Stock assessment of the Queensland Gulf of Carpentaria Spanish mackerel (*Scomberomorus commerson*) fishery

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Queensland Government

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Contents

Summary

Spanish mackerel (*Scomberomorus commerson*) is a pelagic species that forms three genetic populations (stocks) around northern Australia. The first stock is in east coast waters between Cape York in Queensland and Sydney in New South Wales. The second stock is in the Torres Strait. The third stock encompasses much of northern Australia, from the Queensland Gulf of Carpentaria waters, west to Perth in Western Australia. However, otolith microchemistry and parasite analyses suggest that there are many small-scale populations across northern Australia. For the purposes of this assessment we have investigated fish harvested from the Queensland Gulf of Carpentaria portion of the northern genetic stock.

Spanish mackerel are a large, fast growing fish. In the Queensland Gulf of Carpentaria they have been found to live for up to 15 years of age and reach over 27 kg in weight. They reach maturity at approximately two years of age, approximately 80 cm fork length, which is above the current Queensland minimum legal size of 75 cm total length.

Spanish mackerel are found in coastal waters and are commonly caught around the edge of benthic structures, such as reefs and shoals. Seasonally, they form predictable aggregations throughout waters of the Queensland Gulf of Carpentaria, which are harvested mainly by commercial line and net fishers. The estimated recreational harvest is small and highly varied, while reported charter harvests are also low.

This stock assessment was completed using Stock Synthesis. It was set up as an age-structured model with a yearly time step and length-based selectivity. The annual data inputs included total fish harvest, standardised catch rates, length structures and conditional age at length data. The model used data from the anticipated start of fishing in 1940 to 2018.

Harvests by sector were 97 per cent commercial (176 t), 2 per cent recreational (4 t) and 1 per cent charter (1 t) (Figure 1). Of the reported commercial harvest, 79 per cent was taken using line fishing methods, while 21 per cent was taken using nets.

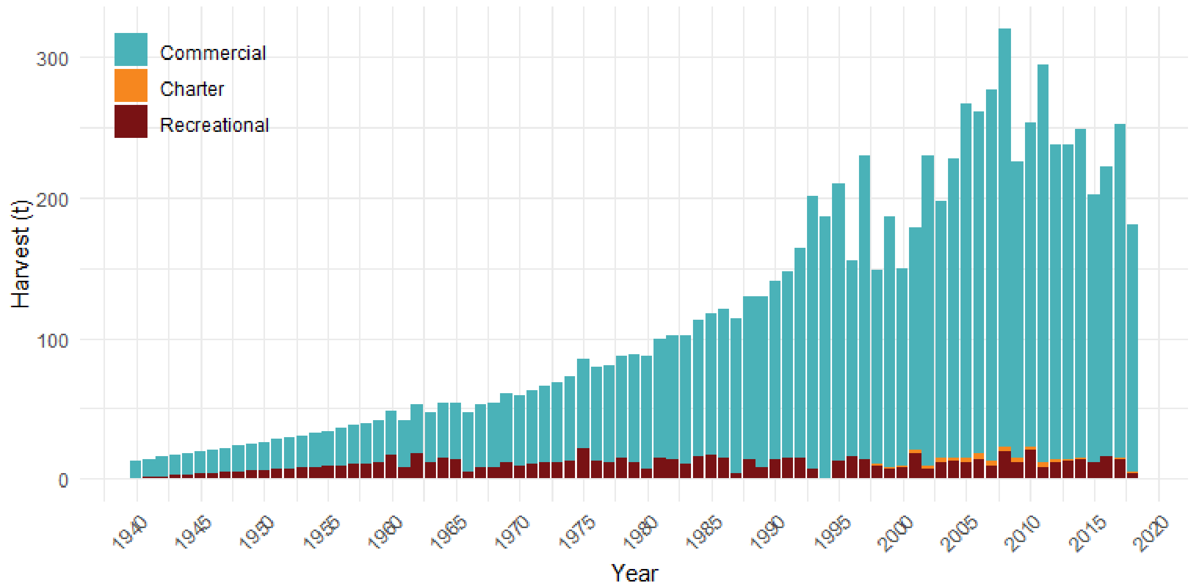

Figure 1: Estimated harvest from commercial, recreational and charter sectors between 1940 and 2018

Commercial catch rates were standardised to estimate an index of Spanish mackerel abundance through time. The analyses considered different aspects of fishing, including years, regions, number of dories, seasons, lunar phase, wind speed and direction and included differences between fishers as a random effect. Standardised catch rates had fishing power adjustments included to account for changes in the effectiveness in fishing through time. The results suggest that standardised catch rates have declined since 2011, and 2018 showed a sharp decline from 2017 to the lowest estimate of the time series (Figure 2).

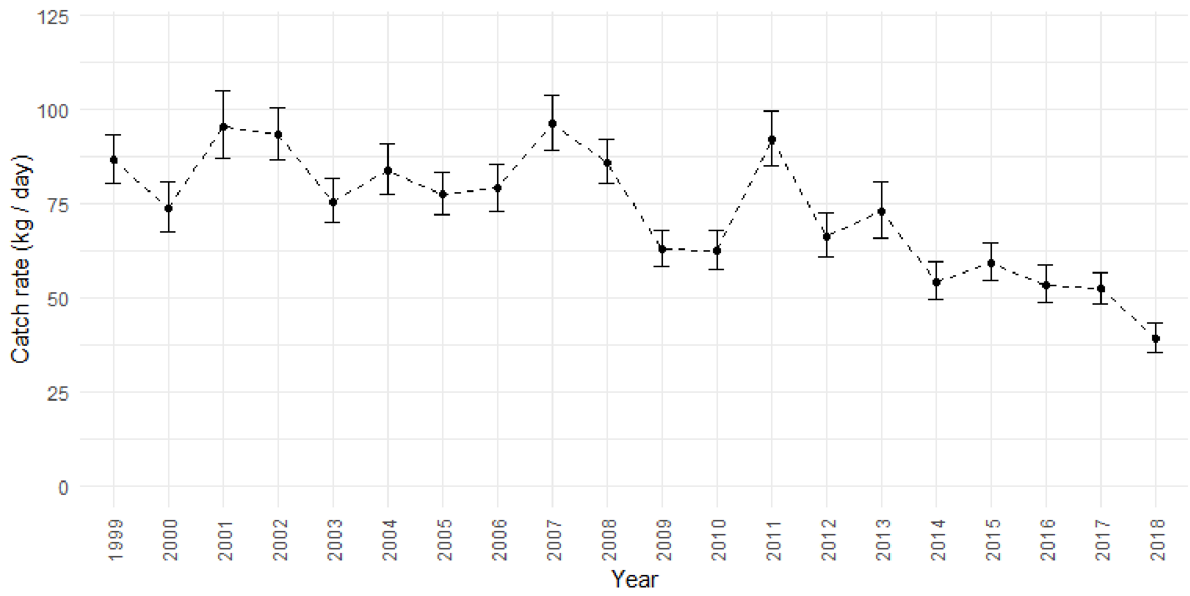

Figure 2: Standardised catch rates for line caught Spanish mackerel between the fishing years of 1999 and 2018, with error bars representing 95% confidence intervals.

Model results suggested that biomass declined between 1940 and 1995 to 60 per cent of unfished, spawning biomass (Figure 3). From this time there was more variability in the decline of spawning biomass, however, since 2011 the downward trend has been steep. The assessment suggests that the stock is currently between 30 and 40 per cent unfished spawning biomass.

The results suggest that the equilibrium maximum sustainable yield harvest is 228 t per year (all sectors). Equilibrium 60% harvest was estimated at 163 t, although considerable rebuilding of the stock is required before this level of harvest is appropriate.

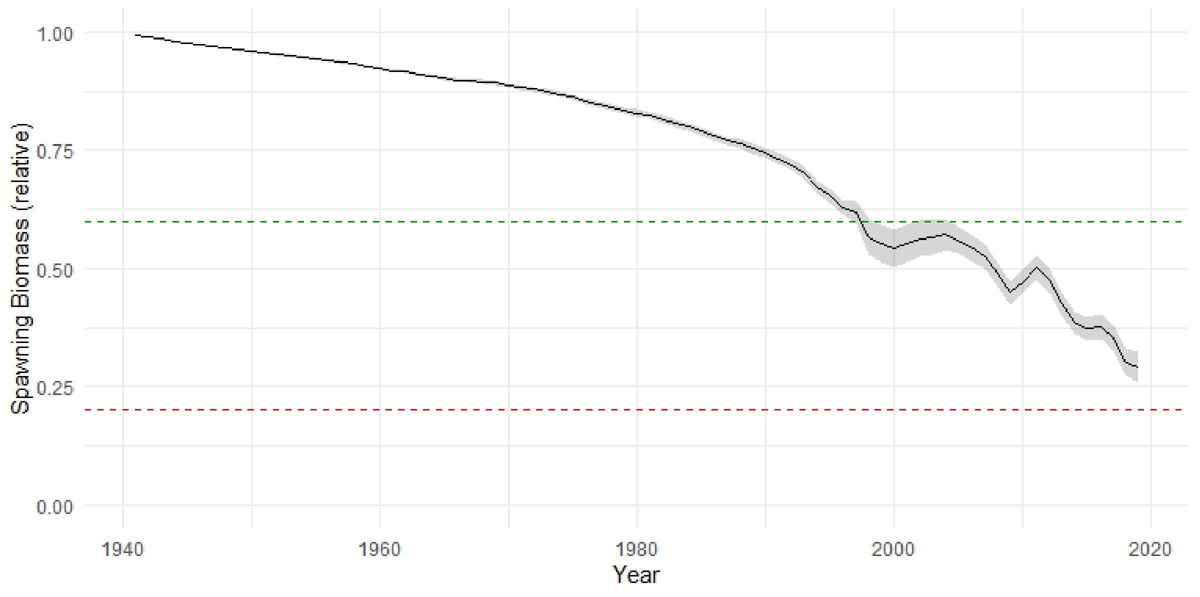

Figure 3: Predicted spawning biomass trajectory relative to virgin spawning biomass. Shaded areas represent 95% confidence intervals. The green dashed line represents the target reference point of 60% and the red dashed line represents the limit reference point of 20%.

The recommended biological catch to rebuild the stocks to the *Queensland Sustainable Fisheries Strategy 2017-2027* target reference point of 60 per cent unfished biomass depend on whether a hockey stick or constant fishing mortality harvest strategy is adopted. Harvest targets, to meet the 20:60:60 hockey stick harvest control rule, result in smaller harvests in early years, which increase through time. The 2019 recommended biological catch under this control rule is estimated at 21 t. If adopting a constant fishing mortality harvest control rule, harvests are higher in the short term, however, are lower in later years, and recovery to the target reference point is extended. The 2019 constant fishing mortality recommended biological catch is estimated to be 89 t. Current harvest is well above both recommended biological catch estimates.

Parameter	Estimate
Current spawning biomass (relative to unfished)	32 per cent
Maximum sustainable yield spawning biomass (relative to unfished)	29 per cent
Maximum sustainable yield harvest	228 tonnes
Current harvest (2018)	181 tonnes
Harvest proportions (2018)	97 per cent commercial, 2 per cent recreational, 1 per cent charter
Equilibrium 60% biomass harvest	163 tonnes
2019 harvest to build to B_{60}, 20:60:60 hockey stick	21 tonnes
2019 harvest to build to B_{60}, constant F	89 tonnes
Time to build to B_{60}, 20:60:60 hockey stick	7 years
Time to build to B_{60} s, constant F	12 years

Acknowledgements

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The authors would also like to acknowledge and thank the many fishers and scientists who contributed to past research on Spanish mackerel. They provided valuable information on the history of the fishery, and samples and measurements of fish as part of studies conducted by the Queensland Government, James Cook University, the University of Queensland and the Australian Government – through the Fisheries Research and Development Corporation (FRDC). Finally, we would like to thank the project team for reviewing and providing comments on parts of the draft report. The research was financed by the Queensland Department of Agriculture and Fisheries.

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1 Introduction

Spanish mackerel (*Scomberomorus commerson*) (Lacepede 1800) are tropical–subtropical pelagic fish found throughout vast areas of tropical and subtropical waters of the Indo-West Pacific (Collette and Russo 1984). Their distribution around Australia is between Sydney on the east coast, north to Perth on the west coast (Munro 1943; Collette and Russo 1984). They form large schools and are generally found around offshore reefs, shoals and bays (Munro, 1943; Buckworth et al., 2007; Tobin & Mapleston 2004; Tobin et al., 2014).

Genetic analysis suggests that Spanish mackerel form three stocks across northern Australia (Moore et al. 2003). One stock is located on the east coast from Cape York in northern Queensland to Sydney in New South Wales (NSW), the second stock is in the Torres Strait, while the third and largest stock ranges from the Gulf of Carpentaria (GoC) in the east to Perth in Western Australia (Buckworth et al. 2007). Evidence from otolith microchemistry and parasite analyses in the large north-west genetic stock suggests limited adult movement and this most likely results in smaller biological stocks with limited mixing (Moore et al. 2003; Lester et al. 2005; Buckworth et al. 2007).

Spanish mackerel are fast growing in early years and reach a maximum size of 240 cm fork length and live to 26 years of age (McPherson 1992, 1993; Fisheries Queensland 2013). There is some difference between the maximum age observed between the three genetic stocks, with older fish observed on the east coast stock, and younger maximum ages observed in the Torres Strait and northern stock. Maturity of 50% of the population is, on average, reached by two years of age and approximately 80 cm fork length (McPherson 1992, 1993; Fisheries Queensland 2013). Spawning generally occurs across their entire range between September and January, producing pelagic eggs and sperm that mix and are dispersed through water currents (Cameron and Begg 2002). Females grow faster and reach larger lengths than males, with females generally dominating larger size classes (Mackie et al. 2003).

Spanish mackerel are a predatory fish, feeding mainly on bait fish species (GBRMPA 2012). They are a popular light game fish species and targeted by recreational fishers throughout their distribution. In addition they are a highly valuable commercial species, where quality line-caught fish are of high demand on local and international markets. The recreational fishing pressure is most likely centered around locations with high population densities.

Fishing for Spanish mackerel in the GoC began in the 1960s. In Queensland, the majority of harvest is taken by line in the Gulf of Carpentaria Line Fishery (GOCLF), with a smaller harvest by nets in the Gulf Of Carpentaria Inshore Fin Fish Fishery (GOCIFFF). Recreational harvest estimates are low and highly variable due to the limited accessibility of the area, small local populations and other species, like barramundi and king threadfin, which are more highly sought after.

There have been various management changes within the Spanish mackerel fishery since 1975 when a minimum legal size of 45 cm was introduced (Table 1). The most meaningful changes were introduced in the 1990s, which included the introduction of a recreational in possession limit of ten fish, and a minimum legal size of 75 cm. For commercial fishers, only the minimum legal size and license limitations apply.

Table 1: History of Spanish mackerel management in the Gulf of Carpentaria for Queensland

Year	Management Change
1957	*Fisheries Act 1957* implemented a minimum legal size (MLS) of 18 inches (45.72 cm) for Spanish mackerel. This provision commenced on 1 January 1958.
1976	*Fisheries Act 1976* implemented a MLS of 45 cm for Spanish mackerel.
1988	Commercial logbook database began.
1990	Recreational fishers prohibited from selling catch.
1993	*Fishing Industry Organisation and Marketing Regulation 1991* implemented a minimum legal size of 75 cm for Spanish mackerel and recreational in-possession limit of 10 fish.
1994	*Fishing Industry Organisation and Marketing Regulation 1991* amended to allow twice the in-possession limit for Spanish mackerel, as part of the reef fish provisions, if taken during an extended fishing charter (extended fishing charters occur over a continuous duration of 48 hours or more).
2003	Investment Warning for Spanish mackerel issued.
2003	*Fisheries Regulation 1995* amended to set a recreational in-possession limit of three fish.

The schooling behavior of Spanish mackerel and the predictable location and timing of aggregations make them susceptible to overfishing and introduce problems with hyper-stability for assessment and management (Walters 2003; Campbell et al. 2012). Hyper-stability occurs when fishers target fish aggregations and catch rates can remain stable even though the population size is decreasing (Hilborn and Walters 1992). This hyper-stability needs to be considered and accounted for when assessing the size and status of Spanish mackerel in the GoC to ensure population estimates are representative of the true size of the stock and not aggregation size.

In 2019, the Queensland Department of Agriculture and Fisheries commissioned the first stock assessment for Spanish mackerel in the GoC. This assessment evaluates recent and historical levels of fish harvest and mortality rates. Due to uncertainty in the fine-scale stock structure throughout the GoC, the assessment covered the Queensland portion of the GoC only. This report informs on estimates of sustainable harvests that will maintain the Queensland fishery and support implementation of Queensland’s Sustainable Fisheries Strategy 2017–2027.

2 Methods

2.1 Data sources

A variety of data sources are included in this assessment and are detailed in Table 2, Figure 4 and in following sections.

Table 2: Data inputs compiled for input into the population model

Data	Years	Source
Commercial	1988–2018	Logbook data collected by Fisheries Queensland
Recreational	2011, 2014	Statewide Recreational Fishing Survey collected by Fisheries Queensland
Charter	1995–2018	Logbook data of charter operator harvest collected by Fisheries Queensland
Age and length	2007–2018	Biological monitoring undertaken by Fisheries Queensland

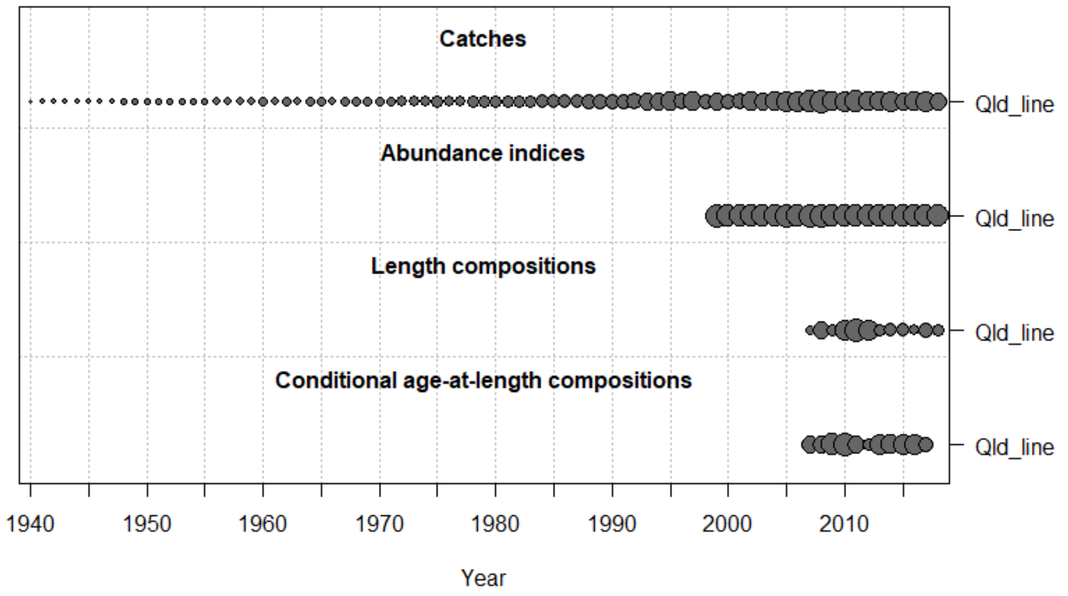

Figure 4: Data presence by year for each fleet, where circle area is relative within a data type.
Note: Circles are proportional to total catch for catches; to precision for indices, discards, and mean body weight observations; and to total sample size for compositions and mean weight- or length-at-age observations. Note that since the circles are scaled relative to maximums within each data type, the scaling within separate plots should not be compared.

2.1.1 Regions

The data sources used for the assessment and detailed below have, in some instances, been grouped into assessment regions for analysis (Figure 5).

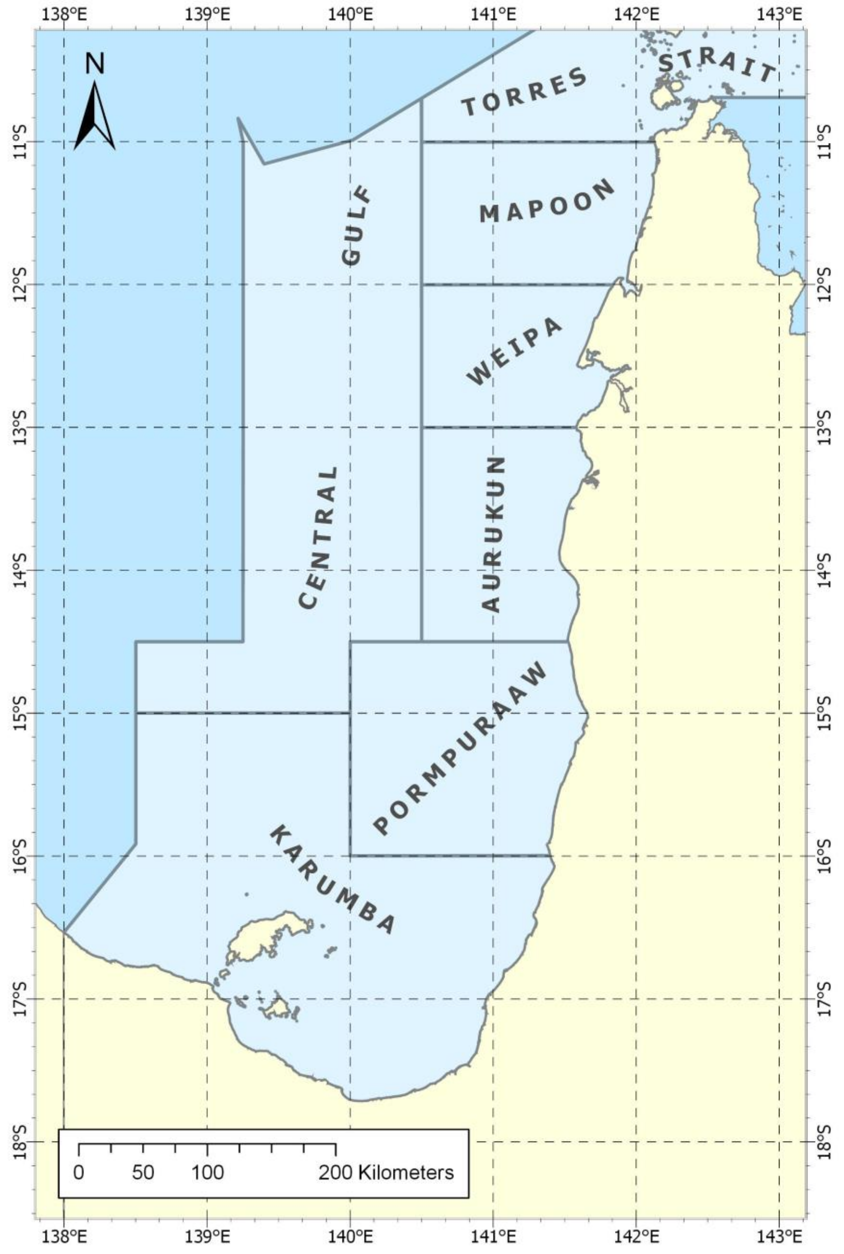

Figure 5: Regions within the Queensland Gulf of Carpentaria used to summarise model inputs

2.2 Harvest

2.2.1 Commercial harvest data

Catch and effort data were analysed from the anticipated start of fishing in 1940 until the end of 2018. Commercial harvests of Spanish mackerel were recorded in the Queensland logbook systems. The Queensland logbook system consists of daily harvests of all fish species from each individual fishing operation (license) since 1988.

2.2.2 Recreational harvest data

Recreational catches of Spanish mackerel (both retained and released) were estimated from eight Queensland statewide surveys, however only two surveys recorded harvest of Spanish mackerel in the GoC. The Queensland recreational statewide diary surveys have included:

- Surveys conducted by Fisheries Queensland, known as RFISH, in 1997, 1999, 2002 and 2005 (Higgs 1999, 2001; Higgs et al. 2007; McInnes 2008).
- An Australian national survey (the National Recreational and Indigenous Fishing Survey, NRIFS) was conducted in 2000 (May 2000 – April 2001), using different methodology to the RFISH surveys (Henry and Lyle 2003).
- The NRIFS methodology was adopted by Fisheries Queensland for statewide surveys in 2011 and 2014 and called the Statewide Recreational Fishing Survey (Taylor et al. 2012).

When calculating total recreational harvests, half of the non-retained estimates of Spanish mackerel were tallied into the retained estimate to account for suspected discard mortality (O'Neill et al. 2018). A portion of the unspecified mackerel catches were allocated to Spanish mackerel by applying the proportion of Spanish mackerel catch from the total of specified mackerel species and including this proportion of unspecified retained and non-retained totals from each survey.

Recreational harvest estimates of Spanish mackerel in the GoC were only present in the two most recent surveys, in 2011 and 2014. These data estimates were low and had high associated error due to limited records. Discussions within the project team confirmed that recreational harvest of Spanish mackerel in the GoC was low and highly variable, and therefore, model inputs were calculated from a mean and standard error from the two survey estimates, and these were used to generate harvest estimates based on a normal distribution.

2.2.3 Charter harvest data

Records of charter harvest began in 1995 and during this time harvest has remained low (below 5 t). These recorded estimates are included in the total harvest and input into the model in records between 1985 and 2018.

2.3 Standardised catch rates

Logbook data on commercial line catches (kg whole weight) of Spanish mackerel per fishing-operation-day were used as an index of legal-sized fish abundance measured by year for Spanish mackerel caught in the Queensland GoC. The methods below outline the concepts and procedures used to standardise mean (average) catch rates. Hereon, the term 'catch rate' refers to standardised catch rate unless otherwise specified.

The catch rate model included every daily Spanish mackerel harvest by each individual fisher. When multiple locations were recorded for a single fisher in a day the first location was retained and all harvest allocated to this location.

Various metrics of catchability were used to standardise catch rates, including the spatial-temporal patterns of exploitation associated with the aggregation patterns of this species (Walters 2003; Carruthers et al. 2011; Marriott et al. 2017). Standardisation components for fish catchability q included:

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

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

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

Standardised mean catch rates were modelled using the software R (version 3.5.2, (R Core Team 2017)). The analyses used a generalized linear mixed model (GLMM). GLMMs were calculated using the 'lmer' function, in the lme4 package (Bates et al. 2015). The prediction of standardised mean catch rates were determined using the effects package (Fox 2003).

To ensure comparability of means between regions, predictions were normalised annually as proportions measured against the mean catch rate. For all predictions 95% confidence intervals were calculated.

The model used a Gaussian distribution with the response variable, harvest per fisher day, log-transformed. The variables modeled included additive effects of year, region, number of boats used in the operation, 12-month seasonal variables (c12 and cs12), 6-month seasonal variables (c6 and cs6), 4-month seasonal variables (c4 and cs4), 3-month seasonal variables (c3 and cs3) and wind variables (wind EW, wind EW2, wind NS and wind NS2). Fisher was included in the model as a random effect. The catch rate was converted to a proportional value by dividing by the average catch rate over the entire time period (1992 to 2018). The log-normal catch rate model was specified as:

- log(harvest) ~ year + region + number of boats + c12 + cs12 + c6 + cs6 + c4 + cs4 + c3 + cs3 + wind EW + wind EW2 + wind NS + wind NS2 + random(fisher)

Three standardised catch rates were calculated with varying levels of fishing power (no, half and full adjustment). Fishing power estimates were taken from O'Neill et al. (2018). As a base case the full fishing power adjustments were taken as a base case for the model and the impact of differing levels of fishing power adjustment on model fit were investigated.

2.4 Biological parameters

2.4.1 Data sources

Commercial catch length and age sampling occurred between March 2007 and November 2017. Recreational catch length sampling occurred between July 2007 and December 2017 although there was no sampling conducted in 2016. Each year, the commercial and recreational line catches were representatively sampled and fish were measured to the nearest 10 mm fork length (Fisheries Queensland 2013).

Where whole fish frames could not be accessed, the upper jaw length of Spanish mackerel heads were measured and converted to fork length using a sex-specific model, where Y is fork length (mm) and X is jaw length (mm). An exponential model with separate parameters, explained 93.2% of the variation. Individual equations are:

Male: $Y = 1533.47 - 2361.45(0.98713851^X)$

Female: $Y = 1575.66 - 2538.55(0.98713851^X)$

Where possible the sex of each fish was recorded. Fish of unknown sex were excluded from the analysis.

The fork lengths (L, cm) were converted to fish weight (W, kg) (Equation 1).

$$W = 3.4e^{-9} \times L^{3.12} \tag{1}$$

Otoliths were sampled from the recreational fishery, and the commercial line and net fisheries. A subsample of up to 20 otoliths in each size class were collected annually. Fish were selected randomly by sex, and therefore the sex ratio was representative of the catch within each length class. The macrostructure of whole otoliths were interpreted to estimate fish age and to calculate age group (Fisheries Queensland 2013). Conditional age-at-length data were input into the model along with length structures.

2.4.2 Growth

Fish growth estimation was calculated using a von Bertalanffy growth curve, based on each age group and corresponding fish lengths and weights, detailed in Equation 2 (von Bertalanffy 1938). In this relationship, L_∞ was the average maximum fish length (cm), k was the growth rate parameter determining how quickly the maximum size was reached and a_0 was the theoretical age at which the fish had zero length or weight. Parameters were fit using nonlinear least square regression (nls in R). A separate curve was calculated for males and females.

$$L_a = L_0 e^{-\kappa a} + L_\infty(1 - e^{-\kappa a}) \tag{2}$$

The parameters estimated by these analyses for males and females were input to the model as initial values for estimation of parameters within the model.

2.4.3 Fecundity and maturity

Model inputs of fecundity and maturity of Spanish mackerel were taken from relationships determined by Mackie et al. (2003). Due to data limitations, fecundity was assumed to be relative to fish weight.

Maturity parameters input into the model were length logistic and the first mature age was two years of age. The 50% female maturity parameter was fixed at 80.94 cm fork length and the slope was -0.25 as determined by Mackie et al. (2003).

The proportion of the population that were females was also inferred from Mackie et al. (2003), who found 50% of the population to be female. This was similar to estimates calculated from commercial monitoring of the Queensland GoC population, which suggested 52% of the population was female.

2.4.4 Weight and length

The weight-length relationship for females is defined in Equation 3, while males are defined in Equation 4, where W is fish weight (kg) and L is length (cm). These parameters were taken from the relationships determined by Begg et al. (2006).

$$W_f = 3.148 \times L^{2.96043e-6} \tag{3}$$

$$W_m = 3.068 \times L^{4.22444e-6} \tag{4}$$

2.5 Population model

A two-sex population dynamic model was fitted to the data to determine the number of Spanish mackerel in each year and each age group using the software package Stock Synthesis (version SS-V3.24Z, Methot 2015). Stock Synthesis is a statistical age-structured model that allows for multiple fishing fleets and data inputs, and is commonly used to assess fish populations throughout the world. A full technical description of Stock Synthesis is detailed in Methot (2015). Some key features of the model are detailed below.

2.5.1 Model assumptions

A variety of assumptions were made when formulating the model, these included:

- The fishery began from an unfished state in 1940.
- There are no sex specific differences in Spanish mackerel selectivity.
- Growth occurs according to the von Bertalanffy growth curve.
- The weight and fecundity of Spanish mackerel are parametric functions of their size.
- The proportion of mature fish depends on age and not size.
- The instantaneous natural mortality rate does not depend on age, size or sex.
- The proportion of fish vulnerable to fishing depends on their size, not time.
- Fixed population length weight, fecundity and proportion female parameters for this biological population in the GoC are the same as the parameters determined from fish in Western Australia.

2.5.2 Model parameters

A variety of parameters were included in the model, with some of these fixed at specified values and others estimated.

The natural log of virgin spawning stock size ($ln(R_0)$) was estimated within the model.

Natural mortality (M) was fixed at 0.34, for male and female fish. This is considered representative of the biology, with a maximum age of 16 and consideration of the equations of Hoenig (2005) and Then et al. (2015), which suggest 0.28 and 0.39 respectively. The base case of 0.34 was taken as the average between these two estimates. Sensitivity of the model to this fixed parameter was investigated.

Stock recruitment steepness (h) was fixed at 0.60 as a base case. This estimate is within the range estimated for the stock on the east coast of Australia, which ranged between 0.3 and 0.8, and for the Torres Straight stock, which was fixed at 0.52. Sensitivity to this fixed parameter was also investigated.

Parameters of the von Bertalanffy growth curve were estimated and fixed and separate curves were used for males and females. For females, all parameters were estimated within the model, including coefficients of variation for young and old fish. For males L_0 and L_∞ were fixed as the difference from the female estimate based on pre-calculated curves, while the other parameters were estimated.

Logistic length based selectivity parameters were estimated, including the length at which fish were 50% selected, and the difference between 50 and 95% selectivity.

Inclusions of recruitment deviations (dt) between 1995 and 2017 improved fits to age structures as variability in recruitment annually allowed for changes in the observed age structures from year to year.

2.5.3 Model weightings

All data inputs were given equal weighting in the model, however, Francis weighting of age and length data within Stock Synthesis was completed (Francis 2011).

2.5.4 Sensitivity tests

Several additional model runs were undertaken to determine sensitivity to fixed parameters and model inputs. Sensitivity to fishing power adjustment of the standardised catch rate times series were investigated, along with the values that stock recruitment steepness (h), natural mortality (M) and recruitment deviation error (σ_r) were fixed at. In addition, the length of the recruitment deviation time series was investigated. Specific tests included:

- h = 0.5
- h = 0.7
- M = 0.3 year^{-1}
- M = 0.4 year^{-1}
- σ_r = 0.3
- σ_r = 0.5
- Recruitment deviations finish in 2015
- Recruitment deviations finish in 2016
- Half fishing power adjustments on standardised catch rates
- Full fishing power adjustments on standardised catch rates

3 Results

3.1 Model inputs

3.1.1 Commercial harvest

At the start of compulsory commercial logbook recording there was a steady increase in harvest from 33 t in 1989 to 61 t in 1991, before a rapid increase in 1992 to 150 t (Figure 6a). During this time the harvest was predominantly line caught, (96%) (Figure 6a). For the 10 years between 1992 and 2002 harvest fluctuated around an average of 175 t (Figure 6a). This period was followed by an increase in harvest to a peak of 297 t in 2008 (Figure 6a). Since 2008 there has been a gradual decline in total harvest, dropping to 176 t in 2018 (Figure 6a). Over the entire logbook time series there has been a gradual increase in harvest by nets from 4% in 1989 to 21% in 2018 (Figure 6a). The recent proportion of net and line catch has been relatively stable between 2010 and 2018 at approximately 20% (Figure 6a).

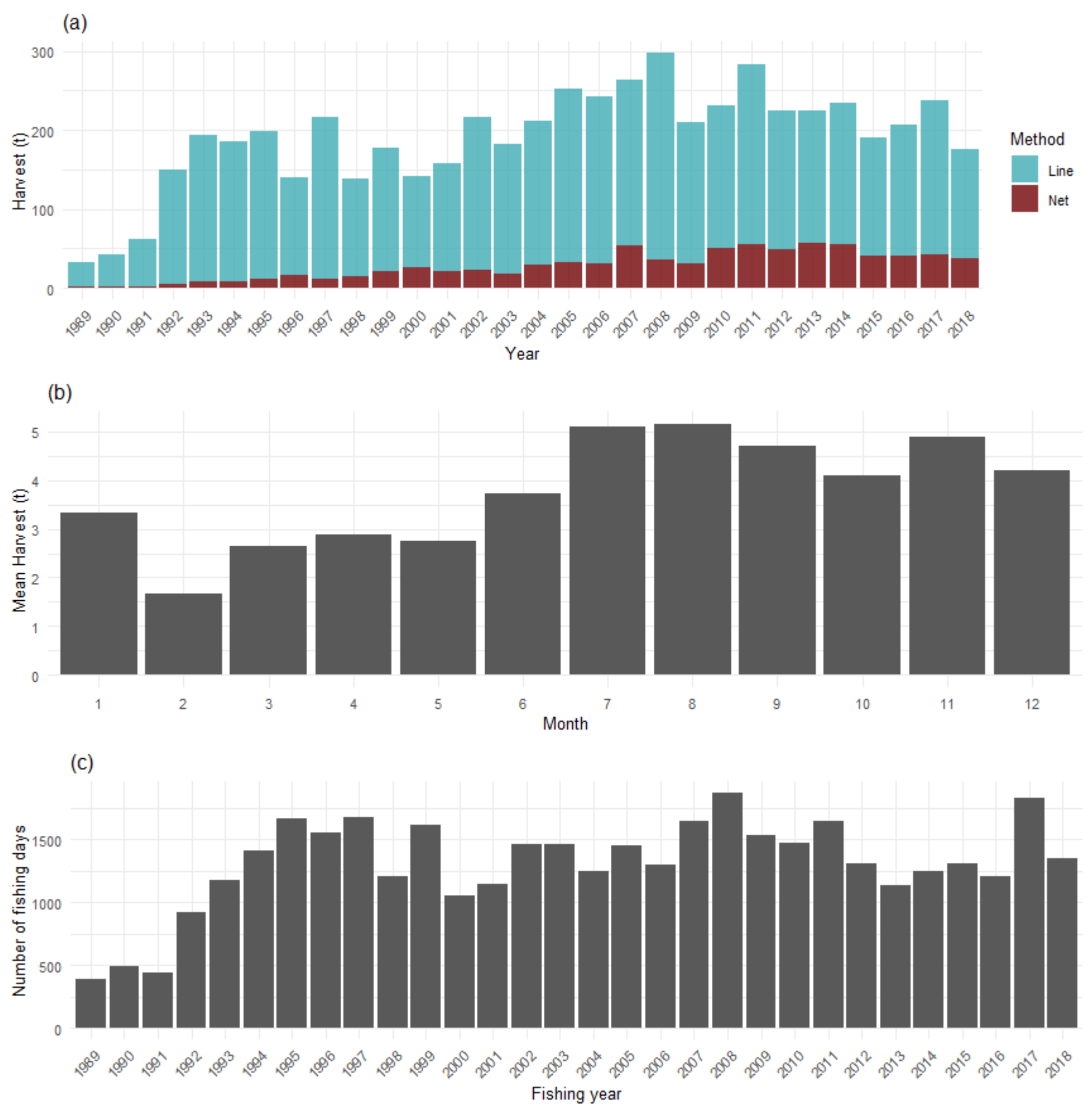

Figure 6: Trends in reported annual commercial harvest (t) of Spanish mackerel between the years of 1988 to 2018. Plots include trends in (a) commercial harvest by gear type, (b) average monthly commercial harvest, and (c) total number of commercial fishing days

The harvest of Spanish mackerel is seasonal, with the majority caught between July and December (Figure 6b). On average the lowest harvests were observed in February (Figure 6b).

Effort in the Spanish mackerel fishery (annual number of days fished) varied throughout the time series (Figure 6c). In the first three years (1989 to 1991), effort was low, below 500 annual fishing days (Figure 6c). Between 1992 and 1995 effort steadily increased to 1664 days in 1995 (Figure 6c). After 1995, effort follows trends of decreasing and then increasing effort, with two low periods apparent in 2000 and 2013 (Figure 6c).

Regional patterns of commercial fishing in each of the six regions showed differing trends (Figure 7). In the Aurukun Region, harvest ranged around 30 t between 1989 and 2011, before increasing to a range of around 80 t between 1990 and 2018 (Figure 7). Harvest in the Central Gulf has been limited and sporadic, not exceeding 14 t over the entire period, with only 10 years containing harvest in this region (Figure 7). Harvest in the Karumba Region was consistently between 25 and 35 t between 1991 and 2004, before a substantial increase to between 85 and 105 t in 2005-2008 (Figure 7). Since 2008 there has been a substantial decline to less than 25 t in 2018 (Figure 7). Harvest in the Mapoon Region has fluctuated between 5 and 50 t throughout the entire time series, however, between 2012 and 2018 there has been a sustained period with harvests less than 17 t (Figure 7). In the Pormuraaw Region, there was a variable increase in harvest between 1989 and 2010 (Figure 7). Between 2011 and 2018, the harvest continued at a reduced level, of around 25 t (Figure 7). Annual commercial harvest in the Weipa Region has been highly variable throughout the time series compared to the other regions, with harvest ranging from 98 t in 1993 to 22 t in 2010 (Figure 7).

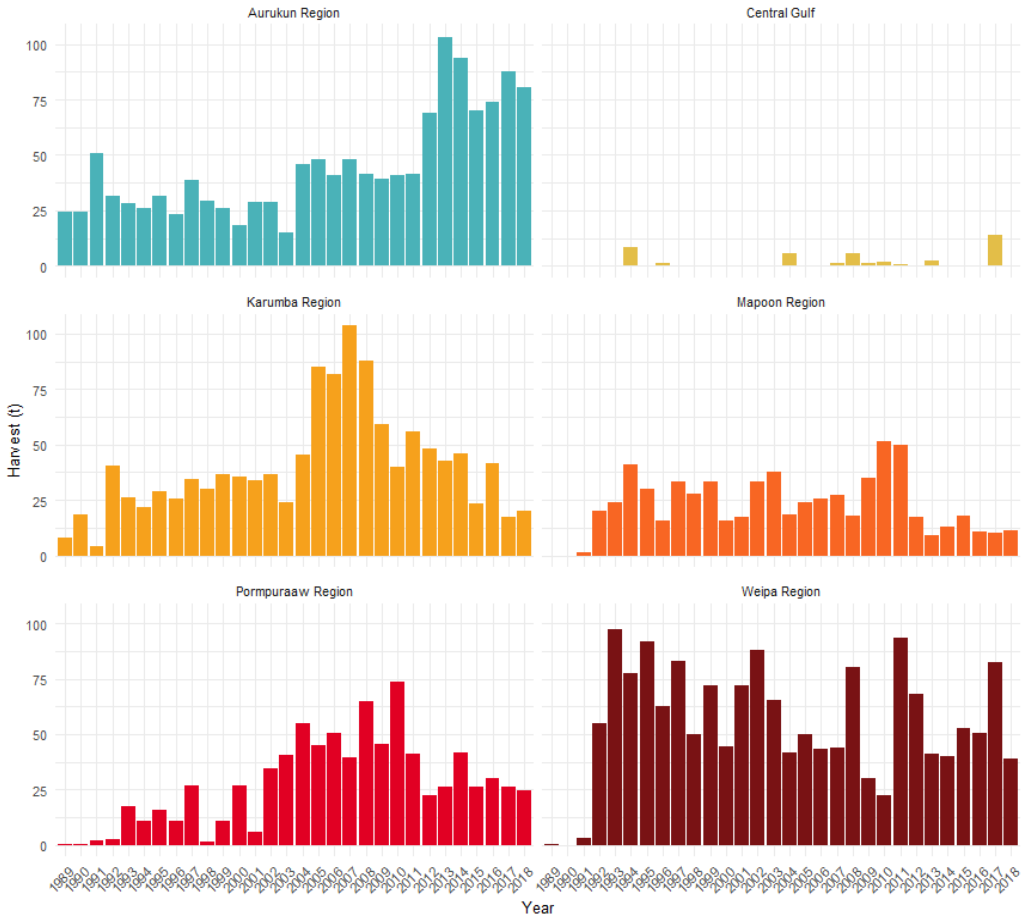

Figure 7: Annual commercial harvest (t) of Spanish mackerel of each of the six regions used to standardise catch rates and summarise age and length data between 1989 to 2018

3.1.2 Estimated harvest

Total harvest was input into the population dynamics model, with this total harvest combining commercial, recreational and charter catch (Figure 8). The total harvest time series shows a steady increase in harvest from the assumed virgin state in 1940 to around 1995 (Figure 8). This peak was followed by a small decline in the late 1990s and early 2000s, before increasing to the highest historical harvest in 2008 of 320 t (Figure 8). Since 2008, the total harvest has been variable but generally shows a declining trend, with the lowest harvest since 2008 caught in 2018 of 181 t (Figure 8).

Of the reconstructed harvest, the vast majority has been caught by commercial fishers, with small and variable harvests attributed to recreational fishers (Figure 8). Charter harvest was lower again, with a maximum harvest of 5 t in 2006 (Figure 8).

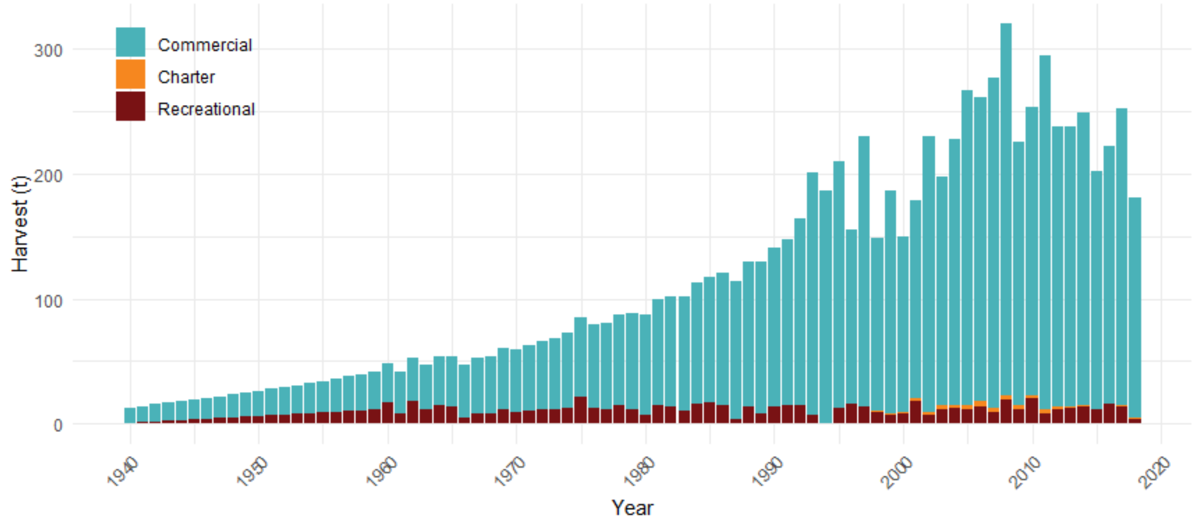

Figure 8: Reconstructed harvest from commercial, recreational and charter sectors between 1940 and 2018

3.1.3 Standardised catch rates

The standardised catch rate is relatively stable for the five years between 1992 and 1996, averaging 67 kg per day (Figure 9a). This was followed by an increase in catch rates, peaking in 2001, at 120 kg per day (Figure 9a). Catch rates were then variable until 2008, ranging between 97 and 129 kg per day (Figure 9a). Two years of below average catch rates were then observed in 2009 and 2010, before increasing to the highest historical catch rate observed of 130 kg per day (Figure 9a). Since this peak there has been a consistent decline in catch rates to the lowest observation in the time series in the most recent year of 57 kg per day (Figure 9a).

Fishing power adjustments were also included in the standardisation process and increased contrast in the time series (Figure 9b). At the start of the time series, fishing power adjustments increased the relative value of the catch rate, while at the end of the time series, this was reversed and adjustments resulted in a reduced relative catch rate compared to that with no adjustment (Figure 9b). The half adjustment of fishing power resulted in intermediary effects between models with no and full adjustment (Figure 9b).

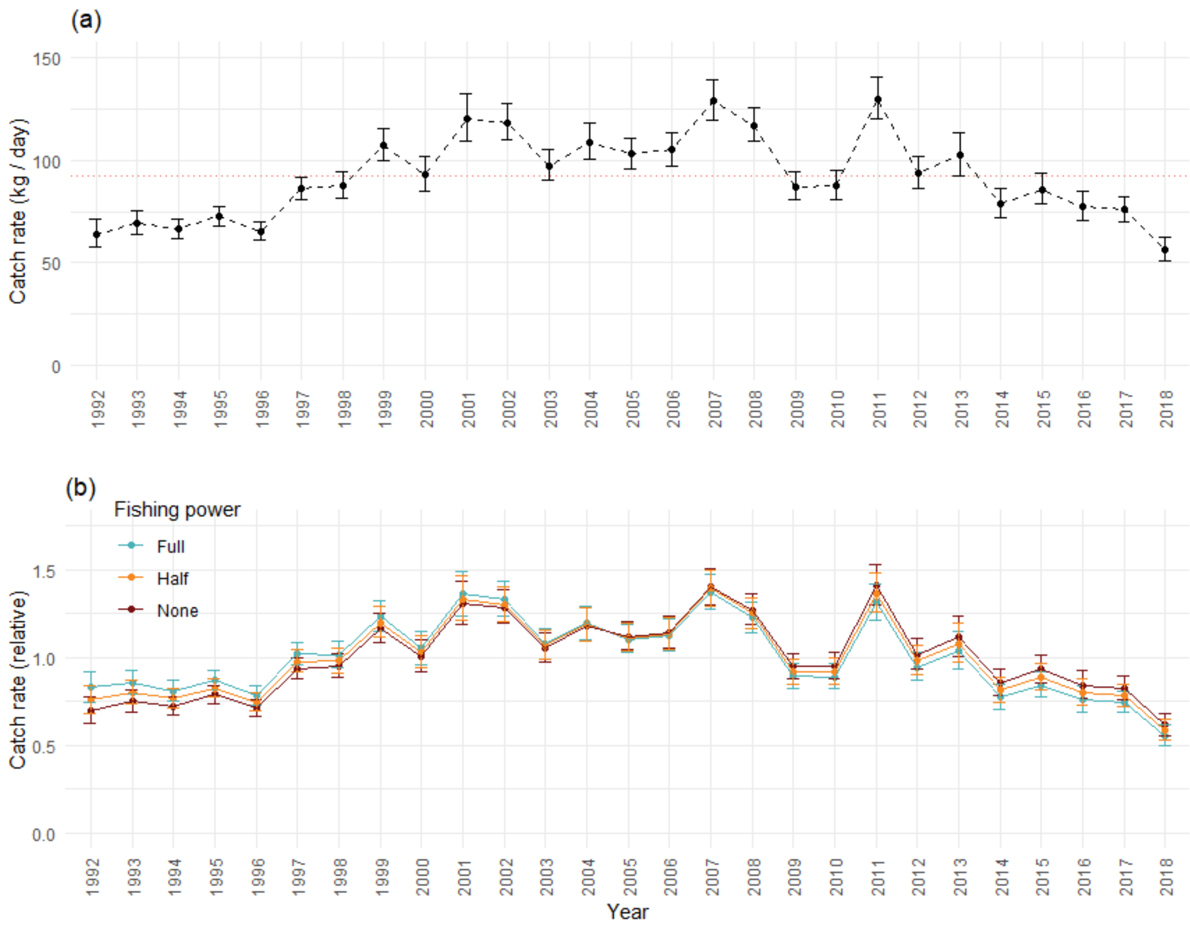

Figure 9: Standardised catch rates for line caught Spanish mackerel between the fishing years of 1988 and 2018, with error bars representing 95% confidence intervals. (a) represents the standardised catch rate without fishing power adjustment in real values, while (b) includes 2 levels of fishing power adjustment and is relative. The dashed red line in (a) represents the average of the time series.

3.1.4 Age-at-length

Routine, fishery-dependent biological monitoring of Spanish mackerel commenced in 2007 and is ongoing, however, only data until 2017 was included in this assessment. This data demonstrates that in the Queensland GoC, Spanish mackerel can live to 15 years of age (Figure 30, Figure ***31*** and Figure ***32***). No zero year old fish were recorded during monitoring.

3.1.5 Length structures

Length data were collected between 2007 and 2017 in conjunction with age structure monitoring. For male and female Spanish mackerel in the Queensland GoC, fork length of fish ranged between 60 and 150 cm (Figure 10). More commonly, fish were observed between 75 and 125 cm, with females observed reaching greater lengths than males (Figure 10). In 2013 and less so 2016 a reduced second peak of small fish was also observed at around 70 cm fork length (Figure 10).

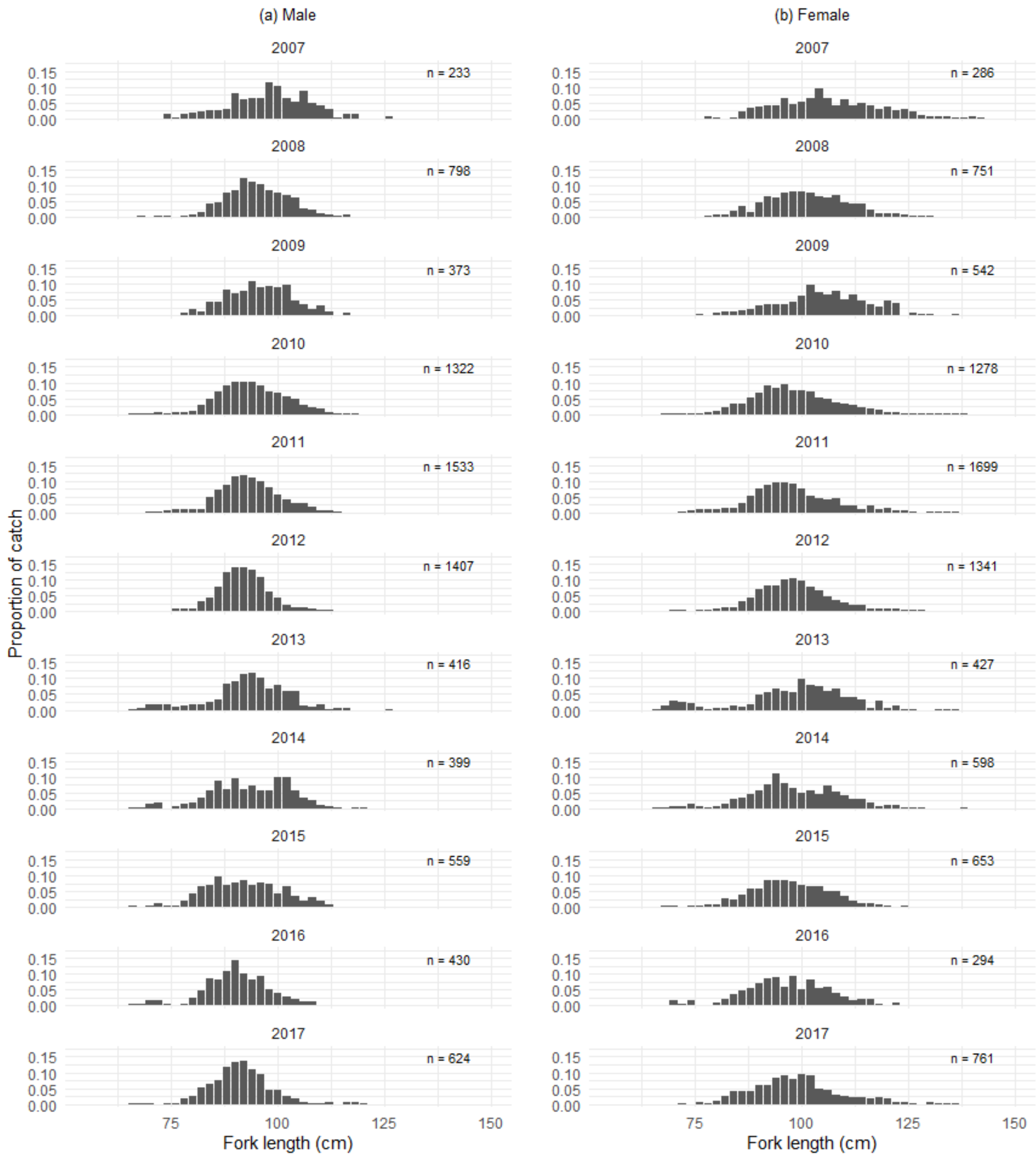

Figure 10: Annual length frequency distributions of male and female Spanish mackerel line caught commercial and recreational fish between 2007 and 2017. The total number of fish sampled in each year (n) is included for each year and sex

3.1.6 Biological parameters

Fixed biological parameters are plotted in Figure 20 to Figure 25 in Appendix A.

3.2 Model outputs

3.2.1 Model parameters

A number of parameters were estimated within the model. These included the natural log of virgin spawning stock size (SR(LN_R0)) and all female growth curve parameters (L_at_Amin_Fem_GP_1, L_at_Amax_Fem_GP_1, VonBert_K_Fem_GP_1, CV_young_Fem_GP_1, CV_old_Fem_GP_1). For males, the kappa parameter and error size were also estimated (VonBert_K_Mal_GP_1, CV_young_Mal_GP_1, CV_old_Mal_GP_1) (Table 3). Length based selectivity parameters (Size_inflection_Qld_line(1) and Size_95%width_Qld_line(1)) were also estimated (Table 3). In addition, an extra parameter estimating extra error associated with the standardised catch rate estimates (Q_extraSD_Qld_line(1)) was also estimated (Table 3).

Table 3: Summary of parameter estimates from the base population model for Spanish mackerel in the Queensland Gulf of Carpentaria

Parameter	Estimate	Phase	Min	Max	Initial value	Standard deviation	Gradient
L_at_Amin_Fem_GP_1	46.01	2	20.00	200.00	39.00	1.69	2.30e-05
L_at_Amax_Fem_GP_1	126.86	2	20.00	200.00	120.00	1.14	-4.20e-06
VonBert_K_Fem_GP_1	0.24	2	0.01	1.00	0.30	0.01	9.80e-06
CV_young_Fem_GP_1	0.14	4	0.00	0.95	0.15	0.01	-4.24e-05
CV_old_Fem_GP_1	-0.82	4	-1.50	0.95	-0.96	0.16	-6.80e-06
VonBert_K_Mal_GP_1	0.40	3	-1.00	1.00	0.28	0.02	-1.30e-06
CV_young_Mal_GP_1	-0.28	4	-0.95	0.95	-0.26	0.11	-1.04e-05
CV_old_Mal_GP_1	-0.61	4	-1.50	0.95	-0.73	0.15	-1.64e-05
SR_LN(R0)	5.70	1	5.00	30.00	12.00	0.04	3.10e-06
Q_extraSD_Qld_line(1)	0.08	4	-0.20	0.50	0.30	0.02	8.80e-06
Size_inflection_Qld_line(1)	87.30	3	30.00	120.00	88.00	0.93	3.00e-06
Size_95%width_Qld_line(1)	10.36	3	0.00	20.00	11.00	1.15	-4.40e-06

3.2.2 Model data input sensitivity

When initially fitting the model with the full time series of standardised catch rates, the model was not able to fit the start of the catch rate time series as it was contradicted by other data inputs, namely the lack of a high harvest prior to 1990. This decoupling of standardised catch rates and the harvest time series suggests that the index over this period was not representative.

As such, it was decided to remove standardised catch rates from 1990–1999 and different time series were tested to determine the most appropriate point to start the time series. Model tests included using the entire time series (1992–2018), removing the first 4 years (1997–2018) and then removing an additional year, one at a time, including the ranges on 1998–2018 and 1999–2018. Log likelihoods suggested that the best time series to use was 1999–2018 and this was included for the remainder of model investigations.

3.2.3 Model fits

Model fit diagnostics are detailed in the Appendix, Figure 26 to Figure 33. Overall, good fits were achieved for standardised catch rates, conditional age at length structures and length structures.

3.2.4 Selectivity

Selectivity of Spanish mackerel in the Queensland GoC was estimated within the model. Estimated parameters suggest that 50% of Spanish mackerel are selected at 87 cm fork length, while 95% are selected at 97 cm (Figure 11 and Table 3). These estimates suggest that in the GoC Spanish mackerel are caught larger than the minimum legal size of 75 cm total length, which corresponds to approximately 67 cm fork length (Figure 11).

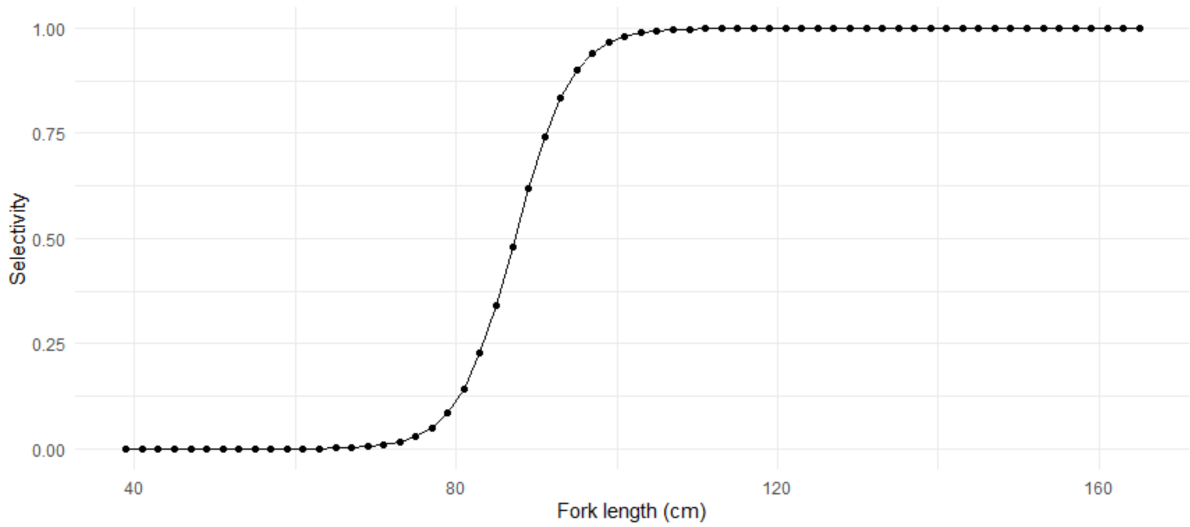

Figure 11: Length based selectivity for males and females estimated within the population model.

3.2.5 Growth curve

The growth curve estimated within the model demonstrates females reaching larger sizes at the same age when compared to males (Figure 12). Separation of the growth curve between genders occurs at approximately 2 years of age (Figure 12).

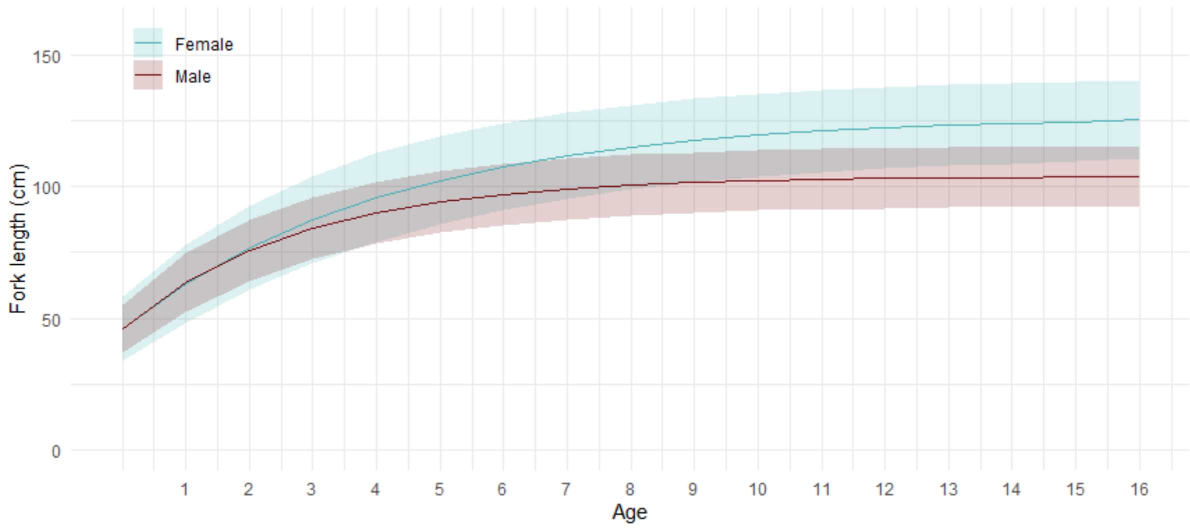

Figure 12: Length at age in the beginning of the year in the final year of the model (2018) for males and females. Shaded area indicates 95% distribution of length at age around estimated growth curve.

3.2.6 Biomass

The predicted size of the Queensland GOC Spanish mackerel stock declined between the virgin state in 1940 to around 60% of unfished biomass in 1997 (Figure 13). From the late 1990s, the decline in biomass was more variable (Figure 13). Since 2011, spawning biomass has declined sharply to 32% of the unfished state in 2018 (Figure 13). The tight confidence intervals were a product of the number of fixed parameters, and model error should be considered wider (Figure 13).

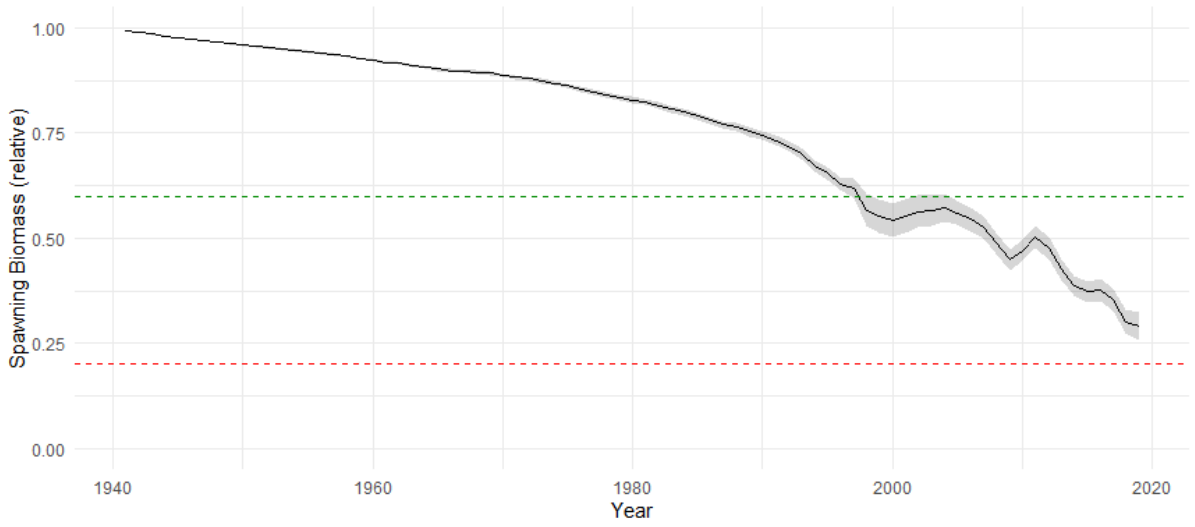

Figure 13: Fraction of unfished with forecast with ~95% asymptotic intervals. Predicted spawning biomass trajectory relative to virgin spawning biomass. Green line represents the biomass target reference point. Red line represents the biomass limit reference point

The equilibrium yield informs on the productivity of the stock at different biomass levels. It is important to note that estimates of maximum sustainable yield (MSY) should be interpreted with caution, as steepness was fixed within the model resulting in an assumed estimation of biomass at MSY, at 29% of unfished biomass (Figure 14).

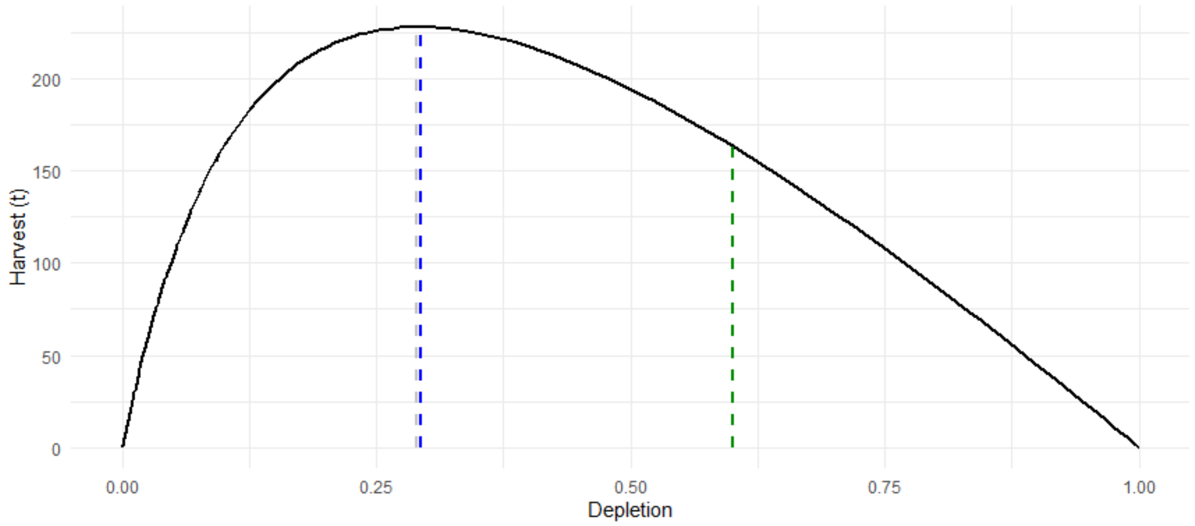

Figure 14: Equilibrium yield per recruit curve. The blue dashed line represents the equilibrium MSY harvest and depletion, while the grey line is the current and the green line is the 60% target harvest and depletion.

3.2.7 Harvest targets

Harvest targets have been calculated to maintain equilibrium biomass at MSY and 60% target reference points for each model, resulting in recommended biological catches (RBCs) of 238 t and 170 t respectively. In addition to equilibrium harvest estimates, harvest estimates which adhere to the *Queensland Sustainable Fisheries Strategy 2017-2027*, using a 20:60:60 hockey stick harvest control rule, are detailed in Table 4.

Table 4: Estimated total harvest to rebuild the Queensland Gulf of Carpentaria Spanish mackerel stock to the target of 60% unfished **spawning** biomass following either a hockey stick harvest control rule or using constant fishing mortality (F) and the corresponding stock depletion.

Year	Hockey stick harvest (t)	Hockey stick depletion	Constant F harvest (t)	Constant F depletion
2019	21.01	0.30	89.12	0.30
2020	40.64	0.37	99.74	0.34
2021	62.35	0.43	110.53	0.39
2022	82.32	0.48	119.81	0.42
2023	99.83	0.51	127.78	0.45
2024	114.69	0.54	134.73	0.48
2025	126.71	0.57	140.74	0.50
2026	136.01	0.58	145.84	0.52
2027	142.95	0.60	150.11	0.53

3.2.8 Likelihood profiles

To determine the sensitivity of the model to fixed parameters, a number of likelihood profiles were calculated. They should be used in any assessment and can be used to determine whether parameters have been fixed at appropriate values. If the parameters is within the 95% confidence interval (within 1.92 units of likelihood), this confirms that the parameter should be fixed. If the parameter is outside the 95% confidence interval, it could be estimated. As integrated stock assessments use numerous data sources, these may be in conflict with each other and likelihood profiles provide a tool to determine these conflicts (Punt 2018).

For Spanish mackerel, the likelihood profile over natural mortality (M), which is fixed in the model, demonstrates changes in the negative log likelihood with different values in this parameter (Figure 15). The darkest line represents the total likelihood, while the other colours represent the influence of various model inputs (Figure 15). The results suggest that the age data are in conflict with the length and index data, while there is little information in the recruitment data (Figure 15). The total negative log likelihood is below the significance value for all but one estimate, therefore confirming that there is insufficient information in the data to estimate this parameter (Figure 15).

The likelihood profile over the stock-recruitment steepness parameter (h) shows that there are inconsistencies in the data inputs (Figure 16). The index (standardised catch rate) shows a strong trend suggesting that lower values of steepness are more appropriate, which contradicts the recruitment and length data (Figure 16). There is little information in the age data to determine this parameter (Figure 16). As many of points investigated here are below the significance value it suggests that there is insufficient information in the data to estimate the parameter, and that the model best fits the available data when steepness is between 0.55 and 0.60 (Figure 16).

The likelihood profile for virgin spawning biomass (SSB_0) is illustrated in (Figure 17). SSB_0 is a derived parameter that is closely linked to the estimated parameter R_0, the average equilibrium recruitment, however, is easier to interpret and understand estimates of virgin spawning stock biomass. The profile over SSB_0 illustrates that the virgin spawning stock biomass was between 1150 and 1350 t, suggesting a small population within the Queensland GoC (Figure 17). The data informing the estimate are in contrast, with recruitment and age data suggesting that a lower SSB_0 is best, while the index data suggests a higher SSB_0, and the length data offers little information (Figure 17).

In addition to the virgin spawning stock biomass likelihood, a likelihood profile over the current spawning stock biomass size, (SSB_{2018}) was conducted (Figure 18). SSB_{2018} shows decline a from the virgin state to between 350 and 550 t (Figure 18). The index data was highly informative of this profile and suggested that a SSB_{2018} of between 300 and 500 t was most appropriate (Figure 18). Age and recruitment data suggested that a higher SSB_{2018} was more appropriate and length data again contained little information to inform these estimates (Figure 18).

A likelihood profile over the level of depletion in 2018 was also calculated to show the potential range of estimates (Figure 19). The profile demonstrates that the current level of depletion is between 30 and 40% of the unfished level (Figure 19). Again, the data informing this parameter are in contrast, with the index data suggesting that the current depletion is between 26 and 38%, while the age, recruitment and length data suggest that values greater than 40% are more appropriate (Figure 19). Overall, this suggests that there is a range of current depletion levels that are possible with the current available data inputs.

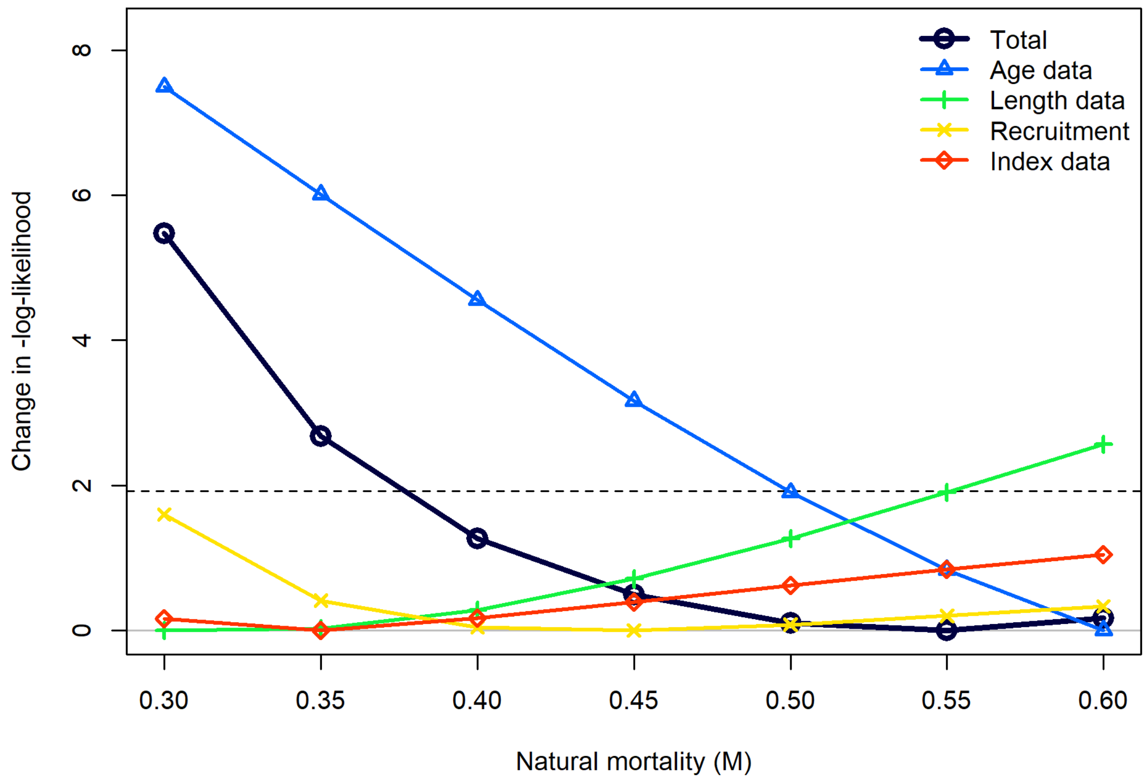

Figure 15: Likelihood profile for natural mortality (M), with fixed values ranging from 0.15 to 0.40. The fixed value in the model is 0.35

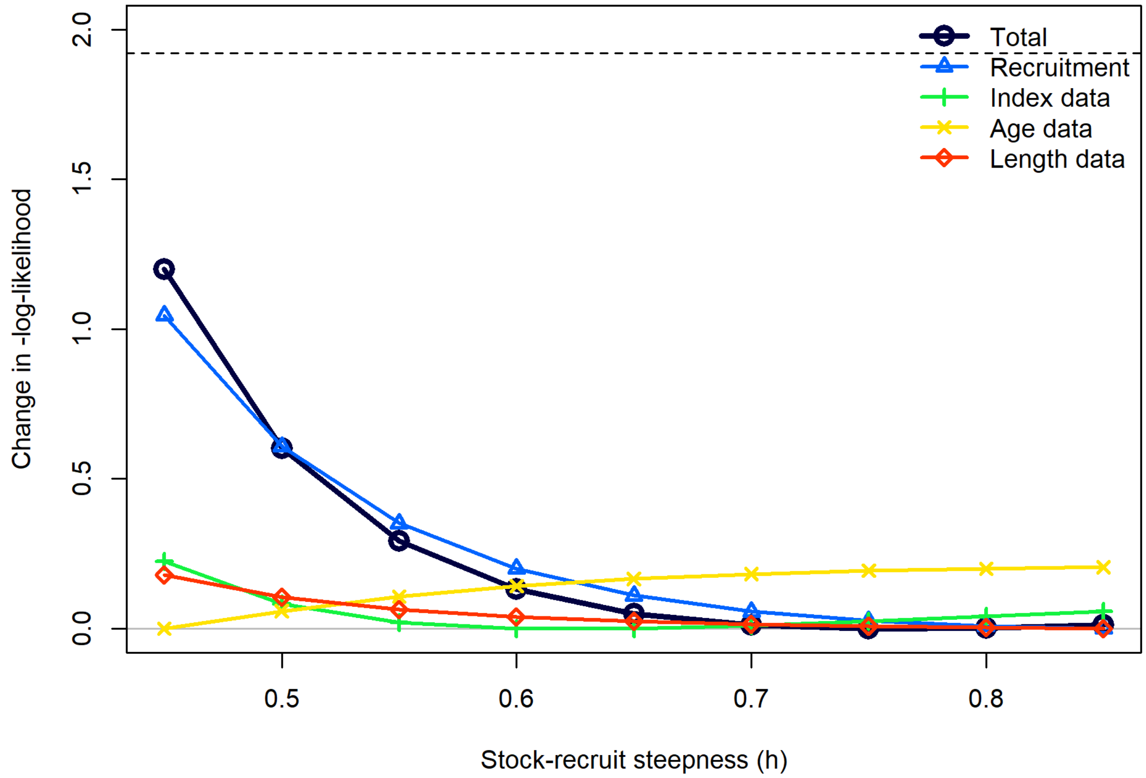

Figure 16: Likelihood profile for steepness (h), with fixed values ranging from 0.5 to 0.8. The fixed value in the model is 0.6

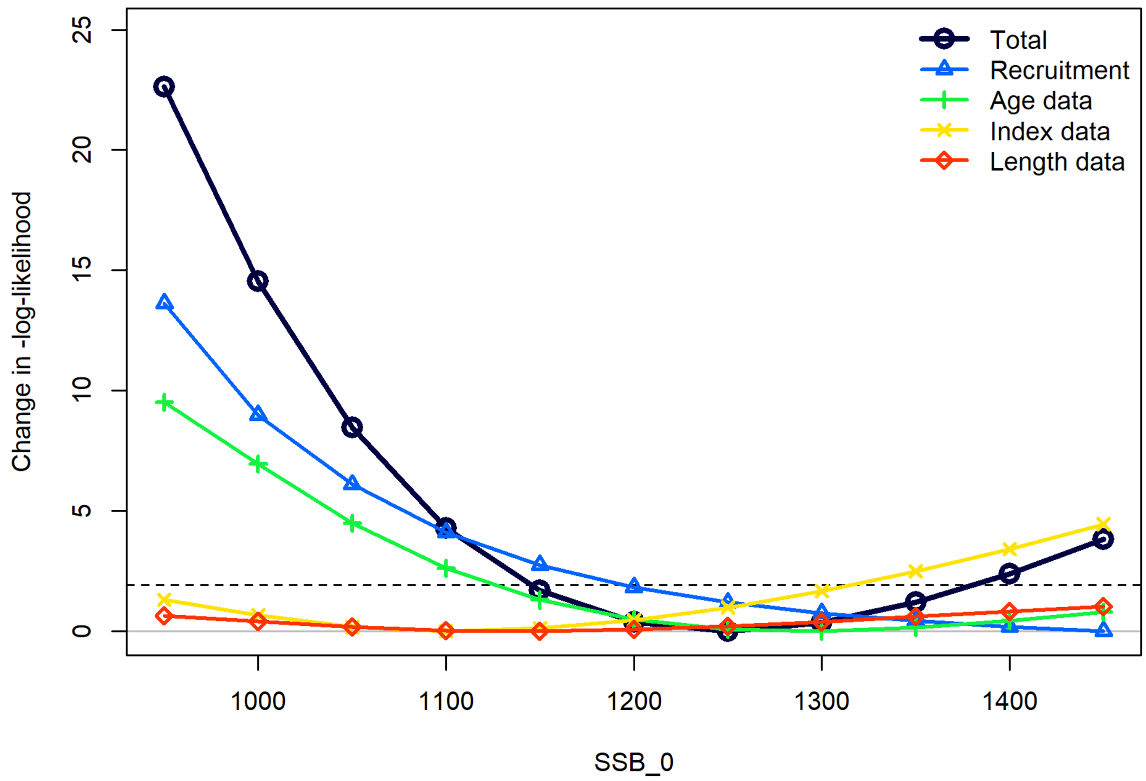

Figure 17: Likelihood profile for virgin spawning stock biomass (SSB_0), ranging from 1050 to 1300 t. The model estimated the biomass to be 1191 t

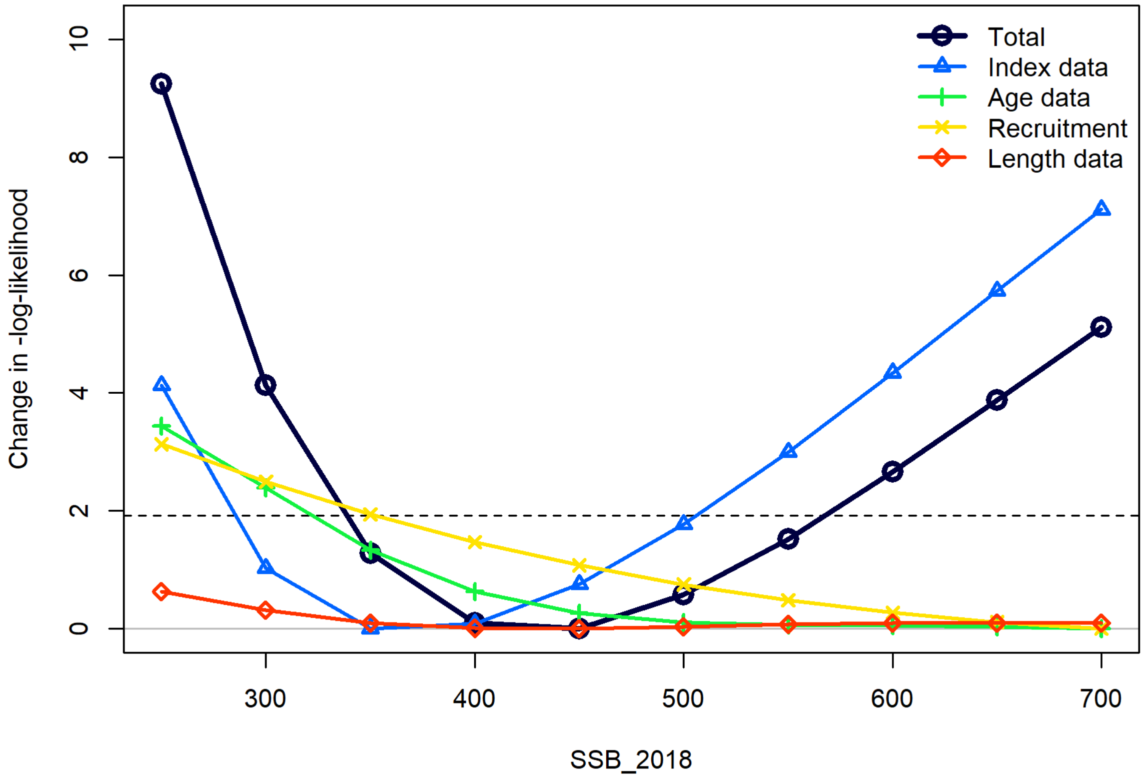

Figure 18: Likelihood profile for spawning biomass in 2018 (SSB_2018), ranging from 300 to 450 t. The model estimated the biomass to be 388 t

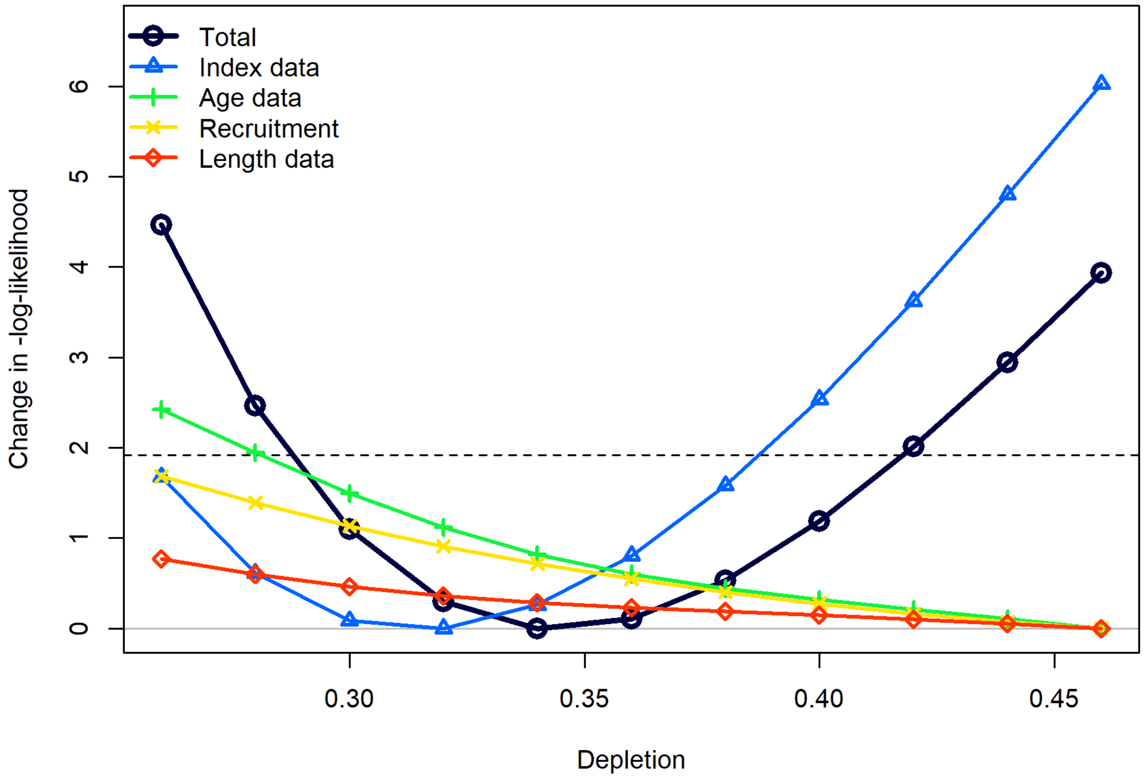

Figure 19: Likelihood profile for relative spawning stock biomass (depletion), ranging from 0.26 to 0.40. The estimated depletion in the model is 0.33, or 33% of unfished spawning biomass

3.2.9 Model sensitivity

A number of additional model runs were undertaken to determine the sensitivity of the model to fixed parameters and data inputs. The results of these sensitivity tests are presented in Table 5. The base case model included steepness (h) fixed at 0.6, natural mortality (M) fixed at 0.35, the standard deviation of log recruitment(σ_r) fixed at 0.4, recruitment deviations (rec devs) finishing in 2017 and full fishing power adjustments. Reduction and increases in h resulted in reduced model fits, however, these were not statistically significant, with log likelihoods within 1.95 of each other (Table 5). Decreasing the fixed value of M resulted in significantly poorer model fits, while increases did significantly improve model fits, however, these higher values are not considered to reflect the biology of the species (Table 5). This result also supports the results illustrated in the likelihood profile, where the model wants to move towards higher estimates of M (Figure 15). Sensitivity tests of σ_r also suggest that the model would prefer lower values of σ_r, however this is not appropriate (Table 5). Again, shortening of the time series of recruitment deviations by one and two years did not improve the model fit (Table 5). Changing of the fishing power adjustment of the standardised catch rate time series did not result in any noticeable changes in model fit or parameter estimates (Table 5).

Table 5: Summary of the results and parameter estimates of each of the models run to test the sensitivity of the base model to changes in fixed parameters

Parameter	Base model	h = 0.5	h = 0.7	M = 0.3	M = 0.4	σ_r = 0.3	σ_r = 0.5	d_t end 2015	d_t end 2016	No FP	Half FP	Full FP
Total NLL	606.4	607.8	606.9	609.5	605.3	604.7	609.7	609.7	609.7	607.1	606.8	606.4
Index NLL	-32.8	-32.5	-32.7	-32.5	-32.5	-32.0	-33.0	-31.4	-31.4	-32.7	-32.6	-32.8
Length NLL	28.8	29.3	29.2	29.2	29.5	29.2	29.2	29.3	29.3	29.2	29.0	28.8
Age NLL	622.5	622.2	622.3	623.5	620.5	622.6	622.1	623.3	623.3	622.3	622.4	622.5
Virgin recruitment	299000	327800	285600	237600	453200	297900	308700	311200	311200	301300	3000100	299000
$ln(R_0)$	5.7	5.8	5.7	5.5	6.1	5.7	5.7	5.7	5.7	5.7	5.7	5.7
h	0.6	0.5	0.7	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6
M	0.3	0.3	0.3	0.3	0.4	0.3	0.3	0.3	0.3	0.3	0.3	0.3
L_∞ **female**	126.9	126.8	126.8	126.7	127.0	126.8	126.9	126.7	126.7	126.8	126.8	126.9
L_∞ **male**	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2
K female	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
K male	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Bratio_2017	0.4	0.4	0.4	0.3	0.5	0.4	0.4	0.4	0.4	0.4	0.4	0.4

4 Discussion

4.1 Stock status

Results from this assessment suggest there has been long-term declines in the Spanish mackerel population in the Queensland GoC, with steeper declines over the past 10 years. The results suggests that the population size currently ranges between 29 and 40% of unfished spawning stock biomass and is declining towards the limit reference point of 20% of unfished spawning stock biomass.

The results suggest that management action to reduce fishing mortality is required to rebuild the stock to the target reference point, taking into account high harvests experienced in 2019 and evidence of poor recruitment in recent years.

The model estimated that the overall population size of Spanish mackerel in the Queensland GoC is small, with a virgin spawning stock size of approximately 1150 to 1350 t. This small population size means that only relatively small harvests are able to be sustainably maintained through time. This is apparent with the equilibrium harvest at 60% of unfished biomass estimated to be 170 t, below the annual harvest since the early 2000s.

4.2 Performance of the population model

The model successfully fit all input data sources and produced sensible results. One exception to this was the early standardised catch rate time series, between 1992 and 1999. In early iterations of the model, this data source was not fit successfully and it was decided that it is not representative. There was insufficient information in the data inputs to estimate either natural mortality (M) or the stock recruitment steepness parameter (h). Fixed parameters were informed by estimates from assessments of similar stocks and known biological traits, however, this increases the assumptions of the model and it would be preferable to estimate these parameters in the future if the data allows.

4.3 Environmental impacts

Declines in population size of Spanish mackerel since around 2010 have been reported throughout northern Australia. This trend is also observed in other species. This is most likely driven by environmental variables as these declines are across large geographic areas, biological stocks and fisheries.

Northern Australia has been impacted by numerous warm water events in recent years, resulting in coral bleaching in 2016 and 2017 (Babcock et al. 2019). In 2016, waters between Papua New Guinea and Australia were the warmest ever recorded (Oliver et al. 2018). Additionally, extensive mangrove dieback was recorded throughout the GoC during late 2015 and early 2016, particularly in the Gulf Plains Bioregion (Accad et al. 2019). These extreme temperature events may have influenced the Spanish mackerel populations in the area. They have most likely influenced recruitment, as temperature is an important determinant of mortality and recruitment in the early life stages of various fish species (Houde 1987; Takasuka et al. 2007). These temperature anomalies may have also influenced spawning location and timing (Frank et al. 1990; Drinkwater 2005; Rose 2005). This is due to water temperature linking to spawning activity and is likely to influence the seasonal development of gonads (McPherson 2007). As periods of elevated sea surface temperatures are predicted to become more severe and frequent with climate change (Cai et al. 2014), their influence on Spanish mackerel requires further investigation and consideration in management across northern Australia.

4.4 Recommendations

4.4.1 Data

It is recommended that improved mechanisms to report daily Spanish mackerel harvests and fishing effort per operation be identified and implemented. This could include use of electronic reporting systems, which are of particular use when calculating catch rates. Data accuracy would be particularly improved from accurate effort measures with fishing time and location recorded for each trip. Additional information on days that Spanish mackerel were targeted but not caught would also be beneficial. More frequent measures of recreational harvest and effort for regional locations in the Queensland GoC would also benefit future assessments. Improving validation of commercial logbook data is a priority for fisheries assessment and management across all fisheries.

4.4.2 Monitoring

Continued annual monitoring of age and length structures, representative of the commercial line fishery is required to ensure that accurate reference points for harvest strategies can be determined into the future. Ensuring there is adequate representation of males and females in this data is also required to ensure a sex structured model can be used into the future.

Information on trends in recruitment would also improve our understanding of potential impacts of environmental variation on the population and would help to confirm the model predictions of poor recruitment in recent years.

4.4.3 Management

The implementation of a harvest strategy and management arrangements, to halt population declines and rebuild the stock to the *Sustainable Fisheries Strategy* biomass target of 60% is required. Current levels of fishing mortality are likely to result in overfishing towards the limit reference point and reduce average catch rates longer-term. In order to rebuild the stock towards 60% biomass for better economic yield and quality of fishing (higher catch rates), fishing pressure will need to reduce to rebuild the fish population to a higher biomass.

Suggested indicators to monitor over time could include periodic biomass estimates from a detailed stock assessment (Smith et al. 2008; Wayte 2009). Using catch rates as an indicator should be done with caution due to the possible hyper-stable nature of this species, particularly until improved fishing effort measures are recorded.

4.4.4 Assessment

This assessment estimated selectivity of larger and older fish than was estimated in assessments of the east coast of Australia and the Torres Strait (Begg et al. 2006; O'Neill et al. 2018). Future assessments should investigate this and whether this estimation is representative of the size and age of Spanish mackerel that are caught in the GoC.

The size of Spanish mackerel populations within the GoC is also unknown. In this region, genetics suggest that there is one very large stock that ranges from the GoC in the east to Perth in Western Australia (Moore et al. 2003). Otolith microchemistry and parasite analyses, however, suggest that there is limited movement of Spanish mackerel, in the range of hundreds of kilometers, that results in smaller biological stocks with limited mixing (Moore et al. 2003; Lester et al. 2005; Buckworth et al. 2007). While this suggests that the Queensland section of the GoC may be an appropriate biological stock, there may also be some mixing with fish in the Northern Territory section and future assessments should include an investigation of how this impacts the results of the assessment.

The first ten years of the standardised catch rate time series were not able to be explained by other data sources and would have needed to be preceded by a period of higher harvests that had then declined. This led us to assume that the catch rates were not explaining abundance, but rather other variables associated with the data collected which were used to standardise catch rates. Future assessments should further investigate the cause of this early increase in standardised catch rates and ensure that they are representative of abundance.

Likelihood profiles of key parameters in the model revealed conflicts in the data sources input into the model. For overall depletion of the stock, the standardised catch rate differed to age, length and recruitment data. While for natural mortality, age data conflicted length and index data, while recruitment data suggested another slight difference. Again, for stock recruitment steepness, age data differed to the standardised catch rate and length data. While these conflicts may never be resolved, it would be helpful to further investigate the cause of these inconsistencies between data inputs and how they influence the model results.

As previously discussed, there is evidence to suggest that something other than fishing pressure is negatively impacting on Spanish mackerel populations throughout Australia. Similar trends in the past 5 years in standardised catch rates across multiple genetic stocks suggests that there may be something other than fishing pressure influencing populations. Poor recruitment has been estimated in recent years in the east coast, Torres Strait and Queensland GoC assessments. Increasing our understanding of what may be driving these declines is important to ensure sustainable management of this species into the future. Incorporating environmental variables into future assessments may be one way to include these changes and improve the assessment moving forward.

4.5 Conclusions

This assessment has informed the status of the GoC Spanish mackerel population. It suggests that there is a strong downward trend in biomass and that fishing pressure has been too high to ensure the population size is maintained at a sustainable level. The results provide RBCs using a hockey stick and constant F harvest control rules that prevent the stock reaching the limit reference point and rebuild the biomass towards the 60% level, consistent with the 2027 biomass targets set in the Queensland Government’s Sustainable Fisheries Strategy.

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6 Appendix A

6.1 Biological data

6.1.1 Fecundity and maturity

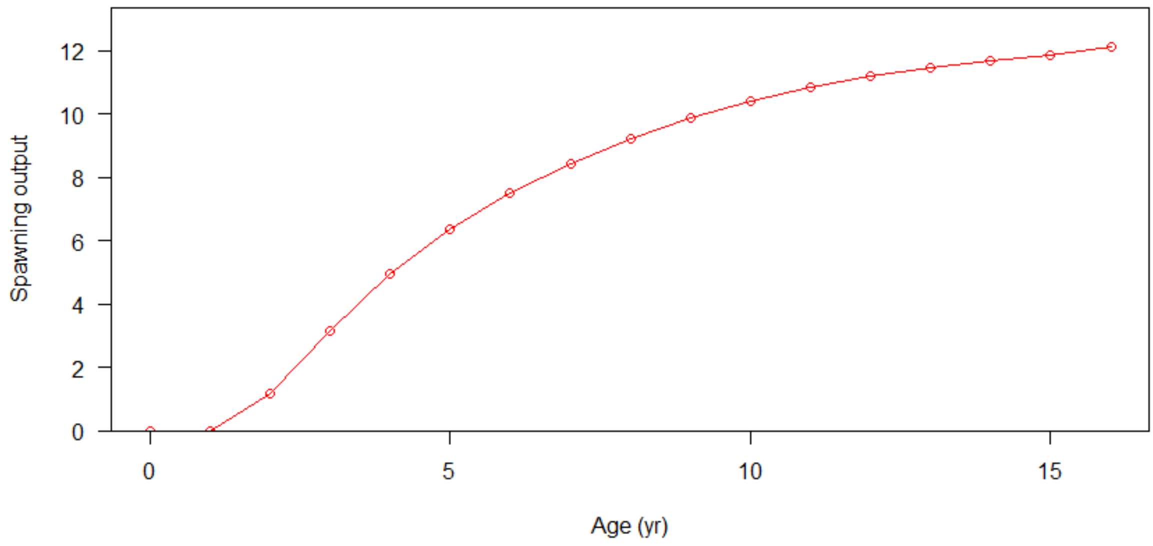

Figure 20: Spawning output at age

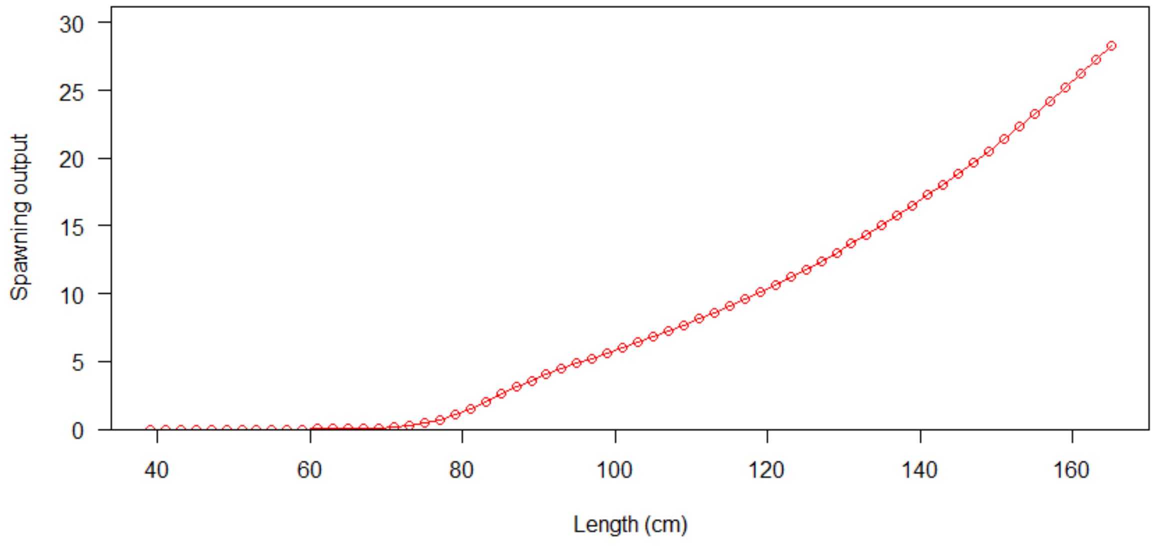

Figure 21: Spawning output at length.

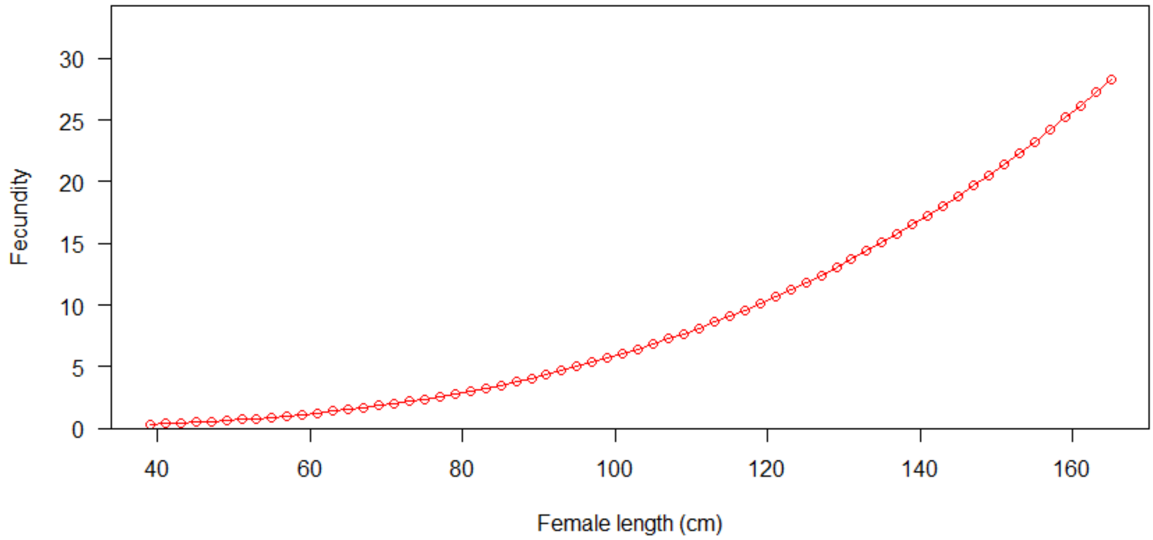

Figure 22: Fecundity at length

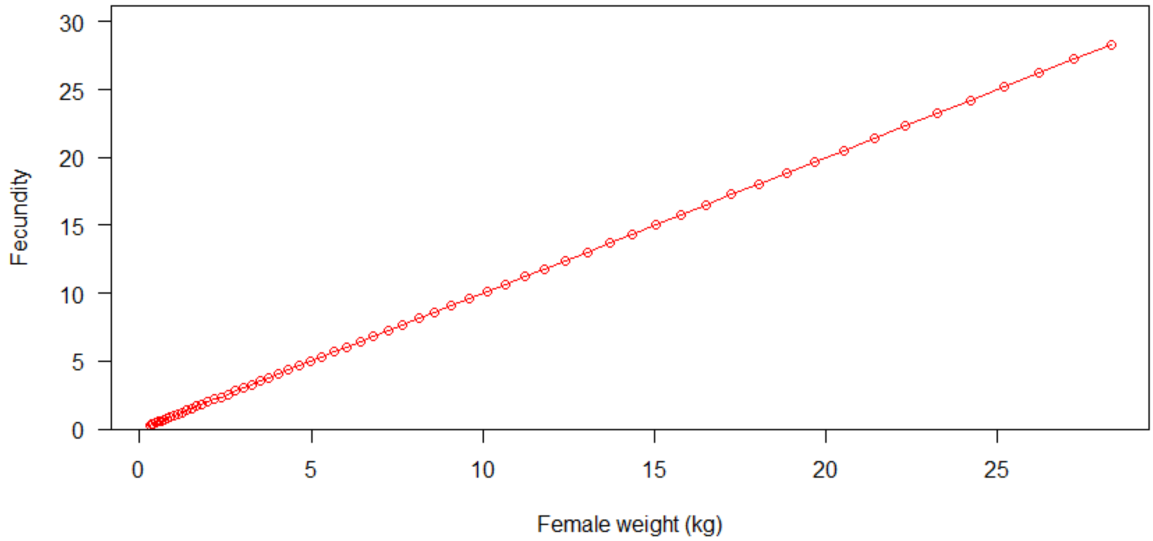

Figure 23: Fecundity at weight

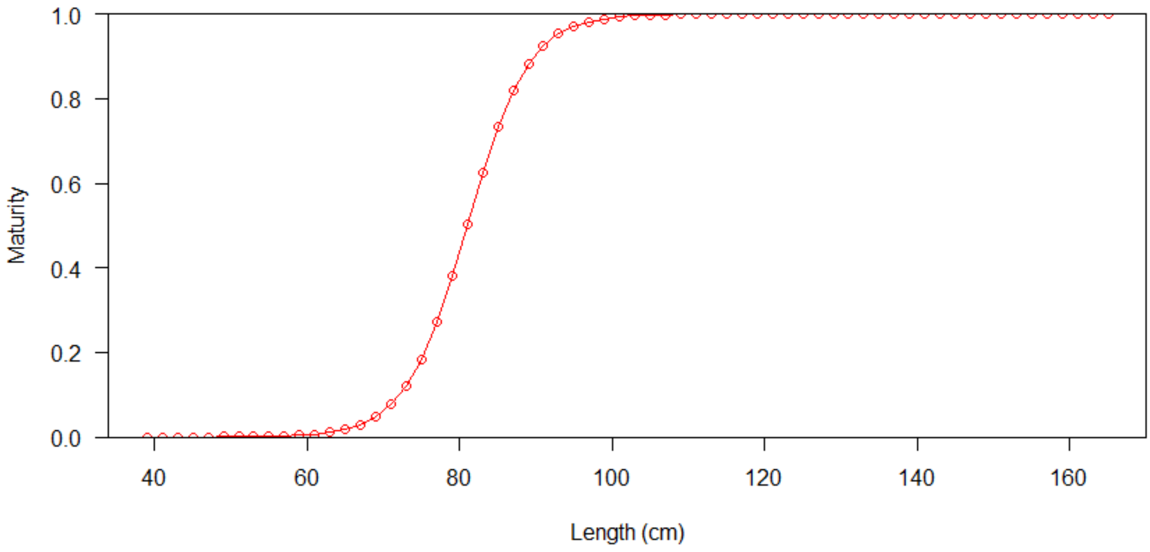

Figure 24: Maturity at length

6.1.2 Weight and length

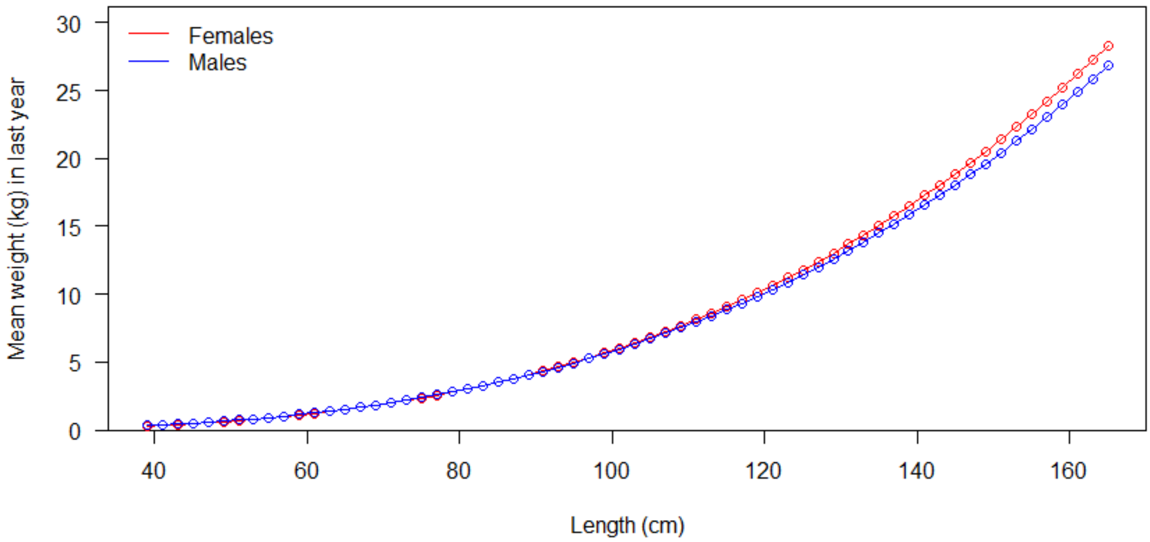

Figure 25: Weight-length relationship

7 Appendix B

7.1 Model Diagnostics

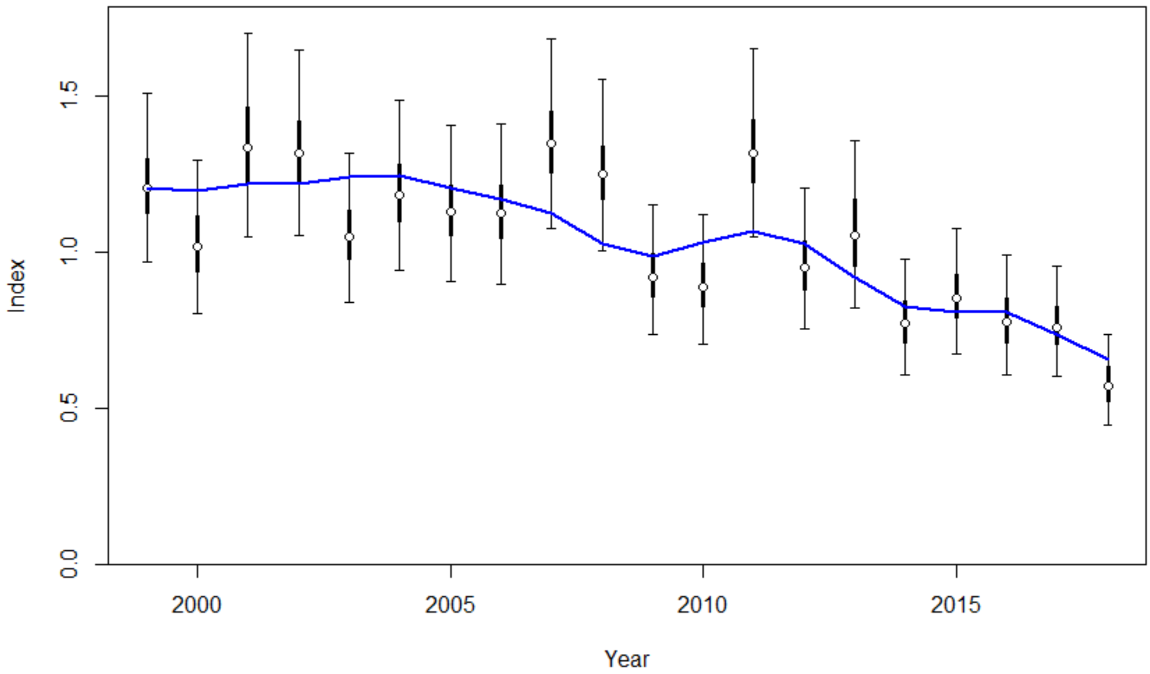

Figure 26: Model fits (blue line) to standardised catch rates (points). Thick black bars represent the standard error input into the model, while the additional thin error bars represent additional error estimated by the model.

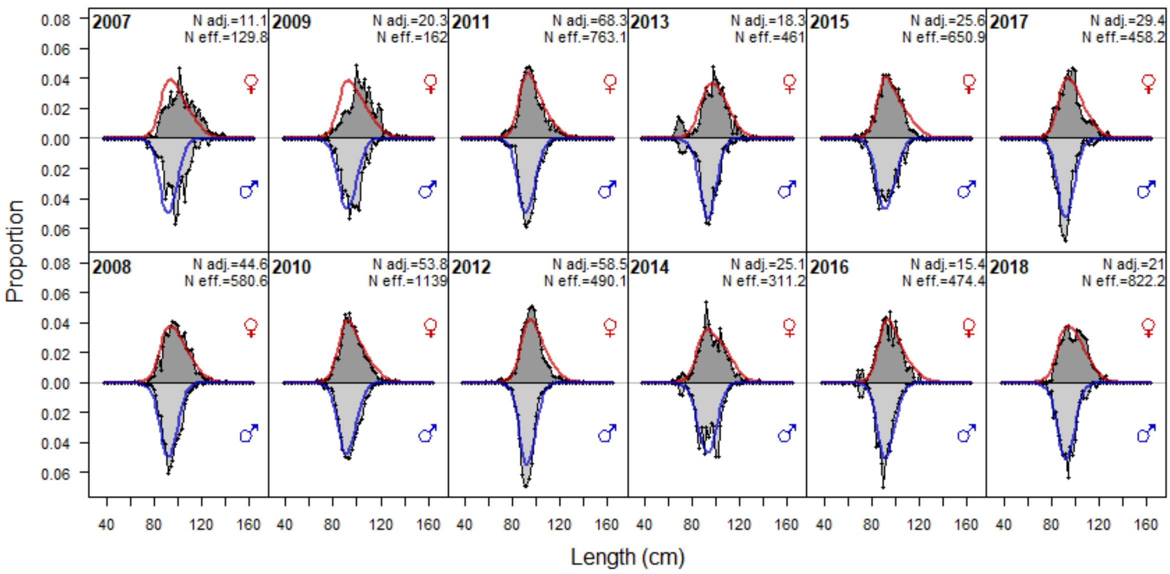

Figure 27: Fits to length structures. 'N adj.' is the input sample size after data-weighting adjustment. N eff. is the calculated effective sample size used in the McAllister-Iannelli tuning method.

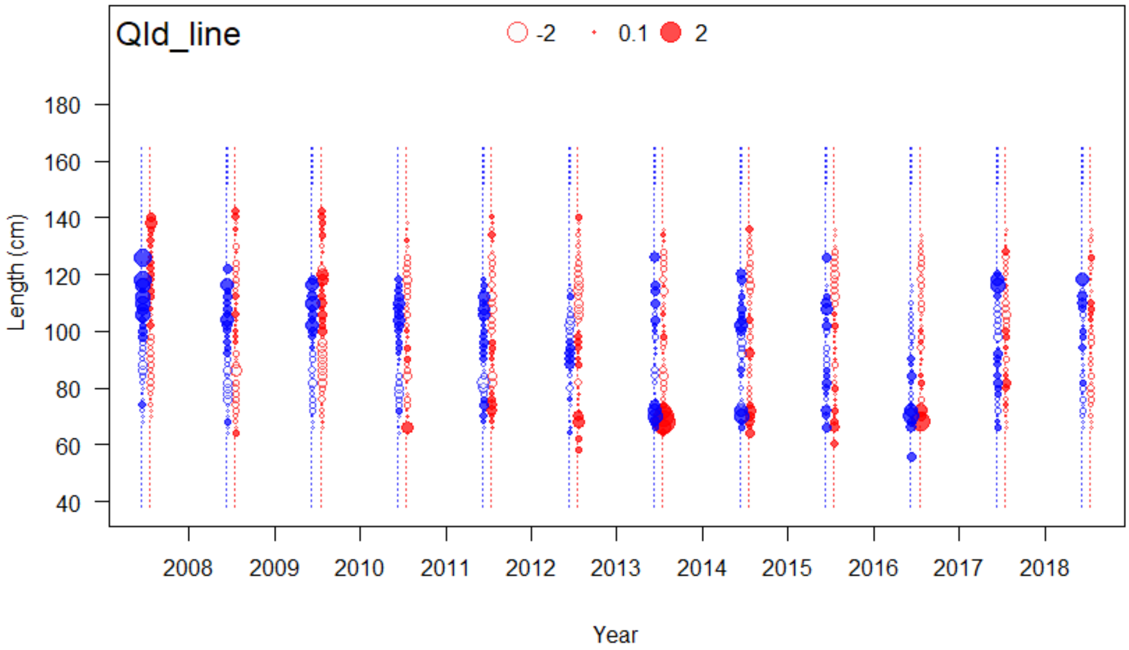

Figure 28: Mean length with 95% confidence intervals based on current samples sizes. Francis data weighting method TA1.8: thinner intervals (with capped ends) show result of further adjusting sample sizes based on suggested multiplier of 0.5992 (with 95% interval

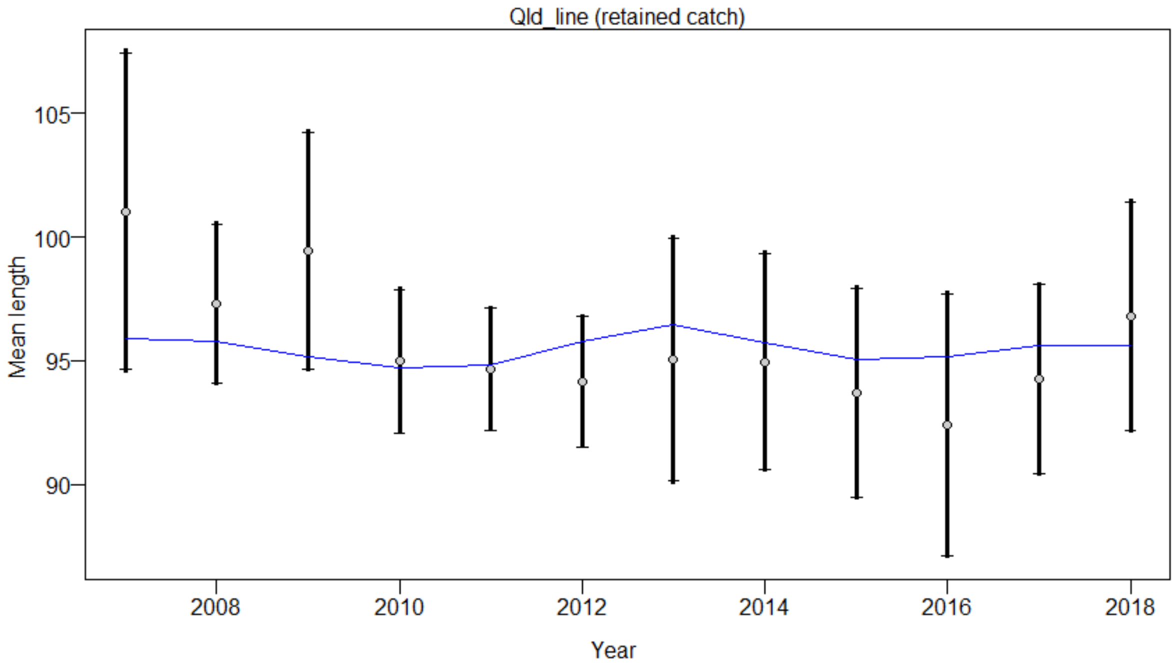

Figure 29: Mean length with 95% confidence intervals based on current samples sizes. Francis data weighting method TA1.8: thinner intervals (with capped ends) show result of further adjusting sample sizes based on suggested multiplier of 0.5992 (with 95% interval

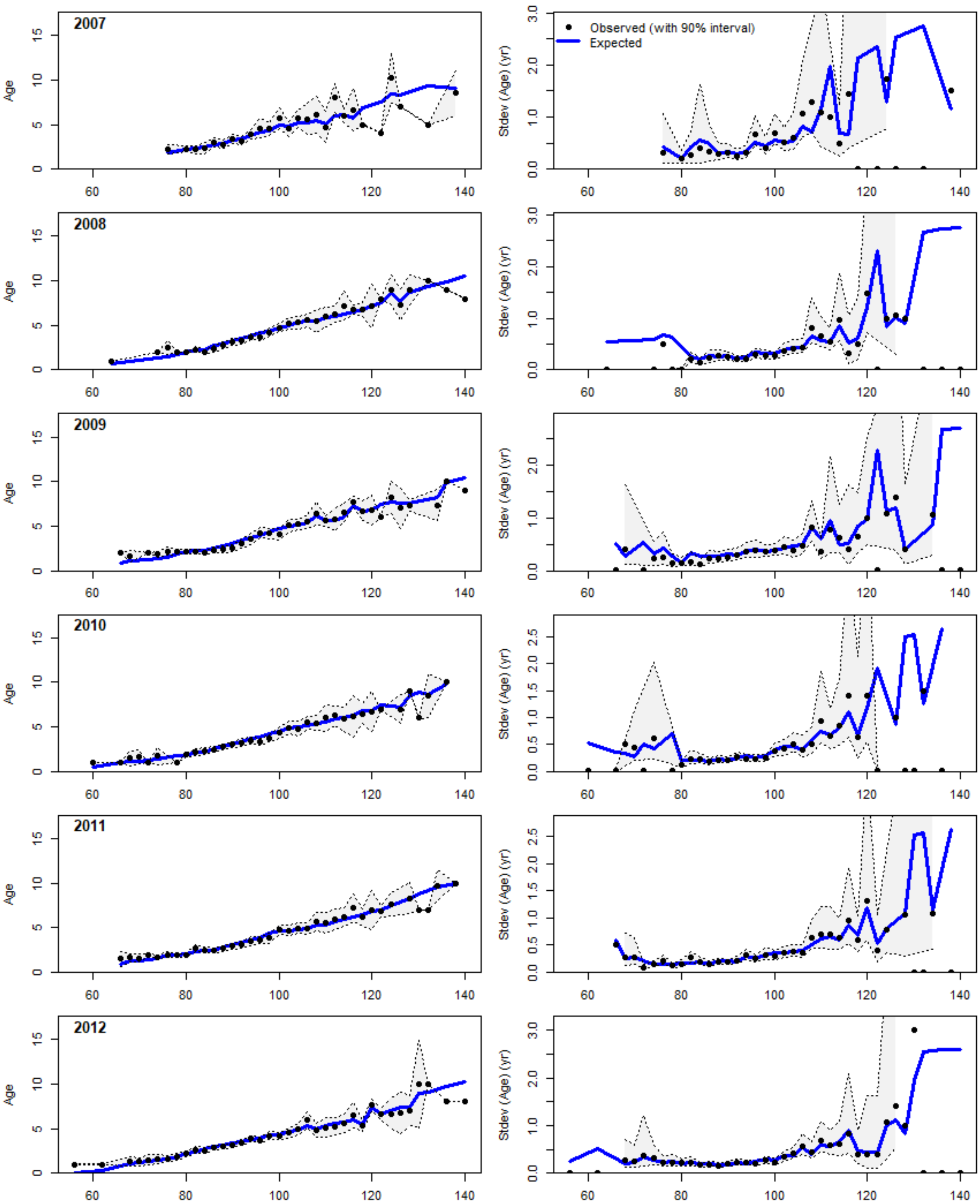

Figure 30: Fits to conditional age at length structures between 2007 and 2012, where the left column represents the model fit to the data, while the right column represents the model fit to the standard error of the ageing process

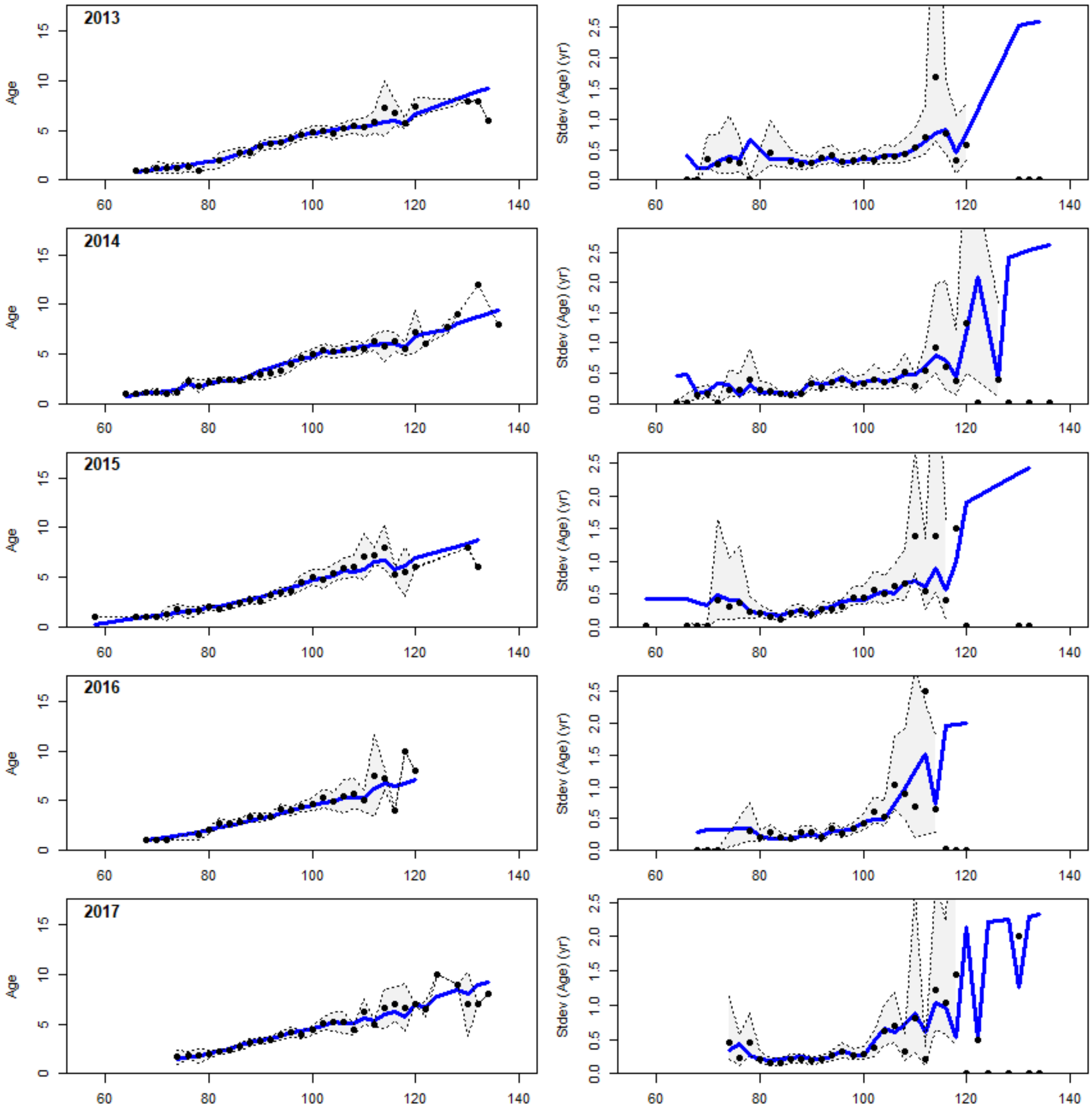

Figure 31: Fits to conditional age at length structures between 2013 and 2017, where the left column represents the model fit to the data, while the right column represents the model fit to the standard error of the ageing process

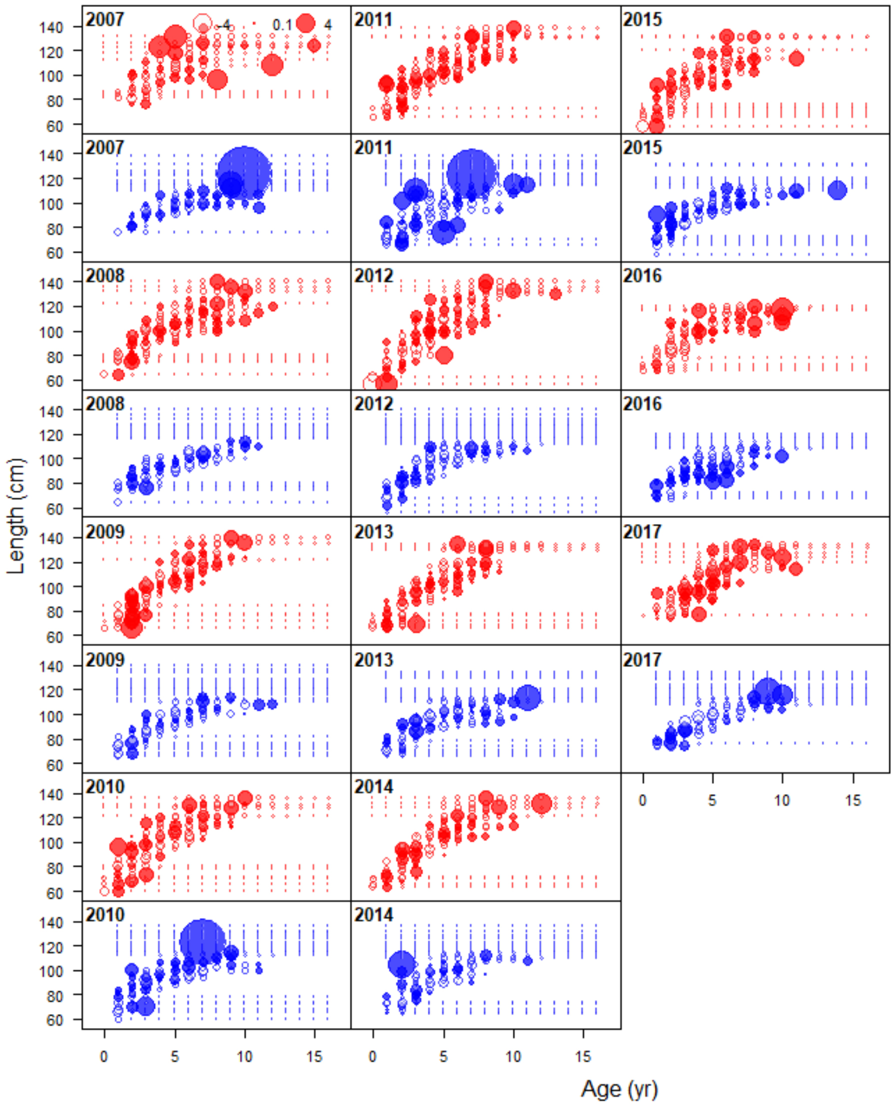

Figure 32: Residual plots of fits to conditional age at length structures

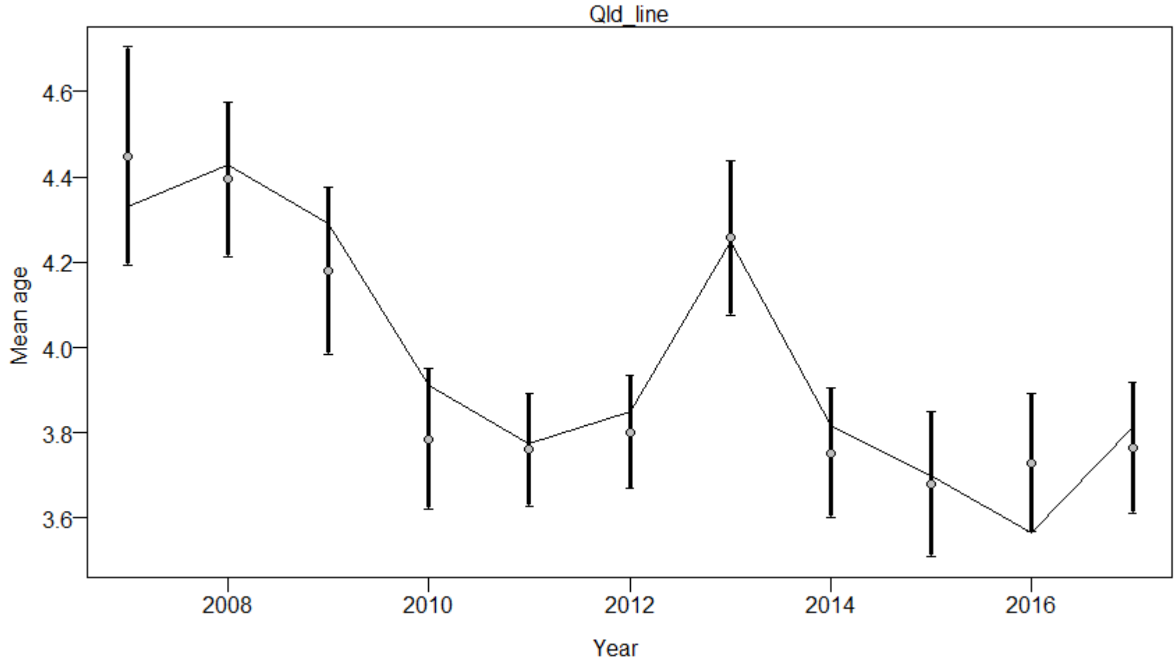

Figure 33: Mean age with 95% confidence intervals based on current samples sizes. Francis data weighting method TA1.8: thinner intervals (with capped ends) show result of further adjusting sample sizes based on suggested multiplier of 3.1465 (with 95% interval).

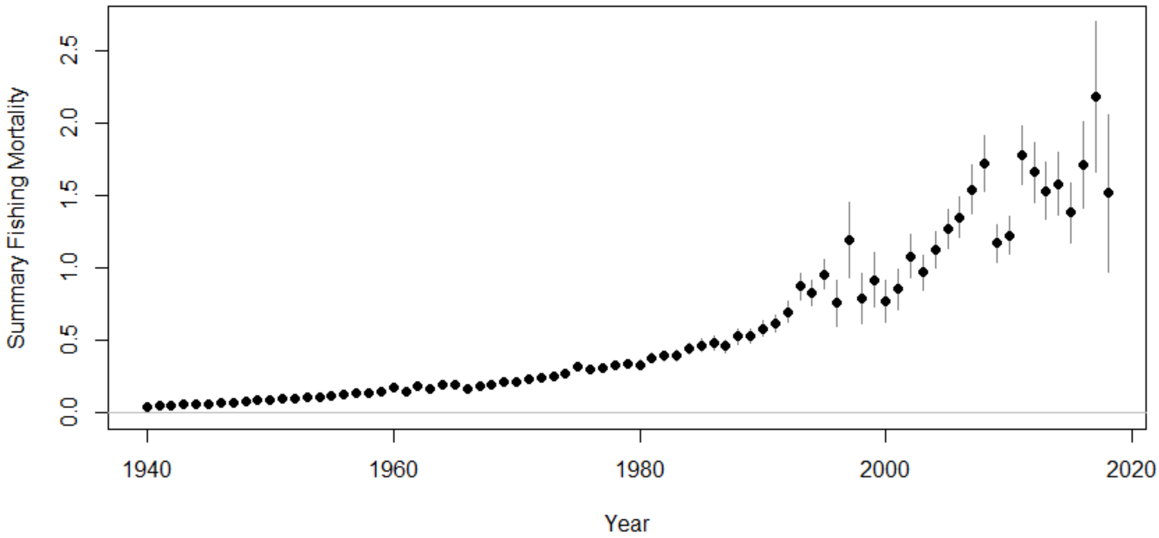

Figure 34: The ratio of an annual fishing mortality relative to the spawning biomass is at 60% of unfished spawning biomass

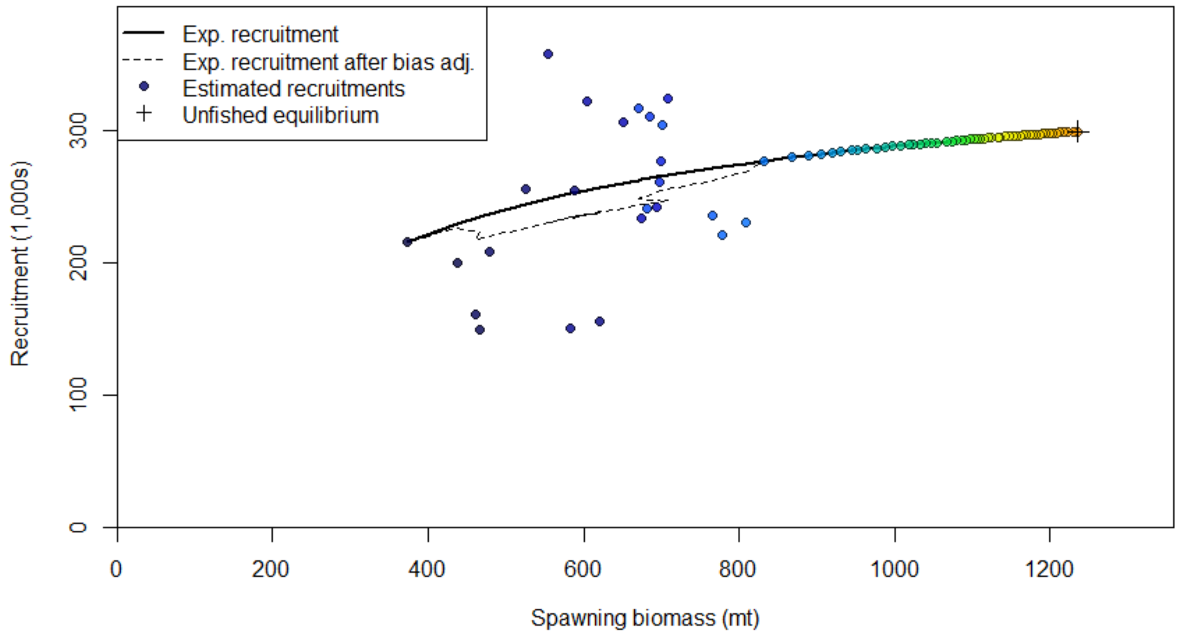

Figure 35: Stock-recruit curve. Point colors indicate year, with warmer colors indicating earlier years and cooler colors in showing later years.

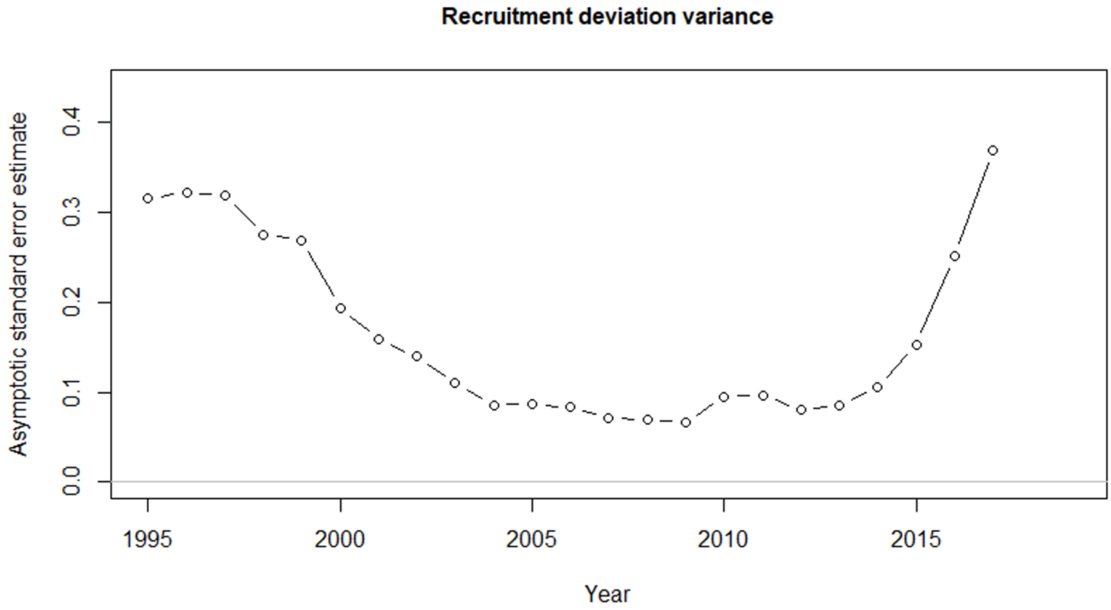

Figure 36: Recruitment deviations variance

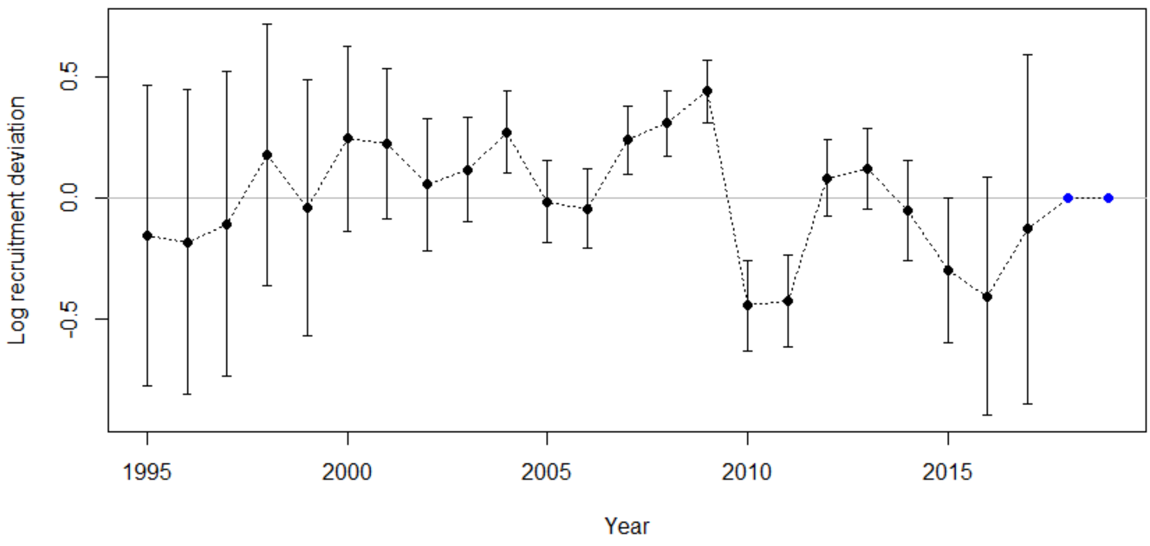

Figure 37: Recruitment deviations with 95% intervals. The blue circles represent projections.