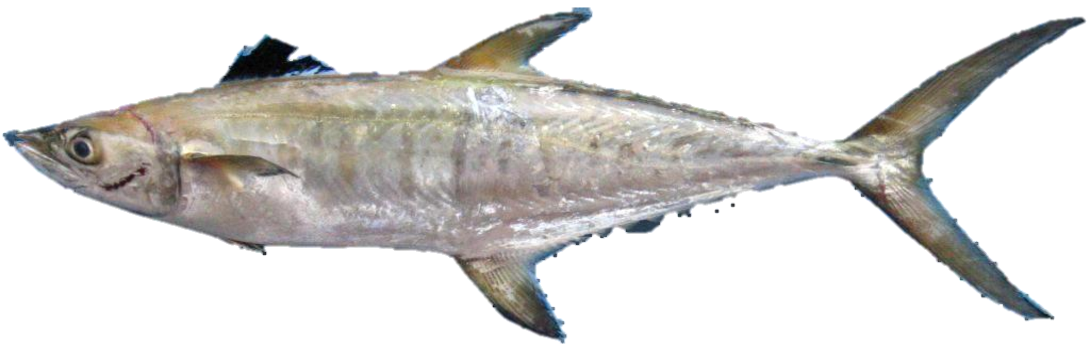

Stock assessment of the Australian east coast grey mackerel (*Scomberomorus semifasciatus*) fishery

2019

Queensland Government

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Executive summary

Grey mackerel is a pelagic species that forms two populations (stocks) along the Queensland's east coast. The stocks separate between Bowen and Proserpine, around the Whitsunday Islands.

Grey mackerel are a fast growing species. They are around one year old when the reach the 60 cm total length minimum legal size and are sexually mature from two years of age.

Grey mackerel are found in nearshore waters, while juveniles can spend time in estuarine locations to feed and seek shelter. They form predictable aggregations along the east coast, which are targeted mainly by commercial net fishers.

Annual commercial harvest between 2013 and 2018 averaged 110 tonnes (t) in the north-east stock and 65 t in the south-east stock. Harvests by sector in the north-east were 94 per cent (77 t) commercial and 6 per cent (4.8 t) recreational, while in the south-east they were 87 per cent (62 t) commercial and 13 per cent (9.3 t) recreational.

This stock assessment used an age structured model with a yearly time step and age based selectivity. Separate models were assessed for each stock. Data inputs included total harvest, standardised catch rates, age and length structures. The model uses data from 1961 to 2018.

For the north-east stock model results suggested that biomass declined between 2003-04 and 2010-11 to 46 per cent (35–56 per cent confidence range) unfished, exploitable biomass. Unfished biomass was considered to occur in 1960-61, before substantial fishing pressure began. The assessment suggests that the north-east stock is currently between 37 and 58 per cent unfished biomass. For the south-east stock the results suggest that biomass declined between 1988-89 and 2010-11 to 38 per cent (31–45 per cent) unfished biomass. The assessment suggests that the south-east stock is currently between 40–61 per cent of unfished biomass.

The results suggest that the equilibrium maximum sustainable yield (MSY) harvest is between 107–144 t per year (all sectors) for the north-east stock and between 87 and 125 t per year for the south-east stock. Equilibrium 60% harvest for the north-east stock was estimated at 82 t, between 52 and 115 t. In the south-east stock, the equilibrium 60% biomass harvest was estimated at 76 t, ranging between 58 t and 91 t.

The recommended total allowable harvest to rebuild the stocks to the Queensland *Sustainable Fisheries Strategy 2017-2027* longer term target of 60% unfished biomass is 81 t (54–115 t range across models) for the for the north-east stock and 61 t (43–84 t range across models) for the south-east stock. Current harvest of both stocks is currently above these recommended levels.

Parameter	North-east	South-east
Current exploitable biomass (relative to unfished)	48% (37–58%)	51% (40–61%)
MSY exploitable biomass (relative to unfished)	35% (36–33%)	37% (35–38%)
MSY harvest	122 t (107–144 t)	105 t (87–125 t)
Current harvest	82 t	71 t
Harvest proportions	94% commercial, 6% recreational	87% commercial, 13% recreational
Equilibrium 60% biomass harvest	82 t (52–115 t)	76 t (58–91 t)
Harvest to build to 60% biomass	81 t (54–115 t)	61 t (43–84 t)
Timeframe to build to 60% biomass	8 years (8–3 years)	8 years (9–1 years)

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1 Introduction

Grey mackerel (*Scomberomorus semifasciatus*) (Macleary 1883) are tropical–subtropical pelagic fish endemic to Australasian waters. Their distribution around Australia is between Coffs Harbour on the east coast and the Abrolhos Islands on the west coast north to south-east regions of Papua New Guinea (Munro 1943; Collette and Russo 1984). Grey mackerel are generally distributed in nearshore waters (between 3 and 30 m depth) and found in similar areas as the other lesser mackerel species, including spotted mackerel (*Scomberomorus munroi*) and school mackerel (*Scomberomorus queenslandicus*) (GBRMPA 2012).

The species form multiple stocks around tropical Australia. On the east coast of Queensland there are two distinct stocks, determined through genetic, tag-recapture and otolith elemental data (Welch et al. 2009, 2015; Charters et al. 2010; Newman et al. 2010; Broderick et al. 2011). The north-east stock ranges from the Gulf of Carpentaria to Mission Beach (-10.5°S to -19.2°S), while the south-east stock ranges from Mackay to the Gold Coast (-20.7°S to -28.2°S). Between the two stocks is a mixing zone, located between Mission Beach and Mackay (Welch et al. 2009). For this assessment the mixing zone has been included as part of the north-east stock.

Grey mackerel can tolerate low salinity conditions, allowing movement into river mouths and estuaries, particularly as juveniles. They obtain a maximum size of approximately 120 cm, 10 kg and can reach 14 years of age (Collette and Russo 1984; Cameron and Begg 2002). Spawning generally occurs across their entire north-east range between September and January, producing pelagic eggs and sperm that mix and are dispersed through water currents (Cameron and Begg 2002). Grey mackerel are a predatory fish, feeding mainly on baitfish species (GBRMPA 2012).

Growth occurs quickly in the first three years of their life. Sexual maturity is generally reached at between 1.5 to 2 years of age for both male and female fish (Cameron and Begg 2002). This corresponds to a 651–-700 mm fork length (FL) in females, and at 551—600 mm FL in males (Cameron and Begg 2002).

Fishing for grey mackerel on the east coast began in the 1960s. The vast majority is caught by the commercial sector, with minimal recreational take. Harvest by the recreational sector is higher in the south-east stock compared to that of the north-east stock. In the commercial fishery, the majority of catch is taken by gill nets, with a negligible line component. Grey mackerel is commonly targeted at the same time as shark species in the East Coast Inshore Fin Fish Fishery. This has meant that changes to the management of shark take influence the harvest of grey mackerel.

The schooling behavior of grey mackerel, and the predictable location and timing of aggregations make them susceptible to overfishing and introduce problems with hyperstability for both assessments and management (Walters 2003; Campbell et al. 2012). Hyperstability occurs when fishing targets aggregations of particular species and catch rates can remain stable even though the population size is decreasing (Hilborn and Walters 1992). This hyperstability needs to be considered and accounted for when assessing the size and status of both grey mackerel stocks to ensure population estimates are representative of the true size of the stock and not school size.

The previous stock assessment was published in 2014, using data up until 2011 (Lemos et al. 2014). The assessment concluded there had been a general increase in grey mackerel abundance in the 24 years up until 2011, and suggested that the 250 t commercial total allowable catch (TACC) was appropriate (Lemos et al. 2014).

In 2018, the Qld Department of Agriculture and Fisheries commissioned a stock assessment update for grey mackerel. This update aimed to evaluate recent levels of fish harvest and mortality rates. The report informs on estimates of sustainable harvests that will maintain the Qld fishery and support implementation of Queensland's *Sustainable Fisheries Strategy 2017–2027*. The two stocks were analysed independently. Both stock analyses incorporated data on harvest (both commercial and recreational), standardised catch rates, length and age structures.

2 Methods

2.1 Harvest

2.1.1 Data sources

Fish harvest and effort data were analysed from the anticipated start of fishing in 1960 until the end of the 2017-18 financial year (June 2018). Commercial harvests of grey mackerel were recorded in the Qld logbook system. This data consisted of daily harvests of all fish species from each individual fishing operation (license) since 1987-88. Recreational catches of grey mackerel (both retained and released) were estimated from eight Qld state-wide surveys.

2.1.2 Management and research history

There have been various management changes within the grey 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 introduction of a recreational possession limit of ten fish, and a minimum legal size of 50 cm. Following this, an annual commercial TACC of 250 t was introduced in 2009, along with an increase in the minimum legal size to 60 cm (Table 1).
During the history of the fishery, numerous research projects improved understanding of the species' biology and population spatial structure and, in turn, informed management of the fishery (Table 2).

Table 1: History of grey mackerel management in Queensland

Year	Management Change
1877-1974	Numerous measures relating to fishing gear and practices, e.g. mesh size, net length and closed seasons
1976	Minimum legal size introduced of 45 cm total length (TL)
1988	Compulsory commercial logbook introduced
1988	Net use by non-commercial fishers banned
1990	Repeal of section 35 of the Fishery and Industry Organisation and Marketing Act making the sale of recreational harvests unlawful
1993	Minimum legal size increased to 50 cm TL, recreational in-possession (bag) limit of 10 grey mackerel per fisher
1998	Declaration of 16 Dugong Protection Areas and resultant netting area restrictions
2004	Representative Area Protection and comprehensive rezoning of the Great Barrier Reef (GBR), increasing the proportion of the GBR closed to fishing from 5% to 33%
2009	*Marine Parks (Moreton Bay) Zoning Plan 2008* closed 16% of the Moreton Bay Marine Park to fishing, and a further 8% to net fishing
2009	Minimum legal size increased to 60 cm TL, recreational in-possession (bag) limit of 5 grey mackerel per fisher, annual TACC of 250 t (1 July – 30 June)
2012	East Coast Inshore Fin Fish Fishery net buyback scheme, focusing on N1 and N2 licenses
2015	Net free zones introduced in Cairns, Mackay and Rockhampton
2016	Net fishing buyback scheme offered to commercial fishers holding a commercial fishing boat license with a N1 or N2 symbol

Table 2: History of grey mackerel research

Year	Author	Research
1943	Munro	Taxonomic review of Australian *Scomberomorus* species, including grey mackerel, describing nomenclature, distribution and morphological features
1984	Lewis	Screened grey mackerel from Australian waters for genetic polymorphisms, as part of a broader study of the ecological genetics of *Scombrids*
2002	Collette and Russo	Described the morphology, systematics and distribution of 18 species of *Scomberomorus*, including grey mackerel, to clarify relationships and systematic position within the Family Scombridae
2003	Cameron and Begg	Fisheries biology and interaction in the northern Australian small mackerel fishery
2007	Ward and Rogers	Review of current and future research needs for mackerel (*Scomberomorus*) in northern Australian waters
2009	Robertson et. al.	Identification of small juvenile Scombrids from northwest tropical Australia
2009	Welch et. al.	Determination of management units for grey mackerel fisheries in northern Australia
2010	Newman et. al.	Stock structure of grey mackerel across northern Australia, based on otolith isotope chemistry
2010	Charters et. al.	Stock structure of grey mackerel in Australia inferred from its parasite fauna
2011	Broderick et. al.	Genetic population structure of grey mackerel in northern Australia
2013	Lemos et. al.	East Queensland grey mackerel stock assessment
2015	Welch et. al.	Integrating different approaches in the definition of biological stocks: A northern Australian multi-jurisdictional fisheries example using grey mackerel

2.1.3 Commercial harvest data

Data has been summarised across two biological stocks along the Australian east coast. The stocks are separated along the latitude of 20.5°S. Within both stocks, the majority of the harvest (from commercial logbooks between 1987-88 and 2017-18) is concentrated in small areas, with the vast majority of waters along the east coast of Qld sustaining low harvests of grey mackerel (< 2 t) (Figure 1). The small areas of targeted effort sustain up to approximately 30 t of harvest annually (Average between 1987-88 and 2017-18, Figure 1). In the north-east stock, the majority of harvest is taken around Townsville, with lesser harvest taken off Cairns and Bowen (Figure 1). For the south-east stock, the majority of effort and harvest is located around the Fraser Island region (Figure 1).

At the start of compulsory commercial logbook recording (1987-88), there was considerable harvest of grey mackerel, with approximately 200t recorded annually between 1988-89 and 1990-91 (Figure 2). Harvest declined between 1993-94 and 1995-95, with commercial harvest approximately 60 t over this period (Figure 2).The lowest harvest on record in 2000-01, was less than 50 t between the two stocks (Figure 2). This was followed by an increase in harvest to a peak of just under 450 t in 2008-09 (Figure 2). In 2009-10 a total allowable commercial catch (TACC) of 250 t was introduced, which reduced total harvest to this level for the remainder of the time series (2009-10 to 2017-18) (Figure 2). Catch shares between the two stocks have been relatively consistent through time, with slightly more harvest taken from the south-east stock in early years, shifting to a larger proportion taken in the north-east stock once the TACC was introduced (Figure 2).

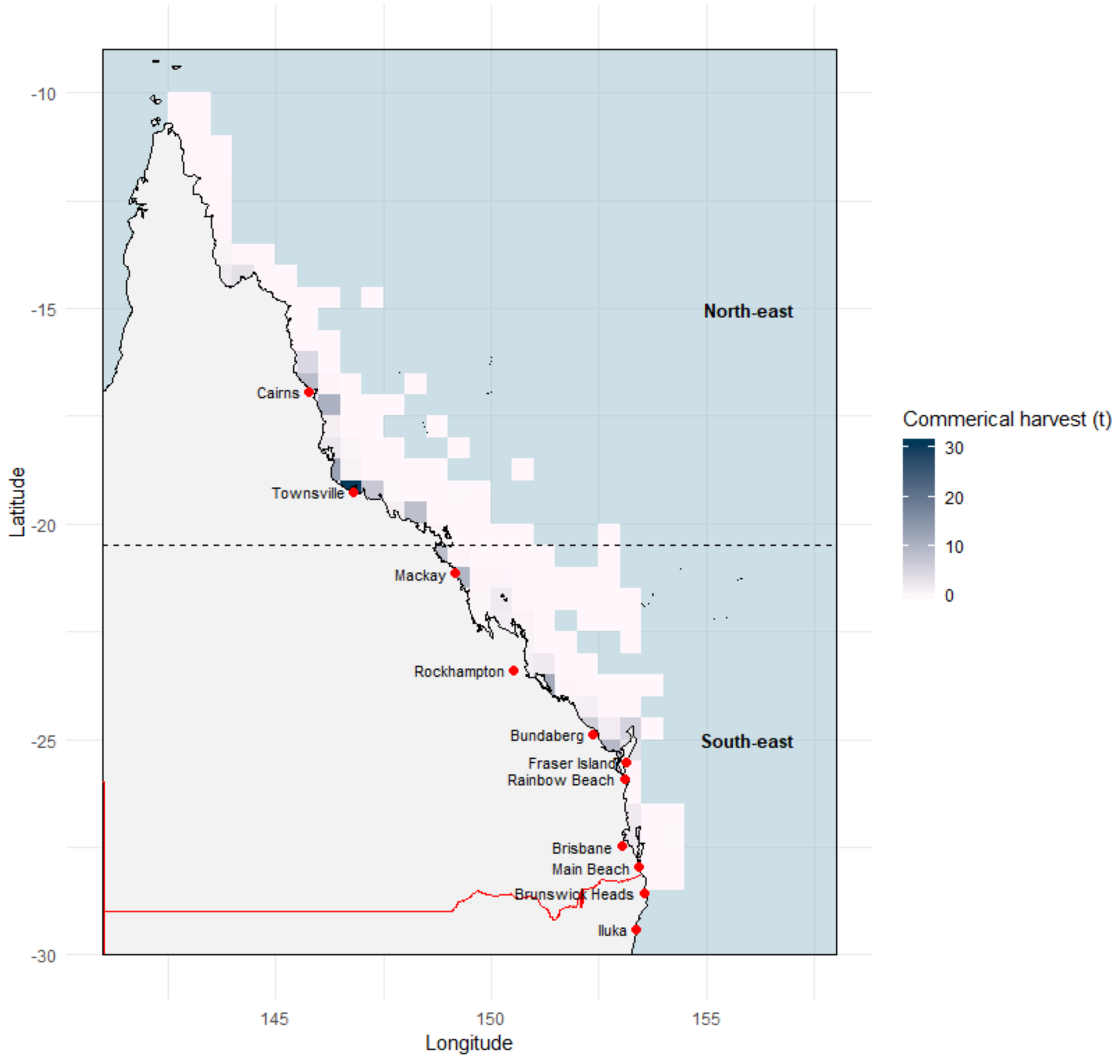

Figure 1: Map illustrating the location of two Queensland east coast grey mackerel stocks, separated by the dashed horizontal line. Average commercial Queensland harvest (t) between 1988-98 and 2017-18 is also shown for each 30-nautical-mile grid square along the Qld east coast (white squares)

The majority of the harvest of grey mackerel is taken by gill nets, with a minimal line component (Figure 3). The line proportion was greatest between 1988-89 to 1990-91, after which it declined for the remainder of the time series (Figure 3). There was also a very minor harvest by trawl in the south-east stock in 1989-90 and 1990-91 (Figure 3).

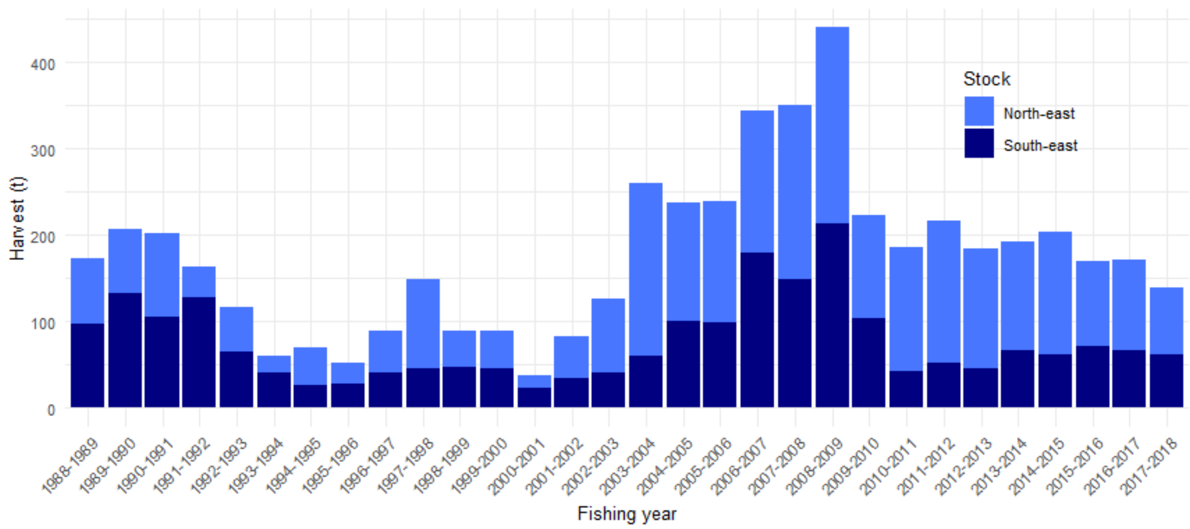

Figure 2: Reported annual commercial harvest (t) of grey mackerel for the north-east and south-east stocks between the fishing years of 1988–89 to 2017–18

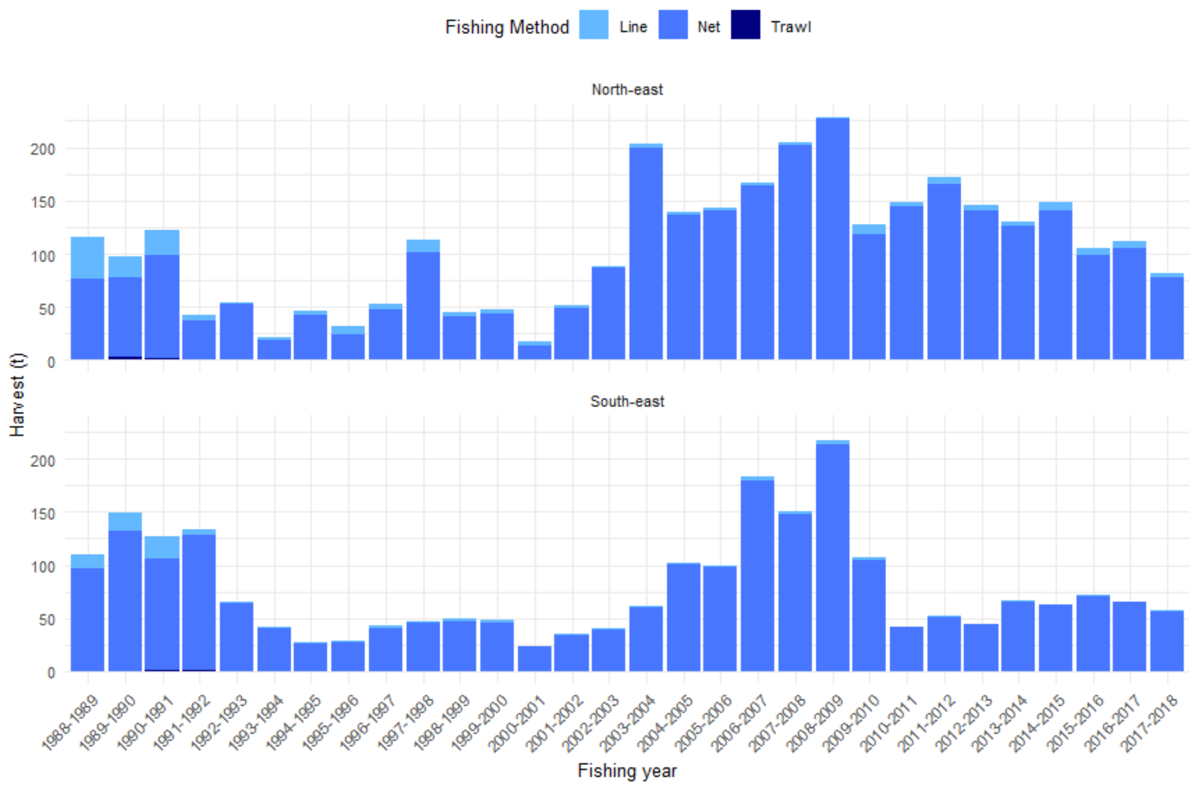

Figure 3: Reported annual commercial harvest (t) of grey mackerel for both north-east and south-east stock, for each fishing method, between the fishing years of 1988–89 to 2017–18

Harvest of grey mackerel in the north-east stock is strongly related to season, with the majority of harvest taken in September and October (Figure 4). In each of these two months the north-east stock's harvest ranged around 90t, while for the remainder of the year, harvest ranged between 25–50 t (Figure 4). In the south-east stock, monthly harvest is more stable, with the median harvest ranging between 17–50 t (Figure 4).

Effort in the grey mackerel fishery, in terms of the annual number of days fished varied throughout the time series (Figure 5). In the first three years (1988-89 to 1990-91), effort was high, at around 3000 fishing days annually before dropping to around 1000 fishing days in 1993-94 (Figure 5). Annual fishing effort increased again between 2003-04 and 2009-10 to around 2500 fishing days (Figure 5). Following the introduction of the TACC, annual fishing days again decreased to around 1500 (Figure 5). Fishing effort has remained relativity consistent between the two stocks, however, reduced fishing effort between 1991-92 and 2002-03 saw a larger decline in effort in the north-east stock compared to that in the south-east (Figure 5). The period of high effort in 2003-04 and the introduction of the TACC in 2009-10 saw a higher proportion of this effort originating from the south-east stock compared to that in the north-east (Figure 5).

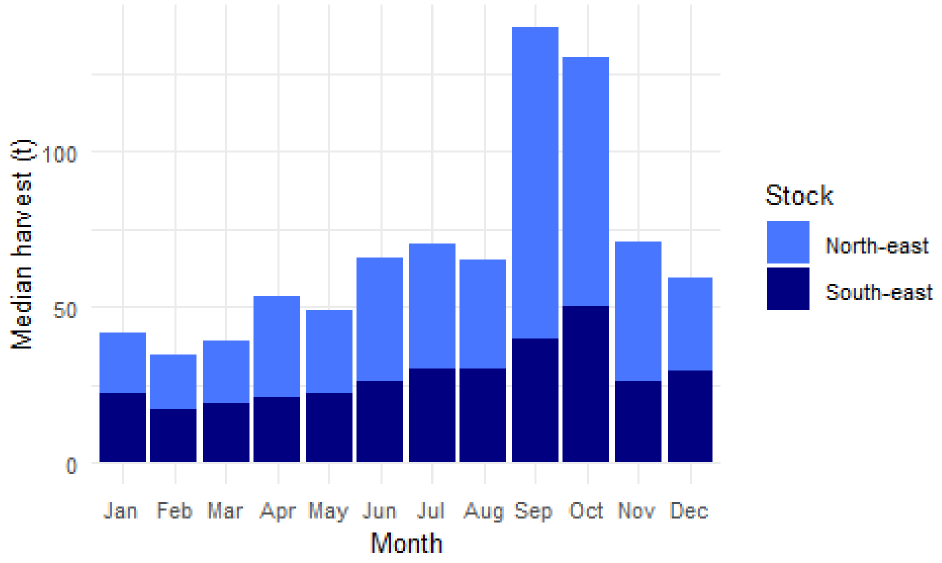

Figure 4: Median commercial harvest (t) of grey mackerel by month between the fishing years of 1988-89 and 2017-18

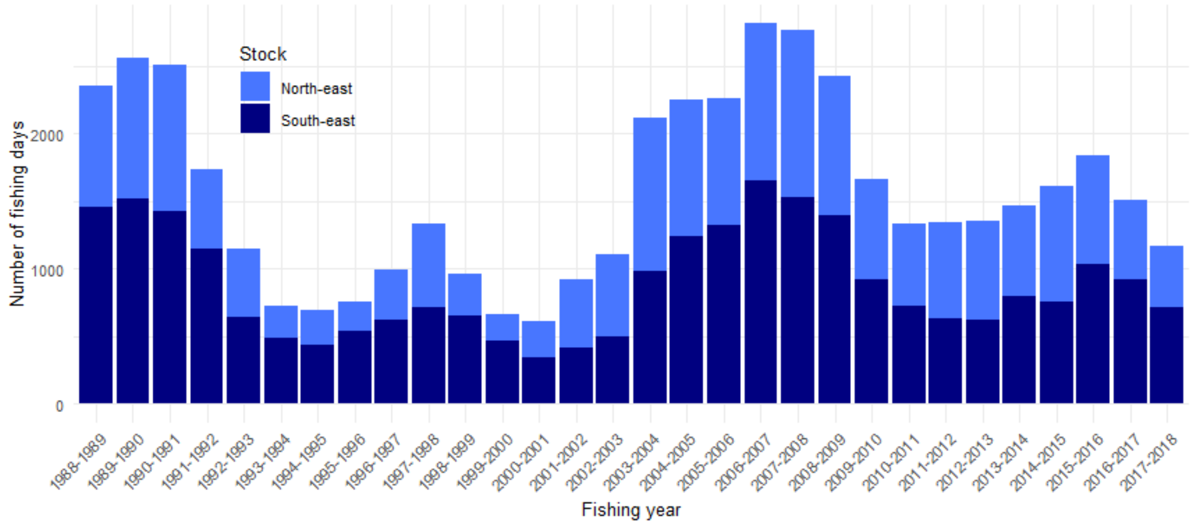

Figure 5: Total number of commercial days fished in the Queensland grey mackerel fishery between the fishing years 1988-89 and 2017-18 for both the north-east and south-east stocks

Regional patterns of commercial fishing on the east coast showed relatively consistent trends through time, particularly in the south-east stock. In the north-east stock, the majority of harvest is taken in the Lucinda region (Figure 6). In the early years in the north there was also some harvest in Bowen, which declined during the period of elevated harvest (2003-04 to 2008-09), before increasing again once the TACC was introduced (2009-10 onwards) (Figure 6). During the middle period of elevated harvest in the north-east, there was also some harvest in the Cairns region, and this harvest has continued following the introduction of the TACC (Figure 6). In the early years in the south-east stock the majority of the harvest was caught in the Fraser Inshore and Gold Coast Estuarine regions, with lesser harvest in Brisbane Offshore and Rockhampton regions (estuarine and offshore) (Figure 6). In the period of lower harvest, there was higher harvest in the Mackay Region, and this continued through the remainder of the time series (Figure 6). Between 2004-05 and 2009-10 there was elevated harvest, with the majority of this originating in the Rockhampton Estuarine region (Figure 6).

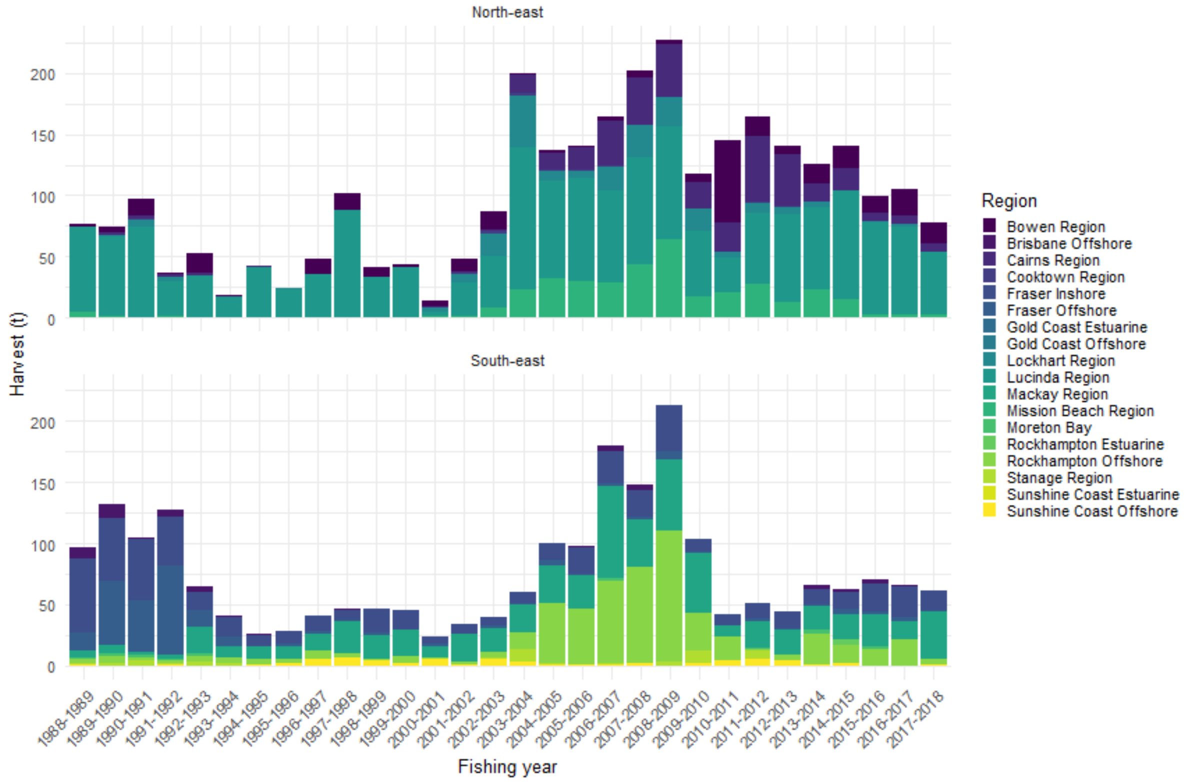

Figure 6: Annual regional commercial harvest (t) of grey mackerel within the north-east and south-east stocks between the fishing years of 1988-89 to 2017-18

2.1.4 Recreational harvest data

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

- A 1995 daily diary survey aimed to estimate the recreational harvest of small mackerel species between December 1994 and November 1995 by resident recreational fishers with boats in Qld waters (Cameron and Begg 2002).
- Surveys conducted by Fisheries Queensland, known as RFISH, in 1997, 1999, 2002 and 2005 (Higgs 1999, 2001; Higgs et al. 2007; McInnes 2008).
- An Australian national survey (the National Recreational and Indigenous Fishing Survey, NIRFS) was conducted in 2000 (May 2000 - April 2001), using different methodology to the RFISH surveys (Henry and Lyle 2003).
- The NIRFS methodology was adopted by Fisheries Queensland for state-wide surveys in 2011 and 2014 and called SWRFS (State-Wide Recreational Fishing Survey) (Taylor et al. 2012).

Surveys conducted in 1995, 2001, 2011 and 2014 had more effective follow-up contact procedures with diarists resulting in less dropout of participants compared to the other survey years using RFISH methodology (Fisheries Queensland, pers. comm.). Therefore, for surveys conducted in 1997, 1999, 2002 and 2005 using RFISH methodologies, estimates were adjusted using the ratio method (O'Neill and Leigh 2007). These adjustments made the estimates of fish catches more comparable between surveys.

When calculating total recreational harvests, half of the non-retained estimates of grey 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 grey mackerel by applying the proportion of grey 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 grey mackerel between the two stocks were vastly different, with only one survey (2013-14) recording recreational harvest for the north-east stock (Figure 7). This estimate in the north-east stock was also lower than all but one of the estimates in the south-east stock, at just under 5 t (Figure 7). In the south-east stock, the early estimates (1994-95, 1996-97 and 1998-99) were higher than some of the middle years (2000-01, 2001-02), before total harvest increased again in 2004-05 to approximately 40 t (Figure 7). Since this time, in 2010-11 and 2013-14 harvest has again fallen to approximately 15 and 10 t respectively (Figure 7).

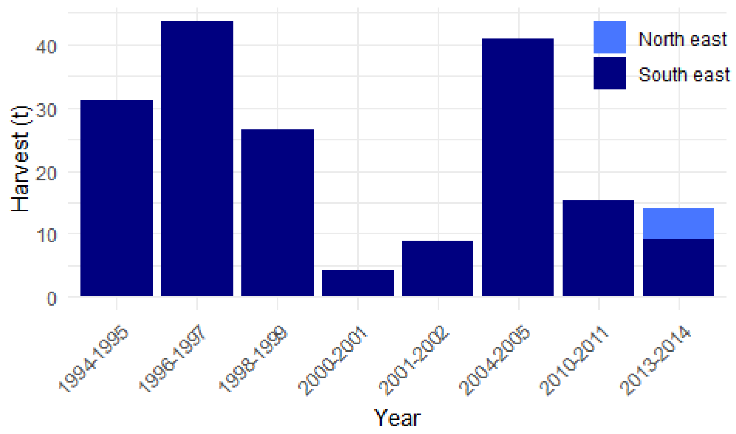

Figure 7: Estimated recreational harvest in the north-east and south-east stocks.

2.1.5 Charter harvest data

Harvest by the charter sector across both the north-east and south-east stocks were low. In the north-east harvest ranged between 0 and 412 kg between 1999-00, while harvest in the south-east stock ranged between 0 and 161 kg over the same time period (Figure 8).

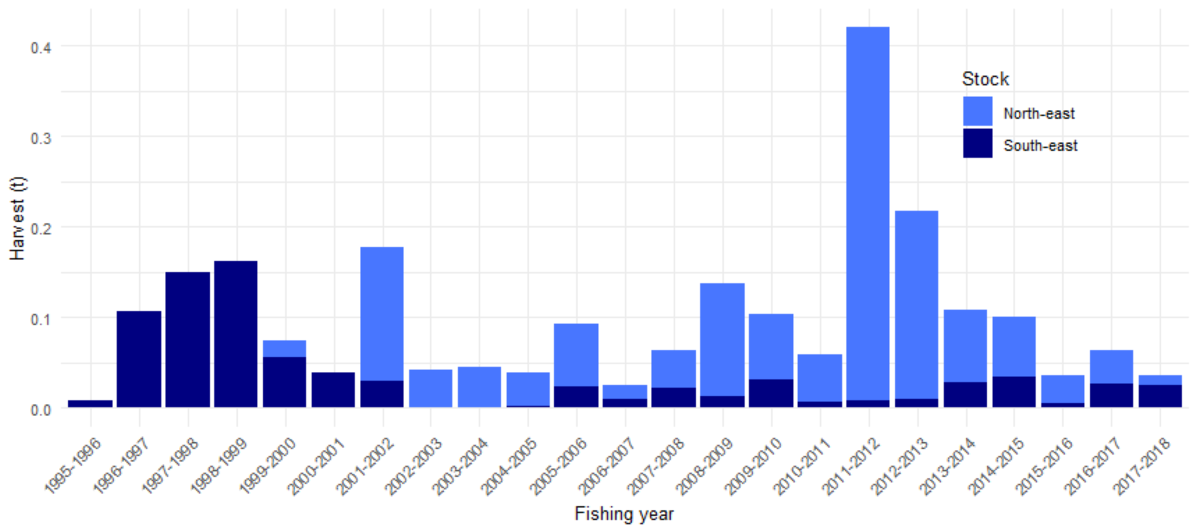

Figure 8: Reported annual charter harvest (t) of grey mackerel for the north-east and south-east stocks between the fishing years of 1988–89 to 2017–18

2.2 Standardised catch rates

Qld logbook data on commercial line catches (kg whole weight) of grey mackerel per fishing-operation-day were used as an index of legal sized fish abundance measured by fishing year for each of the two stocks on the Qld east coast. The methods below outline the concepts and procedures used to standardise mean (average) catch rates. Hereon, the term 'catch rate' means standardised catch rate unless otherwise specified. 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 were modelled using sinusoidal data to identify the time of year. This 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 was collected from 76 representative coastal weather stations along Qld east coast. The recorded measures of wind speed (km hour^{-1}) and direction (degrees for where the wind blew from) were converted to an average daily reading based on recordings between 3 am and 3 pm for each grid square defined in the Qld commercial fishing logbooks. Missing values were imputed from measurements at the next nearest location. From this data the north-south (NS) and east-west (EW) wind components were calculated. Squared wind components were also included for each wind direction variable, resulting in a greater proportional weighting for higher wind speeds.

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

Standardised mean catch rates of each of the grey mackerel stocks 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, both 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. 95% confidence intervals were calculated for all predictions.

The catch rate model included every daily grey mackerel harvest by each individual fisher. When multiple locations were recorded for a single fisher in a day the first location was retained. The model used a Gaussian distribution with the response variable, harvest per fisher day, log transformed. The variables modelled included additive effects of fishing year, fishing month, region, 12-month seasonal variables (c12 and cs12), 4 month seasonal variables (c4 and cs4) 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 (1988–89 to 2017–18 for the north-east stock and 1989-90 for the south-east stock). The individual fisher was included as a random effect. The log normal catch rate model was specified as:

- log(harvest) ~ year + region + month + c12 + cs12 + c4 + cs4 + wind EW + wind EW2 + wind NS + wind NS2 + random(fisher)

2.3 Biology

2.3.1 Data sources

Commercial catch length and age sampling occurred between July 2008 and July 2017. Each year, the commercial net harvest was representatively sampled and fish were measured to the nearest 10 mm fork length (Fisheries Queensland 2012). Where possible the sex of each fish was recorded. The fork lengths of the fish were converted to weight (kg) using formulas developed by Cameron and Begg (2002).

Otoliths were sampled from the recreational fishery, commercial line fishery and the commercial net fishery. A subsample of up to 20 otoliths in each size class were collected from each stock annually. The macrostructure of whole otoliths were interpreted to estimate fish age. From these ages, an annual age-length key (ALK) was calculated. Annual age frequencies were then determined using the age-length key for each stock.

2.3.2 Biological 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 1 (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).

As significant differences were not observed between grey mackerel genders, one analysis was conducted for each stock.

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

The age based maturity of females was taken from the relationship determined by Cameron and Begg (2002).

2.4 Population model

A population dynamic model was fitted to the data to determine the number of grey mackerel in each year and each age group from the start of fishing in 1960-61 to the current year (2017-18). The model takes into account births, growth rates, reproduction and mortality, and how these change though time. This analysis was conducted using R (version 3.5.2) and AD Model Builder (ADMB, version 12.0). The model itself was coded in parallel in ADMB and R: the ADMB version was used to find the maximum likelihood parameter estimates and perform the Markov chain Monte Carlo (MCMC) simulations to determine credible parameter intervals. The R version was used as a check of the ADMB version to ensure they both gave the same result and to summarise and plot results from ADMB.

The model included only one fishing sector, where commercial net, commercial line, charter and recreational harvests were grouped together. As the vast majority of the harvest is taken with commercial gill nets, and representative biological monitoring data was subset for commercial net caught harvests, this was used to define selectivity of the species.

2.4.1 Model assumptions

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

- The fishery began from an unfished state of each of the grey mackerel populations in 1960-61
- There are no sex specific differences in grey mackerel growth or selectivity.
- Growth occurs according to the von Bertalanffy growth curve.
- The weight and fecundity of grey 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 or size.
- The proportion of fish vulnerable to fishing depends on their age, but not size or time.

2.4.2 Population dynamics

The population model indexes the population matrix by time (t) and age (a), Table 3.

Table 3: Equations used to describe grey mackerel population dynamics for each stock

Population Dynamics	
Logistic selectivity function	
$S_l = 1/(1 + \exp[-\ln(19)(a - A_{50})/(A_{50-95})])$	(2)
where A_{50} represents the age at 50% selectivity and A_{50-95} represents the additional age between 50% and 95% selection.	
Initial recruitment	
$R_0 = B_0^{Sp} / \left(f_{a_{max}} \frac{\exp(-M a_{max})}{1 - \exp(-M)} + \sum_{a=0}^{a_{max}-1} f_a \exp(-Ma) \right)$	(3)

where f_a denotes maturity × weight at age for female fish as a proxy for fecundity, B_0^{Sp} and M may be estimated within the model.

Initial age structure

$$N_{0,a} = \begin{cases} R_0 & \text{for } a = 0 \\ N_{0,a-1} \exp(-M) & \text{for } a = 1,2,\dots,a_{max}-1 \\ N_{0,a-1} \exp(-M)/(1-\exp(-M)) & \text{for } a = a_{max} \end{cases} \quad (4)$$

Vulnerable biomass

$$B_t^V = \sum_a N_{t,a} \exp(-\frac{1}{2}M)\, S_a\, w_a \quad (5)$$

where w_a denotes weight at age for both genders. M was fixed for both stocks, however, may also be estimated.

Harvest rate

$$H_t = C_t/B_t^V \quad (6)$$

Spawning biomass

$$B_t^{Sp} = \sum_a f_a\, N_{t,1,a} \qquad \text{for } t > 0 \quad (7)$$

Beverton-Holt recruitment

$$R_t = \frac{4hR_0B_t^{Sp}}{B_0^{Sp}(1-h) + B_t^{Sp}(5h-1)} \times \exp(d_t) \quad (8)$$

where d_t represent estimated recruitment deviations (Goodyear 1977). The h parameter was estimated for the south-east stock and fixed for the north-east stock (Beverton and Holt 1957).

Age structure

$$N_{t,a} = \begin{cases} R_t & \text{for } a = 0, t > 0 \\ N_{t-1,a-1}\exp(-M)(1-H_{t-1}\,S_{a-1}) & \text{for } a = 1,2,\dots,a_{max}-1,\ t > 0 \\ N_{t-1,a-1}\exp(-M)(1-H_{t-1}\,S_{a-1}) & \\ \qquad +N_{t-1,a}\exp(-M)(1-H_{t-1}\,S_a) & \text{for } a = a_{max}, t > 0 \end{cases} \quad (7)$$

Mid-year age structure

$$N_{t,a}^{mid} = N_{t,a}\exp(-\frac{1}{2}M)\sqrt{1-H_tS_a} \quad (9)$$

Predicted mid-year vulnerable biomass

$$B_t^{V_{mid}} = \sum_a N_{t,a}^{mid}\ w_a \quad (10)$$

This equation is used to match catch rates in the negative log likelihood equation 12.

Predicted sample numbers at age

$$\hat{P}_{t,a}^{AF} = \frac{S_aN_{t,a}}{\sum_a(S_aN_{t,a})} \quad (11)$$

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

2.4.3 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 (Table 4). The model optimisation procedure involved estimating model parameters such that the sum of these negative log-likelihoods is minimised. Many of the formulae below are taken from Leigh et al. (2017) section 4.5. Their nonstandard complexity made them differentiable with respect to model parameters, as required by the ADMB software which uses automatic differentiation to efficiently minimise the negative log-likelihood.

Table 4: Negative log-likelihood equations used for model fitting

Negative log-likelihood functions

Recruitment deviations

$$\ell^{(RD)} = y^R \left[\ln(\tilde{\sigma}^{RD}) + \frac{1}{2} (\hat{\sigma}^{RD})^2 / (\tilde{\sigma}^{RD})^2 \right] \quad (12)$$

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

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

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

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

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

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

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

Standardised catch rates

$$\ell_s^{CR} = y_s^{CR} \times \ln(\hat{\sigma}_s^{CR}) \quad (13)$$

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

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

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

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

where $c_{s,t}$ represents the input catch rate for each year and catch rate series. $\sigma_{s,t}^{CR}$ is the standard error for $c_{s,t}$ from the GLM catch-rate analysis.

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

Ages

$$\ell^{(AF)} = \sum_t T_t^{AF} \; P_{t,a}^{AF} \ln\left(\hat{P}_{t,a}^{AF}\right), \quad (14)$$

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

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

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

2.4.4 Model parameters

A variety of parameters were included in the model, with some of these fixed at specified values and others estimated. The von Bertalanffy growth parameters were pre-calculated (see section 2.2). Difficulty estimating parameters was experienced for both stocks. Initially we attempted to estimate natural mortality rate (M), logged unfished spawning stock size ($ln(B_0^{Sp})$) and stock recruitment steepness (h) parameters within each model. With the available data inputs, estimating these three parameters was not possible. M was then fixed at three levels considered representative of the biology, with a maximum age of 13 and consideration of the equations of Hoenig (2005) and Then et al. (2015). A range of three estimates are presented as these values were considered representative of the biology and resulted in successful model convergence. Values of M outside this range did not result in successful model convergence. The three fixed values of M for each stock were 0.34, 0.40 and 0.45. For the south-east stock successful model fits were obtained when M was fixed at these three values and estimating both h and $ln(B_0^{Sp})$ parameters. The first selectivity parameter ($A\ 50$) was also estimated, although model fits were improved when fixing the second selectivity parameter ($A\ 50 - 95$).

Obtaining successful model fits for the north-east stock was more challenging. In order to achieve model convergence, both M and h were fixed at the values estimated in the south-east stock. The steepness (h) parameter was fixed for each value at M at the value estimated during optimization for the south-east stock. Attempts were made to also use the median value estimated during MCMC, however these did not result in successful model fits. Fixing the h parameter allowed for the $A\ 50 - 95$ parameter to be estimated for these models.

Inclusions of recruitment deviations (dt) between 1989-90 and 2017-18 improved fits to age structures as variability in recruitment annually allowed for changes in the observed age structures from year to year. Previous studies have found recruitment estimation, even in years with limited data availability, did not result in biased biomass or depletion estimates (Methot and Taylor 2011).

Parameter descriptions and whether they were fixed or estimated for each stock are detailed in Table 5.

Table 5: Descriptions of parameters included in the models for both the north-east and south-east grey mackerel stocks

Parameter	North-east	South-east	Description
L_0	fixed	fixed	Total length at age zero in von Bertalanffy function
$L\infty$	fixed	fixed	Average maximum total length in von Bertalanffy function
κ	fixed	fixed	Growth rate in von Bertalanffy function
M	fixed	fixed	Natural mortality rate
$ln(B_0^{Sp})$	estimated	estimated	Natural log of virgin spawning stock size
h	fixed	estimated	Beverton-Holt steepness parameter, it represents how quickly a depleted population can recover
A_{50}	estimated	estimated	Age at 50% selectivity
A_{50-95}	estimated	estimated	Difference between the age at 50 and 95% selectivity
dt	estimated	estimated	Log recruitment deviations used to adjust annual recruitment from the deterministic Beverton-Holt calculation, used between 1989-90 and 2017-18

2.4.5 Uncertainty analysis

The ADMB version of the population model found maximum likelihood estimates and then performed Markov chain Monte Carlo (MCMC) to provide random samples of possible parameter values (Fournier et al. 2012) (version 12). A total of 1.1 million simulations were run for each model scenario and every 100th simulation was saved, resulting in 11000 retained estimates. Results from the first 1000 saved simulations were then excluded from mean, median and credible interval analysis.

3 Results

3.1 Model inputs

3.1.1 Reconstructed harvest

Total harvest for each stock was input into the population dynamics model, with this total harvest combining commercial, recreational and charter catch (Figure 9). Differences in trends of total harvest through time were observed for the stocks (Figure 9). The north-east stock has one peak in harvest in 2008-09 of 225 t (Figure 9). In the south-east stock there have been two discrete peaks in total harvest, the first between 1988-89 and 1991-92 of around 125 t, and again between 2006-07 and 2009-10 of around 200 t (Figure 9).

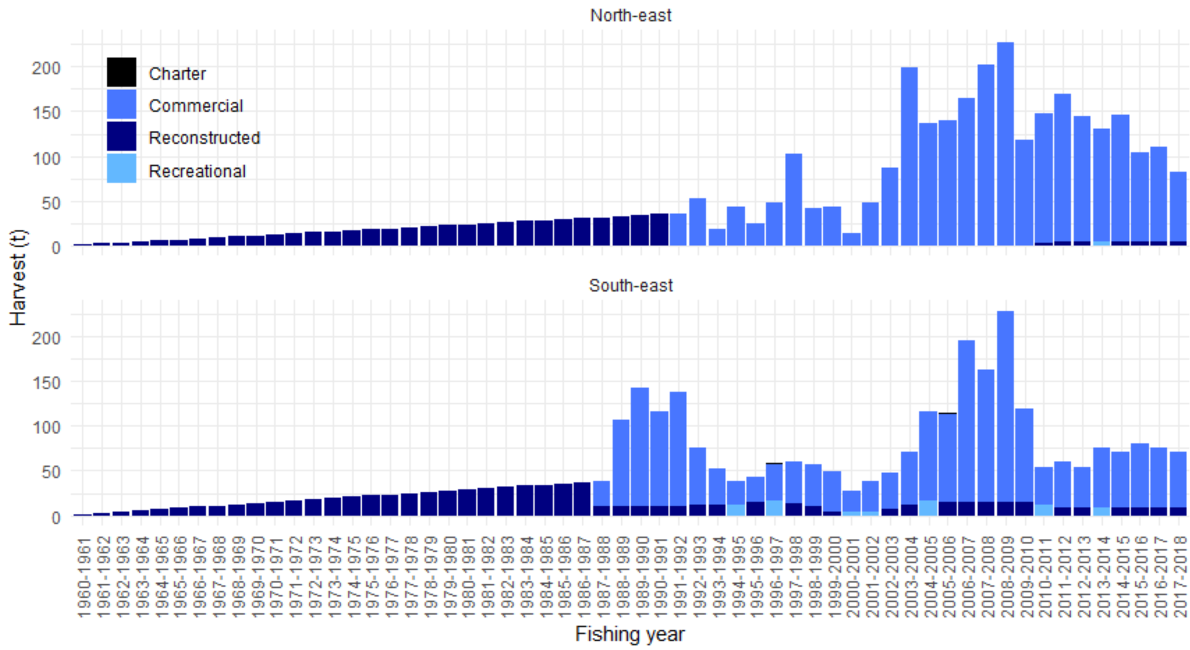

Figure 9: Reconstructed harvest from commercial, recreational and charter sectors between 1960-61 and 2017-18

3.1.2 Standardised catch rates

North-east stock

The north-east catch rate was below the average of the time series between 1987-88 and 1992-93 (Figure 10). Catch rates then increased to their highest point in 1999-2000, with some variation in this increase over this time (Figure 10). A sharp decline in catch rate was observed in 2000-01, with this corresponding with a low total harvest (Figure 9 and 10). Catch rates increased again until 2003-04, where they remained relatively stable until 2011-12 (Figure 10). Since 2011-12, there has been a gradual decline in catch rates, which have reached the average of the time series in the current year (2017-18, Figure 10).

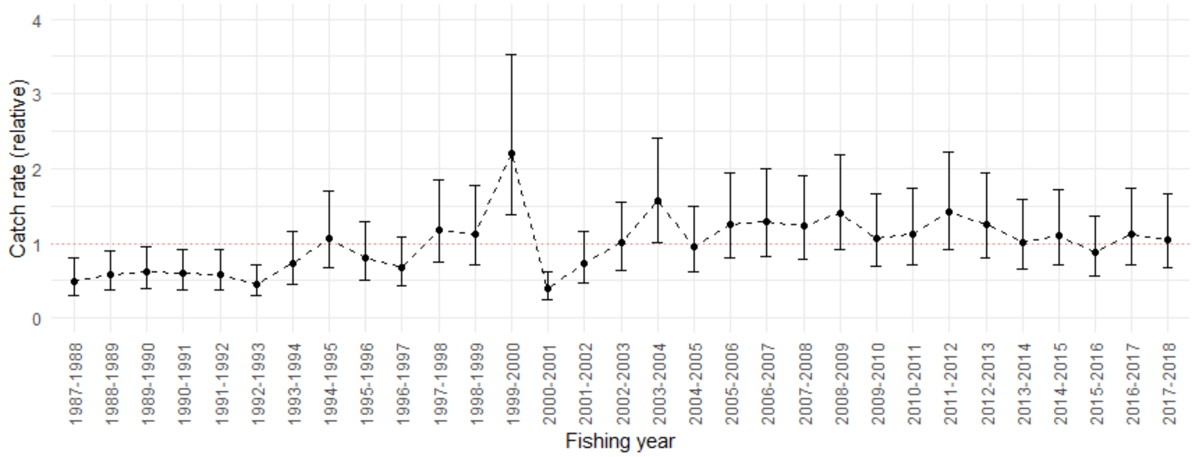

Figure 10: Standardised catch rates for net caught grey mackerel in the north-east stock, between the fishing years of 1987-88 and 2017-18, with error bars representing 95% confidence intervals. The dashed red line represents the average of the time series.

South-east stock

The standardised catch rate for the south-east stock showed a strong increase in catch rates between 1987-88 and 1992-93 (Figure 11). This peak in catch rates was followed by a decline until 1995-96, where catch rates stabilised for 3 years before increasing again in 1998-99 and 1999-2000 (Figure 11). Catch rates then fell below the long term average until 2005-06, where 3 years with above average catch rates were observed (Figure 11). Two years of declining catch rates followed before increasing again in 2013-14 (Figure 11). A slow decline was again observed between 2013-14 and 2016-17, before increasing again slightly in 2017-18 (Figure 11).

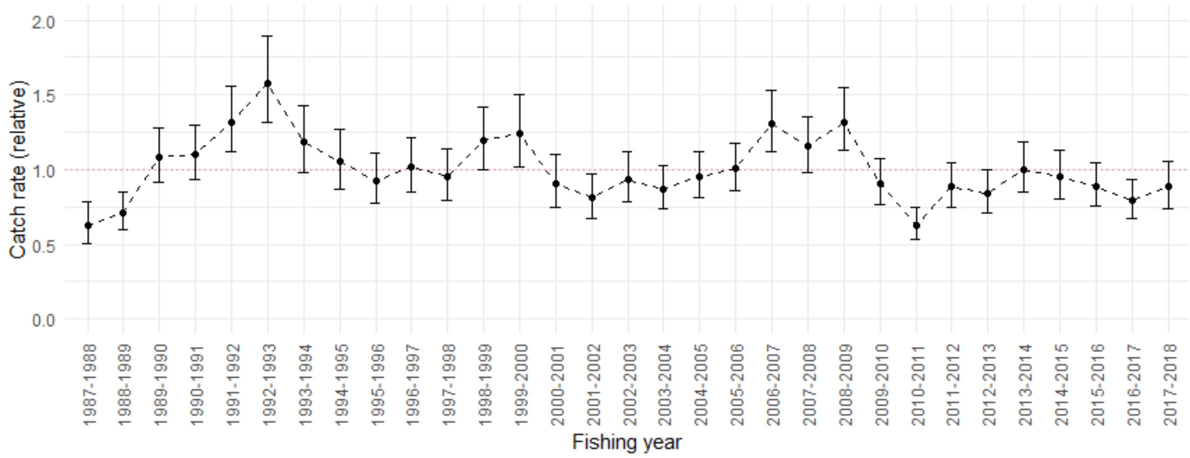

Figure 11: Standardised catch rates for net caught grey mackerel in the south-east stock, between the fishing years of 1988 and 2018, with error bars representing 95% confidence intervals. The dashed red line represents the average of the time series.

3.1.3 Age structures

Routine, fishery-dependent biological monitoring of grey mackerel commenced in the 2008-09 fishing year and did not continue after 2014-15. This data demonstrates that on the east coast of Australia, grey mackerel live to at least 13 years of age. In the north-east stock age structures are relatively consistent through time, with two year olds most commonly caught in all years except 2011-12 (Figure 12). Again, in the south-east stock, two year olds were the most common age class in all years except

2008-09, when three year old fish were most common (Figure 12). Grey mackerel are considered to be fully recruited into the fishery by two years of age, with a relatively high proportion of two year old fish often identifying years of strong recruitment (Figure 12).

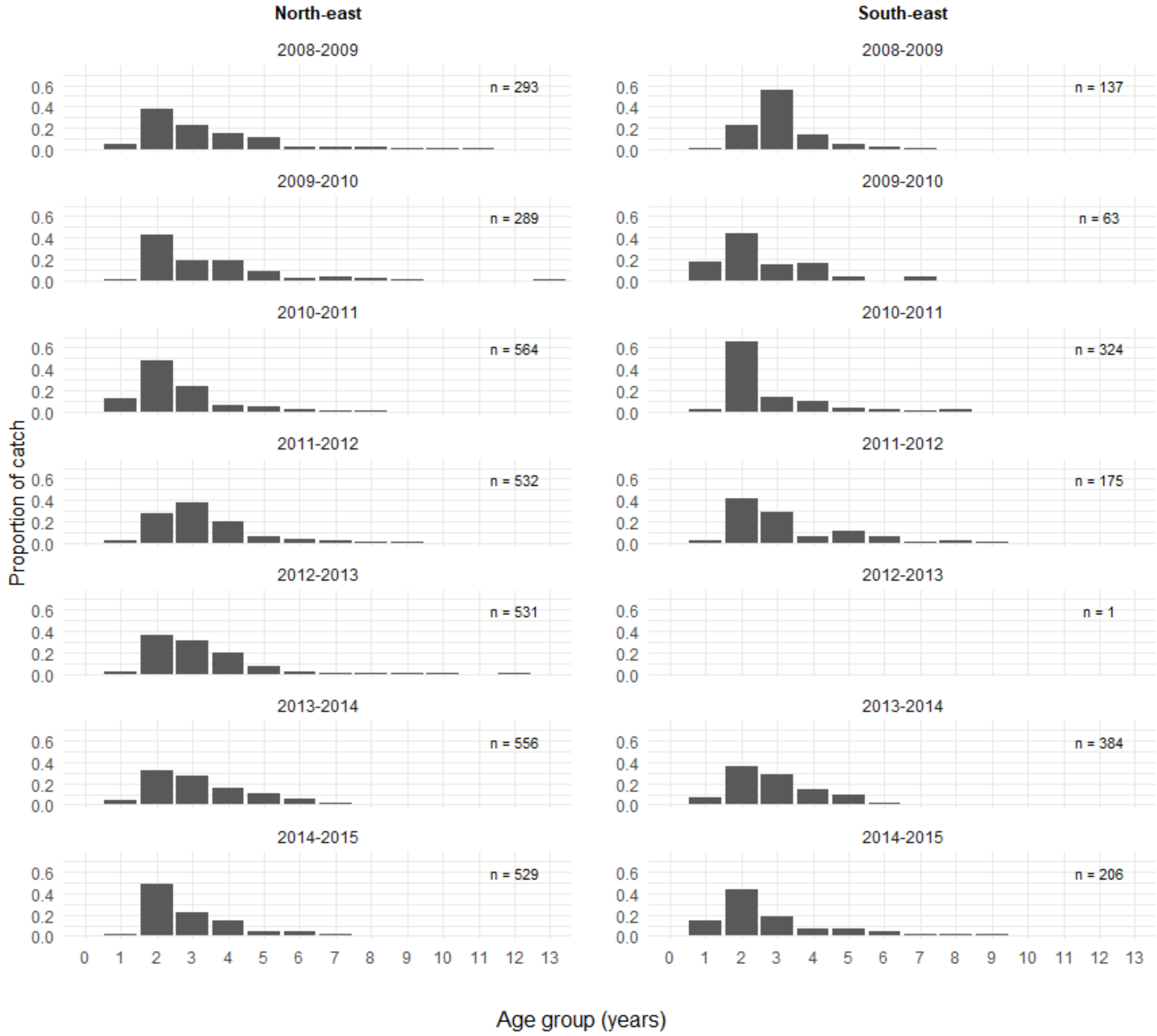

Figure 12: Annual age frequency distributions of grey mackerel retained by the south-east and north-east stock for net caught commercial fish between 2005-06 and 2014-15. The total number of fish sampled in each year (n) is included for each stock.

3.1.4 Length structures

A longer time series of fishery dependent length monitoring is available for grey mackerel than is available for age data. Length data was collected between 2008-09 and 2016-17. There are differences in the length of grey mackerel in each stock, with fish in the south-east stock generally reaching greater lengths (up to 120 cm fork length), than fish in the north-east stock (up to 110 cm fork length) (Figure 13). Length histograms for the north-east stock were mostly uni-modal with a median length of around 95 cm TL (Figure 13). In the south-east stock the length distribution appeared more bi-modal, with two peaks in the proportion of each length class, with these apparent around 80 cm and 110 cm TL (Figure 13). There was also more variation in the length structures in the south-east stock when compared to the north-east stock (Figure 13).

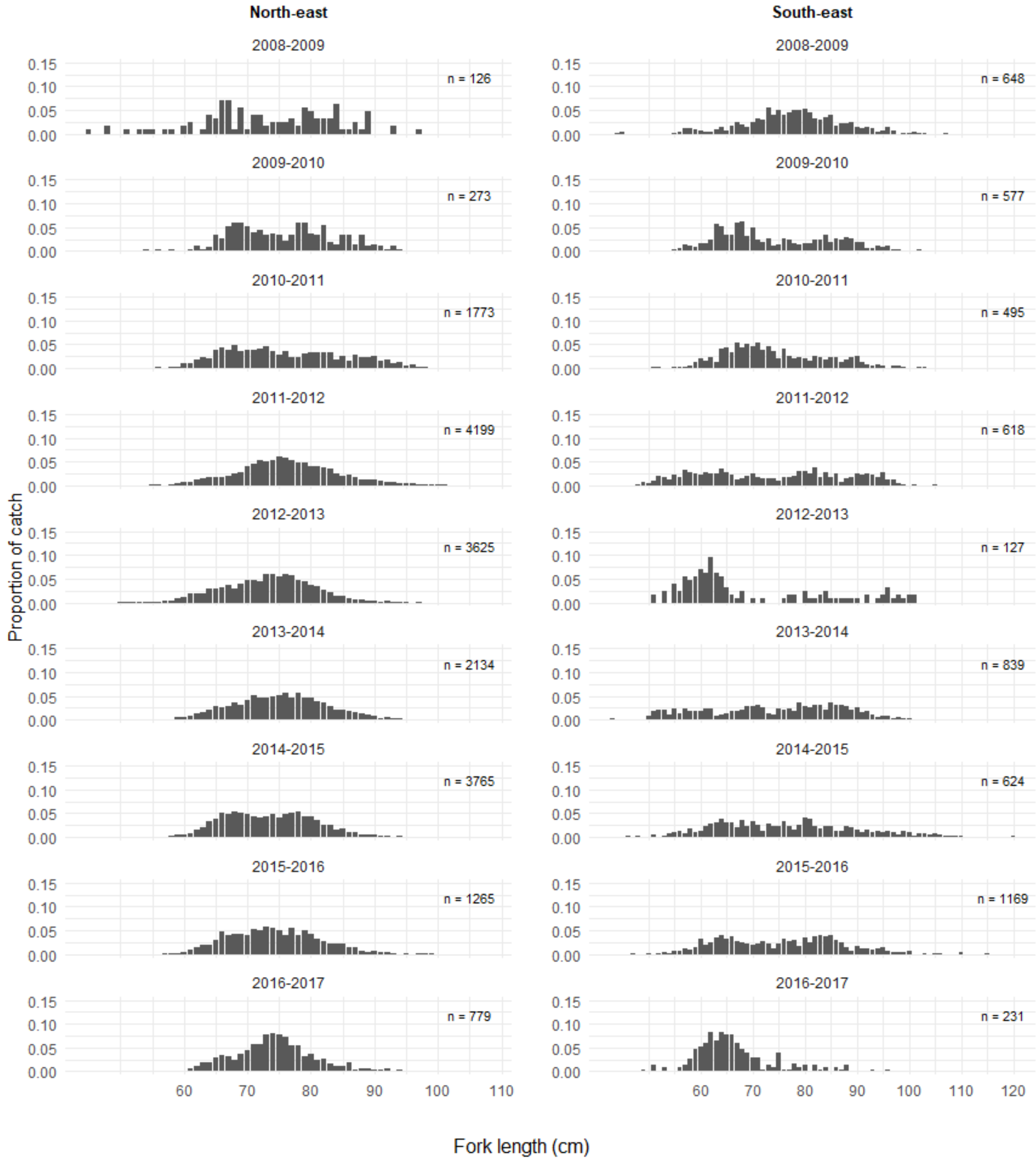

Figure 13: Annual length frequency distributions of grey mackerel retained by the south-east and north-east stock for net caught commercial fish between 2005-06 and 2016-17. The total number of fish sampled in each year (n) is included for each stock

3.1.5 Biological growth

Calculated von Bertalanffy parameters for each stock are detailed in the Appendix, Table 6, while the relationships are depicted in Figure 14. These parameters were used in the model to fit the predicted catch age-length samples. Estimated parameters for both the north-east and south-east stocks are detailed in Table 6. The variability of length within each age class is similar across the north-east and south-east stocks (Figure 24).

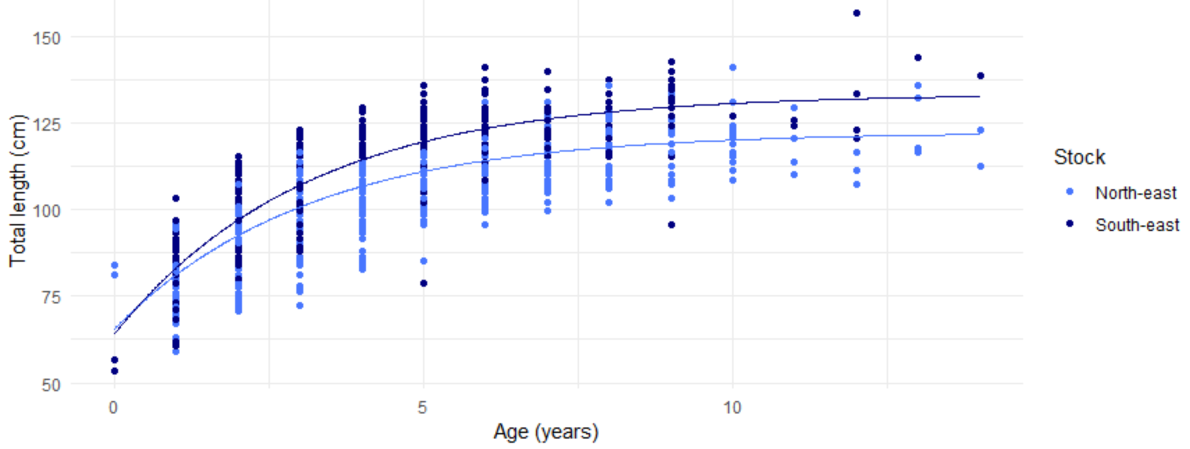

Figure 14: Von Bertalanffy growth curves for the north-east and south-east stocks demonstrating calculated length at age relationships that were used as model inputs. Male and females are aggregated as there were no considerable differences between the two. The analysis includes data collected between 2008-09 and 2014-15.

Table 6: Estimated biological parameters for both the north-east and south-east stock and standard errors (SE), that were used as fixed parameters in the population model.

Stock	Parameter	L_0	L_∞	κ
North-east	Estimate	40	116.20	0.56
	SE	NA	0.28	0.01
South-east	Estimate	30	125.40	0.58
	SE	NA	0.50	0.01

3.2 Model outputs

The model was run numerous times to investigate the impacts of estimating and fixing various parameters within the model. Initially all paramterers were estimated, although this did not result in sucessful model convergence. Different combinations of fixed and estimated parameters were then trialled, with three models presented for each stock, representing the best model fits. Recruitment deviations were included in the model between 1989-90 and 2017-18 for both stocks. These recruitment deviations allowed for annual variation in recruitment and resulted in improved fits to input data. Due to the hyperstable nature of standardised catch rates, the weighting of catch rate fitting to the overall negative log likelihood of the model was down weighted.

3.2.1 Model parameters

Three parameter settings were run for each stock, resulting in a total of six models for both stocks combined. These models were used to test sensitivity to fixed parameters. For both stocks three estimates of natural mortality (M) were analysed to compare the impact of different values on estimates of stock size and status (Table 7). Estimating the steepness parameter (h) for the north-east stock was not possible and this parameter was fixed at the same level estimated for the south-east stock corresponding with each of the fixed M values (Table 7). Other parameters including $ln(B_0^{Sp})$, and the first age selectivity parameter (A_{50}) were estimated for both stocks (Table 7). The second age selectivity parameter ($A_{50\text{-}95}$) was fixed for the south-east stock models and estimated in models for the north-east stock (Table 7).

Table 7: Summary of parameter estimates from each of the models investigated for both the north-east and south-east grey mackerel stock. Asterisks (*) notate parameters that were fixed.

Stock	M		h		$ln(B_0^{Sp})$	A_{50}	A_{50-95}		NLL
North-east	0.34	*	0.48	*	14.10	1.68	0.73		105.43
	0.40	*	0.43	*	14.22	1.70	0.72		101.25
	0.45	*	0.40	*	14.37	1.71	0.72		99.50
South-east	0.34	*	0.62		13.68	1.20	0.25	*	61.98
	0.40	*	0.62		13.73	1.21	0.25	*	60.59
	0.45	*	0.59		13.82	1.21	0.25	*	59.44

Model fit diagnostics are detailed in the Appendix, Figures 25-39. In both the north-east and south-east stocks, model predictions of standardised catch rates were not closely associated to the estimated standardised catch rates (Figure 25 and 26). Predictions for each of the models for each stock were similar (Figure 25 and 26). For both of the stocks the model estimated declines in standardised catch rates between 2004-05 and 2009-10 that were not evident in the estimated time series (Figure 25 and 26). Predicted age structures provided close fits to the measured structures for both stocks (Figure 27 and 28). Convergence of MCMC iterations for each model was satisfactory and are illustrated in Figure 29-39.

3.2.2 Biomass and recruitment: north-east stock

The predicted size of the north-east stock of grey mackerel varied between the three models, with the lowest estimate of M resulting in lower estimates of stock size, and the highest M resulting in the largest stock size estimates (Figure 15). The general trend of stock size saw a small decline in stock size between the start of harvesting in 1960-61 and 2003-04 (Figure 15). A larger decline in population size was observed between 2004-05 and 2010-11 (Figure 15). Following this decline stock size briefly increased (Figure 15). Further declines in stock size were observed between 2011-12 and 2014-15 and stock size has remained stable until the current year 2017-18 (Figure 15). In the current year, stock size was estimated at 39%, 41% and 61% of unfished with M=0.34, M=0.40 and M=0.45 models respectively (Figure 15). These estimates range between the MSY biomass level and 60% of unfished biomass (Figure 15).

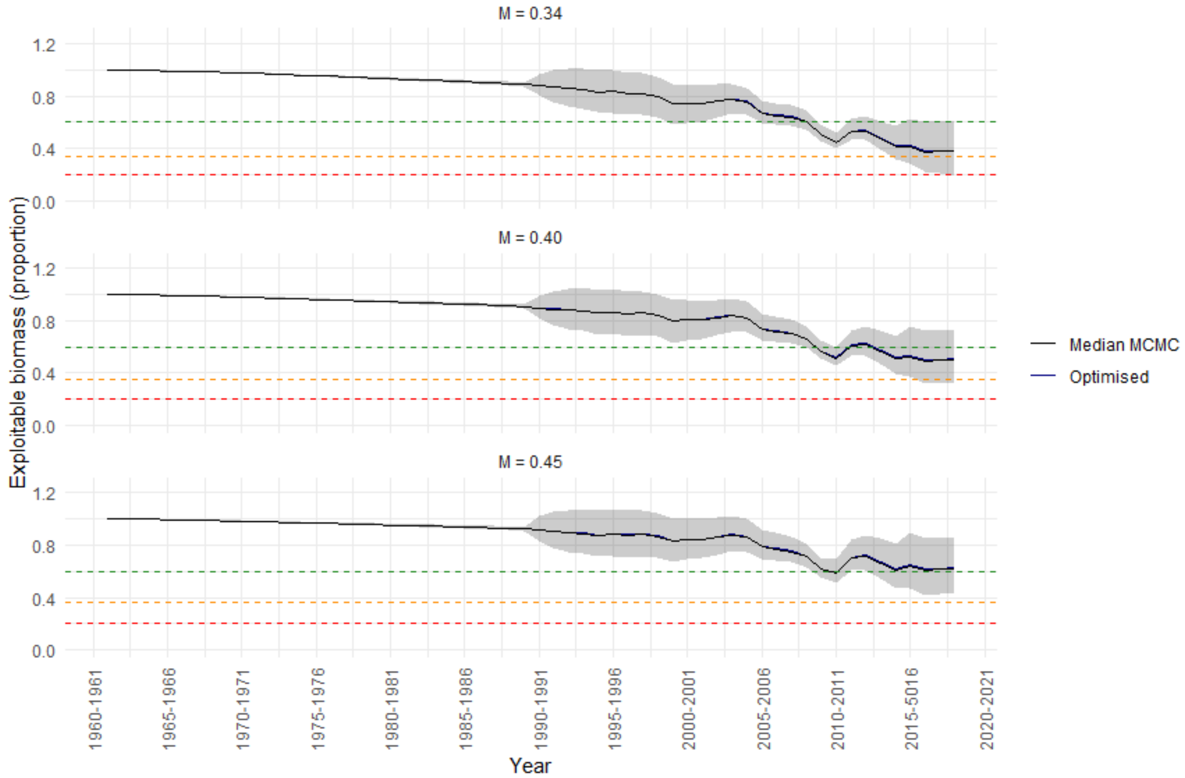

Figure 15: Predicted exploitable biomass trajectory relative to virgin exploitable biomass for each model, with fixed values of natural mortality (M) for the north-east stock. The black line illustrates the optimised prediction, while the blue line represents the median of results produced by MCMC, the shaded area represents the 95% credible interval of MCMC results.

Recruitment of grey mackerel in the north-east stock remained relatively stable between 1960-61 and 2000-01 (Figure 16). There has been variation in recruitment since and this corresponds to the period with recruitment deviations included in the model and larger variations correspond to years when age data is available.

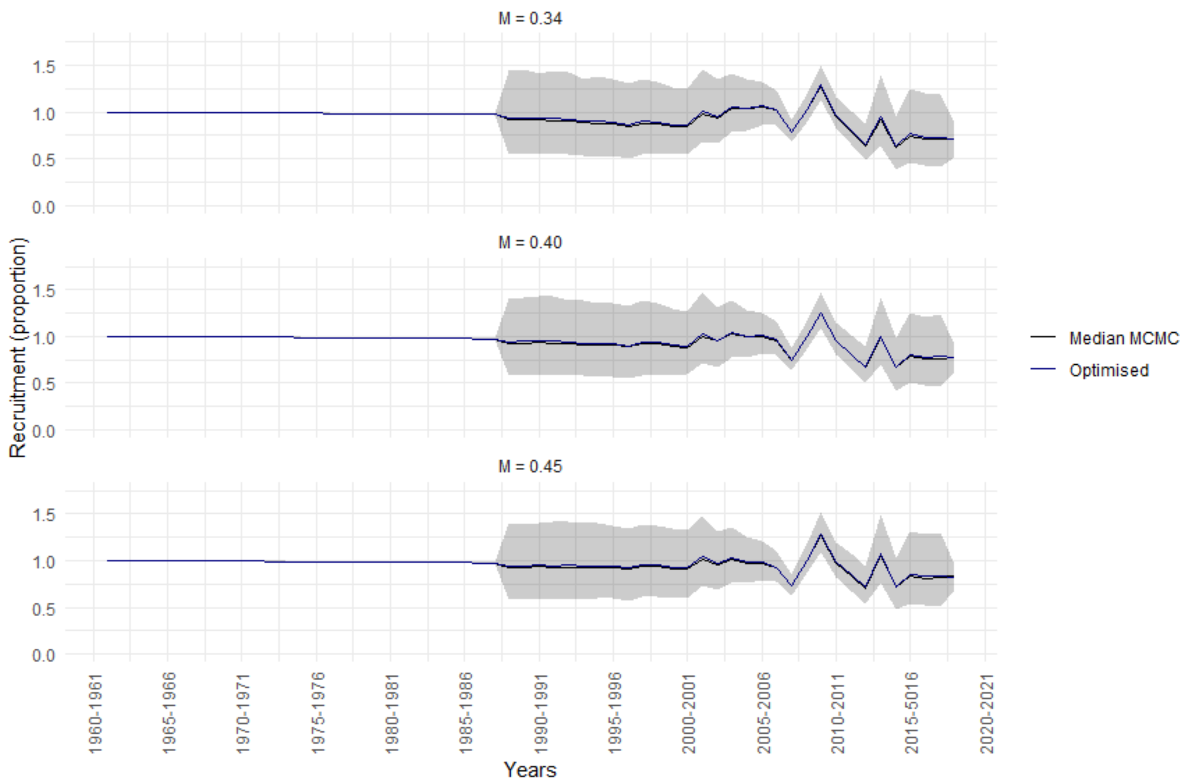

Figure 16: Recruitment deviations relative to virgin recruitment for each model, with fixed values of natural mortality (M) for the north-east stock. The black line illustrates the optimised prediction, while the blue line represents the median of results produced by MCMC, the shaded area represents the 95% credible interval of MCMC results.

The phase plot illustrates the time series relationship between biomass and harvest rate (~fishing pressure) for each of the three model scenarios (Figure 17). Each plot starts with a biomass proportion of 1 and harvest rate of 0 at the start of the time series (196-61, labelled as 1961), with each subsequent point along the line representing that state of the fishery in the following year (Figure 17). Across each of the models, harvest rates peaked at around the MSY level (horizontal orange line) in 2008-09 (labelled 2009) (Figure 17). This resulted in further declines in biomass, with M=0.34 models nearing the MSY biomass reference point (vertical orange line), while the other two models remained above this level (Figure 17).

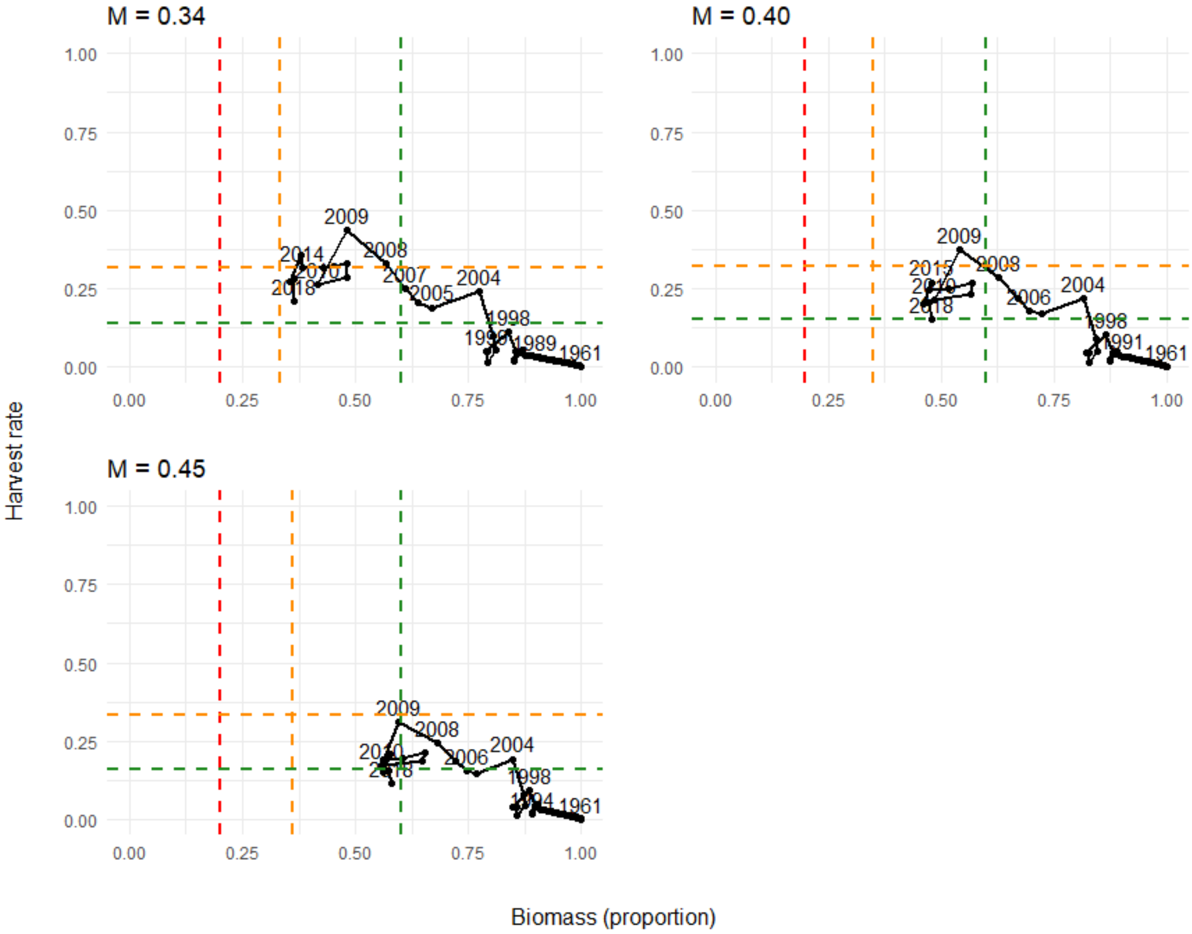

Figure 17: Phase plot with the relationship between harvest rate and exploitable biomass trajectory illustrated through time for each of the four models with fixed natural mortality (M) from the north-east stock. The green reference lines represent the harvest rate and biomass ratio of 60%, while the orange reference line represents the MSY exploitable biomass ratio. The red lines represent the limit reference point of 20% for both harvest rate and exploitable biomass ratio.

3.2.3 Harvest targets: north-east stock

Harvest targets have been calculated to maintain equilibrium biomass at MSY and 60% reference points for each model (Figure 18 and Table 8). Target harvests to maintain MSY levels are similar across all the three models and average 124 t (ranging between 92–176 t, Figure 18A and Table 8). There is a larger difference in estimates between the three models for the 60% target harvest, with lower estimates resulting from the model with M=0.34 (Figure 18B and Table 8). All estimates averaged 83 t and ranged between 24-143 t (full extent of 95% credible intervals) (Figure 18B and Table 8).

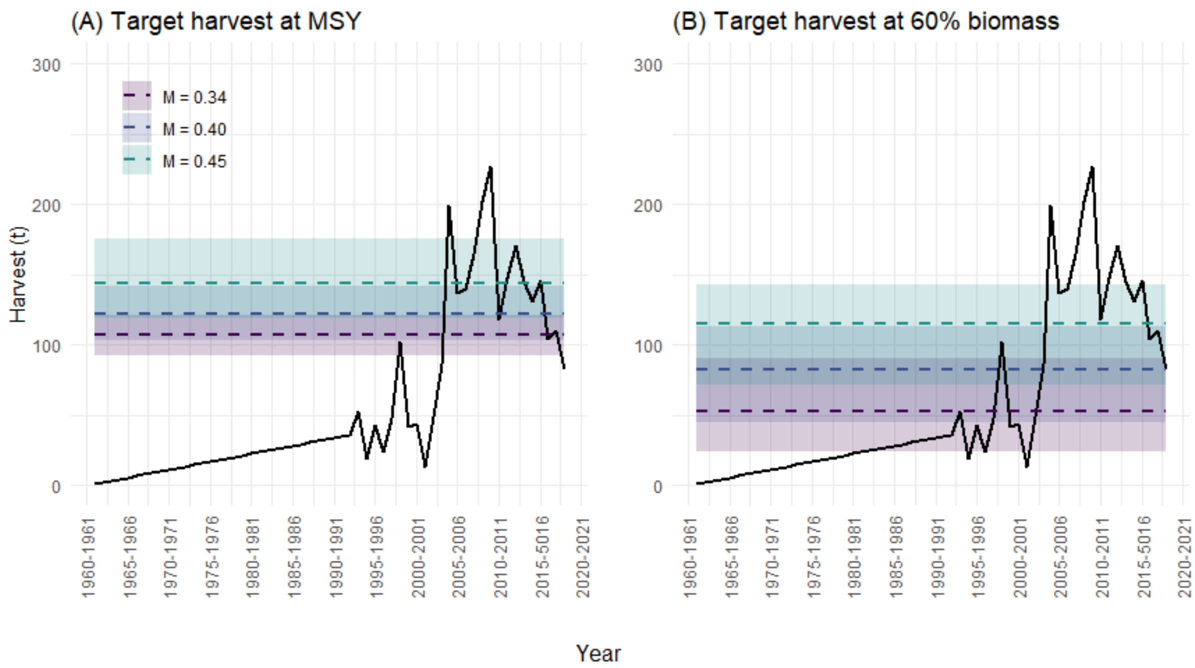

Figure 18: Annual harvest (t) of grey mackerel in the north-east stock with harvest targets estimated from each of the three models with different natural mortality values. Figure (A) demonstrates the range in harvest estimates to maintain biomass at maximum sustainable yield levels. Figure (B) demonstrates the rage in harvest estimates to maintain biomass at 60%. Lines show the median estimate for each model, while the shaded area represents the 95% credible intervals

Table 8: Estimated total harvest (t) to maintain a equilibrium state at maximum sustainable yield (MSY) levels, equilibrium biomass at 60% of unfished and rebuilding harvest targets to achieve 60% of unfished biomass. Lower and upper 95% credible intervals for each target are also presented.

Harvest targets	Estimate	M = 0.34	M = 0.40	M = 0.45
Equilibrium MSY	Median	106.85	122.30	143.61
	Lower	91.85	103.43	119.42
	Upper	120.82	141.89	175.59
Equilibrium 60%	Median	52.48	82.29	114.96
	Lower	24.19	44.72	71.27
	Upper	90.05	113.53	143.05
Rebuilding 60%	Median	54.00	81.00	115.00

3.2.4 Biomass and recruitment: south-east stock

The predicted size of the south-east stock of grey mackerel showed a similar trend across the three models investigated, with lower fixed values of M resulting in more conservative estimates of stock size (Figure 19). The general trend saw a gradual decline of biomass from 1960-61 to 1988-89, before declining more sharply until 1993-94 (Figure 19). Between 1993-94 and 2007-08 biomass increased, before dropping again until 2010-11 (Figure 19). Since 2010-11, biomass has increased relatively consistently (Figure 19). Differences in stock size between optimised and median MCMC estimates were observed from 2005-06 onwards for all modes. These results suggest that biomass declined to the MSY reference point at its lowest point (Figure 19). Credible intervals at the end of the time series are large and this likely reflects the lack of age structure information for recent years (Figure 19).

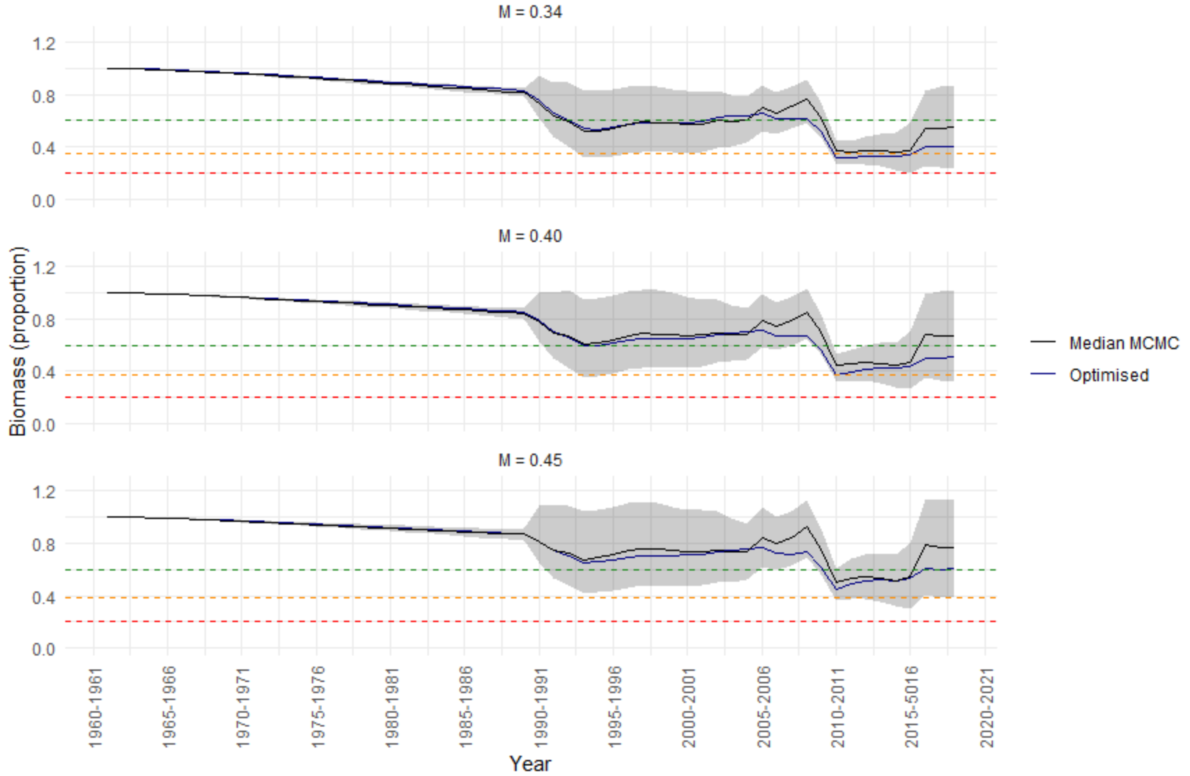

Figure 19: Predicted exploitable biomass trajectory relative to virgin exploitable biomass for each model fit for the south-east stock, with three fixed estimates of natural mortality (M). The black line illustrates the optimised prediction, while the blue line represents the median of results produced by MCMC, the shaded area represents the 95% credible interval of MCMC results.

Recruitment of grey mackerel in the south-east stock displayed variability since 2003-04 for each of the models (Figure 20). This variability corresponded with years that age structure data were available and large credible intervals are observed during the time period where recruitment deviations were included in the model (Figure 20).

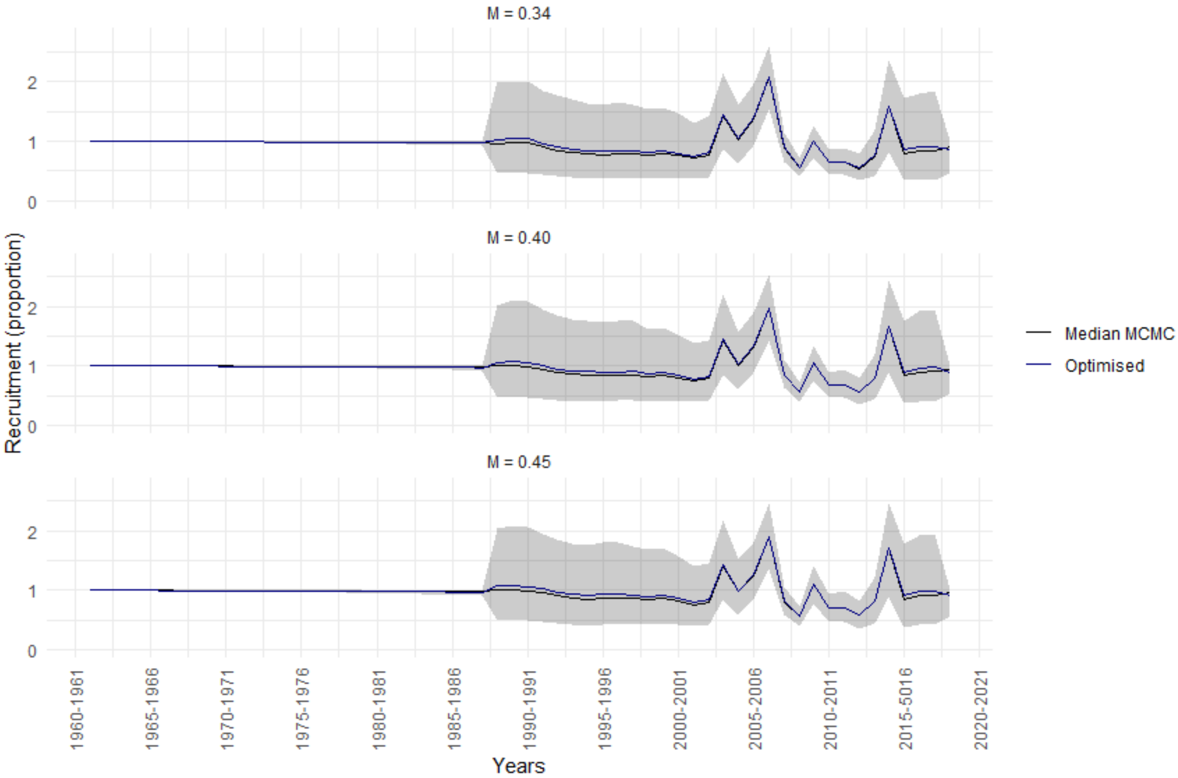

Figure 20: Recruitment deviations relative to virgin recruitment for each model, with fixed values of natural mortality (M) for the south-east stock. The black line illustrates the optimised prediction, while the blue line represents the median of results produced by MCMC, the shaded area represents the 95% credible interval of MCMC results.

Phase plots of the relationship between biomass and harvest rate through time show differences in the predictions from each of the three models (Figure 21). Biomass and harvest rate relationships show similar trends across each of the models (Figure 21). Harvest rates peaked between 2006-07 and 2009-10 in each of the three models and all these estimates were above the MSY reference point (horizontal orange line) (Figure 21). Declines in the harvest rate then have resulted in increasing biomass from around the MSY level (orange vertical line), moving towards the 60% target level (green vertical line) (Figure 21).

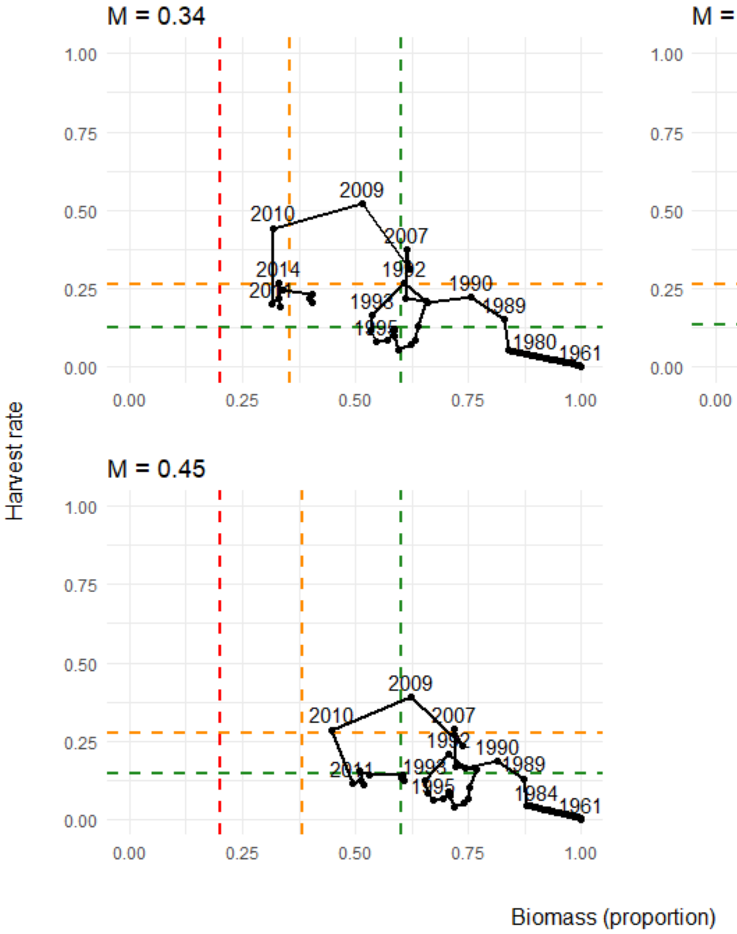

Figure 21: Phase plot with the relationship between harvest rate and exploitable biomass trajectory illustrated through time for each of the four models with fixed natural mortality (M) from the south-east stock. The green reference lines represent the harvest rate and biomass ratio of 60%, while the orange reference line represents the MSY exploitable biomass ratio. The red lines represent the limit reference point of 20% for both harvest rate and exploitable biomass ratio.

3.2.5 Harvest targets: south-east stock

Harvest targets to maintain MSY and 60% of unfished biomass reference points have been estimated for each model (Figure 22 and Table 9). Equilibrium MSY harvest targets averaged 106 t, with estimates ranging between 58–198 t (full range of 95% credible intervals between models) (Figure 22 and Table 9). Target 60% biomass equilibrium harvests averaged 75 t and ranged between 19–132 t (Figure 22 and Table 9).

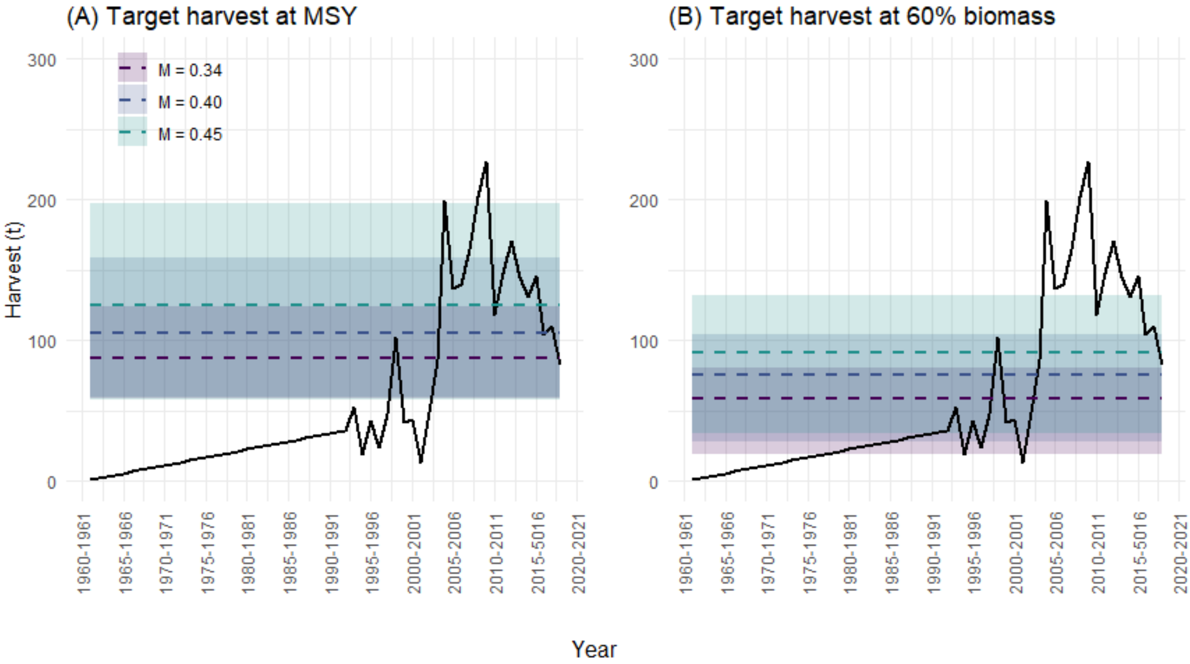

Figure 22: Annual harvest (t) of grey mackerel in the south-east stock with harvest targets estimated from each of the three models with different natural mortality (M) estimates. Figure A demonstrates the range in harvest estimates to maintain biomass at maximum sustainable yield levels while Figure B demonstrates the rage in harvest estimates to maintain biomass at 60%. Lines show the median estimate for each model, while the shaded area represents the 95% credible intervals

Table 9: Estimated total harvest (t) to maintain a equilibrium state at maximum sustainable yield (MSY) levels, equilibrium biomass at 60% of unfished and rebuilding harvest targets to achieve 60% of unfished biomass. Lower and upper 95% credible intervals for each target are also presented.

Harvest targets	Estimate	M = 0.34	M = 0.40	M = 0.45
Equilibrium MSY	Median	87.06	105.32	124.50
	Lower	58.27	59.32	57.83
	Upper	123.92	158.31	197.52
Equilibrium 60%	Median	58.27	75.94	91.20
	Lower	18.93	28.08	34.00
	Upper	80.80	104.35	131.86
Rebuilding 60%	Median	84.00	61.00	43.00

4 Discussion

4.1 Stock status

Grey mackerel on the east coast of Qld are a predominantly commercially caught species, using mainly gill nets in the East Coast Inshore Fin Fish Fishery. Fishing pressure had few regulatory constraints until 2010, when a commercial total allowable catch (TACC) of 250 t was introduced. The TACC aimed to maintain sustainable harvest levels and reduce conflict between recreational and commercial fishers in the north of the state (Fisheries Qld pers. comm.). Since the introduction of the TACC, harvests have been relatively stable at around 200 t, however, the final year included in this analysis saw a drop in total harvest below 150 t. If this reduction in harvest continues, further investigations would be required to determine the cause and whether it is associated with reductions in stock size.

Biomass of the north-east stock is currently estimated between 38 and 62% of unfished biomass, while the south-east stock is estimated between 40 and 61% of unfished biomass. These estimates include commercial, recreation and charter harvests.

As grey mackerel form schools that are predictable in location and timing they are susceptible to overfishing. This trait also means catch rates can be hyperstable (Walters 2003; Campbell et al. 2012). Therefore, some precaution when interpreting results and an understanding of the fishery is required when making classifications of stock status.

The results presented in the current assessment differ to the previous assessment due to different modelling approach and additional data inputs (Lemos et al. 2014). In addition, the previous assessment modelled the stocks as regions within the model, while the current assessment has modelled them separately. There is also additional data included in the current assessment, with an additional three years of age structures. An additional eight years of harvest data is also included. These additional datasets likely account for the different results produced by each assessment.

A previous study investigated bycatch in prawl trawl fisheries between 1996 and 1998 (Stobutzki et al. 2000). In trawl samples undertaken in north-east Queensland (< 22°S), 38 juvenile grey mackerel of less than 30 cm fork length (median of 12 cm fork length) were caught in trawl gear of the banana prawn fishery (Stobutzki et al. 2000). All of the grey mackerel were caught in standard gear, without bycatch reduction devices (BRDs) or grids fitted to reduce turtle catches (turtle exclusion device, TED) (Stobutzki et al. 2000). These 38 fish accounted for 0.02% of the total bycatch in the trawl samples (Stobutzki et al. 2000). Extrapolations suggested that an average of 69 609 grey mackerel individuals (±31 329 standard deviation) caught each year (Stobutzki et al. 2000). This number will have likely declined with the introduction of BRDs and TEDs, and reduced effort in the banana prawn fishery. Further investigation of this mortality on juvenile grey mackerel through time would be required to account for this impact in future assessments.

4.2 Performance of the population model

There was difficulty obtaining successful model fits when estimating the stock recruitment steepness parameter and natural mortality for the north-east stock. This difficulty in estimating parameters is probably due to discrepancies in trends of various data inputs. Attempts to estimate steepness for the north-east stock should be trialed in future assessments, although this will be challenging without additional data on the age structure of the population. The steepness parameter, h, was estimated for the south-east stock. MCMC investigations revealed a large parameter space and convergence of this parameter was limited. The median of MCMC results was used as a estimate of this parameter, however, it is important to note that there was large variability in estimates and future assessments should aim to improve confidence around this parameter. Additional data, see below, should improve parameter estimation in future assessments.

4.3 Environmental impacts

While there is not currently any evidence of major environmental impacts influencing stock size, there are probably some impacts occurring. Previous investigations on the impacts of changes in environmental variables due to climate change identified various potential high risks to grey mackerel (Welch et al. 2010). Impacts of changes in sea surface temperatures and nutrients were both rated as high risks, while rainfall, river flow and salinity were rated as medium risks (Welch et al. 2010). It was also suggested that altered rainfall levels and patterns may influence the survival of juveniles and therefore the population size of grey mackerel (Welch et al. 2010).

Changes in ocean currents may also influence the schooling behaviour of grey mackerel. These changes may influence the location and availability of baitfish, reducing grey mackerel food availability and, potentially their population size. Temperature changes may also influence the timing and location of spawning (Frank et al. 1990; Drinkwater 2005; Rose 2005). Additionally, temperature changes have been found to be an important determinant of mortality in the early stages of multiple fish species (Houde 1987; Takasuka et al. 2007). These environmental impacts have the potential to impact the stock size of grey mackerel and understanding of specific impacts is not well understood. Further targeted research into the various impacts of environmental changes on grey mackerel would benefit future assessments and management of the fishery.

4.4 Recommendations

4.4.1 Data

It is recommended that improved mechanisms to report daily grey mackerel harvests and fishing effort per operation be identified and implemented. This should include potential used 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 grey mackerel were targeted but not caught would also be beneficial. More frequent measures of recreational harvest and effort for regional locations along the Qld east coast 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

The cessation of fishery dependent monitoring of age structures in 2014-15 made this assessment more challenging and increased uncertainty in results. Each additional year without age monitoring makes obtaining sensible results from stock assessment more difficult and results in increased levels of uncertainty. Monitoring of age structures, representative of the commercial gill net fishery for each stock, is required to ensure that accurate reference points for harvest strategies can be determined into the future.

4.4.3 Management

The implementation of a harvest strategy, to initially grow the stock back to the 60% size and then maintain this population size over time is required. Indicators to include in a harvest strategy and monitor over time could include periodic biomass estimated 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 hyperstable nature of this species, particularly until improved fishing effort measures are recorded. If age monitoring recommences, indicators from this data could be developed to overcome potential hyperstability problems with standardised catch rates.

To grow the north-east stock to the target state of 60% of unfished biomass, as specified in the Strategy, total harvests for all sectors need to be in the range of 64—97 t, depending on which model is used for management purposes. While to grow the south-east stock to 60% biomass would require harvests between 50–72 t. These ranges are calculated from estimates from each of the three models fit for each stock. In addition, with increased model uncertainty in the past 5 years a conservative management approach is recommended. This is particularly important for the north-east stock, where the steepness parameter h needed to be inferred from the south-east stock to ensure successful model fits.

4.4.4 Assessment

As biological monitoring of grey mackerel was discontinued 2014-15 future assessments will continue to have difficulty obtaining successful model fits with data that is currently available. Future assessments should focus on estimating both the natural mortality and steepness parameters for both of the stocks. Further investigations into incorporating hyperstability into standardised catch rates may also prove beneficial.

4.5 Conclusions

This study has informed the status of both the north-east and south-east stocks of Australia's east coast grey mackerel. It suggests that fishing pressure was above sustainable levels between 2007-08 and 2010-11 for both stocks. This period of high fishing pressure resulted in declines of stock size. Management intervention with the introduction of a TACC seems to have prevented any further declines in stock size. These results suggest that the high harvests between 2006-07 and 2008-09, which were approximately 350 t for both stocks combined, were above the sustainable limit. The study recommends harvest limits that will grow each stock to levels consistent with 60% of unfished biomass target level, as specified in Qld's *Sustainable Fisheries Strategy*.

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6 Appendix

6.1 Reconstructed data

6.1.1 Recreational harvests

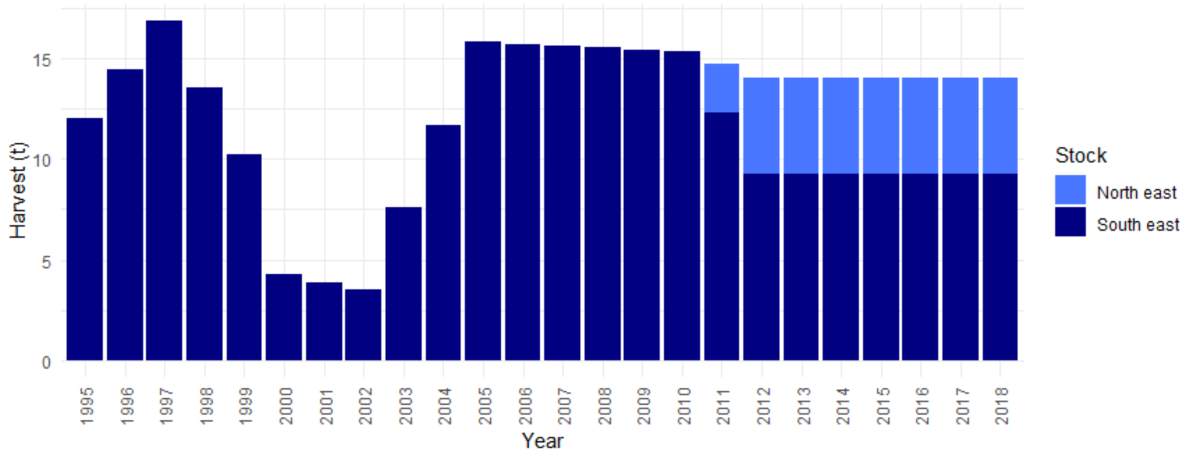

Figure 23: Estimated recreational harvest in the south-east and north-east stocks.

6.2 Biological data

6.2.1 Age and length relationships

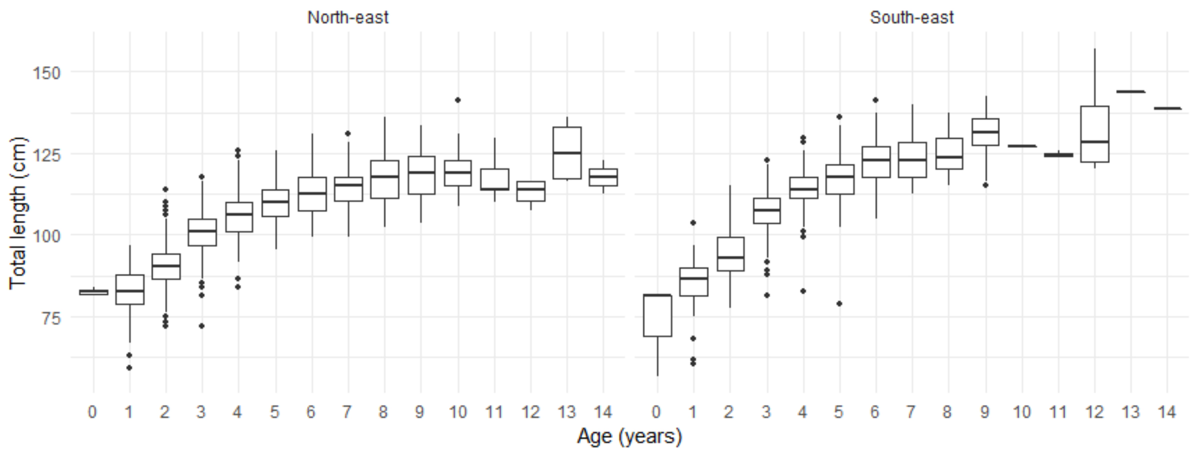

Figure 24: Relationship between the range of lengths in each age group for both the north-east and south-east stock. Each boxplot represents the range of lengths for each age group, the middle line through the box represents the median, while the top and bottom of the box represent the 75th and 25th percentiles respectively. The whisker lines outside the box extend to cover extreme values that were not considered outliers.

6.3 Population model fits

6.3.1 Standardised catch rates

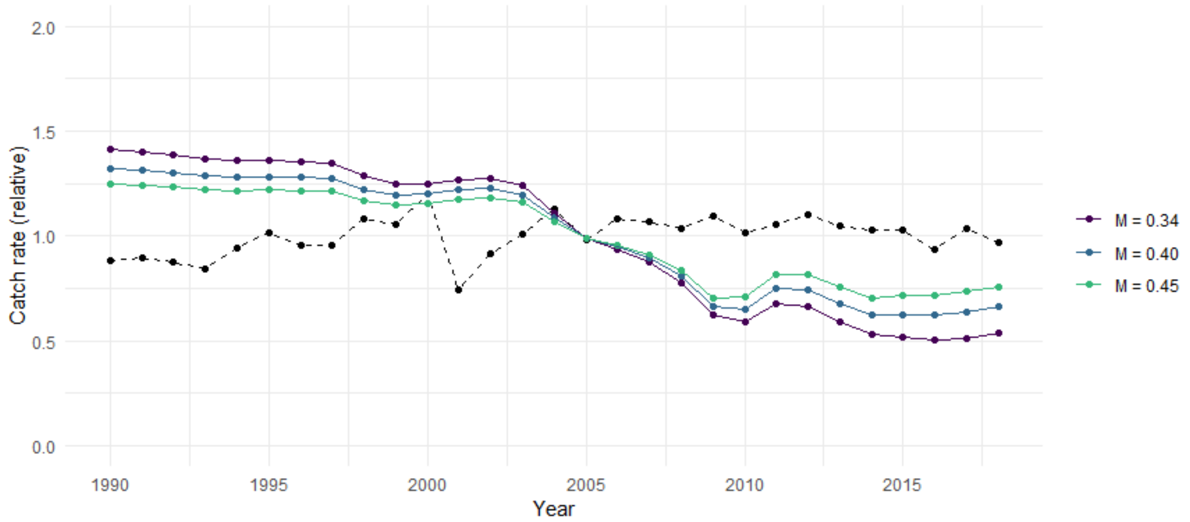

Figure 25: Stock model fitted values to the standardised commercial catch rates of the north-east stock of grey mackerel for each MCMC analysis. The black line represents the calculated catch rate, while the coloured lines represent the fitted catch rate. .Models include natural mortality fixed at three values, M=0.34, M=0.40 and M=0.45. .

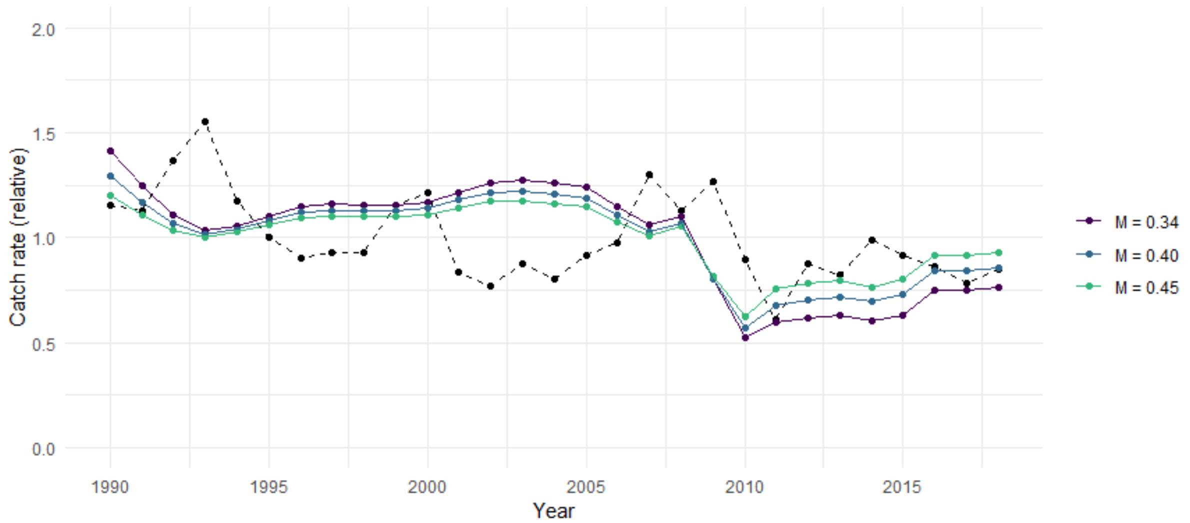

Figure 26: Stock model fitted values to the standardised commercial catch rates of the south-east stock of grey mackerel for each MCMC analysis. The black line represents the calculated catch rate, while the coloured lines represent the fitted catch rate within each of the models. Models include natural mortality fixed at three values, M=0.34, M=0.40 and M=0.45. .

6.3.2 Age structures

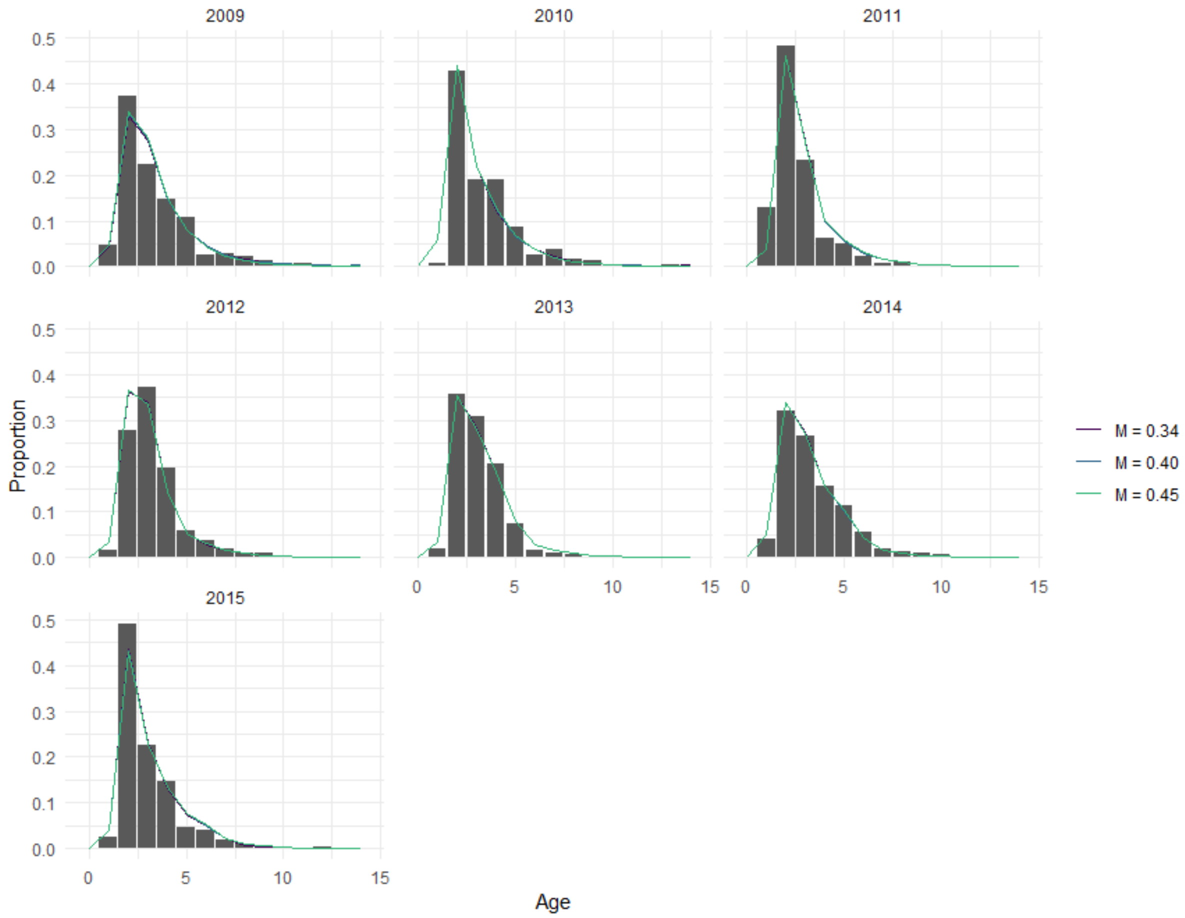

Figure 27: Stock model predictions of grey mackerel ages harvested by commercial operations from the north-east stock. Bars represent the measured values, while the coloured lines represents the model fit for each of the models. Models include natural mortality fixed at three values, M=0.34, M=0.40 and M=0.45. . The frequency of each observation is recorded as a proportion.

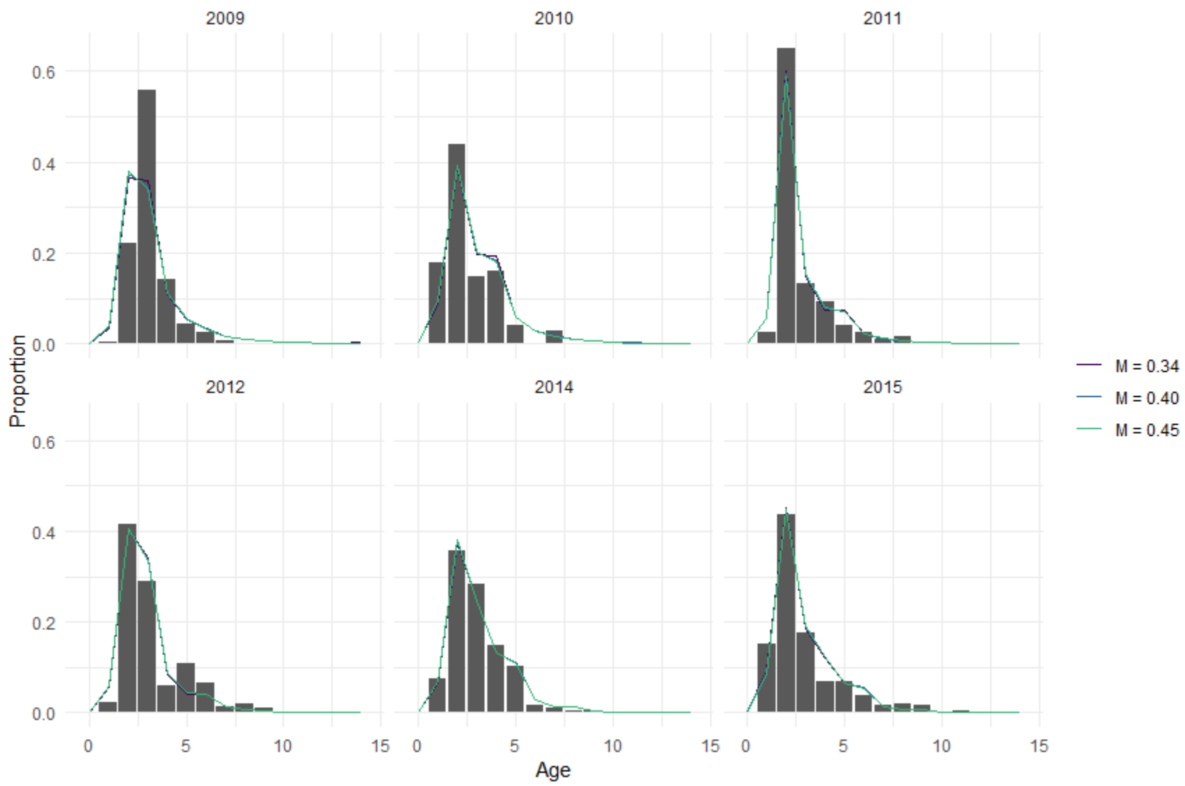

Figure 28: Stock model predictions of grey mackerel ages harvested by commercial operations from the south-east stock. Bars represent the measured values, while the coloured lines represents the model fit for each of the models. Models include natural mortality fixed at three values, M=0.34, M=0.40 and M=0.45. The frequency of each observation is recorded as a proportion.

6.3.3 MCMC convergence

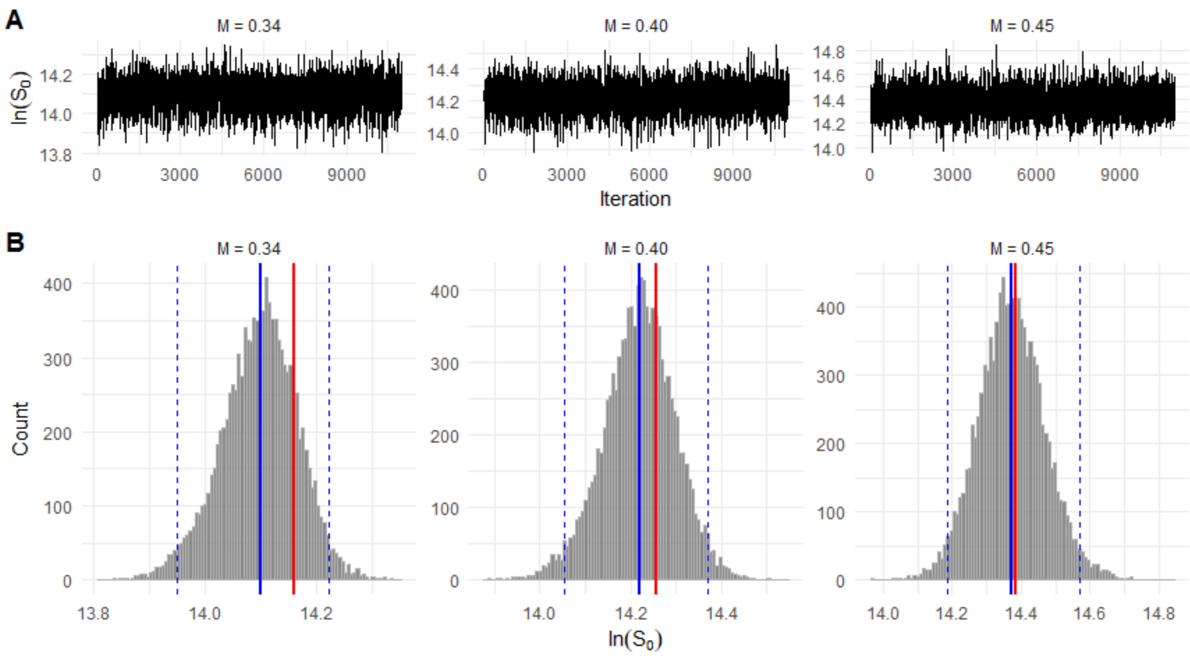

Figure 29: Trace plot and histogram of the ln(S_0) parameter estimates of the north-east stock for each of the models with natural mortality (M) fixed at three values, M=0.34, M=0.40 and M=0.45. The trace plot (A) shows convergence of the MCMC fit, while the histogram (B) shows the distribution of estimates with the median estimate (blue solid line) and 95% credible intervals (blue dashed lines), the optimised estimate is also included (red line).

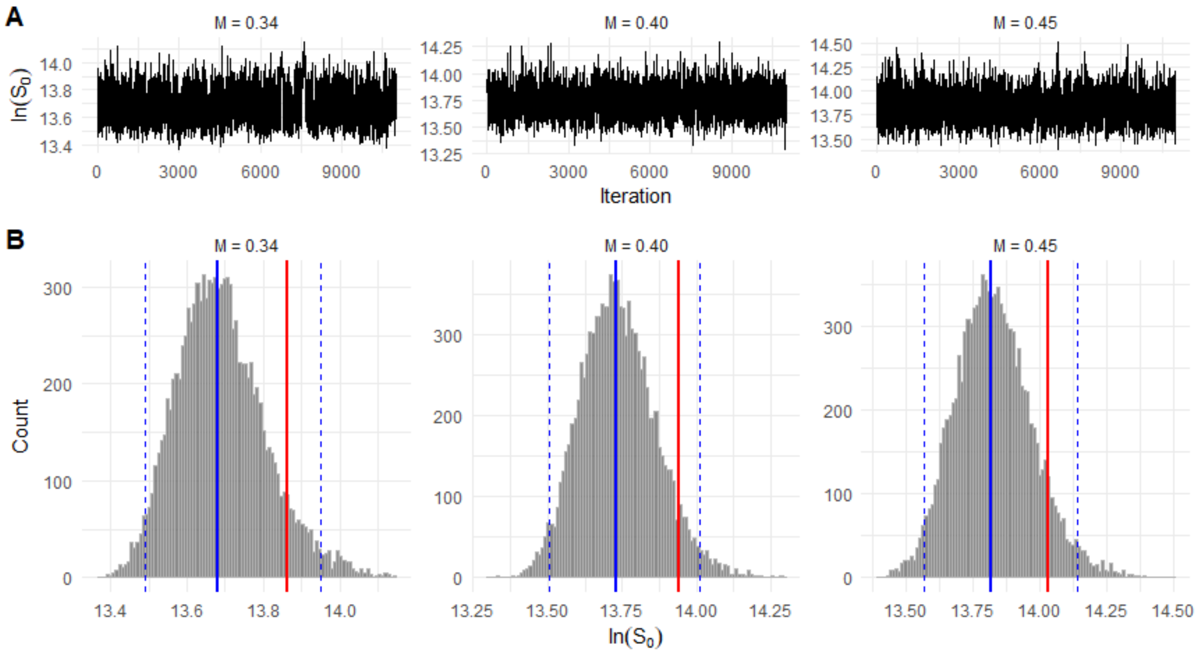

Figure 30: Trace plot and histogram of the ln(S_0) parameter estimates of the south-east stock for each of the models with natural mortality fixed at three values, M=0.34, M=0.40 and M=0.45. The trace plot (A) shows convergence of the MCMC fit, while the histogram (B) shows the distribution of estimates with the median estimate (blue solid line) and 95% credible intervals (blue dashed lines), the optimised estimate is also included (red line).

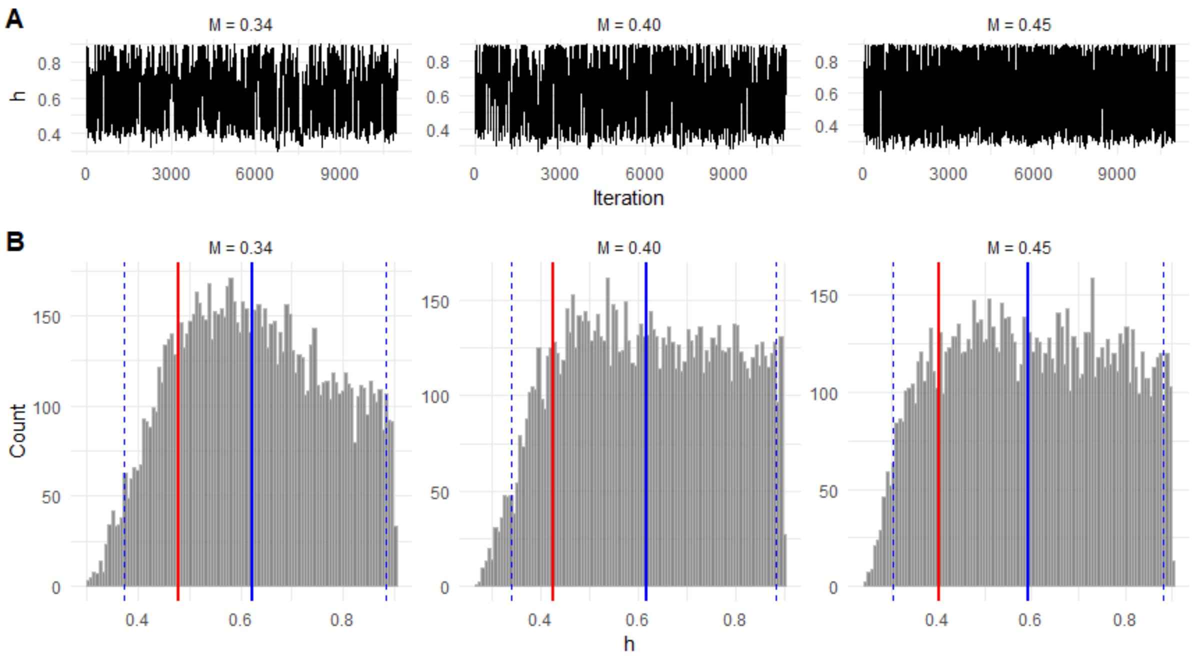

Figure 31: Trace plot and histogram of the steepness (h) parameter estimates of the south-east stock for each of the models with natural mortality fixed at three values, M=0.34, M=0.40 and M=0.45. The trace plot (A) shows convergence of the MCMC fit, while the histogram (B) shows the distribution of estimates with the median estimate (blue solid line) and 95% credible intervals (blue dashed lines), the optimised estimate is also included (red line).

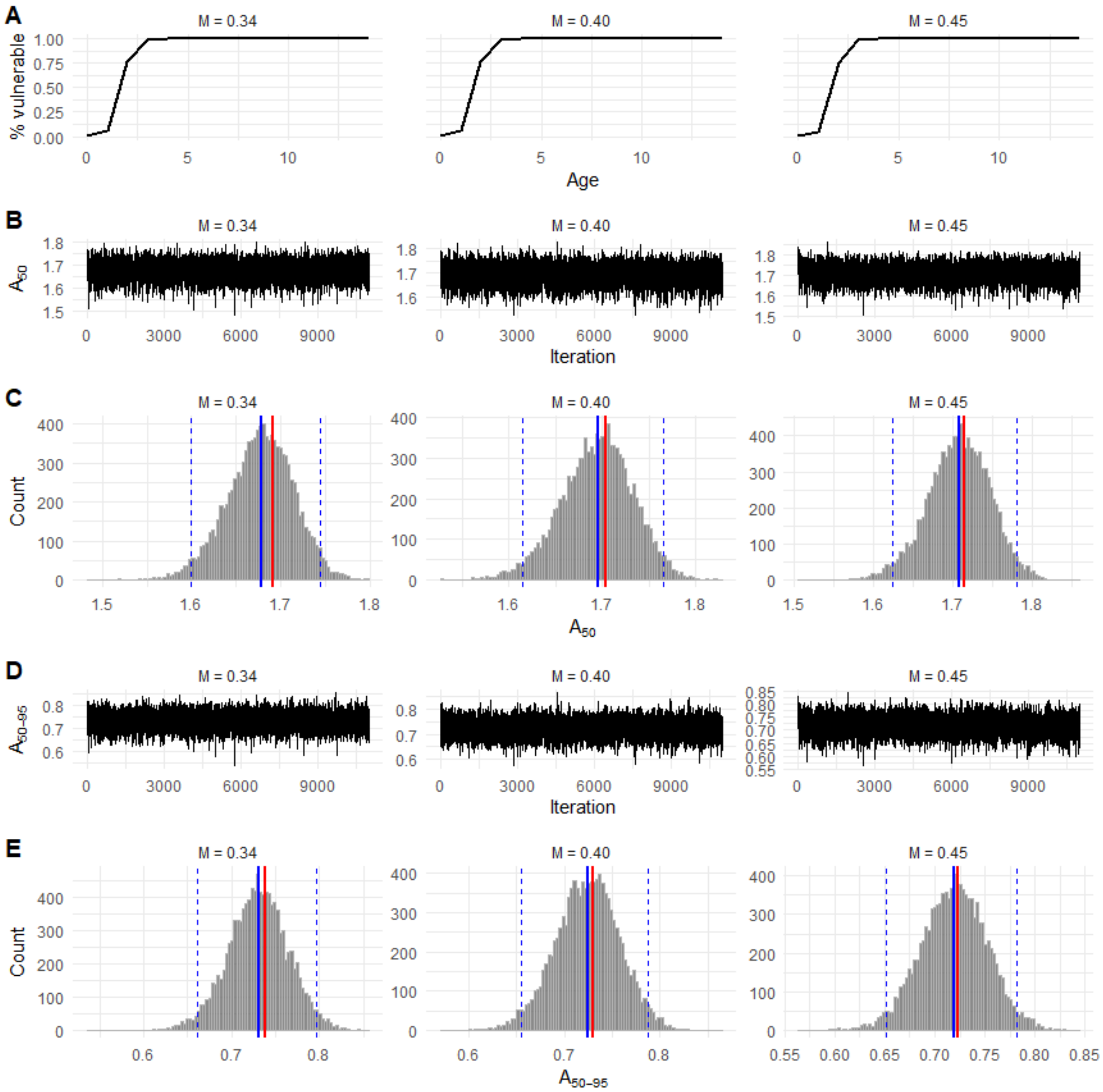

Figure 32: Trace plot and histogram of the selectivity parameter estimates of the north-east stock for each of the models with natural mortality (M) fixed at three values, M=0.34, M=0.40 and M=0.45. The estimated selectivity curve (A) is illustrated, along with the trace plot of the A_{50} parameter (B), which shows convergence of the MCMC fit. The histogram (C) shows the distribution of estimates with the median estimate (blue solid line) and 95% credible intervals (blue dashed lines), the optimised estimate is also included (red line) for the A_{50} parameter. Plots D and E illustrate the same as B and C for the $A_{50\text{-}95}$ selectivity parameter

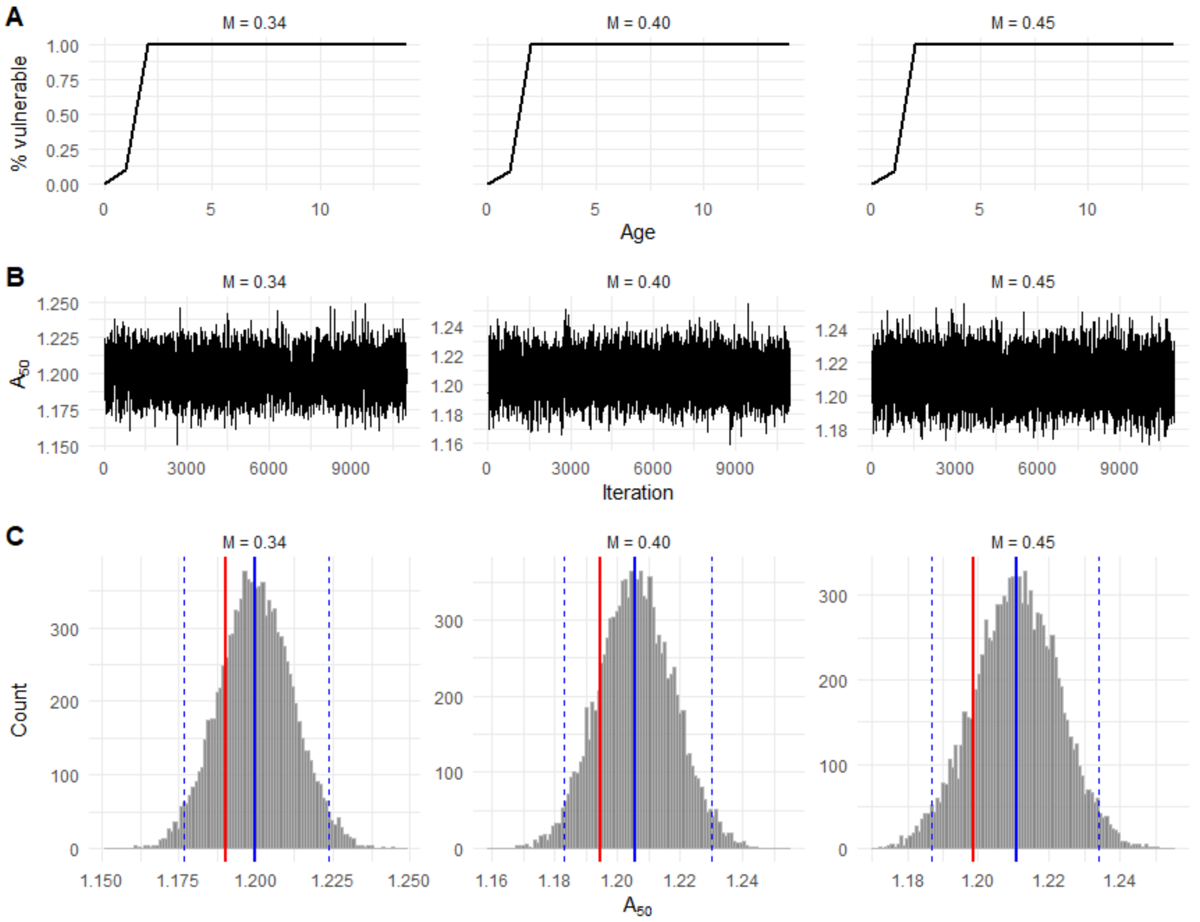

Figure 33: Trace plot and histogram of the selectivity parameter estimates of the south-east stock for each of the models with natural mortality fixed at three values, M=0.34, M=0.40 and M=0.45. The estimated selectivity curve (A) is illustrated, along with the trace plot of the A_{50} parameter (B), which shows convergence of the MCMC fit. The histogram (C) shows the distribution of estimates with the median estimate (blue solid line) and 95% credible intervals (blue dashed lines), the optimised estimate is also included (red line) for the A_{50} parameter.

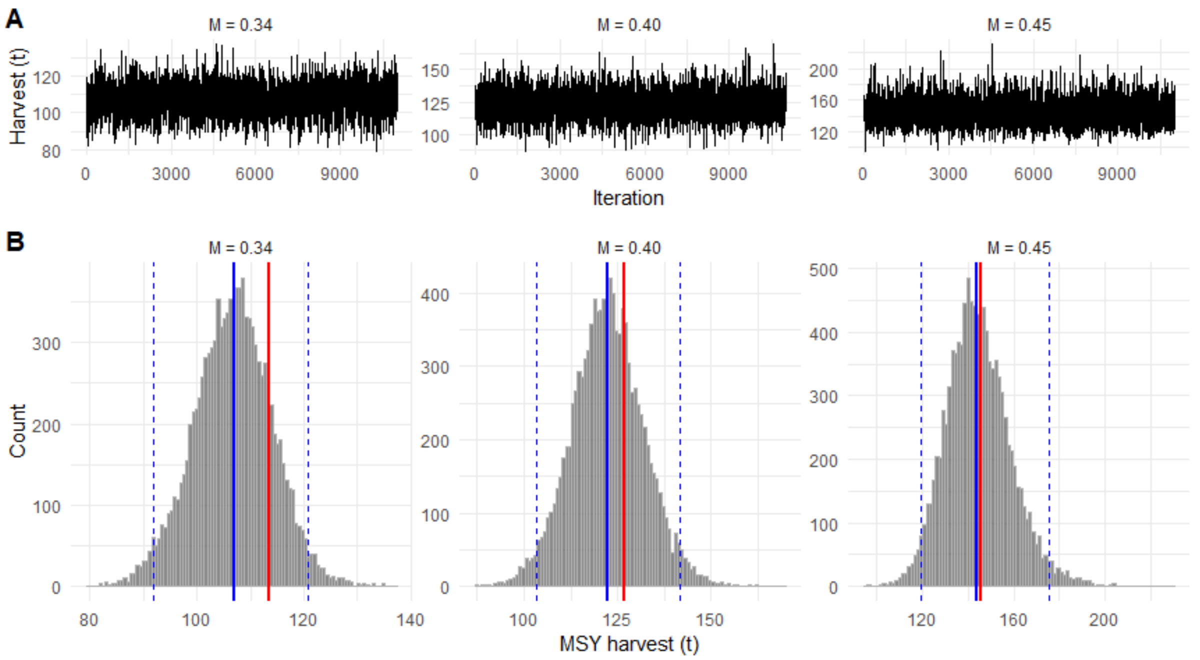

Figure 34: Trace plot and histogram of the maximum sustainable yield (MSY) target harvest estimates of the north-east stock for each of the models with natural mortality (M) fixed at three values, M=0.34, M=0.40 and M=0.45. The trace plot (A) shows convergence of the MCMC fit, while the histogram (B) shows the distribution of estimates with the median estimate (blue solid line) and 95% credible intervals (blue dashed lines), the optimised estimate is also included (red line).

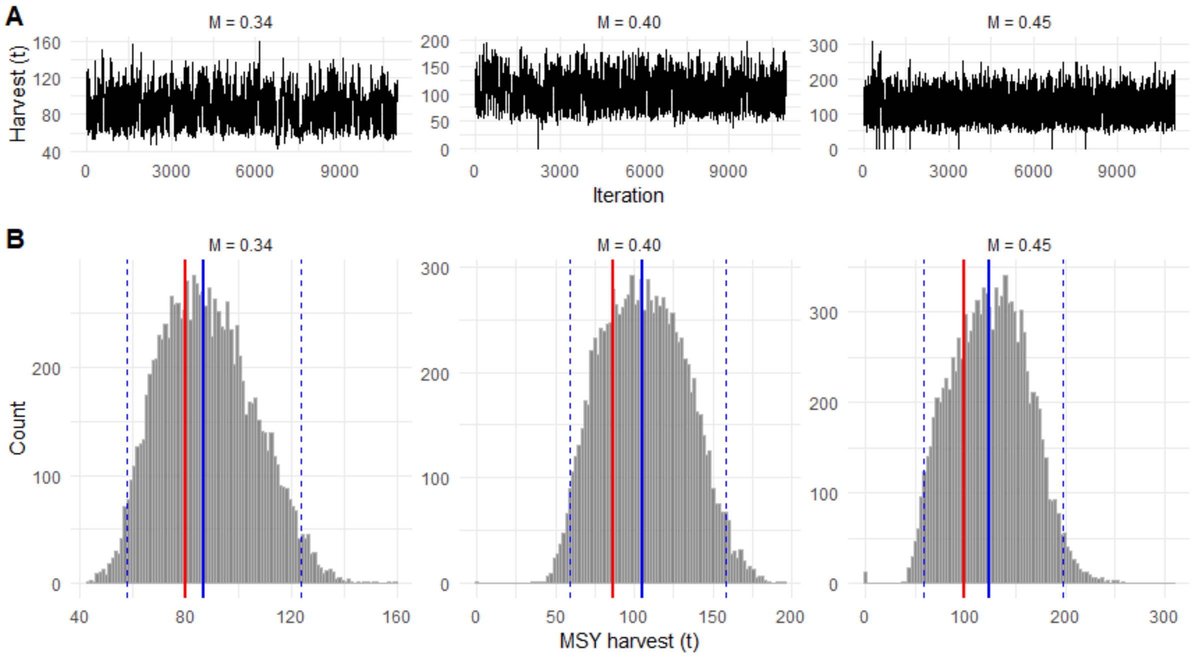

Figure 35: Trace plot and histogram of the maximum sustainable yield (MSY) target harvest estimates of the south-east stock for each of the models with natural mortality fixed at M=0.34, M=0.40 and M=0.45. The trace plot (A) shows convergence of the MCMC fit, while the histogram (B) shows the distribution of estimates with the median estimate (blue solid line) and 95% credible intervals (blue dashed lines), the optimised estimate is also included (red line).

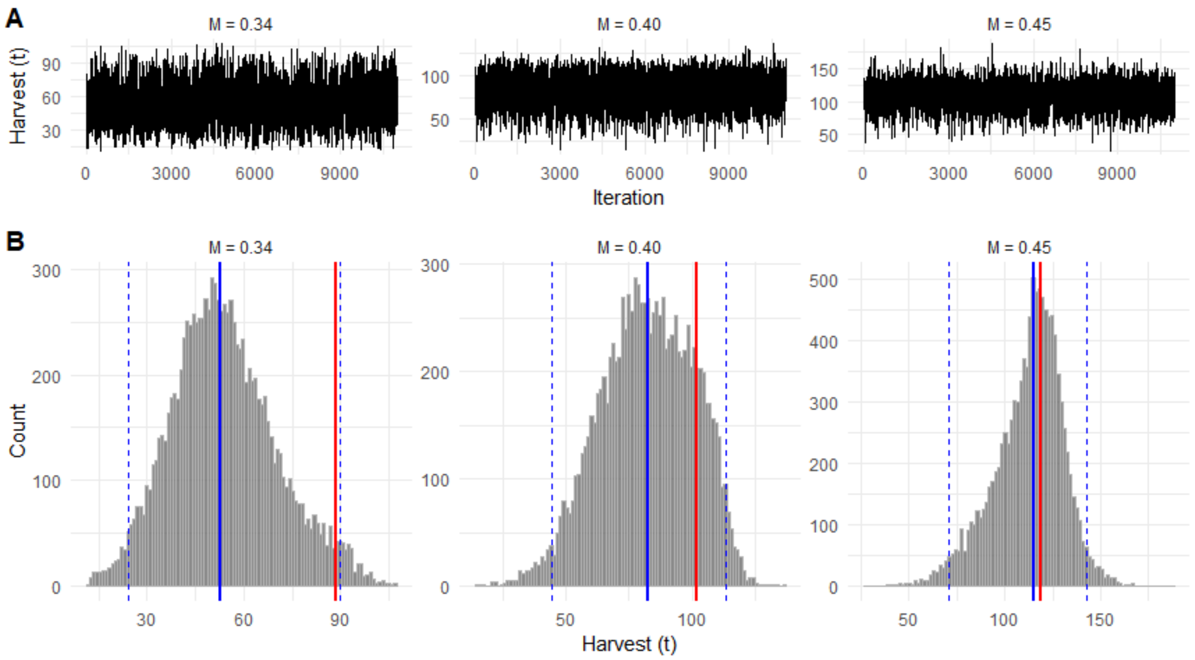

Figure 36: Trace plot and histogram of the 60% biomass target harvest estimates of the north-east stock for each of the models with natural mortality (M) fixed at M=0.34, M=0.40 and M=0.45. The trace plot (A) shows convergence of the MCMC fit, while the histogram (B) shows the distribution of estimates with the median

estimate (blue solid line) and 95% credible intervals (blue dashed lines), the optimised estimate is also included (red line).

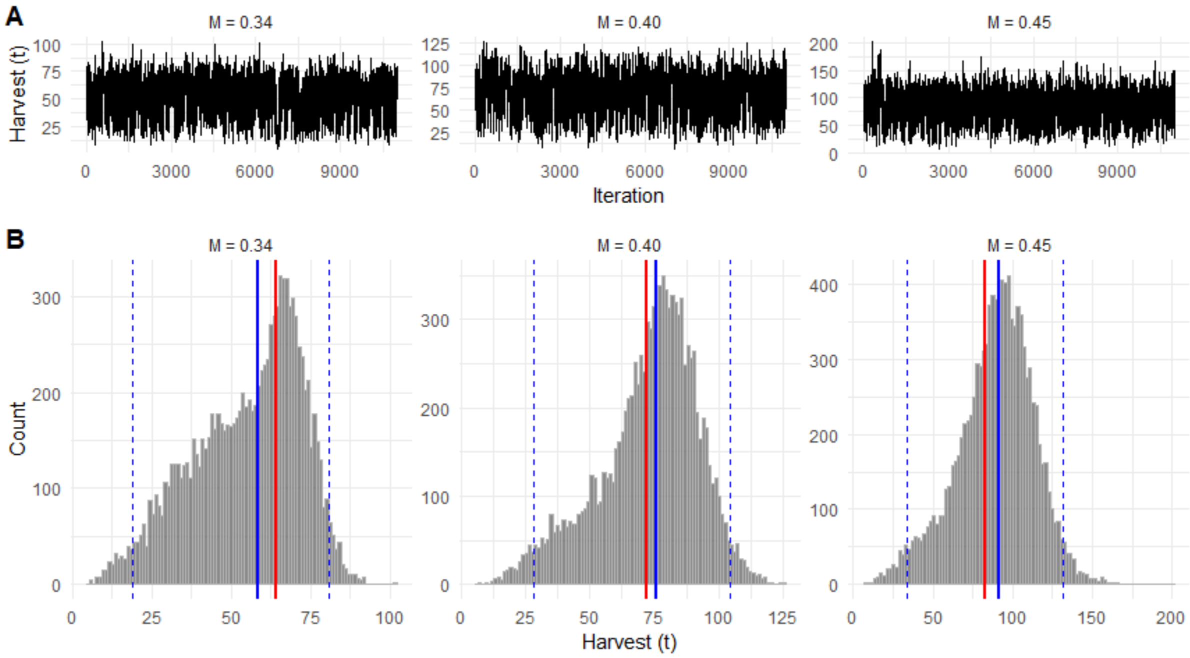

Figure 37: Trace plot and histogram of the 60% biomass target harvest estimates of the south-east stock for each of the models with natural mortality fixed at M=0.34, M=0.40 and M=0.45. The trace plot (A) shows convergence of the MCMC fit, while the histogram (B) shows the distribution of estimates with the median estimate (blue solid line) and 95% credible intervals (blue dashed lines), the optimised estimate is also included (red line).

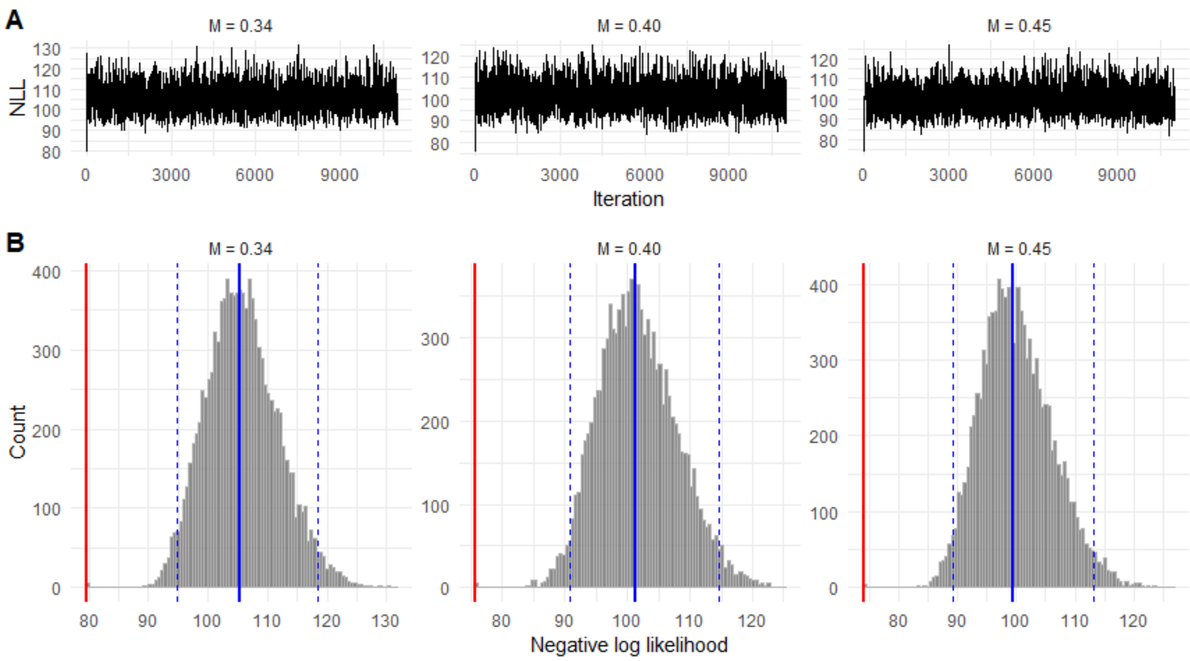

Figure 38: Trace plot and histogram of the negative log likelihood estimates of the north-east stock for each of the models with natural mortality (M) fixed at three values, M=0.34, M=0.40 and M=0.45. The trace plot (A) shows convergence of the MCMC fit, while the histogram (B) shows the distribution of estimates with the median estimate (blue solid line) and 95% credible intervals (blue dashed lines), the optimised estimate is also included (red line).

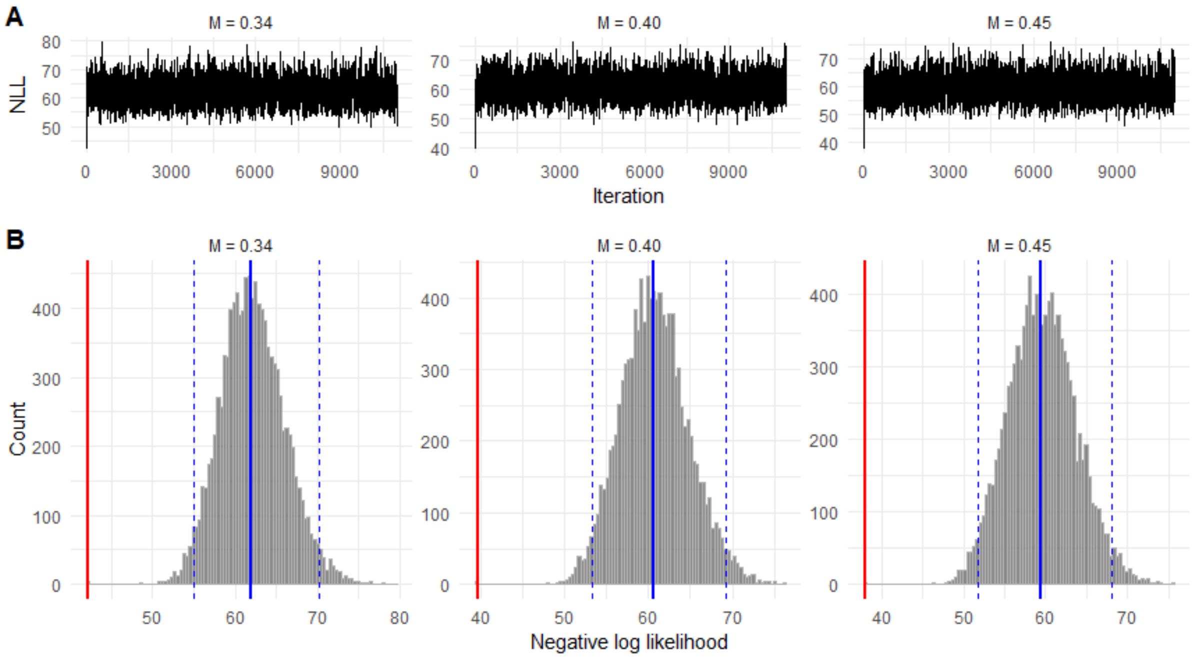

Figure 39: Trace plot and histogram of the negative log likelihood estimates of the south-east stock for each of the models with natural mortality (M) fixed at three values, M=0.34, M=0.40 and M=0.45. The trace plot (A) shows convergence of the MCMC fit, while the histogram (B) shows the distribution of estimates with the median estimate (blue solid line) and 95% credible intervals (blue dashed lines), the optimised estimate is also included (red line).

6.3.4 Recruitment deviations

Table 10: Estimated recruitment deviations for the north-east stock with M=0.34, including the optimised estimate and percentiles of MCMC estimates.

Year	Optimised	Mean	2.5%	25%	50%	75%	97.5%
1990	-0.0007	-0.0007	-0.0007	-0.0007	-0.0007	-0.0007	-0.0007
1991	-0.0012	-0.0012	-0.0012	-0.0012	-0.0012	-0.0012	-0.0012
1992	-0.0019	-0.0019	-0.0019	-0.0019	-0.0019	-0.0019	-0.0019
1993	-0.0029	-0.0029	-0.0029	-0.0029	-0.0029	-0.0029	-0.0029
1994	-0.0043	-0.0043	-0.0043	-0.0043	-0.0043	-0.0043	-0.0043
1995	-0.0060	-0.0060	-0.0060	-0.0060	-0.0060	-0.0060	-0.0060
1996	-0.0082	-0.0082	-0.0082	-0.0082	-0.0082	-0.0082	-0.0082
1997	-0.0113	-0.0113	-0.0113	-0.0113	-0.0113	-0.0113	-0.0113
1998	-0.0064	-0.0064	-0.0064	-0.0064	-0.0064	-0.0064	-0.0064
1999	-0.0074	-0.0074	-0.0074	-0.0074	-0.0074	-0.0074	-0.0074
2000	-0.0103	-0.0103	-0.0103	-0.0103	-0.0103	-0.0103	-0.0103
2001	-0.0155	-0.0155	-0.0155	-0.0155	-0.0155	-0.0155	-0.0155
2002	0.0178	0.0178	0.0178	0.0178	0.0178	0.0178	0.0178
2003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003
2004	0.0337	0.0337	0.0337	0.0337	0.0337	0.0337	0.0337
2005	0.0362	0.0362	0.0362	0.0362	0.0362	0.0362	0.0362

Year	Optimised	Mean	2.5%	25%	50%	75%	97.5%
2006	0.0769	0.0769	0.0769	0.0769	0.0769	0.0769	0.0769
2007	0.0725	0.0725	0.0725	0.0725	0.0725	0.0725	0.0725
2008	-0.1185	-0.1185	-0.1185	-0.1185	-0.1185	-0.1185	-0.1185
2009	0.1120	0.1120	0.1120	0.1120	0.1120	0.1120	0.1120
2010	0.3528	0.3528	0.3528	0.3528	0.3528	0.3528	0.3528
2011	0.1112	0.1112	0.1112	0.1112	0.1112	0.1112	0.1112
2012	-0.0933	-0.0933	-0.0933	-0.0933	-0.0933	-0.0933	-0.0933
2013	-0.2276	-0.2276	-0.2276	-0.2276	-0.2276	-0.2276	-0.2276
2014	0.0968	0.0968	0.0968	0.0968	0.0968	0.0968	0.0968
2015	-0.0574	-0.0574	-0.0574	-0.0574	-0.0574	-0.0574	-0.0574
2016	-0.0046	-0.0046	-0.0046	-0.0046	-0.0046	-0.0046	-0.0046
2017	-0.0025	-0.0025	-0.0025	-0.0025	-0.0025	-0.0025	-0.0025
2018	-0.0034	-0.0034	-0.0034	-0.0034	-0.0034	-0.0034	-0.0034

Table 11: Estimated recruitment deviations for the north-east stock with M=0.40, including the optimised estimate and percentiles of MCMC estimates.

Year	Optimised	Mean	2.5%	25%	50%	75%	97.5%
1990	-0.0002	-0.0002	-0.0002	-0.0002	-0.0002	-0.0002	-0.0002
1991	-0.0003	-0.0003	-0.0003	-0.0003	-0.0003	-0.0003	-0.0003
1992	-0.0005	-0.0005	-0.0005	-0.0005	-0.0005	-0.0005	-0.0005
1993	-0.0008	-0.0008	-0.0008	-0.0008	-0.0008	-0.0008	-0.0008
1994	-0.0016	-0.0016	-0.0016	-0.0016	-0.0016	-0.0016	-0.0016
1995	-0.0026	-0.0026	-0.0026	-0.0026	-0.0026	-0.0026	-0.0026
1996	-0.0038	-0.0038	-0.0038	-0.0038	-0.0038	-0.0038	-0.0038
1997	-0.0060	-0.0060	-0.0060	-0.0060	-0.0060	-0.0060	-0.0060
1998	-0.0002	-0.0002	-0.0002	-0.0002	-0.0002	-0.0002	-0.0002
1999	-0.0002	-0.0002	-0.0002	-0.0002	-0.0002	-0.0002	-0.0002
2000	-0.0027	-0.0027	-0.0027	-0.0027	-0.0027	-0.0027	-0.0027
2001	-0.0079	-0.0079	-0.0079	-0.0079	-0.0079	-0.0079	-0.0079
2002	0.0242	0.0242	0.0242	0.0242	0.0242	0.0242	0.0242
2003	0.0028	0.0028	0.0028	0.0028	0.0028	0.0028	0.0028
2004	0.0290	0.0290	0.0290	0.0290	0.0290	0.0290	0.0290
2005	0.0200	0.0200	0.0200	0.0200	0.0200	0.0200	0.0200
2006	0.0447	0.0447	0.0447	0.0447	0.0447	0.0447	0.0447
2007	0.0282	0.0282	0.0282	0.0282	0.0282	0.0282	0.0282
2008	-0.1589	-0.1589	-0.1589	-0.1589	-0.1589	-0.1589	-0.1589
2009	0.0931	0.0931	0.0931	0.0931	0.0931	0.0931	0.0931
2010	0.3341	0.3341	0.3341	0.3341	0.3341	0.3341	0.3341
2011	0.0914	0.0914	0.0914	0.0914	0.0914	0.0914	0.0914
2012	-0.0967	-0.0967	-0.0967	-0.0967	-0.0967	-0.0967	-0.0967
2013	-0.2167	-0.2167	-0.2167	-0.2167	-0.2167	-0.2167	-0.2167
2014	0.1120	0.1120	0.1120	0.1120	0.1120	0.1120	0.1120
2015	-0.0534	-0.0534	-0.0534	-0.0534	-0.0534	-0.0534	-0.0534
2016	-0.0039	-0.0039	-0.0039	-0.0039	-0.0039	-0.0039	-0.0039
2017	-0.0019	-0.0019	-0.0019	-0.0019	-0.0019	-0.0019	-0.0019
2018	-0.0028	-0.0028	-0.0028	-0.0028	-0.0028	-0.0028	-0.0028

Table 12: Estimated recruitment deviations for the north-east stock with M=0.45, including the optimised estimate and percentiles of MCMC estimates.

Year	Optimised	Mean	2.5%	25%	50%	75%	97.5%
1990	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
1991	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003
1992	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005
1993	0.0007	0.0007	0.0007	0.0007	0.0007	0.0007	0.0007
1994	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003
1995	-0.0003	-0.0003	-0.0003	-0.0003	-0.0003	-0.0003	-0.0003
1996	-0.0009	-0.0009	-0.0009	-0.0009	-0.0009	-0.0009	-0.0009
1997	-0.0025	-0.0025	-0.0025	-0.0025	-0.0025	-0.0025	-0.0025
1998	0.0036	0.0036	0.0036	0.0036	0.0036	0.0036	0.0036
1999	0.0042	0.0042	0.0042	0.0042	0.0042	0.0042	0.0042
2000	0.0018	0.0018	0.0018	0.0018	0.0018	0.0018	0.0018
2001	-0.0033	-0.0033	-0.0033	-0.0033	-0.0033	-0.0033	-0.0033
2002	0.0280	0.0280	0.0280	0.0280	0.0280	0.0280	0.0280
2003	0.0040	0.0040	0.0040	0.0040	0.0040	0.0040	0.0040
2004	0.0260	0.0260	0.0260	0.0260	0.0260	0.0260	0.0260
2005	0.0098	0.0098	0.0098	0.0098	0.0098	0.0098	0.0098
2006	0.0234	0.0234	0.0234	0.0234	0.0234	0.0234	0.0234
2007	0.0006	0.0006	0.0006	0.0006	0.0006	0.0006	0.0006
2008	-0.1801	-0.1801	-0.1801	-0.1801	-0.1801	-0.1801	-0.1801
2009	0.0914	0.0914	0.0914	0.0914	0.0914	0.0914	0.0914
2010	0.3289	0.3289	0.3289	0.3289	0.3289	0.3289	0.3289
2011	0.0809	0.0809	0.0809	0.0809	0.0809	0.0809	0.0809
2012	-0.0953	-0.0953	-0.0953	-0.0953	-0.0953	-0.0953	-0.0953
2013	-0.2081	-0.2081	-0.2081	-0.2081	-0.2081	-0.2081	-0.2081
2014	0.1207	0.1207	0.1207	0.1207	0.1207	0.1207	0.1207
2015	-0.0516	-0.0516	-0.0516	-0.0516	-0.0516	-0.0516	-0.0516
2016	-0.0037	-0.0037	-0.0037	-0.0037	-0.0037	-0.0037	-0.0037
2017	-0.0018	-0.0018	-0.0018	-0.0018	-0.0018	-0.0018	-0.0018
2018	-0.0026	-0.0026	-0.0026	-0.0026	-0.0026	-0.0026	-0.0026

Table 13: Estimated recruitment deviations for the south-east stock with M=0.34, including the optimised estimate and percentiles of MCMC estimates.

Year	Optimised	Mean	2.5%	25%	50%	75%	97.5%
1990	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002
1991	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005
1992	-0.0028	-0.0028	-0.0028	-0.0028	-0.0028	-0.0028	-0.0028
1993	-0.0075	-0.0075	-0.0075	-0.0075	-0.0075	-0.0075	-0.0075
1994	-0.0082	-0.0082	-0.0082	-0.0082	-0.0082	-0.0082	-0.0082
1995	-0.0080	-0.0080	-0.0080	-0.0080	-0.0080	-0.0080	-0.0080
1996	-0.0074	-0.0074	-0.0074	-0.0074	-0.0074	-0.0074	-0.0074
1997	-0.0074	-0.0074	-0.0074	-0.0074	-0.0074	-0.0074	-0.0074
1998	-0.0076	-0.0076	-0.0076	-0.0076	-0.0076	-0.0076	-0.0076
1999	-0.0088	-0.0088	-0.0088	-0.0088	-0.0088	-0.0088	-0.0088
2000	-0.0033	-0.0033	-0.0033	-0.0033	-0.0033	-0.0033	-0.0033
2001	-0.0088	-0.0088	-0.0088	-0.0088	-0.0088	-0.0088	-0.0088
2002	-0.0204	-0.0204	-0.0204	-0.0204	-0.0204	-0.0204	-0.0204
2003	-0.0071	-0.0071	-0.0071	-0.0071	-0.0071	-0.0071	-0.0071
2004	0.1978	0.1978	0.1978	0.1978	0.1978	0.1978	0.1978
2005	0.0495	0.0495	0.0495	0.0495	0.0495	0.0495	0.0495
2006	0.1954	0.1954	0.1954	0.1954	0.1954	0.1954	0.1954
2007	0.5937	0.5937	0.5937	0.5937	0.5937	0.5937	0.5937
2008	-0.1297	-0.1297	-0.1297	-0.1297	-0.1297	-0.1297	-0.1297
2009	-0.4819	-0.4819	-0.4819	-0.4819	-0.4819	-0.4819	-0.4819
2010	0.0789	0.0789	0.0789	0.0789	0.0789	0.0789	0.0789
2011	-0.1326	-0.1326	-0.1326	-0.1326	-0.1326	-0.1326	-0.1326
2012	-0.0730	-0.0730	-0.0730	-0.0730	-0.0730	-0.0730	-0.0730
2013	-0.2259	-0.2259	-0.2259	-0.2259	-0.2259	-0.2259	-0.2259
2014	0.0338	0.0338	0.0338	0.0338	0.0338	0.0338	0.0338
2015	0.3982	0.3982	0.3982	0.3982	0.3982	0.3982	0.3982
2016	-0.0020	-0.0020	-0.0020	-0.0020	-0.0020	-0.0020	-0.0020
2017	-0.0022	-0.0022	-0.0022	-0.0022	-0.0022	-0.0022	-0.0022
2018	-0.0032	-0.0032	-0.0032	-0.0032	-0.0032	-0.0032	-0.0032

Table 14: Estimated recruitment deviations for the south-east stock with M=0.40, including the optimised estimate and percentiles of MCMC estimates.

Year	Optimised	Mean	2.5%	25%	50%	75%	97.5%
1990	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004
1991	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005
1992	-0.0031	-0.0031	-0.0031	-0.0031	-0.0031	-0.0031	-0.0031
1993	-0.0081	-0.0081	-0.0081	-0.0081	-0.0081	-0.0081	-0.0081
1994	-0.0090	-0.0090	-0.0090	-0.0090	-0.0090	-0.0090	-0.0090
1995	-0.0086	-0.0086	-0.0086	-0.0086	-0.0086	-0.0086	-0.0086
1996	-0.0074	-0.0074	-0.0074	-0.0074	-0.0074	-0.0074	-0.0074
1997	-0.0066	-0.0066	-0.0066	-0.0066	-0.0066	-0.0066	-0.0066
1998	-0.0060	-0.0060	-0.0060	-0.0060	-0.0060	-0.0060	-0.0060
1999	-0.0071	-0.0071	-0.0071	-0.0071	-0.0071	-0.0071	-0.0071
2000	-0.0034	-0.0034	-0.0034	-0.0034	-0.0034	-0.0034	-0.0034
2001	-0.0067	-0.0067	-0.0067	-0.0067	-0.0067	-0.0067	-0.0067
2002	-0.0150	-0.0150	-0.0150	-0.0150	-0.0150	-0.0150	-0.0150
2003	-0.0085	-0.0085	-0.0085	-0.0085	-0.0085	-0.0085	-0.0085
2004	0.1508	0.1508	0.1508	0.1508	0.1508	0.1508	0.1508
2005	0.0218	0.0218	0.0218	0.0218	0.0218	0.0218	0.0218
2006	0.1213	0.1213	0.1213	0.1213	0.1213	0.1213	0.1213
2007	0.4907	0.4907	0.4907	0.4907	0.4907	0.4907	0.4907
2008	-0.1779	-0.1779	-0.1779	-0.1779	-0.1779	-0.1779	-0.1779
2009	-0.4636	-0.4636	-0.4636	-0.4636	-0.4636	-0.4636	-0.4636
2010	0.1367	0.1367	0.1367	0.1367	0.1367	0.1367	0.1367
2011	-0.0920	-0.0920	-0.0920	-0.0920	-0.0920	-0.0920	-0.0920
2012	-0.0568	-0.0568	-0.0568	-0.0568	-0.0568	-0.0568	-0.0568
2013	-0.2059	-0.2059	-0.2059	-0.2059	-0.2059	-0.2059	-0.2059
2014	0.0410	0.0410	0.0410	0.0410	0.0410	0.0410	0.0410
2015	0.3353	0.3353	0.3353	0.3353	0.3353	0.3353	0.3353
2016	-0.0029	-0.0029	-0.0029	-0.0029	-0.0029	-0.0029	-0.0029
2017	-0.0018	-0.0018	-0.0018	-0.0018	-0.0018	-0.0018	-0.0018
2018	-0.0013	-0.0013	-0.0013	-0.0013	-0.0013	-0.0013	-0.0013

Table 15: Estimated recruitment deviations for the south-east stock with M=0.45, including the optimised estimate and percentiles of MCMC estimates.

Year	Optimised	Mean	2.5%	25%	50%	75%	97.5%
1990	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004
1991	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002
1992	-0.0038	-0.0038	-0.0038	-0.0038	-0.0038	-0.0038	-0.0038
1993	-0.0092	-0.0092	-0.0092	-0.0092	-0.0092	-0.0092	-0.0092
1994	-0.0104	-0.0104	-0.0104	-0.0104	-0.0104	-0.0104	-0.0104
1995	-0.0099	-0.0099	-0.0099	-0.0099	-0.0099	-0.0099	-0.0099
1996	-0.0085	-0.0085	-0.0085	-0.0085	-0.0085	-0.0085	-0.0085
1997	-0.0074	-0.0074	-0.0074	-0.0074	-0.0074	-0.0074	-0.0074
1998	-0.0065	-0.0065	-0.0065	-0.0065	-0.0065	-0.0065	-0.0065
1999	-0.0077	-0.0077	-0.0077	-0.0077	-0.0077	-0.0077	-0.0077
2000	-0.0052	-0.0052	-0.0052	-0.0052	-0.0052	-0.0052	-0.0052
2001	-0.0079	-0.0079	-0.0079	-0.0079	-0.0079	-0.0079	-0.0079
2002	-0.0145	-0.0145	-0.0145	-0.0145	-0.0145	-0.0145	-0.0145
2003	-0.0111	-0.0111	-0.0111	-0.0111	-0.0111	-0.0111	-0.0111
2004	0.1267	0.1267	0.1267	0.1267	0.1267	0.1267	0.1267
2005	0.0071	0.0071	0.0071	0.0071	0.0071	0.0071	0.0071
2006	0.0821	0.0821	0.0821	0.0821	0.0821	0.0821	0.0821
2007	0.4328	0.4328	0.4328	0.4328	0.4328	0.4328	0.4328
2008	-0.2004	-0.2004	-0.2004	-0.2004	-0.2004	-0.2004	-0.2004
2009	-0.4383	-0.4383	-0.4383	-0.4383	-0.4383	-0.4383	-0.4383
2010	0.1867	0.1867	0.1867	0.1867	0.1867	0.1867	0.1867
2011	-0.0730	-0.0730	-0.0730	-0.0730	-0.0730	-0.0730	-0.0730
2012	-0.0560	-0.0560	-0.0560	-0.0560	-0.0560	-0.0560	-0.0560
2013	-0.2067	-0.2067	-0.2067	-0.2067	-0.2067	-0.2067	-0.2067
2014	0.0341	0.0341	0.0341	0.0341	0.0341	0.0341	0.0341
2015	0.3009	0.3009	0.3009	0.3009	0.3009	0.3009	0.3009
2016	-0.0037	-0.0037	-0.0037	-0.0037	-0.0037	-0.0037	-0.0037
2017	-0.0016	-0.0016	-0.0016	-0.0016	-0.0016	-0.0016	-0.0016
2018	-0.0001	-0.0001	-0.0001	-0.0001	-0.0001	-0.0001	-0.0001