Stock assessment of Queensland east coast school mackerel (*Scomberomorus queenslandicus*)

2019

Queensland Government

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Executive summary

School mackerel is a pelagic species forming two populations (stocks) along the east Queensland coastline. The stocks separate between Ayr and Proserpine, and are generally distributed in nearshore waters.

School mackerel are fast growing and highly fecund reaching sexual maturity at one year (46–51 cm total length for females and 40–46 cm total length for males). Current minimum legal size is 50 cm total length.

Average harvests between 2015-16 and 2017-18 were about 18 tonnes (t) per year for the north-east stock and 97 t per year for the south-east stock. The average harvest shares for the north-east stock were 33% or 6 t commercial and 67 per cent or 12 t recreational. For the south-east stock, the average harvest shares were 83% or 81 t commercial and 17 % or 17 t recreational.

There has been no previous stock assessment for school mackerel.

This stock assessment used an age structured model with a yearly time step and length based selectivity. Only the south-east stock was considered for assessment as harvests for the north-east stock were small. Data inputs included total harvest, standardised catch rates and age and length structures. The south-east coast stock model uses data from the 1988-89 to 2017-18 fishing years (comprising commercial harvest (1988-89 to 2017-18); recreational harvest (1994-95 to 2013-14); length structures (2014-15 to 2017-18) and age-length information (1991-92 to 1994-95)).

Model analyses suggested that biomass declined from the mid-2000s to around 65% of unfished biomass in 2017-18. Maximum sustainable yield (MSY) was estimated at 104–119 t per year, and the yield consistent with a biomass ratio of 60% was estimated at 84–95 t.

The purpose of this report was to estimate biological reference points and harvest targets for management. Results presented in this report reflect the quality and quantity of data available. The time series of harvests modelled may be underrepresented, causing an overestimate of the biomass ratio. Results reflect a low level of confidence, and precautionary interpretations are warranted.

It should be noted that length data obtained from different sources revealed that the available biological data used to determine parameters for the model may not be representative of the stock. Quality age-length monitoring data is required for future assessments to ensure confidence in results.

Indicator	North-east stock	South-east stock
Current exploitable biomass (relative to unfished)	N/A	65%
MSY exploitable biomass (relative to unfished)	N/A	36%
MSY harvest	N/A	104–119 t
Current harvest	4 t commercial, 12 t recreational	67 t commercial, 17 t recreational
Harvest proportions	23% commercial, 77% recreational	80% commercial, 20% recreational
Equilibrium 60% biomass harvest	N/A	84–95t
Harvest to build to 60% biomass	N/A	Already above 60%
Time to build to 60% biomass	N/A	Already above 60%

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1 Introduction

School mackerel (*Scomberomorus queenslandicus*) (Munro 1943) are tropical–subtropical pelagic fish endemic to Australasian waters. Their distribution around Australia is between Coffs Harbour on the east coast and the Abrolhos Islands on the west coast north to south-east regions of Papua New Guinea (Collette and Russo 1984; Kailola et al. 1993).

School mackerel are generally distributed in nearshore waters of less than 100 m depth and found in similar areas to the other lesser mackerel species, including spotted mackerel (*Scomberomorus munroi*) and grey mackerel (*Scomberomorus semifasciatus*) (GBRMPA 2012). School mackerel are more commonly found in nearshore, turbid waters, while spotted mackerel are generally more common in offshore, open waters (Munro 1943; Collette and Russo 1984).

The species forms multiple stocks around tropical Australia, on the east coast there are two distinct stocks, determined through tag-recapture and otolith elemental data (Cameron and Begg 2002; Ward and Rogers 2003). The north-east stock ranges from the Gulf of Carpentaria to Ayr (-10.5°S to -19.50°S), while the south-east stock ranges from the Whitsunday Islands to the Gold Coast (-20.50°S to -28.50°S). Between the two stocks is a mixing zone (Cameron and Begg 2002; Ward and Rogers 2003).

Tag-recapture data suggests that school mackerel only move small distances, with 85% of recaptures less than 50 km (Begg et al. 1997). The largest school mackerel movement observed was a distance of 270 km, occuring when the fish had been at liberty for 199 days (Begg et al. 1997).

Growth of school mackerel occurs quickly in early years. Female school mackerel grow to a greater length, but at a slower rate, than males (Cameron and Begg 2002). They can obtain a maximum size of approximately 95 cm fork length (Fisheries Queensland Fishery Monitoring data) and reach 10 years of age (Cameron and Begg 2002).

Spawning generally occurs between October and January, where they produce pelagic eggs and sperm that mix and are dispersed through water currents (Cameron and Begg 2002). Females generally reach maturity at 40–45 cm fork length (46–51cm total length), while males generally mature at 35–40 cm fork length (40–46 cm total length) (Cameron and Begg 2002).

Fishing for school mackerel on the east coast increased in the early 1960s. Annual harvests built to maximum levels in the early 2000s, reaching a total harvest of just over 200 t. In 2013, total harvest dropped to approximately 100 t and has remained at this level since. For the north-east stock, approximately two thirds of the total harvest is taken by recreational fishers, while the other third is taken by the commercial sector. The vast majority of commercial harvest is caught from the south-east stock which comprises around 83% commercial and 17% recreational fishing. The majority of commercial harvest uses gill nets, with only a small line component.

School mackerel do not form large, easily targeted aggregations and hence may be more resilient to fishing pressure than other *Scomberomorus* species such as spotted mackerel (Begg 1996, 1998).

In 2018, the Qld Department of Agriculture and Fisheries commissioned a stock assessment for school mackerel. This report informs on estimates of sustainable harvests that will maintain the Qld fishery and support implementation of Queensland's *Sustainable Fisheries Strategy 2017–2027* (the Strategy).

This assessment aims to determine the status of the south-east stock on the Queensland east coast. Harvests for the north-east stock are small and hence there is insufficient data to enable its status to be assessed. The report informs estimates of sustainable harvests to ensure the fishery operates at sustainable levels, including commercial, recreational and charter sectors.

2 Methods

2.1 Harvest

2.1.1 Data sources

Processing of the data for stock model inputs involved the use of Queensland Department of Agriculture and Fisheries (DAF) commercial logbook data to determine catch rates. Additional recreational data was sourced to create a total annual harvest (combining commercial and recreational harvests). The data were used according to their quality, quantity and temporal-spatial resolution. Preparation of harvest data was compiled in fishing (or financial) years to remain consistent with the assessment of other mackerel species.

2.1.2 Management and research history

The minimum legal size for school mackerel is 50 cm total length. In 2017-18, there were 30 licenses operating in the north-east stock and 123 licenses operating in the south-east stock. Table 1 outlines the management changes that have taken place in the fishery.

Table 1: Management changes applied to school mackerel in Queensland waters. Source: Queensland state government legislation.

Year	Fisheries Management measure
1877–1974	Numerous measures relating to fishing gear and practices; e.g., mesh size, net length, allowed species, closed seasons, powers of inspectors.
1976 (16 Dec)	Minimum legal size 45 cm TL (*Fisheries Act 1976 (No 80)*).
1988 (1 Jan)	Commercial logbook database began.
1988	Net use by non-commercial fishers banned.
1990	Repeal of section 35 of the *Fishery and Industry Organisation and Marketing Act* making the sale of recreational harvests unlawful.
1993 (1 Jul)	Minimum legal size 50 cm TL (*Fishing Industry Organisation and Marketing Amendment no. 235, 1993*).
1995 (1 Jul)	Confirm minimum legal size 50 cm TL (*Fisheries Regulation no. 325, 1995*).
1998 (12 Jan)	Declaration of 16 Dugong Protection Areas and resultant netting area restrictions.
2004 (1 Jul)	Representative Area Protection (RAP) and comprehensive rezoning of whole GBR; proportion of GBR closed to fishing increases from about 5% to 33%.
2009 (1 Mar)	*Marine Parks (Moreton Bay) Zoning Plan 2008* closed 16% of the area of Moreton Bay Marine Park to all fishing, plus a further 8% to net fishing.
2009	Recreational in-possession (bag) limit of 10 school mackerel per fisher.
2012 (Nov)	East Coast Inshore Fin Fish Fishery net fishing buyback scheme primarily focused on N1 and N2 licences.
2015 (1 Nov)	Net-free fishing zones in Cairns, Mackay and Rockhamption introduced.
2016	Net Fishing Buyback scheme offered to commercial fishers who held a commercial fishing boat licence with a fishery symbol N1 or N2.

During the history of the fishery, research projects have been undertaken to improve understanding of the species' biology, population structure and movement (Table 2).

Table 2: History of school mackerel research.

Year	Author	Research
1943	Munro	Taxonomic review of Australian *Scomberomorus* species, including school mackerel, describing nomenclature, distribution and morphological features.
1982	Okera	Observations on the maturation of school mackerel in northern Australian waters.
1996	Begg	Species coexistence and management of school mackerel and spotted mackerel in Queensland east coast waters.
1997	Begg et al.	Movement of school mackerel in Australian east coast waters.
1998	Begg	Reproductive biology of school mackerel in Queensland east coast waters.
1998	Begg et al.	Stock discrimination of school mackerel and spotted mackerel Australian east coast waters.
1998	Begg and Hopper	Feeding patterns of school mackerel in Queensland east coast waters.
1998	Begg et al.	Genetic variation and stock structure of school mackerel in northern Australian waters.
1998	Begg and Sellin	Age and growth of school mackerel in Queensland east coast waters.
2002	Cameron and Begg	Fisheries biology and interaction in the northern Australian small mackerel fishery.
2003	Ward and Rogers	Review of current and future research needs for mackerel (*Scomberomorus*) in northern Australian waters.

2.1.3 Commercial harvest data

The east Australian school mackerel population stretches along the coast, with most landings occurring along the south-east coastline. Figure 1 displays the cumulative geographic distribution of school mackerel commercial harvest as reported in logbooks since 1988-89. Stock boundaries shown, indicate that the majority of school mackerel harvested are from the south-east Queensland stock (Figure 1).

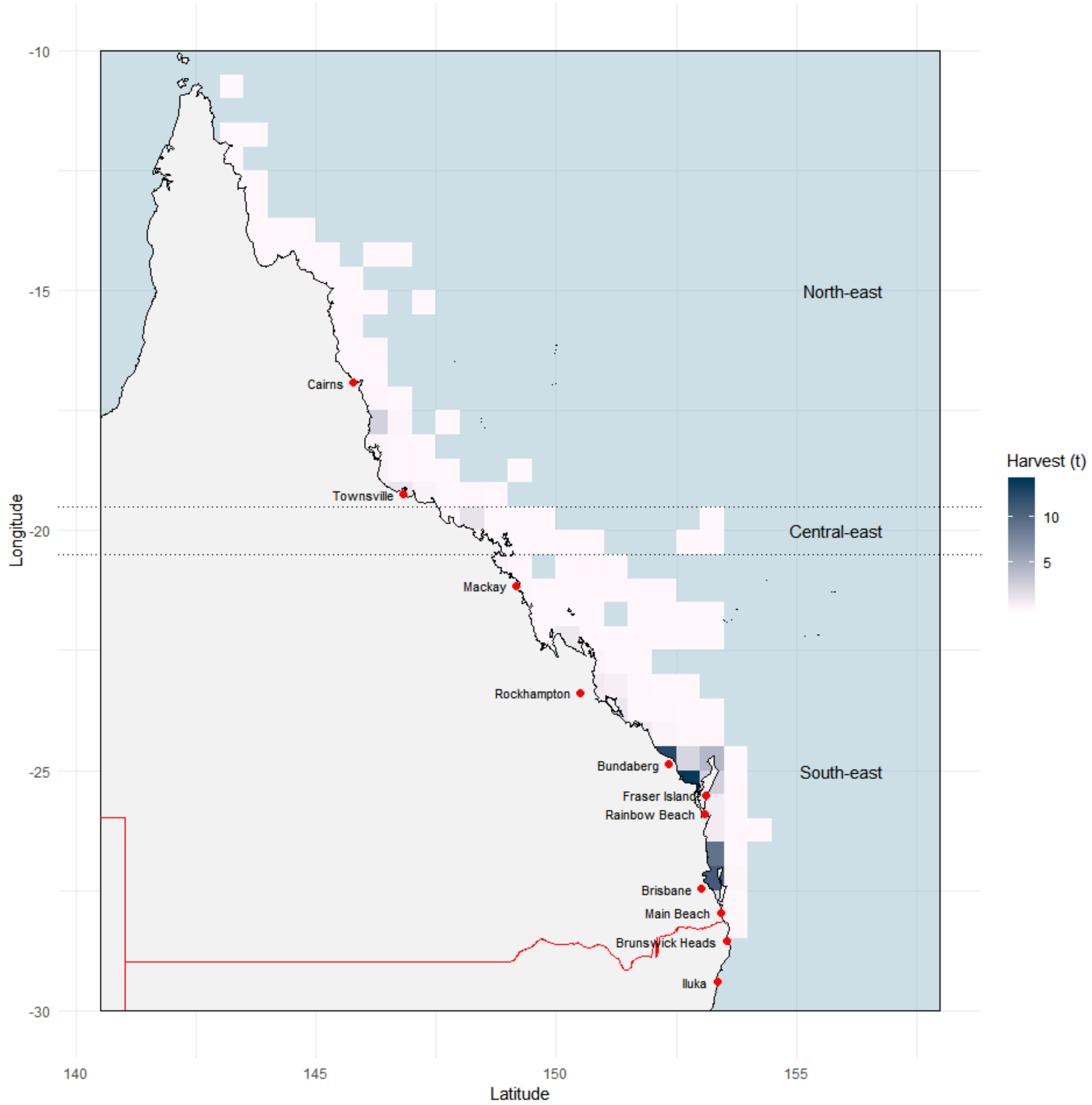

Figure 1: Geographic distribution of commercial school mackerel landings along the Australian east coast based on data July 1988–June 2018. Horizontal dotted lines indicate stock boundaries with the central-east stock playing the role of a mixing region between the north-east and south-east stocks.

Commercial harvest data were sourced from the Queensland Fisheries compulsory logbook records, which began in 1988. These data contained daily entries where fishers recorded their harvest of school mackerel in kilograms, the geographic location of each catch, the catch method used and net size information. Some of these records covered more than one day though this was uncommon.

The requirement to specify school mackerel as the species caught was not introduced into logbook reporting until 2004 (Fisheries Queensland, pers. comm.). Due to this investigation into 'unspecified mackerel' in the logbook records was performed. It was determined that unspecified mackerel harvests were consistent from 1988 to 2018 and the relative proportion was small. It was decided to exclude 'unspecified mackerel' from this assessment.

The Queensland Fish Board annual catch data was not used due to a lack of species resolution.

The annual commercial catch of school mackerel is shown in Figure 2.

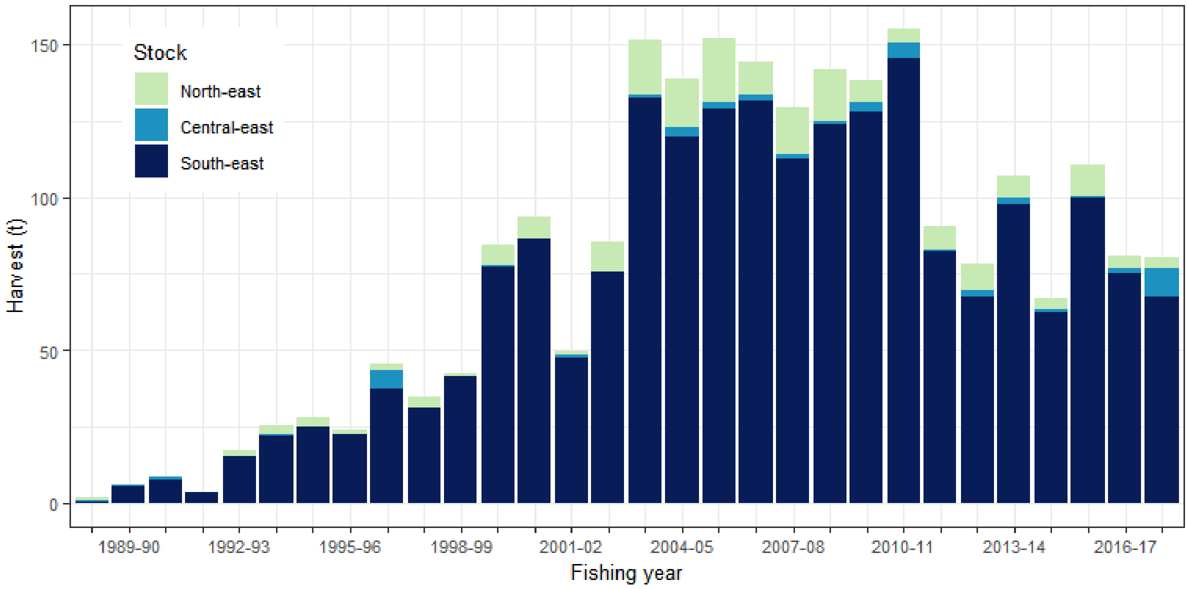

Figure 2: Annual school mackerel commercial harvest data in eastern Queensland for 1988-89 to 2017-18

The main fishing methods used to harvest school mackerel were line and net More than half the annual commercial harvest is taken by net fishing. Figure 3 displays the annual commercial harvest for each fishing method.

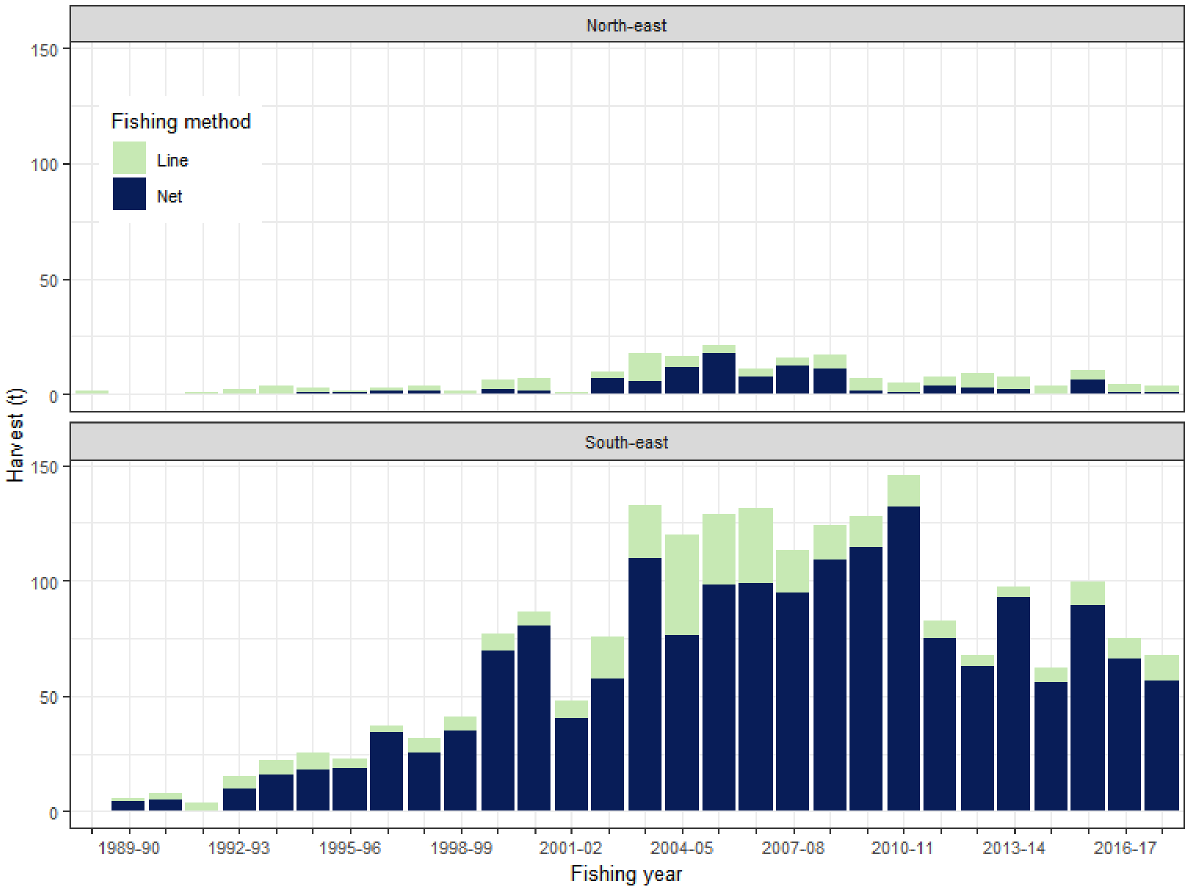

Figure 3: Annual school mackerel commercial harvest data in eastern Queensland for each fishing method and stock, 1988-89 to 2017-18

A breakdown of the median school mackerel catch for each month, stock and fishing method can be seen in Figure 4. This figure displays a peak in harvest sizes over August-September for the south-east stock and July–August for the north-east stock.

As an illustration of the ranges of daily catches of school mackerel that have been taken in each stock, histograms of the daily catch size taken for each fishing method in a fisher-day are presented in Appendix A.

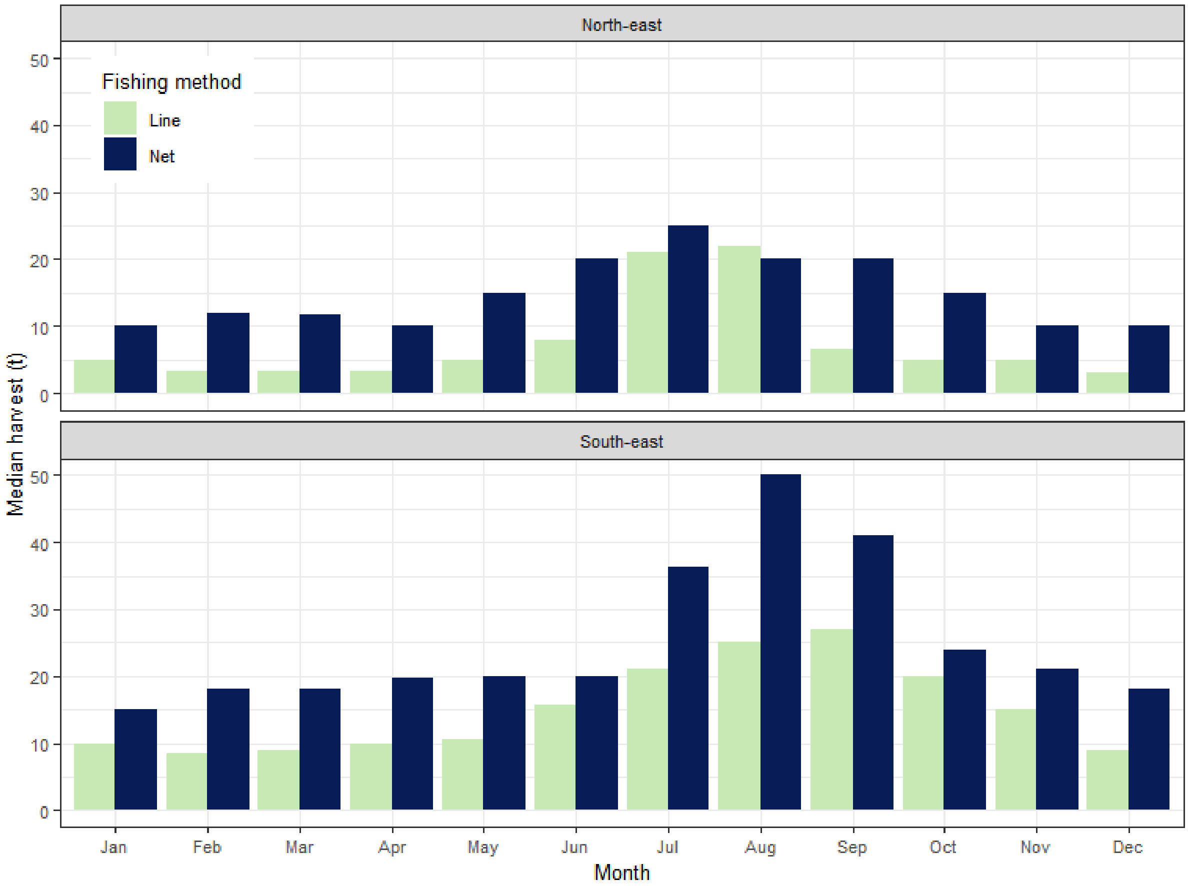

Figure 4: Median school mackerel harvest size for each month and fishing method. Based on data collected during the period 1988-89 to 2017-18

2.1.4 Recreational harvest data

Recreational catches of fish in Queensland have been measured by State-wide diary surveys since 1995. These included:

- A 1995 daily diary survey aimed to estimate the recreational harvest of small mackerel species between December 1994 and November 1995 by resident recreational fishers with boats in Queensland waters (Cameron and Begg 2002).
- Surveys conducted by Fisheries Queensland, known as RFISH, in 1997, 1999, 2002 and 2005 (Higgs 1999, 2001; Higgs et al. 2007; McInnes 2008).
- An Australian national survey (the National Recreational and Indigenous Fishing Survey, NRIFS) was conducted in 2000 (actually May 2000 to April 2001) and used different methodology. It was funded by the Australian Government's Fisheries Research and Development Corporation (FRDC, project number 99/158) (Henry and Lyle 2003).

- The NRIFS methodology was adopted by Fisheries Queensland for the State-wide surveys which ran from October 2010 to September 2011, known as SWRFS (State-Wide Recreational Fishing Survey) (Taylor et al. 2012) and again in 2014.

Surveys conducted in 1995, 2001, 2011 and 2014 had more effective follow-up contact procedures with diarists resulting in less dropout of participants compared to the other survey years using RFISH methodology (Fisheries Queensland, pers. comm.). Therefore, for surveys conducted in 1997, 1999, 2002 and 2005 using RFISH methodologies, estimates were adjusted using the ratio method (Leigh et al. 2017). These adjustments made the estimates of fish catches more comparable between surveys.

The resulting annual recreational harvest of school mackerel in Queensland is shown in Figure 5. Note that recreational surveys do not always align with a calendar or fishing year.

Due to insufficient information, recreational data was not used to calculate catch rates in this assessment.

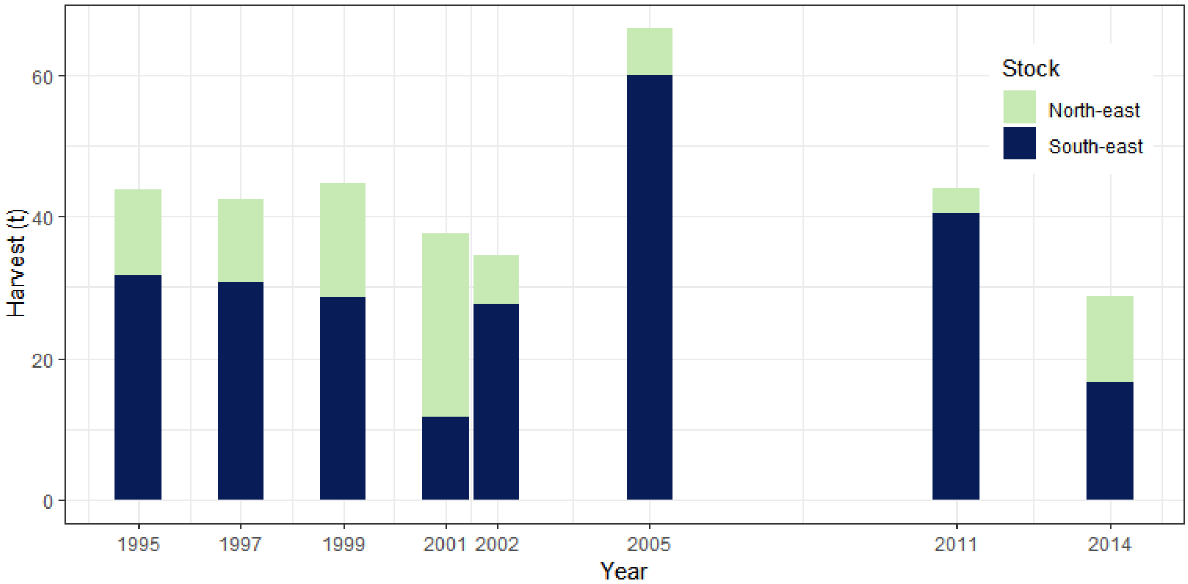

Figure 5: Annual school mackerel recreational harvest data in eastern Queensland for 1988-89 to 2017-18. Data was collected in fish numbers and then an average weight of 2 kg per fish was applied. Data collected in 1996-97, 1998-99, 2001-02 and 2004-05 had been adjusted using methods in Leigh et al. (2017) to account for different survey methodologies.

The annual recreational harvest of school mackerel for the south-east stock was then extrapolated to encompass a broader range of years (1961–2018). The resulting extrapolation is shown in Section 3.1.1.

2.1.5 Charter harvest data

Charter harvest data were sourced from the Queensland Fisheries records which began in 1988. These data contained daily entries in which fishers recorded their harvest of school mackerel in kilograms, the geographic location of each catch, the catch method used and net size information. Some of these records covered more than one day, although this was uncommon.

The annual charter harvest of school mackerel is shown in Figure 6.

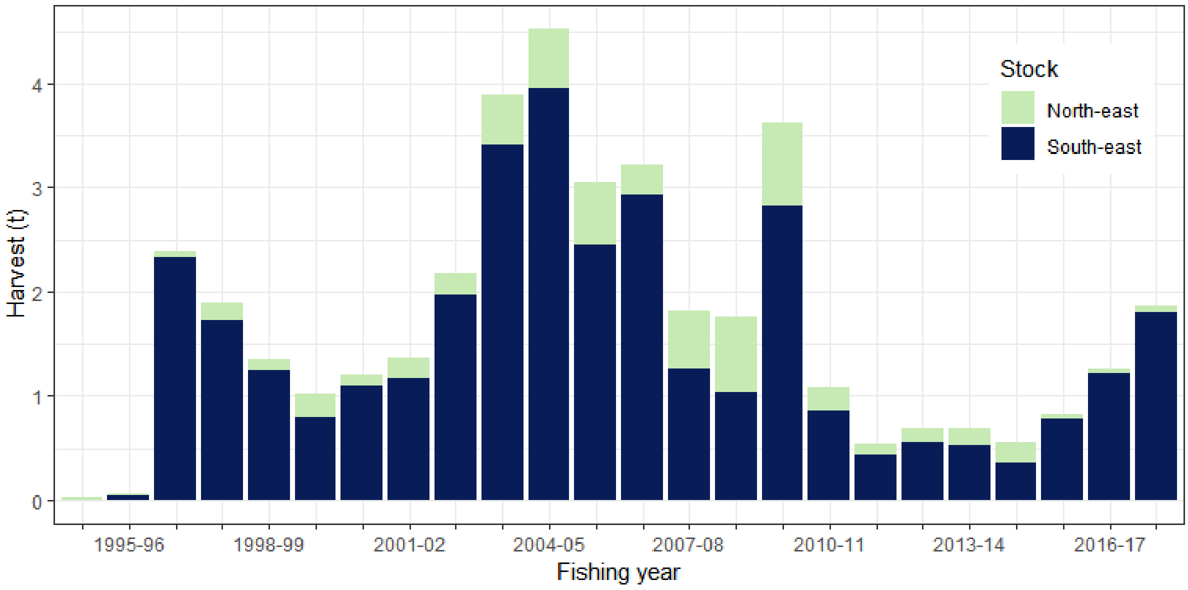

Figure 6: Annual school mackerel charter harvest data in eastern Queensland for 1988-89 to 2017-18

2.2 Standardised catch rates

The quantity of harvest (and hence data records) for the north-east stock led to the inability to determine appropriate catch rates and the decision to only perform population modelling for the south-east stock in this assessment.

Standardised catch rates were determined for each fishing method (line and net) using data based on daily fishing records. Zero catch values included in the analysis were determined by using records for school mackerel fishers who instead caught other associated species on a given day using the same methodology outlined in Leigh et al. (2017).

An exploratory analysis of fishers who had at least 100 kg total catch of line caught school mackerel provided the average catch weights of school mackerel per fisher-day listed in Table 3.

Table 3: School mackerel catches associated with catches of other taxa caught by line. The final column lists the average catch of school mackerel per nonzero record of the taxon in the first column.

	Records	Total harvest (t)	Total school mackerel (t)	Av school mackerel (kg)
School mackerel	11207	311.2	311.2	27.8
Cobia	5299	139.0	15.3	2.9
Spanish mackerel	20403	1094.1	37.8	1.9
Spotted mackerel	10106	437.1	72.2	7.1
Trevally	4510	199.2	17.7	3.9

An exploratory analysis of fishers who had at least 500 kg total catch of net caught school mackerel provided the average catch weights of school mackerel per fisher-day listed in Table 4.

Table 4: School mackerel catches associated with catches of other taxa caught by net. The final column lists the average catch of school mackerel per nonzero record of the taxon in the first column.

	Records	Total harvest (t)	Total school mackerel (t)	Av school mackerel (kg)
School mackerel	27494	1717.0	1717.0	62.5
Grey mackerel	13791	851.3	271.1	19.7
Spotted mackerel	6925	845.1	122.6	17.7
Shark	28825	2100.7	442.9	15.4

Data was extensively pre-processed into a single catch observation for each fisher-day combination, with processing including:

- records for the same fisher fishing on the same day were combined into a single record
- when a fisher fished in multiple locations on the same day, the location with the greatest catch was used
- records with missing data in required fields were omitted
- fishers who fished in only one year were omitted

Various metrics of catchability were used to standardise catch rates, including the spatial-temporal patterns of exploitation associated with the aggregation patterns of this species (Walters 2003; Carruthers et al. 2011; Marriott et al. 2017). The term 'catch rate' has been used to mean standardised catch rate throughout this assessment. Standardisation components for fish catchability included:

- Spatially weighted catch rates through time across each region. This aimed to reduce bias introduced by systematic changes in the spatial distribution of fishing (Carruthers et al. 2011).
- Lunar phases, wind speeds and wind direction on each day, which can influence fish catchability.
- The seasonality of catch rates were modelled using sinusoidal data to identify the time of year.

Fisheries Queensland sourced wind direction and strength data from the Bureau of Meteorology (BOM, Australian Government). The wind data was collected from 76 representative coastal weather stations along the Queensland east coast. The recorded measures of wind speed (km hour-1) and direction (degrees for where the wind blew from) were converted to an average daily reading based on recordings between 3am and 3pm for each grid square defined in the Qld commercial fishing logbooks. Missing values were imputed from measurements at the next nearest location. From this data the north-south (NS) and east-west (EW) wind components were calculated. Squared wind components were also included for each wind direction variable, resulting in a greater proportional weighting for higher wind speeds.

The lunar phase (luminance) was a calculated measure of the moon cycle with values ranging between 0 = new moon and 1 = full moon for each day of the year (Courtney et al. 2002; Begg et al. 2006; O'Neill and Leigh 2006). The luminance measure (lunar) followed a sinusoidal pattern and was copied and advanced 7 days (≈ ¼ lunar cycle) into a new variable to quantify the cosine of the lunar data (O'Neill and Leigh 2006). The two variables were modelled together to estimate the variation of harvest according to the moon phase (i.e. contrasting waxing and waning patterns of the moon phase).

The analysis was performed using generalised linear models (GLM) based on a Poisson distribution with a log link, in which the dispersion parameter was estimated. These were implemented in the R programming environment (R Core Team (2018), version 3.5.2) using the quasi-Poisson glm function in the Stats package.

The initial catch rate analysis performed, determined that the lunar, seasonal and wind variables were not significant and hence these were omitted from the catch rate standardisation. Note that the 'Fisher', 'Year', 'Month' and 'Region' variables were factors and hence were not analysed as continuous variables.

The final models passed to the glm function for the line and net standardisations were:

Line

Daily Catch ~ *Constant* + *Fisher* + *Year* + *Month* + *Region* + *Month* × *Region*

Net

Daily Catch ~ *Constant* + *Fisher* + *Year* + *Month* + *Region* + *Month* × *Region* + *Mesh size* + *Net length*

2.3 Biology

2.3.1 Data sources

School mackerel biological data were sourced from Cameron and Begg (2002) which consisted of fish age, length, weight and sex information. Preparation of biological data was compiled in fishing (or financial) years to remain consistent the assessment of other mackerel species. Sampling was opportunistically taken from commercial and recreational harvests during 1991–1995. Note that during this period a minimum legal size change from 45 cm to 50 cm total length was introduced.

Fishery Monitoring data (Fisheries Queensland), giving length measurements of recreationally caught fish over the period 2015-16 to 2017-18 was also available. This data was sourced predominantly from recreational boat ramp surveys. These data are presented in Figure 7.

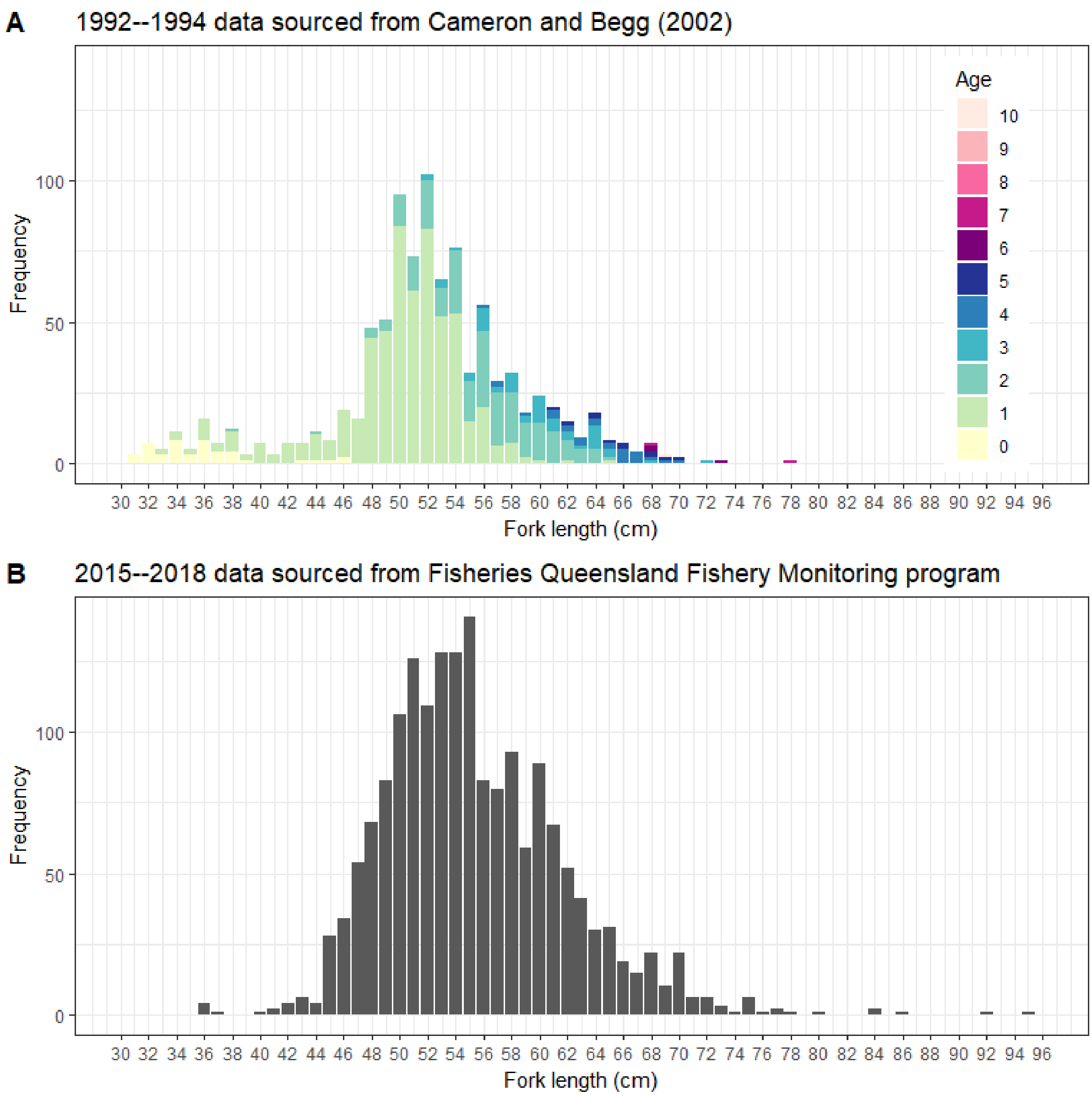

Figure 7: A: Biological sampling of age-length information for school mackerel in south-east Queensland during 1991-92 to 1994-95. Source: Cameron and Begg (2002). Minimum legal size (MLS) changed from 45 cm to 50 cm in July 1993. B: Fishery Monitoring length data for recreationally caught school mackerel in south-east Queensland during the period 2014-15 to 2017-18. Source: Fisheries Queensland Fishery Monitoring program. (Note that MLS 45 cm total length ≈ 39 cm fork length and MLS 50 cm total length ≈ 44 cm fork length.)

Age-length structures presented in Figure 7A show a young demographic of fish that are primarily one year old (pale green). Sampling protocols were not consistent for this study (Fisheries Queensland, pers. comm.). Note the presence of zero year olds in the undersized length bins. Data for 1991-92 consisted solely of zero year old fish and though shown here, this year was excluded from the model inputs.

Length structures displayed in Figure 7B detail a length structure with an upper length limit 18cm longer than the earlier data set obtained by Cameron and Begg (2002) and a larger average length. Data collection methods differed between the two programs. Very few fish in the data set are below minimum legal size as the data was collected using fishery dependent sampling techniques.

Overall, Figure 7 highlights that school mackerel harvest is dominated by 45–70 cm fork length fish.

More comprehensive detail of age and length structures that were used as model inputs can be found in Section 3.1.3 and Section 3.1.4. These structures also state the total sample size in each year.

2.3.2 Biological growth

Biological growth parameters for the following equations were calculated using fish age-length data sourced from Cameron and Begg (2002) and are detailed in Table 5.

Table 5: Equations for fish growth

Biological growth equations	
von Bertalanffy	
$L_a = L_0 e^{-\kappa a} + L_\infty (1 - e^{-\kappa a})$	(1)
Allometric growth	
$W_a = \alpha {L_a}^{\beta}$	(2)

Equation 1 determines the mean length of each individual at a given age (von Bertalanffy 1938). Parameters were fitted using a nonlinear least square regression (nls). Due to lack of quality data and the similarity between male and female age structures, only one set of parameters was calculated.

Allometric growth (Equation 2) parameters were fitted using a simple regression model (linear model, lm) on the log scale. There was little difference noted between the fit for males and females and hence generic parameters were determined.

The models used to determine these parameters were implemented in the R programming environment (R Core Team 2018) using the nls and lm functions in the Stats package.

2.4 Population model

A population dynamic model was fitted to the data to determine the number of school mackerel in each year and each age group from the start of fishing in 1960-61 to the current year (2017–18). Model equations are given in Section 2.4.2. The model included only one fishing sector with commercial (line and net) and recreational fishing group together.

Initially an age structured model with age based selectivity was attempted. However, the model did not perform well and gave poor fits to data and MCMC simulations. Length based selectivity was added to the model, which improved the performance of the model.

The model was coded in parallel in two different software packages: ADMB (Fournier et al. 2012) (version 12) and R (R Core Team 2018) (version 3.5.2). The ADMB version was intended to find maximum likelihood estimates and then perform Markov chain Monte Carlo (MCMC) to provide random samples of possible parameter values. The R version was written both as a check on the ADMB version and as a way to summarise results.

2.4.1 Model assumptions

1. The weight and fecundity of a fish were parametric functions of age. For simplicity in describing the model, we assume that fecundity is proportional to weight.
2. The proportion of mature fish depends on age but not length.
3. The proportion of fish vulnerable to fishing depends on length but not time.
4. Fishing takes place in a pulse in the middle of each year, over a short enough period that natural mortality, although it happens all year round, can be neglected over the duration of the fishing season; i.e., the fishery is a type I fishery in the terminology of Ricker (1975).
5. The instantaneous natural mortality rate M does not depend on age or length.
6. The fishery began from an unfished state prior to 1960-61.

2.4.2 Population dynamics

The population model (Table 6) indexes the population matrix by time (t) and age (a), (Table 6).

Table 6: Population equations

Population Dynamics

Logistic selectivity function

$$S_l = 1/(1 + \exp[-\ln(19)(l - L_{50})/(L_{95-50})]) \qquad (3)$$

where L_{50} is an estimated parameter representing the length at 50% selectivity and L_{95-50} an estimated parameter, represents the additional length between 50% and 95% selection.

As the population model requires age-based selectivity, this length-based selectivity was converted to age-based selectivity with the use of a distribution of length at age ($K_{a,l}$). This was calculated by the methods in Leigh et al. (2017) section 4.3.1.

$$S_a = \sum_l S_l \; K_{a,l} \qquad (4)$$

Initial recruitment

$$R_0 = B_0^{Sp} / \left(f_{a_{max}} \frac{\exp(-M a_{max})}{1 - \exp(-M)} + \sum_{a=0}^{a_{max}-1} f_a \exp(-Ma) \right) \qquad (5)$$

where B_0^{Sp} and M are estimated parameters and f_a denotes maturity × weight at age for female fish as a proxy for fecundity.

Initial age structure

$$N_{0,a} = \begin{cases} R_0 & \text{for } a = 0 \\ N_{0,a-1} \exp(-M) & \text{for } a = 1,2,\ldots,a_{max}-1 \\ N_{0,a-1} \exp(-M)/(1-\exp(-M)) & \text{for } a = a_{max} \end{cases} \qquad (6)$$

Vulnerable biomass

$$B_t^V = \sum_a N_{t,a} \exp(-\frac{1}{2}M) \; S_a \; w_a \qquad (7)$$

where w_a denotes weight at age for both genders.

Harvest rate

$$H_t = C_t / B_t^V \quad (8)$$

Spawning biomass

$$B_t^{Sp} = \sum_a f_a \, N_{t,1,a} \qquad \text{for } t > 0 \quad (9)$$

Beverton-Holt recruitment

$$R_t = \frac{4hR_0 B_t^{Sp}}{B_0^{Sp}(1-h) + B_t^{Sp}(5h-1)} \times \exp(d_t) \quad (10)$$

where h is the estimated Beverton-Holt steepness parameter and d_t represent estimated random recruitment deviations (Beverton and Holt 1957; Goodyear 1977).

Age structure

$$N_{t,a} = \begin{cases} R_t & \text{for } a = 0, t > 0 \\ N_{t-1,a-1}\exp(-M)(1 - H_{t-1}\, S_{a-1}) & \text{for } a = 1,2,\dots, a_{max} - 1,\ t > 0 \\ N_{t-1,a-1}\exp(-M)(1 - H_{t-1}\, S_{a-1}) & \\ \qquad +N_{t-1,a}\exp(-M)(1 - H_{t-1}\, S_a) & \text{for } a = a_{max}, t > 0 \end{cases} \quad (11)$$

Mid-year age structure

$$N_{t,a}^{mid} = N_{t,a}\exp(-\frac{1}{2}M)\sqrt{1 - H_t S_a} \quad (12)$$

Predicted mid-year vulnerable biomass

$$B_t^{V\,mid} = \sum_a N_{t,a}^{mid}\ w_a \quad (13)$$

This equation is used to match catch rates in the negative log likelihood Equation 17.

Predicted sample numbers at length

$$\hat{P}_{t,l}^{LF} = \frac{S_l\ \sum_a N_{t,a}\, K_{a,l}}{\sum_l \left(S_l\ \sum_a N_{t,a}\, K_{a,l}\right)} \quad (14)$$

Note that $\hat{P}_{t,l}^{LF}$ will sum to 1.

Predicted sample numbers at age

$$\hat{P}_{t,a}^{AF} = \frac{S_a N_{t,a}}{\sum_a \left(S_a N_{t,a}\right)} \quad (15)$$

Note that $\hat{P}_{t,a}^{AF}$ will sum to 1.

2.4.3 Matching predictions to data

Negative log-likelihood functions for calibrating population dynamics are shown below (Table 7). These functions describe the likelihood for matching predicted to observed data. The model optimisation procedure involved estimating the model parameters such that the sum of these negative log-likelihoods is minimised.

Many of the formulae below are taken from Leigh et al. (2017) section 4.5. Their nonstandard complexity made them differentiable with respect to model parameters, as required by the ADMB software which uses automatic differentiation to efficiently minimise the negative log-likelihood.

Table 7: Negative log-likelihood equations used in the model

Negative log-likelihood functions

Recruitment deviations

$$\ell^{(RD)} = y^R \left[\ln(\tilde{\sigma}^{RD}) + \frac{1}{2}(\hat{\sigma}^{RD})^2/(\tilde{\sigma}^{RD})^2\right] \quad (16)$$

where y^R denotes the number of recruitment deviation years -1

$$(\hat{\sigma}^{RD})^2 = \left(\sum_t d_t^2\right)/y^R$$

$$\tilde{\sigma}^{RD} = \sqrt{\frac{1}{2}((\sigma_{min}^{RD})^2 + (\sigma_{max}^{RD})^2 + B_1 - B_2)}$$

$$B_1 = \sqrt{\left((\hat{\sigma}^{RD})^2 - (\sigma_{min}^{RD})^2\right)^2 + 4\delta^2(\sigma_{min}^{RD})^4}$$

$$B_2 = \sqrt{\left((\sigma_{max}^{RD})^2 - (\hat{\sigma}^{RD})^2\right)^2 + 4\delta^2(\sigma_{min}^{RD})^4}$$

where $\delta > 0$ is a smoothness parameter that took the value 0.1.

σ_{min}^{RD} and σ_{max}^{RD} are lower and upper bounds and the square-root formulae are to make it differentiable, as required by ADMB.

Standardised catch rates

$$\ell_s^{CR} = y_s^{CR} \times \ln(\hat{\sigma}_s^{CR}) + y_s^{CR}/2 \quad (17)$$

where y_s^{CR} is the (number of years in catch rate series s) -1.

$$\hat{\sigma}_s^{CR} = \frac{1}{2}\left(\sqrt{A_1/y_s^{CR}} + 1\right) + \sqrt{\frac{1}{4}\left(\sqrt{A_1/y_s^{CR}} - 1\right)^2 + \phi}$$

where $\phi = 0.01$ is a smoothing constant.

$A_1 = \sum_t \left(\left(\ln\left(c_{s,t}/B_{s,t}^{V_{mid}}\right) - A_2\right)/\sigma_{s,t}^{CR}\right)^2$,

where $c_{s,t}$ represents the input catch rate for each year and catch rate series. $\sigma_{s,t}^{CR}$ is the standard error for $c_{s,t}$ from the GLM catch-rate analysis, which is used as a lower bound for the standard deviation of the corresponding model catch rate.

$A_2 = \sum_t\left(\ln\left(c_{s,t}/B_{s,t}^{V_{mid}}\right)/(\sigma_{s,t}^{CR})^2\right) / \sum_t\left(1/(\sigma_{s,t}^{CR})^2\right)$ is a log-catchability parameter that converts between standardised catch rate and biomass.

Lengths

$$\ell^{(LF)} = \sum_t T_t^{LF} \; P_{t,l}^{LF} \ln\left(\hat{P}_{t,l}^{LF}\right), \qquad (18)$$

where T_t^{LF} is the total number of fish measured in year t,

$P_{t,l}^{AF}$ represents the input proportions at length indexed by year.

For theoretical justification of this method, see Cope et al. (2003).

Ages

$$\ell^{(AF)} = \sum_t T_t^{AF} \; P_{t,a}^{AF} \ln\left(\hat{P}_{t,a}^{AF}\right), \qquad (19)$$

where T_t^{AF} is the total number of fish aged in year t,

$P_{t,a}^{AF}$ represents the input proportions at age indexed by year.

For theoretical justification of this method, see Cope et al. (2003).

2.4.4 Model parameters

Model parameters used in the model are listed in Table 8.

The von Bertalanffy and allometric growth parameters were pre-calculated using data from Cameron and Begg (2002).

The model was run with parameters fixed as described in Table 8, however model runs were also undertaken where either h, M or both were fixed. The model was also tried with recruitment deviations (d_t) fixed at zero (switched off).

Table 8: Descriptions of fixed and estimated parameters in the model

Parameter	**Description**
Fixed (input)	
L_0	Fork length at age zero in von Bertalanffy function, see Equation 1
L_∞	Average maximum fork length in von Bertalanffy function, see Equation 1
κ	Growth rate in von Bertalanffy function, see Equation 1
α, β	Parameters in length weight relationship, see Equation 2
L_{95-50}	Difference between lengths at 95% and 50% selectivity, see Equation 3
Estimated	
M	Natural mortality rate
h	Beverton-Holt steepness parameter, see Equation 10
$\ln(B_0^{Sp})$	Natural log of the virgin spawning biomass
L_{50}	Length at 50% selectivity, see Equation 3
d_t	Log recruitment deviations used to adjust annual recruitment from the deterministic Beverton-Holt calculation

2.4.5 Model uncertainty

The ADMB version of the population model found maximum likelihood estimates and then performed Markov chain Monte Carlo (MCMC) to provide random samples of possible parameter values (Fournier et al. 2012) (version 12).

When MCMC analysis was performed, a total of 1.1 million simulations were run for each model scenario and saved every 100th simulation for a total of 11 000 simulations. Results from the first 1000 saved simulations were then excluded from mean, median and credible interval analysis.

This report was compiled using R markdown (Allaire et al. 2018). This enabled figures, tables and values to be automatically be updated when any change to the model or input data took place.

3 Results

Due to small harvests in the north-east stock, the stock model was only attempted for the south-east stock.

3.1 Model inputs

3.1.1 Reconstructed harvest

The annual catch of school mackerel for the south-east stock for each of the commercial, recreational and charter sectors were extrapolated to encompass a broader range of years (1960-61 to 2017-18). Three different extrapolated harvest scenarios were considered:

1. Harvest starting at zero in 1961 and increasing with the human population size until the start of the known data time series.
2. Scenario 1 but with 25 t harvest prior to 1988-89
3. Scenario 1 but with 50 t harvest prior to 1992-93

The resulting extrapolations are shown in Figure 8. Of note is that there was very little commercial harvest of school mackerel in the initial years of logbook reporting, hence the majority of the early 1990s harvest numbers comprised recreational fishing. While there is a division of commercial and recreational harvests shown here, both sectors were combined into a single harvest time series for use as a model input.

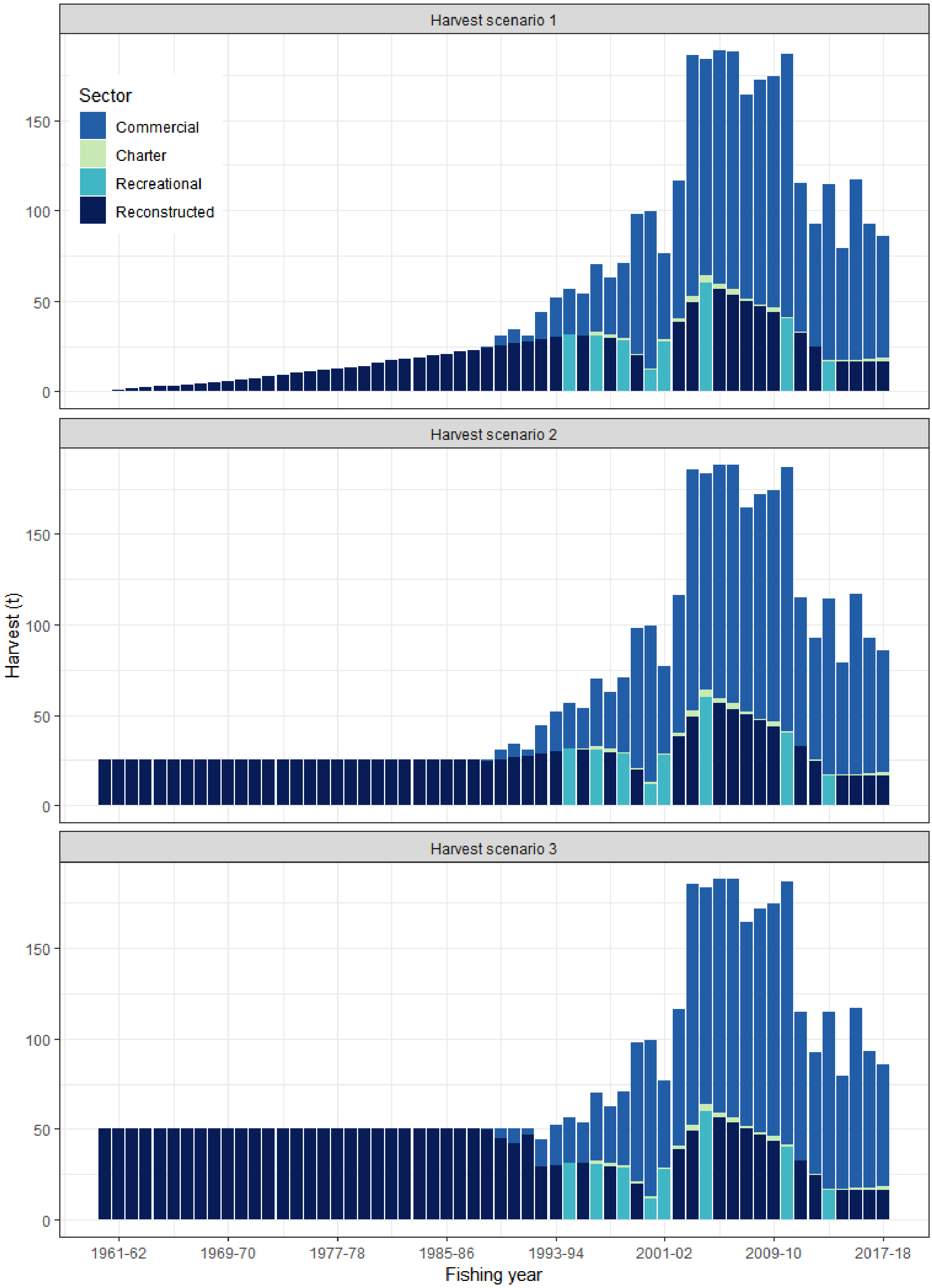

Figure 8: Extrapolated annual school mackerel harvest for 1960-61 to 2017-18 for use as model input. Recreational data was filled between data points as a ratio of end points and extended forward using data for last known year. Total harvest was projected backwards to 1961 under three different scenarios: 1. from 0 to earliest data point for each of recreational and commercial using Queensland human population proportions as a proxy, 2. scenario 1 but with 25 t harvest prior to 1988-99, 3. scenario 1 but with 50 t harvest prior to 1992-93.

3.1.2 Standardised catch rates

The main fishing methods used to harvest school mackerel in south-east Queensland are line and net. The net caught method accounts for more than half of the annual harvest as shown in Figure 3.

Both catch rates (line caught and net caught) are shown in Figure 9. Commercial logbook information was available from 1988-89 onwards, however catch rates shown here are for the 1992-93 fishing year onwards. The 1988-89 to 1991-92 catch rate years were excluded from analysis due to few data points in the early years of logbook reporting.

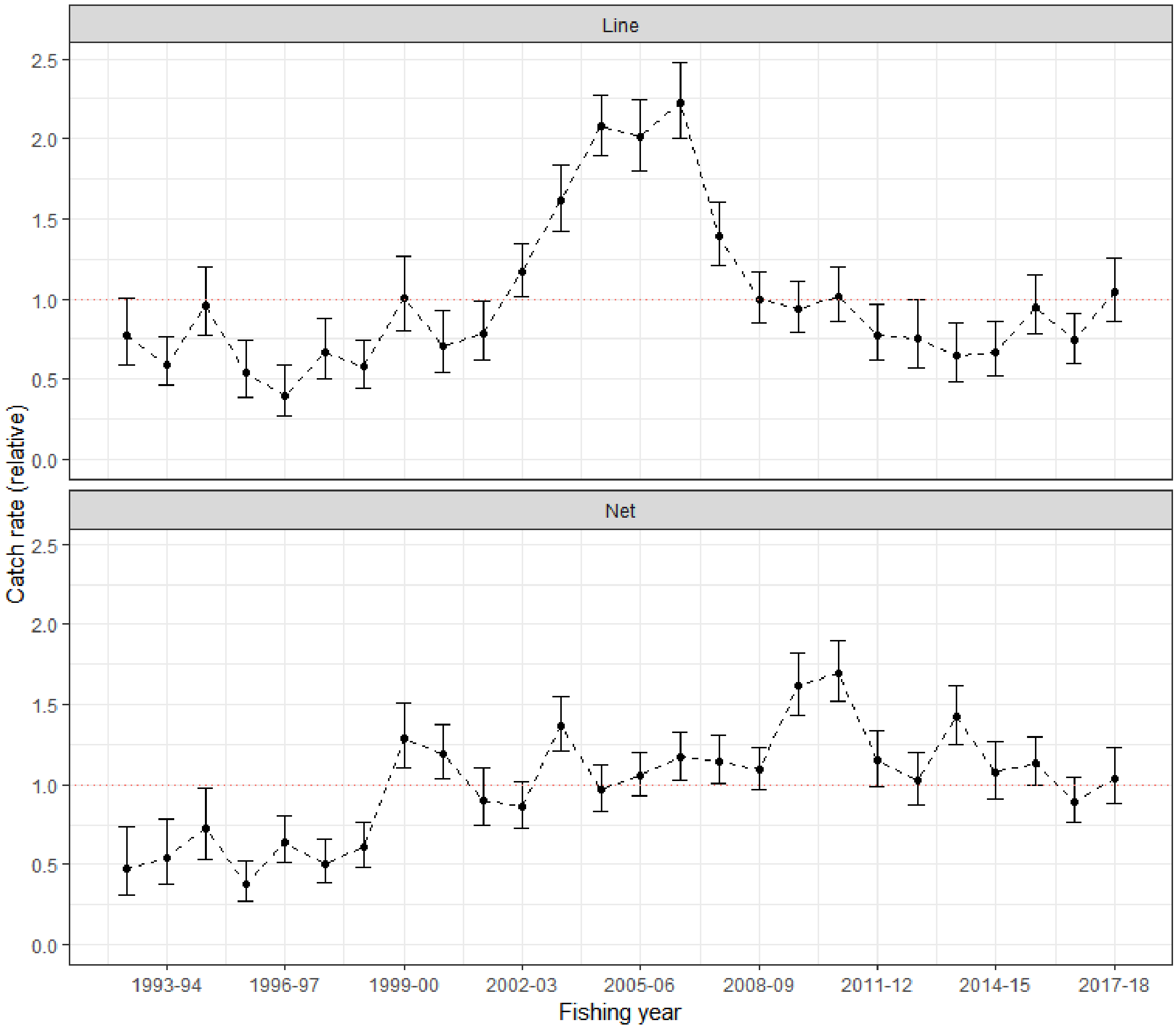

Figure 9: Standardised catch rates for both line and net fisheries with 95% confidence limits. The red dashed line represents the average of the time series.

There is a high peak shown in the line catch rate which rises from 2001-02 and peaks in 2006-07 this corresponds with the start of the period of high harvest (see Figure 8). The line catch rate then drops sharply in 2007-08 and continues to slowly decrease. This peak does not correspond with a peak in the net catch rate. The net catch rate has peaks at 1999-00 and again in 2010-11, with an overall increase over time.

A large proportion of the commercial harvest was caught by net (see, Figure 3), however total annual harvest (Figure 8) is around 20% recreational which is a predominantly line caught method.

Therefore, it was decided to include catch rates from both methods in the model (although line only and net only catch rates were also trialed).

3.1.3 Age structures

Figure 10 displays annual age structures for the south-east Queensland stock sourced from Cameron and Begg (2002). The 1991-92 sample size was small consisting solely of zero year old fish. It was determined that this sample was unsuitable for use as a model input.

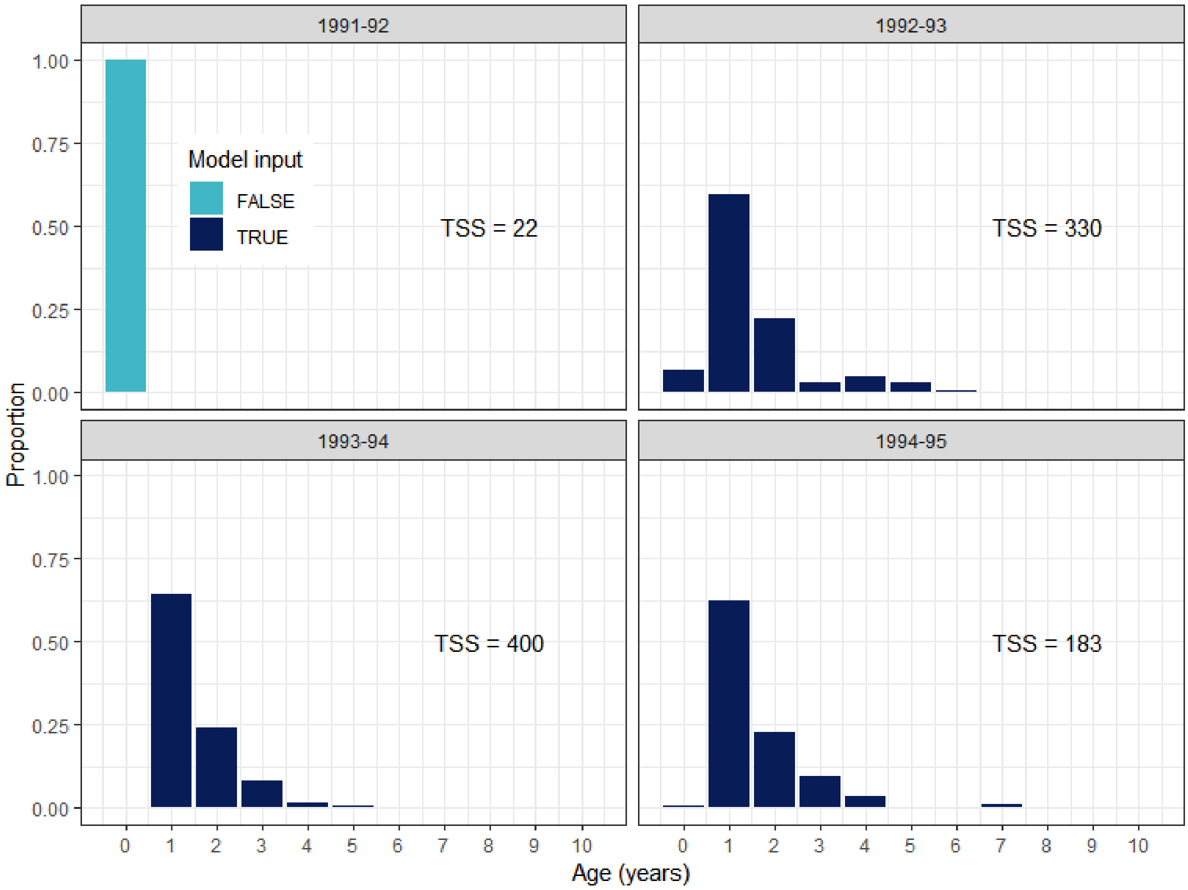

Figure 10: Age frequency distributions of school mackerel for the south-east Queensland stock (1992–1995). Samples shown in light blue were determined unsuitable for use as model inputs. Data source: Cameron and Begg (2002) The total sample size (TSS) is shown for each fishing year.

3.1.4 Length structures

Figure 11 displays annual length structures for the south-east Queensland stock. Length structures sourced from Cameron and Begg (2002) were small in size with no defined structure. Only the 1993-94 year from this data set was determined suitable for use as a model input.

Data collected by Fishery monitoring (Fisheries Queensland) contained larger sample sizes with a more defined structure and were deemed suitable for use as model inputs.

Length structures input to the model are shown in Figure 11.

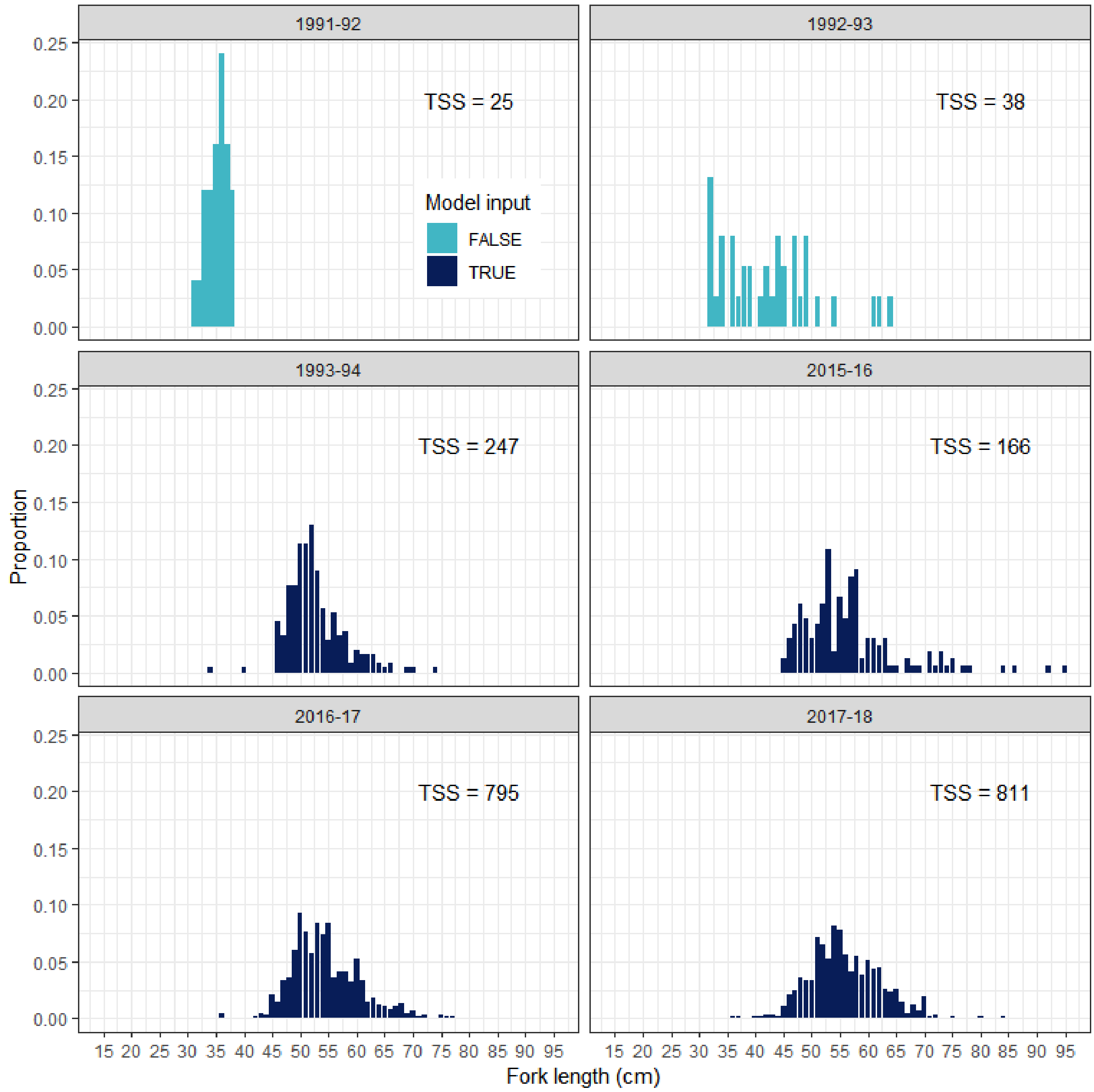

Figure 11: Length frequency distributions of school mackerel for the south-east Queensland stock. Samples shown in light blue were determined unsuitable for use as model inputs. Data sources: 1993-94 (Cameron and Begg 2002), 2015–2018 Fishery monitoring data (Fisheries Queensland). The total sample size (TSS) is shown for each fishing year.

3.1.5 Biological growth

Biological growth parameters were calculated using fish age-length data sourced from Cameron and Begg (2002). Due to small sample sizes and the similarity between male and female age structures (see Appendix C), only one set of parameters was calculated incorporating both sexes. Resulting plots and parameters can be found in Figure 12 and Table 9.

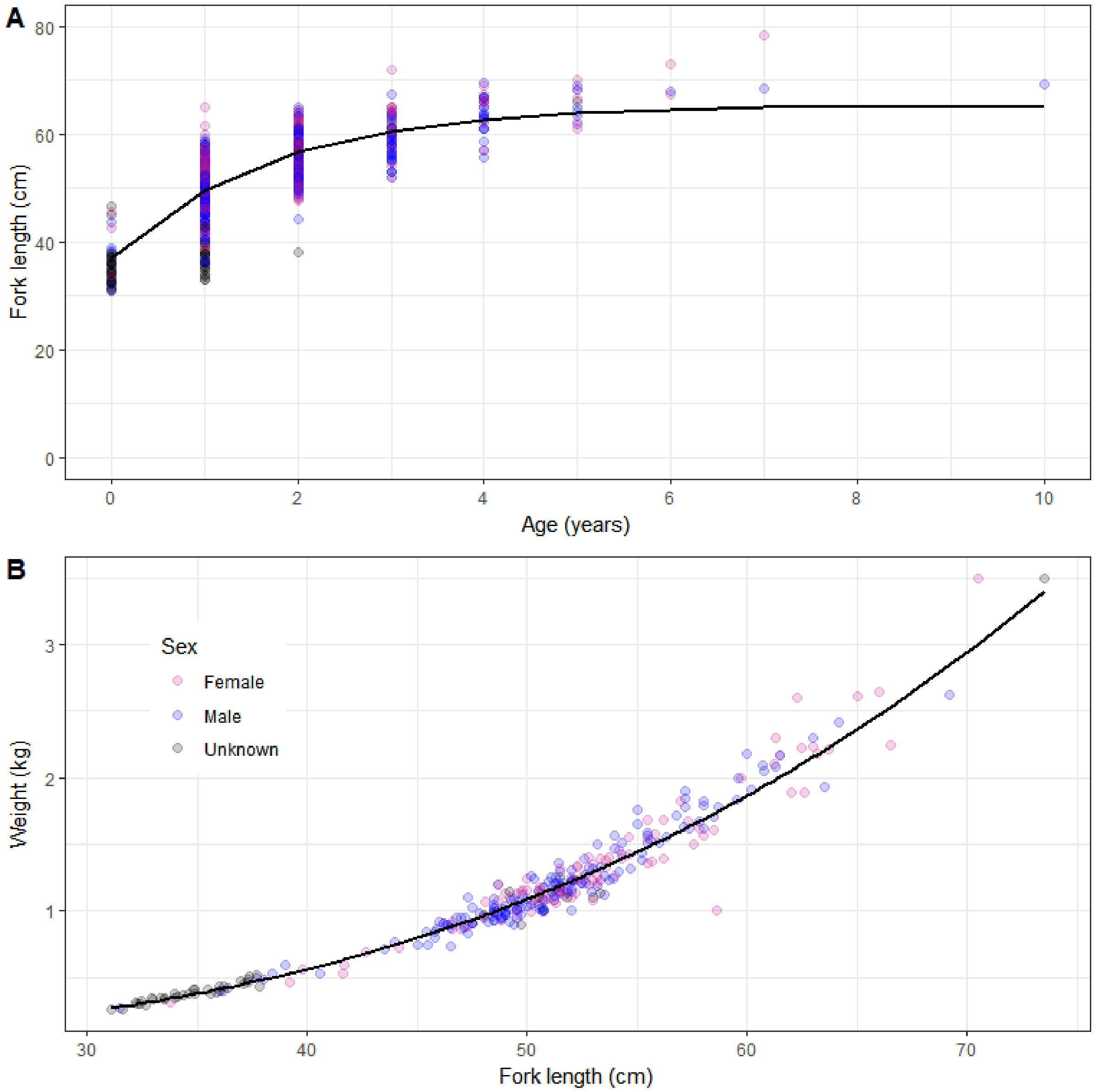

Figure 12: Biological growth curves for the south-east school mackerel stock. A: von Bertalanffy growth curve for length at age. B: allometric growth curve for weight at length. Data sourced from Cameron and Begg (2002)

Table 9: Model parameter values estimated from von Bertalanffy and allometric growth equations. Length parameters are measured in cm fork length. κ is measured in $year^{-1}$.

Parameter	L_0	L_∞	κ	α	β
Value	37.08	65.45	0.58	0.01	2.96
Standard error	1.6842	0.6834	0.0501	0.0011	0.0282

3.2 Model output

The stock model was run many times to identify key results for fisheries management. For each harvest scenario, attempts were made to estimate all parameters.

The model did not converge without the use of recruitment deviations. Without recruitment deviations, the model estimates a very high biomass to explain increasing catch rates during a period with a peak in the harvest time series, and the model does not converge to any plausible outcome. With recruitment deviations, the high peak in harvest is explained by high recruitment during those years, with the implication that this is due to favourable environmental or ecosystem conditions. Both commercial and recreational harvests peak at the same time which lends some evidence to this possibility (Figure 8).

The L_{95-50} parameter was fixed in the model. Early attempts to estimate this parameter often resulted in nonsensical values of both L_{50} and L_{95-50} and a large MCMC parameter space for each. A decision was made to fix this parameter at 1.5cm, which resulted in a more realistic estimation of the L_{50} parameter.

The Beverton-Holt steepness parameter h was then fixed, trying values in the range 0.25–0.85. These attempts, where successful, gave estimated values for M, $\ln(B_0^{Sp})$ and L_{50}. Attempts were also made to estimate h by fixing natural mortality M at values in the range 0.2–1.2.

An exploration into each harvest scenario can be found in Appendix D. From this exploration, two models have been chosen for presentation in this section using harvest scenario 3.

3.2.1 Parameters

Results from the stock model shown below have been determined using recruitment deviations from 1987-88 to 2017-18. This period encompasses available trends shown from catch rates, age structures (Cameron and Begg 2002) and length structures from Cameron and Begg (2002) and the Fisheries Queensland Fishery Monitoring data. Two different models are presented here with fixed M values of 0.56 and 0.59. Estimated parameters are shown in Table 10.

Table 10: Model parameter values. Length parameters are measured in cm fork length, M is measured in yr^{-1}. Fixed parameters are denoted with an asterisk.

M*	h	$\ln(B_0^{Sp})$	L_{50}	L_{95-50}*	Nll
0.56	0.79	13.13	46.53	1.5	493.33
0.59	0.78	12.97	46.55	1.5	485.53

Parameter serial plots and fits to catch rates, age and length structures are shown in Appendix E and Appendix F.

3.2.2 Biomass and recruitment

The biomass trajectory through time was determined as a proportion relative to an assumed unfished biomass prior to 1960-61. Figure 13 shows the exploitable biomass trajectory for each fixed value of M with its MCMC credible interval. The optimised trajectory displayed here shows the biomass through time created with the optimised parameters.

The optimal model outcome does not match fully with the MCMC results. The median and credible interval displayed are not based on a specific group of parameters but rather the median and credible interval outcome for each year and hence will be based on a different group of parameters each year.

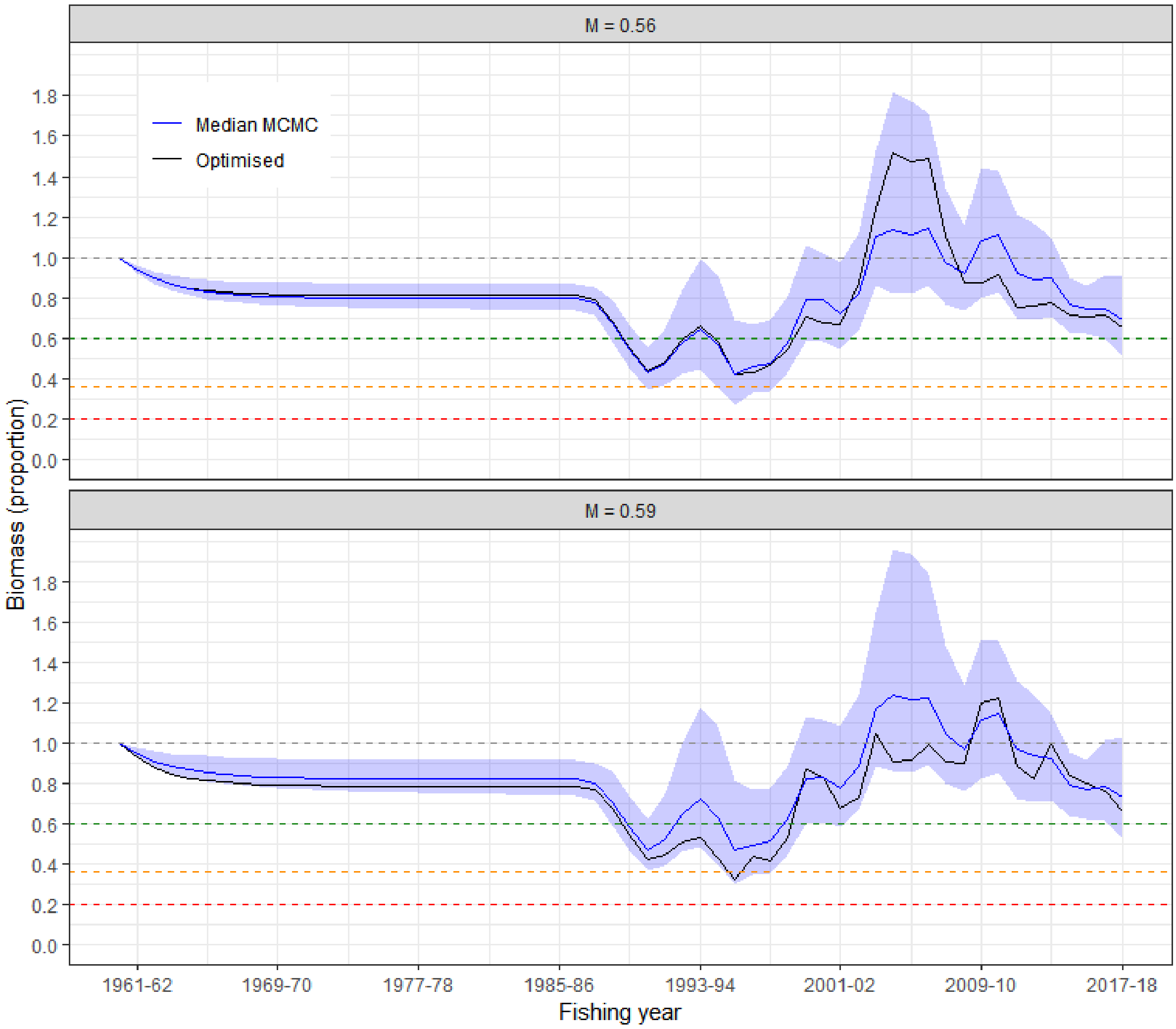

Figure 13: Exploitable biomass relative to virgin exploitable biomass for different fixed values of natural mortality rate M. The black line shows the biomass proportion trajectory for the optimised parameters, while the blue line shows the median MCMC biomass for each year. Shaded areas indicate the 95% credible interval of the MCMC run while the grey, green, red and orange dotted lines represent a 100%, 60%, 20% and MSY biomass.

MCMC results show a fluctuating biomass from 1987-88 onwards when logbook reporting began. Biomass is shown to reduce to less than 50% from 1989-90 to 1997-98 and then rise to above 100% between 2003-04 and 2010-11. The final biomass trajectory in the fishing year 2017/18 is at around 65–70% and tracking downwards. The 95% credible interval of the MCMC run gives a wide range and indicates uncertainty in the model. A serial plot from the MCMC run for the final year of the biomass trajectory is presented in Appendix E.1.

The recruitment proportion shown in Figure 14 shows a high variability in recruitment with a large 95% credible interval. Years of low and high recruitment correspond to the years of low and high biomass proportion shown in Figure 13.

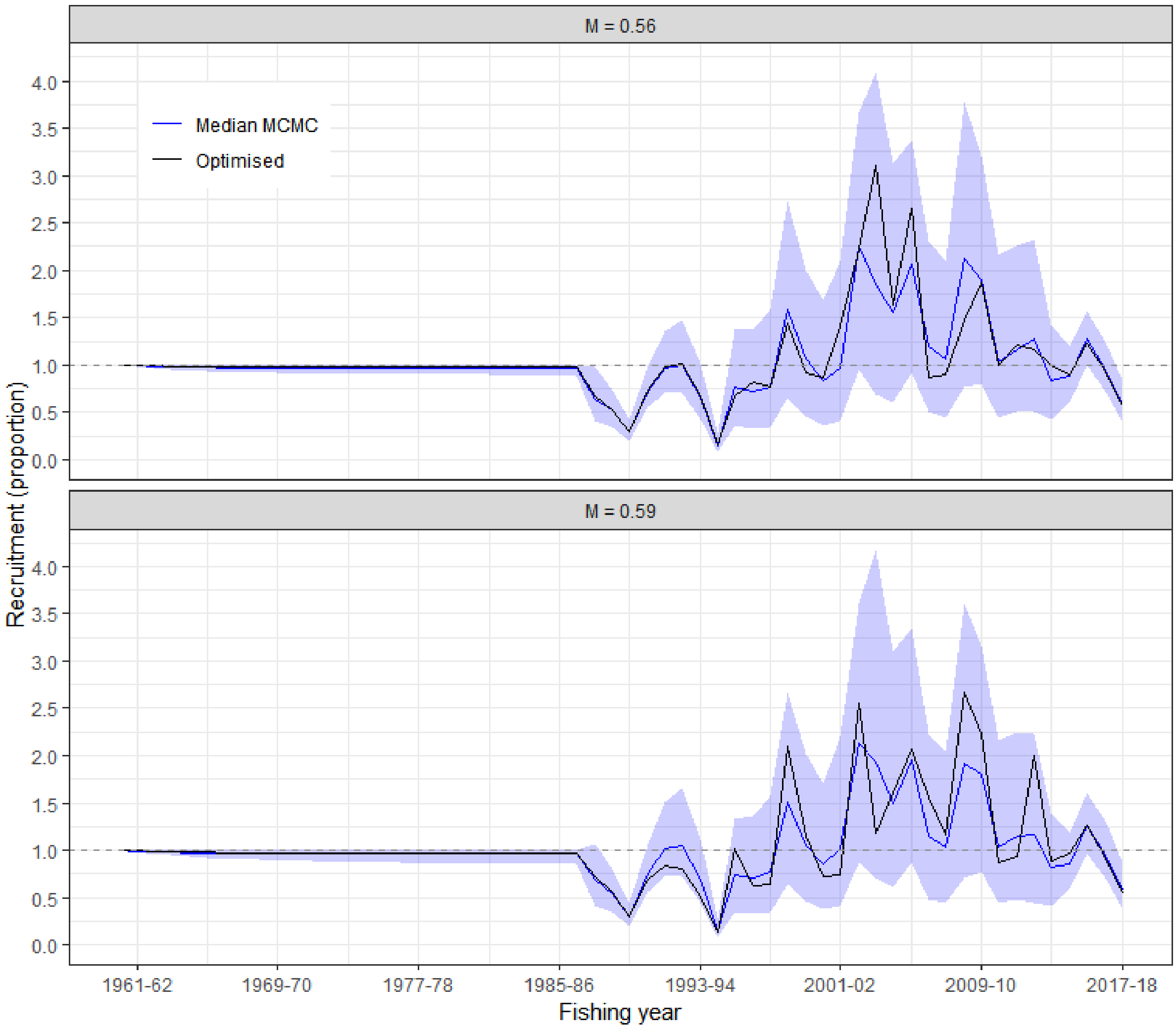

Figure 14: Recruitment relative to virgin recruitment for different fixed values of natural mortality rate M. The black line shows the biomass proportion trajectory for the optimised parameters, while the blue line shows the median MCMC for each year. Shaded areas indicate the 95% credible interval.

The phase plot (Figure 15) illustrates the time series relationship between biomass and harvest rate for both model scenarios. Each plot starts with a biomass proportion of 1 and harvest rate of 0 at the start of the time series (1960-61, labeled as 1961), with each subsequent point along the line representing that state of the fishery in the following year. Of note is that the low and high points of biomass proportion seen in Figure 13 are not always produced by a corresponding harvest rate i.e. an increase in biomass is not always preceded by a decrease in harvest rate.

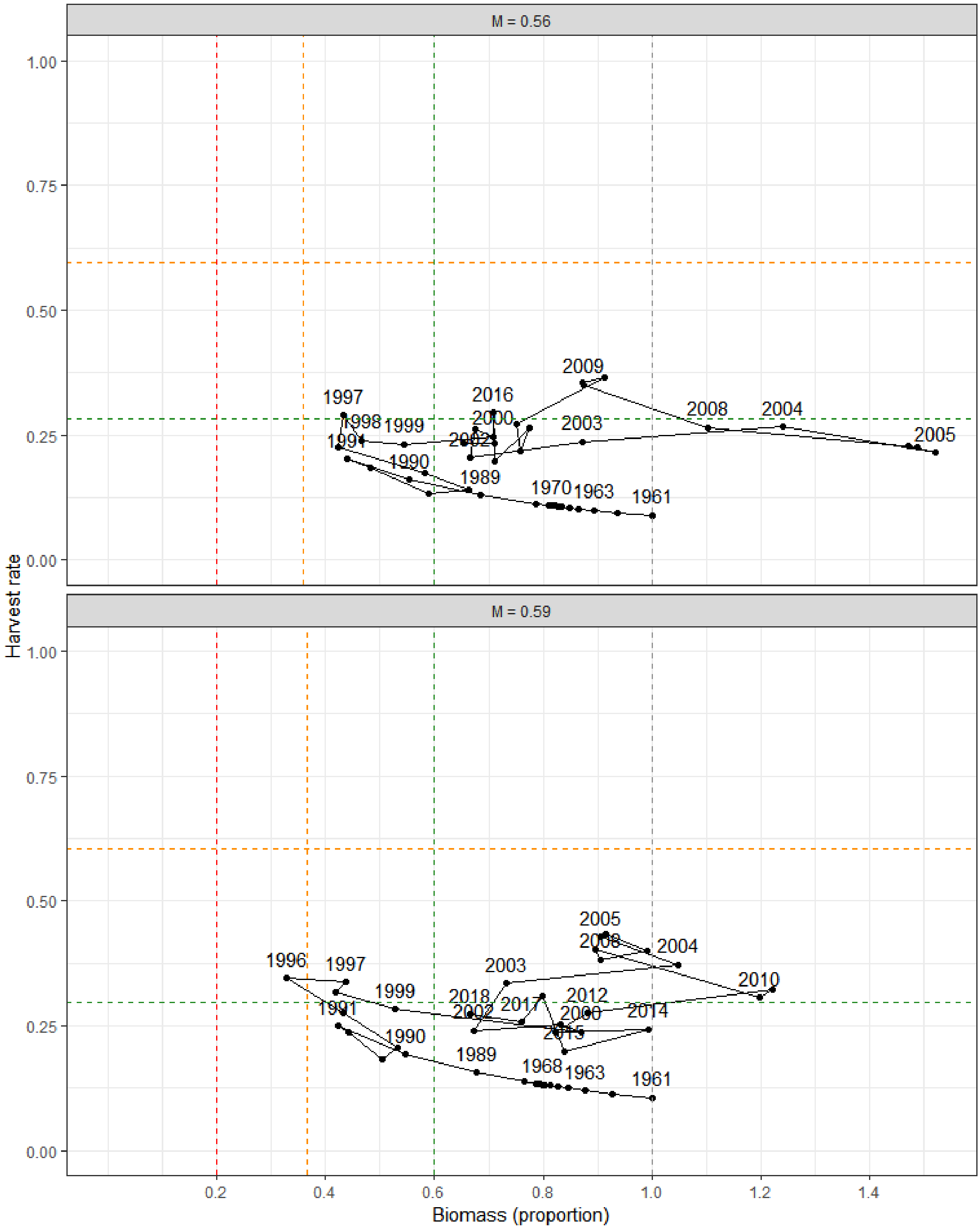

Figure 15: Phase plot of each model showing the trajectory over time of harvest rate vs exploitable biomass proportion relative to virgin exploitable biomass for each year. Vertical dashed lines correspond to 20% biomass, biomass at MSY, 60% and 100% biomass. Horizontal dashed lines correspond to equilibrium harvest rate for 60% biomass (green) and MSY (orange).

3.2.3 Targets

MSY and 60% biomass harvest targets for the combined commercial and recreational sectors were calculated. These targets are presented in Figure 16 shown relative to the total reconstructed harvest (commercial and recreational).

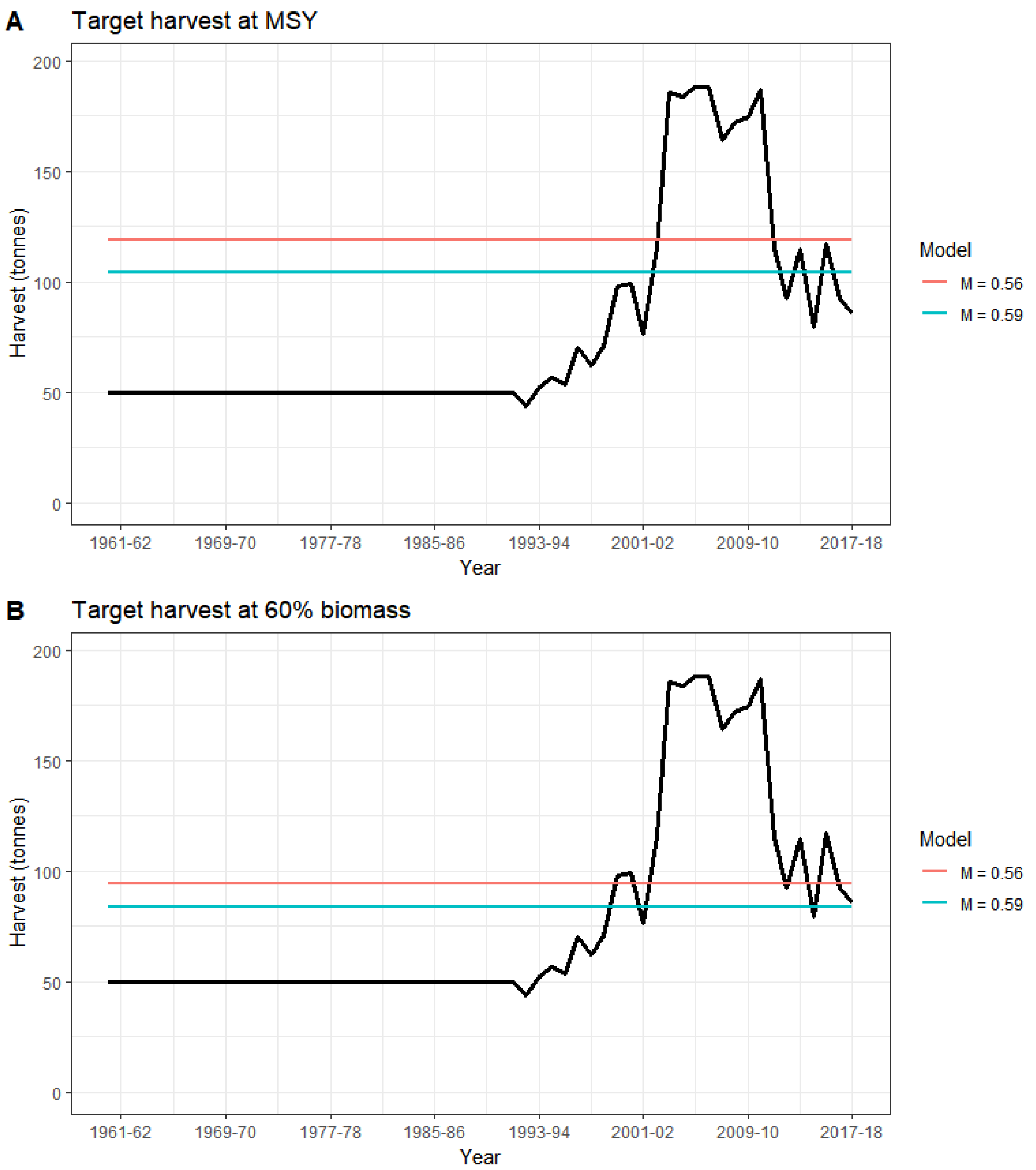

Figure 16: Plots of harvest targets shown relative to the harvest time series for each model. A: the harvest target to remain at MSY B: the harvest target to remain at 60% biomass.

To aid in readability of the harvest targets, Table 12 details the actual values. Serial plots from the MCMC run for MSY and the 60% harvest target are presented in Appendix E.1.

Table 11: MSY and harvest target to maintain 60% biomass (in tonnes) for each model.

Model	MSY	60% target
M = 0.56	119	95
M = 0.59	104	84

4 Discussion

4.1 Stock status

School mackerel is a fast growing species forming two stocks along the eastern Queensland coastline. Current harvests are around 20 t per year for the north-east stock and 100 t per year for the south-east stock. Catch shares over this period for the north-east stock are around 33% commercial and 67% recreational. For the south-east stock, catch shares for this period are around 83% commercial and 17% recreational.

Current management restrictions placed on school mackerel are a minimum legal size of 50 cm total length and a recreational in-possession (bag) limit of 10 school mackerel per fisher. School mackerel generally reach maturity at 46–51 cm total length for females and 40–46 cm total length for males (Cameron and Begg 2002). This indicates there is a small window of protection for newly spawning stock.

For the south-east stock, noting the aforementioned concerns over the performance of the population model, indications are that current school mackerel biomass is above 60%, and is on a downward trend. Recruitment plays a strong role in the increase and decrease of stock biomass, indicating that environmental variables rather than fishing pressure may play a major role in biomass trends for this species.

Research indicates that school mackerel may be more resilient to fishing pressure than other *Scomberomorus* species such as spotted mackerel, as they do not form large, easily targeted aggregations (Begg 1996, 1998). This would explain why the biomass ratio of school mackerel is higher than estimated for other lesser mackerels such as spotted mackerel (Bessell-Browne et al. 2018) and lends support the accuracy of the current results.

4.2 Performance of the population model

This stock assessment used an age-structured model with a yearly time step and length-based selectivity. Only the south-east stock was considered for assessment as harvests for the north-east stock were limited. Data inputs included total harvest, standardised catch rates, age and length structures. The south-east coast stock model used reconstructed harvests from 1960-61 to 2017-18 (comprising commercial harvest (1988-89 to 2017-18); recreational harvest (1994-95 to 2013-14) and length structures (2014-15 to 2017-18) and age-length information (1991-92 to 1994-95)).

The model had difficulty fitting to the input data and did not produce conclusive results. Many different scenarios were attempted but the output of this assessment is limited by the quality and quantity of data available. The stock model was run with each catch rate separately and also with both catch rates. Best results were achieved when both catch rates were included.

Without the use of recruitment deviations, the model estimates an unrealistically high virgin spawning biomass and does not converge, as it could not put an upper limit on the biomass. With recruitment deviations, the model estimates plausible initial biomass by attributing increasing catch rates during a period of peaking harvest to favourable recruitment conditions. While this is a non-precautionary assumption in general, two factors argue in its favour. Firstly, the alternative model structure (no recruitment deviations) led to an even more optimistic outcome for stock status. Secondly, the high levels of recruitment over the period 2002-03 to 2008-09 indicated by the model are supported by high harvests in both the commercial and recreational sector over the 2003-04 to 2010-11 period.

Biological age-length parameters input to the model have been determined by data sourced from Cameron and Begg (2002). The maximum length measured by Cameron and Begg (2002) and the Queensland Fisheries Fishery Monitoring are 18cm different, albeit, similar to the historical length data, few animals greater than 74 cm FL have been recorded. In addition to this, sample sizes from these sources are small.

It is unknown whether larger fish sampled by the Fisheries Queensland Fishery Moitoring are older fish (older than the current maximum age of 10 years) or whether each age class for school mackerel may have a higher length and weight distribution. This leads to questions regarding the validity of the von Bertalanffy parameters L_0, L_∞ and κ and the allometric growth parameters α and β input to the model. Future assessments should aim to calculate these parameters that are representative of the longer lengths currently sampled with updated age information.

Cameron and Begg (2002) have done substantial work in determining fecundity and sexual maturity. If the 18 cm longer fish are older fish, then these fecundity and sexual maturity reference points are likely accurate representations. However, if school mackerel age classes have a higher length and weight distribution, then these reference points used are not representative of the stock and will bias results.

4.3 Environmental impacts

Environmental impacts influencing stock size of school mackerel are unknown, although some impacts are likely occurring. Investigations into the impacts of changes in environmental variables due to climate change have proposed various potential high risks to school mackerel (Welch et al. 2010). Welch et al. (2010) identified school mackerel as having a higher climate change sensitivity than spanish, spotted and grey mackerel species although school mackerel was considered of lower fishery importance.

Changes to temperatures and ocean currents may influence the location and availability of food sources and affect schooling behaviours. Temperature changes may also influence both the timing and location of spawning and natural mortality rates (Houde 1987; Frank et al. 1990; Drinkwater 2005; Rose 2005; Takasuka et al. 2007). These effects have the potential to impact the stock size of school mackerel.

Targeted research into the various impacts of environmental changes on school mackerel would increase understanding and benefit future assessments and management of the fishery.

4.4 Recommendations

The Queensland *Sustainable Fisheries Strategy* states clear aims to build and maintain fisheries in the long term. Target reference points are 40–50% of virgin exploitable biomass by 2020 and 60% biomass by 2027 (Department of Agriculture and Fisheries 2017). Results obtained in this assessment are a reflection of data quality and quantity and hence there is not a high level of confidence in reference points obtained.

4.4.1 Monitoring

Questions have been raised as to the validity of biological parameters used in this assessment due a difference in sampling approaches for the Fisheries Queensland Fishery Monitoring data and data sourced from Cameron and Begg (2002). As such, current data available may not be representative of the stock.

It is recommended that representative age, length and sex sampling data be collected before any future assessments are undertaken. This monitoring data, while fishery dependent sampling would be acceptable, should be comparable from year to year; ie. representative of changes in the stock rather than changes in fishing methodology.

This assessment has focused on the south-east stock due to small harvests for the north-east stock. It is likely that future stock assessments will also focus on the south-east stock and hence the primary focus of monitoring data collection should be on the south-east stock.

Analysis of future monitoring data to determine new von Bertalanffy and allometric growth parameters is likely to play a large role in improving the confidence of future stock assessment outcomes.

4.4.2 Management

Model indications are that the current school mackerel biomass for the south-east is above 60%. Harvest targets produced by the model range between 104–119 t for MSY and 84–95 t to maintain stock biomass at 60%.

As this assessment is limited by the quality and quantity of data available, management should be aware that there is not a high level of confidence in reference points produced by this assessment.

4.4.3 Assessment

Future assessments of school mackerel will be difficult until more age-length sampling has been undertaken. Representative biological parameters play a vital role in the stock assessment model. It is recommended to wait until further investigation and representative age-length monitoring of school mackerel has been undertaken before repeating this assessment. As monthly harvest plots show a peak in harvest mid-year, it is also recommended that future assessments be undertaken with a calendar year time step.

4.5 Conclusions

This assessment has informed the status of the south-east stock of Australia’s east coast school mackerel. Analysis suggest that biomass has been declining since the mid-2000s and is currently at around 65% (for 2017-18). The study recommends harvest limits at around 84–95 t to maintain the stock at levels consistent with 60% of unfished biomass. This 60% of unfished biomass target level, is specified in Qld’s *Sustainable Fisheries Strategy*. Due to limited data, results reflect a low level of confidence and precautionary interpretations are warranted.

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Appendix A - Daily harvest sizes

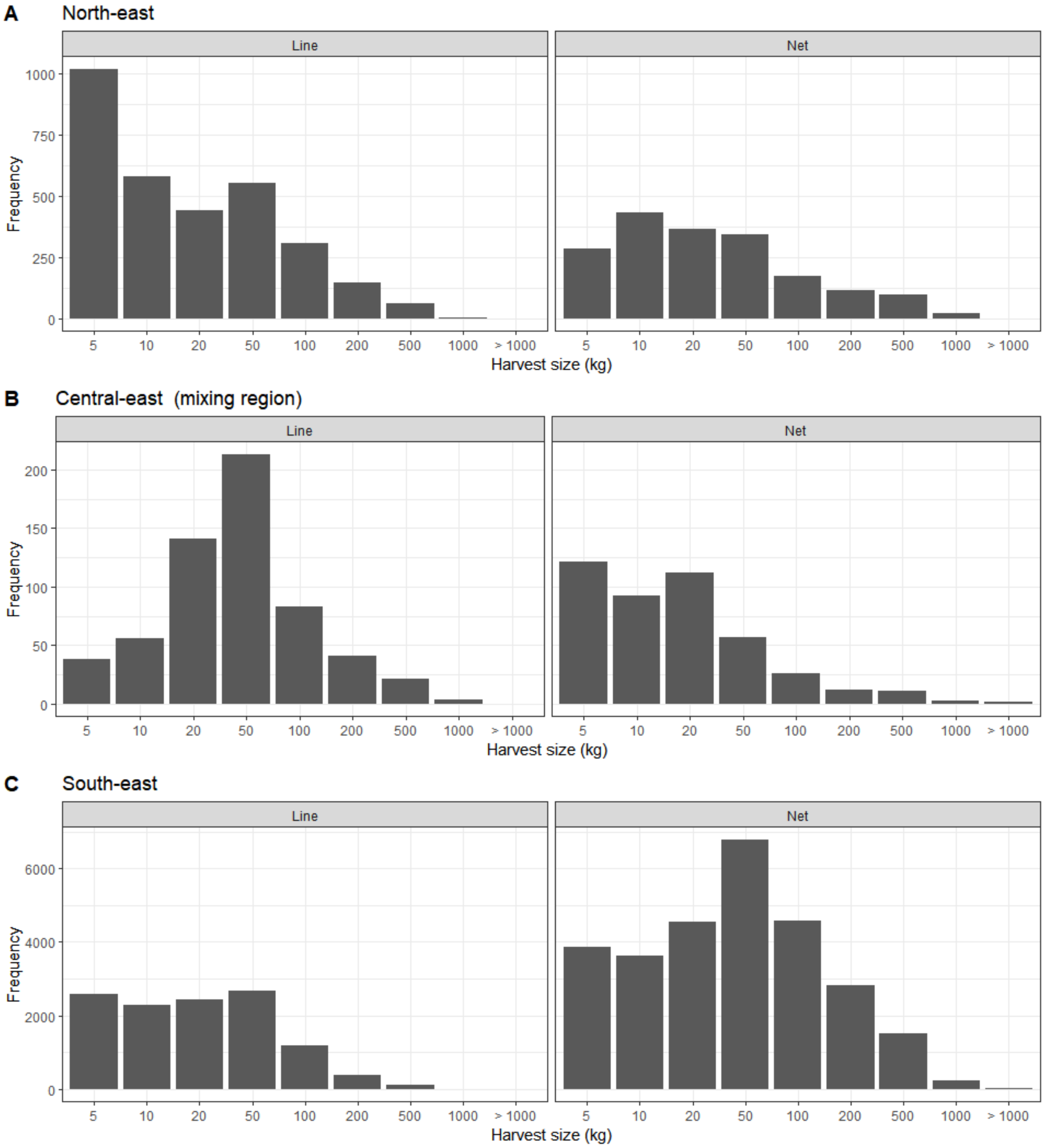

Figure 17: Histograms of catch sizes per fisher-day for each fishing method and stock. Note that y-axes differ for each stock.

Appendix B - Monthly harvests

Figure 18: Histograms of monthly harvests for each fishing method in north-east Queensland for the years 1998–2016.

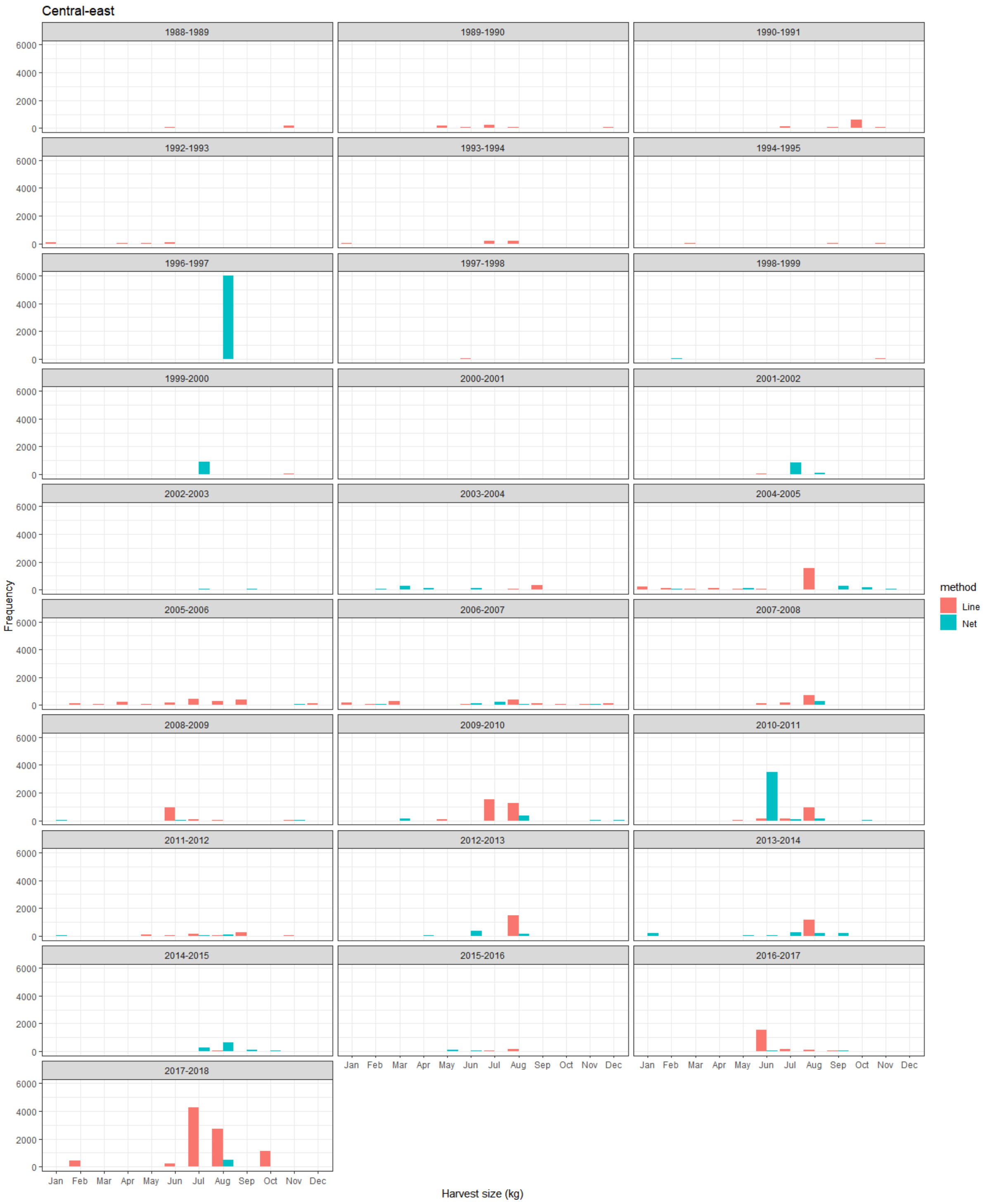

Figure 19: Histograms of monthly harvests for each fishing method in the Queensland east coast mixing region of central-east for the years 1988–2016.

Figure 18: Histograms of monthly harvests for each fishing method in north-east Queensland for the years 1998–2016.

Appendix C - Age-length sampling

Age-length sampling was sourced from data obtained by Cameron and Begg (2002). Overall age-length compositions are displayed in Figure 21.

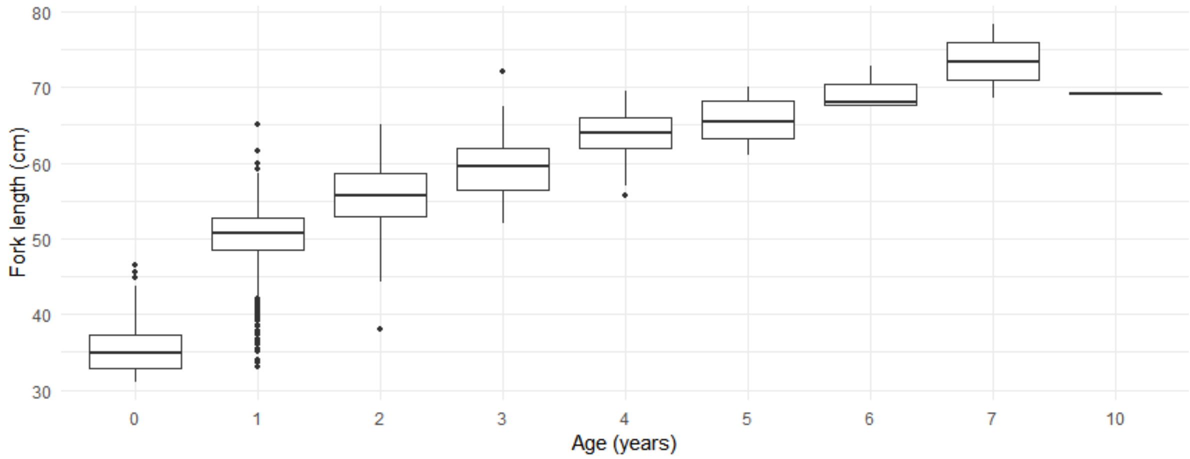

Figure 21: Relationship between the range of lengths in each age group. Each boxplot represents the range of lengths for each age group, the middle line through the box represents the median, while the top and bottom of the box represent the 75th and 25th percentiles respectively. The whisker lines outside the box extend to cover extreme values that were not considered outliers. No data exists for ages 8 and 9, hence they do not exist on the plot. (Note that the MLS 45 cm total length ≈ 39 cm fork length and MLS 50 cm total length ≈ 44 cm fork length.)

Length-sex and age-sex compositions sampled are shown in Figure 22 and Figure 23. Further information on length structures was available from the Fisheries Queensland Fishery Monitoring data (2015-2018). Annual distributions of age and length structures can be found in Appendix F.2 and Appendix F.3.

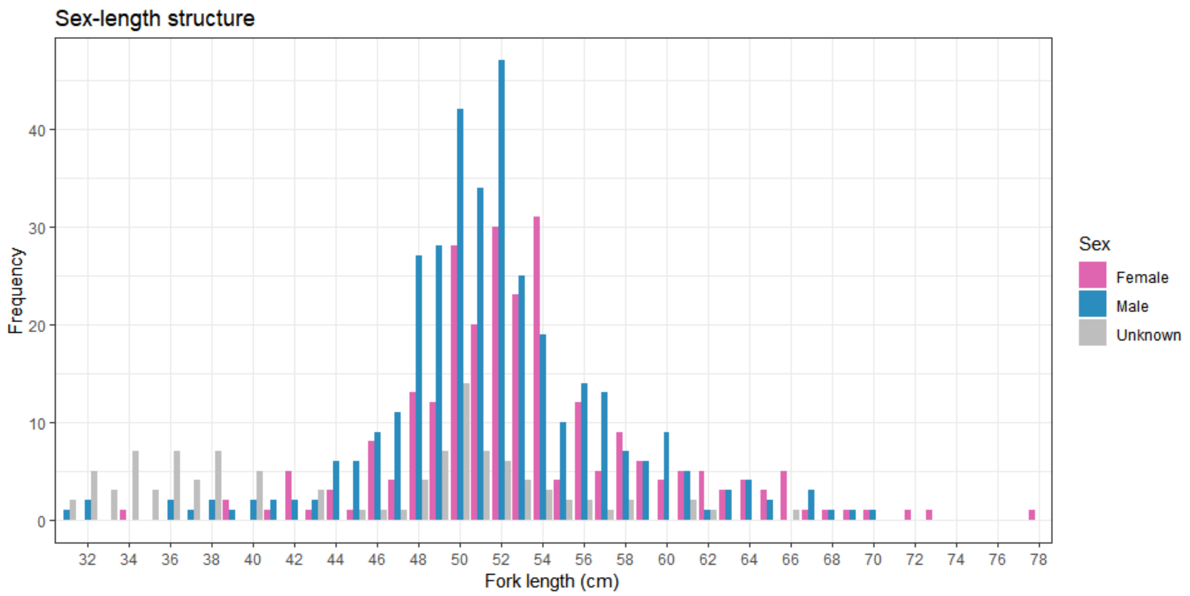

Figure 22: Biological sampling of sex-length information for school mackerel in south-east Queensland during the period 1992–1994. Source: Cameron and Begg (2002). (Note that the MLS 45 cm total length ≈ 39 cm fork length and MLS 50 cm total length ≈ 44 cm fork length.)

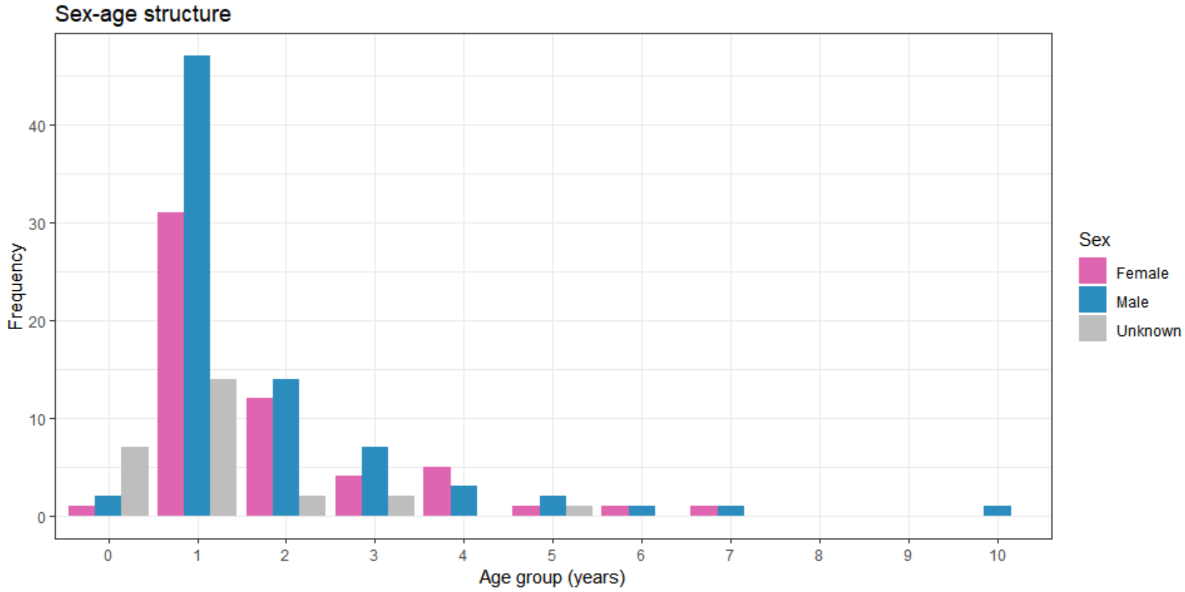

Figure 23: Biological sampling of sex-age information for school mackerel in south-east Queensland during the period 1992–1994. Source: Cameron and Begg (2002). (Note that the MLS 45 cm total length ≈ 39 cm fork length and MLS 50 cm total length ≈ 44 cm fork length.)

Appendix D - Model analysis

D.1 Harvest scenario 1

Table 13 shows estimated parameter values for models that converged successfully with harvest scenario 1. Model fits for M and L_{50} were good. Model fits for h and $\ln(B_0^{Sp})$ were poor. Biomass trajectory fits were also poor and tracked mostly above 100%.

Table 13: Model parameter values for attempts at harvest scenario 1.

Fixed	M	$\ln(B_0^{Sp})$	h	L_{50}	Nll
h	0.76	13.92	0.35	46.63	493.13
h	0.74	13.63	0.45	46.62	493.02
h	0.73	13.54	0.51	46.62	493.01
h	0.72	13.40	0.68	46.61	493.11
M	0.65	13.78	0.62	46.57	497.60
M	0.70	13.30	0.65	46.60	493.21
M	0.72	13.43	0.56	46.61	493.21
M	0.74	13.60	0.48	46.62	493.01

D.2 Harvest scenario 2

Table 14 shows estimated parameter values for models that converged successfully with harvest scenario 2. Model fits for M (with lower fixed values of h) and L_{50} were good. Model fits for h and $\ln(B_0^{Sp})$ were very poor. Biomass trajectory fits were also poor and tracked mostly above 100%.

Table 14: Model parameter values for attempts at harvest scenario 2.

Fixed	M	$\ln(B_0^{Sp})$	h	L_{50}	Nll
h	0.76	14.07	0.30	46.63	493.04
h	0.75	13.83	0.35	46.63	492.95
h	0.74	13.58	0.45	46.62	492.85
h	0.72	13.45	0.55	46.61	492.86
h	0.71	13.35	0.70	46.61	492.98
h	0.79	15.93	0.75	46.64	494.55
h	0.79	16.07	0.80	46.63	494.60
M	0.64	13.03	0.90	46.57	494.19
M	0.67	14.00	0.47	46.58	496.58
M	0.70	13.30	0.61	46.60	492.99
M	0.73	13.51	0.49	46.62	492.84

D.3 Harvest scenario 3

Table 15 shows estimated parameter values for models that converged successfully with harvest scenario 3. Model fits for L_{50} were good. Model fits for h, M and $\ln(B_0^{Sp})$ were poor although for M 0.56 and 0.59, fits to $ln(B_0^{Sp})$ and the biomass trajectory were good. Models with harvest scenario 3 and M fixed at 0.56 and 0.59 were chosen for presentation in the main section of the report.

Table 15: Model parameter values for attempts at harvest scenario 3.

Fixed	M	$\ln(B_0^{Sp})$	h	L_{50}	Nll
h	0.64	13.25	0.45	46.58	488.25
h	0.61	13.11	0.55	46.56	487.34
h	0.58	13.02	0.65	46.55	486.74
h	0.57	12.99	0.70	46.54	486.52
h	0.79	15.55	0.75	46.64	494.45
M	0.56	13.13	0.79	46.53	493.33
M	0.59	12.97	0.78	46.55	485.53
M	0.64	13.08	0.63	46.58	487.52
M	0.69	13.26	0.50	46.61	488.83
M	0.74	13.53	0.39	46.63	490.43

Appendix E - Parameter analysis

Appendix E.1 below shows MCMC serial plots for each parameter or estimated value. Selectivity curves are also plotted in this section. Recruitment deviations with their credible interval and interquartile range are displayed in Appendix E.2.

E.1 Serial plots

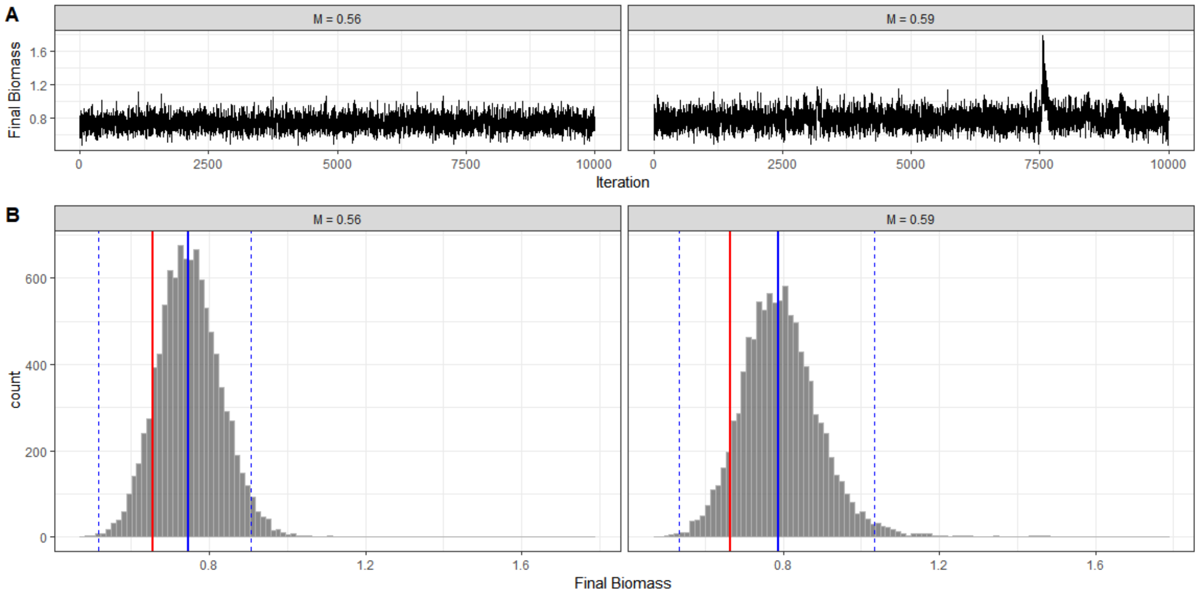

Figure 24: Serial plot and histogram of the biomass proportion final year. The red line in the histogram shows the final year biomass proportion for the optimised model, while the blue line shows the median of the MCMC run. The blue dashed lines show the 95% credible interval of the MCMC run.

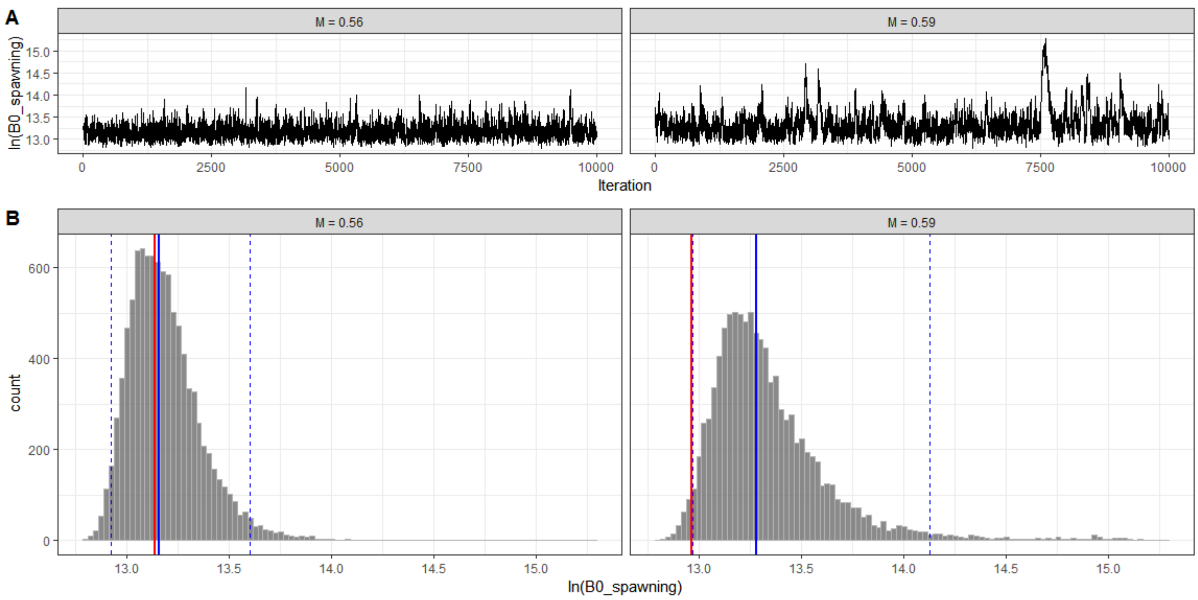

Figure 25: Serial plot and histogram of $ln(B_0^{Sp})$ (log of virgin spawning stock). The red line in the histogram shows the value of $ln(S_0)$ for the optimised model, while the blue line shows the median of the MCMC run. The blue dashed lines show the 95% credible interval of the MCMC run.

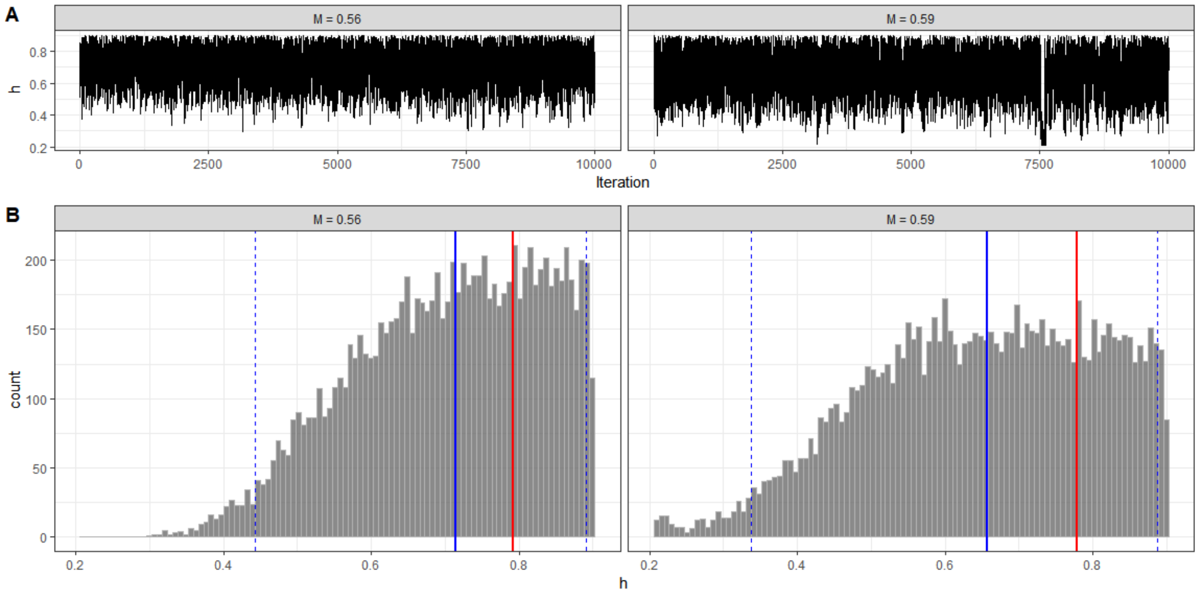

Figure 27: Serial plot and histogram of the Beverton-Holt steepness parameter h. The red line in the histogram shows the value of h for the optimised model, while the blue line shows the median of the MCMC run. The blue dashed lines show the 95% credible interval of the MCMC run.

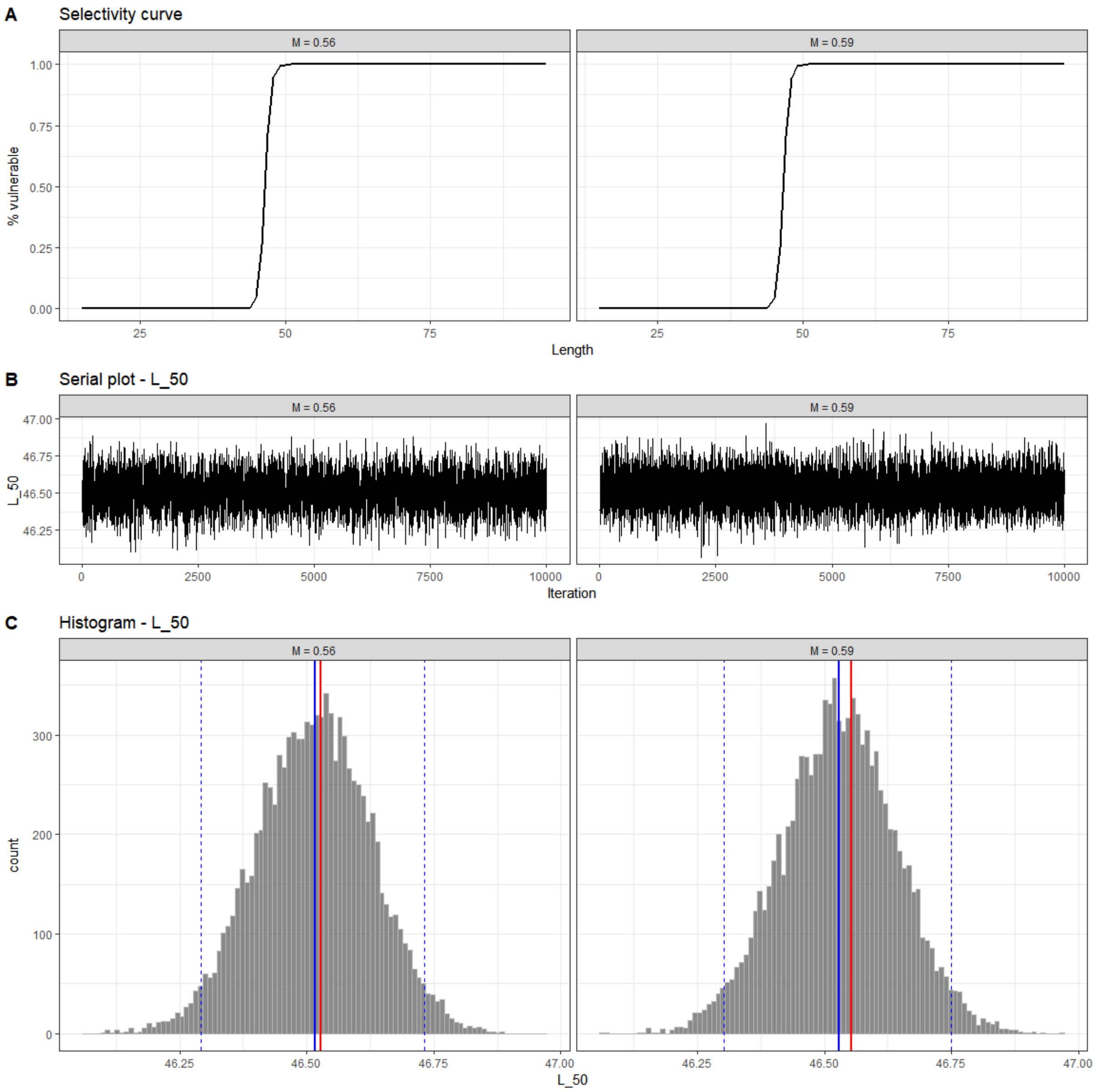

Figure 28: A: selectivity curve, B: serial plot for the L_{50} parameter, C: histogram for the L_{50} parameter. The red line in the histogram shows the value of the parameter for the optimised model, while the blue line shows the median of the MCMC run. The blue dashed lines show the 95% credible interval of the MCMC run.

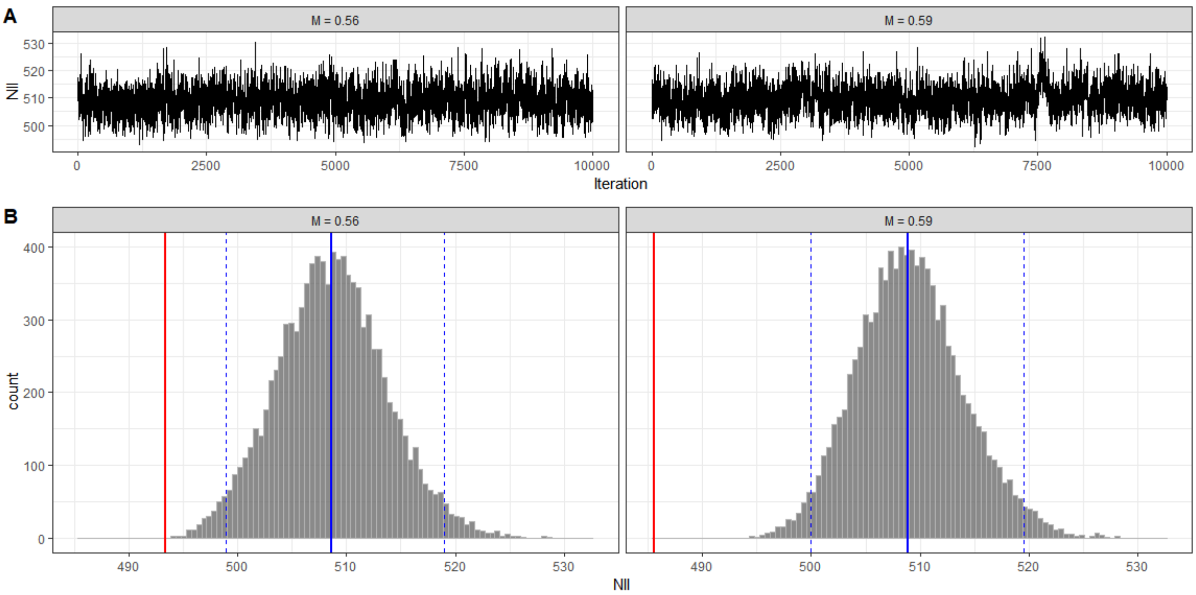

Figure 29: Serial plot and histogram of the model objective function value. The red line in the histogram shows the value of the objective function for the optimised model, while the blue line shows the mean of the MCMC run. The blue dashed lines show the 95% credible interval of the MCMC run.

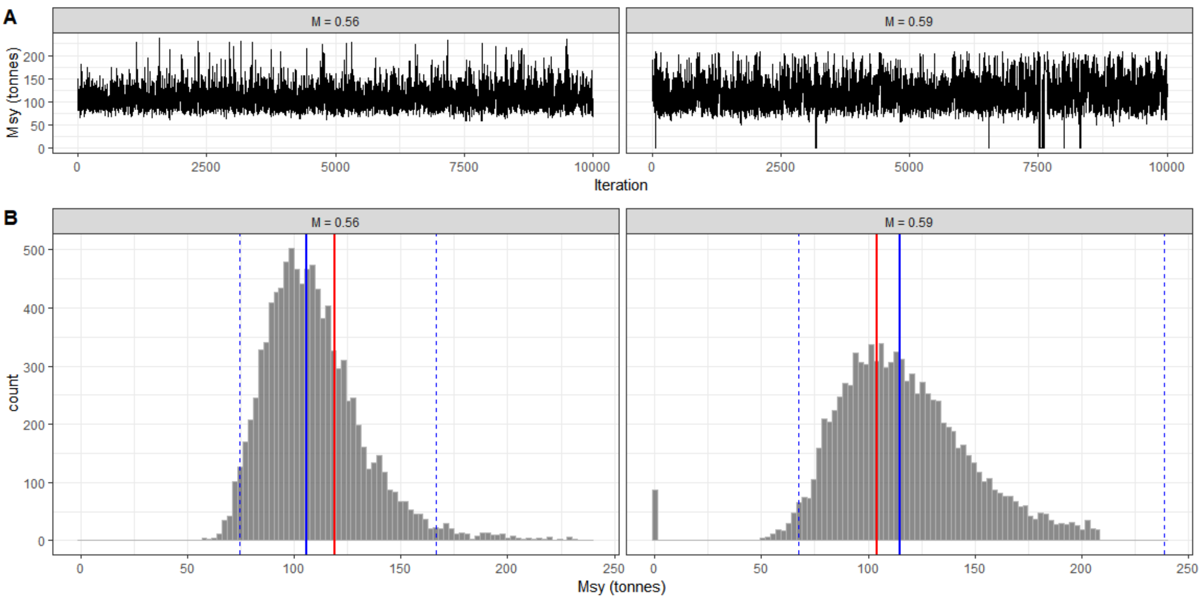

Figure 30: Serial plot and histogram of MSY. The red line shows the value of MSY for the optimised model, while the blue line shows the median of the MCMC run. The blue dashed lines show the 95% credible interval of the MCMC run.

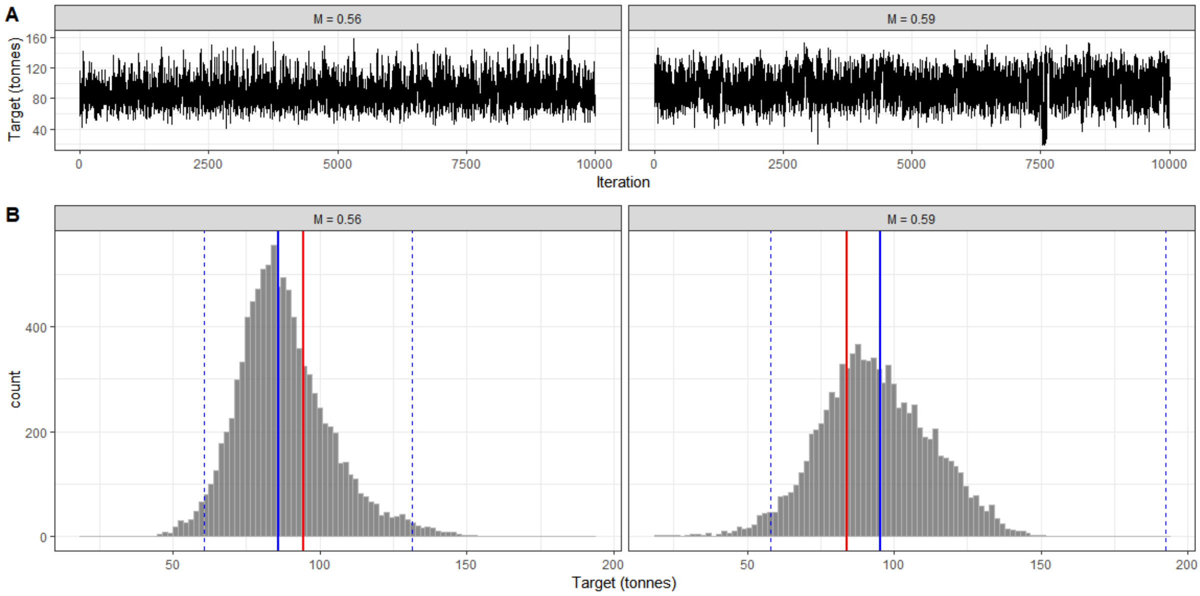

Figure 31: Serial plot and histogram of Target harvest for 60% biomass. The red line shows the value of MSY for the optimised model, while the blue line shows the median of the MCMC run. The blue dashed lines show the 95% credible interval of the MCMC run.

E.2 Recruitment deviations

Table 16: Table of recruitment deviations for model (M = 0.56) with the optimised value, interquartile range and credible intervals of the MCMC run.

Year	Optimised	Mean	2.5%	25%	50%	75%	97.5%	M
1988	-0.3895	-0.4056	-0.8531	-0.5518	-0.4012	-0.2541	0.0116	M = 0.56
1989	-0.6166	-0.6194	-1.0157	-0.7451	-0.6133	-0.4872	-0.2585	M = 0.56
1990	-1.1753	-1.1742	-1.5663	-1.3030	-1.1703	-1.0415	-0.8053	M = 0.56
1991	-0.2257	-0.1760	-0.4282	-0.2691	-0.1814	-0.0874	0.1067	M = 0.56
1992	0.0771	0.1379	-0.1434	0.0276	0.1304	0.2402	0.4622	M = 0.56
1993	0.0908	0.1338	-0.1731	0.0177	0.1277	0.2432	0.4713	M = 0.56
1994	-0.3458	-0.3377	-0.6911	-0.4696	-0.3413	-0.2102	0.0380	M = 0.56
1995	-1.7849	-1.8021	-2.3444	-2.0037	-1.8055	-1.6064	-1.2408	M = 0.56
1996	-0.3346	-0.1387	-0.9429	-0.3941	-0.1169	0.1377	0.5511	M = 0.56
1997	-0.1006	-0.1781	-0.9922	-0.4280	-0.1595	0.0871	0.5350	M = 0.56
1998	-0.1636	-0.0996	-0.9366	-0.3671	-0.0882	0.1835	0.6689	M = 0.56
1999	0.4512	0.5687	-0.3106	0.3303	0.6091	0.8528	1.2057	M = 0.56
2000	-0.0373	0.1082	-0.7187	-0.1448	0.1332	0.3837	0.7966	M = 0.56
2001	-0.0927	-0.1460	-0.9494	-0.4098	-0.1378	0.1256	0.6018	M = 0.56
2002	0.3881	0.0145	-0.8332	-0.2748	0.0256	0.3160	0.8162	M = 0.56
2003	0.8354	0.8278	-0.0186	0.6433	0.8802	1.0682	1.3772	M = 0.56
2004	1.1443	0.6183	-0.3572	0.2970	0.6435	0.9667	1.4348	M = 0.56
2005	0.4770	0.4140	-0.5160	0.1573	0.4511	0.7043	1.1391	M = 0.56
2006	0.9606	0.6873	-0.1046	0.4968	0.7343	0.9277	1.2219	M = 0.56
2007	-0.1677	0.1510	-0.7198	-0.1181	0.1849	0.4497	0.8572	M = 0.56
2008	-0.1156	0.0519	-0.8125	-0.2205	0.0812	0.3465	0.7656	M = 0.56
2009	0.4047	0.7330	-0.2416	0.4834	0.7955	1.0403	1.3811	M = 0.56
2010	0.6505	0.6317	-0.1962	0.4203	0.6755	0.8910	1.2094	M = 0.56
2011	0.0193	0.0314	-0.8003	-0.2494	0.0479	0.3243	0.7974	M = 0.56
2012	0.2217	0.1514	-0.6763	-0.1062	0.1732	0.4346	0.8512	M = 0.56
2013	0.1875	0.2317	-0.6684	-0.0282	0.2779	0.5414	0.8834	M = 0.56
2014	0.0351	-0.1727	-0.8412	-0.3791	-0.1513	0.0560	0.3876	M = 0.56
2015	-0.0781	-0.0882	-0.4442	-0.1926	-0.0781	0.0281	0.2178	M = 0.56
2016	0.2497	0.2994	0.1048	0.2326	0.2984	0.3664	0.4934	M = 0.56
2017	-0.0355	0.0236	-0.2166	-0.0587	0.0224	0.1059	0.2635	M = 0.56
2018	-0.5297	-0.4773	-0.8210	-0.5943	-0.4739	-0.3585	-0.1433	M = 0.56

Table 17: Table of recruitment deviations for model (M = 0.59) with the optimised value, interquartile range and credible intervals of the MCMC run.

Year	Optimised	Mean	2.5%	25%	50%	75%	97.5%	M
1988	-0.2905	-0.3312	-0.8086	-0.4826	-0.3256	-0.1723	0.1007	M = 0.59
1989	-0.5514	-0.5559	-0.9583	-0.6904	-0.5518	-0.4191	-0.1751	M = 0.59
1990	-1.1601	-1.1140	-1.5224	-1.2484	-1.1123	-0.9767	-0.7189	M = 0.59
1991	-0.2864	-0.1053	-0.3768	-0.2114	-0.1159	-0.0110	0.2257	M = 0.59
1992	-0.0682	0.2214	-0.0811	0.0993	0.2077	0.3297	0.6014	M = 0.59
1993	-0.1095	0.2022	-0.1188	0.0766	0.1926	0.3161	0.5768	M = 0.59
1994	-0.5952	-0.2837	-0.6439	-0.4171	-0.2897	-0.1558	0.1089	M = 0.59
1995	-1.9580	-1.7670	-2.2922	-1.9606	-1.7688	-1.5757	-1.2174	M = 0.59
1996	0.1782	-0.1737	-0.9419	-0.4146	-0.1602	0.0872	0.5193	M = 0.59
1997	-0.3232	-0.1700	-0.9584	-0.4222	-0.1587	0.0924	0.5499	M = 0.59
1998	-0.3103	-0.0801	-0.8942	-0.3427	-0.0706	0.1983	0.6810	M = 0.59
1999	0.8696	0.5371	-0.3122	0.2851	0.5719	0.8183	1.2164	M = 0.59
2000	0.1808	0.1100	-0.7191	-0.1427	0.1300	0.3897	0.8140	M = 0.59
2001	-0.3024	-0.1178	-0.9264	-0.3732	-0.1086	0.1572	0.6155	M = 0.59
2002	-0.2657	0.0568	-0.8194	-0.2343	0.0703	0.3643	0.8756	M = 0.59
2003	0.9928	0.7636	-0.1389	0.5643	0.8163	1.0185	1.3559	M = 0.59
2004	0.1957	0.6498	-0.3207	0.3417	0.6779	0.9973	1.4434	M = 0.59
2005	0.4948	0.3667	-0.5409	0.1002	0.3950	0.6616	1.1144	M = 0.59
2006	0.7570	0.6221	-0.1871	0.4164	0.6652	0.8703	1.1988	M = 0.59
2007	0.4729	0.0957	-0.7910	-0.1852	0.1236	0.4063	0.8199	M = 0.59
2008	0.1791	0.0075	-0.8405	-0.2545	0.0284	0.2923	0.7269	M = 0.59
2009	1.0199	0.6236	-0.3669	0.3415	0.6840	0.9497	1.3246	M = 0.59
2010	0.8157	0.5757	-0.3003	0.3547	0.6219	0.8447	1.1957	M = 0.59
2011	-0.1438	0.0237	-0.8269	-0.2550	0.0386	0.3169	0.7975	M = 0.59
2012	-0.0535	0.1272	-0.7353	-0.1321	0.1534	0.4126	0.8495	M = 0.59
2013	0.7283	0.1443	-0.7993	-0.1230	0.1836	0.4587	0.8481	M = 0.59
2014	-0.0963	-0.1891	-0.8831	-0.3915	-0.1699	0.0382	0.3695	M = 0.59
2015	-0.0143	-0.1067	-0.4530	-0.2180	-0.0981	0.0114	0.2033	M = 0.59
2016	0.2622	0.3040	0.0988	0.2320	0.3010	0.3726	0.5287	M = 0.59
2017	-0.0488	0.0342	-0.2255	-0.0534	0.0313	0.1208	0.3061	M = 0.59
2018	-0.5692	-0.4712	-0.8316	-0.5911	-0.4677	-0.3505	-0.1175	M = 0.59

Appendix F - Model fit

F.1 Catch rates

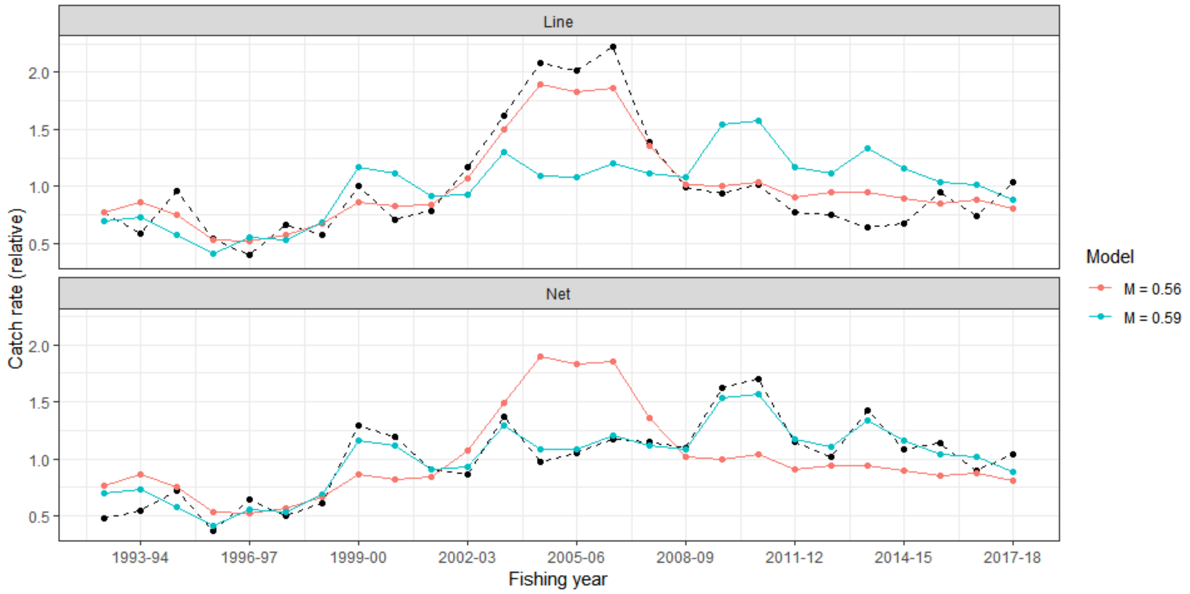

Figure 32: Fit to standardised catch rates for each model. Catch rates input to the model are shown in black dashed lines.

F.2 Age structures

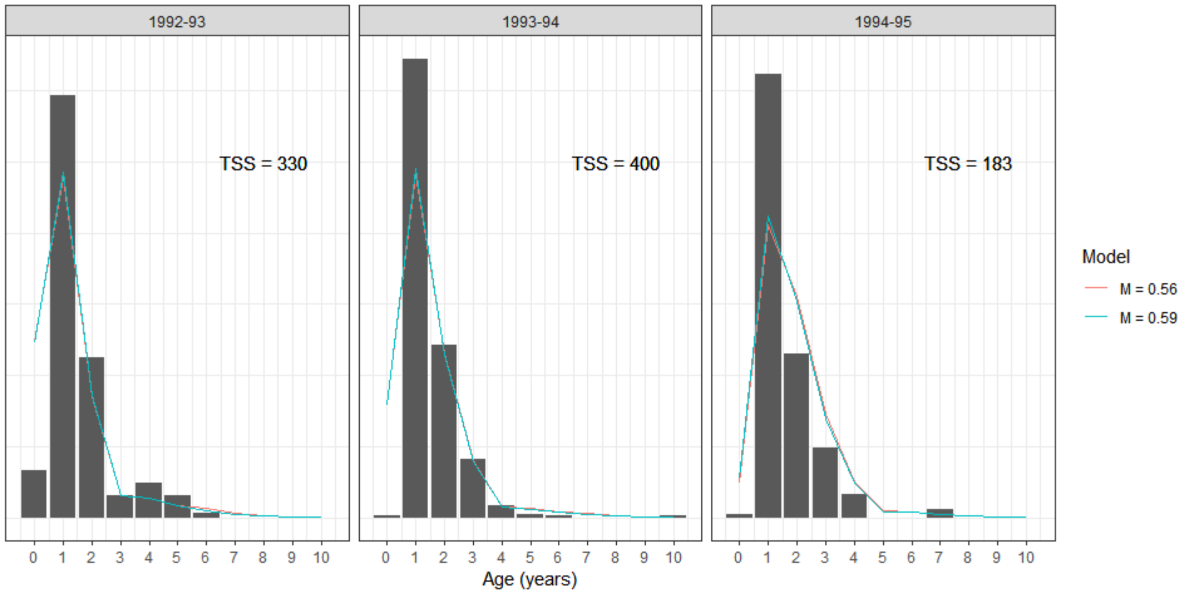

Figure 33: Fit to age composition for each model. Bar plot shown in grey represents input age structure. The total sample size (TSS) is shown for each fishing year.

F.3 Length structures

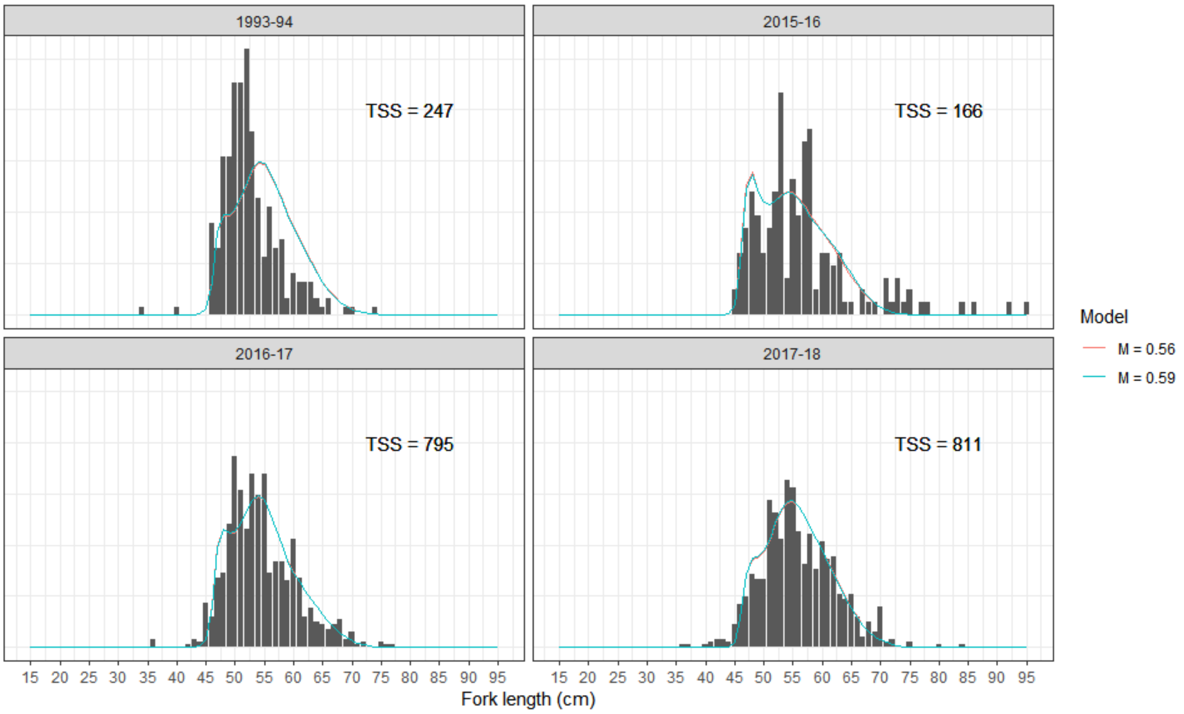

Figure 34: Fit to length composition for each model. Bar plot shown in grey represents input length structure. The total sample size (TSS) is shown for each fishing year.