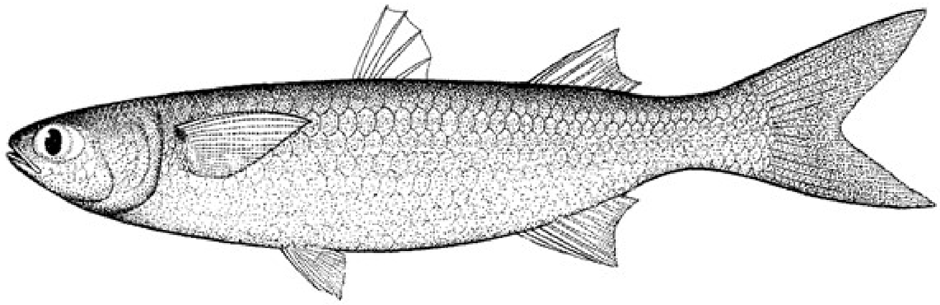

Stock assessment of Australian east coast sea mullet (*Mugil cephalus*) with data to December 2020

April 2022

Queensland Government

This publication has been compiled by R. Lovett [1], A. Prosser [1] and J. Stewart [2].

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Contents

Summary

This stock assessment indicates that biomass declined between 1899 and 1950 to 61% unfished biomass. Following a further period of decline since 1980, the 2021 stock level was estimated to be 37% unfished biomass.

Sea mullet (*Mugil cephalus*) are found in tropical and subtropical waters around the world. On the east coast of Australia, sea mullet occur as one continuous stock between Baffle Creek (24.5° S) in Queensland and Eden (37.5° S) in New South Wales (NSW). They inhabit coastal, estuarine and freshwaters, with notable aggregations forming during winter along the coast line to spawn. The species live around 16 years and have a maximum observed size of 64 cm fork length. Sexual maturity is reached at 3–4 years of age (Smith et al. 2002).

This assessment builds on previous assessments that estimated the stock was at 'clearly less than' 60% and 50% of unfished biomass in 2004 and 2016 respectively. This stock assessment includes updates to input data and methodology.

This stock assessment was conducted on calendar years and included input data through to December 2020. All assessment inputs and outputs will be referenced on a calendar year basis.

This assessment used a two-sex, age-structured population model, fit to age and length data, constructed within the Stock Synthesis modelling framework. The assessment modelled the dynamics of the fishery across four fishing sectors: Queensland estuarine, Queensland ocean beach, New South Wales estuarine, and New South Wales ocean beach.

The model incorporated data spanning the period 1899 to 2020 including Queensland commercial catch from Kesteven (1925–1940), NSW commercial catch from Kesteven (1899–1941), Queensland commercial catch from Thomson (1941–1950), Queensland commercial catch from Halliday (1951–1980), historic commercial catch from NSW Department of Primary Industries (DPI; 1940–1983), monthly logbook commercial catch from NSW DPI (1984–1997), Queensland daily logbook commercial catch (1988–2020), NSW daily logbook commercial catch (2009–2020), Queensland age-length monitoring (1999–2020), NSW age-length monitoring (1990–2000 and 2003–2019) and wind data from the Bureau of Meterology (1988–2020).

Over the last 5 years, 2016 to 2020, total retained catch averaged 4136 tonnes (t) per year, including 1272 t (30.8%) from Queensland and 2864 t (69.2%) from New South Wales waters (Figure 1). 2020 retained catch shares were 1164 t (28.4%) from Queensland and 2938 t (71.6%) from New South Wales.

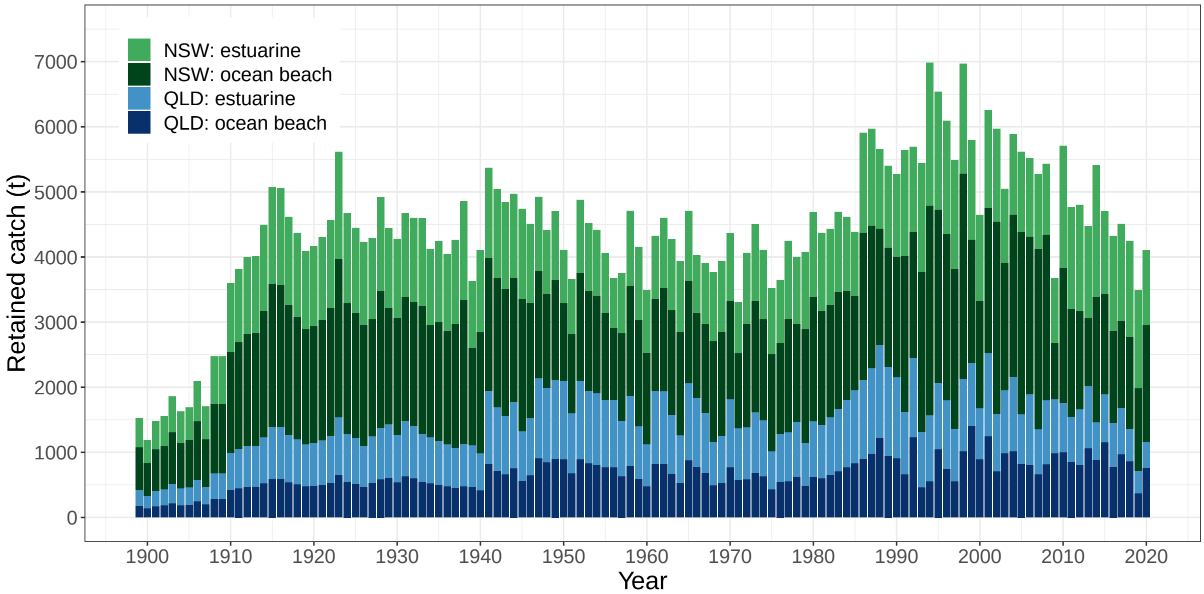

Figure 1: Annual estimated retained catch between 1899 and 2020 for sea mullet

Commercial catch rates from Queensland and New South Wales were standardised to estimate indices of legal sized sea mullet abundance through time. Catch rates were derived for ocean beach and gillnet fishing methods (Figure 2). The unit of standardisation was kg of sea mullet per 'operation-day', defined to be a single day of fishing by a primary vessel. Year, month, latitude, lunar phase and fishing operator were included as explanatory terms. Additionally, ocean beach catch rates included a daily offset for the competing number of fishers in each location.

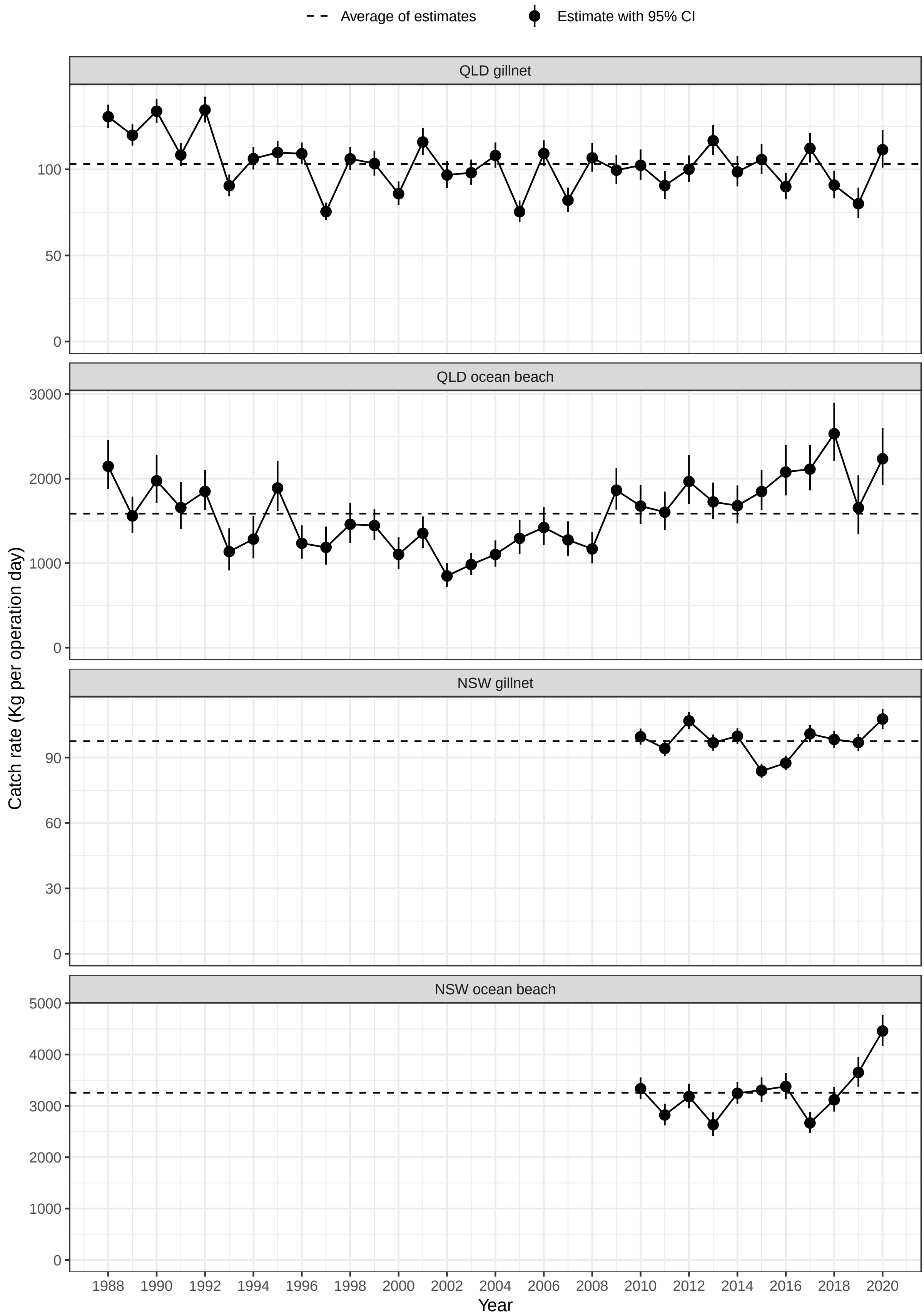

Figure 2: Annual standardised catch rates for Queensland gillnet and ocean beach caught sea mullet between 1988 and 2020 and New South Wales gillnet and ocean beach caught sea mullet between 2010 and 2020

Eight scenarios were run, covering a range of modelling assumptions. Base case (preferred) results suggested that spawning biomass declined between 1899 and 1950 to 61% unfished biomass. Following a further period of decline since 1980, at the beginning of 2021 the stock level was estimated to be 37% (31% to 41% range across scenarios) of unfished spawning biomass (Figure 3).

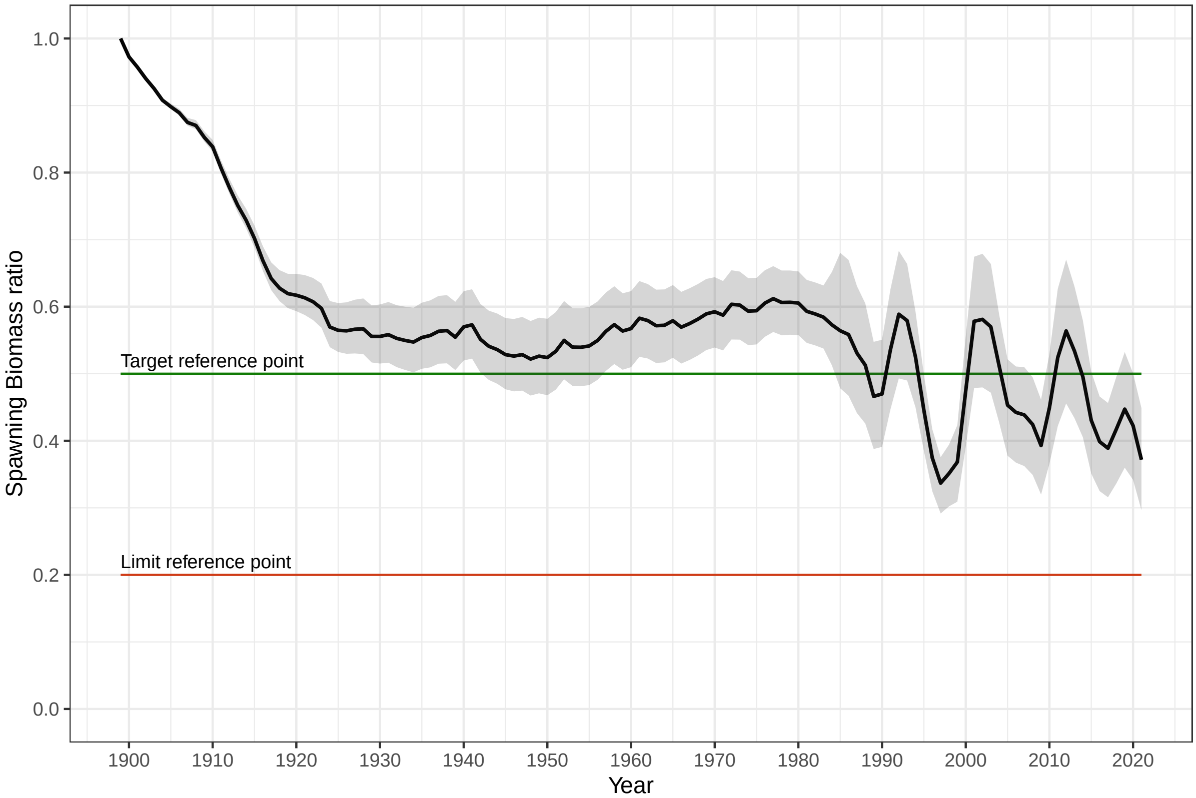

Figure 3: Predicted spawning stock biomass trajectory relative to unfished, from 1953 to 2021

The East coast inshore fishery harvest strategy 2021–2026 sets out a fishery objective for all target species in the fishery to be maintained at, or returned to, a target spawning biomass that aims to maximise economic yield for the fishery. The working group has proposed an initial target of 50% spawning biomass due to the cross jurisdictional nature of the stock. The assessment recommends a biological catch of 2541 t for 2021, with a retained component of 2541 t (Table 1), to allow the stock to rebuild to 50% unfished spawning biomass. This will allow a longer-term biological retained catch of 4801 t to be reached.

The suggested uncertainty discount factor for this assessment is 0.91.

Table 1: Current and target indicators for Australian east coast sea mullet

Indicator	Estimate
Biomass◇ (relative to unfished) at the start of 2021	37% (31% to 41%)
Target biomass (relative to unfished)	50%
Biomass (relative to unfished) at MSY⋆	33%
MSY	5353 t
Retained catch component of MSY	5353 t
Retained catch in 2020	4102 t
Queensland	1164 t (28.4%)
New South Wales	2938 t (71.6%)
Retained catch at 50% biomass target	4801 t
RBC† for 2021 to achieve target	2541 t
Retained component of RBC	2541 t
Time to achieve target	> 8 years

◇ Biomass is defined to be spawning stock biomass.
⋆ MSY (maximum sustainable yield) is defined to be the maximum sustainable dead catch—that is, retained catch plus catch that dies following discarding.
† RBC (recommended biological catch) is the recommended catch according to the control rule. This is dead catch: retained catch plus catch that dies following discarding.

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Glossary

CI	confidence interval
DAF	Department of Agriculture and Fisheries
dead catch	retained catch ('harvest') plus catch that dies following discarding
fishing year	for sea mullet, fishing year is defined to be the same as calendar year
FL	fork length—all length is fork length unless otherwise stated
fleet	a population modelling term used to distinguish types of fishing activity: typically a fleet will have a unique curve that characterises the likelihood that fish of various sizes (or ages) will be caught by the fishing gear
FRDC	Fisheries Research and Development Corporation
GLM	generalised linear model
harvest	see 'retained catch'
ITQ	individual transferable quota
FM	Fisheries Monitoring (managed by Fisheries Queensland)
MLS	minimum legal size
MSY	maximum sustainable yield, is defined to be the maximum sustainable dead catch—that is, retained catch plus catch that dies following discarding.
NSW	New South Wales
operation-day	a single day of fishing by a primary vessel, with year, month, region, number of dories and number of crew and combinations of these as example explanatory terms
QLD	Queensland
QFB	Queensland Fish Board
RBC	recommended biological catch, is the recommended catch according to the control rule. This is dead catch: retained catch plus catch that dies following discarding.
retained catch	component of the catch that is kept by fishers, also referred to as 'harvest' and 'landed catch'
SAFS	Status of Australian fish Stocks (fish.gov.au)
SS	Stock Synthesis
TL	total length

1 Introduction

The eastern Australian sea mullet fishery stretches along the coast, with most landings occurring between 37.5° S (Eden near the border between New South Wales and Victoria) and 24.5° S (Baffle Creek, Queensland). Sea mullet are caught in marine estuarine and ocean beach waters, but also reside in unfished freshwater habitats.

Figure 1.1: Sea mullet fishery in Queensland and New South Wales

The movement of sea mullet was studied by Kesteven (1953) and Virgona et al. (1998) through tagging programs. These studies indicate that mullet generally move northward during the spawning run. Not all mature fish participate in the spawning run each year but there is evidence of multiple movements, i.e. a single fish moving to ocean beach waters year after year (Virgona et al. 1998; Fowler et al. 2016).

Pre-spawning fish aggregate at the mouths of estuaries before exiting to sea during late autumn or winter (Smith et al. 2002; Williams 2002). Spawning fish swim northward along the ocean beaches during winter. These fish take part in what is generally known as the 'ocean beach spawning run', in which eggs are released, fertilised and hatched during the winter months.

After spawning, surviving fish typically return to estuarine or freshwater habitats where they stay for the next two to three years (Williams 2002). In some beach locations, a summertime "hardgut"(non-spawning condition) mullet run used to form an important component of the catch (Smith et al. 2002; Virgona et al. 1998) and this aggregation is still targeted if conditions are suitable.

Sea mullet typically mature from three to four years of age (Smith et al. 2002). This age range constitutes a high proportion of the catch taken during the winter spawning run. The sex ratio of the population can vary greatly with time and location. Ocean beach catches typically comprise more males than females while estuarine catches contain a more even ratio (Stewart et al. 2018).

The maximum observed age from the Australian east coast catch is 16 years old for females and males (Fishery Monitoring data). The maximum observed length from the Australian east coast catch is 64 cm fork length for females and 56 cm fork length for males.

Adult sea mullet are not targeted or caught in any great number by recreational anglers (Prosser 2016). They cannot be taken easily by hook and line due to their diet, which consists predominantly of micro-crustaceans (Smith et al. 2002; Prosser 2016).

Some recreational anglers in Queensland do catch sea mullet (mostly juveniles) using bait and cast nets. These nets are prohibited for anglers in New South Wales; however, they may take various mullet species using bait traps or rod and line (Prosser 2016).

The fishery in each state can be split into two distinct commercial sectors: ocean beach and estuarine.

The ocean beach sector targets sea mullet at the entrances of estuaries and along ocean beaches during the spawning season using highly efficient beach haul nets. These nets measure up to 500 m long during ocean beach season and 800 m long outside of ocean beach season. This activity yields roughly half of the total landings each year.

Sea mullet are caught in the estuarine sector mostly by gillnetting, using nets up to 800 m long. Tunnel and estuarine haul netting methods are also used.

In 1995, New South Wales licensed the ocean beach sector of the fishery, restricting licences to fishers who could demonstrate historical participation. A similar restriction was placed on the estuarine sector in 1997 (Smith et al. 2002). The ocean beach sector in New South Wales was partitioned into seven regions, each with a specific set of licence holders. In 2007 New South Wales introduced share management for the ocean beach and estuarine fisheries.

In Queensland, a limited entry ocean beach (K) licence regulates the targeting of the spawning run of sea mullet. Operative K licences allow their holders to deploy ocean beach haul (seine) nets from April to August each year (Williams 2002). Out of season, any commercial fisher with a general net licence can net ocean beaches. In 2021, there were 373 licences active in the fishery of which 36 were K licences. Changes to spatial and temporal management restrictions in the fishery are listed in Table 1.

In both states, the minimum legal size for sea mullet is 30 cm total length (TL). Various spatial and temporal closures in both the ocean beach and estuarine sectors exist to minimise conflict between operators.

Table 1.1: Management measures applied to sea mullet in Queensland and New South Wales waters

Date	Measure
Queensland	
1877–1914	Numerous measures relating to fishing gear and practices; e.g., mesh size, net length, allowed species, closed seasons, powers of inspectors
3 Dec 1914	Introduced minimum legal size 8 inches (≈ 20 cm) total length (TL) *The Fish and Oyster Act of 1914*
1926–1933	Minimum legal size increased to 11 inches (≈ 28 cm) TL February to July, 10 inches (≈ 25.5 cm) TL August to January (Amendments 1926, 1929 and 1933 by Order in Council to *The Fish and Oyster Act of 1914*)
2 Nov 1952	Minimum legal size increased to 12 inch TL for the months February to June, 11 inches minimum TL during other months. Prior to this, the 12 inch minimum covered only the months March to May (Thomson 1953)
18 Apr 1957	Minimum legal size 12 inches TL year round*Fisheries Act 1957*
16 Dec 1976	Minimum legal size increased to 30 cm TL *Fisheries Act 1976*
10 Mar 1990	Confirm minimum legal sizes from 1976 *Fisheries Organization and Marketing Regulations, 1990*
1 Jul 1993	Confirm minimum legal size 30 cm TL *Fishing Industry Organization and Marketing Amendment Regulation No. 3, Subordinate Legislation 1993 No. 235*
1 Dec 1995	Closure to commercial net fishing on some beaches around populated areas; most of Moreton Bay (all of Moreton Bay at weekends); Great Sandy Strait at weekends; and the eastern (ocean beach) shore of Fraser Island from 1 September to 1 April *Fisheries Regulation, 1995 No. 325*
1 Mar 2009	*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. This Marine Park includes ocean beaches.
1 Jan 2019	Introduction of Vessel Monitoring System (VMS).
New South Wales	
1902–1935	Numerous measures relating to fishing gear and practices; e.g., mesh size, net length, closed seasons, prohibition of explosives and poisons
17 Dec 1935	Introduced minimum legal size 12 inches (≈ 30.5 cm) TL *Fisheries and Oyster Farms Act 1935*
11 May 1951	Minimum length size increased to 14 inches (≈ 35.5 cm) TL. The mesh of permissible nets was raised from 3 inches to 3 1/4 inches (Thomson 1953)

Table 1.1 – *Continued on next page*

Table 1.1 – *Continued from previous page*

Date	Measure
2 Nov 1951	Minimum length of 13 inches (≈ 33 cm) TL (Thomson 1953)
20 Mar 1952	Minimum length of 14 inches TL from 1 March to 30 June and 13 inches TL from 1 July to 28 February (Thomson 1953)
1 Jul 1990	Minimum legal size 30 cm TL *Fisheries and Oyster Farms Act 1935-Regulation no. 357, 1990*
11 Jun 1993	Confirm minimum legal size 30 cm TL *Fisheries and Oyster Farms Act 1935-Regulation no. 199, 1993*
13 Jan 1995	Confirm minimum legal size 30 cm *Fisheries Management (General) Regulation, 1995-No. 11*
May 2002	Thirty Recreational Fishing Havens established. Resulted in 24% of all NSW estuarine waters being closed to commercial fishing, including several major systems
5 Feb 2007	Share management introduced for Ocean Beach Hauling. *Fisheries Management (Ocean Hauling Share Management Plan) Regulation 2006*. Minimum shareholdings required to fish
5 Feb 2007	Share management introduced for the Estuary General Fishery. *Fisheries Management (Estuary General Share Management Plan) Regulation 2006*. Minimum shareholdings required to fish
1 Dec 2017	Business Adjustment Program for ocean beach hauling. Ocean hauling managed by increased regional minimum share holdings. Crewing arrangements modified
1 Dec 2017	Business Adjustment Program for Estuary General Fishery. Mesh netting and hauling managed by regional minimum share holdings and effort quota

The stock was previously assessed with data through to 2016 by Lovett et al. (2019) and predicted an exploitable biomass at around 50.4% (with a confidence interval range of 43.7% to 57.3%) of virgin levels in 2016. Two additional scenarios were modelled in Lovett et al. (2019) testing lower and higher steepness giving exploitable biomass estimates at 51.4% and 51.0% and an overall confidence interval range of 42.4% to 60.4%. This assessment is intended to extend and complement the already available scientific documentation on the resource (Kesteven 1953; Virgona et al. 1998; Dichmont 1999; Smith et al. 2002; Bell et al. 2005; Lovett et al. 2019) and support the development of management procedures.

In 2021, the Queensland Department of Agriculture and Fisheries commissioned an update to the stock assessment for sea mullet. This assessment aims to determine the status of the eastern Australian (Queensland and New South Wales) biological stock. This report informs estimates of sustainable catches to ensure the fishery operates at sustainable levels and support the approved East Coast Inshore Fishery Harvest Strategy 2021–2026 under the Fisheries Act 1994 (Fisheries Queensland 2021).

This assessment contains updates to data and methodology that include:

- Stock Synthesis software was introduced to model the population and estimate parameters.
- Reporting of spawning stock biomass rather than exploitable biomass.

- The assessment modelled dynamics of the fishery into estuarine and ocean beach fishing sectors for each state. The previous assessment grouped Queensland and New South Wales together for each fishing sector.
- Alternate scenarios and sensitivity tests were performed.
- Stochastic recruitment deviations starting from 1982.

2 Methods

2.1 Data sources

The data in this assessment (Table 2.1) were used to determine catch rates, create total annual catches, and length and age compositions. Data were compiled annually in calendar years to align with abundance and reproduction peaks.

Table 2.1: Data sources compiled for input to the sea mullet population model

Data	Years	Source
Queensland catch	1925–1940	Kesteven (1942)
	1941–1950	Thomson (1953)
	1951–1980	Queensland Fish Board (QFB) (Halliday et al. 2007)
	1988–2020	Logbook data collected by Fisheries Queensland
New South Wales catch	1899–1941	Kesteven (1942)
	1940–1983	Historic data collected by New South Wales Department of Primary Industries, Fisheries
	1984–1997	Monthly logbook data collected by New South Wales Department of Primary Industries, Fisheries
	1997–2020	Monthly logbook data (with more detail on fishing methods) collected by New South Wales Department of Primary Industries, Fisheries
	2009–2020	Daily logbook data collected by New South Wales Department of Primary Industries, Fisheries
Queensland biological data	1999–2020	Department of Primary Industries and Fisheries (2007), Fisheries Queensland (2009), and Fisheries Queensland (2014)
New South Wales biological data	1990–2000, 2003–2019	New South Wales Department of Primary Industries, Fisheries
Lunar data	1988–2020	Continuous daily luminous scale of 0 (new moon) to 1 (full moon) (O'Neill et al. 2014)
Wind data	1988–2020	Bureau of Meteorology
Seasonality	1988–2020	Seasonal patterns corresponding to autumn, winter, spring and summer periods (Marriott et al. 2014)

2.1.1 Commercial

Queensland commercial data were sourced from the Fisheries Queensland compulsory logbook records, which began in 1988. These data contained daily entries where fishers recorded retained catch of sea mullet in kilograms and the geographic grid (30 or 6 minute scale) where the majority of it was taken.

Historical commercial data for Queensland (1925–1980) were sourced from published catches in Kesteven (1942), Thomson (1953) and annual reports by the Queensland Fish Board (QFB) state-owned marketing agency (Halliday et al. 2007). The QFB data were annual weights in kilograms with some regional information. Data from Thomson (1953) were annual catches in pounds and data from Kesteven (1942) were reported in units of boxes with an average weight in pounds per box.

New South Wales commercial logbook data were available from 1984. These data were recorded in three separate datasets comprised of monthly regional catch information for the period July 1984–June 1997, monthly regional catch information (including catch method and effort) from July 1997 onwards and detailed daily regional information from July 2009 onwards.

Historical commercial catch data were sourced from New South Wales historical records: 1984–1997 (provided monthly) in kilograms of fish by region and Kesteven (1942) which were reported in units of boxes with an average weight in pounds per box.

2.1.2 Biological data

Fishery dependent age and length compositions of sea mullet were monitored in New South Wales since 1994 and in Queensland since 1999. Biological information from samples were summarised for commercial catches of sea mullet. These data were provided in age group (years) fork length (mm).

In Queensland, long-established access to commercial catch is suitable for direct sampling of age and length information. Negligible catch from the recreational and indigenous sectors allows length and age information to be scaled to total catch, providing age and length structures representative of the fishery. In New South Wales, fisheries monitoring apply a similar spatially (one degree of latitude) and temporally (monthly) stratified sampling regime to produce data that are representative of fishery landings.

Queensland fisheries monitoring apply a scaling factor to the raw age and length data. When 100% of a fisher's catch cannot be sampled (i.e., when time constraints or circumstance do not permit each sea mullet in a catch to be individually measured), a representative sub-sample of the catch is measured and the percentage of the total catch that is sampled is recorded (Department of Primary Industries and Fisheries 2007; Fisheries Queensland 2009; Fisheries Queensland 2014). The raw length and age data are then scaled by the percentage of the catch sampled. The scaled length frequencies are then weighted according to the proportion of the total annual catch reported for each LTMP sampling region thereby ensuring that the derived age and length distributions are representative of the entire Queensland catch. The resulting total sample size from the scaling and weighting process are upweighted to total catch. Age and length inputs are then are scaled down considerably via the modelling process by Francis variance adjustments (see Section 2.5.3).

2.1.3 Other data

Although at least some of the 20+ species of Mugilidae found in Eastern Australia are caught by Indigenous, recreational and charter fisheries, these sectors were not considered in this assessment for *M. cephalus*. This was primarily due to the fact that the fish cannot be taken easily by hook and line and are not targeted or caught in any great number by recreational anglers (Prosser 2016). Traditional Indigenous catch is unknown.

2.2 Catch estimates

Commercial catch data (where available) were analysed to reconstruct the history of retained catch from 1899 until the end of 2020. This section describes how these data were reconstructed to create a history of sea mullet catch (Figure 1). A graphical representation of data used in the reconstruction is shown in Figure 2.1.

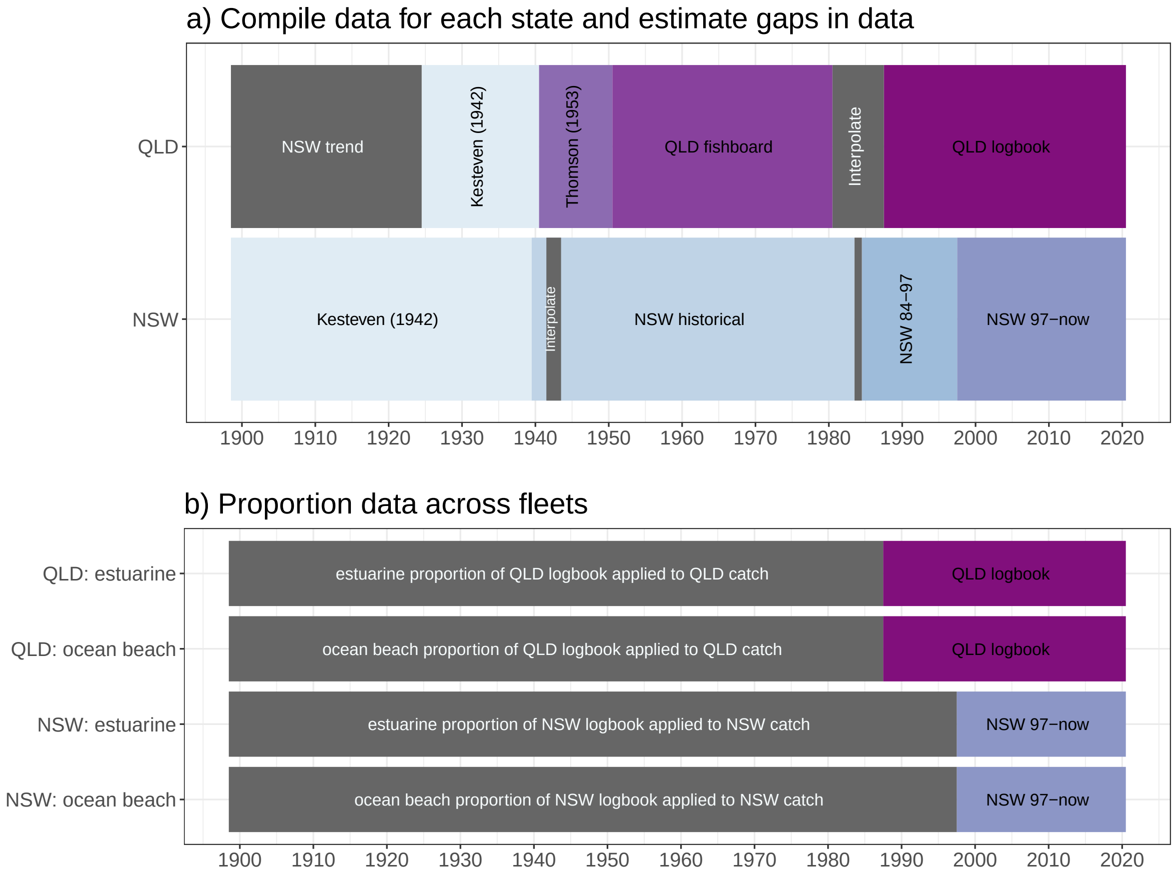

Figure 2.1: Data sources used for retained catch reconstruction of sea mullet for Queensland and New South Wales from 1899 to 2020

1. Compile data for each state:

   New South Wales

   1998–2020: *NSW 97–now* These data were split into ocean beach and estuarine fishing methods. 1997 data were excluded as it was only for the second half of 1997.
   1985–1997: *NSW 84–97* These data included the omitted 1997 data from the *NSW 97–now* dataset and excluded the 1984 data as it was only for the second half of 1984.
   1940–1983: *NSW historical* These data were in financial years and were placed into the calendar year 6 months earlier.
   1899–1939: *Kesteven (1942)* Data were reported annually in units of boxes with a weight in pounds per box. These were converted to metric tonnes.

   Queensland

   1988–2020: *QLD logbook* These data were split into ocean beach and estuarine fishing methods.
   1951–1980: *QLD fishboard* Annual data in kilograms converted to metric tonnes.
   1941–1950: *Thomson (1953)* Data were reported annually in pounds and then converted to metric tonnes.
   1925–1940: *Kesteven (1942)* Data were reported annually in units of boxes with a weight in pounds per box. These were converted to metric tonnes.

2. Estimate data in gaps:

   New South Wales
   1984: Interpolation from 1983 to 1985.
   1942–1943: Interpolation from 1941 to 1944.

   Queensland
   1981–1987: Interpolation from 1980 to 1988.
   1899–1924: 1925 Queensland catch multiplied by trend from New South Wales catch 1899–1925.

3. Proportion data across fleets:

   New South Wales
   Ocean beach 1899–1997: Retained catch from 1899–1997 was multiplied by the proportion of ocean beach fishing relative to total catch in the years 1998–2001.
   Estuarine 1899–1997: The remainder of the catch from 1899–1997 was allocated to estuarine fishing.

   Queensland
   Ocean beach 1899–1987: Retained catch from 1899–1987 was multiplied by the proportion of ocean beach fishing relative to total catch in the years 1988–1991.
   Estuarine 1899–1987: The remainder of the catch from 1899–1987 was allocated to estuarine fishing.

2.3 Abundance indices

Most commercial catches of sea mullet were by either gillnet or ocean beach net. Queensland and NSW daily logbook data on commercial catches (kg whole weight for commercial) of sea mullet per fishing-operation-day were used as an index of legal-sized fish abundance. Methods for sea mullet catch rate standardisations followed those outlined in Lovett et al. (2019) and Leigh et al. (2017). Zero catch values were not included in the analysis as no associated species were found using this methodology.

Data was collated into a single catch observation for each fisher-day combination, with processing including the following:

- Similar fishing methods were grouped together. In the early years of the Queensland database, fishing methods were not well distinguished. The process by which fishing methods were distinguished is outlined in Appendix A.
- 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, all catch for that day was assigned to the location with the greatest individual catch.
- Minor numbers of records with missing data in required fields were omitted.
- Fishers who fished in only one year during the period of analysis were omitted.
- Two sinusoidal variables were included to indicate lunar phases (lunar and lunar advanced by a quarter of a phase).
- Wind vectors were also added. These included linear vectors (north–south and east–west) and their quadratic components.

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, not fixed to 1. The models used to standardise catch rates were computed in the software R (R Core Team 2021, version 4.0.5) using the quasi-Poisson GLM function in the Stats package.

The general catch rate model equation is shown below (Equation 2.1). Variables that were accounted for in each catch rate model to determine the number of kilograms retained per day are shown in Table 2.2.

$$\log(DailyCatch) \sim Fisher + Year + Month + Location + Month : Location + Lunar + Wind\ (linear) + Wind\ (quadratic) + Mesh + Net + Shots - \text{Offset} \quad (2.1)$$

Table 2.2: Explanatory variables included in GLMs for each catch rate

Explanatory variable	QLD		NSW	
	Gillnet	**Ocean beach**	**Gillnet**	**Ocean beach**
fisher ID	yes	yes	yes	yes
calendar year	yes	yes	yes	yes
month	yes	yes	yes	yes
location	yes	yes	yes	yes
month:location	yes	yes	yes	yes
lunar terms	not significant	yes	yes	yes
linear wind terms	yes	yes	not significant	yes
quadratic wind terms	yes	yes	yes	not significant
mesh size	yes	yes	not available	not available
net size	yes	yes	yes	not available
number of shots	not available	not available	not available	yes
offset (number of fishers per location-day)	no	yes	no	yes

2.4 Biological information

2.4.1 Weight conversion

Fishery models are commonly structured by length (fork length) whereas commercial fishery catches are measured by weight. The following formula is used for converting fork length FL, in cm to weight W, in kg (Lovett et al. 2019):

$$W = 9.146 \times 10^{-6}\ FL^{3.134} \quad (2.2)$$

2.4.2 Growth

Von Bertalanffy growth curve parameters were sourced from Stewart et al. (2018). These parameters were based on the relationship:

$$L_a = L_\infty(1 - e^{-\kappa(a-t_0)}) \quad (2.3)$$

where $L_\infty = 43.7$ cm, $\kappa = 0.42$ year^{-1} and $t_0 = -0.68$ years for females and $L_\infty = 36.97$ cm, $\kappa = 0.60$ year^{-1} and $t_0 = -0.36$ years for males. The L_∞ parameters were given in fork length.

2.4.3 Fecundity

Fecundity (f) was input to the model as a function of age where:

$$f_a = [0, 0, 0.2377627, 0.6018496, 0.7043237, 0.7839743, 0.8441852, 0.8888603, 0.9215891, 0.9453562, \\ 0.9625102, 0.9748381, 0.9836709, 0.9899860, 0.9944942, 0.9977091, 1, 1]. \quad (2.4)$$

This vector of fecundity at age was obtained from calculations performed in Lovett et al. (2019).

2.5 Population model

An annual sex and age-structured population model was fitted to the data to determine the number of sea mullet in each year, and each age group and sex using the software package Stock Synthesis (SS; version 3.30.17.01). A full technical description of Stock Synthesis is given in Methot et al. (2019).

2.5.1 Model assumptions

For the base, assumptions for formulating inputs to the model included:

- The fishery began from an unfished state in 1899.
- The fraction of fish that are female at birth is 50%.
- Growth occurs according to the von Bertalanffy growth curve.
- The weight and fecundity of sea mullet are parametric functions of their size.
- The instantaneous natural mortality rate is constant for each sex and does not depend on age.
- Annual recruitment is a Beverton-Holt function of stock size. It was assumed deterministic before 1982 (for the base case) and stochastic between 1982 and 2021.

2.5.2 Model parameters

Parameters were estimated within the model where possible, to enable the best possible fit to available data. Uninformative priors were used.

The natural logarithm of unfished recruitment ($\ln(R_0)$) was estimated within the model. This parameter was the natural logarithm of the number of recruits in 1899.

Stock recruitment steepness (h) was unable to be estimated within the model. Attempts to estimate this parameter resulted in h hitting the upper bound of 1, a likelihood profile of h was performed (Appendix C.7). A base steepness of 0.66 was chosen for this assessment for ease of comparison with Lovett et al. (2019) and scenarios of higher (0.83) and lower (0.49) values from this assessment were also tested. In addition, a value of 0.57 was also tested as estimated by Thorson (2020) at the species level.

Growth curve parameters (Section 2.4.2) were fixed within the model for males and females. Coefficients of variation (CV) for young and old fish were estimated for each sex.

Total mortality is the rate of removal of fish from a population. Analysis presented in Stewart et al. (2018) concluded that total mortality values were different for males and females. Natural mortality rate (M) is the rate of the removal of fish from a population due to causes not associated with fishing (examples include predation or old age). Stewart et al. (2018) did not determine if M was different for each sex or if the difference in total mortality values was due to fishing. This parameter (M) was estimated in the model for each sex to keep in line with Lovett et al. (2019). A scenario with equal M for both sexes was also tested.

Random walk age-based selectivity parameters were estimated in the model, separate selectivity curves were estimated for the ocean beach and estuarine fleets. The random walk selectivity function was selected due to its similarity to the Richards function used in Lovett et al. (2019).

Recruitment deviations improved fits to composition data and abundance indices as variability in recruitment annually allowed for changes in the population on shorter time-scales than fishing mortality alone. It is noted that recruitment deviations started in the year 1989 in Lovett et al. (2019). Due to Stock Synthesis bias adjustment for recruitment deviations and the availability of increased diagnostic outputs, it is apparent that it is appropriate to start recruitment deviations from the year 1982 (Methot et al. 2011). Recruitment deviations starting from 1989 have been included as a scenario for comparison with Lovett et al. (2019).

2.5.3 Model weightings and parameter estimation

Data inputs were given equal weighting in the model. A Francis adjustment was applied to the age and length compositions within Stock Synthesis (Francis 2011). An additional variance to each catch rate coefficient of variation is calculated by Stock Synthesis and shown in the estimates tables (Punt 2019; Tuck 2014).

A Markov chain Monte Carlo (MCMC) was performed on all scenarios over 4 000 000 iterations with every 100th iteration saved to investigate the posterior defined by Stock Synthesis.

Convergence of the MCMC was monitored using a factor ($\hat{R}$) (Gelman et al. 1995). Success was determined for values $0.99 < \hat{R} < 1.01$ (Vehtari et al. 2020).

MCMC results were used to report spawning biomass estimates and catch targets.

2.5.4 Sensitivity tests and alternate scenarios

Seven additional model runs were undertaken to determine sensitivity to fixed parameters, assumptions and model inputs. Methodology was loosely derived from Burch et al. (2018).

Sensitivities were tested in four categories: steepness, one or two-sex natural mortality, start of recruitment deviations and von Bertalanffy parameters used. Each component was varied from the base case to test the difference such a change would make (Table 2.3).

Table 2.3: Summary of the sea mullet base case and scenarios (differences to the base case are highlighted in bold)

Model	h	M	rec dev	growth curve
base	0.66	two sex	1982	Stewart et al. (2018)
1	**0.49**	two sex	1982	Stewart et al. (2018)
2	**0.57**	two sex	1982	Stewart et al. (2018)
3	**0.83**	two sex	1982	Stewart et al. (2018)
4	0.66	**one sex**	1982	Stewart et al. (2018)
5*	0.66	two sex	**1989**	**Lovett et al. (2019)**
6	0.66	two sex	**1989**	Stewart et al. (2018)
7	0.66	two sex	1982	**Lovett et al. (2019)**

*similar to Lovett et al. (2019) assessment

2.5.5 Forward projections

Stock Synthesis's forecast sub-model was used to provide forward projections of biomass, future catch targets and time required to reach target, following a harvest control rule (Fisheries Queensland 2021). The East Coast Inshore Fishery Working Group has proposed an initial target of 50% due to the cross jurisdictional nature of the stock, hence a 20:50:50 harvest control rule has been used for this assessment (Fisheries Queensland 2019).

The harvest control rule has a linear ramp in fishing mortality between 20% spawning biomass, where fishing mortality is set at zero, and 50% spawning biomass, where fishing mortality is set at the equilibrium level that achieves 50% biomass (F_{B50}). Below 20% spawning biomass, fishing mortality remains set at zero, and above 50% spawning biomass fishing mortality remains set at F_{B50} (Figure 2.2). This shifting rate starts out small, which enables the stock to recover more quickly and means that catches are not impacted for as long.

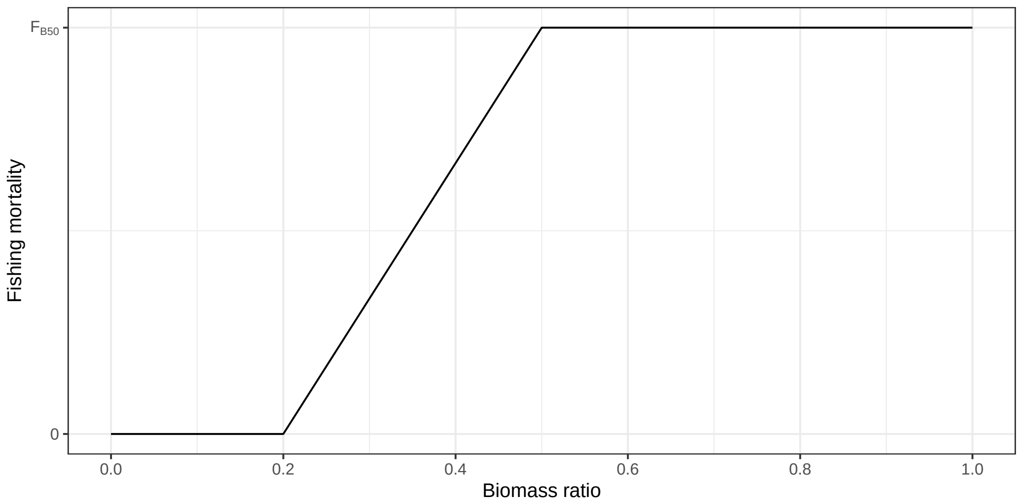

Figure 2.2: The harvest control rule (Fisheries Queensland 2021; Fisheries Queensland 2019)

3 Results

3.1 Model inputs

Figure 3.1 summarises the estimated data used as input to the model.

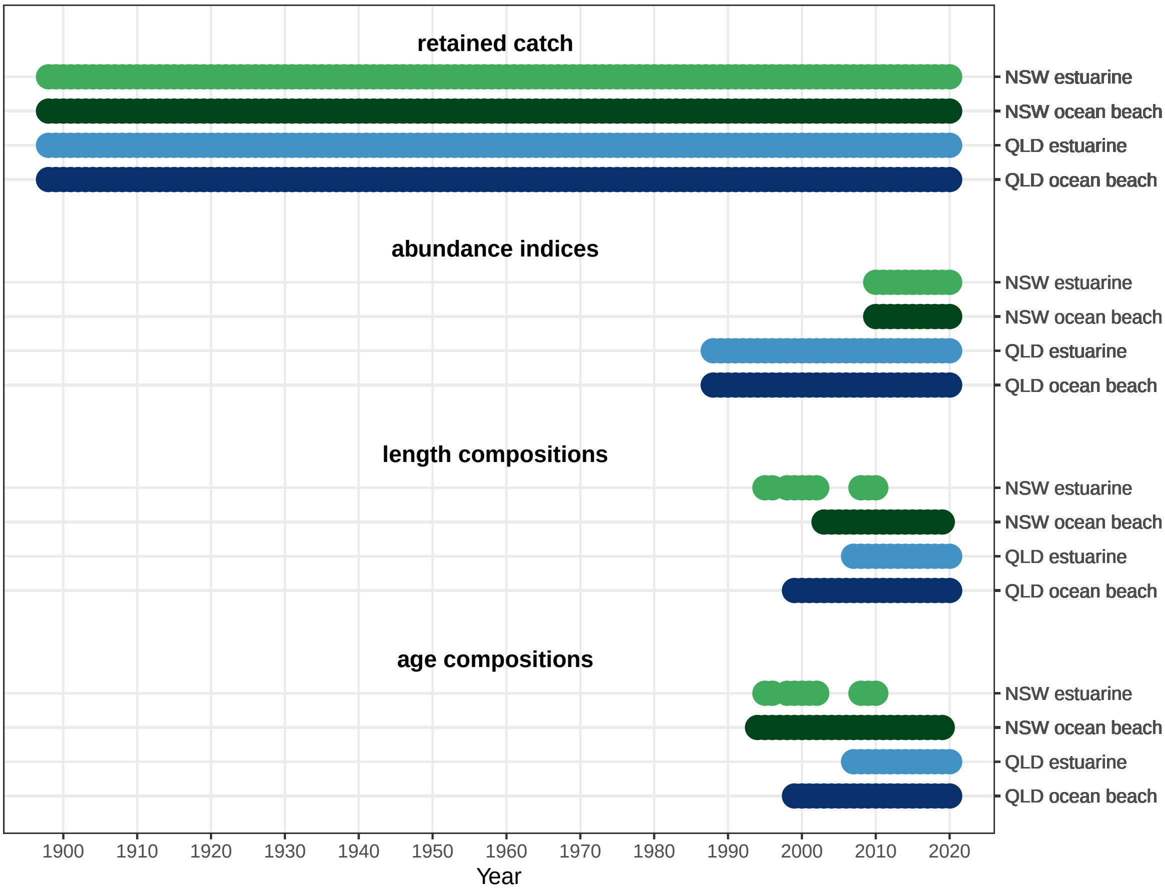

Figure 3.1: Data presence by year for each category of data type and Stock Synthesis fleet for the sea mullet model

3.1.1 Catch estimates

The total retained catch consisted of catch from four fleets: Queensland estuarine, Queensland ocean beach, New South Wales estuarine and New South Wales ocean beach (Figure 3.2). Catches for the period 1910–1985 are consistently around 4000 t. Following this period catches increased to a peak of around 7000 t in 1994 and 1998, and have since declined to 4102 t in 2020.

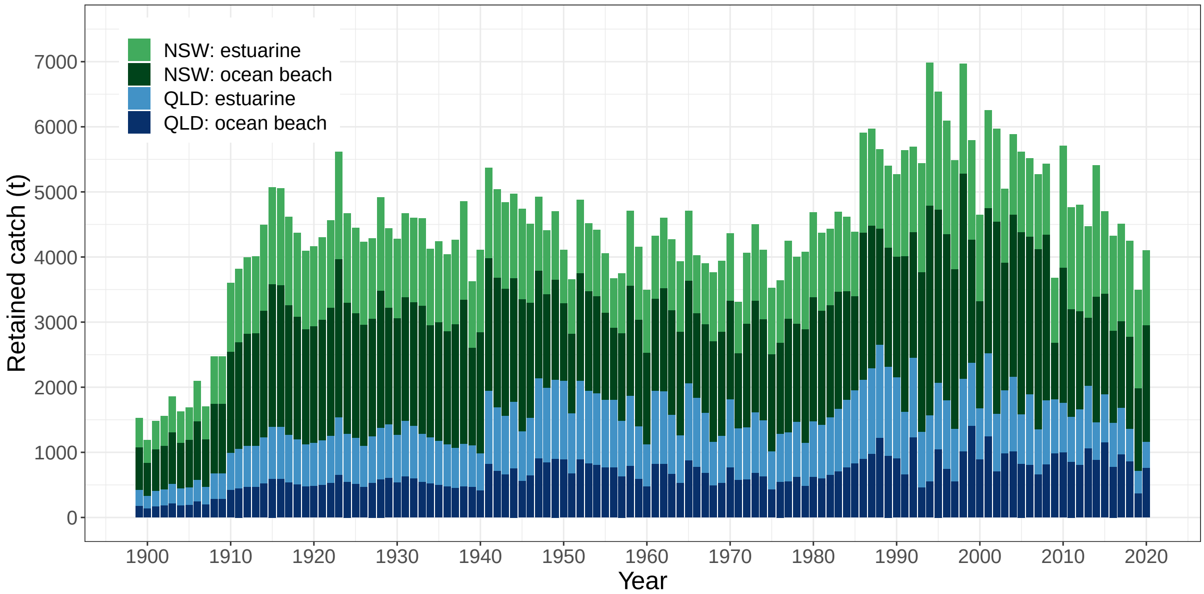

Figure 3.2: Annual estimated retained catch between 1899 and 2020 for sea mullet

Over the last 5 years (2016–2020) total retained catch averaged 4136 t per year, including 1272 t (30.8%) for Queensland and 2864 t (69.2%) for New South Wales. Retained catch shares for 2020 are shown in Table 3.1.

Table 3.1: 2020 catch and catch shares for each fishing sector

Sector	Retained catch (t)	Share (%)
Queensland	1164	28.4
Estuarine	405	9.9
Ocean beach	759	18.5
New South Wales	2938	71.6
Estuarine	1152	28.1
Ocean beach	1786	43.5

3.1.2 Abundance indices

Standardised catch rates were calculated to represent trends in abundance for the sea mullet stock. Four separate catch rate analyses were conducted: one for each of Queensland commercial gillnet and ocean beach and one for each of New South Wales commercial gillnet and ocean beach.

Queensland gillnet catch rates show an initial decline to 1993 followed by a flat long term trend (Figure 3.3a). Ocean beach catch rates for Queensland display a general decline to 2002 followed by an increasing trend to 2018 and then a decrease to 2020 (Figure 3.3b).

New South Wales gillnet catch rates show a relatively level trend with low points in 2015 and 2016 (Figure 3.3c). Ocean beach catch rates for New South Wales display a marked increase from 2017 to 2020 (Figure 3.3d).

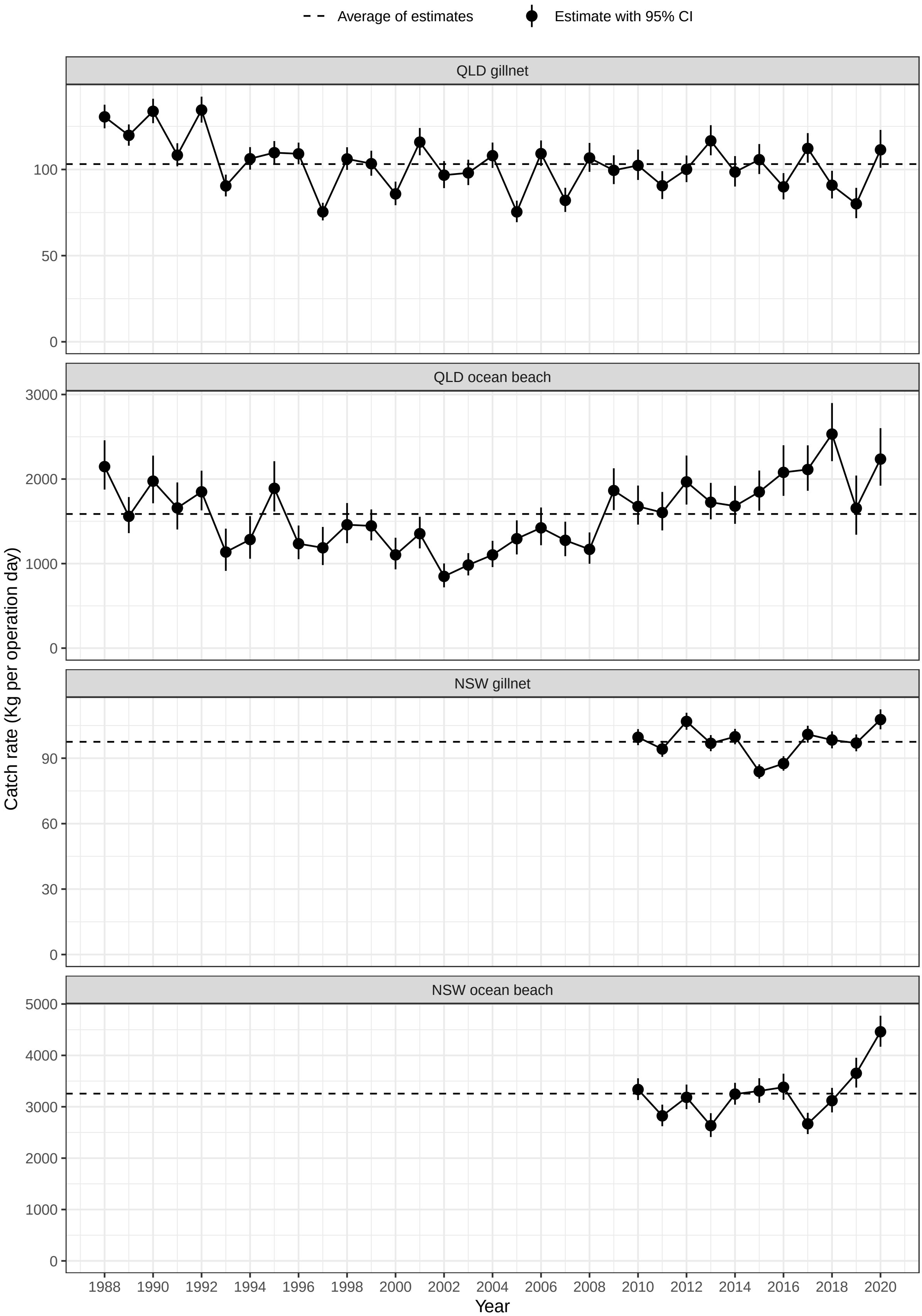

Figure 3.3: Annual standardised catch rates for Queensland gillnet and ocean beach caught sea mullet between 1988 and 2020 and New South Wales gillnet and ocean beach caught sea mullet between 2010 and 2020

3.1.3 Age and Length composition data

Age and length composition data (as well as their fit to the model), are shown in Appendices C.2.2 and C.2.3.

3.2 Model outputs

3.2.1 Model parameters

Several parameters were estimated for the base case model (Table 3.2). The full list of estimated parameters for the base model in optimise mode is given in Section C.1.

Table 3.2: MCMC estimated parameters for the sea mullet base population model

Parameter	Description	Value	2.5%	97.5%
M_{female}	Natural mortality for females	0.312	0.268	0.356
M_{male}	Natural mortality for males	0.281	0.237	0.325
$\ln(R_0)$	Logarithm of the number of recruits in 1899	10.453	10.251	10.671
σ_R	Variability of recruitment into the population	0.268	0.222	0.332
growth$(CV)^{\text{young}}_{\text{female}}$	growth curve coefficient of variation for young females	0.074	0.072	0.076
growth$(CV)^{\text{old}}_{\text{female}}$	growth curve coefficient of variation for old females	0.108	0.104	0.112
growth$(CV)^{\text{young}}_{\text{male}}$	growth curve coefficient of variation for young males	0.042	0.041	0.043
growth$(CV)^{\text{old}}_{\text{male}}$	growth curve coefficient of variation for old males	0.111	0.108	0.114
Q(extra SD)$_{\text{QLD estuarine}}$	extra standard deviation for QLD estuarine catchability	0.090	0.080	0.096
Q(extra SD)$_{\text{QLD ocean beach}}$	extra standard deviation for QLD ocean beach catchability	0.095	0.090	0.098
Q(extra SD)$_{\text{NSW estuarine}}$	extra standard deviation for NSW estuarine catchability	0.073	0.056	0.087
Q(extra SD)$_{\text{NSW ocean beach}}$	extra standard deviation for NSW ocean beach catchability	0.082	0.068	0.092
A_1(estuarine)	Selectivity parameter at age = 1	5.910	0.287	11.698
A_2(estuarine)	Selectivity parameter at age = 2	9.332	5.904	11.866
A_3(estuarine)	Selectivity parameter at age = 3	4.055	3.922	4.193
A_4(estuarine)	Selectivity parameter at age = 4	0.606	0.556	0.659
A_{male}(estuarine)	Selectivity male offset parameter	5.919	0.310	11.684
A_1(ocean beach)	Selectivity parameter at age = 1	6.028	0.320	11.701
A_2(ocean beach)	Selectivity parameter at age = 2	8.557	4.550	11.827
A_3(ocean beach)	Selectivity parameter at age = 3	3.974	3.759	4.205
A_4(ocean beach)	Selectivity parameter at age = 4	2.363	2.303	2.424
A_5(ocean beach)	Selectivity parameter at age = 5	1.173	1.137	1.208
A_6(ocean beach)	Selectivity parameter at age = 6	0.595	0.566	0.624
A_{male}(ocean beach)	Selectivity male offset parameter	5.968	0.299	11.697

Likelihood profiles can be used to determine whether parameters have been fixed at appropriate values. Integrated stock assessments use numerous data sources which may be in conflict with each other, but likelihood profiles provide a tool to determine these conflicts (Punt 2018). A likelihood profile was calculated to explore the assumption on steepness of 0.66 (Appendix C.7). The likelihood profile supports that steepness was unable to be estimated within the model as the total likelihood tended towards 1 and additionally data sets were conflicting.

3.2.2 Model fits

Model fits to data including abundance indices, and age and length compositions are shown in Appendix C.2. MCMC convergence statistics, comparisons and trace plots are presented in Appendix C.3.

3.2.3 Biomass

The spawning biomass trajectory through time was determined as a proportion relative to an assumed unfished spawning biomass in 1899 (Figure 3.4). The biomass trajectory shows that biomass initially declined in the early 1900s during the start of the fishery and then remained relatively steady between around 50% and 60% until peaking in the late 1970s. This peak in the late 1970s coincided with a low point in catches in the mid-1970s. Following this, biomass declined coinciding with an increase in fishing pressure. The addition of recruitment deviations to the model since 1982 has revealed a cyclic fluctuation in biomass. The model has predicted that spawning biomass at the start of 2021[1] is around 37% of virgin spawning biomass (with a confidence interval ranging 30 % to 45 %).

The relationship between the spawning biomass estimate and fishing mortality over time are presented in Appendix C.4.

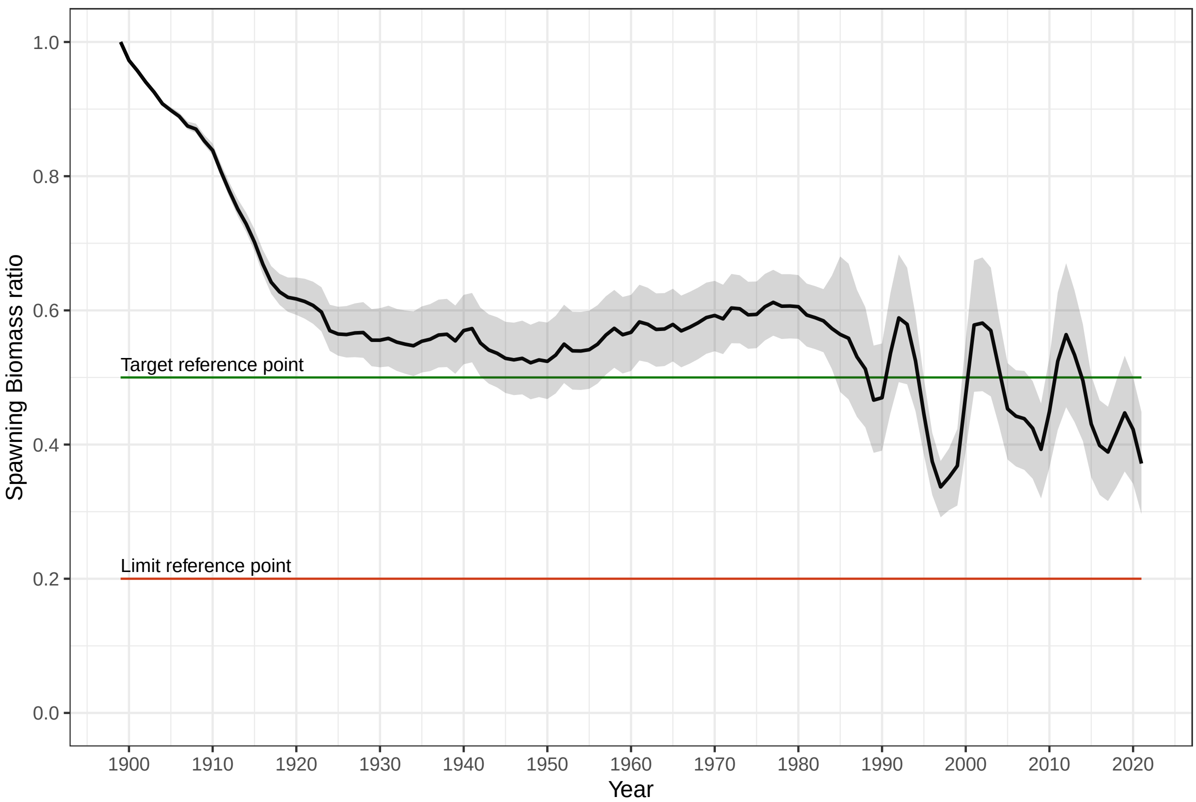

Figure 3.4: Predicted spawning stock biomass trajectory relative to unfished, from 1953 to 2021

[1] Stock Synthesis reports spawning stock biomass at the beginning of each year. Following this convention, the spawning stock biomass estimate is reported for 2021, the year after the input data end (2020).

3.2.4 Catch targets

Catch targets have been calculated to spawning stock biomass at the 50% target reference point for the base model, and a number of sensitivity test models, resulting in a recommended biological catch (RBC) for all sectors and jurisdictions (Queensland and New South Wales).

The retained catch consistent with a biomass ratio of 50% (a proxy for maximum economic yield) was estimated at 4801 t across all sectors and jurisdictions (Table 3.3). Maximum sustainable yield (MSY) was estimated at 5353 t per year (Figure 3.5).

Table 3.3: Current and target indicators for Australian east coast sea mullet

Indicator	Estimate
Biomass$^{\diamond}$ (relative to unfished) at the start of 2021	37% (31% to 41%)
Target biomass (relative to unfished)	50%
Biomass (relative to unfished) at MSY*	33%
MSY	5353 t
Retained catch component of MSY	5353 t
Retained catch at 50% biomass target	4801 t
RBC† for 2021 to achieve target	2541 t
Time to achieve target	> 8 years

$^{\diamond}$ Biomass is defined to be spawning stock biomass.
* MSY (maximum sustainable yield) is defined to be the maximum sustainable dead catch—that is, retained catch plus catch that dies following discarding.
† RBC (recommended biological catch) is the recommended catch according to the control rule. This is dead catch: retained catch plus catch that dies following discarding.

The equilibrium yield informs on the productivity of the stock at different biomass levels (Figure 3.5).

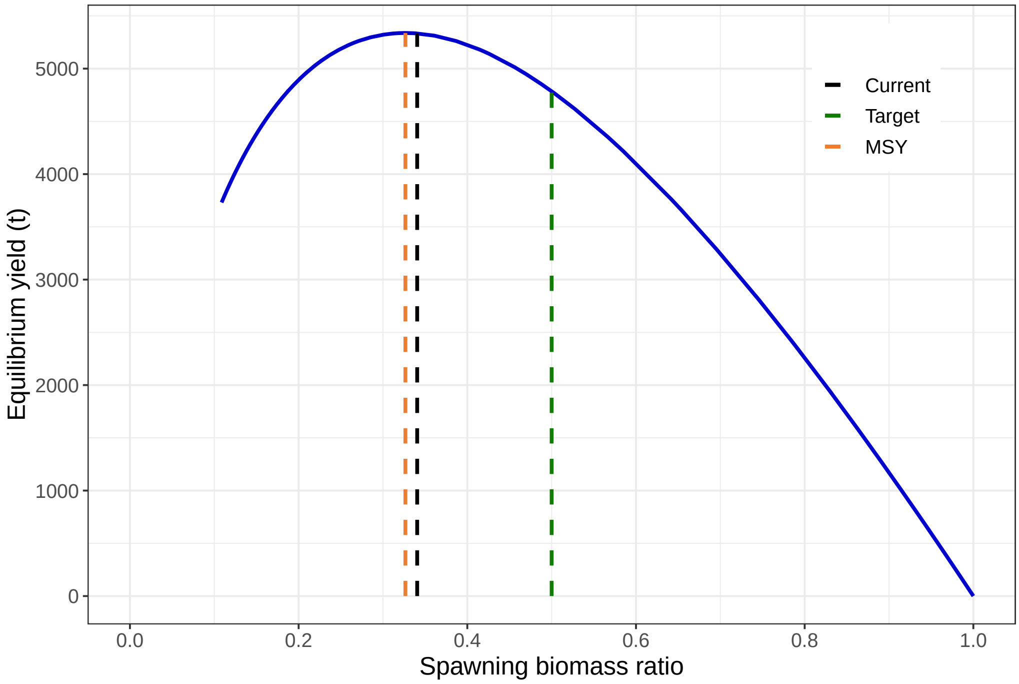

Figure 3.5: Equilibrium yield curve for sea mullet

Modelling estimates a RBC of about 2541 t initially to allow stocks to return to 50% spawning biomass. This RBC could then be increased to 4801 t over time.

These RBCs are the first in a schedule of projected recommended catches for Queensland's Harvest Strategy 2021–2026 (Fisheries Queensland 2021), using a 20:50:50 harvest control rule (Fisheries Queensland 2019). The schedule is presented here for the base case (Table 3.4).

Table 3.4: Estimated total catches and biomass ratios of sea mullet for the base case to return to and maintain the stock at the target reference point of 50% unfished spawning biomass, following a 20:50:50 harvest control rule (Fisheries Queensland 2021; Fisheries Queensland 2019)

Year	Retained catch (t)	Biomass ratio
2021	2541	0.37
2022	2955	0.4
2023	3499	0.43
2024	3930	0.45
2025	4212	0.46
2026	4340	0.47
2027	4417	0.47
2028	4466	0.48
2029	4492	0.48
2030	4508	0.48

3.3 Sensitivities

Table 3.5, and Figure 3.6 show the differences between model runs where sensitivities to steepness (h), natural mortality (M), recruitment deviations and von Bertalanffy parameters have been tested. Results from these scenarios give spawning biomass ratios ranging from 31% to 41% (and a confidence interval range of 20% to 49%).

Table 3.5: Summary of the sea mullet base case and scenario and sensitivity tests (changes are highlighted in bold)

Model	h	M_{female}	M_{male}	rec dev	growth [1]	B_{2021}	H_{50} (t)	RBC (t)
base	0.66	0.312	0.281	1982	a	0.37	4801	2541
1	**0.49**	0.324	0.294	1982	a	0.31	4568	1277
2	**0.57**	0.316	0.285	1982	a	0.34	4663	1849
3	**0.83**	0.309	0.279	1982	a	0.41	5054	3632
4	0.66	0.304	—	1982	a	0.36	4739	2291
5 [2]	0.66	0.293	0.236	**1989**	**b**	0.37	4506	2079
6	0.66	0.318	0.288	**1989**	a	0.39	4894	2978
7	0.66	0.256	0.245	1982	**b**	0.32	4357	1254

1. growth curve (von Bertalanffy): **a** Stewart et al. (2018), **b** Lovett et al. (2019)
2. similar to Lovett et al. (2019) assessment

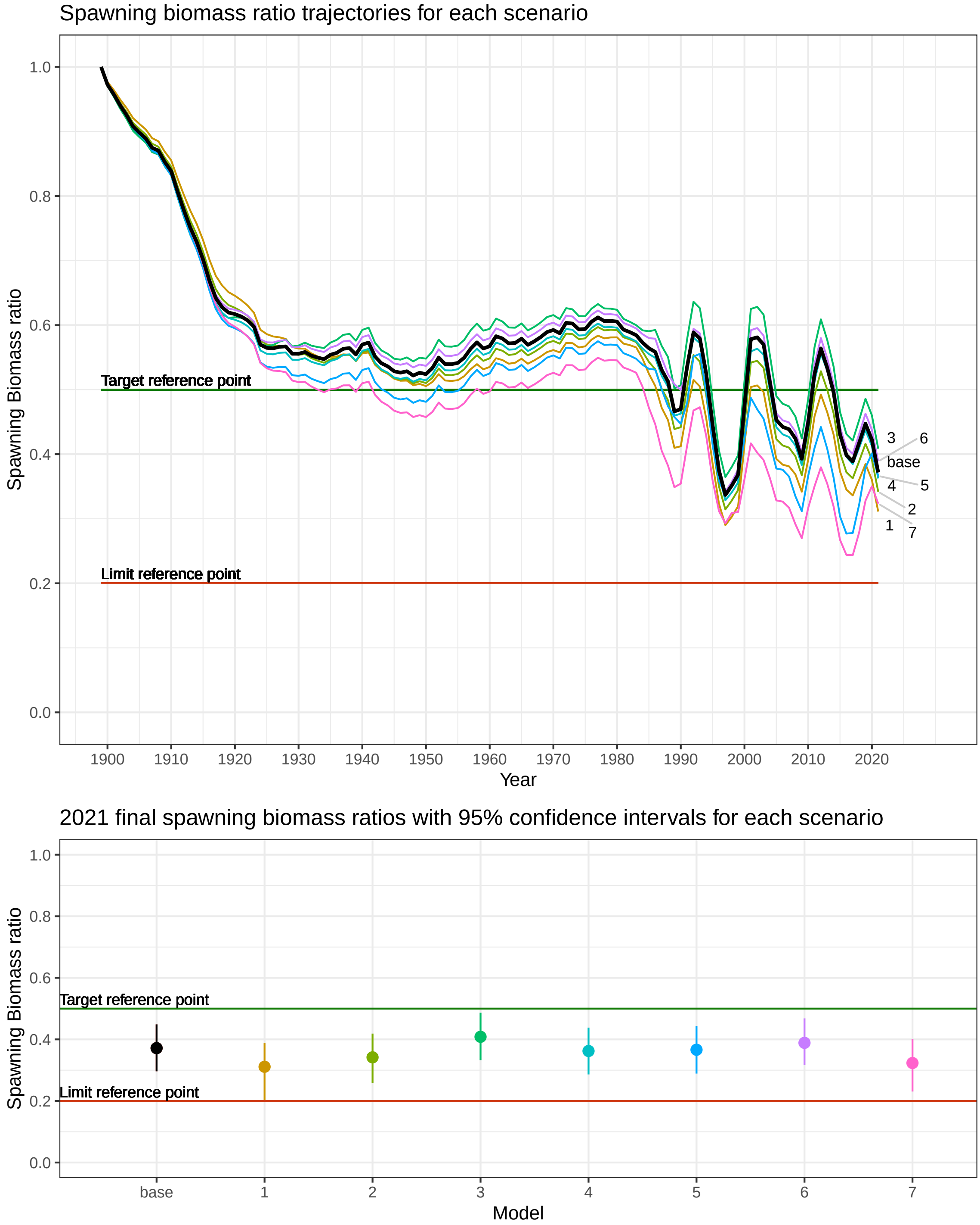

Figure 3.6: Spawning biomass ratio (relative to virgin) scenarios for sea mullet, from 1899 to 2021—scenarios are 1) $h = 0.49$, 2) $h = 0.57$, 3) $h = 0.83$, 4) single M, 5) growth curve from past assessment and recruitment deviations start 1989, 6) recruitment deviations start 1989, 7) growth curve from past assessment

4 Discussion

The Queensland Sustainable Fisheries Strategy aims to build and maintain fisheries in the long term (Department of Agriculture and Fisheries 2017). The aim is to implement management that would retain at or return the stock to the sea mullet tier 2 species target reference point of 50% unfished spawning biomass (Fisheries Queensland 2021; Fisheries Queensland 2019).

Historical records show a long standing sea mullet catch of around 4000 t from around 1910 to the mid-1980s indicating that catches of this size were sustainable at the time. Since this time, catches have peaked at around 7000 t in the mid-1990s and have since declined to 4102 t in 2020 (Figure 3.2). It should be noted that if high fishing pressure since the mid-1980s has caused the stock reduction, catches similar to pre-1980 level of fishing pressure may not be sustainable until a period of decreased fishing pressure has occurred (Section C.4).

Standardised catch rates showed differing trends for each fishing method. Gillnetting catch rates have shown a long term level trend. Ocean beach catch rates have shown an increasing trend in recent years. Model results were mainly driven by catch and recruitment (derived from biological parameters and data).

Results show that spawning biomass is currently at around 37% of virgin levels and is required to return to target levels under the East Coast Inshore Fishery Harvest Strategy 2021–2026 for tier 2 species (Fisheries Queensland 2021). The yield consistent with maintaining a biomass ratio of 50% was estimated at 4801 t per year and MSY was estimated at 5353 t per year and across all sectors and jurisdictions. The default harvest strategy harvest control rule suggests a target of 2541 t initially to return spawning biomass back to 50%. Forward projections of the model suggest that returning to a 50% spawning biomass would take around 8 years if catches are reduced to the recommended levels outlined in Table 3.4.

Exploratory analysis into exploitable biomass for this assessment produced similar trends to spawning biomass and therefore was not explored further.

4.1 Performance of the population model

This stock assessment used an age and length-based model with an annual time step, with age-based selectivities for each fishing method. Data inputs included total catch (Queensland estuarine and ocean beach, and New South Wales estuarine and ocean beach), standardised catch rates (Queensland gillnet and ocean beach, New South Wales gillnet and ocean beach), fishery-dependent length compositions and age data.

The MCMC routine performed well with a convergence statistic of $\hat{R}$ = 1.000028 (Appendix C.3). The model achieved good fits to age and length composition data. Although catch rates showed similar overall trends for each fishing method, year to year fluctuations were not the same and hence fits to individual catch rates were not close.

A number of sensitivities were tested to better understand which assumptions and parameters are most influential on the model (Section 3.3).

The largest changes to the outcome during scenario testing were achieved with the differing steepness (h) values of 0.49, and 0.57 and 0.83. The likelihood profile on h (Figure C.17) indicates that steepness cannot be estimated and hence it was important to test a range of options.

Sex specific natural mortality rates were estimated at 0.312 for females and 0.281 for males. The single M parameter for both sexes was estimated at 0.304 which is close to values achieved for each sex.

Differing start years for recruitment deviations were tested. The starting year of 1982 as used in the base case is the better option (see Section 2.5.2) however it was necessary to test the effect of using 1989 as a start year for comparison with Lovett et al. (2019).

There have been some concerns on the validity of using ocean beach catch rates as an index of fish abundance (Leigh et al. 2017). The major form of fishing effort for this method is search time, which is not recorded. It was considered important however, to include gillnet and ocean beach catch rates in the population model as gillnet and ocean beach catch rates are not independent of each other (Lovett et al. 2019).

As with Lovett et al. (2019), cyclic fluctuations were found in the biomass trajectory from the mid 1980s. However, the peaks and troughs from these cyclic fluctuations did not match all of those found in Lovett et al. (2019). Catch rates did not show strong evidence of cyclic behaviour. A decision was made to treat the cyclic patterns in the age-length data as real, and therefore to implicitly down weight the catch rate contributions. It is possible however, that these cyclic patterns are at least partly spurious. This will be discussed further in Section 4.2.3. Regardless of the presence of a cyclic trend, the overall pattern for the last 30 years has been one of overall decline.

Model limitations of note include:

- The productivity parameter “steepness” (h) was fixed and a likelihood profile confirmed the model was unable to estimate this parameter. The results indicated the model was not highly sensitive to this assumption (Section 3.3).
- Regional variation in biological characteristics has not been taken into account.
- Estimation of von Bertalanffy growth parameters were not sensible and published values were used.

These limitations suggest further analysis and development will improve model performance (see Section 4.2.3).

4.2 Recommendations

4.2.1 Research and monitoring

Monitoring data in the form of fishery-dependent length and age data were advantageous to this assessment. In particular, data collected in recent years by the Queensland Fishery Monitoring team and New South Wales Department of Primary Industries were of high quality. Continued monitoring of sea mullet age and length information that are representative of the fishery is important for the ongoing assessment and management of sea mullet.

Important estuaries in the northern part of the Queensland stock range (Bundaberg to Noosa) have experienced reduced catches, possibly due to environmental changes (Lovett et al. 2019). This has not yet been investigated. Targeted research into the impacts of environmental changes on sea mullet would increase understanding and benefit future assessments and management of the fishery.

4.2.2 Management

Stock biomass levels are currently below the target reference point (as defined in the East Coast Inshore Fishery Harvest Strategy 2021–2026 for tier 2 species) of 50% of unfished spawning stock biomass and above the limit reference point of 20% of unfished spawning stock biomass.

The catch consistent with a biomass ratio of 50% (a proxy for maximum economic yield) was estimated at 4801 t per year, and maximum sustainable yield was estimated at 5353 t for all sectors and jurisdictions. The assessment, following the East Coast Inshore Fishery Harvest Strategy 2021–2026 for tier 2 species, recommends lower biological catches for approximately 8 years.

The recommended discount factor for this assessment is 0.91 based on a qualitative tier assignment process and Ralston et al. (2011) (σ is 0.36, P^* (risk aversion) is 0.4). Applying this gives a discounted 2021 retained catch of 2312 t.

4.2.3 Assessment

Limitations with the performance of the current model have been discussed in this document. Specific recommendations for a future sea mullet assessment include:

- Investigation of the cyclic biomass trend. Methods used could be data weighting to put more emphasis on catch rates or limiting amplitude of recruitment deviations.
- Investigation and analysis of methods to improve ocean beach catch rates.
- Investigate methods of parameter reduction and model simplification such as using a single M parameter to improve model convergence and stability.

4.3 Conclusion

This assessment has estimated the status of the eastern Australian sea mullet stock. Analysis suggests that spawning biomass has declined and is currently at around 37% ((31% to 41% range across scenarios) in 2021. The study presents biological catch levels that would be required under the East Coast Inshore Fishery Harvest Strategy 2021–2026 for tier 2 species to begin returning the stock to levels consistent with 50% of unfished biomass.

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Appendix A Specifying sea mullet fishing methods in Queensland logbooks

In the early years of Fisheries Queensland logbook reporting, fishing methods were not always recorded as accurately as they are today. Many entries were recorded as a default of unspecified gillnetting—i.e., fishing method code (FMC) 04.

The method shown below was developed by the Fishery Monitoring team to tease out obvious tunnel netting, haul netting and ocean beach netting from gillnetting for catches with the unspecified netting category. For catch rate analysis, only the gillnet and ocean beach fishing methods are used. For catch estimates, all fishing methods that are not ocean beach are grouped as 'estuarine'.

Steps to correct fishing methods should be done in the following order:

1. Keep ocean beach as is for dates 1 April to 31 August:
    - records with a FMC of either 34 or 234 with dates from April to August are assumed to be ocean beach
2. Correct gillnetting that should be ocean beach:
    - records with a FMC of 04 that have been fished from April to August in ocean beach only grids[1] are assumed to be ocean beach
    - records with a FMC of 04 that have been fished from April to August in ocean beach grids[2] with a catch weight $>$ 1000 kg are assumed to be ocean beach
3. Correct haul netting that should be ocean beach:
    - records with a FMC of 64 that have been fished from April to August in ocean beach grids[2] with a catch weight $>$ 1000 kg are assumed to be ocean beach

[1] Ocean beach only grids refer to grids and sites: 10W33, 10W37, 10W39, 12W34, 12W35, 12W36, 13W33, 13W34, 13W35, 13W36, 14W32, 14W33, 15W37, 16X37, 16X38, 17W33, 17W34, 17W35, 17W36, 17X37, 18W33, 18W34, 18W36, 19W32, 19W33, 19W36, 1W34, 1X37, 1X38, 1X39, 21X36, 21X37, 21X38, 22W33, 22W34, 22W35, 22W36, 22X37, 23W31, 23W33, 23W34, 23W35, 23W36, 24W31, 24W32, 24W36, 25W32, 25W36, 2W34, 2W35, 2W36, 2X38, 3W32, 3W34, 3W35, 3W36, 4W32, 4W33, 5W33, 5W37, 6W34, 6X37, 6X38, 6X39, 7W34, 7W35, 7X39, 8W32, 8W33, 8W34, 8W35, 8W36, 9W32, 9W33, W31, X36, X37, X38, X39.

[2] Ocean beach grids refer to those grids and sites in ocean beach only plus: 10W38, 11W34, 11W35, 13W32, 15W38, 16W34, 16W35, 18W32, 1W36, 20W37, 20W38, 21W35, 23W32, 25W37, 25W38, 3W37, 4W37, 5W38, 5W39, 6W35, 6W36, 7W36, W32, W33, W34, W35, W36, W37, W38, W39.

Appendix B Biological data

B.1 Age and length sample sizes

Sample sizes for age (Table B.1) and length (Table B.2) data collected are input to the model to form a starting point for data set weighting.

Table B.1: Raw sample sizes of aged fish input to the model for sea mullet

Year	QLD estuarine	QLD ocean beach	NSW estuarine	NSW ocean beach
1994				107
1995			789	734
1996			437	523
1997				55
1998			962	1022
1999		590	409	601
2000		599	908	563
2001		590	1824	1191
2002		599	233	736
2003		489		434
2004		499		196
2005		499		552
2006		595		607
2007	775	800		744
2008	747	992	256	573
2009	691	841	415	475
2010	763	638	442	619
2011	896	693		419
2012	920	789		612
2013	1221	998		630
2014	775	947		630
2015	946	735		390
2016	667	1093		595
2017	455	674		615
2018	434	633		836
2019	617	400		658
2020	459	600		

Table B.2: Raw sample sizes of fish lengths input to the model for sea mullet

Year	QLD estuarine	QLD ocean beach	NSW estuarine	NSW ocean beach
1995			789	
1996			437	
1998			962	
1999		2904	409	
2000		2400	908	
2001		2691	1824	
2002		2399	233	
2003		1545		1649
2004		2762		1076
2005		2000		4629
2006		7232		3232
2007	3392	3186		3195
2008	3163	4173	256	2349
2009	2876	5099	415	2291
2010	3415	4005	442	2919
2011	3644	3795		1445
2012	3853	4981		2984
2013	5198	6604		2835
2014	775	949		2913
2015	948	736		1706
2016	670	1098		1463
2017	459	676		2235
2018	439	638		3907
2019	618	400		3566
2020	460	600		

B.2 Biology

Age-based biological schedules input to the population model are shown in Figure B.1. The growth curve shown in Figure B.1(c) also shows the variance of fish growth input to the population model.

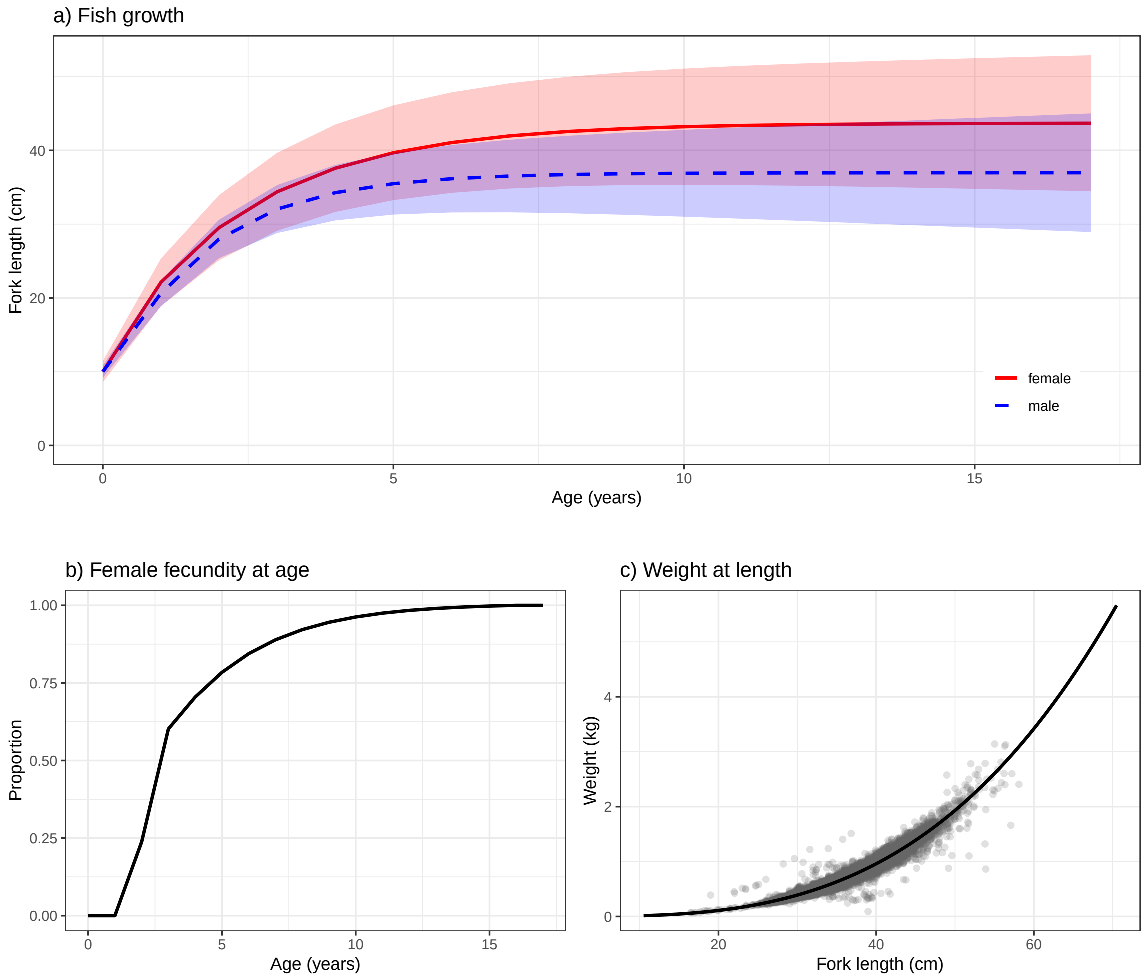

Figure B.1: Sea mullet age-based biological schedules for a) growth, b) fecundity and c) fish weight

Appendix C Model outputs

C.1 Parameter estimates

The model estimates parameters within the model incrementally. Each estimated parameter has an initial value and an upper and lower bound (Max and Min). The model will at first estimate only those parameters with a Phase value of 1, keeping other parameters fixed at the initial value. Once the model has reached a best solution, it will then open up the next phase and again estimate all parameters of that phase value and lower. This process will continue until all parameters are estimated and a best solution is found.

Table C.1 displays the model setup for each parameter and its corresponding estimated values and outputs in optimise mode.

Table C.1: Estimated parameters for the sea mullet base population model in optimise mode

Parameter	Estimate	Phase	Min	Max	Initial value	Standard deviation	Gradient
M_{female}	0.30	9	0.010	0.99	0.26	0.0242	0.0000385331
M_{male}	0.27	9	0.000	0.99	0.26	0.0242	0.0000373654
$\ln(R_0)$	10.43	1	3.000	31.00	14.00	0.1145	-0.0004602870
σ_R	0.34	4	0.000	2.00	0.30	0.0444	0.0000102007
growth$(CV)^{\text{young}}_{\text{female}}$	0.07	3	0.010	5.00	0.10	0.0009	-0.0000081292
growth$(CV)^{\text{old}}_{\text{female}}$	0.11	3	0.010	5.00	0.10	0.0021	-0.0000039263
growth$(CV)^{\text{young}}_{\text{male}}$	0.04	3	0.010	5.00	0.10	0.0006	-0.0000019970
growth$(CV)^{\text{old}}_{\text{male}}$	0.11	3	0.010	5.00	0.10	0.0016	-0.0000018197
Q(extra SD)$_{\text{QLD estuarine}}$	0.09	5	0.001	0.10	0.00	0.0039	-0.0000000056
Q(extra SD)$_{\text{QLD ocean beach}}$	0.10	5	0.001	0.10	0.00	0.0020	-0.0000000111
Q(extra SD)$_{\text{NSW estuarine}}$	0.07	5	0.001	0.10	0.00	0.0088	0.0000000080
Q(extra SD)$_{\text{NSW ocean beach}}$	0.08	5	0.001	0.10	0.00	0.0063	0.0000000125
A_1(estuarine)	6.00	4	0.000	12.00	0.10	134.1610	-0.0000000018
A_2(estuarine)	11.45	4	0.000	12.00	0.10	12.9460	0.0000000231
A_3(estuarine)	4.04	4	0.000	12.00	0.10	0.0707	-0.0000002070
A_4(estuarine)	0.60	4	0.000	12.00	0.10	0.0273	-0.0000022786
A_{male}(estuarine)	6.00	4	0.000	12.00	0.10	134.1610	-0.0000000018
A_1(ocean beach)	6.00	4	0.000	12.00	0.10	134.1610	-0.0000000018
A_2(ocean beach)	10.28	4	0.000	12.00	0.10	29.2647	-0.0000000064
A_3(ocean beach)	3.96	4	0.000	12.00	0.10	0.1143	-0.0000000480
A_4(ocean beach)	2.36	4	0.000	12.00	0.10	0.0315	-0.0000016681
A_5(ocean beach)	1.17	4	0.000	12.00	0.10	0.0186	-0.0000048338
A_6(ocean beach)	0.59	4	0.000	12.00	0.10	0.0148	-0.0000044673
A_{male}(ocean beach)	6.00	4	0.000	12.00	0.10	134.1610	-0.0000000018

C.1.1 Selectivity

Selectivity of sea mullet was estimated within the model using an age-based random-walk function. Queensland and New South Wales selectivity were “mirrored” such that only one selectivity function was used to represent each of ocean beach and estuarine fishing methods (Figure C.1).

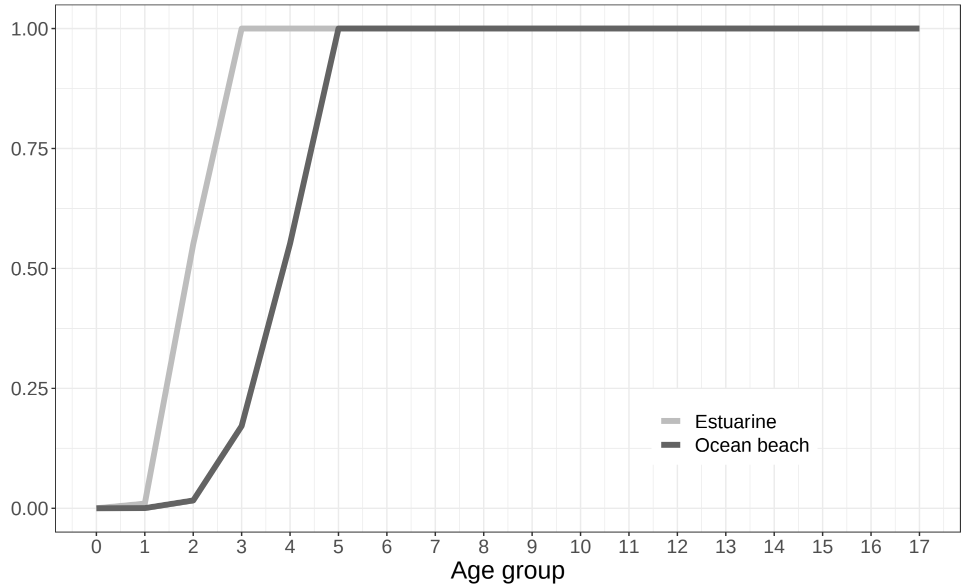

Figure C.1: Model estimated age-based selectivity for sea mullet by fishing method

C.2 Goodness of fit

C.2.1 Abundance indices

Although catch rates showed similar overall trends for each fishing method, year to year fluctuations were not the same. Model projected catch rates therefore do not fit all that well to each individual catch rate (Figure C.2).

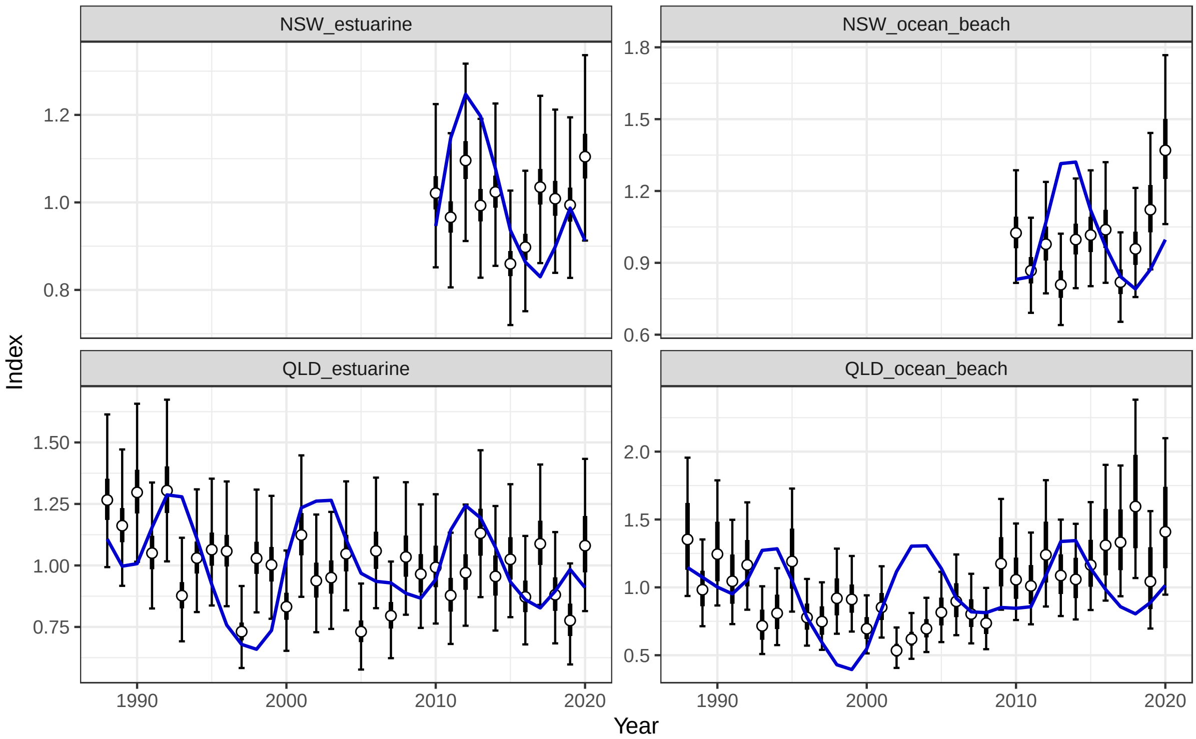

Figure C.2: Model predictions (blue line) to standardised catch rates (points) for sea mullet—thick black bars represent the standard error input into the model, while the thin error bars represent additional error estimated by the model

C.2.2 Age compositions

Age compositions along with corresponding model fits for Queensland estuarine and ocean beach, and New South Wales estuarine and ocean beach are shown below (Figures C.3, C.4, C.5, C.6).

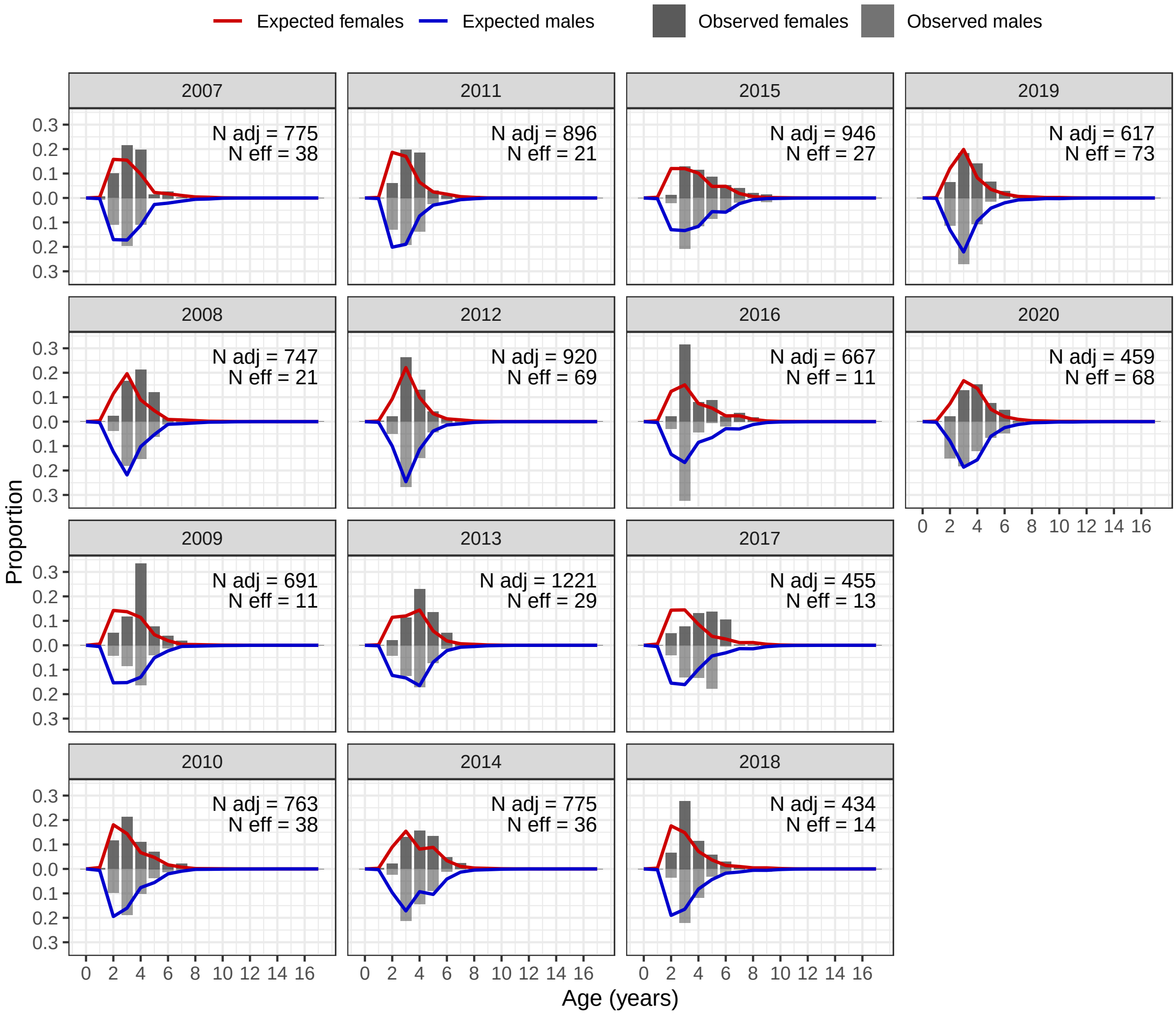

Figure C.3: Fits to age structures for the Queensland estuarine fleet for sea mullet—N adj. is the input sample size after data-weighting adjustment. N eff. is the calculated effective sample size used in the Francis tuning method

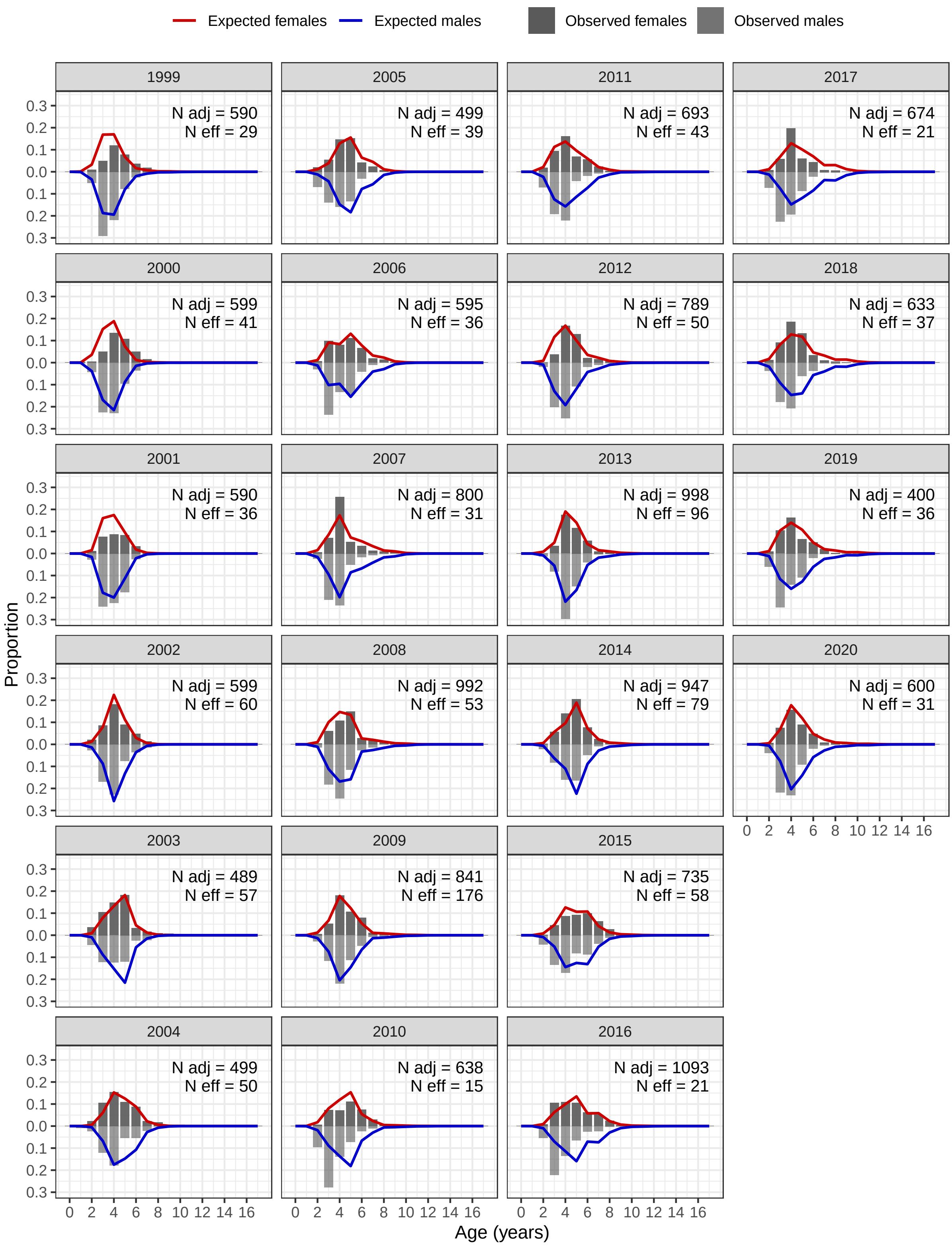

Figure C.4: Fits to age structures for the Queensland ocean beach fleet for sea mullet—N adj. is the input sample size after data-weighting adjustment. N eff. is the calculated effective sample size used in the Francis tuning method

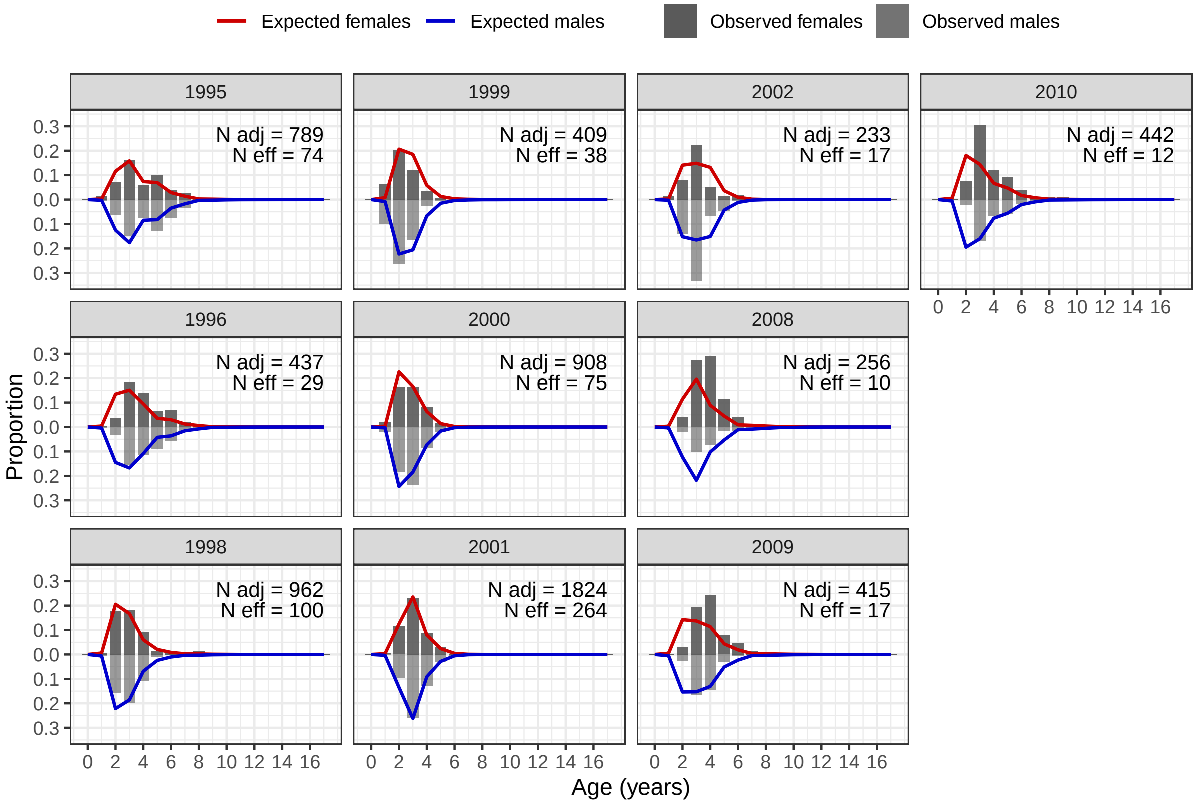

Figure C.5: Fits to age structures for the New South Wales estuarine fleet for sea mullet—N adj. is the input sample size after data-weighting adjustment. N eff. is the calculated effective sample size used in the Francis tuning method

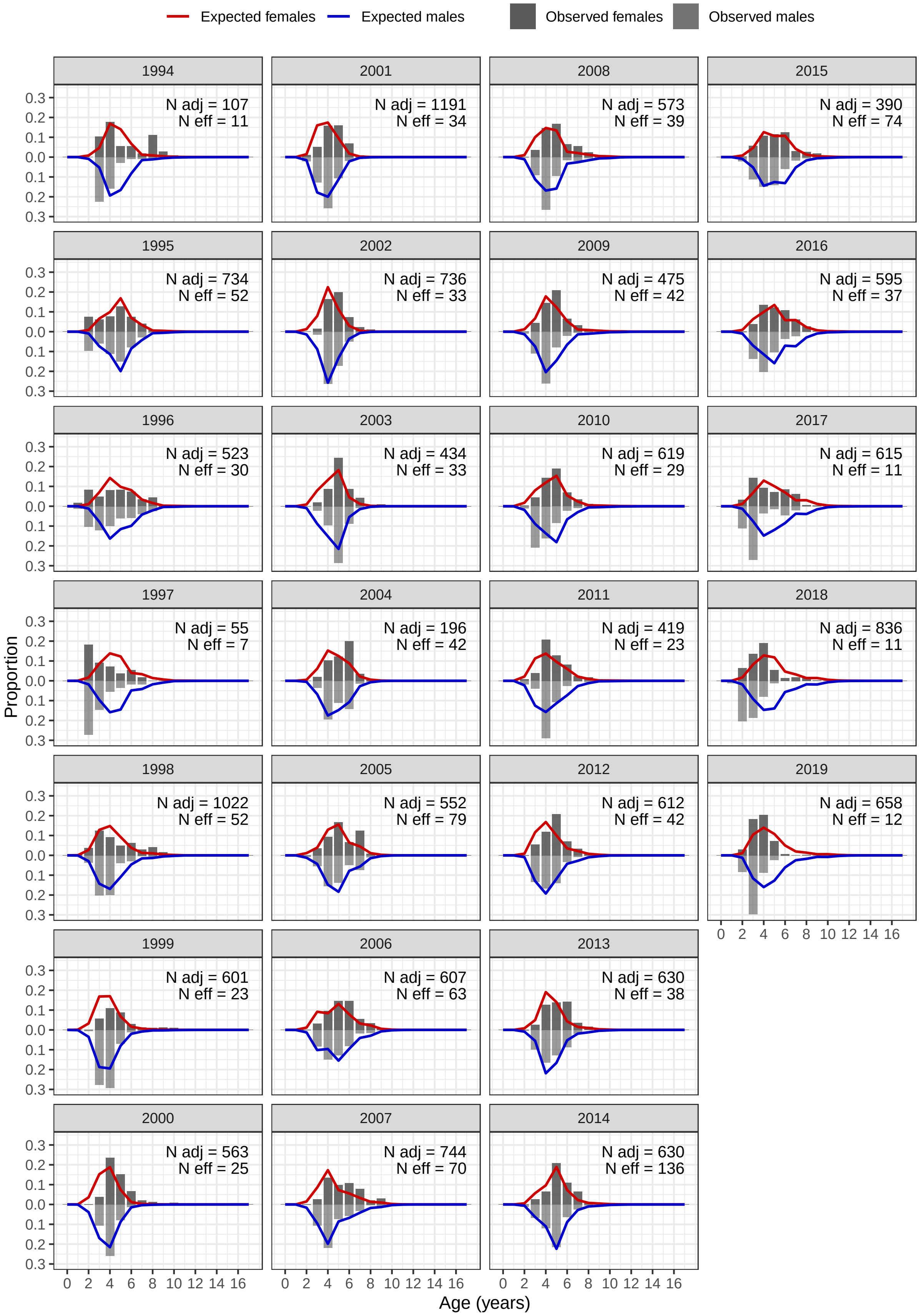

Figure C.6: Fits to age structures for the New South Wales ocean beach fleet for sea mullet—N adj. is the input sample size after data-weighting adjustment. N eff. is the calculated effective sample size used in the Francis tuning method

C.2.3 Length compositions

Length compositions along with corresponding model fits for Queensland estuarine and ocean beach, and New South Wales estuarine and ocean beach are shown below (Figures C.7, C.8, C.9, C.10).

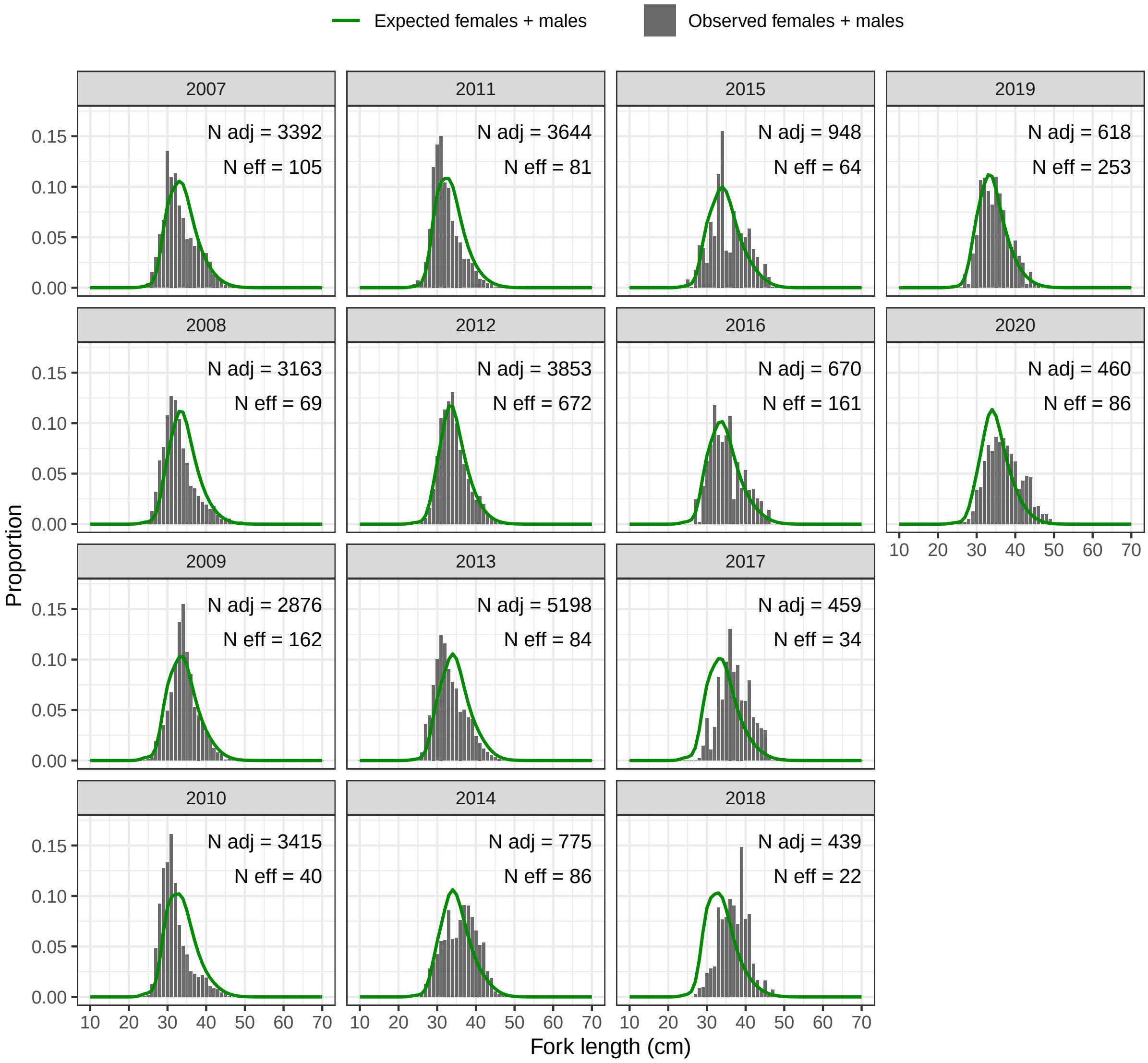

Figure C.7: Fits to length structures for the Queensland estuarine fleet for sea mullet—N adj. is the input sample size after data-weighting adjustment. N eff. is the calculated effective sample size used in the Francis tuning method

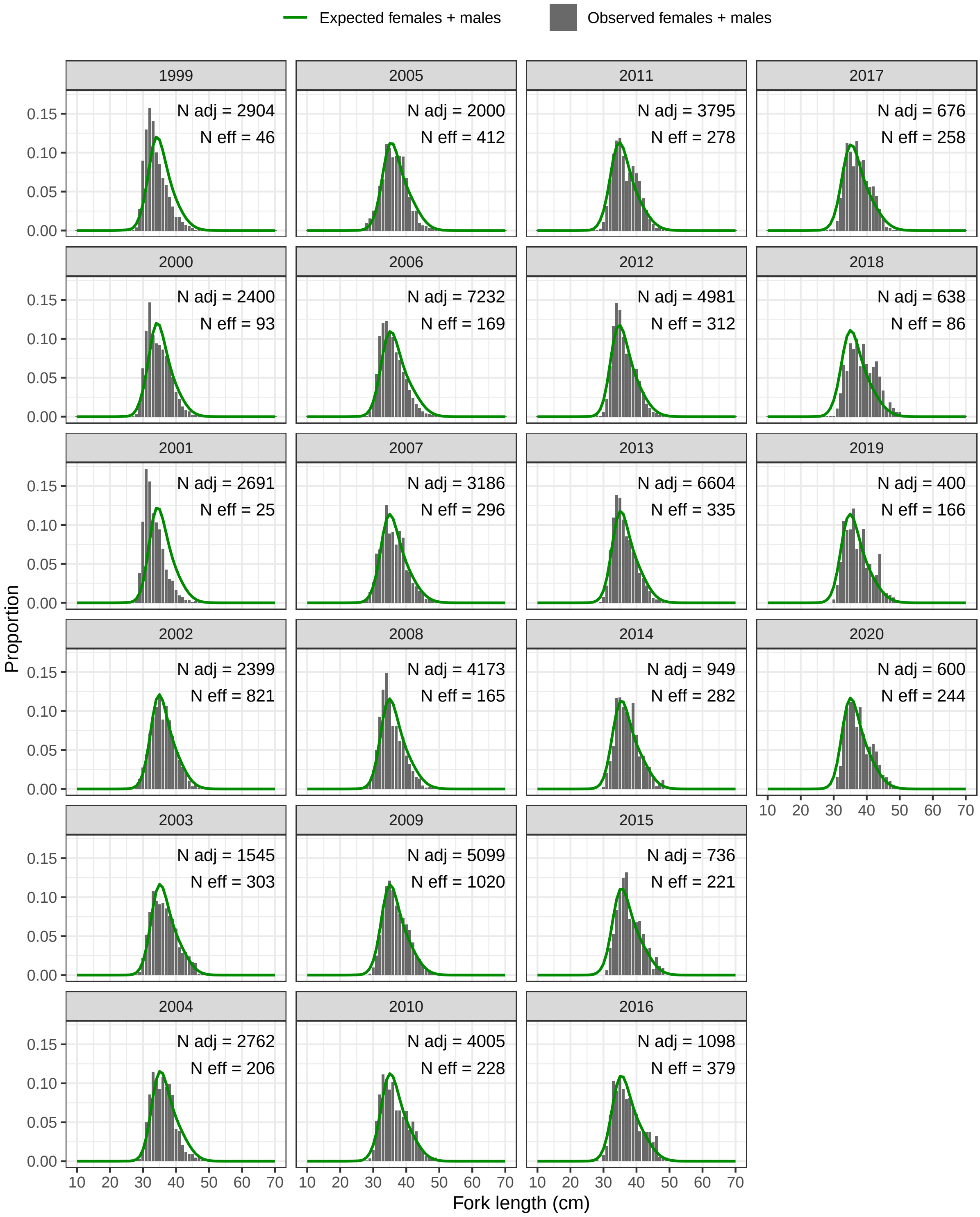

Figure C.8: Fits to length structures for the Queensland ocean beach fleet for sea mullet—N adj. is the input sample size after data-weighting adjustment. N eff. is the calculated effective sample size used in the Francis tuning method

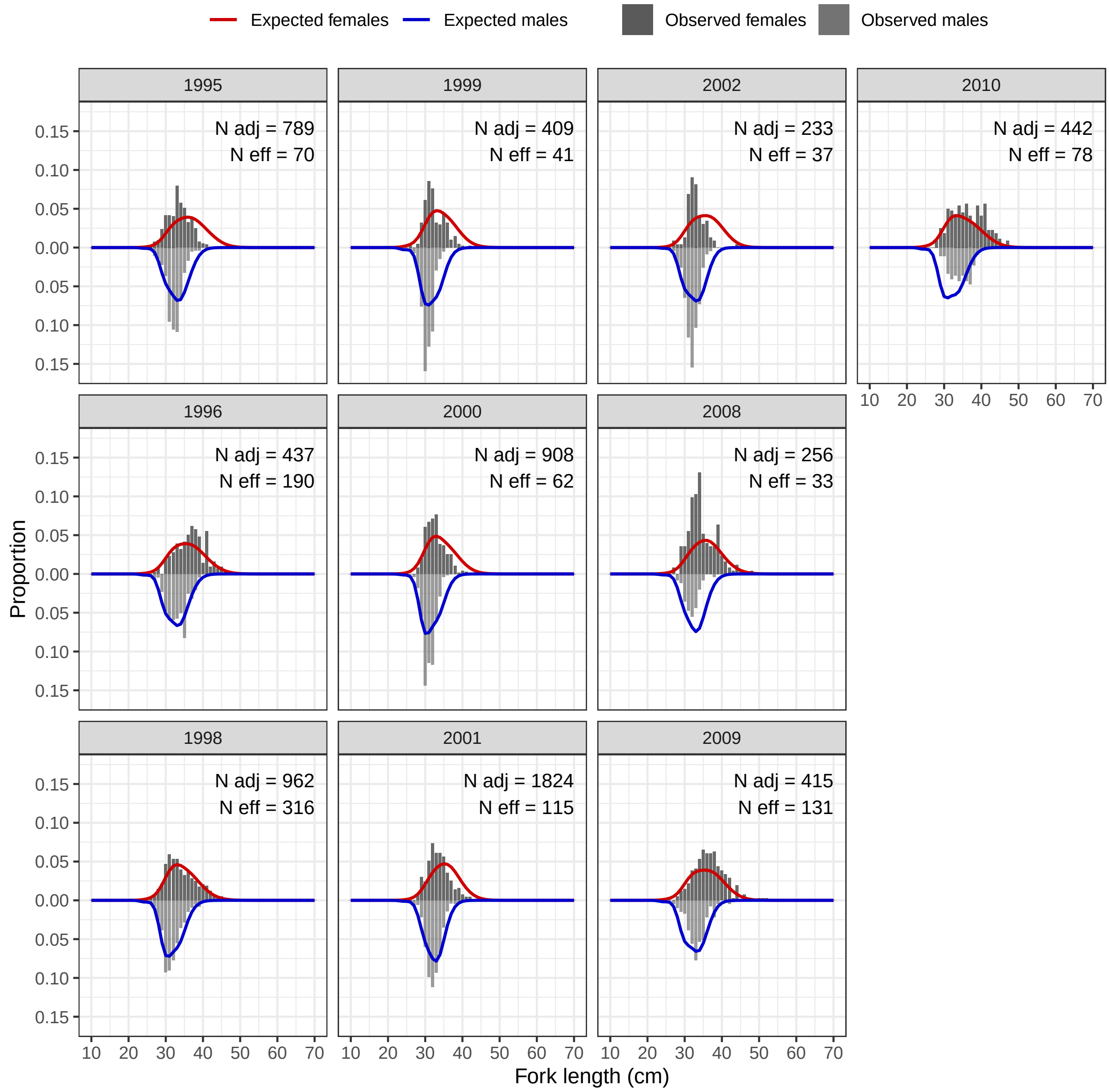

Figure C.9: Fits to length structures for the New South Wales estuarine fleet for sea mullet—N adj. is the input sample size after data-weighting adjustment. N eff. is the calculated effective sample size used in the Francis tuning method

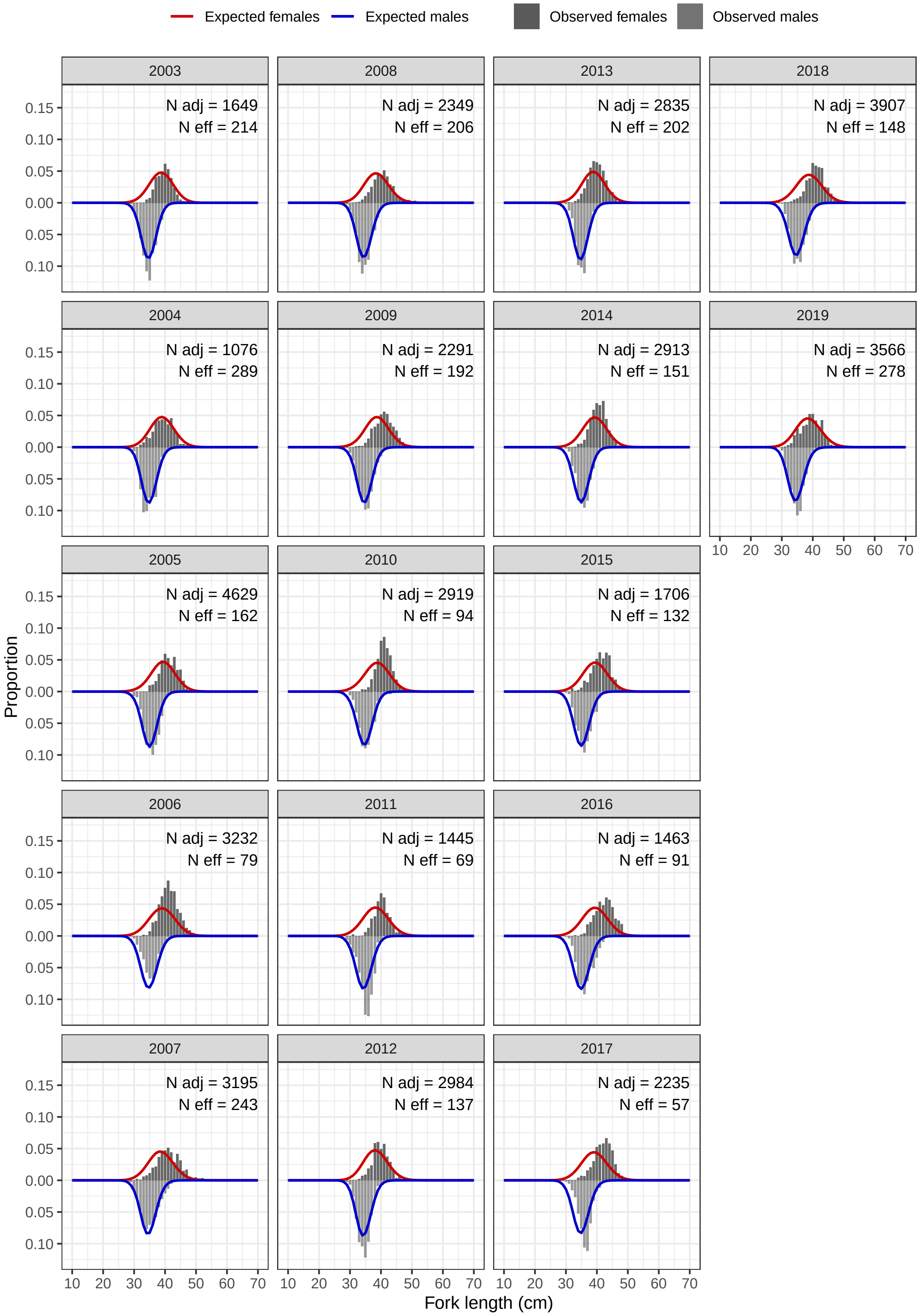

Figure C.10: Fits to length structures for the New South Wales ocean beach fleet for sea mullet—N adj. is the input sample size after data-weighting adjustment. N eff. is the calculated effective sample size used in the Francis tuning method

C.3 Markov chain Monte Carlo

A Markov chain Monte Carlo (MCMC) was performed on the base case scenario over 4 000 000 iterations with every 100th iteration saved to investigate the posterior defined by Stock Synthesis.

Convergence of the MCMC was monitored using a factor ($\hat{R}$) by which the scale of the distribution at the end of the chain might be reduced if the simulations were continued infinitely (Gelman et al. 1995).

This value was calculated to be $\hat{R}$ = 1.000028 ≈ 1 which does not indicate non-convergence. The calculation was performed using the *rhat* function in the R package "*posterior*" (Bürkner et al. 2020; Vehtari et al. 2020).

MCMC results presented in the main body of this report showed a similar trajectory to optimised results (Figure C.11). A median MCMC spawning biomass of 37 % was derived which is slightly higher than optimised results of 34 %.

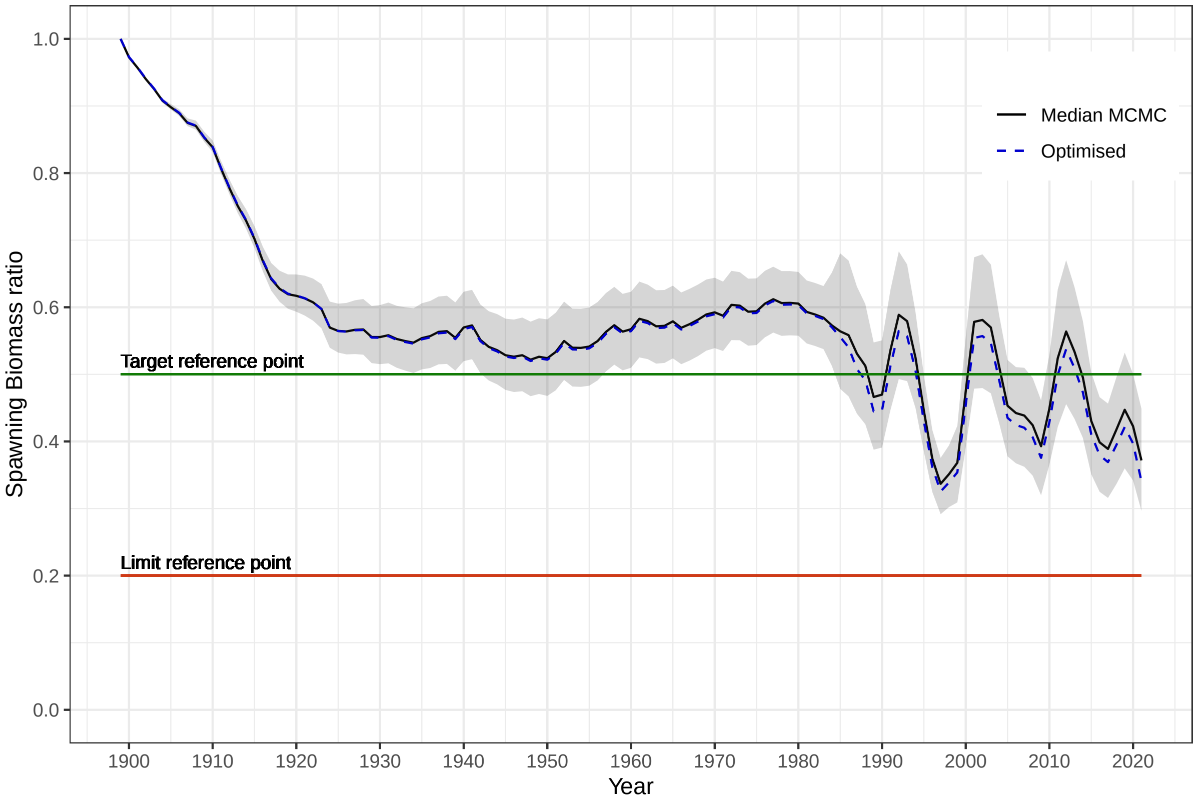

Figure C.11: Comparison of MCMC and optimised predicted spawning biomass trajectories relative to virgin for sea mullet from 1899 to 2021

Stock synthesis MCMC results and optimal results are displayed for comparison in Table C.2.

Table C.2: MCMC model outputs and comparisons for sea mullet

Indicator	Optimised	MCMC median	MCMC 2.5%	MCMC 97.5%
B_{2021}	0.34	0.37	0.3	0.45
B_{MSY}	0.33	0.33	0.32	0.33
MSY (t)	5338	5353	4975	5872
Retained catch at B_{50} (t)	4785	4801	4450	5277
B_{2021} retained catch to return to 50% (t)	1915	2541	1025	4803
Total log likelihood	29868.9	29880.7	29859.8	30078.7
M_{female}	0.3	0.31	0.27	0.36
M_{male}	0.27	0.28	0.24	0.33
$\ln(R_0)$	10.42	10.45	10.25	10.67
σ_R	0.34	0.27	0.22	0.33

Further MCMC diagnostic plots are shown in Figures C.12 and C.13.

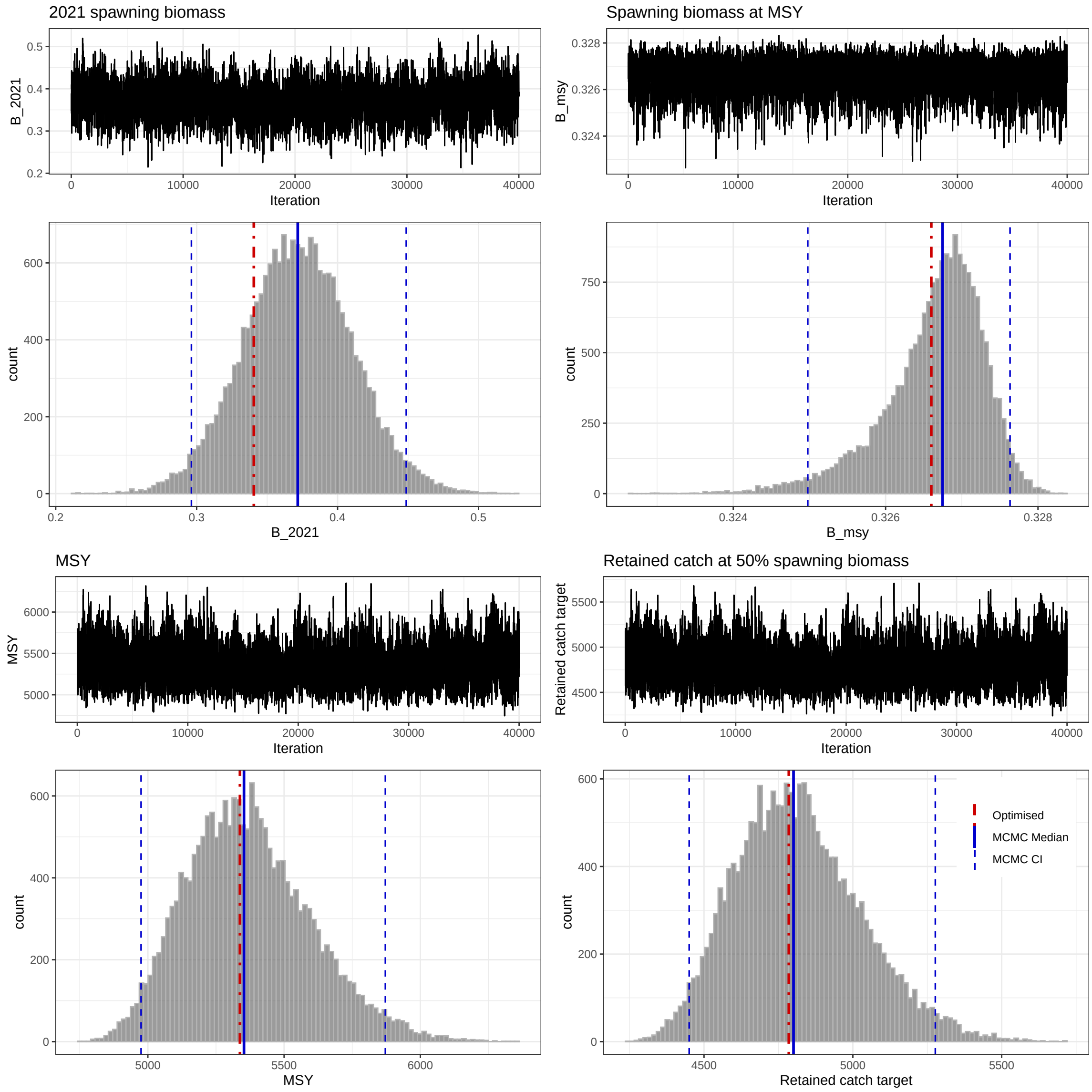

Figure C.12: MCMC diagnostic plots for sea mullet 2021 spawning biomass, spawning biomass at MSY, MSY and Retained catch at 50% spawning biomass

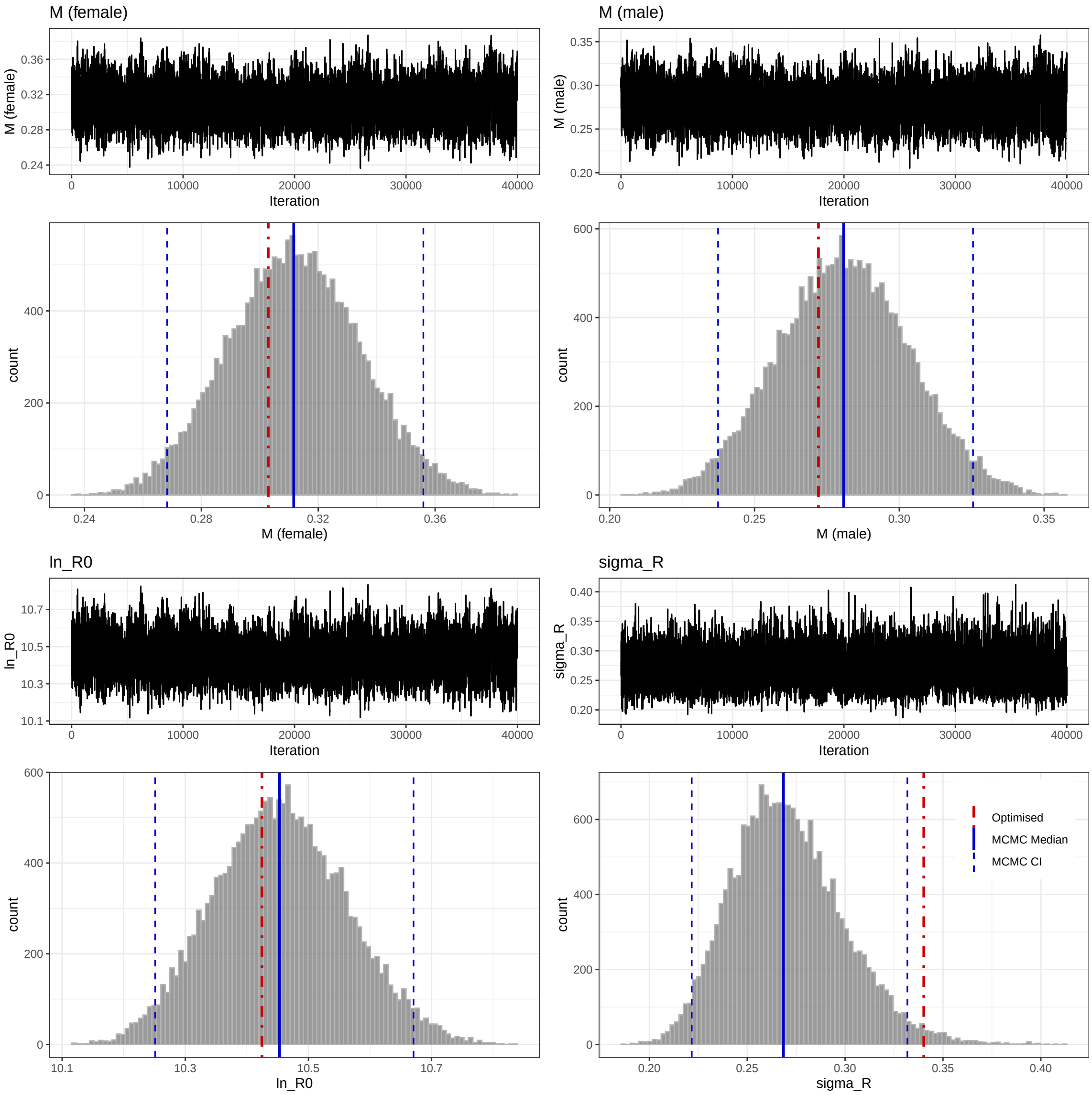

Figure C.13: MCMC diagnostic plots for sea mullet natural mortality (female and male), $\ln(R_0)$ and σ_R

C.4 Status of Australian Fish Stocks classification

The purpose of this stock assessment was to report on the health of the stock and provide information to support fishery management. Results were assessed and classified against fishery target and limit reference points outlined in the harvest strategy and harvest strategy policy for Queensland (Fisheries Queensland 2021; Fisheries Queensland 2019).

Separate to this report and other Queensland government reporting, stock assessment results may be used and cited in the 'Status of Australian Fish Stocks' (SAFS) reports (Fisheries Research & Development Corporation 2020). The SAFS classification system applies different inferences and reference points.

The SAFS classification system was designed by the Status of Australian Fish Stocks Reports Advisory Group. The classification system evaluates the status of a stock based on the fishing mortality (F) and biomass (B) relative to a 20% biological limit reference point. The terms 'sustainable stock' and 'stock status' in the *Status of Australian Fish Stocks Reports 2020* refer specifically to the biological status against the limit reference point. The status of a stock is classified as sustainable, depleting, depleted, recovering, negligible or undefined.

Broader biological, economic or social considerations are not yet classified in SAFS. Reference points relating to these considerations may include maximum sustainable yield (B_{MSY}) or biomass at maximum economic yield (B_{MEY}). B_{MSY} generally ranges 35–40%, when catches from surplus production (the annual amount by which the fish population would increase from growth and recruitment) is maximized (Punt et al. 2013). B_{MEY} generally ranges 50–60%, minimising potential loss in profit (Punt et al. 2013).

A phase plot assists in defining SAFS stock status relative to limit reference points for biomass and fishing mortality (Fisheries Research & Development Corporation 2021). The plot tracks the annual stock biomass ratio relative to the unfished level, against the fishing mortality relative to the target reference point (Figure C.14).

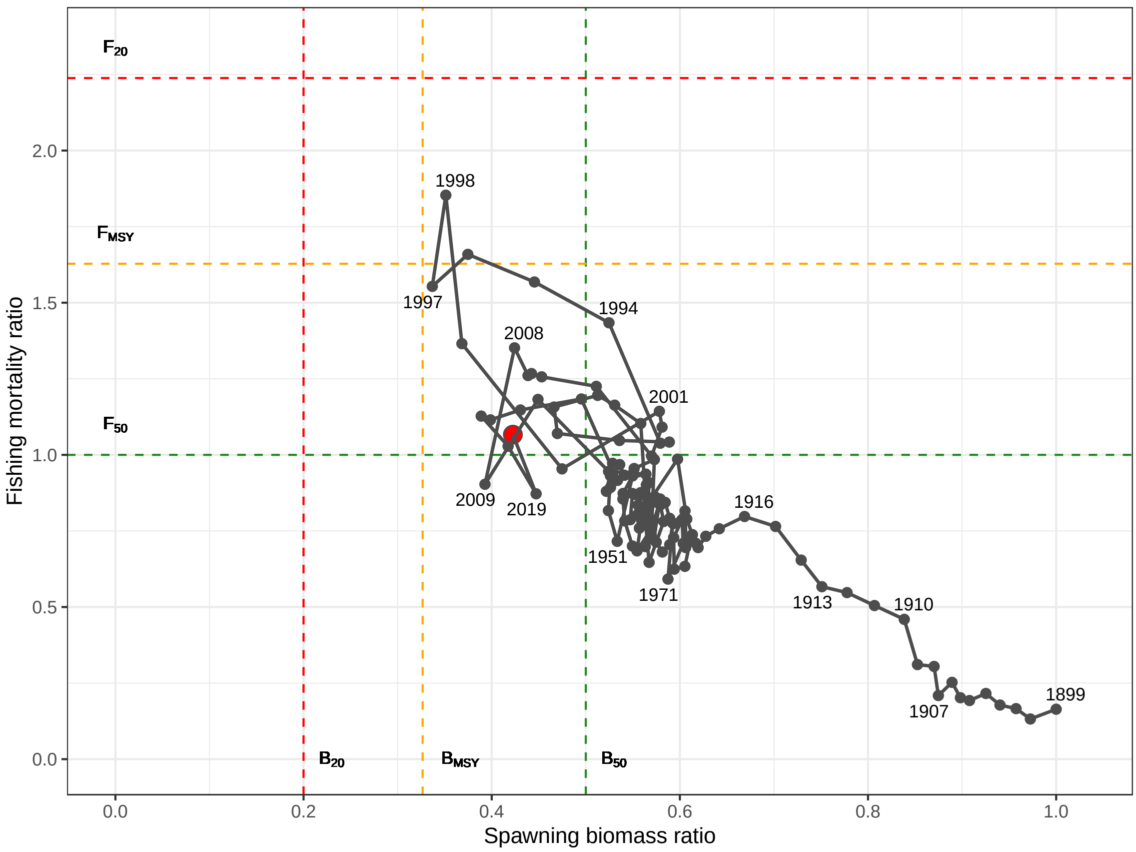

Figure C.14: Annual trajectory of fishing mortality relative to spawning biomass for sea mullet 1899 to 2020—final year indicated by red dot

C.5 Recruitment

Fluctuations in annual recruitment play a key role in stock biomass over time. This influential component of the population model was assumed to be deterministic before 1982 (for the base case) and then stochastic between 1982 and 2021. Figure C.15 shows the modelled annual recruitment as a function of spawning output, while Figure C.16 shows the log of the deviations from deterministic recruitment for the stochastic recruitment period.

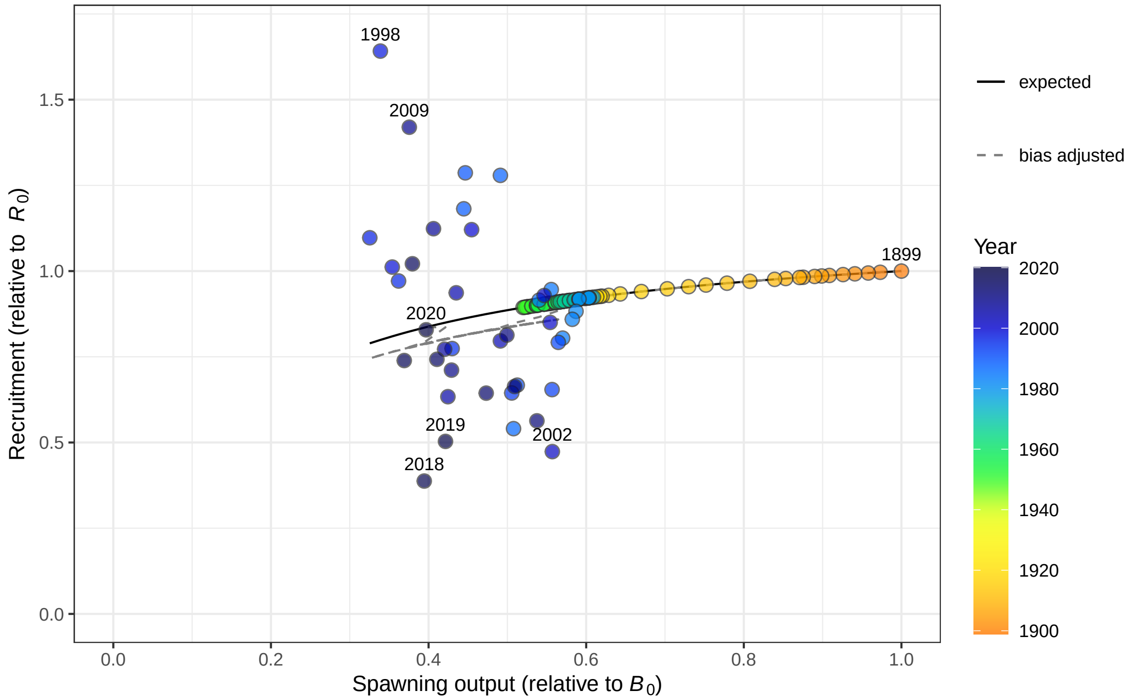

Figure C.15: Annual recruitment as a function of spawning output for sea mullet 1899 to 2020—labels are on first, last, and years with log deviations > 0.5)

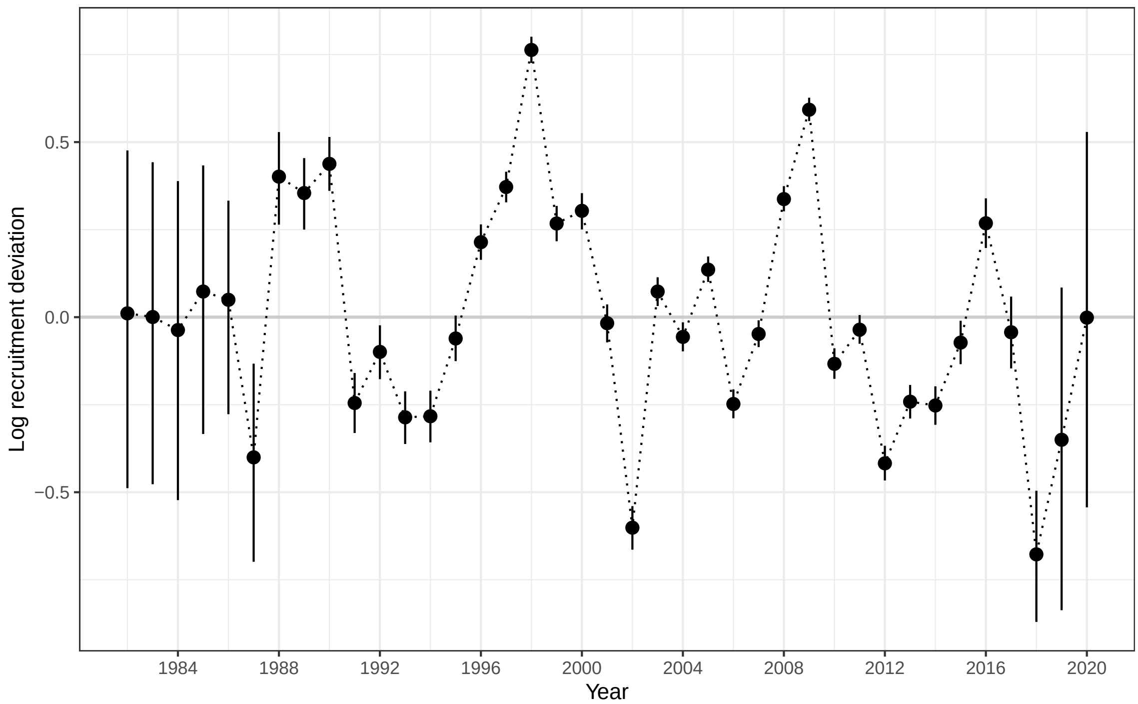

Figure C.16: Log recruitment deviations with 95% confidence intervals for sea mullet

C.6 Model likelihoods

Likelihood components for the base model further broken down into sub-components to allow insight into model behaviour are displayed below (Table C.3).

Table C.3: Log likelihood values for the base sea mullet model

Type	Likelihood	Lambdas
TOTAL	29868.9000	
Catch	0.0000	
Equil_catch	0.0000	
Survey	-6.3583	
Length_comp	14926.9000	
Age_comp	9212.0900	
Recruitment	-19.1588	1
InitEQ_Regime	0.0000	1
Forecast_Recruitment	0.0000	1
Parm_priors	5755.4600	1
Parm_softbounds	0.0075	
Parm_devs	0.0000	1
Crash_Pen	0.0000	1

C.7 Likelihood profile

Steepness (h) was unable to be estimated in the model. The likelihood profile shown below (Figure C.17) shows a reduction in the change in log-likelihood for most data as steepness tends towards 1, with the exception of length compositions where there is a conflict in the log-likelihood change comparative to other data sets. A steepness of 0.66 has been chosen for this assessment for ease of comparison with (Lovett et al. 2019). Additional scenarios with steepness higher and lower have been tested.

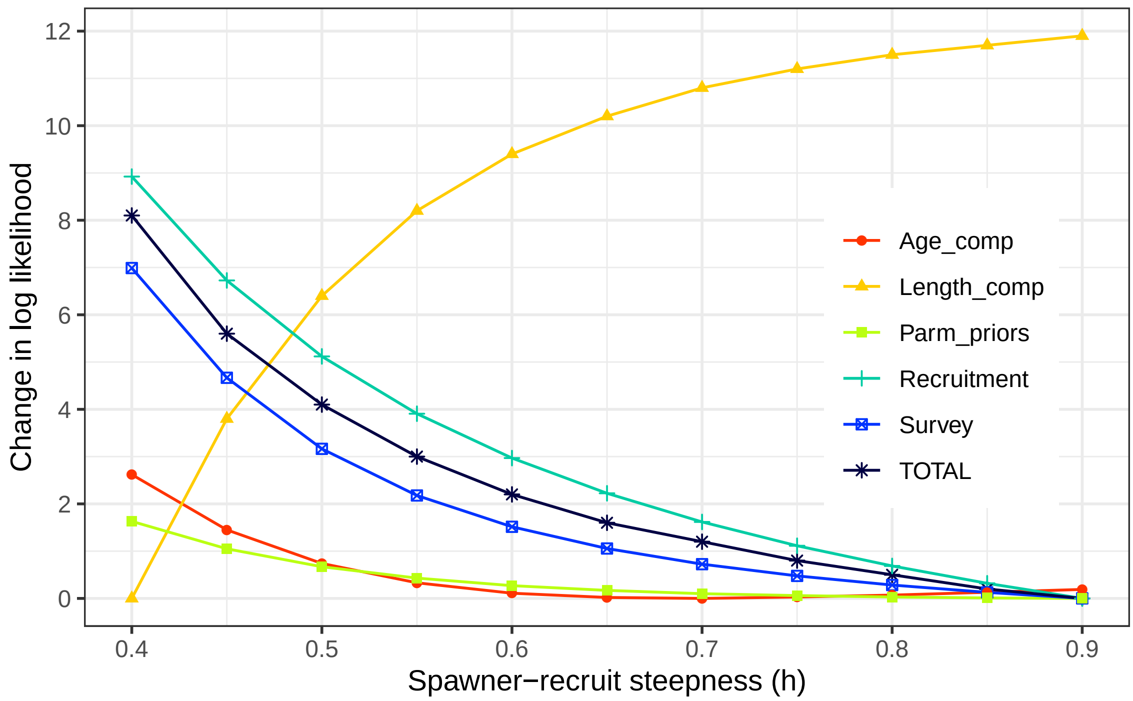

Figure C.17: Likelihood profile for the steepness parameter h