Scomberomorus commerson

Torres Strait Spanish mackerel
Stock assessment II, 2015

Update of stock assessment I published in 2006. Results are for consideration for defining target goals for fishery management and community benefits.

Torres Strait AFMA Project Number: RR2014/0823

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Summary

Torres Strait Spanish mackerel are harvested by line and troll fishing from ocean waters between Cape York Peninsula (north-east Australia) and the western province of Papua New Guinea. Spanish mackerel are an important economic and traditional food source, with historical commercial harvests ranging in order of 200 tonnes (t) per year. The commercial fishery is highly seasonal between September and November and located in the eastern Torres Strait and Bramble Cay.

This report has been prepared to update the inaugural 2006 stock assessment with the latest data and inform management agencies on revised estimates of sustainable harvest for consideration in defining future management objectives and harvest strategies.

The Torres Strait commercial finfish logbook data was analysed for the fishing years 1989–2013. From the logbook data, the estimated Spanish mackerel annual harvests ranged from 98–233 t between 1989 and 2006. The estimated annual harvest of Spanish mackerel declined to 64–105 t between 2007 and 2014. The estimated catch rate indices of Spanish mackerel abundance showed a general decline between 1989 and 2002. After 2002 the logbook design was changed and improved. From 2003 onwards the catch rate index was estimated to be either increasing or stable around the 2002 level. The two results were dependent on the assumed fishing behaviour of recording Spanish mackerel harvests before and after the change in logbook design in 2003; i.e. different or similar. The two time series quantified uncertainty in the catch rate signal and identified significant variation in the harvest reported between fishing vessels.

The age-structured stock analyses of Torres Strait Spanish mackerel inputted and assessed the time series data on harvests, catch rates and fish age-length. The assessment results were uncertain and show a range of variation in estimated population size. In spite of this uncertainty, the recent harvests for 2007–2014 (64–105 t) and population estimates were all sustainable.

Management should adopt a precautionary approach to setting target levels of commercial harvest until further data on total catches (commercial + non-commercial) and fish age structures are available. If future average harvests increase above 150 t and/or fishing effort increases above 1000 operation days (of the main vessel, not dory days; Figure 20), then future catch rates of Spanish mackerel may erode.

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Introduction

Torres Strait Spanish mackerel, *Scomberomorus commerson*, are large pelagic fish that are harvested by line and troll fishing from ocean waters between Cape York Peninsula (north-east Australia) and the western province of Papua New Guinea. Management of fisheries in the Torres Strait is shared between Australia and Papua New Guinea (Figure 1). The Australian sector for Spanish mackerel is an important economic and traditional food source for all Torres Strait communities (Begg et al., 2006). Historically, the Australian commercial sector have harvested in order of 200 t of Spanish mackerel year^{-1}, with lesser harvests taken by Torres Strait and Papua New Guinea communities (Begg et al., 2006; Busilacchi et al., 2015).

Torres Strait waters connect to the Coral Sea in the east and Great Barrier Reef to the south, and the Arafura Sea and the Gulf of Carpentaria to the west. Separate stocks of Spanish mackerel reside in these surrounding waters, with the most recent stock structure research recommending that Torres Strait Spanish mackerel be regarded as a discrete meta-population for management (Buckworth et al., 2007). This recommendation formed the spatial boundary for stock assessment and harvest monitoring.

The inaugural stock assessment for Torres Strait Spanish mackerel was completed using data up to the 2003 fishing year (Begg et al., 2006). The assessment described the biological parameters, management and research histories and estimated the stock as being fully fished with annual harvests (mean = 173 t and standard deviation = 31 t) judged to be nearing or exceeding maximum sustainable levels (146–264 t) (Begg et al., 2006). The Australian Government fishery status reports have monitored nominal harvest trends since 2003 and in 2015 classified Torres Strait Spanish mackerel as not overfished and not subject to overfishing (Patterson et al., 2015).

In 2014 the Torres Strait Scientific Advisory Committee, on behalf of the Protected Zone Joint Authority (PZJA), funded the need to revisit and update the previous 2006 stock assessment (Begg et al., 2006) for consideration in defining future management objectives and harvest strategies. The report informs the PZJA and associated management agencies on updated estimates of sustainable harvest that will maintain the fishery long term. The outputs of the research will better inform management decision processes and catch leasing arrangements.
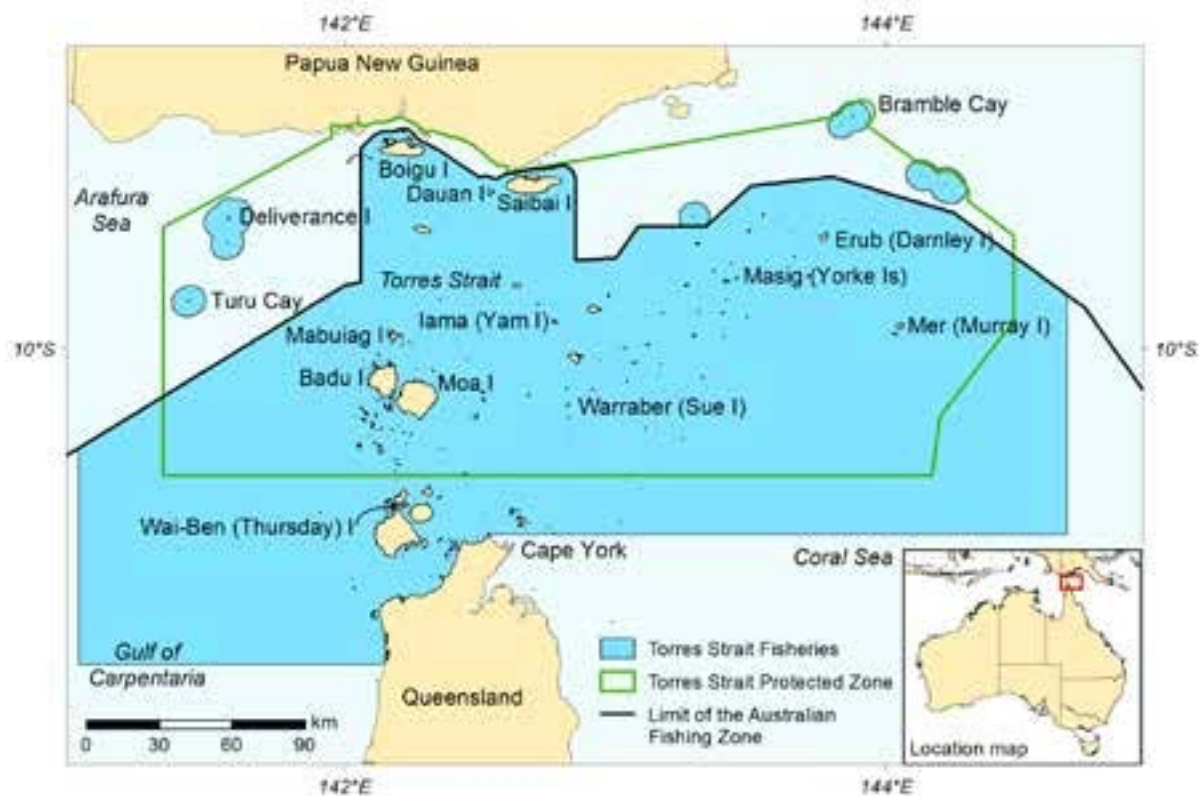
Figure 1. Area of the Torres Strait Fisheries. The management area for the Australian (Torres Strait) component is shaded blue. The map was sourced from the ABARES Fishery status report 2015.

Methods

Harvest and catch rate data

The Spanish mackerel harvest data were supplied by the Australian Fisheries Management Authority (AFMA) on 3rd September 2015 (job # 65833). The data were updated from the previous request dated 3rd August 2014 (job # 65368). The AFMA 'deed of confidentiality' was signed by the project Principal Investigator at James Cook University (JCU) on the 27th August 2015. This included the authority for the project co-investigator (Queensland Department of Agriculture and Fisheries – DAF) to analyse the data for stock assessment under project objective I.

The raw data tables were imported and stored in the MS Access database 'spanish_ts_catch_afma'. The database was filed in the computer directory for 'spanish_mackerel_ts'. The directory was a part of the 'Stock Assessment Security Group' on the Queensland Government DAF server. The security group ensured access only by approved staff and confidentiality, integrity and backup of the data. The data were only authorised for use in AFMA project # RR2014/0833. A copy of the 'spanish_ts_catch_afma' database is available to AFMA under the 'deed' agreement.

The data on Torres Strait Spanish mackerel harvest were collated from two sources: 1) AFMA compulsory logbook (Log) database and 2) AFMA docket (Doc) book records. The commercial licence and endorsement conditions for logbooks is compulsory for Spanish mackerel, as the Protected Zone Joint Authority (PZJA) has determined a logbook form for recording harvests (Australian Government, 2013). This is a condition of all commercial endorsement holders fishing for Spanish mackerel to ensure that the information required by the logbook about fish taken and effort expended in the fishery is accurately and fully recorded in accordance with the instruction (Australian Government, 2013). The docket (Doc) book records are important supplementary information for harvest validation. At the time of this report the Doc data was deemed non-compulsory and the database was not readily maintained or up-to-date (French et al., 2015).

The following data tables were created and linked in the MS Access database for the purpose of summarising total harvests and fishing efforts and modelling to standardise catch rates (* indicates non AFMA data sourced and created by JCU or DAF):

o LogOperation – logbook client, vessel, fishing date and location data.

o LogEffort – number of crew, tenders and the fishing method.

o LogCatch – tender number, species harvested, numbers and weights (kilograms: kg)

o LogBoat – grouping factors for different vessels and operators.

o LogSpp – defines species categories / families.

o LogWtConversions – for different product forms (e.g. kg of fillets to kg whole fish).

o Regions* – latitude and longitude borders for the six fishing regions; see Figure 5.

o DayYear* – daily sinusoidal data for modelling within year fishing seasons.

o LeapYear* – binary factor identifying leap years; links with DayYear.

o Winds* – daily mean wind speed, direction and components (NS and EW).

o LunarPhases* – continuous moon phase data.

o Setup_meanwt – mean fish weights by species (kg); calculated from AFMA data.

o DocOperation – Docket book records of processed harvest by island and fisher/seller.

o DocCatch – species weights (kg) and prices (AUD$).

o DocSpp – defines species categories / families.

The Torres Strait wind data were sourced by JCU on 27th September 2015 from the Bureau of Meteorology (BOM, Australian Government; www.bom.gov.au). The wind data encompassed the time series from the 1/1/1989 to 15/9/2015 for the Horn and Coconut Islands weather stations. The recorded measures of wind speed (km hour^{-1}) and direction (degrees from where the wind blew) was collated by JCU and converted to an average daily reading. From this data the north-south (NS) and east-west (EW) wind components were calculated (Figure 2):

$$NS = km \ hr^{-1} \times cos(radians(degrees)), \ and$$

$$EW = km \ hr^{-1} \times sin(radians(degrees)).$$
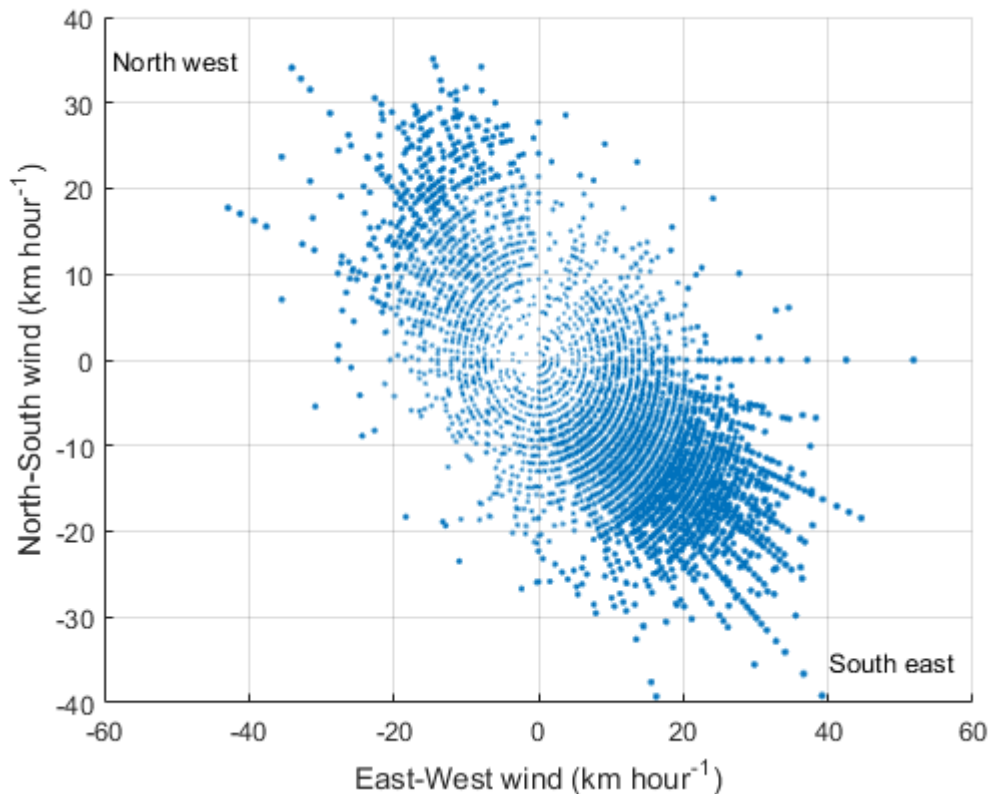
Figure 2. Plot of the Torres Strait average daily wind components 1989–2015, showing a predominant south-east wind pattern.

The component functions considered the BOM defined wind directions as degrees measured clockwise from true north (http://www.wmo.int/pages/prog/www/IMOP/publications/CIMO-Guide/Ed2008Up2010/Part-I/WMO8_Ed2008_PartI_Ch5_Up2010_en.pdf; http://www.wmo.int/pages/prog/www/IMOP/CIMO-Guide.html); 0 degrees = North, 90 degrees or $\pi/2$ radians = East, 180 degrees or π radians = South, and 270 degrees or $3\pi/2$ radians = West.

In total 9% (850 out of 9341 records) of the wind data were not observed and recorded by the BOM. The missing wind components were assumed equal to the overall average values (NS = -10.4334 and EW = 9.9282). The wind components were used to standardise Spanish mackerel catch rates for different wind directions and strengths.

The lunar phase (luminance) data 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 data were sourced from the Department of Agriculture and Fisheries (DAF), Queensland Government. The luminance measure (lunar)

followed a sinusoidal pattern and was copied and advanced 7 days (≈ ¼ lunar cycle) into a new variable (lunar_adv) to quantify the cosine of the lunar data (O'Neill and Leigh, 2006); Figure 3. The two variables were modelled together to estimate the variation of Spanish mackerel harvest according to the moon phase (i.e. contrasting waxing and waning patterns of the moon).
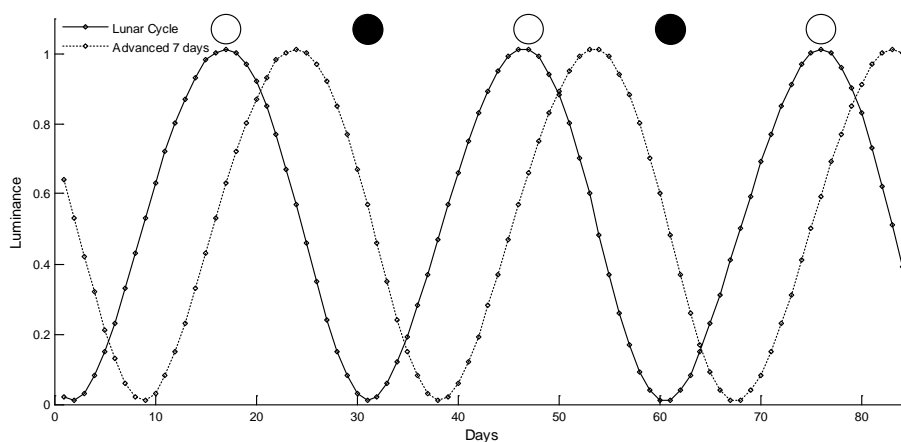
Figure 3. The lunar phase cycle (solid line) illustrated over 85 days. The dashed line illustrates the lunar cycle advanced by seven days. Together these lines were used to model catch rates allowing for new moon, waxing moon, full moon and waning moon effects.

The seasonality of Spanish mackerel catch rates was modelled using sinusoidal data (DayYear) to identify the time of year. The data was calculated and used to minimise the number of model parameters with the purpose to reduce temporal confounding with the regional and/or vessel parameters. For Torres Strait Spanish mackerel, parameter confounding was a concern given the limited temporal and spatial patterns of fishing by some vessels; particularly if more parameters were used to model the explicit monthly or weekly factorisations of the data. In total four trigonometric covariates were used, which together modelled an average monthly pattern of catch (Marriott et al., 2013): $s_1 = \cos\left(2\pi d_y / T_y\right)$, $s_2 = \sin\left(2\pi d_y / T_y\right)$, $s_3 = \cos\left(4\pi d_y / T_y\right)$, $s_4 = \sin\left(4\pi d_y / T_y\right)$, where d_y was the cumulative day of the year and T_y was the total number of days in the year (365 or 366); Figure 4. The reason for using both sine and cosine functions together was similar to modelling lunar phases, where the functions together identify the seasonal patterns of catch rates corresponding to autumn, winter, spring and summer periods.
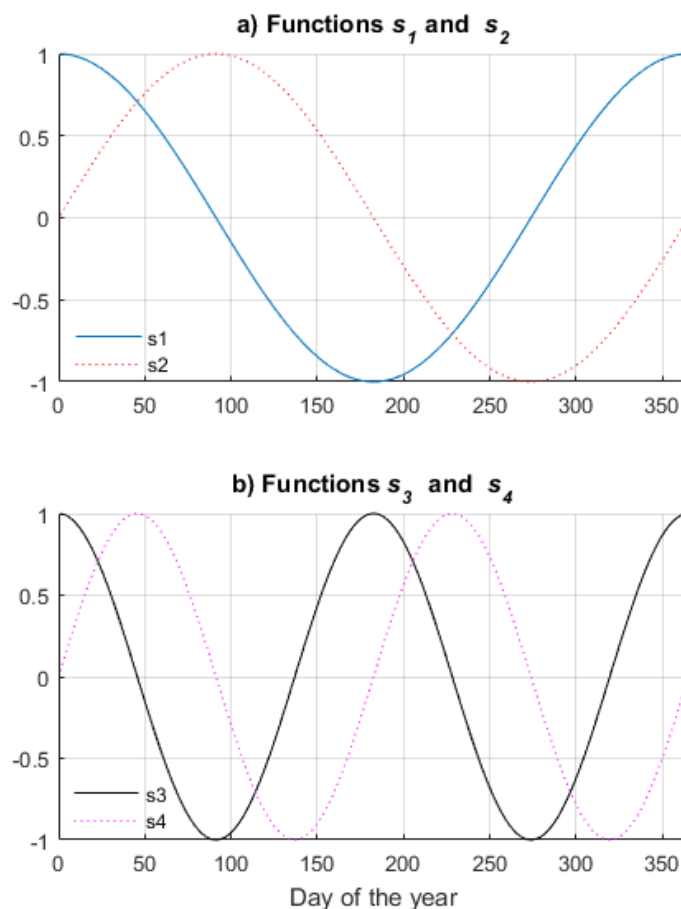
Figure 4. Illustration of the sinusoidal DayYear data for a) the annual cycle and b) the 6-monthly cycle. For the x-axis day of the year, 1 = 1st January and 365 = 31st December and the y-axis is the function value. For more information on the relationship between unit circles and the sine and cosine function, see https://en.wikipedia.org/wiki/Trigonometric_functions (webpage last accessed 16th November 2015).

The different data tables in MS Access were merged for analysis and to standardised catch rates of Spanish mackerel. The analysis data formed records of each vessel's daily harvest, together with the associated variables for the main vessel name, date, number of specified tenders, numbers and weight of Spanish mackerel harvested, lunar phase and wind components. Analysing harvests at the primary vessel unit aimed to match the daily recording format (Appendix 4), avoid correlation between tenders and to use appropriate sample sizes for estimating confidence intervals. The following aspects were noted for creating the daily catch rate data:

- o The Log Boat and LogOperation data was grouped to each vessel, day and record number, and filtered for only Spanish mackerel vessels, gear code TR and logbook types SM02 and TSF01. This included the corresponding location data.

o The LogCatch and LogEffort data were merged with the selected LogOperation data based on the linked record number. The merged data was for the LogSpp codes for Spanish mackerel.

o In addition to the above data, the lunar phase, day-year and wind components data were merged based on the linking fishing dates.

o The region data was not merged or used in the catch rate analysis due to the amount of missing data prior to the introduction of the TSF01 logbook in 2003. It was also uncertain whether the locations recorded by fishers was consistent based on the fishing trip's start grid, start location name and start latitude/longitude (as labelled in the database; or port of departure in logbook) or the actual daily fishing location (GPS position of the primary vessel as defined in the logbook; Appendix 4). In total about 50% of the database fishing-location fields was blank and missing. Categorisation of the available location data into regions suggested 35% of the Spanish mackerel records were from Bramble Cay, 32% Eastern Islands, 19% Central Islands, 5% north/south/west and 9% missing. Plot of the latitude and longitude data showed less fishing around Bramble Cay compared to the central and eastern areas (Figure 5). Often the latitude and longitude data did not match the specified start location name in the database.

o The course spatial stratification of Begg et al. (2006) was not used, as many of the recorded fishing locations bordered on the Bramble, central, eastern and southern regions (Figure 5) and that vessels were easily capable of travelling between regions each day. The variation in daily harvests was assumed to primarily relate to the vessel stratification (vessel name).

o Some client/fisher names and their fishing regions were found to be inconsistent (Dr A. Tobin pers. comm.). The degree of this problem was unknown. Catch rates were therefore analysed by vessel name (also called a boat), which accurately grouped the clients, and no region codes were used as noted above.

o The harvests of Spanish mackerel were recorded in three different data fields: 1) number of fish n, 2) weight of whole fish in kilograms w_{old}, calculated based on different product forms and 3) number of cartons c. The data fields were 94%, 5% and 56% complete, respectively. The catch rate analysis was therefore based the numbers of fish as this data was the most complete. Also, numbers generally index abundance more accurately than weight, given the average size and weight of fish can vary between different areas, times and schools of fish. Records of zero harvest were not analysed as they may be inconsistent and under reported (Dr A. Tobin pers. comm.). The conversions used to fill in missing records are listed in Table 1.

o The harvest tonnages of Torres Strait Spanish mackerel were estimated based on an assumed mean fish weight of 6.909 kg (Table 1). In the 2006 stock assessment report, Begg et al. (2006) estimated a mean fish weight of 8.5 kg based on logbook data for whole fish only (n = 64). In Table 1 the same calculation method was used for consistency, but updated to include both whole and filleted fish; i.e. all available mean weight data was used. This resulted in a mean estimate of 6.909 kg that was more

consistent with the mean of 7.145 kg (median = 6.562, std = 2.2797) from the age-length monitoring data. The estimate of 6.909 kg was also near the mean values of 7.229 kg and 7.279 kg from northern Queensland and the Gulf of Carpentaria, respectively (Figure 6).

- o The final catch rate analysis data grouped record numbers identifying different dories and fishing sessions to form records of each vessel's daily harvest. The data were also filtered to remove vessels that had fished less than 30 days in total between 1989 and 2014, fished in only one year between 1989 and 2014 and had recorded 'bulk' trip harvests. In total the filter removed 2% of the recorded harvests (from 23098 daily records down to 22545) and reduced the number of vessels analysed from 64 to 40.

- o The number of dories/tenders/vessels used each day by each fishing operation was tallied by counting the listed 'tender number' from the LogCatch data table. The tallied vessel numbers ranged 1–5. The catch rate analysis compared the significance of this covariate data against the categorisation of the data into the groups of 1, 2, and ≥3 vessels. It was noticed that the number of tenders, ranging 1–9, in the LogOperation data table varied from the LogCatch table. The LogOperation tender data was not used as it as it did not match the expected number of 1–4 tenders per operation used to catch Spanish mackerel in the Torres Strait (Appendix 4).

- o To group the seasonal biology and fishing patterns of Spanish mackerel, the fishing-year was defined for the months from July to June (Begg et al., 2006); i.e. fiscal year, where for example the time period from the 1st July 2014 to 30th June 2015 was labelled as fishing year 2014.

- o In June 2003 a new Torres Strait finfish daily fishing logbook (TSF01) was formalised by AFMA (Appendix 4). Examination of the nominal data suggests that this may have improved reporting rates (Figure 13). To consider this possibility, a binary factor for pre and post 1st June 2003 was created to model the time series effect.

Table 1. Equations for converting numbers of fish and weights (kg).

Equation	Condition
$w_{new} = n \times 6.909$, where 6.909 kg was the mean weight of a whole fish calculated using whole and filleted fish data (n = 86, s.d. = 2.93).	$n > 0$
$w_{new} = \left(w_{old}/v_{old}\right) \times v_{new}$, where v_{old} was the original and v_{new} was the corrected product conversion weights (fillets, trunk, gilled and gutted or whole; Begg et al., 2006).	$n = 0, w_{old} > 0$
$w_{new} = c \times 13 \times 1.608$, where 13 kg was the mean carton weight for fillets (≈ 3 fish carton^{-1}; s.d = 1.47, n = 6828) and 1.608 kg was the mean conversion for fillets to whole fish.	$n = 0, w_{old} = 0, c > 0$
$n = w_{new}/6.909$	$n = 0$
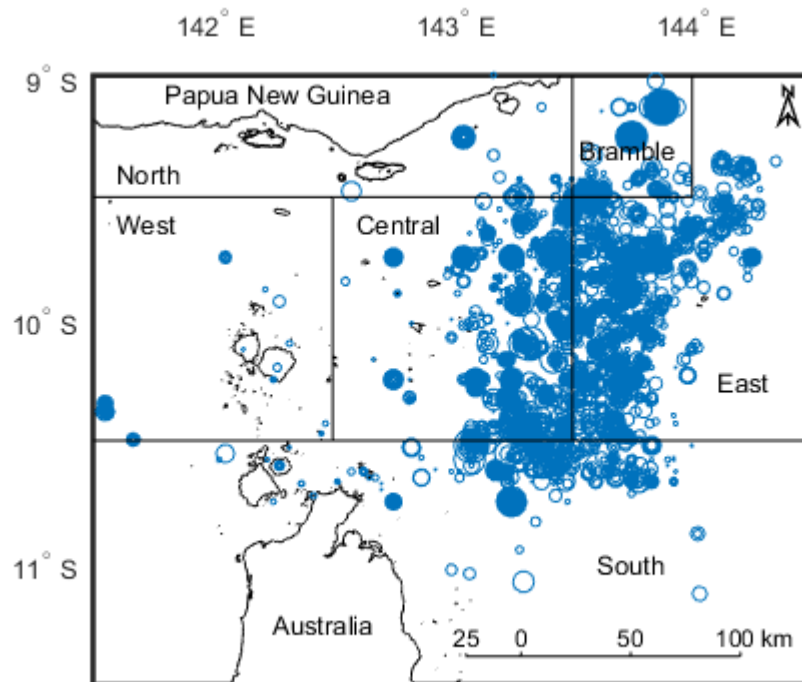
Figure 5. Map of the Torres Strait and regional stratifications (Bramble Cay, east, south, central, west and north island waters) used by Begg et al. (2006), with blue circles indicating the numbers of Spanish mackerel harvested per vessel day 1989–2015 by logbook recorded start-latitude and start-longitude. The circles are scaled proportionally, with larger circles showing larger daily harvests.
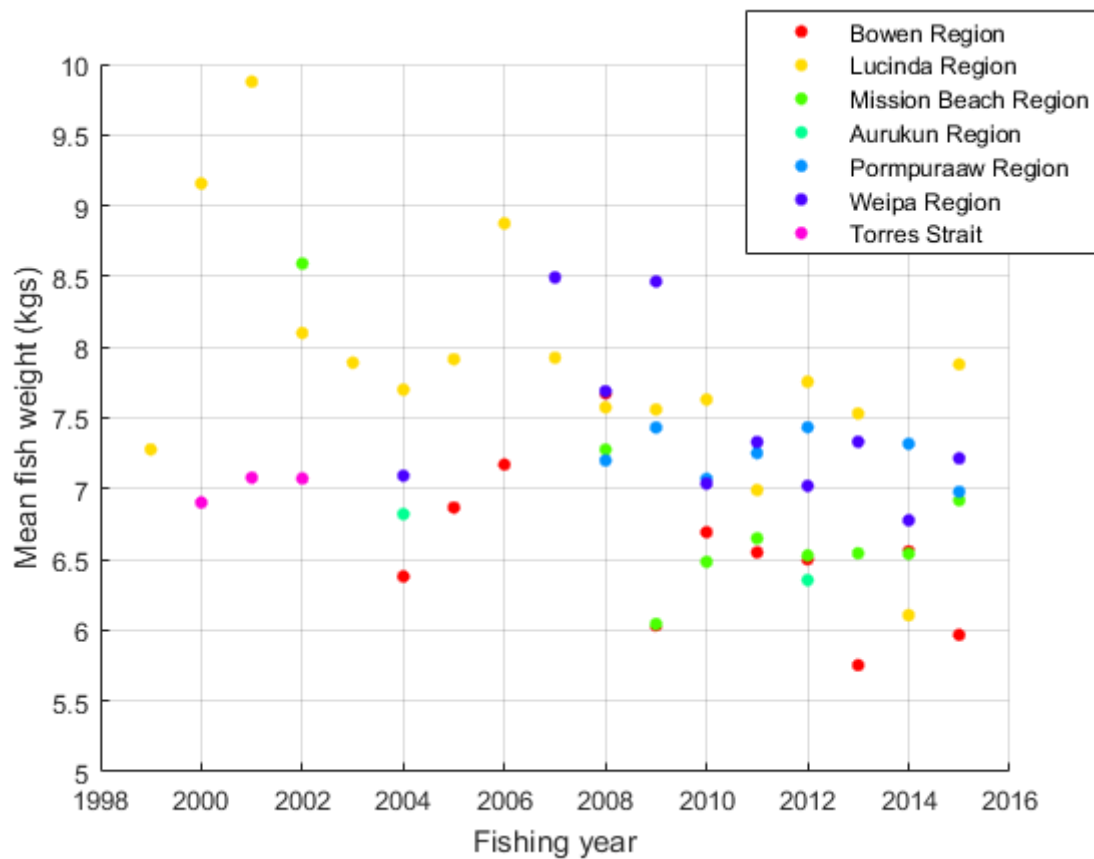
Figure 6. Comparison of the mean weight of Spanish mackerel by fishing years and regions nearby to the Torres Strait. Each mean point was calculated on a sample of between 100–2680 fish. The figure illustrates the variability between years and regions, with only a small number of means at or above 8.5 kg.

Fish age-length composition data

The Queensland Government (DAF) conducted monitoring of Torres Strait Spanish mackerel between 2000 and 2002 to obtain biological data and parameters on fish age and length (McPherson, unpublished). The monitoring was conducted through commercial fishing operations, which generally fished within 2 km of Bramble Cay. The sampled fishing locations and times was dependent on the commercial operation of vessels.

In each year an observer monitored the troll fish catches of as many vessels and days as possible (Table 2). The observer operated from a nominated vessel that provided sample processing and accommodation. Commercial operators were paid a stipend to provide and deliver filleted fish frames (McPherson, unpublished). The fish frames were processed for length, otoliths, gonads and genetic samples, with most fish sampled from morning catches. See Begg et al. (2006), Langstreth (2015) and McPherson (unpublished) for more detail.

Queensland Government monitoring ceased after 2002, but a CRC Torres Strait research project (T1.14) adopted the above protocols to sample fish in 2005 (Begg et al., 2006). The 2005 Spanish mackerel data were unable to be found on JCU computer servers or through the past stock assessment author Begg et al. (2006) (emails: A. Tobin 24th August 2015; G. Begg 17th August 2015).

The observed fish-otolith increment counts were assigned to an age (cohort) group based on the otolith edge types (Appendix 2). Fish sampled in October were assigned an age group as follows:

- o New edge type (code 0): age group = increment count,

- o Intermediate edge type (codes 1 and 2): age group = increment count, and

- o Wide edge type (code 3): age group = increment count +1.

The fish aged in the year 2000 samples had no edge type data. To adjust to age groups, 23% of these fish were assumed to have a wide edge type (Appendix 2). Fish aged 0+ (13 fish) were allocated to the 1+ age group (Appendix 2).

As most fish (~90%) were both measured and aged, the age group classifications were used directly to form the age structure proportions for input into the stock model (no age-length key was applied).

Table 2. Number of Spanish mackerel sampled for length and age. The 12 fish sampled (9 were aged) in April 2007 were not used.

Year	Month	Days	Vessels	Number of fish	Number aged
2000	Oct-Nov	15	1	915	827
2001	Oct	11	5	942	860
2002	Oct	8	3	654	579

In addition to the above data, the records on Spanish mackerel total lengths (cm) from the 2004 AFMA voluntary fisher logbook was used in the stock model (data from Begg et al., 2006).

Catch rate analysis

The Spanish mackerel data consisted of counts of fish (>0) harvested per vessel-operation day (Figure 11). Count data of this form can be analysed as an over-dispersed Poisson-like process (McCullagh and Nelder, 1989; Lee et al., 2006). Analyses that deal with over-dispersion are essential to accurately assess the significance of model parameters and to calculate appropriate confidence intervals on mean predictions. For Spanish mackerel, the over-dispersion arises due to fish aggregating (schooling) with various levels of abundance through time and area.

Over the time-series of data, two different logbook data forms were used to report harvests of fish: SM02 for 1989–2003 and TSF01 for 2003–2014. There was a clear increase in the catch rates of Spanish mackerel reported in the TSF01 logbook over SM02 (Figure 13); more than could be explained only by an increase in stock abundance. Thus the change in logbook reporting from SM02 to TSF01 was considered in the analyses to standardise catch rates. In total four analyses were conducted to standardise catch rates and explore different vessel and logbook effects.

The analyses were completed using the statistical software GenStat (VSN International, 2013) and standard errors were calculated for all estimates. The analyses were defined based on different logbook effects (Table 3):

a) No logbook effect – the generalised linear model (GLMa) assumed the change in logbook to TSF01 had no influence on reported harvests between 1989–2014;

b) TSF01 logbook effect – the GLMb modelled different logbook effects pre and post 31st June 2003. The effects were assumed constant over vessels;

c) By vessel-logbook effect – the generalised linear mixed model (GLMM) assumed the change in logbook influenced vessels reporting differently pre and post 31st June 2003; and

d) Reduced time series – the GLMd analysed only TSF01 reported harvests since 1st July 2003; no logbook effect required.

The importance of individual model terms (Table 9 and Table 10) was assessed formally using F statistics by dropping individual terms from the full model.

The over-dispersed Poisson models were used as they conformed easily to the discrete nature of the count (numbers of fish) data. The Poisson models suitably weighted the data giving greater but no excessive emphasis to harvests with large fitted values, they were consistent with respect to different time scales and it should be noted that the residual plots do not have to appear to be normal (Leigh, 2016).

The calculation of standardised catch rates involved predicting mean catch rates from the different model terms; using GenStat's 'PREDICT' and 'VPREDICT' procedures for the GLM and GLMM respectively (VSN International, 2013). For example, annual standardised catch rates were predicted from the fishing-year model term, keeping all other model terms constant. For reasons to ensure comparability and confidentiality, the final predictions were normalised against their overall mean. Standard errors for all predictions were adjusted up according to the sqrt(residual mean deviance); where the residual mean deviance = over dispersion parameter.

Table 3. The GenStat statistical models used to analyse Spanish mackerel harvests. Models a–c analysed all time-series data 1989–2014, whereas model d analysed only 2003–2014 data.

a) **GLMa: Main fixed effects model with no logbook effect.**

```
MODEL [DISTRIBUTION=poisson; LINK=logarithm; DISPERSION=*] nfish
FITINDIVIDUALLY [PRINT=model,summary,estimates,accumulated; \
 CONSTANT=estimate; FPROB=yes; TPROB=yes; FACT=2;\
selection=%variance,%ss,adjustedr2,r2,seobservations,dispersion,%meandeviance,%deviance,aic,sic;]\
fishyear+boat+s1+s2+s3+s4+tenders+lunar+lunar_adv+windns+windnsQ+window+windowQ
RWALD
```

The variables windnsQ = windns^2 and windowQ = window^2 were quadratic model terms.

b) **GLMb: Main fixed effects model with logbook effect.**

```
MODEL [DISTRIBUTION=poisson; LINK=logarithm; DISPERSION=*] nfish
FITINDIVIDUALLY [PRINT=model,summary,estimates,accumulated; \
 CONSTANT=estimate; FPROB=yes; TPROB=yes; FACT=2;\
selection=%variance,%ss,adjustedr2,r2,seobservations,dispersion,%meandeviance,%deviance,aic,sic;]\
fishyear+boat+logbook+c12+cs12+c6+cs6+tenders+lunar+lunar_adv+windns+windnsQ+window+windowQ
RWALD
```

c) **GLMM: Main fixed effects model with a boat x logbook random effect term.**

```
GLMM [PRINT=model,monitor,components,vcovariance,means,backmeans,effects,wald; DISTRIBUTION=poisson;\
 LINK=logarithm; DISPERSION=*;
FIXED=fishyear+c12+cs12+c6+cs6+tenders+lunar+lunar_adv+windns+windnsQ+window+windowQ;\
 RANDOM=boat+boat.logbook; CONSTANT=estimate; FACT=9; PSE=differences,estimates; MAXCYCLE=20;\
 FMETHOD=all; MVINCLUDE=*; CADJUST=mean] nfish
```

d) **GLM: Main fixed effects model with hours fished data included for the reduced time series 2003–2014.**

```
MODEL [DISTRIBUTION=poisson; LINK=logarithm; DISPERSION=*] nfish
FITINDIVIDUALLY [PRINT=model,summary,estimates,accumulated; \
 CONSTANT=estimate; FPROB=yes; TPROB=yes; FACT=2;\
selection=%variance,%ss,adjustedr2,r2,seobservations,dispersion,%meandeviance,%deviance,aic,sic;]\
fishyear+boat+c12+cs12+c6+cs6+tenders+hours2+lunar+lunar_adv+windns+windnsQ+window+windowQ
RWALD
```

Population dynamics model

The population dynamic model (Table 4) calculated numbers (*N*) of Spanish mackerel by the following categories:

- yearly (*t*) time categories from the fishing year 1989 to 2014,

- sex (*s*) with level 1 = female and 2 = male, and

- age-group (*a*) from 1+ to the maximum age.

The model accounted for the processes of fish births, growth, reproduction and mortality in every fishing year (time step *t*; Table 4). The model was run in two phases: (i) historical estimation of the Spanish mackerel stock from the fishing years 1989–2015 and (ii) simulations of model values and errors to evaluate reference points (Figure 7).

The Torres Strait commercial fishery for Spanish mackerel commenced in the 1940's (Begg et al., 2006) and it was unrealistic to start the model in 1989 from an unexploited state (virgin population). To initialise population conditions in 1989 the model assumed an estimated annual harvest from 1940 to 1988 with respect to the building trend in harvests reported by McPherson (1986) for the years 1957, 1959, 1960, 1962, 1975-77 and 1979 (Table 4.1 x 1.185, in Begg et al., 2006) up to the average annual harvest 1989–1993.

The method to initialise population conditions using 1940–1988 predicted harvests was similar to the model runs by Begg et al. (2006), however a logistic shaped increase was assumed rather than linear or exponential-like. The logistic increase was estimated from a binomial GLM assuming the 1989–1993 harvests were at 100% and the McPherson (1986) data a fraction of the 1989–1993 average annual harvests. The logistic-shape assumption aimed to create a realistic long term pattern of expansion of the fishery in order to initialise suitable model conditions. Begg et al. (2006) used the fishing year 1940 to represent the start time for modelling when fishing pressure was low.
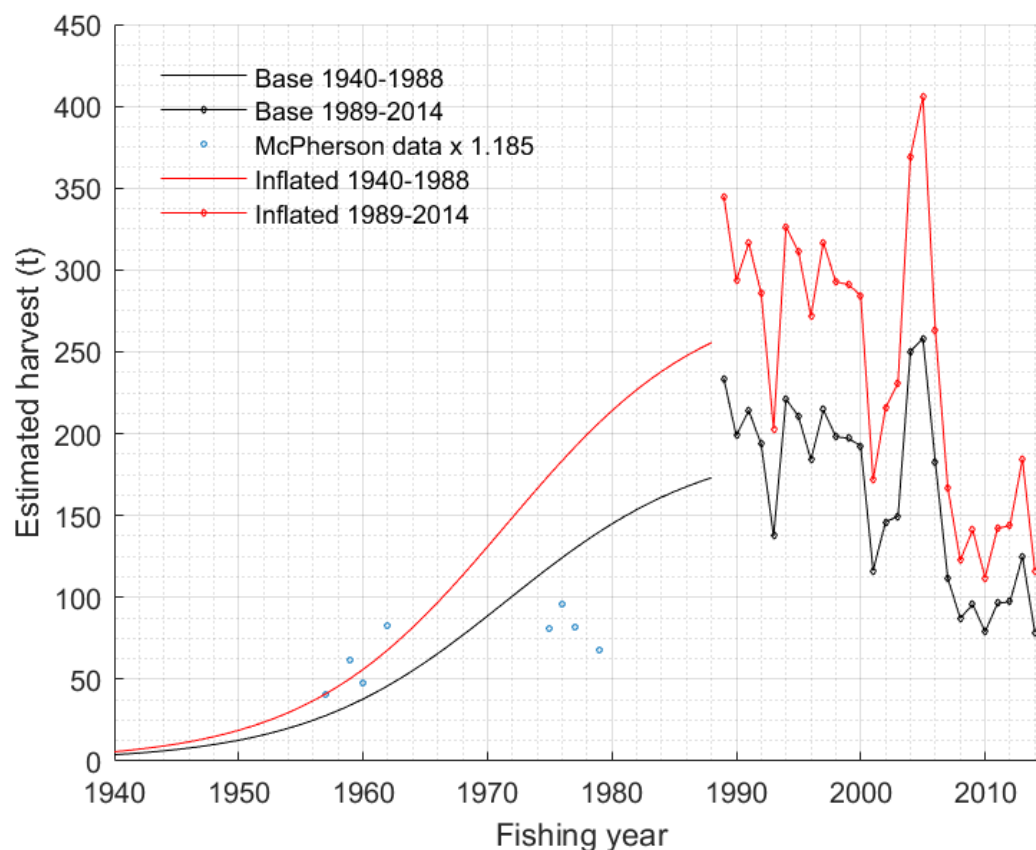
Figure 7. Comparison of pre 1989 estimated harvests used to initialise model dynamics in 1989.

For the Torres Strait, Spanish mackerel harvests are taken by commercial (islander and non-islander fishers), traditional subsistence fishers, recreational fishers and charter fishers. Estimates of harvests taken by all these sectors were not available. Harvests were assumed to be mostly taken by the commercial non-islander sector, with the other sectors harvests considered minor in comparison (Begg et al., 2006); see also the comment under the 'data inputs' section for harvests. Due to the limited availability of sectoral data the assessment was constrained to follow this assumption, including that fish vulnerabilities were the same between fishing sectors f. This assumption simplified the calculation of harvest rates (u_t) to be based on a single value for the total harvest C_t in each fishing year ($\sum_f C_{f,t}$). No iterative method for different sectoral harvests (Leigh et al., 2014; O'Neill and Leigh, 2014) or negative log-likelihood for predicting harvests was required.

The estimation of fish growth and modelling of discrete lengths were not attempted in the stock model given the short time series of observed fish age-length data. An externally estimated von Bertalanffy growth curve (Table 4, equation 6; described in Haddon (2001)) for each fish sex based on age-groups (defined on page 11) and 2001–2002 data was used; where l^∞ is the average maximum fish total-length (cm), κ is the growth rate parameter that determines how quickly l^∞ is attained and a^0 is the is the theoretical age at which the expected length is zero – the value is typically negative and needed so that the function best represents the growth of exploitable (legal) sized fish; data on small undersized fish are less vulnerable and under sampled in the Torres Strait.

From the growth curve, fish length at age was assumed to follow a normal distribution using the parameters from Table 7 for mean fish length and variance. For a given fish sex and age the normal distribution calculated the proportions of fish $p_{s,a}(l)$ at length l, such that $\sum_l p_{s,a}(l) = 1$.

The stock model length distributions of Spanish mackerel for each time and sex group was approximated using the theory of Gaussian finite mixture models (McLachlan and Peel, 2000). The normal probability densities can be combined over any of the groups to form a multivariate normal distribution of fish lengths. The multivariate normal distributions can be calculated, where the individual normal densities (with mean $\bar{l}_{s,a}$ and standard deviation $\sqrt{\sigma_s^2}$.) are summed based on the mixing proportions $\pi_{t,s,a}$ calculated from the exploitable population numbers of fish $N_{t,s,a}v_a$.

Model parameters (Table 5) were estimated by calibrating the model to standardised catch rates and age-length composition data (Table 6). Primary importance was placed on fitting the standardised catch rates (Francis, 2011). Effective sample sizes for scaling multinomial negative log-likelihoods were calculated within the model in order to give realistic weighting to the age-length composition data. Additional negative log-likelihood functions were also considered for predicting natural mortality (M) and annual recruitment variation (η_t) (Table 6).

The model estimation process was conducted in Matlab® (MathWorks, 2015) and consisted of a maximum likelihood (ML) step followed by Markov Chain Monte Carlo sampling (MCMC). The flow of the estimation process is summarised in Figure 7. The maximum likelihood step used Matlab global optimisation (Quasi-Newton method, MathWorks, 2015), followed by a customised simulated annealing program to find and check the parameter solutions and estimate the parameter covariance matrix. The maximum likelihood step was effective for searching and locating optimal estimates over the negative log-likelihood (combined NLL fitting functions) search space. The simulated annealing was started from a NLL scaling factor of 100 and then reduced to 10 and then 1. For each scaling factor, the annealing process was run for 5000 iterations of each parameter. The covariance matrix was built up by measuring the differences in the negative log-likelihood with each parameter jump.

The MCMC followed on from the simulated annealing using a NLL scaling factor of 1 with fixed covariance. The MCMC used parameter-by-parameter jumping following the Metropolis-Hastings algorithm described by Gelman et al. (2004). The final parameter distributions were based on 1000 posterior MCMC samples thinned from 1 solution stored per 100 samples. MCMC parameters traces and autocorrelations were assessed for convergence and independence (Plummer et al., 2006).

The calculation of the fishery equilibrium reference points were based on optimising the population model dynamics through an average harvest rate ($u = 1 - \exp(-F)$) for each MCMC posterior parameter sample. All parameter uncertainties were included except stochastic recruitment variation (error term $\exp(\eta_t)$ in equation 3, Table 4) was fixed equal to one.

The age-model biomass equilibrium reference points for maximum sustainable yield ($B_{MSY} \approx 0.4B_0$) and a proxy for maximum economic yield ($B_{MEY} \approx 0.6B_0$) were calculated. The Australian Government's current proxy for B_{MEY}/B_{MSY} is 1.2 (Australian Government, 2007). The origin of this proxy is not clear (Dr Sean Pascoe, CSIRO, personal communication at the Fisheries Queensland harvest strategy workshop 4-5th August 2015), but likely based on the symmetric surplus production theory of $B_{MSY} \approx 0.5B_0$ (Zhou et al., 2013; Pascoe et al., 2014). This corresponds to $B_{MEY}/B_{MSY} = 1.5$ for the non-symmetric age-model dynamics.

In model development and testing the estimation of annual recruitment variation was deemed inestimable due to the limited time series of age-length data. This was because the number of parameters would exceed the amount of data and saturate the model fit; given that an extra 25 annual recruitment parameters are needed to cover the model years 1989–2014. The calculation of annual fish recruitment was therefore assumed deterministic according to the Beverton-Holt function with no error.

In addition the model testing of fish length dependent vulnerability proved inadequate due to the growth curve and age-length data indicating that the sampled fish were fully size selected and that only the age 1+ group was not. Therefore the model was simplified for age dependent vulnerability to improve model fit and estimation. The initial method for fish length dependent vulnerability followed the Cabezon stock model conversion technique (Leigh, 2016) for sex-and-age dependent vulnerability, where:

$$v_{t,s,a} = \sum_l p_{s,a}(l) v_{t,l} \qquad (16), \text{ and}$$

$$v_{t,l} = \frac{1}{1 + \exp\left(-\log(19)\frac{(l - l_{50})}{(l_{95} - l_{50})}\right)} [l \geq \text{mls}_t] \qquad (17).$$

The mls was the minimum legal size at time t. Before 1985 there was no mls, in 1985 an insignificant 45cm total length (TL) mls was introduced and then in 2004 a 75cm TL mls was enforced (Begg et al., 2006). These management measures appeared to have no influence on the data.
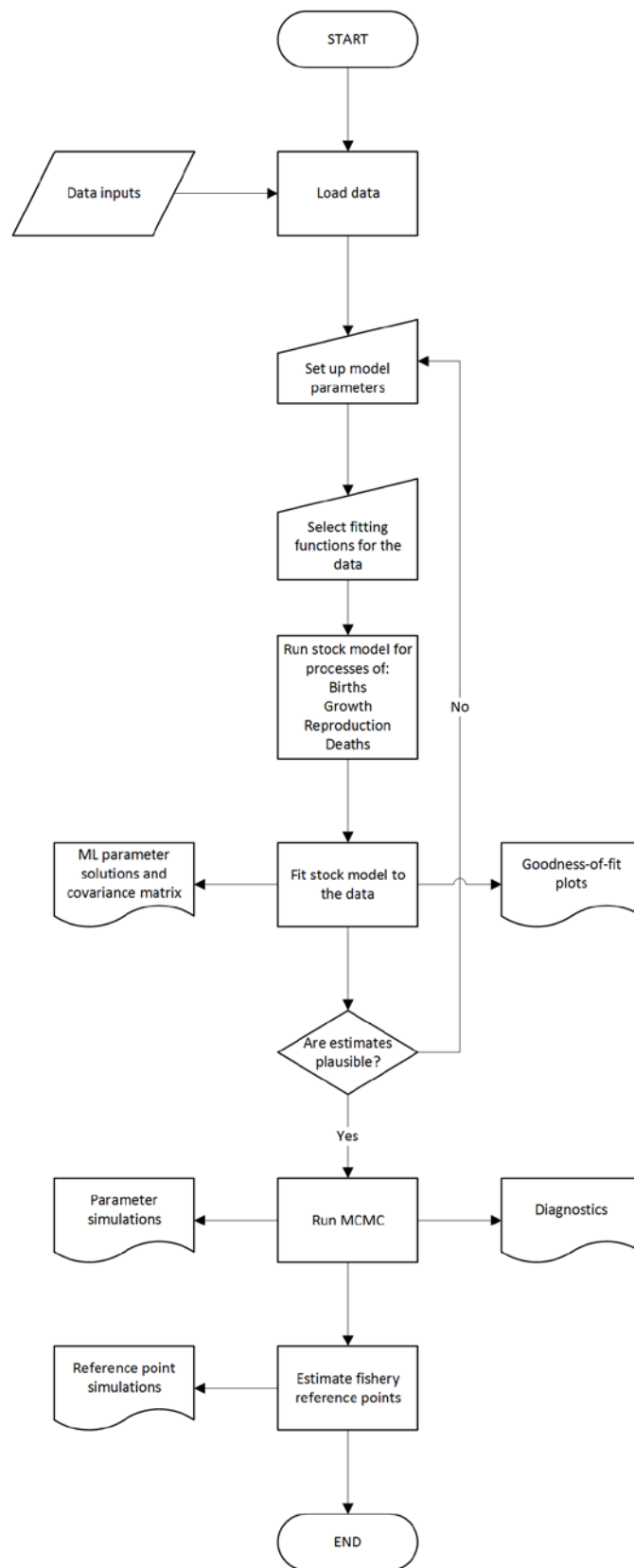
Figure 8. Flow of operations for the stock model from loading the data to evaluating model predictions.

Table 4. Equations for calculating the Spanish mackerel population dynamics.

Population dynamics	Equations

Numbers of fish in the 1st year 1940 (t=1):

$$N_{t,s,a} = 0.5 R_t \exp\left(-M\left(a-1\right)\right)$$

(1)

Numbers of fish after the 1st year 1940 (t>1):

$$N_{t,s,a} = \begin{cases} 0.5 R_t & \text{for} & a = 0 \\ N_{t-1,s,a-1} \exp\left(-Z_{t-1,s,a-1}\right) & \text{for} & a = 1 \ldots \max\left(a\right) \end{cases}$$

(2)

Recruitment number of fish – Beverton-Holt formulation:

$$R_t = \frac{S_{t-1}}{\alpha + \beta S_{t-1}} \exp\left(\eta_t\right)$$

(3)

Spawning index – annual egg production:

$$S_t = \sum_a N_{t,s,a} m_a \vartheta_a \qquad \text{for} \quad s = 1$$

(4)

Fish survival:

$$\exp\left(-Z_{t,s,a}\right) = \exp\left(-M\right)\left(1 - v_a u_t\right)$$

(5)

Mean fish length in each cohort:

$$\bar{l}_{s,a} = l_s^\infty \left(1 - \exp\left(-\kappa_s\left(a - a_s^0\right)\right)\right)$$

(6)

Fish vulnerability to fishing:

$$v_a = \frac{1}{1 + \exp\left(-\log\left(19\right)\dfrac{\left(a - a_{50}\right)}{\left(a_{95} - a_{50}\right)}\right)}$$

(7)

Harvest rate:

$$u_t = C_t / B_t^1$$

(8)

Midyear exploitable biomass – forms 1 and 2:

$$B_t^1 = \sum_s \sum_a N_{t,s,a} \bar{w}_{s,a} v_a \exp\left(-0.5M\right)$$

(9)

$$B_t^2 = \sum_s \sum_a N_{t,s,a} \bar{w}_{s,a} v_a \exp\left(-0.5M\right)\sqrt{1 - u_t}$$

(10)

Catch rate:

$$c_t = q B_t^2$$

(11)

Table 5. Parameter definitions for the Spanish mackerel population dynamics model.

Parameter	Equations and values	Notes
Assumed		
$\text{Max}(a)$	25	Based on considering the maximum fish age recorded from the Torres Strait (12 yrs), the Gulf of Carpentaria (15 yrs) and the Queensland East Coast (26 yrs). Larger values can be set in the model as no plus-group was programmed in the dynamics for combining very old fish.
l	$TL = 4.274 + 1.06 \times l$	Fish length conversion from fork length (l) to total length (TL) measured in cm (Begg et al., 2006).
	$l_s^\infty, \kappa_s, a_s^0$	The estimated von Bertalanffy growth curve parameters for each sex s (Table 7).
w	$w_s = x_s l^{y_s}$	Fish weight (kg) at total length for each sex s, based on the exponential curve parameters x_s and y_s. Females: x = 2.960e-6 and y = 3.148; Males: x = 4.224e-6 and y = 3.068 (Begg et al., 2006).
m	$m_{s,l} = \dfrac{\exp(\varsigma)}{1+\exp(\varsigma)}$ $\varsigma = -10.349 + 0.0128 \times l$	Logistic maturity schedule $p(\text{mature}\|l_{s,a})$ by fork length (cm) for female fish (s = 1). The schedule was estimated using binomial regression and logit link (Mackie et al., 2005; Begg et al., 2006). The length-dependent maturity was converted to sex-and-age dependent maturity following the process for length vulnerability (Equation 16).
ϑ	$\vartheta_l = xl + yl^2$	Mature gonad weight (kg as an index of fecundity) at total length for female fish. The relationship was estimated from only mature ripe stage 7 fish using Begg et al. (2006) data. The quadratic curve parameters were: x = -0.008858 and y = 0.000124; R^2 = 0.4906 and n = 83. The length-dependent fecundity was converted to sex-and-age dependent fecundity following the process for length vulnerability (Equation 16).
Estimated		
Υ and ξ	$\alpha = S_0(1-h)/(4hR_0)$ $\beta = (5h-1)/(4hR_0)$ $R_0 = \exp(\Upsilon) \times 10^6$ $h = r_{comp}/(4 + r_{comp})$ $r_{comp} = 1 + \exp(\xi)$	Two parameters for the Beverton-Holt spawner-recruitment function, equation 3 Table 4, that define α and β (Haddon, 2001). Virgin recruitment (R_0) was estimated on the log scale for the first model year. One estimated value of steepness (h) was assumed for the stock. S_0 was the calculated as the overall virgin egg production in the first model year from equation 4 Table 4. The r_{comp} parameter is the recruitment compensation ratio (Goodyear, 1977), based on the log scale coefficient ξ.
a_{50} and a_{95}		Two parameters for the logistic vulnerability, equation 7 Table 4 (Haddon, 2001). a_{50} was the fish age (years) at 50% vulnerability to fishing and a_{95} at 95%.
M		One parameter for instantaneous natural mortality year^{-1}, according to the log-likelihood equation 14 Table 6. The prior distribution allowed for a lifespan of about 20 years in the Torres Strait. Begg et al. (2006) considered empirical estimates of 0.37 based on the Hoenig (1983) equation assuming the maximum age of 12 years and 0.28 year^{-1} using the Pauly's (1983) schooling equation. Estimates from east-coast waters of Queensland ranged 0.26 to 0.34 year^{-1} using the same methodology (Campbell et al., 2012). Another estimate of using the age based estimator of Then et al. (2015) was 0.25 year^{-1} assuming a maximum age of 26 years from Queensland east coast waters.
ζ	$\boldsymbol{\eta} = \zeta\mathbf{e}$ e = zeros(nparRresid, nparRresid+1); for i = 1:nparRresid hh = sqrt(0.5 * i ./ (i + 1)); e(i, 1:i) = -hh ./ i; e(i, i + 1) = hh; end; e= e ./ hh;	Recruitment parameters to ensure log deviations sum to zero with standard deviation σ, equation 15 Table 6. ζ were the estimated parameters known as barycentric or simplex coordinates, distributed $NID(0,\sigma)$ with number nparRresid = number of recruitment years – 1 (Möbius, 1827; Sklyarenko, 2011). **e** was the coordinate basis matrix to scale the distance of residuals (vertices of the simplex) from zero (O'Neill et al., 2011).
q		Fish catchability parameter measuring the proportion of the exploitable stock taken by one unit of standardised fishing effort. The parameter was derived as a closed-form median estimate of standardised catch rates divided by the midyear biomass form 2 (Table 4) (Haddon, 2001).

Table 6. Negative log-likelihood functions for calibrating population dynamics.

-*LL* functions for:	Theory description	Equations
Log standardized catch rates for each fishing sector ($c_{f,t}$):		
$\frac{n}{2}\left(\log\left(2\pi\right)+2\log\left(\hat{\sigma}\right)+1\right)$, or simplified as $n\log\left(\hat{\sigma}\right)$, where $\hat{\sigma}=\sqrt{\sum\left(\left(\log\left(c_t\right)-\log\left(\hat{c}_t\right)\right)^2\right)\Big/n}$ and n was the number of annual catch rates c.	Normal distribution (Haddon, 2001)	(12)
Fish length (l) and age (a) composition data:		
$-\sum\left(\log\left(T^{(\tilde{n}-1)/2}\right)-\left(\frac{1}{2}\left(\tilde{n}-1\right)\frac{T}{\hat{T}}\right)\right)$, or simplified as $-\sum\frac{1}{2}\left(\tilde{n}-1\right)\left(\log T-T\big/\hat{T}\right)$, where $\tilde{n}$ was the total number of categories (l or a) with proportion-frequency > 0, $\hat{T}=\left(\tilde{n}-1\right)\big/2\sum\hat{p}\log\left(\hat{p}\big/p\right)$, $T=\max\left(2,\hat{T}\right)$ specified sample size bounds, $\hat{p}$ were the observed proportions > 0 and p were predicted.	Effective sample size (T) in multinomial likelihoods (Leigh, 2011; O'Neill et al., 2011; Leigh et al., 2014; Leigh, 2016)	(13)
Instantaneous natural mortality M year^{-1}:		
$0.5\left(\frac{M-0.3}{\sigma}\right)^2$, where $\sigma=0.06$ defined the prior distribution $\cong$ 20% CV.	O'Neill et al. (2014)	(14)
Annual log recruitment deviates η:		
$\frac{n}{2}\left(\log\left(2\pi\right)+2\log\left(\sigma\right)+\left(\hat{\sigma}\big/\sigma\right)^2\right)$, or simplified as $n\left(\log\sigma+\frac{1}{2}\left(\hat{\sigma}\big/\sigma\right)^2\right)$, where $\sigma=\min\left(\max\left(\hat{\sigma},\sigma_{min}\right),\sigma_{max}\right)$, $\sigma_{min}=0.1$ and $\sigma_{max}=0.4$ specified bounds, $\hat{\sigma}=\sqrt{\sum\eta^2\big/n}$ and n was the number of recruitment years modelled with variance.	O'Neill et al. (2014)	(15)

Results and discussion

The results and discussion section describes notable trends in Spanish mackerel data, predictions from analyses and general conclusions and recommendations. The key data and analyses results are structured under two sub-headings for the 'data inputs' into the model and the 'population dynamic model' estimates and diagnostics. The flow of stock model operations from data inputs to evaluating outputs are illustrated in Figure 7.

Data inputs

Harvests

The Torres Strait AFMA finfish logbook data was analysed for the fishing years 1989–2014. The data analyses were summarised to financial or fishing years (e.g. the 2014 fishing year grouped harvests between 1st July 2014 and 30th June 2015). The descriptive terms 'fishing year' or 'year' are synonymous.

From the logbook data, the estimated Spanish mackerel annual harvests ranged 98–233 t between 1989 and 2006 (Figure 8a). The estimated annual harvest of Spanish mackerel declined to 64-105 t between 2007 and 2014. The corresponding estimated numbers ranged 14–34 thousand fish harvested each year between 1989 and 2006, and 9–15 thousand fish each year between 2007 and 2014 (Figure 8b).

The number of vessels reporting Spanish mackerel harvest through logbooks ranged 10–28 between 1989 and 2006 (Figure 9a). These operations fished in order of 750–1400 days a year (Figure 9b). The numbers of operations reporting harvest dropped to 4–6 per fishing year between 2007 and 2013, with less than 500 boat days fished. The number of tender days were tallied, but are under estimated in some years (Figure 9c).

The docket database of Spanish mackerel harvests averaged about 22 t each fishing year from 2003–2010 (Figure 10). The harvest tallies from other years were very low (Figure 10). Begg et al. (2006) also documented low harvests from the docket database of 1–9 t each year 1989–2002. It was noted through the AFMA Torres Strait Smart Phone project that the Islander freezer and docket database was not up-to-date (French et al., 2015). This database is important to verify harvest trends and to tally commercial Islander harvest into stock assessment. From the AFMA database supplied, data for the fishing years 1989–2000 were missing (years 1989 to 2000 were present in Fig 3.11, in Begg et al., 2006). For the years 2003–2010, the docket

database corresponded to about 18.5% (standard deviation = 4.6%) of the Spanish mackerel logbook tonnages.

For data input into the population dynamic model, two scenarios of total Spanish mackerel harvest were considered to cover the range of uncertainty in unreported catches:

1. Base reported harvests: logbook harvest 1989–2014 + docket book harvest 2003–2010 + 18.5% of logbook harvest for the unaccounted years of docket book harvest (1989–2002, 2011–2014). This scenario is similar to Begg et al. (2006), except a larger docket book harvest was assumed.

2. Inflated harvests: logbook harvest 1989–2014 was multiplied by 1.75 to examine the inference of larger harvests on stock status predictions.

The base harvest schedule above included all reported Spanish mackerel catches from both Islander and Non-Islander commercial fishers. Additional unreported catches and fishing effort are likely (Patterson et al., 2015). This uncertainty is examined under the inflated harvest schedule.

As reported and assumed by Patterson et al. (2015) and Begg et al. (2006), the traditional Islander subsistence, recreational, historical foreign fishing and Papua New Guinea harvests were assumed small and not accounted in the base schedule. This uncertainty is examined under the inflated harvest schedule.
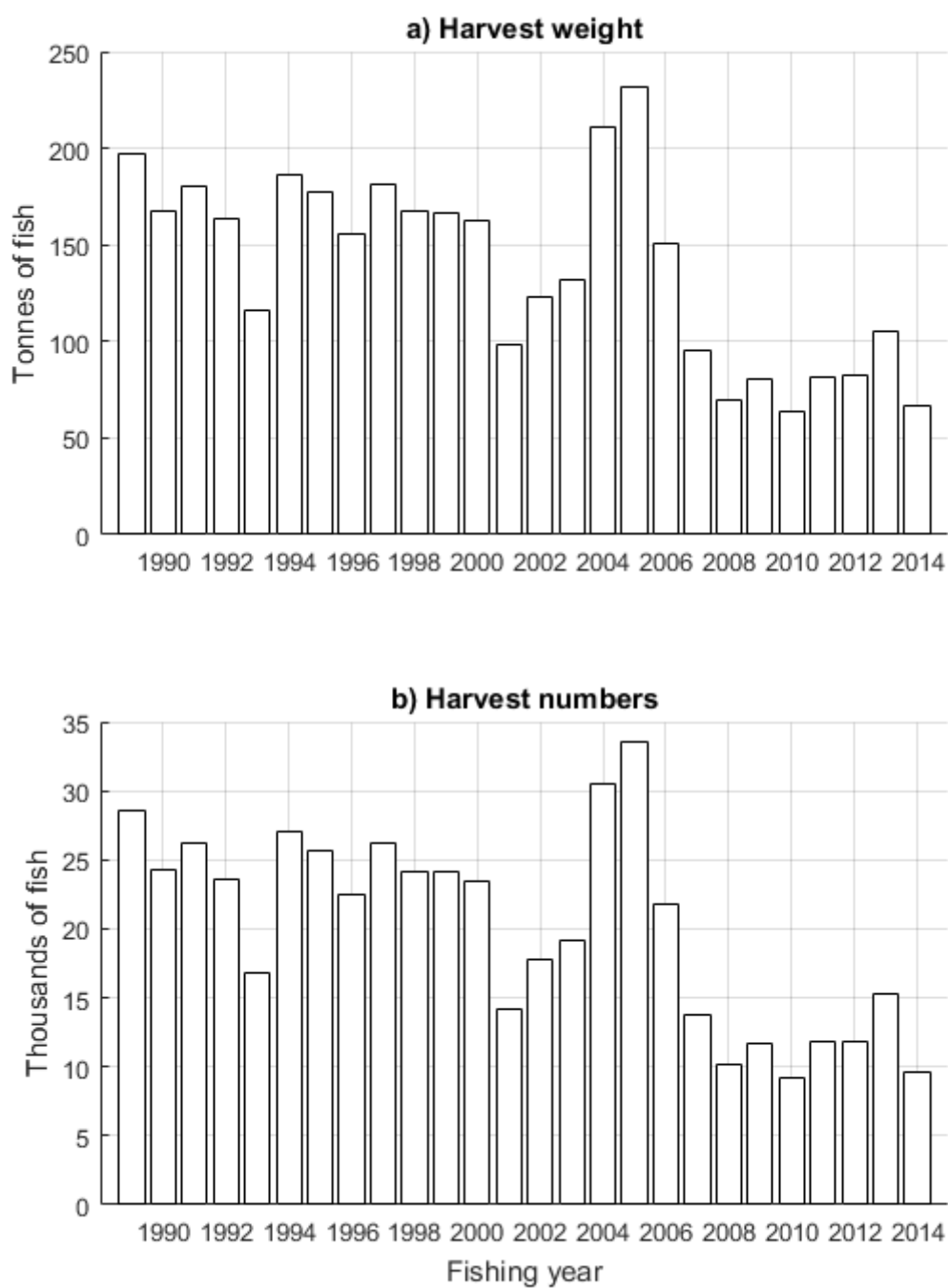
Figure 9. Estimated total harvests of Spanish mackerel by fishing year from the logbook data for a) fish weight measured in tonnes (t) and b) numbers measured in thousands of fish.
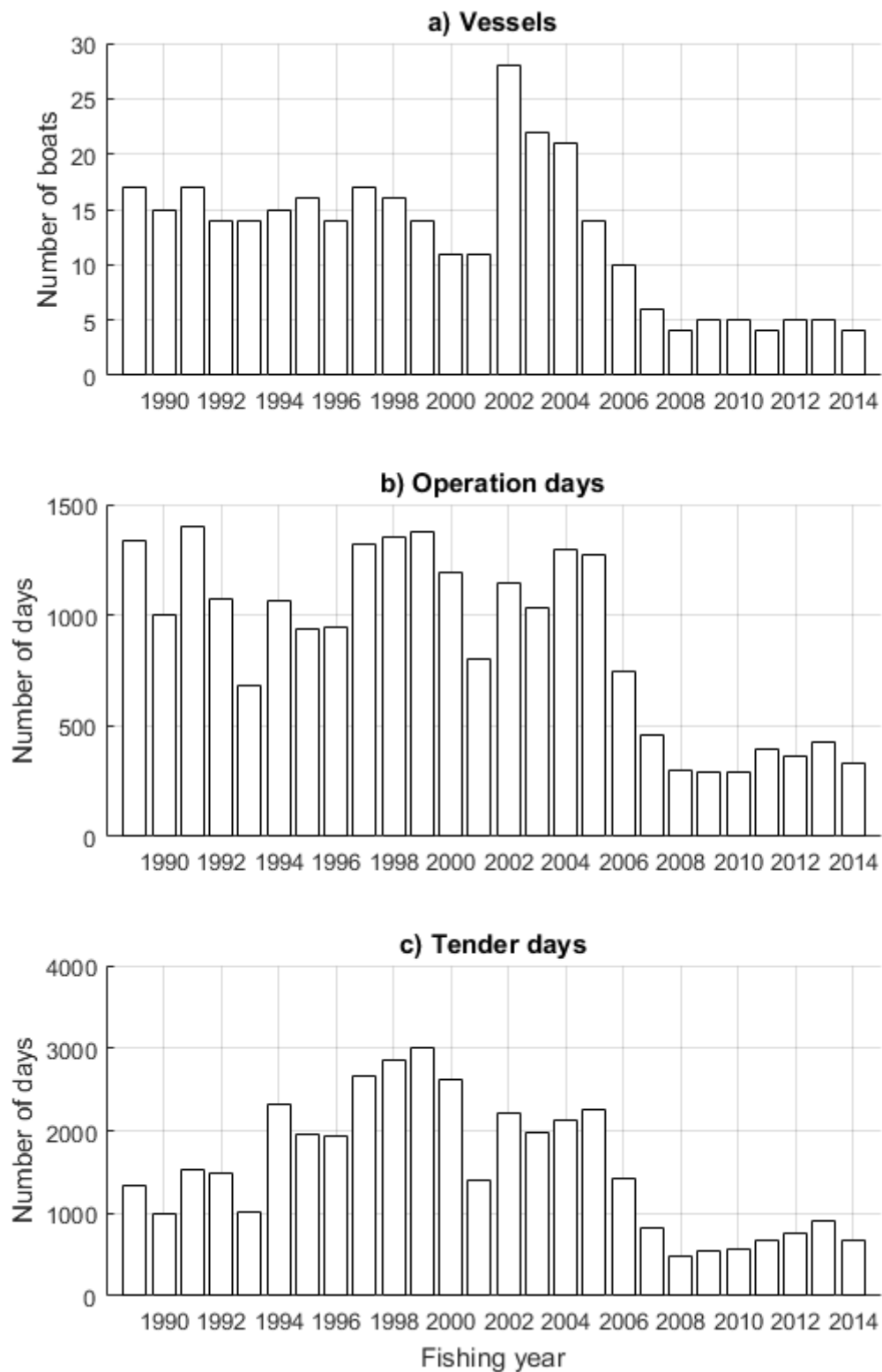
Figure 10. Estimated nominal measures of total fishing effort by year for a) number of fishing operations (vessels), b) number of days fished by the vessels and c) number of days fished by all vessel tenders. Note: early 1990's tender days may be underestimated due to logbook complexities.
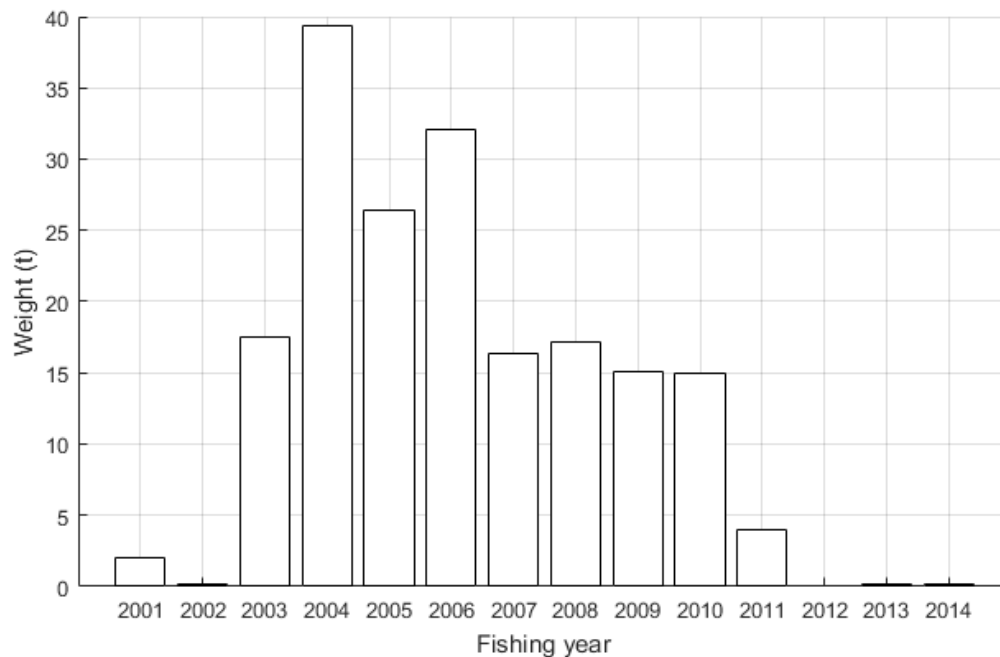
Figure 11. The Docket database tally of Spanish mackerel harvest (tonnes) by fishing year. The 2003–2010 mean = 22.3 t year^{-1}, corresponding to about 3238 fish, with standard deviation = 9.2 t.

Catch rates

At this time for Torres Strait Spanish mackerel, relative trends in fish abundance can only be inferred from a logbook standardised catch rate. This index is of great importance to the stock assessment model as it informs proportionally on the magnitude of change in the Spanish mackerel fished (exploitable) population; this was the primary assumptions for the stock model. It is also a limitation as the stock model has to place emphasis on the index as no recent monitoring of Spanish mackerel age-length or fishery-independent survey data was available.

The assumption of proportionality was made only after employing a regression model (Hilborn and Walters, 1992), in order to standardise the biases or variation in the data by accounting for factors affecting relative fish abundance and fishing efficiency. The result aims to generate a time series of standardised catch rates that is more representative of trends in the fished population. If a catch rate trend measure is calculated on only raw catch and effort data, then this could produce a false outcome unless sources of variability are identified and corrected as needed. This error can occur due to efficiency changes in fishing effort and locations fished through time and between fishing vessels.

The Spanish mackerel catch rate data (numbers of fish) between 1989 and 2014 was first summarised to understand the distributional properties. The catch rate data had high variance

and was highly skewed with a nominal median = 15 fish vessel-day^{-1}, mean = 23 fish and standard deviation = 25 fish (CV = 109%); most (94%) harvests were reported as numbers of fish and not weight. Significant variance in catch rates between primary vessels was evident (Figure 11), with some surprisingly large harvests (> 100 fish day^{-1}). The variance in catch rate data by fishing year is illustrated in Figure 12. Control chart analysis of the data further illustrates the skewness and magnitude of some harvests (Appendix 1, Figure 20).
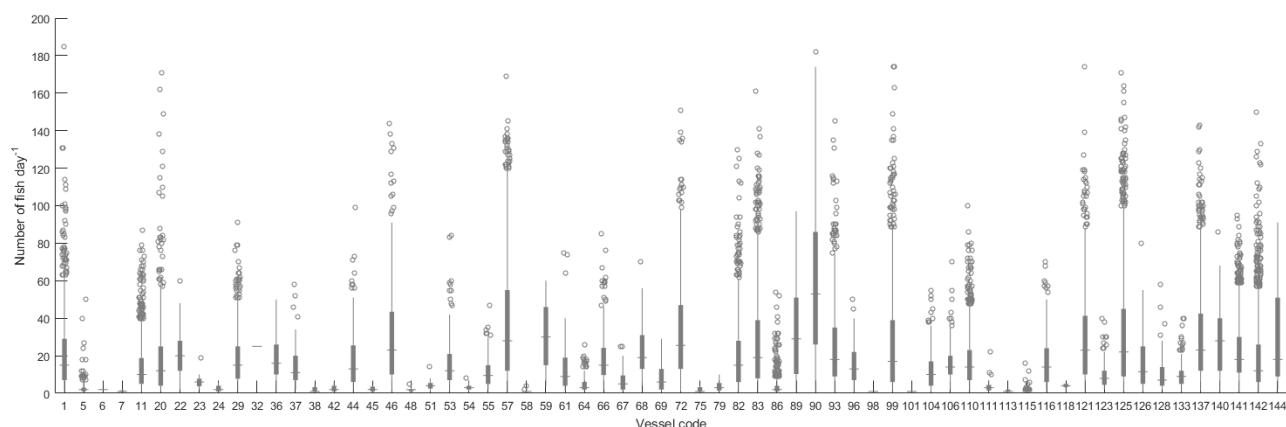
Figure 12. Box plot of each vessel's daily harvest of Spanish mackerel. The plot displays the skewed distributions of harvest around their medians (line in the middle of each box). The bottom and top of each box were the 25th and 75th percentiles. The whisker lengths indicate about 99% coverage of each vessel's harvest. Outlier points are drawn as circles. To improve the display the y-axis was limited to 200 fish, with 6 outlying harvests between 201 and 500 fish not shown. Overall, the upper skewness of the data was 2.096 (s.e. = 0.0163) and the calculated box-cox power transformation to normalised the data and analysis residuals was λ = 0.12. Total number of data points N = 23098 (unfiltered).
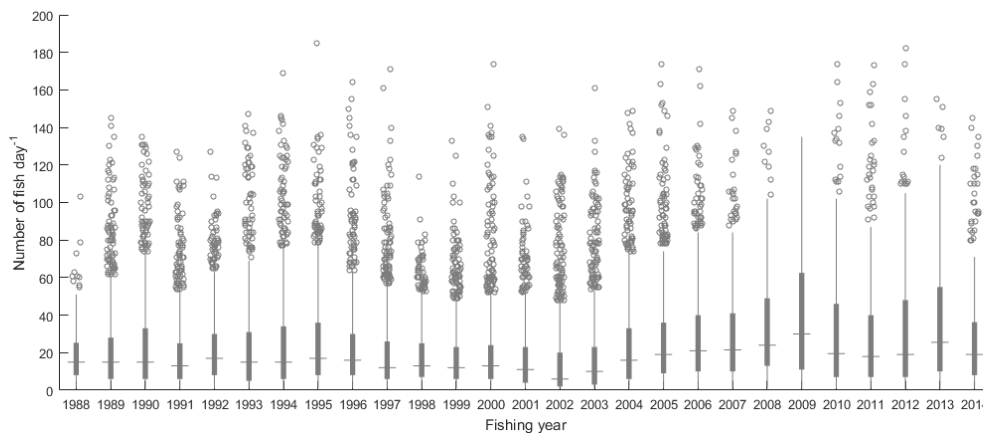
Figure 13. Box plot of daily harvests of Spanish mackerel by fishing year. The plot displays the skewed distributions of harvest around their medians (line in the middle of each box). The bottom and top of each box were the 25th and 75th percentiles. The whisker lengths indicate about 99% coverage of each vessel's harvest. Outlier points are drawn as circles. To improve the display the y-axis was limited to 200 fish, with 6 outlying harvests between 201 and 500 fish not shown.

Figure 13 compared three different catch rate indices of Spanish mackerel abundance between the fishing years 1989 and 2014. A fourth analysis was conducted to verify trends separately on the 2003–2014 data (Figure 22, Appendix 1). The indices from all analyses were scaled relative to their overall time series mean. The following results are noted:

o   All indices illustrated a general decline between 1989 and 2002.

o   The nominal (unstandardised) and GLMa indices increased strongly post 2002.

o   The GLMb indices were adjusted for the change in logbook reporting and showed no increasing trend post 2002.

o   The GLMM, which allowed for different logbook reporting effects between primary vessels, predicted increasing indices post 2002.

o   All indices indicated a strong decline in 2014.

o   Figure 14 illustrated separately the increasing confidence intervals for the GLMa, GLMb and GLMM predictions.

o   The significance of the GLMa, GLMb and GLMM model terms used to standardise catch rates are listed in Table 9 (Appendix 1). Significance variance was identified between the primary fishing vessels and the number of tenders operated.

o   Scatter plot of the standardised residuals against fitted values is displayed in Figure 21 (Appendix 1). The residual plot showed no lack of model fit for GLMb. The scatter plot was typical for Poisson models and was similar between models.

o   The separate analysis of the 2003–2014 data produced indices that was most similar (ρ=0.96) to the GLMM (Figure 22, Appendix 1). The inclusion of the hour's fished data

was significant, but not as important as the number of fishing tenders (Table 10, Appendix 1).

- o Figure 15 illustrates the GLMb predicted relationships of increasing catch rates using more tenders, fishing during the spring and autumn months, on the early waxing moon phase and timed with good weather of light SE winds.

The annual standardised catch rate trends from the GLMb and GLMM models were assessed in the stock model.
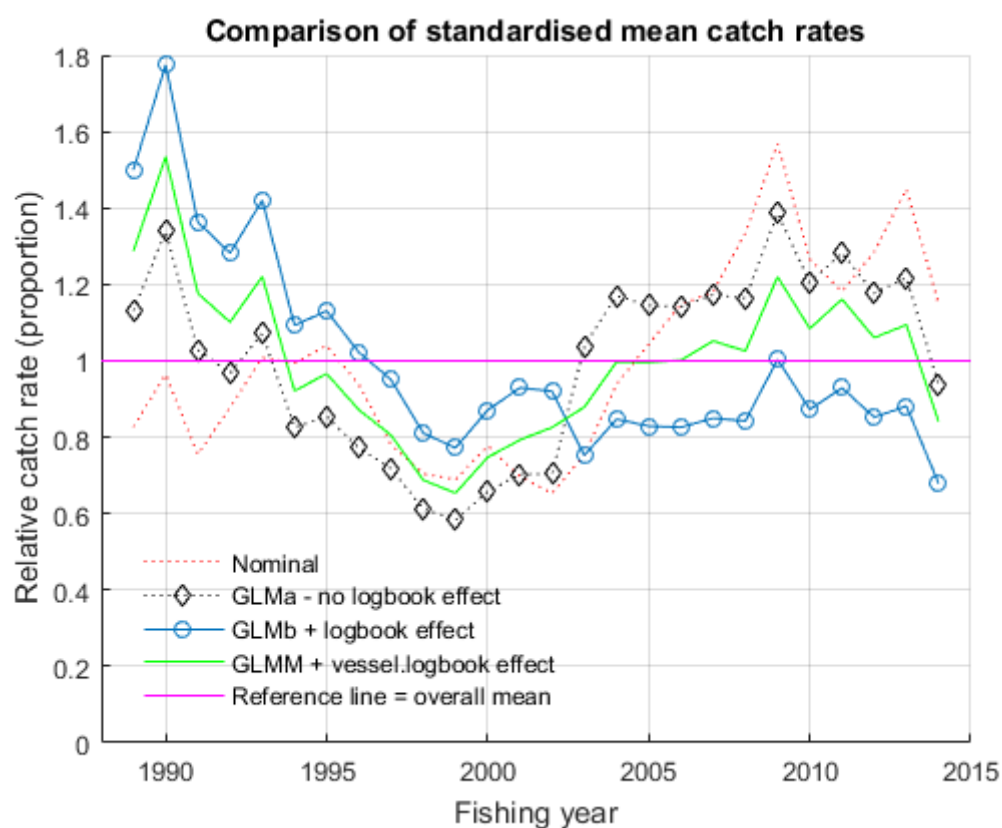
Figure 14. Comparison of Spanish mackerel average catch rates by fishing year 1989–2014. The plot compares nominal reported catch rates against three different standardised predictions. Each catch rate time series was scaled relative to its overall mean (y-axis = 1, reference point line for overall mean catch rate). Note the new TSF01 logbook was introduced in 2003 fishing year.
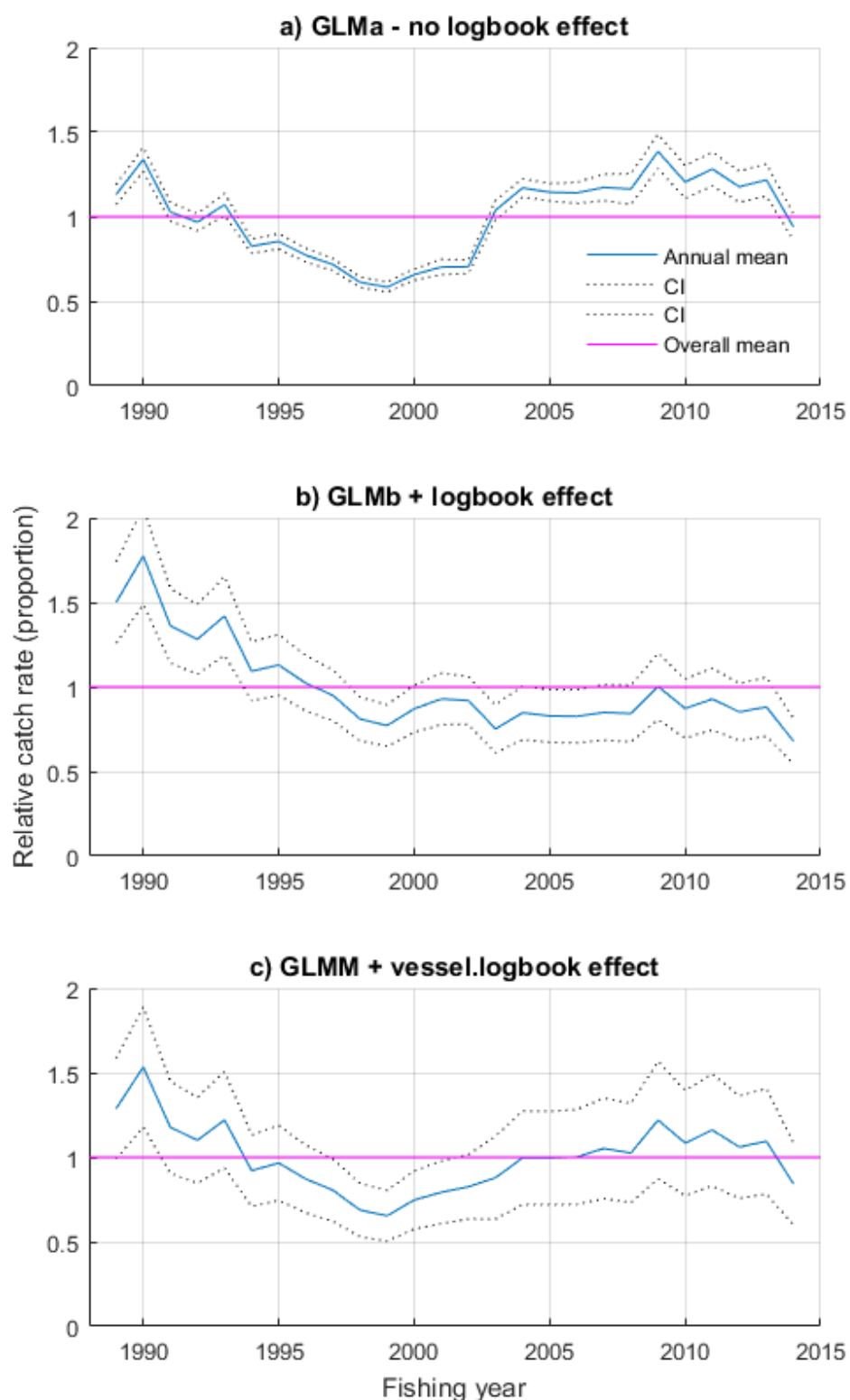
Figure 15. Spanish mackerel average catch rates by fishing year 1989–2014 for the a) Poisson GLMa without logbook effects, b) Poisson GLMb with logbook main effects, and c) Poisson GLMM with logbook effects by vessel. Each catch rate time series was scaled relative to its overall mean (y-axis = 1, reference point line for the overall mean catch rate). The error lines indicate the 95% confidence intervals (CI) on the yearly means.
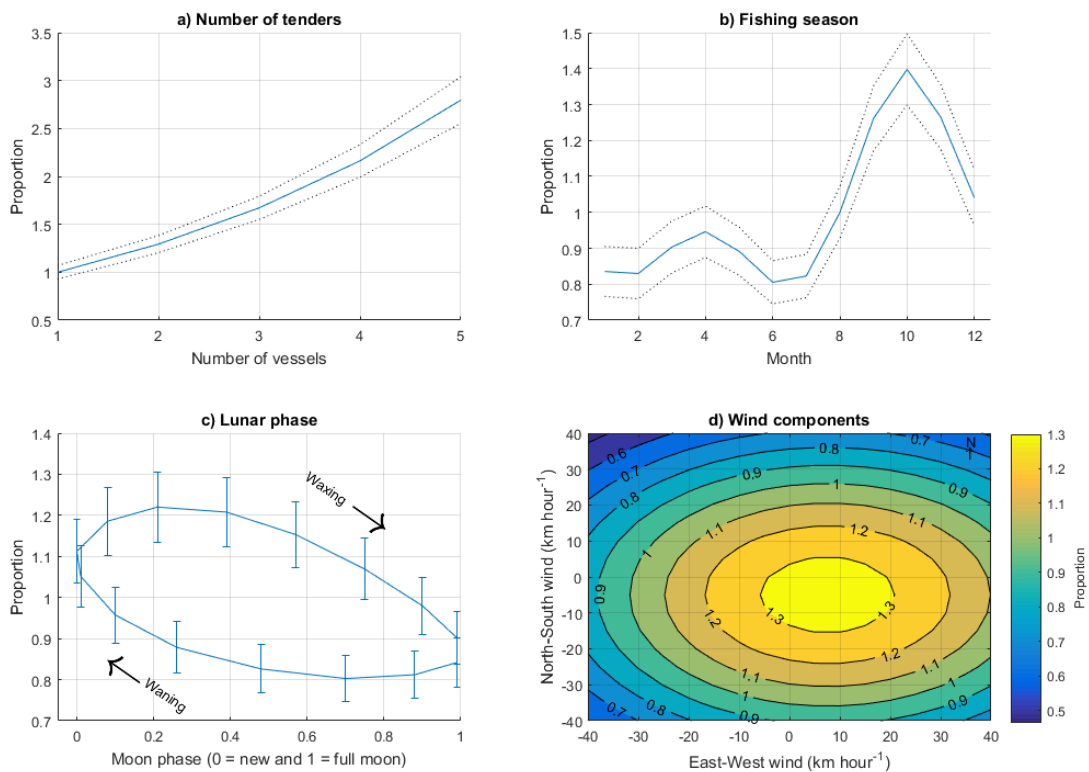
Figure 16. Predicted proportional change in Spanish mackerel catch rates for a) increasing the number of tender vessels per fishing operation, b) the fishing months, c) the lunar phase, and d) the wind speed and direction. The predictions were estimated from the Poisson GLMb with the logbook main effect. Subplot A was scaled relative to the catch rate of one vessel (=1) and subplots b–d were scaled proportional to the overall mean (=1). Subplots a–c outlines the 95% confidence intervals (CI) on the mean predictions.

Fish age-length composition data

The age-length structure of Torres Strait Spanish mackerel has not been monitored for many years. The available age frequencies show limited numbers of old fish from Bramble Cay waters 2000–2002 (Figure 16). Most of the sampled fish were aged in the 2+ to 4+ cohort age-groups. The maximum fish age determined was 10 years, much less than the maximum age found in waters on the Queensland east coast (26 years; Campbell et al., 2012; Langstreth et al., 2014). In recent years, more 4+ to 6+ year old fish have been reported in the Queensland east coast waters (Fisheries Queensland data). No recent data are available to verify if this trend has occurred in the Torres Strait.

For the 2000–2002 samples, female fish were on average slightly larger (Figure 17; females: overall mean = 109 cm TL and std = 10, males: mean = 102 cm TL and std = 8 cm). The average weight of Spanish mackerel from the Torres Strait was not too different to surrounding waters of the Queensland east coast and Gulf of Carpentaria (Figure 6, page 11).

The absence of older fish in the Torres Strait samples is of interest. Reason why are unknown, but may relate to movement patterns of fish and the lack of spatial samples collected across the Torres Strait. On face-value, the truncated age structures may indicate high fish mortality.

The length and age frequencies (Figure 16 and Figure 17) were input into the population dynamic model. High values of natural mortality were explored to explain the lack of old fish.
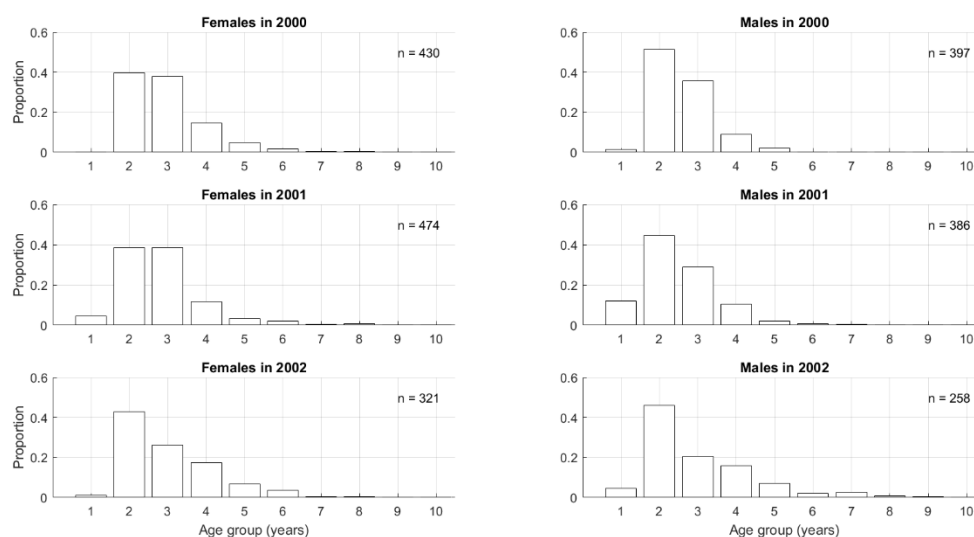
Figure 17. Age group frequencies of Spanish mackerel by fishing year and sex; n is the number of fish.
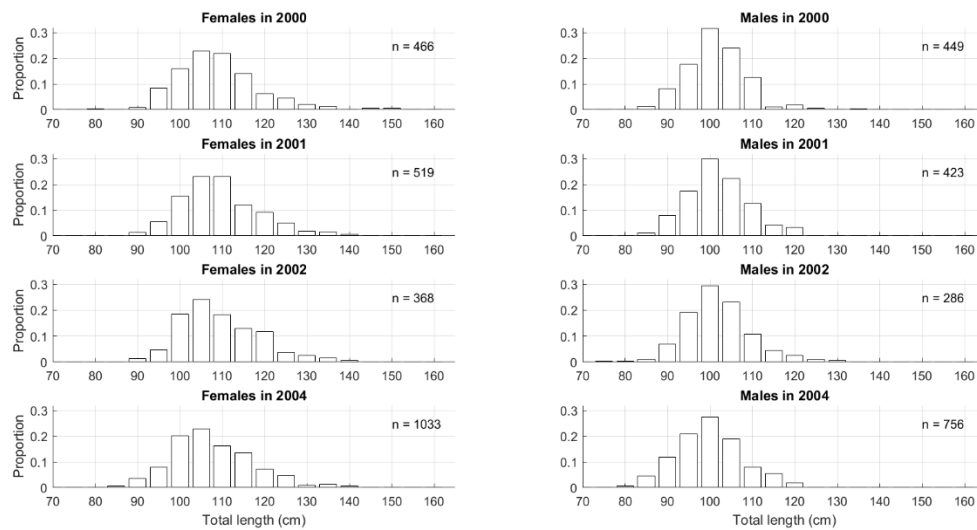
Figure 18. Total length frequencies of Spanish mackerel by fishing year and sex; n is the number of fish. The 2000–2002 data was collected through DAF monitoring and the 2004 data was from AFMA voluntary fisher recordings.

Table 7. Sex specific von Bertalanffy growth parameters used to predict fish total length (cm) from age group data (years). Parameter standard errors are in brackets.

Parameter	Female	Male
l^∞	160.320 (11.697)	159.950 (24.304)
κ	0.133 (0.033)	0.081 (0.034)
a^0	-5.781 (0.979)	-9.926 (2.310)
RMSE (std)	6.2	5.2
d.f.	792	644
Adjusted R^2	0.58	0.52

Population dynamics model

In total four stock analyses were conducted to explore uncertainty in the input data. The analyses varied the assumed level of harvest, the catch rate index and natural mortality (M):

1. Base reported harvests, GLMb catch rates and M estimated;

2. Base reported harvests, GLMb catch rates and M fixed = 0.3 year^{-1};

3. Base reported harvests, GLMM catch rates and M estimated; and

4. Inflated harvests, GLMb catch rates and M estimated.

Estimation of natural mortality was conducted to explain the lack of old fish in the 2000–2002 aging data. The fixed M value in analysis 2 was tested to explore a lower value consistent with

the previous Torres Strait and the Australian east coast stock assessments (Begg et al., 2006; Campbell et al., 2012).

The estimated parameters for the four analyses are listed in Table 8, with MCMC parameter traces and variation displayed in Appendix 3. All four analyses resulted in model convergence and sound fits to the input data of catch rates and fish age-length structures (Appendix 3). The results differed between models and suggest precaution is needed for interpreting stock productivity and for setting of management targets for harvest and fishing effort.

The model results assumed deterministic stock-recruitment relationships, constant M, age-based vulnerability calibrated on 2000–2002 Bramble Cay data, standardised catch rates were proportional to the exploitable population biomass and that Torres Strait Spanish mackerel comprise of a single stock.

The estimate of recruitment compensation ($r_{comp} = r_{max}$) or steepness (h) was not achieved in the first stock assessment due to the limited time series of data (Begg et al., 2006). The estimation was successful herein but varied with model settings (Table 8). The values of steepness are more easily interpreted than r_{comp} and the formulation measured the expected proportion of virgin recruitment at 20% of virgin egg production (Myers et al., 1999; Begg et al., 2005; Begg et al., 2006). The estimated steepness values from analyses 2 and 3 were higher than analyses 1 and 4 and suggested a more resilient fish stock when M was lower or catch rates were increasing (GLMM). The lower estimates of steepness from analyses 1 and 4 resulted from the lower GLMb catch rates and when M was estimated. The estimates of virgin recruitment numbers-of-fish (R_0) were positively correlated with steepness and ranged between 78000 and 259000 fish year[-1] (Table 8).

The estimates of fish 50% and 95% age-at-vulnerability were consistent between analyses, with $a_{50} \approx 1.6$ years and $a_{95} \approx 2.4$ years (Table 8). Spanish mackerel aged older than or equal to the 2+ age group were mostly fully vulnerable to fishing.

The Spanish mackerel age structures used in the analyses were quite truncated with few older fish (Figure 16). In order to fit this pattern, the analyses estimated high values of M (>0.39 year^{-1}; analyses 1, 3 and 4 in Table 8). The high values of M were greater than those considered on Australia's east coast (described in Table 5) and may indicate the Bramble Cay samples were not representative of the broader Torres Strait waters or that older fish are moving to surrounding areas (e.g. Papua New Guinea and northern Queensland waters north of 15°S). Spatially stratified fish samples are required to test these questions and confirm stock boundaries. The sampling of Spanish mackerel along the east coast of Australia was expanded in 2003 to account for spatial biases and variation (Sumpton and O'Neill, 2004; Tobin and Mapleston, 2004). Monitoring options for spatial sampling of Spanish mackerel through Torres

Strait waters were modelled in the previous stock assessment and suggested 30 to 40 operation catches were needed from each fishing region per year to approximate the underlying fish length and age structures of the exploited population (Begg et al., 2006).

Table 8. Maximum likelihood parameter estimates for the four sensitivity analyses. Standard errors for all estimates are shown in parenthesis; natural mortality M yr⁻¹ was fixed in analysis 2, r_{comp} is the recruitment compensation ratio, h = steepness (proportion) and was calculated from r_{comp}, R_0 = virgin recruitment-numbers of fish, a_{50} = age at 50% vulnerability and a_{95} = age at 95% vulnerability.

| Analysis | Settings | | Estimates | | | | | |
	Catch rates	Harvest	r_{comp}	h	$R_0 / 10^6$	a_{50}	a_{95}	M
1	GLMb	Base	2.218 (0.442)	0.357 (0.044)	0.167 (0.042)	1.562 (0.106)	2.378 (0.239)	0.447 (0.040)
2	GLMb	Base	5.815 (0.818)	0.592 (0.030)	0.078 (0.003)	1.508 (0.107)	2.328 (0.264)	0.3
3	GLMM	Base	4.432 (3.304)	0.526 (0.109)	0.112 (0.030)	1.561 (0.115)	2.390 (0.264)	0.396 (0.047)
4	GLMb	Inflated	2.137 (0.415)	0.348 (0.042)	0.259 (0.069)	1.569 (0.105)	2.391 (0.233)	0.456 (0.040)

The previous stock assessment of Spanish mackerel used data up to the end of the 2003 fishing year. The assessment concluded the Torres Strait stock was fished near maximum sustainable yield (MSY) and exploitable biomass was 26–67% of virgin levels (Begg et al., 2006). Now for this updated assessment, 11 more years of data have been analysed where harvests and fishing effort have declined since 2007 (Figure 8 and Figure 9). The following predictions were made for the 2014 fishing year:

- o For all four analyses the fishing mortality indicators were sustainable ($F_t < F_{MSY}$, Figure 18a).

- o However, analyses 1 and 4 still measured possible high fishing pressure in the last five years 2010–2014 ($F_{\max} \approx F_{MSY}$, Figure 18b).

- o Levels of median fish recruitment appeared healthy (Figure 18c).

- o For analyses 1, 2 and 4, the estimated mature female spawning stock was at about 40% of virgin levels (Figure 18d). The estimate was near 60% for analysis 3. There was no suggestion of stock collapse or recruitment overfishing ($E_t > E_{20\%}$). The lower E_t predictions of analyses 1, 2 and 4 used GLMb catch rates that assumed little increase in the stock since about 1999 (Figure 14b).
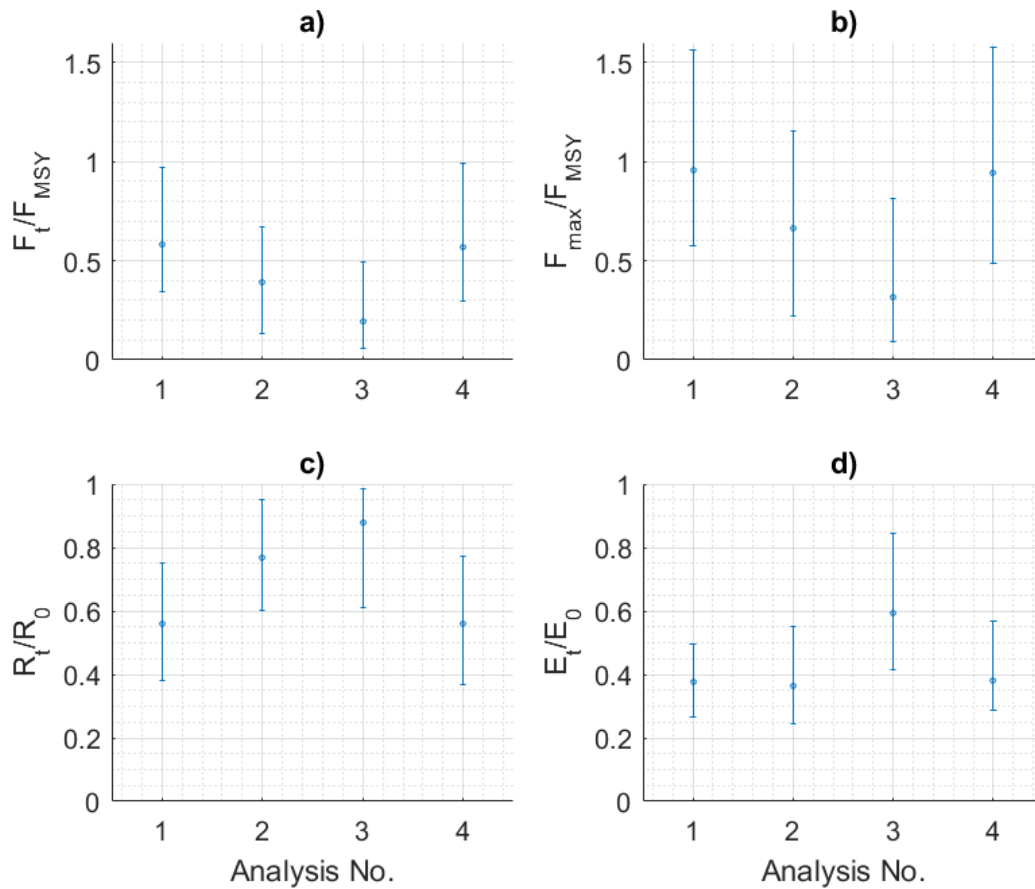
Figure 19. The estimated stock status ratios of Spanish mackerel for a) fishing mortality (F) in the t = 2014 fishing year compared against F for MSY, b) maximum F from the last 5 years 2010–2014, c) fish recruitment compared against virgin and d) female egg production compared against virgin. The errors bars cover the minimum and maximum estimates and the point estimates (circles) are the medians from the MCMC simulations.

As outlined in the methods section, fishery management reference points were estimated corresponding to equilibrium (average) B_{MSY} and assumed $B_{MEY} \approx 0.6B_0$. The reference points correspond to the concepts used by the Australian Government (Australian Government, 2007). No formal or other reference points have yet been set for Torres Strait finfish (Patterson et al., 2015). In the draft management plan for Torres Strait finfish only reference is made to ensuring the total catch of target species is at or below agreed annual limits (Australian Government, 2013).

The reference point estimates and their variances are displayed in Figure 19. The estimates varied with analysis settings and the exact true values remain unclear; and will so without improved long term monitoring. The estimates suggest the harvests taken prior to 2007 (Figure 8a) were near or exceeding maximum sustainable levels (as noted by Begg et al., 2006). The reference point predictions are summarised as follows:

- MSY was estimated near 150 t for analyses 1 and 2 (Figure 19a).

- MSY was higher near 200 t for analyses 3 and 4 with larger error (Figure 19a).

- Analysis 4 had the highest reference point harvests assuming the inflated harvest schedule (Figure 19a & b).

- Annual harvests below 150 t was estimated from analyses 1–3 to maintain heathy biomass and catch rates (Figure 19b).

- The fishing effort E_{MSY} estimate from analysis 3 (Figure 19c) was uncertain due to greater error on r_{comp} and steepness (Table 8).

- E_{MSY} from analyses 1, 2 and 4 ranged 800–1250 operation days (Figure 19c).

- The total fishing effort levels to attain average $B_{0.6}$ ranged 400–700 operation-days year^{-1} across analyses (Figure 19d).

- Average catch rate levels for implying B_{MSY} were about 23 Spanish mackerel operation-day^{-1} for analyses 1, 2 and 4 (Figure 19e). The analysis 3 catch rate was lower at about 14 fish.

- Average catch rates for implying $B_{0.6}$ were highest at 45 fish for analysis 2 assuming lower M, lowest at 28 fish for analysis 3 assumed the GLMM index and about 35 fish for analyses 1 and 4 (Figure 19f)
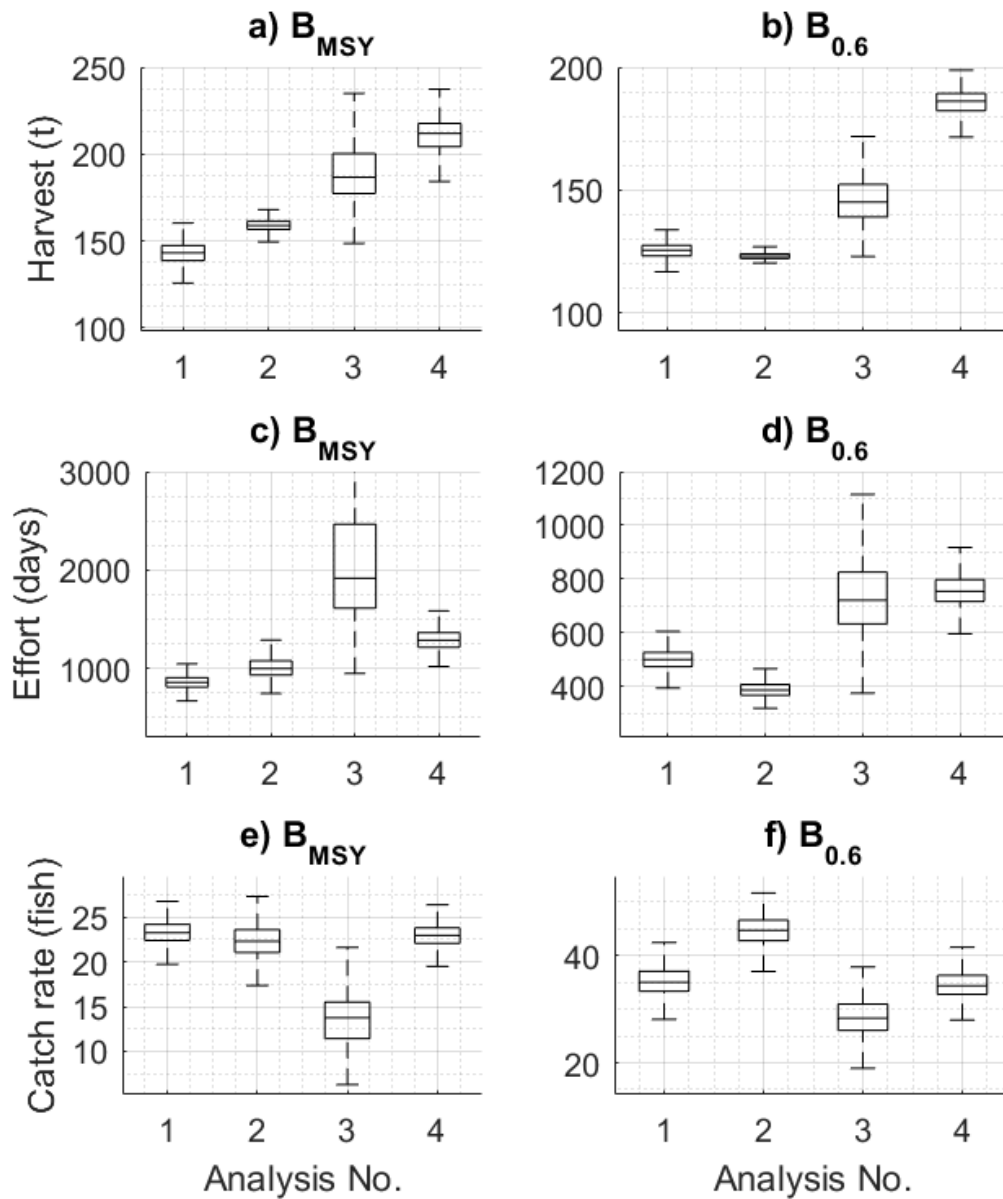
Figure 20. The estimated equilibrium reference points for Spanish mackerel, where the first column of boxplots (a, c and e) were for the exploitable biomass at MSY ($B_{MSY} \approx B_{0.4}$) and the second column of boxplots (b, d and f) were for a higher exploitable biomass at 60% of virgin ($B_{MEY} \approx B_{0.6}$); each row of the reference point boxplots were for harvest, fishing effort (operation days) and catch rate operation-day^{-1}. Each boxplot illustrates the distribution around the median (line in the middle of each box). The bottom and top of each box were the 25th and 75th percentiles. The whisker lengths indicate about 99% coverage of the MCMC simulations. For boxplot c) analysis 3, the upper effort estimates extended above 3000 days.

Conclusions

The stock assessment analyses of Torres Strait Spanish mackerel conclude that the recent harvests 2007–2014 and population estimates were sustainable. Since 2008 the Torres Strait Finfish Fishery has been reserved for Traditional Inhabitants, on whose behalf the Torres Strait Regional Authority (TSRA) leases out fishing licences to non-Traditional Inhabitants. Over this time commercial fishing effort had eased compared to before 2008 (Figure 9). Despite the reduction, the leasing process should still consider the revised estimates of sustainable harvests for Spanish mackerel, with the aim to generate sustainable markets and revenue for the benefit of Torres Strait communities. Future management should also consider benchmarking a target reference point above B_{MSY} to ensure healthy population biomass and catch rates of Spanish mackerel; in order to achieve and balance sustainability, economic, social and cultural objectives (Australian Government, 2007; Australian Government, 2013; Australian Government, 2015). If future average harvests increase above 150 t and/or fishing effort increases above 1000 operation days (Figure 20), then catch rates of Spanish mackerel may erode long term.

A harvest strategy framework (Sloan et al., 2014) for the finfish fishery has been sought by the PZJA (Torres Strait Scientific Advisory Committee project call, 2016) to guide decisions on future monitoring, harvests and fishing effort and leasing arrangements. Stock status indicators and reference points have been calculated herein that can support design of a harvest strategy, but further investment in monitoring data is required to reduce indicator variances and biases. A total of nine monitoring data recommendations were listed in the 2006 stock assessment report (Begg et al., 2006). A number of these are outstanding after 10 years. In order to service future harvest strategy procedures for Torres Strait Spanish mackerel (empirical or stock model based) improvements in the data are required:

- o Verify records on fishing effort and harvest through logbook, docket book and electronic reporting systems [*for harvest and/or standardised catch rate assessments*]. This involves recording and validating:
    - ➢ trip harvests and average fish weights using unload/sale receipts,
    - ➢ number of dories used and hours fished each operation day,
    - ➢ the number of and fishing locations of the primary operation and dories using VMS/GPS latitude and longitude coordinates,
    - ➢ number of fish caught each operation and dory day,
    - ➢ zero catches, and
    - ➢ days when fishing is stopped due to capacity limitations (too many fish).
- o Monitor and estimate Spanish mackerel harvests taken by non-commercial sectors [*for stock model assessments*].

- Conduct regular (annual or biennial) long term monitoring of fish age-length structures that are spatially representative of the Torres Strait [*for mortality and/or stock model assessments*].
- Collect fine scale spatially representative genetic fish samples to test the single stock assumption and define stock boundaries [*for stock model assessments*].

Review of the stock structure literature is complex and the single stock hypothesis is not clear cut for Torres Strait Spanish mackerel. Genetic results suggest Spanish mackerel exists as localised assemblages and experience attenuated levels of reciprocal gene flow that is biased towards males (Buckworth et al., 2007). However, otolith isotopes suggest some similarity between Torres Strait and Gulf of Carpentaria Spanish mackerel (Newman et al., 2009). No stock structure data have been evaluated from north east Queensland (north of 15°S) or Papua New Guinea waters.

This stock structure uncertainty does not undermine the management and assessment of Torres Strait Spanish mackerel as a single unit and at this time it would be detrimental to combine Torres Strait data into a larger area with other jurisdictions. This is so because of the seasonal and spatial predictability of Spanish mackerel aggregations and risks of localised overfishing. This risk and event has been documented for spawning aggregations along Queensland's east coast (Tobin et al., 2013; Tobin et al., 2014). The stock structure uncertainty highlights that finer spatial scaled sampling is required to further discriminate Spanish mackerel between the Torres Strait and surrounding waters.

If future improvement in data is not cost effective or supported, then use of precautionary reference points to judge abundance (standardised catch rate) indicator signals is essential for mitigation of indicator variance and uncertain management decisions.

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Appendix 1: Catch rate diagnostics
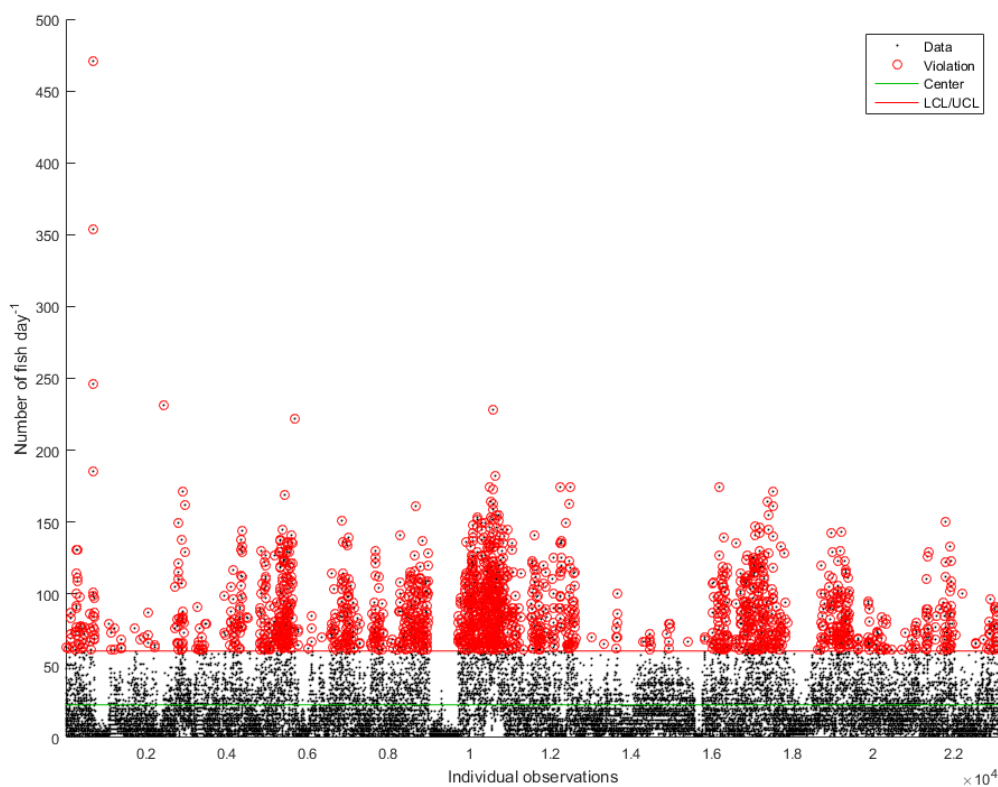
Figure 21. Shewhart control chart for each daily Spanish mackerel harvest by vessel (observed data unfiltered). The centre green line is the overall mean and upper and lower control limits (UCL, LCL) at three standard errors from the centre line. Out of control limits for normally distributed data/expectations are marked with a red circle.
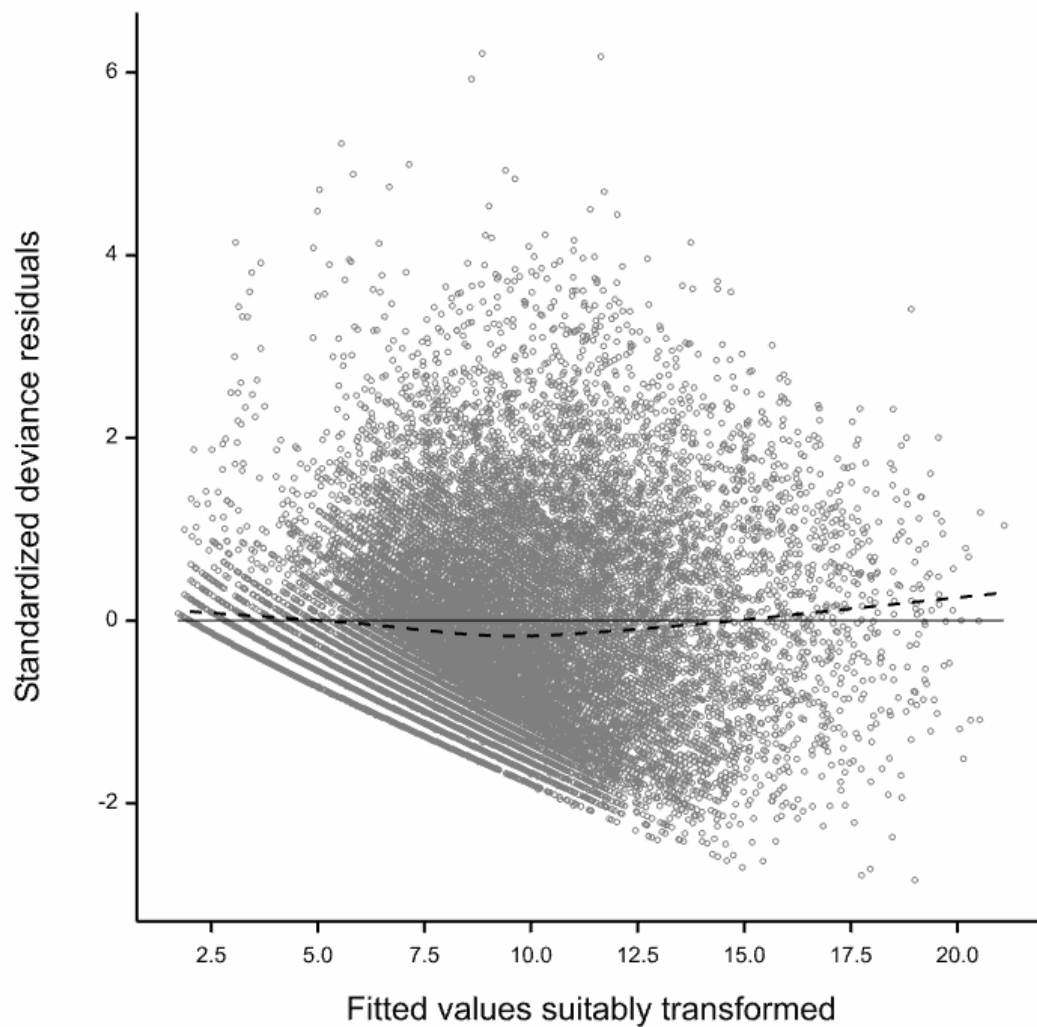
Figure 22. Plot of standardised residuals against fitted values from the Poisson GLMb analysing numbers of Spanish mackerel with vessel and logbook main effects (model b, Table 9). The plot shows circle symbols for the goodness-of-fit data, a solid zero reference line and a dashed smoothed trend line.

Table 9. Analysis of deviance tables for the over-dispersed Poisson models used to standardise catch rates: a) Poisson generalised linear model (GLM) with no modelled logbook effect, b) Poisson GLM with logbook main effect, and c) Poisson generalised linear mixed model with nested random effects of logbook by vessel.

a) <u>Poisson GLMa with no logbook effect</u>
Adjusted R^2 = 0.38
Residual mean deviance = 13.0
Residual degrees of freedom (d.f.) = 22468

Fixed terms	d.f.	F statistic	pr.
Fishing year	26	53.86	<0.001
Vessel	39	96.87	<0.001
s_1	1	19.16	<0.001
s_2	1	384.56	<0.001
s_3	1	270.74	<0.001
s_4	1	74.15	<0.001
Number of tenders	1	1028.99	<0.001
Lunar phase	1	203.16	<0.001
Lunar phase advanced	1	571.81	<0.001
windns	1	6.07	0.014
windnsQ	1	13.12	<0.001
windew	1	5.8	0.016
windewQ	1	60.92	<0.001

b) <u>Poisson GLMb with logbook main effect</u>
Adjusted R^2 = 0.38
Residual mean deviance = 13.0
Residual degrees of freedom (d.f.) = 22467

Fixed terms	d.f.	F statistic	pr.
fishyear	26	32.61	<0.001
boat	39	97.1	<0.001
logbook	1	13.17	<0.001
c12	1	21.06	<0.001
cs12	1	385.1	<0.001
c6	1	274.9	<0.001
cs6	1	71.2	<0.001
tenders	1	1032.94	<0.001
lunar	1	203.02	<0.001
lunar_adv	1	571.24	<0.001
windns	1	6.15	0.013
windnsQ	1	12.94	<0.001
windew	1	5.85	0.016
windewQ	1	60.89	<0.001

c) <u>Poisson GLMM with Normal random boat.logbook effects</u>
Residual mean deviance = 14.75 (s.e. = 0.14)
Residual degrees of freedom (d.f.) = 22504

Fixed terms	d.f.	F statistic	pr.
fishyear	26	28.64	<0.001
c12	1	20.47	<0.001
cs12	1	315.21	<0.001
c6	1	243.59	<0.001
cs6	1	62.76	<0.001
tenders	1	938.21	<0.001
lunar	1	181.04	<0.001
lunar_adv	1	499.67	<0.001
windns	1	4.9	0.027
windnsQ	1	11.57	<0.001
windew	1	4.85	0.028
windewQ	1	54.46	<0.001
Random terms		**component**	**s.e.**
boat		0.3	0.11
boat.logbook		0.18	0.07

Table 10. Analysis of deviance table for the over-dispersed Poisson model used to standardise catch rates between 2003 and 2015. The reduced time-series data included the total hours fished per vessel day.

d) **Poisson GLM with logbook data after June 2003**

Adjusted R^2= 0.49

Residual mean deviance = 12.6

Residual degrees of freedom (d.f.) = 7030

Fixed terms	d.f.	F statistic	pr.
Fishing year	11	11.07	<0.001
Vessel	17	121.16	<0.001
s_1	1	2.81	0.0094
s_2	1	103.72	<0.001
s_3	1	89.9	<0.001
s_4	1	42.18	<0.001
Number of tenders	1	205.06	<0.001
Hours fished (combined for all tenders)	1	90.01	<0.001
Lunar phase	1	110.02	<0.001
Lunar phase advanced	1	199.18	<0.001
windns	1	12.71	<0.001
windnsQ	1	5.4	0.020
windew	1	9.26	0.002
windewQ	1	18.55	<0.001
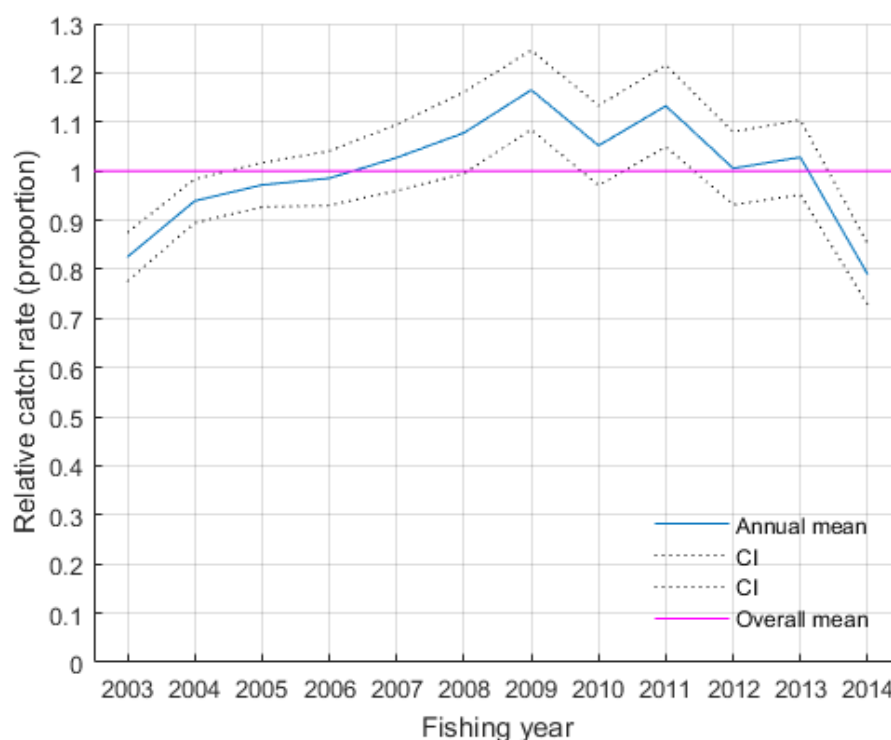
Figure 23. Spanish mackerel average catch rates by fishing year 2003–2014 as predicted from the over-dispersed Poisson GLM (Table 10; analysis d). The data set included the total hours fished per vessel day. The catch rate time series was scaled relative to the overall mean (y-axis = 1, reference point line for the overall mean catch rate). The error lines indicate the 95% confidence intervals (CI) on the yearly means.

Appendix 2: Calculation of fish age group

J. Langstreth, Fisheries Queensland, 2015

Recommendation on assigning age group to Torres Strait Fish

- **For fish caught in April** (9 fish): age group = increment count. (No adjustment required). However, as April is 6 months after October, if you choose to use them in the ALK, then you should consider adjusting the length as they are likely to have had significant growth from the same cohort of fish caught back in October (possibly in the order of 5-10 cm growth for the main age groups)

- **For fish caught in October :**
  - **New edge types –** age group = increment count
  - **Intermediate edge types (codes 1 & 2) –** age group = increment count
  - **Wide edge types –** age group = increment count **+ 1**

Information to base recommendation

For the GOC & EC Spanish (based on LTMP data), the trend in the timing of edge types being laid down on the otolith are very similar (Figure 23 and Figure 24). (I have plotted EC by fin yr & GOC by calendar year based on our respective LTMP sampling seasons). New edge types are mostly visible on the otolith from June/July, and as spring growth occurs, we can observe intermediate growth (translucent material) on the edge from September.
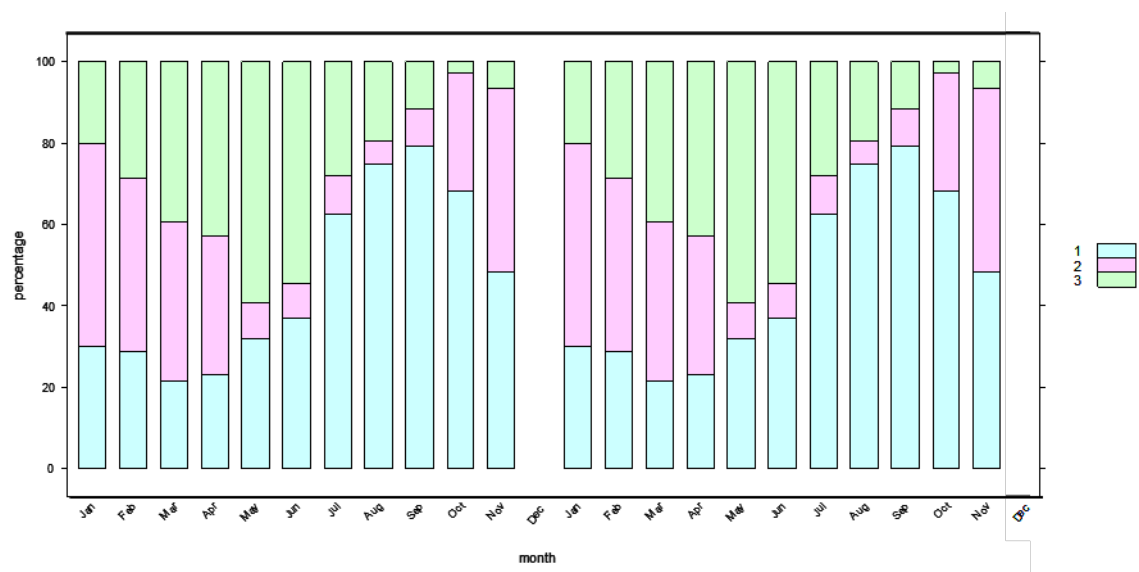
Figure 24. Gulf trend for edge type by month.
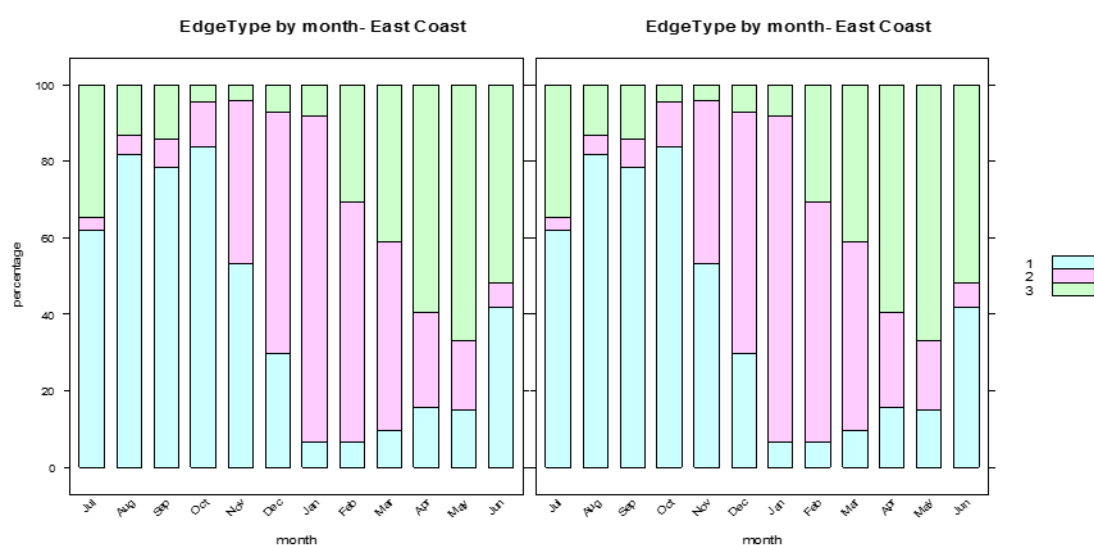
Figure 25. EC trend for edge type by month.
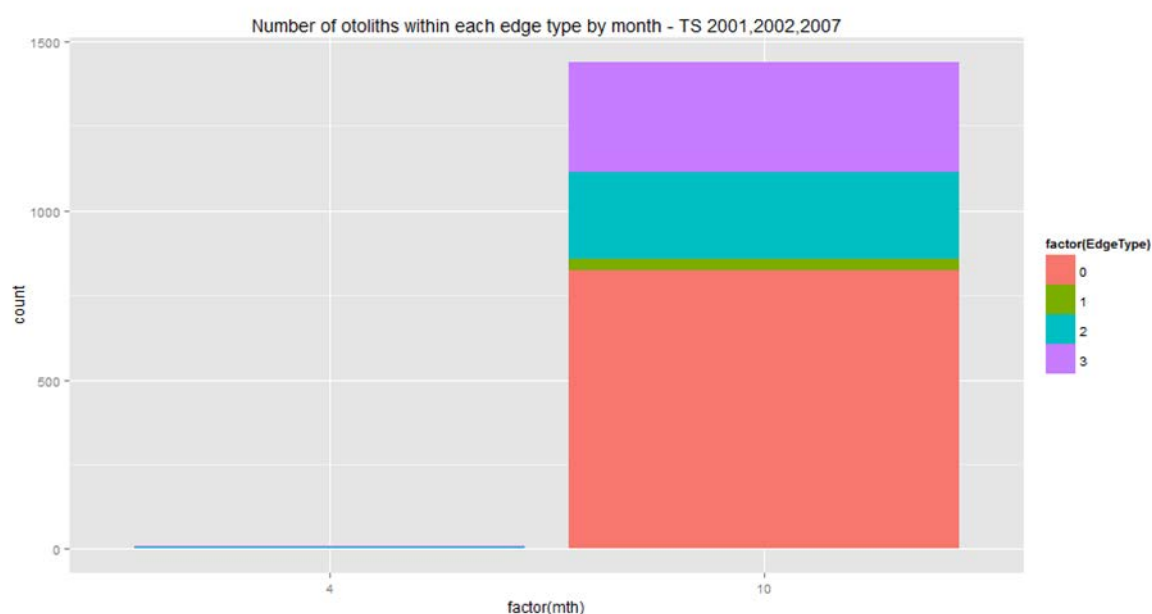
Figure 26. Torres Strait - edge type by month.

Note –edge type was not recorded during the first year of sampling in 2000.

- The majority (57%) of TS fish sampled during October are in the '**New'** Edge type (Figure 25). This suggests that for these, their increment count accurately reflects their age group (i.e. age that these fish will attain in that financial year). E.g. a 2 year old fish with a new increment shows 2 increments and will not show another new increment until the next August-Oct period in the following financial year.

- However, for fish that have a **wide** edge (23%), the increments showing on the otoliths are one less than would be if the fish lasted for the remainder of the financial year. They should be kept in the same cohort with fish that have just shown their 'new' edge type. Therefore the fish would be in one higher than increment count. This is supported by the fact that there are 13 0-wide fish in the TS data, which have to be in the 1-year age group to have reached minimum legal size (it is highly unlikely these fish are under 4 months old). So we should plus one to the increment count for fish with wide edge types as the age class and age group should be one higher than the otolith shows.

- For **intermediates** (20%), at this time of year, fish have most likely had some significant growth already since "winter" and therefore laid down some translucent material following laying down their opaque increment. This is in line with what occurs on the EC & in GOC fisheries (see plots above). These fish will not lay down another opaque band/increment before the end of the financial year, and are therefore their increment count represents the age group (max. age they will attain in that financial year).

- **For fish caught in April**, they are either intermediates or wides. In April, being near the end of the financial year, fish will have laid down their increment for that financial year already & not go through the cycle to lay down another before the end of June. If there were 'news' caught in April (but there aren't), we would take one increment off to calculate age group.

Code recording the interpretation of the otoliths margin (For Torres Strait Data). This is different for EC & GOC data.
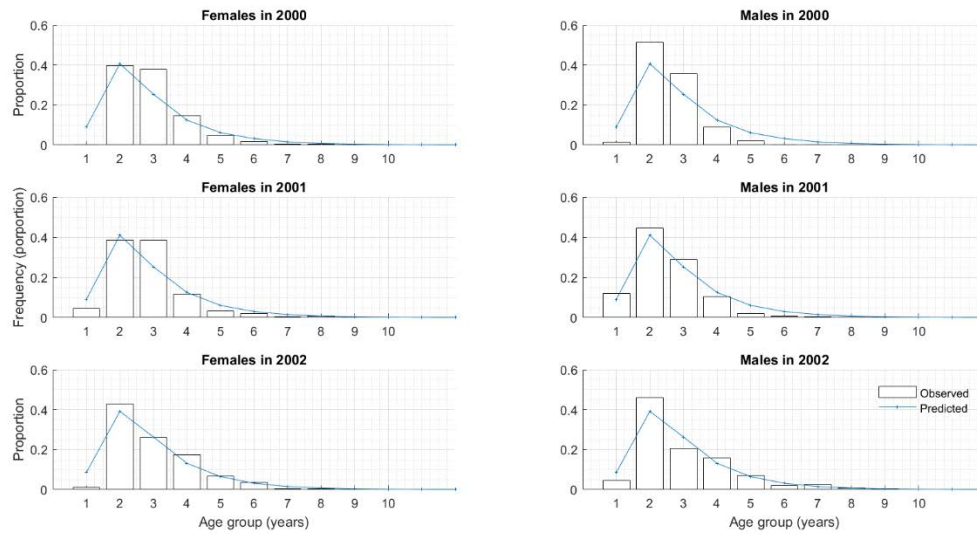
0. Opaque on the margin (New)

1   0-33% of the margin is translucent (Intermediate)

2   34-66% of the margin is translucent (Intermediate)

3   67-100% of the margin is translucent (Wide)
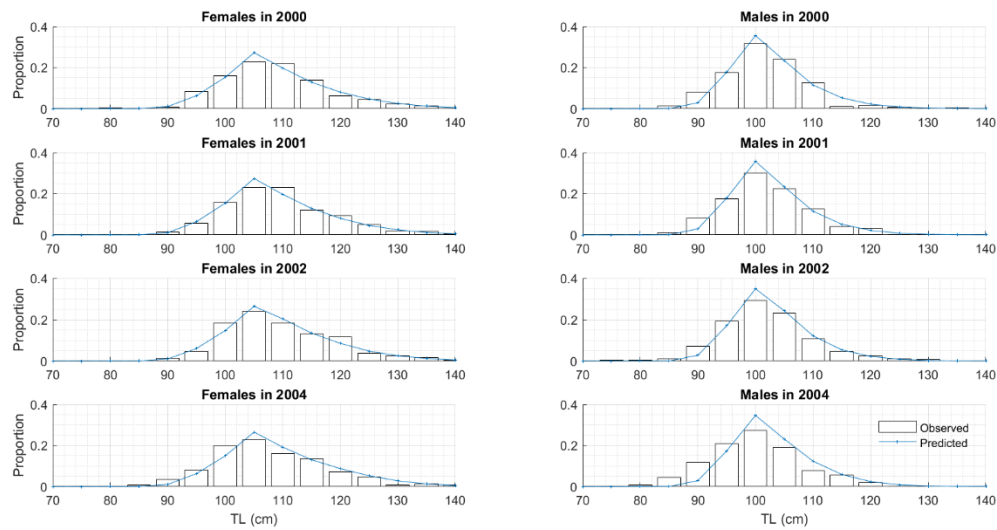
For East Coast – 1 – New, 2 – Intermediate, 3 - Wide

Appendix 3: Stock model diagnostics
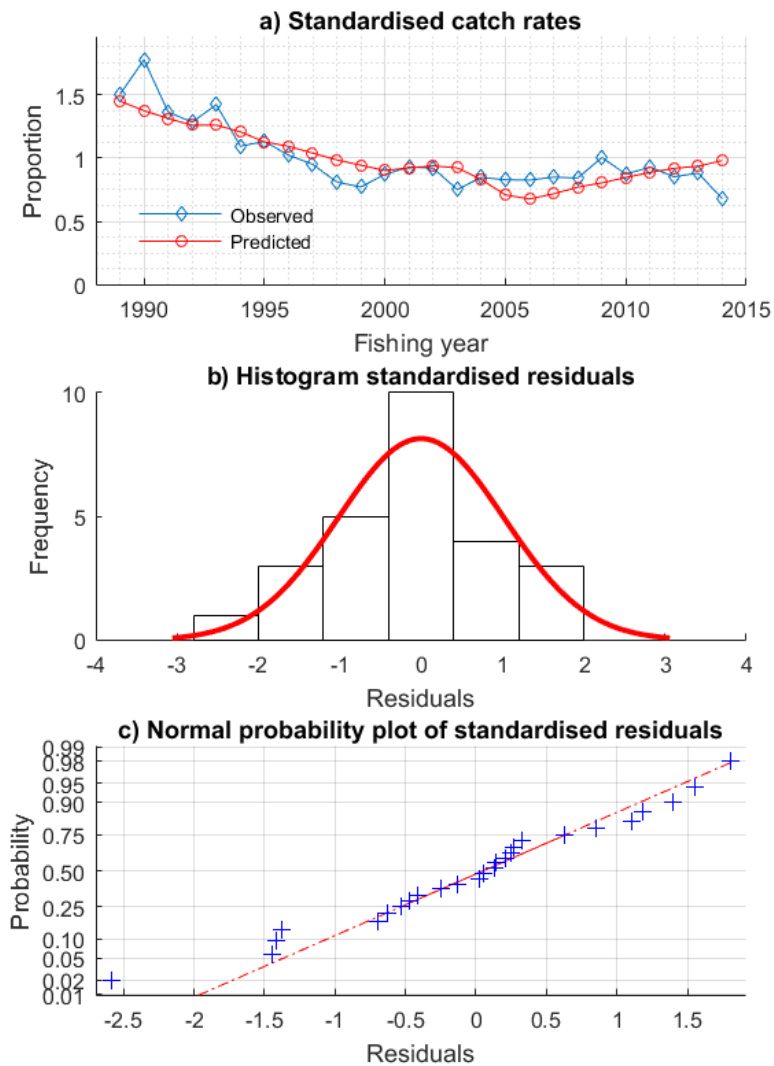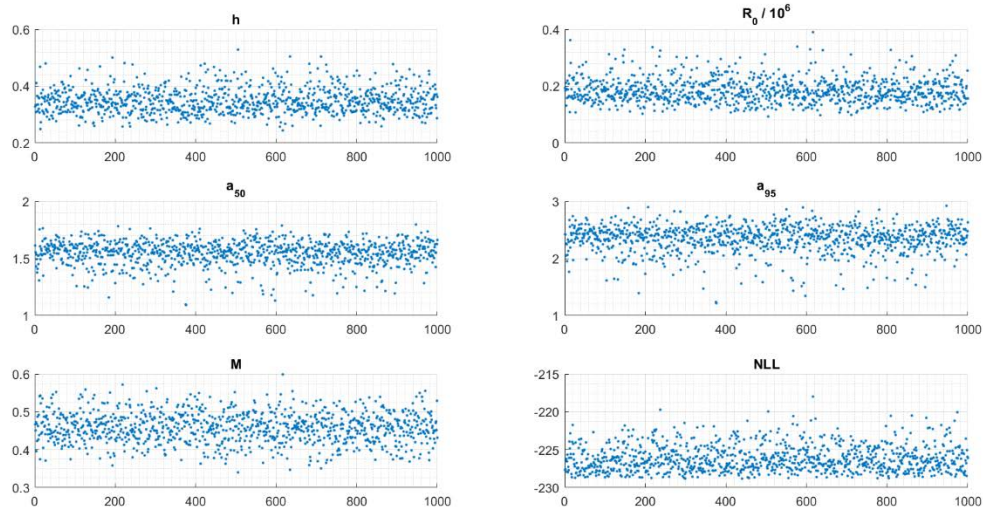

Figure 27. Stock analysis 1 catch rate fit and standardised residuals.

*Figure 28. Stock analysis 1 prediction of fish ages. The predicted model fits were similar for other analyses.*

Figure 29. Stock analysis 1 prediction of fish total lengths. The predicted model fits were similar for other analyses.
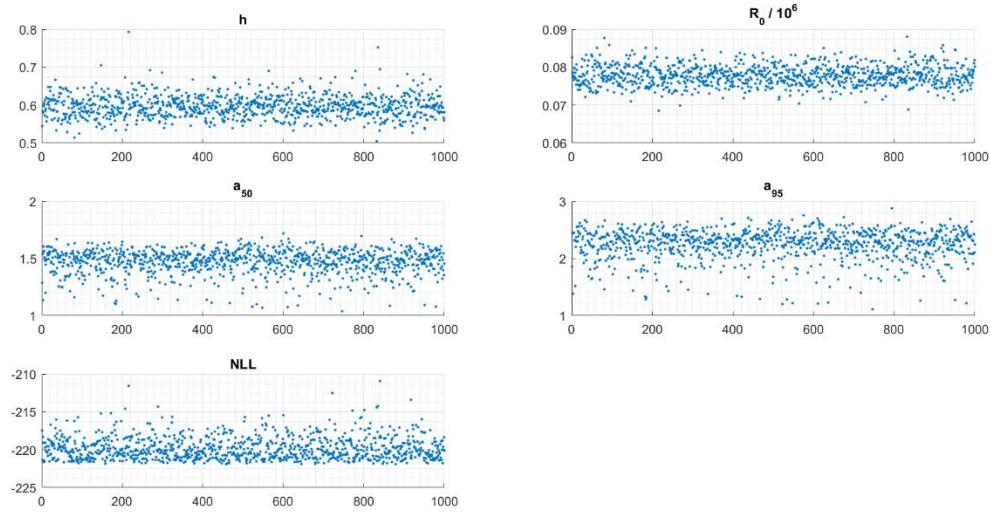
Figure 30. Serial plot of the retained values from the stock model analysis 1 Markov chain Monte Carlo optimisation (MCMC), where h = steepness (proportion), R_0 = virgin recruitment-numbers of fish, a_{50} = age at 50% vulnerability, a_{95} = age at 95% vulnerability, M = natural mortality yr^{-1} and NLL = combined negative log-likelihood. n = 1000 data points per subplot. Auto correlations were low and nonsignificant between -0.05 and 0.05 and the heidel test nonsignificant and passed stationary for all parameters p>0.1.
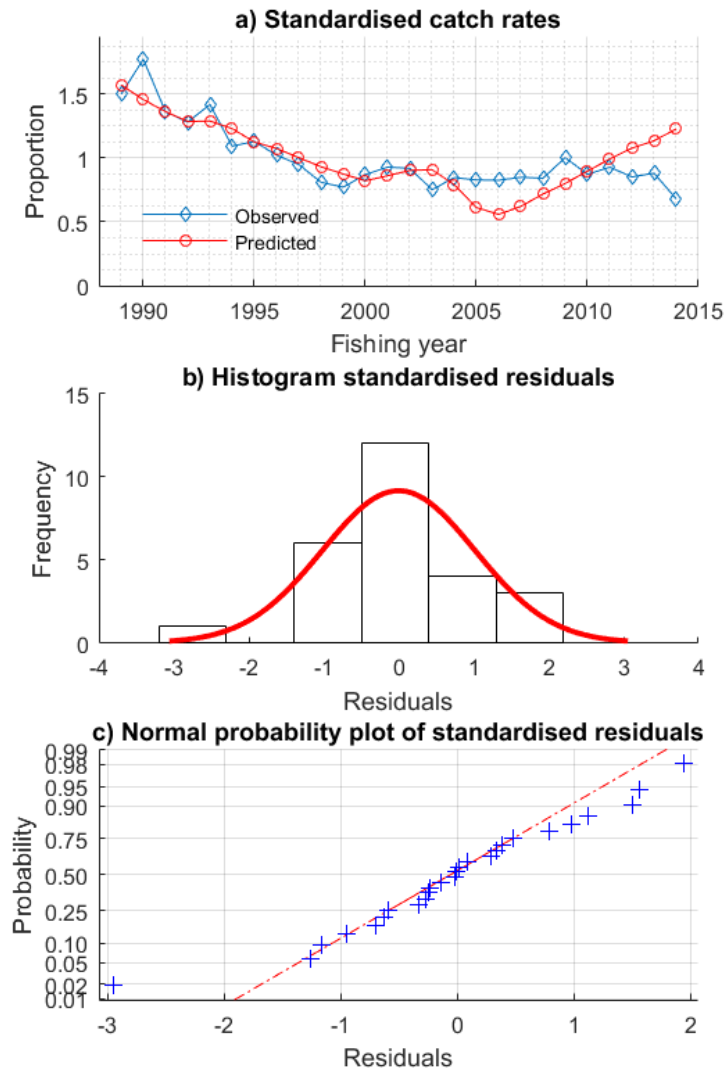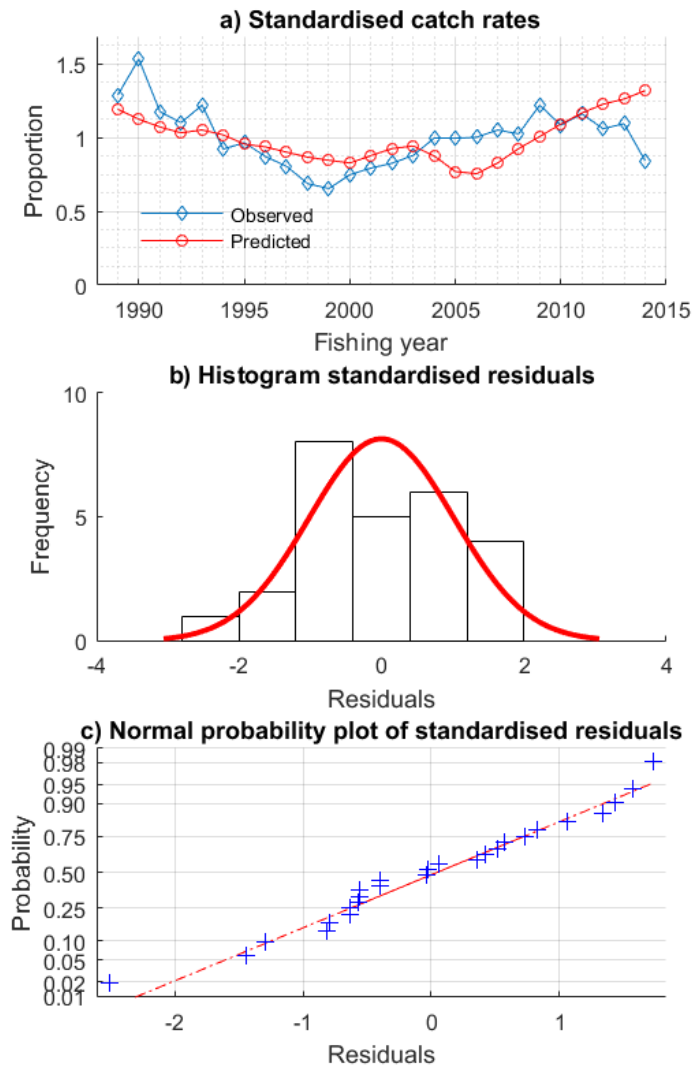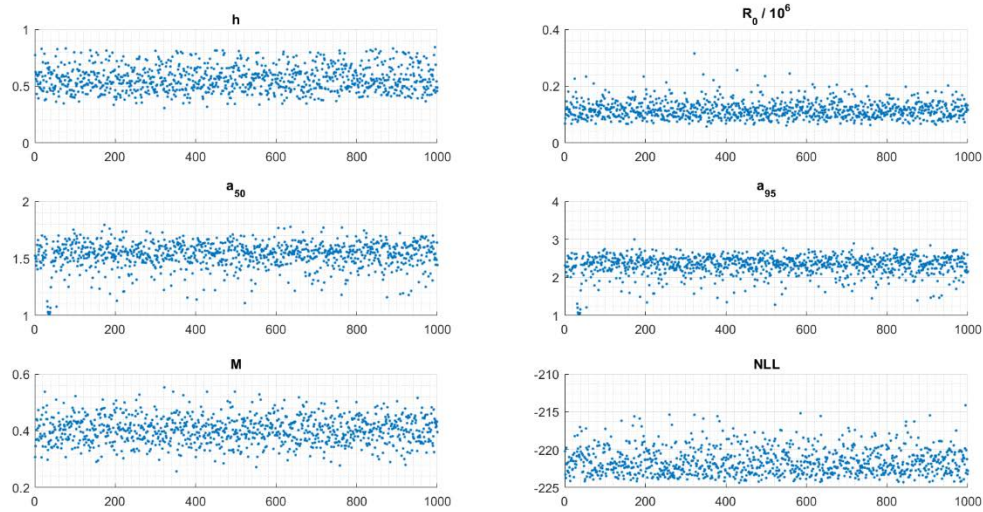
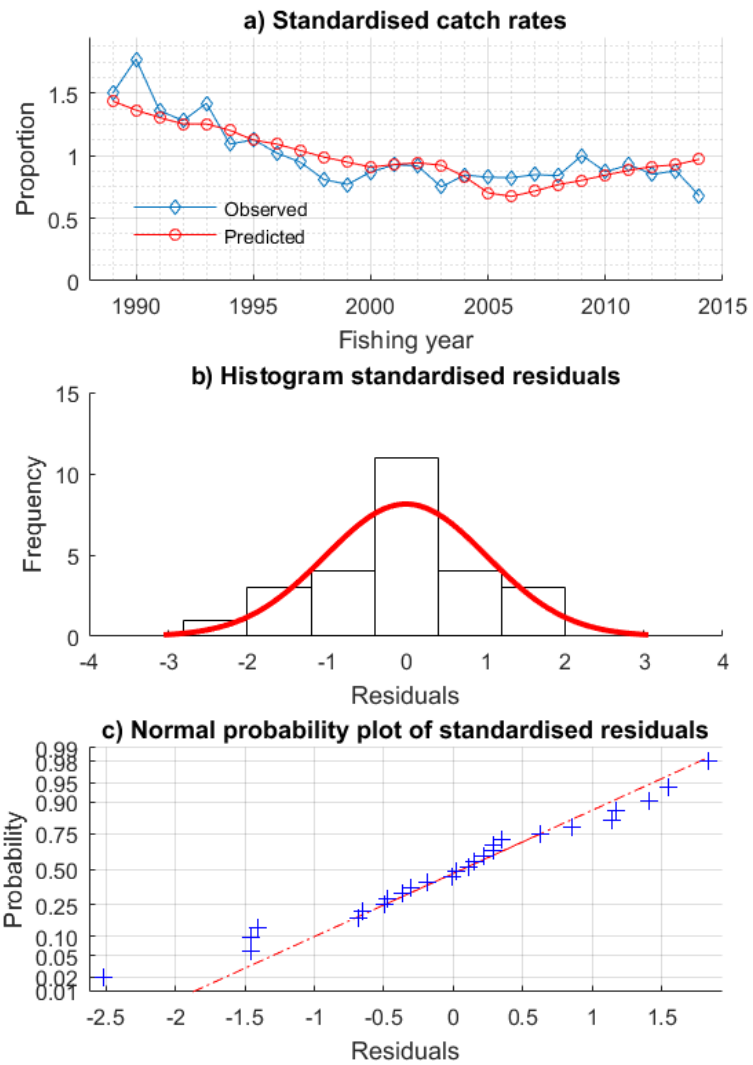*Figure 31. Stock analysis 2 catch rate fit and standardised residuals.*

Figure 32. Serial plot of the retained values from the stock model analysis 2 Markov chain Monte Carlo optimisation (MCMC), where h = steepness, R0 = virgin recruitment, a50 = age at 50% vulnerability, a95 = age at 95% vulnerability and NLL = combined negative log-likelihood; natural mortality M was fixed = 0.3 yr⁻¹. n = 1000 data points per subplot. Auto correlations were low and nonsignificant between -0.03 and 0.03 and the heidel test nonsignificant and passed stationary for all parameters p>0.5.
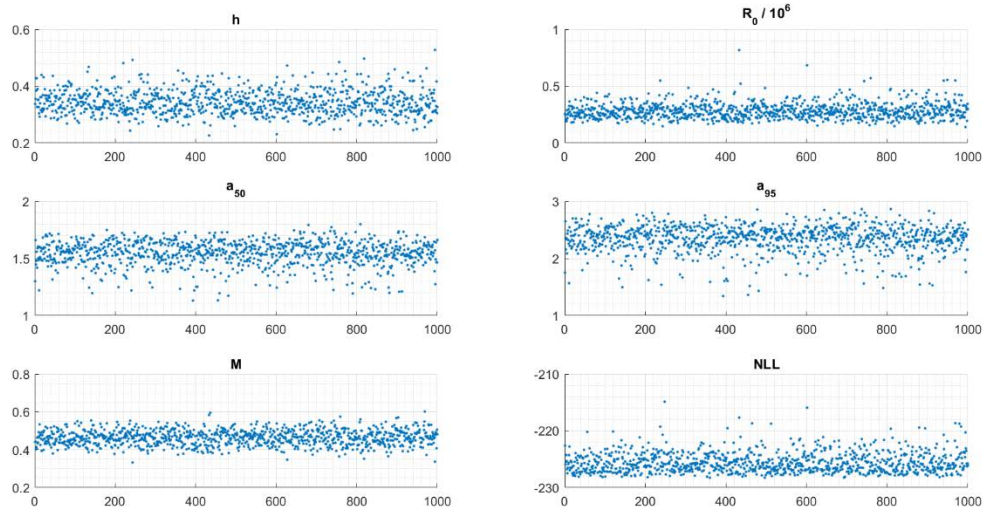
Figure 33. Stock analysis 3 catch rate fit and standardised residuals.

Figure 34. Serial plot of the retained values from the stock model analysis 3 Markov chain Monte Carlo optimisation (MCMC), where h = steepness, R_0 = virgin recruitment, a_{50} = age at 50% vulnerability, a_{95} = age at 95% vulnerability, M = natural mortality and NLL = combined negative log-likelihood. n = 1000 data points per subplot. Auto correlations were low and nonsignificant between -0.04 and 0.12 and the heidel test nonsignificant and passed stationary for all parameters p>0.2.

Figure 35. Stock analysis 4 catch rate fit and standardised residuals.

Figure 36. Serial plot of the retained values from the stock model analysis 4 Markov chain Monte Carlo optimisation (MCMC), where h = steepness, R_0 = virgin recruitment, a_{50} = age at 50% vulnerability, a_{95} = age at 95% vulnerability, M = natural mortality and NLL = combined negative log-likelihood. n = 1000 data points per subplot. Auto correlations were low and nonsignificant between -0.08 and -0.02 and the heidel test nonsignificant and passed stationary for all parameters p>0.15.

Appendix 4: Commercial fishing log – TSF01