 2).

There was a seasonal trend in the distribution of the target tarakihi trawl catch along the southeast coast of the North Island (Statistical Areas 012 to 015). Off the southern Wairarapa coast (015), catches peaked during May (Figure 1). Catches from the northern statistical areas (014 and 013) peaked over the following months, while catches from Statistical Area 012 peaked during August. Catches off the Wairarapa coast (014 and 015) were low during August–September. There was a secondary peak in the monthly catches off the Wairarapa coast during October–December, while catches during January–April were low. This seasonal pattern in catch was not observed in the non-target trawl catch, with the exception of the winter peak in catch in Statistical Area 012 (Figure 2).

The set net fishery accounted for 6% of the 2004/05 to 2009/10 tarakihi catch. Catches in the Bay of Plenty fishery (008–010) were limited to January–May (Figure 3). Catches in the main Kaikoura fishery peaked during December–February with a secondary peak in April–May. Catches were very low in all other statistical areas.

These general patterns in tarakihi catch may provide some insight into the spatial and temporal distribution of tarakihi. However, the patterns are also likely to be strongly influenced by the operation of a range of different target fisheries and the commercial requirements of the fishery, as well as mediating the trends through the level of fishing effort (see Section 2.3).

Nonetheless, the distribution of tarakihi catch is suggestive of a number of seasonal trends in tarakihi abundance that may be linked to the migration of tarakihi pre- and post-spawning. Firstly, the relatively high level of target tarakihi catches in Statistical Areas 016, 017 and 018 during December–April may indicate the operation of a fishery directed at spawning fish. The seasonal peak in catches from Statistical Area 016 appears to be preceded by a southern trend in the distribution of the target trawl catch along the Wairarapa coast during October–December and a reciprocal northward trend in the catch distribution during May–July. The seasonal distribution of catch may reflect changes in the distribution of tarakihi in relation to the main spawning period.

Secondly, there is a trend in the distribution of the target tarakihi catch through the Bay of Plenty (Statistical Areas 011 to 008) during March to May that may correspond to the north-western emigration of fish from the spawning ground around East Cape.

2.2 Fine scale catch distribution

Since 1 October 2007, the location of the starting position (latitude and longitude to the nearest minute) for almost all inshore trawl tows has been recorded on the Ministry of Fisheries statutory reporting forms. This enables the examination of the fine-scale spatial distribution of the tarakihi catch from the inshore trawl fishery, whereas previously they had only been required to report the Statistical Area of the catch.

The distribution of tarakihi catch is virtually continuous along the east coast of the North Island, through Cook Strait and along the northeastern coast of the South Island (Figure 4). Within this area, the highest catches were taken throughout an area encompassing the western Bay of Plenty, East Cape and extending southwards to Mahia Peninsula. This area spans the boundary of the TAR 1 and TAR 2 fishstocks. Two smaller areas that supported high tarakihi catches in recent years are off the northern Wairarapa coast (TAR 2) and off Cape Campbell (TAR 3) (Figure 4). By comparison, tarakihi catches within Pegasus Bay, Canterbury Bight and off the northeastern coast of the North Island were lower and more widely distributed.

2.3 Seasonal CPUE trends

Average unstandardised monthly target trawl catch rates (kilogrammes per trawl) were determined for the main statistical areas fished (Figure 5). Overall, average target catch rates were broadly comparable among statistical areas although catch rates were highest in the areas off East Cape (Statistical Areas 010, 011 and 012).

The Bay of Plenty (008, 009 and 010) and East Cape (011) target fisheries had a strong seasonal peak in catch rate during February–May and lower catch rates in June–September. Similarly, catch rates in the trawl fisheries in Statistical Areas 016–018 were highest during November–April and lower during June–September (Figure 5 and Figure 6). The other main target fishing areas (012–015) had higher catch rates during May–June and October–December and low catch rates in the intervening months (Figure 5).

The seasonal trends in tarakihi CPUE for the statistical areas comprising QMA 2 are comparable to those derived by Bentley & Kendrick (unpublished results) and the month-statistical area interaction terms derived from the standardised CPUE analyses for the main TAR 2 and TAR 3 trawl fisheries (Starr & Kendrick 2012) (Figure 7 and Figure 8).

The catch rates from the tarakihi set net fishery are similar to the monthly distribution of catch from these fisheries. For the Bay of Plenty set net fishery, catch rates were relatively high during January–May and low during July–October. Catch rates in the Kaikoura set net fishery peaked in December–February, with a secondary peak in catch rates during May (Starr & Kendrick 2012).

Bentley & Kendrick (unpublished results) analysed recent fine-scale catch and effort data from the TAR 2 trawl fishery. These data were applied to investigate trends in monthly catch rates at $1/10^{th}$ degree spatial resolution. This analysis highlighted areas of higher catch rate that were consistent with the month-statistical area interaction terms derived from the standardised CPUE analyses. The analysis did not reveal any strong pattern in the areas of high or low catch rates that would be suggestive of a strong seasonal migration of fish through the TAR 2 area.

Nonetheless, the analysis did indicate that catch rates were more homogeneous during October–December and May–July. During February–April, higher catch rates were evident around East Cape and in the southern Wairarapa, while catch rates were lower from northern Wairarapa to Mahia. One interpretation of these observations is that fish are migrating from the central area of TAR 2 during October–December to spawning grounds either in the north (around East Cape) or in the southern area, returning to the central area in May–July. However, the demarcation of the resident fish to a particular spawning area (northern or southern) cannot be inferred from these data.

A similar approach was applied to investigate spatio-temporal trends in trawl catch rates within TAR 3. However, there was no evidence of a seasonal trend in the trawl catch rates that would be suggestive of fish movements within this region.

2.4 Annual CPUE trends

Standardised CPUE indices have been derived for the main tarakihi fisheries off the east coast: east Northland trawl, Bay of Plenty trawl, TAR 2 trawl, TAR 3 trawl and TAR 3 set net (Figure 9; Starr & Kendrick 2012). The TAR 2 trawl CPUE indices increased steadily from 1993/94 to 2001/02 and steadily declined from 2001/02 to 2006/07. The indices fluctuate over the subsequent years, increasing in 2008/09 and 2009/10 and declining in 2010/11. The CPUE indices from the Bay of Plenty (TAR 1) bottom trawl fishery exhibit an almost identical trend (upper left panel, Figure 9).

A similar trend, although less pronounced, is apparent for the TAR 3 set net CPUE indices, with a peak in 2001/02 followed by a steady decline in the indices until 2007/08 (lower left panel, Figure 9). The sets of indices deviate during the earlier period (1989/90–1992/93) when relative catch rates from the TAR 3 set net fishery were higher than the TAR 2 trawl fishery.

The CPUE indices from the TAR 3 bottom trawl fishery are more variable than the TAR 2 indices, although the TAR 2 indices tend to follow the same underlying trend with a 2-year lag (upper right panel, Figure 9). The TAR 3 indices tend to increase from 1992/93 to 1999/2000 and then steadily decline until 2004/05. Correspondingly, the TAR 2 indices increase steadily from 1993/94 to 2001/02 and then steadily decline from 2001/02 to 2006/07. The TAR 3 fishery predominantly catches young

(2–5 year old) fish and it is postulated that a proportion of these cohorts subsequently recruit to the TAR 2 fishery. The observed trends in the corresponding sets of CPUE indices are consistent with this hypothesis.

The trends in the CPUE indices from the east Northland bottom trawl fishery differ considerably from the TAR 2 bottom trawl fishery (lower right panel, Figure 9). The CPUE indices from the east Northland fishery exhibit a steep decline during the early 1990s and while the two sets of indices exhibit similar fluctuations over the subsequent period there is a 2–3 year lag in the increases and decreases in the TAR 2 CPUE indices relative to the east Northland indices.

The output from the standardised CPUE analyses was examined to determine CPUE trends for the constituent statistical areas. It was considered that the finer spatial resolution could provide further insights into the spatial domain of the individual stock units and/or fishery operation. The individual statistical area indices were derived by calculating the sum of the annual CPUE index and the mean of the model residuals for the individual year and statistical area (Figure 10; Starr & Kendrick 2012). This approach is somewhat analogous to including a statistical area, year interaction term in the standardised CPUE model.

The analysis revealed that the annual CPUE indices were consistent for the three statistical areas constituting the Bay of Plenty area (Figure 10). Similarly, annual indices were comparable among the TAR 3 statistical areas (017, 018, 020, 022 and 024). However, there is some variation in the annual CPUE trends from the statistical areas comprising TAR 2. The CPUE trend from statistical area 013 is very similar to the Bay of Plenty CPUE trend (Statistical Area 010) with a strong peak in CPUE between 2000/01 and 2003/04 (Figure 10).

A similar pattern also occurs in Statistical Area 014 although the period of peak CPUE commences earlier (1998/99). For Statistical Area 015, the peak in CPUE commences in the same year although the subsequent decline in CPUE is less pronounced than for other areas (012, 013 and 014). Conversely, Statistical Areas 011 and 012 reveal a more protracted period of higher catch rates with a steady increase in catch rates commencing in 1991/92 (Figure 10).

The CPUE trends from Statistical Area 016 differ markedly from all the other statistical areas examined (Figure 10).

2.5 Length and age compositions

Length and age frequency data have the potential to provide information regarding recruitment patterns and fishery exploitation rates. Recruitment patterns should be similar within stock units, leading to the conclusion that differences in recruitment patterns between areas indicate separate stock units. Similarly, differences in exploitation rates between adjacent areas, inferred from age composition data, may indicate that the recruited component of the population in each area remains relatively discrete. This may suggest that the areas represent distinct biological stocks or, at a minimum, separate stock units for the purposes of fishery management.

Limited length and age frequency data are available from the east coast tarakihi fisheries. Estimates of population age compositions derived from trawl surveys are available from the East Cape area in 1971 (Vooren & Tong 1973), Pegasus Bay in 1970 and 1978 (Tong 1979), and Pegasus Bay–Cape Campbell 1987 (Annala et al. 1990) (Figure 11).

There is considerable variation in year class strength evident from these individual age compositions. The single sample from the East Cape fishery revealed strong 1956 (15 year old fish), 1964 (7 years) and 1965 (6 years) year classes (Figure 11). The 1964 and 1965 year classes also appeared strong in the 1970 Pegasus Bay sample along with the 1957 (13 years) and 1950 (20 years) year classes. There is some suggestion that the strong 1964 and 1965 year classes persisted in the 1987 Pegasus Bay–

Cape Campbell age composition (as the 22 and 21 year age classes, respectively), although these year classes do not appear as strong cohorts in the 1978 Pegasus Bay sample (Figure 11).

Overall, the early age frequency data provide limited capacity to compare annual recruitment strengths between regions. However, there do appear to be some similarities in recruitment strength between the East Cape and Pegasus Bay tarakihi fisheries.

More recent length frequency data are available from inshore trawl surveys off the east coast of the North Island (ECNI) and from winter and summer trawl surveys off the east coast of the South Island (ECSI) (Figure 12). Age frequency distributions are not available from any of these modern trawl surveys (although otoliths were collected from ECNI surveys and recent ECSI surveys, see Hanchet & Field 2001). The length compositions of tarakihi from the ECNI trawl surveys are comprised of a single mode of adult fish (Hanchet & Field 2001) and are uninformative regarding the relative strength of individual cohorts.

In contrast, the ECSI trawl survey monitors juvenile cohorts, sampling the 0+, 1+ and 2+ year classes (Figure 12). Direct age frequency data are not available; however, the modal structure of the individual juvenile year classes appear to be reasonably distinct, enabling year class strength estimates to be derived from the time series of length compositions (e.g. via an age structured population model). The resulting year class strength estimates indicate strong 1994 and 2005–2008 year classes and weak 1990, 1993, 1998 and 1999 year classes (see Section 3.4) (Figure 13).

Recent age frequency sampling of the commercial fisheries has occurred from the east Northland bottom trawl fishery (2007/08, Armiger et al. 2010), Bay of Plenty bottom trawl fishery (2007/08, Armiger et al. 2010), TAR 2 bottom trawl fishery (2009/10, Parker & Fu 2011; 2010/11, Beentjes et al. 2012), and the set net and bottom trawl fisheries in TAR 3 (2009/10, Beentjes 2011; 2010/11, Beentjes et al. 2012) (Figure 14 and Figure 15).

The 2009/10 and 2010/11 TAR 3 age compositions are dominated by the recent (2005–2008) strong year classes, consistent with the results of the recent trawl surveys (Figure 15). These year classes were also dominant in the TAR 2 age frequency distributions (Figure 15). Sampling from east Northland and Bay of Plenty fisheries occurred prior to the recruitment of these four year classes to either fishery and hence the relative strength of the 2005–2008 cohorts is unknown for these fisheries (Figure 14).

The strong 1994 year class estimated from the ECSI trawl survey data was also evident as a strong year class in the East Northland age composition (age 14 years) (Figure 14). However, few old fish were sampled from the other fisheries and hence these data are not informative regarding the year class strength of the older cohorts.

There are some inconsistencies between the year class strengths inferred from the ECSI trawl surveys and the East Northland age composition. Firstly, the weak 1998 and 1999 year classes are present as strong cohorts in the East Northland age composition (age classes 10 and 9 years, respectively) (Figure 14). Conversely, these age classes appear weak in the Bay of Plenty age composition samples. Similarly, the weak 1993 year class is present as a strong cohort in the East Northland age composition (age 15 years), while the moderate 1996 and 1997 year classes appear relatively weak in comparison in the Bay of Plenty samples (Figure 14). Some of the differences in the age compositions (and year class assignment) between the East Northland and Bay of Plenty samples may be caused by the change in ageing protocol which was developed in the period between the ageing of these two data sets (J. McKenzie, *pers. comm.*), although the differences in YCS between these two areas appear to be too large to be explained entirely by this change.

Another key observation from the age frequency data is the underlying structure of the age compositions. The Bay of Plenty and TAR 2 bottom trawl fisheries are both dominated by age 3–7 year fish, with older age classes (8+) representing only 12% and 9% of the sampled catch, respectively (Figure 14 and Figure 15). In contrast, 57% of the sampled East Northland catch was comprised of fish aged 8 years and older (Figure 14). Thus, if age-specific trawl selectivity and/or availability are considered comparable between the two areas, these age samples are indicative of substantially lower exploitation rates in the East Northland fishery compared to the Bay of Plenty fishery, and there must be negligible movement of fish between the two areas.

An alternative explanation for the observed difference in the age structure between the two regions is the emigration of older fish northward from Bay of Plenty/East Cape to the East Northland fishery. However, this hypothesis is not supported by the differences in the apparent strength of the same year classes and differing trends in CPUE between the two areas.

The recent catch sampling of the TAR 3 fisheries reveals a number of important differences in the age structure between the consecutive years (Figure 15). For the bottom trawl fishery, there was a marked reduction in the proportion of the catch comprised of the 2005 and 2006 cohorts between the two samples. This may reflect the magnitude of the strong 2008 cohort recruiting into the fishery (at age 3 in 2010/11) and/or be attributable to a decline in the catchability of older age classes due to declining vulnerability or to emigration.

Similarly, there is a considerable change in the age composition of the set net fishery between the two consecutive years (Figure 15). There is a reduction in the proportion of fish in the 2003 and 2004 cohorts (age 7 and 8 in 2010/11) in the second sample, along with a substantial decline in the proportion of fish in the 2005 year class relative to the 2006 year class (ages 6 and 5 years, respectively, in the 2010/11 sample). Again, these changes in age composition are likely to be attributable to a combination of variable cohort strengths and age specific patterns in selectivity and/or availability. However, it is not possible to separate these potential processes with only two years of catch sampling.

The age structure of the TAR 2 bottom trawl fishery was similar between the two consecutive years, with the 2003–2006 year classes persisting in the fishery (Figure 15). There was an increase in the proportion of 3 year old fish in the catch, suggesting the recruitment of a strong 2008 year class in line with the same strong year class in the TAR 3 bottom trawl fishery (Figure 15).

2.6 Biological characteristics

Von Bertalanffy growth parameters have been estimated for the TAR 3, TAR 4 and TAR 7 Fishstocks (Ministry of Fisheries 2011). The growth functions are very similar for the three areas, with the exception being some deviation in the mean length at age for male tarakihi in the two youngest age classes (1 and 2 years). The growth curves converge at 3 years of age and the deviations in the younger age classes could be potentially be attributed to incomplete sampling of the juvenile male age classes.

The recent length-at-age data collected from TAR 2 (Parker & Fu 2011) included too few age classes (especially older fish) to reliably estimate growth rate parameters for the TAR 2 fishstock area. Nonetheless, for the most abundant age classes sampled (4–8 years), the estimates of mean length at age for TAR 2 male and female fish were very similar to the values derived from the TAR 3, TAR 4 and TAR 7 growth models, indicating that these separate areas appear to share similar growth patterns.

Overall, there does not seem to be any significant regional variation in growth rates for tarakihi, leading to the conclusion that these data are unlikely to be informative regarding stock structure of tarakihi in New Zealand waters.

Sexual maturity in tarakihi is reached at 25–35 cm fork length (FL), corresponding to age 4–6 years (Ministry of Fisheries 2011). Recent age samples from the TAR 2 and TAR 3 fisheries are consistent with the upper end of this range. For TAR 2, 50% of male and female fish were estimated to be mature at 32 cm and 34 cm fork length, respectively (Parker & Fu 2011). Similarly, for TAR 3, 50% maturity was reached at 32 cm and 33 cm for male and female fish (Beentjes 2011). Maturity ogives were not derived from the recent sampling of the TAR 1 fisheries.

2.7 Spawning locations and nursery grounds

Beentjes (2011) recently reviewed the available information regarding the known locations of tarakihi spawning. The following statement is an excerpt from his report with the relevant citations.

"Tarakihi spawn in summer/autumn off the outer continental shelf (McKenzie 1961, Ayling & Cox 1982). Known spawning areas include Bay of Plenty (Vooren & Tong 1973), outer Pegasus Bay, Conway Ridge, Cape Campbell, Cook Strait (Tong & Vooren 1972, Robertson 1973, Fenaughty & Bagley 1981), and the west coast South Island (Vooren 1975)."

Robertson (1973) documented the spatial distribution of tarakihi eggs. Three main areas were identified: i) off the southern west coast of the South Island, ii) around East Cape from the western Bay of Plenty to Mahia Peninsula, and iii) from central Wairarapa to Banks Peninsula, including Cook Strait.

This is broadly consistent with the distribution of ripe and running ripe fish from trawl surveys (Hurst et al. 2000), with the exception that the distribution of actively spawning fish was almost contiguous along the east coast of the North Island from the western Bay of Plenty to Cape Palliser. As well, a small number of running ripe fish were recorded off the west coast of the North Island.

Pre spawning female fish ("ripe" ovaries) were sampled from the Pegasus Bay/Canterbury Bight trawl fishery and the Kaikoura set net fishery during February–March (Beentjes 2012). A trawl survey designed to determine the distribution and abundance of spawning tarakihi between Cook Strait and Pegasus Canyon found spawning tarakihi at most locations, with highest concentrations on the Conway Rise and off Point Gibson (Annala et al. 1990). Ripe female fish were sampled from the TAR 2 trawl fishery during March–May (Parker & Fu 2011).

The long pelagic larval phase of 7–12 months suggests that larvae will be widely dispersed. The distribution of 0+ year tarakihi catches from trawl surveys were limited to Canterbury Bight and Pegasus Bay. The distribution of 1+ year tarakihi was broader, including the western Bay of Plenty and a limited number of trawl stations within Hawke Bay (Hurst et al. 2000). The compilation of trawl survey records reveals that immature and adult tarakihi are distributed throughout the coastal waters of New Zealand.

Hanchet & Field (2001) concluded that the relatively low density of juvenile tarakihi off the east coast of the North Island was insufficient to sustain the commercial fisheries in these areas. The authors considered that "*it seems more likely that the east coast South Island is in fact the main nursery ground for the entire east coast of both islands and possibly other areas as well. The trawl survey estimates of 10–20 million pre-recruits on the east coast South Island and of 0.5–1 million adults from the west coast North Island, east coast North Island, and west coast South Island are also more consistent with this explanation. A link between the east coast South Island and the other areas is also consistent with the extensive movements of tagged fish, most of which have been to the north* (see below)".

2.8 Tagging

A considerable number of tarakihi were tagged off Kaikoura and in Pegasus Bay during 1986 and 1987 (Annala 1988). A summary of the results of the tagging study is provided in Annala (1988). Overall recovery rates of tagged fish were low, although a considerable proportion of the tag recoveries occurred beyond the area of release. The location of these tag recoveries are described by Annala (1988) as follows:

"A number of the tagged tarakihi recovered outside the tagging area had moved long distances. Of those moving north, 2 were recaptured near Great Barrier Island, 1 near Waiheke, 1 near Whale Island, 7 between Table Cape and Lottin Point, 6 between Cape Campbell and Cape Turnagain, 1 near Kaipara Harbour, and two between Mana Island and Otaki.Three of the returns that moved south were recaptured between Banks Peninsular and Timaru."

These results are consistent with a northward dispersal of some fraction of the tarakihi population from the Kaikoura area and the subsequent recruitment of tarakihi to the fisheries off the east coast of the North Island. There also appears to be a component of the stock that recruits to the fishery off the west coast of the North Island. No information is available regarding the size of the tagged fish.

In recent years, juvenile tarakihi were tagged in Tasman Bay during the 2007 (773 tagged fish), 2009 (614) and 2011 (912) trawl surveys. To date, there have been no recoveries of the tagged tarakihi (M. Stevenson *pers. comm.*).

2.9 Movement model

A spatially stratified, age structured population model was applied to evaluate a range of potential stock structure hypotheses for the east coast tarakihi stock. A total of eight movement hypotheses were tested, in which scenarios linked fish from specific statistical areas to a known (or assumed) spawning location. The main spawning locations considered were East Cape (012), eastern Bay of Plenty (008), Cook Strait (016) and Pegasus Bay (020). The primary data incorporated in the models were seasonal catch rates of tarakihi for the key fisheries operating in each model area. The model estimated the distribution of recruitment among areas and the seasonal movement of fish between areas to attain the best overall fit to the observed year-season trends in catch rate from all of the areas. A key assumption of the approach was that trends in CPUE within an area represent changes in the relative abundance of tarakihi, rather than changes of the seasonal catchability of tarakihi. A detailed description of the modelling approach is provided in Appendix A.

Initially, the range of models was evaluated based on the fit obtained to the observed catch rates. The resultant models tended to be strongly influenced by the high seasonal variation in the catch rates of the fisheries in a small number of fishery areas. The models tended to attempt to fit the observed catch rates in these regions at the expense of fitting the observed catch rates in the fishery areas that account for a high proportion of the total catch from the fishery. For example, the model estimated that a high proportion of the total recruitment occurs in Statistical Area 016, whereas comparatively low levels of recruitment occur in the East Cape area (Statistical Areas 011 and 012). Consequently, a high level of recruited biomass was estimated in the area of the northern Wairarapa where catches are relatively low, while biomass was low in the areas that support the highest catch (Statistical Areas 010–013).

Overall, the performance of the individual models was inconsistent with the general understanding of the tarakihi fishery. Thus, it was was concluded that the seasonal catch rate data were inadequate to sufficiently inform the models regarding the spatial dynamics of the tarakihi stock(s) and/or the underlying stock structure. On that basis, the results of the movement models were disregarded from any further consideration of tarakihi stock structure.

2.10 Summary and conclusions

In their comprehensive review, Hanchet & Field (2001) concluded that *"the stock structure (of tarakihi) is complex and poorly understood. We can see no immediate way to address stock structure issues, because genetic and tagging studies which have already been attempted suggest widespread dispersal and a single tarakihi stock........ We consider that assessments of the main Fishstocks (or sub-Fishstocks) is probably the most practical way forward, and is probably the most realistic, on the basis that once tarakihi have recruited to a particular ground they probably remain there."*

Since the publication of the review by Hanchet & Field (2001), there has been a considerable amount of information collected and analysed from the tarakihi fisheries. While most of these data were not collected (or collated) with the specific purpose of defining tarakihi stock structure, inferences from the various data sets provide information regarding the stock structure of tarakihi along the east coast of mainland New Zealand.

The new key data sets are the trends in biomass and length composition from the ECSI trawl surveys, trends in CPUE from key commercial fisheries and all associated catch-at-age data. The reliance on fishery dependent data (catch, CPUE and catch-at-age) means that patterns in stock abundance and age composition may be obscured by trends in the operation of the fishery. Further, as noted in previous sections, the limited catch-at-age sampling means that it is difficult to separate fishery selectivity from the underlying population age structure.

Nonetheless, several key observations emerge from the analysis of these data sets which are informative regarding stock structure.

1. There exists a continuous distribution of relatively high catches of tarakihi from eastern Bay of Plenty to Mahia Peninsula (Statistical Areas 010 to 013).
2. The annual trends in tarakihi standardised CPUE from the bottom trawl fishery are similar from the four statistical areas encompassing the eastern Bay of Plenty to Mahia Peninsula (Statistical Areas 010 to 013), with the strongest similarity between the two most distant areas (010 and 013). Similar trends in standardised CPUE are also apparent for the western Bay of Plenty (Statistical Areas 008 and 009).
3. The available catch-at-age data from the TAR 2 and Bay of Plenty trawl fisheries are not directly comparable, as the sampling was conducted in different years. However, there are no substantive differences in relative year class strength evident between the samples from these two fisheries.
4. Annual trends in the standardised CPUE from the southern areas of TAR 2 (Statistical Areas 014 and 015) are comparable to the CPUE trends from northern TAR2/Bay of Plenty. However, annual indices from north-western Cook Strait (Statistical Area 016) are markedly different.
5. Annual trends in standardised CPUE from the TAR 3 trawl fishery are very similar for all constituent statistical areas (017, 018, 020, 022 and 024). The annual trend in TAR 3 set net CPUE is comparable to the TAR 3 trawl fishery, although there is a lag of about 2 years between the two sets of indices. The two year lag is consistent with the differences in the age composition of the catch from the two fisheries, indicating that the difference is attributable to differences in the age of recruitment to the respective fisheries.
6. The trend in CPUE indices from the TAR 2 target trawl fishery closely follows the CPUE trend from the TAR 3 setnet fishery and less well the TAR 3 trawl fishery, the latter requiring about a two-year lag.
7. The catch-at-age samples from the TAR 2 and TAR 3 fisheries (and ECSI trawl survey length data) reveal a consistent period of strong recruitment (2005–2008 year classes). However, for all fisheries, the catch is comprised of a relatively small number of age classes (3–7 year old fish), resulting in a limited comparison of year class strengths between the areas.
8. The most compelling data linking TAR 3 and TAR 2 are the observed movements of a considerable number of tagged fish from Kaikoura to Wairarapa, East Cape and the Bay of

Plenty. However, insufficient available information and the voluntary design of these programmes preclude applying these data to estimate movement rates and consequently the degree of interdependence between the two fishery areas.

9. Limited age frequency data of uncertain reliability are available from the East Northland trawl fishery (a single year of sampling in 2007/08). However, there are marked differences in the age structure of the East Northland catch compared to the other fisheries in the Bay of Plenty, TAR 2 and TAR 3. The East Northland sample was comprised of a substantially higher proportion of older (over 7 years) age classes in the population, suggestive of considerably lower exploitation rates on these cohorts compared to the fishery areas further south. There are also apparent differences in the relative strength of individual year classes between East Northland and these other areas.
10. Trends in standardised CPUE indices from the East Northland fishery are broadly similar to the Bay of Plenty/TAR 2 fisheries. However, the trend in East Northland CPUE tends to precede the Bay of Plenty/TAR 2 fisheries by about two years. For example, CPUE in the East Northland fishery increased to a peak in 1999/2000 and then declined, whereas the CPUE indices from the Bay of Plenty fishery peaked in 2001/02. These trends in CPUE are not indicative of a linkage between the two fishery areas. Instead, the trends appear to be reflective of the differences in age structure. The peak in East Northland CPUE corresponded to the recruitment of the strong 1998 and 1999 year classes, although there is no indication that these year classes were strong in the other areas.

A key objective of the current study is to formulate a stock hypothesis (or hypotheses) for the assessment of tarakihi off the east coast of mainland New Zealand. Based on the available observations from the fishery, there is good evidence for the amalgamation of the Bay of Plenty and East Cape–Mahia areas (Statistical Areas 008–013) into a single stock unit. This stock area may also extend further south to include the Wairarapa coast, although there is also some suggestion (from catch and CPUE data only) that fish in this area may migrate to spawn in the southern area of TAR 2.

The limited data from the East Northland fishery indicate that tarakihi in this area (Statistical Areas 002–004) are relatively distinct from the other fishery areas along the east coast of mainland New Zealand.

Fishery trends in TAR 3 are generally consistent with the observations from the Bay of Plenty/TAR 2 fishery in terms of CPUE and age structure of the catch. However, comparative data are limited and, while there are strong similarities between the two areas, there is insufficient information to conclude that these areas constitute a single stock unit. Other observations from the two fishery areas are somewhat contradictory. While there are distinct spawning grounds in the two areas (off East Cape in the northern area and off Cape Campbell in the south), there is a preponderance of juvenile fish in the southern area and low densities of juvenile tarakihi within the Bay of Plenty and TAR 2 areas (Hanchet & Field 2001). While juvenile tarakihi have a long pelagic phase, the mechanism for the southward transfer of larvae and juvenile fish from the East Cape spawning grounds to settle in the Canterbury Bight/Pegasus Bay nursery grounds is not apparent. Nonetheless, the northward movement of fish from the Kaikoura coast to the Wairarapa, East Cape and Bay of Plenty has been well established from tagging.

The above observations are consistent with a degree of mixing between the two main east coast fishery areas, with the southern area (TAR 3) representing a source of recruitment to the northern area. However, it is not possible to assess the extent of mixing between the two areas and/or whether any movement of adult fish occurs in the opposing direction (from TAR 2 to TAR 3). Thus, the current stock hypotheses represent a continuum between two extremes 1) the TAR 2 and TAR 3 fisheries represent discrete stocks and 2) there is substantial mixing (possibly consisting of both northerly and southerly movements) of the fish between these two areas. The most plausible working hypothesis is that there is local recruitment in both areas, with the TAR 2 fishery being augmented by additional recruitment from the TAR 3 fishery area. The juvenile tarakihi that settle and reside in the TAR 3 nursery grounds potentially include the progeny of fish spawning in areas outside of TAR 3.

For management purposes, it has generally been accepted that the WCSI fishery and the northern North Island fishery (TAR 1W and East Northland) represent two distinct management units. Nonetheless, results from previous tagging studies indicate a degree of connectivity between the Kaikoura fishery area and the west coast North Island fishery. Limited data are currently available to examine the relationship between the fisheries in these two areas. However, it is important to consider that the TAR 3 fishery could also represent a significant source of recruitment to other areas (beyond the Bay of Plenty and TAR 2).

The marked difference in the trend in CPUE for the north-eastern Cook Strait fishery (Statistical Area 016) also indicates potentially different stock dynamics in this area compared to the remainder of TAR 2 and TAR 3. Nonetheless, the relatively small level of catch from this area (about 90–100 t per annum) means that any stock assessment of TAR 2 and/or TAR 3 will be relatively insensitive to the inclusion of the catch from this area.

Clearly, the stock structure of tarakihi around mainland New Zealand in general and, more specifically along the eastern coast of both islands, is complex and poorly understood. Some progress has been made to refine the understanding of the stock relationships; however, pertinent data are lacking or limited for the main fishery areas. Tarakihi stocks clearly exhibit strong variability in recruitment strength that may differ among the main fishery areas. Comparative sampling of the age composition of the catch from the main fishery areas, in tandem with CPUE data, will continue to provide information on possible stock relationships; however, a considerable time-series (more than five years) of age frequency samples is probably required to adequately resolve differences in year class strength from the underlying pattern of fishery selectivity. Current analyses could also be strengthened by ageing existing otolith collections from the ECSI and ECNI trawl surveys and establishing an ongoing ageing programme from future trawl surveys.

Of the more direct approaches used to investigate stock structure, tagging studies would appear to have the greatest likelihood of improving our understanding of stock relationships based on the success of the early Kaikoura tagging study. However, the lack of recoveries of tarakihi which were recently tagged in Tasman Bay/Golden Bay indicates that such tagging projects are high risk. Within the scope of the current study, a tagging project targeted at the Bay of Plenty/East Cape area has the potential to increase the understanding of the stock relationships along the east coast of New Zealand by determining the degree of residence of adult fish in this area.

3. STOCK ASSESSMENT MODELS

3.1 Data sets

3.1.1 Commercial catch

A time series of commercial catches for the TAR 2 fishery was compiled for the period 1931 to 2011 (Figure 16). The catches from 1931 to 1985 were sourced from the documented domestic landings from the East coast–Hawke Bay fishing region (Table 1 Annala 1998b). No additional allowance was included for catch by foreign fishing vessels on the basis that only negligible catches of tarakihi were reported by Japan during 1977/78 to 1985/86 (from off the east coast of the North Island, i.e. EEZ area *B*) (Table 4 Annala 1998b).

TAR 2 commercial catches for 1985/86 to 2010/11 were sourced from Ministry of Fisheries (2011) and Starr & Kendrick (2012). Catches reported by fishing year were assigned to the calendar year at the end of the fishing year (e.g. the 1985/86 fishing year was assigned to the 1986 calendar year).

Similarly, historical tarakihi catches for the Bay of Plenty fishery were obtained from the domestic catches documented for the Bay of Plenty fishing region (Table 1 Annala 1998b). More recent catches were based on the reported TAR 1 catches documented in the Plenary report (Ministry of Fisheries 2011). The proportion of the total annual TAR 1 catch taken from the Bay of Plenty (Statistical Areas 008–010) was sourced from Kendrick (2009). On average, the Bay of Plenty fishery accounted for about 50% of the total TAR 1 catch.

Historical TAR 3 commercial catches are documented in Starr et al. (2009). Recent catches, from 1986/87 onwards were obtained from Ministry of Fisheries (2011). Annual catches were apportioned by fishing method (trawl and set net) based on the proportion of the catch reported from fishing effort returns.

The final catch histories included an additional allowance for unreported and illegal commercial catches. Following the approach adopted for the northern snapper fisheries (SNA 1 and 8, Ministry of Fisheries 2011), it was assumed that prior to the introduction of the QMS system (prior to 1986) the annual unreported catch represented 20% of the annual reported catch. From 1986 onwards, it was assumed that illegal catches represented 10% of the annual reported catch. Illegal catches include the mis-reporting or non-reporting of landed tarakihi catches and the dumping of legal-sized tarakihi.

No allowance was made for the discarding of catches of small tarakihi or other sources of fishing mortality.

3.1.2 Non commercial catch

Recreational catch estimates for tarakihi in TAR 1 and TAR 2 are available for recent years (Ministry of Fisheries 2011). However, the catch estimates derived from telephone/diary surveys are considered to be unreliable. The most reliable recreational catch estimate for QMA 1 was obtained from the 2004–05 aerial overflight survey. The survey yielded a recreational catch estimate of 89.5 t (c.v. 18%) (Hartill et al. in press). A specific estimate was not available solely for the Bay of Plenty area; however, it was assumed that approximately 50 t of the recreational catch was taken from the area. This level of recreational catch was assumed for all years (1931 to 2011).

Limited information regarding the level of recreational tarakihi catch is available for TAR 2. The single recreational catch estimate of 191 t from the 1999–2000 national diary survey is considered to be unrealistic. A nominal annual recreational catch of 50 t was assumed for the entire catch history (1931 to 2011).

Recreational catches of tarakihi in TAR 3 are considered to be negligible and were not included in the catch history.

The catch histories did not include any customary or illegal catch.

3.1.3 CPUE indices

Annual CPUE indices were available for 1989/90–2010/11 for the four main commercial fisheries operating off the east coast of the North and South Islands: the trawl fishery in the Bay of Plenty, the TAR 2 trawl fishery, the Pegasus Bay–Canterbury Bight trawl fishery and the Kaikoura target set net fishery (Starr & Kendrick 2012) (Figure 9).

Vooren (1973) presented qualitative assessments of the East Cape tarakihi fishery which included the observation that between 1962 and 1973 landings declined by 54%, whereas fishing effort decreased by only 17%. These observations correspond to a 45% decline in CPUE between the two years. These two relative CPUE observations were incorporated as a separate time-series of indices for the TAR 2 trawl fishery. Because the indices are unstandardised and span a considerable time period they are considered to be relatively uninformative and were assigned a c.v. of 30%.

3.1.4 Trawl survey data

Inshore trawl surveys off the east coast of the North Island and east coast South Island have been conducted by R.V. *Kaharoa*. Tarakihi was one of the main target species of these trawl surveys. Trawl survey data were available from the three ECNI trawl surveys (1994, 1995 and 1996) that covered an equivalent survey area. The survey area and stratification of an earlier (1993) survey differed from the subsequent surveys and was excluded from the time-series.

Inshore trawl surveys of ECSI were conducted in winter (1991, 1992, 1993, 1994, 1996, 2007, 2008 and 2009) and summer (1996, 1997, 1998, 1999 and 2000). The two sets of seasonal surveys are considered to represent two separate time-series of trawl surveys due to the likelihood of seasonal differences in the catchability of tarakihi (Ministry of Fisheries 2011).

Relative biomass estimates and length frequency distributions for male and female tarakihi were derived from the trawl survey data following Vignaux (1994). Otoliths were collected from some surveys; however, these have not been aged.

3.1.5 Age frequency data

Sampling of the commercial catch from the main tarakihi fisheries has been conducted in recent years. A single age frequency observation was available from the 2007/08 Bay of Plenty trawl fishery (Armiger et al. 2010) and age frequency data were available from the 2009/10 and 2010/11 TAR 2 trawl fishery (Parker & Fu 2011, Beentjes et al. 2012). For the TAR 3 fishery, age frequency samples were available from the trawl and set net fisheries from 2009/10 and 2010/11 (Beentjes 2011, Beentjes et al. 2012).

In addition, age frequency data were available from a number of surveys conducted during the 1970s and 1980s. These surveys conducted relatively systematic sampling of the respective survey areas, although the trawling was not conducted at randomly located station positions and, hence, the results cannot be applied to estimate tarakihi biomass. Nonetheless, the surveys were considered to provide a "*reasonable random sample of the tarakihi population in the area*" (Annala et al. 1990) and the resulting age frequency distributions should be informative regarding population age structure at the time of survey.

A survey of the East Cape region (from Cape Runaway to Mahia Peninsula) was undertaken using *James Cook* in March 1971 (Vooren & Tong 1973). A total of 20 trawls were conducted in the 40–160 m depth range, with 7 trawls catching at least 50 tarakihi. The individual samples were dominated by tarakihi in the 6–10 year age classes and a small proportion of fish in the older age classes. A cumulative age composition was derived for the survey (Figure 11).

A similar survey was undertaken off the northern east coast of the South Island in April 1987 using the *James Cook* (Annala et al. 1990). The prime objective of this survey was to locate spawning schools of tarakihi and map their distribution. The survey conducted approximately 60 trawls between Cook Strait and Banks Peninsula in 100–200 m depth. An age-length key was derived from the 655 tarakihi otoliths sampled from the trawl catches.

In addition, Tong (1979) presented age frequency distributions of tarakihi from research trawling in Pegasus Bay during January–March 1970 and January 1978 (Figure 11). Descriptions of the details of these surveys, including the design followed, are not available.

3.2 Biological parameters

Biological parameters incorporated in the individual models are presented in Table 1.

Von Bertalanffy growth parameters and length-weight parameters for male and female tarakihi are available from TAR 3 (Annala et al. 1990). No corresponding values are available for TAR 2 and the values from TAR 3 were assumed.

A value of natural mortality (*M*) of 0.1 was derived from the age sample collected from the 1987 research trawl survey (Annala et al. 1990). This value was adopted for all model options.

Sexual maturity is reached at 25–35 cm fork length (FL) at an age of 4–6 years (Ministry of Fisheries 2011). All models assumed 25% and 50% maturity at ages 4 and 5 years and full maturity at 6 years of age.

3.3 Model structure

The spatial domain and structure of the initial models were based on the recommendations outlined in Section 2.10. On that basis, three individual models were configured:

i. A *TAR2/BPLE* model encompassing the Statistical Areas 008, 009–016;
ii. A *TAR3* model encompassing the Statistical Areas 017, 018, 020, 022 and 024; and
iii. A *combined* model encompassing two separate regions equivalent to the *TAR2/BPLE* and *TAR3* model areas.

The three models were configured as age structured population models and implemented in Stock Synthesis software (version 3.2.1, Methot 2005, 2011). The models were configured to include both sexes and 40 age classes with the oldest age class encompassing fish 40 years and older ("plus group"). All three models were configured with a single, annual time step and annualised recruitment.

The *TAR2/BPLE* model included four fisheries: a commercial fishery and a recreational fishery in each of the two areas (TAR 2 and Bay of Plenty). The recent trends in the stock were indexed by the standardised CPUE indices from the TAR 2 fishery (Figure 9), while the two early CPUE observations (from 1962 and 1973) were included as a separate series. The recent Bay of Plenty indices were not included. These indices were very similar to the TAR 2 CPUE indices and the inclusion of this additional CPUE series would result in the CPUE data having undue influence in the model, without adding much new information.

The *TAR2/BPLE* model also included the three *Kaharoa* relative trawl survey biomass estimates (1994, 1995 and 1996) and the associated male and female length frequency distributions (Table 1). The individual biomass indices were assigned a c.v. equivalent to the empirically derived c.v. for the individual survey biomass estimates (15–24%). Initial model runs also included the age frequency distribution from the 1971 East Cape trawl survey. The three recent observations of the age composition of the catch were included in the model: one observation from the Bay of Plenty trawl fishery (2008) and two observations from the TAR 2 trawl fishery (2010 and 2011).

The *TAR3* model incorporated data from the two main commercial fisheries (set net and trawl fisheries). Annual CPUE indices were available for the two fisheries for 1990–2010 and estimates of the age composition of the fishery specific catch were available for each fishery from 2009 and 2010. Relative biomass indices and length frequency distributions from the time-series of winter (1991, 1992, 1993, 1994, 1996, 2007, 2008 and 2009) and summer (1996, 1997, 1998, 1999 and 2000) ECSI trawl surveys were also incorporated. In addition, age frequency data were available from early research trawl surveys in Pegasus Bay–Cape Campbell area (1970, 1978 and 1987) (Figure 11).

The *combined* model included all the data from the two spatially discrete models (Table 1). This model was configured with two regions corresponding to each of the discrete stock models. This model estimated the proportional distribution of recruitment between the two regions and a uni-directional age-specific movement of fish between the two regions (from south to north).

Preliminary runs for the two discrete stock models included the entire catch history period (beginning in 1932), assuming that the population was in an unexploited, equilibrium state at the start of the model. Selectivity for commercial fisheries was assumed to be age-specific, while length-based selectivities were estimated for the recent *Kaharoa* trawl surveys, as only length frequency data were available. A range of alternative parameterisations for the commercial fishery selectivities were investigated.

Recruitment was parameterised with a Beverton-Holt stock-recruitment relationship with steepness (*h*) fixed at 0.75. Recruitment deviates were estimated for the more recent years for which trawl survey and/or age frequency data were available to inform the model regarding recruitment variation (from about 1987, depending on the model) (Table 1). Recruitment deviates were assumed to have a standard deviation (*sigmaR*) of 0.6.

For all models, the relative abundance indices (CPUE and trawl survey) were assumed to have a lognormal error structure, while the length and age frequency distributions were assumed to have a multinomial error structure.

3.4 Preliminary model runs

Preliminary modelling investigated a range of key assumptions: the selectivity of the commercial fisheries, the utility of the early age frequency data sets and the relative weightings of the key input data sets (CPUE and age frequency data). The following paragraphs provide a summary of the key observations from the preliminary model runs.

***TAR2/BPLE* model**

For the *TAR2/BPLE* base model run, the commercial trawl fisheries were assumed to fully select the older age classes in the population, with the fishery selectivity parameterised with a logistic function. Selectivity was assumed to be the same for the two sexes. Initially, separate selectivities were estimated for the commercial fisheries in TAR 2 and the Bay of Plenty; however, the resulting selectivities were very similar and subsequent model runs assumed an equivalent selectivity for the two fisheries. In the absence of age or size data, the selectivity of the recreational fishery was assumed to be the same as the commercial fisheries. The length-based selectivity of the *Kaharoa* trawl survey was parameterised using a double normal function.

The early age frequency data (1971) were obtained from a research trawl survey. The survey was conducted during the spawning period (March) and covered the main depth range of tarakihi. On that basis, it was considered that the survey could be expected to adequately sample the older age classes in the population and, consequently the survey selectivity was parameterised using a logistic function, which precluded a descending right-hand limb.

All *TAR2/BPLE* model options assumed a c.v. of 20% for the TAR 2 CPUE indices on the basis that these indices represented the primary source of abundance information included in the model and the observation that individual indices exhibited relatively low variation between successive years. The age frequency data were assigned an effective sample size (ESS) of 10 following the approach for weighting of the age frequency data sets developed by Francis (2011).

This *TAR2/BPLE* model yielded a very poor fit to the early (1971) age frequency sample, most notably estimating a large accumulated age class (plus group) that was not evident in the observed age frequency. Furthermore, the model estimated a high proportion of fish in the 3 and 4 year age classes and a substantially lower proportion of 6 and 7 year age classes. This poor fit was possibly the result of the failure to fit individual year classes because recruitment deviates were not estimated prior to 1990.

Alternative model options were explored that started the model in 1970 from a non-equilibrium position, excluding the early catch history from the model on the basis that these data were less reliable. However, this approach was reliant on early age frequency data to estimate initial fishing mortality rates to determine the initial (exploited) equilibrium population age structure. These estimates in turn were dependent on the assumptions regarding the selectivity of the 1971 research trawl survey and the assumption of equilibrium recruitment in the period preceding the initialisation of the model. The resulting models yielded initial conditions and biomass trajectories that were implausible: high initial exploitation rates and a steady increase in biomass during the 1970s and 1980s, causing this approach to be abandoned.

Overall, the 1971 age frequency data were considered to be incompatible with the modelling approach, particularly with respect to the assumptions relating to selectivity and recruitment variation during the early period of the model. The single age frequency observation during this early period did not provide sufficient information to investigate alternative model assumptions and was subsequently excluded.

These initial models, based on an assumed logistic trawl selectivity which precluded a descending right-hand limb to the selectivity function, produced a reasonable fit to the trawl survey length compositions (Figure 17). However, the models exhibited poor fits to the recent commercial age frequency data (Figure 18). Overall, the models over-estimated the proportion of older (8–20 year) fish in the population and consequently substantially under-estimated the proportion of younger age classes (4 and 5 years). More strikingly, the models estimated a very strong recruited age class (corresponding to the 1996 or 1997 year class) that was not observed in any of the age samples (Figure 18). This lack of fit to the age frequency data indicated a degree of conflict between the available age composition data with the CPUE indices (Figure 19). The CPUE indices increase from 1997–2002 without there being evidence of the corresponding strong year classes in the age frequency data to support an increase in biomass. Stronger recruitments are estimated for 1994–97 (Figure 20) in an attempt to fit the increase in CPUE, but the model is unable to fit the full extent of the CPUE increase due to the inconsistency with the age frequency data (Figure 19).

Furthermore, the CPUE declines sharply between 2002 and 2007 and the decline is fitted by estimating weak recruitment deviates for 1998–2003 (Figure 20). The high proportion of younger fish in the age composition after 2007 are fitted by estimating relatively high recruitment deviates for 2004–06; however, because the CPUE indices remain relatively low during 2007–10 the model cannot increase the relative strength of the year classes sufficiently to fit the younger (4 and 5 year) age classes in the age compositions (Figure 18). These conflicts between the CPUE and age composition data stem from the low annual natural mortality and the failure to observe sufficient older fish in the catch to be consistent with the logistic selectivity assumption and the continuing high catch levels.

Models that relaxed the selectivity assumptions resulted in a considerable improvement in fit to both the CPUE indices and the age frequency data (Figure 18 and Figure 19). The double normal parameterisation yielded selectivity estimates with a full selectivity at age 4 years and negligible selectivity for age classes 10 years and older. There is limited information in the catch-at-age data to inform the model about recruitment (year class strengths) prior to 2000 and consequently the model has considerable freedom to estimate recruitments that are consistent with the observed CPUE indices.

The model estimates of spawning biomass are highly sensitive to the assumptions related to commercial selectivity, especially given that the selectivity mediates the CPUE indices which represent the primary index of stock abundance. The contrasting selectivity options resulted in approximately an order of magnitude difference in the level of recent spawning biomass (Figure 21), each with a considerably different population age structure.

TAR3 model

Initial *TAR3* model runs included data from the three early age frequency observations from research surveys (1970, 1978 and 1987). These research surveys were assumed to have a common, non-decreasing, age-specific selectivity parameterised with a logistic function. However, initial model runs had very poor fits to the 1970 and 1978 age compositions and, overall, there was inconsistency between the two early age frequency data sets with the 1987 age distribution (Figure 22). The fit to the 1987 age composition was good using a logistic selectivity assumption. No information was available documenting the design of two early research surveys, whereas the 1987 survey is described in detail in Annala et al. 1990. Consequently, there was more confidence in using the age frequency data from this survey than from the two earlier surveys. On this basis, the two earlier data sets were excluded.

As done for the TAR 2/BPLE model, initial model runs assumed that the trawl fishery fully selected the older age classes in the population by using a logistic parameterisation. Conversely, the selectivity of the set net fishery was assumed to be size specific related to the mesh size of the fishing gear. However, the limited age frequency data available from these fisheries revealed that, in recent years at least, the trawl fishery caught younger fish than observed in the set net fishery. This suggests that the selectivity of older fish was greater in the set net fishery than in the trawl fishery. This was also evident in the poor initial fits to the age frequency data from the TAR 3 trawl fishery. In response, a revised parameterisation for the trawl fishery using a double normal function was adopted, while the selectivity of the set net fishery was parameterised with a logistic function.

The time series of summer and winter *Kaharoa* trawl survey biomass indices were included as two separate abundance indices. The individual abundance indices were assigned the estimated observation error from the survey (summer c.v. 13–25%, winter c.v. 24–55%). Separate length-based selectivities were estimated for the seasonal trawl survey indices, parameterised using the double normal functional form.

Two sets of recent CPUE indices were incorporated in the model: CPUE indices for the target TAR set net fishery and CPUE indices for a mixed target species bottom trawl fishery. All observations were assumed to have a c.v. of 20% for both sets of indices. The relatively high precision associated with these indices reflects the presumption that the CPUE indices represent the best available abundance indices for the TAR 3 stock and show little variability between adjacent years. The age frequency samples were assigned an effective sample size of 10 based on an initial examination of the data weighting, following the approach of Francis (2011).

Preliminary model runs incorporated the entire catch history and started the model at equilibrium in 1932. However, there is considerable uncertainty associated with the annual catches prior to 1980, particularly the earliest period, and an alternative model option was configured that started in 1980. This approach initialised the model by estimating the initial (equilibrium) fishing mortality rates for the two commercial fisheries based on the observed age structure from the 1987 research survey. Recruitment was assumed to be at equilibrium levels during the early model period. The resulting model yielded substantially higher estimates of 1980 biomass and lower estimates of fishing mortality compared to the full catch history model and a considerably different trajectory of absolute biomass from 1980 to 2010. These comparative model results highlight the sensitivity to assumptions relating to initial starting conditions. Nonetheless, given the uncertainties associated with the early catch history, the model starting in 1980 was selected as the preferred model option (base model). Subsequent model results are presented for this option only.

The base model produced a relatively poor fit to the trawl survey indices, partly reflecting the high variability associated with the indices (Figure 23). There was a good fit to the BT CPUE indices, while the model fit to the SN CPUE indices was poor, particularly to the CPUE peak in 2002 and the steep decline in CPUE during 2002–07 (Figure 23). Fits to the length frequency data from the winter and summer trawl surveys were acceptable (Figure 24 and Figure 25).

There was a good fit to the two years of age frequency observations from the TAR 3 trawl catch (2010 and 2011) (Figure 26). The trawl fishery selectivity was estimated to peak for the 3–5 year age classes and to decline for older ages, with a low selectivity (less than 0.1) for the 10+ year age classes. This meant that the age frequency data provided only very limited information regarding relative year class strengths prior to 2005 and that the model had considerable freedom to estimate recruitment deviates to fit the BT CPUE indices.

In contrast, there was a poor fit to the set net age frequency data (Figure 26). The model over-estimated the proportion of older (8+ year) fish in the catch and, correspondingly under-estimated the proportion of younger fish (3–7 years). Relaxing the selectivity assumptions of the set net fishery by allowing lower selectivity of the older age classes (by assuming a double normal rather than logistic selectivity function) improved the fit to the SN CPUE indices and SN age composition data (Figure 26) while not substantially changing the pattern of recent recruitment. This change in the SN selectivity assumption also resulted in a small improvement in the fit to the BT CPUE indices (Figure 27). These results appear to be insensitive to a range of other model assumptions (especially steepness and *sigmaR*), given the assumed level of natural mortality.

Levels of total stock biomass and spawning biomass were highly sensitive to the assumptions relating to the set net selectivity. Virgin spawning biomass levels were comparable between the two setnet selectivity models; however, the initial (1980) biomass levels differed considerably between these two models (Figure 28): with the logistic SN model initial biomass being 7 212 t compared to 12 817 t for the model with double normal setnet selectivity. Nonetheless, in the absence of sufficient age frequency data from the commercial fisheries, it is not feasible to reliably estimate domed selectivity in the set net fishery. This conclusion was highlighted by the very high upper confidence limit estimated for the spawning biomass using a McMC approach (Figure 29).

Combined model

One plausible hypothesis to account for the lack of older fish in the observed age structure in the TAR 3 catch is the emigration of older fish to other areas. There is strong evidence from the tagging data that fish move from TAR 3 to TAR 2 and the Bay of Plenty, as well as to other areas. The structure of the *combined* model enabled the estimation of source-sink dynamics parameterised by estimating the distribution of recruitment between the two regions and age-specific movement from the southern region (TAR 3) to the northern region (TAR 2/BPLE).

The proportion of fish moving from south to north by age class was parameterised as a ramp function from the proportion that move at the age of first movement (2 years old) to the proportion that move at a maximum age (8 years old) . The proportion of fish moving at older age classes was assumed to be the same as the proportion that moved at the maximum age of the ramp. The estimated movement pattern was assumed to be temporally invariant.

The selectivity of the TAR 3 set net fishery and the shared selectivity of the TAR 2 and Bay of Plenty trawl fisheries was assumed to be logistic. The selectivity of the TAR 3 trawl fishery was assumed to be double normal.

The *combined* model included the entire model period (1932–2010) as the early age frequency data from TAR 2 were not adequate to reliably estimate the initial (exploited) population age structure for the northern region of the model. The remainder of the data assumptions were equivalent to those made for the spatially discrete models.

Overall, the model fits to the individual trawl survey biomass estimates were comparable to the two spatially discrete models (Figure 30). There was a good fit to the TAR3 BT CPUE indices; however the fits to the CPUE indices from the TAR 3 SN and TAR 2 BT fisheries were poor (Figure 30). In both cases, the models were unable to fit the peak in CPUE during the early 2000s and the subsequent decline in CPUE to 2007.

The poor fits to the age frequency data from the TAR 3 SN fishery were similar to the corresponding *TAR3* model (with logistic selectivity for the set net fishery) (Figure 31) and, given these results, it appeared that the inclusion of movement dynamics (emigration) in the model only marginally improved the fit to the TAR 3 SN age frequency data.

The fits to the TAR 2 and BPLE trawl age frequency were also poor, with the model over estimating the proportion of older fish in the age frequency distribution (Figure 32). It appeared that the model had limited freedom to move older fish from the southern region, as it is penalised by the poor fit to the age frequency data in the northern region, and the associated TAR 2 trawl CPUE indices. The quality of the fits to these data sets was insensitive to the assumed minimum and maximum ages of the movement parameterisation.

As with previous analyses, a reasonable fit to all CPUE and age frequency data sets could be achieved if the selectivity assumptions were relaxed for the main fisheries. For the two region model, the crucial assumption was the selectivity of the northern trawl fisheries. By assuming a double normal selectivity for these fisheries, the model was able to increase the movement of fish from the southern region, thereby substantially improving the fit to the TAR3 set net fishery data. The alternative model also had considerably greater freedom to fit the northern age frequency data and associated trawl CPUE indices.

Relaxing the selectivity assumptions resulted in a considerably higher level of spawning biomass, which was approximately 250% larger in the last 10 years compared to the equivalent model using a logistic selectivity (Figure 33). More crucially, the model options with a double normal selectivity for the northern trawl fisheries resulted in a much higher level of uncertainty, particularly at the upper bound, suggesting that very large biomass levels were possible (Figure 34).

3.5 Stock Assessment Conclusions

There is a high degree of uncertainty associated with the three assessment model options investigated. The two major sources of uncertainty are the lack of understanding of the stock structure of tarakihi off the east coast and the vulnerability of older tarakihi to the principal fisheries operating in these areas. To some extent, these sources of uncertainty are linked as stock hypotheses which may account for the varying population age structures observed in the different fishery areas.

The development of the assessment models was limited by the lack of adequate data from key components of the specific fisheries. The data from the early period of the fishery (prior to 1970) are limited to the reported catch from the fishery and there is concern regarding the reliability of these early data. There is virtually no information concerning trends in the relative abundance of the stock(s) prior to about 1990, with the exception of a pair of observations which indicate the trend in the TAR 2 stock during the 1960s and early 1970s. This is the period that is likely to have followed the greatest decline in stock biomass as total catches peaked during the 1950s and 1960s.

Uncertainty in the early catches will directly contribute to uncertainty in the estimates of the productivity of the stock. Alternative model options were investigated that attempted to estimate the exploited population age structure informed by age frequency samples collected in the fishery areas following the initial period of exploitation. These model options relied on early single age samples from the TAR 3 (1987) and TAR 2 (1971) fisheries to set the initial exploited age structure. Both samples were collected by research surveys that were designed to sample the entire tarakihi population. By necessity, it was assumed that the older age classes in the population were fully vulnerable to these surveys in each area. However, the lack of additional age samples from the period meant that the model estimates of initial fishing mortality were confounded with the estimates of the research trawl selectivity which were, in turn, sensitive to the relative strengths of recruitment at the time. Because the single age observations precluded the estimation of relative recruitment strengths, equilibrium recruitment had to be assumed.

These simplifying assumptions are likely to substantially influence the estimates of the initial age structure. This appeared to have been particularly problematic for the TAR 2/BPLE model, as discussed above. This age composition sample was dominated by younger age classes which may simply reflect the strength of the recruiting year classes or reduced vulnerability of older ages. However, the model interprets the relatively low proportion of older fish in the age composition as representing the accumulated impact of relatively high fishing mortality in the preceding period. For stocks that exhibit strong variability in recruitment, a single age sample is clearly inadequate to derive reliable estimates of the initial, exploited population age structure.

The 1987 TAR 3 age sample appeared to exhibit a lower level of recruitment variability and was composed of a broad range of age classes. This sample potentially represented a reasonable estimate of the underlying age composition, although without subsequent samples the extent of the interannual variability in the observed age structure (with observation error) is unknown. Nonetheless, Annala et al. (1990) considered these data sufficiently reliable to derive estimates of natural mortality and fishing mortality for the TAR 3 stock. The estimate of natural mortality was applied in the current analysis. It is worth noting that the *TAR3* model estimates of age-specific fishing mortality in 1987 were comparable to the published fishing mortality rates (0.02–0.06) from Annala et al. (1990), although this result is not surprising given that the model structure was consistent with the earlier study (i.e., fixed natural mortality and fully selected older age classes).

As noted above, a key source of uncertainty for all three models relates to the vulnerability of the older age classes to the fishery. Age frequency data from the commercial fishery are only available for the two final years of the model and show low frequencies of older fish. The limited number of age classes observed in the catch of the main fisheries can either be interpreted as the result of high fishing mortality rates or low vulnerability of the older age classes.

For the TAR 3 trawl fishery, it appears that the depth range of the main fishery (50–100 m) may be too shallow to adequately encounter the older fish in the population. An analysis of the length of tarakihi sampled by the ECSI *Kaharoa* trawl surveys revealed that larger tarakihi (greater than 30 cm F.L.) tended to increasingly dominate the catch in water deeper than 100 m. Conversely, fish less than 25 cm F.L. were generally limited to depths less than 100 m. Hence, the depth distribution of the TAR 3 commercial trawl catch is likely to be skewed towards the younger age classes in the population.

The assessment models reveal that the age structure of the set net catch and the trends in set net CPUE are inconsistent with the assumption that the older age classes are fully vulnerable to the fishery. The model predicts that, in the recent years, there should remain a considerable proportion of older fish in the population, given the assumed low natural mortality and the apparent exploitation rate, resulting from the relatively stable levels of catch from the fishery (informing estimates of R_0 and, therefore, potential yields).

The model runs that have the freedom to estimate a lower vulnerability for the older age classes to the set net fishery produce results that are much more consistent with the range of observations from the TAR 3 fishstock. However, these models estimate that a large (80–85%) proportion of the current adult biomass is invulnerable to the fishery and, therefore, not monitored by the principal abundance indices (primarily SN CPUE). The model estimates of fishery selectivity are dependent on the two recent observations of catch-at-age from the set net fishery. These estimates are also partly confounded by the model estimates of recent recruitment and, consequently, the estimates of selectivity are highly uncertain. A considerable time series of catch-at-age data would be required to reliably estimate the apparent domed selectivity of the set net fishery.

The lack of older fish in the TAR 3 catch composition immediately raises the question as to where this component of the stock may reside. The set net fishery appears to catch mainly pre-spawning fish (Beentjes 2011, 2012) whereas it might be expected that it would catch the full age range of adult spawning fish. Tarakihi are known to spawn off Cape Campbell and this region was the focus of trawling conducted by Annala (1990). The trawl fishery in this area was not included in the recent catch sampling programme and future sampling of this component of the fishery may provide additional information about the underlying age composition of the adult spawning population.

Similarly, recent sampling of the TAR 2 trawl fishery also yielded few fish in the older (8+ year) age classes. This sampling was representative of the distribution of the commercial trawl catch and encompassed the main depth range of tarakihi (Parker & Fu 2011). Furthermore, the sampled landings included catches from around East Cape (Statistical Areas 011 and 012) which has been identified as an important spawning area. As with the *TAR3* model, the *TAR2/BPLE* models were unable to reconcile the observed lack of older fish in the catch unless it was assumed that the selectivity of these older age classes was (very) low. The resulting models estimated that a large (about 80%) proportion of the spawning biomass was invulnerable to the commercial fishery and, therefore, not monitored by the main stock abundance indices (TAR 2 CPUE).

A potential explanation for the low proportion of older fish observed in the TAR 3 fishery is the emigration of tarakihi from the main fishery areas. The *combined* model investigated the linkage between the TAR 3 and TAR2/BPLE areas via the estimation of movement from the southern area to the northern area. Such movement is consistent with the range of observations from the fisheries. This additional modelled spatial structure resulted in a large proportion of the fish recruited in the southern region migrating to the northern region. While the resulting model improved the fit to the TAR 3 set net data (compared to discrete stock models that assumed logistic selectivity), the model still substantially over estimated the proportion of older fish in the set net catch, indicating that the introduction of the movement dynamics was not sufficient to address the conflict amongst the TAR 3 data sets.

Furthermore, the spatially structured model did not address the lack of fit to the TAR 2 age frequency data and resulted in a substantial deterioration in the fit to the TAR 2 trawl CPUE indices. It is possible that further increasing the complexity of the spatial structure of the model could improve the fit to the TAR 2 data sets. For example, one potential hypothesis is that tarakihi continue to migrate northwards from the TAR2/BPLE areas thus reducing the availability of the older fish to the TAR2/BPLE trawl fisheries. However, the limited observations from the east Northland fishery are not consistent with this stock hypothesis and insufficient data are available to attempt to model the associated movement dynamics.

Given the uncertainty associated with the key model assumptions, particularly related to fishery selectivity and stock structure, it was concluded by the NINS WG that the range of models investigated were not suitable for the formulation of management advice for the tarakihi stocks along the east coast of New Zealand. It is considered unlikely that a more definitive stock assessment could be undertaken until a reasonable time-series (5–10 years) of age frequency data was available from the main commercial fisheries. These data would improve the model estimation of fishery selectivity as well as year class strengths. In addition, a range of other analyses and additional data would improve the current models and contribute towards increasing the understanding of tarakihi stock relationships.

4. RESEARCH RECOMMENDATIONS

This study highlights the lack of information currently available to adequately monitor and assess the stock (or stocks) of an important inshore fish species. We have identified a number of key research requirements to progress our understanding of the stock structure of tarakihi along the east coast of mainland New Zealand and over a wider area. Many of the data sets generated by these proposals would also have direct application to the monitoring and assessment of discrete tarakihi stocks (either biological stocks or unit stocks defined for the purpose of fisheries management). The following represent our main research recommendations, listed in an approximate order of priority based on the likely utility of the resulting data.

1. Continued analysis of CPUE data from the key tarakihi fisheries within TAR 1, 2, 3 and, for comparative purposes, TAR 7 (following the methodology of Starr & Kendrick 2012): The ongoing comparison of CPUE index series from the individual fisheries (and sub-areas) will provide further insights into the relative trends in stock abundance among areas, providing an indication of possible stock linkages. In the short-term, CPUE indices from the main fisheries will continue to provide the principal monitoring tool for these tarakihi stock units, which should be updated and reviewed on a regular basis (every 2–3 years). Over the longer term, CPUE indices are likely to be a key source of stock abundance information in any future stock assessment models.
2. Age frequency sampling of the commercial catch from key tarakihi fisheries: this will provide comparative information regarding patterns of recent recruitments in the main fishery areas. This information has already enabled some discrimination of variable recruitment processes in separate fishery areas, indicating potential stock boundaries. However, given the limited number of age classes that dominate the catch in the TAR 2 and TAR 3 fisheries, a sustained period (at least 5 years, possibly longer) of annual sampling is required to construct a time-series of age frequency data that will be adequate to resolve the relative strength of annual recruitments over a reasonable time period (say 10 years). To reduce the costs of such a sampling programme, it may be preferable to restrict sampling to a number of key fisheries, specifically the TAR 2 trawl fishery, the TAR 3 set-net fishery and the east Northland trawl fishery. It would also be worthwhile to extend sampling to include the WCNI trawl fishery, at least for a short period, to allow direct comparison of this age structure with other fisheries. The collection of age frequency data would, over the longer term, be incorporated in the respective tarakihi stock assessments. A reasonable time series of data is required to enable the estimation of key parameters in the stock assessment models (selectivity and recruitments) which are necessarily highly confounded.
3. Ageing of existing otolith collections from the *Kaharoa* inshore trawl surveys (ECSI and ECNI) and the establishment of an ongoing ageing programme from future trawl surveys (ECSI): the existing otolith collections provide an essential opportunity to use existing data to improve historical estimates of tarakihi year class strengths. Furthermore, the ECNI survey is considered to have adequately sampled larger (recruited) tarakihi and the available age frequency data may be adequate to derive estimates of the age composition of the tarakihi population at the time of the surveys (mid 1990s). It would be informative to compare the resulting survey age compositions with the recent age frequency samples from the TAR 2 commercial catch.
4. Directed sampling of the age composition of the spawning, adult component of TAR 2 and TAR 3 populations: the recent age frequency samples derived from catch sampling of the trawl and set net fisheries have been characterised by a very low proportion of fish in the older age classes (greater than 7 years). The preliminary stock assessment models suggested that one explanation of this observation was that older fish in these fisheries were subject to a

lower vulnerability. However, there are no direct observations that support this conclusion and the stock status conclusions from these assessment models were very sensitive to the assumptions related to selectivity. Directed sampling of the main spawning areas for tarakihi in TAR 2 (off East Cape) and TAR 3 (off Cape Farewell) may provide a better understanding of the age composition of the adult component of the stock (compared to sampling the main components of the catch). Sampling of the spawning population could be undertaken either by sampling the catch from directed (research) fishing or from a dedicated research survey (following the earlier surveys of Vooren & Tong 1973 and Annala et al. 1990).

5. Tagging of the spawning population of tarakihi off East Cape: The recovery of tagged fish from releases in this area has the potential to increase understanding of the stock relationships along the east coast of New Zealand. This can be achieved by determining the degree of residence of adult fish in this area and the linkage between other areas (especially TAR 3 and the east Northland fishery area). Quantitative tagging projects are expensive to design and conduct.
6. Conduct a trawl survey along ECNI: this should be designed to be comparable with the time series of *Kaharoa* surveys undertaken during the mid 1990s. The earlier surveys appeared to adequately monitor tarakihi. Repeating such a survey would generate an estimate of tarakihi biomass approximately 20 years after the last survey (in 1996). This additional survey index value could assist the validation of the time-series of TAR 2 CPUE indices as a monitoring tool for this component of the stock. However, a single survey is likely to be inadequate to establish a new, recent base-line and a minimum of three surveys is probably required.

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Table 1: Stock assessment model parameters and assumptions for the three different base model options.

	Base model		
	TAR2/BPLE	*TAR3*	*Combined*
Model period	1933–2011	1980–2011	1932–2011
SRR R_0	Estimated	Estimated	Estimated
SRR *h*	0.75	0.75	0.75
sigmaR	0.6	0.6	0.6
Recruitment deviates	1990–2008	1987–2008	1987–2008
Recruit distribution	-	-	Yes
Biological parameters			
(female, male)			
Natural mortality *M*	0.1, 0.1	0.1, 0.1	0.1,0.1
Length-weight *a*	4.0×10^{-5}, 4.33×10^{-5}	4.0×10^{-5}, 4.33×10^{-5}	4.0×10^{-5}, 4.33×10^{-5}
b	2.79, 2.77	2.79, 2.77	2.79, 2.77
Growth *Lmin*	15.37, 16.56	15.37, 16.56	15.37, 16.56
Lmax	44.6, 42.1	44.6, 42.1	44.6, 42.1
k	0.2009, 0.2085	0.2009, 0.2085	0.2009, 0.2085
Movement	No	No	Yes
Minimum age	-	-	2
Maximum age	-	-	8
Trawl survey LF			
ECSI summer	-	ESS = 10, double normal	ESS = 10, double normal
ECSI winter	-	ESS = 10, double normal	ESS = 10, double normal
ECNI	ESS = 10, double normal	-	ESS = 10, double normal
Trawl survey biomass			
ECSI summer	-	Yes	Yes
ECSI winter	-	Yes	Yes
ECNI	Yes	-	Yes
CPUE			
TAR 2 early	c.v. 30%	-	c.v. 30%
TAR 2 BT	c.v. 20%	-	c.v. 20%
TAR 3 BT	-	c.v. 20%	c.v. 20%
TAR 3 SN	-	c.v. 20%	c.v. 20%
Age frequency			
1987 survey	-	ESS = 10, logistic	ESS = 10, logistic
TAR 1 BPLE	ESS=10, logistic[1]	-	ESS=10, logistic[1]
TAR 2 BT	ESS=10, logistic[1]	-	ESS=10, logistic[1]
TAR 3 BT	-	ESS=10, double normal	ESS=10
TAR 3 SN	-	ESS=10, logistic	ESS=10, logistic

Notes:

[1] Selectivities for the TAR 2 and BPLE trawl fisheries are assumed to be equivalent.
[2] ESS is Effective Sample Size.

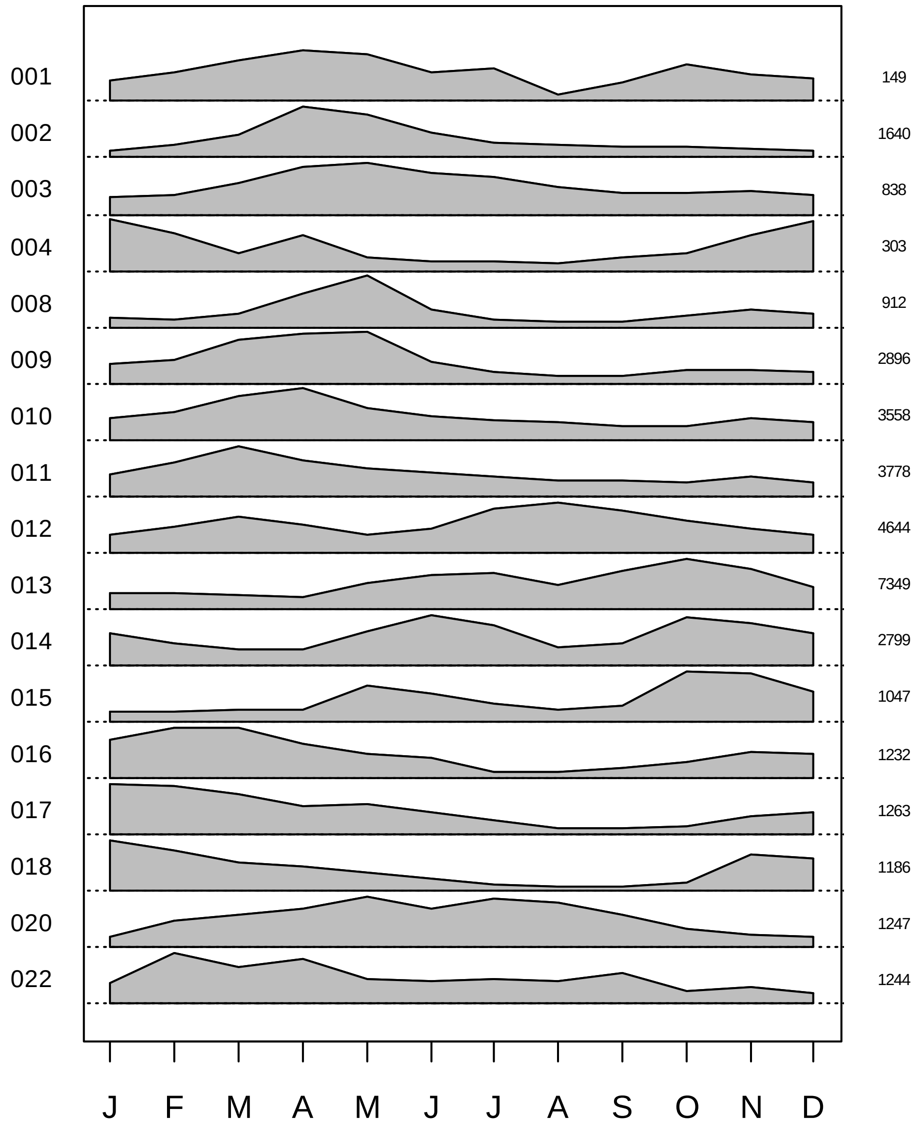

Figure 1: Proportional monthly distribution of tarakihi catch by the target bottom trawl fishery by statistical area (panels) aggregated over the 1989/90–2009/10 fishing years. For each statistical area, the monthly catch is expressed relative to the maximum monthly catch for the area. The total catch (tonnes) from each statistical area for the period is presented in the right margin.

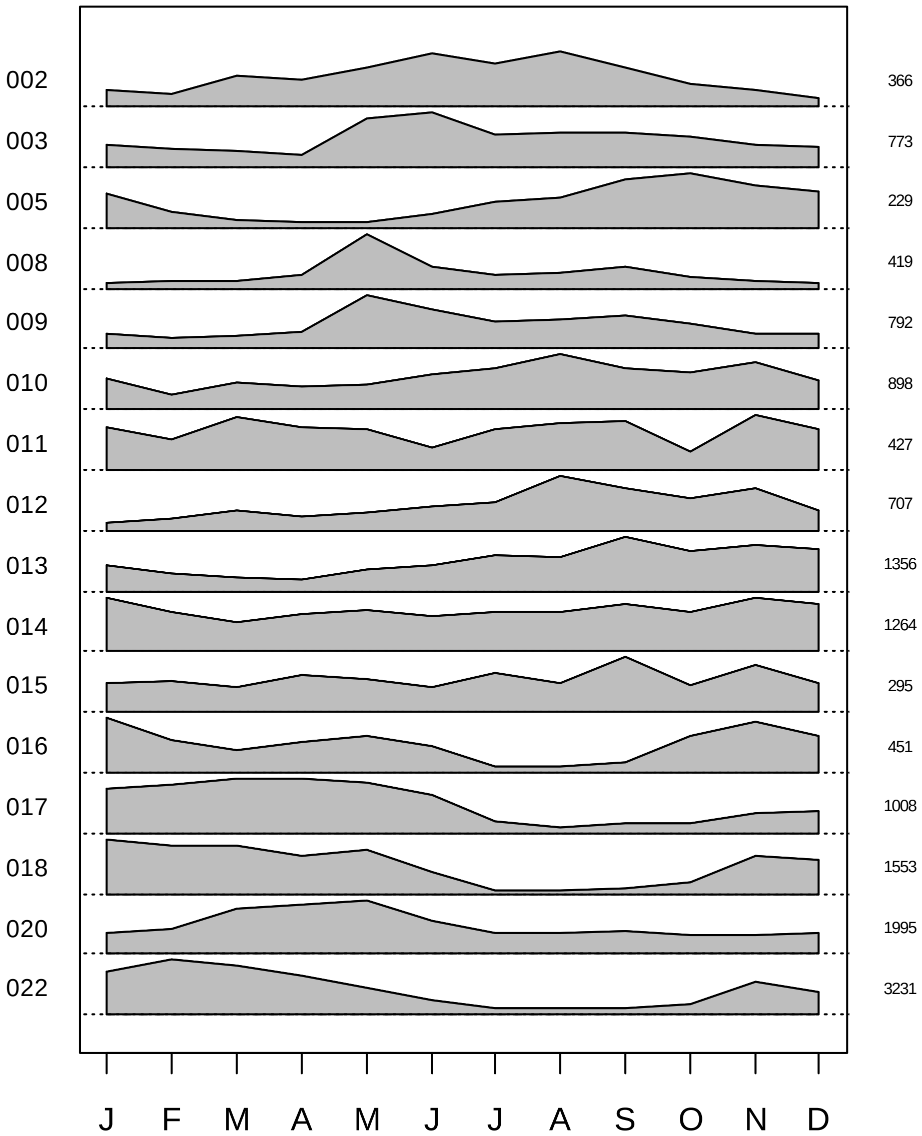

Figure 2: Proportional monthly distribution of tarakihi catch by the non target bottom trawl fishery by statistical area (panels) aggregated over the 1989/90–2009/10 fishing years. For each statistical area, the monthly catch is expressed relative to the maximum monthly catch for the area. The total catch (tonnes) from each statistical area for the period is presented in the right margin.

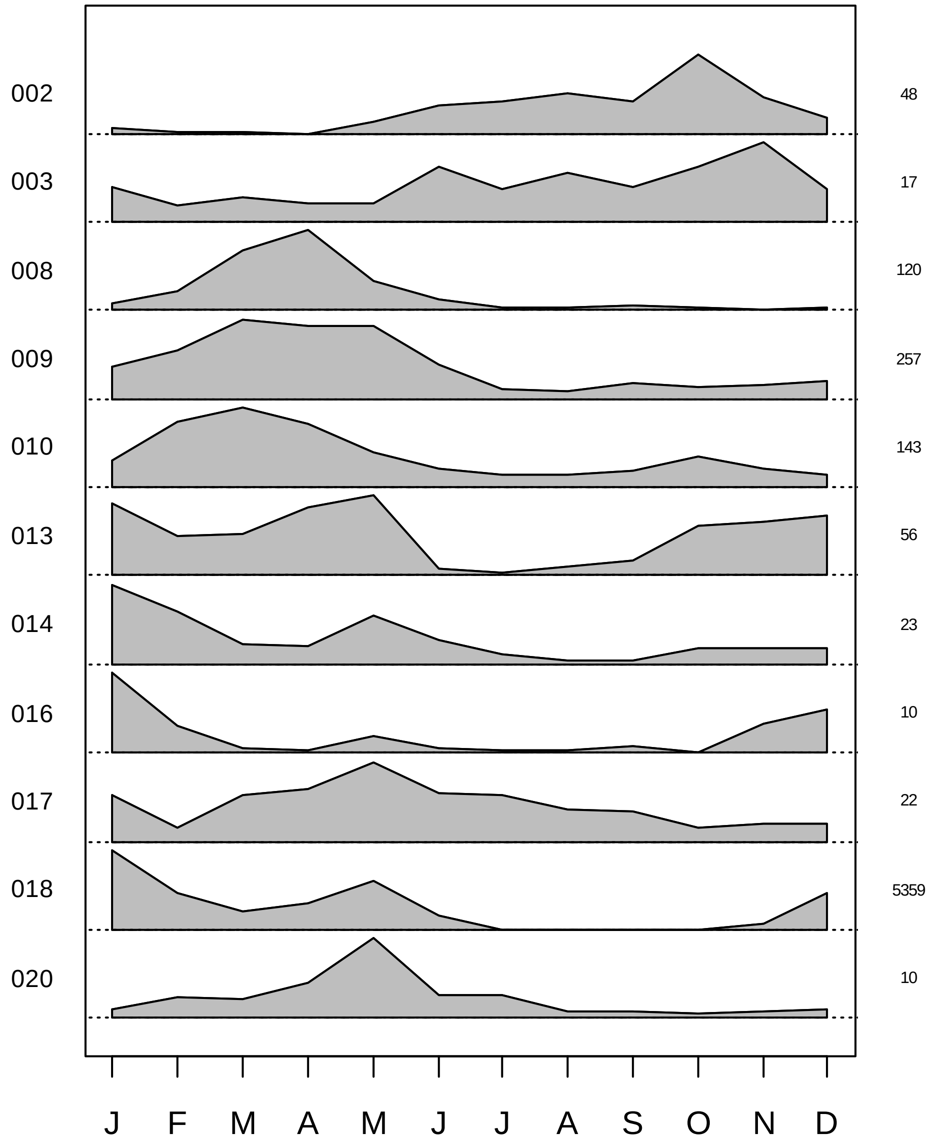

Figure 3: Proportional monthly distribution of tarakihi catch by the set net fishery by statistical area (panels) aggregated over the 1989/90–2009/10 fishing years. For each statistical area, the monthly catch is expressed relative to the maximum monthly catch for the area. The total catch (in tonnes) from each statistical area for the period is presented in the right margin.

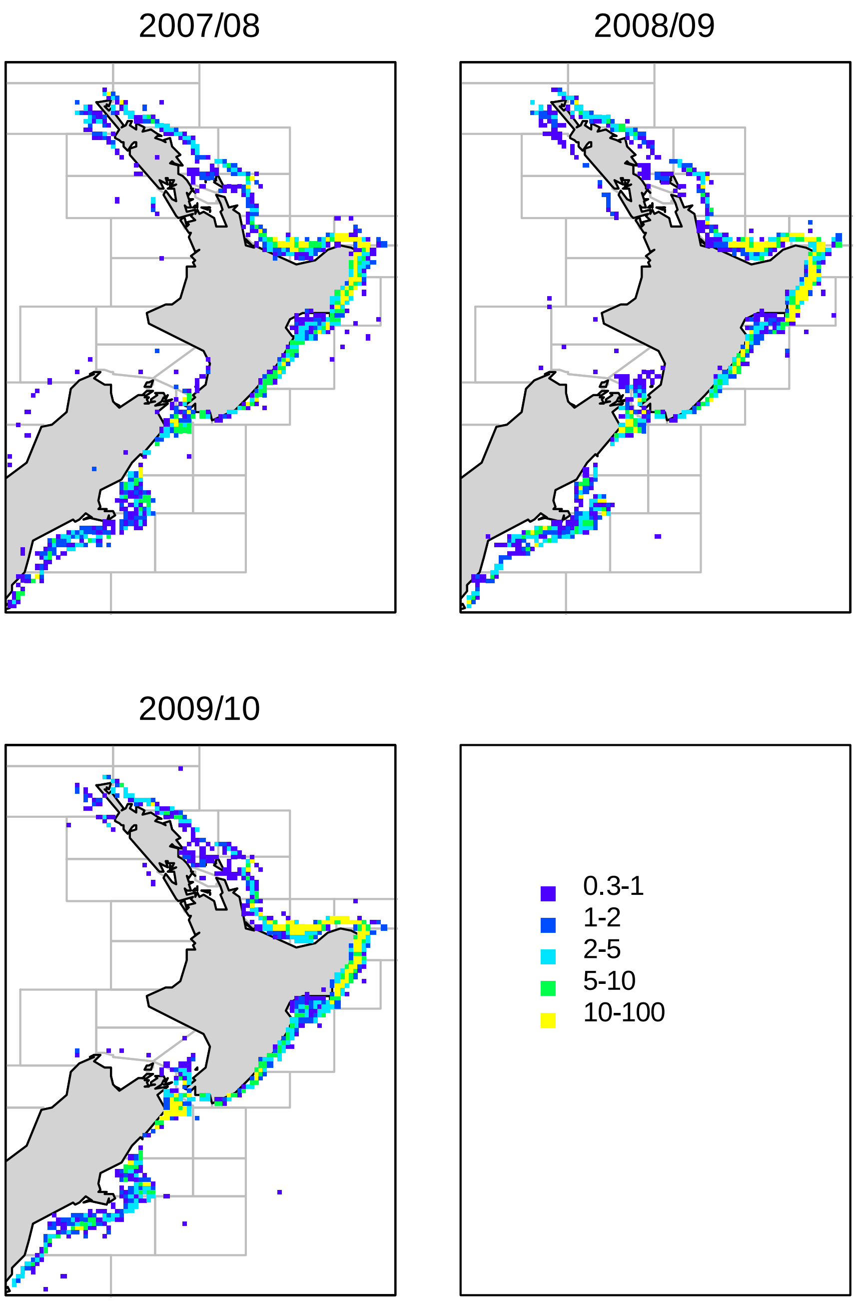

Figure 4: Distribution of total annual tarakihi trawl catch (t) by 0.1 degree lat/long cell for 2007/08, 2008/09 and 2009/10. Data are only included from fishing trips that caught tarakihi within statistical areas 001–024.

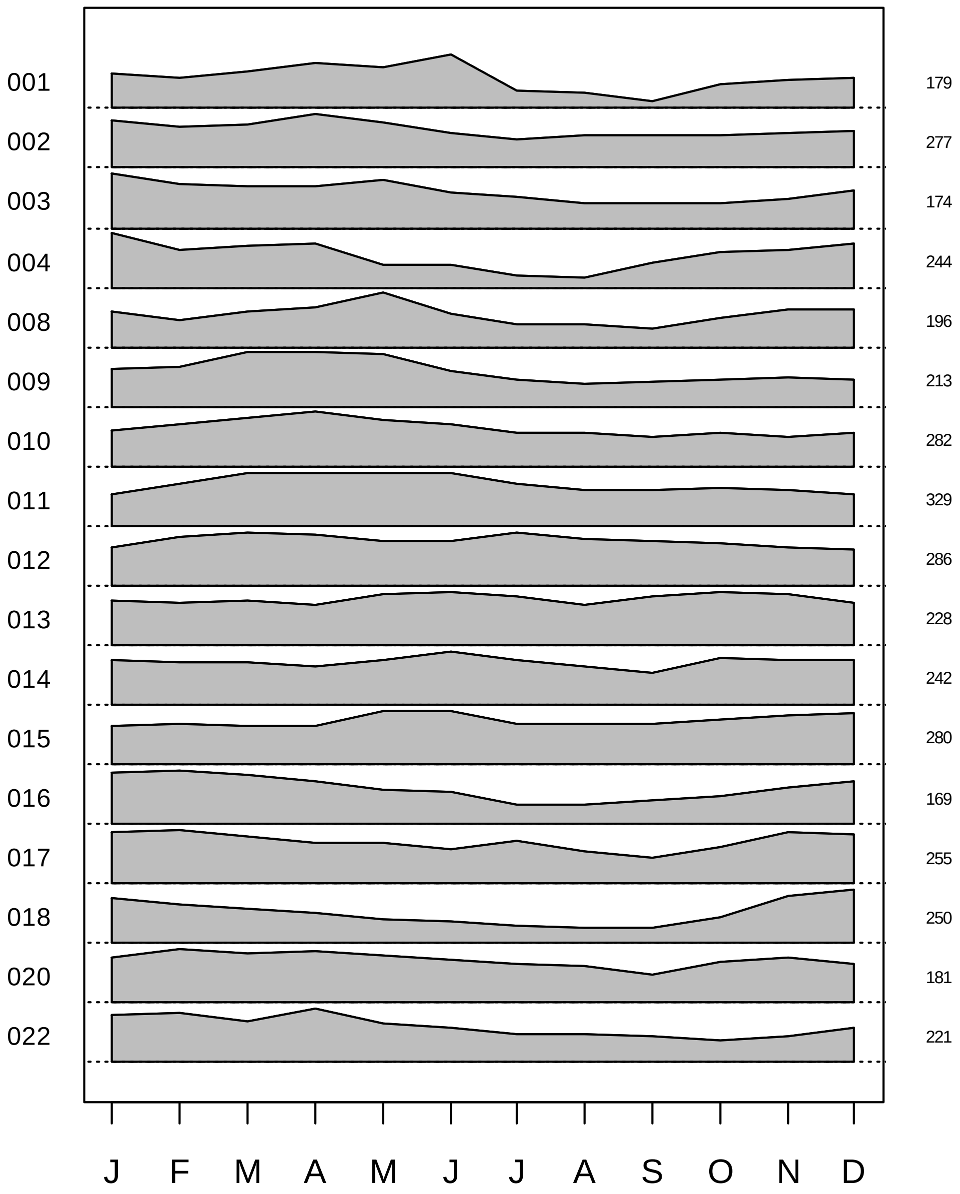

Figure 5: Proportional monthly average catch rate (kg per trawl) of tarakihi by the target bottom trawl fishery by statistical area (panels) aggregated over the 1989/90–2009/10 fishing years. For each statistical area, the monthly catch rate is expressed relative to the maximum monthly catch rate for the area. The average of the monthly catch rates for each statistical area is presented in the right margin.

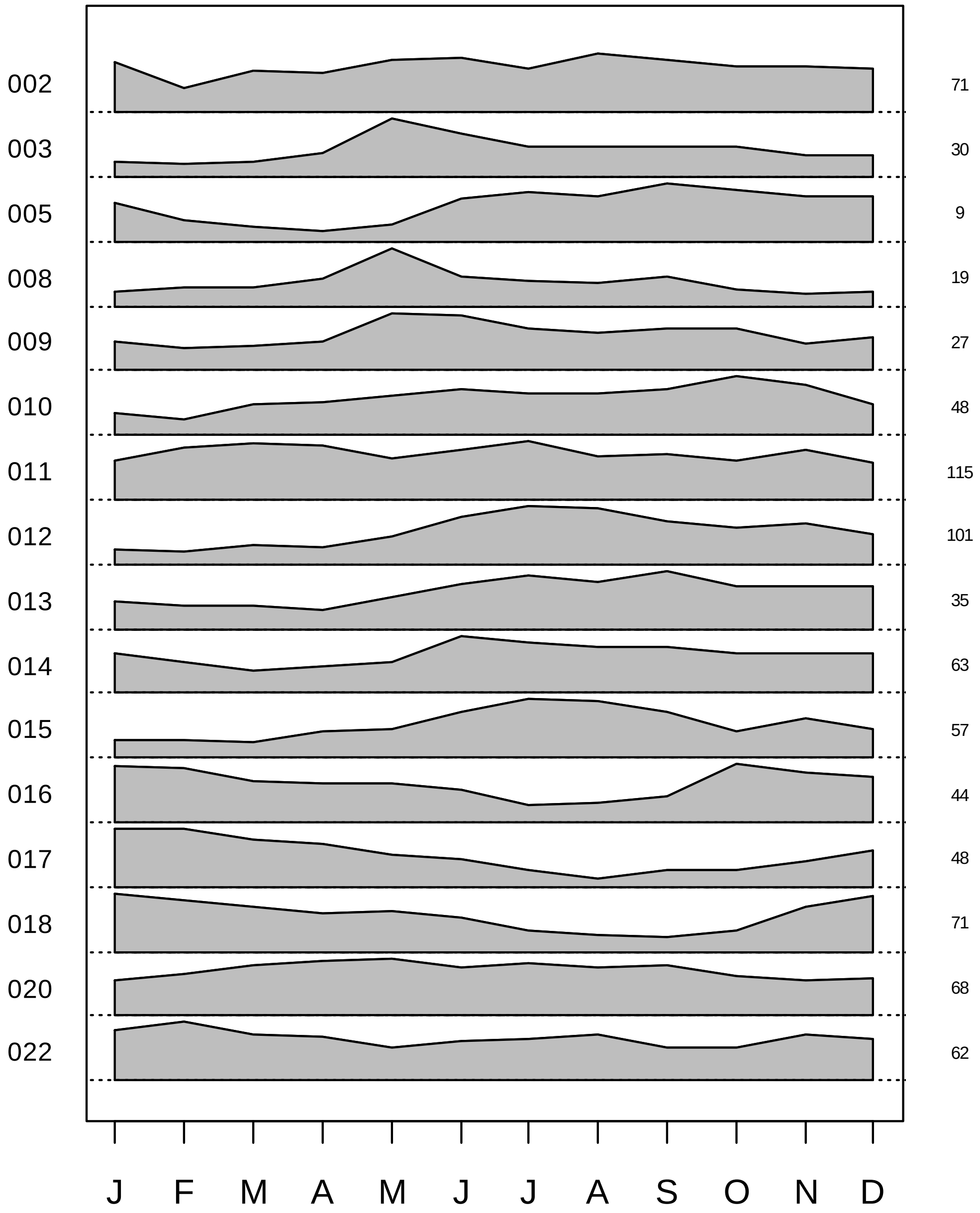

Figure 6: Proportional monthly average catch rate (kg per trawl) of tarakihi by the non target bottom trawl fishery by statistical area (panels) aggregated over the 1989/90–2009/10 fishing years. For each statistical area, the monthly catch rate is expressed relative to the maximum monthly catch rate for the area. The average of the monthly catch rates for each statistical area is presented in the right margin.

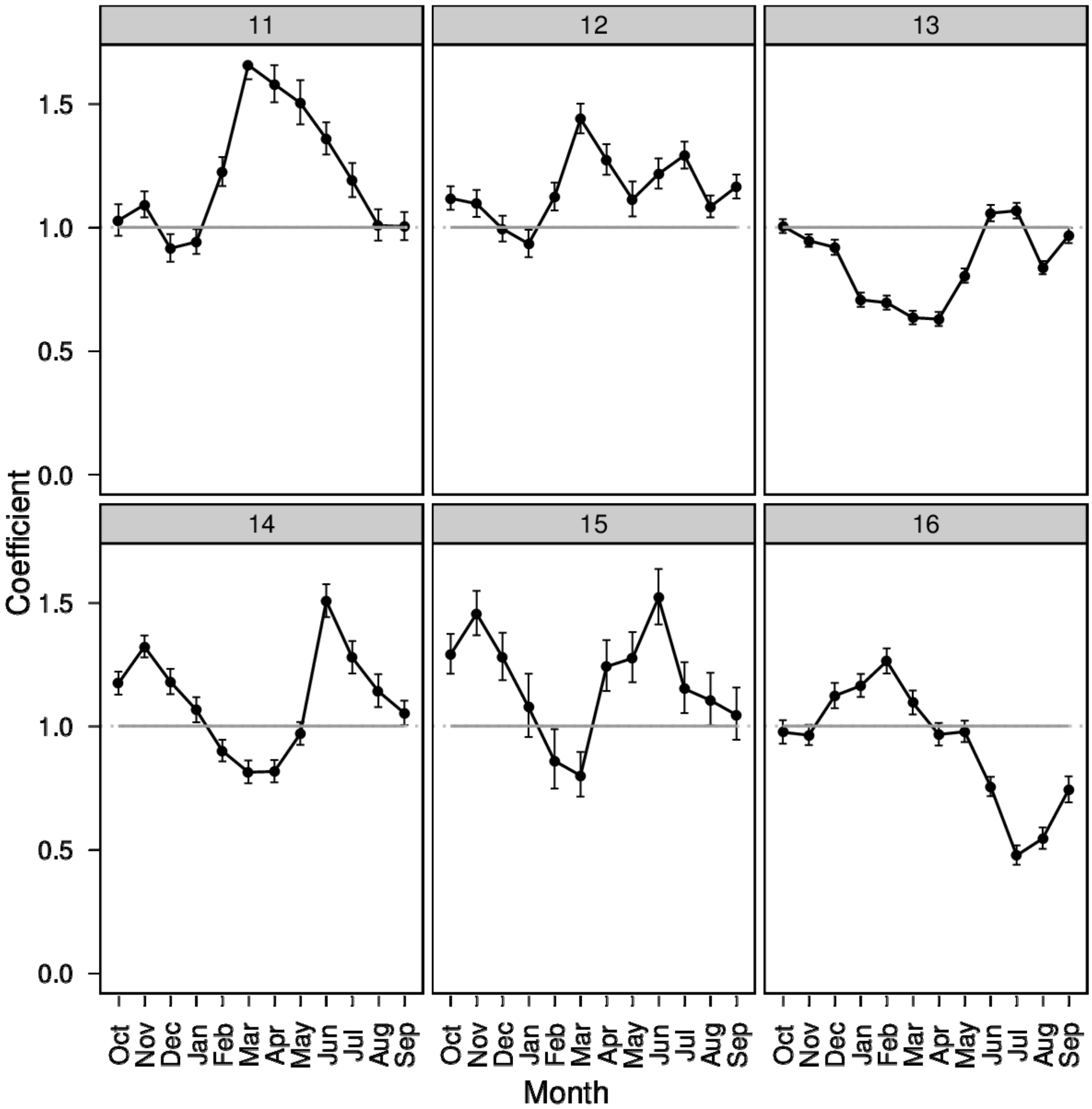

Figure 7: Residual implied coefficients for area×month interactions for the TAR2_BT_MIX CPUE analysis. Implied coefficients are calculated as the mean of the sum of area and month coefficients (if any; grey line) plus residuals (black points and line). The error bars indicate one standard error of residuals (from Starr & Kendrick 2012).

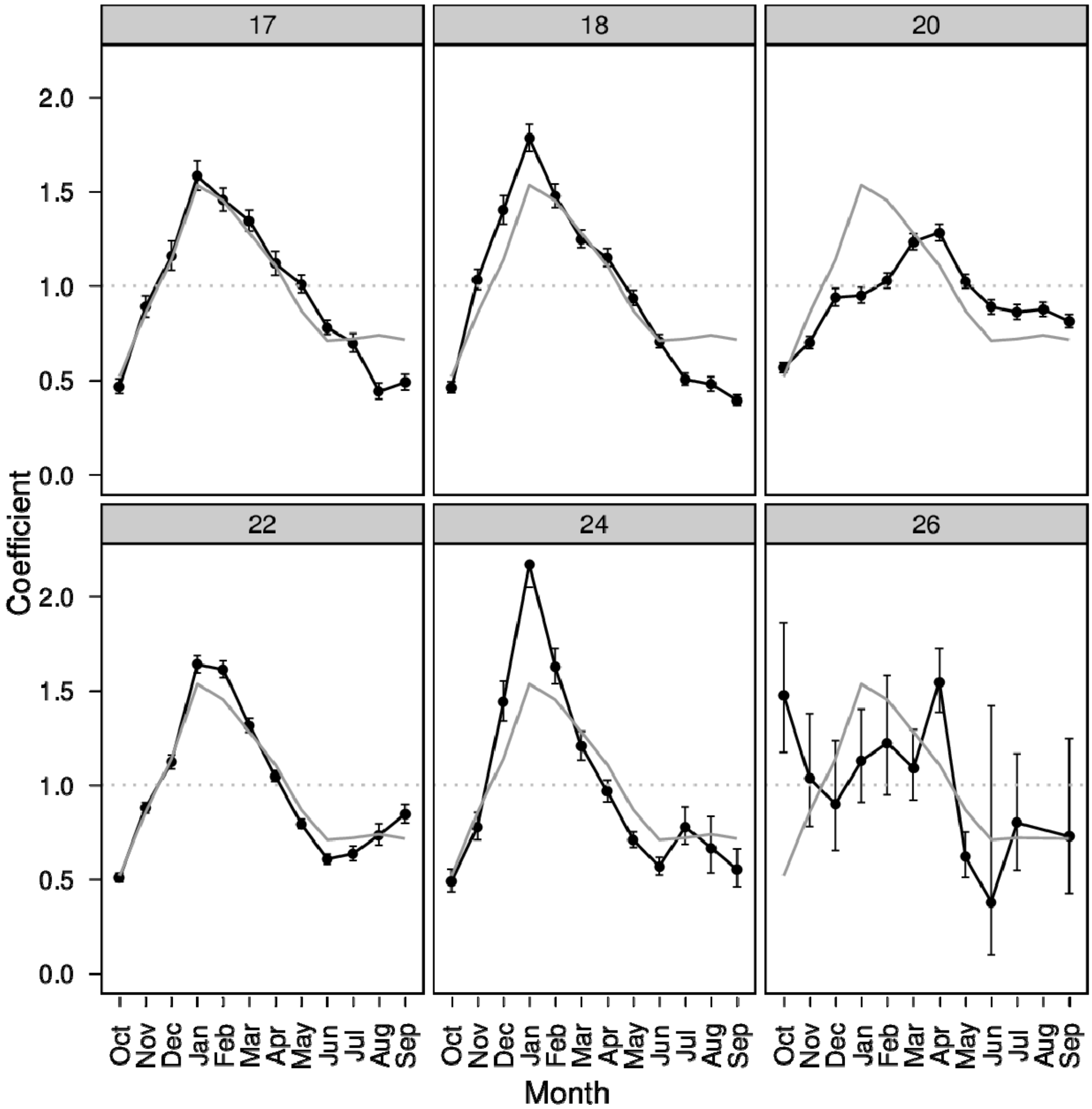

Figure 8: Residual implied coefficients for area/month interactions for the TAR3_BT_MIX CPUE analysis. Implied coefficients are calculated as the mean of the sum of area and month coefficients (if any; grey line) plus residuals (black points and line). The error bars indicate one standard error of residuals (from Starr & Kendrick 2012).

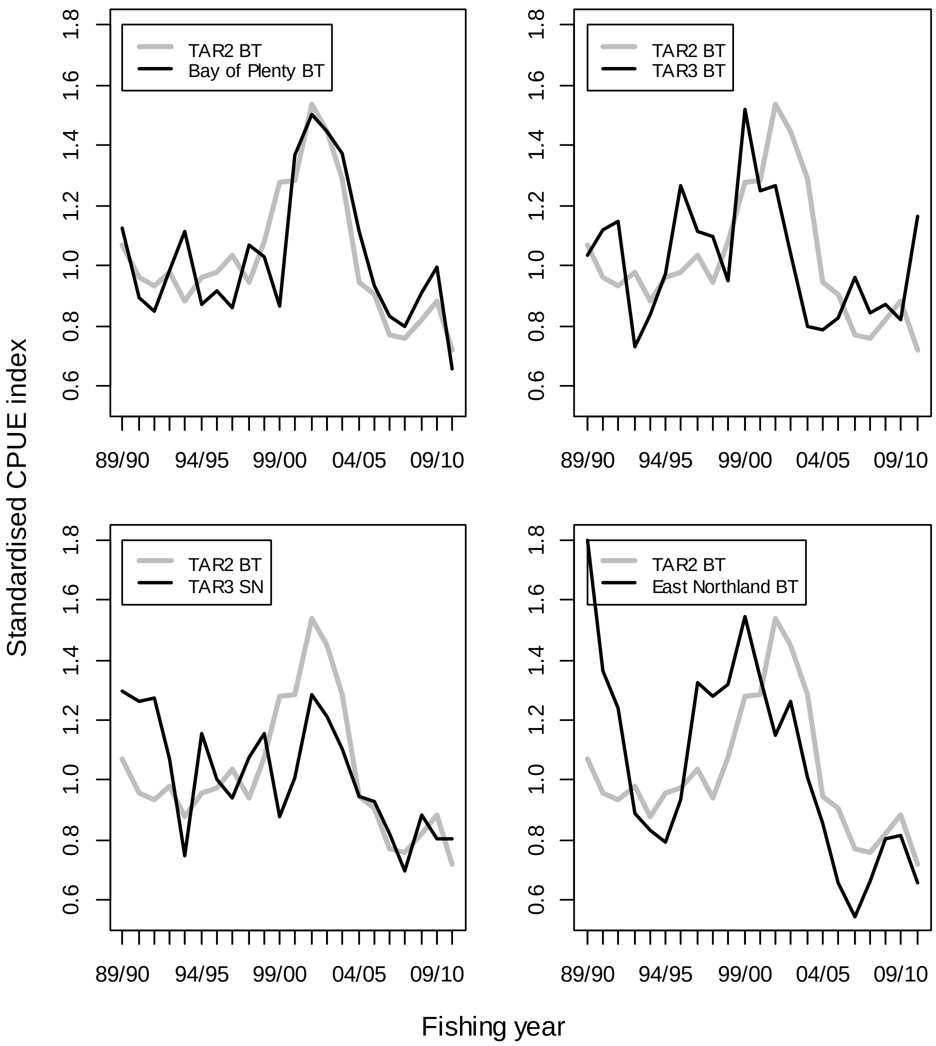

Figure 9: A comparison of fishery specific standardised CPUE indices for the main tarakihi fisheries along the east coast of mainland New Zealand (source: Starr & Kendrick 2012).

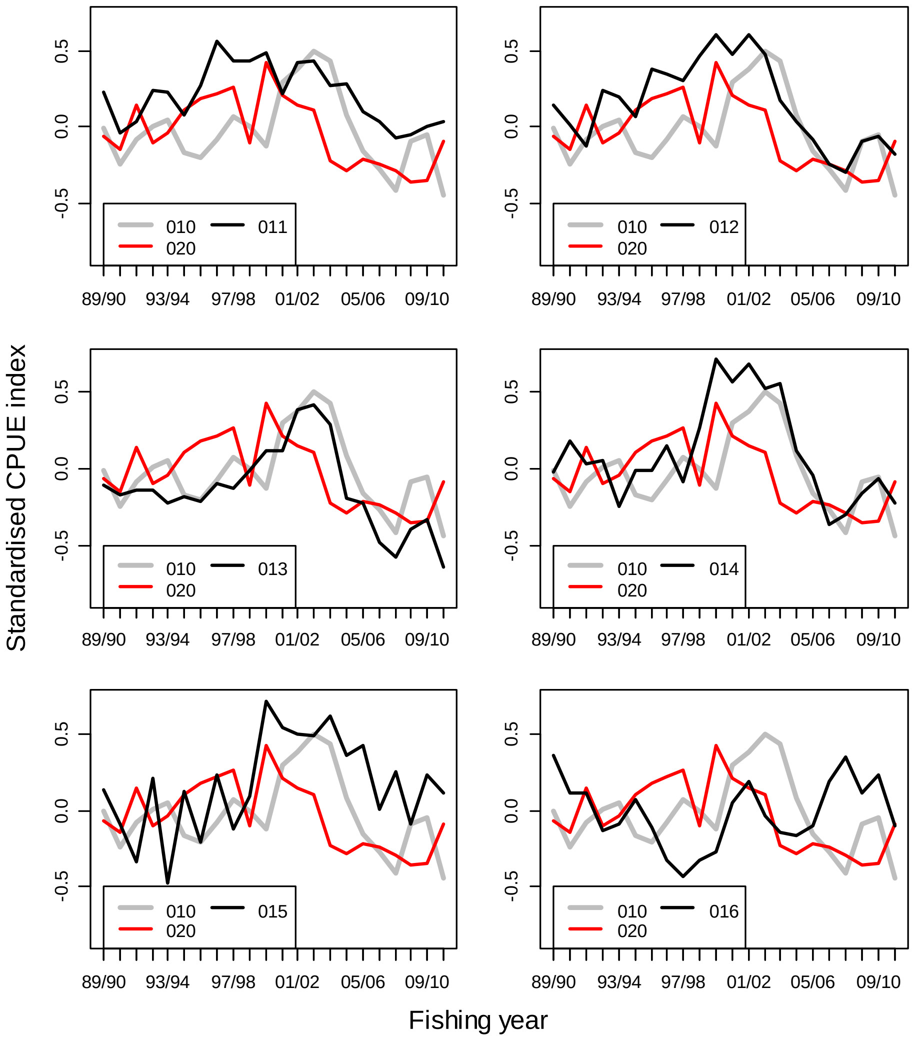

Figure 10: The statistical area: year interaction terms for the constituent statistical areas of TAR 2 (011–016) derived from the standardised CPUE analysis (MIX) (from Starr & Kendrick 2012). The indices from each statistical area are compared to CPUE indices from the Bay of Plenty fishery (statistical area 010) and the Canterbury Bight (020).

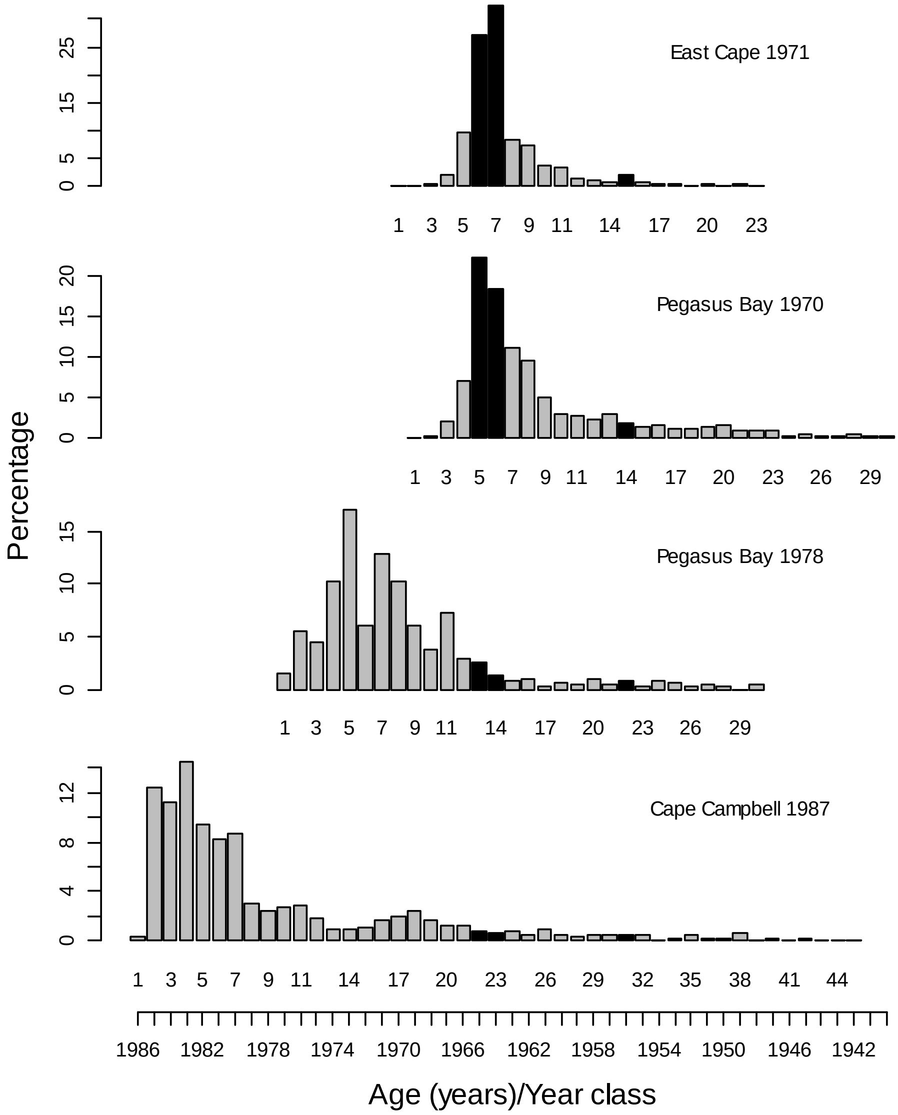

Figure 11: Age frequency distributions from *James Cook* trawl surveys off East Cape and within TAR 3. The age compositions are plotted against the respective year class of the cohort (x-axis). The black bars illustrate the 1956, 1964 and 1965 year classes that were evident as strong year classes in the East Cape sample.

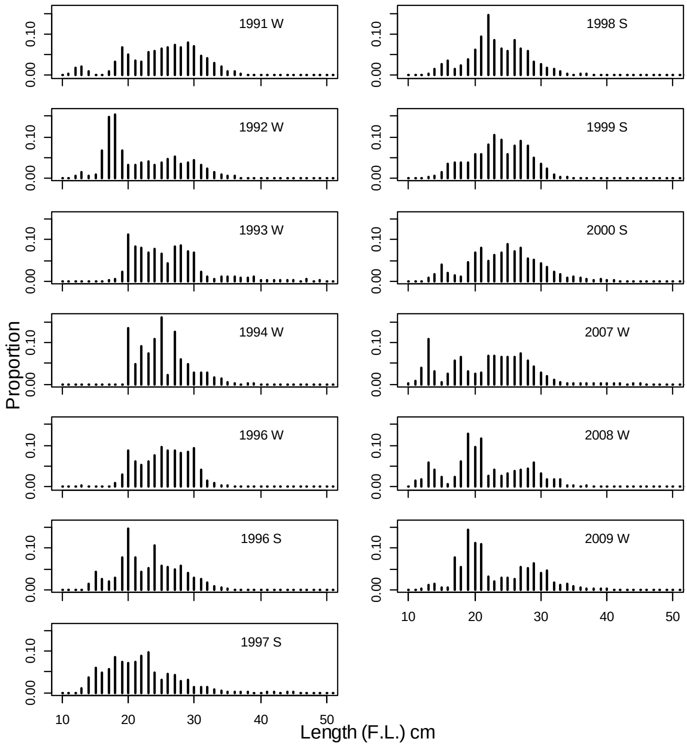

Figure 12: Scaled length frequency distributions of tarakihi from the series of winter (W) and summer (S) *Kaharoa* trawl surveys off the east coast of the South Island.

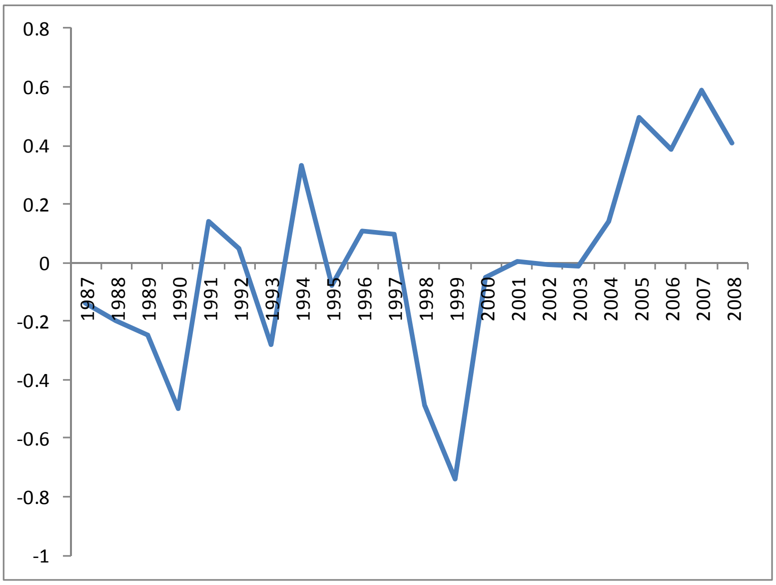

Figure 13: Estimated recruitment deviates from the *TAR3* assessment model (see Section 3.4).

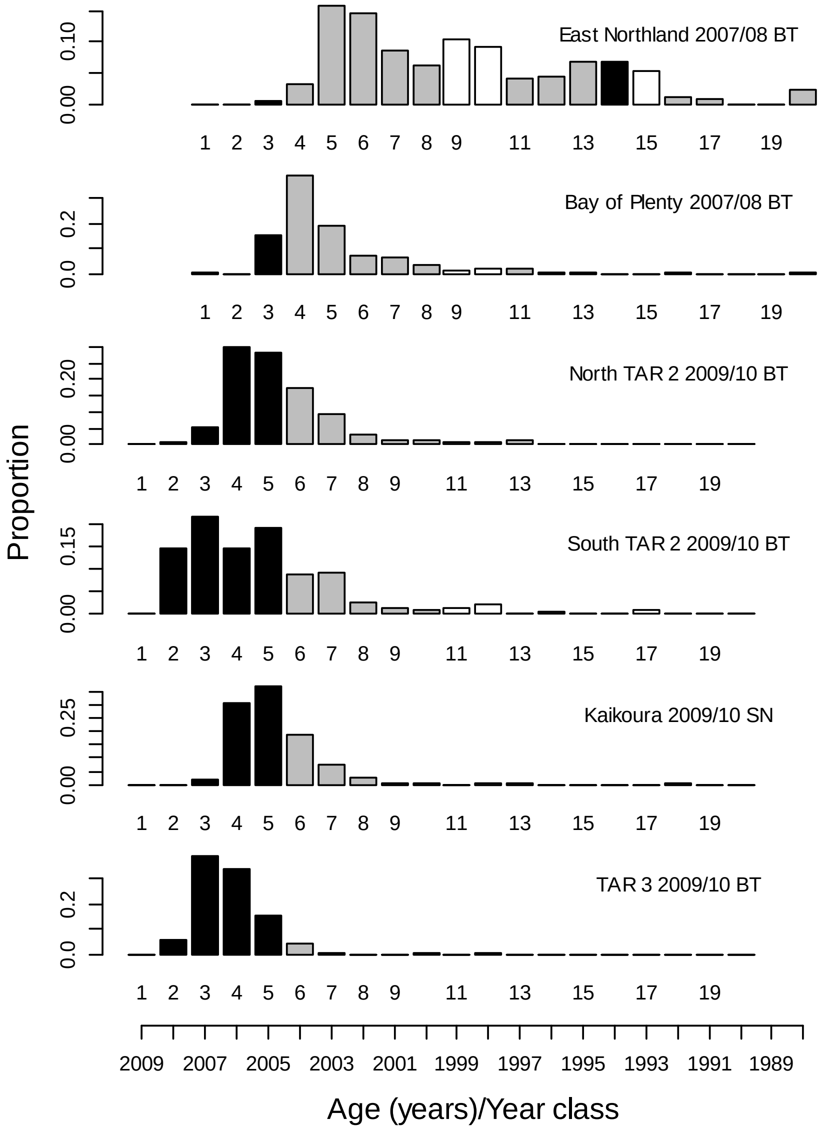

Figure 14: Age frequency distributions from recent sampling of the commercial tarakihi catch by area and fishing method. The primary x-axis corresponds to the year of spawning while the secondary x-axis is the age class when sampled. The black bars represent strong tarakihi year classes from the ECSI trawl survey (1994, 2005–2008) and white represents weak year classes (1990, 1993, 1998 and 1999).

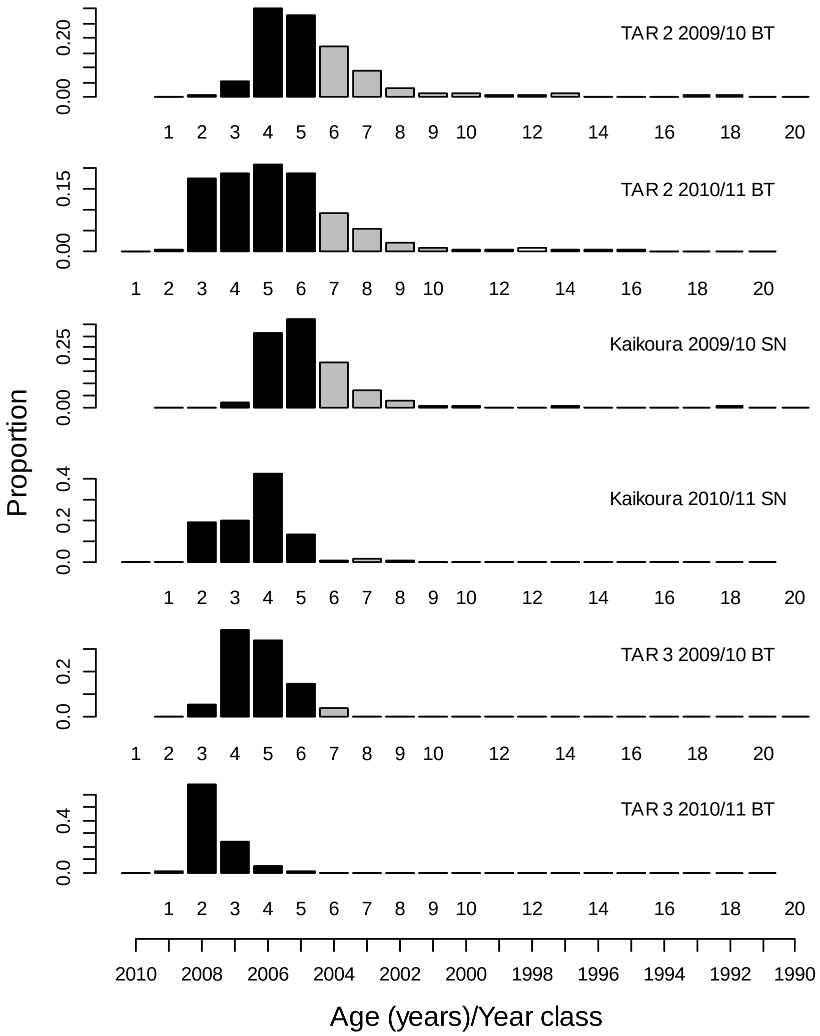

Figure 15: Age frequency distributions from consecutive years of sampling from the bottom trawl fisheries in TAR 2 and TAR 3 and the TAR 3 set net fishery. The primary x-axis corresponds to the year of spawning while the secondary x-axis is the age class when sampled. The black bars represent strong tarakihi year classes from the ECSI trawl survey (1994, 2005–2008) and white bars represent weak year classes (1990, 1993, 1998 and 1999).

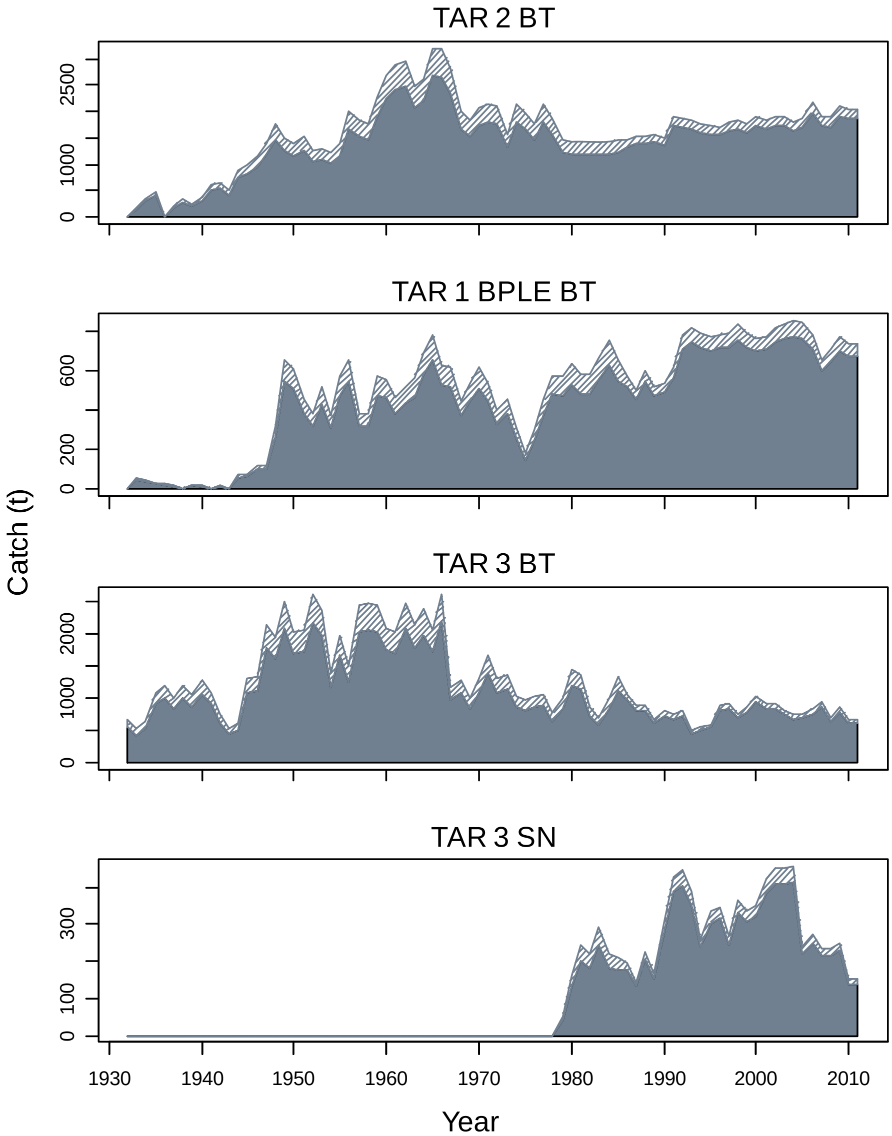

Figure 16: Annual catch of tarakihi for the main commercial fisheries included in the stock assessment. The solid portion represents the reported catch, while the shaded portion represents the assumed level of unreported catch.

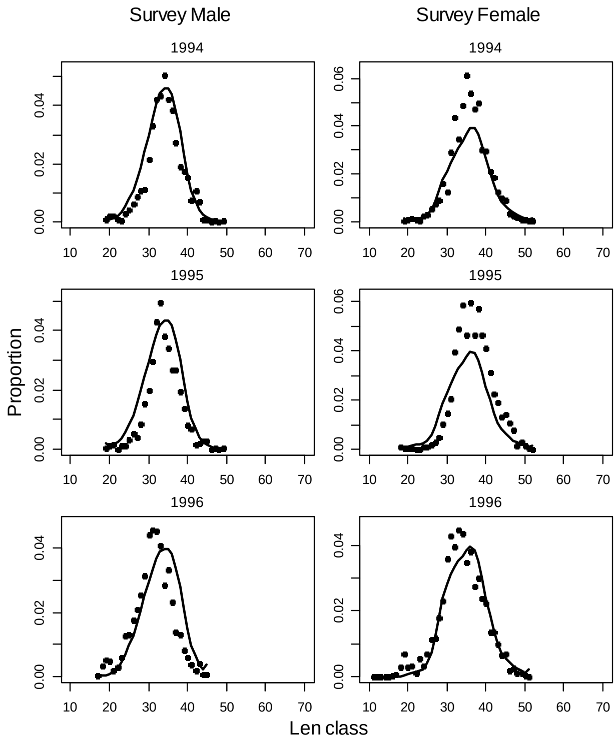

Figure 17: Observed (points) and predicted (lines) proportional length frequency distributions for the ECNI Kaharoa trawl survey length compositions included in the *TAR2/BPLE* base model.

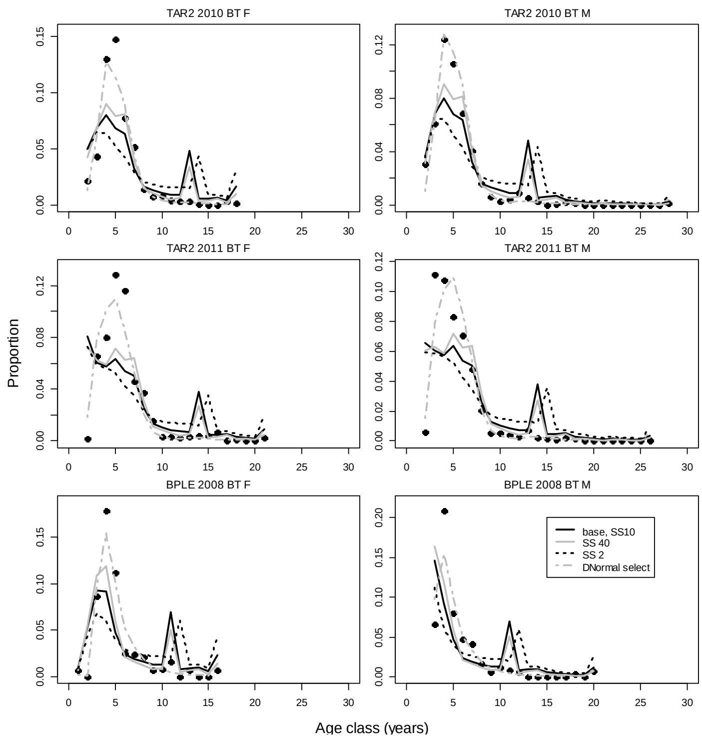

Figure 18: Observed (points) and predicted (lines) proportional age frequency distributions for the recent TAR 2 and Bay of Plenty trawl catch samples included in the TAR2/BPLE base model and alternative model options examining different weighting of the age frequency data (Effective Sample Size 2 and 40) and alternative selectivity function for the trawl fishery (DNormal select).

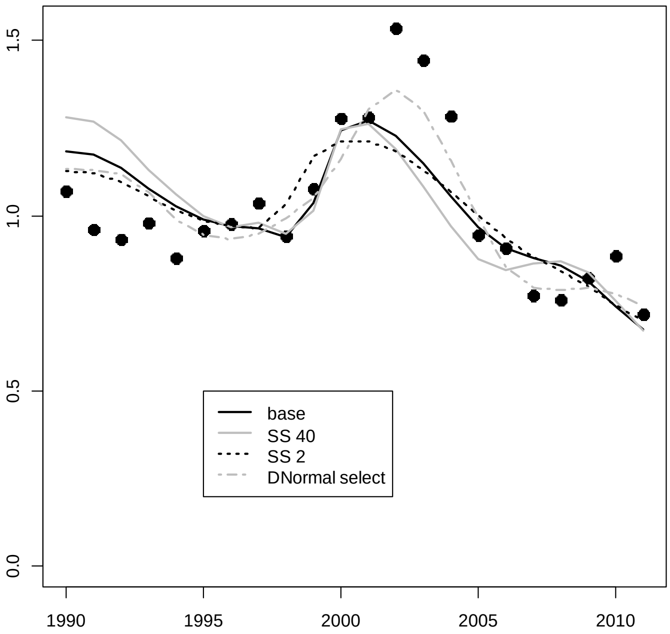

Figure 19: Observed (points) and predicted (lines) TAR 2 trawl CPUE indices from the *TAR2/BPLE* base model and alternative model options examining different weighting of the age frequency data (Effective Sample Size 2 and 40) and alternative selectivity function for the trawl fishery (DNormal select).

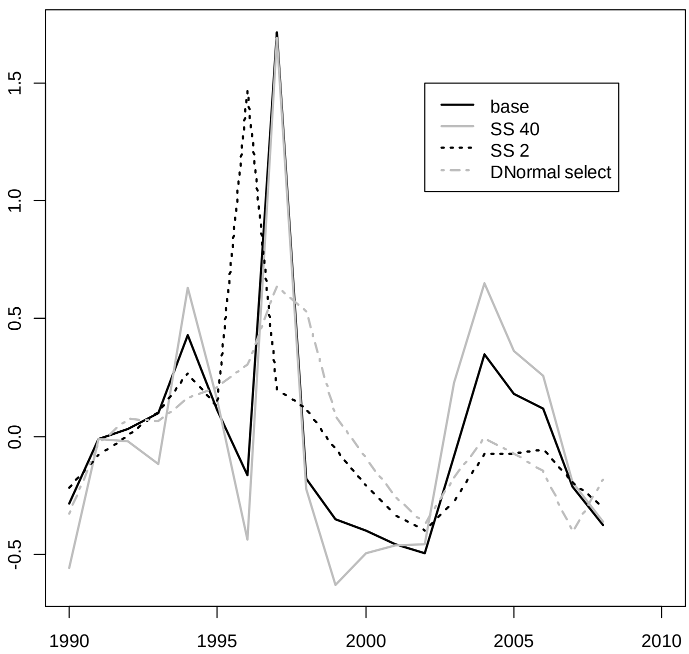

Figure 20: Estimated recruitment deviates from the *TAR2/BPLE* base model and alternative model options examining different weighting of the age frequency data (Effective Sample Size 2 and 40) and alternative selectivity function for the trawl fishery (DNormal select).

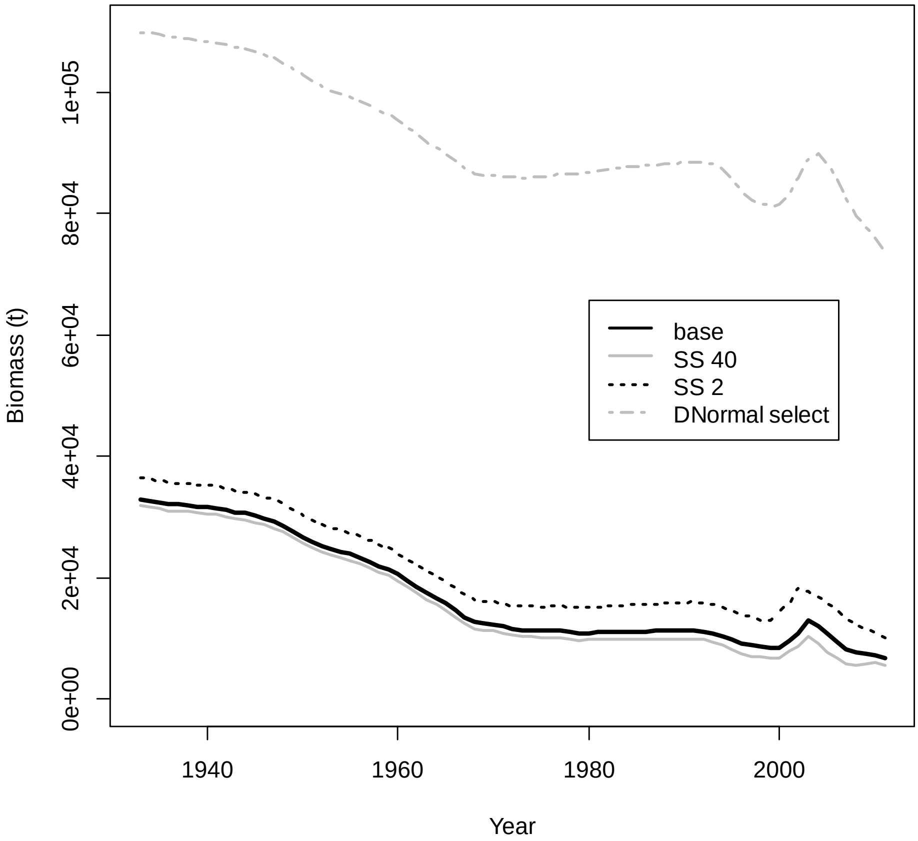

Figure 21: Estimated annual spawning biomass (female only) from the *TAR2/BPLE* base model and alternative model options examining different weighting of the age frequency data (Effective Sample Size 2 and 40) and alternative selectivity function for the trawl fishery (DNormal select).

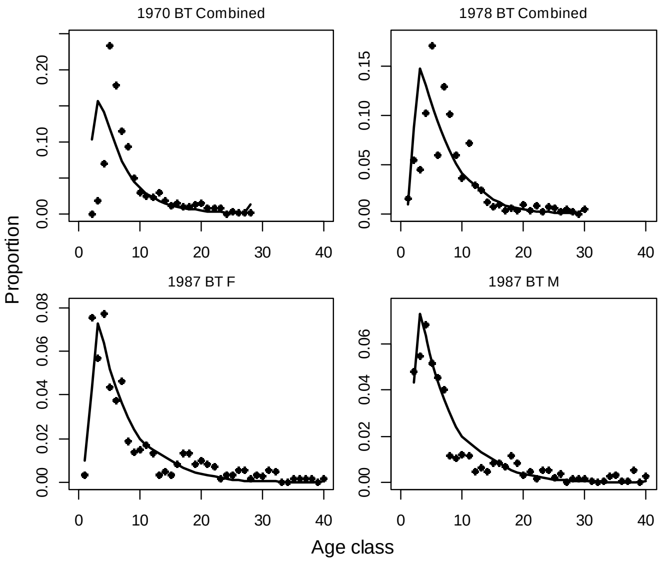

Figure 22: Initial *TAR3* model fits (observations, points; predictions, line) to the age frequency samples derived from three early research trawl surveys of the Pegasus Bay–Cape Campbell area of TAR 3.

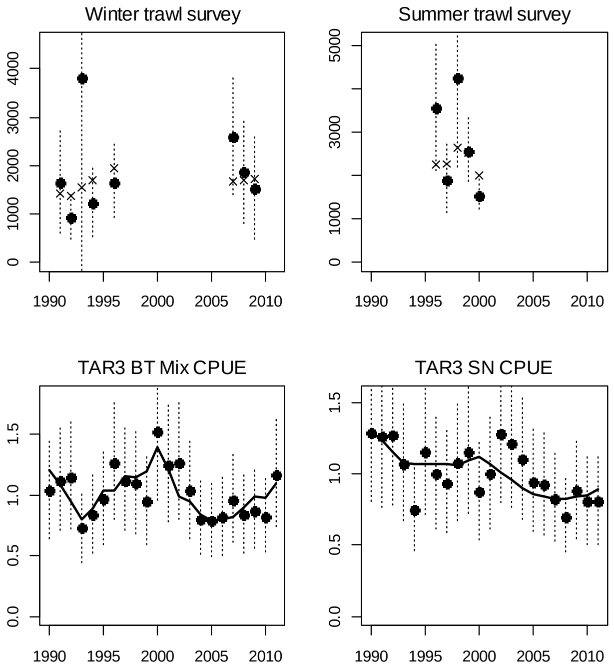

Figure 23: Observed (points) and predicted (lines) values for the four sets of abundance indices included in the base *TAR3* model with the selectivity of the set net fishery parameterised with a logistic function. The dashed vertical lines represent the 95% confidence interval associated with the observed values.

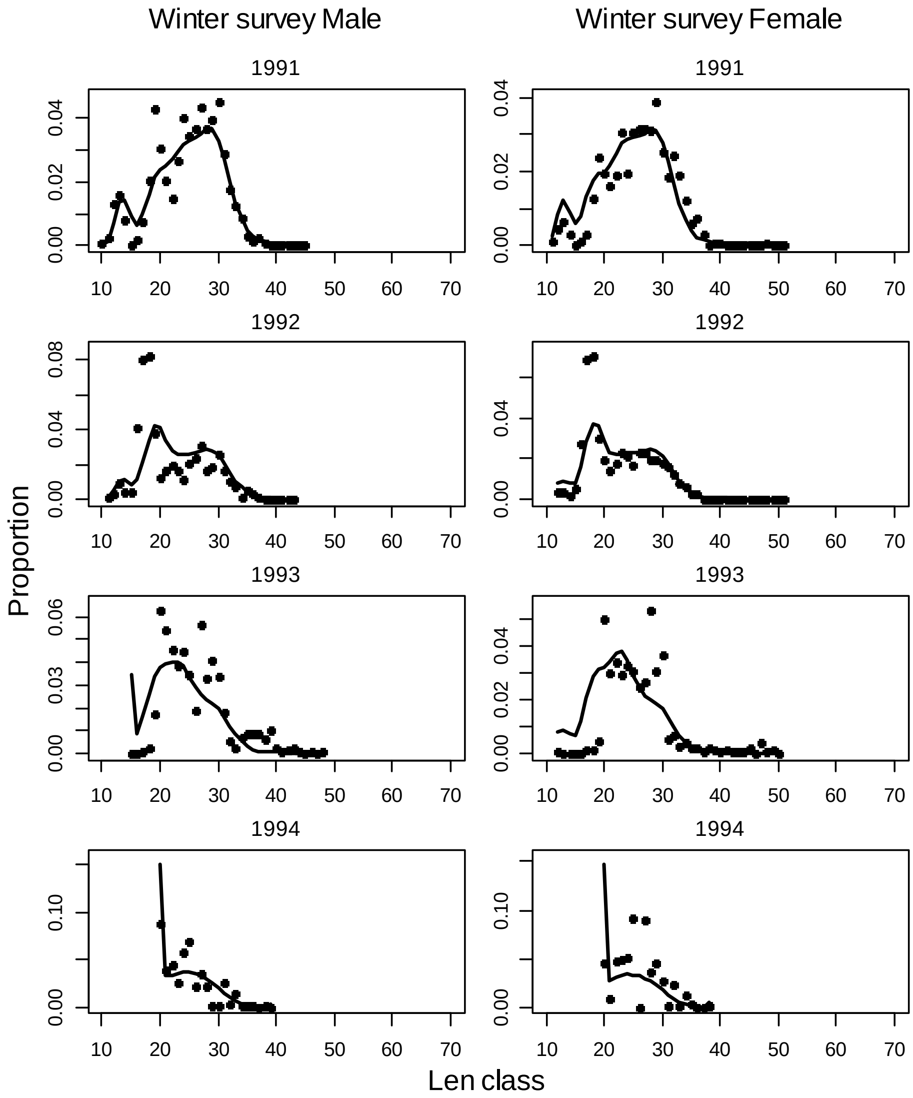

Figure 24a: Observed (points) and predicted (lines) proportional length frequency distributions for the winter ECSI Kaharoa trawl survey length compositions included in the *TAR3* base model.

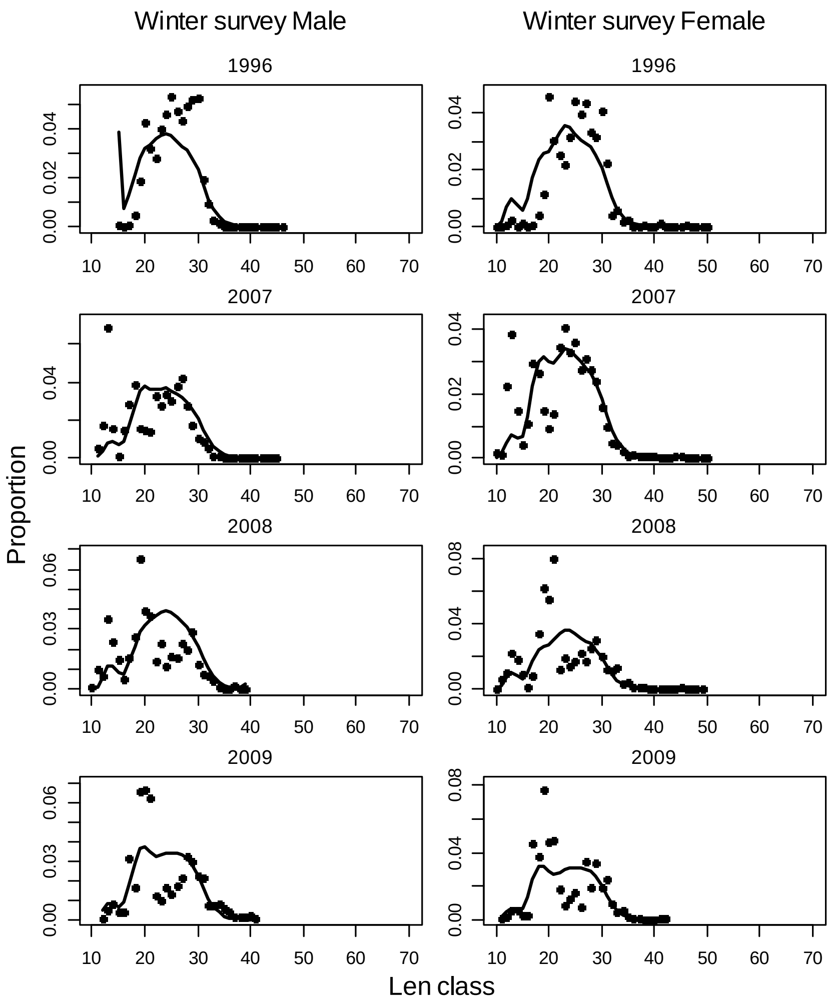

Figure 24b. Continued.

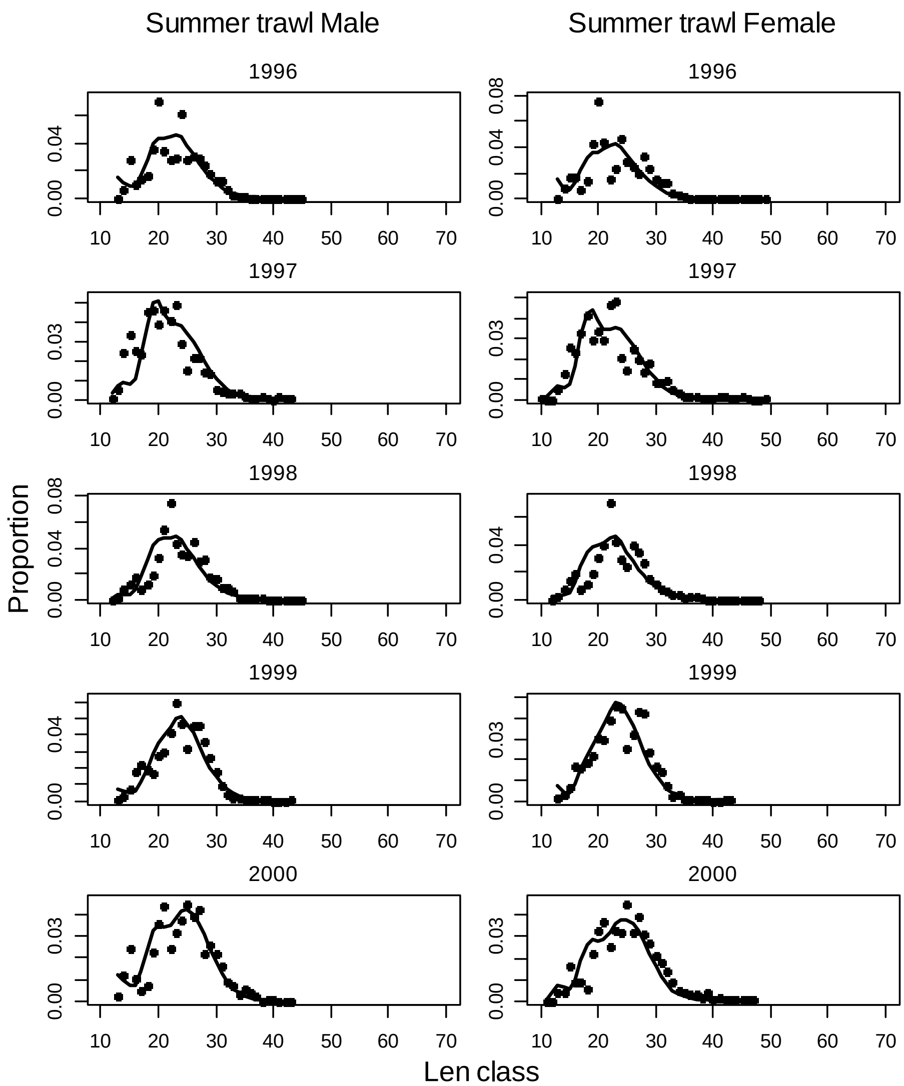

Figure 25: Observed (points) and predicted (lines) proportional length frequency distributions for the summer ECSI Kaharoa trawl survey length compositions included in the *TAR3* base model.

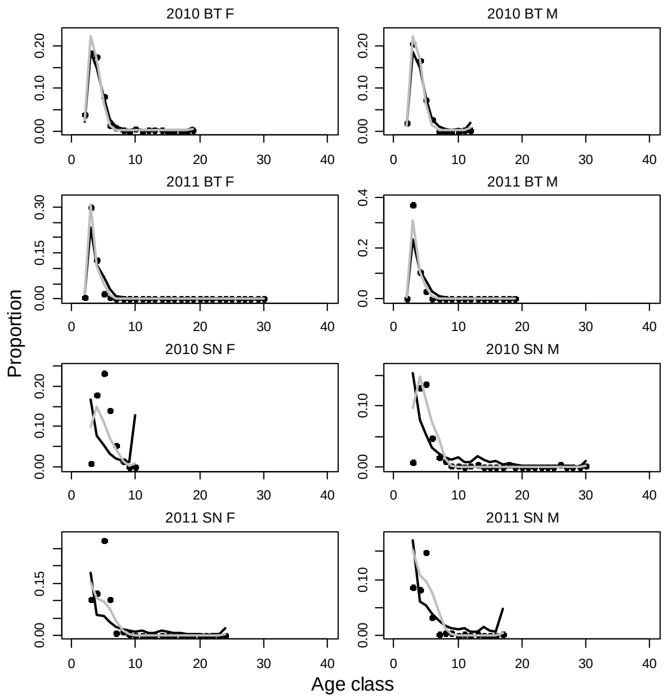

Figure 26: Observed (points) and predicted (lines) proportional age frequency distributions for the recent trawl and set net catch samples included in the *TAR3* model. The black line represents the fit to the data assuming a logistic selectivity for the set net fishery while the grey line represents the fit assuming a double normal selectivity.

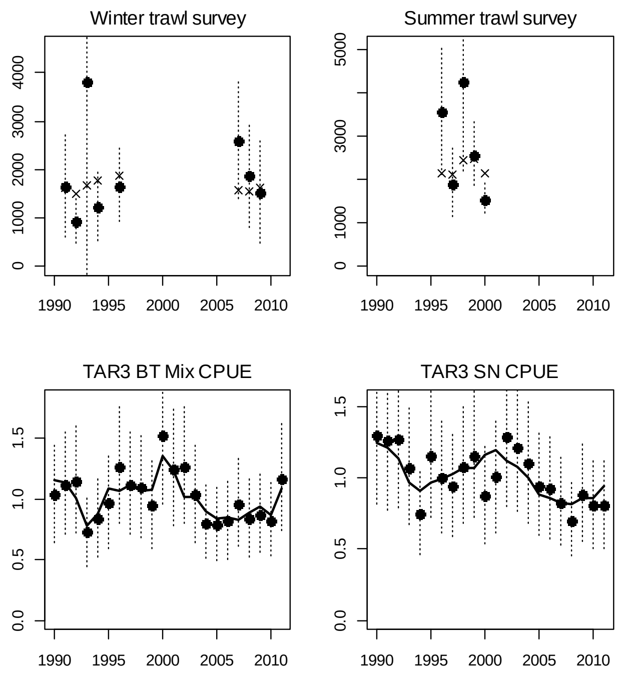

Figure 27: Observed (points) and predicted (lines) values for the four sets of abundance indices included in the alternative *TAR3* model with the selectivity of the set net fishery parameterised with a double normal function. The dashed vertical lines represent the 95% confidence interval associated with the observed values.

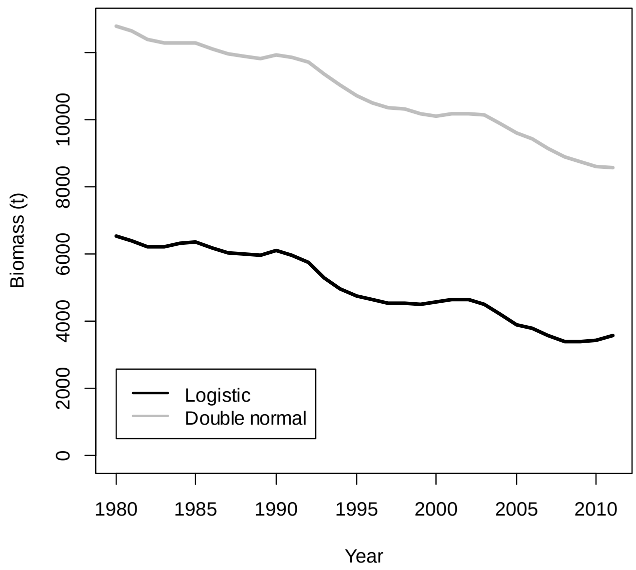

Figure 28: A comparison of the TAR3 model spawning biomass trajectory with the selectivity of the set net fishery parameterised with a logistic or double normal functional form.

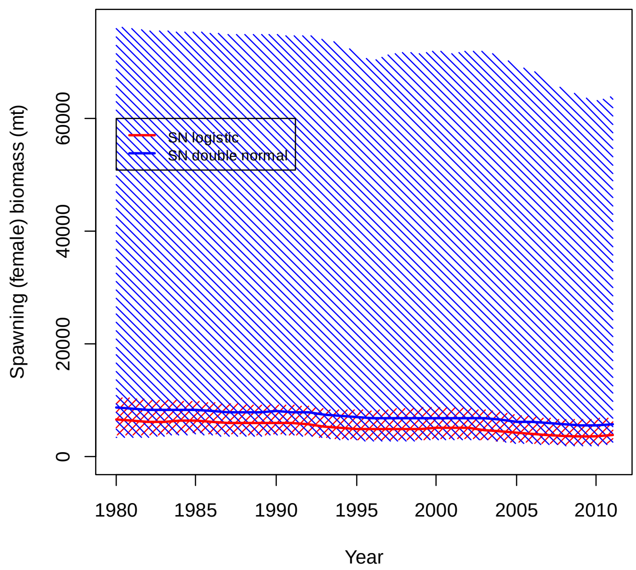

Figure 29: Biomass trajectory and confidence interval (derived from McMC) from the *TAR 3* model assuming logistic or double normal selectivity for the TAR 3 set net fishery. The red and blue lines represent the median of the McMCs and the shaded regions represent the 95% confidence intervals.

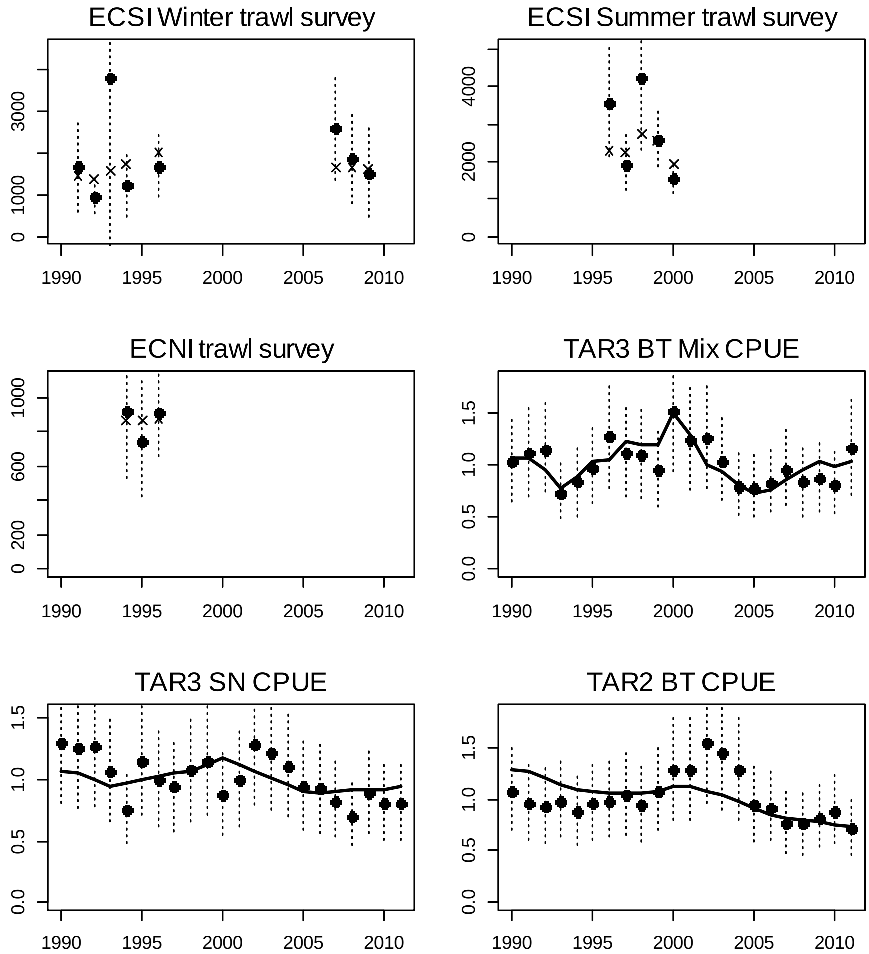

Figure 30: Observed (points) and predicted (lines) values for the six sets of abundance indices included in the *combined* (two region) model with the selectivity of the TAR 2 and Bay of Plenty trawl fisheries parameterised with a logistic function. The dashed vertical lines represent the 95% confidence interval associated with the observed values.

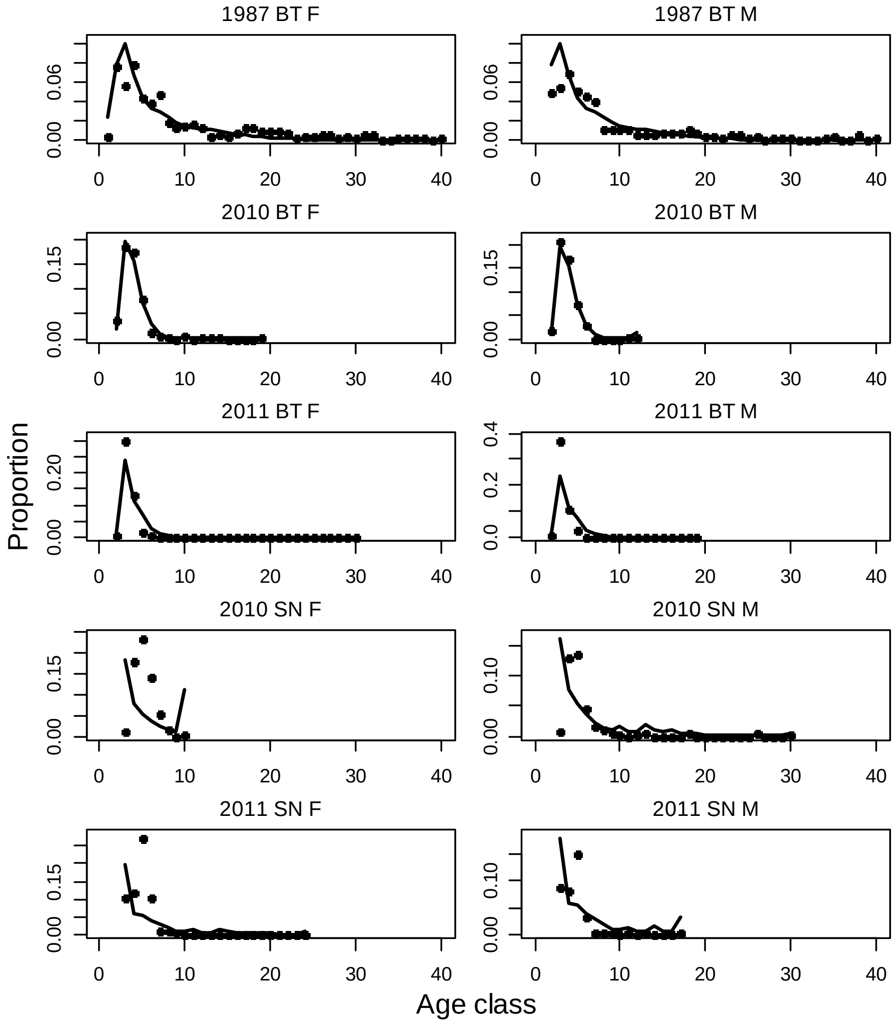

Figure 31: Observed (points) and predicted (lines) proportional age frequency distributions for the TAR 3 age samples included in the *combined* (two region) model.

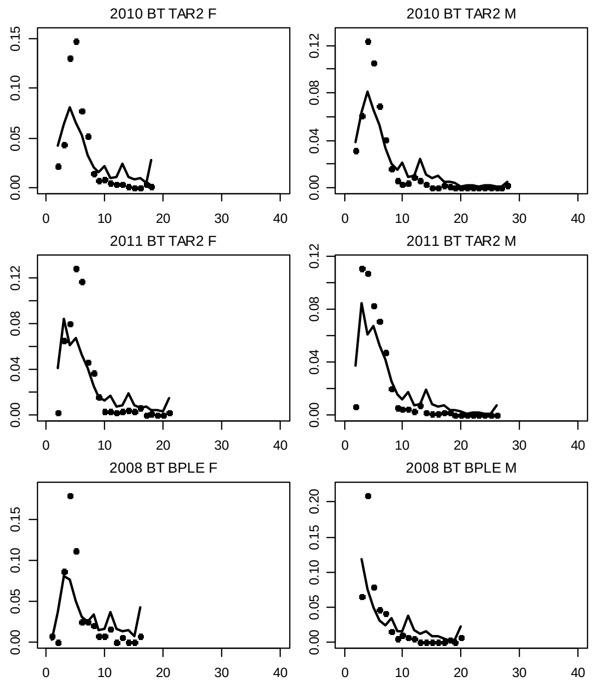

Figure 32: Observed (points) and predicted (lines) proportional age frequency distributions for the TAR 2 age samples included in the *combined* (two region) model.

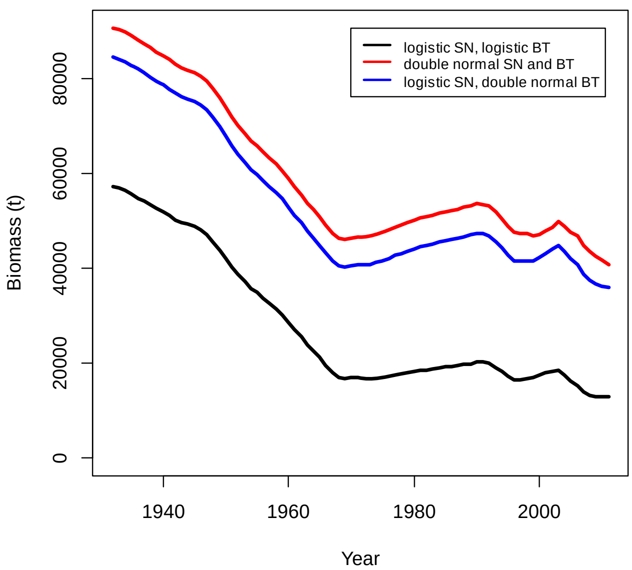

Figure 33: A comparison of the biomass (female, spawning biomass) trajectories for three *combined* (two region) model options with different assumptions regarding the selectivity of the TAR 3 set net (SN) fishery and the TAR2 and Bay of Plenty trawl fisheries (BT).

Figure 34: Biomass trajectory and confidence interval (derived from McMC) from the combined (two region) model assuming logistic selectivity for the TAR 3 set net fishery and double normal selectivity for the TAR 2 and Bay of Plenty trawl fisheries. The red line represents the median of the McMCs and the shaded regions represent the inter-quantile range (25–75%) (solid grey) and the 95% confidence interval (lines).

Appendix 1. Tarakihi movement model.

A spatially stratified, age structured population model was applied to evaluate a range of potential stock structure hypotheses for the east coast tarakihi stock (Table A1 and Figure A1). The principal objective of the modelling approach was to identify movement hypotheses that were consistent with the observed seasonal patterns in the catch rate of tarakihi from the main fisheries in each statistical area. The modelling approach was implemented using Stock Synthesis software (version 3.22, Methot 2011).

Table A1. Summary of the tarakihi movement hypotheses linking the destination statistical area(s) with the corresponding source statistical areas. The resulting negative loglikelihood values for the individual model options, the associated number of estimated model parameters and the Akaike Information Criteria (AIC) are also presented.

Movement model	Destination areas	Source areas	Likelihood		N. pars	AIC
			Total	CPUE component		
1	012 016	008–015 016–018,020	11 983.7	9 363.1	427	24 821.4
2	012 016	008–013 014–018,020	11 999.9	9 358.2	403	24 805.8
3	008 012 016	008–010 011–013 014–018,020	6 788.6	6 554.0	319	14 215.2
4	008 012 016 020	008–010 011–013 014–017 018,020	7 321.1	7 132.0	259	15 160.2
5	012 020	008–015 016–018,020	11 779.1	9 174.1	427	24 412.2
6	008 012 016	008–010 011–015 016–018,020	6 807.4	6 583.4	343	14 300.8
7	008 012 016	008–010 011–014 015–018,020	12 128.1	9 471.3	319	24 894.2
8	008 012 015 016	008–010 011–013 014,015 016–018,020	6 833.8	6 596.4	295	14 257.6
No movement			14 225.4	11 879.3	43	28 536.8
Full movement			4 915.2	4 678.6	751	11 332.4

The spatial domain of the analysis encompassed the 13 inshore fishery statistical areas from the western Bay of Plenty (Statistical Area 008) to Canterbury Bight (Statistical Area 022). The east

Northland region was excluded from the analysis from the outset due to the differences in the age structure of the catches and trends in catch rates from this area (see Sections 2.4 and 2.5 above).

The spatial structure of the model was based on 13 statistical areas (008–018, 020 and 022), each representing a separate model area. Tarakihi spawn during late summer–autumn and the temporal structure of the model was configured to accommodate the spawning period and pre- and post-spawning movements. The temporal resolution of the model was defined to reflect the observed seasonality in the variation in the fishery catch rates. On that basis, six two-month seasons were defined (Jan–Feb, Mar–Apr, May–Jun, Jul–Aug, Sep–Oct, and Nov–Dec), representing a balance between accommodating the temporal variation in fishery CPUE and minimising the number of movement parameters estimated in the fitting procedure.

The model period was limited to 1990–2009, encompassing the period for which reliable catch and effort data were available. A single trawl fishery was defined for each area and tarakihi catch data were compiled by fishery and year/season (**Error! Reference source not found.**). Nominal year/season CPUE indices were derived for the tarakihi target trawl fishery in each statistical area (unstandardised CPUE expressed as sum(total catch)/sum(total number of trawls) per year/season/area). Target set net fisheries for tarakihi operated in the Bay of Plenty (008, 009 and 010) and Kaikoura (018). A separate CPUE index was derived for each of these four set net fisheries (tarakihi catch per fishing day). The seasonal CPUE indices are assumed to reflect the relative abundance of tarakihi in each area. No fishery specific age or length frequency data were (readily) available for inclusion in the model. Consquently assumed fixed selectivities were imposed.

The main structural assumptions of the model are as follows.

- Two sexes and 40 age classes (including plus group).
- Biological parameters (M, growth, length-weight relationship) from TAR 3 (Ministry of Fisheries 2011).
- Deterministic recruitment derived from a Beverton-Holt stock-recruitment relationship with a steepness of 0.95. No recruitment deviates were estimated.
- Model commenced in 1990 with equilibrium exploited conditions based on 1990 catch level.
- Annual cycle comprised of six 2-month seasons with spawning occurring during the second season (March–April).
- Recruitment of year 0 fish occurred in the third season (May–June). The constant proportion of the distribution of recruitment among the 13 statistical areas was estimated.
- All CPUE indices had a lognormal error structure with an assumed c.v. of 15%.
- A separate (ln) catchability coefficient (*q*) was estimated for the trawl CPUE indices for each statistical area. The trawl catchability coefficients shared a common normally distributed prior (mean = -2.1, s.d. = 0.5).
- SN CPUE indices from the Bay of Plenty fisheries (008, 009 and 010) have a common *q*. A separate q was estimated for the Kaikoura (018) set net fishery.
- All fisheries (both trawl and set net) were assumed to have an equivalent age specific selectivity. The selectivity was parameterised using a logistic function (50% selectivity at age 2 and 95% selectivity at age 3; b1=2, b2=1), with no descending righthand limb.
- The age specific movement of fish between areas was parameterised as a ramp function from the proportion that move for the youngest age classes (1–4 years old) to the proportion that move at a maximum age (6 years old). The proportion of fish moving at older age classes was assumed to be the same as the proportion that moved at the maximum age of the ramp.
- Pre-spawning movements occur during seasons 1, 2 and 6 and were unidirectional, either directly to the assumed spawning area or to an intermediate statistical area. For example, for model movement scenario 6 (Table A1 and Figure A1f), fish in Statistical Area 014 were linked to the East Cape (012) spawning grounds. During the pre-spawning seasons (1, 2 and 6), fish in Statistical Area 014 could move to Statistical Areas 013 or 012. Fish that moved to Statistical Area 013 in either season 1 or 2, could move to Statistical Area 012 in a subsequent

season (along with the other fish resident in Statistical Area 013). Fish within Statistical Area 012 in the pre-spawning period must remain within the area. There was no constraint for fish to complete the movement to the destination area. Thus fish moving from Statistical Area 014 to Statistical Areas 013 in season 6 may remain in that area during seasons 1 and 2.

- Conversely, post-movements (seasons 3, 4, 5) were unidirectional from the designated spawning spawning area. Thus, for the previous example, fish that spawned within 012 may move directly to Statistical Area 013 or 014 during the post spawning seasons or move to Statistical Area 014 via Statistical Area 013. There was no constraint on individual fish returning to a specific statistical area and the reciprocal movement rates may differ considerably.
- Spawning was not limited to the fish present in the destination areas during the spawning period. Rather, the total spawning biomass was composed of all mature fish regardless of fishery area. Subsequent recruitment was distributed among areas in proportion to the estimated recruitment distribution.

The model was applied to test a range of movement scenarios. These scenarios linked fish from specific statistical areas to a known (or assumed) spawning location. The main spawning locations considered were East Cape (012), eastern Bay of Plenty (008), Cook Strait (016) and Pegasus Bay (020).

A total of eight movement hypotheses were tested (Table A1). The movement parameters of the model were reconfigured to represent each movement hypothesis. The model fitting procedure typically involved the estimation of a large number of movement parameters (259–427 parameters).

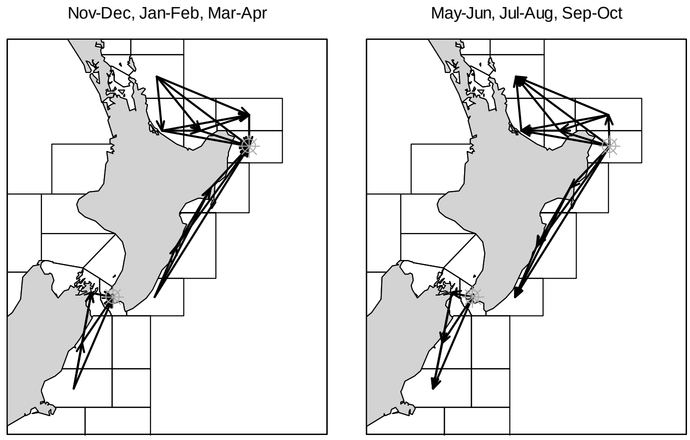

Figure A1a: Graphical depiction of the prespawning (left) and post spawning (right) movements for movement scenario 1. The grey star represents the destination area for pre-spawning movements.

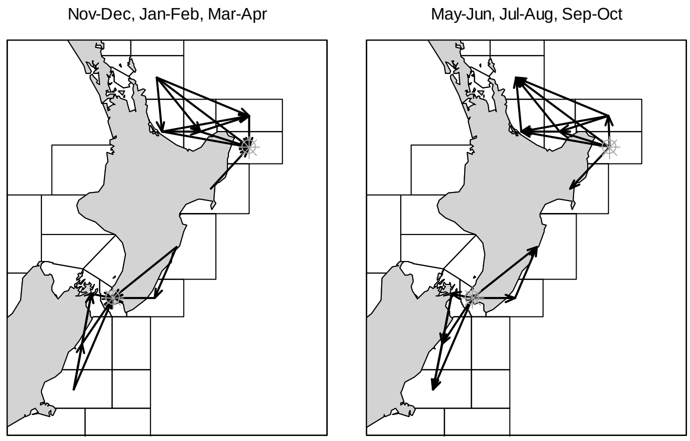

Figure A1b: Movement scenario 2.

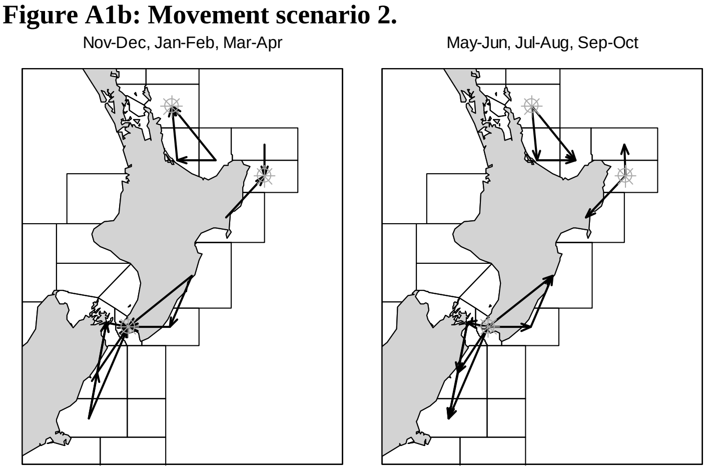

Figure A1c: Movement scenario 3.

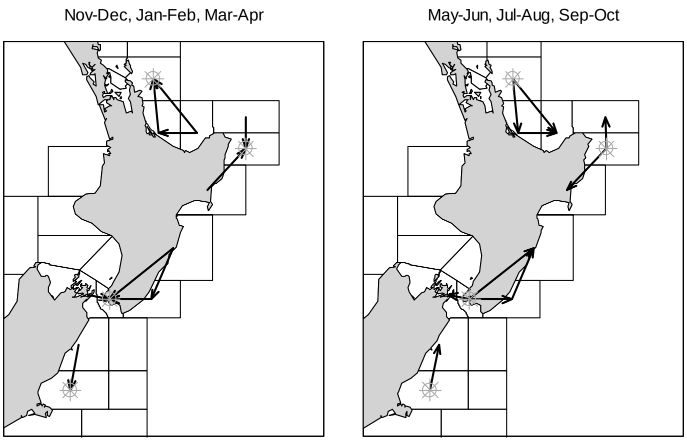

Figure A1d: Movement scenario 4.

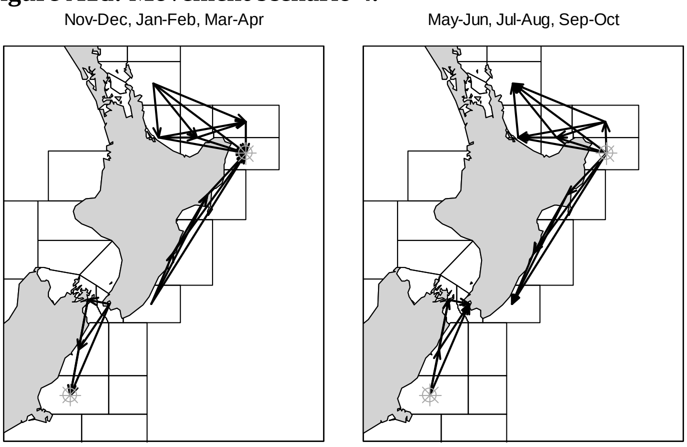

Figure A1e: Movement scenario 5.

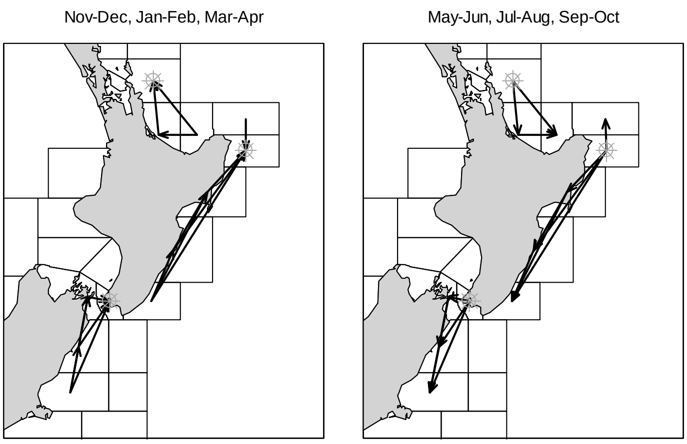

Figure A1f: Movement scenario 6.

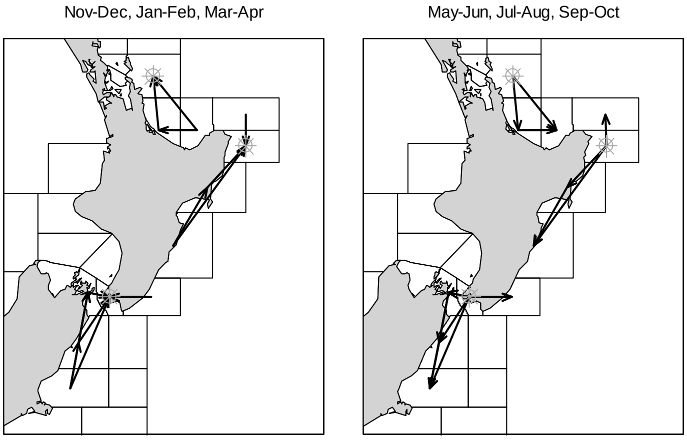

Figure A1g: Movement scenario 7.

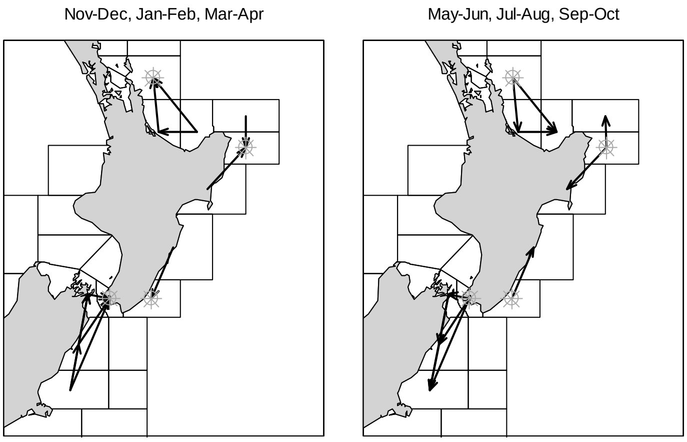

Figure A1h: Movement scenario 8.

This modelling approach provides an objective approach to evaluating these alternative movement hypotheses to explain the observed seasonal patterns in tarakihi CPUE from the fisheries in each statistical area. However, the modelling approach is limited by the underlying structural assumptions of the model and the lack of informative data, which should have been length/age frequency data at the temporal and spatial scale of the model. A key assumption of this approach is that trends in CPUE within an area represent changes in the relative abundance of tarakihi, rather than changes of the seasonal catchability of tarakihi.

The eight movement hypotheses were evaluated using this modelling approach and compared to two alternative null models. The *"No movement"* model constrained recruits to remain within the natal area, whereas the *"full movement"* model allowed fish movement to any neighbouring area in each season. Of the eight movement scenarios, the scenarios with multiple spawning locations (destinations) had the best overall fit to the CPUE indices. This is not a surprising result, as the larger number of destinations tends to increase the freedom of the model to estimate more complex movement patterns and thereby approach the *full movement* model (Table A1). Nonetheless, based on the Akaike Information Criterion, movement scenario 3 (Figure A1c) was selected as the preferred model option and was examined in more detail.

For movement scenario 3, the largest estimated movement rates, in terms of the number of fish moving in a season averaged across all ages, occurred northwards from Statistical Area 018 to Statistical Area 017 in seasons 6 (Nov–Dec) and 1 (Jan–Feb) (Figure A2). There were high southward movement rates from Statistical Area 017 in season 3 (May–Jun) and Statistical Area 018 in season 4 (Jul–Aug). The movement rates between other areas are estimated to be relatively low (10–20%) or minimal (less than 5%) (Figure A2).

The pattern is somewhat different when expressed in terms of biomass of fish moving in a season, again averaged across all ages, (Figure A3). There is estimated to be a relatively large transfer of biomass from Statistical Area 014 to 016 in Nov–Dec and a reciprocal movement during May–June. Further, during May–June there is a relatively large movement of fish from Statistical Area 016 to 017 and a smaller movement of fish from Statistical Area 017 to 020. Moderate movements of fish are also estimated to occur from Statistical Area 016 to 018 (Sep–Oct) and 009 to 010 (May–June) (Figure A3).

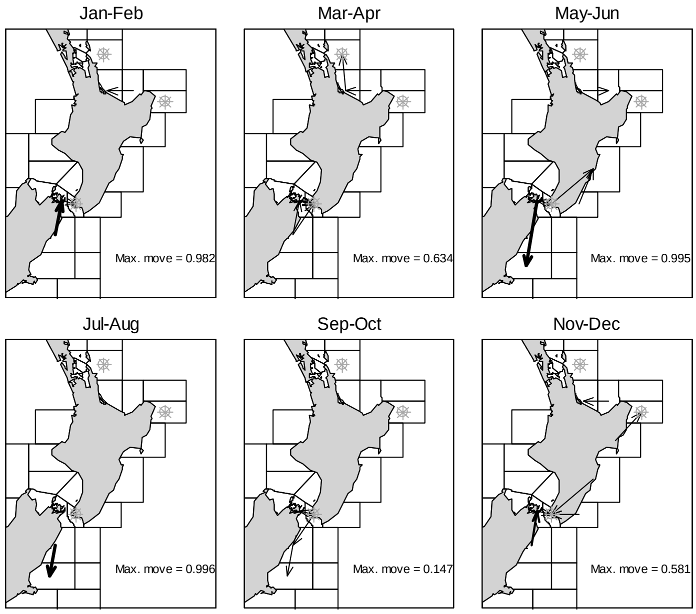

Figure A2: Seasonal proportional movement rates estimated for movement scenario 3. Only rates exceeding 5% are presented. The line width is proportional to the movement rate and the maximum seasonal movement rate is presented.

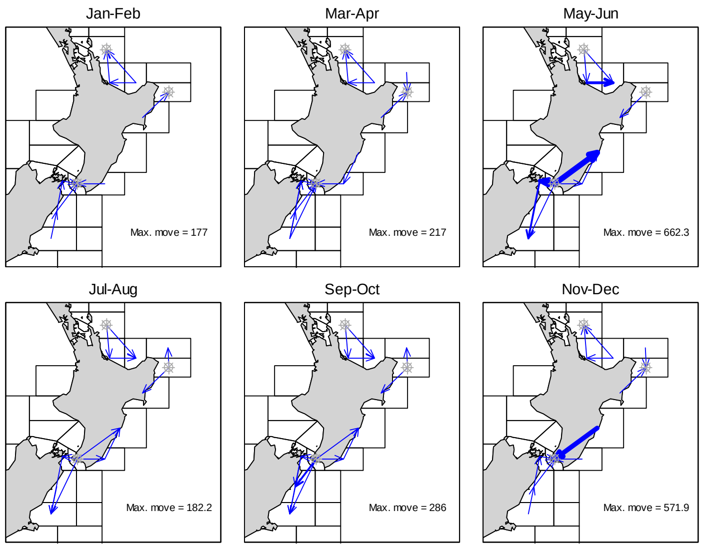

Figure A3: Seasonal movements predicted by movement model scenario 3. The movements are expressed in terms of 2009 adult female biomass (t). The line width is proportional to the biomass and the maximum seasonal movement is presented.

The model fit appears to be largely dominated by the CPUE indices from the fisheries in Statistical Areas 016, 017, 018 and, to a lesser extent, 009. These areas exhibited considerably higher and more consistent fluctuations in seasonal catch rates than the fisheries in the other areas. The movement model approximates the seasonal fluctuations in catch rates for these areas. However, for the southern statistical areas (017–018), the periods of low and high catch rates correspond between the two areas (July–August and January–February, respectively) and, hence, the CPUE trends are unlikely to be informative regarding movement.

Movement model scenario 3 assigns a substantial proportion of the total recruitment into Statistical Area 016 and comparatively low levels of recruitment to the East Cape area (Statistical Areas 011 and 012) (Figure A4). A high proportion of the total adult biomass (averaged over the model period) was assigned to the northern Wairarapa, while there is a relatively low level of biomass in the main area of the fishery (Statistical Areas 010–013) (Figure A5). These observations are inconsistent with the general understanding of the tarakihi fishery and on that basis it was concluded that the data were inadequate to sufficiently inform the models regarding the spatial dynamics of the stock and/or the underlying stock structure.

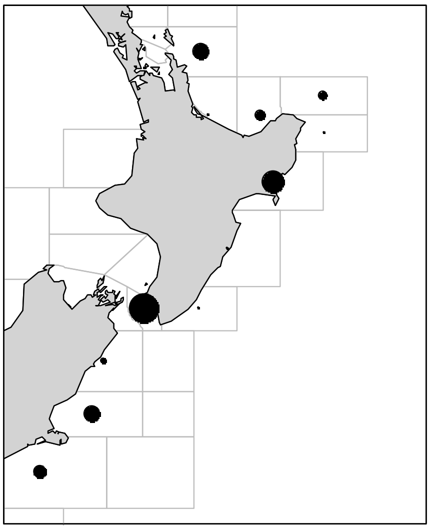

Figure A4: Distribution of recruitment by statistical area from the scenario 3 movement model. Circle size is proportional to the relative recruitment in each statistical area. The maximum circle size (statistical area 016) represents 36% of total recruitment.

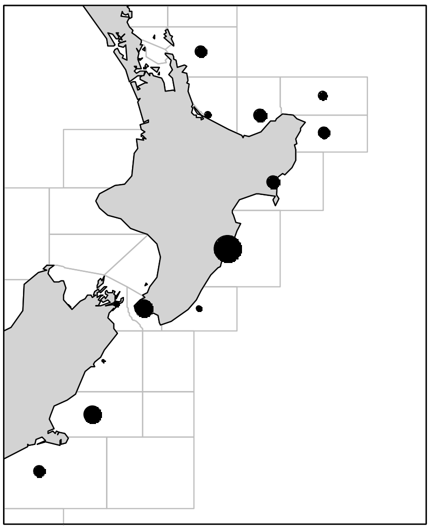

Figure A5: The relative distribution of total tarakihi biomass from the scenario 3 movement model. Circle size is proportional to the relative adult biomass in each statistical area during Nov–Dec 2009. Maximum circle size (in statistical area 014) represents 32% of total biomass.

Appendix 2. Age frequency data (proportion at age) from historical research trawl surveys.

The age frequency data from historical research trawl surveys were sourced from the original reports. The data were not available in tabulated form requiring the data to be obtained by digitising the relevant figures in the documents.

East Cape		Pegasus Bay			Cape Farewell	
Age	1971[1]	Age	1970[2]	1978[3]	Age	1987[4]
1	0.0000	1	0.0000	0.0158	1	0.0033
2	0.0000	2	0.0022	0.0544	2	0.1235
3	0.0022	3	0.0198	0.0453	3	0.1114
4	0.0184	4	0.0703	0.1025	4	0.1456
5	0.0951	5	0.2220	0.1705	5	0.0950
6	0.2726	6	0.1824	0.0595	6	0.0829
7	0.3241	7	0.1110	0.1290	7	0.0866
8	0.0822	8	0.0956	0.1014	8	0.0298
9	0.0733	9	0.0484	0.0598	9	0.0240
10	0.0366	10	0.0297	0.0368	10	0.0268
11	0.0315	11	0.0264	0.0724	11	0.0286
12	0.0125	12	0.0231	0.0293	12	0.0180
13	0.0086	13	0.0297	0.0247	13	0.0097
14	0.0060	14	0.0176	0.0125	14	0.0097
15	0.0184	15	0.0132	0.0080	15	0.0115
16	0.0057	16	0.0165	0.0096	16	0.0163
17	0.0031	17	0.0110	0.0036	17	0.0201
18	0.0030	18	0.0110	0.0068	18	0.0248
19	0.0000	19	0.0121	0.0038	19	0.0166
20	0.0027	20	0.0165	0.0101	20	0.0131
21	0.0001	21	0.0077	0.0040	21	0.0131
22	0.0038	22	0.0077	0.0087	22	0.0087
23	0.0000	23	0.0088	0.0027	23	0.0067
		24	0.0022	0.0074	24	0.0085
		25	0.0033	0.0060	25	0.0056
		26	0.0022	0.0030	26	0.0089
		27	0.0022	0.0046	27	0.0054
		28	0.0033	0.0032	28	0.0030
		29	0.0022	0.0000	29	0.0048
		30+	0.0022	0.0048	30	0.0043
					31	0.0057
					32	0.0047
					33	0.0004
					34	0.0027
					35	0.0049
					36	0.0020
					37	0.0024
					38	0.0066
					39	0.0002
					40	0.0016
					41	0.0001
					42	0.0025
					43	0.0001
					44	0.0000
					45	0.0000

Source: [1] Vooren & Tong (1973), [2] Tong (1979), [3] Tong (1979), [4] Annala et al. (1987).