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Stock assessment of tarakihi off the east coast of mainland New Zealand

New Zealand Fisheries Assessment Report 2018/05

A.D. Langley

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EXECUTIVE SUMMARY

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The stock structure of tarakihi off the east coast of mainland New Zealand was reviewed, incorporating new sources of information; specifically: age composition data from the main commercial fisheries, age compositions from east coast South Island trawl surveys and updated CPUE indices from the main tarakihi fisheries. The fisheries in Canterbury Bight/Pegasus Bay are dominated by younger fish and there is a progressive increase in the proportion of older fish in the catches from TAR 2, the Bay of Plenty and east Northland, while the relative strength of individual year classes is comparable amongst these areas. Trends in CPUE indices are also comparable among these fisheries when lagged by the relative age of recruitment to the respective fishery.

Spawning of tarakihi occurs throughout the eastern areas off the North and South Islands, although two main spawning areas have been identified around East Cape and off Cape Campbell. There is a preponderance of juvenile fish in Canterbury Bight/Pegasus Bay and low densities of juvenile tarakihi in East Northland, the Bay of Plenty and TAR 2. The long pelagic phase of tarakihi may provide a mechanism for the transfer of the progeny from the latter areas to the nursery grounds in Canterbury Bight/Pegasus Bay.

Tagging studies indicate that there is a considerable northward movement of fish from the east coast of the South Island to the Wairarapa coast, East Cape and the Bay of Plenty. Earlier tagging studies also indicated northward movements of fish from Mahia Peninsula to East Cape and the Bay of Plenty and a general eastward movement of tagged fish through the Bay of Plenty. There was also some movement of tagged fish around East Cape from the western Bay of Plenty prior to the main spawning period.

These observations indicate considerable connectivity between tarakihi along the east coast of the South and North Islands. The current stock hypothesis is that the Canterbury Bight/Pegasus Bay area represents the main nursery area for the eastern stock unit. At the onset of maturity, a proportion of the fish migrate northwards to recruit to the East Cape area and, subsequently, the Bay of Plenty and east Northland areas. Thus, the eastern stock unit is considered to represent a series of connected sub-populations (of adult fish) that is derived from a common pool of juvenile (pre-recruit) fish.

The results from previous tagging studies also indicate some connectivity between Kaikoura and the west coast North Island. However, limited data are available from the west coast North Island to elucidate the degree of the linkage between these areas. Recent age composition data from the west coast North Island identified similarities and differences in the relative strength of individual year classes compared to the east coast fisheries, while growth rates of older fish from the west coast North Island differ from East Northland, suggesting a lack of connectivity between the fisheries around the north of the North Island.

Limited direct comparisons are available between the age compositions from the east coast tarakihi fisheries and the west coast South Island (TAR 7) fishery. A more comprehensive analysis of the available data sets is required to further investigate the stock relationships between east coast tarakihi and tarakihi off the west coast of the North and South Islands.

The current stock hypothesis was applied to define the spatial domain of the stock assessment of tarakihi off the east coast of mainland New Zealand. The assessment encompasses the eastern North and South Islands, including the entire area of TAR 3 and TAR 2 and the eastern portion of TAR 1 (i.e., Fisheries Management Area 1). The model also includes the eastern area of TAR 7 (Cook Strait) which accounts for approximately 15% of the annual catch of TAR 7.

The stock assessment of east coast tarakihi was conducted using a statistical, age-structured population model implemented in Stock Synthesis. The assessment incorporated the available catch, CPUE indices, trawl survey biomass estimates and age/length frequency distributions, and recent commercial age compositions. The model data sets were structured into three areas: east coast South Island (including

eastern Cook Strait), central east coast North Island and the Bay of Plenty combined (BPLE-TAR2), and East Northland. The east coast South Island area included three commercial fisheries: the Canterbury Bight/Pegasus Bay trawl fishery, Kaikoura set net fishery and the eastern Cook Strait trawl fishery. The other two areas included a commercial trawl fishery and a relatively small non-commercial fishery. For each area, a corresponding time-series (or multiple series) of CPUE indices was available.

The range of model options included different levels of spatial complexity to represent the current stock hypothesis. The spatially stratified models provided reasonable results when configured at relatively broad spatial scales. However, there were limited data available to reliably estimate some of the key spatial parameters (especially movement) and a single region (spatially disaggregated) model was adopted as the preferred (base) assessment model.

The base assessment model provides a good fit to the four sets of CPUE indices, mediated by the fishery specific selectivity functions informed by the commercial age composition data. These data are generally coherent with the abundance indices from the trawl surveys and associated age and length compositions. The model estimates considerable variation in annual recruitment, especially from 1990 onwards. The overall results of the modelling were robust to a wide range of model assumptions related to spatial structure, initial conditions and the relative weighting of key data sets (CPUE indices and age compositions).

Spawning biomass is estimated to have been depleted to about the default soft limit of 20% *SB0* by the initial period of the assessment model in 1975, following a period of relative high catches (5000–7000 t) during the 1950s and early 1960s. Spawning biomass remained below the default soft limit since the mid-2000s and 2015/16 spawning biomass is estimated to be at 17% of the unfished, equilibrium biomass level (SB_{2016}/SB_0 = 0.170) from the base case model. There is a high probability (89%) that the spawning biomass is below the soft limit (20% SB_0) but a very low probability (less than 1%) of being below the hard limit of 10% SB_0. The stock status is similar for the range of model options, although the stock status is slightly more pessimistic for the model sensitivity analyses with lower productivity parameters (natural mortality, steepness and maturity).

Equilibrium yields at the target biomass level of 40% SB_0 are estimated to be about 4100 t which is slightly lower than the 2015/16 catch of 4442 t (including a 10% allowance for under reporting).

The projections indicate that a catch reduction of approximately 20% is required to minimise the risk of reducing the stock below the hard limit (10% *SB0*) during the next 10 years and improving the probability that the stock will increase to a level above the soft limit (20% *SB0*). However, substantially larger reductions in catch are required to rebuild the stock to the 40% *SB0* default target level within a 10-year period.

1. INTRODUCTION

Tarakihi (*Nemadactylus macropterus*) are caught in coastal waters of the North and South Islands, Stewart Island and the Chatham Islands, down to depths of about 250 m. The fishery for tarakihi developed with the introduction of steam trawlers in the 1890s (Paul 2014). By the mid-1930s, annual catches had increased to reach about 2000 t. During the late 1940s, annual catches increased substantially following the introduction of motor trawlers (Vooren 1974). Total catches stabilised at about 5000–6000 t per annum during 1950–1981 (Francis & Paul 2013).

Most (approximately 80%) of the tarakihi catch has been taken off the east coast of the North and South Islands, with catches concentrated in the Canterbury Bight, Pegasus Bay, around Cape Campbell and the eastern approaches to Cook Strait, around East Cape (Mahia Peninsula–Cape Runaway), the Bay of Plenty and off east Northland (Langley 2017). These areas are encompassed within the eastern area of TAR 1, and in TAR 2 and TAR 3, and the eastern area of TAR 7. Since 1989/90, these areas have cumulatively accounted for total annual catches of about 3500–4000 t with catches distributed amongst the fishstocks in the approximate proportions of 40–45% TAR 2, 20–25% TAR 3, 20–25% TAR 1, and 5–10% TAR 7.

Recent trends in the east coast fisheries have been summarised in Langley (2017) following earlier studies (Field & Hanchet 2001, Kendrick 2006, Kendrick 2009, Starr & Kendrick 2014). Most of the catch is taken by the inshore trawl fisheries operating in each area, either targeting tarakihi or catching tarakihi in association with a range of other inshore finfish species. In addition, a set net fishery targets tarakihi off the Kaikoura coast. Annual CPUE indices have also been derived for each of the main commercial fisheries (Langley 2017) and these indices represent the main information available for monitoring each of the tarakihi fishstocks (eastern area of TAR 1, TAR 2 and TAR 3) (Starr & Kendrick 2014, MPI 2017).

Tarakihi off the east coast of the North and South Islands are considered to belong to a single biological stock (Hanchet & Field 2001). A previous attempt to conduct an assessment of eastern tarakihi stock was not successful, primarily due to the limited age composition data available from the commercial catch (Langley & Starr 2012). To address these deficiencies, intensive age frequency sampling of the commercial catches from the main fisheries was conducted during 2013/14 and 2014/15 (McKenzie et al. 2017). Age compositions were also derived for the tarakihi sampled by the time-series of East Coast South Island trawl surveys (Beentjes et al. 2017).

The resultant age compositions and updated CPUE indices (Langley 2017) provided additional information to further investigate the stock relationships of tarakihi along the eastern coasts and progress the assessment of the stock, including estimating biomass and sustainable yields. These elements represent the second component of project TAR 2016-01 funded by the Ministry for Primary Industries. The first component of the project included the fishery characterisations and CPUE analyses conducted for TAR 1, TAR 2 and TAR 3 and is documented in Langley (2017).

The report is structured in four main sections: the first section reviews the available data sets from the east coast tarakihi fisheries; the second reviews the main life history parameters for tarakihi; the third reviews the stock structure of tarakihi; and the fourth presents the results of stock assessment modelling based on the conclusions of the preceding sections.

2. DATA SETS

This section summarises the main data sets available for tarakihi from the eastern North and South Islands and adjacent areas. These data are examined in detail in the investigation of tarakihi stock structure (Section 4). The data also represent key inputs in the stock assessment modelling (Section 5).

2.1 CPUE indices

Standardised CPUE analyses have been conducted for each of the main tarakihi fisheries within TAR 1, TAR 2 and TAR 3, updating and refining previous CPUE analyses to include data from the 1989/90–2015/16 fishing years (Langley 2017). The fishery-specific standardised CPUE series are the primary indices of relative abundance for TAR 3 (trawl and set net fisheries), TAR 2 (trawl) and the three fishery areas that constitute TAR 1 (trawl) (Figure 1).

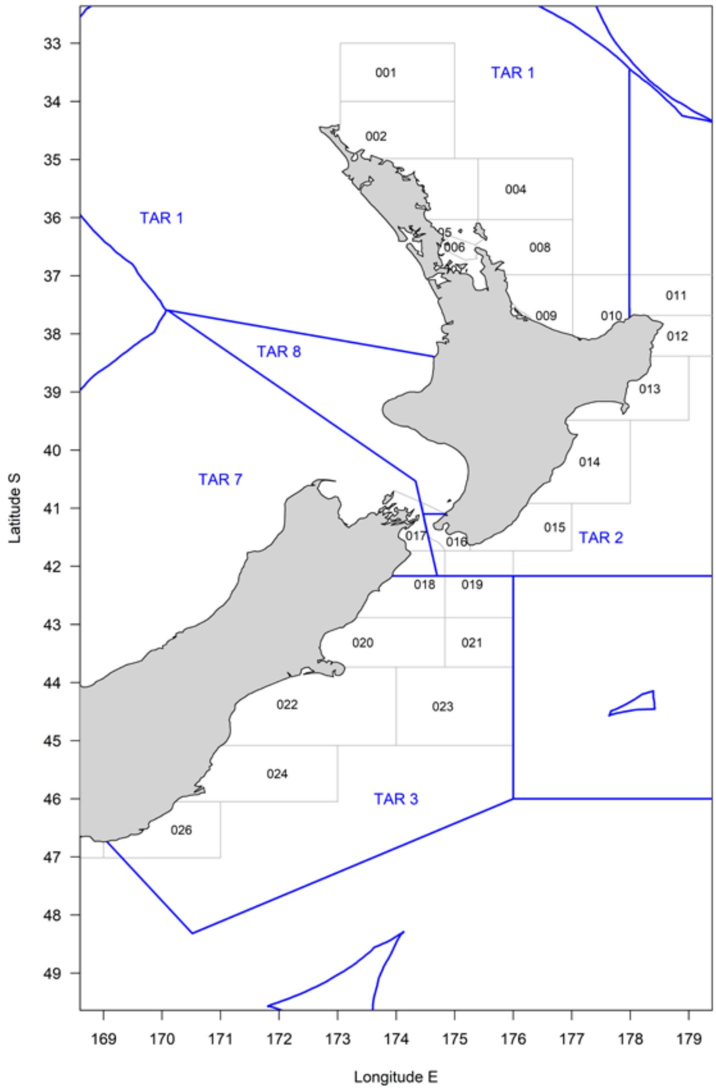

Figure 1: Tarakihi fishstock areas and Statistical Areas that constitute the domain of the east coast tarakihi assessment.

In addition, preliminary CPUE analyses were conducted for each fishery using data collected by the Fisheries Statistics Unit (FSU) during 1983–1988. However, the CPUE indices were not considered to be informative regarding trends in stock abundance due to the short time series (5–6 years) and the lack of contrast. Further, there was some concern regarding the reliability of the reporting of catch and effort data during that period and the indices were not included in the final analyses.

Historical trends in tarakihi catch rates are available for the trawl fisheries operating in the East Cape area (TAR 2) during 1961–1970 (Vooren 1973, 1974) and in Canterbury Bight (TAR 3) during 1963–1973 (Sullivan 1981). The CPUE indices for East Cape were calculated as the average annual catch (t) of tarakihi per fishing day for the Gisborne trawl fleet (Vooren 1974). There was a considerable decline in the catch rate of tarakihi over the period that was attributed to a decline in stock abundance following the peak in the total catches of tarakihi during the early–mid-1960s (Vooren 1974) (Appendix 4).

The Canterbury Bight CPUE indices were derived from the February–September fishing season for tarakihi (Sullivan 1981) (Appendix 4). The average of the monthly catch rates of tarakihi (kg per day) by the Timaru trawl fleet was used to determine the annual CPUE index. Sullivan (1981) considered the indices from 1967–1969 to be unreliable due to the absence of larger vessels from the fishery during the Chatham Island rock lobster (crayfish) boom. Overall, CPUE declined by 45% from 1963–1966 to 1970–1973 (Sullivan 1981).

2.2 Commercial age compositions

Over the last decade, there has been a considerable amount of sampling of the commercial catches from the main tarakihi fisheries along the east coast of the North and South Island. For most of the fisheries, four annual age compositions are available, including sampling from successive years in 2013/14 and 2014/15 (Table 1). Sampling from the East Northland trawl fishery was limited to these two years, while the trawl fishery in the eastern area of Cook Strait was limited to 2013/14. In addition, two comparable age compositions are available from the west coast North Island fishery (WCNI) (McKenzie et al. 2017).

Table 1: Summary of recent commercial catch sampling conducted from the tarakihi fisheries off the east coast of the North and South Island.

Fishery area	Method	Stat Areas	Fishing years	Reference
TAR 3	SN	018	2009/10	Beentjes (2011)
			2010/11	Beentjes et al. (2012)
			2013/14, 2014/15	McKenzie et al. (2017)
TAR 3	BT	020,022,024	2009/10	Beentjes (2011)
			2010/11	Beentjes et al. (2012)
			2013/14, 2014/15	McKenzie et al. (2017)
Cook Strait	BT	016–018	2013/14	McKenzie et al. (2017)
TAR 2	BT	011–015	2009/10	Parker & Fu (2011)
			2010/11	Beentjes et al. (2012)
			2013/14, 2014/15	McKenzie et al. (2017)
Bay of Plenty	BT	008–010	2007/08	Armiger el al. (2010)
(BPLE)			2010/11	McKenzie et al. (2015)
			2013/14, 2014/15	McKenzie et al. (2017)
East Northland (ENLD)	BT	002–004	2013/14, 2014/15	McKenzie et al. (2017)

The age determination protocol for tarakihi was revised following the publication of the results of the commercial catch sampling conducted in 2009/10 and 2010/11 (Walsh et al. 2016). The study identified that the previous ageing procedure had resulted in the otoliths being under-aged by one year. For the current study, these earlier age structures were corrected by the addition of a year to all age classes. This correction was applied to the age compositions documented in Beentjes (2011), Beentjes et al. (2012), Parker & Fu (2011) and Armiger el al. (2010).

The more recent sampling of the trawl fishery in TAR 3, derived separate age compositions for the components of the trawl fishery in Pegasus Bay and Canterbury Bight (McKenzie et al. 2017). The age compositions differed somewhat between the two areas with a higher proportion of older (over 6 years) fish in the catch sampled from the Pegasus Bay area. Previous sampling had not partitioned the fishery by area (Beentjes 2011, Beentjes et al. 2012). For comparability between the two sampling periods, the more recent annual age compositions from the two areas were amalgamated, weighted by the relative catch (in number of fish) from each area.

An additional age composition was derived for the ENLD BT fishery in 2007/08 (Armiger el al. 2010). However, the study was based on a limited number of samples and the resulting age composition was poorly determined. The age composition also differed considerably from the age structure in the more recent years (2014 and 2015). On that basis, the 2007/08 age data were excluded from the current analysis.

For the final assessment model data sets, the data from the trawl fisheries in TAR 2 and BPLE were amalgamated (Appendix 3). The annual age compositions from the two areas were combined by weighting the area specific age compositions by the relative tarakihi catch in each area.

2.3 Trawl surveys

2.3.1 *Kaharoa* inshore trawl surveys

Inshore trawl surveys off the east coast of the South Island (ECSI) have been conducted by *Kaharoa* since 1991 (Table 2). Tarakihi has been one of the main target species for the surveys and the survey area has consistently encompassed the main depth range of the species (30–400 m) from Pegasus Bay to Shag Point. The surveys are grouped in two separate series: winter (April–June) surveys conducted during 1991–1996 (Beentjes & Stevenson 2000) and 2007–2016 and summer (December–January) surveys during 1996–2000 (Table 2). All trawl surveys used the same set of trawl gear, with the exception of different codends used between the winter (60 mm inside mesh measurement) and summer (28 mm mesh) surveys.

Area swept biomass estimates of tarakihi have been derived from the individual trawl surveys (Table 2, MPI 2017). Due to the differences in seasonal timing of the survey, the winter and summer trawl surveys have been considered to represent two separate series of abundance indices for tarakihi. A comparison of biomass estimates from the early winter surveys and summer surveys indicated that the availability of tarakihi differed between seasons (Hanchet & Field 2001).

Scaled length compositions of tarakihi (unsexed, male and female) are also available from each of the trawl surveys and are presented in the primary reference document for the individual survey (Table 2). The final length compositions aggregated all fish by 1 cm length intervals (i.e., unsexed, male and female combined).

For six of the more recent ECSI trawl surveys, otoliths were collected from the sampled catches of tarakihi. The otoliths were read to determine the age of the individual fish sampled and length and age distributions were determined for two depth zones (shallow and deep) (Beentjes et al. 2017). Subsequently, the otoliths collected from the 2016 ECSI trawl survey were also aged (unpublished data held by NIWA).

For the current study, composite age compositions were determined for each of the seven trawl surveys by partitioning the scaled length compositions using an age-length key derived from the corresponding survey age samples. The final age compositions were aggregated by sex for inclusion in the stock assessment modelling (Appendix 2).

Four trawl surveys were conducted off the east coast of the North Island (ECNI) during 1993–96 (Stevenson & Hanchet 2000). The survey timing and boundaries were changed after the first survey and the results from the initial survey are not considered directly comparable with the other three surveys (conducted in February–March). The survey series was considered to be monitoring tarakihi but was discontinued as the survey was not reliably monitoring other key species (Stevenson & Hanchet 2000). Biomass estimates and scaled length compositions are available for tarakihi from the three surveys (Table 2). Age compositions are not available from the ECNI trawl surveys.

Trawl survey biomass estimates from the Bay of Plenty, Hauraki Gulf and East Northland *Kaharoa* inshore trawl surveys were not considered to effectively monitor tarakihi due to the restricted depth range of the trawl surveys (Morrison et al. 2013).

2.3.2 Previous trawl surveys

Previous inshore trawl surveys off the east coast of the South Island are summarised in Hanchet & Field (2001). Trawl survey biomass estimates from earlier surveys are summarised in Annala (1988). A series of nine surveys of the Canterbury Bight were conducted by *James Cook* during 1980–1982, primarily targeting barracouta (Hurst & Fenaughty 1985). The survey biomass estimates for tarakihi were low and relatively imprecise (CV 32–86%) (table 9 of Annala 1988). It is considered that the data collected from these surveys were unlikely to be particularly informative in the current study due to the short time-series and the low precision of the biomass estimates for tarakihi.

Additional *James Cook* surveys targeting tarakihi were conducted off East Cape in 1971 and off the east coast South Island during the 1970s and 1987 (Table 3). These surveys do not provide estimates of tarakihi biomass but have been used to derive age compositions of tarakihi. Limited documentation is available for some of these surveys.

Table 2: Summary of the *Kaharoa* inshore trawl surveys and tarakihi biomass estimates (total biomass, t) and coefficient of variation (CV).

Series	Year (Calendar/Model)	Depth range	Biomass (CV)	Age comp	Length comp	Reference
ECSI, winter	1991/1991	30–400 m	1 712 (0.33)	No	Yes	Beentjes & Wass (1994)
	1992/1992	30–400 m	932 (0.26)	No	Yes	Beentjes (1995a)
	1993/1993	30–400 m	3 805 (0.55)	No	Yes	Beentjes (1995b)
	1994/1994	30–400 m	1 219 (0.41)	No	Yes	Beentjes (1998a)
	1996/1996	30–400 m	1 656 (0.24)	No	Yes	Beentjes (1998b)
	2007/2007	30–400 m	2 589 (0.24)	Yes	Yes	Beentjes & Stevenson (2008)
	2008/2008	30–400 m	1 863 (0.29)	Yes	Yes	Beentjes & Stevenson (2009)
	2009/2009	30–400 m	1 519 (0.36)	Yes	Yes	Beentjes et al. (2010)
	2012/2012	30–400 m	1 661 (0.25)	Yes	Yes	Beentjes et al. (2013)
	2014/2014	30–400 m	2 380 (0.23)	Yes	Yes	Beentjes et al. (2015)
	2016/2016	30–400 m	1 444 (0.31)	Yes	Yes	Beentjes et al. (2016)
ECSI, summer	1996/1997	10–400 m	3 818 (0.21)	No	Yes	Stevenson (1997)
	1997/1998	10–400 m	2 036 (0.24)	No	Yes	Stevenson & Hurst (1998)
	1998/1999	10–400 m	4 277 (0.24)	No	Yes	Stevenson & Beentjes (1999)
	1999/2000	10–400 m	2 606 (0.15)	No	Yes	Stevenson & Beentjes (2001)
	2000/2001	10–400 m	1 510 (0.13)	Yes	Yes	Stevenson & Beentjes (2002)
ECNI	1993/1993	20–400 m	-	No	-	Kirk & Stevenson (1996)
	1994/1994	20–400 m	1 128 (0.20)	No	Yes	Stevenson & Kirk (1996), Stevenson & Hanchet (2000)
	1995/1995	20–400 m	791 (0.23)	No	Yes	Stevenson (1996a), Stevenson & Hanchet (2000)
	1996/1996	20–400 m	943 (0.15)	No	Yes	Stevenson (1996b), Stevenson & Hanchet (2000)

2.4 Trawl survey age compositions

Age compositions have been derived from the more recent ECSI *Kaharoa* inshore trawl surveys (Table 2). In addition, tarakihi age compositions are available from individual trawl surveys conducted by *R.V. James Cook* during the 1970s and in 1987 (Table 3).

Table 3: Summary of tarakihi age composition data from James Cook trawl surveys conducted in the 1970s and in 1987.

Area	Year	Vessel	Reference(s)
Cape Runaway–Mahia Peninsula, 40–155 m	March 1971	James Cook	Vooren & Tong (1973)
Pegasus Bay	Jan–Mar 1970	James Cook	Vooren (1973) Tong (1979)
Pegasus Bay	January 1978	James Cook	Tong (1979)
Cape Campbell–Kaikoura	March 1978	James Cook	Tong (1979)
Pegasus Bay–Cape Campbell, 100–200 m	April 1987	James Cook	Annala et al. (1990)

The 1971 survey of the East Cape area conducted trawling throughout the area that supports the main TAR 2 fishery. The age composition of the tarakihi sampled was broadly comparable amongst the individual trawl stations (Vooren & Tong 1973).

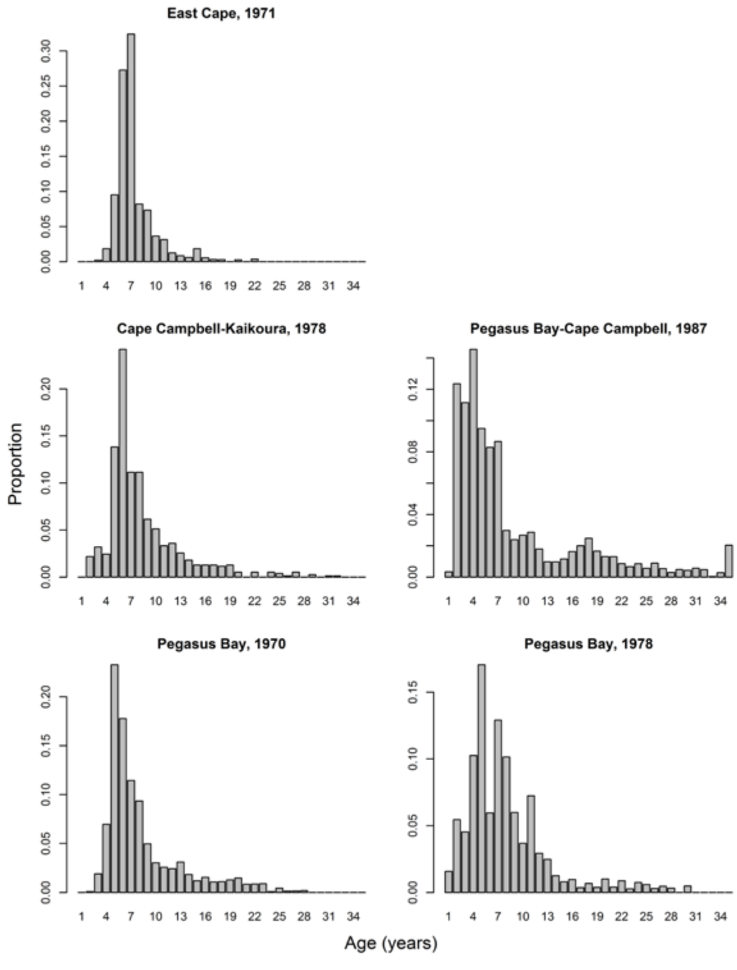

Figure 2: Tarakihi age compositions (both sexes combined) from *James Cook* trawl surveys (see Table 3). For the 1987 age composition, the terminal age class represents the proportion of fish aged 35 years and older (aggregated age class).

The 1987 survey conducted trawl sampling across most of the depth range of tarakihi in the area from Banks Peninsula to Cape Campbell and Annala et al. (1990) concluded that the *"sample design probably provided a reasonable random sample of the tarakihi population in this area"*.

There is no documentation available to describe the derivation of the age compositions determined from the James Cook trawl surveys in Pegasus Bay in 1970 and 1978 and Cape Campbell–Kaikoura in 1978.

There is considerable variability in the age compositions from the individual surveys both between areas and between years (Figure 2). The lack of a consecutive series of surveys from an individual area or areas means that the utility of these data is limited.

3. BIOLOGICAL PARAMETERS

3.1 Age and growth

Tarakihi growth has been defined using the Von Bertalanffy growth model. Annala (1987) summarised the results of earlier growth studies, including growth estimates from East Cape (McKenzie 1961, Vooren & Tong 1973) and the Bay of Plenty (Tong & Vooren 1972), and concluded that there were no obvious differences in the growth of tarakihi among the areas.

Annala et al. (1990) derived Von Bertalanffy growth parameters for the TAR 3 fishstock from otoliths collected from fish sampled during the 1987 *James Cook* trawl survey of Pegasus Bay–Cape Campbell. Length-weight relationships for male and female tarakihi were also derived from allometric data (length and weight) collected during the survey (Annala et al. 1990). The growth parameters derived for TAR 3 were consistent with the growth parameters derived from the earlier studies in the other areas.

An examination of age samples collected from the 2007–2016 *Kaharoa* ECSI trawl surveys (Section 2.3.1) indicated that the average length-at-age observations were consistent with the growth parameters for TAR 3 derived by Annala et al. (1990).

The length-at-age data collected from TAR 2 in 2009/10 (Parker & Fu 2011) included insufficient observations in the older age classes to reliably estimate the parameters of the VB growth model. Nonetheless, for the age classes that dominated the sample (4–8 years), the average length-at-age for male and female fish were similar to the values derived from the TAR 3, TAR 4 and TAR 7 growth models, indicating similar growth patterns of tarakihi amongst these areas.

Recent commercial catch sampling in TAR 1, TAR 2 and TAR 3 sampled the age of tarakihi in each of the main fisheries (McKenzie et al. 2017). These data provided the opportunity to compare the average length-at-age amongst six areas: TAR 3 (Canterbury Bight and Pegasus Bay), Cook Strait, TAR 2 (primarily East Cape–Mahia Peninsula), the Bay of Plenty, East Northland and the northern west coast of the North Island (TAR 1W). For each area, individual observations were aggregated by area, sex and fish age. The average length-at-age (and standard deviation) was determined for area/sex/age categories with at least four observations (Figure and Figure 3).

The results show that the average length-at-age of male and female fish from the TAR 3, Cook Strait and TAR 2 fisheries are consistent with the lengths predicted from the established TAR 3 growth models (Annala et al. 1990) (Figure). The average length-at-age from the northern west coast of the North Island fishery is also similar to the TAR 3 growth model (Figure 3).

For East Northland and the Bay of Plenty, the average length-at-age of male and female fish is similar to TAR 3 for the 4–6 year age classes; i.e., the age range that fish recruit to the fisheries in these two areas. However, from age 6 years the average length-at-age of fish sampled from the two areas was consistently lower than predicted from the TAR 3 growth models (Figure 3). This difference in length was about 2–3 cm for the older age classes (13–20 years) in the sampled population.

These results indicate that initial growth rates of tarakihi in East Northland and the Bay of Plenty are comparable to the other areas, although there is a more rapid attenuation of growth from age 6 years. One hypothesis that could explain these regional patterns in growth is that the fish in the East Northland and the Bay of Plenty share a common nursery ground with the fish from the other areas and, consequently, exhibit a similar initial growth to age 4–6 years. With the onset of sexual maturity, some fish may migrate from the nursery grounds and recruit to the fisheries within the East Northland and

Bay of Plenty areas. The subsequent growth rates could be suppressed if the productivity of fish in these areas is lower than the other fishery areas and/or there was an earlier onset of sexual maturity or a higher spawning frequency for the fish in the East Northland and Bay of Plenty areas.

The average length-at-age of older (6+ years) tarakihi in the East Northland fishery is lower than from the northern west coast North Island fishery (Figure 3), despite the close proximity of the main fisheries in these two areas. This may indicate a demarcation of the tarakihi populations between the two areas, at about North Cape.

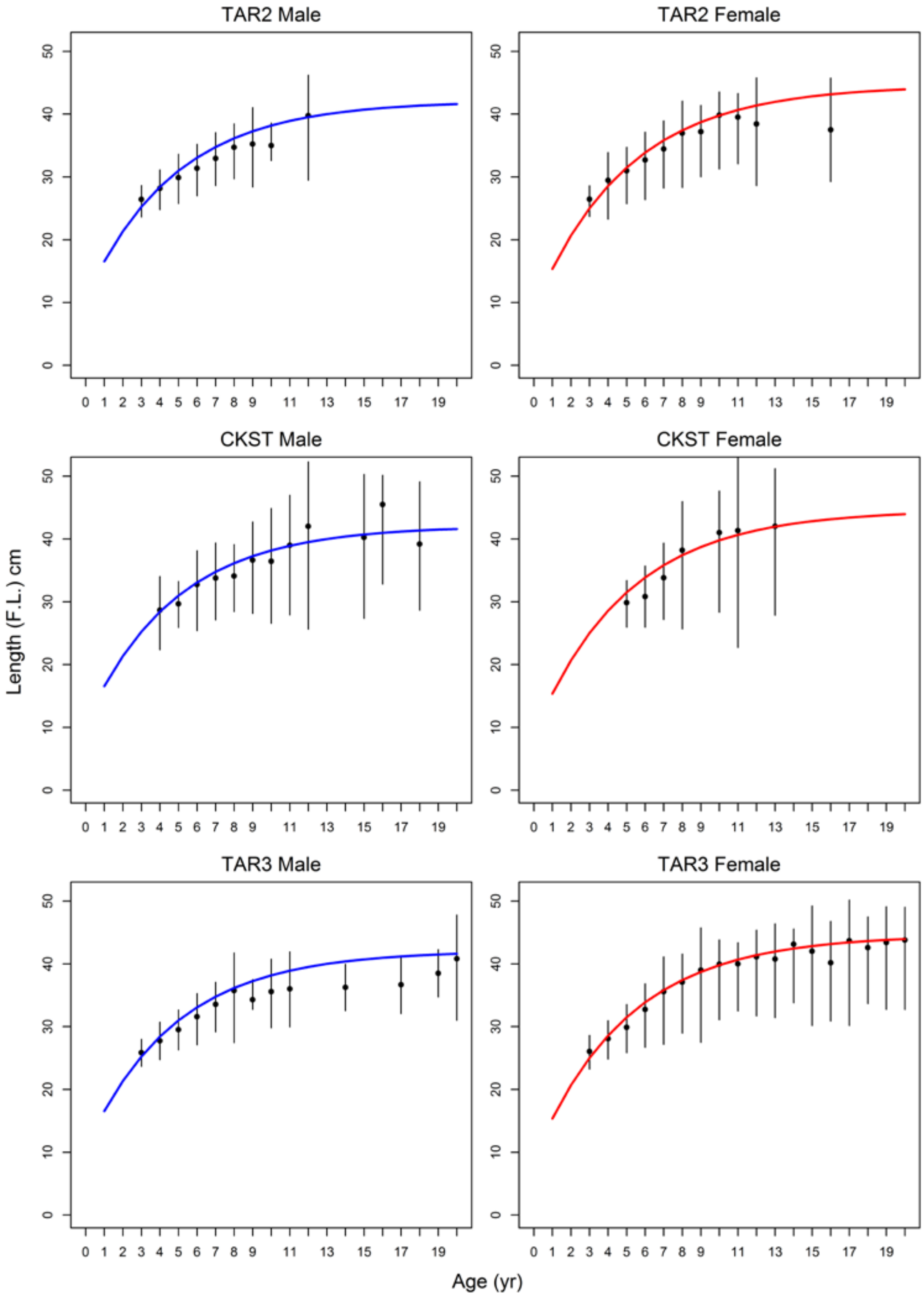

Figure 3: Average lengths at age (points) and confidence interval (1.96 standard deviations) for male and female tarakihi aged otolith samples from 2013/14 and 2014/15 commercial catch sampling programmes for TAR 2 (top), Cook Strait (middle) and TAR 3 (bottom). For comparison, the growth curve of male (blue lines) and female (red lines) tarakihi from TAR 3 (derived from Annala et al. 1990) is also presented.

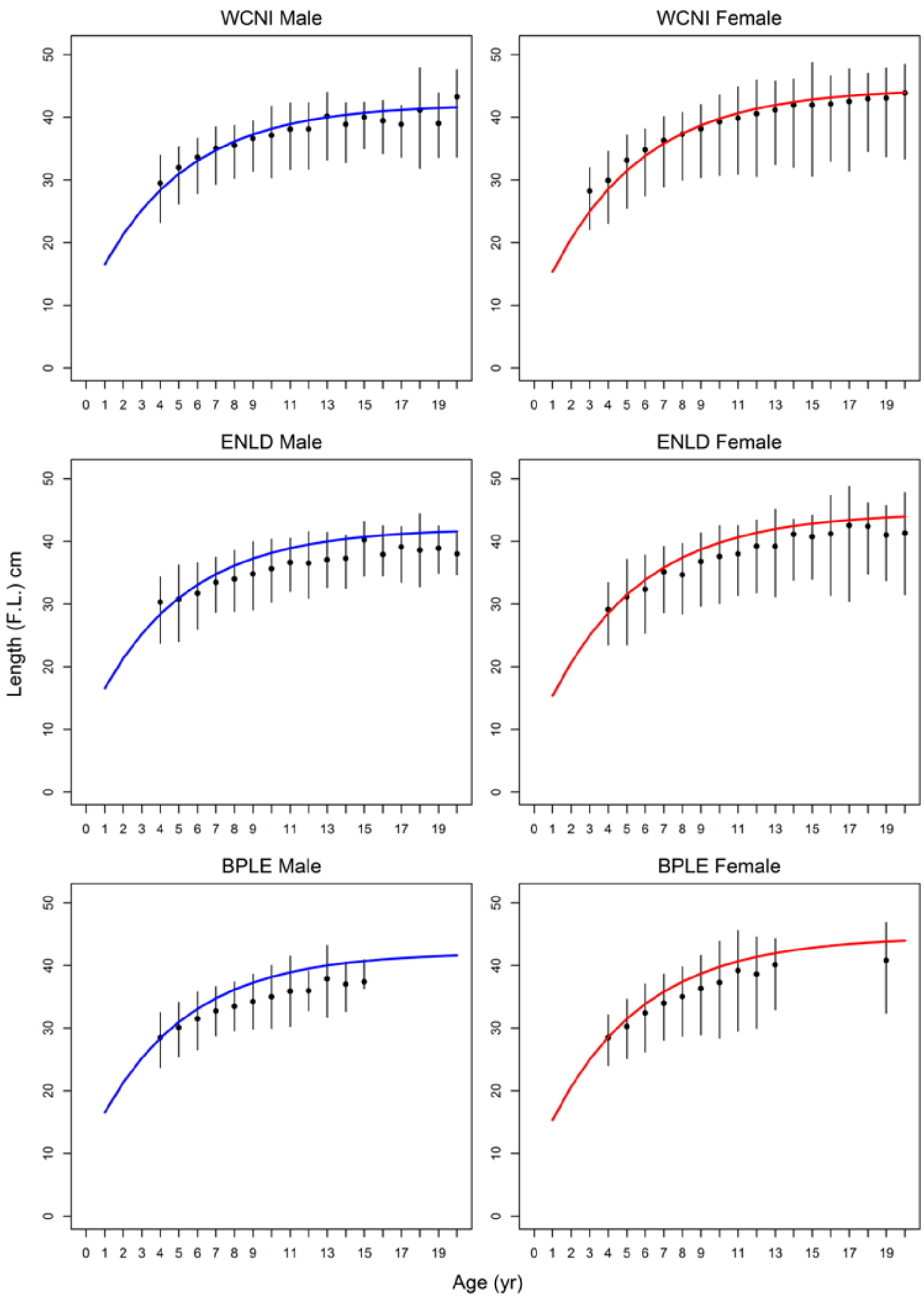

Figure 3: Average length at age (points) and confidence intervals (1.96 standard deviations) for male and female tarakihi aged otolith samples from the 2013/14 and 2014/15 commercial catch sampling programmes for the West Coast North Island (top), East Northland (middle) and the Bay of Plenty (bottom). For comparison, the growth curve of male (blue lines) and female (red lines) tarakihi from TAR 3 (derived from Annala et al. 1990) is also presented.

3.2 Natural mortality

An estimate of natural mortality for tarakihi was derived by Vooren (1977) from the age structures of lightly exploited populations sampled from the west coast South Island in 1971 and 1972. A catch curve analysis yielded total mortality estimates of 0.13 from both samples. An additional age sample was available from an unfished population of tarakihi around the Chatham Islands sampled in 1972. However, that age composition showed considerable variation in the strength of individual year classes and the total mortality estimates from a catch curve analysis are not considered to be reliable.

Age compositions were also available from surveys conducted in the Kaikoura area during 1970 and 1971. A catch curve analysis of these data estimated total mortality values of 0.147 and 0.159 and a value of natural mortality of 0.15 was proposed (Vooren 1973). Vooren (1977) considered the estimate of 0.15 to be too high and stated that "*M values not greater than 0.1 should be used*".

Annala et al. (1990) analysed the population age structure from Pegasus Bay–Cape Campbell in 1987. A catch curve analysis of the male and female age compositions estimated total mortality (Z) values of 0.12–0.16 for males and 0.12–0.15 for females. An approximation of M was also derived from the oldest age observed in the sample (42 years) yielding an estimate of $M = 0.11$. Annala et al. (1990) concluded that the available information suggested that M is no greater than 0.10.

3.3 Sexual maturity

Tong & Vooren (1972) found that tarakihi in the western Bay of Plenty reached first maturity at 25 cm and 24 cm for males and females, respectively. For males, the length at 50% and 100% maturity was 27 cm and 31 cm, respectively, while the corresponding length metrics of female fish were 28 cm and 35 cm. Annala (1987) summarised the results of previous biological studies and concluded that both sexes reach sexual maturity at 4–6 years of age.

Parker & Fu (2011) estimated length at maturity for male and female tarakihi from data collected during the 1993 east coast North Island trawl survey. A maturity ogive was determined for female and male fish assuming a logistic function. For female fish, L50% and L95% were estimated to be 33.56 cm and 40.13 cm, respectively. For male fish, L50% and L95% were estimated to be 31.55 cm and 39.78 cm, respectively. For TAR 3, 50% maturity was reached at 33 cm and 32 cm for female and male fish (Beentjes 2011). The lengths at maturity derived from these recent studies are considerably larger than determined by Tong & Vooren (1972).

4. REVIEW OF STOCK STRUCTURE

A comprehensive review of tarakihi stock structure was conducted by Hanchet & Field (2001) and updated by Langley & Starr (2012). This section provides a further compilation of the information summarised in the previous documents. Since then, additional age composition data have become available from commercial catch sampling and the ECSI trawl surveys and the CPUE indices have been updated. These data were examined to make inferences about potential stock linkages between fishery areas.

4.1 Distribution and relative abundance

4.1.1 Distribution of spawning and juveniles

The information available to characterise the distribution of spawning and juvenile tarakihi has been summarised in detail by Hurst et al. (2000) and Morrison et al. (2014).

Ripe and running ripe fish have been recorded from all around mainland New Zealand (Hurst et al. 2000). Vooren (1975) identified important spawning grounds off the east coast of the South Island coast, mainly in the deep water (100–200 m) in southern Cook Strait off Kaikoura Peninsula, in Pegasus Bay, and in the Canterbury Bight. Sampling of the catch from the Kaikoura set net and TAR 3 trawl fisheries indicated that mature and spawning fish were most common during January–March (Beentjes 2011). Annala et al. (1990) noted that ripe and running ripe fish were taken at most stations during a trawl survey of Pegasus Bay–Cape Campbell during April 1987. Mature and ripe tarakihi were also observed from FMA 3 during May–June (Hurst et al. 2000).

Recent samples of the commercial catches from East Northland, the Bay of Plenty, TAR 2 and Cook Strait had a higher proportion of female fish with ovaries in the ripe and/or running ripe stages of development during February–April (Hurst et al. 2000, Parker & Fu 2011; Jeremy McKenzie, NIWA, unpublished data). A trawl survey of tarakihi in the East Cape area during March 1971 caught ripe and recently spawned tarakihi (Vooren & Tong 1973).

Eggs in surface plankton samples indicated main spawning areas near East Cape, Kaikoura, and Fiordland (Robertson 1978). The larval stage is followed by a pelagic post-larval stage, and the post-larvae metamorphose into bottom-living juveniles when they are 8–10 months old, at a fork length of

70–90 mm (Vooren 1972, 1973, Tong & Saito 1977). Limited pre-juveniles have been collected. Robertson (1978) collected a single sample of 30 pre-juveniles (mean length 70 mm) at the surface at night, using a light and a dip net. These specimens were taken 1 km offshore in water 15 m deep. Robertson (1978) postulated that these pre-juveniles, which occurred in Otago waters in late spring and early summer, were probably spawned in southern Fiordland in the previous summer and autumn period and would have spent the next 7–10 months drifting northwards in the Southland Current, along the south and east coasts of the South Island. Annala (1987) considered that larvae from the west coast South Island spawning grounds may be transported north or south. Those carried south may settle mainly along the Otago coast and in the Canterbury Bight (Annala 1987).

Vooren & Tong (1973) noted a "scarcity of juveniles up to 4 years old" from the 1971 survey of the East Cape area and noted that this result was consistent with earlier sampling in the East Cape area in October 1969. Trawl sampling (141 stations) of the Bay of Plenty during 1961–63 in the 0–100 fathoms (0–183 m) depth range caught few tarakihi less than 10 inches (25.4 cm) in length (Tong & Elder 1968).

Vooren (1975) identified the main nursery grounds of tarakihi as the south-western coast of the North Island, Tasman Bay and along the entire eastern coast of the South Island (from Cape Campbell to Otago Peninsula) and around the Chatham Islands. Juvenile tarakihi (age groups 1 and 2) were also occasionally recorded from trawl sampling in Hawke Bay (Vooren 1975).

Hurst et al. (2000) mapped the distribution of catches of 0+ and 1+ year tarakihi from trawl surveys. The catches of 0+ juveniles were mainly off the east coast of the South Island in less than 100 m depth. 1+ juveniles were more widespread around mainland New Zealand. Catches were recorded from the western Bay of Plenty and from a small number of observations along the central east coast of the North Island. Negligible catches of juvenile tarakihi were recorded from around the east and west coasts of the northern North Island. Overall, catch rates of juvenile tarakihi were much larger from the Canterbury Bight compared to any of the other areas (Hurst et al. 2000).

Annala (1987) presented a synthesis of published and unpublished information on the recruitment of tarakihi and available information on current systems. The proposed mechanism for the recruitment of tarakihi involves the migration of the late juveniles and young adults against the prevailing current to their parental spawning grounds. The larval distribution was described for four main spawning grounds: west coast South Island, East Cape–Bay of Plenty, Conway Ridge–Pegasus Bay and Chatham Islands (Annala 1987). The distribution of larvae from the two main spawning grounds along the east coast was described, as follows:

"Larvae from the East Cape–Bay of Plenty spawning grounds are transported by the East Cape Current south along the east coast of the North Island, east towards the Chathams by the eddy system, and then north by the counter current offshore. Larvae settle along the entire east coast of the North Island on their way south and may be carried around the whole system back to the parental spawning grounds. Some larvae may reach the Chathams.

The Conway Ridge–Pegasus Bay spawning population may be an important link between tarakihi "stocks". Because of the complicated nature of the current systems in this area, larvae may be transported out and settle along the east coast of central New Zealand from Pegasus Bay to the Wairarapa coast, be carried through Cook Strait, be entrained in the eddy system off the east coast of the North Island and carried north towards East Cape, or be carried out to the Chathams" (Annala 1987).

For this study, preliminary modelling was conducted to investigate the passive drift from the known spawning locations over the seven months following main spawning period (assumed to be in April) for each year from 2007–2013. The analysis used the monthly average current flow at 5 m depth derived from the NCEP Global Ocean Data Assimilation System (GODAS) (Behringer & Xue 2004) (http://iridl.ldeo.columbia.edu/). The results indicated that passive drift from spawning locations off the east Northland, the Bay of Plenty and East Cape areas resulted in eastward displacement terminating in areas well offshore from the east coast of the North Island. In contrast, passive drift from a spawning site at Cape Campbell tended to retain larvae in the vicinity of the Wairarapa coast. The analysis is not considered to be particularly informative, although it does highlight that the passive drift in the surface waters is unlikely to provide a mechanism for the progeny of tarakihi from the northern-east coast of the North Island to reach the nursery grounds off the east coast of the South Island.

4.1.2 Distribution of adults

Trawl surveys show that adult tarakihi are distributed around mainland New Zealand concentrated in the 100–300 m depth range (Anderson et al. 1998 and Hurst et al. 2000). Langley (2017) defined the areas of highest tarakihi abundance based on the relative catch rates from the commercial trawl fisheries in TAR 1, TAR 2 and TAR 3. These areas were relatively contiguous along the eastern coast of the North and South Islands, although the largest areas of prime tarakihi habitat were around East Cape (western Bay of Plenty to Mahia Peninsula), in eastern Cook Strait (off Cape Campbell), in the Canterbury Bight and off east Northland.

Langley (2017) investigated seasonal patterns in trawl catch and effort data by Statistical Area to identify spatio-temporal variation in tarakihi CPUE that might be indicative of changes in the availability of tarakihi associated with spawning. Peaks in tarakihi CPUE during the March–May spawning period occurred off East Northland and in the Bay of Plenty. There is no strong seasonal peak in CPUE in the East Cape–Mahia Peninsula area. In the areas off the east coast of the South Island, tarakihi CPUE was highest during December–March and lowest during July–October. Off the Wairarapa coast, tarakihi CPUE increased during May–June from a lower level in December–March.

4.2 Age compositions

Over the last decade, a comprehensive series of age composition data has been compiled from the *Kaharoa* ECSI trawl surveys (Table 2) and the sampling of commercial catches from the tarakihi fisheries along the east coasts of the South Island and North Island (Table 1). The age compositions are characterised by the presence of a number of strong and weak year classes. These individual year classes can be followed through successive sampling events from the same fishery area (Figure 4, Figure 5 and Figure 6). In addition, over subsequent sampling events these year classes are emergent in the age compositions from the fisheries in the more northern areas of the east coasts of the South Island and North Island. Specific observations from the age composition data are as follow.

- The ECSI survey age compositions are dominated by fish aged 1–5 years (Figure 4). The age composition from the 2009 winter trawl survey was dominated by a strong 2007 year class (age 2 years). This year class persisted in the 2012 trawl survey age composition (Figure 4).
- The age composition from the 2012 winter trawl survey also included a strong 2009 year class (age 3 years). The 2008 year class (age 4 years) was relatively weak compared to the two adjacent year classes (Figure 4).
- The 2007 year class dominated the age composition from the TAR 3 trawl fishery in 2011 (age 4 years) (Figure 4). This year class was a trivial component of the age composition of the TAR 3 trawl fishery from 2014 and 2015 (at age 7 and 8 years).
- The 2009 year class dominated the age composition from the TAR 3 trawl fishery in 2014 (age 5 years) but represented a relatively small proportion of the age composition in 2015 (at age 6 years) (Figure 4).
- The 2007 year class recruited to the TAR 3 set net fishery in 2011 (age 4 years) and dominated the age composition of the catch in the subsequent sample in 2014 (age 7 years) (Figure 4). The 2009 year class had also recruited to the fishery by 2014 (age 5 years). This year class was more dominant in 2015 (age 6 years), while the relative proportion of fish in the 2007 year class (age 8 years) decreased.
- The 2007 and 2009 year classes were also prominent in the 2014 age composition from the Cook Strait trawl fishery (at ages 7 and 5 years, respectively) (Figure 4). The age composition also includes a relatively strong year class at age 10 years (2004 year class). The 2004 year class had also been prominent in the TAR 3 set net age composition in 2010 (age 6 years).
- The 2007 year class recruited to the TAR 2 trawl fishery in 2011 (age 4 years) (Figure 5). The 2014 and 2015 TAR 2 age compositions were similar to the corresponding TAR 3 set net age compositions. The two 2014 age compositions were dominated by the 2007 (age 7 years) and 2009 (age 5 years), although the 2009 year class was more prominent in the TAR 2 trawl age

composition (Figure 5). The dominance of the 2009 year class increased in the 2015 age compositions, although the relative importance of the 2007 year class (compared to the 2009 year class) was higher in the TAR 3 set net fishery than the TAR 2 trawl fishery (Figure 5).

- The 2004 year class represented a significant proportion of the TAR 2 age composition in 2010 (age 6 years) and 2011 (age 7 years). This year class represented a negligible component of the TAR 2 age composition in 2014 (age 10 years) and 2015 (age 11 years) (Figure 5).
- The 2007 year class also recruited to the Bay of Plenty trawl fishery in 2011 (age 4 years) (Figure 6). This year class persisted in 2014 and 2015 while the 2009 year class became increasingly dominant. The 2014 and 2015 age compositions from the Bay of Plenty fishery are similar to the corresponding age compositions from both the TAR 3 set net fishery and the TAR 2 trawl fishery. There was a slightly higher proportion of older fish in the Bay of Plenty trawl fishery compared to the TAR 2 trawl fishery, although overall there was a relatively small proportion of fish in age classes older than 10 years for both fisheries (Figure 6).
- For the East Northland trawl fishery, the strong 2007 year class had recruited to the fishery by 2014, while the 2009 year class (age 5 years) appears to have partially recruited (Figure 6). The 2009 year class is considerably more prominent in the 2015 age composition (at age 6 years). By comparison to the other fisheries, there was a relatively high proportion of older fish in the East Northland age composition, especially within the 17–22 age classes (1993–1997 year classes) (Figure 6).

In addition to the above observations, Parker & Fu (2011) partitioned the TAR 2 trawl age composition data from 2010 into two areas; i.e. south and north of Mahia Peninsula. The sampled catch from south of Mahia Peninsula was composed of younger fish, including a significant proportion of 3 year old fish (previous aged 2 and corrected to age 3 based on the revised ageing protocol).

McKenzie et al. (2017) derived separate age compositions for the TAR 3 trawl fisheries in Canterbury Bight and Pegasus Bay for 2014 and 2015. The age compositions from the Canterbury Bight were dominated by age 4–5 year fish and fish older than 6 years were virtually absent. The catches from Pegasus Bay were also dominated by young fish (4–6 years) although a broad range of older age classes was also sampled (7–20 years).

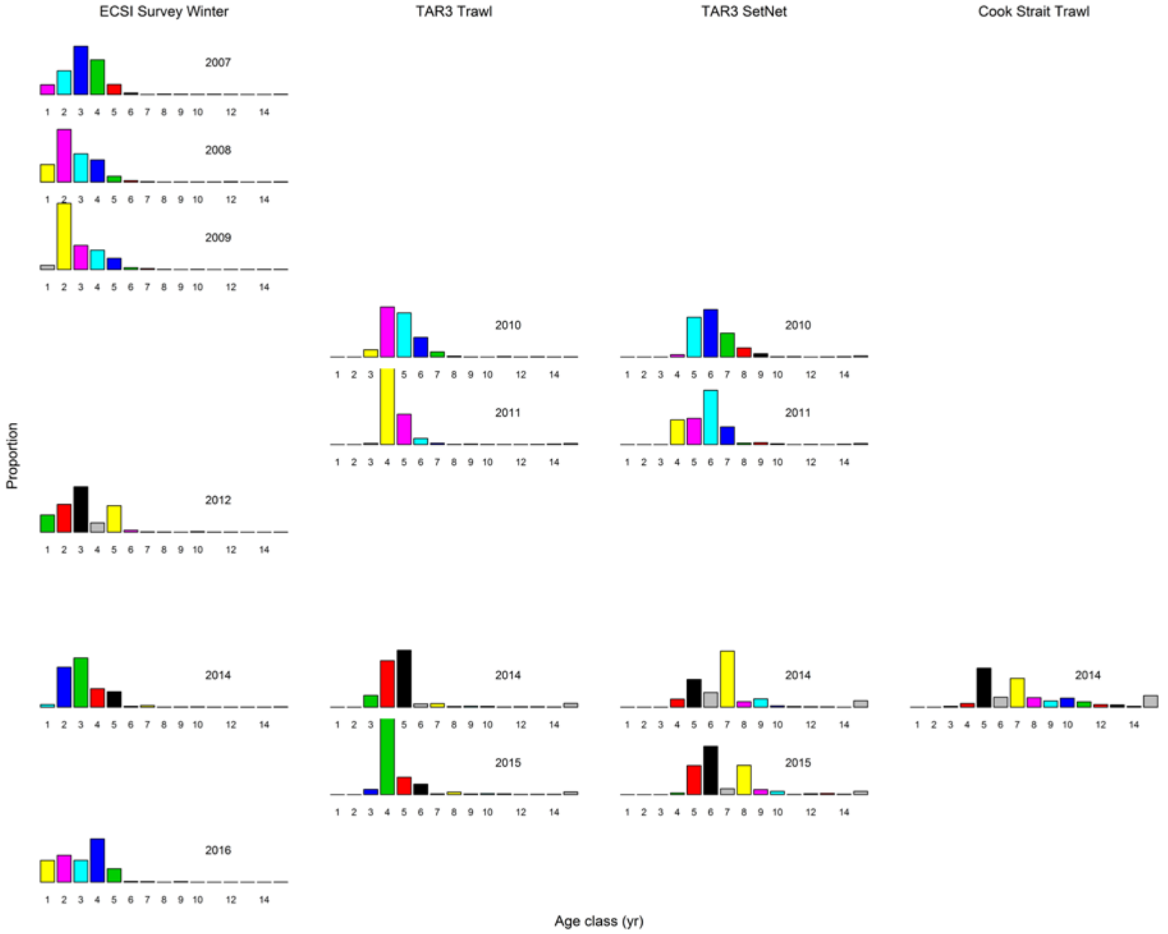

Figure 4: A comparison of annual age compositions collected from the ECSI winter trawl survey (left) and commercial fisheries in TAR 3 and eastern Cook Strait. Individual year classes are colour coded to follow the cohorts through successive years. The proportion of fish older than 14 years are aggregated into the oldest age class.

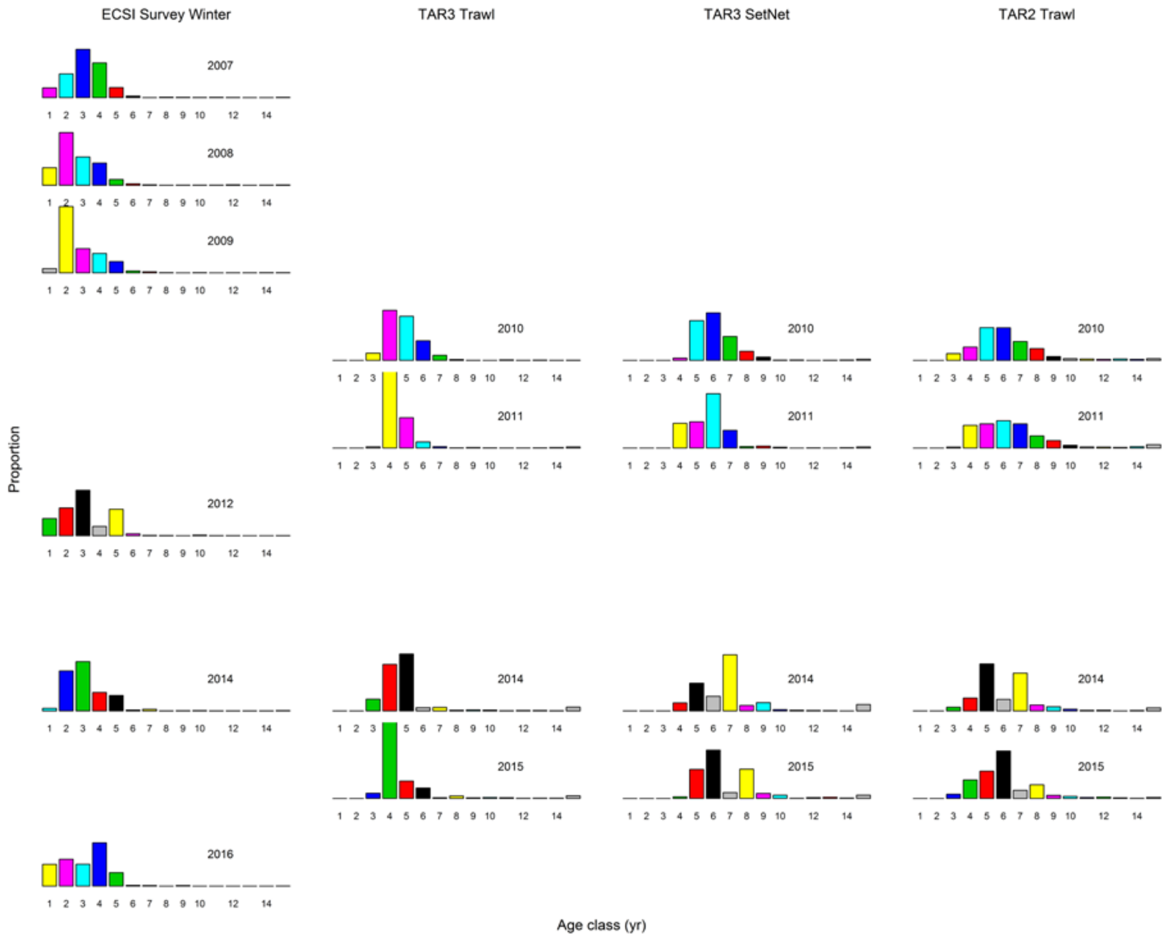

Figure 5: A comparison of annual age compositions collected from the ECSI winter trawl survey (left) and commercial fisheries in TAR 3 and TAR 2. Individual year classes are colour coded to follow the cohorts through successive years. The proportion of fish older than 14 years are aggregated into the oldest age class.

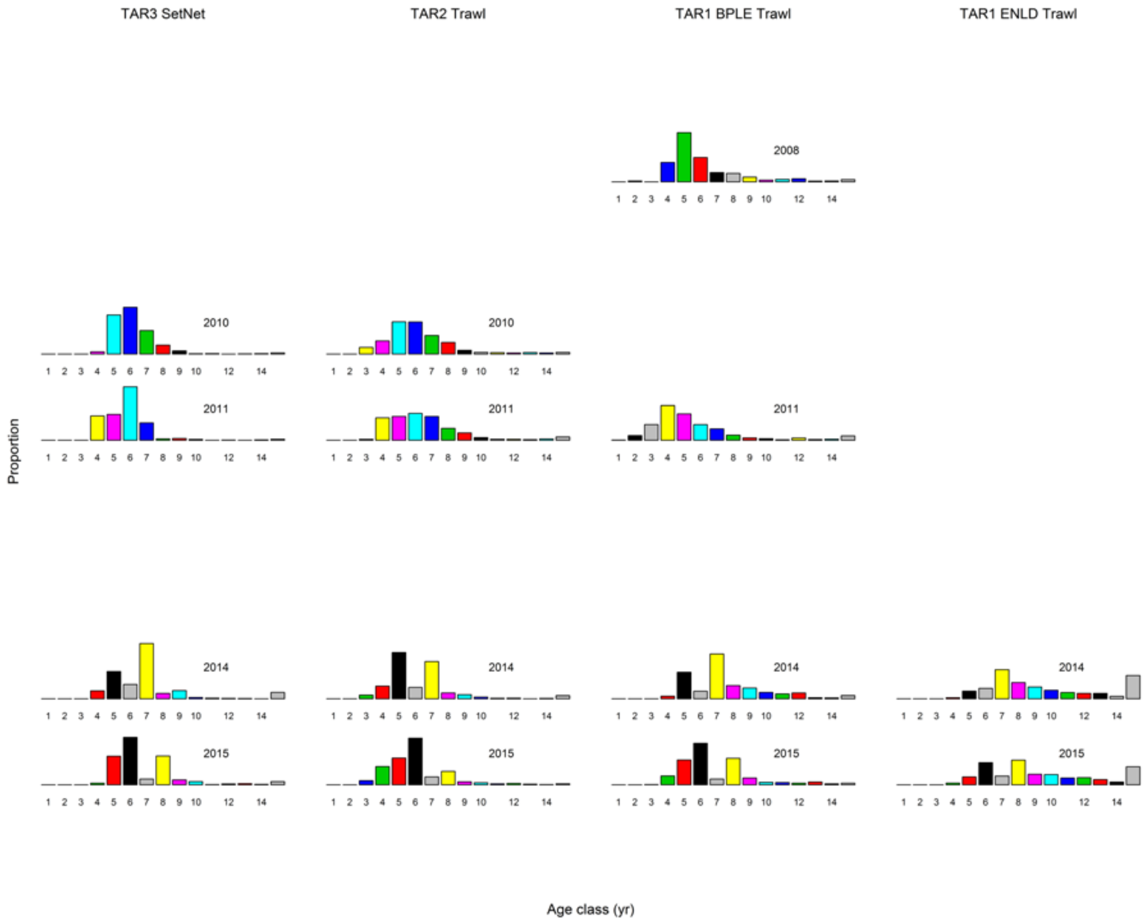

Figure 6: A comparison of annual age compositions collected from the TAR3-SN, TAR2-BT, BPLE-BT and ENLD-BT commercial fisheries. Individual year classes are colour coded to follow the cohorts through successive years. The proportion of fish older than 14 years are aggregated into the oldest age class.

Limited age composition data are available from the WCNI trawl fishery with sampling conducted in 2014 and 2015 only (McKenzie et al. 2017). The age compositions indicate the presence of the strong 2007 year class which is also present in the east coast age compositions. Nonetheless, while the 2006 year class appears to be weak throughout the age compositions from the east coast fisheries, there is no indication that this year class is weak in the WCNI fishery (McKenzie et al. 2017). Further, the 2005 year class appears to be relatively strong in the WCNI fishery, although it was only present as a relatively pronounced year class in the TAR 3 set net fishery in 2011 (age 6 years) and appeared to be of moderate strength in the age compositions from the other east coast fisheries.

The age composition data from the west coast South Island (WCSI) trawl surveys (in 1995, 1997, 2000, 2003 and 2005) and 2004/05 TAR 7 commercial catches indicate the presence of a strong year class in 1991 and weak year classes in 1989, 1999, 2003 and 2004 (Manning et al. 2008). These limited observations are broadly consistent with estimates of recruitment strength derived from the stock assessment modelling of the east coast tarakihi stock which incorporates the age composition data from the east coast fisheries (see Section 5.5.1). The east coast stock assessment estimates a moderate 1991 year class, weak 1989 and 1999 year classes and moderate 2003 and 2004 year classes. Nonetheless, a more comprehensive analysis of the age composition data is required to compare the age structure between the two areas, including an evaluation of the full range of year classes sampled from the WCSI fishery.

Further, estimates of the abundance of pre-recruit tarakihi from Tasman Bay/Golden Bay (TAR 7) indicate relatively strong recruitment in 2006, 2008, 2010, 2012 and lower recruitment of the 2014 year class (MPI 2017). These observations are broadly consistent with the strength of the corresponding

2006, 2010, 2012 and 2014 year classes estimated from the east coast assessment model, whereas the 2008 year class was estimated as very weak (see Section 5.5.1).

4.3 Recent trends in stock abundance

Langley (2017) compared annual trends in the CPUE indices derived from the TAR 3 trawl and set net fisheries and trawl fisheries in TAR 2, the Bay of Plenty (TAR 1), East Northland (TAR 1) and west coast North Island (TAR 1) (Figure 7). The main conclusions of these comparisons are summarised as follows:

- The Bay of Plenty and TAR 2 trawl CPUE indices both exhibit a strong peak in the annual CPUE indices during 2000/01–2004/05 (Figure 7). There is a short lag between the two sets of indices during this period; the increase in TAR 2 CPUE indices preceded the increase in the Bay of Plenty CPUE indices by one year, while the higher level of CPUE indices from the Bay of Plenty was maintained for a further year.
- There was also a peak in the CPUE indices from the TAR 3 set net fishery during 2001/02–2003/04 (Figure 7).
- The increase in CPUE indices for the Bay of Plenty and TAR 2 trawl fisheries was preceded by a peak in the TAR 3 trawl CPUE indices during 1999/2000–2001/02 (Figure 7). The catch from the TAR 3 trawl fishery is dominated by younger fish compared to the other two fisheries.
- For the East Northland trawl fishery, there was a period of higher CPUE during 2001/02–2005/06 that followed the peak in the Bay of Plenty trawl CPUE by one year (Figure 7). Both sets of indices also exhibited another peak during 1995/96–1997/98. This earlier peak in CPUE was not evident in the indices from the TAR 2 trawl fishery.
- There was a general decline in the CPUE indices from the Bay of Plenty during 2009/2010–2015/16 which was consistent with the recent trend in the CPUE indices from the East Northland fishery (Figure 7).
- The CPUE indices from the TAR 3 trawl fishery increased from about 2009/10 to 2015/16. This increase was been followed by a smaller increase in the CPUE indices from the TAR 2 trawl fishery (Figure 7).
- The CPUE indices from the northern WCNI fishery do not exhibit the period of higher CPUE during 2000/01–2004/05 that was evident for TAR 2, the Bay of Plenty and, to a lesser extent, East Northland (Figure 7).

For the east coast tarakihi fisheries, there are significant positive correlations amongst each set of CPUE indices once a lag period was incorporated (between individual sets of CPUE indices) (Langley 2017). In general, the lag intervals that provided the best correlation tended to coincide with the differences in the age composition of the catches between the corresponding fisheries (i.e., the ages of first recruitment).

The general increase in the CPUE indices from multiple fisheries during the late 1990s–early 2000s is consistent with a period of strong recruitment. The age composition data from East Northland indicate the presence of a series of stronger 1993–1997 year classes that are not present in the age compositions from the other fisheries. Nonetheless, the timing of the recruitment of these year classes to the individual fisheries is consistent with the period of higher CPUE indices.

Trends in the range of CPUE indices derived from the TAR 1, TAR 2, and TAR 3 fisheries (Langley 2017) differ from the time-series of tarakihi biomass estimates from the *Kaharoa* inshore WCSI trawl survey (MPI 2017) (Figure 7). Similarly, the CPUE trends from the TAR 1, TAR 2, and TAR 3 fisheries are not consistent with the trends in the CPUE indices from the TAR 7 WCSI MIX trawl fishery (Langley 2014). The WCSI CPUE indices are characterised by two periods of higher CPUE during 1994/95–1999/2000 and 2002/03–2007/08 and lower CPUE during the intervening period (Figure 7).

Tarakihi recruit to the TAR 7 trawl fishery at age 2–3 years and catches (in numbers of fish) are dominated by 3–8 year old fish (Manning et al. 2008). Thus, the age composition of the catch can be considered broadly comparable to the TAR 3 set net, TAR 2 trawl and the Bay of Plenty trawl fisheries. The CPUE indices from these fisheries do not correspond with the CPUE indices from the TAR 7 WCSI MIX trawl fishery, especially during 2000/01–2001/02 when CPUE from the latter fishery was relatively low while CPUE indices from the eastern fisheries were at the highest level for each series (Figure 7).

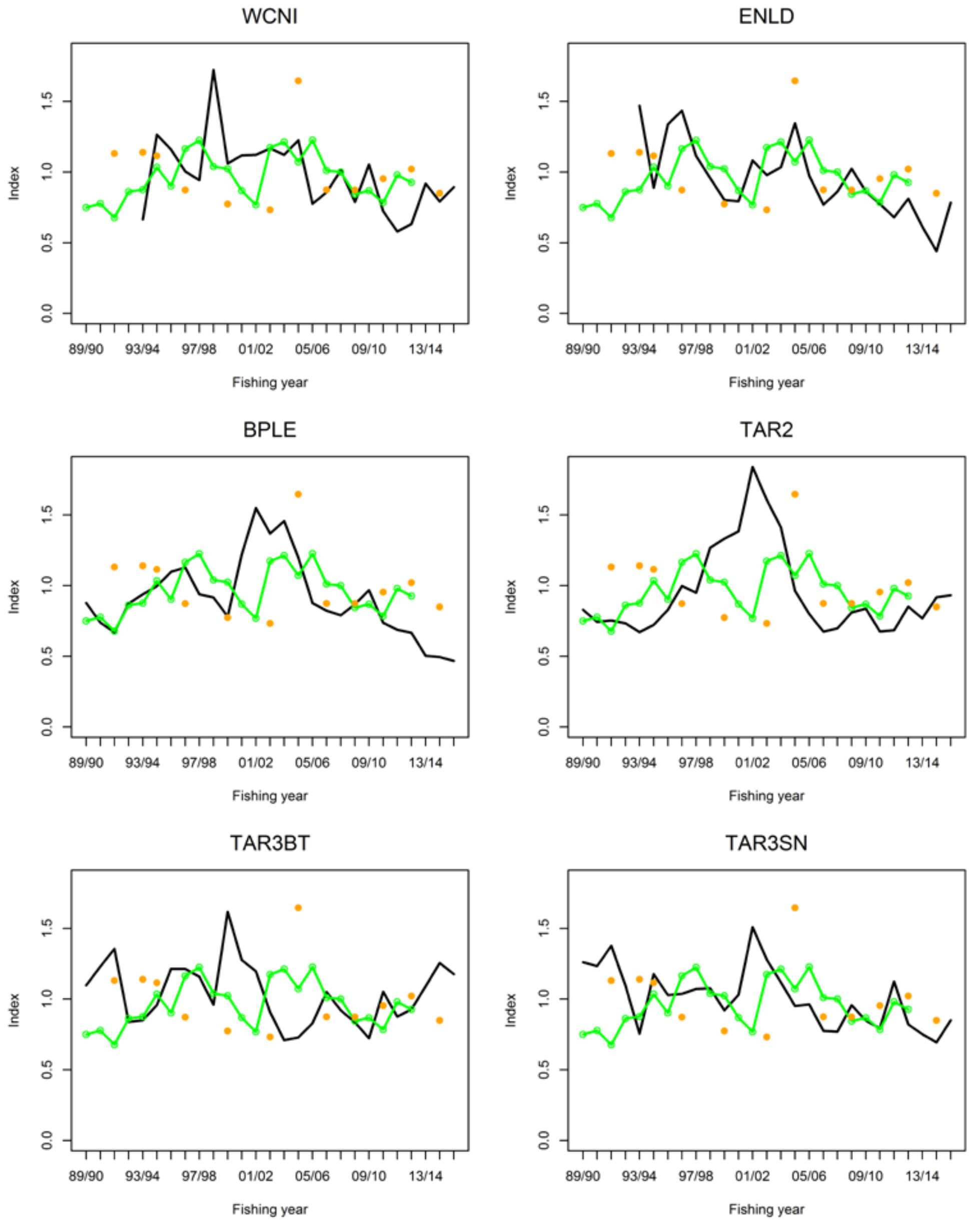

Figure 7: A comparison of the annual CPUE indices derived for the TAR 1, TAR 2 and TAR 3 fisheries (black lines; Langley 2017), the tarakihi trawl survey biomass estimates from the Kaharoa WCSI trawl surveys (orange points) and the TAR 7 WCSI MIX CPUE indices (green lines; Langley 2014). Each set of indices is normalised to the average of the 1993/94–2012/13 years.

4.4 Tagging studies

A number of tagging studies have been conducted to investigate the movements of tarakihi around mainland New Zealand. These data do not provide definitive information regarding stock boundaries but they do provide useful information to corroborate potential linkages between areas.

During the 1950s, a tagging study was conducted in the area around East Cape (McKenzie 1961). A summary of the movement of tagged fish concluded that *"the great majority of the recoveries have been made north of their points of release, many of them on, near or beyond the spawning grounds of East Cape near the spawning season"* (McKenzie 1961) (see Appendix 7). A notable exception to this trend was the longer distance movement reported for one tarakihi released off Mahia Peninsula (Portland Island) and recovered from Cook Strait 10 months later (McKenzie 1961).

Crossland (1982) further summarised the results of tagging studies from the East Cape area and observed that the movement of tarakihi was relatively limited during the first year at liberty. However, wide-ranging movements were quite common over longer periods at liberty. Fish tagged in summer and autumn, particularly from release locations around Mahia Peninsula, tended to be recovered at the release location or further north around East Cape. A relatively small number of tarakihi released in spring and early summer in the eastern Bay of Plenty were recaptured around East Cape (Appendix 7).

The recoveries of tagged tarakihi released in the Bay of Plenty (during 1955–1969) indicated a general westward movement of tarakihi within the Bay of Plenty (Gauldie & Nathan 1977). Crossland (1982) also described a number of other tagging studies from Pegasus Bay (1969), East Cape (1971), Tasman Bay (1971) and Tasman Bay and Golden Bay (1973). However, the detailed information of the subsequent tag recoveries is not presented.

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 recaptured outside the tagging area moved long distances. Of those moving north, 2 were recaptured near Great Barrier Island, 1 near Waiheke Island, 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 Peninsula and Timaru.".

In recent years, juvenile tarakihi were tagged in Tasman Bay during the 2007 (773 tagged fish), 2009 (614) and 2011 (912) *Kaharoa* trawl surveys. Tagging of tarakihi was not continued in subsequent surveys due to a lack of tag recoveries.

4.5 Other studies

A range of discrimination techniques have been applied to investigate the stock structure of tarakihi although the results of the studies were not very informative.

Vooren & Tracey (1976) compared the parasite faunas of tarakihi from three areas around New Zealand: East Cape, Tasman Bay and the Chatham Islands. The tarakihi populations in these areas differed from each other in the incidence and intensity of at least one of the three commonest parasites. However, the spatial scale of the study sites does not provide sufficient resolution to define the geographic boundaries of the tarakihi populations.

Gauldie & Johnston (1980) compared allele frequencies from tarakihi collected all around New Zealand and showed that variation over the whole region was not significantly different from the yearly variation at Pegasus Bay. They concluded that slight differences between adjacent areas were more likely to constitute selective climes than genetically isolated stocks.

Grewe et al. (1994) investigated the mitochondrial DNA diversity from eight southern Australian localities and one New Zealand location (west coast South Island). No differentiation was detected among the Australian localities. The New Zealand sample showed weak but significant divergence from the Australian samples. The study concluded that there is appreciable nuclear and mitochondrial DNA gene flow among Australian localities, while the Tasman Sea separating Australia from New Zealand acts as a partial barrier. However, a subsequent genetic study using microsatellite DNA markers did not indicate significant divergence among Australian samples, or between Australian and New Zealand samples (Burridge & Smolenski 2003).

Gauldie & Nathan (1977) identified regional variation in the iron content of tarakihi otoliths around mainland New Zealand and postulated that differences in iron content between subpopulations of fish may be linked by heredity or environmental conditions. A subsequent study attributed the regional variation in otolith iron to a relationship between otolith iron and sea temperature (Gauldie et al. 1980).

Smith et al. (1996) used two genetic techniques to determine that king tarakihi (*Nemadactylus* sp.) from northern New Zealand is a separate species from tarakihi (*N. macropterus*).

4.6 Summary

The relatively continuous distribution of adult tarakihi around coastal New Zealand indicates that stock discrimination techniques may not be very useful in defining tarakihi stock boundaries and/or stock units. For the purpose of this study, a stock unit has been defined as a relatively discrete population or connected sub-populations (of adult fish) that are derived from a common pool of juvenile fish. There is potential for the pool of juvenile fish to also contribute to other stock units.

The trends in CPUE indices and age compositions from the TAR 1, 2 and 3 fisheries were examined to investigate the stock structure of tarakihi along the east coasts of mainland New Zealand. The fisheries in Canterbury Bight/Pegasus Bay are dominated by younger fish and there is a progressive increase in the proportion of older fish in the catches from TAR 2, the Bay of Plenty and east Northland, while the relative strength of individual year classes is comparable amongst these areas. Trends in CPUE indices are also comparable among these fisheries, lagged by the relative age of recruitment to the respective fishery.

Spawning of tarakihi occurs throughout the eastern areas off the North and South Islands, although two main spawning areas have been identified around East Cape and off Cape Campbell. There is a preponderance of juvenile fish in Canterbury Bight/Pegasus Bay and low densities of juvenile tarakihi in East Northland, the Bay of Plenty and TAR 2. The long pelagic phase of tarakihi may provide a mechanism for the transfer of the progeny from the latter areas to the nursery grounds in Canterbury Bight/Pegasus Bay.

Tagging studies indicate a considerable northward movement of fish from the east coast of the South Island to the Wairarapa coast, East Cape and the Bay of Plenty. Earlier tagging studies indicated northward movements of fish from Mahia Peninsula to East Cape and the Bay of Plenty and a general eastward movement of tagged fish through the Bay of Plenty. There was also some movement of tagged fish around East Cape from the western Bay of Plenty prior to the main spawning period.

These observations indicate considerable connectivity of tarakihi along the east coast of the South and North Islands. The current stock hypothesis is that the Canterbury Bight/Pegasus Bay area represents the main nursery area for the eastern stock unit. At the onset of maturity, a proportion of the fish migrate northwards to recruit to the East Cape area and, subsequently, the Bay of Plenty and east Northland areas.

The results from previous tagging studies also indicate some connectivity between Kaikoura and the west coast North Island. However, limited data are available from the west coast North Island to elucidate the degree of the linkage between these areas. Recent age composition data from the west coast North Island identified similarities and differences in the relative strength of individual year classes compared to the east coast South and North Island fisheries. Further, growth rates of older fish sampled from the west coast North Island differed from east Northland suggesting a lack of connectivity between the fisheries around the north of the North Island.

Limited direct comparisons are available between the age compositions from the east coast tarakihi fisheries and the west coast South Island (TAR 7) fishery. The age composition data from the WCSI trawl surveys (in 1995, 1997, 2000, 2003 and 2005) and 2004/05 TAR 7 commercial catches indicates broadly similar patterns in the strength of individual year classes to the east coast fisheries. However, there are considerable differences in the trends in the abundance indices from the WCSI area and the eastern areas indicating a degree of separation of the tarakihi populations. A more comprehensive analysis of the available data sets is required to further investigate the stock structure between tarakihi in TAR 7 and the east coast areas, especially around the South Island.

5. STOCK ASSESSMENT

Stock assessment modelling of east coast tarakihi was conducted using a statistical, age-structured population model implemented in Stock Synthesis (Version 3.24Z) (Methot 2015, Methot & Wetzel 2013). Stock Synthesis can incorporate a range of data components, including abundance indices (survey and CPUE) and length and age composition data. The modelling framework provides considerable flexibility in the parameterisation of key model processes such as selectivity, including a range of different functional forms, a range of prior distributions, and incorporating temporal variation in parameter estimation.

Stock Synthesis enables the spatial partitioning of the model population. The specification of the spatial structure includes the apportionment of recruitment amongst the model regions, age-specific movement amongst model regions and the regional removals of catch (via the assignment of individual fisheries to specific regions). Observational data were assigned to the individual model regions.

The potential to model the spatial structure of the population has direct application to the modelling of the east coast tarakihi stock by structuring the model to represent the stock hypothesis described in Section 4.6; i.e., the recruitment of juvenile tarakihi to the main nursery areas in the Canterbury Bight and Pegasus Bay (TAR 3) and the general northward movement of fish to the main fishery areas: Kaikoura (TAR 3), Eastern Cook Strait (eastern TAR 7, TAR 2), East Cape (TAR 2), the Bay of Plenty (TAR 1) and east Northland (TAR 1). Levels of fishing mortality may differ amongst the regions of the model, potentially resulting in different trends in stock abundance amongst regions.

During the preliminary modelling phase, a range of alternative spatial structures was investigated. The spatial structures considered were predicated on the spatial resolution of the individual data sets and the level of information available to inform the associated model parameters (especially movement parameters). The results of the preliminary modelling informed the configuration of the final set of model options.

5.1 Data sets

5.1.1 Fishery definitions

Previous summaries of the tarakihi fisheries along the east coast of the South and North Islands have identified six main fisheries defined by fishing method and Statistical Area (e.g. Langley 2017, McKenzie et al. 2017) (Table 4). The fishery definitions also maintain the approximate demarcation of the relevant fishstock boundaries (Figure 1).

The individual fisheries may be characterised by differences in the length and age compositions of the tarakihi catches. These fishery definitions were adopted by the recent catch sampling programmes and, hence represent the basic level of resolution for the age composition data. Estimates of age compositions at a finer spatial resolution are available from some of the sampling programmes, e.g. TAR 3 trawl sampling partitioned by Pegasus Bay and Canterbury Bight from McKenzie et al. (2017). However, to derive a consistent time-series of age composition data from each fishery it was necessary to aggregate all data sets at the spatial resolution of the fishery definitions (Table 4).

Table 4: Definition of main east coast tarakihi fisheries.

Fishery code	Method	Statistical Area(s)	Main fishery area(s)
TAR3-BT	Bottom trawl	020, 022, 024	Canterbury Bight, Pegasus Bay
TAR3-SN	Set net	018	Kaikoura
Cook-BT	Bottom trawl	016, 017, 018	Eastern Cook Strait
TAR2-BT	Bottom trawl	011–015	East Cape, Wairarapa
BPLE-BT	Bottom trawl	008, 009, 010	Bay of Plenty
ENLD-BT	Bottom trawl	002, 003, 004, 005	East Northland

5.1.2 Commercial catch history

Francis & Paul (2013) compiled reported landings of tarakihi by the domestic and foreign fleets by Fishery Management Areas from 1931–1982. These catches were derived primarily based on the port of landing of the catch, especially for the inshore fleet. More recent annual catches by fishstock (to 2015/16) are documented in MPI (2017). From 1989/90, catches were reported by fishing year and the catches were assigned to the calendar year at 1 January (e.g., catches from the 2015/16 fishing year were assigned to 2016).

The reported catches from FMAs 1–3 were compiled for the derivation of the catch history included in the stock assessment. In addition, the proportion of the TAR 7 (FMA 7) catch taken from the eastern Cook Strait area was also included in the catch history. For the 1989/90–2015/16 fishing years, the reported annual catches were allocated amongst the defined fisheries based on the proportional distribution of catches derived from an extract of commercial catch and effort data from the MPI warehou database (Ministry of Fisheries 2010) (described in Langley 2017).

The TAR 3 set net fishery commenced in the late 1970s and all catch from TAR 3 (FMA 3) prior to 1979 was allocated to the TAR 3 trawl fishery. The set net fishery was assumed to account for 20% of the TAR 3 catch during 1982–88 based on the proportion of catch taken by the set net method in the early 1990s.

The catches from FMA 1 from 1931–1982 (Francis & Paul 2013) were apportioned between East Northland and the Bay of Plenty based on the regional domestic catches documented in table 2 of Annala (1988). Catches reported from Hauraki Gulf were included in the catch from East Northland. However, there is concern regarding the reliability of the large catches assigned to the Hauraki Gulf region in the earlier years (i.e., prior to 1965).

The regional catches from Annala (1988) were also applied to determine the proportion of the catch allocated to the eastern Cook Strait trawl fishery during 1931–1982. It was assumed that catches from this area had been included within the FMA 2 catches documented in Francis & Paul (2013) based on the assignment of Wellington landings to FMA 2.

The extent of unreported commercial catches (including illegal, under-reported and misreported) from the tarakihi fisheries is unknown but may have been substantial, particularly prior to the introduction of the QMS. The current assessment adopted the approach used in other inshore fishery stock assessments (most notably SNA 1 and SNA 8) and assumed unreported catches represented 20% of the reported annual catch in the years prior to the introduction of the QMS (in 1986) and 10% of the annual reported catch in subsequent years.

The catch history included in the assessment modelling is presented in Table A1 (Appendix 1). The compiled annual catches from the ENLD-BT fishery were relatively high during 1932–1960, peaking at about 2000 t in the early 1950s (Figure 8). Catches declined during the 1960s and fluctuated between 200–450 t during 1975–2016.

By contrast, catches from the Bay of Plenty fishery (BPLE-BT) were low during the 1930s and 1940s (Figure 8). Reported catches increased in 1950 and fluctuated between 400–800 t over 7–10 year intervals during 1960–2015.

During the late 1940s, catches from TAR 2 (TAR2-BT) increased considerably and continued to increase in the early 1960s, reaching a peak of about 2600 t in 1961–1967 (Figure 8). Catches declined sharply in the late 1960s and early 1970s and declined further in the early 1980s. Catches recovered in the late 1980s and were maintained at about 1700–1900 t during the subsequent period.

Annual catches from the eastern Cook Strait fishery (Cook-BT) increased to the mid-1960s, reaching a peak of about 1000 t, and then declined in the early 1970s (Figure 8). From the early 1980s, annual catches were maintained at between 400–600 t in most years.

The TAR 3 set net fishery (TAR3-SN) developed in the early 1980s and catches fluctuated between 250–350 t during 1983–2004, at intervals of about 5–7 years (Figure 8). The annual catch declined in 2005 and remained at about 100–200 t during 2005–2016.

There was a general increase in the annual catch from the TAR 3 trawl (TAR3-BT) fishery (Canterbury Bight and Pegasus Bay) during 1940–1967 (Figure 8). This was followed by a peak in catch during 1973–77 when a large proportion of the annual catch (50–80%) was caught by the foreign trawl fleet operating in the Canterbury Bight (Sullivan 1981, Francis & Paul 2013). The annual catch dropped sharply following the declaration of the EEZ in 1978 and then rapidly recovered to about 1000 t during 1981–1986. Annual catches declined to about 350–450 t in 1993–1994 and were maintained at between 700–900 t through most of the subsequent period (Figure 8).

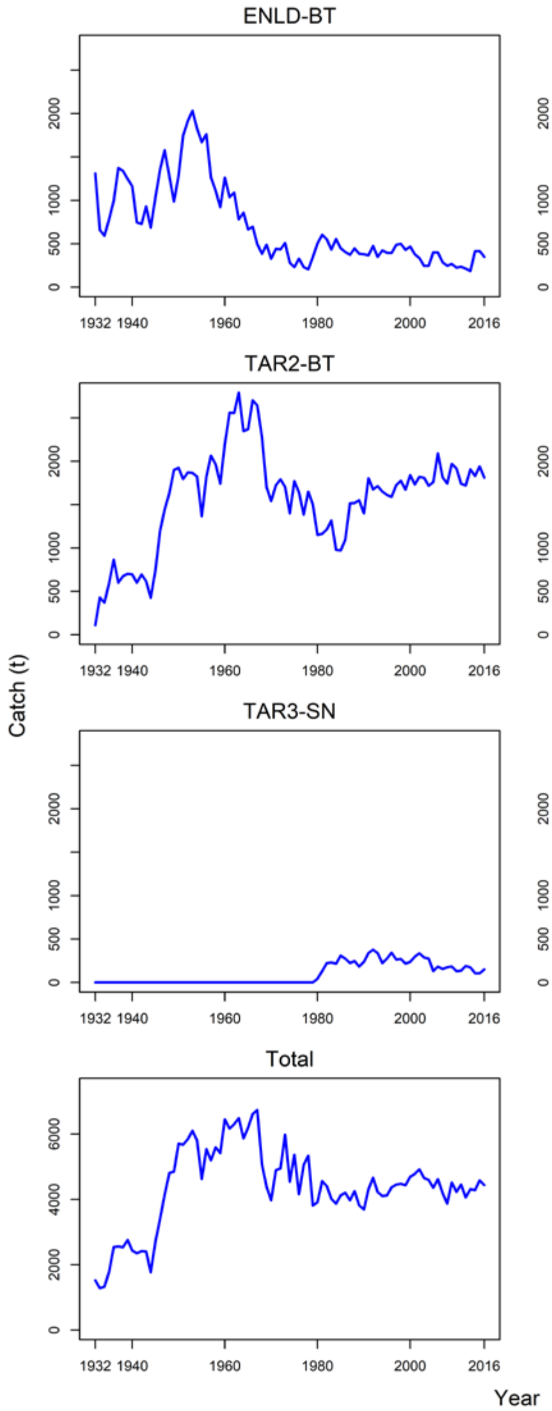

Figure 8: Annual catches (t) of tarakihi by commercial fishery and total (including recreational catch) compiled for the east coast stock assessment (1932–2016). Annual catches include allowances for unreported catch.

King tarakihi are caught at the northern extent of the range of tarakihi (North Cape and Three Kings Islands) (Smith et al. 1996). Due to concerns that some tarakihi catches were being misreported, king tarakihi was included within the species definition of the tarakihi QMS fishstocks (under Fisheries (Commercial Fishing) Regulations 2001). All subsequent catches of king tarakihi should have been included within the TAR 1 TACC. However, modest commercial catches (20–30 t per annum) of king tarakihi (KTA) were reported from FMA 1 during the 2002/03–2004/05 fishing years. Since then, no additional catches of king tarakihi have been reported separately.

The magnitude of king tarakihi catches reported within TAR 1 is considered to be small due to the distribution of the main fisheries relative to the known distribution of king tarakihi. Similarly, the magnitude of tarakihi catch misreported as king tarakihi is also considered to be small.

5.1.3 Non commercial catch

The most reliable estimates of the recreational catch of tarakihi in the eastern area of TAR 1 (FMA 1) (97 t), TAR 2 (71 t) and TAR 3 (3 t) are available from the 2012 National panel survey (Wynne-Jones et al. 2014, Hartill et al. 2013, MPI 2017). These surveys indicated that tarakihi catches by the recreational sector were relatively low in TAR 1 and TAR 2 and negligible in TAR 3.

In the absence of a time-series of recreational catch estimates, a constant level of recreational catch, equivalent to the panel survey estimates, was assumed for the eastern area of TAR 1 and for TAR 2 for 1981–2016 (i.e., 97 t and 71 t, respectively). It was assumed that recreational catches from these two areas were negligible in 1932 and that there was a linear increase in the recreational catches from zero in 1932 to the level of the recreational catch estimates in 1981. It was assumed that there was no recreational catch from TAR 3 for the entire period (1932–2016).

No information was available to determine the level of customary catch although catches are considered to be negligible and are not included in the catch history.

5.1.4 Abundance indices

For the main east coast tarakihi fisheries, standardised CPUE indices are available for 1989/90–2015/16 (Langley 2017). Five sets of area specific CPUE indices were available for inclusion in the assessment modelling: TAR 3 trawl, TAR 3 set net, TAR 2 trawl, the Bay of Plenty trawl and east Northland trawl. During the preliminary modelling phase, the relative weighting of these five sets of CPUE indices was determined following the approach of Francis (2011). For each set of indices, the standard deviation of the residuals from an initial model was used to determine the precision (CV) of the time-series of the indices. Each of the five sets of indices yielded residuals with standard deviations approximating 0.20 and, for simplicity, this value was adopted for each series.

In the final model options, the TAR 2 and Bay of Plenty fishery areas were amalgamated and accordingly the two sets of trawl CPUE indices were combined to form a single time-series (TAR2BPLE-BT). Two different approaches for combining the indices were investigated: 1) calculating an average annual index weighted by the annual catch in each area and 2) refitting a delta-lognormal CPUE model from the composite data set (TAR 2 and the Bay of Plenty). Both approaches yielded virtually identical CPUE indices for the combined area and for simplicity the indices from the first approach were adopted in the final assessment models. The final sets of CPUE indices included in the assessment modelling are presented in Appendix 4.

Unstandardised CPUE indices were also available for the East Cape and Canterbury Bight trawl fisheries during the 1960s–1970s (Vooren 1973, Sullivan 1981) (Appendix 4). These CPUE indices were considered to be less reliable than the more recent CPUE data and were assigned a lower level of precision (CV 0.3).

Trawl survey biomass estimates were available from three time-series of *Kaharoa* inshore trawl surveys: winter ECSI (N obs = 11), summer ECSI (N obs = 5) and ECNI (N obs = 3). The precision of each trawl survey biomass estimate was assumed to be equivalent to the coefficient of variation (CV) from the individual survey (Table 2).

5.1.5 Commercial age compositions

The age composition data available from the commercial fisheries are summarised in Table 1. For the final assessment models, the data from the trawl fisheries in TAR 2 and BPLE were amalgamated. The annual age compositions from the two areas were combined by weighting the area specific age compositions by the relative tarakihi catch in each area.

Recent commercial age composition data: TAR3-BT (n=4), TAR3-SN (n=4), Cook-BT (n=1), TAR2-BT and BPLE-BT combined (n=5), and ENLD-BT (n=2) (Appendix 3, Tables A5 and A6).

5.1.6 Trawl survey length and age compositions

The length and age composition data available from the *Kaharoa* inshore trawl surveys are summarised in Table 2. The assessment models included length composition data for those surveys for which age composition data were not available.

The final model options included two age compositions from the earlier *James Cook* trawl survey: 1) the age composition derived from the survey of Pegasus Bay–Cape Campbell in 1987 (JC1987) and 2) the age composition derived from the survey off East Cape in 1971. For both surveys, the methodology is well documented and the resultant age compositions were derived from relatively intensive trawl sampling throughout the main area of the tarakihi fishery (Table 3). Therefore, these data may provide useful information regarding the age structure of the tarakihi population.

Additional age compositions were available from other *James Cook* trawl surveys off the east coast of the South Island (Table 3). No information was available regarding the design of these surveys or the extent of sampling of the tarakihi population. These age compositions were included in the initial model development phase. However, the data were generally uninformative due to the assumptions regarding the survey selectivities and/or inconsistencies in the age compositions amongst the surveys. These data were excluded from the final set of model options.

5.2 Biological parameters

Preliminary modelling incorporated a sex-specific population structure. However, growth and natural mortality parameters for male and female tarakihi are similar and the increased complexity of the sex-specific model was not considered to be warranted given the sex aggregated nature of some of the data sets. A comparison of the results from the sex-specific and sex aggregated models did not demonstrate an appreciable difference in the overall model results. On that basis, the sex aggregated model structure was adopted, with model growth assumed to be equivalent to the Von Bertalannfy growth model for female tarakihi in TAR 3 (Annala et al. 1990). For the sex aggregated model, the sex specific length and age compositions were amalgamated.

Table 5: Biological parameters included in the east coast tarakihi assessment model for the base model.

Component	Parameters, values	Source
Growth, Von Bertalanffy	*L_at_Amin* = 15.37 cm *k* = 0.2009 *Linf* = 44.6 cm	Annala et al. (1990)
Natural mortality	0.1 yr^{-1}	Annala et al. (1990)
Length-weight relationship (length, cm; weight kg)	*a* = 0.00004 *b* = 2.79	Annala et al. (1990)
Maturity (age specific)	Ages 1–3 0; Age 4 0.25; Age 5 0.5; Ages 6+ 1.0	Annala et al. (1990)
Beverton Holt SRR	Steepness (*h*) 0.9	
Recruitment variation	*SigmaR* 0.6	

5.3 Structural assumptions

5.3.1 Population structure

The model population comprised 41 age classes; fish recruited to the model population at age 0+ years and individual cohorts were monitored over 1–39 age classes. The terminal age class aggregated fish aged 40 years and older (plus group).

Initial modelling was conducted using a two sex (sex disaggregated model). The main biological parameters are similar for the two sexes and model trials comparing single sex (sex aggregated) and two sex models did not show substantive differences in the model results. Thus, for simplicity the sex aggregated model was adopted for the final model options.

The annual time-step of the model was based on the fishing year (October–September) and partitioned into two seasons: October–March and April–September (Table 6). The seasonal structure was adopted to define the spawning period and ensure annual growth was consistent with the theoretical birthday of 1 May (Walsh et al. 2016) (Table 6). Spawning was assumed to occur at the start of the second season. The model year was denoted based on the calendar year of the January–September (e.g., the 2016 model year represents the 2015/16 fishing year).

A range of alternative spatial structures were investigated in the preliminary modelling. These ranged from a spatially aggregated model with a single model region to a model with five regions (Table 7).

Table 6: Annual timing of the fisheries and surveys and population processes and the average length of the first three age classes in the model population. Movement occurs in the spatially structured models.

Season	Timing (fraction of season)	CPUE/Survey/Fishery	Population dynamics			Age class Length (F.L) cm
October–March	0.0			0.5 yr 8.5 cm	1.5 yr 15.1 cm	2.5 yr 20.5 cm
	0.3	ECSI_Tsurvey S				
	0.5	ECNI_Tsurvey				
	1.0	TAR3-BT TAR3-SN TAR2BPLE-BT ENLD-BT Cook-BT	Catch removal			
April–September	0.0		Spawn, Recruit (Movement)	1.0 yr 12.0 cm	2.0 yr 17.9 cm	3.0 yr 22.8 cm
	0.1	ECSI_Tsurvey W				
	1.0					

Table 7: Assignment of the individual fishery areas to specific regions (R) within each spatial configuration of the assessment model. The final set of model options are highlighted.

Model					Fishery Area/CPUE indices
	Canterbury Bight–Pegasus Bay	Kaikoura, eastern Cook Strait	Wairarapa, East Cape (TAR 2)	Bay of Plenty	East Northland
	TAR3-BT	TAR3-SN	Combined TAR2BPLE-BT		ENLD-BT
1 Region	R1				
3 Region	R1		R2		R3
			TAR2-BT	BPLE-BT	
4 Region	R1		R2	R3	R4
5 Region	R1	R2	R3	R4	R5

5.3.2 Recruitment

Recruitment (at age 0) was assumed to occur at the start of the second season. Annual recruitments were derived from a Beverton-Holt spawner-recruit relationship (SRR). Spawning biomass was defined as the total mass of the mature portion of the population at the start of the spawning season. The base model options assumed a high value for steepness (h = 0.9) on the basis that recruitment was considered to be most strongly influenced by the prevailing oceanographic conditions during the long pelagic phase of post larval tarakihi. Inter-annual variability in recruitment was estimated as deviates from the SRR for the period that was informed by the age composition data and recent abundance indices (i.e. 1980–2015). Recruitment deviates were assumed to have a relatively high degree of variability (sigmaR 0.6).

For the spatially stratified models, all recruitment was assigned to the southern region of the model (R1).

5.3.3 Fishing mortality

Fishery catches are removed from the model population as a function of numbers of fish mediated by the fishery selectivity. Fishing mortality rates (by fishery and year) were derived using a hybrid method that includes a Pope's approximation to provide initial estimates of F values that are then iteratively adjusted to closely approximate the observed catch (Methot & Wetzell 2013).

All fisheries (and associated CPUE indices) were assigned to the first season (October–March) of the model year (Table 6), although the timing within the season was set to approximate the removal of catch halfway through the year (i.e. season timing = 1.0) (see Methot 2015).

The summer ECSI and ECNI trawl surveys were assigned to the first season, while the winter ECSI trawl survey series was assigned to the second season (Table 6). The timing within each season approximated the timing of each survey. The timing is used to specify the amount of age-specific mortality that occurs before the expected values are calculated.

5.3.4 Initial conditions

The catch history for tarakihi is available from 1931 onwards (Francis & Paul 2013). Annual catches from the eastern area of TAR 1 were relatively high (500–1000 t per annum) during the early and mid-1930s and, consequently, the tarakihi stock is likely to have been in a partially fished state by the beginning of the 1930s.

Stock Synthesis has the provision to estimate the initial fishery-specific fishing mortality to initialise the numbers-at-age at the start of the model (Methot & Wetzell 2013). Initial fishing mortality rates are estimated based on an assumed level of initial equilibrium catch for each fishery. The deviance between the predicted and observed level of initial equilibrium catch is included as a component of the overall likelihood function of the model (Methot & Wetzell 2013). The degree of influence of the initial equilibrium catches in the model likelihood can be varied by the magnitude of the error associated with the initial equilibrium catches.

For model options incorporating the entire catch history (from 1932), initial equilibrium catches were assigned to the two fisheries with a significant catch in the early years (TAR 2 trawl and ENLD trawl) and fishing mortality rates were estimated for both fisheries. The initial equilibrium catches were specified as the average annual fishery catch from 1932–36 and were assumed to be known with high precision.

There was concern related to the assignment of FMA 1 catches between the East Northland and Bay of Plenty fisheries during 1931–1960 based on the large catches attributed to East Northland. Thus, an additional set of models was configured that commenced in 1975 and estimated initial fishing mortality for the five fisheries that were operating at that time (TAR3-BT, Cook-BT, TAR2-BT, BPLE-BT, and ENLD-BT) based on initial equilibrium catches set at the average annual catches from 1965–74.

5.3.5 Selectivity

Beentjes et al. (2017) compared the age structure of tarakihi sampled by the ECSI *Kaharoa* trawl survey by depth zone. They concluded that tarakihi from areas deeper than 80 m were larger and older (by about 1 to 2 years) than fish in shallower waters. Recent catch samples from the TAR 3 trawl fishery were mostly taken from fishing conducted in depths greater than 70 m (McKenzie et al. 2017), which was consistent with the general depth distribution of the commercial catch from the fishery (Langley 2017).

Similar observations were also evident from the limited data available from the Bay of Plenty area. For the 1999 trawl survey, older fish were present in samples from depths greater than 150 m (Beentjes et al. 2017), while most of the commercial catch was taken from the 80–230 m depth range (Langley 2017). These results indicate that the main tarakihi trawl fisheries tend to operate in the areas where older fish are most abundant. Therefore, it is reasonable to assume that the older fish in the local population are available (vulnerable) to the main trawl fisheries operating in the area. These observations inform the model assumptions regarding the selectivity of the individual fisheries included in the assessment models.

To accommodate spatial differences in the age composition of fishery catches, the modelling of the age-specific vulnerability of tarakihi in each of the (area based) fisheries was predicated by the spatial configuration of the assessment model. For example, the age compositions of the TAR 2 and Bay of Plenty catches are composed of a lower proportion of older fish (10+ years) than the East Northland fishery. In the framework of a spatially stratified model, the lower vulnerability of the older fish in the former areas may be accommodated by the estimation of movement of fish from TAR 2-Bay of Plenty region to the East Northland region. Conversely, in a spatially aggregated model the differences in availability of the older fish can only be accommodated by fishery (i.e. area) specific selectivity functions.

Thus, selectivity assumptions differed among model options depending on the spatial structure of the model (Table 7). For the spatially disaggregated models, the fisheries in each region that caught the highest proportion of older were assumed to have a logistic selectivity, i.e. all the fish in the older age classes in the region were fully vulnerable to those fisheries. Conversely, for the spatially aggregated models, only the East Northland fishery fully selected the older age classes (via a logistic function), while more flexible selectivity functions were estimated for all the other fisheries (double normal parameterisations). The specific details of the individual model selectivity parameters are provided for the final set of models in Table 9.

The TAR3-BT fishery primarily catches younger fish. For all model options, with the exception of the five region model, the selectivity of the TAR3-BT fishery was parameterised using a double normal selectivity function. The five region model used a logistic selectivity.

All selectivity functions were assumed to be age-specific with the exception of the ECNI trawl survey for which no age composition data were available. A double normal length-based selectivity function was estimated for the ECNI *Kaharoa* trawl survey. The selectivities of the two ECSI *Kaharoa* trawl survey series (winter and summer) were assumed to be equivalent.

For each set of CPUE indices, the selectivity was assumed to be equivalent to the selectivity of the corresponding commercial fishery. Length and age data for the recreational fisheries is limited and the selectivities of these fisheries were assumed to be equivalent to the trawl fishery in the area (TAR 2 and/or BPLE).

The selectivity of the recreational fisheries was assumed to be equivalent to that of the trawl fishery in the fishery area. All selectivity functions were assumed to be temporally invariant.

5.3.6 Movement

For the spatially structured models, northward movements were estimated between adjacent regions for age classes age 2 years and older. Movement between regions occurred instantaneously at the beginning of the second season (1 April).

Movements were assumed to be age-specific, parameterised using a ramp function derived from two parameters: a parameter estimating the movement of fish for ages 2–3 years and a parameter for the movement of fish for ages 8–40 years. Thus, for each regional boundary, two parameters were estimated. The movement of fish in the intermediate age classes was derived from extrapolation between the two movement parameters. The ages of the two inflection points were defined to coincide with the onset of maturity and full maturity and were also informed by the region specific age composition data. Movement coefficients were expressed as the proportion of fish in the source region that moved to the recipient region. In the final model options, all movement parameters were temporally invariant.

5.4 Model configuration

The current stock hypothesis assumes a relatively complex spatial structure for the east coast tarakihi population; juvenile tarakihi reside predominately in the Canterbury Bight/Pegasus Bay area and, coinciding with the onset of sexual maturity, a proportion of the population migrates along the east coast, extending progressively northwards with increased age and terminating in the East Northland area. During the model development phase, a range of options were investigated to determine the appropriate degree of spatial stratification for the assessment model, given the spatial scale and information content of the various input data sets (Table 7).

The most highly structured spatial model (five regions), estimated stock dynamics in the southern regions that were not realistic, including excessively high levels of fishing mortality in R1 (Canterbury Bight/Pegasus Bay) corresponding to very low biomass levels in R1. It was concluded that insufficient data were available from the two southern partitions of the five region model, especially from the Cook-BT fishery in R2, to reliably estimate the additional parameters (movement and selectivity) associated with the regional structure of the model. Further, CPUE indices are not available for the Cook-BT fishery and the assumption that the TAR3-SN CPUE indices provided a reliable index of stock abundance for R2 may not be valid (Table 7).

The results from the three region model, amalgamating the Bay of Plenty and TAR 2, were similar to the four region model (Table 7). This was attributed to the strong similarities in the two sets of CPUE indices and age composition data from the Bay of Plenty and TAR 2 fisheries. On that basis, it was considered that the additional complexity of the four region model was not warranted.

The final model options structured the input data into three areas: east coast South Island (including eastern Cook Strait), central east coast North Island and the Bay of Plenty combined (TAR2-BPLE), and East Northland (Figure 9). The east coast South Island region included three commercial fisheries: the Canterbury Bight/Pegasus Bay trawl fishery (TAR3-BT), Kaikoura set net fishery (TAR3-SN) and the eastern Cook Strait trawl fishery (Cook-BT) (Figure 9). The combined TAR2-BPLE area retained the catches from the two separate trawl fisheries (TAR2-BT and BPLE-BT) and assumed that the selectivity of the two fisheries was equivalent, while the CPUE indices and age composition data were combined (TAR2BPLE-BT) to mimic a single area fishery. The East Northland area included the single corresponding trawl fishery (ENLD-BT) (Figure 9).

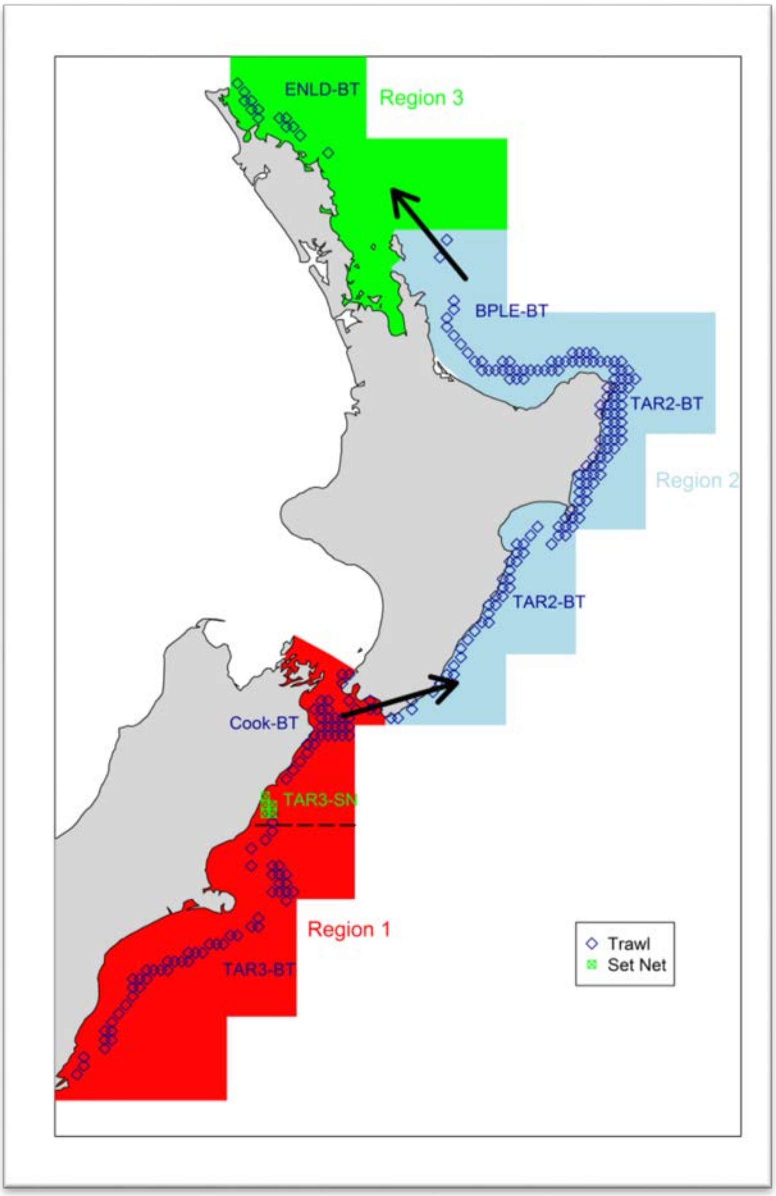

Figure 9: Fishery areas and regional structure of the three region model. The points represent locations (0.1 degree cells) where at least 25 t of tarakihi were caught during 2007/08–2015/16. The dashed line represents the southern boundary of Statistical Area 018 and partitions the TAR3-BT and Cook-BT fisheries within Region 1. The arrows represent the movements estimated in the model.

For the final model options, two contrasting models were configured: a three region, spatially disaggregated model and a single region, spatially aggregated model. The three region model was configured to approximate the stock hypothesis; i.e., each region included a discrete population with recruitment in the southern (ECSI) region only and age-specific movement of fish northwards between adjacent regions (Figure 9). Within each region, the oldest age classes in the population were assumed to be fully vulnerable to the key fisheries (TAR3-BT, Cook-BT, TAR2BPLE-BT and ENLD-BT). Catches were taken from the population in the respective region and the abundance indices (CPUE and trawl survey) represented trends in stock abundance in the respective regions.

In contrast, the single region model comprised a single population. The age composition of the catch from each fishery was mediated by the selectivity of the individual fisheries. For the ENLD-BT fishery, the oldest age classes were assumed to be fully vulnerable (logistic selectivity) based on the high proportion of older age classes observed in the fishery age composition compared to the other fisheries. The selectivities of these other fisheries (and surveys) were parameterised using a double normal function, allowing for lower vulnerability of the older age classes. Thus, all sets of CPUE indices and surveys monitored the relative abundance of a single population mediated by the selectivity.

The relative weightings applied to the main data sets were equivalent for the final range of model options, allowing a direct comparison of the model fits (likelihood components) among the individual models. For the recent CPUE indices, each series was assigned a coefficient of variation (CV) of 20%, while the individual trawl survey biomass estimates were weighted by the CV from the individual survey.

The Effective Sample Size (ESS) for each series of age composition data was determined following the approach of Francis (2011) using Method TA1.8. For comparability amongst model options, the equivalent weighting (ESS) was assumed for the range of model options. Most of the recent commercial age composition data sets were assigned a moderate weighting (ESS = 30), while the TAR3-SN was given a lower weighting (ESS =15). The ECSI trawl survey age compositions were assigned an ESS of 30. Substantial changes in the relative weightings of individual age composition data sets did not appreciably change the model results, indicating broad consistency amongst the key input data sets. Trawl survey length compositions were assigned an ESS of 10.

Initial model options included the entire catch history from 1932 and estimated initial levels of fishing mortality for the two fisheries that caught modest quantities of tarakihi during the early 1930s. However, for the three region model, the fits to the CPUE and age composition data from the East Northland model were very poor and the model estimated an implausibly large biomass for the East Northland region. These issues could not be resolved within the modelling framework and appeared to be attributable to the large catches allocated to the East Northland fishery prior to 1965. For this period, the allocation of catches to each region was based on port of landing and all landings in Auckland were attributed to East Northland. This assumption is likely to be incorrect, although no other information is available to apportion the early catch amongst the East Northland and Bay of Plenty fisheries. On that basis, the full catch history, three region model was rejected. In contrast, the full catch history, single region model yielded credible results, including a good fit to the East Northland CPUE and age composition data. It appears that the constraints imposed by the spatial structure of the three region model resulted in conflict between the distribution of catch (and therefore biomass) and the other data sets. These constraints do not exist in the single region model (*1Region_Start1932*).

The regional distribution of catch is considered to be more reliable from about 1965 onwards. Additional model options were configured that were initialised in 1975 (*1Region_Start1975* and *3Region_Start1975*). Initial (1975) conditions were determined by estimating (five) fishery specific levels of fishing mortality (Initial Fs) that were informed by an assumed equilibrium level of catch in the initialisation period. The fishery specific levels of equilibrium catch were set at the average of fishery catch from the preceding 10 years (i.e. 1965–1974). For the main model options, equilibrium catches were assumed to be known with a high level of precision. The influence of these assumptions was investigated by increasing the uncertainty associated with the values of the equilibrium catches (model sensitivity *InitialCatchVar*).

5.4.1 Parameter estimation

The estimated parameters for each of the main models are summarised in Table 8. The logistic selectivity functions included two parameters: the age at inflection (*p1*) and the width of 95% selection (*p2*). Double normal selectivity functions were configured using six parameters: *p1* age (or length) at peak, *p2* width of the plateau, *p3* ascending width, *p4* descending width, *p5* selectivity of first age (or length), *p6* selectivity of last age (or length) (Methot 2015).

The first age class in the model was 0 year fish and the corresponding parameter for the double normal selectivity (*p5*) was fixed at a value that corresponded to a selectivity of zero. There were limited data available to reliably estimate all of the other DN selectivity parameters. The *p2* and *p3* parameters were usually highly correlated as they were both informed by the proportion of older fish in the age composition data. For the main model options, the *p2* was fixed at a value of -6 corresponding to a narrow plateau about the peak selectivity, while *p3* and *p6* were estimated to allow for considerable flexibility in the estimation of the selectivity of fish older than the peak selectivity.

Table 8: The number of estimated parameters included in each of the main model options.

Parameters	Model option		
	1Region_Start1932	*1Region_Start1975*	*3Region_Start1975*
Ln R0	1	1	1
RecDevs	37	37	37
Selectivity	28	28	18
Initial F	2	5	5
Movement	-	-	4
Total	68	71	65

Table 9: Model parameters (initial values, range [], and priors) for the age specific fishery selectivity functions and initial fishing mortality.

Parameters	Model option		
	1Region_Start1932	*1Region_Start1975*	*3Region_Start1975*
Selectivity			
TAR3-BT	Double normal *p1* 4 [0–10] Norm(4,1) *p2* -6 fixed *p3* -0.5 [-10–9] Norm(-0.5,1) *p4* 1 [-9–9] Norm(1,2) *p5* -6 fixed *p6* -2 [-9–9] Norm(-2,2)	Double normal *p1* 4 [0–10] Norm(4,1) *p2* -6 fixed *p3* -0.5 [-10–9] Norm(-0.5,1) *p4* 1 [-9–9] Norm(1,2) *p5* -6 fixed *p6* -2 [-9–9] Norm(-2,2)	Double normal *p1* 4 [0–10] Norm(4,1) *p2* -6 fixed *p3* -0.5 [-10–9] Norm(-0.5,0.5) *p4* 3 fixed *p5* -6 fixed *p6* -2 [-9–9] Norm(-2,3)
TAR3-SN	Double normal *p1* 6 [0.5–40] Norm(6,1) *p2* -6 fixed *p3* 0 [-15–9] Norm(0,2) *p4* 1 [-3–9] Norm(1,2) *p5* -6 fixed *p6* 0 [-9–9] Norm(0,2)	Double normal *p1* 6 [0.5–40] Norm(6,1) *p2* -6 fixed *p3* 0 [-15–9] Norm(0,2) *p4* 1 [-3–9] Norm(1,2) *p5* -6 fixed *p6* 0 [-9–9] Norm(0,2)	Logistic *p1* 5 [-5–14] Norm(5,1) *p2* 1 [-5–14] Norm(1,1)
Cook-BT	Double normal *p1* 6 [0.5–40] Norm(6,1) *p2* -6 fixed *p3* 0 [-15–9] Norm(0,2) *p4* 1 [-3–9] Norm(1,2) *p5* -6 fixed *p6* 0 [-9–9] Norm(0,2)	Double normal *p1* 6 [0.5–40] Norm(6,1) *p2* -6 fixed *p3* 0 [-15–9] Norm(0,2) *p4* 1 [-3–9] Norm(1,2) *p5* -6 fixed *p6* 0 [-9–9] Norm(0,2)	Logistic *p1* 5 [-5–14] Norm(5,1) *p2* 1 [-5–14] Norm(1,1)
TAR2BPLE-BT	Double normal *p1* 6 [0.5–40] Norm(6,1) *p2* -6 fixed *p3* 0 [-15–9] Norm(0,2) *p4* 1 [-3–9] Norm(1,2) *p5* -6 fixed *p6* 0 [-9–9] Norm(0,2)	Double normal *p1* 6 [0.5–40] Norm(6,1) *p2* -6 fixed *p3* 0 [-15–9] Norm(0,2) *p4* 1 [-3–9] Norm(1,2) *p5* -6 fixed *p6* 0 [-9–9] Norm(0,2)	Logistic *p1* 5 [-5–14] Norm(4.5,0.5) *p2* 1 [-5–14] Norm(1,0.5)
ENLD-BT	Logistic *p1* 6 [-5–14] Norm(6,1) *p2* 1 [-5–14] Norm(1,0.5)	Logistic *p1* 6 [-5–14] Norm(6,1) *p2* 1 [-5–14] Norm(1,0.5)	Equivalent to TAR2BPLE-BT
ECSI Trawl survey (W and S)	Double normal *p1* 3 [0–10] Norm(3,1) *p2* -6 fixed *p3* 0 [-10–9] Norm(0,0.5) *p4* 1 [-6–9] Norm(1,1) *p5* -6 fixed *p6* -5 fixed	Double normal *p1* 3 [0–10] Norm(3,1) *p2* -6 fixed *p3* 0 [-10–9] Norm(0,0.5) *p4* 1 [-6–9] Norm(1,1) *p5* -6 fixed *p6* -5 fixed	Double normal *p1* 2 [0–10] Norm(2,1) *p2* -6 fixed *p3* 0 [-10–9] Norm(0,0.5) *p4* 1 [-6–9] Norm(1,1) *p5* -6 fixed *p4* -2 [-9–9] Norm(-2,2)
Initial F			
TAR3-BT	-	0.2 [0–1] Norm(0.2,0.1)	0.2 [0–1] Norm(0.2,0.1)
Cook-BT	-	0.1 [0–1] Norm(0.1,0.1)	0.1 [0–1] Norm(0.1,0.1)
TAR2-BT	0.05 [0–1] Norm(0.05,0.05)	0.2 [0–1] Norm(0.2,0.1)	0.2 [0–1] Norm(0.2,0.1)
BPLE-BT	-	0.1 [0–1] Norm(0.1,0.1)	0.1 [0–1] Norm(0.1,0.1)
ENLD-BT	0.05 [0–1] Norm(0.05,0.05)	0.1 [0–1] Norm(0.1,0.1)	0.1 [0–1] Norm(0.1,0.1)

For the *3Region_Start1975 model*, an additional constraint was imposed on the DN selectivity of the TAR3-BT fishery by fixing the parameter that determines the descending width (*p4*) of the selectivity function. Without this constraint, the model failed to reach the convergence criteria. The model results were relatively insensitive to a range of reasonable values assumed for the parameter. There is likely to be a strong interaction between this parameter and the movement parameters from region 1 to region 2.

The model objective function included contributions from the fishery catches, initial equilibrium catches, indices of abundance (CPUE and survey), age-compositions (commercial and survey), length-compositions, (survey) recruitment, and priors and penalties. The formulation of the individual likelihood components is documented in Methot & Wetzell (2013).

The estimation procedure minimises the negative log-likelihood of the objective function to determine the mode of the joint posterior distribution (MPD). The Hessian matrix computed at the MPD was used to obtain estimates of the covariance matrix, which was used in combination with the Delta method to compute approximate confidence intervals for model parameters.

Model uncertainty was determined using Markov chain Monte Carlo (MCMC) implemented using the Metropolis-Hastings algorithm. For each model option, 1000 MCMC samples were drawn at 1000 intervals from a chain of 1.1 million following an initial burn-in of 100 000. The performance of the MCMC sampling was evaluated using a range of diagnostics.

5.5 Model results

5.5.1 Parameter estimates

For the single region models, all selectivities were parameterised using a double normal function, except for the ENLD-BT selectivity. For this fishery, selectivity was parameterised using a logistic selectivity and 50% selectivity was estimated at 6 years and full selectivity at 8 years. For the other commercial fisheries, the selectivity was strongly modal with a narrow range of age classes fully vulnerable to the fishery. Full selectivity was at ages 4–5 years, 6–7 years and 6–8 years for the TAR3-BT, TAR3-SN and TAR2BPLE-BT fisheries, respectively (Figure 10). For each of these fisheries, selectivity declined sharply with increasing age and selectivity of the age classes greater than about 10–12 years was relatively low. The selectivity function for the Cook-BT fishery was broadly similar with a peak at 6–9 years, although the selectivity of the older age classes was considerably higher than the other fisheries. However, the selectivity of the older age classes was poorly estimated, reflecting the limited number of samples available from the fishery (Figure 10).

For the ECSI trawl surveys, the single region model estimated that tarakihi were partially vulnerable at age 1 and fully selected at ages 2–4 years (Figure 10). The vulnerability of fish in the age classes older than 8 years was estimated to be negligible. The selectivity for the 1987 James Cook trawl survey was poorly determined, although the model estimated a relatively high selectivity for the oldest age classes, reflecting the proportion of older fish in the age composition.

In contrast to the single region model, the three region model assumed a logistic function for the fisheries catching the oldest fish in each region. For both the TAR3-SN and Cook-BT fisheries, 50% selectivity was estimated at about age 5 years and full selectivity was attained at age 6 years (Figure 11). Selectivity was shared between the TAR2BPLE-BT and ENLD-BT fisheries and the selectivity function was estimated to be similar to the other two fisheries, again with full selectivity at age 6 years. For the TAR3-BT fishery and ECSI trawl survey, the selectivity of the youngest age classes was comparable to the selectivity estimated for the single region model. However, there was a higher selectivity for the 6–20 year age classes for the three region model, although the selectivity of the older age classes (greater than 20 years) was poorly determined (Figure 11). The selectivity of the oldest age classes by the 1987 James Cook trawl survey was also estimated to be higher than for the single region model.

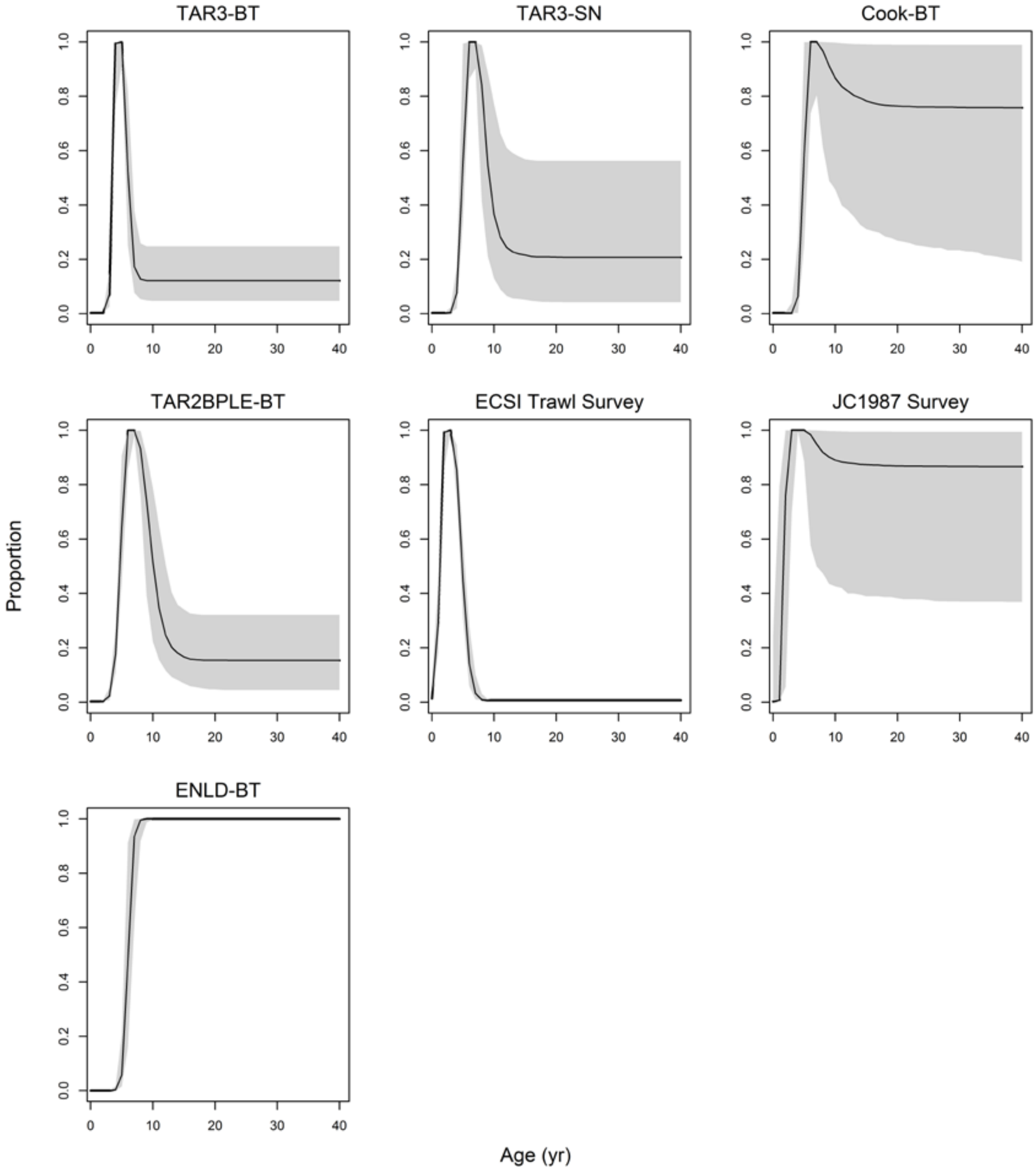

Figure 10: Age-specific selectivities estimated for commercial fisheries and trawl surveys from the base model (*1Region_Start1975*). The lines represent the medians of the MCMCs and the shaded regions represent the 95% confidence intervals derived from the MCMC samples.

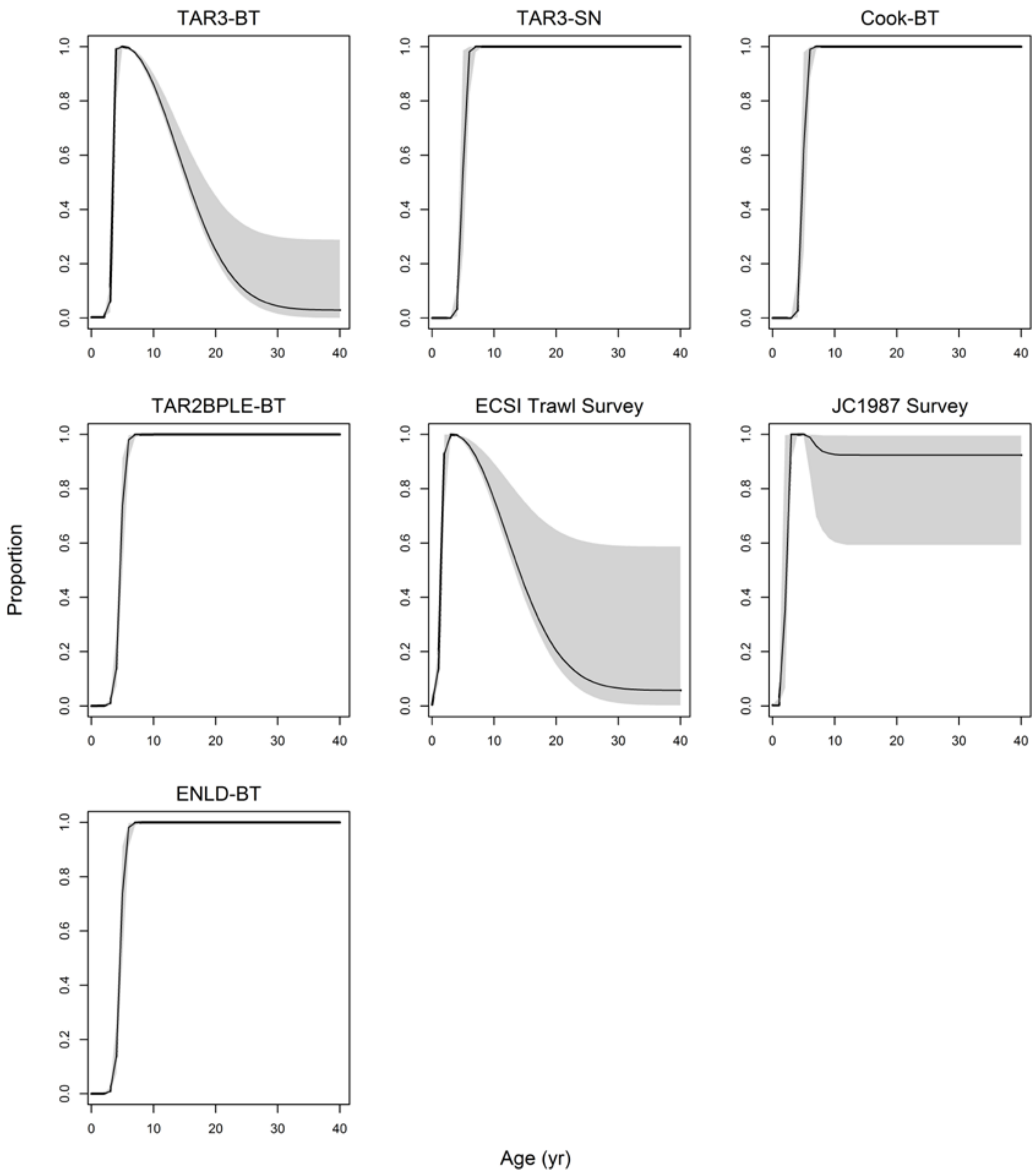

Figure 11: Age specific selectivities estimated for commercial fisheries and trawl surveys from the three region model (3*Region_Start1975*). The lines represent the medians of the MCMCs and the shaded regions represent the 95% confidence intervals derived from the MCMC samples.

The differences in the selectivity functions between the three region and single region models are largely attributable to age-specific movements estimated among the individual regions of the three region model. For the three region model, all recruitment occurs in the southern region (R1) and movement does not occur until fish reach 2 years of age. The model estimates that approximately 60% of the age 2 year fish move to the central region (R2) (Figure 12). The rate of movement declines with increasing age and movement from R1 to R2 is estimated to be negligible from age 8.

Movement from the central region to the northern region (R3) is negligible for fish younger than age 5. Movement rates are estimated to increase for the older age classes, reaching 9% per annum for age classes 8 years and older (Figure 12).

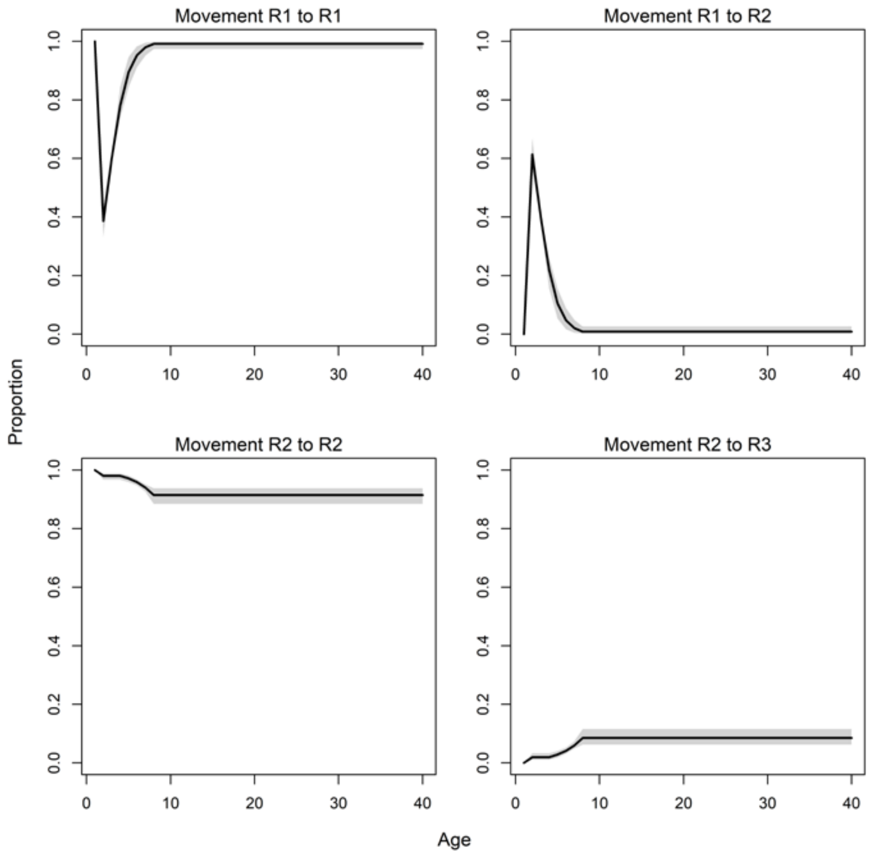

Figure 12: Age specific movement rates (expressed as the proportion of fish in the region after movement) estimated for region 1 (R1) and region 2 (R2), from R1 to R2, and from R2 to region 3 (R3) from the three region model (3*Region_Start1975*). The lines represent the medians of the MCMCs and the shaded regions represent the 95% confidence intervals derived from the MCMC samples.

Recruitment deviates estimated for the comparable single region (*1Region_Start1975*) and three region models (*3Region_Start1975*) are similar, with the exception of the sequence of five initial negative recruitment deviates (1980–84) estimated for the three region model (Figure 13). The three region model also estimates higher recruitment deviates for the last five years of the sequence.

The models estimated strong year classes in 1996, 2007 and 2011–2012 and a moderate year class in 2009 (Figure 13). The 1999–2000 and 2008 year classes were estimated to be weak, while the single region model also estimated relatively weak 2013–2014 year classes.

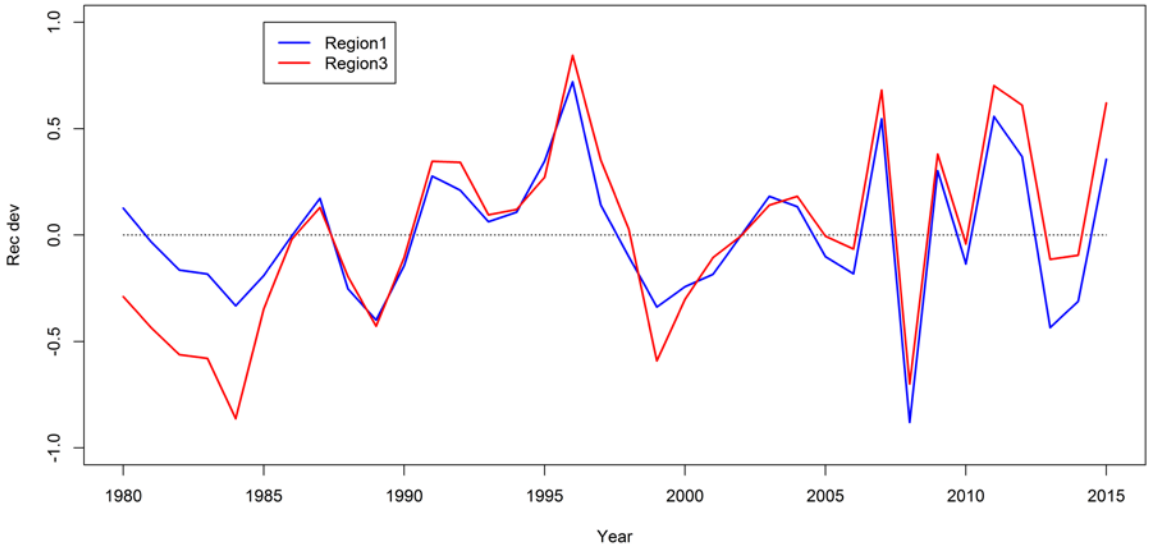

Figure 13: Recruitment deviates (MPDs) estimated from the single region base model (*1Region_Start1975*) and the three region model (3*Region_Start1975*).

Five fisheries caught a significant quantity of tarakihi in the period immediately preceding the initialisation of the *1Region_Start1975* in 1975. The estimation of initial fishing mortality rates for these fisheries was informed by the corresponding initial equilibrium catches for each fishery and relatively broad priors. Estimates of initial fishing mortality rates were relatively low for the Cook-BT, BPLE-BT and ENLD-BT fisheries (Figure 14) reflecting the relatively low initial equilibrium catches (684.3 t, 622.0 t and 472.3 t, respectively). Considerably higher estimates of initial fishing mortality rates were estimated for TAR3-BT and TAR2-BT corresponding to higher levels of initial equilibrium catch (1442.6 t and 1985.2 t, respectively). There was a higher level of uncertainty associated with the estimate of initial fishing mortality for the TAR2-BT fishery (Figure 14).

The sensitivity of the final model results to the precision associated with the initial equilibrium catches for the five fisheries is presented in Section 5.5.6. Substantially reducing the precision associated with the catches resulted in a higher level of initial biomass in 1975, with correspondingly lower estimates of initial fishing mortality. However, the model trajectories converged by 1990 and the biomass trajectories were virtually identical for the subsequent years (to 2016).

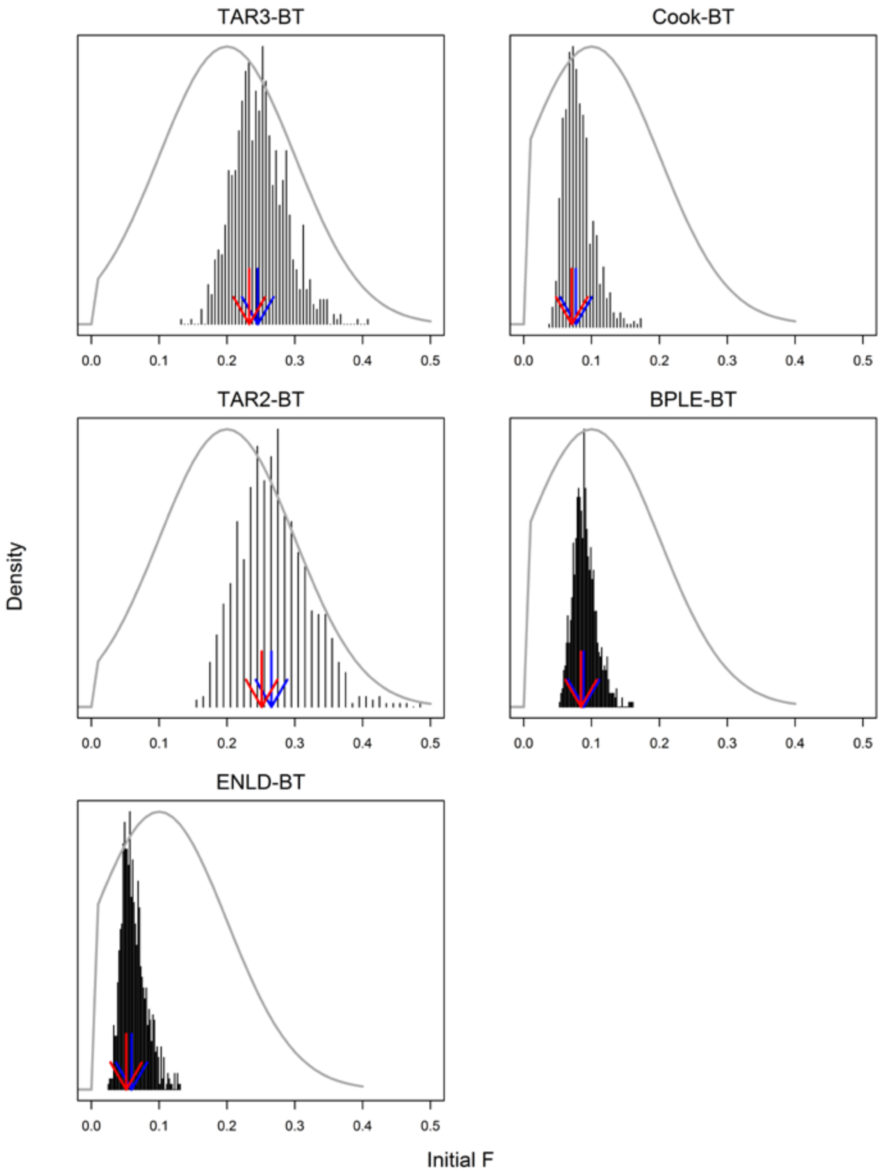

Figure 14: Estimates of the levels of initial fishing mortality from the base model (initialised in 1975) for the five fisheries that accounted for a significant quantity of catch prior to 1975. The red arrows represent the point estimates from the MPDs, the grey lines represent the distributions of the priors, the histograms represent the distributions of the MCMCs and the blue arrows represent the medians of the MCMC values.

The three model options included comparable sets of input data, with the exception that the *1Region_Start1932* model also included the early CPUE indices from East Cape and Canterbury Bight trawl fisheries. Also, a different set of parameters was included in the individual model options. Consequently, the total likelihoods are not directly comparable among the models.

However, it is possible to compare the individual components of the likelihoods as the relative weightings of the various data sets are equivalent. The values of the likelihoods associated with each of the abundance indices (CPUE and trawl survey) and age composition data sets were similar for the two single region models (Appendix 5). However, the three region model had a considerably worse fit (higher likelihood value) for the TAR3-BT and TAR2BPLE-BT CPUE indices. The three region model also provided a substantially worse fit to the age composition data, in particular from the TAR3-BT and Cook-BT commercial fisheries and the winter ECSI and JC1987 trawl surveys.

Overall, the deterioration in fit associated with three region model was primarily due to the data from the southern region. This may relate to the constraints imposed by the assumptions of logistic selectivity for the TAR3-BT and Cook-BT fisheries, the distribution of recruitment and the movement parameterisation. The single region models had considerably more flexibility to simultaneously fit the abundance indices and age composition data via the double normal selectivity parameterisation.

For the three region model, there was a relatively large penalty associated with the fit to the magnitude of the initial equilibrium catches (Appendix 5, Table A9).

The influence of individual model data sets was investigated using likelihood profiling. Likelihood profiles were derived for the total recruitment parameter (*lnR0*) for the *1Region_Start1932*. This model was selected as it incorporates all the data sets, including the early CPUE indices, while being similar in structure and performance to the *1Region_Start1975* model. The changes in the model objective function for each data set were examined relative to the change in the *lnR0*. For all data components, the model likelihoods were high for lower values of *lnR0*, indicating that these levels of recruitment are very unlikely to have been sufficient to support the historical level of catch (Appendix 6). The MPD estimate from the model is 9.54 and there is correspondingly a well-defined minimum in the total likelihood profile. The age composition data are generally uninformative about the upper range of recruitment, with the exception of the ENLD-BT age composition data which indicates that higher levels of recruitment are slightly less likely. The recent CPUE indices are the most informative data component regarding the *lnR0* parameter, although the ECSI trawl survey biomass indices and early CPUE indices are quite consistent with these data. Of the recent CPUE indices, the ENLD-BT and TAR2BPLE-BT data sets dominate the likelihood. The TAR3-SN CPUE provides little information regarding the upper range of the total recruitment parameter, while the TAR3-BT CPUE indices are uninformative (Appendix 6).

5.5.2 Model base case

The two single region model options (*1Region_Start1975* and *1Region_Start1932*) yielded similar estimates of stock biomass during the overlapping period (1975–2016) (see Section 5.5.4). The two model options also yielded similar fits to the individual data sets, excluding the two additional sets of CPUE indices from the 1960s and early 1970s that were only included in the full catch history model (*1Region_Start1932*).

The *3Region_Start1975* model also yielded a similar biomass trajectory to the two single region models. However, the model was discounted due to the deterioration in the fit to key data sets relative to the single region models. The three region model was more highly constrained by the model structural assumptions and there were limited data to reliably estimate the regional specific parameters independently from other key parameters (especially selectivity).

The *1Region_Start1975* model was selected as the base model as it was the simplest, most internally consistent model. It also yielded results that were not substantively different from the *1Region_Start1932*.

5.5.3 Model diagnostics

The MPD fits to the observational data are presented for the base model option (*1Region_Start1975*). In general, the model fitted well to the TAR3-BT, TAR3-SN and TAR2BPLE-BT CPUE indices from 1995 onwards (Figure 15). The model fitted the strong temporal progression of the peak in the CPUE indices from the late 1990s–early 2000s in TAR3-BT through the TAR3-SN and TAR2BPLE-BT CPUE indices in the early 2000s. The model also fitted the recent increase in the TAR3-BT CPUE indices. There was a poor fit to the TAR2BPLE-BT CPUE indices for the initial years of the series (1990–1993) (Figure 15).

For the ENLD-BT CPUE indices, the model predicted a peak in the CPUE during 2002–2004 corresponding to the peak in the CPUE indices for the other fisheries (Figure 15). This trend in the abundance was less pronounced for the ENLD-BT CPUE indices, although the CPUE indices for 2003–2006 were higher than the adjacent years. The model fitted the general decline in the ENLD-BT CPUE indices during 2005–2016. However, the fit to the CPUE indices from 1994–1998 was poor (Figure 15).

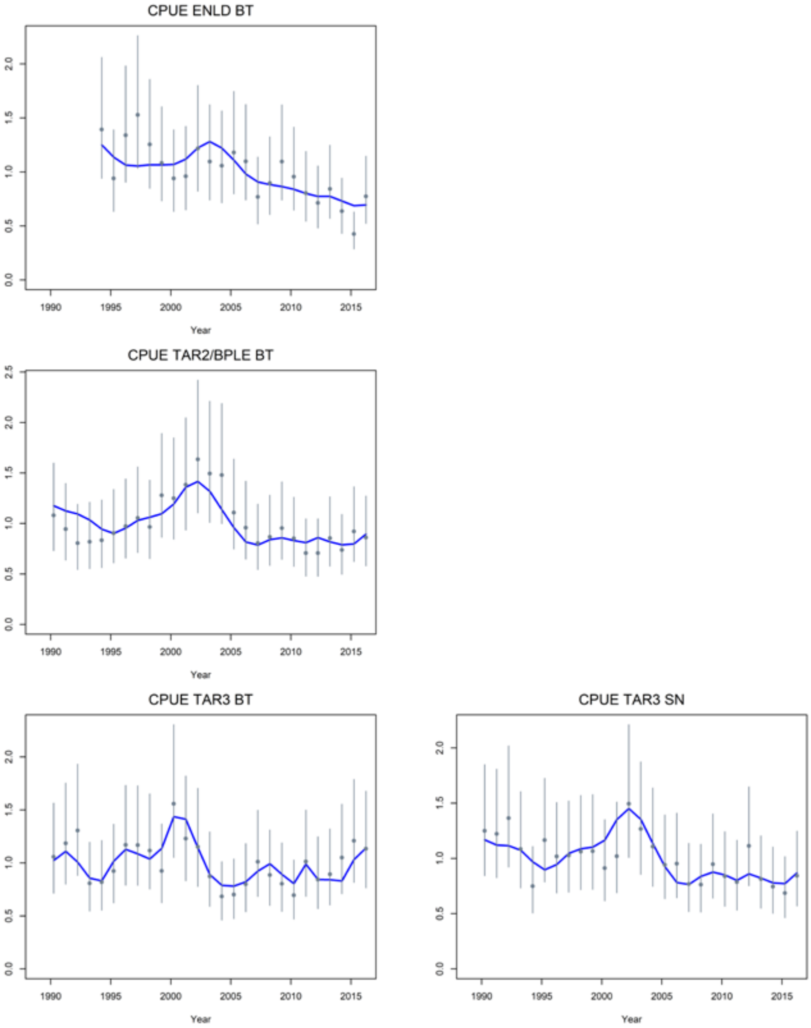

Figure 15: A comparison of the observed (points) and predicted (lines) CPUE indices for each of the sets of recent CPUE indices included in the base model (*1Region_Start1975*). The CPUE indices were derived by fishing year and were assigned to the calendar year at 1 January to correspond to the model structure (e.g., the 2015/16 fishing year was assigned to the 2016 model year).

The TAR3-BT commercial age compositions are dominated by 4–5 year old fish. The model had good fits to the proportions at age from the four recent age observations from the fishery (Figure 16 and Figure 17).

There was considerably more variability in the age compositions from the TAR3-SN fishery, with a poorer fit to these data (Figure 18) compared to other fisheries, which partly reflected the lower weighting associated with the observations (ESS 15). The model consistently under-estimated the proportion of fish in the 2007 year class sampled at age 4 years in 2011, 7 years in 2014, and 8 years in 2015 (Figure 18). This cohort was also evident as a strong year class in the age compositions from the Cook-BT (2014), TAR2BPLE-BT fishery (2011, 2014 and 2015), and ENLD-BT (2014 and 2015). Overall, the model accurately predicted the relative strength of the year class in each of these age observations.

The model represented a good fit to the single age composition from the Cook-BT fishery (Figure 19). The sampled catch was predominantly composed of 6–11 year old fish and dominated by 5 and 7 year old fish (2009 and 2007 year classes, respectively). Notably, the relatively high proportion of fish in the 18 year age class (in 2014) was consistent with the presence of a strong year class in the ENLD-BT age composition (the 1996 year class at ages 18 and 19 years in 2014 and 2015, respectively). There is also an indication that the strong 1996 year class was present in the tail of the distribution of the 2008 TAR2BPLE-BT age composition (age 12 years) (Figure 20).

In addition to the strong 2007 year class, the recent TAR2BPLE-BT age compositions were dominated by a strong 2009 year class. The model under-estimated the relative strength of the 2009 year class in 2015 at age 6 years) (Figure 20). Nonetheless, overall the model gave a good fit to the five observations of the age composition from the TAR2BPLE-BT fishery (Figure 20).

The 2009 year class recruited into the ENLD-BT fishery in 2015. The model provided a good overall fit to the two ENLD age compositions, including the broad distribution of older (> 15 years) fish sampled from the fishery (Figure 21). The model had some flexibility to fit the age compositions as recruitment deviates were estimated for the year classes that correspond to the full range of age classes.

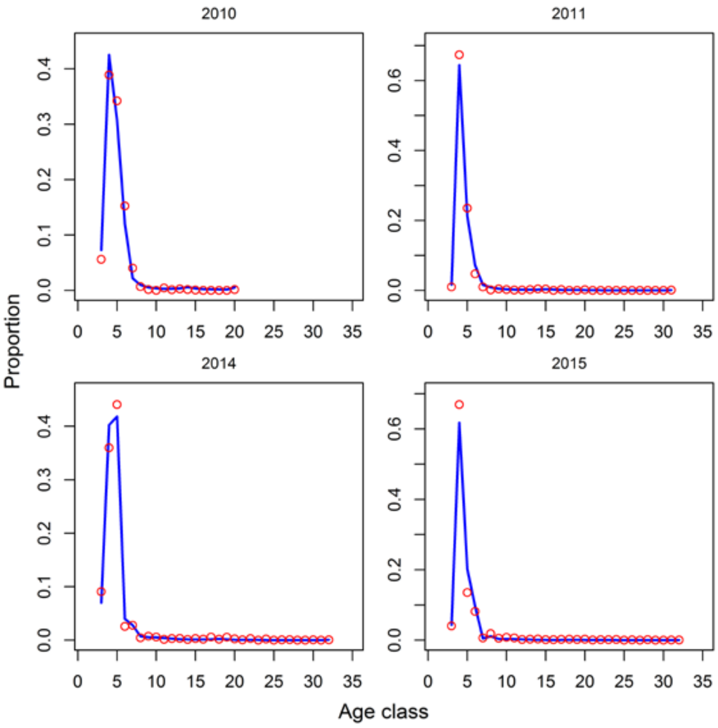

Figure 16: A comparison of the observed (red points) and predicted (blue lines) age compositions from the TAR3-BT commercial fishery included in the base model (*1Region_Start1975*).

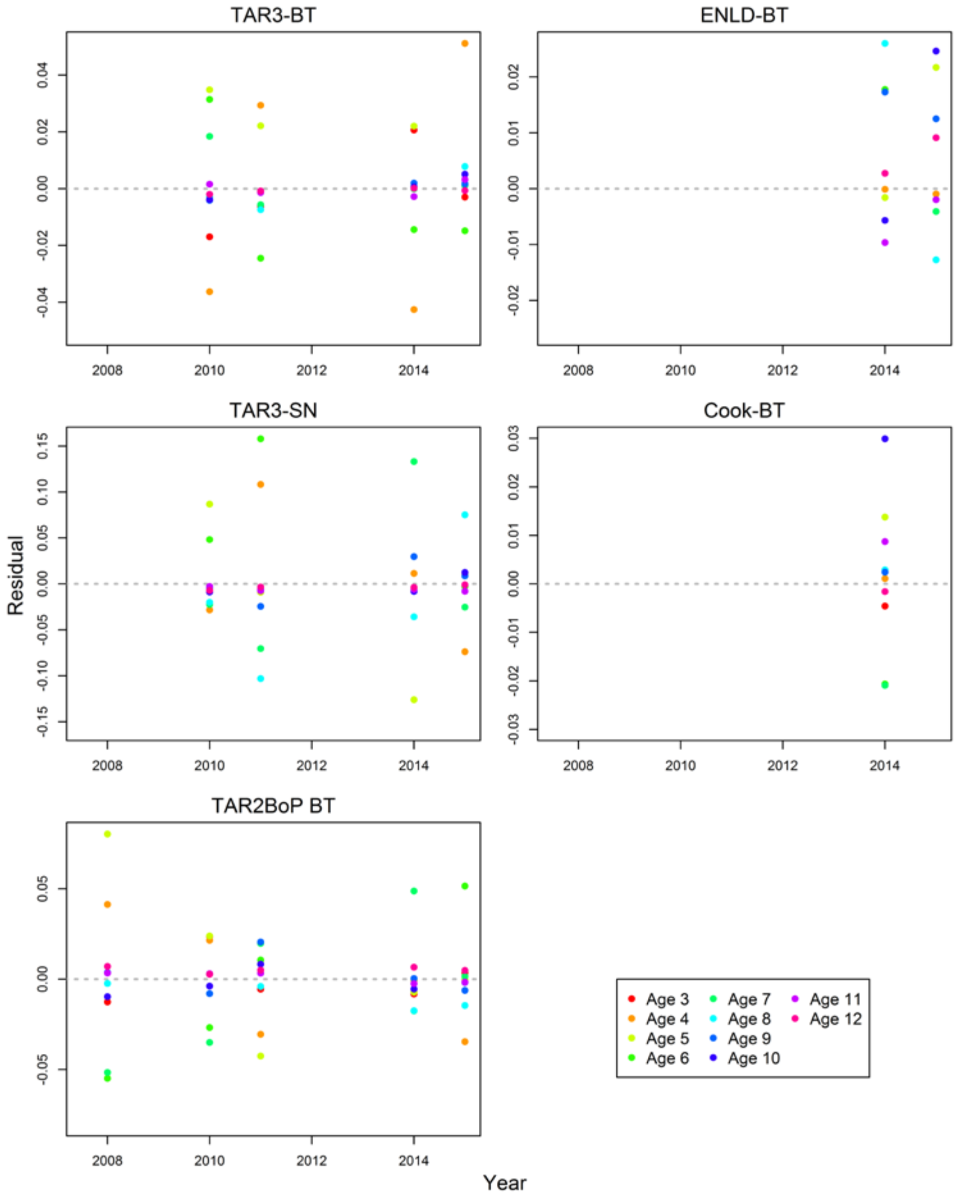

Figure 17: Residuals (unstandardised) from the fits to commercial age compositions for the main age classes (3–12 years) (base model *1Region_Start1975*).

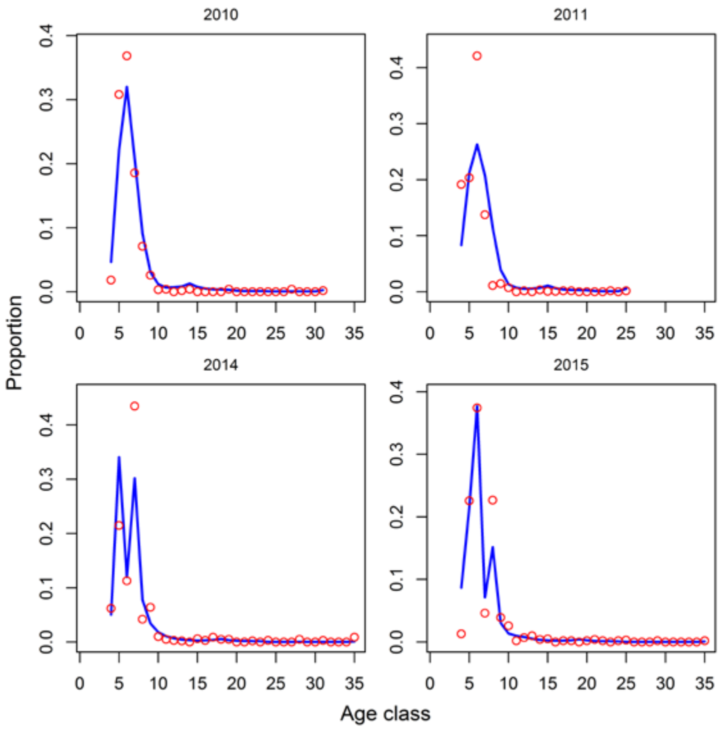

Figure 18: A comparison of the observed (red points) and predicted (blue lines) age compositions from the TAR3-SN commercial fishery included in the base model (*1Region_Start1975*).

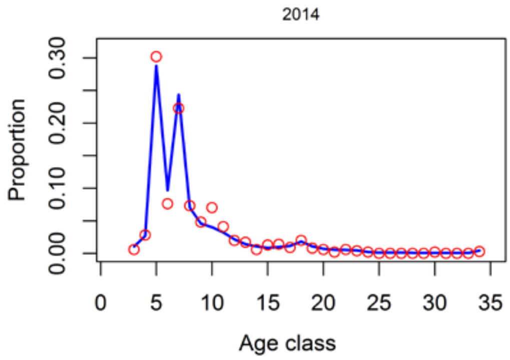

Figure 19: A comparison of the observed (red points) and predicted (blue lines) age compositions from the Cook Strait trawl fishery included in the base model (*1Region_Start1975*).

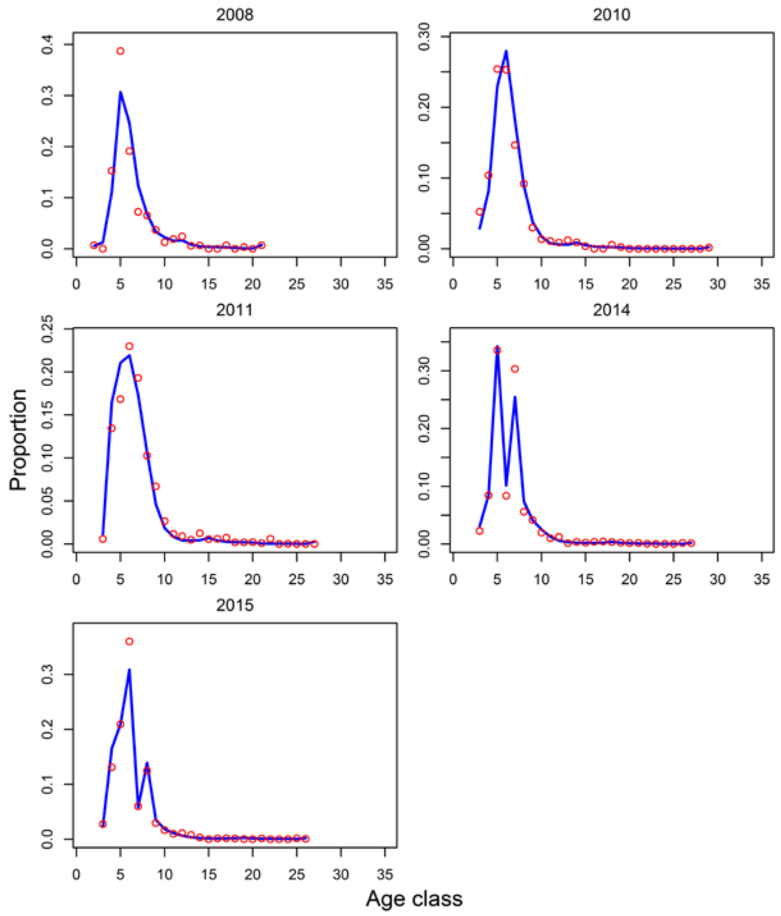

Figure 20: A comparison of the observed (red points) and predicted (blue lines) age compositions from the TAR2BPLE-BT commercial fishery included in the base model (*1Region_Start1975*).

Figure 21: A comparison of the observed (red points) and predicted (blue lines) age compositions from the ENLD-BT commercial fishery included in the base model (*1Region_Start1975*).

The model gave a good fit to the winter ECSI trawl survey biomass estimates from the latter period (2007–2016) (Figure 22). This is the period for which corresponding age composition data are available from each trawl survey. The model tended to over-estimate the trawl survey biomass for the earlier (1991–1996) winter ECSI trawl surveys (Figure 22).

The fits to the summer ECSI trawl survey biomass estimates were relatively poor with the model under-estimating the magnitude of the 1997 and 1999 biomass estimates (Figure 22). Limited age composition data (n=1) were available from the summer trawl surveys and the selectivity (age based) of the survey was assumed to be equivalent to the winter ECSI trawl survey.

For the ECNI trawl survey, the model approximated the average of the three survey biomass estimates (Figure 22).

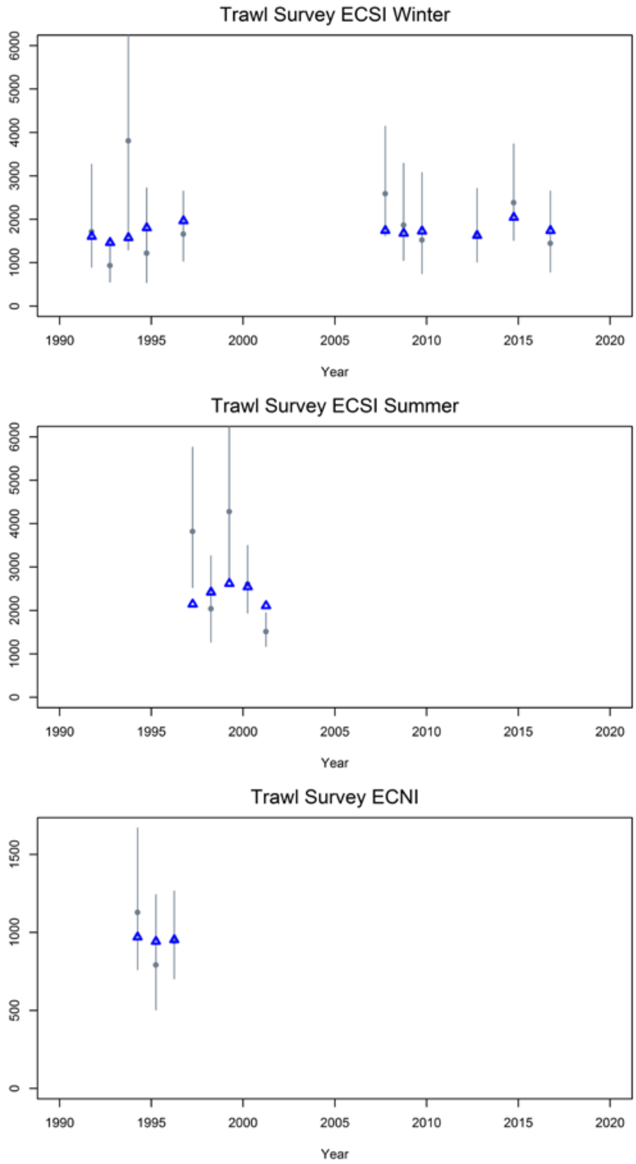

Figure 22: A comparison of the observed (grey points) and predicted (blue triangles) abundance indices for the three sets of trawl surveys included in the base model (*1Region_Start1975*).

The model fitted the winter ECSI trawl survey age compositions (from 2007–2016) well (Figure 23). There is no strong pattern in the residuals with respect to age for the main age classes sampled by the survey (1–6 years), although the proportion of age 2 fish was under-estimated for the last three surveys (Figure 24).

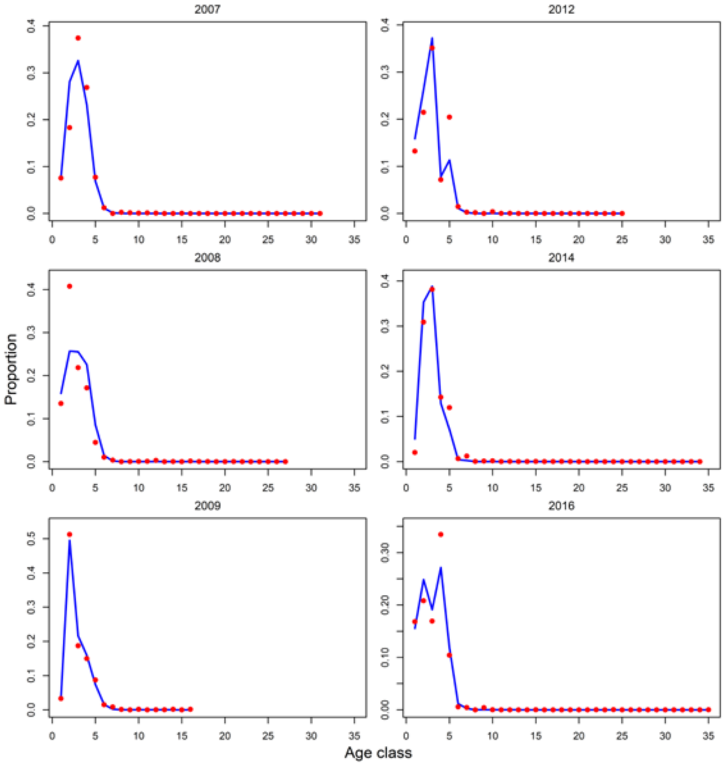

Figure 23: A comparison of the observed (red points) and predicted (blue lines) age compositions from the winter ECSI trawl surveys included in the base model (*1Region_Start1975*).

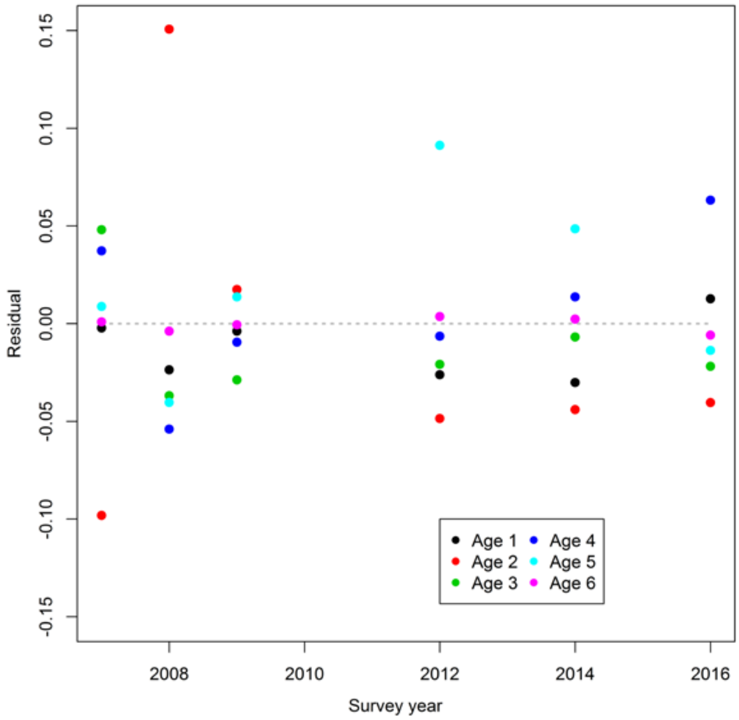

Figure 24: Residuals (unstandardised) from the fits to the winter ECSI trawl survey age compositions for the main age classes (1–6 years) (base model *1Region_Start1975*).

Length composition data were included in the assessment model for those trawl surveys with no available age composition data. The overall selectivity for the trawl surveys was primarily informed by the age frequency data available from the more recent surveys. In general, the model approximated the observed length compositions from the surveys although the modal structure of individual trawl survey length compositions was poorly estimated (Figure 25). Notably, the model did not predict the strong modes evident in the 1992 and 1993 trawl surveys (likely to represent the 1990 year class) or the strong mode in the 1996 survey length composition (1994 year class).

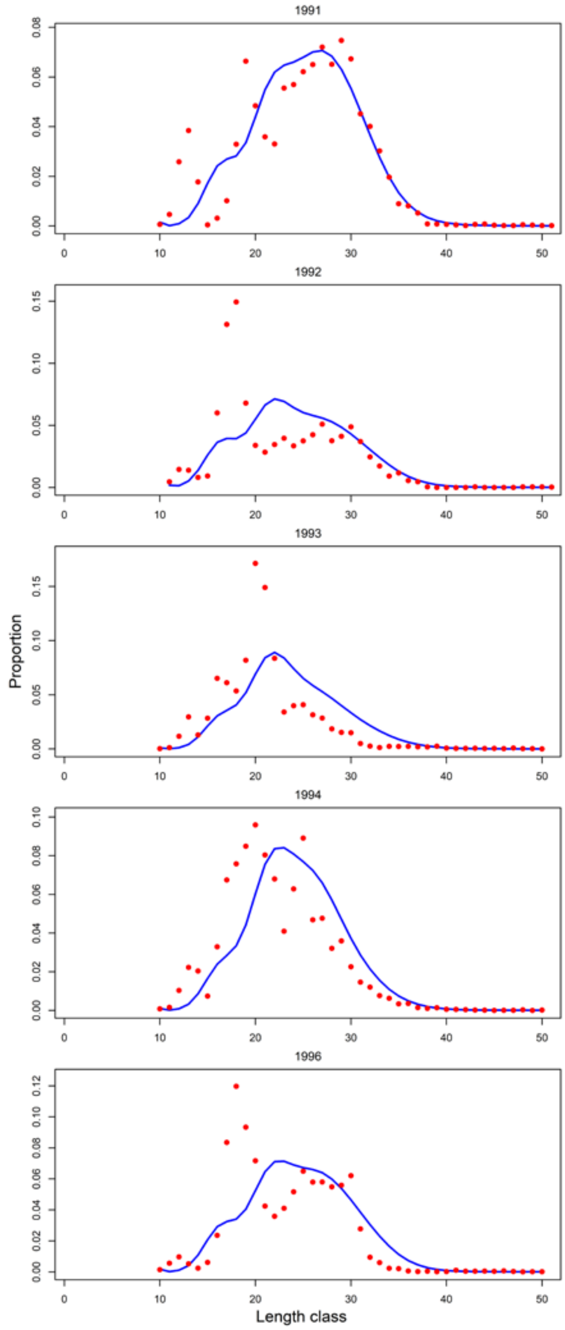

Figure 25: A comparison of the observed (red points) and predicted (blue lines) length compositions from the winter ECSI trawl surveys included in the base model (*1Region_Start1975*).

A single age composition is available from the summer ECSI trawl surveys. The age-based selectivity of the survey is assumed to be equivalent to the winter ECSI trawl survey. However, the fit to the 2001 survey age composition was poor (Figure 26). The model substantially under-estimated the proportion of 5 year old fish in the age composition. This age class corresponds to the strong 1996 year class that persisted in the age compositions of the commercial fisheries throughout the subsequent years. The model also substantially over-estimated the proportion of 2 year old fish in the survey age composition (Figure 26).

The model provided a reasonable fit to the length compositions from the 1997–2000 summer ECSI trawl surveys (Figure 27). The notable exception was the over-estimation of the proportions in the smallest vulnerable length classes (corresponding to the 1+ year age class) in 1997. This represented the model's prediction of the relative strength of the 1996 year class that dominated the 1998 survey length composition (mode about 19 cm FL) (Figure 27).

Overall, the model fitted the length composition of the fish sampled by the ECNI trawl survey reasonably well, although it did not adequately represent the decrease in the modal size of fish sampled in the 1996 survey (from 33–36 cm to 30–34 cm) (Figure 28).

Figure 26: A comparison of the observed (red points) and predicted (blue line) age composition from the summer ECSI trawl survey included in the base model (*1Region_Start1975*).

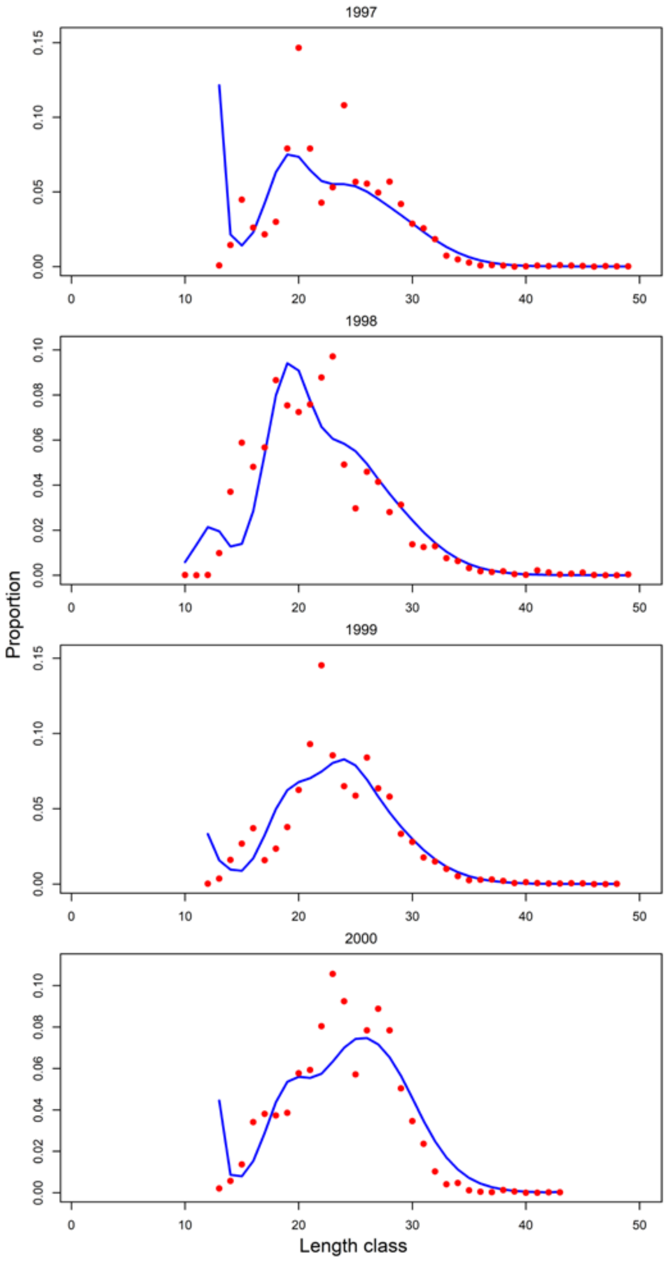

Figure 27: A comparison of the observed (red points) and predicted (blue lines) length compositions from the summer ECSI trawl surveys included in the base model (*1Region_Start1975*).

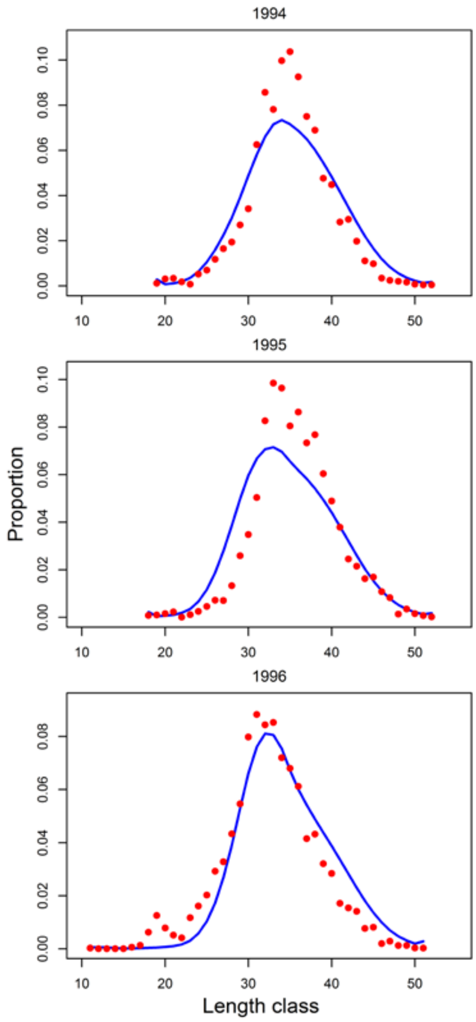

Figure 28: A comparison of the observed (red points) and predicted (blue lines) length compositions from the ECNI trawl surveys included in the base model (*1Region_Start1975*).

Figure 29: A comparison of the observed (red points) and predicted (blue line) age composition from the 1987 *James Cook* Pegasus Bay–Cape Campbell trawl survey included in the base model (*1Region_Start1975*).

The model fit to the 1987 *James Cook* trawl survey age composition was relatively poor (Figure 29). The model had considerable flexibility to fit the age composition via the parameterisation of the selectivity function. However, the population age structure (numbers at age) was derived assuming equilibrium conditions prior to 1980. Therefore, the model could not fit the variation in the observed age structure for age classes greater than 8 years. The lack of recruitment variation probably accounted for the under-estimation of the proportions in the relatively strong 16–20 age classes, although there was also a systematic under-estimation of the proportions in the older age classes too, including the terminal age class (aggregated at 35 years) (Figure 29).

In general, the fits to the abundance (CPUE and trawl survey) and age/length composition data were similar for the base model and the full catch history single region model (*1Region_Start1932*). The latter model included two additional sets of CPUE indices from the 1960s–early 1970s.

The model fitted the general decline in the TAR2-BT-Early CPUE indices (Figure 30). However, the fit to the TAR3-BT-Early CPUE indices was poor (Figure 30). The latter series was derived from the trawl fishery operating in Canterbury Bight. This fishery primarily catches younger tarakihi and, consequently, CPUE indices will be strongly influenced by variation in recruitment which may account for the high degree of inter-annual variation in the TAR3-BT-Early CPUE indices. There were no additional data to inform the model regarding the relative strength of individual year classes during the 1960s–early 1970s and recruitment was assumed to be at equilibrium levels during that period.

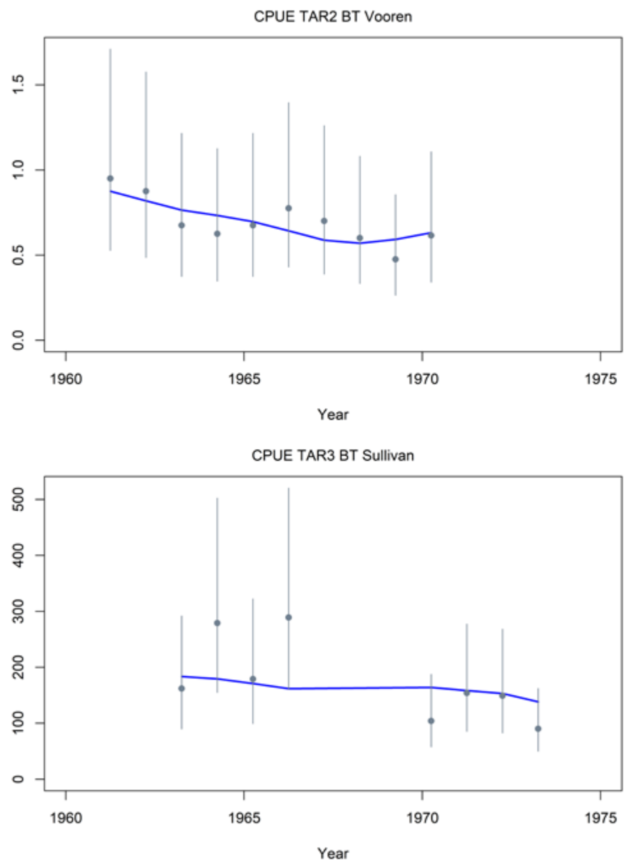

Figure 30: A comparison of the observed (points) and predicted (lines) CPUE indices for the sets of historical CPUE indices included in the single region full catch history model (*1Region_Start1932*). The CPUE indices were derived by fishing year and were assigned to the calendar year at 1 January to correspond to the model structure (e.g., the 2015/16 fishing year was assigned to the 2016 model year).

5.5.4 Model comparisons

Overall, the model options that commenced in 1975 yielded similar results to the full catch history model (*1Region_Start1932*) in terms of the biomass trajectory from 1985–2016 and the estimate of equilibrium, unfished spawning biomass (SB_0) (Figure 31). Some differences existed between the three region model and the single region models following the initialisation of the population(s) although the biomass trajectories converged during the subsequent period. The alternative model options both had a relatively poor fit to the CPUE indices from ENLD-BT and TAR2BPLE-BT during the early 1990s although the lack of fit was more pronounced for the three region model. Overall fits to some of the other abundance indices (CPUE and survey) were also somewhat worse for the three region model. The fits to the age composition data sets were also considerably worse for the three region model. The greater flexibility of the parameterisation of the selectivity functions for the single region model appears to be the main reason for the improved fit to these two main data components.

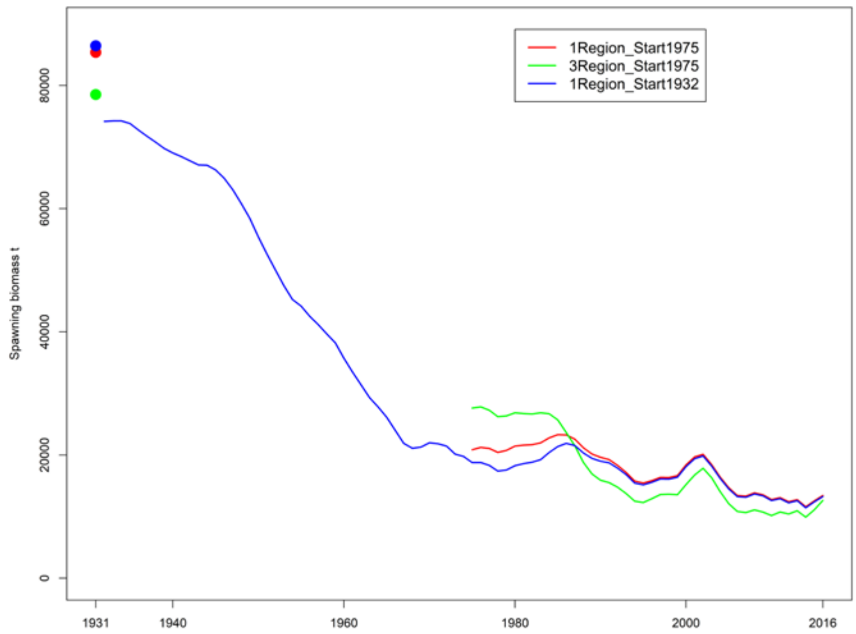

Figure 31: A comparison of the biomass trajectories (MPDs) from the three main model options and the corresponding estimates of the equilibrium, unfished biomass SB_0 (points) plotted (arbitrarily) at 1931.

5.5.5 Derived quantities

The base model estimated spawning biomass from 1975 (Figure 32). There was a general decline in stock biomass over the model period, moderated by short-term fluctuations that corresponded to variations in recruitment (Figure 33). Recruitment was relatively high during the early–mid-1990s corresponding to a peak in spawning biomass during the early 2000s (Figure 32). Conversely, recruitment was below average during the late 1980s and late 1990s–early 2000s corresponding to lower biomass levels in the mid-1990s and early 2000s, respectively.

Recruitment was relatively strong in 2011 and 2012 (Figure 33) contributing to the slight increase in spawning biomass in the most recent years (2015 and 2016) (Figure 32). Estimates of recruitment in the most recent years (2013–2015) were poorly determined.

Estimates of annual recruitment were also relatively uncertain during the 1980s and, correspondingly, estimates of spawning biomass were relatively uncertain prior to 1990 (Figure 32). The uncertainty in the initial (1975) biomass was also influenced by the precision of the estimates of the initial levels of fishing mortality.

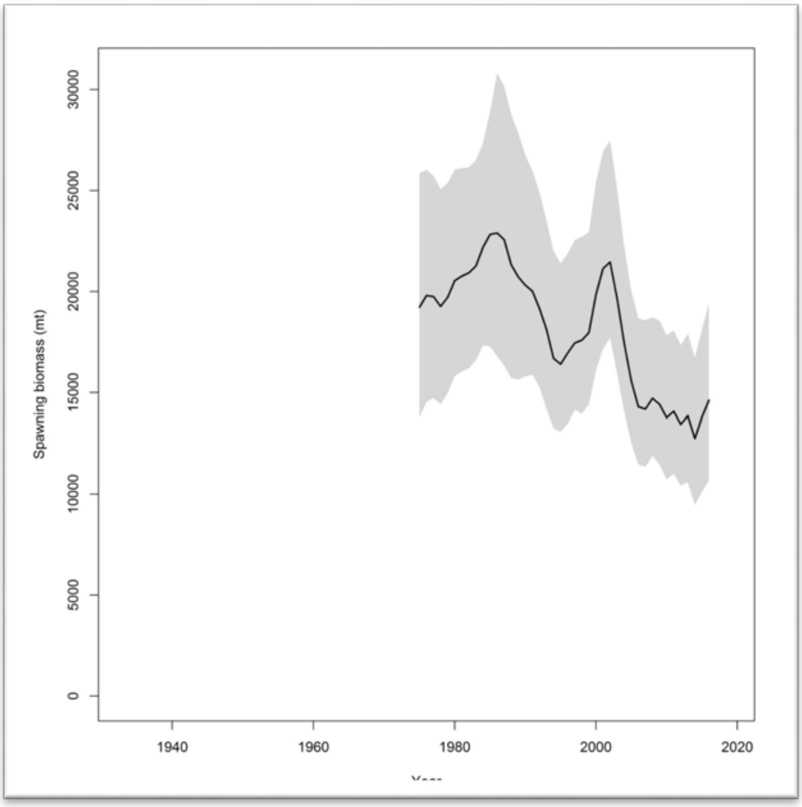

Figure 32: Annual spawning biomass (t) from 1975 for the base model. The line represents the median of the MCMCs and the shaded area represents the 95% confidence interval.

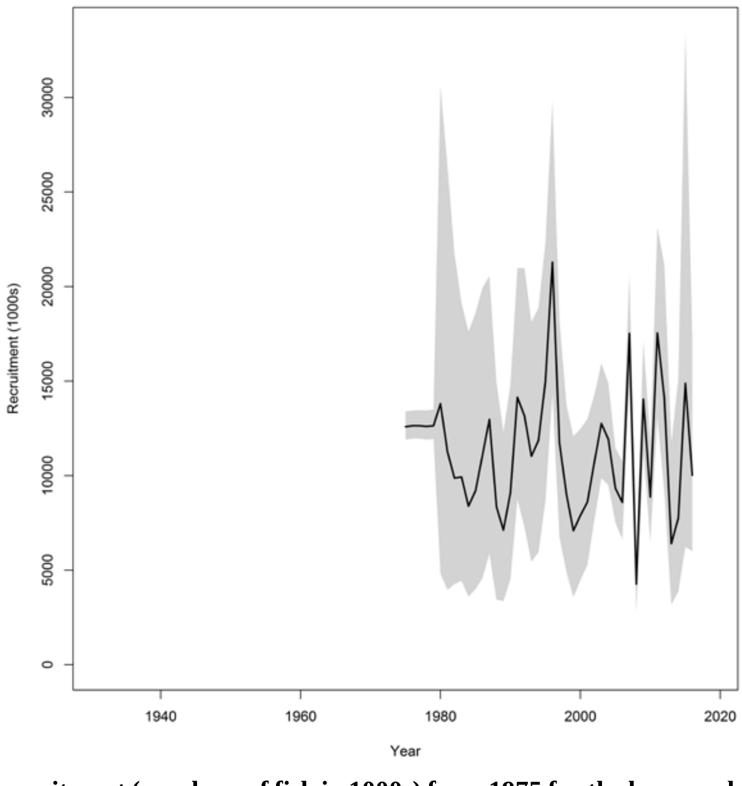

Figure 33: Annual recruitment (numbers of fish in 1000s) from 1975 for the base model. The line represents the median of the MCMCs and the shaded area represents the 95% confidence interval.

5.5.6 Stock status

Estimates of stock status were determined for each model option using an MCMC approach. Model sensitivity analyses were conducted for the base model option (*1Region_Start1975*) to investigate the influence of four key assumptions (Table 10). Stock status for the final year of the analysis was defined as the mid-year spawning biomass (male and female fish) in 2015/16 relative to the equilibrium, unfished biomass (SB_{2016}/SB_0). Absolute exploitation rates were calculated as the ratio of the total annual catch (in biomass) to the summary biomass at the start of the year. Fishing mortality in 2015/16 was estimated relative to a reference fishing mortality that corresponds to the default target biomass of 40% of SB_0 (i.e., $F_{2016}/F_{SB40\%}$) (Ministry of Fisheries 2008, 2011).

Table 10: Description of model sensitivity analyses relative to the base model.

Sensitivity Analysis	Description
InitialCatchVar	Uncertainty associated with Initial Equilibrium Catches SE of ln(Catch) = 1.0
LowM	M = 0.08
Maturity	Length based maturity OGIVE (Parker & Fu 2011) Logistic function parameters *Mat50* = 33.56, *Matslp* = -0.45
Steepness 0.8	h = 0.8

Spawning biomass was estimated to have been depleted to about the default soft limit of 20% *SB0* by the initial period of the assessment model in 1975 (Figure 34). This was preceded by a period of relatively high catches (5000–7000 t) during the 1950s and early 1960s (Figure 8). Spawning biomass tended to decline over the subsequent years, following an increase in total catches during the 1990s and moderated by variation in recruitment, especially a period of higher recruitment during the mid- to late 1990s. Since the mid-2000s, spawning biomass was estimated to have been below the default soft limit (Figure 34) and, for the base model, the 2015/16 spawning biomass was estimated to be about 17% of the unfished, equilibrium biomass level (SB_{2016}/SB_0 = 0.170) (Table 11). Spawning biomass increased slightly from the lowest level in 2014 (Figure 34), following above average recruitment in 2011/12.

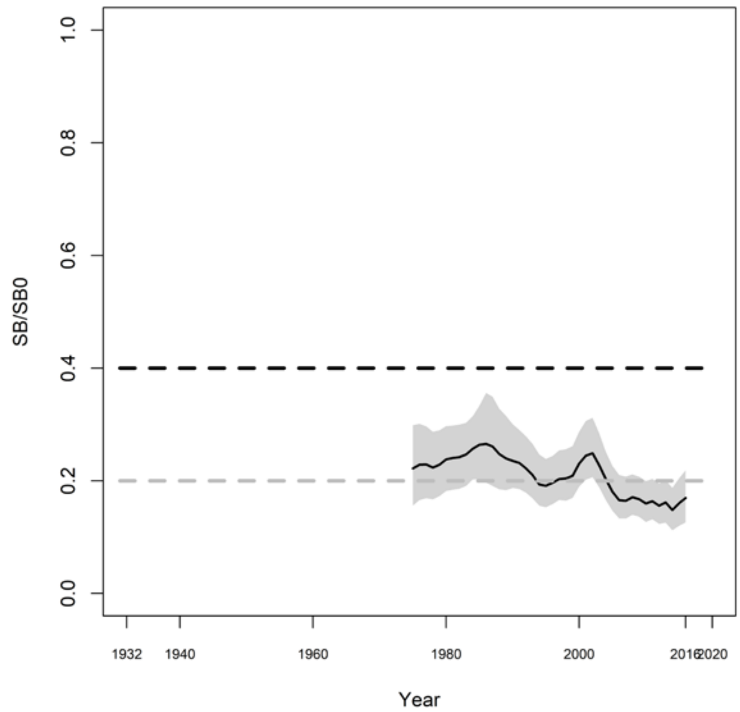

Figure 34: Annual trend in spawning biomass relative to the 40% SB_0 interim target biomass level and 20% SB_0 soft limit for the base model. The line represents the median of the MCMCs and the shaded area represents the 95% confidence interval.

The stock status was similar for the range of model options, although it was slightly more pessimistic for the model sensitivity analyses with lower productivity parameters (Table 11). For the base case, there is a high probability (89%) that the 2015/16 spawning biomass was below the soft limit (20% SB_0) and a very low probability (less than 1%) of being below the hard limit of 10% SB_0 (Table 11).

Table 11: Estimates of the 2015/16 spawning biomass (*SB_{2016}*) and equilibrium, unfished spawning biomass (*SB_0*) (medians and 95% confidence intervals from the MCMCs) and probabilities of 2015/16 biomass being above specified levels.

Model option	SB_0	SB_{2016}	SB_{2016}/SB_0	Pr (SB_{2016} > X% SB_0)		
				40%	20%	10%
Base Region1_Start1975	86 321 (81 977–91 907)	14 620 (10 685–19 413)	0.170 (0.126–0.219)	0.000	0.112	0.997
Region3_Start1975	79 796 (77 016–82 957)	14 170 (10 281–17 850)	0.178 (0.131–0.222)	0.000	0.163	0.998
Region1_Start1932	86 988 (83 194–91 140)	14 614 (11 021–19 283)	0.168 (0.127–0.218)	0.000	0.102	0.999
InitialCatchVar	84 281 (78 864–90 153)	14 172 (10 314–18 749)	0.169 (0.125–0.22)	0.000	0.096	0.999
LowM	102 094 (97 065–107 398)	12 832 (8 295–16 878)	0.126 (0.081–0.166)	0.000	0.000	0.890
Maturity	73 392 (70 030–77 494)	10 350 (7 062–13 780)	0.14 (0.099–0.184)	0.000	0.001	0.970
Steepness 0.8	93 638 (88 334–99 012)	14 464 (8 907–19 488)	0.156 (0.097–0.205)	0.000	0.040	0.969

Annual fishing mortality rates were estimated to have exceeded the level of fishing mortality that corresponds to the default target biomass level (i.e. $F_{SB40\%}$) throughout the model period (from 1975) (Figure 35). From 2000, fishing mortality rates were estimated to have increased steadily and for the base model, the 2016 fishing mortality rates were estimated to be more than double the reference level (i.e. $F_{2016}/F_{SB40\%}$ = 2.23). The estimates of the 2016 fishing mortality rates are similar for the range of model options (Table 12).

For the base model, MPD estimates of deterministic yields were maximised at 4596 t at 0.215 SB_0 (Figure 36). This is comparable to the 2015/16 level of total annual catch of 4442 t included in the assessment model. Equilibrium yields at the target biomass level were estimated to be about 4100 t (Table 12). Fishing at the $F_{SB40\%}$ level of fishing mortality would have yielded considerably lower levels of catch in 2016 (Table 12). However, estimates of recent potential yields are relatively uncertain due to the uncertainty associated with estimates of recent recruitment.

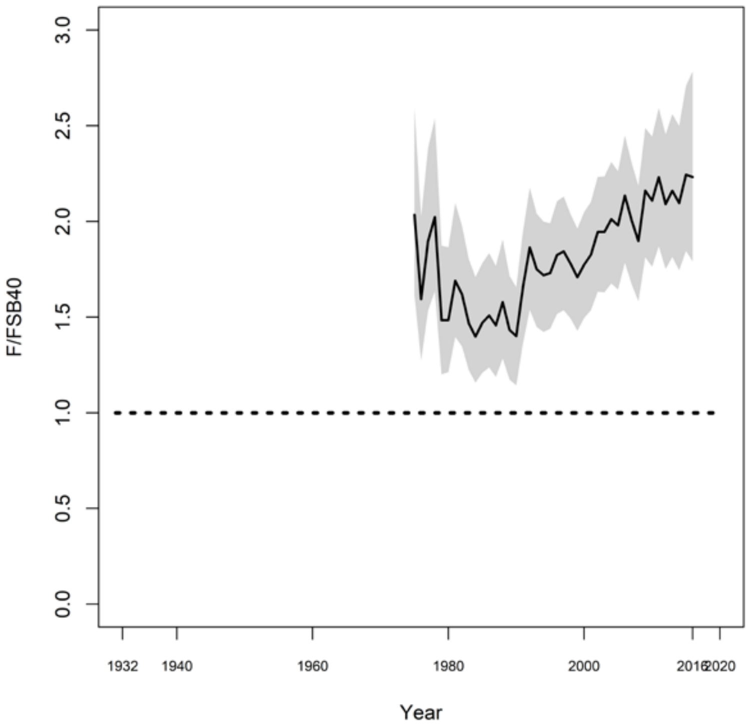

Figure 35: Annual trend in fishing mortality relative to the $F_{SB40\%}$ interim target biomass level for the base model. The line represents the median of the MCMCs and the shaded area represents the 95% confidence interval.

Table 12: Estimates of the 2015/16 fishing mortality (F_{2016}) and reference levels of fishing mortality ($F_{SB40\%}$) (medians and 95% confidence intervals from the MCMCs) and the probability of fishing mortality being below the level of fishing mortality associated with the interim target biomass level. The associated levels of $F_{SB40\%}$ equilibrium yield and 2016 yield at $F_{SB40\%}$ are also presented.

Model option	$F_{SB40\%}$	$F_{2016}/F_{SB40\%}$	Pr(F_{2016}<$F_{SB40\%}$)	$F_{SB40\%}$ Yield	Yield 2016
Base	0.0839	2.231	0.00	4 175	2 448
(Region1_Start1975)	(0.0801–0.0877)	(1.791–2.785)		(3 979–4 379)	(1 819–3 216)
Region3_Start1975	0.0924	2.055	0.00	4 166	2 616
	(0.0896–0.0946)	(1.72–2.629)		(4 003–4 340)	(1 889–3 318)
Region1_Start1932	0.0839	2.231	0.00	4 202	2 451
	(0.0802–0.0873)	(1.816–2.741)		(4 068–4 355)	(1 839–3 201)
InitialCatchVar	0.0838	2.293	0.00	4 072	2 371
	(0.0799–0.0871)	(1.851–2.906)		(3 825–4 319)	(1 730–3 163)
LowM	0.0722	2.905	0.00	4 186	1 842
	(0.0687–0.0752)	(2.37–3.866)		(3 979–4 408)	(1 217–2 411)
Maturity	0.076	2.504	0.00	4 055	1 569
	(0.0732–0.0784)	(2.034–3.166)		(3 855–4 250)	(1 096–2 078)
Steepness 0.8	0.0781	2.451	0.00	4 187	2 264
	(0.0747–0.0811)	(1.918–3.449)		(3 978–4 406)	(1 412–3 034)

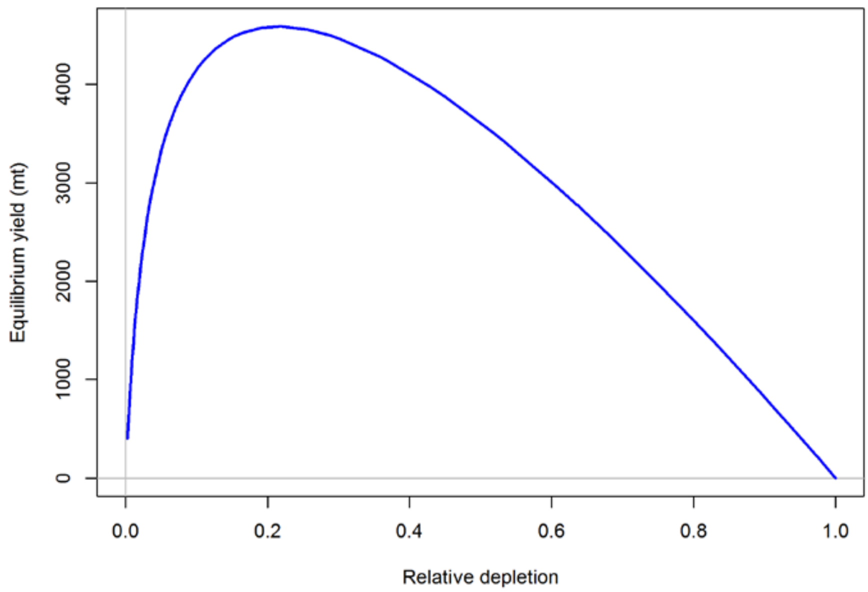

Figure 36: Estimates of equilibrium yields (t) relative to levels of depletion of spawning biomass derived from the MPD of the base model.

5.5.7 Forward Projections

For the base model option, stock projections were conducted for the 10-year period following the terminal year of the model (i.e. 2017–2026) using the MCMC approach. During the projection period, individual annual recruitment deviates were sampled from the lognormal distribution (sigmaR = 0.6) and the annual recruitments were derived from the spawner-recruit relationship (SRR).

Stock projections were based on multiples of the status quo (2016) commercial and recreational catches: i.e., 40%, 60%, 80% and 100% of the total 2016 catch of 4442 t, including the 10% allowance for unreported catch. The recruitment deviates in the projection period were compared to the recruitment deviates estimated for the last 10 years of the estimation period (i.e., 2006–2015). Both sets of recruitment deviates approximated a mean of zero, although the distributions differed considerably due to the high variation in individual recruitment deviates in the modelled estimation period (Figure 37). The geometric mean of the number of recruits in the projection period varies between catch scenarios due to the magnitude of the spawning biomass. Nonetheless, for the projection at 80% of the 2016 catch, the geometric mean of the number of recruits in the projection period was virtually identical to the estimation period (10367.08×10^3 compared to 10283.06×10^3). The levels of recruitment in the other projection scenarios were also similar to the level of recruitment in the estimation period. Thus, while the projected recruitments do not have exactly the same distribution as the recent recruitments, it is considered that the projections are adequate for the purpose of comparing the relative performance of alternative catch and fishing mortality scenarios.

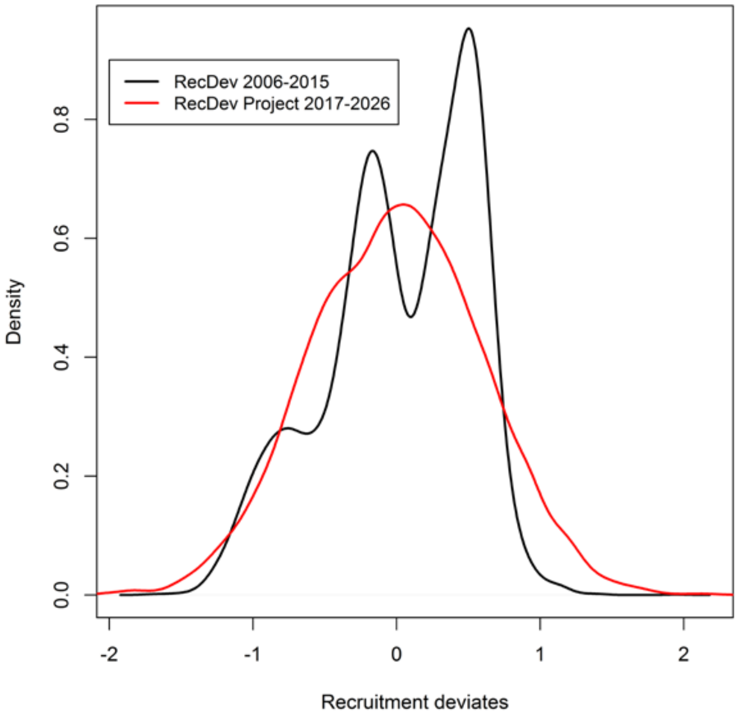

Figure 37: A comparison of the distribution of the recruitment deviates estimated for 2006–2015 and the recruitment deviates in the 10-year projection period. The two sets of recruitment deviates are from the MCMCs for the 80% catch projection.

The minimum period (*Tmin*) required to rebuild the stock to the target biomass level was determined from a stock projection with no catch. *Tmin* was estimated to be 4 years for a target biomass of 35% *SB0* and 5 years for a target biomass of 40% *SB0*. Projections were also conducted at specified levels of fishing mortality levels: $F_{SB35\%}$, $F_{SB40\%}$, and the level of fishing mortality required to rebuild the stock to the target biomass level by twice *Tmin* (i.e., 8 years for 35% *SB0* and 10 years for 40% *SB0*) (Ministry of Fisheries 2008, 2011).

The projections indicate that a catch reduction of approximately 20% is required to minimise the risk of reducing the stock below the hard limit (10% *SB0*) during the next 10 years and substantially improving the probability that the stock will increase to a level above the soft limit (20% *SB0*) (Table 13). However, substantially larger reductions in catch (approaching a reduction of 60%) are required to rebuild the stock to the 40% *SB0* default target level within the 10-year projection period (Table 13).

Table 13: Estimated stock status (and 95% confidence intervals) and the probabilities of the spawning biomass being above default biomass limits and interim target level in 2021 (5 years) and 2026 (10 years) from catch based projections for the base case.

Percent of 2016 catch	SB_{2021}/SB_0	Pr (SB_{2021} > X% SB_0)			
		10%	20%	35%	40%
100%	0.149 (0.062–0.277)	0.850	0.206	0.002	0.001
80%	0.201 (0.117–0.331)	0.988	0.504	0.014	0.002
60%	0.253 (0.169–0.383)	1.000	0.859	0.062	0.014
40%	0.304 (0.220–0.433)	1.000	0.994	0.220	0.063
	SB_{2026}/SB_0	Pr (SB_{2026} > X% SB_0)			
		10%	20%	35%	40%
100%	0.148 (0.0–0.399)	0.681	0.290	0.041	0.026
80%	0.253 (0.089–0.477)	0.966	0.700	0.156	0.084
60%	0.347 (0.192–0.574)	1.000	0.963	0.482	0.278
40%	0.436 (0.279–0.669)	1.000	1.000	0.828	0.632

Projections that reduced the level of fishing mortality to $F_{SB35\%}$ or $F_{SB40\%}$ from 2017 onwards resulted in a very high probability of the stock rebuilding to above the soft limit within 5 years due to a large initial reduction in catch (approx. 40–50% reduction) (Table 14). Under the constant fishing mortality scenarios, annual catches increased as the biomass increased and the rate of rebuild attenuated as the biomass approached the corresponding target level (35% SB_0 or 40% SB_0). Consequently, target biomass levels were not achieved within the 10-year projection period. To attain the target biomass levels within a period of twice *Tmin* a larger reduction in fishing mortality was required, equating to a reduction in fishing mortality to approximately 25% of the F_{2016} level (Table 14). The problem with constant fishing mortality scenarios is that they approach their corresponding biomass levels asymptotically.

Table 14: Estimated stock status (and 95% confidence intervals) and the probabilities of the spawning biomass being above default biomass limits and interim target level in 2021 (5 years) and 2026 (10 years) from fishing mortality based projections for the base case.

Fishing mortality	SB_{2021}/SB_0	Pr (SB_{2021} > X% SB_0)			
		10%	20%	35%	40%
$F_{SB35\%}$	0.246 (0.191–0.34)	1.000	0.942	0.020	0.003
$F_{SB40\%}$	0.264 (0.206–0.364)	1.000	0.983	0.042	0.007
25% of F_{2016}	0.304 (0.238–0.417)	1.000	0.999	0.159	0.036
	SB_{2026}/SB_0	Pr (SB_{2026} > X% SB_0)			
		10%	20%	35%	40%
$F_{SB35\%}$	0.283 (0.156–0.52)	1.000	0.870	0.240	0.129
$F_{SB40\%}$	0.311 (0.188–0.553)	1.000	0.953	0.347	0.202
25% of F_{2016}	0.384 (0.25–0.638)	1.000	0.998	0.658	0.431

6. DISCUSSION

The stock assessment was strongly dependent on CPUE indices as the primary indices of stock abundance. Fisheries-independent surveys are conducted within the ECSI area only and principally monitor the abundance of juvenile tarakihi. Consequently, the CPUE indices and trawl survey data are not directly comparable. Nevertheless, the assessment model indicates that the trends in the various sets of CPUE indices are generally coherent with the data from the trawl surveys (biomass and age/length compositions) and commercial age composition data. This indicates that the various sets of CPUE indices probably provide a reasonable index of stock abundance in each of the fishery areas.

The overall results of the modelling were relatively robust to a wide range of model assumptions. During the development and testing of the assessment model, a wide range of additional model runs were conducted, including alternative weightings of the main CPUE indices and age composition data sets and alternative parameterisations of key fishery selectivity functions (especially ENLD-BT and TAR2BPLE-BT). These changes did not appreciably influence the model estimates of stock status and yields. This supports the conclusion that the main input data sets are relatively coherent amongst fisheries and areas and consistent with the key biological parameters (especially natural mortality and growth), as well as the current stock structure hypothesis.

There is an indication that growth rates of older fish are slower in the northern areas of the model (East Northland and the Bay of Plenty). It was not feasible to incorporate region specific growth rates in the assessment model. However, model trials with a lower maximum length growth parameter did not appreciably change the model results, although there was a minor improvement to the model likelihood objective function.

Overall, the model results are strongly informed by the recent CPUE indices and associated age composition data from the commercial fishery. These data, in conjunction with the fishery catches, inform the model regarding the magnitude of recruitment during the main model period (1975–2016) and, hence, the estimate of the recruitment parameter *R0* and the corresponding estimates of virgin biomass (*SB0*).

Estimates of stock depletion and 2015/16 stock biomass are derived from the initial equilibrium catches and the catch history incorporated in the model. The largest catches occurred during the late 1940s–late 1960s and the stock was estimated to be in a relatively depleted state by 1975 (approximately 20% *SB0*). The stock status in 1975 was comparable for the two single region models, regardless of whether the model was initiated in 1932 or 1975 (base model). For the former model, the magnitude of the decline in stock biomass prior to 1975 was generally consistent with the decline in catch rates observed from the main East Cape trawl fishery during the period of high catches (Vooren 1973).

There is anecdotal evidence that the trawl fisheries off the east coast of the South Island may catch substantial quantities of tarakihi below the Minimum Legal Size (MLS) of 25 cm (F.L.). These catches are discarded and their magnitude has not been quantified. Thus, no information was available to explicitly account for this additional source of mortality in the assessment models. The models implicitly account for the additional sources of mortality in the estimation of the recruitment parameters (*R0* and recruitment deviates), although systematic changes in the magnitude of the catch of sub-MLS tarakihi have the potential to introduce bias in the estimation of *R0* and stock status. It is recommended that the magnitude of the recent catches of sub-MLS tarakihi be determined to enable an evaluation of the sensitivity of the model results to this source of mortality.

There is sufficient information available to support the current hypothesis that tarakihi along the east coast of the North and South Island belong to a single stock. However, the broader stock structure around mainland New Zealand, including the west coast of the North and South Islands, is poorly understood. There is evidence from tagging studies that some tarakihi migrate from the ECSI to the west coast of the North Island. In addition, there is the possibility that tarakihi off the west coast of the North and South Islands could contribute recruits to the ECSI nursery grounds, contributing to the abundance of tarakihi in the area.

The current stock assessment assumed that east coast tarakihi represents a discrete stock. The level of recruitment estimated for the stock determines the overall level of reference biomass (*SB0*) and stock status. Biases in the estimation of recruitment due to the mis-specification of recruitment processes could influence the estimates of stock status for east coast tarakihi. Some preliminary modelling was conducted to investigate the sensitivity of the model results to more complex stock relationships. However, these issues were not fully investigated due to limitations in the data available from the other (west coast) areas and the scope of the assessment project.

7. RESEARCH AND MANAGEMENT IMPLICATIONS

The Stock Assessment Plenary (12 November 2017) accepted the results of the assessment and formulated the summary of the stock status of east coast tarakihi primarily from the results of the base assessment model.

The east coast tarakihi stock was estimated to be below the soft limit of 20% *SB0* and, on that basis, the Harvest Strategy Standard (HSS) specifies that a strategy is required to rebuild the stock to the target biomass level (Ministry of Fisheries 2008). There was considerable inter-annual variation in the recruitment of east coast tarakihi and the initial rate of the rebuild will be influenced by the magnitude of recruitment in recent and subsequent years. During the rebuilding phase, ongoing monitoring of stock will be necessary to ensure adequate recovery of the stock. The monitoring is likely to include an update of the stock assessment in 3–5 years supported by the collection of age composition data from the fisheries and trawl surveys and an update of the CPUE indices. Increased emphasis should be put on the collection of data from the East Northland fishery to ensure monitoring of the full age structure of the population. Additional sampling of the age composition of the eastern Cook Strait fishery (Cook-BT) would also be beneficial as limited data are currently available from this area.

The current assessment was reliant on CPUE indices from the main commercial fisheries to provide indices of stock abundance. Future updates of the CPUE indices should consider changes in fishing technology; for example, the adoption of Precision Seafood Harvesting (PSH) trawl gear and changes in trawl codend mesh size and design. Further refinement of the ENLD-BT CPUE indices is recommended to account for changes in the operation of the target tarakihi trawl fishery (that resulted in a decline in the CPUE indices due to a decline in the probability of catching tarakihi predicted by the binomial model). There may be potential to develop an additional time-series of CPUE indices for the eastern Cook Strait fishery (Cook-BT).

A broader research requirement is to improve the understanding of the stock relationships of tarakihi around mainland New Zealand. This could be progressed by extending the current assessment model to integrate the data available from the west coast of the South Island (catch, trawl surveys, CPUE indices and age compositions), Tasman Bay/Golden Bay (trawl surveys) and the west coast of the North Island (catch, CPUE indices and age compositions). This would provide a framework to evaluate the extent of variation in recruitment dynamics amongst regions and, thereby, provide an indication of the potential stock linkages between the east coast and other regions. The study would also highlight limitations of the data currently available from the other main fishery areas and enable the formulation of targeted research to improve the discrimination of stock boundaries (e.g. tagging studies).

The development of management recommendations from the stock assessment needs to fully consider the spatial domain of the assessment model and the overlay with the current tarakihi fishstock boundaries. The assessment encompasses the eastern North and South Islands, including the entire area of TAR 3 and TAR 2 and the eastern portion of TAR 1 (i.e., Fisheries Management Area 1). The model also includes the eastern area of TAR 7 (Cook Strait) which accounts for approximately 15% of the annual catch of TAR 7.

The preferred (base) model is configured with a single population and the catch from individual area (and method) fisheries is mediated by specific fishery selectivity functions; exploitation rates are equivalent throughout the model domain. The impact of the individual fisheries on the stock biomass can be approximated within the modelling framework, although it is assumed that the impacts are equivalent throughout the model domain, rather than occurring at the spatial scale of the fishery. The spatially disaggregated model has the potential to explicitly account for the impact of regional catches; however, the model is not considered to be sufficiently robust for the purposes of management advice, including the determination of estimates of stock status and yield at the regional level.

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APPENDIX 1. MODEL CATCH HISTORY

Table A1: Annual tarakihi catch (t) by fishery and total included in the stock assessment models.

Year	Fishery								Total
	TAR3-BT	TAR3-SN	Cook-BT	TAR2-BT	TAR2-Rec	BPLE-BT	BPLE-Rec	ENLD-BT	
1932	0	0	38	110	0	64	0	1 310	1 522
1933	0	0	148	429	0	47	0	658	1 282
1934	182	0	128	370	0	50	0	591	1 321
1935	152	0	207	600	0	42	0	786	1 787
1936	341	0	298	865	0	29	0	996	2 528
1937	340	0	207	601	0	26	0	1 372	2 545
1938	250	0	233	676	0	16	0	1 340	2 515
1939	534	0	242	703	0	7	0	1 246	2 732
1940	287	0	240	696	0	24	0	1 164	2 411
1941	749	0	207	601	0	19	0	746	2 322
1942	713	0	240	695	0	6	0	728	2 381
1943	589	0	213	617	0	17	0	932	2 368
1944	469	0	147	426	0	1	0	686	1 729
1945	559	0	257	747	0	68	0	1 039	2 671
1946	323	0	412	1 196	0	74	0	1 352	3 358
1947	460	0	498	1 444	0	113	0	1 579	4 093
1948	1 164	0	563	1 634	0	117	0	1 277	4 756
1949	952	0	655	1 900	0	301	0	986	4 794
1950	1 168	0	663	1 925	0	604	0	1 284	5 644
1951	892	0	619	1 795	0	561	0	1 747	5 614
1952	926	0	645	1 871	0	421	0	1 916	5 779
1953	1 138	0	643	1 865	0	353	0	2 032	6 031
1954	971	0	629	1 825	0	477	0	1 829	5 731
1955	694	0	470	1 365	0	345	0	1 670	4 543
1956	719	0	627	1 820	0	532	0	1 763	5 460
1957	461	0	711	2 063	0	615	0	1 265	5 116
1958	1 380	0	677	1 963	0	377	0	1 110	5 507
1959	1 680	0	600	1 742	0	380	0	922	5 324
1960	1 578	0	758	2 199	0	555	0	1 261	6 350
1961	1 034	0	882	2 559	0	557	0	1 037	6 070
1962	1 202	0	881	2 556	0	472	0	1 090	6 202
1963	1 288	0	962	2 790	0	558	0	782	6 378
1964	1 162	0	810	2 349	0	581	0	858	5 759
1965	1 500	0	817	2 370	0	731	0	665	6 084
1966	1 346	0	931	2 701	0	822	0	695	6 496
1967	1 847	0	912	2 645	0	715	0	498	6 617
1968	788	0	784	2 274	0	715	0	384	4 945
1969	1 004	0	587	1 702	0	484	0	488	4 265
1970	864	0	531	1 541	0	578	0	327	3 841
1971	1 344	0	594	1 724	0	657	0	441	4 760
1972	1 384	0	617	1 790	0	587	0	435	4 813
1973	2 603	0	588	1 706	0	438	0	509	5 844
1974	1 746	0	482	1 399	0	493	0	281	4 402
1975	2 296	0	498	1 769	0	426	0	231	5 220
1976	1 327	0	449	1 643	0	260	0	327	4 006
1977	2 312	0	590	1 384	0	385	0	231	4 902
1978	1 978	0	744	1 649	0	600	0	205	5 176
1979	448	0	559	1 502	0	797	0	347	3 653

Year	Fishery								Total
	TAR3-BT	TAR3-SN	Cook-BT	TAR2-BT	TAR2-Rec	BPLE-BT	BPLE-Rec	ENLD-BT	
1980	816	43	500	1 150	0	735	0	503	3 746
1981	1 186	132	504	1 164	71	805	97	603	4 561
1982	1 266	223	394	1 213	71	594	97	553	4 411
1983	915	229	216	1 316	71	743	97	433	4 020
1984	866	216	362	979	71	730	97	554	3 877
1985	1 232	308	384	971	71	615	97	448	4 125
1986	1 101	275	486	1 096	71	670	97	406	4 202
1987	771	225	416	1 514	71	507	97	373	3 974
1988	853	246	416	1 519	71	607	97	446	4 256
1989	598	182	416	1 550	71	522	97	384	3 821
1990	770	237	322	1 400	71	416	97	379	3 692
1991	625	339	384	1 804	71	627	97	368	4 315
1992	714	378	452	1 675	71	803	97	475	4 667
1993	356	337	445	1 713	71	855	97	349	4 224
1994	462	223	355	1 651	71	821	97	424	4 103
1995	376	275	581	1 612	71	715	97	395	4 122
1996	660	342	531	1 590	71	682	97	394	4 368
1997	786	263	449	1 727	71	574	97	489	4 455
1998	746	272	406	1 776	71	613	97	500	4 481
1999	843	216	519	1 674	71	586	97	429	4 434
2000	1 022	238	495	1 839	71	467	97	467	4 696
2001	745	297	777	1 731	71	682	97	379	4 779
2002	688	336	779	1 821	71	791	97	335	4 918
2003	732	288	545	1 809	71	870	97	244	4 656
2004	722	275	533	1 716	71	935	97	247	4 596
2005	642	131	492	1 760	71	763	97	402	4 358
2006	683	183	473	2 090	71	626	97	399	4 621
2007	827	155	443	1 814	71	502	97	286	4 195
2008	613	175	374	1 743	71	552	97	247	3 872
2009	752	185	429	1 970	71	742	97	268	4 514
2010	399	129	611	1 916	71	781	97	224	4 228
2011	964	135	464	1 742	71	747	97	236	4 455
2012	585	190	578	1 721	71	607	97	213	4 062
2013	730	173	611	1 907	71	538	97	186	4 314
2014	770	108	578	1 829	71	416	97	414	4 284
2015	903	106	628	1 939	71	421	97	417	4 583
2016	974	151	641	1 811	71	349	97	348	4 443

APPENDIX 2. TRAWL SURVEY AGE AND LENGTH COMPOSITIONS

Table A2: Proportional age compositions derived for the recent East Coast South Island (ECSI) inshore trawl surveys. The survey years denote the years in the stock assessment model. The ECSI summer survey was conducted in December 2000-January 2001 and was assigned to the 2001 model year. For the ECSI winter surveys, the model years are equivalent to the year of the survey.

Age						ECSI winter	ECSI summer
(years)	2007	2008	2009	2012	2014	2016	2001
1	0.0729	0.1336	0.0322	0.1324	0.0202	0.1676	0.0000
2	0.1765	0.4030	0.5006	0.2145	0.3066	0.2074	0.0773
3	0.3603	0.2161	0.1827	0.3511	0.3785	0.1687	0.2483
4	0.2590	0.1696	0.1464	0.0717	0.1415	0.3336	0.2486
5	0.0745	0.0444	0.0852	0.2044	0.1186	0.1039	0.3358
6	0.0118	0.0103	0.0147	0.0148	0.0067	0.0057	0.0552
7	0.0002	0.0034	0.0082	0.0028	0.0123	0.0044	0.0003
8	0.0025	0.0001	0.0012	0.0018	0.0006	0.0000	0.0100
9	0.0014	0.0003	0.0000	0.0002	0.0013	0.0041	0.0119
10	0.0008	0.0005	0.0015	0.0038	0.0019	0.0002	0.0006
11	0.0012	0.0008	0.0000	0.0004	0.0004	0.0000	0.0032
12	0.0008	0.0031	0.0004	0.0005	0.0006	0.0000	0.0003
13	0.0001	0.0000	0.0003	0.0000	0.0003	0.0000	0.0007
14	0.0000	0.0003	0.0016	0.0002	0.0003	0.0000	0.0042
15	0.0006	0.0000	0.0000	0.0002	0.0004	0.0001	0.0009
16	0.0002	0.0015	0.0015	0.0000	0.0002	0.0000	0.0007
17	0.0000	0.0003	0.0000	0.0001	0.0002	0.0000	0.0008
18	0.0001	0.0002	0.0000	0.0000	0.0006	0.0000	0.0003
19	0.0001	0.0000	0.0000	0.0000	0.0003	0.0000	0.0003
20	0.0001	0.0000	0.0000	0.0001	0.0000	0.0000	0.0000
21	0.0000	0.0004	0.0000	0.0000	0.0001	0.0000	0.0003
22	0.0001	0.0001	0.0000	0.0000	0.0003	0.0002	0.0000
23	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
24	0.0000	0.0000	0.0000	0.0000	0.0000	0.0004	0.0000
25	0.0000	0.0000	0.0000	0.0001	0.0000	0.0000	0.0000
26	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0003
27	0.0000	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000
28	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
29	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
30	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
31	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
32	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
33	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
34	0.0000	0.0000	0.0000	0.0000	0.0001	0.0000	0.0000
35+	0.0000	0.0000	0.0000	0.0000	0.0000	0.0002	0.0000

Table A3: Proportional length compositions derived for the East Coast South Island (ECSI) inshore trawl surveys for which age compositions are not available. The survey years denote the years in the stock assessment model. For the ECSI winter surveys, the model years are equivalent to the year of the survey.

Length	ECSI winter					ECSI summer			
(cm)	1991	1992	1993	1994	1996	1997	1998	1999	2000
10	0.0007	0.0000	0.0002	0.0008	0.0014	0.0000	0.0001	0.0000	0.0000
11	0.0046	0.0045	0.0012	0.0016	0.0056	0.0000	0.0000	0.0000	0.0000
12	0.0259	0.0145	0.0117	0.0103	0.0097	0.0000	0.0001	0.0002	0.0000
13	0.0384	0.0139	0.0296	0.0223	0.0052	0.0007	0.0098	0.0036	0.0021
14	0.0177	0.0081	0.0129	0.0204	0.0024	0.0144	0.0370	0.0160	0.0057
15	0.0004	0.0092	0.0283	0.0074	0.0061	0.0448	0.0588	0.0268	0.0137
16	0.0032	0.0600	0.0651	0.0329	0.0236	0.0261	0.0481	0.0371	0.0341
17	0.0102	0.1314	0.0611	0.0675	0.0835	0.0216	0.0567	0.0158	0.0381
18	0.0330	0.1495	0.0535	0.0758	0.1197	0.0300	0.0865	0.0235	0.0373
19	0.0664	0.0679	0.0819	0.0849	0.0934	0.0791	0.0753	0.0378	0.0386
20	0.0484	0.0338	0.1713	0.0960	0.0717	0.1466	0.0724	0.0625	0.0577
21	0.0359	0.0284	0.1491	0.0804	0.0424	0.0791	0.0758	0.0929	0.0593
22	0.0330	0.0346	0.0837	0.0680	0.0359	0.0428	0.0877	0.1453	0.0804
23	0.0555	0.0397	0.0341	0.0410	0.0410	0.0531	0.0970	0.0854	0.1056
24	0.0569	0.0335	0.0399	0.0629	0.0517	0.1081	0.0491	0.0650	0.0924
25	0.0622	0.0375	0.0408	0.0891	0.0650	0.0568	0.0297	0.0587	0.0571
26	0.0650	0.0424	0.0314	0.0469	0.0579	0.0555	0.0459	0.0840	0.0784
27	0.0720	0.0510	0.0284	0.0476	0.0580	0.0495	0.0414	0.0635	0.0888
28	0.0651	0.0376	0.0186	0.0321	0.0549	0.0569	0.0280	0.0580	0.0784
29	0.0747	0.0412	0.0153	0.0360	0.0559	0.0419	0.0313	0.0333	0.0504
30	0.0673	0.0489	0.0150	0.0226	0.0621	0.0287	0.0137	0.0280	0.0346
31	0.0452	0.0370	0.0050	0.0146	0.0277	0.0256	0.0125	0.0176	0.0236
32	0.0401	0.0246	0.0026	0.0120	0.0095	0.0184	0.0129	0.0150	0.0103
33	0.0302	0.0173	0.0012	0.0076	0.0060	0.0073	0.0076	0.0101	0.0041
34	0.0196	0.0092	0.0024	0.0063	0.0024	0.0048	0.0063	0.0052	0.0047
35	0.0089	0.0117	0.0022	0.0034	0.0021	0.0027	0.0032	0.0025	0.0012
36	0.0081	0.0056	0.0024	0.0036	0.0006	0.0007	0.0018	0.0028	0.0005
37	0.0052	0.0046	0.0020	0.0014	0.0002	0.0009	0.0015	0.0030	0.0003
38	0.0008	0.0004	0.0018	0.0011	0.0005	0.0006	0.0018	0.0021	0.0013
39	0.0008	0.0000	0.0025	0.0014	0.0001	0.0000	0.0005	0.0006	0.0006
40	0.0006	0.0000	0.0007	0.0006	0.0002	0.0001	0.0002	0.0012	0.0000
41	0.0004	0.0000	0.0005	0.0005	0.0010	0.0006	0.0022	0.0006	0.0000
42	0.0002	0.0000	0.0005	0.0004	0.0004	0.0003	0.0013	0.0003	0.0002
43	0.0006	0.0004	0.0006	0.0002	0.0004	0.0009	0.0004	0.0003	0.0002
44	0.0008	0.0000	0.0004	0.0001	0.0005	0.0006	0.0007	0.0005	0.0000
45	0.0003	0.0000	0.0005	0.0000	0.0004	0.0004	0.0012	0.0004	0.0000
46	0.0002	0.0000	0.0002	0.0001	0.0007	0.0000	0.0001	0.0000	0.0000
47	0.0002	0.0000	0.0009	0.0001	0.0003	0.0003	0.0000	0.0000	0.0000
48	0.0005	0.0004	0.0002	0.0003	0.0001	0.0001	0.0000	0.0001	0.0000
49	0.0003	0.0004	0.0002	0.0000	0.0001	0.0001	0.0004	0.0000	0.0000
50	0.0002	0.0004	0.0001	0.0002	0.0001	0.0000	0.0000	0.0000	0.0000
51	0.0002	0.0002	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
52	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
53	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
54	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
55	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
56	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
57	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
58	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
59	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
60	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

Table A4: Proportional length compositions derived for the East Coast North Island (ECNI) inshore trawl surveys for which age compositions are not available. The survey years denote the years in the stock assessment model. For the ECNI surveys, the model years are equivalent to the year of the survey.

Length (cm)	1994	1995	1996
10	0.0000	0.0000	0.0000
11	0.0000	0.0000	0.0002
12	0.0000	0.0000	0.0000
13	0.0000	0.0000	0.0000
14	0.0000	0.0000	0.0000
15	0.0000	0.0000	0.0000
16	0.0000	0.0000	0.0006
17	0.0000	0.0000	0.0013
18	0.0000	0.0008	0.0062
19	0.0012	0.0010	0.0125
20	0.0031	0.0016	0.0078
21	0.0034	0.0023	0.0051
22	0.0018	0.0001	0.0041
23	0.0008	0.0011	0.0117
24	0.0053	0.0025	0.0161
25	0.0070	0.0046	0.0202
26	0.0118	0.0072	0.0292
27	0.0165	0.0071	0.0328
28	0.0194	0.0133	0.0433
29	0.0270	0.0259	0.0546
30	0.0342	0.0348	0.0798
31	0.0625	0.0504	0.0883
32	0.0856	0.0826	0.0844
33	0.0781	0.0985	0.0853
34	0.0996	0.0964	0.0720
35	0.1036	0.0805	0.0680
36	0.0925	0.0863	0.0612
37	0.0750	0.0734	0.0415
38	0.0689	0.0768	0.0432
39	0.0476	0.0604	0.0320
40	0.0448	0.0489	0.0284
41	0.0283	0.0379	0.0171
42	0.0295	0.0245	0.0154
43	0.0198	0.0215	0.0141
44	0.0111	0.0163	0.0076
45	0.0098	0.0169	0.0081
46	0.0035	0.0108	0.0019
47	0.0025	0.0083	0.0028
48	0.0021	0.0014	0.0012
49	0.0017	0.0035	0.0012
50	0.0008	0.0016	0.0003
51	0.0005	0.0007	0.0002
52	0.0005	0.0002	0.0000
53	0.0000	0.0000	0.0000
54	0.0000	0.0000	0.0000
55	0.0000	0.0000	0.0000
56	0.0000	0.0000	0.0000
57	0.0000	0.0000	0.0000
58	0.0000	0.0000	0.0000
59	0.0000	0.0000	0.0000
60	0.0000	0.0000	0.0000

APPENDIX 3. FISHERY AGE COMPOSITIONS

Table A5: Proportional age compositions derived for the TAR 3 set net and trawl fisheries and Cook Strait trawl fishery (both sexes combined). The years denote the years in the stock assessment model.

Age	TAR 3 Set Net				TAR 3 Trawl				Cook
(years)	2010	2011	2014	2015	2010	2011	2014	2015	2014
1	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
2	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
3	0.000	0.000	0.000	0.000	0.056	0.010	0.091	0.041	0.006
4	0.018	0.192	0.062	0.013	0.389	0.673	0.360	0.669	0.028
5	0.308	0.203	0.215	0.225	0.342	0.235	0.440	0.135	0.301
6	0.368	0.421	0.113	0.373	0.152	0.047	0.026	0.082	0.076
7	0.186	0.137	0.435	0.046	0.040	0.010	0.028	0.006	0.222
8	0.071	0.011	0.042	0.226	0.007	0.001	0.005	0.019	0.073
9	0.026	0.015	0.064	0.039	0.001	0.004	0.007	0.005	0.048
10	0.003	0.007	0.010	0.026	0.000	0.002	0.006	0.008	0.070
11	0.004	0.000	0.005	0.002	0.004	0.001	0.001	0.006	0.041
12	0.000	0.002	0.003	0.007	0.001	0.001	0.003	0.002	0.020
13	0.002	0.000	0.002	0.010	0.003	0.002	0.003	0.003	0.017
14	0.004	0.003	0.000	0.004	0.002	0.004	0.001	0.003	0.006
15	0.000	0.001	0.006	0.005	0.001	0.004	0.003	0.001	0.013
16	0.000	0.001	0.003	0.000	0.000	0.000	0.002	0.002	0.014
17	0.000	0.002	0.009	0.002	0.000	0.002	0.006	0.002	0.009
18	0.000	0.002	0.005	0.002	0.000	0.000	0.002	0.003	0.020
19	0.004	0.000	0.005	0.000	0.000	0.000	0.006	0.002	0.008
20	0.000	0.000	0.000	0.002	0.002	0.002	0.002	0.003	0.006
21	0.000	0.000	0.000	0.004	0.000	0.000	0.001	0.001	0.002
22	0.000	0.000	0.002	0.002	0.000	0.000	0.003	0.002	0.006
23	0.000	0.002	0.000	0.000	0.000	0.000	0.000	0.002	0.004
24	0.000	0.000	0.003	0.002	0.000	0.000	0.002	0.002	0.002
25	0.000	0.002	0.000	0.003	0.000	0.000	0.000	0.000	0.000
26	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.001	0.000
27	0.004	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.000
28	0.000	0.000	0.005	0.000	0.000	0.000	0.000	0.001	0.000
29	0.000	0.000	0.000	0.002	0.000	0.000	0.000	0.000	0.000
30	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.002
31	0.002	0.000	0.003	0.000	0.000	0.001	0.000	0.000	0.000
32	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.001	0.000
33	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
34	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.003
35+	0.000	0.000	0.009	0.002	0.000	0.000	0.000	0.000	0.000

Table A6: Proportional age compositions derived for the trawl fisheries in the Bay of Plenty, TAR 2 and east Northland (both sexes combined). The age compositions from TAR 2 and the Bay of Plenty are aggregated in the years when sampling occurring in both areas. The years denote the years in the stock assessment model.

Age	BPLE	TAR 2	TAR 2/BPLE combined			ENLD	
(years)	2008	2010	2011	2014	2015	2014	2015
1	0.000	0.000	0.000	0.000	0.000	0.000	0.000
2	0.014	0.000	0.000	0.000	0.000	0.000	0.000
3	0.000	0.052	0.006	0.023	0.027	0.000	0.000
4	0.305	0.104	0.134	0.084	0.131	0.008	0.014
5	0.775	0.254	0.168	0.334	0.209	0.060	0.063
6	0.382	0.253	0.230	0.083	0.360	0.082	0.176
7	0.145	0.147	0.193	0.302	0.060	0.229	0.070
8	0.131	0.092	0.103	0.056	0.124	0.127	0.196
9	0.074	0.030	0.067	0.042	0.029	0.093	0.084
10	0.026	0.014	0.027	0.020	0.017	0.066	0.082
11	0.039	0.011	0.012	0.010	0.010	0.049	0.055
12	0.048	0.009	0.009	0.012	0.011	0.042	0.057
13	0.012	0.012	0.005	0.001	0.008	0.042	0.042
14	0.014	0.009	0.013	0.004	0.003	0.019	0.022
15	0.000	0.004	0.006	0.003	0.000	0.012	0.004
16	0.000	0.000	0.006	0.004	0.002	0.014	0.011
17	0.014	0.000	0.008	0.004	0.002	0.025	0.007
18	0.000	0.006	0.002	0.004	0.001	0.043	0.010
19	0.007	0.003	0.002	0.003	0.001	0.026	0.023
20	0.000	0.000	0.002	0.002	0.000	0.024	0.020
21	0.014	0.000	0.001	0.002	0.002	0.003	0.014
22	0.000	0.000	0.006	0.000	0.000	0.016	0.014
23	0.000	0.000	0.000	0.000	0.000	0.001	0.005
24	0.000	0.000	0.000	0.000	0.000	0.004	0.006
25	0.000	0.000	0.000	0.000	0.002	0.005	0.007
26	0.000	0.000	0.000	0.002	0.001	0.002	0.003
27	0.000	0.000	0.000	0.002	0.000	0.004	0.002
28	0.000	0.000	0.000	0.000	0.000	0.002	0.010
29	0.000	0.002	0.000	0.000	0.000	0.000	0.006
30	0.000	0.000	0.000	0.000	0.000	0.000	0.000
31	0.000	0.000	0.000	0.000	0.000	0.000	0.000
32	0.000	0.000	0.000	0.000	0.000	0.000	0.001
33	0.000	0.000	0.000	0.000	0.000	0.000	0.000
34	0.000	0.000	0.000	0.000	0.000	0.000	0.000
35+	0.000	0.000	0.000	0.000	0.000	0.001	0.000

APPENDIX 4. CPUE INDICES

Table A7: Recent CPUE indices included in the final set of stock assessment models.

Year	TAR3-BT	TAR3-SN	TAR2BPLE-BT	ENLD-BT
1990	1.057	1.249	1.081	
1991	1.185	1.222	0.944	
1992	1.305	1.364	0.805	
1993	0.808	1.085	0.818	
1994	0.819	0.748	0.833	1.393
1995	0.923	1.165	0.904	0.940
1996	1.169	1.018	0.974	1.340
1997	1.168	1.027	1.054	1.529
1998	1.116	1.061	0.966	1.255
1999	0.924	1.065	1.279	1.083
2000	1.557	0.912	1.250	0.940
2001	1.230	1.020	1.384	0.961
2002	1.152	1.493	1.635	1.217
2003	0.873	1.266	1.494	1.096
2004	0.683	1.107	1.480	1.057
2005	0.701	0.942	1.107	1.180
2006	0.799	0.953	0.958	1.098
2007	1.011	0.768	0.806	0.769
2008	0.886	0.762	0.866	0.896
2009	0.804	0.948	0.954	1.095
2010	0.695	0.839	0.852	0.956
2011	1.012	0.786	0.707	0.804
2012	0.842	1.113	0.707	0.713
2013	0.893	0.813	0.855	0.843
2014	1.050	0.745	0.737	0.637
2015	1.208	0.687	0.922	0.426
2016	1.133	0.842	0.860	0.774

Table A8: Nominal CPUE indices from the trawl fisheries in TAR 2 (Vooren 1973) and TAR 3 (Sullivan 1981) during the early period of the fishery. * CPUE indices not included in assessment models.

Year	TAR 2	TAR 3
1961	0.950	-
1962	0.875	-
1963	0.675	162
1964	0.625	279
1965	0.675	179
1966	0.775	289
1967	0.700	65*
1968	0.600	58*
1969	0.475	75*
1970	0.615	104
1971	-	154
1972	-	149
1973	-	90

APPENDIX 5. MODEL LIKELIHOODS

Table A9: Total objective function values for each component of the model likelihoods for the main model options.

Model option	Total	Likelihood component					
		Indices	Length	Age	Recruitment	Priors	Penalties
1Region_Start1975	-105.47	-152.78	20.16	33.23	-8.72	1.85	0.80
1Region_Start1932	-120.94	-167.73	20.13	33.42	-8.76	1.90	0.10
3Region_Start1975	-43.08	-141.51	24.70	67.50	-5.33	3.62	7.93

Table A10: Individual likelihood components for each of the sets of CPUE indices and trawl survey abundance indices included in each of the main model options.

Model option	Total	Recent CPUE indices				Trawl surveys			Early CPUE indices	
		TAR3-BT	TAR3-SN	TAR2BPLE-BT	ENLD-BT	ECSI W	ECSI S	ECNI	TAR 2	TAR 3
1Region_Start1975	-152.78	-39.23	-37.47	-37.32	-27.74	-7.67	1.05	-4.40		
1Region_Start1932	-167.73	-39.23	-37.50	-37.04	-27.57	-7.62	1.12	-4.40	-11.09	-4.39
3Region_Start1975	-141.51	-36.38	-37.55	-33.92	-26.06	-6.56	3.49	-4.53		

Table A11: Individual likelihood components for each of the sets of age composition data included in each of the main model options.

Model option	Total	Commercial fishery					Trawl survey		
		TAR3-BT	TAR3-SN	TAR2BPLE-BT	ENLD-BT	Cook-BT	ECSI W	ECSI S	JC1987
1Region_Start1975	33.23	3.71	8.19	3.46	3.10	0.93	7.65	2.57	1.62
1Region_Start1932	33.42	3.70	8.16	3.42	3.05	0.89	7.67	2.59	1.89
3Region_Start1975	67.50	16.02	7.25	5.12	5.59	9.37	12.86	4.03	6.22

APPENDIX 6. LIKELIHOOD PROFILES

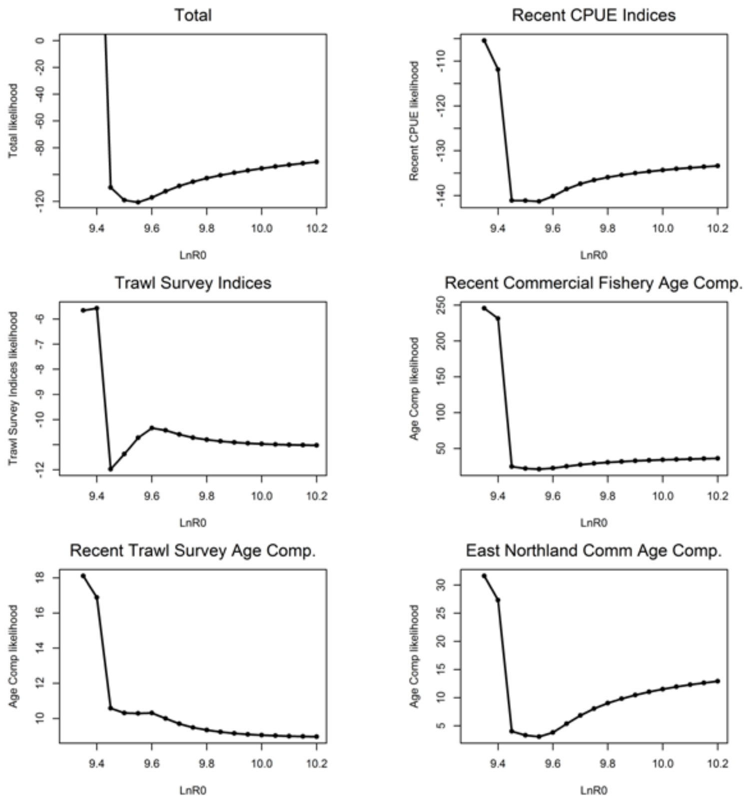


Figure A1: Likelihood profiles for the *LnR0* parameter of the *1Region_Start1932* model for the total likelihood and individual data components.

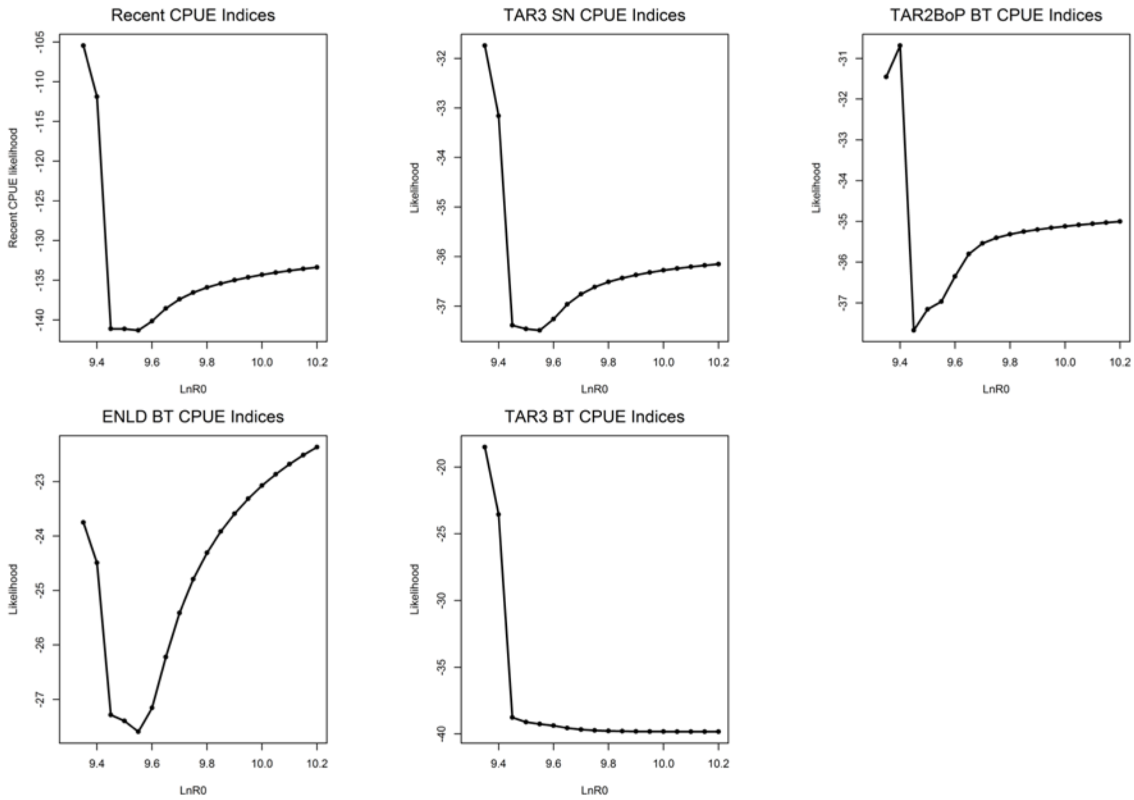


Figure A2: Likelihood profiles for the *LnR0* parameter of the *1Region_Start1932* model for the individual recent CPUE indices and the combined likelihood profile for the four series.

APPENDIX 7. MCMC DIAGNOSTICS

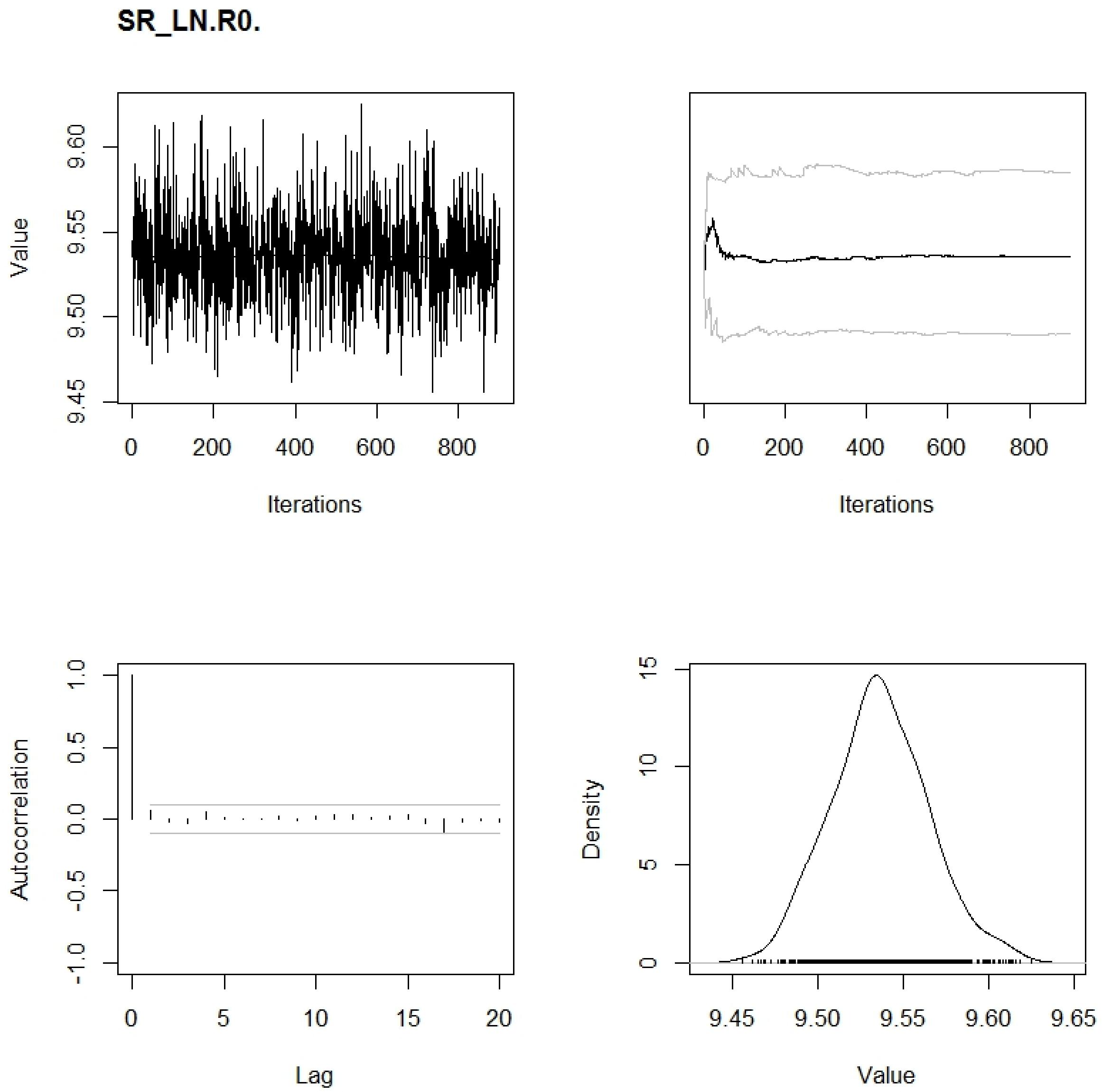


Figure A3: Diagnostics for the *LnR0* parameter estimates from the MCMCs from the *1Region_Start1975* model.

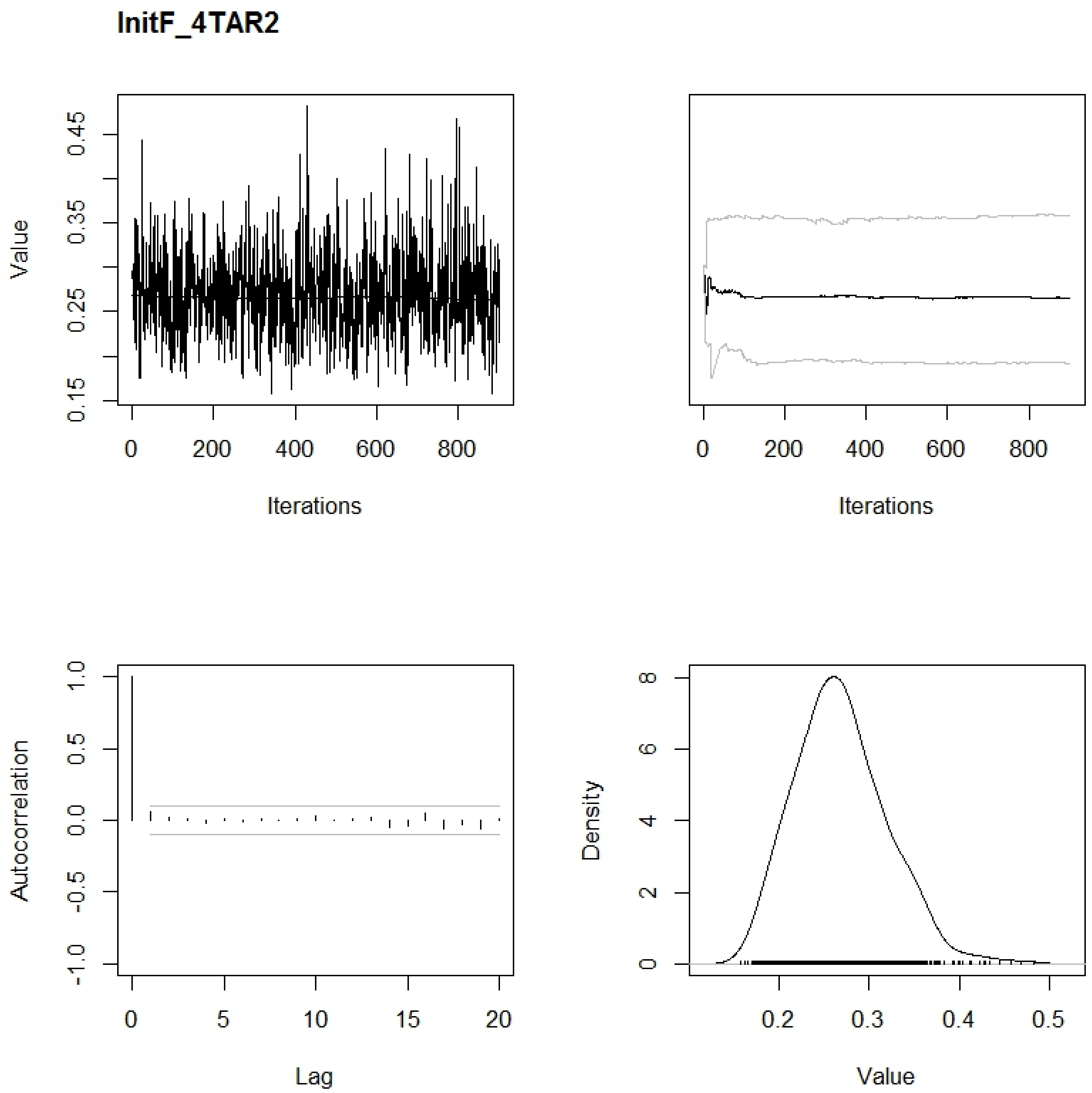


Figure A4: Diagnostics for the TAR2-BT *Initial F* parameter estimates from the MCMCs from the *1Region_Start1975* model.

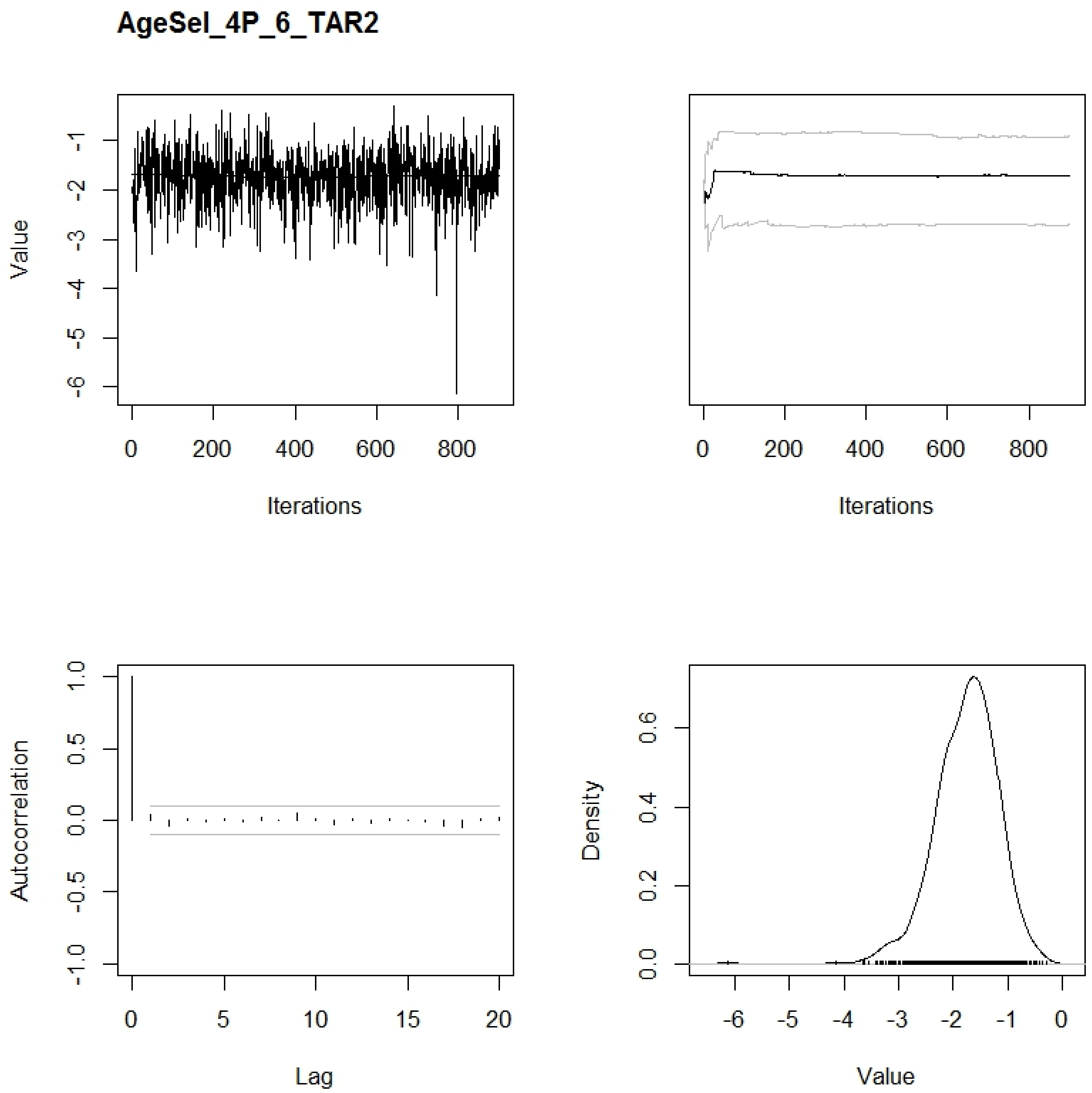
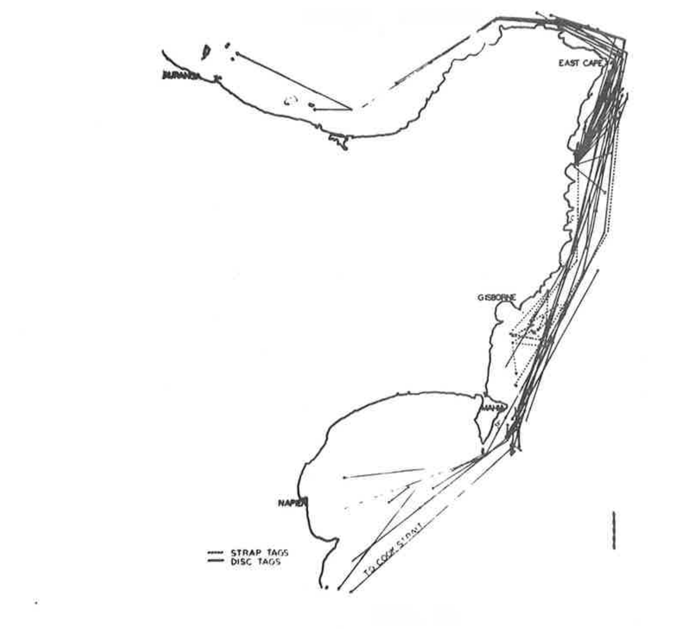


Figure A5: Diagnostics for the TAR2-BT double normal selectivity parameter *p6* parameter estimates from the MCMCs from the *1Region_Start1975* model.

APPENDIX 7. MOVEMENTS OF TARAKIHI FROM EARLY TAGGING STUDIES



From McKenzie (1961)

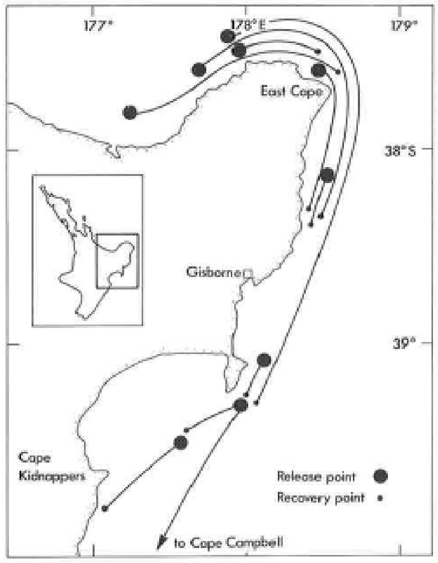
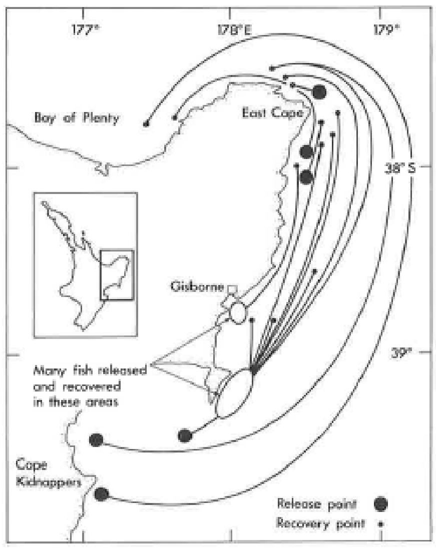


Fig. 15: Movements of tarakihi tagged in the East Cape area: above, fish tagged in spring and early summer; below, fish tagged in summer and autumn.



From Crossland (1982)