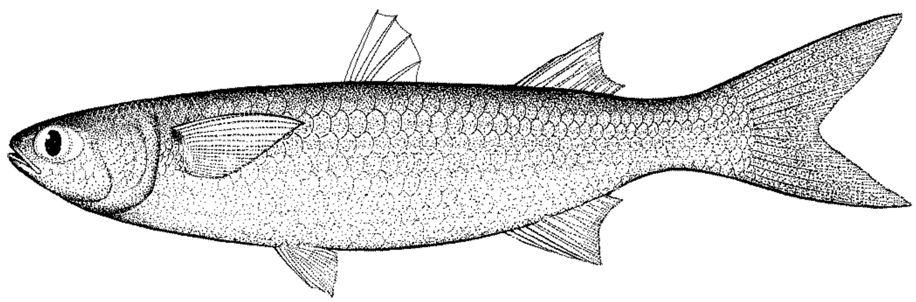

Stock assessment of the Australian east coast sea mullet (*Mugil cephalus*) fishery

2018

Queensland Government

This publication has been compiled by R. A. Lovett and A. Prosser of Fisheries Queensland, Department of Agriculture and Fisheries, G. M. Leigh, and M. F. O'Neill of Agri-Science Queensland, Department of Agriculture and Fisheries, and J. Stewart of New South Wales Department of Primary Industries.

Summary

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 in Queensland and Eden in NSW. They inhabit coastal, estuarine and freshwaters and undertake annual migrations along ocean beaches to spawn.

This stock assessment covers the Australian east coast and incorporates Queensland and NSW catch data up to 2016. The vast majority of the catch is taken in the commercial fishery, with the catch in NSW exceeding the Queensland catch (approximately 65% and 35% of the catch respectively).

Historically, east coast fishing for sea mullet has been relatively stable with an average annual harvest of roughly 4000 tonnes (1910 – 1985). Harvest increased from the late 1980s to a peak at over 6000 tonnes in the mid-1990s. From the mid-1990s, harvest steadily reduced although were still slightly above the pre-1986 historical levels.

A previous stock assessment was completed in 2004, with harvest recommendations in the range 3620 – 5046 tonnes.

This stock assessment indicates that increased fishing pressure from the late-1980s onwards has contributed to a decrease in sea mullet abundance. Biomass ratios prior to the late 1980s were around 60% of virgin exploitable biomass. The biomass estimates for the final year of the assessment (2016) were around 50%, up from estimates of 40% in 2009 and 1993−1994.

The modelling estimates an equilibrium Maximum Sustainable Yield between 5900 – 6700 tonnes per year to maintain the stock at approximately 35% of virgin exploitable biomass. Estimated sustainable harvests under Queensland's Sustainable Fisheries Strategy range between 2400 – 3250 tonnes per year which would build sea mullet to around 60% of virgin exploitable biomass. This 60% target can be used as a proxy for Maximum Economic Yield (MEY). We note that the 60% target is not current NSW policy.

Biological information for sea mullet (available from 1990 onwards) has revealed a cyclic pattern of new fish recruitment over years. This has produced a cyclic fluctuation in the exploitable biomass results with a midpoint at around 50% of virgin levels which is trending downward.

It is important to note that the final year of the model occurs during a downward phase in a long term cycle of biomass peaks and troughs and that fishing could exacerbate this downward biomass trend.

The biomass results are dependent on the estuary gillnet and ocean beach trends of sea mullet catch rates. The catch rate indices may contain some level of hyperstability, where catch rates can remain steady even though fish abundance may be down, which suggests a level of caution is required.

It was noted by the assessment's Project Team that the Bundaberg to Noosa stock range was experiencing below average harvests. Further assessment of the extent of regional decline would be useful to investigate historical levels of fishing related to environmental changes.

Regular stock assessment of the sea mullet fishery will support and gauge the effectiveness of management procedures and assess how the stock is responding to any future biomass down cycle or change.

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Acknowledgements

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Definitions

B	Biomass, total weight of a population or of a component of a population. For example, the weight of exploitable biomass is the combined weight of vulnerable sized fish. It can be measured differently in terms of all fish, exploitable fish or spawning fish.
B_0	Mean equilibrium virgin unfished biomass: average biomass level if fishing had not occurred. Virgin state was subscript labelled as 0, which corresponded to the first year assessed in 1899.
B_0^{sp}	Mean equilibrium virgin unfished spawning biomass: average spawning biomass level if fishing had not occurred. Virgin state was subscript labelled as 0, which corresponded to the first year assessed in 1899.
B_{MSY}	Biomass at maximum sustainable yield: average exploitable biomass corresponding to maximum sustainable yield.
$B_{0.6}$	Target biomass: the desired biomass of the population. The reference point refers to the target objective, e.g. the 60% biomass target by 2027 in the Queensland Sustainable Fisheries Strategy. It is referred to as B_{MEY} by the Australian Government where B_{MEY} is the biomass at maximum economic yield (MEY).
U_{MSY}	Harvest rate at maximum sustainable yield: proportion of average exploitable biomass harvested corresponding to maximum sustainable yield.
$U_{0.6}$	Target harvest: the harvest rate required to sustain the biomass of the population at 60% once a 60% biomass has been achieved.
Harvest target	The harvest level required to rebuild or maintain the biomass at a particular target level.
Catch rate	Index of fish abundance, referred to as average (mean) catch rates standardised (adjusted) to a constant vessel and fishing power through time. All references to catch rates were standardised unless specified to be different.
Fishery	The stock assessment evaluated Australian east coast spotted mackerel. The assessment was conducted for the whole (genetic) stock across jurisdictions and included commercial, charter, recreational and research data from both New South Wales and Queensland. The fishery covers all fishing sectors: commercial, charter, recreational and traditional indigenous.
FRDC	Fisheries Research and Development Corporation, Australian Government, www.frdc.com.au
GLM	Generalised linear model. A flexible linear model that allows distributions that are not normal.
LTMP	Now formally known as 'Fishery Monitoring' – Fisheries Queensland's long-term monitoring program, Queensland Department of Agriculture and Fisheries.
MCMC	Monte Carlo Markov Chain: statistical computer simulation method for estimating population model parameters and their variance.
MEY	Maximum Economic Yield: the sustainable catch or effort level for a fishery that allows net economic returns to be maximised (the value of the largest positive difference between total revenues and total costs of fishing, which equals the maximum profit).

MSY	Maximum Sustainable Yield: the maximum average annual catch that can be removed from a population over an indefinite period under historical environmental conditions.
Overfished	A fish population with a biomass below the biomass limit reference point (B_{LIM} or B_{LRP}).
Overfishing	The condition where a population is experiencing too much fishing and the removal rate is unsustainable (fishing mortality $F > F_{MSY}$). F measured the level of fish harvested by different fishing sectors.
Reference point	An indicator of the level of fishing, harvest or size of a fish population, used as a benchmark for interpreting the results of an assessment.
Vulnerability	Probability of fish being exposed to fishing mortality. This varies for different sized fish. This is generally a result of fish being present in the fishing area (fishery) and is subject to their susceptibility of being caught by the fishing gear.

1 Introduction

This document reports on the past and current status of eastern Australian sea mullet (*Mugil cephalus*) for New South Wales and Queensland coastal waters with the aim of providing information and advice for the future management of the stock.

The New South Wales and Queensland sea mullet fisheries are among the most important commercial fisheries in Australia. In both States, the annual catch of sea mullet is higher than that of any other species and sea mullet is considered the mainstay of fish trade (Virgona et al. 1998).

To ensure the long-term sustainability of the resource, it is important that sound scientific information is made available to individuals responsible for managing the fishery. This information may take many different forms, such as biological research and monitoring activity or research into fishing activity. In this case, the information being provided is a quantitative assessment of the fishery by mathematical modelling.

This assessment is intended to extend and complement the already available scientific documentation on the resource (Bell et al. 2005; Smith and Deguara 2002; Department of Primary Industries 1999; Kesteven 1953; Virgona et al. 1998) and support the development of contemporary management procedures. The previous stock assessment (Bell et al. 2005) recommended harvests in the range 3620 – 5046 tonnes.

The eastern Australian sea mullet population is considered a single stock across New South Wales and Queensland waters. As such, this project is framed in a collaborative context, incorporating data and research from both States. It is important that any future management or research decisions made on the basis of this work are undertaken in consideration of the outcomes for both States.

Estimated harvest reference points for sea mullet apply to the population across waters and fishing methods of both States combined.

1.1 Sea mullet biology

Once sea mullet hatch, the larvae drift in ocean waters until large enough to swim, at which stage they enter estuaries (Virgona et al. 1998). This occurs around 28 to 42 days after hatching at a size between 10 and 15 mm standard length (SL) (Koutrakis 2016). Schools of juvenile fish do not seek a specific salinity level within estuarine waters but scatter from the estuary mouths all the way to freshwater (Thomson 1955). They typically remain and grow in these waters until sexually mature.

Pre-spawning fish aggregate at the mouths of estuaries before exiting to sea during late autumn or winter (Smith and Deguara 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. In some beach locations, a summertime “hardgut” (non-spawning condition) mullet run used to form an important component of the catch (Smith and Deguara 2002; Virgona et al. 1998) and this aggregation is still targeted if conditions are suitable.

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).

Mullet typically mature from three to four years of age (Smith and Deguara 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 harvests typically comprise more males than females while estuarine catches contain a more even ratio (Stewart et al. 2018).

1.2 Fishery location

The eastern Australian sea mullet population 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 harvested from marine estuarine and ocean beach waters, but also reside in unfished freshwater habitats. As shown in Figure 1, a larger proportion (≈ 65%) of sea mullet were harvested in New South Wales than in Queensland during the last two decades.

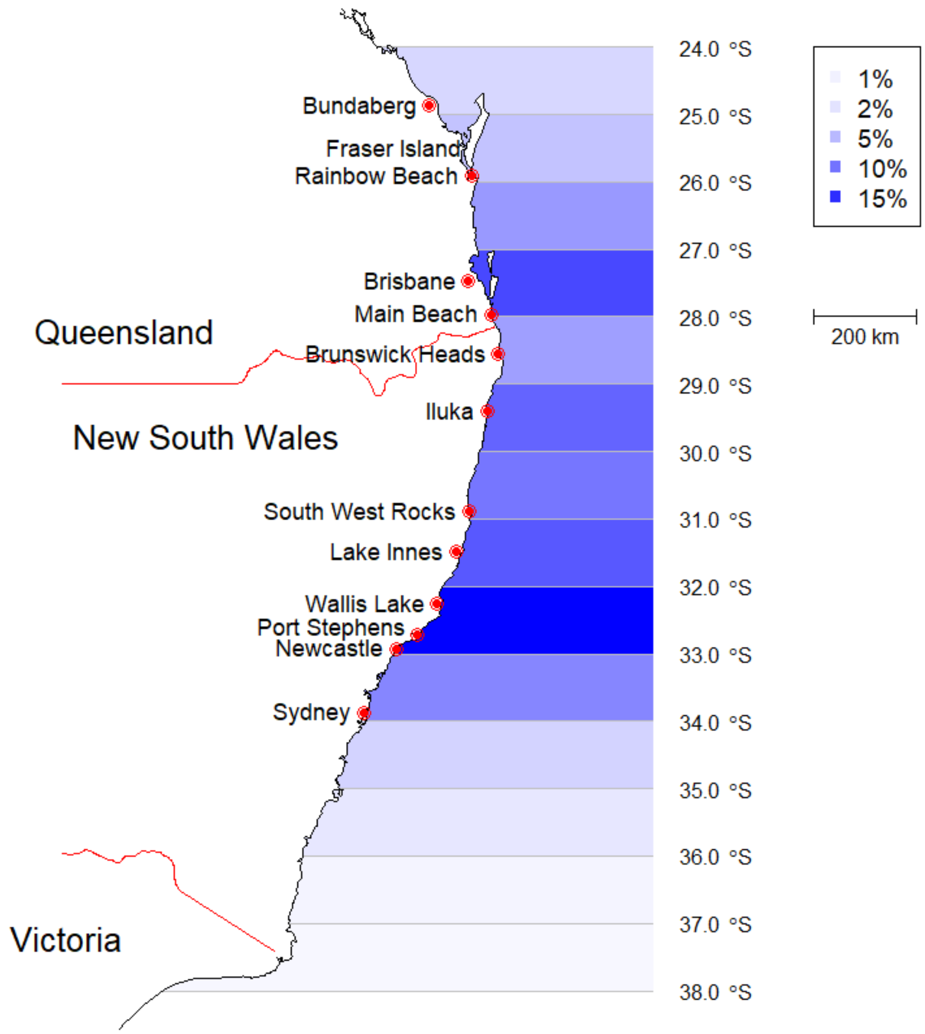

Figure 1: Geographic distribution of commercial sea mullet landings along the Australian east coast. Based on data July 1997 – December 2016.

1.3 Fishing sectors

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

The ocean-beach sector targets 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.

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.

Figure 2: Commercial fishers hauling ocean beach net. (Photo by Ricky Midgley © State of Queensland).

1.4 Recreational take

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 within the plankton (Smith and Deguara 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 mullet using bait traps or rod and line (Prosser 2016).

Because of sea mullet's feeding characteristic and the lack of clear species data, the recreational catch was not considered in this assessment.

1.5 Management

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

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. Changes to spatial and temporal management restrictions in the fishery are shown in Table 1.

In both States, the minimum legal size for sea mullet is 30 cm total length. In 2016, there were 339 licences operating in New South Wales and 244 licences operating in Queensland. Various spatial and temporal closures in both the ocean beach and estuarine sectors exist to minimise conflict between operators.

Table 1: Management changes applied to sea mullet in New South Wales and Queensland waters. Source: New South Wales and Queensland state government legislation and Thomson (1953).

Date	State	Measure
1877−1974	Qld	Numerous measures relating to fishing gear and practices; e.g., mesh size, net length, allowed species, closed seasons, powers of inspectors
1902−1994	NSW	Numerous measures relating to fishing gear and practices; e.g., mesh size, net length, closed seasons, prohibition of explosives and poisons
3 Dec 1914	Qld	Minimum legal size 8 inches (≈ 20 cm) total length (TL) (*The Fish and Oyster Act of 1914*)
1926−1933	Qld	Minimum legal size 11 inches (≈ 28 cm) TL February to July, 10 inches (≈ 25.5 cm) August to January (Amendments 1926, 1929 and 1933 by Order in Council to *The Fish and Oyster Act of 1914*)
17 Dec 1935	NSW	Minimum legal size 12 inches (≈ 30.5 cm) TL (*Fisheries and Oyster Farms Act 1935*)
11 May 1951	NSW	Minimum length of 14 inches (≈ 35.5 cm) TL. The mesh of permissible nets was raised from 3 inches to 3 1/4 inches (Thomson 1953)
2 Nov 1951	NSW	Minimum length of 13 inches (≈ 33 cm) TL (Thomson 1953)
20 Mar 1952	NSW	Minimum length of 14 inches from 1 March to 30 June and 13 inches from 1 July to 28 February (Thomson 1953)
2 Nov 1952	Qld	12 inch minimum length for the months February to June, 11 inches minimum length during other months. Prior to this, the 12 inch minimum covered only the months March to May (Thomson 1953)
18 Apr 1957	Qld	Minimum legal size 12 inches TL (*Fisheries Act 1957*)
16 Dec 1976	Qld	Minimum legal size 30 cm TL (*Fisheries Act 1976*)
10 Mar 1990	Qld	Confirm minimum legal sizes from 1976 (*Fisheries Organization and Marketing Regulations, 1990*)
1 Jul 1990	NSW	Minimum legal size 30 cm TL (*Fisheries and Oyster Farms Act 1935-Regulation no. 357, 1990*)
11 Jun 1993	NSW	Confirm minimum legal size 30 cm TL (*Fisheries and Oyster Farms Act 1935-Regulation no. 199, 1993*)
1 Jul 1993	Qld	Confirm minimum legal size 30 cm (*Fishing Industry Organization and Marketing Amendment Regulation No. 3, Subordinate Legislation 1993 No. 235*)
13 Jan 1995	NSW	Confirm minimum legal size 30 cm (*Fisheries Management (General) Regulation, 1995-No. 11*)
1 Dec 1995	Qld	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	Qld	*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.

2 Data

Data were sourced from a combination of: current NSW Department of Primary Industries: Fisheries (DPI Fisheries) logbook and biological information; Queensland Department of Agriculture and Fisheries (DAF) logbook and biological information; Historical information from Kesteven (1942) and Thomson (1953); and wind observations from the Bureau of Meteorology. The data were used according to their quality, quantity and temporal-spatial resolution.

2.1 Fishery harvests

Harvest information was reported separately for each State using different record keeping systems. This resulted in differing time periods of data collection and resolution.

2.1.1 New South Wales

The following data sources were used:

- Kesteven (1942) annual catch data for the period 1899 to 1941. These data were reported in units of boxes with a weight in pounds per box, which was converted to metric tonnes.
- NSW historical annual catch data for the period 1940 to 1983. These data were in kilograms and were also split into geographic regions.
- NSW DPI Fisheries compulsory logbook records which began in 1984. These data have been recorded in three separate datasets comprised of monthly regional catch information for the period July 1984 to June 1997, monthly regional catch information from July 1997 onwards (including catch method and effort) and detailed daily regional catch information from July 2009 onwards.

The annual catch of sea mullet in New South Wales (and Queensland) is shown in Figure 3. Note that for New South Wales the years 1942, 1943 and 1984 were missing due to lack of data.

The data used to calculate catch rates covered the period from July 1997 to December 2016. Data obtained for the years prior lacked sufficient detail for such a calculation. While there were logbook entries recorded from July 1984, it was considered that these entries did not accurately record fishing methods used and hence were omitted from the catch-rate calculations.

The main fishing methods used to harvest sea mullet in New South Wales were ocean beach, estuary haul and gillnet. The ocean beach method accounts for more than half of the annual harvest with most of the catch for both ocean beach and estuary haul occurring in the months of April and May. Gillnetting produced a relatively steady harvest throughout the year.

2.1.2 Queensland

Data sources consisted of:

- Kesteven (1942) annual catch data for the period 1925 to 1940. These data were reported in units of boxes with a weight in pounds per box, which were converted to metric tonnes.
- Thomson (1953) annual catch data for the period 1941 to 1950. These data were in pounds which were also converted to metric tonnes.
- The Queensland Fish Board annual catch data for the period 1951 to 1980. These data were in kilograms and split into geographic regions. They were compiled by Halliday and Robins (2007).
- Queensland Fisheries compulsory logbook records which began in 1988. These data contained daily entries in which fishers recorded their harvest of mullet 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 annual catch of sea mullet in Queensland is shown in Figure 3. Note that for Queensland, data collection began in 1925 and the period 1981 – 1987 was missing due to lack of data.

The data used to calculate catch rates in this assessment covered the period from January 1988 to December 2016. Data obtained for the years prior lacked sufficient detail for such a calculation.

Figure 3 shows the total recorded catch for New South Wales and Queensland detailing the proportions harvested by different fishing methods where such data is available.

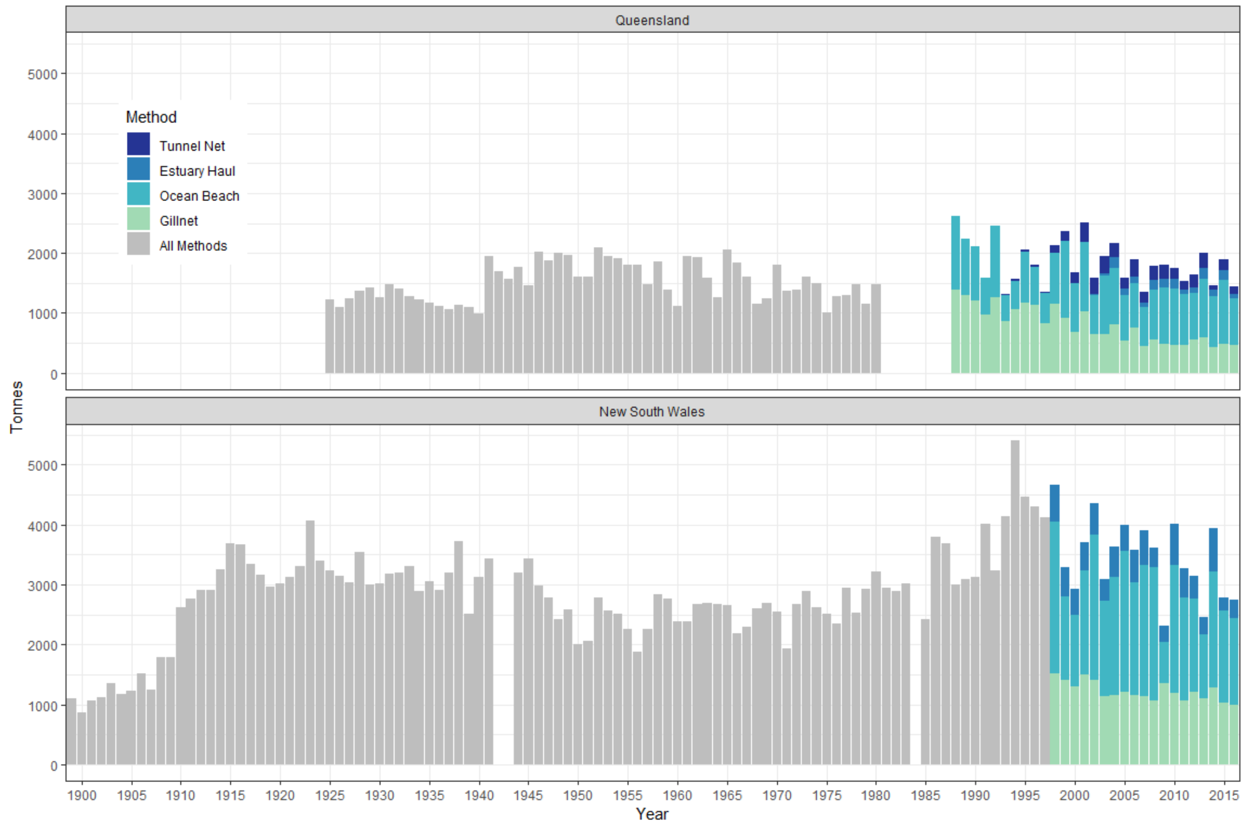

Figure 3: Annual sea mullet harvest in Eastern Australia for 1899 – 2016.

An additional figure was produced showing New South Wales and Queensland annual harvests and harvest fractions/shares where the missing years of data were estimated based on averaging existing data (Figure 4). To aid in readability of the Queensland harvest share, Table 2 details the actual values since 2010.

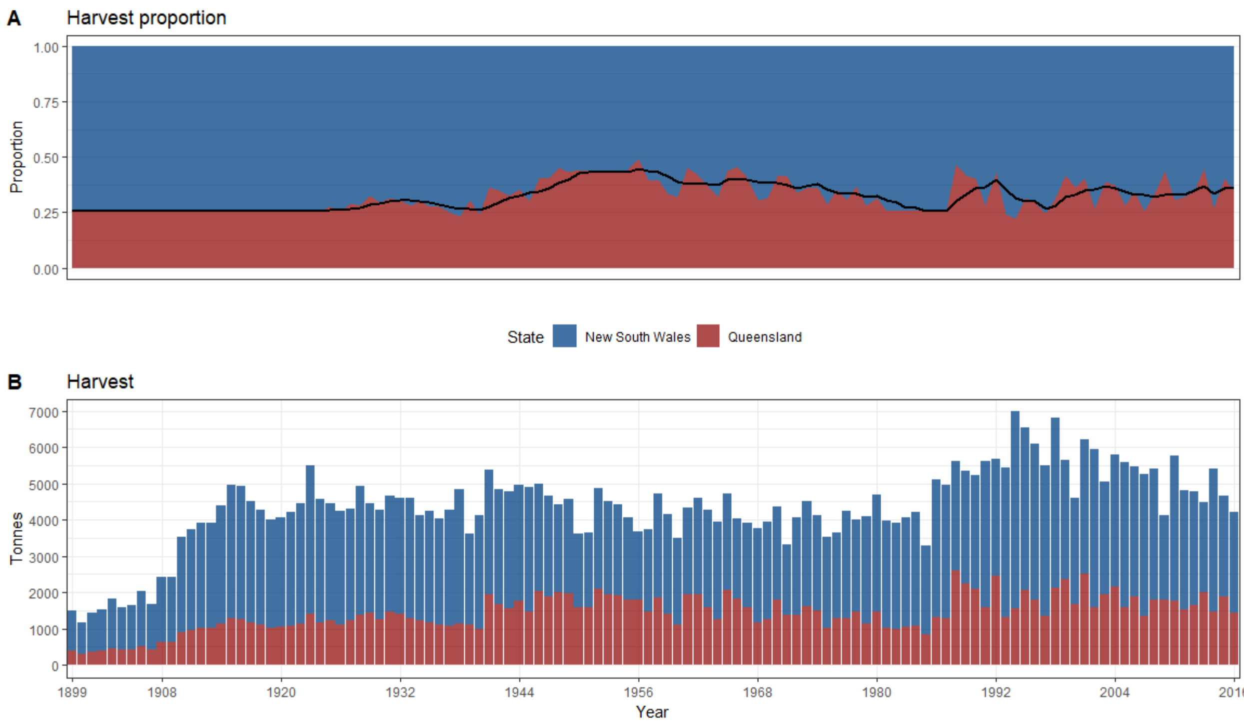

Figure 4: A: Annual sea mullet New South Wales and Queensland harvest shares for 1899 – 2016. The black trend line is the Queensland running 5-year average. B: Estimated annual sea mullet harvest in New South Wales and Queensland.

Table 2: Queensland sea mullet harvest share 2010 – 2016.

Year	Qld harvest fraction	5 year average (Qld)
2010	30%	34%
2011	32%	33%
2012	34%	35%
2013	45%	37%
2014	27%	34%
2015	40%	36%
2016	35%	36%

Of note is that there was an increase in annual sea mullet harvest from the late 1980's onwards. In recent years the harvest has decreased again but still appears to be slightly above historic levels.

The main fishing methods used to harvest sea mullet in Queensland are ocean beach, estuary haul, gillnet and tunnel net. A monthly breakdown of the proportion of sea mullet caught each year for each fishing method can be seen in Figure 5. The ocean beach method accounts for more than half of the annual harvest with most of the catch for both ocean beach and estuary haul occurring in the months of April and May. The gillnetting and tunnel netting methods produce a relatively steady harvest throughout the year. Annual plots of monthly catch sizes for each fishing method can be found in Appendix B. The duration of the fishing season has decreased since the early 1990s in Queensland. It's unknown why this happened, but it did correspond to additional spatial restrictions on the fishery.

As an illustration of the ranges of daily catches of sea mullet that can be taken in each state, histograms of the daily catch size taken for each fishing method in a fisher-day are presented in Appendix A.

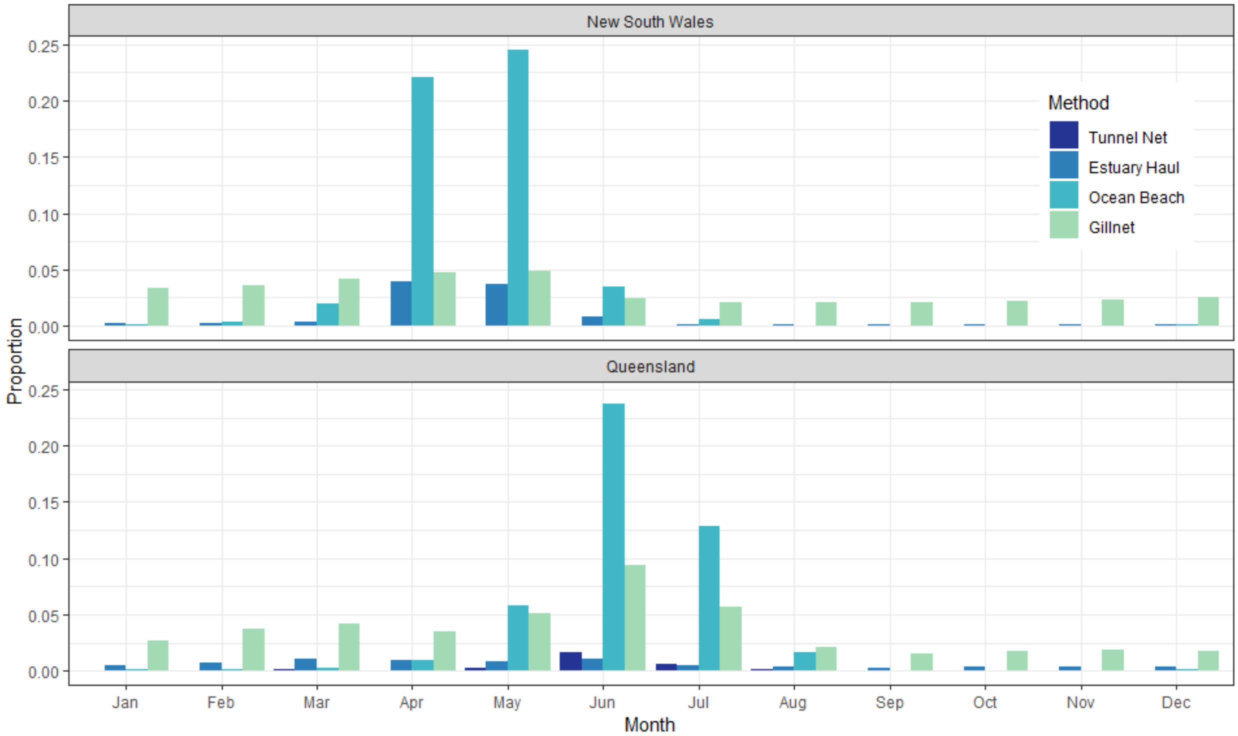

Figure 5: Proportions of sea mullet harvest by month. Based on data collected during the period 1998 – 2016 for New South Wales and 1988 – 2016 for Queensland.

2.2 Biological

Sea mullet biological data were collected by the New South Wales DPI Fisheries and Fisheries Queensland's monitoring teams. These data consisted of fish age, length, weight and sex information. Samples were taken from commercial harvests reflecting the biological distribution of harvested individuals rather than the entire population.

New South Wales fish lengths were sampled during the years 1990 – 2000 and 2003 – 2016. Fish ages were from 1990 – 2000 and 2005 – 2016. Queensland data collected identified the region and fishing method used and covered the period 1999 – 2016.

The data suggest that the method used to harvest sea mullet results in a qualitatively different age and length structure removed from the population. The distribution of age, length and sex information for estuary (Figure 6) and ocean beach (Figure 7) is shown below. It is noted that the ocean-beach sector harvests both larger females and a larger proportion of older fish. More detailed information on the structure of these data can be found in Appendix C.

The age and length of sea mullet at first maturity can vary, with fish maturing earlier in warmer waters (Thomson 1963). First maturity for sea mullet off Eastern Australia occurs at approximately 3 to 4 years of age (Kesteven 1942; Virgona et al. 1998; Smith and Deguara 2002). Age-length structures presented in Appendix C show an older demographic of harvested fish in New South Wales compared to Queensland.

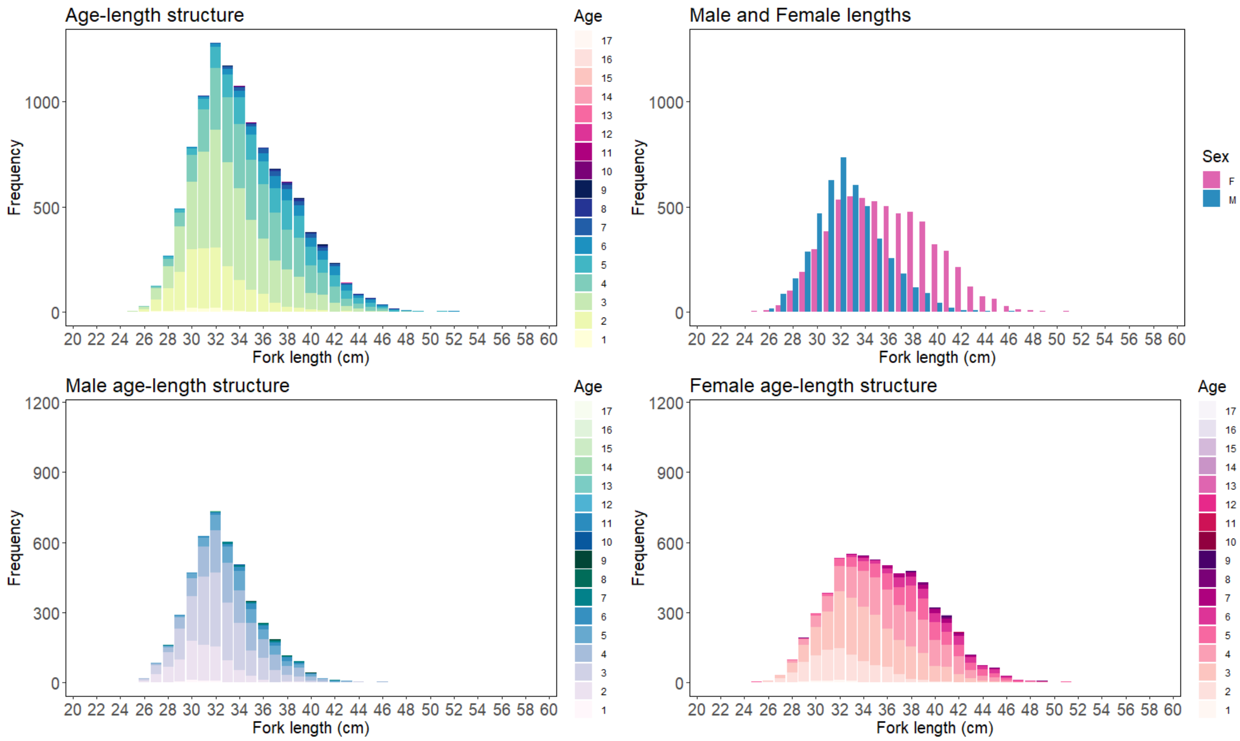

Figure 6: Sampled age-length and sex distributions for fish taken by gillnets 1990 – 2016. (Note that the MLS ≈ 27 cm fork length).

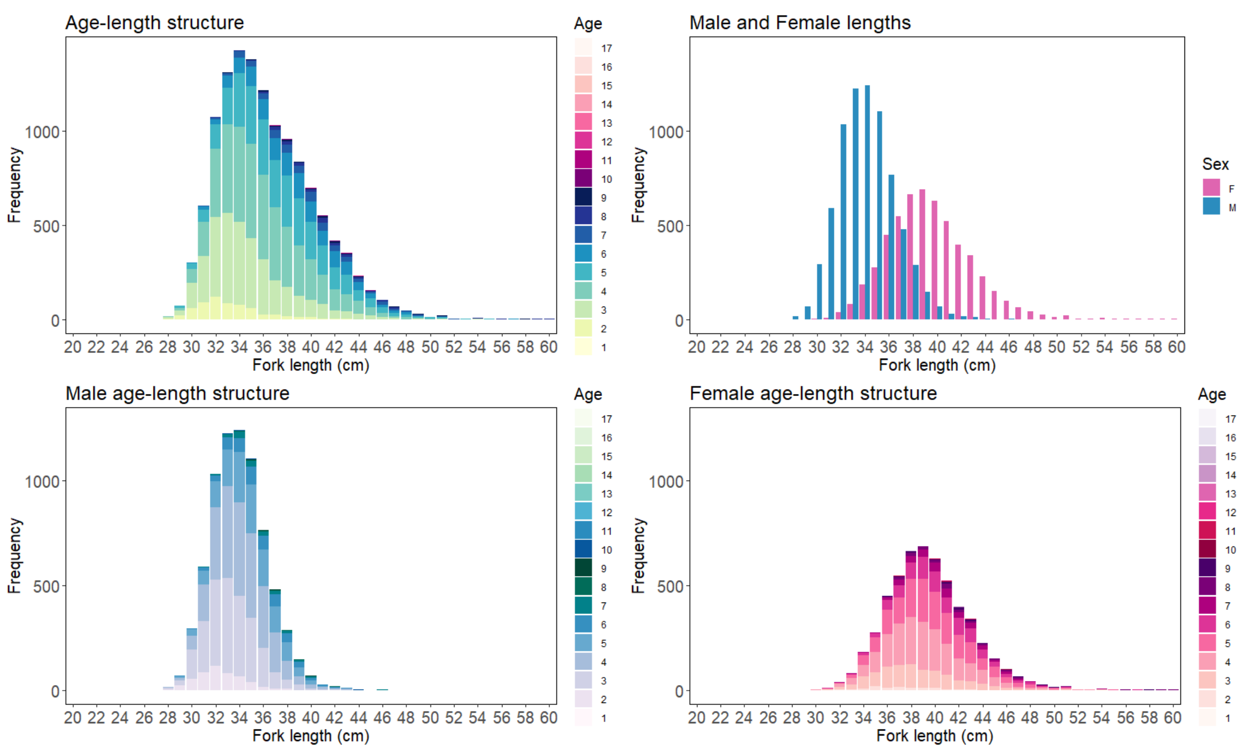

Figure 7: Sampled age-length and sex distribution for ocean-beach fishing 1990 – 2016. (Note that the MLS ≈ 27 cm fork length).

Figure 8: Fishery monitoring staff measuring sea mullet catch. (Photo by Andrew Prosser © State of Queensland).

3 Methods

Processing of the data for stock model inputs involved the use of commercial logbook data to determine catch rates. Biological data sourced from monitoring programs was also analysed to establish biological parameters. The model was then formulated to accommodate species characteristics and available data.

Annual data represented “Gillnet” (comprised of all estuarine methods) and “Ocean-beach Net” harvests for the east coast sea mullet stock (Queensland and New South Wales; Baffle Creek to Eden). Harvest data prior to 1988 were State based with no fishing method recorded. Post 1987 fishing method ratios classified harvest-methods before 1988.

3.1 Catch rates

Most commercial harvests of sea mullet were by either gillnet or ocean-beach net. There have been some concerns on the validity of using ocean-beach catch rates as an index of fish abundance (Leigh, O’Neill, and Stewart 2017). The major form of fishing effort for this method is search time, which is not recorded. The harvest data are also susceptible to hyperstability: the average size of a school of mullet, and hence the catch per record of mullet, may remain the same even if the number of schools in the sea and the total population size change.

Search time is an unrecorded component in ocean beach fishery logbook data. Ocean beach fishing only occurs once a school has been spotted by searchers. It is assumed that searching occurs every day of the ocean beach season and hence, treating every day as a fishing day alleviates some of the uncertainty with regards to ocean beach fishing catch rates.

There is an interaction between the gillnet and ocean-beach sectors - they are not independent. If gillnet fishing is successful before the ocean beach sea mullet (spawning) season, then fewer fish will remain for the spawning run and hence available to the ocean-beach sector.

In addition, as sea mullet school and prepare to exit the estuaries to spawn, gillnetters may take advantage and harvest, either breaking up or reducing the size of schools to be harvested by the ocean-beach sector. It can be seen in Figure 5, that the gillnet sector harvests higher numbers of fish during the spawning season than during the non-spawning period.

As gillnet and ocean-beach catch rates are not independent of each other, it is therefore important to include both gillnet and ocean-beach catch rates in the population model.

Due to the differing nature of data collection in New South Wales and Queensland and their corresponding datasets, catch rates were calculated separately for each state.

3.1.1 New South Wales

New South Wales standardised catch rates were determined for each fishing method (Gillnet, Ocean-beach and Haul Net). There were two datasets available: one based on monthly fishing records (July 1997 – December 2016) and another based on daily records (July 2009 – December 2016).

The monthly dataset catch rates were standardised using variables for each fisher, year, month, location, fishing days (number of days in the month spent fishing) and interactions between month and location.

The daily dataset catch rates were standardised using factors for each fisher, year, month, location, net size or number of shots, wind, lunar phase and interactions between month and location.

It was decided that the estuary haul catch rates were unsuitable for use due to insufficient data. The standardised catch rates from the monthly dataset were also considered unsuitable for use due to the unreliability of the reported number of days fishing in the month.

3.1.2 Queensland

Queensland standardised catch rates were determined for each fishing method (Gillnet, Ocean-beach, Estuary Haul and Tunnel Net) using data based on daily fishing records. These catch rates were standardised using variables for each fisher, year, month, location, net length, mesh size, wind, lunar phase and interactions between month and location.

Ocean-beach catch rates were offset against the number of fishers operating in the fishery that year, on the principle that competition on the beach may be a factor in fewer fish caught per fisher.

Estuary haul and tunnel net catch rates were unsuitable for use due to insufficient data.

3.1.3 Catch rate equations

Data was collated into a single catch observation for each fisher-day combination.

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 (Team 2018) (version 3.5.1) using the quasi-Poisson glm function in the Stats package. Zero catch values included in the analysis were determined by using records for mullet fishers who instead caught other associated species on a given day using the same methodology outlined in Leigh, O'Neill, and Stewart (2017). An exploratory analysis of fishers who had at least 500 kg total catch of sea mullet provided the average catch weights of mullet per fisher-day listed in Table 3 and Table 4.

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 ($\approx$ 1/4 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).

Table 3: Sea mullet catches associated with catches of other taxa in the Queensland gillnet fishery. The final column lists the average catch of mullet per nonzero record of the taxon in the first column.

Taxon	Records	Total harvest (t)	Total Mullet (t)	Av Mullet (kg)
Mullet	149805	18705.972	18705.972	124.9
Barramundi	201	6.321	10.819	53.8
Bream	70376	2186.730	5508.886	78.3
Flathead	79321	1114.031	4857.790	61.2
Garfish	8764	271.893	921.177	105.1
Pilchard	16213	634.265	685.400	42.3
Shark	23775	707.630	1107.227	46.6
Tailor	34900	1469.412	1709.065	49.0
Threadfin	6912	181.179	313.128	45.3
Trevally	14071	803.063	743.946	52.9
Whiting	95938	4585.092	3907.930	40.7
Other	58296	2076.747	3863.543	66.3

Table 4: Sea mullet catches associated with catches of other taxa in the Queensland ocean beach fishery. The final column lists the average catch of mullet per nonzero record of the taxon in the first column.

Taxon	Records	Total harvest (t)	Total Mullet (t)	Av Mullet (kg)
Mullet	15108	19754.728	19754.728	1307.6
Bream	3799	207.468	2920.696	768.8
Dart	2997	502.506	1838.569	613.5
Pilchard	603	95.839	211.627	351.0
Tailor	4270	1423.069	2784.058	652.0
Whiting	4787	363.727	1831.640	382.6
Other	3300	173.267	1488.188	451.0

Wind direction and strength data was sourced by Fisheries Queensland from the Bureau of Meteorology (BOM, Australian Government). The wind data was collected from 76 representative coastal weather stations along Qld east coast. The recorded measures of wind speed (km hr^{-1}) and direction were converted to an average daily reading based on recordings between 3 am and 3 pm, within each latitudinal band along the coast. Missing values were imputed from the next nearest available measurement. 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.

Ocean Beach

*Daily Catch ~ Constant + Fisher + Year + Month + Location + Month * Location + Mesh size + Net length + wind.EW + wind.NS + wind.EW2 + wind.NS2 + wind.NS.EW - offset (number of fishers in the year)*

Gillnet

*Daily Catch ~ Constant + Fisher + Year + Month + Location + Month * Location + Mesh size + Net length + wind.EW + wind.NS + wind.EW2 + wind.NS2 + lunar + lunar_adv + seasonal sinusoidal variables*

3.2 Biological growth

Biological growth parameters for the following equations were calculated using fish age-length monitoring data.

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)   Equation 1 determines the mean length of each individual at a given age (Beverton and Holt 1957). Parameters were fit using a nonlinear least square regression (nls). Although data from Kesteven (1942) could be used to determine a more realistic fit, it was decided that von Bertalanffy parameters used in the model should be based on catch information as model fits would be based on this. Separate parameters were determined for males and females, as females grow larger than males. More information can be found in Appendix E.1.
Allometric growth $W_a = \alpha {L_a}^{\beta}$ (2)   Allometric growth (Equation 2) parameters were fit 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. More information can be found in Appendix E.2.

The models used to determine these parameters were computed in the software R (Team 2018) using the nls and lm functions in the Stats package.

3.3 Model formulation

3.3.1 Model assumptions

Several assumptions were made in formulating the model:

1. Instantaneous natural mortality rate (M) was different for each sex and fixed throughout time.
2. The weight and fecundity of a fish were parametric functions of size. For simplicity in describing the model, we assume that fecundity is proportional to weight.
3. The proportion of mature fish depends on age but not size.
4. The proportion of fish vulnerable to fishing depends on age, sex and fishing method but not time.
5. 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).

3.3.2 Population dynamics

The population model indexes the population matrix by time (t), age (a) and gender (g). The data show there were differences in the growth and vulnerability to fishing of male and female sea mullet (Figure 6 and Figure 7). Considering this, natural mortality rates (M) specific to each sex were estimated within the model. Selectivity (Equation 3) was based on the Richards function (an asymmetric version of the logistic function) as there is no reason to assume that selectivity (as a function of age) is symmetric. As the selectivity function is age based, ages corresponding to minimum legal size are used to fit the selectivity parameters. The minimum legal size has been the same (30 cm total length) for the whole period over which we have age and length data.

Table 6: Population equations.

Population Dynamics

Richards selectivity function

$$S_{s,g,a} = \begin{cases} \left(1/(1+\exp\left[-\ln(19)(a - A_{50,s,g})/(A_{95-50,s,g})\right])\right)^{\gamma_{s,g}} & \text{for } a < 5 \\ 1 & \text{for } a \geq 5 \end{cases} \quad (3)$$

where γ, A_{50} and A_{95-50} are selectivity parameters.

initial age structure

$$N_{0,g,a} = \begin{cases} R_{0,g} & \text{for } a = 0 \\ N_{0,g,a-1}\exp(-M_g) & \text{for } a = 1,2,\dots,15 \\ N_{0,g,a-1}\exp(-M_g)/((1-\exp(-M_g)) & \text{for } a = 16 \end{cases} \quad (4)$$

vulnerable biomass

$$B_{s,t}^{V} = \sum_{g}\sum_{a} N_{t,g,a}\exp(-\frac{1}{2}M_g)\, S_{s,g,a}\, w_{g,a} \quad (5)$$

where $w_{g,a}$ denotes weight at age for each gender.

harvest rate

$$H_{t,s} = C_{t,s}/B_{s,t}^{V} \quad (6)$$

predicted catch at age

$$\hat{C}_{t,g,a} = \sum_{s} H_{t,s}\; N_{t,g,a}\exp(-\frac{1}{2}M_g)\, S_{s,g,a} \quad (7)$$

spawning biomass

$$B_t^{Sp} = f_a N_{t,1,a} \qquad \text{for } t > 0 \quad (8)$$

where f_a denotes maturity × weight at age for female fish as a proxy for fecundity.

Beverton-Holt recruitment

$$R_{t,g} = \begin{cases} \dfrac{4hR_t B_t^{Sp}}{B_0^{Sp}(1-h) + B_t^{Sp}(5h-1)} \times \dfrac{1}{2} & \text{for } 0 < t < \xi \\[2ex] \dfrac{4hR_t B_t^{Sp}}{B_0^{Sp}(1-h) + B_t^{Sp}(5h-1)} \times \dfrac{1}{2} \times \exp(d_t) & \text{for } t \geq \xi \end{cases} \quad (9)$$

where d_t represents a random recruitment deviation and ξ represents the first year of age-length information (Beverton and Holt 1957).

age structure

$$N_{t,g,a} = \begin{cases} R_{t,g} & \text{for } a = 0, t > 0 \\ N_{t-1,g,a-1}\exp(-M_g) - \hat{C}_{t-1,g,a-1}\exp(-\frac{1}{2}M_g) & \text{for } a = 1,2,\ldots,15,\ t > 0 \\ N_{t-1,g,a-1}\exp(-M_g) - \hat{C}_{t-1,g,a-1}\ \exp(-\frac{1}{2}M_g) & \\ \qquad +N_{t-1,g,a}\exp(-M_g) - \hat{C}_{t-1,g,a}\exp(-\frac{1}{2}M_g) & \text{for } a = 16, t > 0 \end{cases} \tag{10}$$

predicted mid-year vulnerable biomass

$$B_{s,t}^{V_{mid}} = \sum_{g,a} S_{s,g,a}\ w_{g,a}\left(N_{t,g,a}\exp(-\frac{1}{2}M_g) - \frac{1}{2}\hat{C}_{t,g,a}\right) \tag{11}$$

where s represents each catch rate series. This equation is used to match catch rates in the negative log likelihood Equation 15.

predicted numbers at length

$$\hat{P}_{s,t,g,l}^{LF} = \frac{\sum_a N_{t,g,a}\ L_{s,g,a,l}\ S_{s,g,a}}{\sum_l\left(\sum_a N_{t,g,a}\ L_{s,g,a,l}\ S_{s,g,a}\right)} \qquad \text{for } t \geq \xi \tag{12}$$

where $L_{s,g,a,l}$ represents the input length distribution at age which is also indexed by fleet & gender. Note that $\hat{P}_{s,t,g,l}^{LF}$ will sum to 1.

predicted numbers at age

$$\hat{P}_{s,t,g,a}^{AF} = \frac{N_{t,g,a}\ S_{s,g,a}}{\sum_a\left(N_{t,g,a}\ S_{s,g,a}\right)} \qquad \text{for } t \geq \xi \tag{13}$$

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

3.3.3 Matching predictions to data

Negative log-likelihood functions for calibrating population dynamics are shown below. 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.

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

Negative log-likelihood functions

Many of the formulae below are taken from G. M. Leigh, O'Neill, and Stewart (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.

recruitment deviations

$$\ell^{(RD)} = y\left[\ln(\tilde{\sigma}^{RD}) + \frac{1}{2}(\hat{\sigma}^{RD})^2/(\tilde{\sigma}^{RD})^2\right] \tag{14}$$

where y denotes the number of recruitment deviation years -1

$$(\hat{\sigma}^{RD})^2 = \left(\sum_{t=1}^{y} d_t^2\right)/y$$

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

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

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

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.

cpue

$$\ell_s^{CR} = y_s \times \ln(\hat{\sigma}_s^{CR}) + y_s/2 \qquad (15)$$

where y_s is the number of years in catch rate series s.

$$\hat{\sigma}_s^{CR} = 0.5 \times \left(\sqrt{A_1}/y_s + 1\right) + \sqrt{\left(0.5 \times \left(\sqrt{A_1}/y_s - 1\right)\right)^2 + \phi}$$

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

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

$c_{s,t}$ represents the input catch rate,

$A_2 = \sum_t\left(\ln\left(c_{s,t}/B_{s,t}^{V_{mid}}\right)(\sigma_s^{CR})^2\right) / \sum_t 1/(\sigma_s^{CR})^2$.

and σ_s^{CR} is the standard error for $\ln(c_{s,t})$ from the GLM catch-rate analysis.

lengths

$$\ell^{(LF)} = \sum_{s,t,g,l} T_{s,t,g}^{LF} \; P_{s,t,g,l}^{LF} \ln\left(\hat{P}_{s,t,g,l}^{LF}\right) \qquad (16)$$

where $T_{s,t,g}^{LF}$ denotes the effective sample size, which was estimated by the methods in G. M. Leigh, O'Neill, and Stewart (2017) section 4.5.2.

$P_{s,t,g,l}^{LF}$ represents the input proportions at length indexed by series, year and gender.

The provided length distribution was based on a growth transition matrix, which used a von Bertalanffy growth curve with normally distributed experimental error in the length at age. The parameters for this curve were set outside the model and not estimated.

ages

$$\ell^{(AF)} = \sum_{s,t,g,a} T_{s,t,g}^{AF} \; P_{s,t,g,a}^{AF} \ln\left(\hat{P}_{s,t,g,a}^{AF}\right) \qquad (17)$$

where $T_{s,t,g}^{AF}$ denotes the effective sample size and

$P_{s,t,g,a}^{AF}$ represents the input proportions at age indexed by series, year and gender.

3.3.4 Model parameters

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

The von Bertalanffy and allometric growth parameters were pre-calculated using biological monitoring data. Fixed values for γ were used as there were difficulties estimating both γ and M in the model at the same time. The fixed values were chosen by incrementally changing the values of γ and rerunning the model until the best objective function value was achieved. It is important to note that due to the addition of γ in the selectivity function, A_{50} is no longer the age at 50% vulnerability to fishing and A_{95-50} is no longer the difference between the ages at 95% and 50% vulnerability.

The Beverton-Holt steepness parameter h was unable to be estimated in the model even if other parameters such as M were fixed. Hence, low, middle and high values for h were chosen creating three separate analyses. This happened because there was a lack of contrast in the data; catches had been stable for over 100 years.

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
γ	Richards selectivity function power, see Equation 3
h	Beverton-Holt steepness parameter, see Equation 9 Three different values were tested.
Estimated	
M	natural mortality rate
$\ln(B_0^{Sp})$	natural log of the virgin spawning biomass
A_{50}	age at 50% selectivity before the Richards power transformation, see Equation 3
A_{95-50}	difference between ages at 95% and 50% selectivity before the Richards power transformation, see Equation 3
d_t	log recruitment deviations used to adjust annual recruitment from the deterministic Beverton-Holt calculation

3.3.5 Coding and operation of the software

The model was coded in parallel in two different software packages: ADMB (Fournier et al. 2012) and R (Team 2018). 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.

A total of 550,000 MCMC simulations were run for each value of the Beverton-Holt steepness parameter h (4.9, 6.6 and 8.3) and saved every 50th simulation for a total of 11,000 simulations. Results from the first 1,000 saved simulations were then excluded from mean, median and credible interval analysis. The results presented in Appendix F are from the MCMC output of ADMB.

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

3.3.6 Model analysis

After the model was optimised, the maximum sustainable yield (MSY) was calculated. A simplified version of the model, using fitted model parameters without recruitment deviations was created based on the technique used in Leigh, O'Neill, and Stewart (2017). This simplified model was then optimised to find the maximum possible long term yield (MSY).

Target yields were also calculated in a similar way. The simplified model was optimised for a long term target biomass proportion (exploitable biomass relative to virgin exploitable biomass), such that a target yield was produced.

4 Results

4.1 Catch rates

After investigation into an appropriate method for calculating catch rates (see Appendix D), it was concluded that the catch rates shown in Figure 9 were the most suitable to be run in the model.

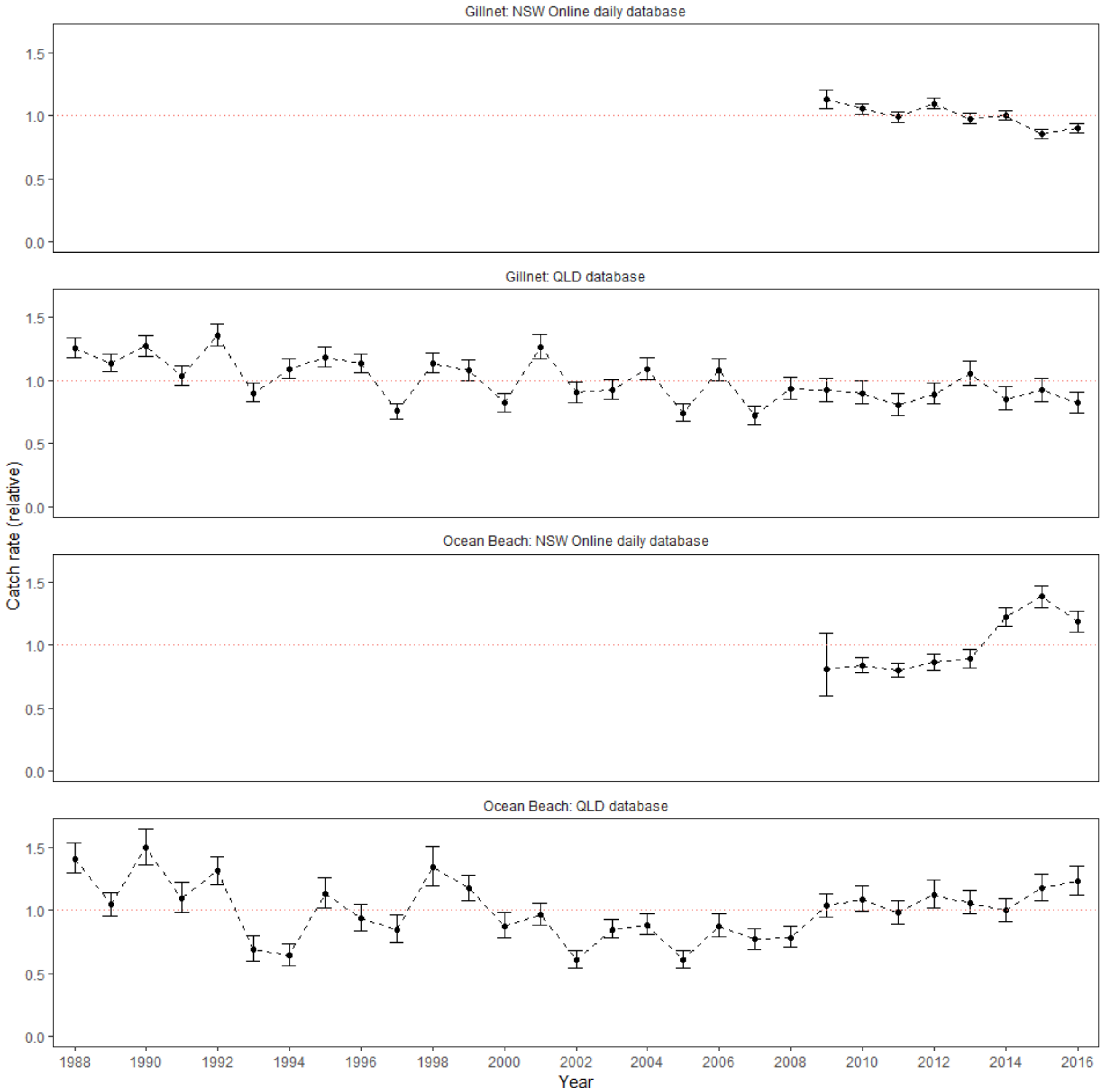

Figure 9: Standardised catch rates for ocean beach netting and gillnetting. (New South Wales and Queensland data).

These catch rates show an initial decline for both gillnet and ocean-beach net until the mid-2000s. After this point, ocean-beach catch rates show an increase, however, gillnet catch rates continue to decline. As stated in Section 3.1, there is an interaction between the gillnet and ocean-beach sectors - they are not independent. It is therefore important to include catch rates from both methods in the model. Further information on catch rate analysis can be found in Appendix D.

4.2 Model output

The stock model was run three times with different values for h (low, medium and high) to identify key results for fisheries management. For each, the model fits to data were maximised. Model parameters and fits are presented in Appendix G.

4.2.1 Biomass and recruitment

A plot of the predicted biomass proportions for each model (Figure 10) indicates the highest level of certainty for Model 2 ($h = 0.66$). The plot shows a historical biomass average of around 60%. From 1988, a cyclic fluctuation of biomass (following the introduction of age-length data to the model) can be seen with a midpoint declining from the historical 60% to around 50% in 2013.

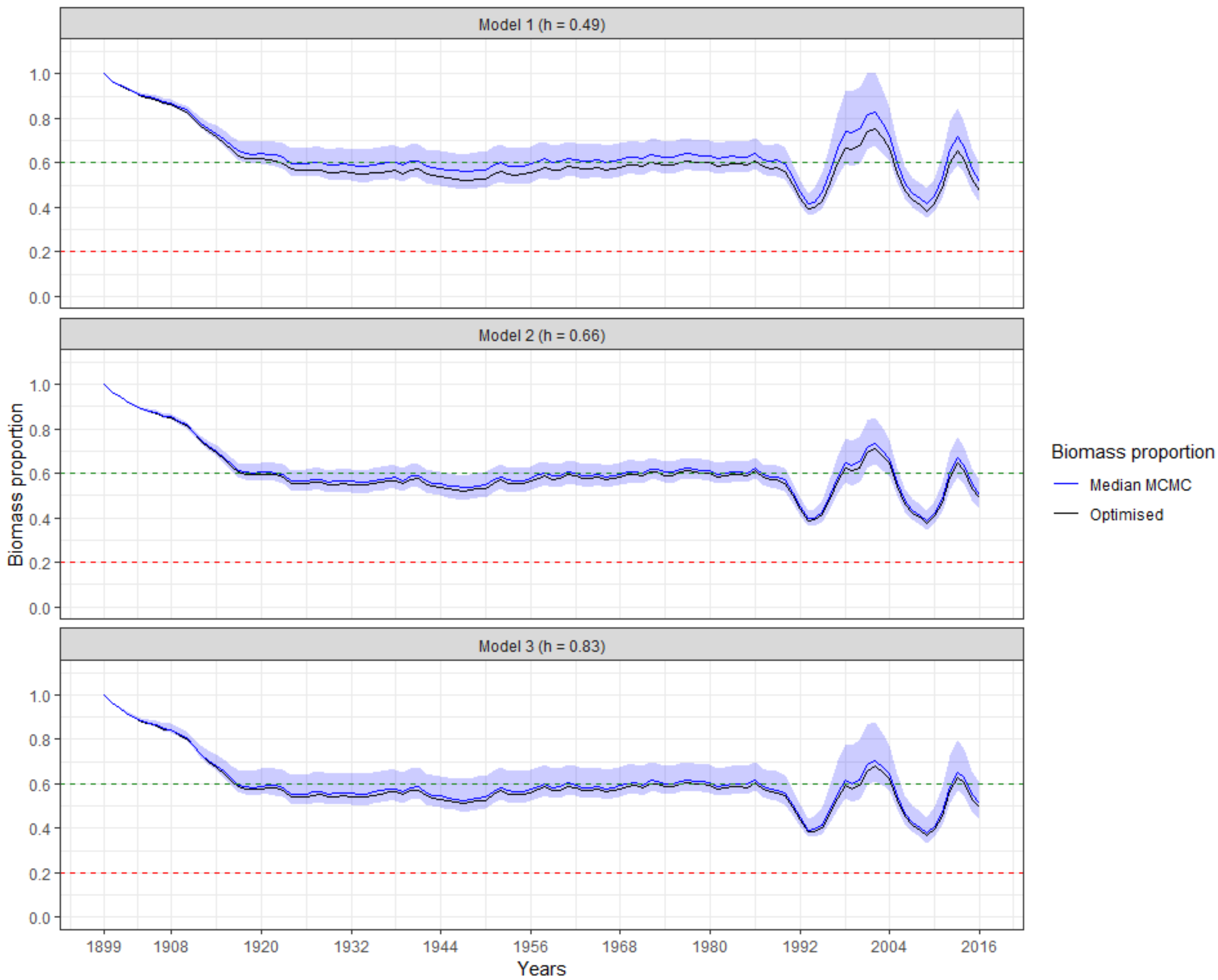

Figure 10: Exploitable biomass proportion relative to virgin exploitable biomass for different fixed values of h. The black line shows the optimised biomass proportion, while the blue line shows the median of the MCMC run. Shaded areas indicate the 95% credible interval of the MCMC run.

Recruitment proportion shown in Figure 11 indicates that the highest level of certainty is for Model 2 ($h = 0.66$) and Model 3 ($h = 0.83$). The plot shows a fluctuation in recruitment proportion after 1988 once age-length structures are available to the model. These fluctuations have the same trend as the fluctuations in the biomass proportions shown in Figure 10, indicating that recruitment is a driver of the changes that we see in biomass.

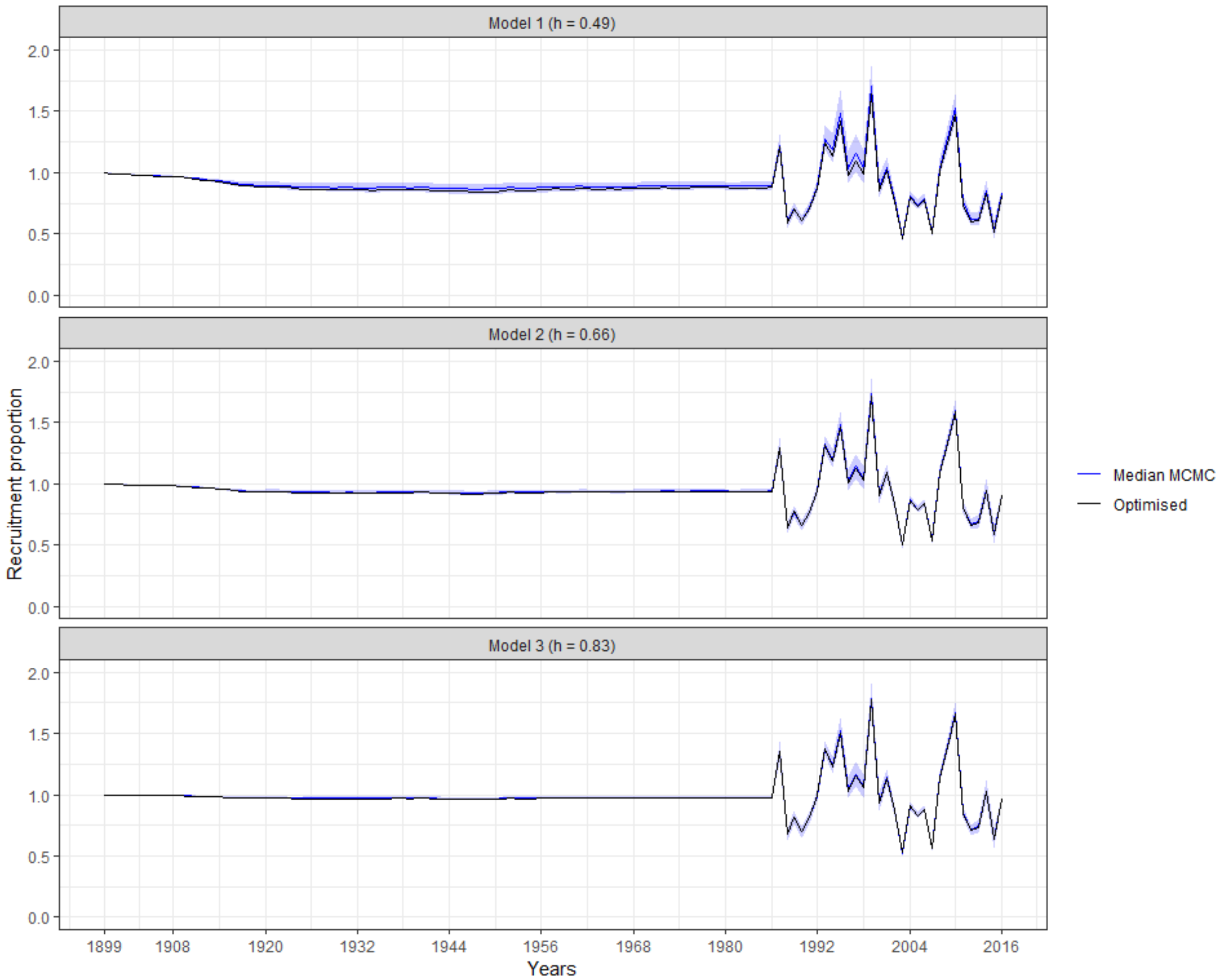

Figure 11: Recruitment deviations relative to virgin recruitment for different fixed values of h. The black line shows the optimised recruitment deviations, while the blue line shows the median of the MCMC run. Shaded areas indicate the 95% credible interval of the MCMC run.

It has already been noted from Figure 10 that we achieve the greatest certainty with Model 2 and Model 3. A plot overlaying the biomass proportions produced for each model is presented in Figure 12. From this plot we can see that while Model 3 has produced a slightly lower estimate of biomass proportion than the other models, the three models were actually very closely aligned in their resulting biomass estimates.

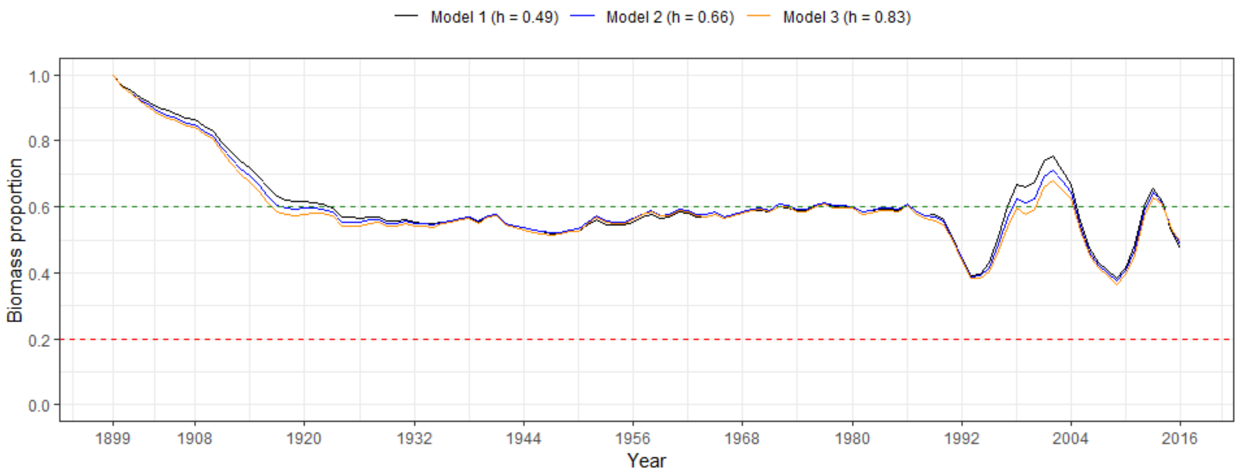

Figure 12: Plot of exploitable biomass proportion relative to virgin exploitable biomass for each model.

A phase plot (Figure 13) shows how the harvest rate and biomass proportion have changed over time. Of note is that the low points cyclic fluctuations seen in Figure 10 and Figure 12 are not produced by the same harvest rate. The harvest rate during the biomass low point in 1994 is almost 70%, which is much higher than the harvest rate of around 40% during the 2009 biomass low point. Phase plots for each model are shown in Appendix H

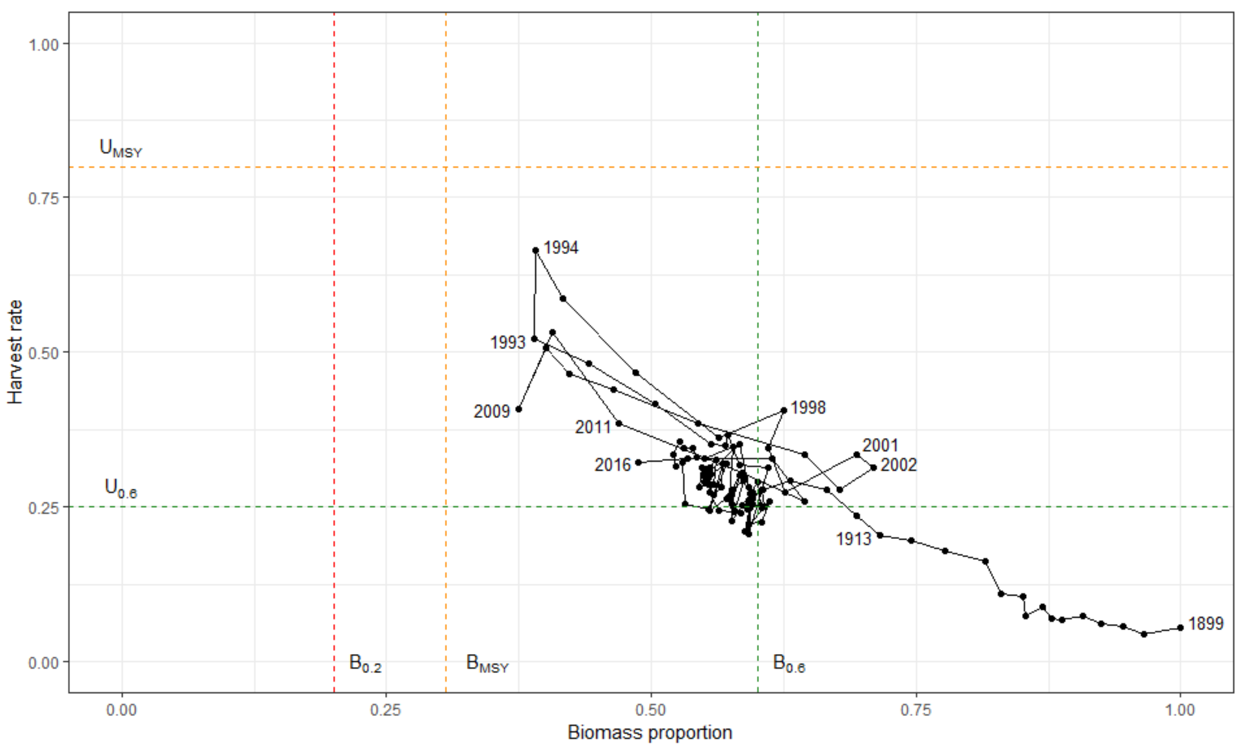

Figure 13: This phase plot follows the trajectory over time of harvest rate vs exploitable biomass proportion relative to virgin exploitable biomass for each year for Model 2 ($h = 0.66$).

4.2.2 Fishing targets

Various harvest targets were calculated (see Figure 14). These harvest targets include the Maximum Sustainable Yield (MSY), a harvest target to achieve 60% biomass that is the target under the Queensland Sustainable Fisheries Strategy (Agriculture and Fisheries 2017) and harvest targets for 55%, 50% and 40% biomass. These harvest calculations were based on biomass in 2016 and 2009 (the biomass low point).

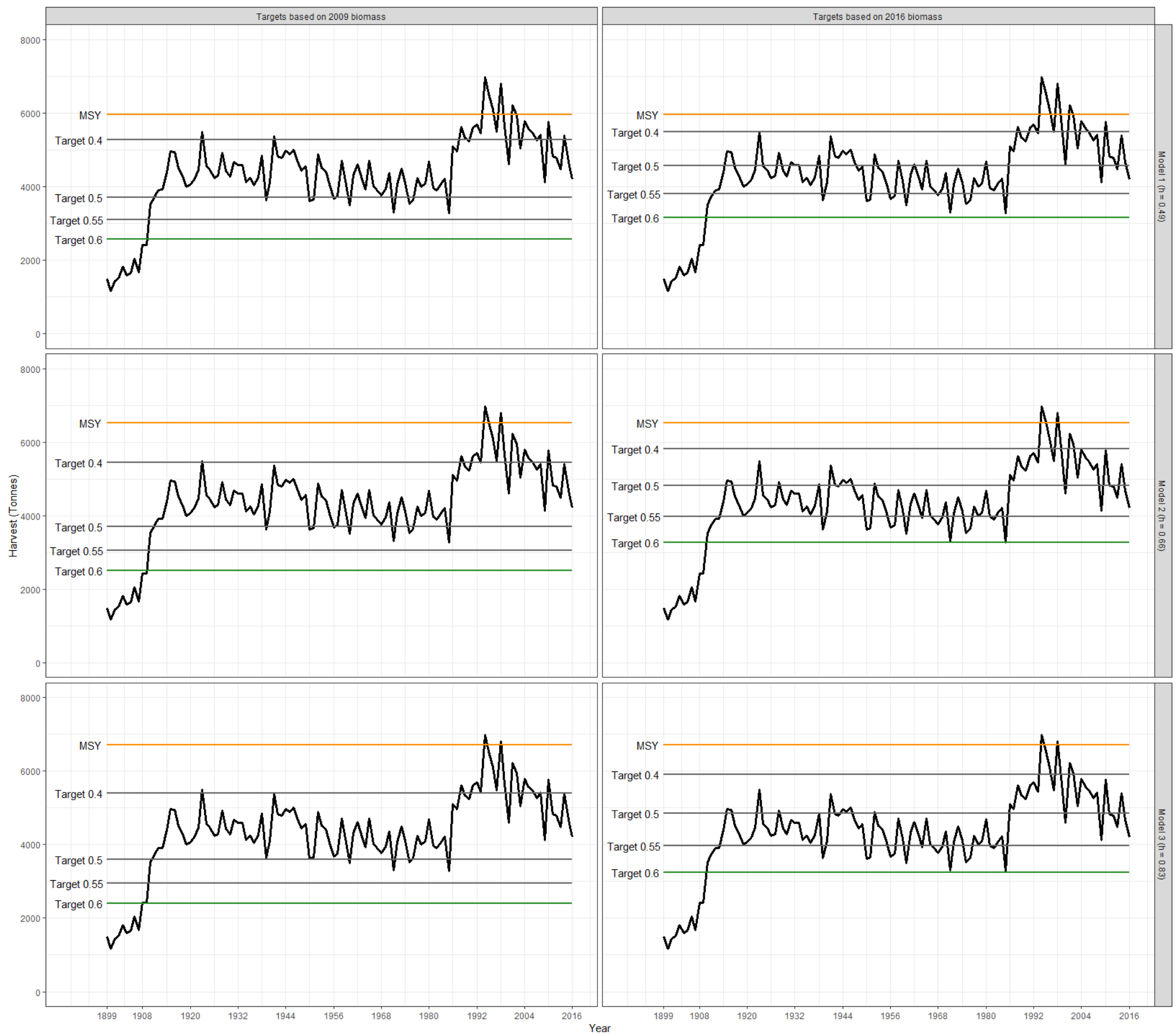

Figure 14: Plot of annual harvest with MSY and harvest targets for each model. Target scenarios are based on biomass levels for 2009 (biomass low point) and 2016 (most recent biomass).

To aid in readability of harvest targets Table 9 details the actual values. Serial plots from the MCMC run for MSY and the 60% harvest target are presented in Appendix F.2.

Table 9: MSY and harvest targets (tonnes) for each model. Target scenarios are based on biomass levels for 2009 (biomass low point) and 2016 (most recent biomass).

Harvest target	Based on	Model 1 ($h = 0.49$)	Model 2 ($h = 0.66$)	Model 3 ($h = 0.83$)
MSY		5,969	6,526	6,709
40% Biomass	2009	5,271	5,436	5,390
	2016	5,493	5,810	5,910
50% Biomass	2009	3,705	3,699	3,596
	2016	4,562	4,817	4,851
55% Biomass	2009	3,096	3,053	2,946
	2016	3,811	3,975	3,974
60% Biomass	2009	2,569	2,507	2,404
	2016	3,164	3,265	3,243

5 Discussion

5.1 Performance of the population model

The population model (Section 3.3) handles important effects in the age-length structure of sea mullet harvested for each sex. This population model accounts for that with both fishing harvest and natural mortality determined separately for each sex within the model.

The model was unable to estimate the Beverton-Holt steepness parameter, h (the model hit the upper bound regardless of changes/fixing of other parameters). We believe that this happened because of lack of contrast in the data, whereby the harvest has not varied much since catch-rate data became available in 1988. Due to this three different scenarios were modelled, $h = 0.49,\ 0.66$ and 0.83. This corresponded to the lowest value that the model could take and still produce results, the highest value that is biologically reasonable and a value in between. Results from the MCMC run of the models indicate a slightly greater consistency for Model 2 ($h = 0.66$) compared to Model 3 ($h = 0.83$), although Model 3 gave rise to the highest likelihood.

This assessment and its population model have used the ageing data on individual fish aged by the monitoring teams in QLD and NSW. A randomly selected subset of fish were aged. They were selected without reference to their length: therefore an age-length key was not required.

Selectivity was age based rather than length based. Length based selectivity was initially tested, however due to the poor correlation between age and length of sea mullet the model did not perform very well. Age based selectivity was modelled using a Richards function to account for the asymmetric shape of the selectivity function.

It is suggested that future implementations of the model could separate fleets into QLD and NSW in addition to gillnet and ocean-beach net. As data is sourced separately for each state this would be possible and might add a level of insight on how each of the QLD and NSW components of the stock are doing separately.

5.2 Stock Status

Prior to the late 1980s, fishing for sea mullet was relatively stable with an average annual harvest of roughly 4000 tonnes. This harvest has increased since the late 1980s to a peak of over 6000 tonnes in the mid-1990s. Since the mid-1990s, harvest has been steadily decreasing although it is still slightly above average levels prior to the late 1980s (see Figure 14).

Model results indicate that biomass levels were around 60% of virgin exploitable biomass prior to the late 1980s, assuming deterministic recruitment. After the late 1980s, annual recruitment variation was estimated from the fish age-length data. Resulting biomass proportions experienced a cyclic fluctuation influenced by the addition of recruitment information to the model (see Figure 10, Figure 11 and Figure 12).

A trend line through the midpoint of these cyclic fluctuations indicates a downward trend in biomass to around 50% of virgin levels. Indications are that the increased fishing pressure in the mid-1990s has contributed to a fall in stock.

The final year of the model occurs during a biomass downcycle. It is unclear how low the future biomass downcycle will go. It is therefore important to consider that fishing levels during the biomass downcycle could exacerbate the downward trend of the biomass cycle midpoint.

It has been reported by the Project Team that important estuaries in the northern part of the Queensland stock range (Bundaberg to Noosa) are experiencing reduced harvests. This is not clearly shown by the data presented herein (e.g. Figure 1), but is an important consideration and should be monitored closely in the future. This may be due to environmental changes (i.e. increasing average local temperatures, physical barriers and seagrass dieback from recent flooding in addition to fishing pressure). A decline in estuary habitat can cause difficulty for juveniles to grow and migrate impacting on stock levels in the area (Whitfield and Elliott 2002; Ficke, Myrick, and Hansen 2007).

5.3 Recommendations

The Queensland Sustainable Fisheries Strategy states clear aims to build and maintain fisheries for long term sustainability. Target reference points are 40 – 50% of virgin exploitable biomass by 2020 and 60% biomass by 2027 (Agriculture and Fisheries 2017). These reference points are, however, restricted to Queensland and are not New South Wales Government policy.

5.3.1 Management

For sea mullet, results show that biomass may be at around the 50% level and trending slightly downwards. Management strategies based on the Queensland Sustainable Fisheries Strategy's 60% target implies a combined QLD-NSW harvest in the range 2400 – 3250 tonnes, which is the range of rounded harvest sizes from the three different model runs and from the biomass levels in 2009 (low point) and 2016 (latest year of data). This 60% target can also be used as a proxy for Maximum Economic Yield (MEY).

The 60% target biomass level is not current policy in NSW. As an example, the harvest range for a 50% biomass target would be 3600– 4850 tonnes. Table 9 and Figure 14 display reference point outcomes.

It is important to note that the fishery is currently in a biomass downcycle (see Figure 10 and Figure 12). Biomass during a low point is even more sensitive to fishing pressure than at other times. This is a key consideration when setting harvest limits and management procedures.

5.3.2 Monitoring

Monitoring data provided for this assessment were of high quality. These data provided annual recruitment information to the model revealing the cyclic nature of sea mullet biomass. Continued monitoring of sea mullet age, length and sex structures that are representative of the fishery/population is therefore important for the ongoing assessment and management of sea mullet.

As stated in Section 5.2, there is some concern that there may be some degradation of estuaries between Bundaberg and Noosa. It is therefore also recommended that an assessment of the extent and impact of any changes to freshwater and estuary habitats be undertaken; and any TACC setting consider this regional circumstance.

5.3.3 Assessment

Stock assessment of the sea mullet fishery every two years is required to monitor the pattern of biomass down cycle. It will also be important to gauge the effectiveness of management procedures.

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Appendix A - Daily harvest sizes

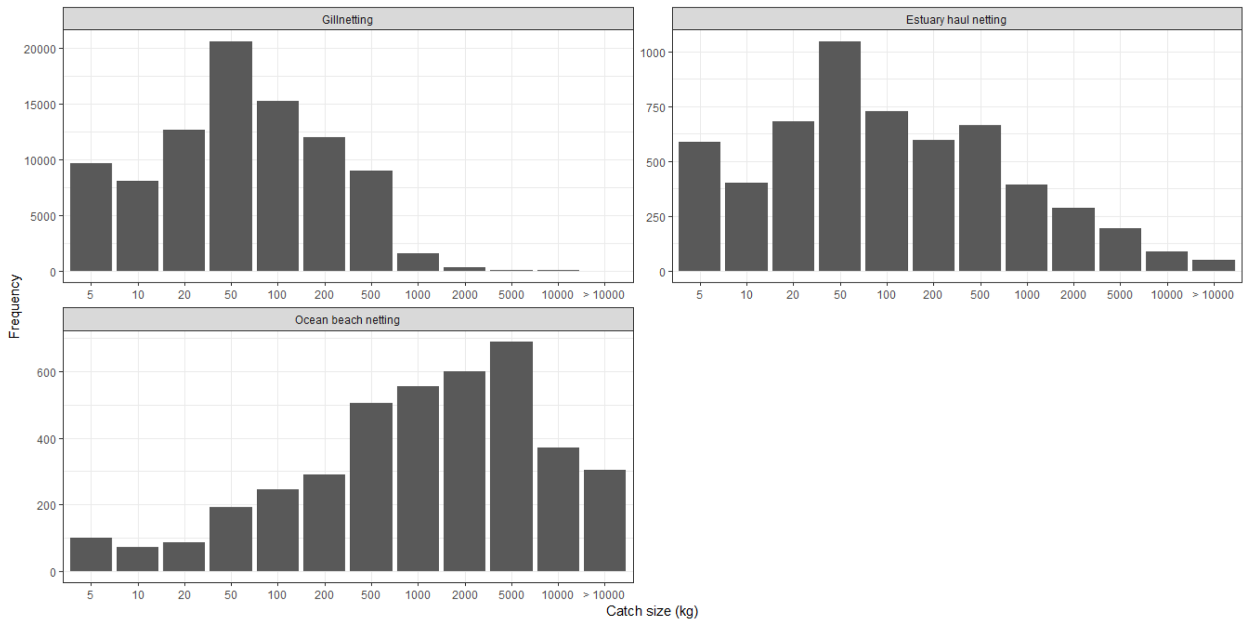

Figure 15: Histograms of catch sizes per fisher-day for each fishing method in New South Wales. Note that y-axes differ for each fishing method.

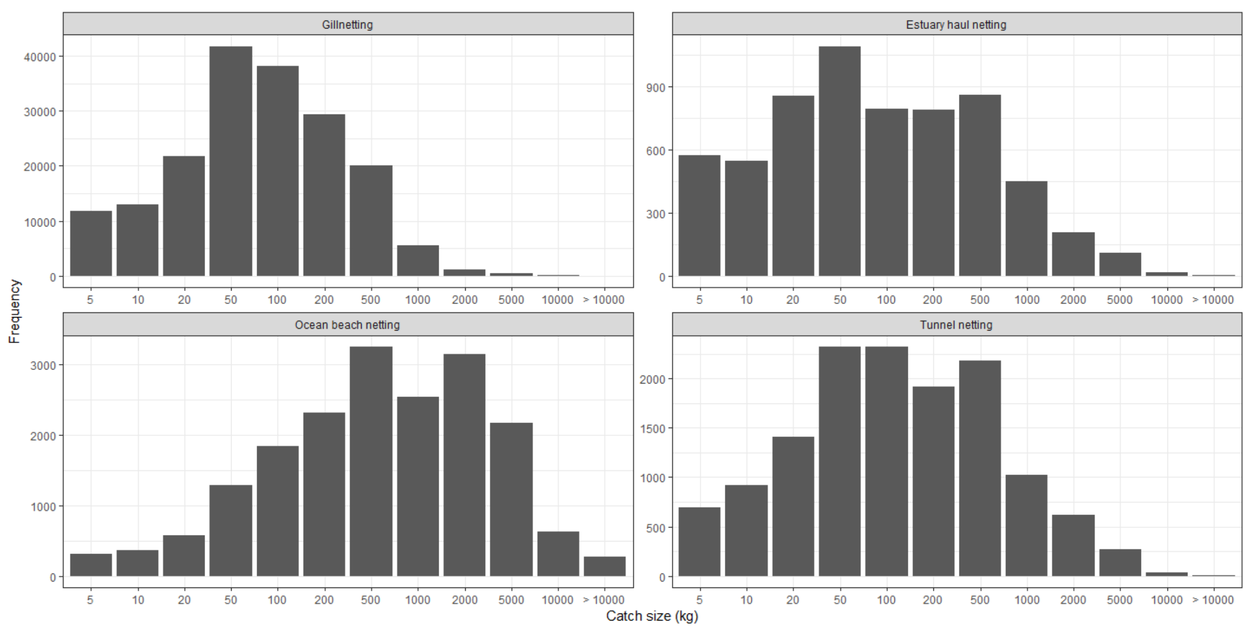

Figure 16: Histograms of catch sizes per fisher-day for each fishing method in Queensland. Note that y-axes differ for each fishing method.

Appendix B - Monthly harvest sizes

Monthly harvest sizes in each year for each fishing method are produced in Figure 17 for New South Wales and Figure 18 for Queensland. Note that accurate reporting of fishing methods in Queensland did not begin until the early 2000s. Prior to this the majority of harvest was assigned to gillnetting. A set of rules was applied to the Queensland fishing method data to correct data previously assigned as gillnetting to the ocean-beach method.

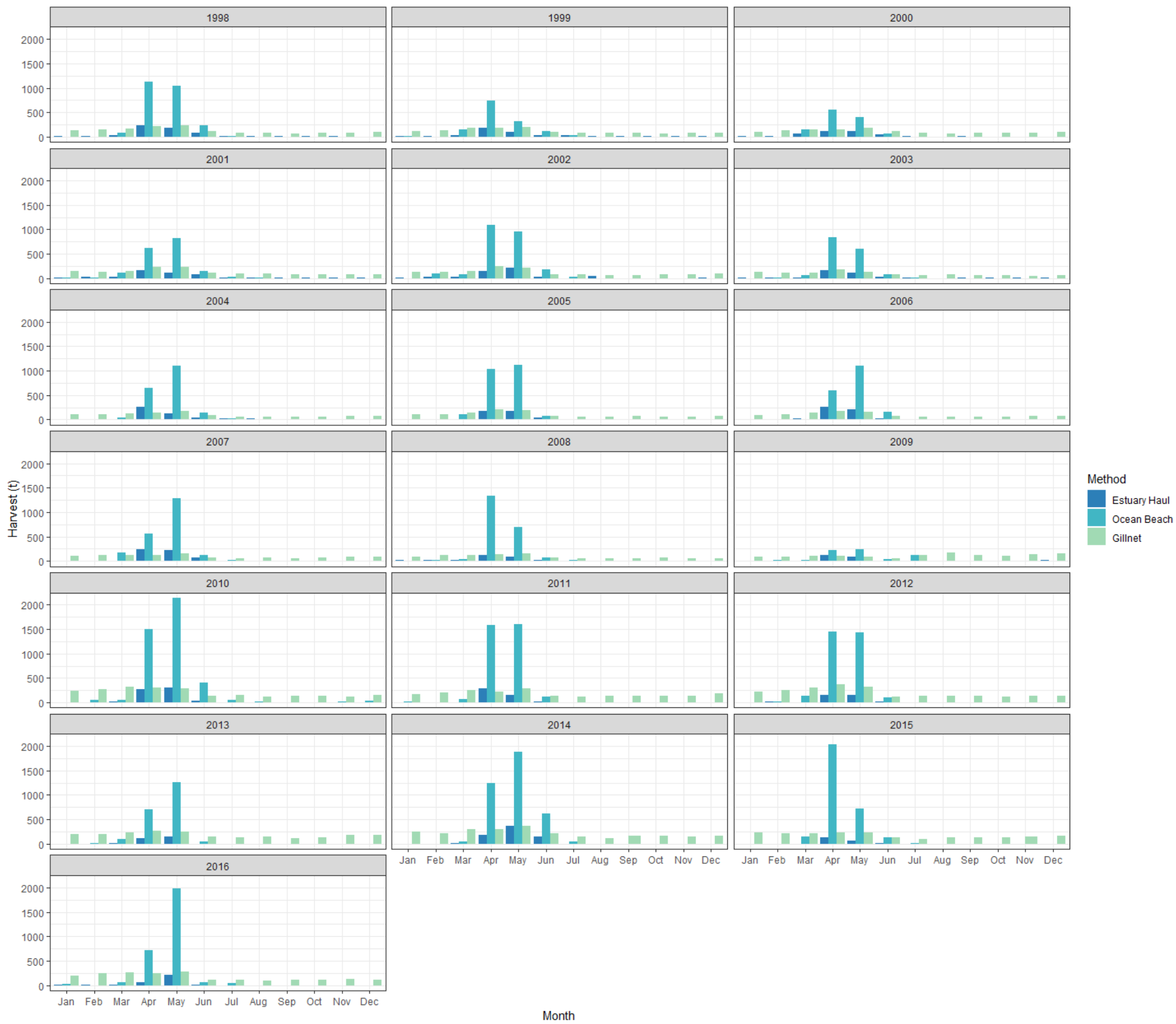

Figure 17: Histograms of harvest sizes per month for each fishing method in New South Wales for the years 1998 - 2016.

Figure 18: Histograms of harvest sizes per month for each fishing method in Queensland for the years 1988 - 2016.

Appendix C - Age-length sampling

Biological sampling for both states consisted of two sets of data. Sea mullet lengths were sampled over a number of years by fishery monitoring and research programs. Fish otoliths were used to estimate fish age from a subset of this data.

Figure 19: Biological sampling of age information for each fishing method in Queensland and New South Wales.

Overall age-length compositions for each state and fishing method sampled are shown below. Annual distributions of age and length structures for each sex and fishing method can be found in Appendix G.2 and Appendix G.3.

C.1 Queensland

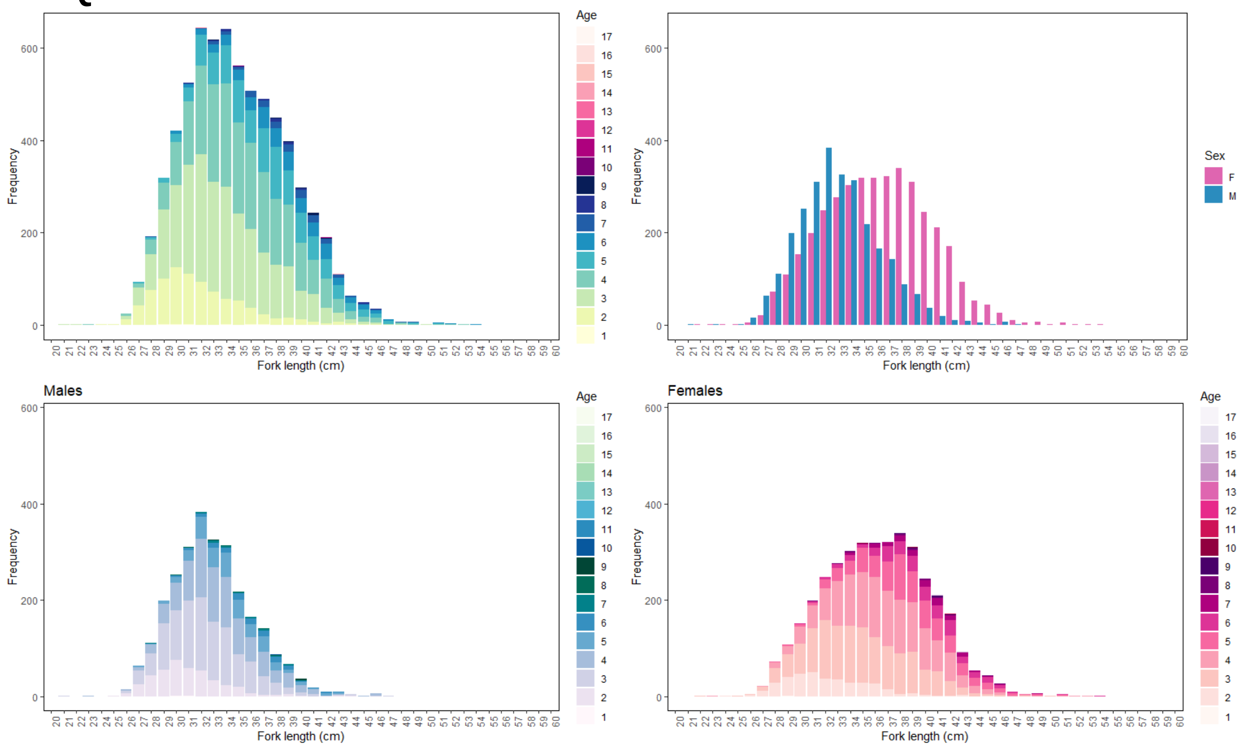

Figure 20: Sampled age-length and sex distribution for QLD Gill Net, all years combined.

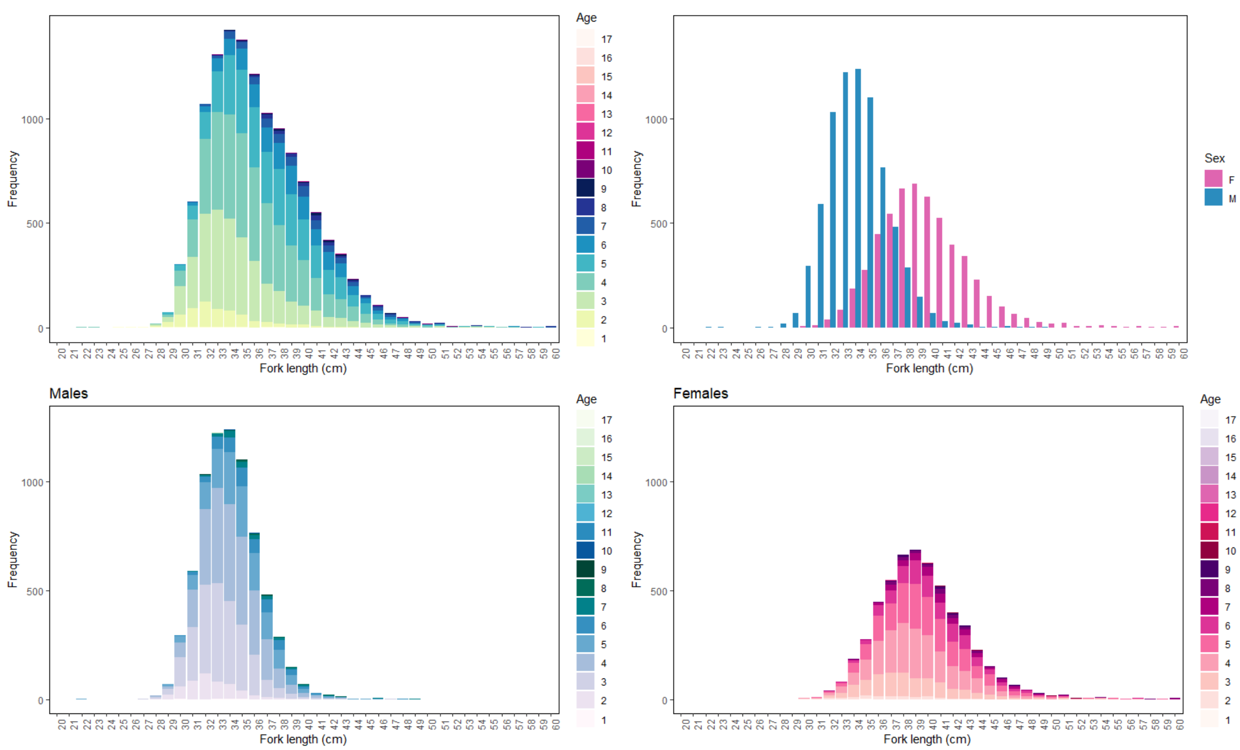

Figure 21: Sampled age-length and sex distribution for QLD Ocean Beach Net, all years combined.

C.2 New South Wales

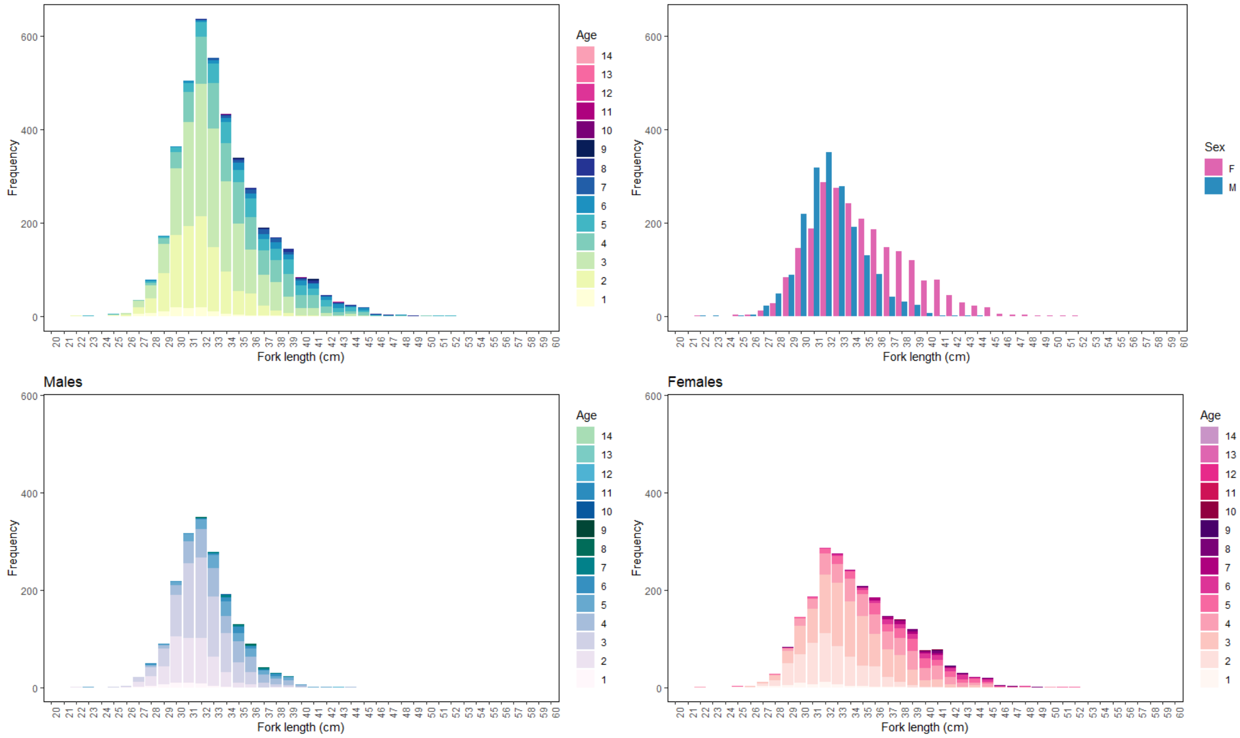

Figure 22: Sampled age-length and sex distribution for NSW Gill Net, all years combined.

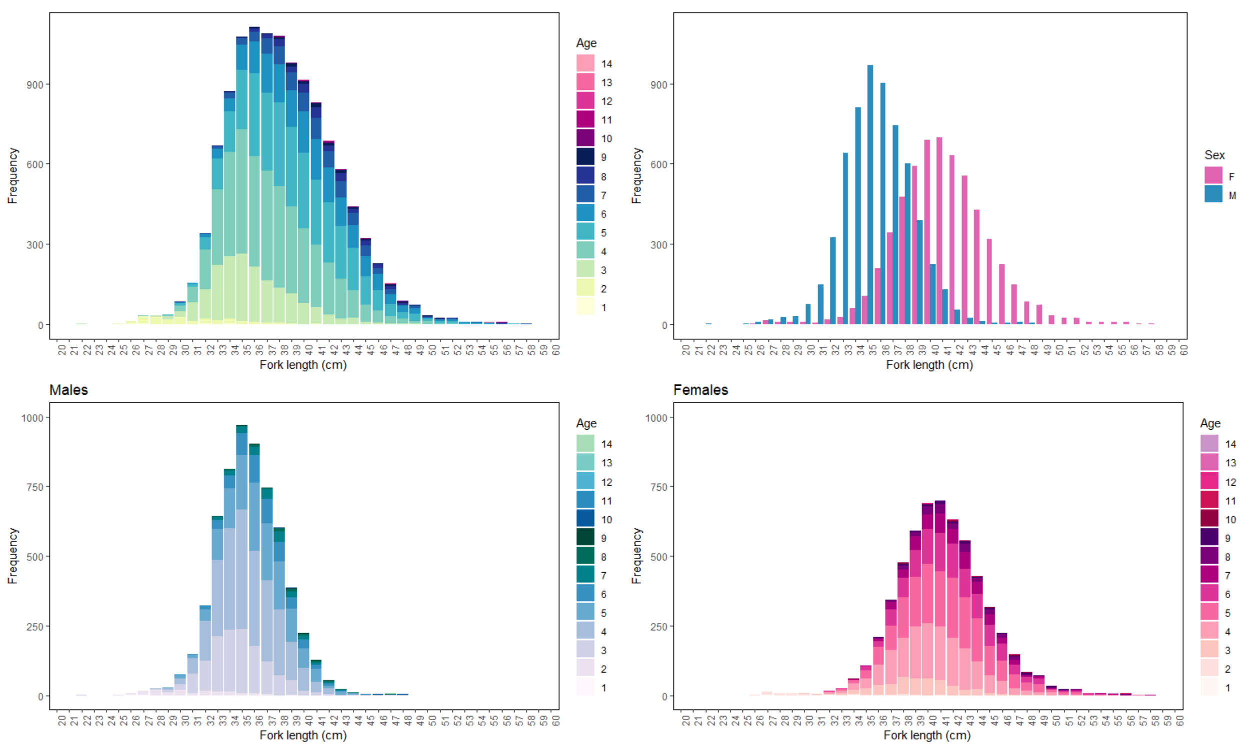

Figure 23: Sampled age-length and sex distribution for NSW Ocean Beach, all years combined.

Appendix D - Catch rate analysis

Extensive analyses were made in an effort to determine the best possible set of catch rates.

D.1 Catch rates by method

Catch rates were first determined for each fishing method and state.

New South Wales logbook information was compiled in two separate databases; one based on monthly records from 1997 onwards and another based on daily records from 2009 onwards. It was decided that tunnel net (QLD only) and estuarine haul net catch rates were unsuitable for use due to insufficient data. It was also concluded that the catch rates determined using the monthly dataset were unsuitable for use due to the unreliability of the reported number of days fishing in the month.

Figure 24 and Figure 25 show that the catch rates determined using the New South Wales monthly dataset do not follow the same trend as the catch rates determined using the New South Wales and Queensland daily datasets.

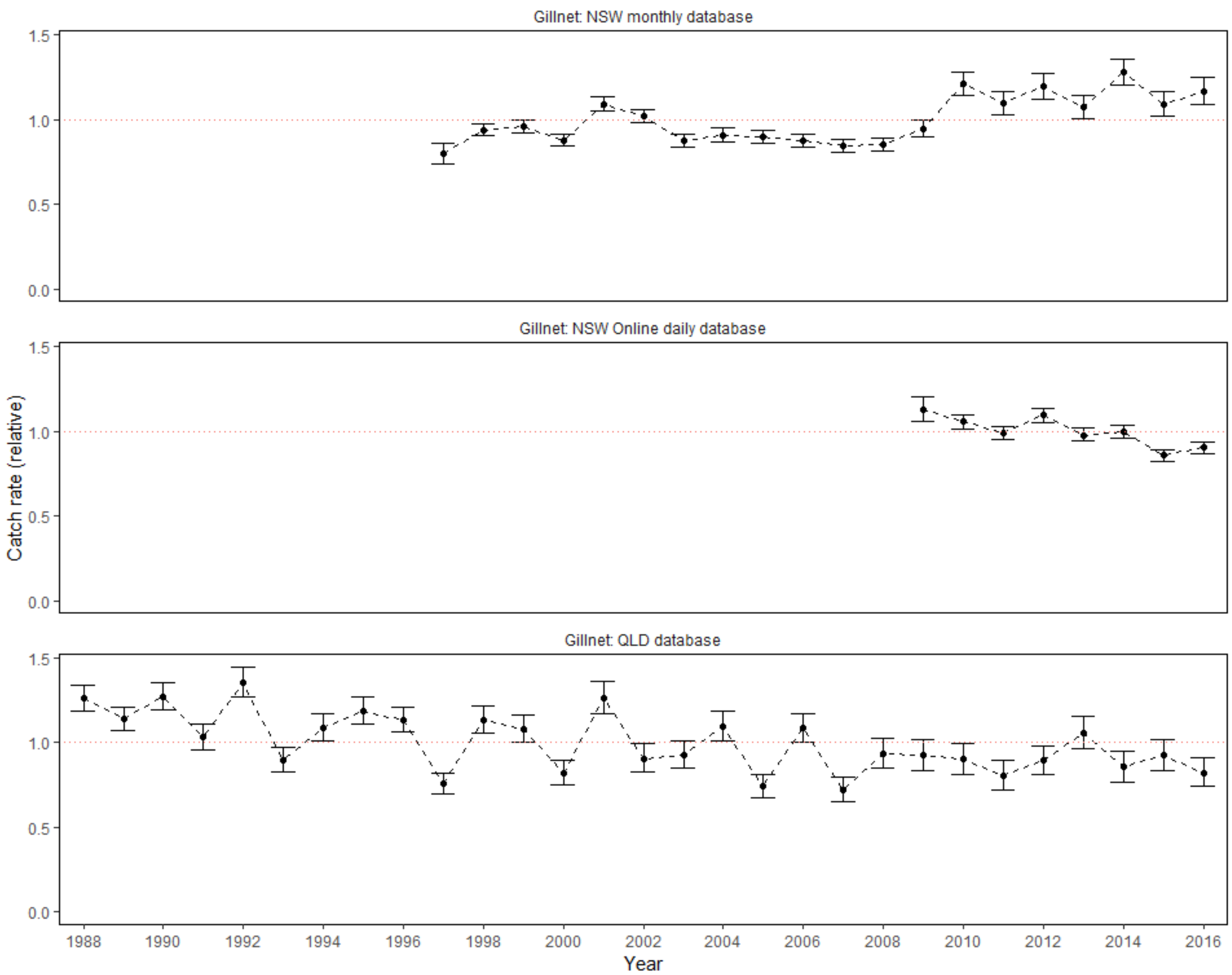

Figure 24: Standardised catch rates for gillnetting.

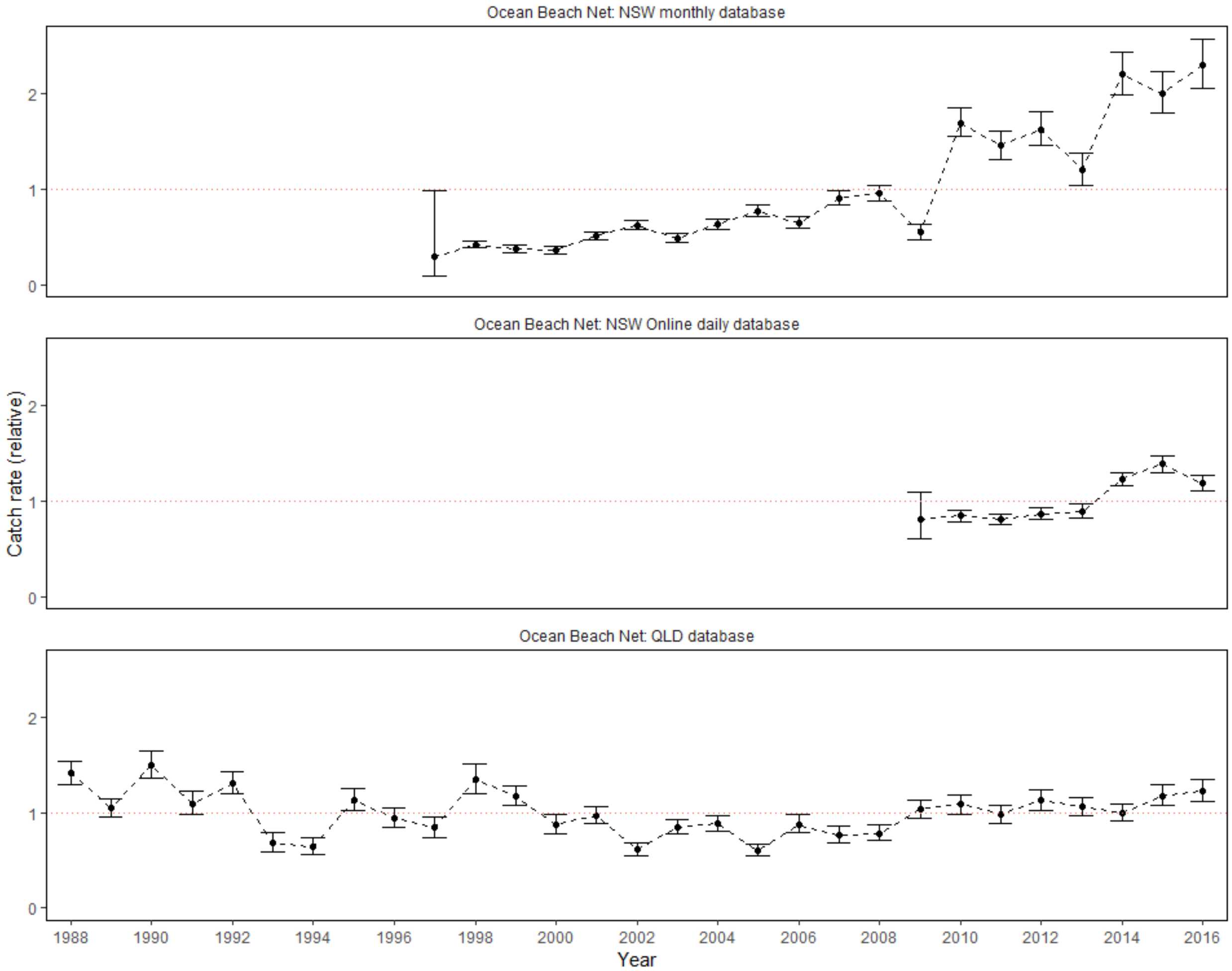

Figure 25: Standardised catch rates for ocean beach netting.

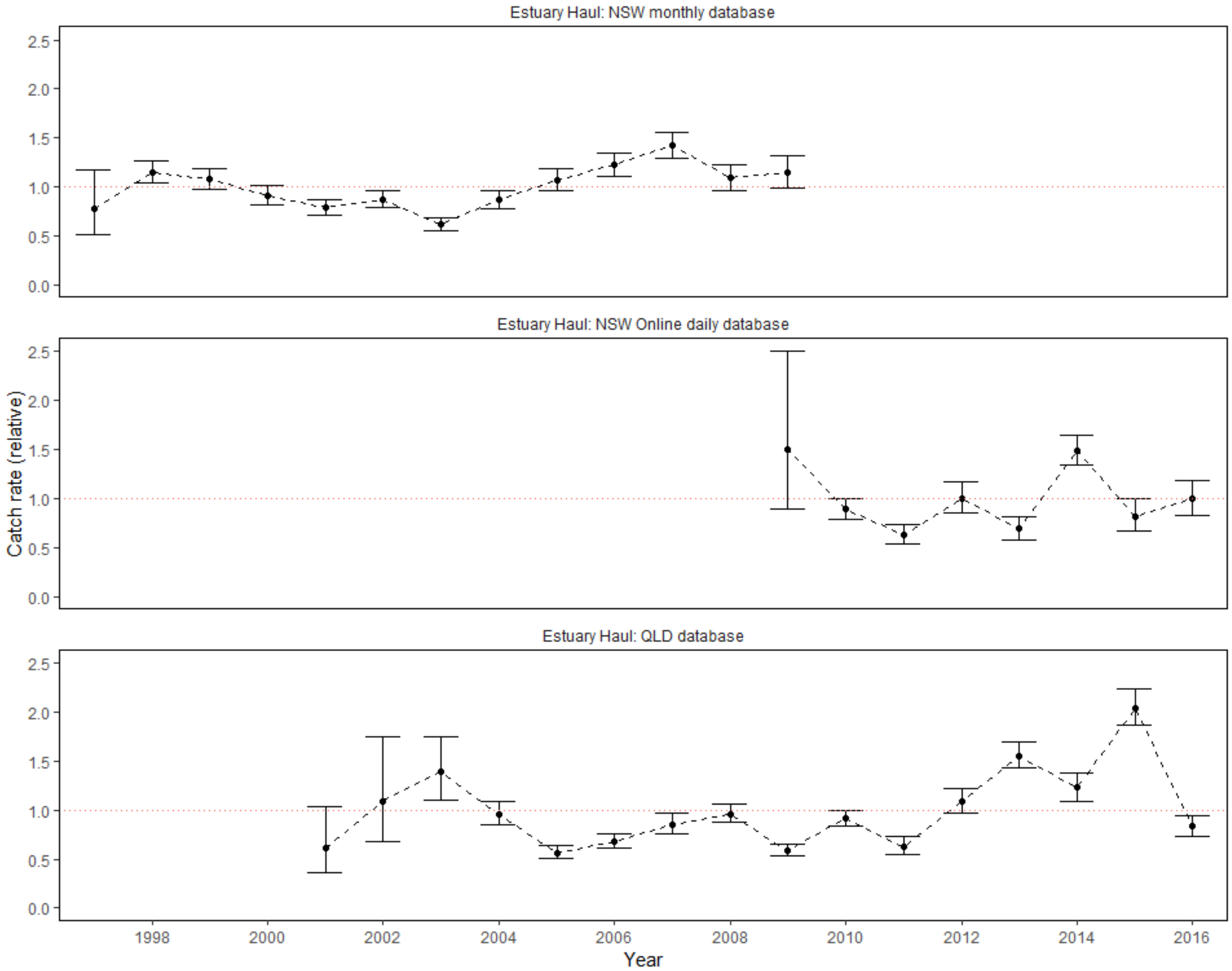

Figure 26: Standardised catch rates for estuary haul netting.

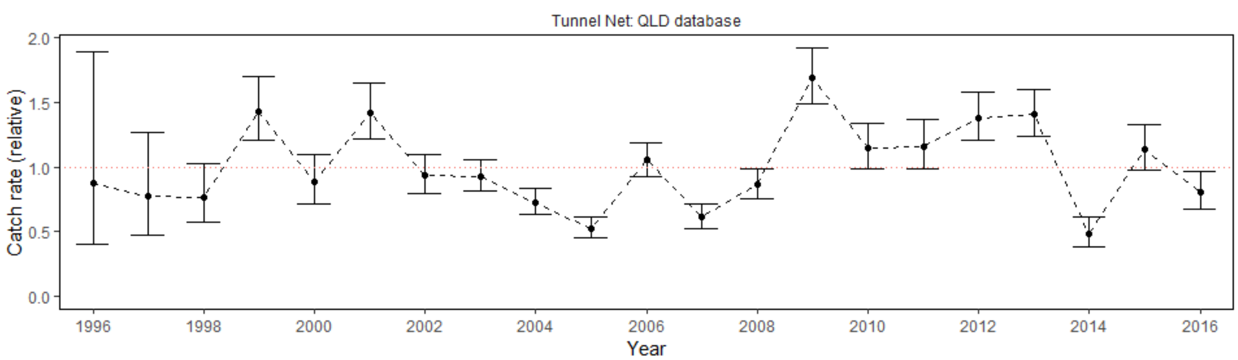

Figure 27: Standardised catch rates for tunnel netting.

D.2 Queensland catch rates by location

In an effort to understand the annual trend displayed by the ocean-beach catch rate, catch rates for each year, region and fishing method (gillnet or ocean-beach net) were assessed.

Locations were broken up by latitude and also whether the location is in a bay/estuary or beach.

Some catch rates showed unrealistic levels of year-to-year variation when there were large amounts of ocean beach fishing present. Due to this, it was considered that perhaps only gillnet catch rates should be used.

However, gillnet and ocean beach net methods are linked. If the gillnet method is highly successful, there will be less fish in the school to be caught by the ocean beach method. If there are less fish caught by gillnetting, more will be caught with the ocean beach method. It was therefore decided to abandon the idea of using gillnet only catch rates as ocean-beach fishing is too important a component in the population dynamics.

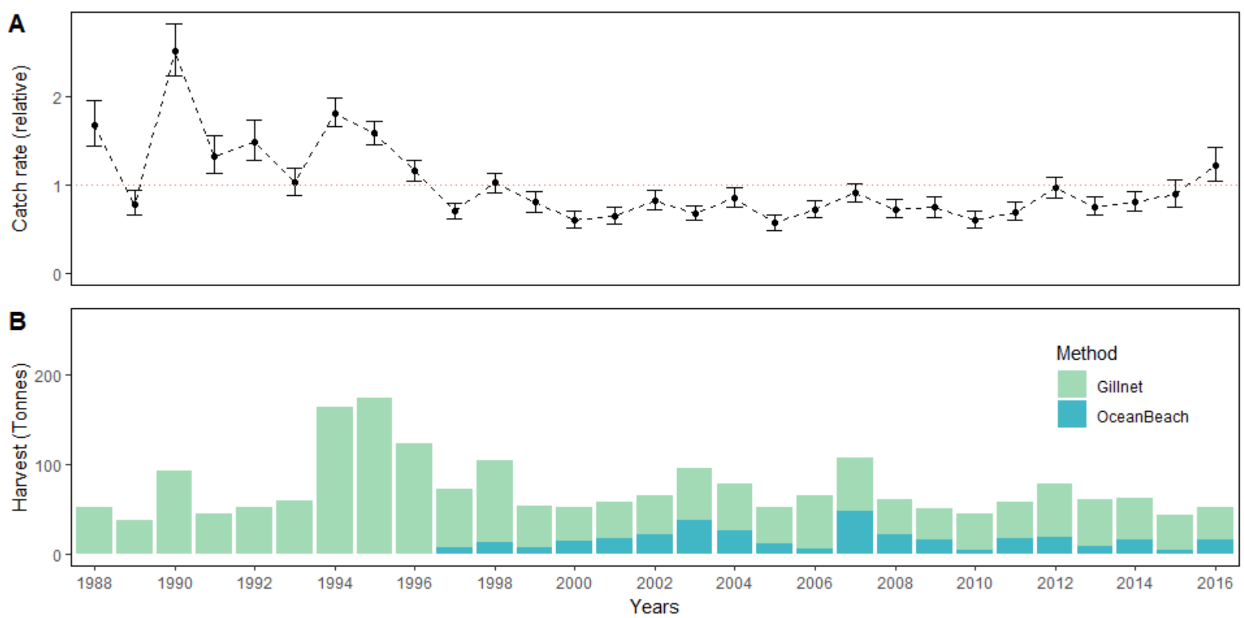

Figure 28: Standardised catch rate and Mullet landings for Bay 24.75 degrees south in Queensland.

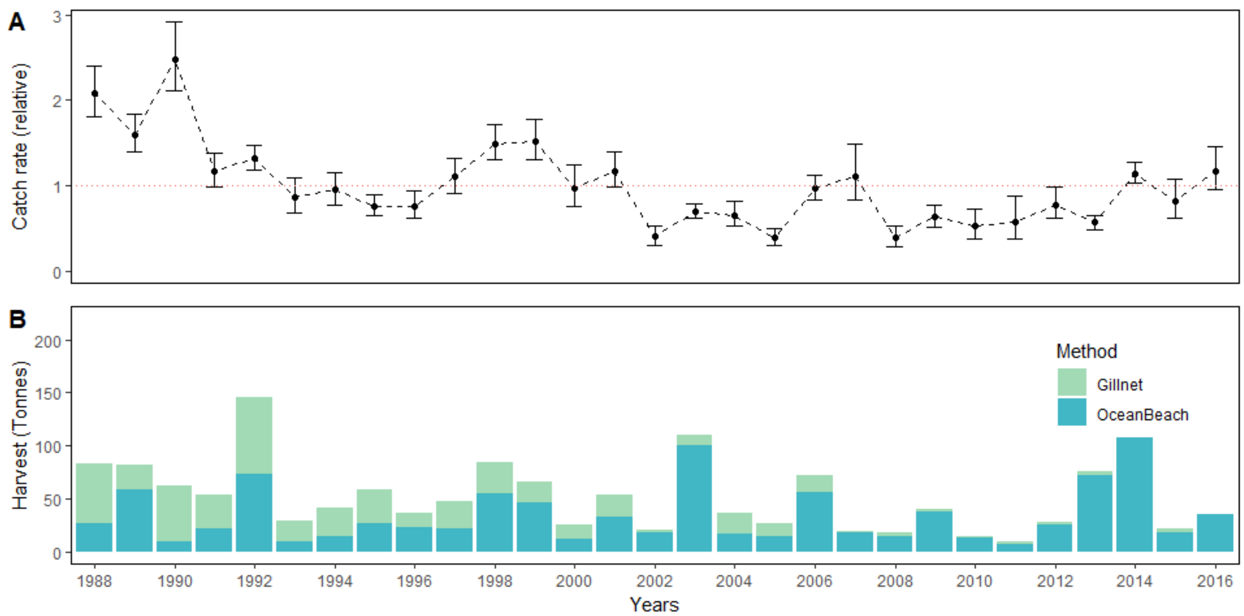

Figure 29: Standardised catch rate and Mullet landings for Beach 24.75 degrees south in Queensland.

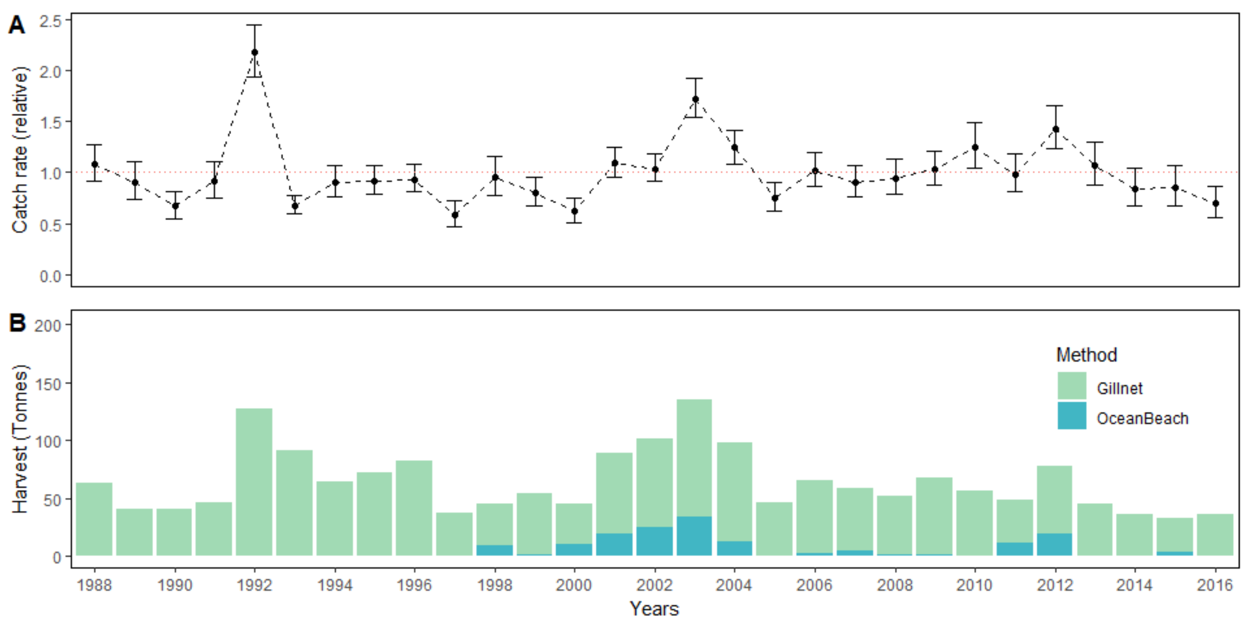

Figure 30: Standardised catch rate and Mullet landings for Bay 25.25 degrees south in Queensland.

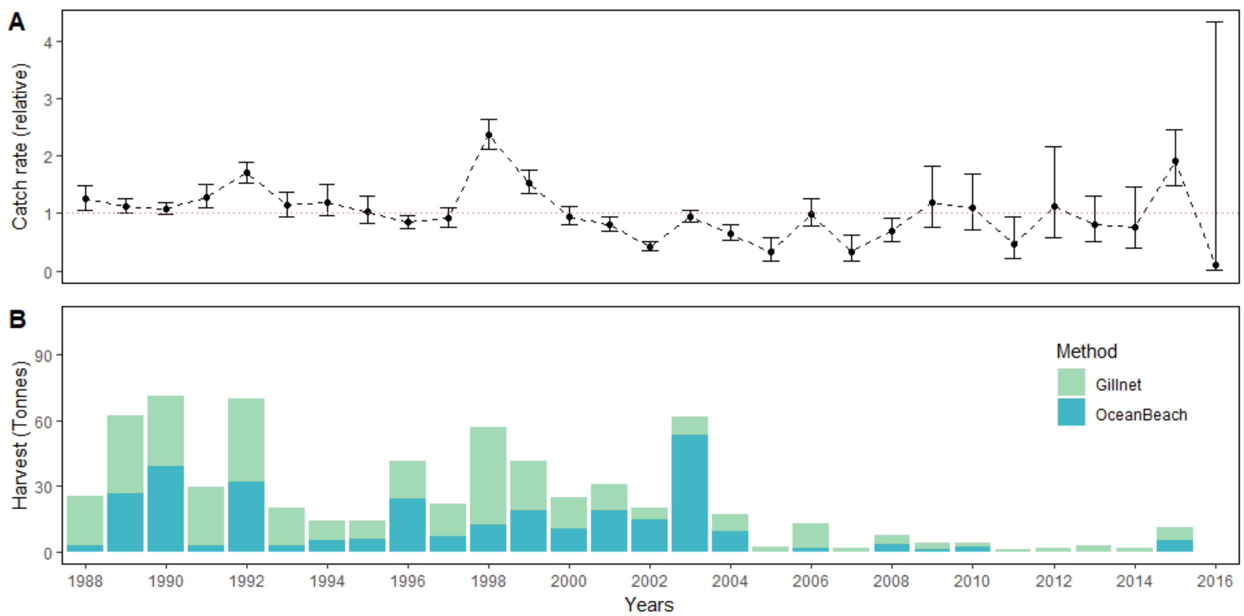

Figure 31: Standardised catch rate and Mullet landings for Beach 25.25 degrees south in Queensland.

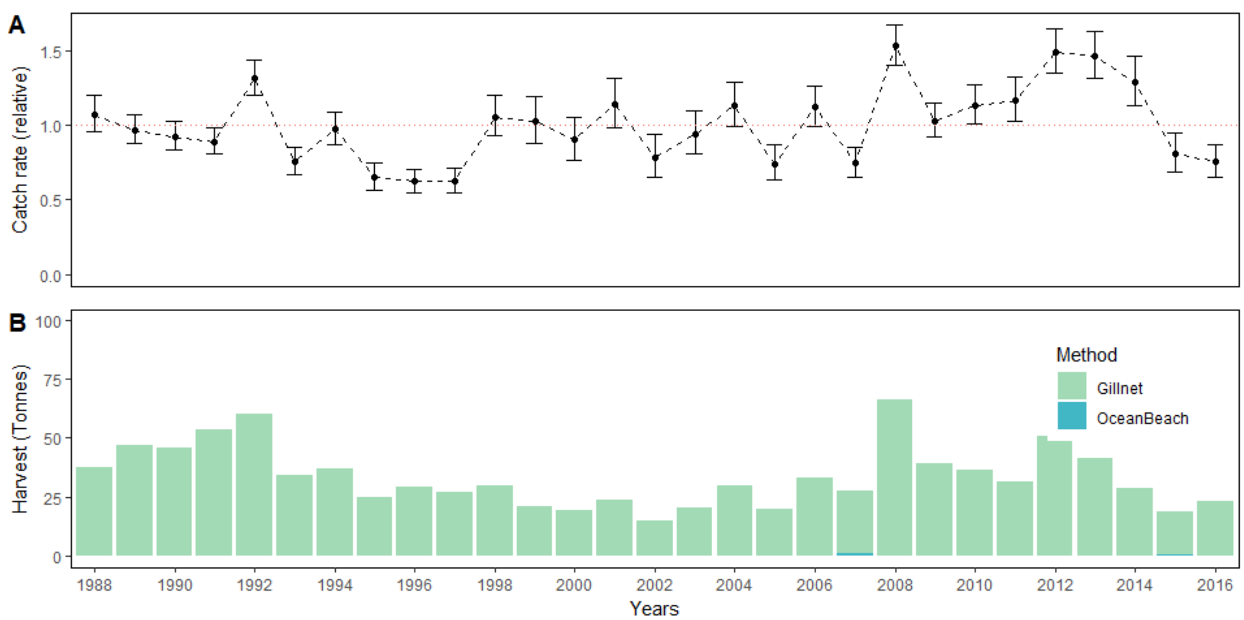

Figure 32: Standardised catch rate and Mullet landings for Bay 25.75 degrees south in Queensland.

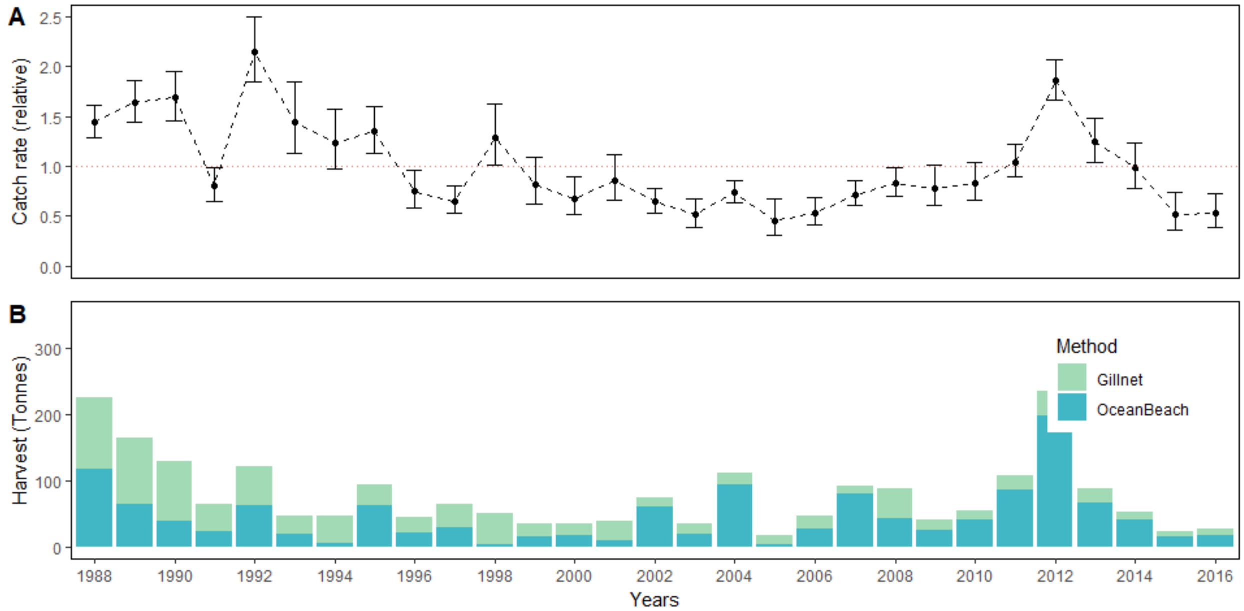

Figure 33: Standardised catch rate and Mullet landings for Beach 25.75 degrees south in Queensland.

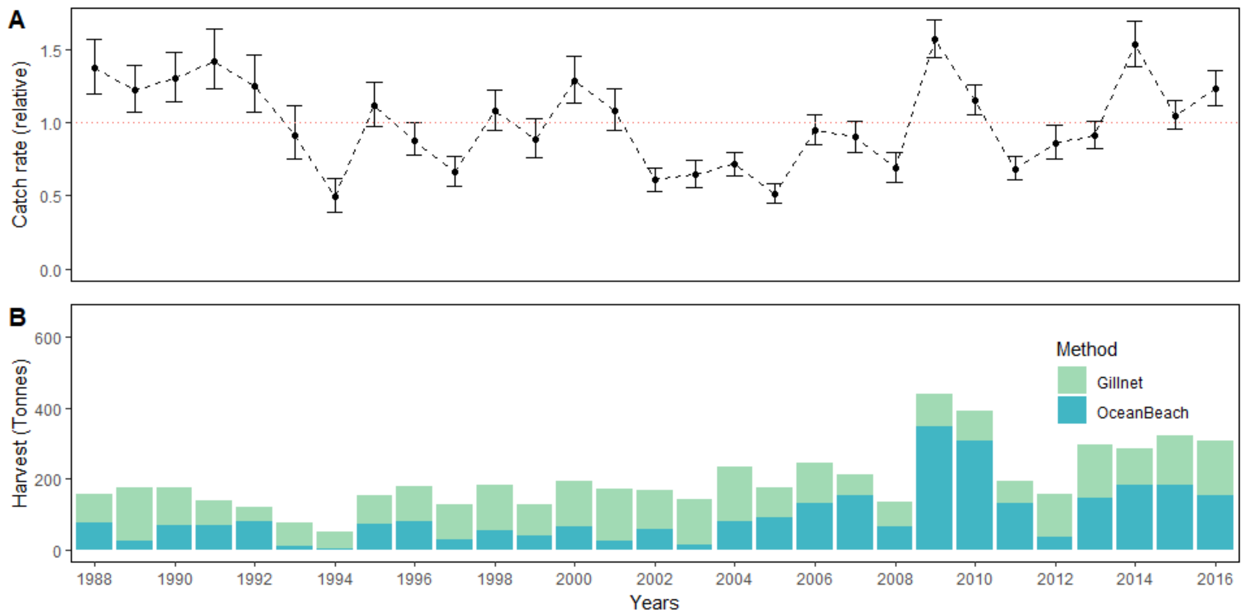

Figure 34: Standardised catch rate and Mullet landings for Beach 26.25 degrees south in Queensland.

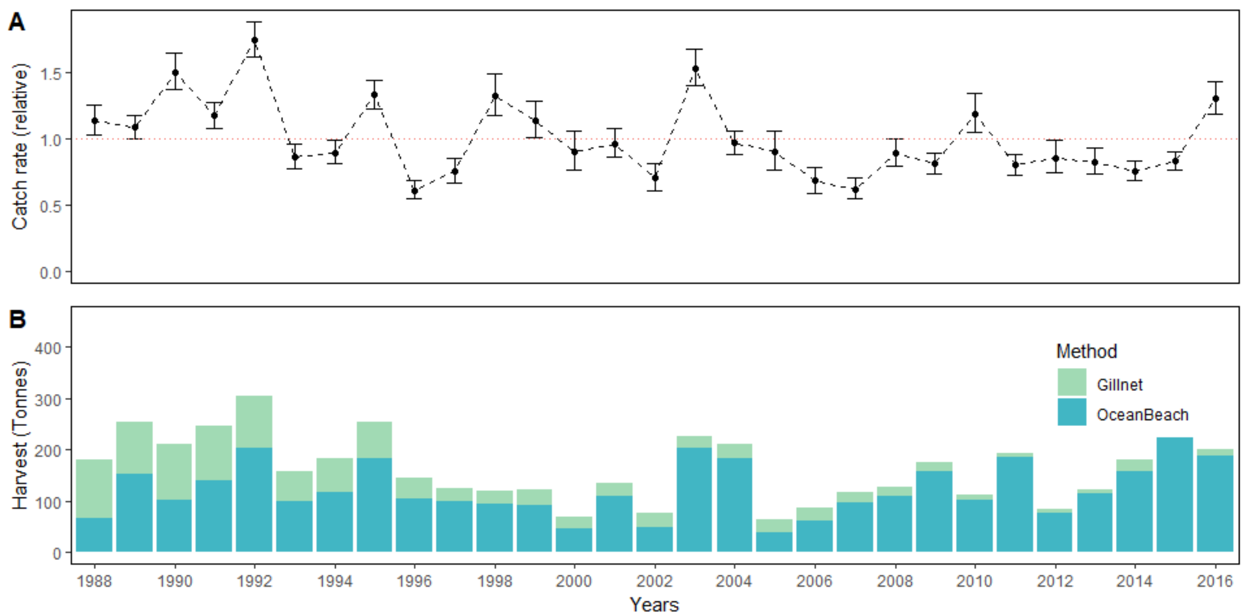

Figure 35: Standardised catch rate and Mullet landings for Beach 26.75 degrees south in Queensland.

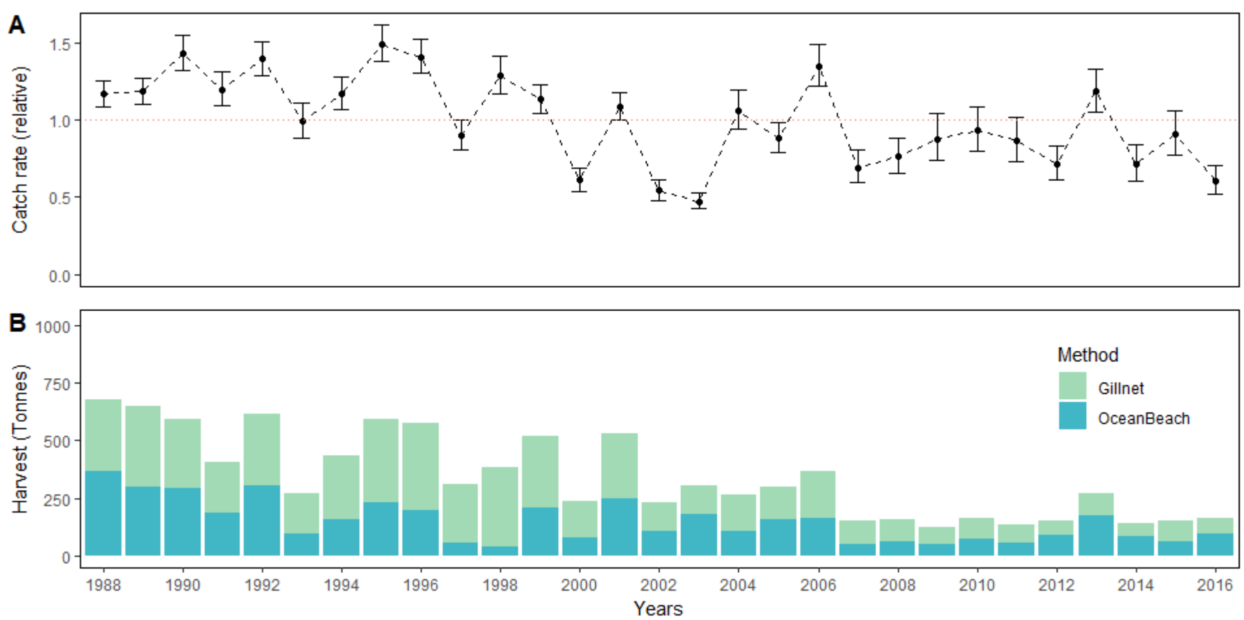

Figure 36: Standardised catch rate and Mullet landings for Bay 27.25 degrees south in Queensland.

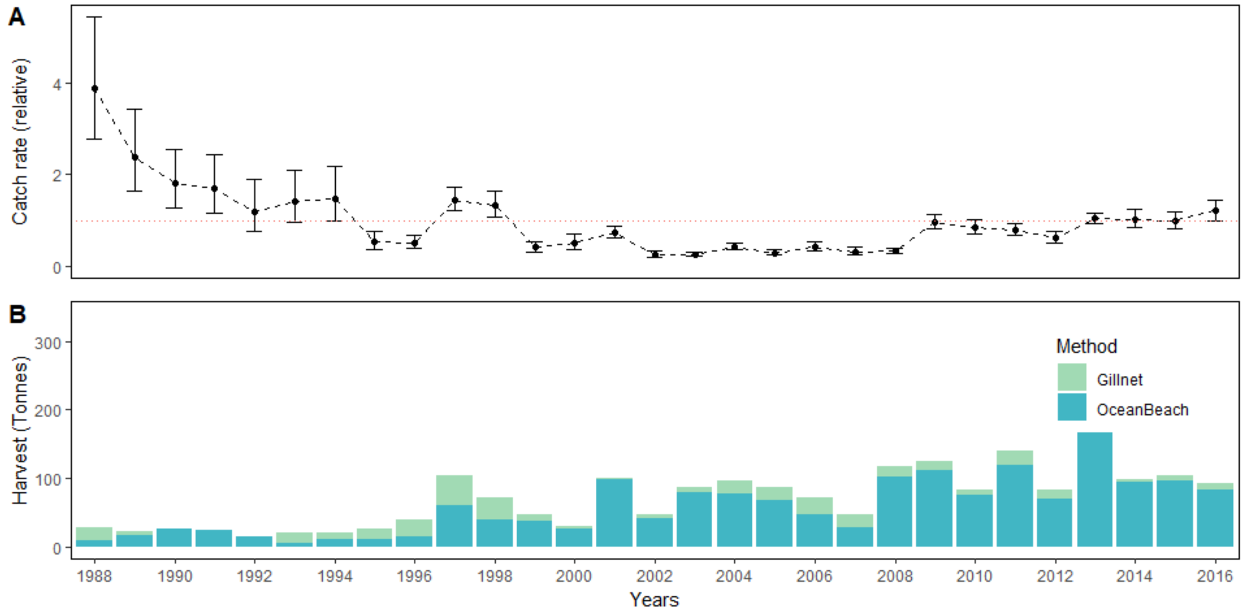

Figure 37: Standardised catch rate and Mullet landings for Beach 27.25 degrees south in Queensland.

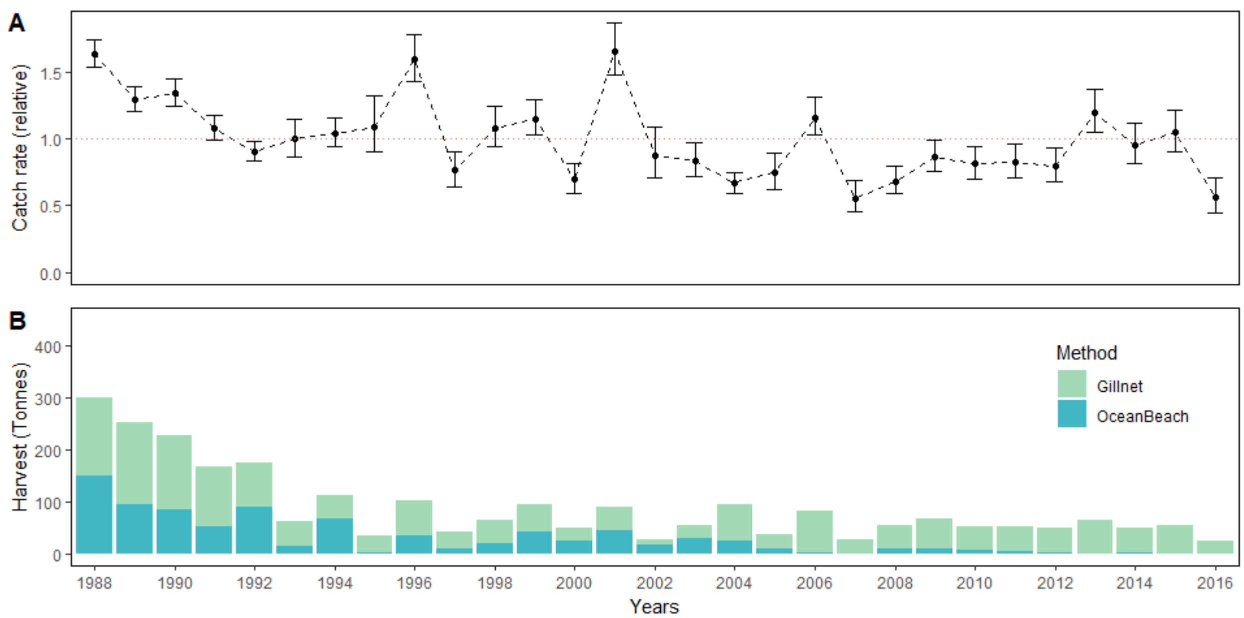

Figure 38: Standardised catch rate and Mullet landings for Bay 27.75 degrees south in Queensland.

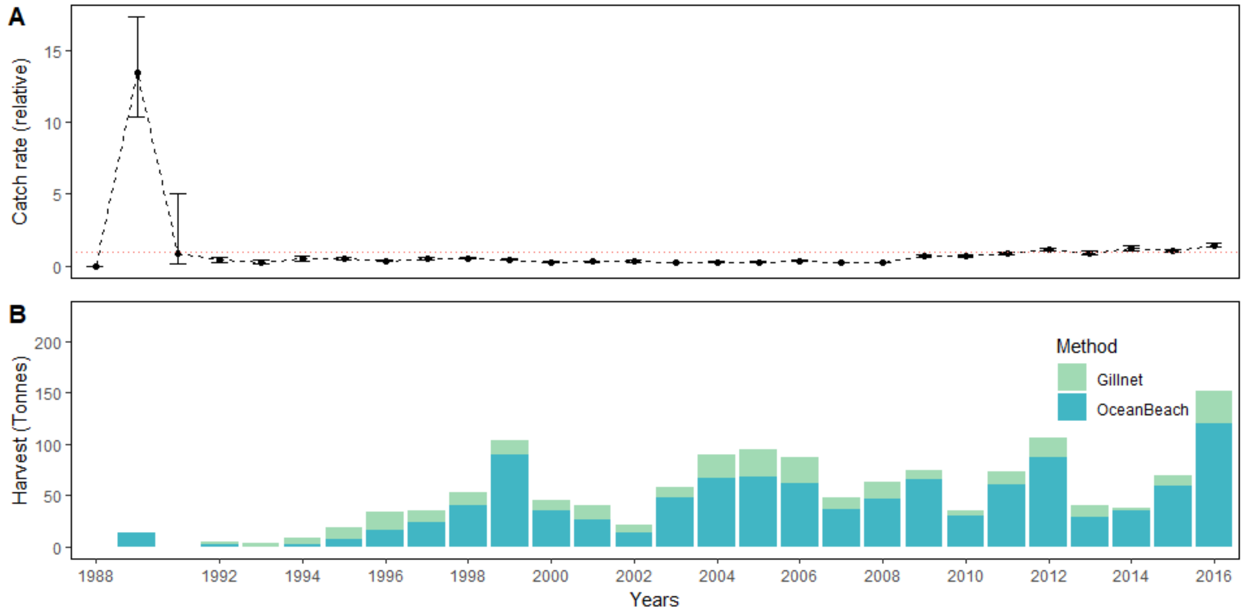

Figure 39: Standardised catch rate and Mullet landings for Beach 27.75 degrees south in Queensland.

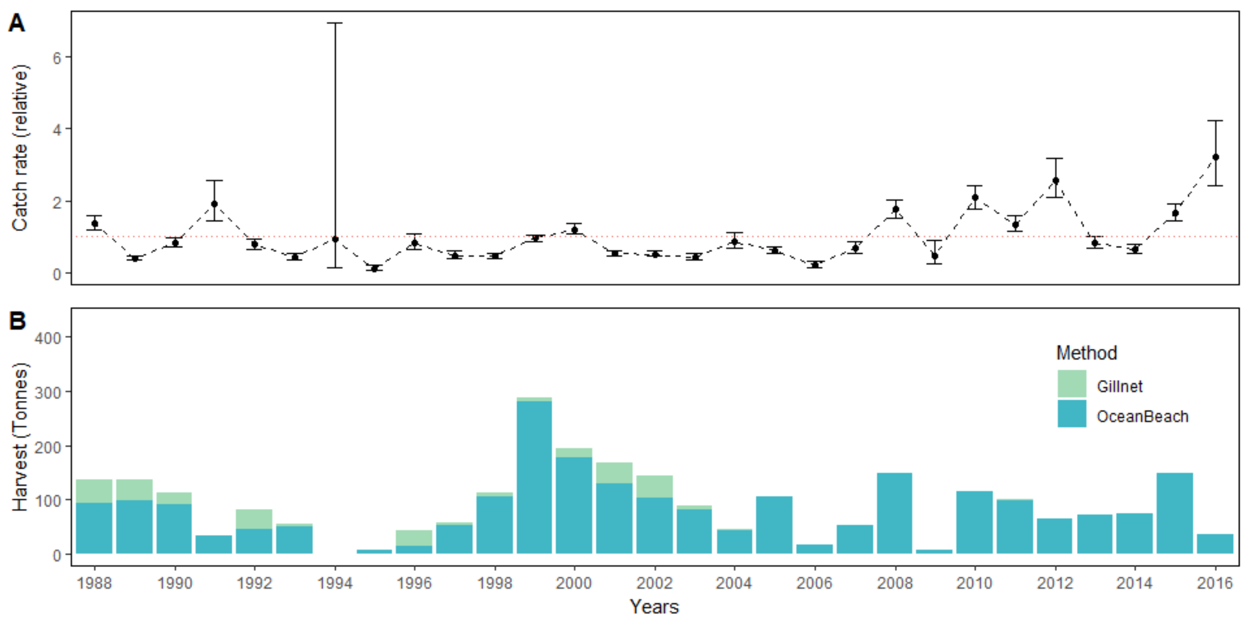

Figure 40: Standardised catch rate and Mullet landings for Beach 28.25 degrees south in Queensland.

D.3 Ocean-beach catch rates

It was considered that competition on the beach may be a factor in less fish caught per fisherman. In an effort to account for this, ocean-beach catch rates were offset against the number of fishers operating in the fishery each year (see Figure 41). This approach yielded results that were more sensible and hence ocean-beach catch rates used in the model were calculated by applying this additional technique.

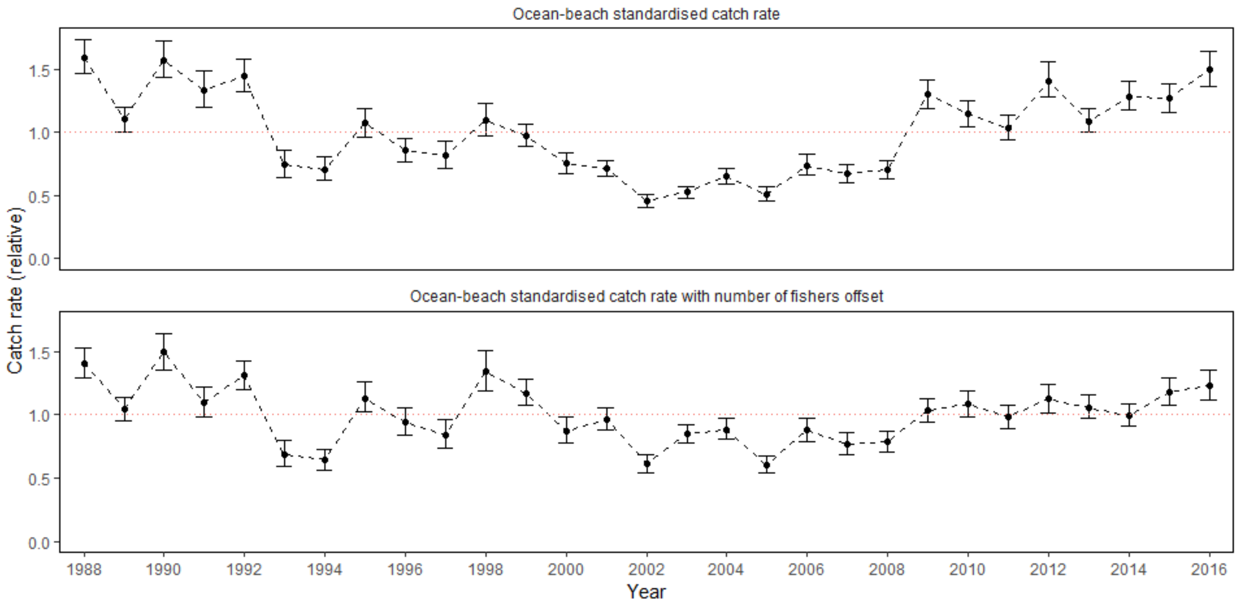

Figure 41: A: Standardised catch rate for QLD ocean-beach netting. B: Standardised catch rate for QLD ocean-beach netting including an offset for the number of fishers each year.

Appendix E - Biological growth

E.1 von Bertalanffy

The von Bertalanffy equation is a mathematical model which expresses the length l as a function of the age of the fish t, such that

$$l_t = L_\infty\left(1 - e^{-\kappa(t-t_0)}\right),$$

where L_∞ is the asymptotic length at which growth is zero, κ is the growth rate and t_0 is the age at length zero. This equation can be rearranged so that the equation is in terms of l_0 (length at age zero) instead of t_0 and is given by

$$l_t = l_0 e^{-\kappa t} + l_\infty(1 - e^{-\kappa t}).$$

The von Bertalanffy parameters shown in Figure 42 are calculated based on observed data and are used in the model to fit to predicted catch age-length samples.

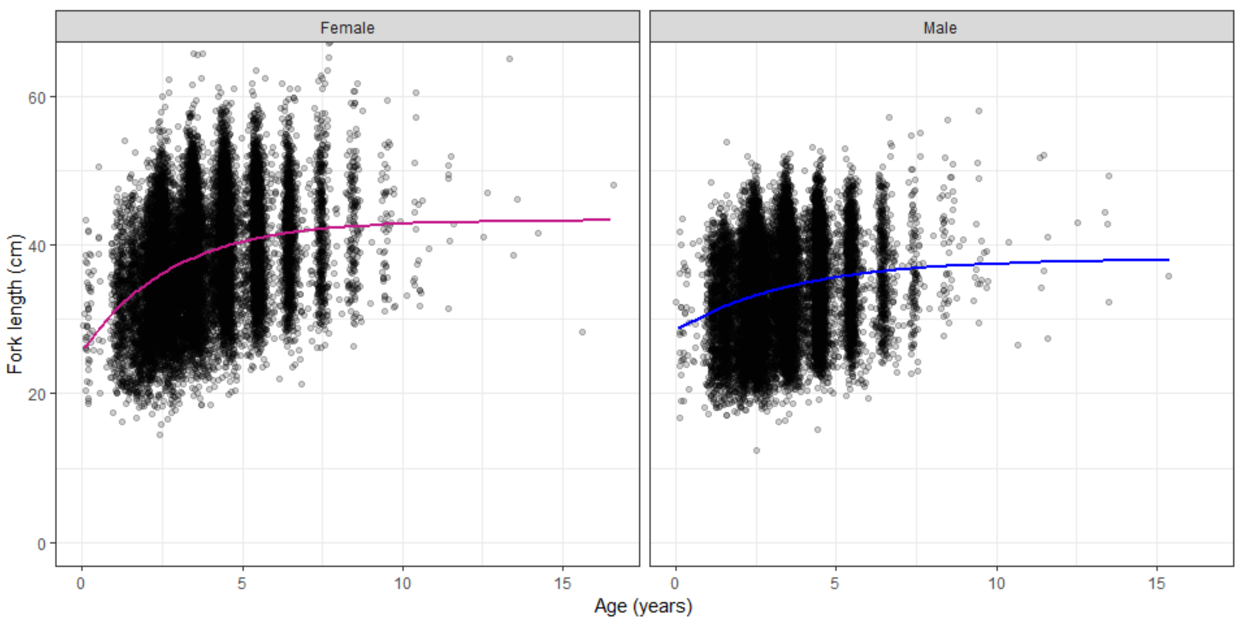

Figure 42: von Bertalanffy curves for males and females: $l_t = l_0 e^{-\kappa t} + l_\infty(1 - e^{-\kappa t})$
Females: l_∞ *= 43.31 ,*l_0 *= 25.69 ,* κ *= 0.36*
Males: l_∞ *= 38.14 ,*l_0 *= 28.55 ,* κ *= 0.27*
(New South Wales & Queensland data combined).

The von Bertalanffy parameters produced here are based on samples taken from harvested sea mullet. As such these parameters are not representative of the sea mullet population (as they do not include small fish). Rather, they are representative of the harvested population and are used in the model to predict vulnerable biomass.

E.2 Length-weight relationship

The relationship between the length and weight of sea mullet follows an allometric growth function. This is defined by $W = \alpha L^{\beta}$. The parameters shown in Figure 43 are calculated using observed data.

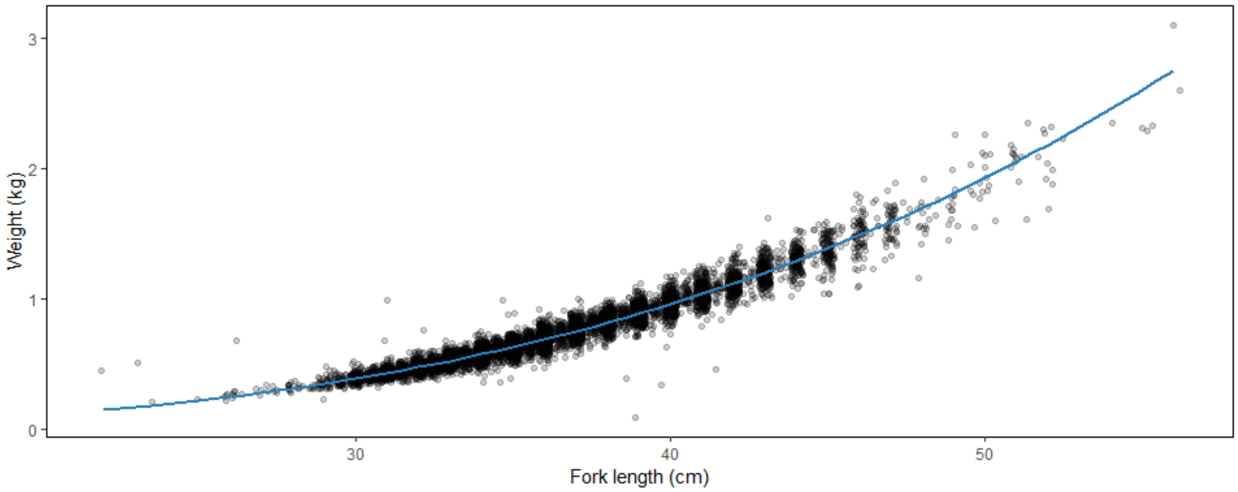

Figure 43: Length weight relationship - $W = \alpha L^{\beta}$, where $\alpha = 9.15 \times 10^{-6}$ and $\beta = 3.13$ (Queensland & NSW data).

Appendix F - Parameter analysis

F.1 Model parameters

Table 10 shows the key estimated and fixed parameters estimated for the fitted models; recruitment deviations are displayed in Appendix F.3. It is important to note that due to the addition of γ in the selectivity function, A_{50} and A_{95-50} are no longer representative parameters (e.g. while A_{50} (Gillnet, female) = 0.24, this does not mean that Gillnet females are 50% selected to the fishery at age 0.24). The age at selection to the fishery is shown in Table 11. Selectivity curves are plotted in Appendix F.2

Table 10: Model parameter values Length parameters are measured in cm fork length. Age parameters are measured in years. κ and M are measured in $year^{-1}$.

Parameter	Model 1	Model 2	Model 3	Notes
M (female)	0.4	0.36	0.33	
M (male)	0.57	0.53	0.5	
$\ln(B_0^{sp})$	18.08	17.99	17.95	
A_{50} (Gillnet, female)	0.31	0.26	0.24	(see Table 11 below)
A_{50} (Ocean-beach, female)	1.52	1.48	1.45	(see Table 11 below)
A_{50} (Gillnet, male)	1.17	1.14	1.12	(see Table 11 below)
A_{50} (Ocean-beach, male)	2.31	2.3	2.29	(see Table 11 below)
A_{95-50} (Gillnet, female)	3.33	3.31	3.29	(see Table 11 below)
A_{95-50} (Ocean-beach, female)	3	3	3	(see Table 11 below)
A_{95-50} (Gillnet, male)	2.25	2.25	2.25	(see Table 11 below)
A_{95-50} (Ocean-beach, male)	1.12	1.13	1.14	(see Table 11 below)
fixed parameters				
h	0.49	0.66	0.83	
γ (Gillnet, female)	8	8	8	
γ (Ocean-beach, female)	4	4	4	
γ (Gillnet, male)	4	4	4	
γ (Ocean-beach, male)	1	1	1	
L_∞ (female)	43.31	43.31	43.31	
L_∞ (male)	38.14	38.14	38.14	
L_0 (female)	25.69	25.69	25.69	
L_0 (male)	28.55	28.55	28.55	
κ (female)	0.36	0.36	0.36	
κ (male)	0.27	0.27	0.27	

Table 11: Age (in years) at selectivity to the fishery for each model, sex and fishing method.

	Model 1	Model 2	Model 3
Age 50% selected to fishery			
Gillnet, female	3.03	2.97	2.93
Ocean-beach, female	3.24	3.2	3.17
Gillnet, male	2.48	2.45	2.43
Ocean-beach, male	2.35	2.34	2.33
Additional age from 50% to 95% selected			
Gillnet, female	1.78	1.83	1.86
Ocean-beach, female	1.58	1.62	1.65
Gillnet, male	1.99	1.99	2
Ocean-beach, male	1.35	1.36	1.36

F.2 Serial plots

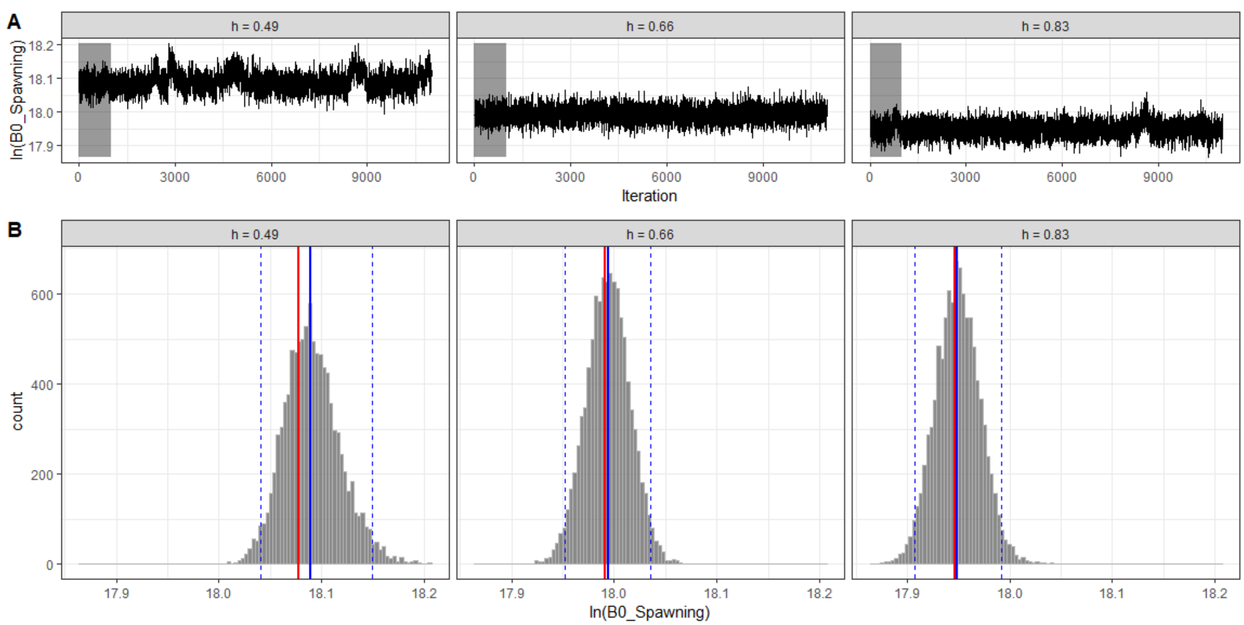

Figure 44: Serial plot and histogram of $ln(B_0^{sp})$ (log of virgin spawning biomass) for different fixed values of h. The shaded area in the serial plot indicates burn in of the MCMC. The red line in the histogram shows the value of $ln(B_0^{sp})$ for the optimised model, while the blue line shows the median of the MCMC run. The blue dashed lines show the 95% credible interval of the MCMC run.

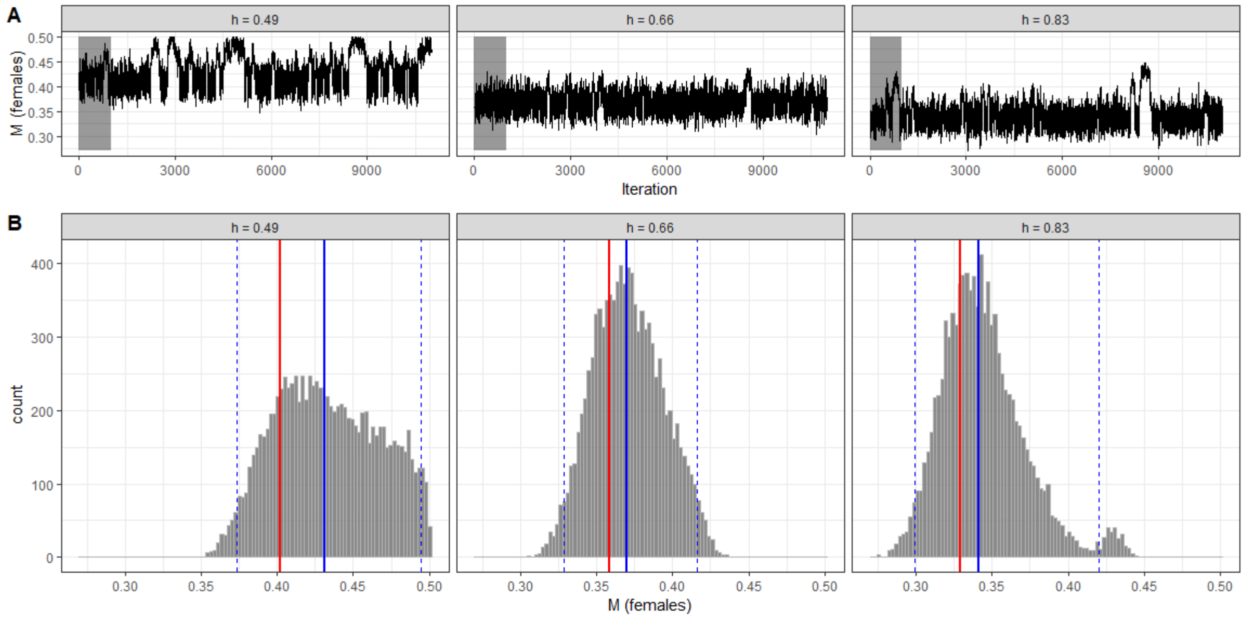

Figure 45: Serial plot and histogram of M (females) for different fixed values of h. The shaded area in the serial plot indicates burn in of the MCMC. The red line in the histogram shows the value of M (females) for the optimised model, while the blue line shows the median of the MCMC run. The blue dashed lines show the 95% credible interval of the MCMC run.

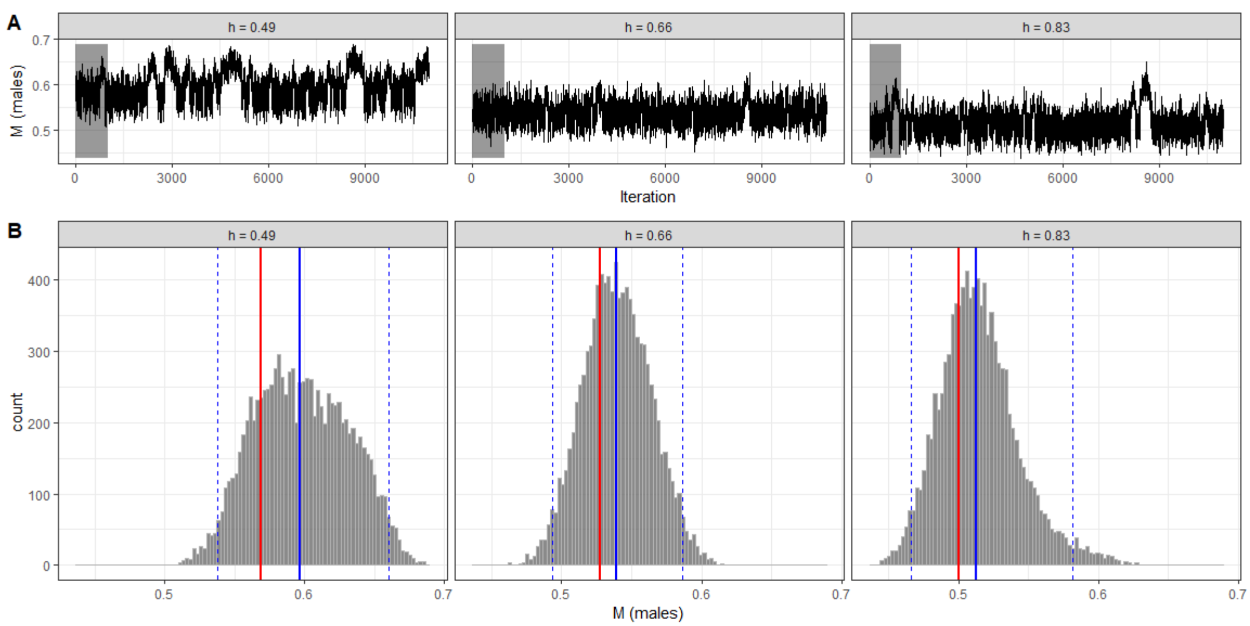

Figure 46: Serial plot and histogram of M (males) for different fixed values of h. The shaded area in the serial plot indicates burn in of the MCMC. The red line in the histogram shows the value of M (males) for the optimised model, while the blue line shows the median of the MCMC run. The blue dashed lines show the 95% credible interval of the MCMC run.

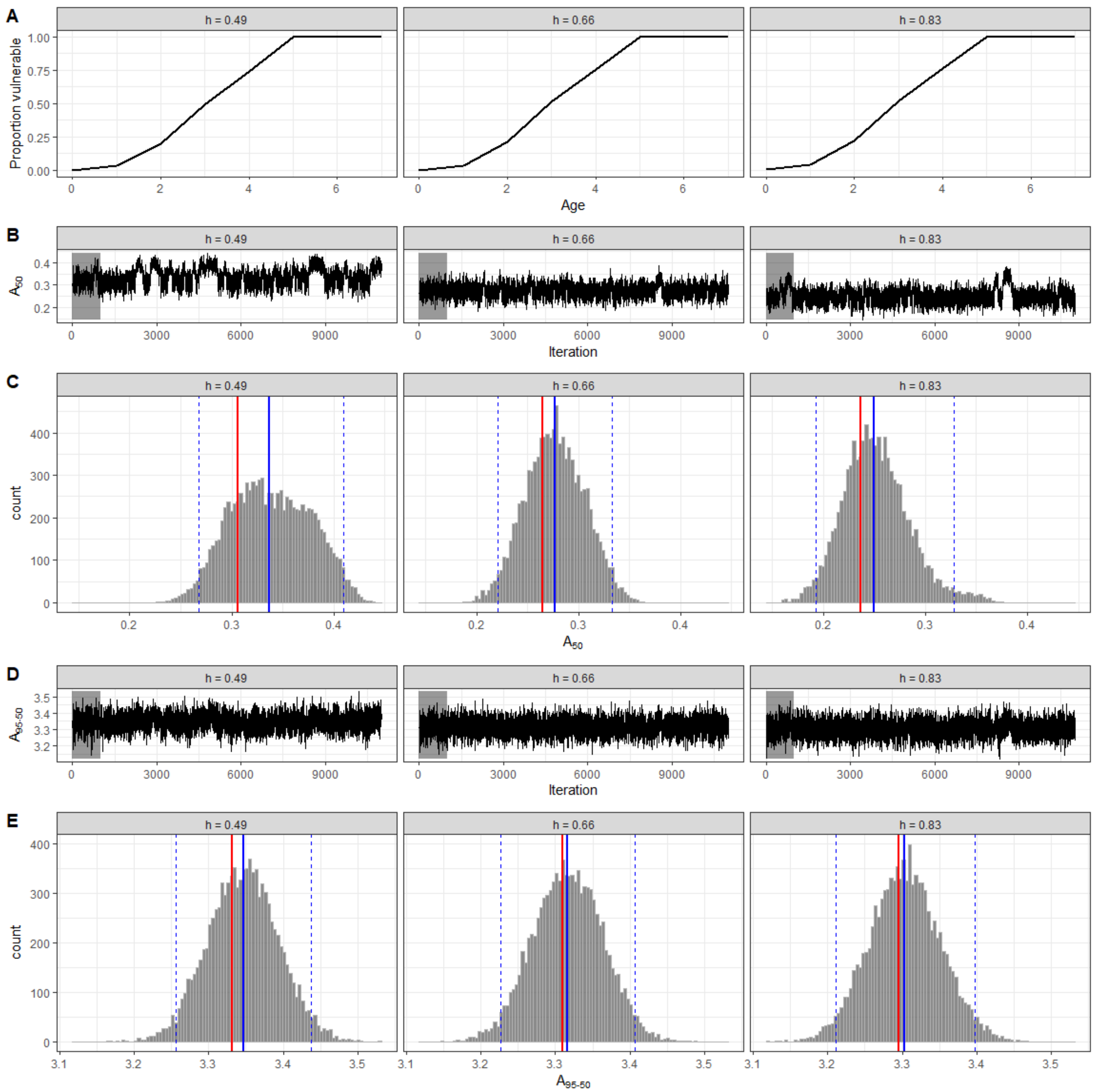

Figure 47: Gillnet (females) selectivity for different fixed values of h. A: selectivity curve, B: serial plot for the A_{50} parameter, C: histogram for the A_{50} parameter, D: serial plot for the A_{95-50} parameter, E: histogram for the A_{95-50} parameter. The shaded area in the serial plot indicates burn in of the MCMC. 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.

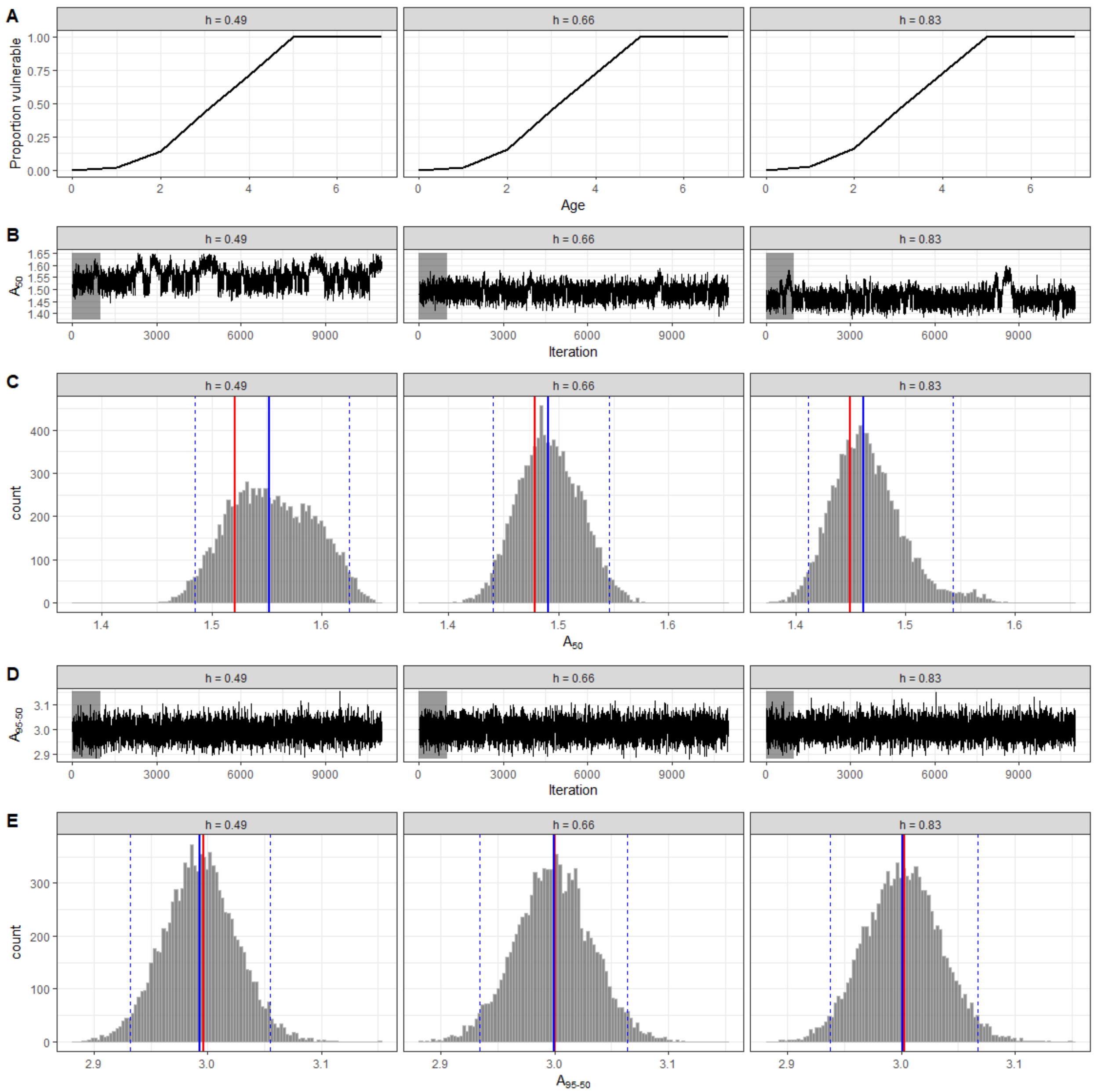

Figure 48: Ocean-beach (females) selectivity for different fixed values of h. A: selectivity curve, B: serial plot for the A_{50} parameter, C: histogram for the A_{50} parameter, D: serial plot for the A_{95-50} parameter, E: histogram for the A_{95-50} parameter. The shaded area in the serial plot indicates burn in of the MCMC. 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.

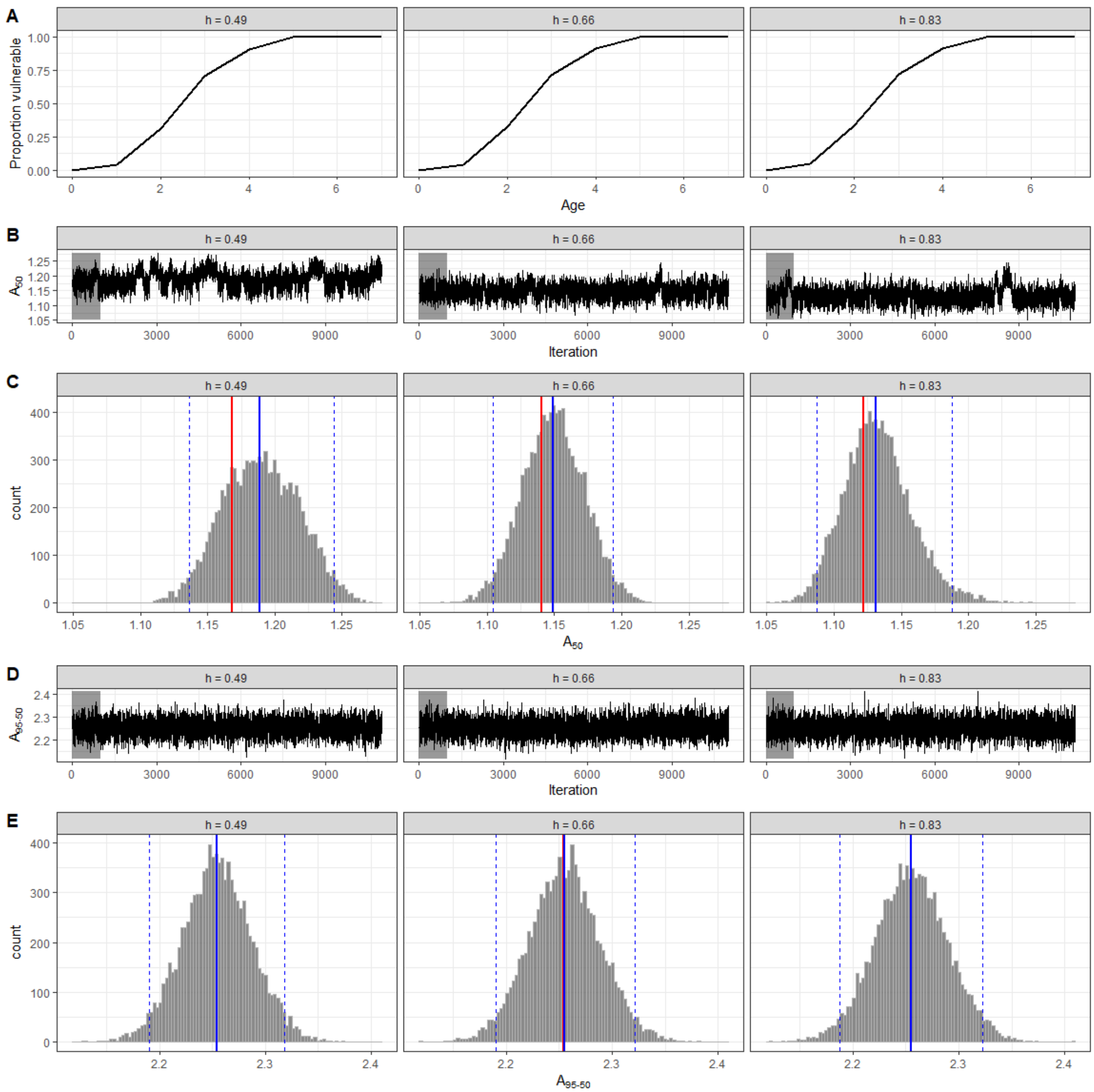

Figure 49: Gillnet (males) selectivity for different fixed values of h. A: selectivity curve, B: serial plot for the A_{50} parameter, C: histogram for the A_{50} parameter, D: serial plot for the A_{95-50} parameter, E: histogram for the A_{95-50} parameter. The shaded area in the serial plot indicates burn in of the MCMC. 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.

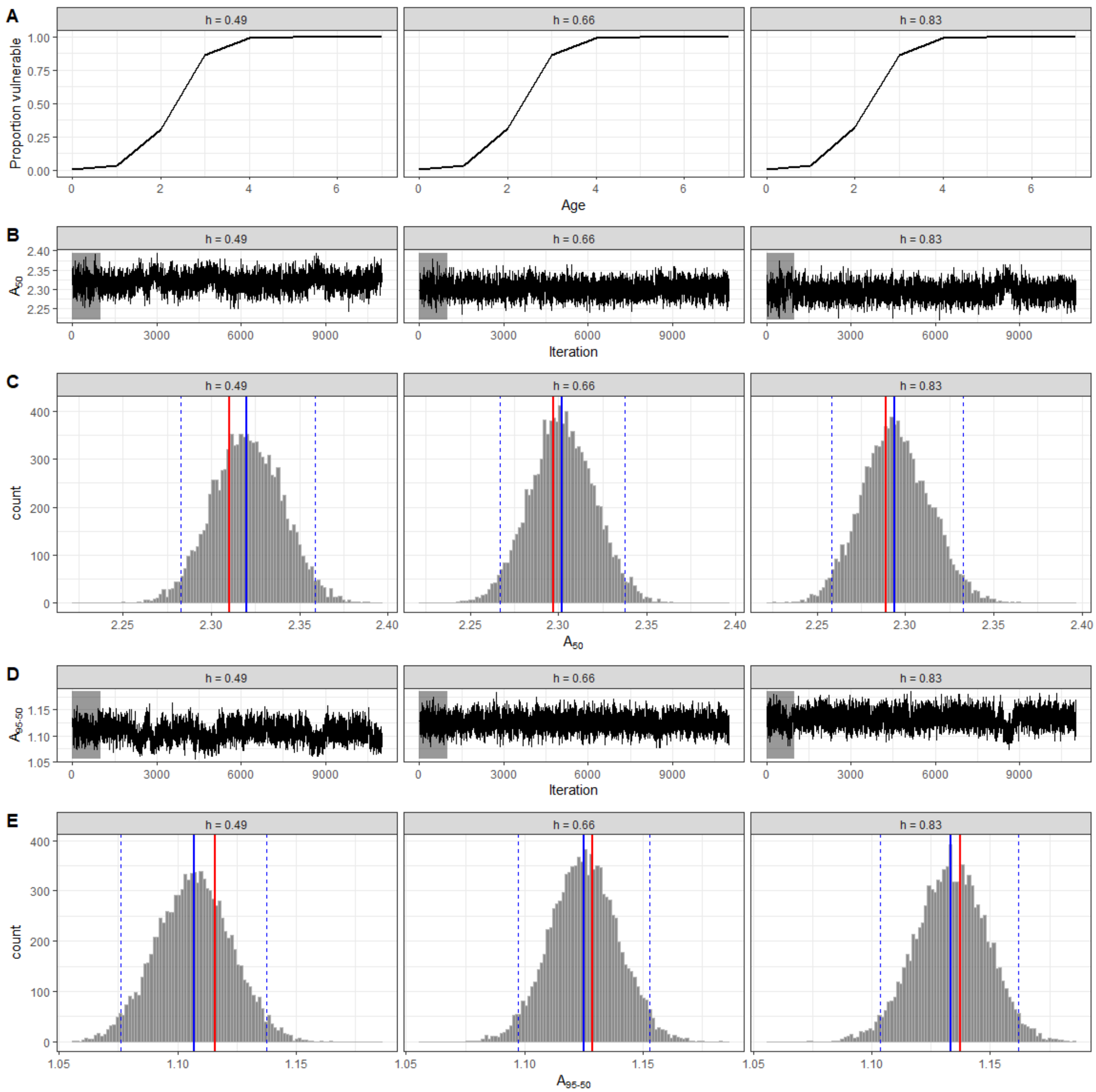

Figure 50: Ocean-beach (males) selectivity for different fixed values of h. A: selectivity curve, B: serial plot for the A_{50} parameter, C: histogram for the A_{50} parameter, D: serial plot for the A_{95-50} parameter, E: histogram for the A_{95-50} parameter. The shaded area in the seial plot indicates burn in of the MCMC. 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.

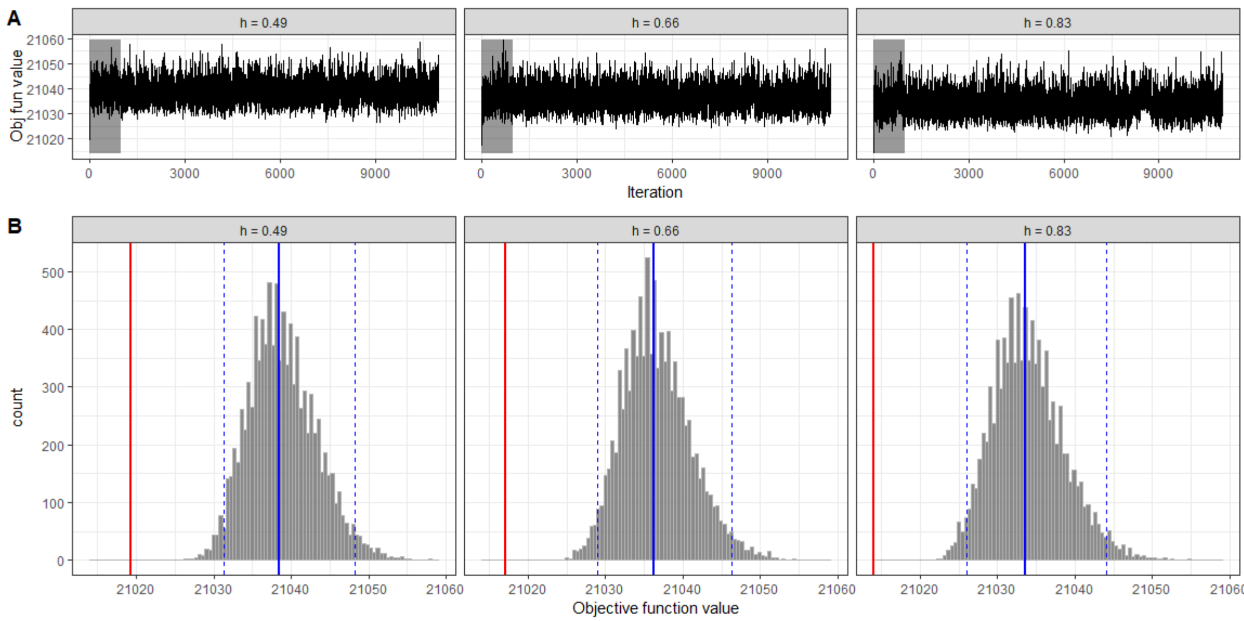

Figure 51: Serial plot and histogram of the model objective function value for different fixed values of h. The shaded area in the serial plot indicates burn in of the MCMC. The red line in the histogram shows the value of the objective function for the optimised model, while the blue line shows the mean of the MCMC run. The blue dashed lines show the 95% credible interval of the MCMC run.

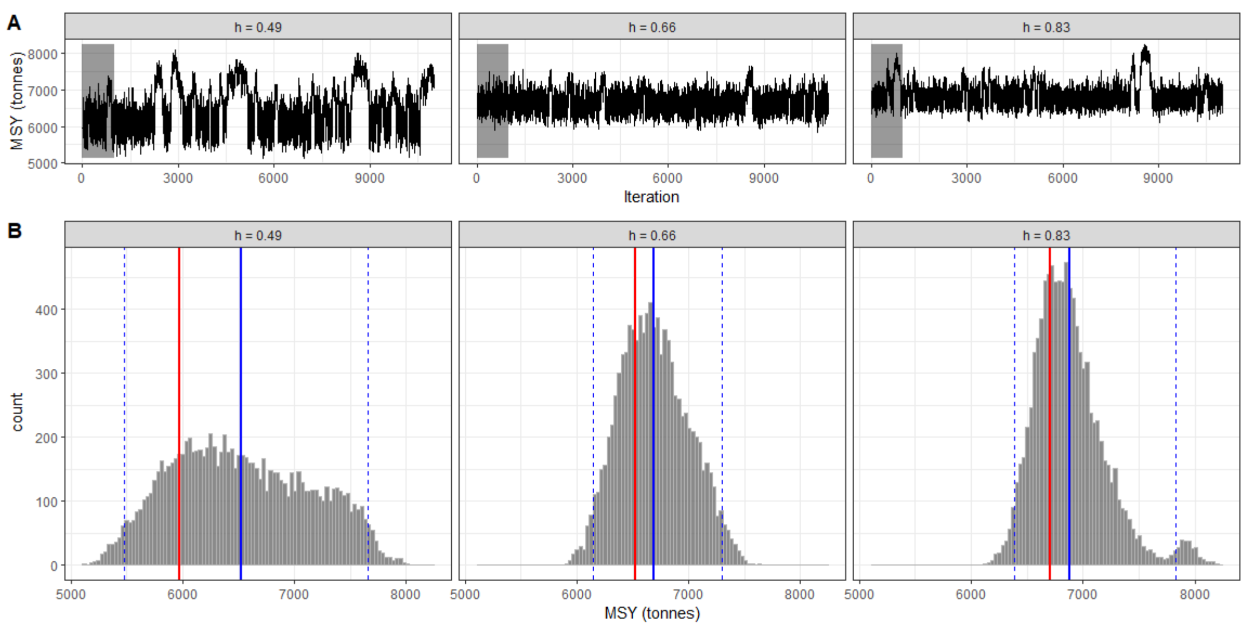

Figure 52: Serial plot and histogram of MSY for different fixed values of h. The shaded area in the serial plot indicates burn in of the MCMC. The red line shows the value of MSY for the optimised model, while the blue line shows the median of the MCMC run. The blue dashed lines show the 95% credible interval of the MCMC run.

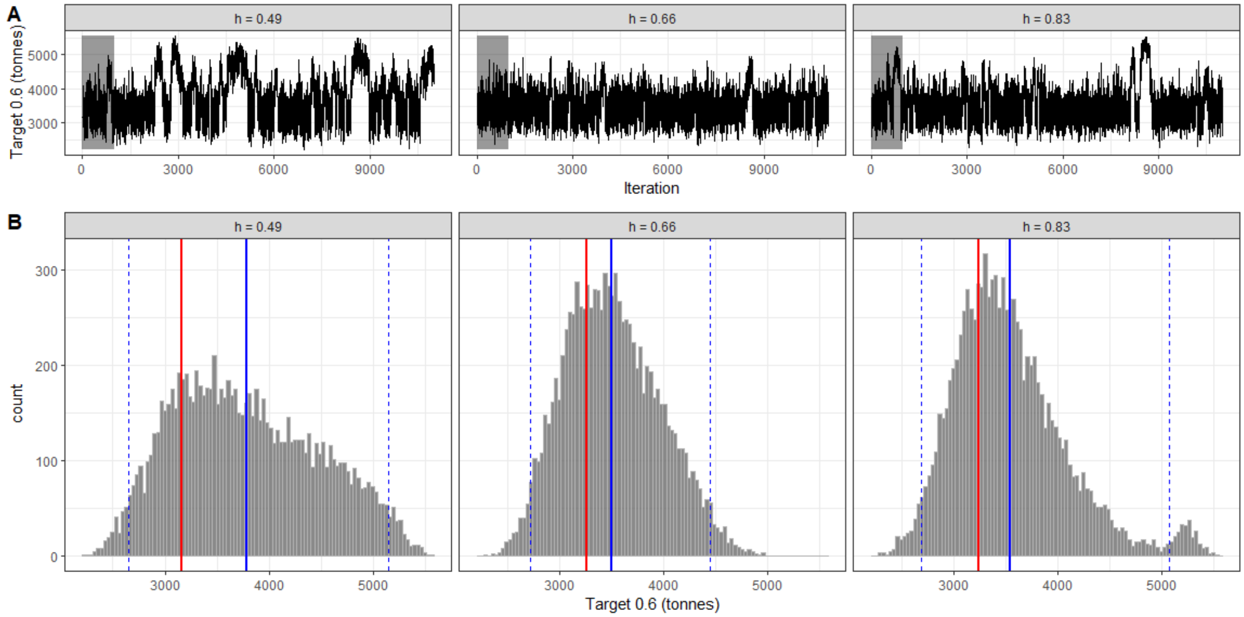

Figure 53: Serial plot and histogram of Target 0.6 for different fixed values of h. The shaded area in the serial plot indicates burn in of the MCMC. The red line shows the value of MSY for the optimised model, while the blue line shows the median of the MCMC run. The blue dashed lines show the 95% credible interval of the MCMC run.

F.3 Recruitment deviations

Table 12: Table of recruitment deviations for model 1 (Beverton-Holt steepness = 0.49) with the optimised value, median and credible intervals of the MCMC run.

Year	Optimised	Mean	2.5%	25%	50%	75%	97.5%
1989	-0.5003	-0.5064	-0.5761	-0.5309	-0.5064	-0.4818	-0.4345
1990	-0.1621	-0.1702	-0.2372	-0.1933	-0.1702	-0.1469	-0.1027
1991	-0.2316	-0.2334	-0.3035	-0.2569	-0.2336	-0.2095	-0.1660
1992	0.0056	0.0069	-0.0531	-0.0133	0.0067	0.0271	0.0663
1993	0.2442	0.2512	0.2008	0.2339	0.2510	0.2683	0.3036
1994	0.5728	0.5895	0.5344	0.5691	0.5887	0.6088	0.6490
1995	0.4005	0.4235	0.3596	0.3988	0.4218	0.4465	0.4961
1996	0.4976	0.5200	0.4571	0.4962	0.5192	0.5425	0.5870
1997	0.0378	0.0609	-0.0141	0.0330	0.0602	0.0876	0.1394
1998	0.0882	0.1087	0.0262	0.0788	0.1086	0.1381	0.1904
1999	-0.0288	-0.0141	-0.1001	-0.0444	-0.0142	0.0174	0.0714
2000	0.4675	0.4706	0.4078	0.4489	0.4707	0.4932	0.5332
2001	-0.1923	-0.1959	-0.2738	-0.2219	-0.1956	-0.1694	-0.1200
2002	-0.0500	-0.0571	-0.1190	-0.0784	-0.0569	-0.0358	0.0041
2003	-0.3180	-0.3279	-0.3892	-0.3486	-0.3275	-0.3067	-0.2681
2004	-0.7674	-0.7786	-0.8389	-0.7994	-0.7789	-0.7572	-0.7176
2005	-0.1693	-0.1789	-0.2236	-0.1936	-0.1783	-0.1639	-0.1358
2006	-0.1756	-0.1833	-0.2248	-0.1969	-0.1830	-0.1694	-0.1442
2007	-0.0536	-0.0595	-0.0981	-0.0725	-0.0593	-0.0463	-0.0219
2008	-0.4663	-0.4698	-0.5154	-0.4848	-0.4694	-0.4547	-0.4257
2009	0.2553	0.2551	0.2173	0.2421	0.2550	0.2680	0.2936
2010	0.4851	0.4872	0.4467	0.4731	0.4873	0.5010	0.5290
2011	0.5938	0.5950	0.5534	0.5800	0.5948	0.6094	0.6385
2012	-0.1888	-0.1915	-0.2451	-0.2096	-0.1919	-0.1732	-0.1374
2013	-0.4690	-0.4696	-0.5330	-0.4908	-0.4693	-0.4482	-0.4080
2014	-0.4423	-0.4429	-0.5161	-0.4674	-0.4428	-0.4186	-0.3703
2015	-0.0710	-0.0712	-0.1527	-0.0991	-0.0711	-0.0434	0.0105
2016	-0.4664	-0.4655	-0.5914	-0.5077	-0.4659	-0.4227	-0.3440

Table 13: Table of recruitment deviations for model 2 (Beverton-Holt steepness = 0.66) with the optimised value, mean and credible intervals of the MCMC run.

Year	Optimised	Mean	2.5%	25%	50%	75%	97.5%
1989	-0.4910	-0.4943	-0.5651	-0.5189	-0.4941	-0.4699	-0.4244
1990	-0.1412	-0.1454	-0.2124	-0.1680	-0.1450	-0.1229	-0.0793
1991	-0.2268	-0.2296	-0.2972	-0.2527	-0.2295	-0.2058	-0.1625
1992	-0.0148	-0.0164	-0.0733	-0.0361	-0.0162	0.0035	0.0393
1993	0.1971	0.1983	0.1527	0.1824	0.1982	0.2145	0.2437
1994	0.4990	0.5042	0.4597	0.4888	0.5039	0.5195	0.5501
1995	0.3309	0.3397	0.2887	0.3211	0.3392	0.3578	0.3933
1996	0.4601	0.4690	0.4167	0.4501	0.4684	0.4875	0.5235
1997	0.0274	0.0377	-0.0294	0.0143	0.0377	0.0604	0.1064
1998	0.1035	0.1110	0.0351	0.0847	0.1113	0.1371	0.1853
1999	-0.0003	0.0059	-0.0743	-0.0225	0.0056	0.0340	0.0876
2000	0.5011	0.5037	0.4424	0.4829	0.5043	0.5248	0.5637
2001	-0.1555	-0.1555	-0.2304	-0.1805	-0.1548	-0.1302	-0.0814
2002	0.0124	0.0099	-0.0477	-0.0095	0.0100	0.0300	0.0662
2003	-0.2536	-0.2572	-0.3122	-0.2760	-0.2572	-0.2378	-0.2037
2004	-0.7161	-0.7197	-0.7759	-0.7387	-0.7199	-0.7002	-0.6643
2005	-0.1327	-0.1363	-0.1757	-0.1497	-0.1362	-0.1229	-0.0976
2006	-0.1781	-0.1807	-0.2172	-0.1930	-0.1805	-0.1684	-0.1452
2007	-0.0819	-0.0837	-0.1179	-0.0953	-0.0835	-0.0720	-0.0495
2008	-0.5011	-0.5013	-0.5444	-0.5162	-0.5013	-0.4864	-0.4583
2009	0.2172	0.2183	0.1823	0.2058	0.2185	0.2306	0.2536
2010	0.4252	0.4283	0.3889	0.4147	0.4279	0.4418	0.4692
2011	0.5602	0.5636	0.5218	0.5486	0.5631	0.5782	0.6071
2012	-0.1709	-0.1692	-0.2227	-0.1874	-0.1690	-0.1508	-0.1163
2013	-0.3999	-0.3982	-0.4608	-0.4194	-0.3984	-0.3769	-0.3358
2014	-0.3607	-0.3585	-0.4325	-0.3839	-0.3585	-0.3330	-0.2852
2015	-0.0092	-0.0075	-0.0907	-0.0370	-0.0071	0.0209	0.0768
2016	-0.4392	-0.4390	-0.5652	-0.4823	-0.4396	-0.3946	-0.3142

Table 14: Table of recruitment deviations for model 3 (Beverton-Holt steepness = 0.83) with the optimised value, median and credible intervals of the MCMC run.

Year	Optimised	Mean	2.5%	25%	50%	75%	97.5%
1989	-0.4855	-0.4903	-0.5628	-0.5150	-0.4901	-0.4652	-0.4185
1990	-0.1291	-0.1337	-0.1999	-0.1564	-0.1336	-0.1108	-0.0669
1991	-0.2227	-0.2260	-0.2928	-0.2483	-0.2257	-0.2032	-0.1597
1992	-0.0251	-0.0277	-0.0831	-0.0470	-0.0277	-0.0083	0.0278
1993	0.1692	0.1699	0.1251	0.1550	0.1698	0.1851	0.2136
1994	0.4516	0.4577	0.4155	0.4425	0.4569	0.4724	0.5041
1995	0.2846	0.2952	0.2423	0.2760	0.2934	0.3127	0.3575
1996	0.4314	0.4430	0.3900	0.4224	0.4413	0.4615	0.5091
1997	0.0155	0.0277	-0.0405	0.0022	0.0264	0.0515	0.1077
1998	0.1074	0.1175	0.0412	0.0903	0.1167	0.1441	0.1986
1999	0.0123	0.0207	-0.0622	-0.0079	0.0203	0.0491	0.1053
2000	0.5152	0.5191	0.4606	0.4988	0.5191	0.5397	0.5790
2001	-0.1391	-0.1383	-0.2106	-0.1639	-0.1381	-0.1123	-0.0648
2002	0.0466	0.0452	-0.0121	0.0263	0.0452	0.0645	0.1011
2003	-0.2159	-0.2196	-0.2748	-0.2374	-0.2193	-0.2011	-0.1673
2004	-0.6850	-0.6895	-0.7464	-0.7092	-0.6888	-0.6698	-0.6342
2005	-0.1088	-0.1134	-0.1541	-0.1263	-0.1130	-0.0997	-0.0756
2006	-0.1780	-0.1818	-0.2189	-0.1939	-0.1816	-0.1692	-0.1462
2007	-0.0999	-0.1018	-0.1359	-0.1131	-0.1018	-0.0903	-0.0691
2008	-0.5242	-0.5241	-0.5655	-0.5385	-0.5244	-0.5097	-0.4820
2009	0.1906	0.1931	0.1585	0.1810	0.1928	0.2051	0.2289
2010	0.3819	0.3868	0.3469	0.3725	0.3863	0.4004	0.4297
2011	0.5339	0.5394	0.4951	0.5237	0.5391	0.5550	0.5848
2012	-0.1632	-0.1599	-0.2146	-0.1790	-0.1600	-0.1413	-0.1043
2013	-0.3571	-0.3540	-0.4177	-0.3763	-0.3540	-0.3321	-0.2896
2014	-0.3068	-0.3045	-0.3786	-0.3308	-0.3047	-0.2789	-0.2290
2015	0.0354	0.0372	-0.0489	0.0075	0.0374	0.0663	0.1247
2016	-0.4135	-0.4127	-0.5491	-0.4570	-0.4119	-0.3669	-0.2820

Appendix G - Model fit

G.1 Catch rates

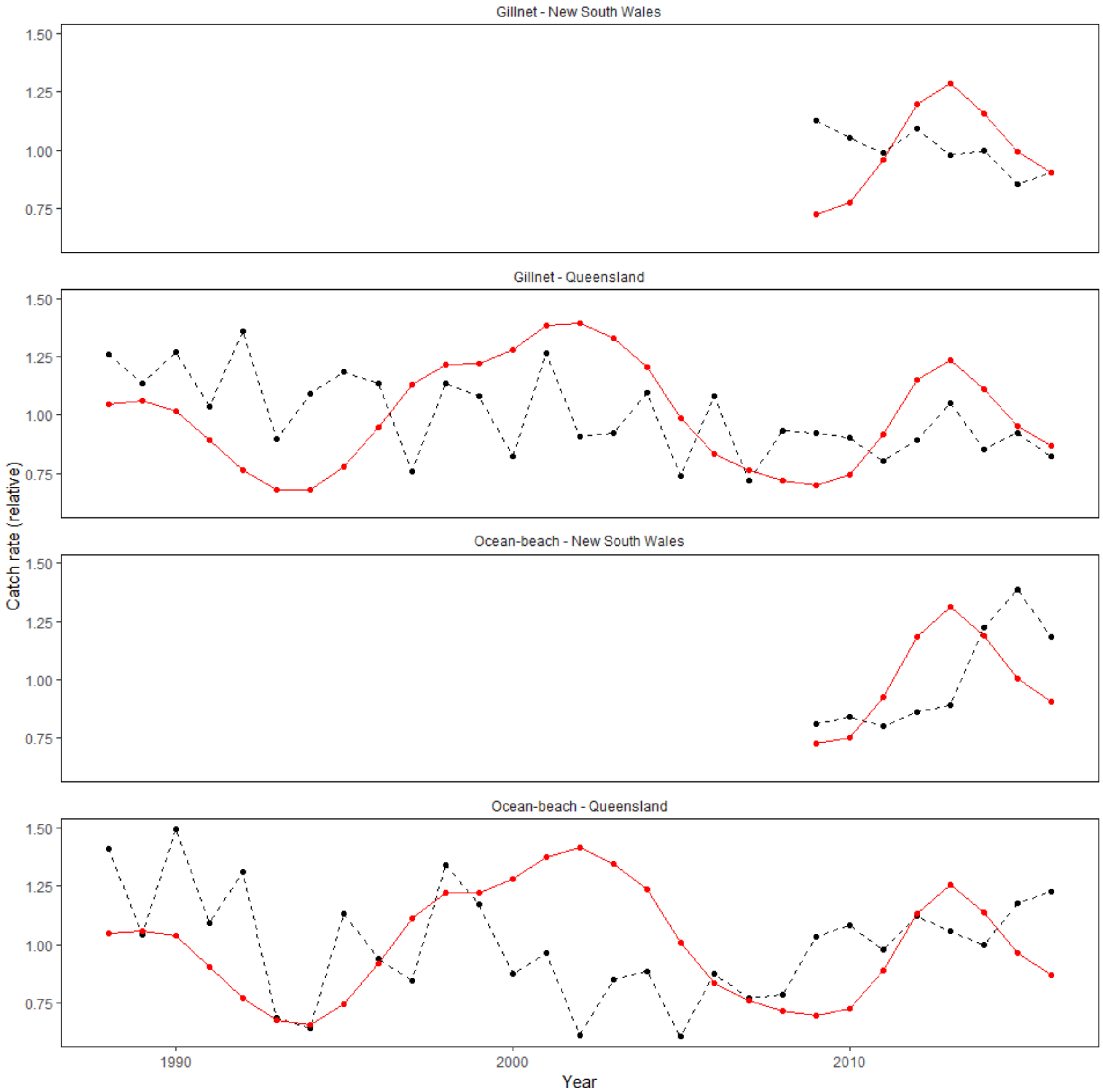

Figure 54: Model fit to standardised catch rates for ocean beach netting and gillnetting: Model 1 (h = 0.49).

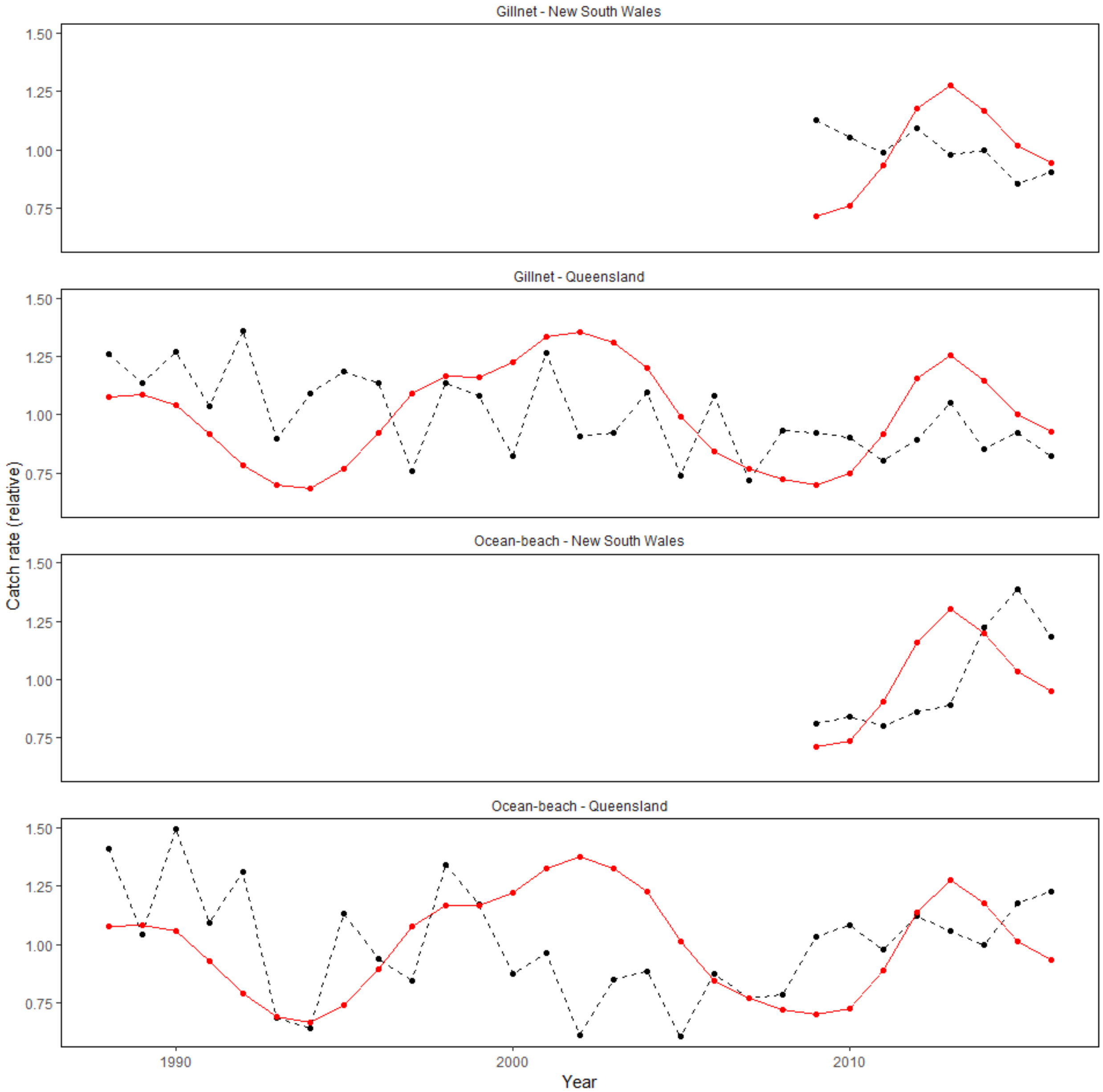

Figure 55: Model fit to standardised catch rates for ocean beach netting and gillnetting: Model 2 (h = 0.66).

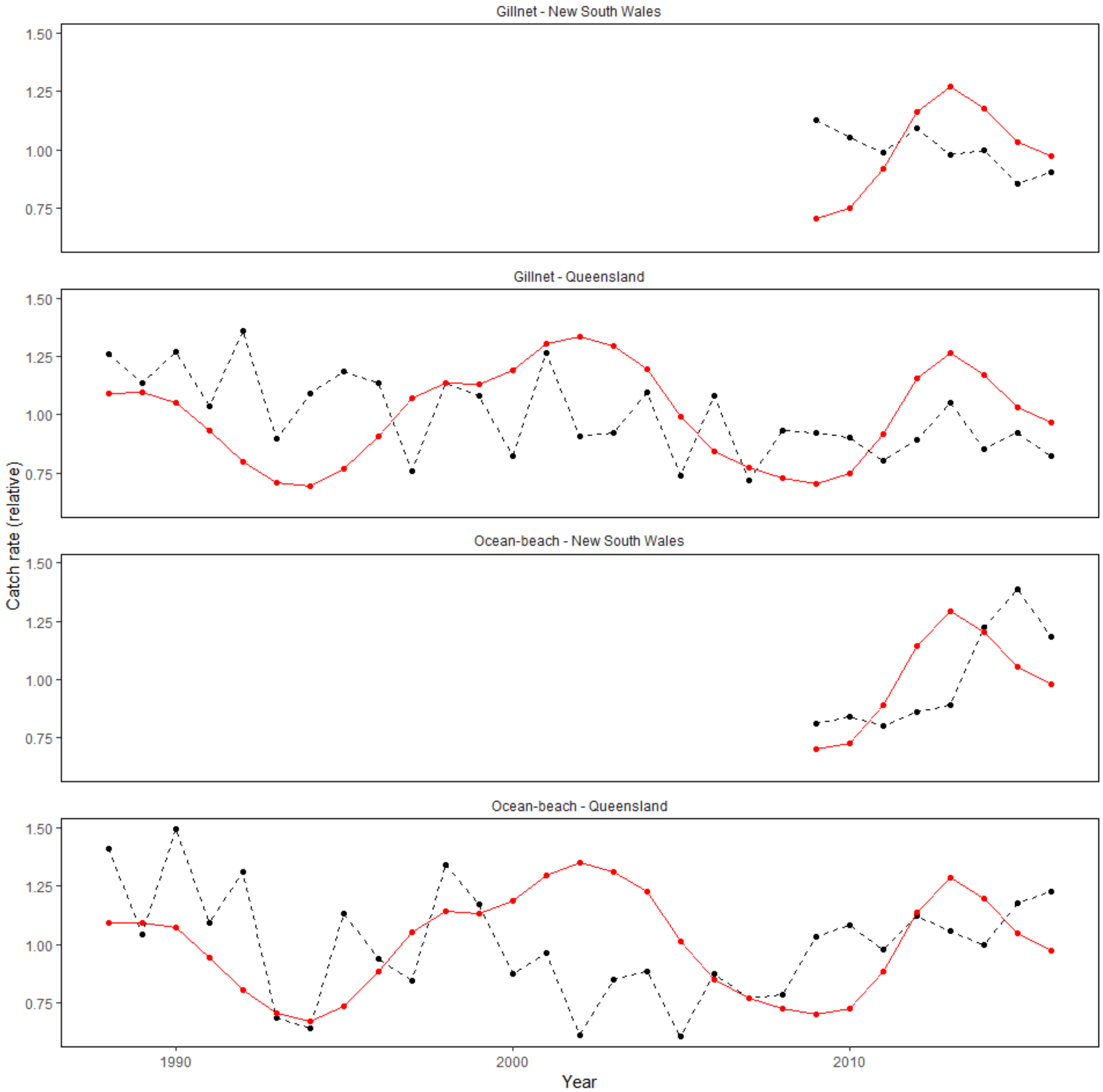

Figure 56: Model fit to standardised catch rates for ocean beach netting and gillnetting: Model 3 (h = 0.83).

G.2 Age structures

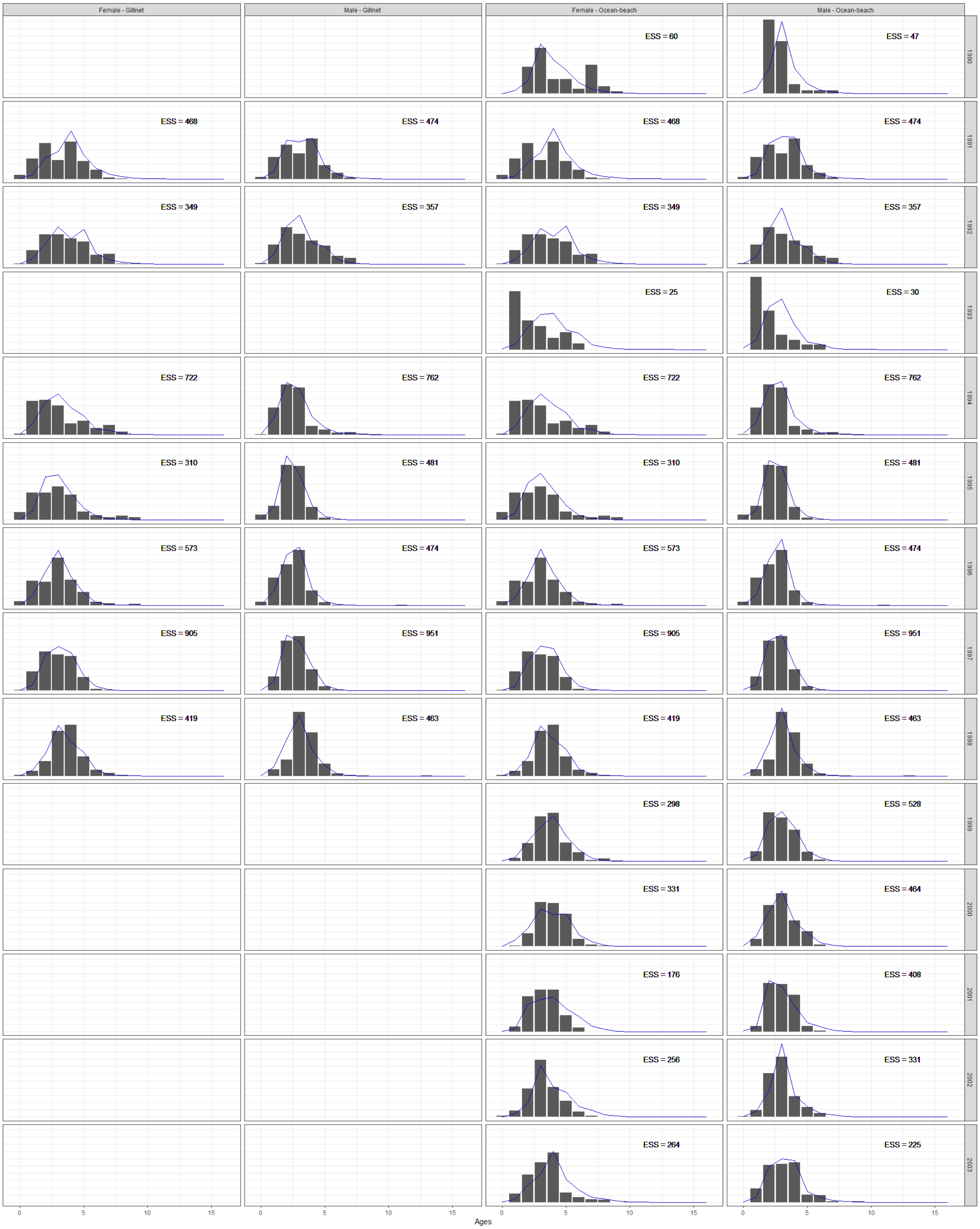

Figure 57: Model fit to age composition for ocean beach netting and gillnetting (males and females): Model 1 (h = 0.49), year range 1990 2003.

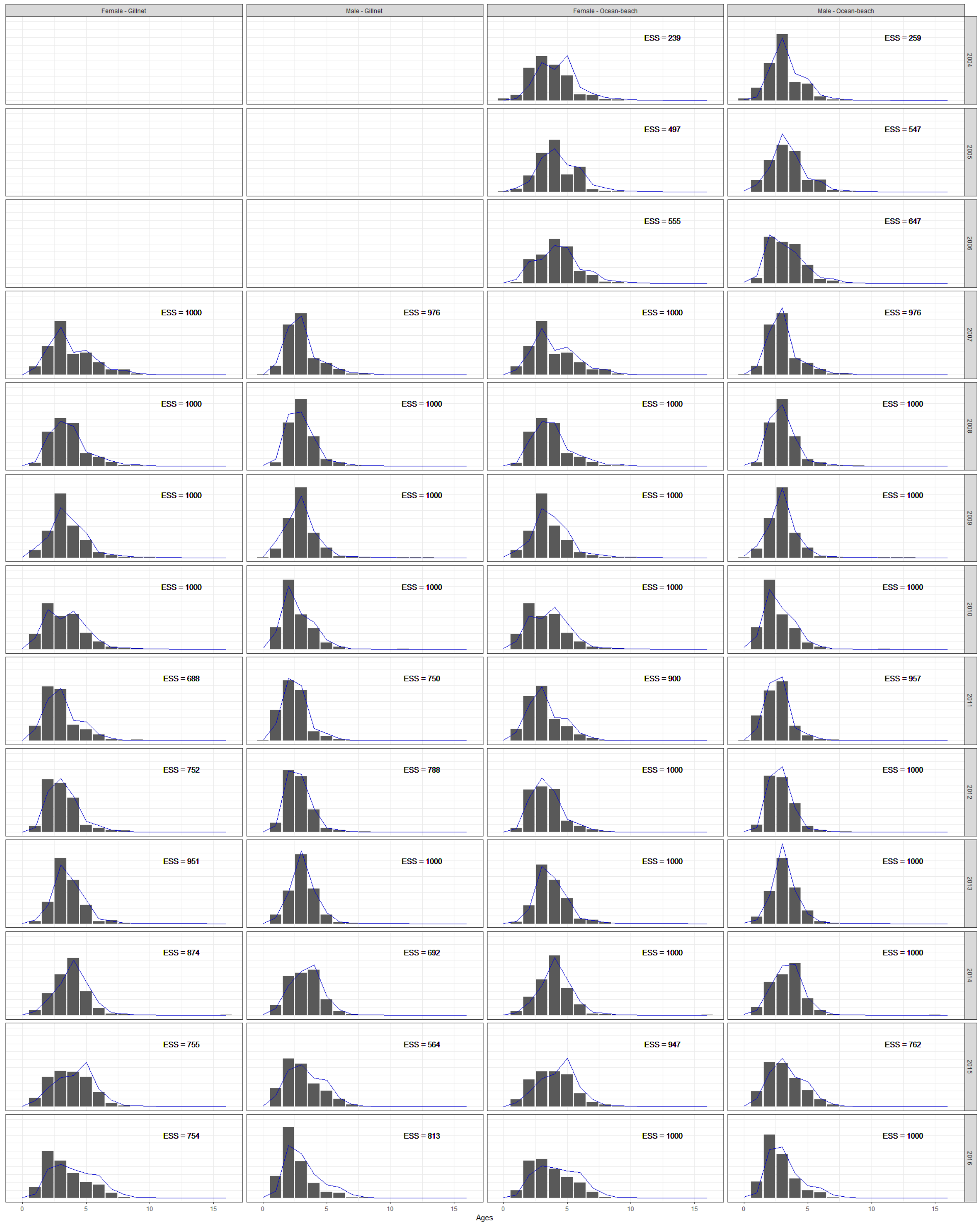

Figure 58: Model fit to age composition for ocean beach netting and gillnetting (males and females): Model 1 (h = 0.49), year range 2004 - 2016.

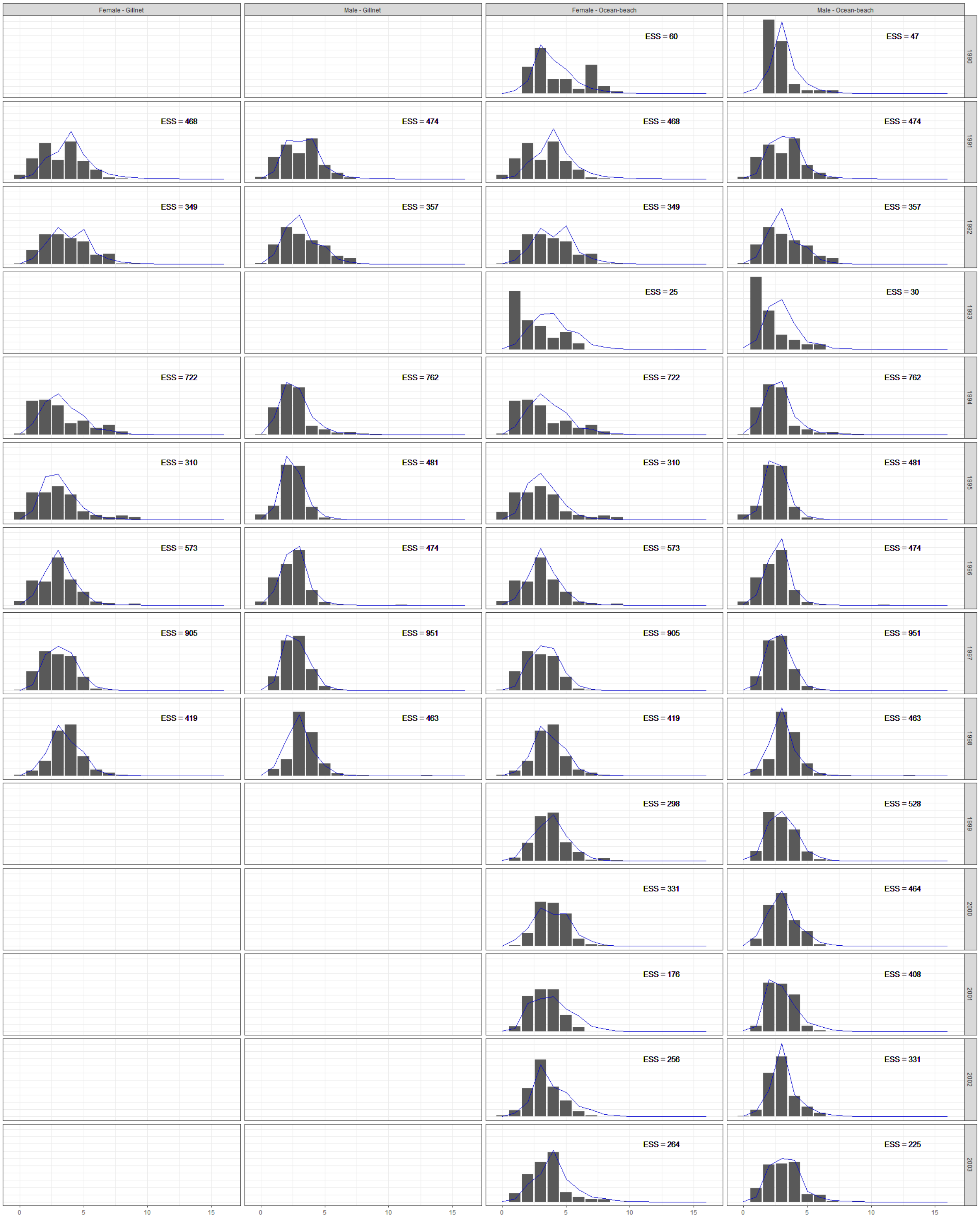

Figure 59: Model fit to age composition for ocean beach netting and gillnetting (males and females): Model 2 (h = 0.66), year range 1990 - 2003.

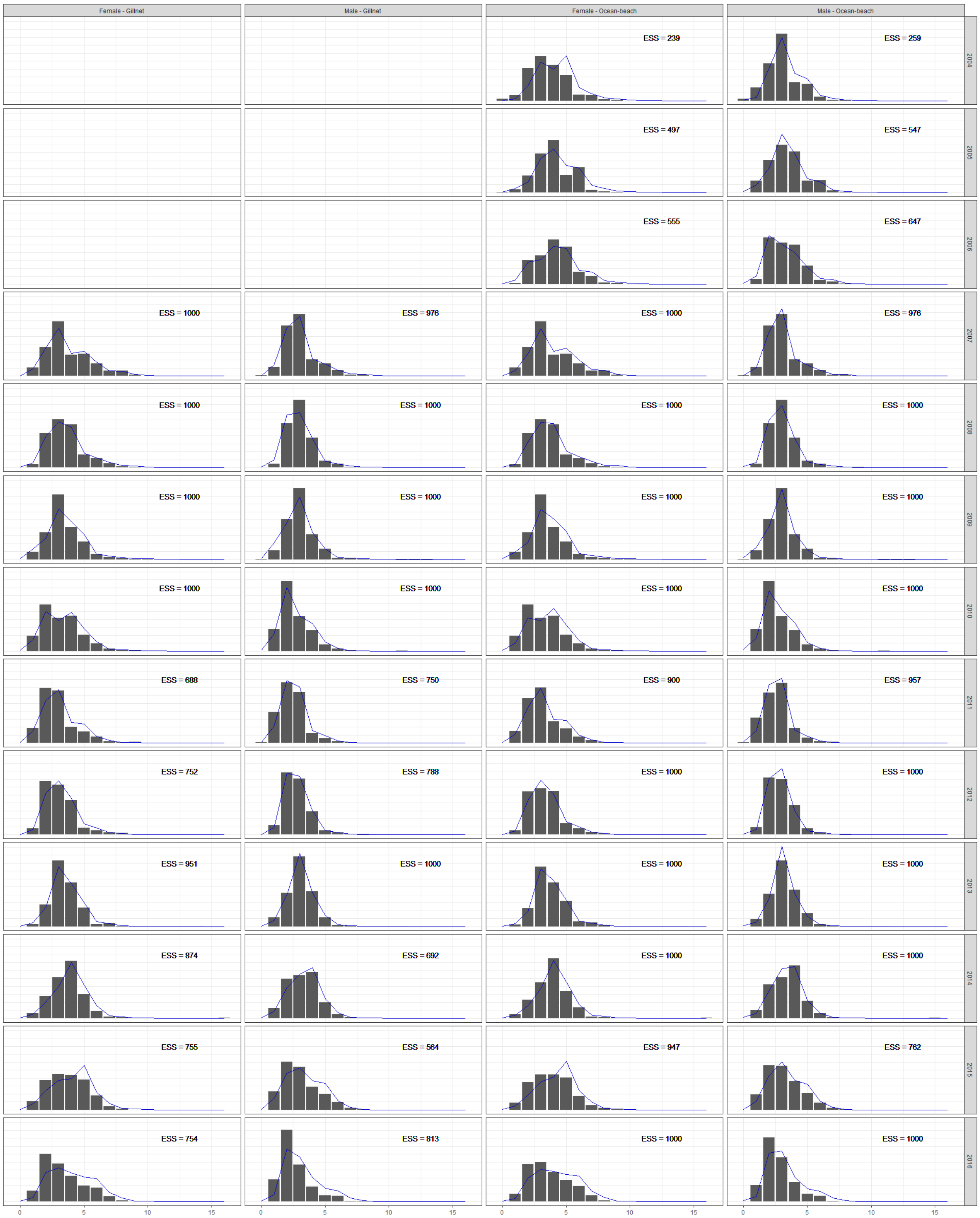

Figure 60: Model fit to age composition for ocean beach netting and gillnetting (males and females): Model 2 (h = 0.66), year range 2004 - 2016.

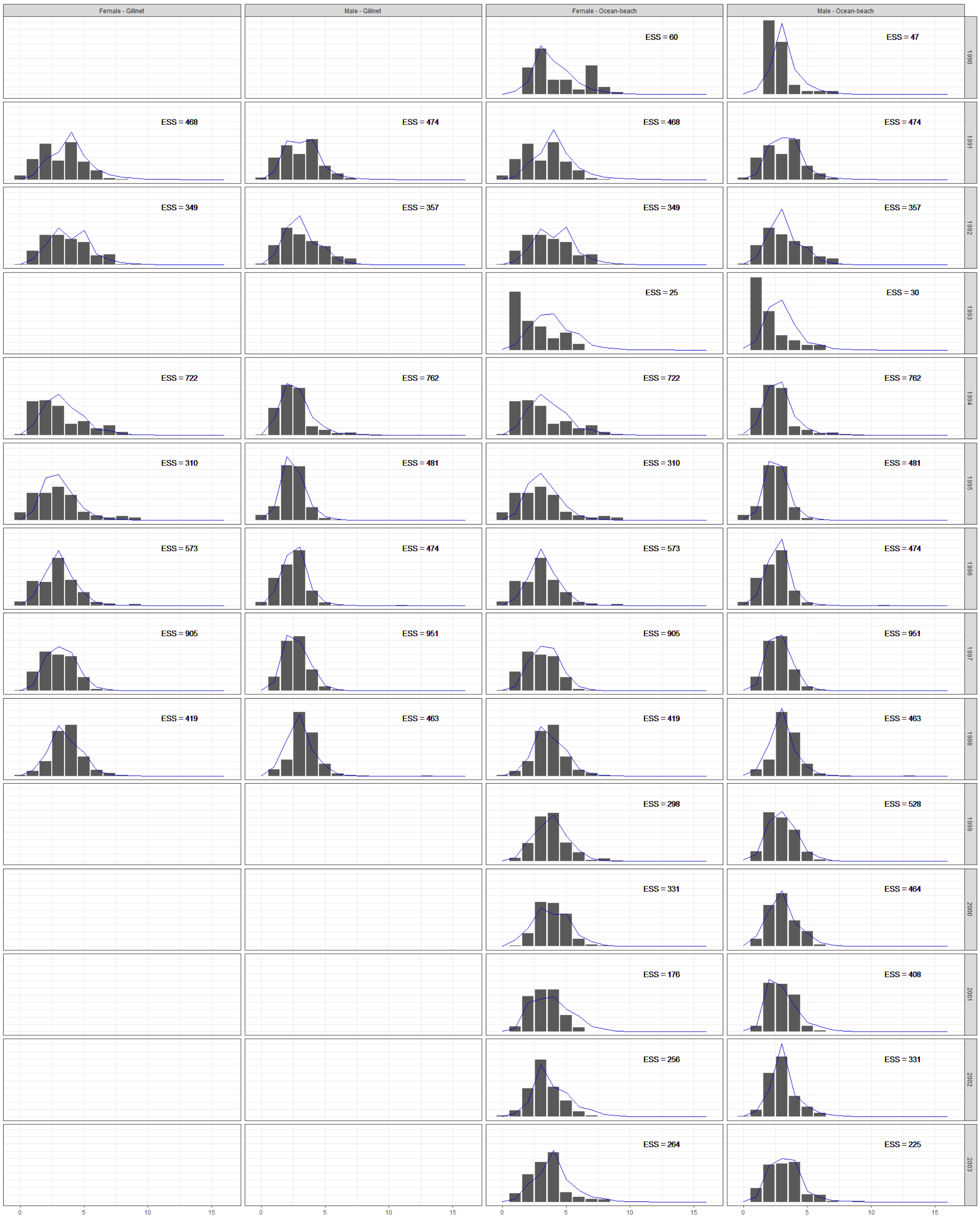

Figure 61: Model fit to age composition for ocean beach netting and gillnetting (males and females): Model 3 (h = 0.83), year range 1990 - 2003.

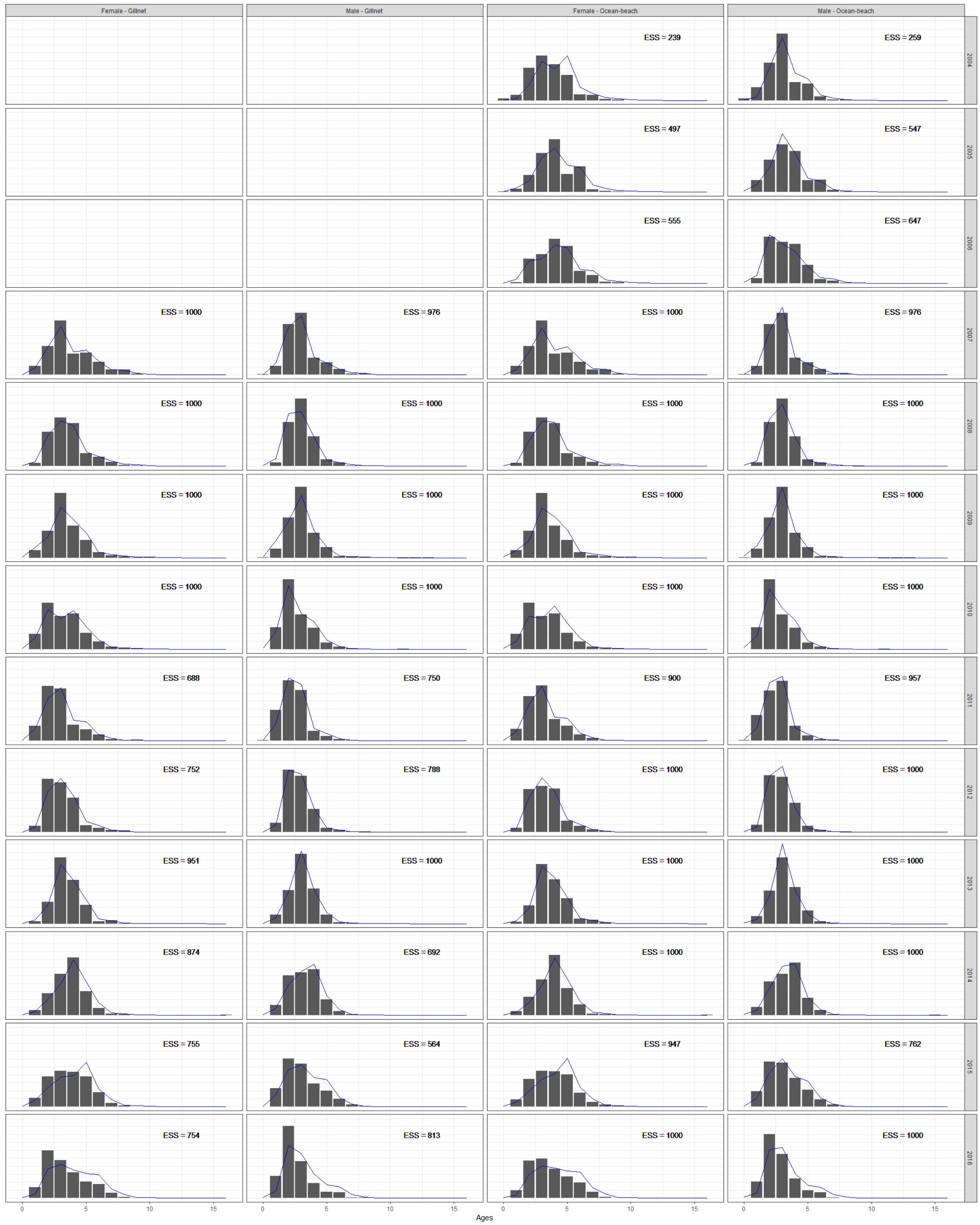

Figure 62: Model fit to age composition for ocean beach netting and gillnetting (males and females): Model 3 (h = 0.83), year range 2004 - 2016.

G.3 Length structures

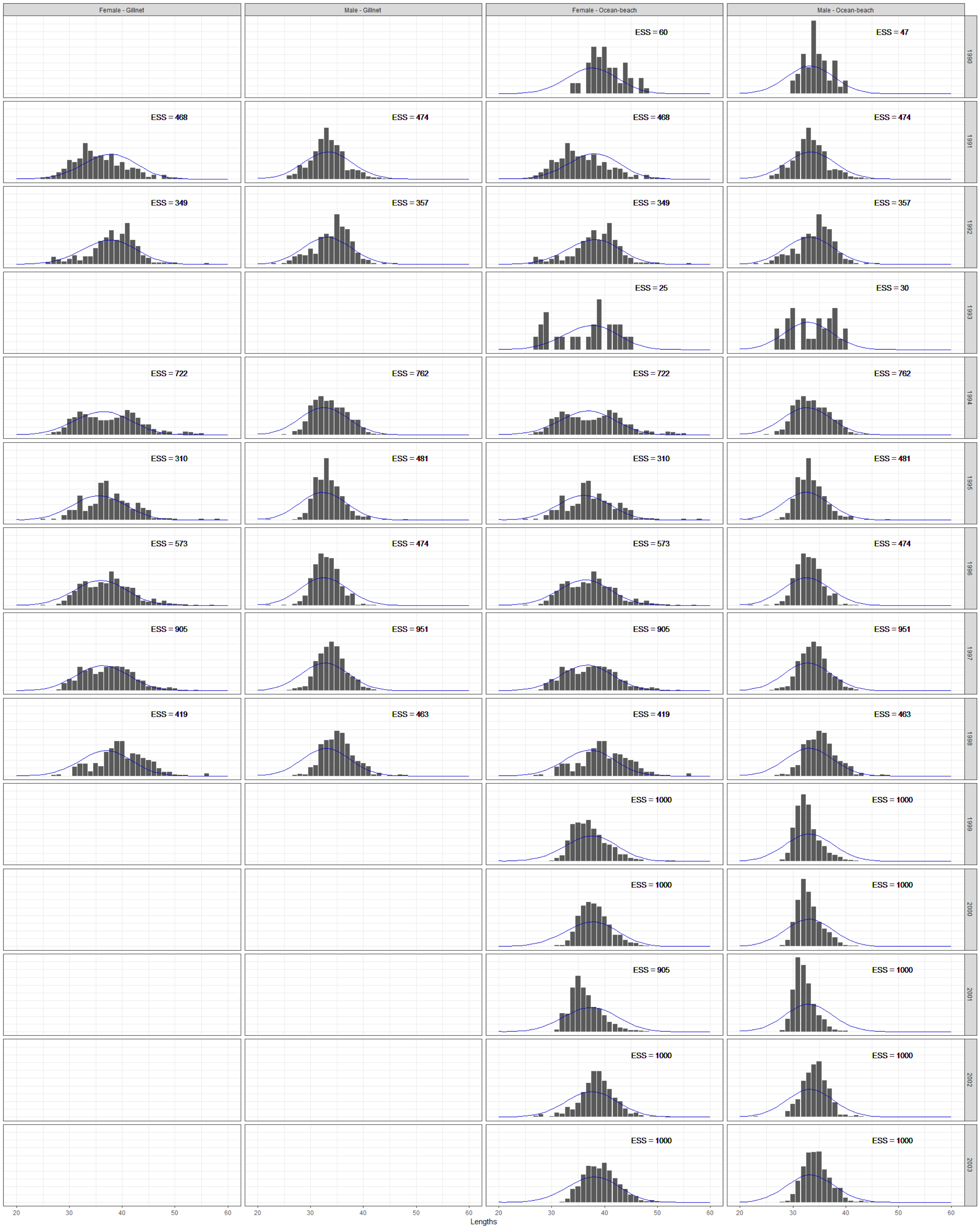

Figure 63: Model fit to length composition for ocean beach netting and gillnetting (males and females): Model 1 (h = 0.49), year range 1990 - 2003.

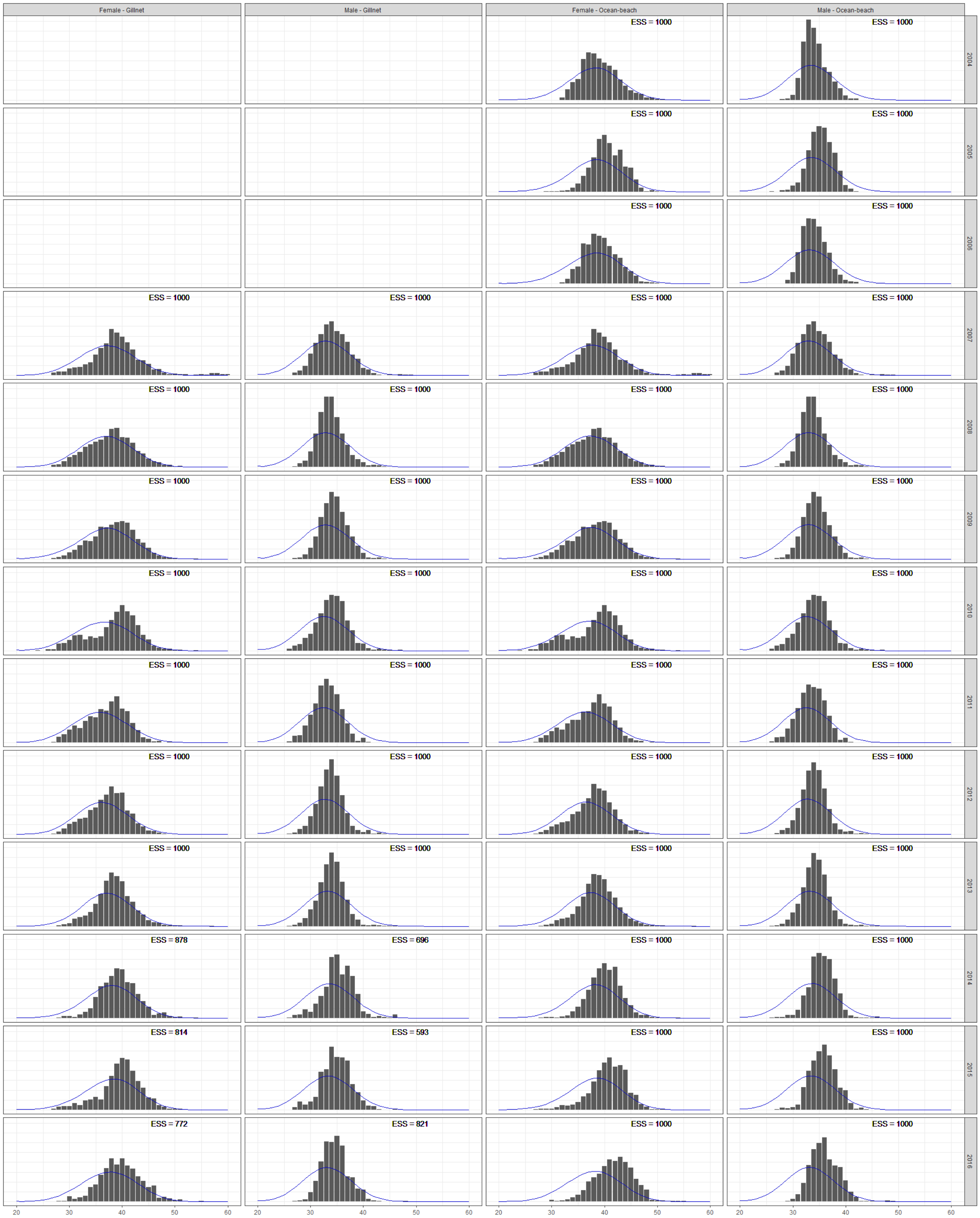

Figure 64: Model fit to length composition for ocean beach netting and gillnetting (males and females): Model 1 (h = 0.49), year range 2004 - 2016.

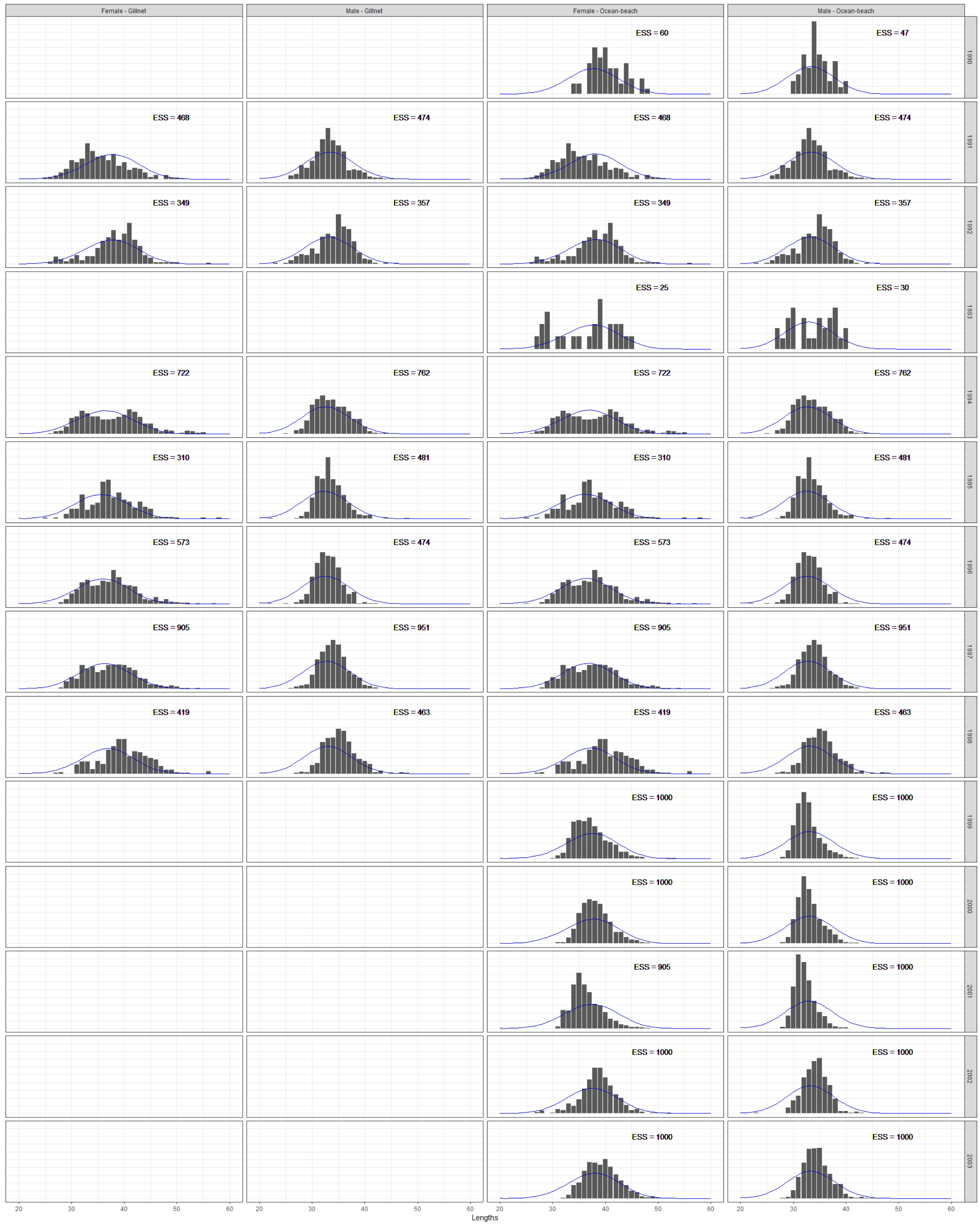

Figure 65: Model fit to length composition for ocean beach netting and gillnetting (males and females): Model 2 (h = 0.66), year range 1990 - 2003.

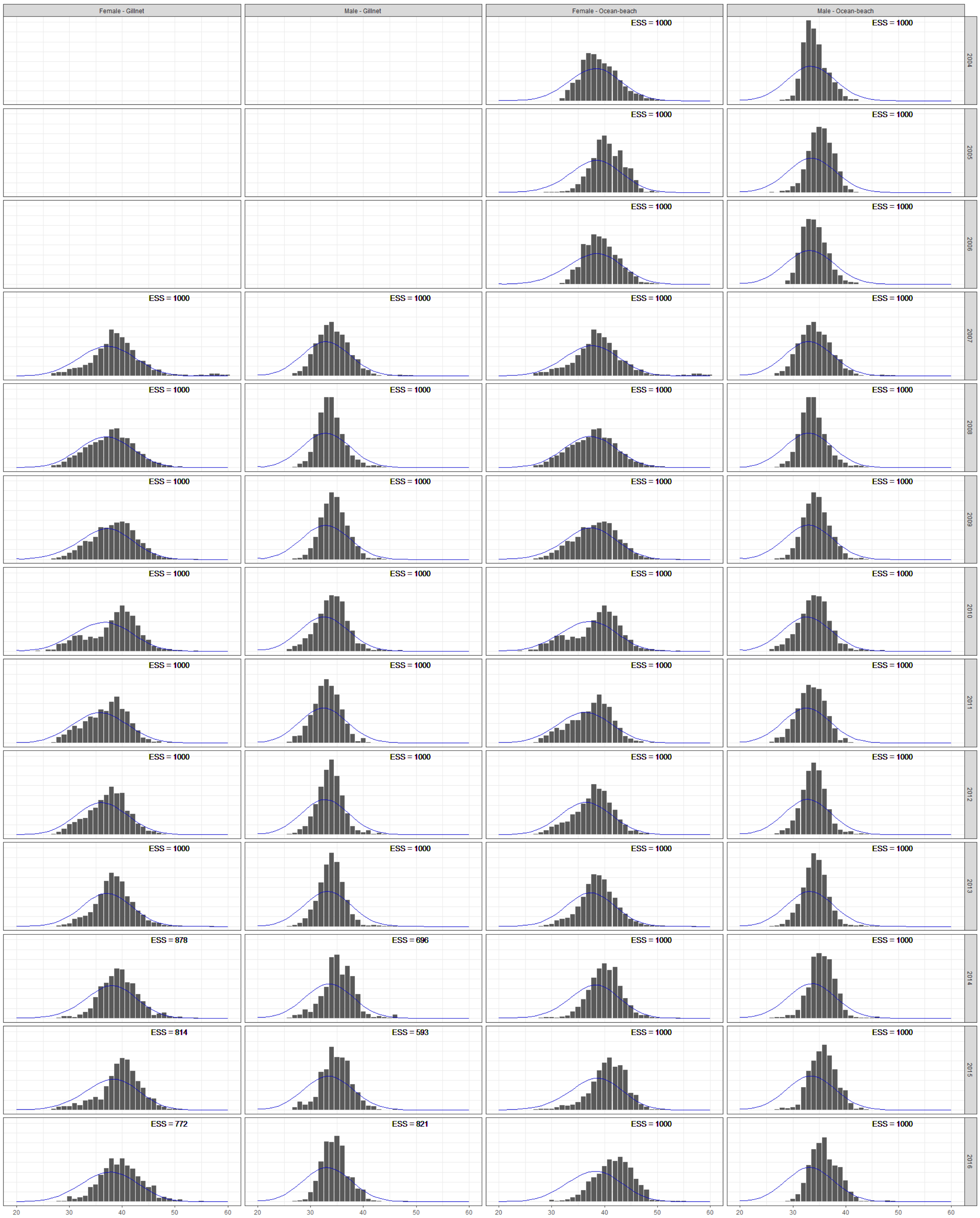

Figure 66: Model fit to length composition for ocean beach netting and gillnetting (males and females): Model 2 (h = 0.66), year range 2004 - 2016.

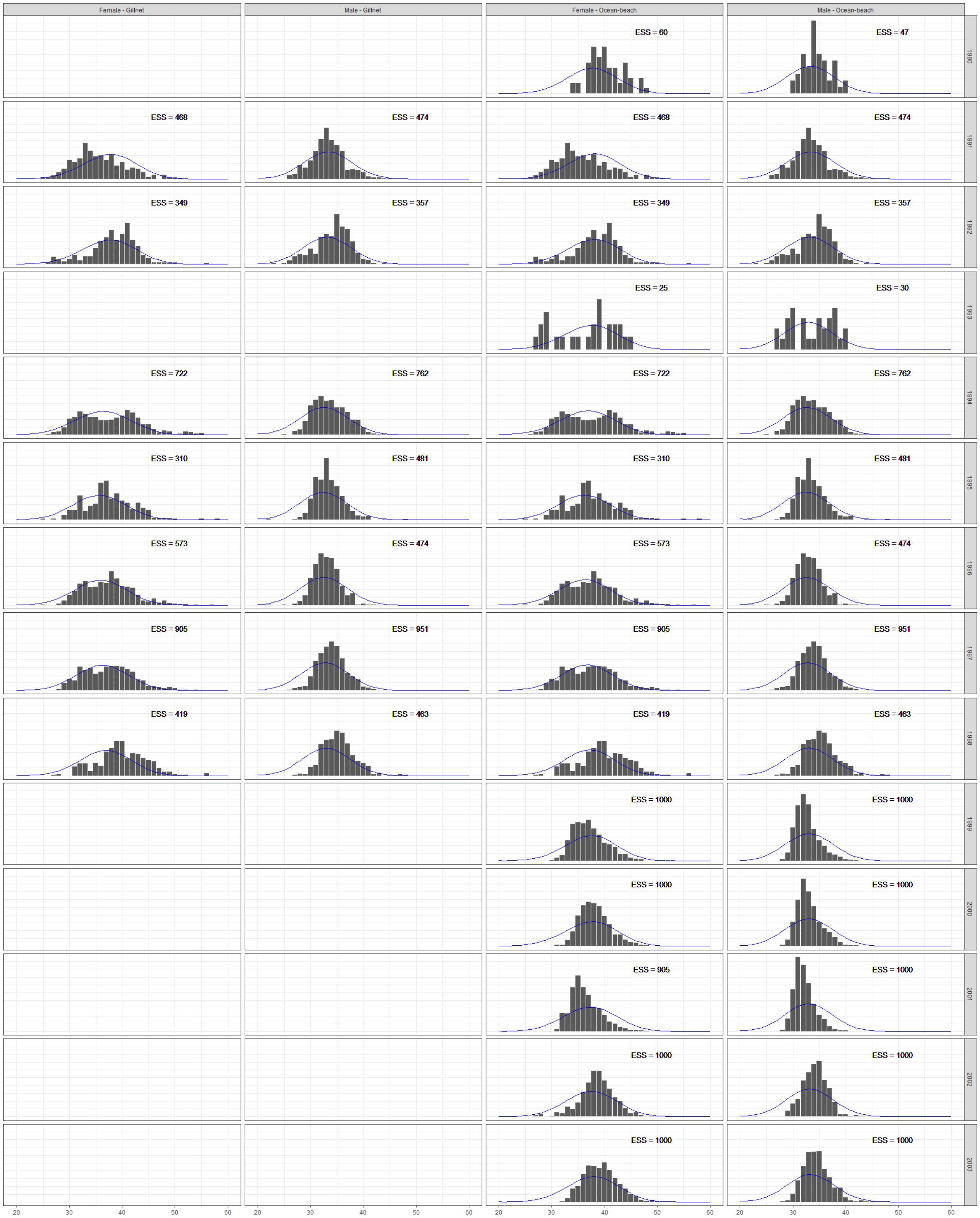

Figure 67: Model fit to length composition for ocean beach netting and gillnetting (males and females): Model 3 (h = 0.83), year range 1990 - 2003.

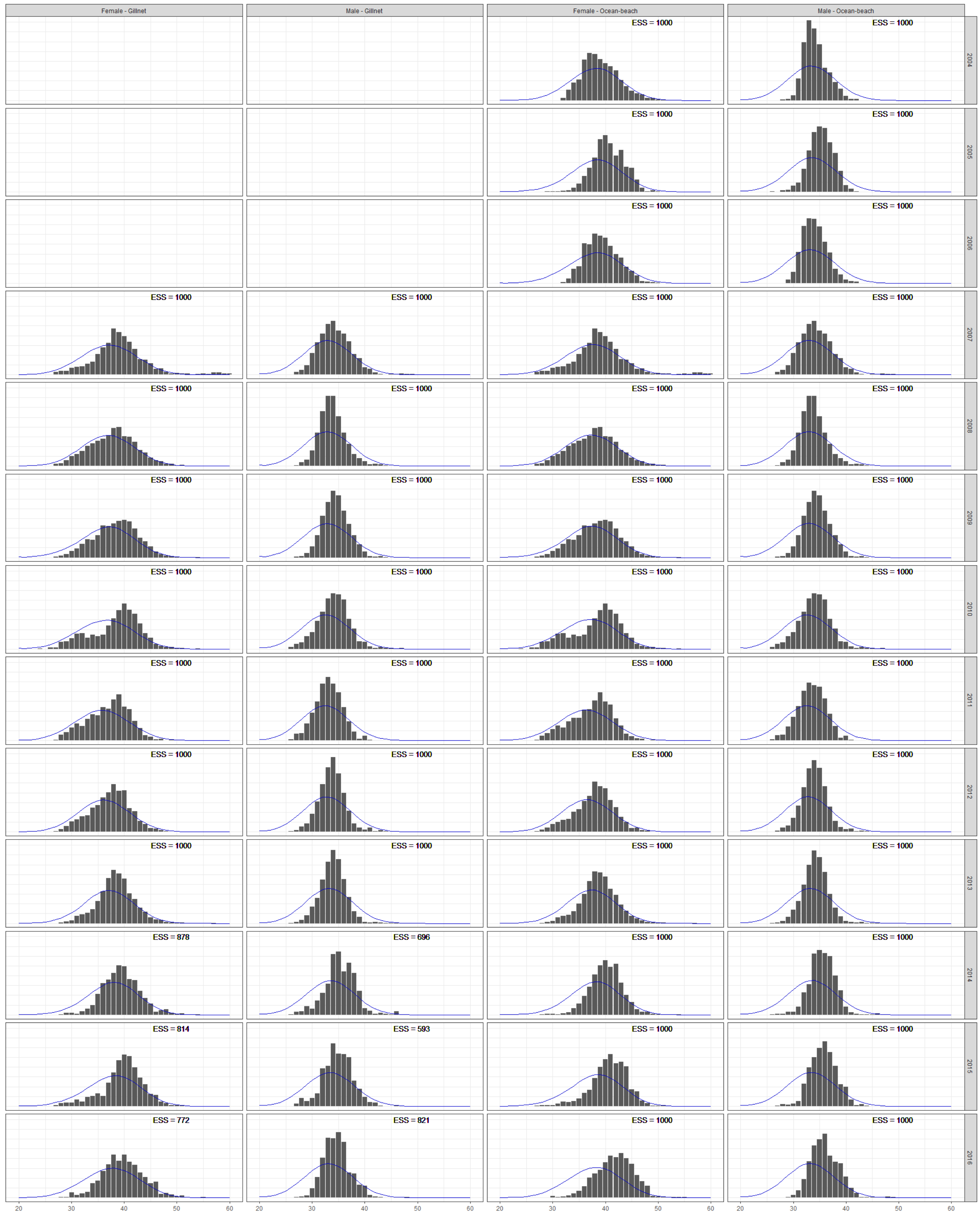

Figure 68: Model fit to length composition for ocean beach netting and gillnetting (males and females): Model 3 (h = 0.83), year range 2004 - 2016.

Appendix H - Phase plots

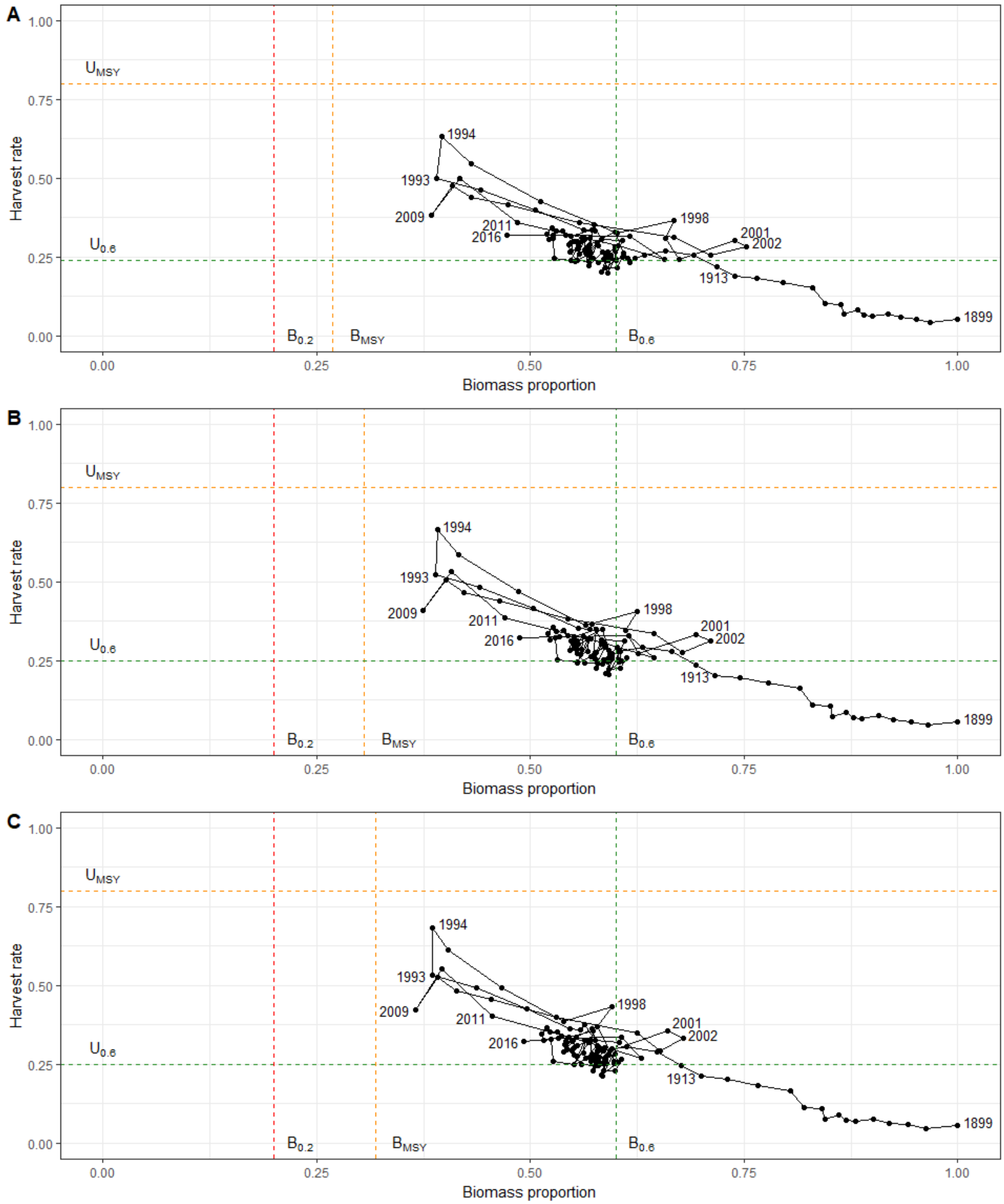

Figure 69: Phase plots following the trajectory over time of Harvest rate vs exploitable biomass proportion relative to virgin exploitable biomass for each year. A: Model 1 (h = 0.49), B: Model 2 (h = 0.66), C: Model 3 (h = 0.83).