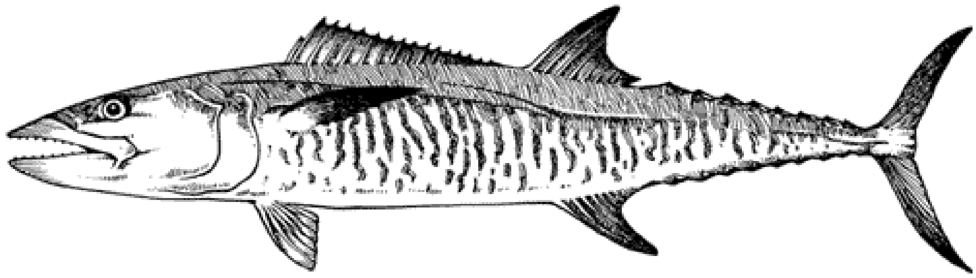

Torres Strait Finfish Fishery:

Spanish mackerel stock assessment, with data to June 2021

Year One Report

AFMA Project Number: 2020/0815

Queensland Government

Australian Government
Australian Fisheries Management Authority

Sea Sense

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This publication has been compiled by M. F. O'Neill, J. C. Langstreth and A. G. Trappett of Fisheries Queensland, Department of Agriculture and Fisheries, and R. C. Buckworth of Sea Sense Australia Pty Ltd.

Enquiries and feedback regarding this document can be made as follows:

Email: info@daf.qld.gov.au
Telephone: 13 25 23 (Queensland callers only)
(07) 3404 6999 (outside Queensland)
Monday, Tuesday, Wednesday and Friday: 8 am to 5 pm, Thursday: 9 am to 5 pm
Post: Department of Agriculture and Fisheries GPO Box 46 BRISBANE QLD 4001 AUSTRALIA
Website: daf.qld.gov.au

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Contents

Summary

This stock assessment indicates the Torres Strait Spanish mackerel biomass declined to 29 percent of unfished biomass in the 2020 fishing year. This was after a period of decline in young fish since 2010 when the biomass was estimated to be at 38 percent.

Spanish mackerel, *Scomberomorus commerson*, sustain an important finfish line fishery within the Torres Strait and are managed as a single stock. In these waters the species have been recorded to live for up to 13 years, weigh in excess of 20 kg and mature from two years of age.

The Australian Fisheries Management Authority (AFMA) commissioned annual updates to the Torres Strait Spanish mackerel stock assessment for three years 2021–2023. This was to monitor biomass estimates that were close to the 20 percent limit reference point for declaring an overfished stock.

Previous stock assessments estimated the biomass at 30 percent of unfished biomass in 2019 and at 23 percent in 2018 (Figure D.1, Appendix). All stock assessments were reviewed and overseen by the Torres Strait Finfish Fishery Resource Assessment Group (TSFFRAG). This stock assessment includes updates to input data and methodology.

This stock assessments was conducted on financial (fishing) years. The convention for labelling fishing years in this assessment is to refer to the year in which the fishing year begins, for example fishing year 2020 in this assessment refers to the period July 2020 to June 2021. This is consistent with previous Torres Strait Spanish mackerel assessments, but differs from the convention used in other Fisheries Queensland stock assessments. All assessment inputs and outputs will be referenced on this fishing year basis.

This stock assessment combined all data inputs into an annual age-structured population model. The assessment analysed different combinations of data that included three annual rates of natural mortality and two estimates of annual fish harvest.

The assessment incorporated data spanning from 1 July 1940 to 30 June 2021. The key annual data inputs were standardised catch rates from the Sunset fishing sector since 1989, fish age frequencies from 12 years since 1974 and estimated total harvests for all years including all fishing sectors and foreign fishing; see glossary for Sunset description.

The Torres Strait Spanish mackerel fishery commenced in 1940 (Figure 1). Fishery harvests, taken by all fishing sectors, increased to 200–280 tonnes (t) of Spanish mackerel per year during the 1980's. There were illegal intrusions of Taiwanese gill net fishers between 1979 and 1993, possibly harvesting in order of 100 t of Spanish mackerel per year. Net fishing was and is illegal in the Torres Strait.

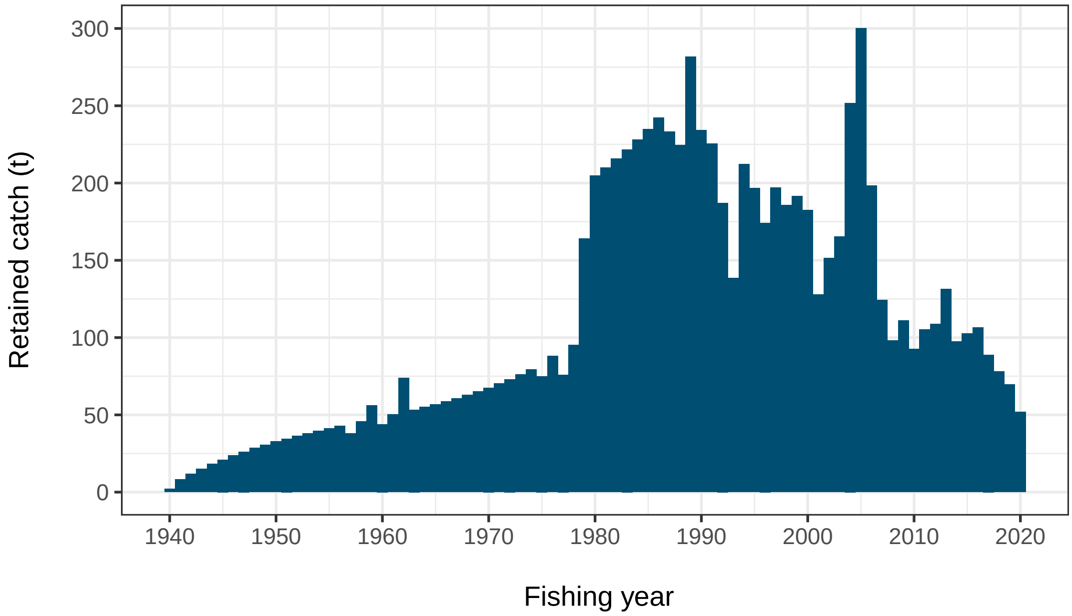

Figure 1: Annual estimated retained catch of Torres Strait Spanish mackerel between 1940 and 2020.

Spanish mackerel harvest peaked at 300 t in the 2005 fishing year, prior to fishery quota and allocation reforms. Since 2007, harvests declined to below 131 t per year. In 2020, 52 t of Spanish mackerel (62 percent commercial take) was harvested. Over the last five fishing years, up to 2020, the annual harvest averaged 79 t per year, with commercial fishing taking about 82 percent; commercial Sunset boats averaged 61 t per year and commercial traditional inhabitant boats (TIB) averaged 3.5 t.

Commercial fish catch rates (annual standardised mean number of Spanish mackerel harvested per Sunset operation day) fell near 50 percent between 2009 and 2018 (Figure 2). Catch rates since 2019 improved by about 25 percent. The longer time series of Sunset catch rates since 1989 showed a general decadal pattern of increase or decrease. Catch rates were standardised using a generalised linear model, with fishing year, zone, boat-operation, seasonality, lunar cycle, wind strength and direction, and fishing power as explanatory terms.

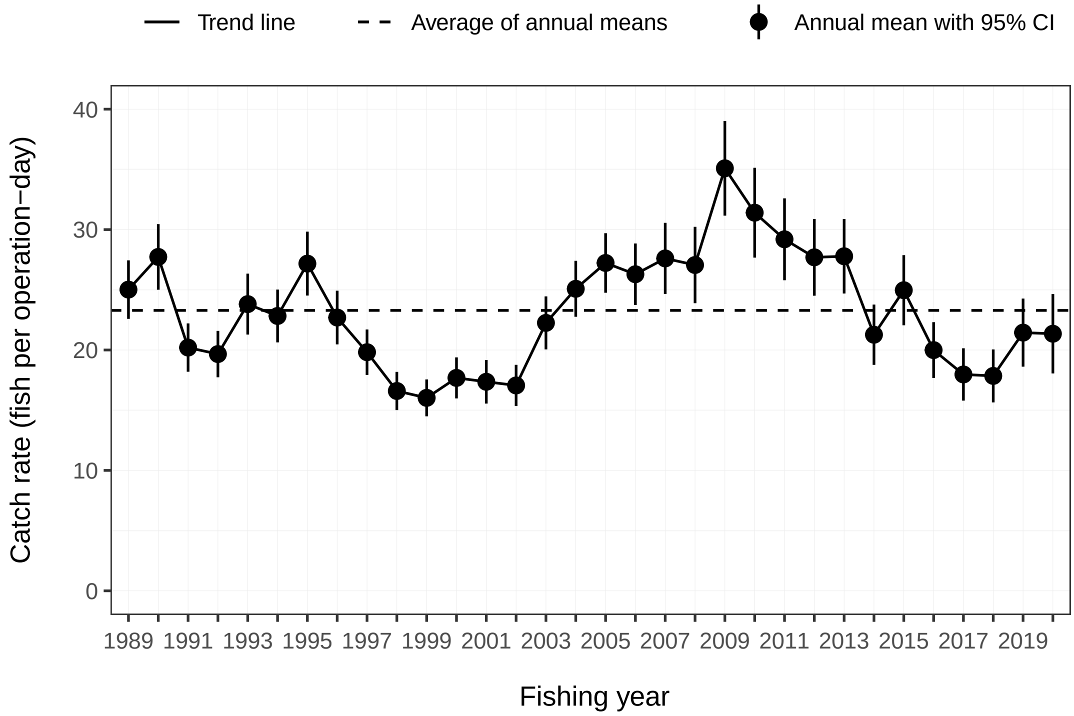

Figure 2: Annual standardised catch rates of Torres Strait Spanish mackerel.

Across analyses of different fish natural mortality and harvest, the median estimated spawning biomass of Spanish mackerel in 2020 was 29 percent of unfished estimates at the start of the fishery in 1940 (Figure 3). The low biomass result was due to the high harvests between 1980 and 2006 and the downturn in Spanish mackerel catch rates 2010–2019.

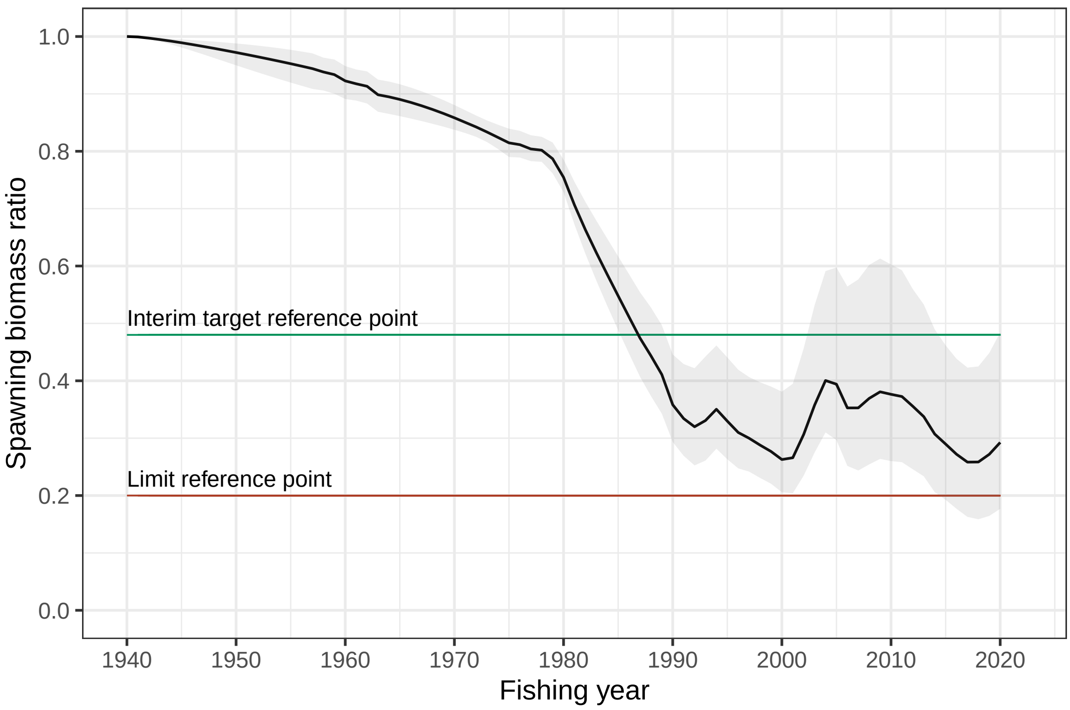

Figure 3: Estimated spawning biomass trajectory for Torres Strait Spanish mackerel, from 1940 to 2020.

The 2022–2023 recommended biological catch (RBC) of Spanish mackerel for all fishing sectors in the Torres Strait was 95 t based on the median forecast estimate (Table 1). This RBC was forecast to build Spanish mackerel towards a target biomass of 48% within 12 years, and have less than 10% risk of reducing to the 20% biomass limit reference point.

The assessment work also initiated the first comparison of the packaged stock assessment software stock synthesis (SS), which was used for assessing Australian east coast and Gulf of Carpentaria Spanish mackerel. The SS estimate of spawning biomass ratio in 2020 was similar compared against the current model developed by the Department of Agriculture and Fisheries and reported herein. SS performance and results will be further tested in years two and three of this AFMA project, noting that future provision of a streamlined stock assessment is to transition to stock synthesis after TSFFRAG review.

Table 1: Current and forecast indicators for Torres Strait Spanish mackerel.

Indicator	Median estimate
Biomass$^{\diamond}$ (relative to unfished) in 2020–2021	29% (18% to 48%)
Interim target$^{\odot}$ biomass (relative to unfished)	48%
Limit biomass reference point (relative to unfished)	20%
Biomass (relative to unfished) at MSY*	39.8%
Harvest taken in 2020–2021	52 t
$F_{MSY}^{\star}$ harvest for 2022–2023	131 t
$F_{40}^{\star}$ harvest for 2022–2023	129 t
$F_{48}^{\star}$ harvest for 2022–2023	102 t
$F_{50}^{\star}$ harvest for 2022–2023	95 t
$F_{60}^{\star}$ harvest for 2022–2023	68 t
Overfishing limit$^{\wedge}$	102 t
RBC† for 2022–2023 to achieve interim target	95 t
RBC selected to achieve target within	12 years

$^{\diamond}$ Biomass (B) was defined to be spawning egg production biomass, measured as a percentage of unfished estimates in 1940. 95 percent confidence interval was shown in parenthesis.

$^{\odot}$ B_{48} was the interim target reference point for 48% spawning biomass. This was a target proxy for B_{MEY} under the Commonwealth Harvest Strategy Policy for maximum-economic-yield (MEY).

* F_{MSY} was the annual fishing mortality (F) for maximum sustainable yield (MSY), applied to calculate the maximum retained catch for all fishing sectors for the forecast year. Calculations also applied F corresponding to 40%, 48%, 50% and 60% biomass. Estimates of actual rates of F were in Table 3.2 and Figure C.5.

$^{\wedge}$ Overfishing limit was the retained catch that would result from fishing in the forecast year at the fishing pressure F_{48}, consistent with a target 48% biomass. Fishing above the overfishing limit would likely result in not achieving the target biomass.

† Recommended biological catch (RBC) was the TSFFRAG recommended maximum harvest to be taken by all fishing sectors in the forecast year. The RBC recommendation was based on achieving the interim target biomass within 12 years. Higher RBCs had greater than 10% risk of triggering the limit biomass reference point.

Median: median estimate across analyses 1–6. The median is the value separating the higher half from the lower half of estimates. It may be thought of as ”the middle” value, and provides a better representation of a ”typical” value when the range of estimates might be skewed.

Acknowledgements

The authors acknowledge the continuing custodianship of Torres Strait fisheries by Islanders and Traditional Owners whose rich cultures, heritage values, enduring connections and shared efforts protect the Torres Strait waters for future generations. Spanish mackerel are important to the Torres Strait people and fishing culture.

The project team gratefully respect and thank past and present Torres Strait islanders, communities, scientists, and fishers who supplied information and knowledge on Torres Strait Spanish mackerel.

Special thanks also go to:

- Geoff McPherson (retired Queensland Government Senior Fisheries Scientist) for his past research in collating, reviewing and verifying historical Spanish mackerel harvest and fish age-length data, and sharing historical insights on the Torres Strait mackerel fishery.
- Dr Bruce Mapstone for collating and supplying the 2005–2006 Spanish mackerel age-length data from James Cook University (JCU) research – the Effects of Line Fishing (ELF) and Fishing and Fisheries (F&F) projects.
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- The Torres Strait Finfish Resource Assessment Group (TSFFRAG) and the Finfish working group (TSFFWG) for reviewing, shaping and interpreting the assessment methodology and results. The TSFFRAG collaborated to make decisions on assessment data, methodology and results in an open and transparent manner. TSFFRAG and TSFFWG meeting records can be access here: https://www.pzja.gov.au/torres-strait-finfish-groups.
- Past technical subgroups of TSFFRAG for advice on aspects of the assessment data and methodology. This team of people have included past Torres Strait Spanish mackerel stock assessment authors, Ashley Williams, Eva Plaganyi, Selina Stoute and Trevor Hutton. Their support was greatly valued.
- Tony Vass, industry member on TSFFRAG, for his shared insights into the fishery and history.
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The stock assessment and research funds were from the Australian Government, the Queensland Government and Sea Sense Australia Pty Ltd. Funding and project administration was by AFMA, through the Torres Strait Scientific Advisory Committee – project number 2020/0815.

Results from this project inform the Protected Zone Joint Authority (PZJA, https://www.pzja.gov.au/) through its committees. The PZJA is responsible for management of commercial and traditional fishing in the Australian area of the Torres Strait Protected Zone (TSPZ) and designated adjacent Torres Strait waters. A number of Government Ministers and Agencies supports the PZJA: The Australian Fisheries Management Authority (AFMA), The Department of Agriculture and Water Resources (DAWR), The Queensland Department of Agriculture and Fisheries (DAF) and The Torres Strait Regional Authority (TSRA).

The authors proudly acknowledge First Nations (Aboriginal peoples and Torres Strait Islanders) and the Traditional Owners of the country on which we live and work.

Glossary

ABARES	Australian Bureau of Agricultural and Resource Economics and Sciences.
AFMA	Australian Fisheries Management Authority.
Age	Age group representing a cohort of fish born in the same year. Age group was determined by counting growth rings in fish otoliths (ear bones).
B	Spawning biomass ratio. Measured as egg production from female fish.
BOM	Bureau of Meteorology, Australian Government.
Catchability *q*	The ability to catch fish. It was the average probability of catching a fish with a single unit of standardised fishing effort.
Catch rate	Annual index of legal sized fish abundance. Catch rates were standardised in a GLM.
CDR	Catch disposal record. Verified landings on fish catch weights per primary operation.
CI	Confidence interval for an estimate.
DAF	Department of Agriculture and Fisheries, Queensland.
Fishery	The assessment covered all Torres Strait managed waters and fishing sectors.
Fishing year	Financial year from 1 July to 30 June.
Fleet	SS modelling term used to distinguish types of fishing activity or sectors. Typically a fleet will have a unique vulnerability curve that characterises the sizes or ages of fish caught by that sector's fishing gear.
FM	Fisheries Monitoring. Managed by Fisheries Queensland in DAF.
FL	Fork length measured from the tip of the snout to the middle end of the caudal tail.
FP	Fishing power. Refers to a deviation in actual fishing effort from a standard unit.
FRDC	Fisheries Research and Development Corporation.
Git	Version control system used to record code and analysis history.
GLM	Generalised linear model. The method used to standardise catch rates.
Harvest rate *u*	Fraction of vulnerable aged fish harvested each year. This signifies the fishing mortality F.
Hyperstability	When catch rates or age frequencies remain consistent as fish abundance declines.
IUU	Illegal, unreported and unregulated fishing. For example, foreign fishing.
Kai kai	Traditional islander take of fish for food.
kg	Weight measured in kilograms.
MEY	Maximum economic yield. The harvest and effort level that allows maximum commercial profit for fishers.
MLS	Minimum legal size, total length 75 cm.
MSY	Maximum sustainable yield. The maximum level that can be routinely fished without long-term depletion and overfishing.
Naigai	Naigai is the season of hot dry weather and calm winds (Sept–Nov).
Operation day	A single day of fishing by a primary vessel operation, using a number of dories, crew, hours and locations fished. Also called a boat day.
Over-dispersion	In statistics, over-dispersion is the presence of greater variability in the data than would be normally expected.
Overfished	A spawning biomass ratio below the limit reference point of 20%.
Overfishing	When a fish population is experiencing too much fishing effort, and the removal rate exceeds the target level.
Overleaf	Overleaf is an online LaTeX editor that enables writing and reviewing to take place.
PNG	Papua New Guinea.
PZJA	Protected Zone Joint Authority. www.pzja.gov.au
Quantile	A set of values which divide a frequency distribution into equal groups.

R	Free computer programming language for statistical computing and graphics.
RBC	Recommended biological catch. The total allowable annual harvest of Spanish mackerel by all fishing sectors, as advised by the PZJA and its committees.
Recruitment	Recruitment is the number of new young fish that enter a population in a year. They were called the 0+ age group herein.
Reference point	Fishery health indicators on the level of fishing, harvest or spawning biomass. It is a benchmark for interpreting results and gauging the status of a fishery.
RStudio	The computer interface used to run R code, Git, and the Spanish mackerel project.
SAFS	Status of Australian fish stocks (www.fish.gov.au).
Sector	A term used to distinguish types of fishing activity or fleets.
SFS	Sustainable Fisheries Strategy, by the Queensland Government.
Simulated annealing	Simulated annealing was a method for solving an optimization problem.
SRFS	State-wide recreational fishing survey, by DAF.
SS	Stock Synthesis, stock assessment software package.
SST	Sea surface temperature in degrees celsius.
Sunset	A leased commercial licence primary-tender package. Historically they were called Transferable Vessel Holder (TVH) boats. The were operated by non-traditional inhabitants.
TL	Fish total length in centimeters (cm).
Survival rate	Fraction of fish surviving each year after fishing (F) and natural mortality (M).
t	Metric unit of weight equal to 1000 kilograms.
TACC	Total allowable commercial catch.
Tender	Tender is a small open boat used for fishing. Usually 1–5 tenders were associated with a parent (mother) vessel. They are also known as dories.
TIB	Torres Strait traditional inhabitant commercial fishing boat licence.
TSFFRAG	Torres Strait Finfish Fishery Resource Assessment Group, PZJA scientific committee.
TSFFWG	Torres Strait Finfish Fishery Working Group, PZJA committee for fishery management.
TSRA	Torres Strait Regional Authority.
TSSAC	Torres Strait Scientific Advisory Committee.
Vulnerability *v*	Probability of catching a fish. This varies for different aged fish. This is a result of fish being present in the fishing area (fishery) and their susceptibility to the fishing gear. Vulnerability defines the exploitable component of fish biomass.
Zone	A stock assessment region in the Torres Strait. Five zones were stratified (z1 ... z5).

Scope

The following paragraphs summarise the report spatial, temporal and sectoral coverage, and objectives of the work. The stock assessment was based on whole-stock annual data-inputs and dynamics.

Results encompassed Torres Strait Spanish mackerel (the genetic stock). Estimates of fish population size and harvest limits cover the entire fishery and all fishing sectors. This was for all fished waters between Cape York Peninsula and the western province of Papua New Guinea (Figure 4).

The assessment encompassed all sources of past fishing. This included harvests by traditional subsistence fishing, commercial traditional and leased operations, commercial PNG, charter and recreational fishers, and historical events of illegal, unreported and unregulated (IUU) foreign fishing.

The assessment covered the fishing years 1940–2020. Fishing years were equal to financial years. For an example, labeling of the fishing year from 1 July 2020 to 30 June 2021 was 2020 or 2020–2021. The definition of fishing year encompassed the seasonal patterns of fishing and the biological patterns of fish recruitment, growth and spawning. The peak fishing months were from September to November, the Naigai season of calm winds.

For Torres Spanish mackerel, the initial reference year for original (unfished) population size was 1940 (Begg et al. 2006).

Fishery management in 2021 had no formally adopted harvest strategy or target reference points for Spanish mackerel. Therefore, the outputs from this assessment provided a range of values for potential interim target points, to support the continuing quota setting process and work on harvest strategies from Hutton et al. (2019) . This covered different fishing rates (fishing mortality reference points) associated with fish spawning biomass between 40–60% of the 1940 level.

Objectives of the year one report were to:

- Describe the data, stock status results, reference points, harvest forecasts and risks associated with the RBC estimates. The assessment will include data up to 30 June 2021 and forecast the RBC for the 2022–2023 fishing year.
- Work in collaboration with AFMA and the TSFFRAG. This included producing results for TSFFRAG input and review, and creating a summary power point presentation for TSFFWG.
- Produce stock assessment results using the DAF custom-built population model for Torres Strait Spanish mackerel. The model has calculated the annual RBC quota of Spanish mackerel since the 2017–2018 fishing year, and was understood by TSFFRAG and TSFFWG members. The assessment has been the subject of annual peer review by the TSFFRAG (see the PZJA website for meeting records, such as AFMA (2021a)). The core model methods were also independently reviewed in other stock assessments (Klaer 2018).
- In year one of the project initiate the TSSAC request to use a packaged stock assessment software, instead of the current model. For this, a comparison was made to the stock synthesis (SS) software (Methot et al. 2013). DAF stock assessment staff have completed training in this software (O'Neill et al. 2020). This software was used for east coast Spanish mackerel and other finfish fisheries in Queensland (Tanimoto et al. 2021; Klaer 2021). The results will be evaluated by TSFFRAG, to guide transition to SS if appropriate, and streamline the stock assessment. The initial

SS comparison will use project year one data, and run on a single base case dataset to compare with the custom model.

The main objectives (and performance indicators) for each annual stock assessment, over the three year project, were to:

1. Update datasets, tally total harvests, standardise fish catch rates and calculate fish age compositions (For TSFFRAG data review, meeting 1, in October).
2. Conduct stock assessments for each TSFFRAG agreed data scenario. This includes the RBC estimates (Deliver stock assessments to TSFFRAG for technical review, meeting 2, in November).
3. Create a summary power point presentation and infographic for the Finfish Working Group (For TSFFWG, meeting 3, after the TSFFRAG technical review meeting 2).
4. Publish the annual stock assessment on DAF's e-research archive (DAF formatted report by the following May).
5. Additional objectives:
   (a) Compare and evaluate spawning biomass ratio and RBC results from the custom and Stock Synthesis (SS) software (TSFFRAG to review, and if SS is appropriate, then guide transition to the SS model for future fishery management after years 2 or 3 of the project).
   (b) Streamline the Spanish mackerel stock assessment system (completed by year 3 of the project).

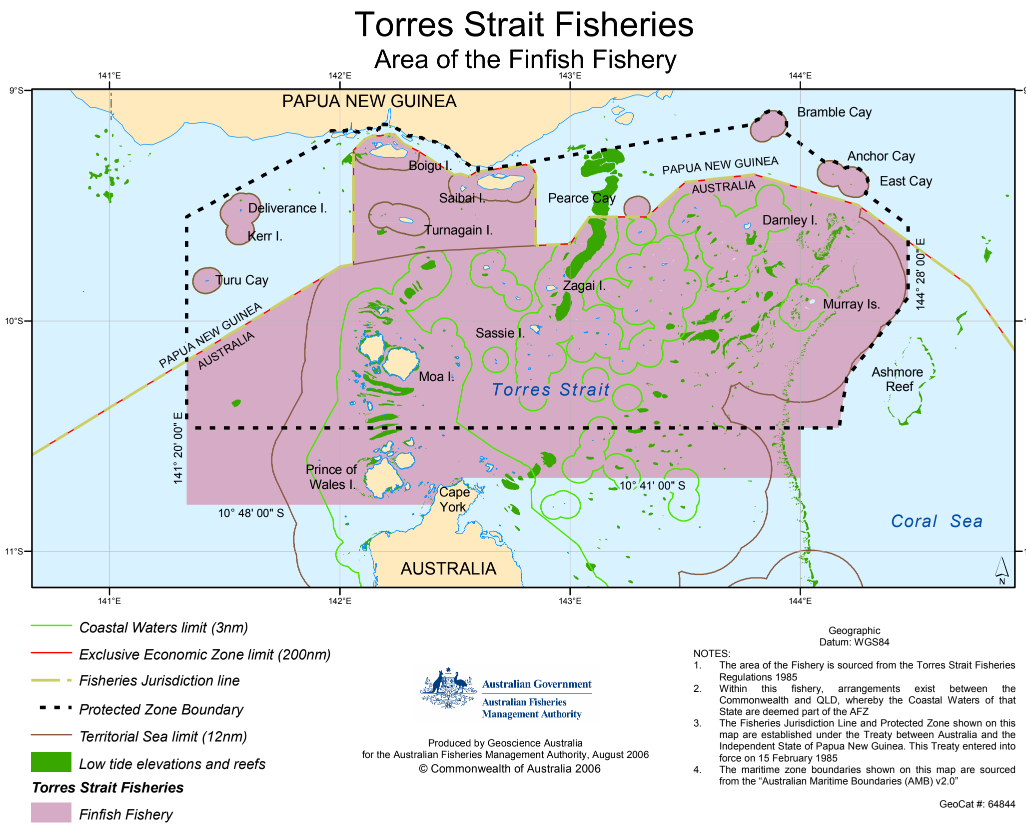

Figure 4: The management zones of Torres Strait finfish fishery; sourced from the PZJA website.

1 Introduction

Spanish mackerel, *Scomberomorus commerson*, are large pelagic fish growing to more than 20 kg. The high-quality eating and powerful sports fish are primarily caught using line trolling techniques. They frequent offshore reefs, shoals and bays, and sometimes from specific beaches and headlands. Spanish mackerel reach sexual maturity above the minimum legal size limit of 75 cm total length, at between two and four years of age (Begg et al. 2006).

Spanish mackerel are an obligate transient aggregator (Tobin et al. 2014). This means they are a large species physically able to travel great distances, but their general movement behaviour can be restricted to only a few key reef locations during spawning. Spanish mackerel movement depends on their spawning and feeding behaviour, water temperatures and currents, and availability of food. Some fish can remain localised, whereas some fish may travel and later return to aggregate in their home grounds (Buckworth et al. 2007).

In the Torres Strait, Spanish mackerel form peak spawning aggregations between October and November (Begg et al. 2006). Particularly in the northeast, around the key fishing and spawning ground of Bramble Cay (Maizab Kaur) (Figure 4). Locations of schooling fish are seasonally predictable, particularly around Bramble Cay, when they are easier to locate and catch.

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 were assumed to reside in these surrounding waters, with published stock-structure research recommending that Torres Strait Spanish mackerel were a discrete population for fish management (Buckworth et al. 2007). This recommendation formed the spatial boundary for stock assessment.

The Australian area of the protected zone is an important economic and traditional food source for all Torres Strait communities (Begg et al. 2006). Historically, all fishing sectors have harvested around 50–300 t of Spanish mackerel per year; estimated non-commercial harvests were small at around 20 t per year. Access to the commercial fishery was restricted to holders of a Torres Strait traditional inhabitant fishing boat licence (called TIB boats) or leased sunset licence primary-tender packages (called Sunset boats) (PZJA 2022b). All licenced commercial fishing operated under the 'MK' fishery symbol for Spanish mackerel, managed by AFMA.

The Torres Strait Treaty was ratified in 1985, between Australia and Papua New Guinea (Department of Foreign Affairs and Trade 2022). From this, Australia and PNG share commercial catch allocations for cross endorsement within the Torres Strait protected zone (Figure 4). Spanish mackerel catch shares were allocated 60% to Australia and 40% to PNG (PZJA 2022a). There has been no historical Spanish mackerel harvest leased to or reported by Papua New Guinea fishing operations to date.

Fishery management and catch shares were centred around the annual recommended biological catch (RBC quota) of Spanish mackerel for all fishing sectors in the Torres Strait. RBC settings were based on stock assessment results, that considered the history of the fishery (Table A, Appendix A). The RBC process was to forecast two years ahead of the stock assessment, and consider potential RBC's that achieved 48% biomass within 12 years and had less than 10% risk of triggering the limit reference point of 20% biomass (AFMA 2021a).

Recent stock assessments of Spanish mackerel up to 2019–2020 were pessimistic on stock status and RBC (AFMA 2019; Hutton et al. 2019; AFMA 2020b; Buckworth et al. 2021; AFMA 2021a). Regular annual harvests of less than 100 t, recent declines in fish catch rates and the absence of older fish in age samples were present signs for a small sustainable fishery. The assessment data suggested high harvests like 200–300 t pre-2007 were not sustainable in the long term.

Given the reductions in total fishery catch over the last decade, the assessment results were lower than expected but nevertheless reflected declining catch rates. For some years, abundance had not responded to the RBC reductions as would be expected. This has been of significant concern to stakeholders. Given that the stock assessments accounted for operational aspects in the fishery, it was suggested in TSFFRAG meetings that environmental conditions might have led to this observed downtrend as shown by the negative recruitment deviations that were estimated by the stock assessment (AFMA 2020b; Buckworth et al. 2021).

Similar declines in Spanish mackerel catch rates and recruitment deviations have occurred in neighbouring Queensland fisheries (O'Neill et al. 2018a; Bessell-Browne et al. 2020; Tanimoto et al. 2021). This raised speculation that the broader regional environment may have influenced aspects of fish biology, such as Spanish mackerel spawning, recruitment, survival, and spatial distribution. Exploratory analyses reviewed the influence of environmental factors sea surface temperature, rainfall and the Southern Oscillation Index on catch rates and recruitment deviations, and found no strong direct or lagged relationships for Torres Strait Spanish mackerel (Buckworth et al. 2021).

In 2021, the Torres Strait Scientific Advisory Committee, on behalf of the Protected Zone Joint Authority, funded updates to the stock assessment for three years 2021–2023. This year one report, delivered updated stock assessment results for consideration in defining future harvest strategies, reviewing RBC settings and automation of stock assessment processes. The report informs fishery management agencies and stakeholders on estimates of sustainable harvest that will build and maintain the fishery in the long term.

2 Methods

2.1 Data sources

A summary of the times series data collated for the stock assessment is in Table 2.1.

Table 2.1: Summary of the data collated for the stock assessment.

Type	Fishing year	Source
Commercial harvest	pre 1989	Sunset harvests recorded from 8 years between 1959 and 1979 (McPherson 1986).
	1989–2020	Sunset harvests and catch rates from compulsory logbooks.
	1989–2017	TIB harvests from docket (doc) book records.
	2018–2020	CDR version TDB02 records for Sunset harvests and TIB harvests and catch rates.
Traditional harvest	1989–2020	Estimated kai kai harvests (AFMA 2021b). This considered traditional knowledge and survey data (Busilacchi et al. 2015).
IUU harvest	1980–1992	Estimated IUU harvest taken by Taiwanese drift netters (AFMA 2021b).
Recreational harvest	2014–2015	Survey estimates between 2 and 5 t (Webley et al. 2015; AFMA 2021b).
Fish age-length data	1974–1975	Survey of Fisheries Resources - Torres Strait, 1974. Length data only from the Sunset sector.
	1978–1979	Fisheries Research Branch fish age-length sampling from the Sunset sector at Bramble Cay.
	1983–1984	Length data only from a pilot fish tagging program.
	1998–2000	Length data only from the Sunset sector, sampled by a FRDC stock definition study.
	2000–2003	Sunset at-sea catch sampling from Bramble Cay (Begg et al. 2006).
	2005-2006	Age-length data collected by James Cook University research. At-sea sampling from Sunset vessels fishing Bramble Cay.
	2019–2020	Annual monitoring undertaken by Fisheries Queensland (Langstreth et al. 2020; Trappett et al. 2021).

2.2 Harvest data

AFMA supplied the commercial Spanish mackerel harvest data. The project agreement covered data confidentiality. This included the authority for the project investigators to analyse the data in confidence for the purpose of stock assessment.

The commercial Spanish mackerel harvests since 1989 were from three sources:

1. Compulsory logbook (Log) records for Sunset operations 1989–2020,
2. Docket (Doc) book records for TIB landings 1989–2018, and

3. Compulsory catch disposal records (CDR, version name TDB02) since 2018 for TIB and Sunset boats.

The CDR records provided verified information on fish catch weights from Sunset and TIB fishing operations. The CDR reports calculated annual harvest tonnages since 2018 (for the Sunset CDR summary, see Appendix B Table B.2). Annual harvests pre 2018 were tallied from logbook harvest data for Sunset fishing, and docket records for TIB.

The docket (Doc) book recorded TIB harvests from community processor-freezer establishments. TSFFRAG discussed the data and it was accepted as mostly complete based on when the freezers were operating and islander reports (AFMA 2020a).

Aspects of the Log and Doc data tables were previously described (Begg et al. 2006; O'Neill et al. 2018b; Hutton et al. 2019; Buckworth et al. 2021). These reports detailed the methods for summarising annual total harvests and catch rates per operation day. There was one method change to the Log data in 2020. The TSFFRAG endorsed use of annual average fish weights, rather than a constant average fish weight (AFMA 2020a; Buckworth et al. 2021). The availability of more years of fish age-length data supported the modification and estimates.

The Sunset Log data tables were analysed to form records of each vessel-operation's daily harvest, together with the associated variables for the main vessel name (anonymous codes were used), date, fishing zone, number of specified tenders, numbers and weight of Spanish mackerel harvested, lunar phase and wind components.

Analyses of harvests at the primary vessel-operation-day unit aimed to match the daily recording format. This avoided correlations in catch rates between tenders on an operation day (not independent), artificially increasing the number of data into per tender-day units, bias towards operations using more tenders and mixed recording of fisher/crew names operating each tender.

The following aspects were for creating the Sunset Log harvest and daily catch rate data:

- The Log Boat and LogOperation data tables grouped each vessel-operation, day and record number, and filtered for only Spanish mackerel vessels, gear code TR for line trolling, and logbook types SM02 and TSF01. This included the corresponding location data.
- The LogCatch and LogEffort data tables, linked with the selected LogOperation data based on the record number. The merged data was for the Spanish mackerel species code.
- Wind, lunar phase and seasonal components data were calculated from the fishing dates.
- The five fishing zones (z1 to z5) were calculated and categorised using latitude and longitude decimal degree data (Buckworth et al. 2021). The TSFFRAG sub-technical group defined the five-zone stratification in 2018 (Figure 2.1).
- Some client/fisher names were inconsistent (O'Neill et al. 2018b). Catch rates were therefore analysed by their vessel name (also called a boat operation), which grouped the clients.
- The recorded harvests of Spanish mackerel were 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 for numbers of fish was the primary recorded information. Records of zero harvest were not analysed, as they were generally not reported (O'Neill et al. 2018b). Table 2.2 lists the conversions used.

- Estimated harvest tonnages used a new schedule of annual fish weights (Buckworth et al. 2021). The schedule used data in years when such data were present and valid. For years with no data, the annual fish weights were calculated according to a proportional gap scheme (Filar et al. 2021).
- The final catch rate data grouped record numbers identifying different dories and fishing sessions to form records of each vessel operation's daily harvest. The catch rate data removed vessel operations that had fished less than 20 days over all years analysed and had fished in only one year. Reported bulk trip harvests, for more than one day, were excluded from catch rates. In total, these filters removed about 1–2% of catch rate data (see data selection report, Appendix B.5.3).
- The tallied number of tenders used each day by each fishing operation was from the listed 'tender number' in the LogCatch data table. The tallied tender numbers typically ranged 1–5. The final catch rate analysis did not use this data. This was due to missing information and inconsistencies in the low number of tenders reported in 1989– 1992.

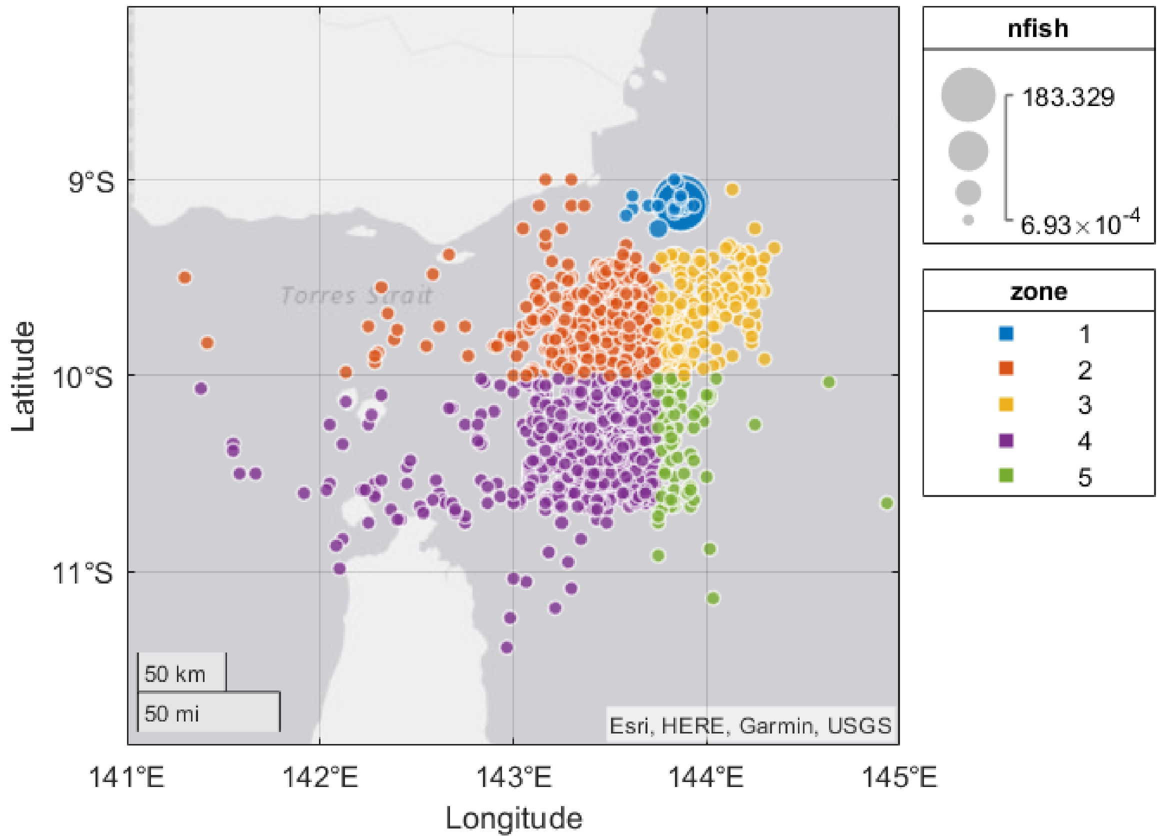

Figure 2.1: Map of the Torres Strait zones illustrated by colour (Bramble Cay zone 1 - blue, Ugar zone 2 - orange, east/anchor zone 3 - yellow, dugong zone 4 - purple, and southeast zone 5 - green). Map circles indicate the numbers of Spanish mackerel harvested by Sunset operations 1989–2020 at unique logbook latitude and longitude coordinates. Larger circles showed the main harvest locations, like for the Bramble Cay hotspot. The map units of fish were thousands (numbers divided by 1000).

Table 2.2: Equations for converting Sunset numbers of fish (n), weights (w) and cartons (c) harvested per operation day.

Equation	Parameters	Condition
$w_{new} = n \times wt_y$	where wt was the mean weight (kg) of a whole fish in year y	$n > 0$
$w_{new} = (w_{old}/pc_{old}) \times pc_{new}$	where pc_{old} was the original and pc_{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 per carton; s.d = 1.47, n = 6,828) and 1.608 kg was the mean conversion for fillets to whole fish.	$n = 0, w_{old} = 0$, $c > 0$
$n = w_{new}/wt_y$		$n = 0$

The Torres Strait wind data was from the Bureau of Meteorology (BOM), for the Horn Island weather station (the nearest station with a complete series of data for the period of interest). Measures of wind speed (km per hour) and direction (degrees from where the wind blew) between 6am and 6pm were averaged to a daily reading. The averages were then converted to north-south (windns) and east-west (windew) wind components:

$$\begin{aligned} \text{windns} &= \text{km hr}^{-1} \times \cos(\text{radians(degrees)}), \\ \text{windew} &= \text{km hr}^{-1} \times \sin(\text{radians(degrees)}). \end{aligned} \tag{2.1}$$

The wind components standardised catch rates for different wind directions and strengths. The component functions considered the BOM defined wind directions as degrees measured clockwise from true north (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).

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 catch date. The data were calculated using the lunar R software package, for illumination values with a shift setting of 9.5 hours (Lazaridis 2014) . The luminance measure (lunar) followed a sinusoidal pattern and was advanced 7 days (≈ quarter lunar cycle) into a new variable (lunaradv) to quantify the cosine of the lunar data (O'Neill et al. 2006). The two variables were modelled together to estimate the variation in catch rate according to the moon phase (i.e. contrasting waxing and waning patterns of the moon).

The seasonality of Spanish mackerel was modelled using sinusoidal data to standardise catch rates for the time of year. The data was calculated and used to minimise the number of parameters in the catch rate analysis, and to avoid any temporal confounding with the zone and vessel data. In total six trigonometric covariates were used, which together modeled the seasonal patterns of catch (Marriott et al. 2013):

$$\begin{aligned} s1cos &= cos(2\pi d_y/T_y),\ s1sin = sin(2\pi d_y/T_y) \\ s2cos &= cos(4\pi d_y/T_y),\ s2sin = sin(4\pi d_y/T_y) \\ s3cos &= cos(6\pi d_y/T_y),\ s3sin = sin(6\pi d_y/T_y) \end{aligned}$$

The d_y numbers were the cumulative day of the year $(1 \cdots T_y)$, and T_y was the total number of days in the year (365 or 366 for a leap year). The reason for using both cosine and sine data together was similar to modelling lunar phases, where the data operated together in pairs to identify the period in the cycle. The pairs of data were in order such that s1 first tested for a 12-month cycle, s2 for a 6-month cycle, and s3 for a 4-month cycle. The result of combining the three pairs of data quantified the seasonal patterns of catch rates (Figure B.6, Appendix B.5.1).

2.3 Catch rates

The standardisation of catch rates (mean catch of Spanish mackerel per operation-day of standardised effort) was calculated using a statistical model. The catch rates formed the annual indicator of legal sized fish abundance. They were standardised as trends in nominal catch rates can vary with temporal and spatial changes in fishing effort and fish catchability. The data used for catch rates were 'fishery dependent', as reported by commercial fishers.

2.3.1 Sunset

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

Annual mean catch rates of Spanish mackerel were standardised using the computer software R (R Core Team 2020). Predictions were checked against GenStat (VSN International 2022), as previous assessments (Buckworth et al. 2021) were undertaken using that package. Standard errors were calculated for all estimates. The importance of individual model terms was assessed formally using F statistics by dropping individual terms from the full model.

The Sunset GLM response variable consisted of the daily catch (nfish) taken by each fishing-operation (boat). Explanatory model terms included main effects for the fishing years, zones, boats, seasonality, lunar cycle and winds.

An annual gear-only fishing-power effect was log offset. This information was from north Queensland commercial Spanish mackerel vessels, noting, no additional fishing power data were available since 2014 (O'Neill et al. 2018a). No increase from the 2014 fishing power level was used for subsequent years.

The annual fishing power offset was according to the square root scenario (O'Neill et al. 2018b; O'Neill et al. 2018a). It represented combinations of increased use of global positioning systems, colour depth sounders, down riggers and baiting technique. The square root scenario recognised potential fishing power increases, but this was a constrained (about half) effect to align with the long-term consistency in fishing methods used around Bramble Cay and differences from the Queensland fishery. TSFFRAG endorsed this based on Torres Strait industry advice (AFMA 2020a).

The R equation form of the commercial Sunset GLM was:

$$
\begin{aligned}
\text{nfish} \sim \exp(&\text{year} + \text{zone} + \text{boat} + \text{s1cos} + \text{s1sin} + \text{s2cos} + \text{s2sin} + \\
&\text{s3cos} + \text{s3sin} + \text{lunar} + \text{lunaradv} + \text{windns} + \text{windns}^2 + \text{windew} + \text{windew}^2 + \\
&\text{offset}(\log(\text{fishingpower})))
\end{aligned} \tag{2.2}
$$

where the GLM type and variables were:

- *nfish*: daily harvest per boat operation of Spanish mackerel (number)
- *year*: fishing year 1989 to 2020 (factor)
- *zone*: five spatial zones within the Torres Strait (factor)
- *boat*: anonymous codes for different operations (factor)
- *s1 to s3*: six seasonal variables defined by cosine and sine functions (variates)
- *lunar*: luminance measure followed a sinusoidal pattern (variate)
- *lunaradv*: lunar adjusted by a quarter cycle (variate)
- *windns*: north-south wind strength component (variate)
- *windns*^{2}: north-south quadratic term (variate)
- *windew*: east-west wind strength component (variate)
- *windew*^{2}: east-west quadratic term (variate)
- *fishingpower*: annual proportional change (variate; log transformed and offset)
- *GLM family and link function*: Over-dispersed (quasi) poisson and log link

From the GLM, standardised catch rates were formed following GenStat's PREDICT procedure (VSN International 2022). This was done in R by using two steps, to ensure a) consistency with previous analyses and reports, b) appropriate spatial averaging, and c) averaging the appropriate way over levels of factors. Prediction of a full interaction table was formed in step A. Secondly this table was then averaged in step B. This method works for models with main effects and interaction terms.

Step A was to calculate the full table of predictions using R's PREDICT command, classified by every factor in the GLM. For any variate in the model, the predictions were formed at its mean, unless they were otherwise specified for the prediction table. If so, the variate values were then taken as a further classification of the full table of predictions. By default, the predictions were made to the last year of the log fishing power offset.

Step B was then to average the full table of predictions from step A. Factors that were not specified in prediction, were averaged by what was called marginal weights applied to each factor level. That was, by the number of data occurrences, scaled to proportions, of each of it's factor levels in the whole dataset. This averaging is usually the appropriate way of combining predicted values over levels of a factor (VSN International 2022).

The resulting predictions from step B were standardised numbers of Spanish mackerel per boat-operation-day (the logbook reporting unit). The prediction settings for the annual index of fish abundance by year, over steps A and B, were:

- *year*: all years predicted.
- *zone*: marginal weight for an average spatial pattern of fishing.
- *boat*: marginal weight for an average boat-operation.
- *s1 to s3*: seasonality variables calculated for the mean day fished within year (= 231, for mid August)
- *lunar*: luminance for a mid point (median) lunar setting
- *lunaradv*: corresponding to the mid point lunar setting

- *windns*: mean north-south wind component
- *windns*^{2}: quadratic for the north-south mean
- *windew*: mean east-west wind component
- *windew*^{2}: quadratic for the east-west mean
- *fishingpower*: last year, which was the maximum offset.

2.3.2 TIB

The CDR recorded TIB catch rate data. The TIB sector recorded no catch-rate data pre 2018. Similar GLM and prediction methods were employed for TIB catch rates of Spanish mackerel.

The TIB Spanish mackerel catch rate data consisted of weights of fish (> 0; kg) harvested per client boat-day. Explanatory model terms included main effects for the fishing years, anonymous client code, seasonality, winds and number of crew fishing in the client's boat. Other model data/terms from the Sunset analysis were not significant in the short time series of data. The number and significance of model terms will build in time with this new data set. No fishing-power offset was applied.

The R equation form of the commercial TIB GLM was:

$$\mathrm{kg} \sim \exp(\mathrm{year} + \mathrm{client} + \mathrm{s1cos} + \mathrm{s1sin} + \mathrm{windew} + \mathrm{crew}) \tag{2.3}$$

where the GLM type and variables were:

- *kg*: daily harvest per client-boat of Spanish mackerel (kg)
- *year*: fishing year 2018 to 2020 (factor)
- *client*: anonymous codes for different clients (factor)
- *s1*: two seasonality variables defined by cosine and sine functions (variates)
- *windew*: east-west wind strength component (variate)
- *crew*: number of people fishing in the boat (variate)
- *GLM family and link function*: Over-dispersed (quasi) poisson and log link

The resulting predictions were standardised kg of Spanish mackerel per boat-day (the CDR reporting unit). The prediction settings for the annual index of fish abundance by year were:

- *year*: all years predicted.
- *client*: marginal weight for an average client boat.
- *s1*: seasonality variables calculated for the mean day number fished (= 310, for early November)
- *windew*: mean east-west wind component
- *crew*: mean number of crew (= 1.667 people).

2.4 Age compositions

Monitoring projects sampled fish age and/or length compositions of Spanish mackerel in 12 years. Sample details are in Table B.3 (Appendix B.3).

Since 2019, a new sampling program aged Spanish mackerel from both TIB and Sunset harvests (Langstreth et al. 2020; Trappett et al. 2021). The program aimed to collect fish length and age information to cover the spatial and temporal patterns of harvest. Spanish mackerel target sample numbers were determined prior to the commencement of annual sampling. Annual target numbers were maintained the same in 2019 and 2020, and were a total of 1500 fish lengths from around 50 individual ungraded catches, and otoliths and sex information from around 500 fish (Trappett et al. 2021).

Many fishers and community members assisted to collect samples of fish frames or heads, and measure the lengths of fish. Fish samples were provided after fishing trips. Since 2019, there has been no at-sea sampling by fishery observers.

Commercial fishers recorded the fork lengths of Spanish mackerel from whole (ungraded) catches onto waterproof measuring sheets with measurements to the nearest 1 cm (Trappett et al. 2021). Where fishers could not measure an entire catch, they recorded the percentage of the catch measured.

Some fishers collected samples of whole filleted fish frames (Trappett et al. 2021). Fish were selected randomly by sex, and therefore the sex ratio was representative of the catch within each length class. The samples were freighted back to the laboratory at the DAF Northern Fisheries Centre in Cairns.

Together with the biological material and length data, information on the catch including date caught, a general catch location and vessel name were provided by fishers (Trappett et al. 2021).

To allow length conversion between samples provided as a whole frame or a fish head, all Spanish mackerel upper jaw lengths were measured by using callipers to the nearest 1 mm (Trappett et al. 2021). Spanish mackerel fork length and total length were also measured to the nearest 1 mm in the laboratory.

DAF Fisheries Queensland followed a standardised approach for routinely estimating the age of fish using otoliths. For Spanish mackerel, this process involved examining whole sagittal otoliths under a microscope and identifying alternating opaque and translucent zones on the otoliths. The interpretation of the otolith banding followed quality assurance criteria (Trappett et al. 2021).

Fish ageing was first carried out on a training set of otoliths with agreed interpretations. A competency test on 200 randomly selected otoliths from the reference set was undertaken by the staff member. When passed, all sampled otoliths were then interpreted for:

- increment count – the number of opaque zones counted between the primordium (nucleus) and the distal (outside) edge of the otolith,
- edge type - the edge of the otolith was classified as new, intermediate or wide. Intermediate and wide classifications were based on the relative stage of completion of the marginal translucent zone, and
- readability – classifications included not-confident, confident, unreadable, or processing error.

Otolith increment counts were tested for bias and precision, and edge classifications were tested for overall agreement (Trappett et al. 2021). Standard bias, precision and agreement measures were assessed and fell within acceptable levels Table B.4.

Langstreth et al. (2020) and Trappett et al. (2021) detailed the full sampling and fish ageing processes, including age allocation, age-length keys and formation of annual age structures.

Before 2019, monitoring was conducted only from Sunset fishing operations, which mostly fished within 2 km of Bramble Cay. Sampling was dependent on the trip times by commercial vessels. In each year sampled, an observer monitored at-sea the fish catches from as many vessels and days as possible.

Buckworth et al. (2021) advised TSFFRAG that a range of fish age-length datasets were now available for inclusion as input into the stock assessment. The project advised that some years of fish data had different sampling agendas, and five years of data only had measures of fish length (no ages).

To form age frequencies in these five years, the nearest year's known age-length key converted the observed fish lengths into annual age groups. The TSFFRAG recommended that, on principle, all available data be used (AFMA 2020a; AFMA 2020b). There was no evidence from patterns in the data to discard any year as not representative.

The fish ageing methods across years were similar (Begg et al. 2006; Hutton et al. 2019; Langstreth et al. 2020; Trappett et al. 2021). No aspects of the data appeared conspicuous. Ageing protocols and precision statistics were inspected in each year where available (Buckworth et al. 2021).

Table 2.3: Mean fish weight (kg) by year and data source.

Fish year	Mean	Standard deviation	Median	Number of fish	Data source
1974-75	8.11	3.09	7.56	124	DAF – lengths only
1978-79	7.14	2.61	6.35	242	DAF – age and lengths
1983-84	8.07	3.41	7.33	350	DAF – lengths only from tagging
1998-99	6.83	2.42	6.35	216	DAF – lengths only
1999-00	8.62	2.72	8.53	309	DAF – lengths only
2000-01	6.90	2.37	6.42	915	DAF – age and lengths
2001-02	7.08	2.31	6.64	942	DAF – age and lengths
2002-03	7.07	2.19	6.42	654	DAF – age and lengths
2004-05	7.22	2.19	6.78	1789	AFMA – lengths only
2005-06	7.62	2.26	7.45	744	JCU – age and lengths
2019-20	7.65	2.44	7.19	1592	DAF – age and lengths
2020-21	7.45	2.32	6.99	3091	DAF – age and lengths
All years	7.48	2.53	7.00	914	Summary means

2.5 Population models

2.5.1 Custom-built model

The population dynamic model calculated numbers of Spanish mackerel by year and age group. The 1940–2020 model accounted for annual processes of fish births, growth, reproduction and mortality (O'Neill et al. 2018b; Hutton et al. 2019; Buckworth et al. 2021).

The model operation was in two phases: 1) model fitting to data to estimate the population parameters, and 2) simulation of parameters to evaluate confidence intervals on predictions, reference points and forecasts.

Model parameter estimates were by maximum likelihood. This involved fitting the model to fish catch rate and age composition data. Primary importance was placed on fitting the standardised catch rates using normal negative log-likelihoods (Francis 2011). Estimated effective sample sizes scaled the multinomial negative log-likelihoods to the age composition data. Additional normal negative log-likelihoods supported estimates of annual recruitment variation and recruitment compensation ratio.

The model estimation process was conducted in Matlab® (MathWorks 2022). The estimation used Matlab global optimisers, followed by a customised simulated annealing (MCMC) program to find and check the parameter solutions and estimate the parameter covariance matrix.

The custom annealing method herein first simulated the combined negative loglikelihood (objective) process at large steps, and then slowly decreased the step size, thus, to minimize the negative loglikelihood.

At each iteration of the simulated annealing, a new parameter value was randomly generated based on the step size and building covariance. The distance of the new value from the current value, or the extent of the search (for the step size), was based on a probability distribution with a scale proportional to the negative loglikelihood. The algorithm accepted all new values that lowered the objective, but also, with a certain probability, values that raised the objective. By accepting values that raise the objective, the algorithm avoided being trapped in local minima in early iterations and was able to explore globally for better solutions.

The estimation steps located optimal estimates over the combined negative log-likelihood functions. The simulated annealing started from a scaling factor of 100 and then reduced to 10, 1, 0.1 and then 0.01. For each scaling factor, the annealing process ran for 10000 iterations of each of the estimated parameters. The covariance matrix measured the differences in the negative log-likelihood with each parameter jump. From the maximum likelihood estimates and their covariance matrix, one thousand multivariate normal parameter vectors generated the confidence intervals on model predictions (Richards et al. 1998).

In model development and testing (Hutton et al. 2019), the estimation of annual recruitment variation from 1989 was necessary to fit the cycles of annual harvests and catch rates. Statistically, this added 31 estimated parameters for the data.

The calculations of the fishery reference points were by solving the equilibrium annual harvest rates (u = 1-exp(-F)). The harvest rates were for MSY and spawning biomass ratios 40%, 48%, 50% and 60%. The 60% target level was consistent with the 2027 management goals set in the Queensland Government's Sustainable Fisheries Strategy (Department of Agriculture and Fisheries 2017). The Australian Government's biomass proxy for B_{MEY}/B_0 was 48% (Australian Government 2007; Australian Government 2018).

From the reference points, the RBC was calculated and TSFFRAG endorsed a change in method in 2020 (AFMA 2020a; AFMA 2020b. There was an issue of a two-year time lag between the last assessment year and the RBC year of fishing. TSFFRAG agreed that, rather than use the last biomass year for the RBC, the model should forecast biomass two years ahead (Buckworth et al. 2021). The forecast assumed average stock recruitment from the Beverton-Holt function (mean log recruitment deviation = 0; so no deviation applied in RBC calculation) (Buckworth et al. 2021). The RBC setting process followed Figure 2.2.

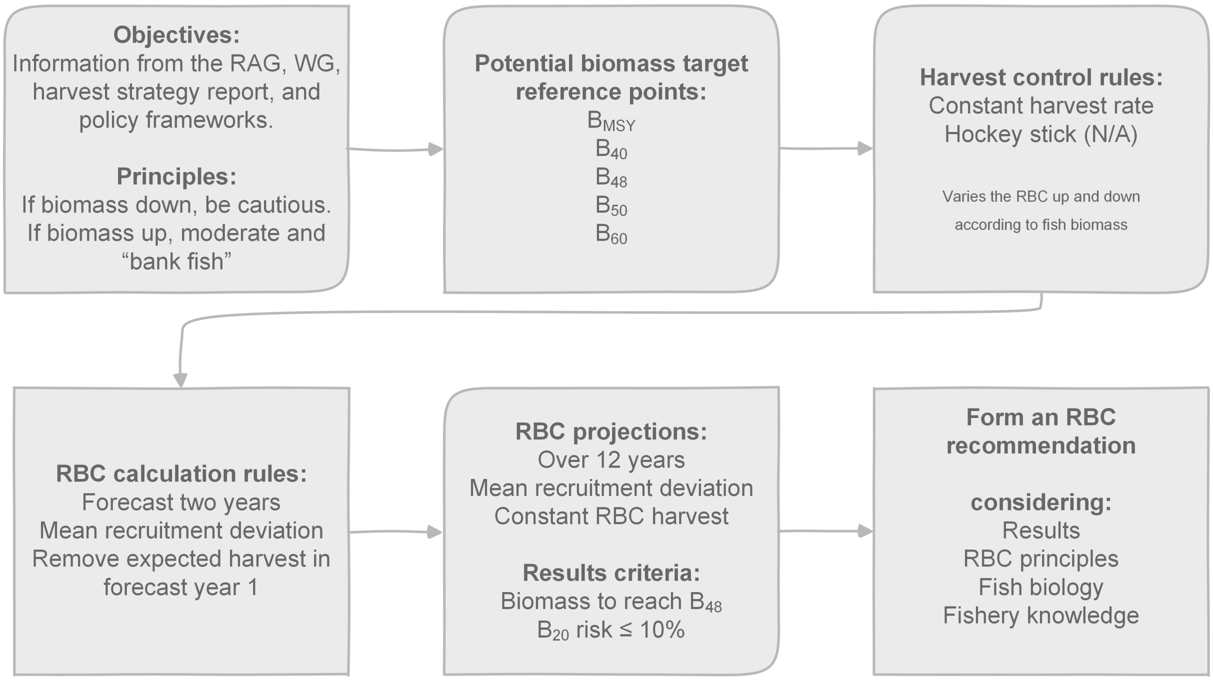

Figure 2.2: Flow chart of the considerations in RBC calculation and recommednations. Hockey-stick harvest control rules were not applied in this assessment.

Model details, equations, parameter definitions and negative log-likelihood equations were published by Buckworth et al. (2021).

2.5.2 Stock synthesis (SS)

SS is an age-structured population model that has been applied to a variety of fish stock assessments globally (Methot et al. 2013). The software package has been used to analyse a range of demersal and pelagic fish species, including tuna, marlin, snapper, cod, flatfish, and many U.S. ground fish species. CSIRO have used the software to assess a number of AFMA-managed finfish fisheries in southern Australia, which have ongoing fish age-length monitoring programs (https://www.afma.gov.au/fisheries/southern-eastern-scalefish-shark-fishery).

SS can combine many different kinds of fishery and survey data. This normally includes, but is not limited to, annual harvest, catch rate, fish age-length and biological data. The analysis of this data estimates time series of spawning biomass and management quantities for RBC. The software propagates uncertainty, and can run Markov Chain Monte Carlo (MCMC) simulations to generate confidence intervals on estimates.

For the SS analysis herein, a simple age structured model was defined through the data inputs and model settings, requiring large and complex text input files. The input files defined the detail of fish age-dynamics, the biology and life history characteristics of the species such as longevity, natural mortality rates, growth rates and reproduction, and functions for fish recruitment, selectivity and catchability.

For this project, the SS software was operated through Rstudio/R using command-prompt code, and R code was developed to generate the four input text files – starter, data, control and forecast:

- The ‘Starter file’ specified the data and control file names and other set-up specifications. This file had about 40 lines of code including comment lines. It defined settings for outputs, MCMC/bootstrapping, and jittering of parameters to test maximum likelihood solutions.
- The ‘Data file’ specified the information on which the assessment will be based (and the initial sample sizes and CVs) for the data. This file, including comment lines, was very long based on the amount of data ($>$ 200 lines of code). The file also defined the number of years, seasons, genders, areas, fleets and units (kg) of the data.
- The ‘Control file’ specified the model that was be fitted to the data (growth, selectivity, recruitment, etc.) as well as how the data was to be statistically weighted. This file was about 300 lines of code including comments. Understanding of the settings in this file was critical for an accurate stock assessment. Example settings included parameters for natural mortality, growth, maturity, fecundity, recruitment distribution and selectivity.
- The ‘Forecast file’ had about 60 lines of code, including comments lines, to specify the reporting outputs. The file defined the reference points, type and years of forecasting. This is tailored for USA harvest control rules, but is also suitable for some Australian harvest strategies. The target and limit biomass reference points, such as between B_{60} and B_{20} can be specified.

SS was written in AD Model Builder (ADMB). Correctly specified and aligned input files were critical. The r4ss package allowed for output plotting, statistics and diagnostics.

Key methods for SS were published in peer reviewed journals and reports by NOAA in the USA (Methot et al. 2013; Methot et al. 2021).

In this report SS was setup with the same annual data inputs and biology as in the custom-built model for scenario analysis number two only (Table 2.4). This was to enable initial comparison between models. The SS software version used was SS 3.30.16.1.1.

The base assumptions for formulating inputs into the SS model included:

- The fishery began from an unfished state in 1940.
- The fraction of fish that were female or male at birth was 50%. The model combined the sexes.
- Fish growth occurred according to the von Bertalanffy growth curve.
- The weight and fecundity were functions of their age.
- The instantaneous natural mortality rate was constant and did not depend on age.
- Annual recruitment was a Beverton-Holt function of spawning stock size. It was assumed deterministic before 1989 and stochastic with recruitment deviations thereafter.

Parameters in SS were estimated within the model where possible, to enable the best possible fit to available data. Uninformative priors were used. The same parameters were estimated as in the custom model. The estimation details for SS were:

- The natural logarithm of unfished recruitment ($\ln(R_0)$) was estimated within the model. This parameter was the average natural logarithm of the number of recruits in 1940.
- Stock recruitment steepness (h) was estimated within the model for the Beverton-Holt formulation.
- Growth curve parameters and CVs were fixed within the model. Buckworth et al. (2021) detailed these settings.
- Natural mortality rate (M) was the annual rate of the removal of fish from the population due to causes not associated with fishing (examples include predation or old age). The scenario with M equal to 0.35 per year was tested.

- Logistic age-based vulnerability parameters were estimated in the model.
- Annual recruitment deviations were estimated to improved fits to the age composition data and catch rates. This allowed for changes in the population on shorter time-scales than fishing mortality alone. It was noted that recruitment deviations started in the fishing year 1989. The log scale deviations were estimated to have a mean of zero.
- The designated level of recruitment variability (SigmaR) and catchability quotients (as simple q) were also estimated in the model with no set priors.
- Data inputs were given equal weighting in the SS model. A Francis adjustment was applied to the age compositions within SS (Francis 2011).

2.5.3 Analyses

Six analyses were undertaken for consideration in RBC and stock status results. This was to evaluate uncertainty in historical harvests and the key fixed parameter of natural mortality. In addition, seven exploratory analyses were conducted to test fixed settings of high steepness h, and the influence of including standardised TIB catch rates 2018–2020 and nominal Sunset catch rates from 1974–1982 (Table 2.4). Analyses were advised by TSFFRAG and used the custom model.

The key stock assessments 1–6 for RBC analysed six combinations of data (Table 2.4):

- Two series of annual harvest, considering commercial line fishing and Taiwanese gill netting (Appendix B.1).
- Three rates of fish natural mortality M (0.3, 0.35, 0.4 per year).

Table 2.4: Summary of the stock assessment analyses. Inclusion of additional standardised catch rates for TIB (2018–2020) and nominal catch rates for Sunset (1974–1982) were noted as Yes (fitted) or No (not fitted in the analysis).

Analysis	Natural mortality M	Harvest series	Steepness h	TIB	Sunset
1*	0.30	Polynomial, IUU	Estimated	No	No
2*	0.35	Polynomial, IUU	Estimated	No	No
3*	0.40	Polynomial, IUU	Estimated	No	No
4*	0.30	Logistic, IUU	Estimated	No	No
5*	0.35	Logistic, IUU	Estimated	No	No
6*	0.40	Logistic, IUU	Estimated	No	No
7	0.35	Polynomial, IUU	0.6	No	No
8	0.35	Polynomial, IUU	0.7	No	No
9	0.5	Polynomial, IUU	0.7	No	No
10	0.7	Polynomial, IUU	0.7	No	No
11	0.35	Polynomial, IUU	Estimated	Yes	No
12	0.35	Polynomial, IUU	Estimated	No	Yes
13	0.35	Polynomial, IUU	Estimated	Yes	Yes

*same as the Buckworth et al. (2021) assessment

3 Results

3.1 Model inputs

Figure 3.1 summarised the time-series data available for input into the stock assessment. The abundance index data were commercial (fishery dependent) catch rates of Spanish mackerel. Sunset catch rates 1989–2020 was the primary index. TIB and historical Sunset catch rates were included in exploratory analyses (Table 2.4)

Figure 3.1: Data compiled for input into the model by year for each category of data type for the Spanish mackerel stock assessment.

3.1.1 Harvest

The annual estimates of Spanish mackerel harvest considered data from all fishing sectors (Appendix B.1). Historical gaps in this data resulted in two scenarios to estimate trends in building harvests 1940–1988 (Figure 3.2). This was to examine the influence on stock assessment of the different long-term patterns of expansion in fishing. Harvest estimates were the same and largely known for 1989 onwards. Data input into stock assessment combined harvests across all fishing sectors, given the sector similarities of line fishing and fish age-length data.

From 1940–1978 annual harvests built steadily to around 100 t per year (Figure 3.2). The two pre 1989 historical scenarios varied by only 20–30 t in these years.

Estimated harvests increased between 1979–1988 (Figure 3.2). This was a result of increased Sunset fishing effort and the presence of IUU fishing. A 100 t per year of IUU harvest was included for 1979–1986, and then was tapered down annually to zero t by 1993.

By its unregulated nature, IUU fishing was difficult to quantify. Nevertheless, it was an important component of the catch history to be accounted. The amount and pattern of IUU harvest was evaluated after extensive discussion by TSFFRAG and with input from several sources (Buckworth et al. 2021).

Since 1989, Sunset fishing dominated total harvests per year (Appendix B.1, Table B.1). Total harvests ranged 128–300 t per year between 1989 and 2006. This equated to around 20–40 thousand harvested Spanish mackerel per year. Over these years, 10–28 Sunset operations per year recorded harvests, and expended 679–1375 operation days per year (Appendix B.1, Figure B.2).

From 2007, total harvests declined to less than 130 t per year. The decline was associated with the fishery structural adjustment and buyout, shifting ownership entitlements to Torres Strait Islanders, reduced quota setting and since 2010 catch rates declined.

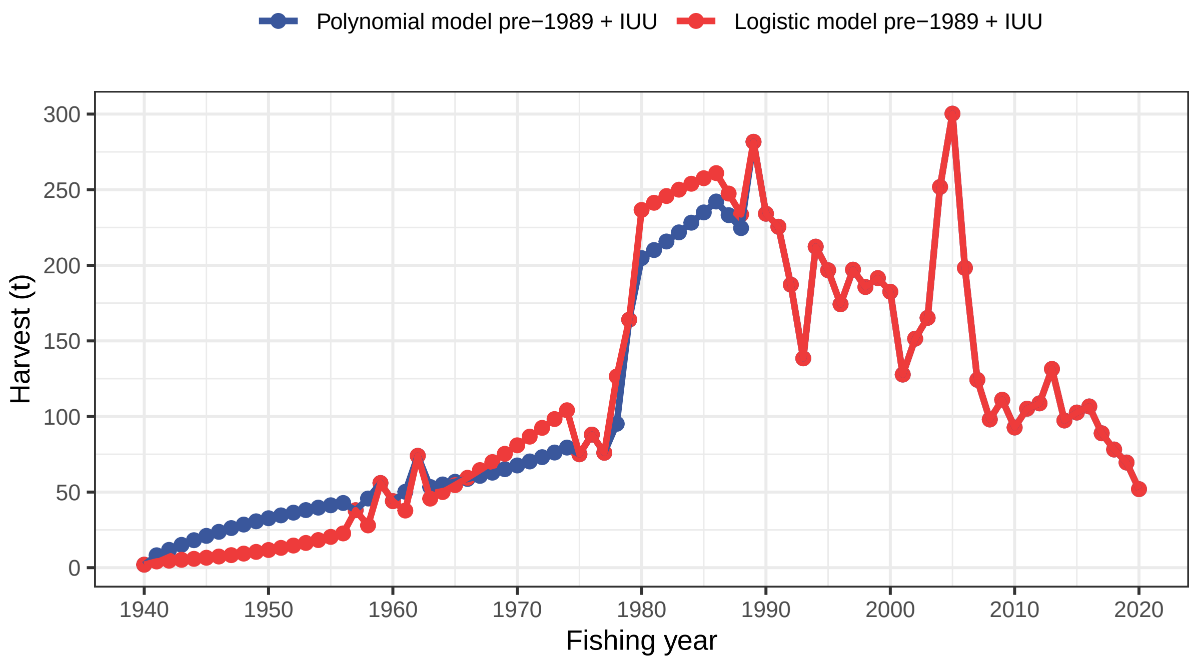

Figure 3.2: Estimated harvest (retained catch) taken by all fishing sectors since 1940 for Spanish mackerel. Two scenarios were modelled prior to 1989.

3.1.2 Catch rates

The annual change in Sunset standardised catch rates was used to measure Spanish mackerel abundance. The catch rate index was important to inform on the proportional change in the Spanish mackerel (exploitable) population. This was the primary assumption in the stock assessment.

The assumption of proportionality was made only after employing a regression model, in order to standardise the biases or variation in the data by accounting for factors affecting fish abundance and fishing efficiency (Hilborn et al. 1992). The result aimed to generate a time series of standardised catch rates that was more representative of trends in the fished population than nominal catch rates (catch per unit effort). Standardisation was required to account for efficiency changes in fishing effort and locations fished through time and between fishing operations (boats).

The nominal catch rate data (numbers of Spanish mackerel harvested per operation day) between 1989 and 2020 had skewed distributional properties. The data had high variance and was skewed with a nominal median = 15 fish per operation-day, mean = 24 fish and standard deviation = 26 fish (CV = 109%).

Significant variance in catch rates was evident between fishing operations, with some surprisingly large harvests above 100 Spanish mackerel per operation day. The estimated box-cox λ parameter, for normalising the residual properties of the data, had decreased with this year's new data to around 0.15. For analysis, the smaller λ, approaching zero and less than 0.33 for a cube-root transformation, suggested a log transformation on the number of fish caught might be more appropriate than using a log link. However, a log link was still applied to standardise catch rates. This was for consistency with past assessments, to maintain the same data assumptions and model likelihood weights between small and big catches per day; so that larger catches and modelling trends in means (by log link) rather than medians (log transformation) provided more insight on fish abundance (Leigh et al. 2014).

Figure 3.3 showed the Sunset standardised catch rate of Spanish mackerel for the fishing years from 1989. The following results were noted:

- Catch rates experienced apparent cycles, and statistical differences were detected between years (Table B.5, Appendix B.5.1). This started with a decrease to increase to decrease between 1989–1999, then an increase 1999–2009, and a downturn for 2009–2018. The catch rate increased significantly in 2019, and leveled in 2020. The scale (amplitude) in cycle from 1999 onwards was about 30–40% from the overall mean. The time series indicated significant years of improved and reduced catch rates.
- The catch rate declined about 50% between 2009 and 2018. This trend was in all operators' data, particularly the declines in 2016–2018.
- The measure of statistical error on the mean catch rates in Figure 3.3 was a CV $\approx$ 5.5%, and 95% confidence intervals about $\pm$ 2–3 fish. The low error indicated standardised catch rates were sufficient for use in stock assessment and harvest strategies.
- A box plot of the standardised residuals against fitted values was in Figure B.4 (Appendix B.5.1). The residual plot showed no lack of model fit, with few large residuals exceeding -2 and +2. The box plot pattern was typical for Poisson type models applied to skewed data. The model percentage of mean deviance accounted for was 36.7%, with a dispersion of 14 fish.
- Subset analysis of the 2003–2019 data (TSF01 logbook, using hours and tenders data) produced indices that were similar and confirmed the later decline (Buckworth et al. 2021).
- The inclusion of boat-operation, seasonal and fishing power terms were important in the standardisation of catch rates (Figure B.5, Appendix B.5.1). The 2016–2018 and 2020 years were associated with the better fishing vessels, and therefore catch rates were standardised down (Figure B.7, Appendix B.5.1).
- In general, the GLM predicted relationships of higher catch rates during August–November, on the early waxing moon phase and timed with good weather of light winds (Figure B.6, Appendix B.5.1). Catch rates were higher from Bramble Cay (zone 1) compared to the other fishing zones. Only one fishing operation essentially fished in 2020, the highest catching boat (Figure B.6d), and the standardisation effect was large compared to the nominal catch rate (Figure B.5).

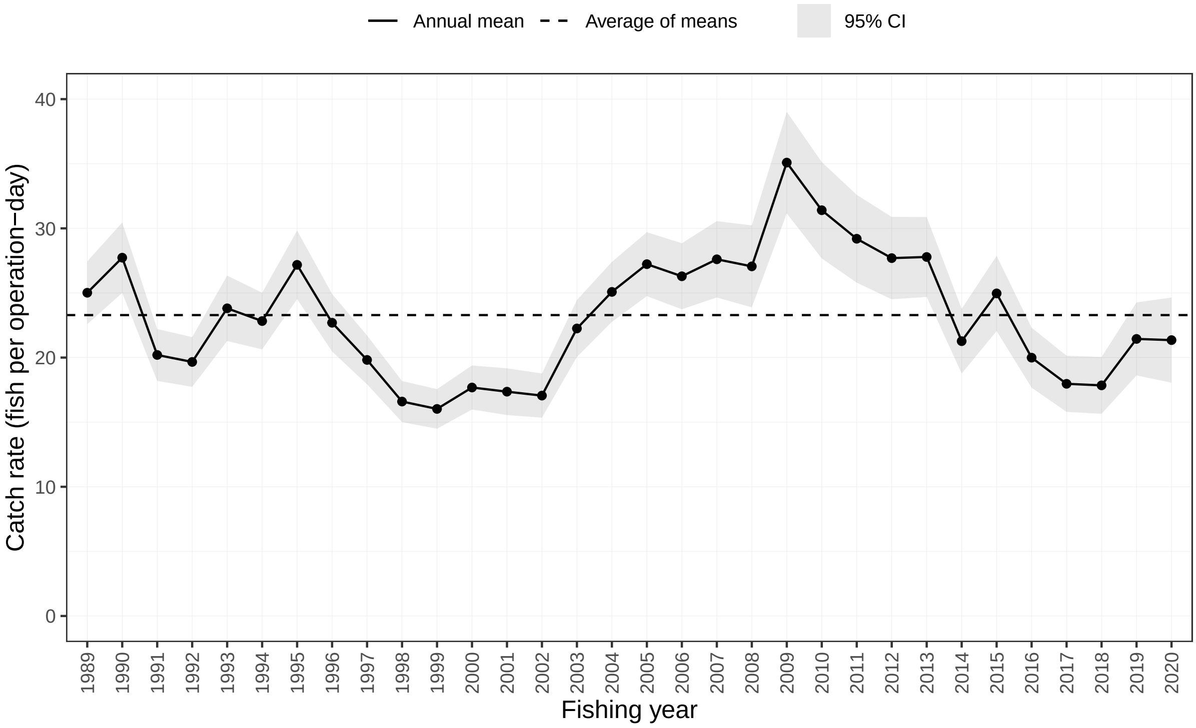

Figure 3.3: Spanish mackerel average catch rate (number of fish per Sunset operation-day) by fishing year. The standardisation included a fishing power (FP) offset, but excluded tender and hours fished data which was incomplete over the time series. Note the logbook type changed in 2003. The 95 percent confidence intervals (CI = 2 x standard error) on predictions typically extended 2–3 fish.

TIB-CDR reports on Spanish mackerel fishing varied between fishing years, with 104 client boat-days fished in 2018, 65 in 2019 and 50 in 2020 (Table B.9, Appendix B.5.3).

Nominal catch rate statistics also varied with clients (Table B.9), and had skewed distributional properties. The nominal median was 34.5 kg per client boat-day, mean = 54.8 kg and standard deviation = 72.4 kg (CV = 132%). The estimated box-cox λ parameter, for normalising the residual properties of the data, was low at 0.05.

Limited standardisation was applied for the short 3 years of TIB-CDR catch rates. GLM methods were kept similar to the Sunset anlaysis. The standardised catch rates suggested a decline in non-Bramble Cay waters from 2018 to 2019 (Figure 3.4). The decline did not correlate with increased Sunset catch rates from Bramble Cay (Figure 3.3). TIB catch rates in 2019 and 2020 were similar (Figure 3.4), as were the 2019 and 2020 Sunset catch rates. Statistical differences in catch rates between years was marginal (Appendix B.5.2, Table B.6).

Appendix B.5.2 summarised the TIB catch rate diagnostics. Residuals were typical for the amount of data and skewness (Figure B.8). Seasonal trends were modelled simply for a single annual cyle, indicating higher catch rates associated with November and December (Figure B.9). Higher catch rates also associated with easterly winds and the catch per number of boat crew was not proportional (Figure B.9).

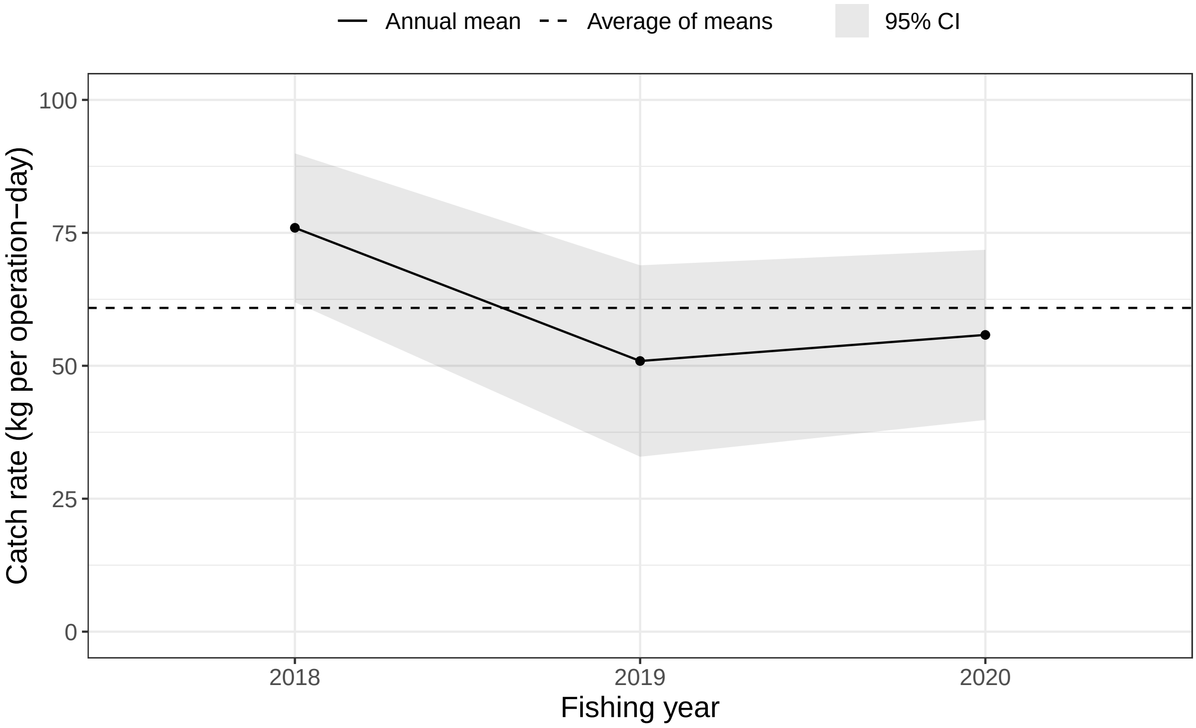

Figure 3.4: Standardised catch rates for commercial line-caught Spanish mackerel by the TIB sector.

3.1.3 Age composition

The Spanish mackerel age frequencies showed limited numbers of older fish (Figure 3.5). Most of the sampled fish were aged in the 2+ to 4+ cohort-age-groups from Bramble Cay. Fish vulnerability and recruitment to the fishery was by 2–3 years of age. Harvests of young 0+ and 1+ year old fish were few, as they had not entered the fishery.

The maximum fish age was 13 years, less than the maximum ages found in waters on the Queensland east coast (26 years; Tanimoto et al. 2021) and the eastern Gulf of Carpentaria (16 years; Bessell-Browne et al. 2020).

Catch curve estimates on the decline in frequency by age suggested past levels of fishing mortality were near or exceeding natural mortality (M) (Figure 3.6). In the population model, a range of natural mortalities were tested to explain the decline in old fish.

The rate of decline in age frequency from young to old fish might suggest: 1) past levels of fish mortality were high, 2) old fish less regularly frequented the focused fishing/sampling zone of Bramble Cay, 3) spatial movement patterns of older fish were not captured by the time-frame of sampling within years, and/or 4) potential longevity was less compared to other stock areas.

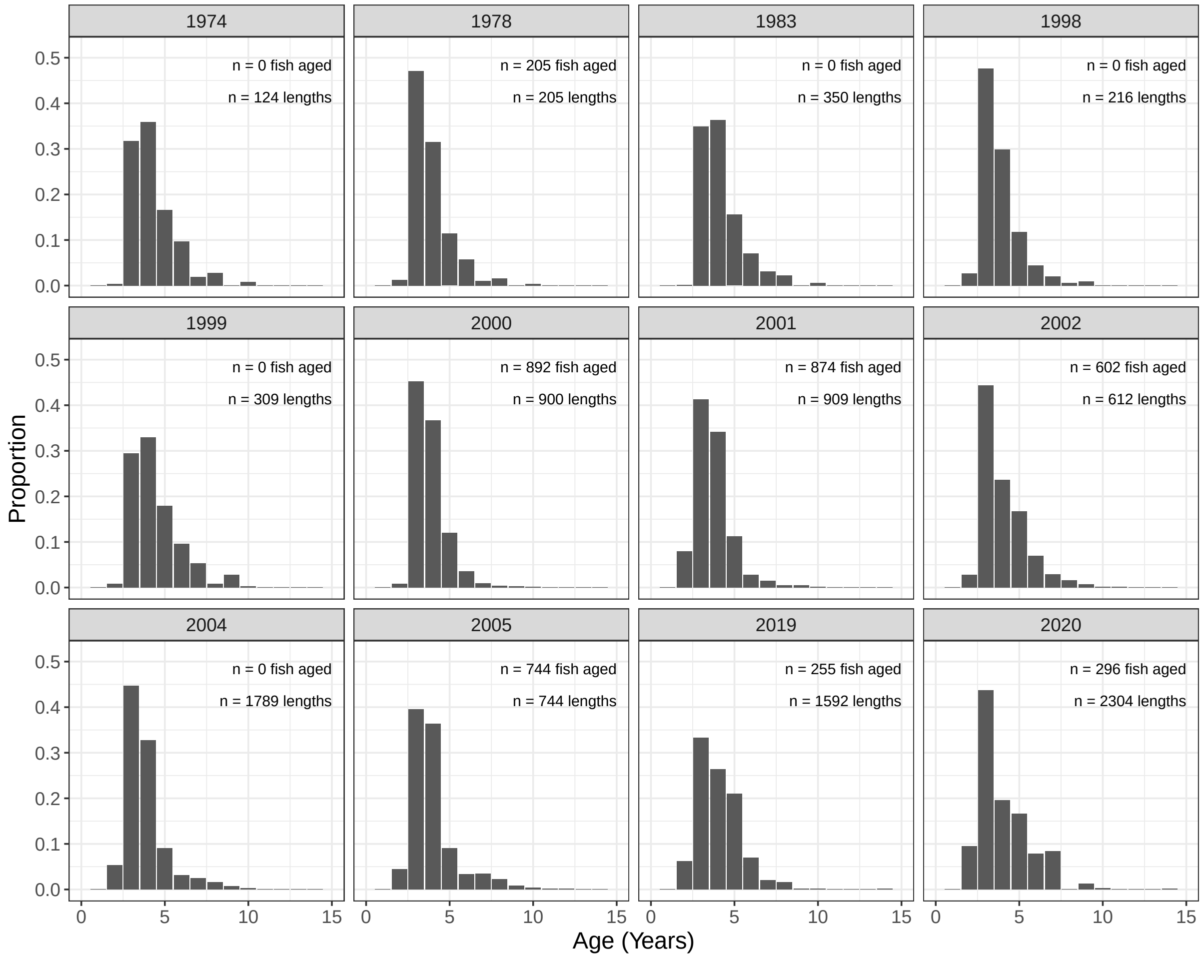

Figure 3.5: Age group frequencies of Spanish mackerel by fishing year. n was the number of fish sampled.

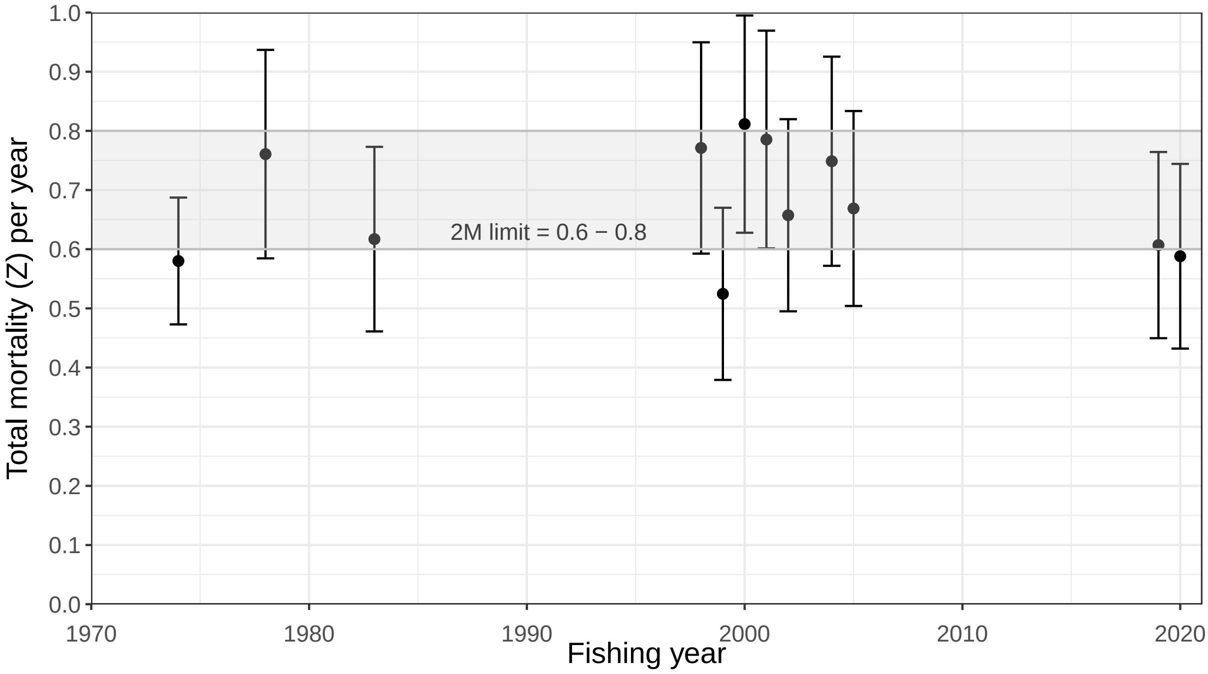

Figure 3.6: Catch curve estimates of total mortality (Z) by year.

3.2 Model outputs

3.2.1 Analyses 1–6

The custom age-structured population model analysed six combinations of data. They were two series of historical annual harvest (polynomial and logistic) and three rates of fish natural mortality (0.3, 0.35, and 0.4 per year).

All six analyses resulted in model convergence and sound fits to the input data (Appendix C). The negative log-likelihood statistics (negLL) suggested good fits to the data (Table 3.1); the more negative the better the fit. Of the six analyses, analysis 6 had the best catch rate fit and analysis 3 was best for the age data fit. Better model fits were associated with 0.4 natural mortality per year and lower steepness (Table 3.1); there were parameter correlations between natural mortality, steepness and unfished-recruitment.

The estimates of recruitment steepness (*h*) were consistent with the last stock assessment (Buckworth et al. 2021). The values of steepness measured the expected proportion of virgin recruitment at 20% of virgin spawning biomass (egg production) (Myers et al. 1999; Begg et al. 2005; Begg et al. 2006). The median steepness value was 0.39 over the six analyses.

Estimates of virgin recruitment (R_0) negatively correlated with steepness. Over past stock assessments, R_0 estimates have tended smaller from the decline in Sunset catch rates after 2010 (Buckworth et al. 2021). The R_0 estimates herein were similar to the previous stock assessment, with a median of 156000 fish (Table 3.1). The median standard deviation of annual log recruitment was 0.29 (Table 3.1).

Estimates of fish 50% and 95% age-at-vulnerability were consistent between analyses, with median age a_{50} = 1.77 years and age a_{95} = 2.48 years (Table 3.1). Spanish mackerel older than or equal to the 2+ age group were generally vulnerable to fishing (Buckworth et al. 2021).

The following stock status estimates were for 2020–2021:

- All fishing mortality (F) indicators were sustainable (less than natural mortality, Appendix C.2, and less than the F_{MSY} harvest rate of 0.23 in Table 3.2).
- The spawned egg production was at or below the level for MSY (40%). Egg production was below the interim target reference point of 48% (Figure 3.7). The median estimate and confidence intervals signified a stock status at or below the biomass level for maximum sustainable yield (Figure 3.8).
- The latest catch rate and fish age data estimated larger recruitment deviations after the down cycle 2008–2017 (Figure C.6, Appendix C.3).
- All analysis outputs were consistent and similar in terms of informing on potential management responses (Table 3.1).

Table 3.1: Summary of the analyses and estimates. 95 percent confidence intervals are in parentheses.

Data	Analysis 1	Analysis 2	Analysis 3	Analysis 4	Analysis 5	Analysis 6
Harvest	Polynomial, IUU	Polynomial, IUU	Polynomial, IUU	Logistic, IUU	Logistic, IUU	Logistic, IUU
Natural mortality M	0.3	0.35	0.4	0.3	0.35	0.4
Steepness h	0.463 (0.416–0.514)	0.396 (0.358–0.439)	0.345 (0.315–0.38)	0.445 (0.404–0.489)	0.382 (0.346–0.424)	0.333 (0.307–0.365)
Unfished recruitment R0 / 10^6	0.113 (0.101–0.126)	0.15 (0.133–0.17)	0.199 (0.174–0.23)	0.121 (0.11–0.133)	0.161 (0.143–0.182)	0.214 (0.189–0.243)
Age at 50% vulnerabilty	1.775 (1.581–1.976)	1.778 (1.588–1.981)	1.779 (1.584–1.996)	1.775 (1.59–1.954)	1.775 (1.58–1.972)	1.768 (1.577–1.967)
Age at 95% vulnerability	2.491 (2.201–2.802)	2.487 (2.209–2.78)	2.476 (2.199–2.757)	2.491 (2.235–2.766)	2.481 (2.2–2.787)	2.455 (2.2–2.728)
Catch rate negLL	-42.418	-45.77	-50.277	-43.694	-47.739	-54.166
Fish age negLL	-177.203	-179.45	-180.899	-176.764	-178.669	-179.107
Fish age, annual eff sample size	147 (12–224)	143 (14–224)	141 (16–215)	145 (16–232)	141 (16–225)	138 (21–223)
Spawning ratio S1989/S0	0.391 (0.348–0.443)	0.426 (0.38–0.48)	0.461 (0.41–0.519)	0.361 (0.32–0.406)	0.396 (0.353–0.447)	0.431 (0.386–0.484)
Spawning ratio S2020-21 / S0	0.272	0.303	0.335	0.251	0.282	0.315

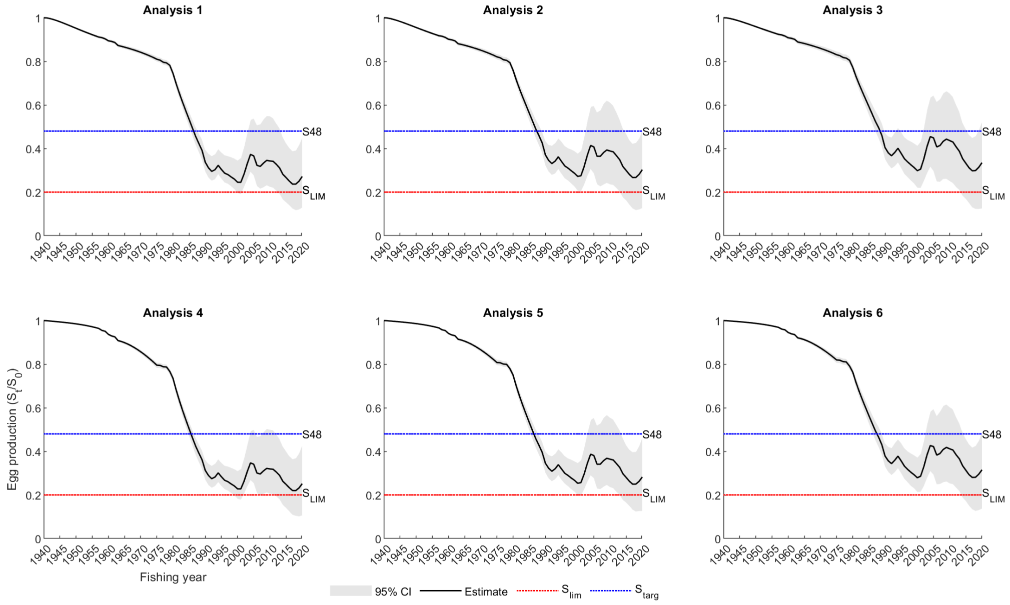

Figure 3.7: Estimated spawning biomass (egg production) ratio by year, measured against 1940. Each subplot represented one of the six analyses.

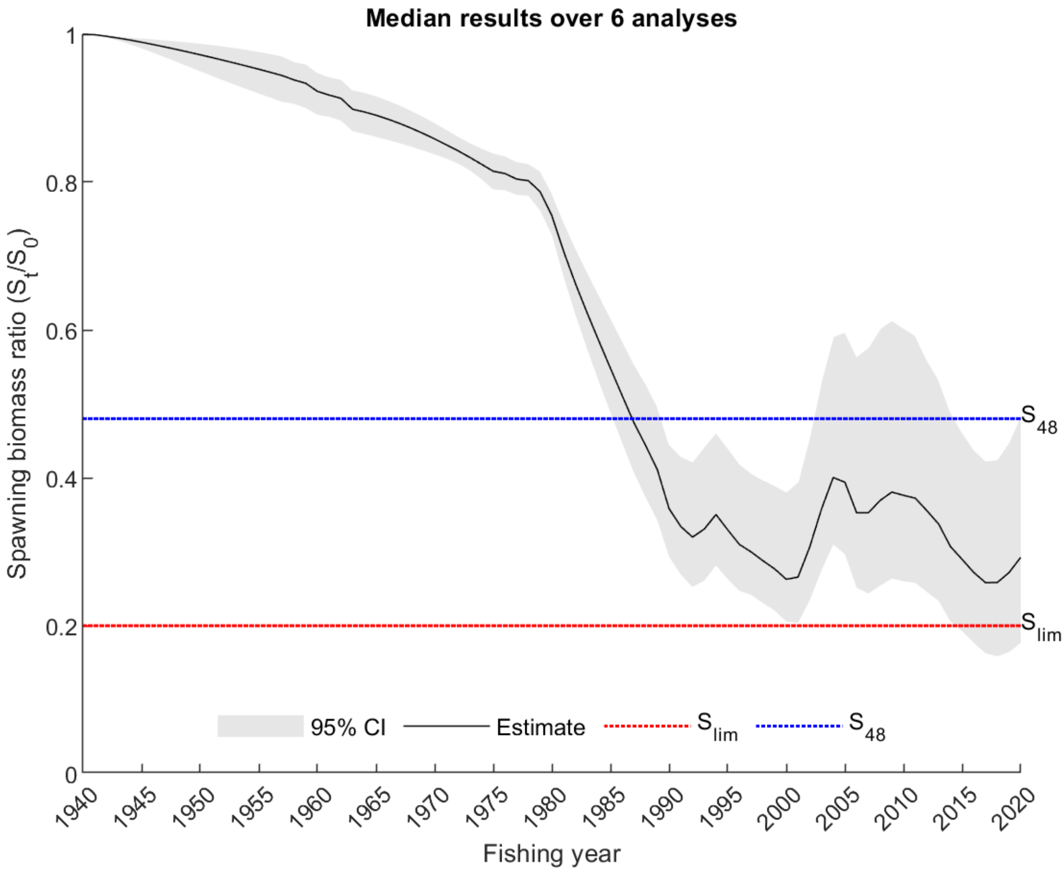

Figure 3.8: The median spawning biomass (egg production) ratio by year, measured against 1940, over the six analyses.

The median RBC reference points were in Table 3.2. The RBC estimates varied with reference point. The TSFFRAG principles (Figure 2.2) and results for RBC options were to consider:

- Median estimates over the six analyses.
- Forecast risk of less than 10% probability of spawning biomass falling below 20%. Risks were calculated over all 6000 simulations (6 analyses x 1000 simulations each) and 12-year forecasts (3 times age at full maturity = 4 years). TSFFRAG also discussed forecast risks for a reduced number of simulations, referred to as the 'feasible simulations' that removed unlikely parameter combinations (AFMA 2021a).
- Forecasts generally reached a spawning biomass of 48% by the end of 12 years (Figure 3.9).
- Reference points 4 and 5 met the TSFFRAG principles (Table 3.2).
- Forecast graphs suggested harvests at or below 95 t per year should promote increases in Spanish mackerel towards 48% spawning biomass, with an acceptable risk level.

Table 3.2: Median RBC estimates for five fishing-mortality (F) reference-points, for the 2022–2023 fishing year.

No.	Reference point$^{\diamond}$	Risk* (%)	RBC† (t)
1	F_{MSY}	12.8	131
2	F_{40}	12.6	129
3	F_{48}	10.4	102
4	F_{50}	9.9	95
5	F_{60}	8.6	68

$^{\diamond}$ The median fishing mortality estimates per year, in order of the reference points, were 0.23, 0.22, 0.17, 0.16, and 0.12.

* Percentage of forecasts that fell below the spawning biomass limit reference point of 20%. Forecasts were over 12 years, 1000 simulations and six analyses. Forecasts assumed average recruitment and a constant RBC per year. TSFFRAG considered no more than 10% risk of triggering the limit biomass reference-point (AFMA 2021a).

† Median recommended biological catch (RBC) over the six analyses. This was the recommended maximum harvest to be taken by all fishing sectors in the forecast fishing-year of 2022–2023.

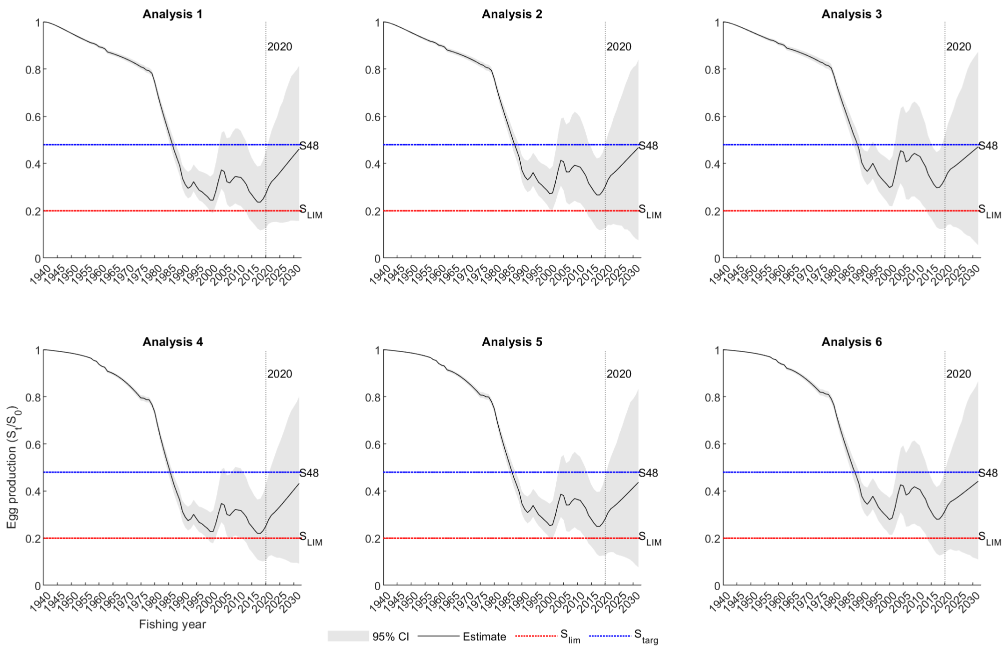

Figure 3.9: Spawning biomass (egg production) forecast for 95 t, from RBC reference point 4.

3.2.2 Analyses 7–13

Seven additional analyses were run to explore model effects of high recruitment steepness (*h*; analyses 7–10) and use of extra catch rate data (analyses 11–13) (Table 2.4, Method report section 2.5.3). These analyses were for TSFFRAG to gauge the possibility of high steepness for Spanish mackerel (Klaer 2021), and assess if more catch rate data can be used in future stock assessment.

The analyses were run with the same negative log-likelihood (negLL) equations and settings. NegLL results identified changes in model performance (more negative was better and less negative, worse). The negLLs were compared against analysis 2, for the middle natural mortality rate equal to 0.35 per year (Table 3.3). The extra catch rate negLLs were only switched on for fitting in analyses 11–13 (Table 2.4), but for additional information they were calculated across all analyses.

The findings from the exploratory analyses were:

- Analysis 7 fixed and increased steepness to 0.6. This improved the age data negLL to -189.709. However, higher steepness compromised the model fit to the Sunset catch rate data (worse negLL = 8.4143). High steepness could not fit the temporal variation in catch rates, with assumptions of constant fish availability or catchability, and natural mortality. Estimated recruitment deviations undesirably trended to zero, as signalled by the negLL near -36. The same results occurred for analysis 8, with steepness equal to 0.7.
- Analyses 9 and 10 used steepness equal to 0.7, but explored an increase in natural mortality (M) to 0.5 and 0.7 per year respectively. This was in attempt to improve the Sunset catch rate negLL from analysis 8, recognising that the high values of M were biologically extreme for Spanish mackerel. Marginal improvements to the catch rate negLL were noted, but still sub optimal compared to analysis 2. The results of high M improved the age negLL to less than -200.
- Analyses 11–13 tested the use of TIB (Figure 3.4) and historical (old pre-1989) Sunset catch rate data (Figure 3.10). Both data sets were small with only a few years of catch rates, and therefore

only had low statistical weight in the overall model combined negLL. Irrespective, the model time series appeared to fit these data and no parameter influences/changes were noted when fitting or not fitting to these extra catch rates. Parameter estimates were the same as in analysis 2 (Table 3.1).

- Further testing of these aspects are recommended in stock synthesis.

Table 3.3: Comparison of negative log-likelihood components, for the extra analyses 7–13.

Analysis	Sunset catch rate	Age	Rec devs	TIB catch rate	Sunset old catch rate	Total combined
1	-42.4671	-177.171	6.1255	0.1842	-4.6643	-213.513
2	-45.8954	-179.374	4.9190	0.1593	-4.6429	-220.350
3	-50.0925	-181.004	4.5950	0.1557	-4.6091	-226.502
4	-43.4609	-176.920	6.5718	0.1860	-4.7368	-213.809
5	-48.2519	-178.362	5.9748	0.1689	-4.7554	-220.639
6	-54.1745	-179.102	6.4680	0.1880	-4.7595	-226.809
7	8.4143	-189.709	-35.9572	0.1248	-4.5150	-217.252
8	9.6235	-189.592	-36.6381	0.0764	-4.3964	-216.607
9	0.4100	-200.884	-36.6052	-0.1065	-4.4640	-237.079
10	-9.0476	-204.717	–36.0700	-0.3483	-3.9698	-249.834
11	-45.4504	-179.642	4.7552	0.1313	-4.6426	-220.206
12	-45.9536	-179.337	4.9408	0.1592	-4.6432	-224.993
13	-45.4967	-179.615	4.7750	0.1315	-4.6429	-224.848

Negative log-likelihoods were comparable across analyses within each data component (table column). Smaller values (stronger negatives) signaled better custom model fits to the data. Rec devs - for annual recruitment deviations.

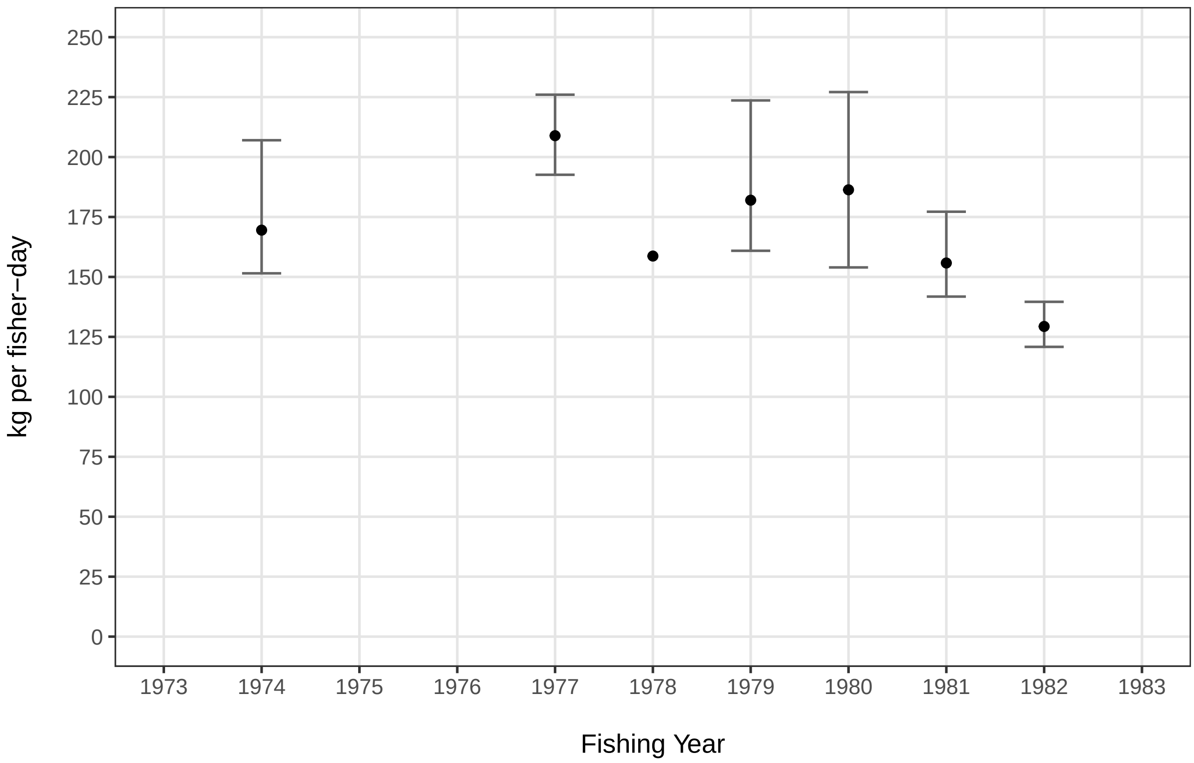

Figure 3.10: Pre 1983 nominal catch rates of Torres Strait Spanish mackerel reported by a single Sunset vessel. The mean was for kg of whole fish per fisher per day. The error bars show the reported range of trip means. The data was extracted from Figure 1 in McPherson (1986), using Matlab. No catch rate range was available to publish in 1978.

3.2.3 Stock synthesis

Stock synthesis (SS) was run to compare with analysis 2, using the middle natural mortality rate fixed at 0.35 per year (Table 2.4, Method report section 2.5.3). The results presented here were run at the time of the TSFFRAG meeting in November 2021 (AFMA 2021a).

The SS spawning biomass predictions, as ratios, were similar to the custom model (Figure 3.11). Both models estimated near 30% in the last fishing year 2020.

SS biomass ratios exhibited an initial difference being below the virgin state in 1940 (Figure 3.11). This caused a lower parallel trend through the time series compared to the custom model in early years.

The difference was identified later in SS by using the maturity data input setting of 4=read age-fecundity. The data input through this setting allowed for a small amount of spawning by young fish (less than two years of age). This was a result of the fish-length maturity relationship from Begg et al. (2006) not being age based, and integrated with the growth curve formed on mostly legal sized fish (greater than 1 years old). The difference at virgin state can be rectified by limiting spawning to only start from two years of age.

Confidence intervals on the SS biomass ratios were small (Figure 3.11). Both SS and custom models calculated 95% confidence intervals. However, the methods of forming the parameter covariance matrix, by differentiation in SS and simulation in the custom model, might explain differences. The effect of not estimating early recruitment deviations before 1989 might impact more on the differentiation method (Methot et al. 2021).

Parameter estimates from both models were similar (Table 3.4). Estimates for recruitment variation (sigmaR, standard deviation) and logistic age vulnerability parameters were aligned. SS estimates of virgin recruitment (R0) were marginally lower and steepness marginally higher compared to the custom model. The small differences possibly relate to different negative log-likelihood specifications, the way SS estimated steepness as a bounded (0.2,1) untransformed parameter, and the custom model used a biological transformation that required no bounding (Buckworth et al. 2021). Both analyses assumed no Bayesian prior.

In addition to support close parameter estimation, the estimated recruitment deviations were similar (Figure 3.12).

SS comparisons and testing will be expanded in year two of the project.

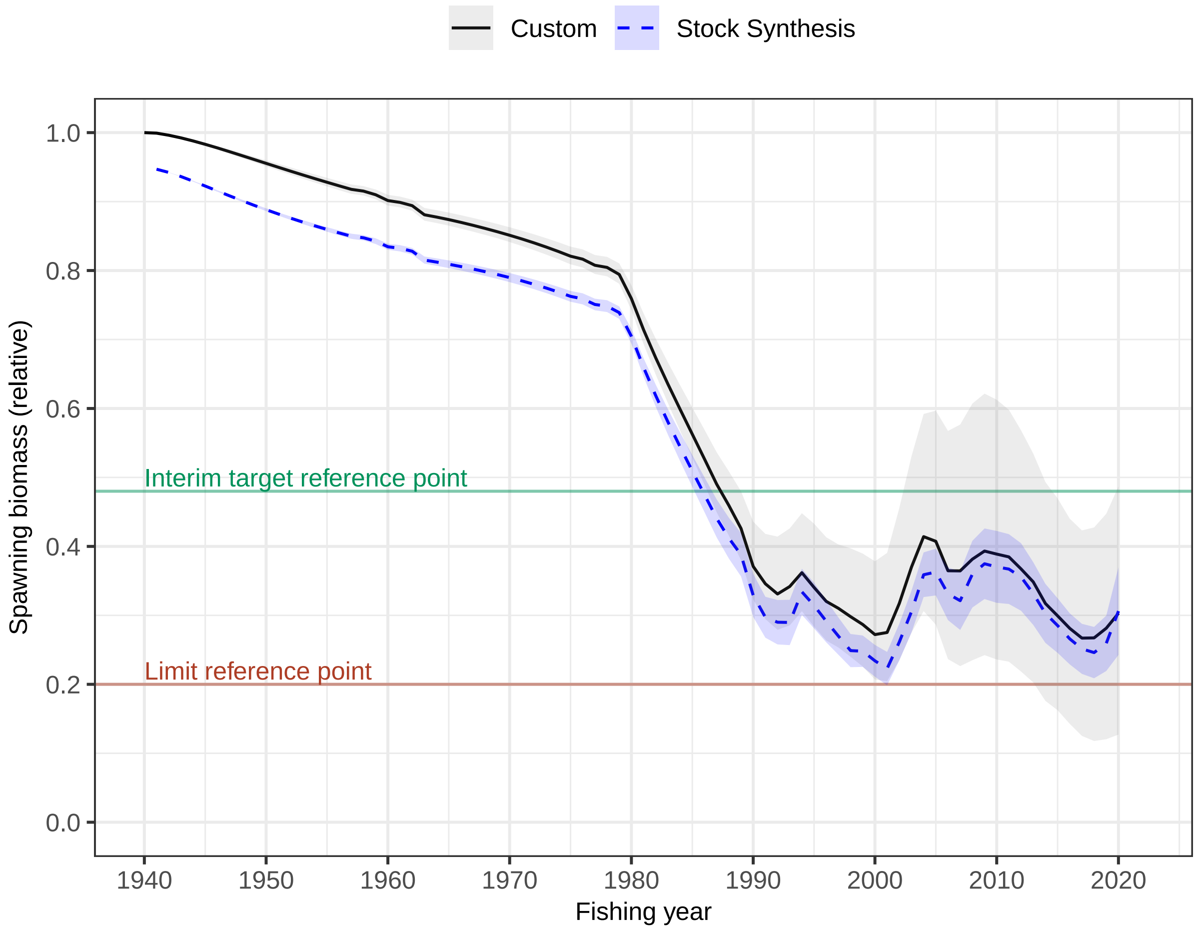

Figure 3.11: Predicted spawning stock biomass trajectory relative to unfished, from 1940 to 2020, for both the custom and stock synthesis models.

Table 3.4: Key parameter estimates from the custom stock model and Stock Synthesis software, for analysis 2 data.

Key parameter	Stock synthesis	Custom model
Log(R0)	11.75	11.90
Steepness h	0.47	0.40
sigmaR	0.29	0.28
Age_{50}	1.72	1.77
Age_{95}	2.41	2.47

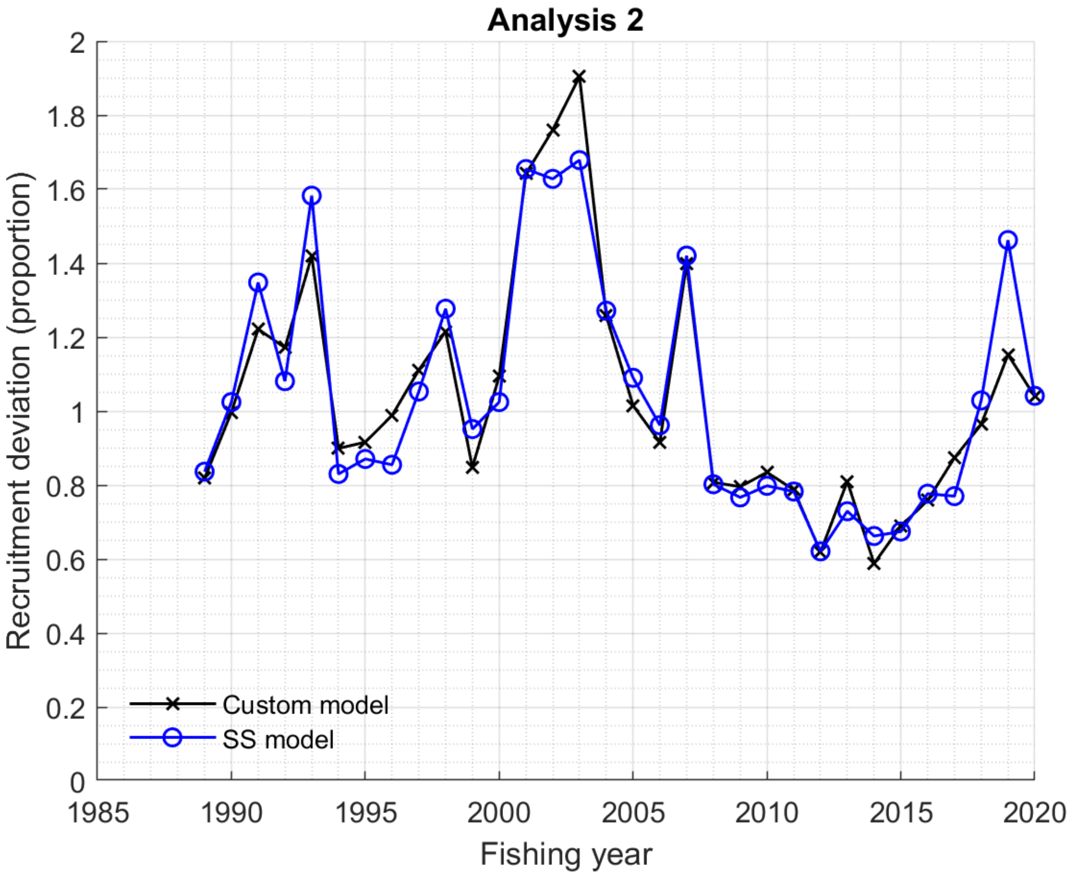

Figure 3.12: Recruitment deviations estimated by the custom and stock synthesis (SS) models, using analysis 2 data.

4 Discussion

4.1 Stock status

The analyses of Torres Strait Spanish mackerel indicated that recent harvests were sustainable. However, across analyses, estimated spawning biomass (egg production) of Spanish mackerel in fishing year 2020 was around 29% of estimates for the start of the fishery in 1940. The biomass results related to the downturn in Spanish mackerel catch rates 2009–2018. We caution that fish catch rates, and age data, may indicate local patterns, as more data were from Bramble Cay than other locations in the Torres Strait.

Since 2008, the Torres Strait Finfish Fishery has been reserved for Traditional Inhabitants, on whose behalf the Torres Strait Regional Authority (TSRA) has leased out fishing licences to non-Traditional Inhabitants (Sunset operations). Over this time, commercial fishing had eased compared to before 2008. Despite the reduction, the setting of RBCs and leasing quota should consider the revised estimates of sustainable harvests for Spanish mackerel.

4.2 Model performance

This stock assessment used an age based model with an annual time step, with age-based selectivities common for all fishing sectors. Data inputs included total dead catch (harvest), standardised catch rates, and fishery-dependent fish-age compositions. Overall, the model performed well, achieving good fits to all data. The model was appropriately weighted and fitted remarkably well to the Sunset catch rates.

A number of sensitivities were tested to better understand which assumptions and parameters were most influential on the model (Section 2.5.3). This extended stock-assessment provided further learning and results to add to past research (see past stock assessment reports and TSFFRAG meeting records online).

The estimates of steepness h indicated a general uncertainty range between 0.3 and 0.51. This range was in alignment with values from the last stock assessment (Buckworth et al. 2021), the Thorson (2020) *Scomberomorus* life-history prediction of $h = 0.461$, and the values used for east coast Spanish mackerel (Tanimoto et al. 2021). The estimation of steepness in earlier assessments, with less data, varied 0.35–0.8 based on model settings, with a median of 0.5 from many model scenarios (O'Neill et al. 2018b; Hutton et al. 2019).

Contrasting this, high steepness was suggested by Klaer (2021), but this assumption did not match the catch rate data when tested in exploratory analyses 7–10. If high steepness was true, then this would question how the trends in catch rates occurred and suggest more complex hypotheses such as a strong temporal change in fish availability or catchability, and natural mortality. In context of the age composition data, settings of high steepness and natural mortality can in general explain (better fit) patterns in fish age compositions (such as a lack of older fish), but scientific caution should be applied if model fits to catch rates were compromised (Francis 2011).

The estimate of recruitment steepness was not achieved in the first stock assessment due to the limited time series of data (Begg et al. 2006). Begg et al. (2006) compared values of steepness at 0.38, 0.53 and 0.70 (Tables 2.12 and 6.2, Begg et al. 2006). These settings were based on the reproductive rates for Scombridae (mackerel and tuna species, with median h = 0.52, 20th percentile = 0.3 and 80th percentile = 0.72; Table 1, Myers et al. 1999). Myers et al. (1999) concluded that steepness will vary with species, natural mortality and age-at-maturity, with the number of annual replacement spawners typically ranging 1–7 per spawner per year. Using Myers et al. (1999) generalisation, an expected steepness h for Spanish mackerel could range 0.4 to 0.87; noting this range is higher than the values summarised for Scombridae.

Assumptions surrounding natural mortality gave a spread of biomass results ranging around ± 3% on the final median spawning biomass ratio of 29%. Previous sensitivity testing indicated rates of natural mortality above 0.4 per year resulted in unacceptable model fits to catch rates and parameter R0 estimates (Buckworth et al. 2021).

The choice of alternative catch history trajectory for the earlier years (pre-1989) of the fishery had a small influence on the estimated status of the fishery.The polynomial harvest scenario estimated a 2% higher final median spawning biomass, and 6 t higher median RBC than the logistic harvest scenario. Catch rate negative log-likelihoods appeared marginally better for the logistic harvest and the fish age composition fits were marginally better for the polynomial scenario (Table 3.1). Likelihood-ratio tests expressed as -2 times the difference between the log-likelihoods suggested statistical differences between the harvest scenarios, when comparing the catch rate and age model fits in Table 3.1.

At this time, it is not recommended to reduce analyses on different harvest scenarios. A level of uncertainty remained in the harvest estimates due to IUU fishing and missing years of data (Table B.1 and Figure B.1). The current annual IUU and model (polynomial or logistic) estimates informed best predictions from each analysis and for RBC. However, stock assessment confidence intervals and risk calculations might be better represented by expanding harvest scenarios; a discussion for TSFFRAG. Truncating the time series of data to start in 1989, to hide and simplify the harvest uncertainty, would deny the stock assessment the history we know. This approach was tested in the last stock assessment with mixed and more uncertain results (Buckworth et al. 2021). This could be further tested in stock synthesis, but still required an input of constant annual-average fishing mortality and/or harvest that was not realistic of a building pattern of annual harvests before 1989 as seen in Figure 3.2.

Analyses 11–13 tested the use of TIB and historical Sunset catch rate data. Inclusion of both data sets did not influence the model results. If RBC analyses were expanded to include these data, more so for including the TIB catch rates, then Sunset only analyses should still be retained to consider and assess any future data conflicts; as different catch rate trends can occur with TIB and Sunset vessels fishing different locations. A solution for such a problem would be to spatially average catch rates into one index through the standardisation process, outside of the stock model (Carruthers et al. 2010; Carruthers et al. 2011).

Further analyses and model development in stock synthesis will assess potential improvements in model performance. However, expected benefits might just simply relate to the transition and use of stock synthesis as a platform for finfish stock assessment, and joining a community of scientists using the same methods in other fisheries.

4.3 Environmental influences

In recent Torres Strait assessments, Spanish mackerel harvests, catch rates and recruitment deviations were lower than would be expected. This indicated that some years fish abundance had not responded as expected to reductions in the total fishery harvest. Given that the assessments accounted for known biology of the species as well as operational changes in the fishery such as the number and experience of operators, it was suggested in the TSFFRAG that environmental conditions may have contributed to this observed trend (AFMA 2019; AFMA 2020b).

As well as undertaking annual assessments, the last stock assessment for 2019 discussed the impact of environmental drivers on the Spanish mackerel Torres Strait fishery (Buckworth et al. 2021). There were many ways in which environmental drivers might affect Torres Strait Spanish mackerel: they might impact recruitment (i.e. the number of young fish that enter the fishery), the survival and growth of fish that have already entered the fishery (fishery productivity) or catchability (effects on the behaviour of the fish, that impact on distribution as well as their reaction to fishing operations).

Some factors such as tides or winds might also impact on catchability via behaviour of fishers e.g. windy weather makes fishing operations more difficult and may change the behaviour of both fish and fishers; we note that, for this reason, wind was already used in stock assessment (Figure B.6).

Despite the substantial importance to fisheries throughout the tropical and subtropical Indo-West Pacific, information on the detailed life history of Spanish mackerel, *Scomberomorus commerson*, was scant. Adults were marine, with most fishing in coastal and oceanic waters. Spawning was in oceanic conditions on reef slopes and edges and the eggs were presumably pelagic; they have a large oil droplet and float (Mackie et al. 2005). Spawning was mainly in spring to early summer. The duration of egg and larval stages was thought to be a few weeks. The spatial distribution and dynamics of the larvae and juveniles were poorly known.

In Great Barrier Reef (GBR) shelf waters, larvae of *S. commerson* were found only in oceanic conditions of the lagoon (Jenkins et al. 1985). Juveniles were found inshore, in coastal and estuarine areas which may include mangrove areas as well as near-shore reefs. The timing of spawning and transport was such that the young juveniles arrive inshore at the seasonal peak in productivity. Adults, juveniles and all but the earliest of larvae were mostly piscivorous (Jenkins et al. 1984; McPherson 1986).

Environmental drivers potentially affect transport, distribution, survival and growth, as well as duration, of all life history stages of Spanish mackerel, as well as those of the species on which they prey. The potential relationships between measures of abundance of Spanish mackerel and environmental drivers were thus likely to be complex (Buckworth et al. 2021).

An understanding of why catch rates and apparent recruitment in the fishery appeared to have been depressed for much of the last decade was important for future management of the fishery. Recruitment variation was estimated in the stock assessments, capturing potential environmental effects, but the environmental influences (drivers) were not identified.

Buckworth et al. (2021) initiated exploration of the role of environmental influences on catch rates and recruitment to the fishery, with candidate environmental factors, but with no relationships revealed. Fish recruitment, and subsequent growth, survival and distribution were complex interacting-dynamics, and environmental influences on them were simply not identifiable with the limited information available for north-east Torres Strait (Buckworth et al. 2021).

4.4 Spawning aggregations

A fish spawning aggregation was the gathering of a large number of fish for the purpose to reproduce (Erisman et al. 2017). Some spawning aggregations form in the same locations and seasons each year. This spatial and temporal predictability of fish spawning (aggregating) was a life-history characteristic adapted to seasonal ocean currents, specific habitat features and particular environmental or ecological processes in order to maximise reproductive potential (Erisman et al. 2017).

During September–November each year, Spanish mackerel school to form spawning aggregations of fish on the Great Barrier Reef and Torres Strait reefs. The most notable and predictable aggregations of Spanish mackerel occur in two prominent locations: the reef waters north of Townsville and at Bramble Cay in the Torres Strait. Here they gather to breed mostly over a period of two lunar months (Tobin et al. 2014).

Spanish mackerel are transient aggregators (Tobin et al. 2014), where they travel distances to the key reef locations in order to school and spawn. Transient aggregations usually form for just short durations from a few weeks to months in a year. Buckley et al. (2017) described the historical importance of spawning aggregations of Spanish mackerel off Cairns and Lucinda. It was noted that fishing on these aggregations began inshore and then expanded further offshore and then contracted to the reefs of the Lucinda region. The documentation of the decline in fish aggregations and the Cairns fishery was important to understand the spatial extent of east coast Spanish mackerel spawning aggregations (Buckley et al. 2017).

The decline in spawning aggregations on the east coast has implications for the management of Torres Strait Spanish mackerel particularly the small fishing ground of Bramble Cay. Harvests need to be managed safely using an agreed harvest strategy to maintain fish egg production and limit vessel numbers. Catch quota management was currently in place, and this was important to mitigate the risks of recruitment and catch rate declines such as those experienced 2010–2018. If management levers such as spatial and temporal closures were not used, then safe reference points, such as B_{MEY} or B_{50}–B_{60}, might be needed to limit RBC levels and vessel numbers. Annual harvests should not result from overly concentrated high-fishing-effort (high harvest rates) on spawning aggregations.

Historically for the September to November spawning months at Bramble Cay, commercial line harvests represented at least 40% of the annual harvest. Typical Bramble Cay harvests were 15–93 (25th – 75th percentiles, mean = 70) Spanish mackerel per day across fishing operations (maximum was 965). The accumulation of these daily harvests of fish over time during the spawning season can be substantial when many vessels operate. With Spanish mackerel aggregated to spawn and a general focus of fishing effort around Bramble Cay, harvest rates (fishing mortality) could easily exceed those estimated annually for the complete stock area. The catchability of Spanish mackerel at Bramble Cay during the spawning season will likely be higher than other areas and times. Density dependence in catchability and risk of increased fishing mortality on spawning fish is important to manage (Walters et al. 2004).

In 2012 a genetic tag-recapture study on Spanish mackerel in Northern Territory produced the first experimental estimates of commercial-line harvest-rates (% of active feeding fish caught) from aggregations of fish (Buckworth et al. 2012). Estimates of harvest rates for single fishing days from schools of fish averaged 41% (95% confidence interval 6–90%). Estimated harvest rates over multiple fishing days, measured from the number of actively feeding Spanish mackerel over the duration of a fishing trip, ranged between 7% and 45%. Mean estimates on the numbers of Spanish mackerel in a feeding aggregation were varied and ranged between 75–1382 fish on a single day. This expanded to 1006–2421 exploitable fish on a fishing trip over multiple days.

The confidence intervals (uncertainty) around the genetic estimates were wide due to sampling and technical challenges. Only six or so fishing trips were able to be sampled effectively and measured the potential harvest rates at those times and areas. Irrespective of the uncertainty, the results help interpret fish harvest rates and their sustainability. For the Northern Territory, results indicate that commercial fishing operations can have significant fishing power and may at times take large proportions of exploitable fish from a location (7% to 55%, Table 23, in: Buckworth et al. (2012)). This was likely to be true for Spanish mackerel in the Torres Strait during the spawning season and on other aggregations.

4.5 Recommendations

4.5.1 Management

Spawning biomass levels were currently below the reference point of 48% of unfished spawning stock biomass. From the analyses it can be concluded that Torres Strait Spanish mackerel was likely to be depleted below the spawning biomass at maximum sustainable yield (Table 1). The assessment, following TSFFRAG process, recommended a maximum biological catch (RBC) of 95 t (AFMA 2021a).

No formal harvest strategy was in place at the time of this stock assessment. However, a similar annual stock assessment and RBC process was used by AFMA and the PZJA (AFMA 2021a). In reporting against general fishery harvest strategy policies (Australian Government 2007; Department of Agriculture and Fisheries 2021), the recommended uncertainty (discount) factor for this assessment was 0.91 based on a qualitative tier assignment process and Ralston et al. (2011). Future stock assessment will formally calculate the Ralston sigma factor for uncertainty (σ; Ralston et al. 2011).

Future management should consider benchmarking a target reference point for fishing to ensure healthy population biomass (safely above B_{MSY}) and catch rates of Spanish mackerel, in order to achieve and balance sustainability, economic, social and cultural objectives (Australian Government 2007; Australian Government 2018; Department of Agriculture and Fisheries 2017; Australian Government 2013; Australian Government 2016). Quota setting should aim to follow a formal harvest strategy procedure to recommend annual harvests (Sloan et al. 2014; Hutton et al. 2019). Settings should be precautionary until improvements in spawning biomass achieve at least 40% biomass.

4.5.2 Assessment and monitoring

Stock status indicators and reference points calculated herein can support design of a harvest strategy for Torres Strait Spanish mackerel. In order to service a harvest strategy, further improvements in data are required, as was summarised by Begg et al. (2006):

- Verify records on fishing effort and harvest through CDR and logbook reporting systems [for harvest and/or standardised catch rate assessments].
  - The new CDR since 2018 is recording and validating trip harvests and average fish weights using unload/sale receipts.
  - However, improved frequency of TIB reporting and clarification on TIB and Sunset number of tenders used and hours fished per operation day is required to improve fishing effort and catch rate indicators.
  - A review of the Sunset tender data was recommended, to potentially impute or develop an offset for early years, as use of this data in future years might be important to monitor stock rebuilding.
  - The number of fishing locations of the primary operation and dories utilising VMS/GPS latitude and longitude coordinates is important for improving the spatial resolution of data, in order to mitigate hyperstability from the way data might be recorded (O'Neill et al. 2018a).

  - recording of zero catches for each fishing day, and days when fishing was stopped due to capacity limitations (too many fish).
- Monitor and estimate Spanish mackerel harvests taken by non-commercial sectors [for stock model assessment].
- Continue annual long term monitoring of fish age-length structures that were spatially representative of the Torres Strait [for mortality and/or stock model assessments].
- Continue, in association with fish monitoring, the collection of spatially representative genetic fish samples to examine stock boundaries and enable genetic population studies [for stock model assessments and management. e.g. close kin estimates].
- Conduct further investigation with the stock assessment models to consider the influence of pre 1989 data and IUU estimates and conduct retrospective analyses to demonstrate stability in results [for stock model assessments].
- Conduct further bridging analysis to show consistency between the custom and stock synthesis models.
- Link key environmental data and report on trends that can support TSFFRAG discussions.

4.6 Conclusions

Across analyses, the median estimated spawning biomass of Torres Strait Spanish mackerel in 2020–2021 was 29 percent of unfished estimates at the start of the fishery in 1940.

The recommended Spanish mackerel RBC for 2022–2023, inclusive of all fishing sectors in the Torres Strait, was 95 t based on the median forecast estimates.

Initial comparison of the packaged stock assessment software stock synthesis (SS) produced an estimate of spawning biomass ratio in 2020–2021 that was similar to the custom model results, meaning that management recommendations that would arise from either package would be much the same. The positive link between models will support further investigations into using stock synthesis during year two of the project.

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Appendix A History of the fishery

Table A.1 was a record compiled from TSFFRAG notes, summarising historical fishery and management events for the Torres Strait Spanish mackerel fishery (AFMA 2020a). The historical record was last updated by TSFFRAG on 23 October 2020 (Buckworth et al. 2021). There were no new events for 2020–2021.

Table A.1: History of the Spanish mackerel fishery and relevant management changes in Torres Strait.

Year	Management	Source
1942	Start of commercial fishing for Spanish mackerel, reportedly to supply Torres Strait Army Hospitals augment food supply during WW2. Army Fishing Unit (although mackerel catches were likely occurring for local consumption prior to WW2)	McPherson 1986 in Haines et. al summary of 1985 Port Moresby seminar.
1945-1957	Skipper Snowy Whitaker was known to have a vessel prior to the Trader Horn after WW2. This might have been *AFV Saint Hillaire* or *AFV Sawfish*.	McPherson pers. comm. AFMA interview Oct 2020.
1957-1962	*AFV Winston* reportedly the major mackerel catching boat from 57-62 and the only Torres Strait fleet boat of a size and seaworthiness to fish at Bramble Cay. *AFV Winston* reportedly fished two dories for all years active. (Geoff McPherson holds logbook data for *AFV Winston* and is reviewing)	McPherson pers. comm. AFMA interview Oct 2020.
1957-1969	*AFV Trader Horn* active in TSFF from 1957 working Spanish mackerel until it refitted as a prawn trawler in the late 60's. Once this vessel moved to prawn other mackerel boats entered the Torres Strait (skipper Snowy Whitaker was protective of his fishing marks and market).	Kenny Bedford report at FFRAG 7 (AFMA 2020a), McPherson pers. comm. AFMA interview Oct 2020.
1970s-1980s	Four boats reported to be commonly working from Ugar at two sites with occasional fishing at Bramble Cay. One primary boat reportedly had 7-8 dories linked.	Rocky Stephen interview with father Daniel Stephen report given to (AFMA 2020a).
1974	Torres Strait Fisheries Survey including mackerel, Aboriginal and Torres Strait Island Commission engaged in the survey.	Begg et al. (2006)
1975-1979	Catch data available from this time period from the Queensland Fish Board (or North Queensland Fish Board).	McPherson 1986
1974-1986	Taiwanese gillnet fishery operated in Australian EEZ from NW Shelf to north of Gulf of Carpentaria, 8-16km driftnets targeting shark, tuna and mackerel.	CSIRO (1990) and Stevens et al. (1991)
1976-1993	Taiwanese gillnet fishery in operation in the adjacent Gulf of Papua under PNG licences. Mainly targeting sharks but known that up to 10 percent of catch was bony fishes from earlier years where catch reports are available.	Chapau et al. (1986)
1977-1982	TSSMF Research conducted aboard *AFV Winston*, scientist John Carlton (QLD Fisheries) and skipper Jack Jarret. Same vessel and procedures each year meaning this study is likely a good insight into the fishing at this time in history.	McPherson pers. comm. AFMA interview Oct 2020.
1979	Australian Fishing Zone (AFZ) declared as the NT gillnet fishery develops in late 70s. This declaration limited the impact of Taiwanese gillnet fishery. Taiwanese catch dropped from 25,000t of all species p.a. to 10,000 t for all species p.a. post 1979.	CSIRO (1990) and Stevens et al. (1991)
Late 1970s-early 1980s	Thursday Island local Tony Tardent worked as a deckhand on *AFV Trader Horn*.	Kenny Bedford report to FFRAG 7 (AFMA 2020a).

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Table A.1 – *Continued from previous page*

Year	Management	Source
1984-1985	*AFV Winston* was sold by the Jarret family after fishing Torres Strait.	McPherson pers. comm. AFMA interview Oct 2020.
1985	Torres Strait Treaty established and Torres Strait Fisheries Act. Establishment of Torres Strait Protected Zone Joint Authority (PZJA) to regulate all fisheries in Torres Strait. Transferable licences issued to non-traditional inhabitants who could demonstrate history and commitment to fishing in Torres Strait. Licences subject to strict vessel replacement regulations related to vessel size. Vessels restricted to less than 20 m in length. Traditional inhabitants could obtain the commercial fishing license from PZJA. Ban on netting of Spanish mackerel. Minimum legal size of 45 cm TL for Spanish mackerel	AFMA
1986	Aust. Govt. limits length of gillnets to 2.5km within EEZ to lower risk to dolphins which makes the legal Taiwanese gillnet fishery uneconomical (and it generally means requests for legal licences cease soon after).	FRDC Report 1990 Analysis of Taiwanese Gill-net Data (CSIRO 1990)
1988	AFMA SM01 daily fishing logbook introduced – compulsory for non- islander and PNG fishers, replaces Queensland LF03 logbook	Begg et al. (2006)
1989	Tarawa Declaration signed 11 July 1989 by Pacific Island nations - calls on Japan and Taiwan to cease driftnet fishing. `https://www.forumsec.org/1989/07/10/tarawa-declaration/` Convention for the Prohibition of Fishing with Long Driftnets in the South Pacific limits driftnets to 2.5km which impacts Taiwanese legal operations `https://en.wikipedia.org/wiki/Wellington_Convention`	Begg et al. (2006)
1989	6-7 Dec 1989 Environmental Management Committee: Australian government seeking information from PNG on a PNG licenced Taiwanese driftnet vessel "Mao Hua" drift-netting near the TSPZ. Issue raised in the Australian Senate in connection with wildlife impacts.	Environment Management Committee Meeting Record 6-7 December 1989
1990	AFMA SM02 daily fishing logbook introduced	Begg et al. (2006)
1990	Skipper Tony Vass (TSFFRAG member) begins fishing Torres Strait mackerel until 2007 buyout.	TSFFRAG
1991	December 1991: United Nations resolution calling for worldwide moratorium on driftnet fishing.	
1992	IUU incident with two Taiwanese vessels FFV Sheng Fu and FFV Hwa Si, apprehended. One running aground at Turu Cay, ghost nets retrieved afterwards up to 10miles in length.	AFMA 2020 advice to Spanish mackerel project team.
1998	Minimum size limit of 45cm TL introduced for Torres Strait for all mackerel species. Fishing methods restricted to trolling, hand-lining and drop-lining.	Begg et al. (2006)
1999	Management transferred from DAF to PZJA with AFMA engaged. Traditional inhabitants required to hold a current Torres Strait Traditional Inhabitant Fishing Boat Licence (TIB) or Torres Strait Fishing Boat Licence for commercial fishing in TSPZ. Fishery expanded to include spotted, school, shark and grey mackerel in addition to Spanish mackerel.	Begg et al. (2006)
2001-2002	Investment warnings issued by Australian Government ahead of TSFF structural adjustment (6 Nov 2001 and 15 Feb 2002)	AFMA
2003	Voluntary islander docket book (TDB01) introduced 2003, in use until mandatory Torres Strait Fish Receiver System (AFMA CDRs) started in December 2017.	AFMA

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Table A.1 – *Continued from previous page*

Year	Management	Source
2004	AFMA led (John Marrington) voluntary industry sampling program provides 1789 fish samples (length and sex data only).	AFMA 2004 Torres Strait Mackerel Fishery Mackerel/Linefish Logbook Supplementary information
2004	Minimum legal size increased to 75 cm TL for Spanish mackerel. Minimum legal size increased to 60 cm TL for spotted mackerel. Minimum legal size increased to 50 cm TL for school, shark and grey mackerel.	AFMA
2005	PZJA decision on total ban of gillnetting in the Torres Strait for commercial purposes.	AFMA
2006	First stock assessment of Torres Strait Spanish mackerel.	Begg et al. (2006)
2007	Structural adjustment and buyout - fishery access becomes 100 percent owned by Traditional Inhabitants	PZJA
2013	Torres Strait Finfish Management Plan 2013 implemented.	
2016	Stock assessment update for Torres Strait Spanish mackerel fishery.	O'Neill et al. (2018b)
2017	1 July 2017, vessel monitoring systems introduced in the Torres Strait for primary tender operation vessels. (TIB and Sunset - no VMS on tenders or sole operating dinghies)	AFMA
2017	Torres Strait Finfish Resource Assessment Group inaugural meeting to progress harvest strategy (November)	PZJA website meeting record
2017	TDB02 Catch Disposal Records become mandatory for all Torres Strait (1 Dec 2017) commercial catch (TIB and Sunset sectors)	AFMA
2019	Torres Strait Biological Sampling Program for Spanish mackerel to collect length, sex and age information.	Project led by DAF

Appendix B Data and model inputs

B.1 Harvest estimates

Annual estimates of Spanish mackerel harvest used the data from Table (B.1). Estimates considered all sources of fishing mortality by each sector. TSFFRAG documented aspects of this data (AFMA 2020a; AFMA 2021b), with the following assumptions:

- The Torres Strait fishery for Spanish mackerel commenced in 1940 (Begg et al. 2006).
- Pre 1989, Sunset harvests were reported in only eight years by McPherson (1986), for the main fishing operation. Based on TSFFRAG advice, the October 2020 video meeting with Geoff McPherson and the McPherson (1986) report, the eight years of data was assumed complete.
- TIB harvests before 1989 were estimated from Islander traditional knowledge (AFMA 2020a; AFMA 2021b).
- Kai-kai harvests for food were estimated by TSFFRAG, and considered traditional knowledge and published survey data (Busilacchi et al. 2015).
- No valid records existed for charter fishing. The sector's harvest was considered a part of recreational fishing.
- Recreational harvest estimates were low based on an initial survey (Webley et al. 2015). From the variance estimates, the assumed recreational harvest was randomised between two and five tonnes per year. A constant of 5 t per year was assumed for 2020–2021 and onwards (AFMA 2021b).
- Papua New Guinea fishing operations have not leased or reported any harvest.
- Two analyses compared polynomial and logistic models to estimate the missing pre 1989 years of total harvest in Table B.1. The approach, illustrated in Figure B.1, was similar to Begg et al. (2006).
- An assumed 100 t per year of IUU harvest was included for 1979–1986, and then tapered down annually to zero harvest by 1993. The IUU component was a separate add-on harvest in the final overall estimates and was not included in the polynomial or logistic models. The history and impact of IUU fishing was documented by TSFFRAG and in the 2019–2020 stock assessment (Buckworth et al. 2021; AFMA 2020a; AFMA 2021b).

The polynomial and logistic models used Table B.1 combined totals between 1940 and 1993. A third-degree polynomial was best fit in a least-squares sense for modelling the total harvests against the years. Model predictions estimated the missing pre 1989 total harvests.

The logistic estimates used a binomial GLM (with logit link function). The analysis data scaled the average annual 1989–1993 total harvest to 100%, to represent the full catch expansion of the fishery. The lesser pre 1989 harvests was scaled to a fraction of the 1989–1993 average. The logistic model estimated the harvest fractions, and they were multiplied by the 1989–1993 average harvest to form the missing estimates. The logistic-shape by year aimed to create a different long-term pattern of harvest expansion in the fishery, to compare against the polynomial scenario.

Overall, the Islander subsistence (kai kai), recreational, TIB and Papua New Guinea harvests were small, compared to Sunset harvests (Table B.1). Nominal Sunset effort was reduced since 2007 (Figure B.2).

Table B.1: Harvest estimates (t) by year and fishing sector. Data were from reports, publications and traditional knowledge.

Fishing year	Financial year	TIB	Traditional	Sunset	Recreational	Charter	PNG	Total
1940	1940-41	0	2	0	0	0	0	2
1957	1957-58	0	2	34	2	0	0	38
1959	1959-60	0	2	52	2	0	0	56
1960	1960-61	0	2	40	2	0	0	44
1962	1962-63	0	2	70	2	0	0	74
1975	1975-76	3	2	68	2	0	0	75
1976	1976-77	3	2	81	2	0	0	88
1977	1977-78	3	2	69	2	0	0	76
1979	1979-80	3	2	57	2	0	0	64
1989	1989-90	3	10	215	4	0	0	232
1990	1990-91	4	10	182	5	0	0	201
1991	1991-92	1	10	194	4	0	0	209
1992	1992-93	2	10	173	2	0	0	187
1993	1993-94	3	10	121	4	0	0	138
1994	1994-95	5	10	192	5	0	0	212
1995	1995-96	2	10	182	3	0	0	197
1996	1996-97	3	10	157	4	0	0	174
1997	1997-98	4	10	181	2	0	0	197
1998	1998-99	4	10	167	5	0	0	186
1999	1999-00	9	10	168	5	0	0	192
2000	2000-01	5	10	164	4	0	0	183
2001	2001-02	8	10	108	2	0	0	128
2002	2002-03	7	10	129	5	0	0	151
2003	2003-04	13	10	137	5	0	0	165
2004	2004-05	14	10	225	3	0	0	252
2005	2005-06	10	10	277	3	0	0	300
2006	2006-07	14	10	171	3	0	0	198
2007	2007-08	7	10	105	2	0	0	124
2008	2008-09	6	10	77	5	0	0	98
2009	2009-10	8	10	89	4	0	0	111
2010	2010-11	8	10	71	4	0	0	93
2011	2011-12	2	10	89	4	0	0	105
2012	2012-13	3	10	91	5	0	0	109
2013	2013-14	1	10	116	4	0	0	131
2014	2014-15	2	10	81	4	0	0	97
2015	2015-16	2	10	86	5	0	0	103
2016	2016-17	3	10	90	4	0	0	107
2017	2017-18	2	10	75	2	0	0	89
2018	2018-19	6	10	58	4	0	0	78
2019	2019-20	2	10	54	3	0	0	70
2020	2020-21	3	15	29	5	0	0	52

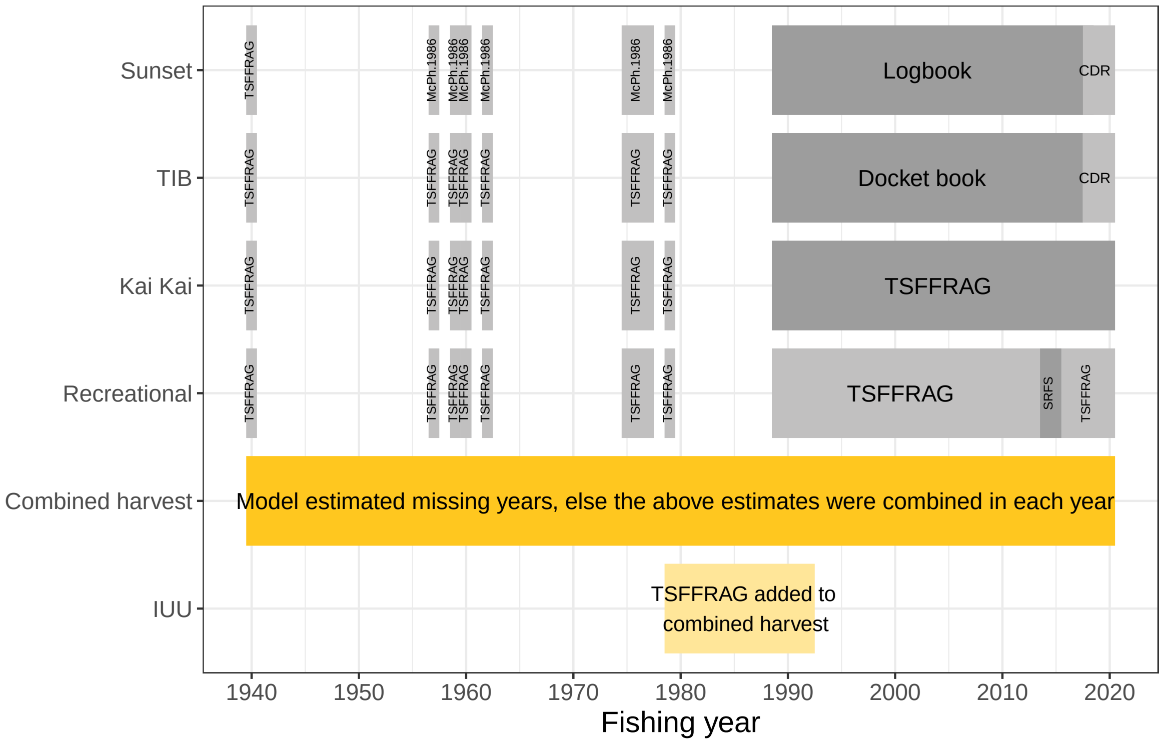

Figure B.1: Overview of the information and process used to reconstruct the history of Torres Strait Spanish mackerel harvest. The years of data (shaded grey) note the estimates from the harvest table above, where the labels: TSFFRAG - was the agreed estimate based on reports, publications and traditional knowledge; McPh.1986 - was the McPherson (1986) harvest data; and SRFS - was the state-wide recreational fishing survey by Fisheries Queensland for Torres Strait. Harvest estimation (shaded orange) was conducted across the fishery and not separately for each sector.

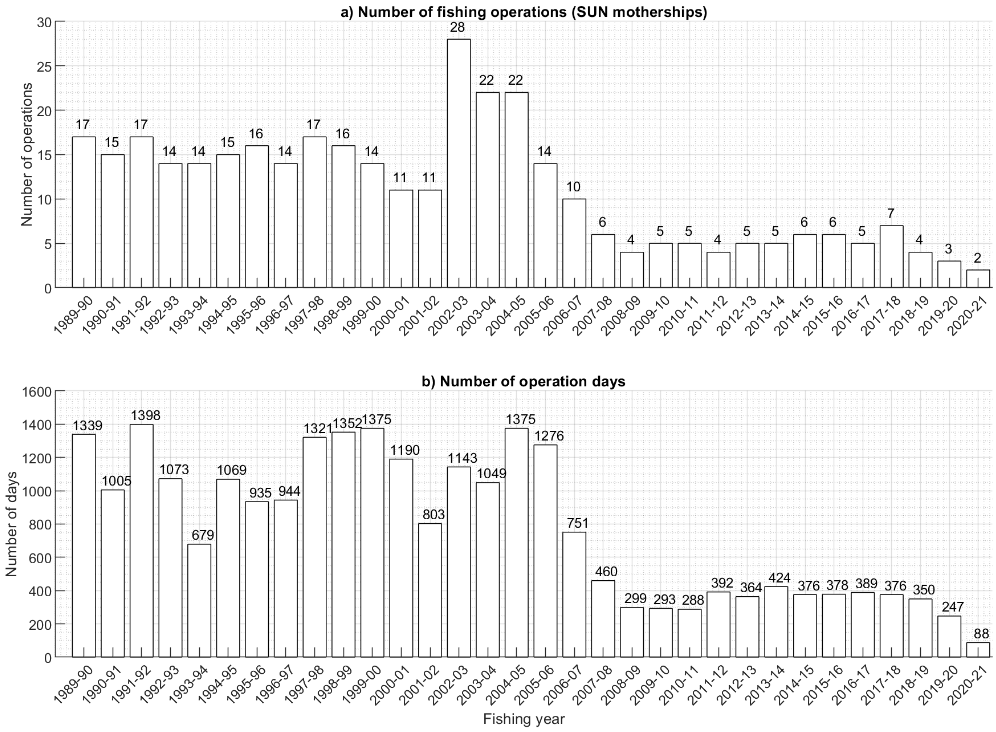

Figure B.2: Sunset logbook reports of total fishing effort by year for a) number of primary fishing operations, and b) number of days fished by the primary operations.

B.2 CDR Sunset report

- The TDB02 CDR reported landings information on Spanish mackerel catch weights.
- The CDR reported fillet weights. This was converted by AFMA to whole fish weights (kg).
- Estimated average fish weight per year was calculated using the annual CDR weight (kg) divided by the annual logbook numbers of fish.
- Extra CDR information was published by AFMA on the the PZJA website https://www.pzja.gov.au/fishery-catch-watch-reports.
- No biological monitoring occurred in 2018 to compare average fish weight with the CDR.

Annual summary of CDR data (Table B.2).

Table B.2: Summary of Catch Disposal Records

Fishing year	Fish count n(logbook)	Total whole fish weight (CDR, kg)	Average fish weight CDR (kg)	Average fish weight measured (kg)
2018	8645	57730	6.68	
2019	6427	54097	8.42	7.65
2020	4126	28813	6.98	7.45

B.3 Age-length samples

Table B.3: Summary of biological data sample sizes by fishing year.

Fishing year	Number of fish lengths	Number of fish aged
1974	124	0
1978	205	205
1983	350	0
1998	216	0
1999	309	0
2000	900	892
2001	909	874
2002	612	602
2004	1789	0
2005	744	744
2019	1592	255
2020	2304	296

Fish length-composition data were not a direct input into the population model. Instead, annual length data (Figure B.3) was used in the construction of annual age compositions through the application of annual age-at-length keys (Langstreth et al. 2020; Trappett et al. 2021).

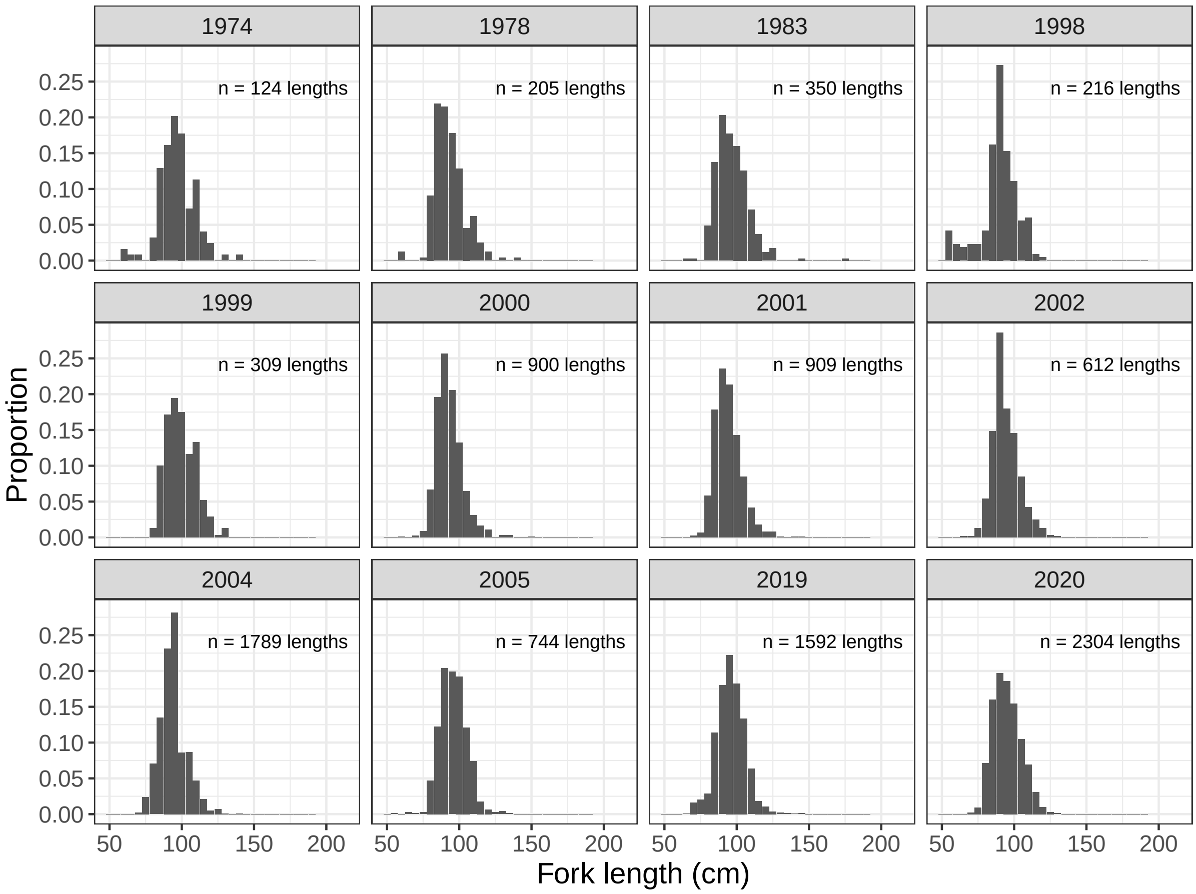

Figure B.3: Annual length compositions of Spanish mackerel harvested in the Torres Strait for sampled years between 1974 and 2020.

B.4 Ageing statistics

Table B.4: Fish ageing statistics by fishing year from Fisheries Queensland's biological monitoring. IAPE was an index of average percent error (IAPE) of the increment assignment between read 1 and read 2 when fish samples are aged twice.

Ageing	2019	2020
number otoliths aged	256	301
number otoliths re-aged	200	200
% increment agreement	92	88.5
IAPE increment count	1.201	3.38
% agreement news	90.7	87
% agreement intermediates	73.5	83
% agreement wides	90.5	73
count news	130	102
count intermediates	44	58
count wides	25	37
count unreadable	1	3

B.5 Catch rates

B.5.1 Sunset diagnostics

Table B.5: Anaylsis of variance table for the Sunset commercial catch rate analysis. F statistics were derived from the R drop1 procedure.

Term	Df	Deviance	F value	Pr(>F)
residual	24347	340250		
fishyear	31	356066	36.508	0.000
zone5	4	345845	100.088	0.000
boat	46	417201	119.703	0.000
s1cos	1	340412	11.608	0.001
s1sin	1	345931	406.552	0.000
s2cos	1	342730	177.498	0.000
s2sin	1	341480	88.036	0.000
s3cos	1	340351	7.257	0.007
s3sin	1	340321	5.116	0.024
lunar	1	343317	219.446	0.000
lunaradv	1	349076	631.582	0.000
windns	1	340405	11.076	0.001
windns2	1	340527	19.834	0.000
windew	1	340251	0.096	0.757
windew2	1	340783	38.122	0.000

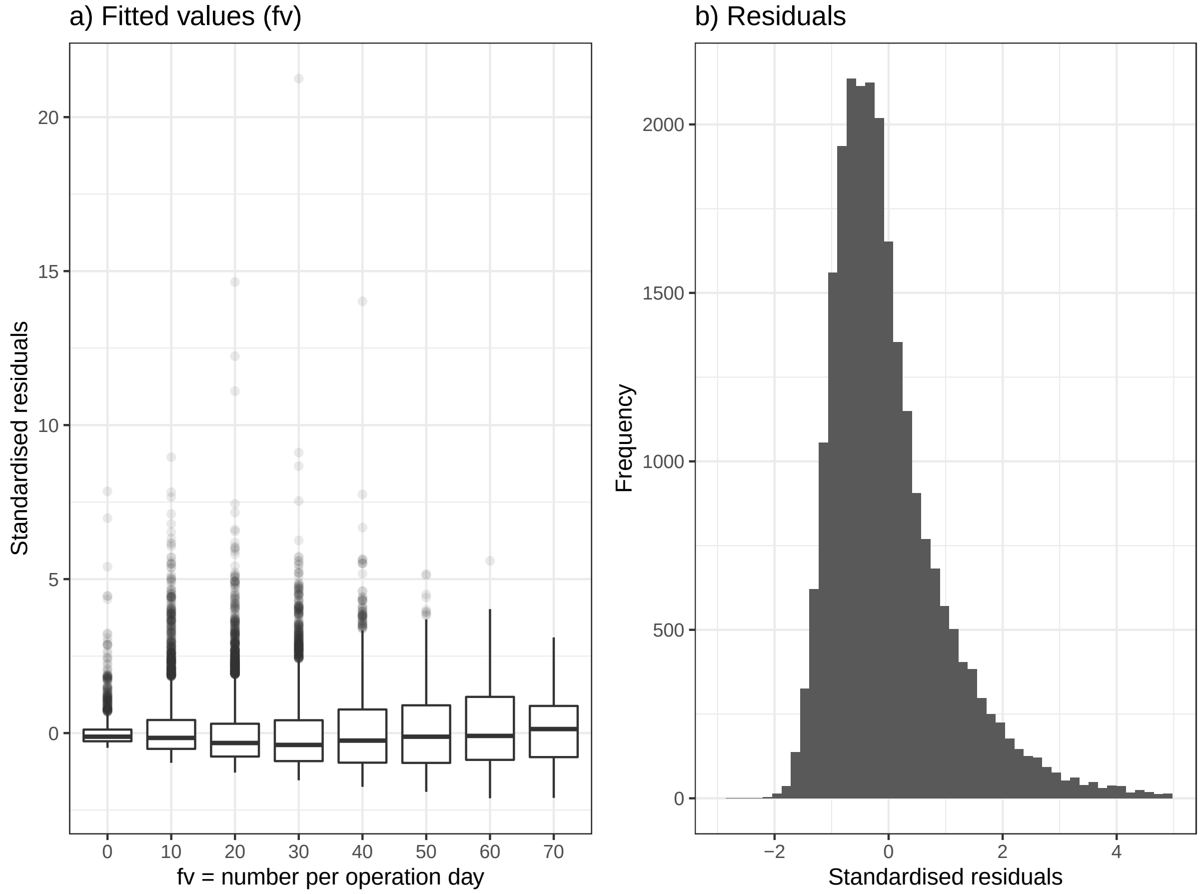

Figure B.4: Sunset catch rate residual plots for a) box plot of fitted values and residuals, and b) histogram of residuals. Fitted values > 70 fish were grouped. Residuals were standardised by the sqrt(variance * dispersion).

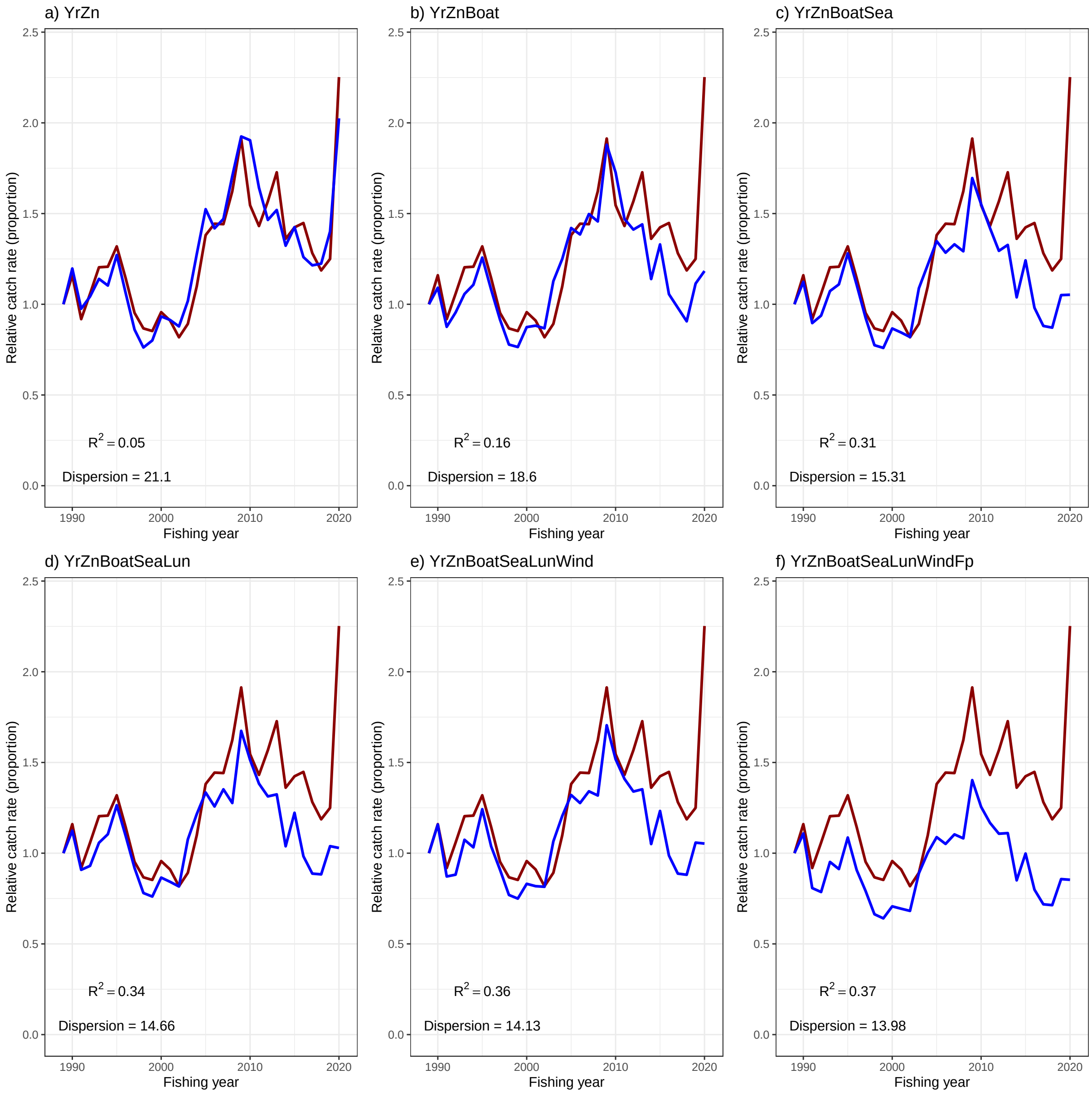

Figure B.5: Influence plot comparing the GLM effects on standardised catch rates against the nominal mean catch rate (red line). Sub-plot: a) compared a year (Yr) and zone (Zn) model; b) compared a Yr, Zn and Boat model; c) compared a Yr, Zn, Boat and Seasonality (Sea) model; d) compared a Yr, Zn, Boat, Sea and Lunar (Lun) model; e) compared a Yr, Zn, Boat, Sea, Lun and Wind model; and f) compared the full standardisation model by adding the fishing power offset (Fp). Each subplot annotated the improvement in model fit, with the adjusted R-squared increasing, and decreasing dispersion measured by the mean deviance.

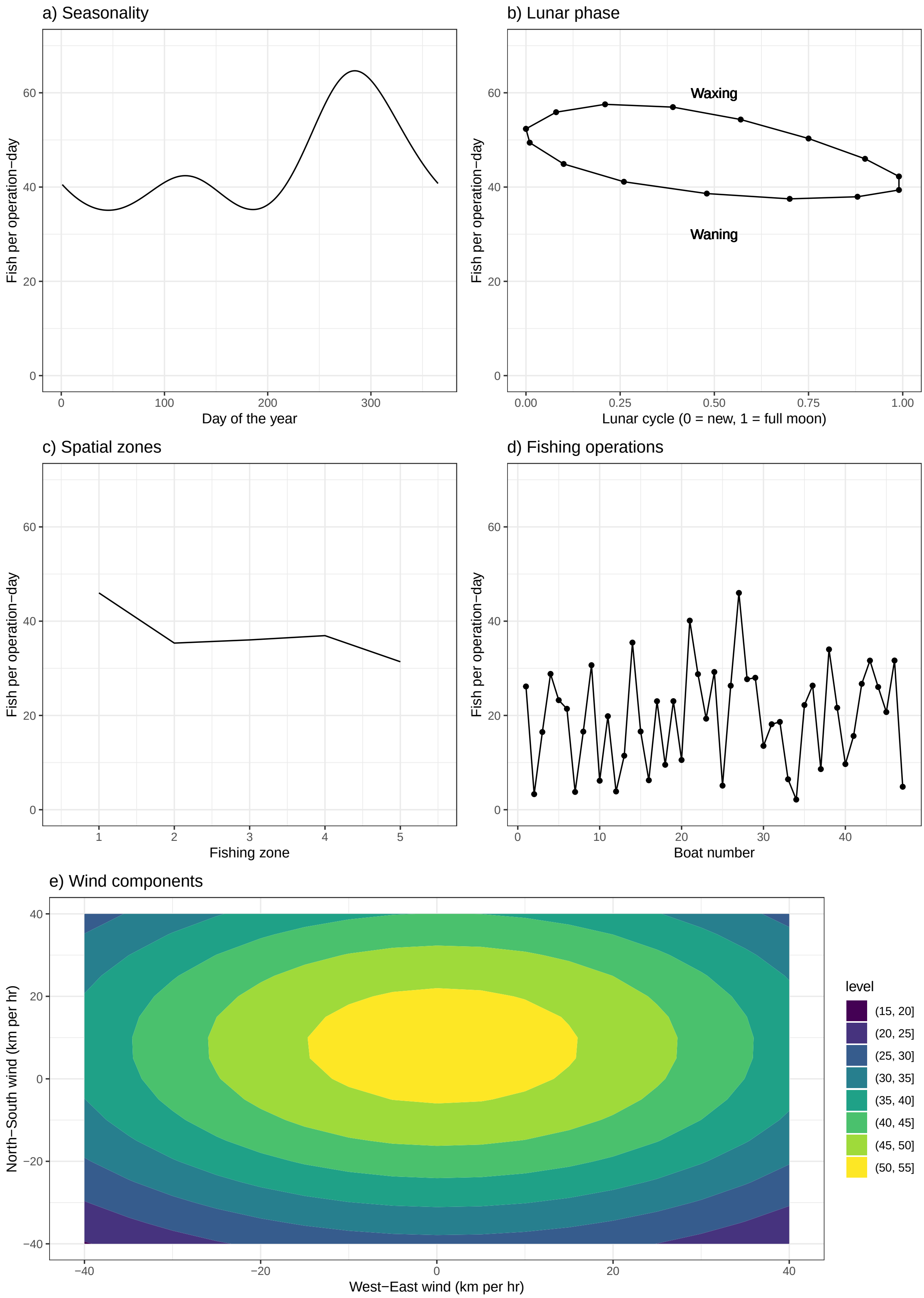

Figure B.6: Mean catch rate effects estimated by the Sunset GLM. Subplot a) by time-of-year, b) lunar cycle, c) areas fished, d) differences between boats (fishing power effect, where the main 2020-2021 boat was the highest catching), and e) the wind speed and direction.

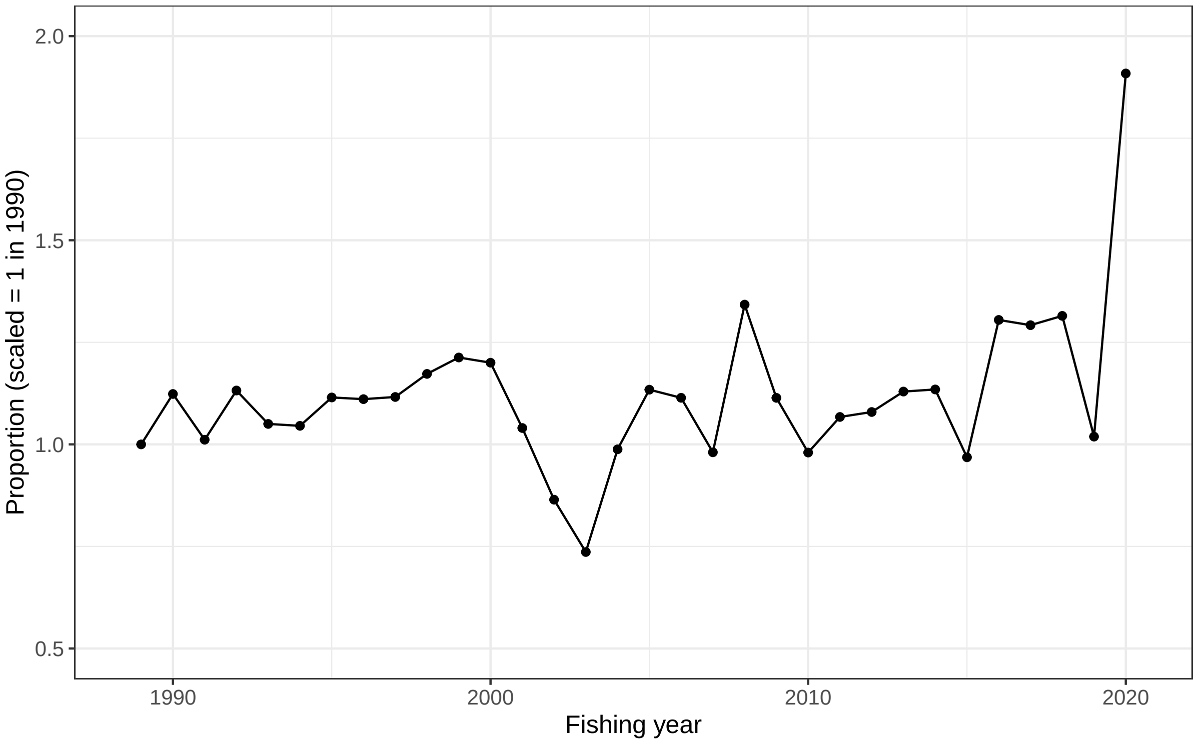

Figure B.7: Relative average Sunset-fleet fishing power by year as estimated from the GLM boat factor.

B.5.2 TIB diagnostics

Table B.6: Anaylsis of variance table for the TIB commercial catch rate analysis. F statistics were derived from the R drop1 procedure.

Term	Df	Deviance	F value	Pr(>F)
residual	174	5812		
fishyear	2	5989	2.647	0.074
client	32	10373	4.268	0.000
s1cos	1	6157	10.335	0.002
s1sin	1	5928	3.486	0.064
windew	1	6034	6.660	0.011
crew	1	5980	5.024	0.026

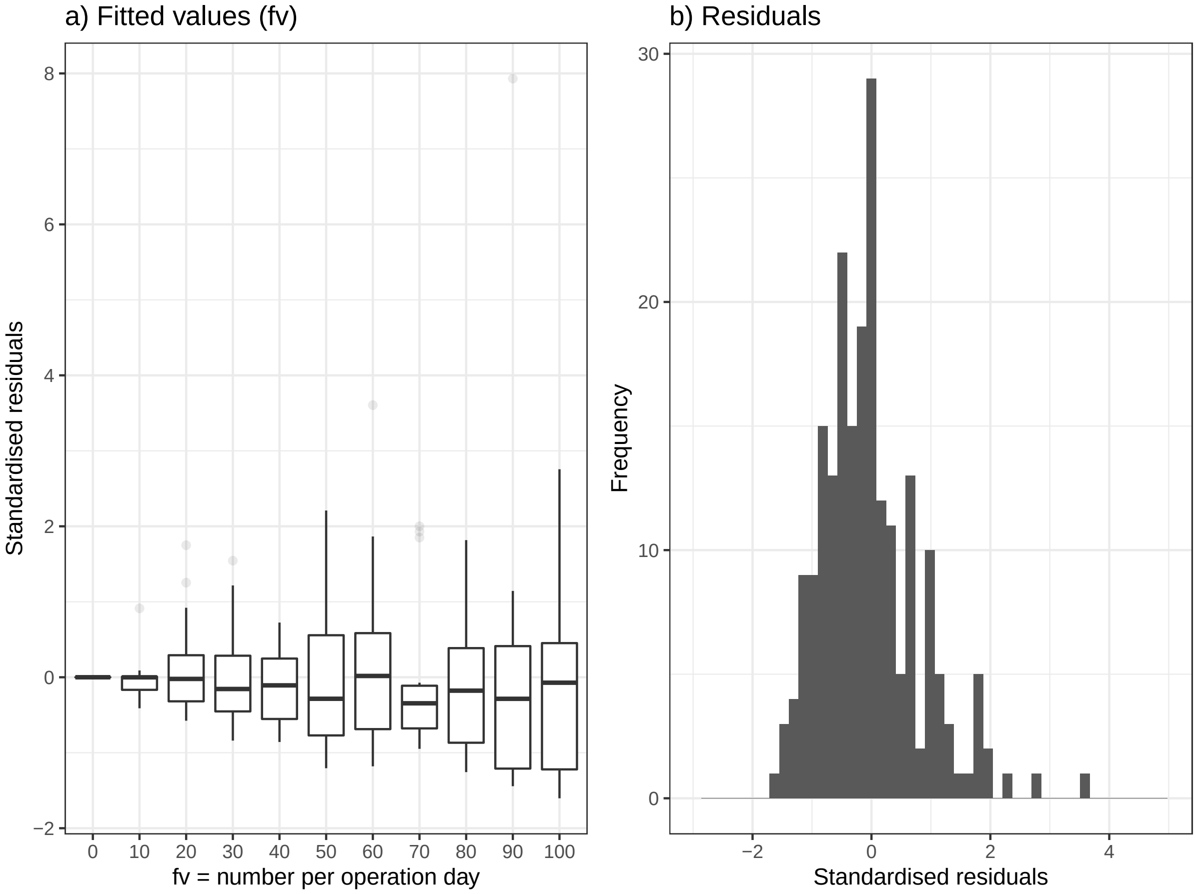

Figure B.8: TIB catch rate residual plots for a) box plot of fitted values and residuals, and b) histogram of residuals. Fitted values > 100 kg were grouped. Residuals were standardised by the sqrt(variance * dispersion).

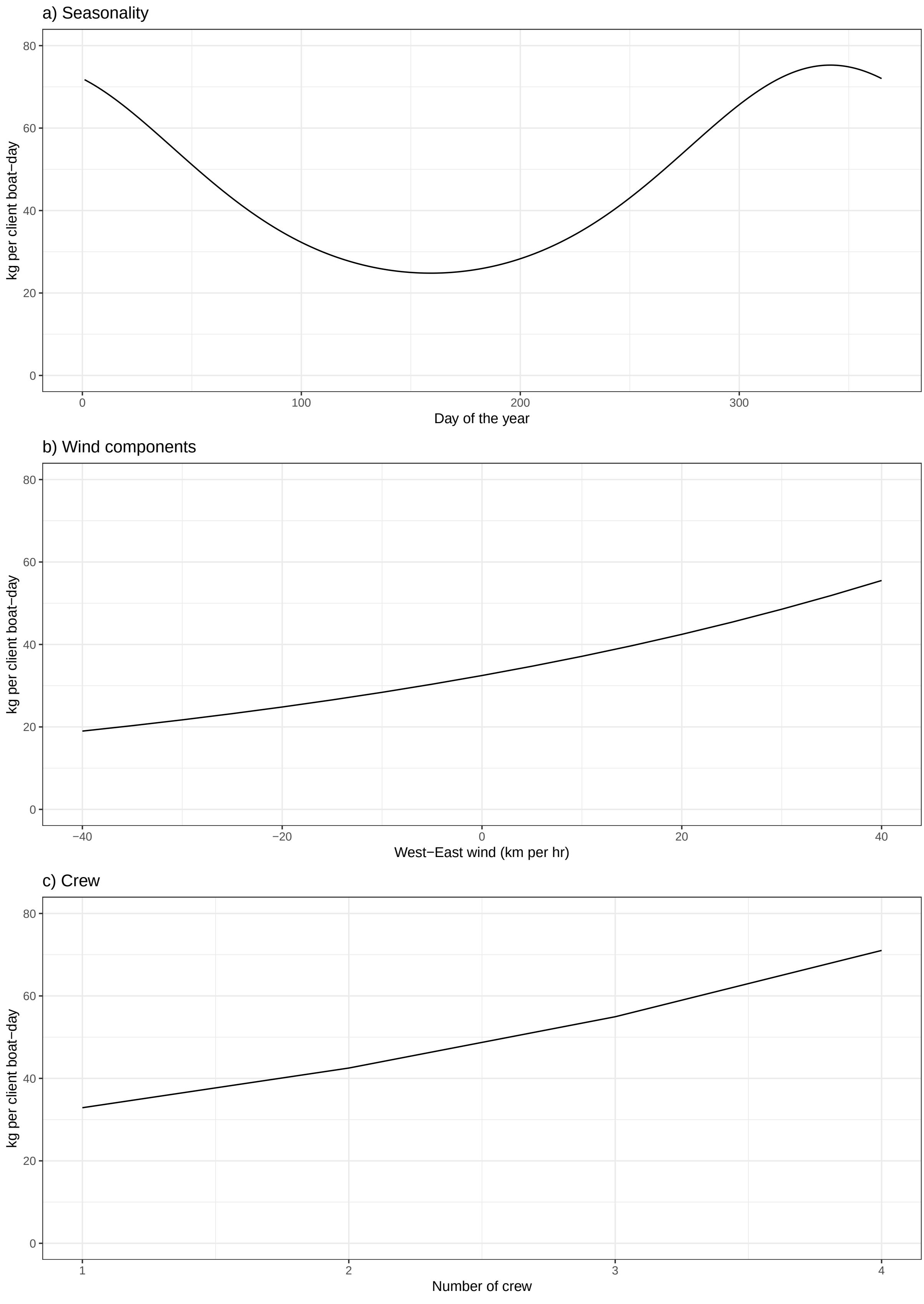

Figure B.9: Mean catch rate effects estimated by the TIB GLM. Subplot a) by time-of-year, b) the wind speed and direction and c) number of crew on the client boat.

B.5.3 Data selection

A number of data selection (filtering) rules for Sunset catch rates were assessed through past stock assessments and by TSFFRAG. The purpose was to check key trends, particularly for the decline post 2010. Data selections and annual catch rates were compared across all fishing operations (boats) and subsets.

The rules gradually removed boats, to assess catch rates by key operations, but also to gauge effects on biasing data. For this, a data report was tabulated to record the number of available data. The data report provided nominal values for three summary data-types, being a) number of daily boat operations (N), b) mean catch rates (Mn - number of fish) and c) number of boats (B). As a result, the data report can be used to track and reference data records by subsets and years, and between stock assessments for consistency.

The subsets of Sunset catch rate data were defined as follows:

- The full data was for all boats and their available daily logbook data. Any bulk catch-records for more than one day of fishing were removed. The tabulated data-types were for their 'total' or use of 'all N' in means.
- The data rule 'used' was for the selected catch rates in the GLM. This was for boats that had harvested Spanish mackerel in more than one year and reported at least 20 days of fishing effort over all years. This was the default and minimum data rule for statistical analysis and standardised catch rates.
- Data rule 'filter95' was for the top 95% of boats harvesting Spanish mackerel over all years of data.
- Data rule 'filter75' was for the top 75% of boats.
- Data rule 'filter50' was for the top 50% of boats.

The filter95, filter75 and filter50 rules were not used herein for any stock assessment analyses. The example rules were reported for TSFFRAG to gauge thresholds in removing data.

Table B.7 summarised the effects of the data selection rules on catch rates. This was a before and after effect on yearly data without any model or transformations applied, measured against the full data. Obvious differences in means occurred for the filter75 and filter50 rules, when 36% and 56% of the data were removed respectively. However, all rules confirmed a decline in data, catch rates and boats post 2010–2011.

Table B.8 summarised the statistical differences between data rules. The paired T tests on annual catch rates between all data and the used data was not significantly different, and the linear slope between these data was 1:1 (for a zero intercept regression). The 1:1 relationship signalled no data selection bias in the default rule, on both the nominal catch rate and normalised scales. Statistical differences were reported on the nominal scale for the filter95, filter75 and filter50 rules. This signalled higher catch rates were being generated by removing boats, but their annual trends on the normalised scale were not different to the all data.

Table B.9 summarised the data report for TIB catch rates. The data rule 'used' was for the selected catch rates in the TIB GLM. This was for clients (boats) that had harvested Spanish mackerel in more than one year. The 20 days of fishing rule was not applied, given the short time-series. The 'used' data rule removed about 30% of data. The TIB catch rate data was only three years young, with some fisher clients just commencing reporting, and no significant differences detected.

Table B.7: Summary of the Sunset number of boat operation days (N), nominal mean catch rates (Mn - number of Spanish mackerel) and number of boats (B) for different data selection (filtering) rules.

Component	N. total	N. used	N. filter95	N. filter75	N. filter50	Mn. all N	Mn. N used	Mn. filter95	Mn. filter75	Mn. filter50	B. total	B. N used	B. filter95	B. filter75	B. filter50
1990	1339	1309	912	651	336	21	21	24	24	19	17	16	9	6	3
1991	1005	1005	859	538	328	24	24	27	26	25	15	15	10	6	3
1992	1398	1246	978	635	372	19	19	23	22	23	17	15	10	5	3
1993	1073	1073	1001	570	372	22	22	23	24	24	14	14	11	5	3
1994	679	641	544	380	259	25	25	28	33	30	14	13	10	5	3
1995	1069	1069	897	582	243	25	25	27	29	30	15	15	11	5	2
1996	935	935	813	557	328	27	27	30	31	31	16	16	11	5	3
1997	944	944	853	648	356	24	24	25	26	26	14	14	11	7	4
1998	1321	1321	1247	943	647	20	20	20	22	23	17	17	15	9	5
1999	1352	1352	1231	981	649	18	18	18	18	18	16	16	13	8	5
2000	1375	1375	1203	999	744	18	18	19	19	17	14	14	11	7	5
2001	1190	1190	1081	866	595	20	20	21	23	19	11	11	10	7	5
2002	803	803	734	640	521	19	19	20	21	18	11	11	9	7	5
2003	1143	1065	945	671	574	16	17	19	24	23	28	16	12	7	5
2004	1049	1031	858	484	484	18	19	21	29	29	22	14	9	5	5
2005	1375	1357	1174	734	550	23	23	25	30	33	22	17	12	7	5
2006	1276	1265	1208	833	448	29	29	30	30	31	14	13	11	7	5
2007	751	747	747	562	282	30	30	30	31	31	10	9	9	5	3
2008	460	460	460	340	203	30	30	30	35	32	6	6	6	4	2
2009	299	299	299	277	167	34	34	34	33	34	4	4	4	3	2
2010	293	293	293	241	147	40	40	40	44	46	5	5	5	3	2
2011	288	288	288	241	195	32	32	32	38	37	5	5	5	4	2
2012	392	392	392	341	192	30	30	30	34	40	4	4	4	3	2
2013	364	364	364	322	203	33	33	33	37	38	5	5	5	3	2
2014	424	424	424	278	176	36	36	36	42	42	5	5	5	3	2
2015	376	376	372	300	216	28	28	29	32	33	6	6	5	3	2
2016	378	378	342	282	200	30	30	32	37	34	6	6	5	3	2
2017	389	389	389	252	252	30	30	30	29	29	5	5	5	2	2
2018	376	365	365	226	226	26	27	27	27	27	7	5	5	2	2
2019	350	350	350	272	272	25	25	25	27	27	4	4	4	2	2
2020	247	247	247	200	200	26	26	26	32	32	3	3	3	2	2
2021	88	88	88	81	81	47	47	47	51	51	2	2	2	1	1
Total	24801	24441	21958	15927	10818						68	47	26	12	6
N. removed	0	360	2843	8874	13983										
% removed		1	11	36	56										

Table B.8: T statistics for testing differences between Sunset nominal (Mn. - number of Spanish mackerel) and relative mean catch rates (Relmn. - normalised mean) for different data selection (filtering) rules.

Component	Mn. used	Mn. filter95	Mn. filter75	Mn. filter50	RelMn. used	RelMn. filter95	RelMn. filter75	RelMn. filter50
Mean difference	-0.00	-1.00	-4.00	-3.00	0.00	0.00	0.00	0.00
T statistic	-1.79	-5.04	-7.37	-5.64	0.40	0.07	0.02	0.05
Pr(>T)	0.08	0.00	0.00	0.00	0.69	0.95	0.99	0.96
Slope	1.00	0.96	0.88	0.88	1.00	1.01	1.00	0.99
T statistic	-1.35	-4.12	-8.11	-7.05	0.78	0.71	-0.02	-0.38
Pr(>T)	0.19	0.00	0.00	0.00	0.44	0.48	0.98	0.71

Table B.9: Summary of the number of TIB operation days (N), nominal mean catch rates (Mn - weight kg of Spanish mackerel) and number of client boats (B) for different data selection (filtering) rules, including T statistics for differences.

Component	N. total	N. used	N. filter95	N. filter75	N. filter50	Mn. all N	Mn. N used	Mn. filter95	Mn. filter75	Mn. filter50	B. total	B. N used	B. filter95	B. filter75	B. filter50
2019	104	90	87	68	45	62.00	64.00	66.00	76.00	86.00	15	11	10	5	2
2020	65	30	27	17	1	38.00	49.00	52.00	58.00	129.00	20	9	7	3	1
2021	50	33	31	26	16	63.00	55.00	56.00	61.00	68.00	13	7	6	4	2
Total	219	153	145	111	62						33	12	10	5	2
N. removed	0	66	74	108	157										
% removed		30	34	49	72										
Mean difference							-2.00	-4.00	-11.00	-1.00					
T statistic							-0.30	-0.60	-1.62	-0.58					
Pr(>T)							0.79	0.61	0.25	0.62					
Slope							0.98	0.94	0.84	0.51					
T statistic							-0.24	-0.56	-1.64	-2.71					
Pr(>T)							0.83	0.63	0.24	0.11					

Appendix C Model outputs

C.1 Diagnostics

C.1.1 Abundance indices

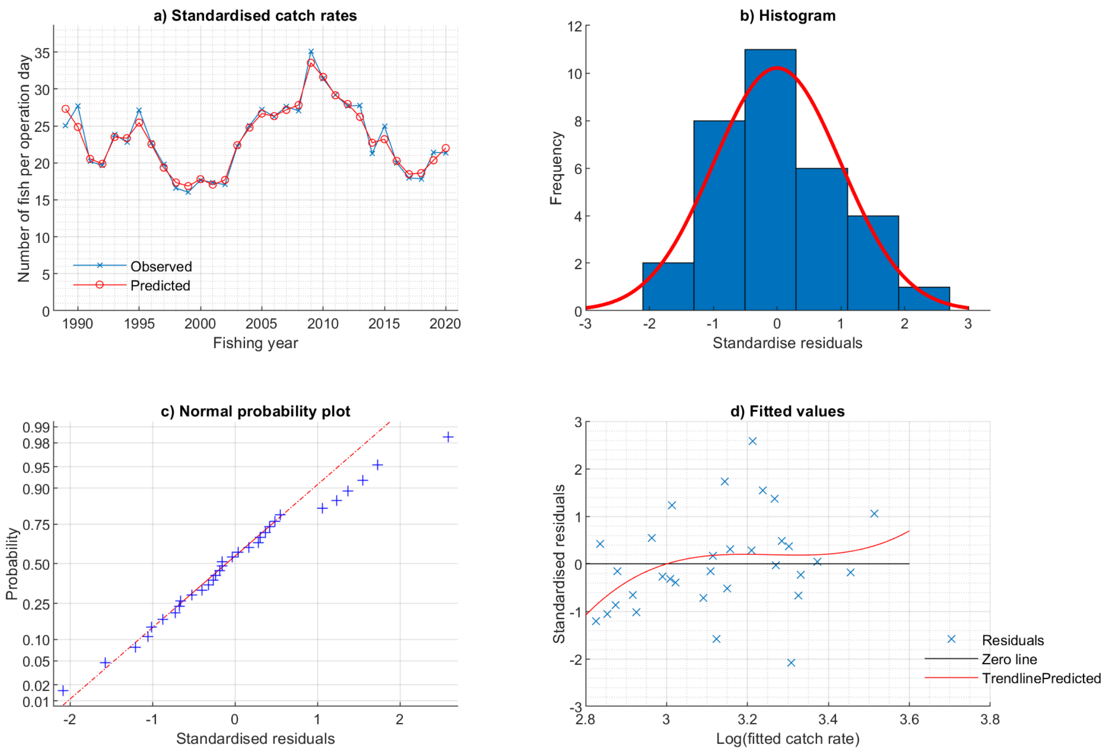

Figure C.1: Example custom model analysis 6 fit to catch rates. The level of fit was similar between analyses. Negative log-likelihood = -54.166. There were no influential standardised-residuals, particularly beyond the values of -2 and 2, that suggested any lack of model fit.

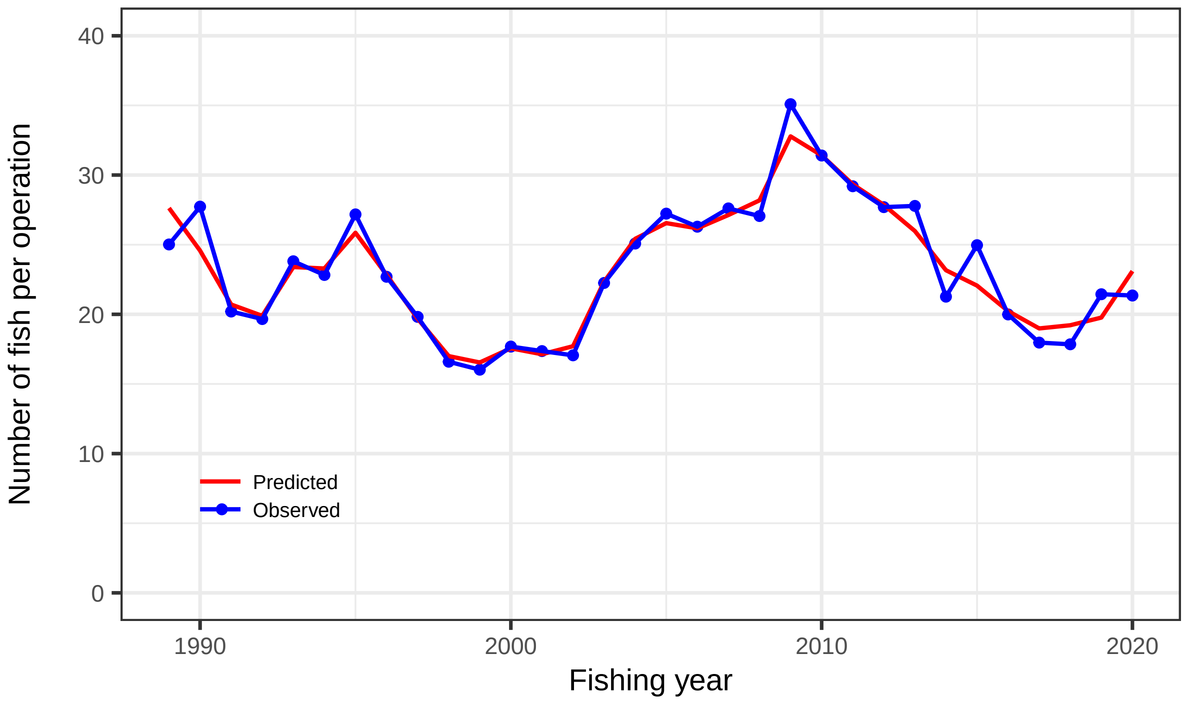

Figure C.2: Stock synthesis model (analysis 2) fit to standardised catch rates.

C.1.2 Age compositions

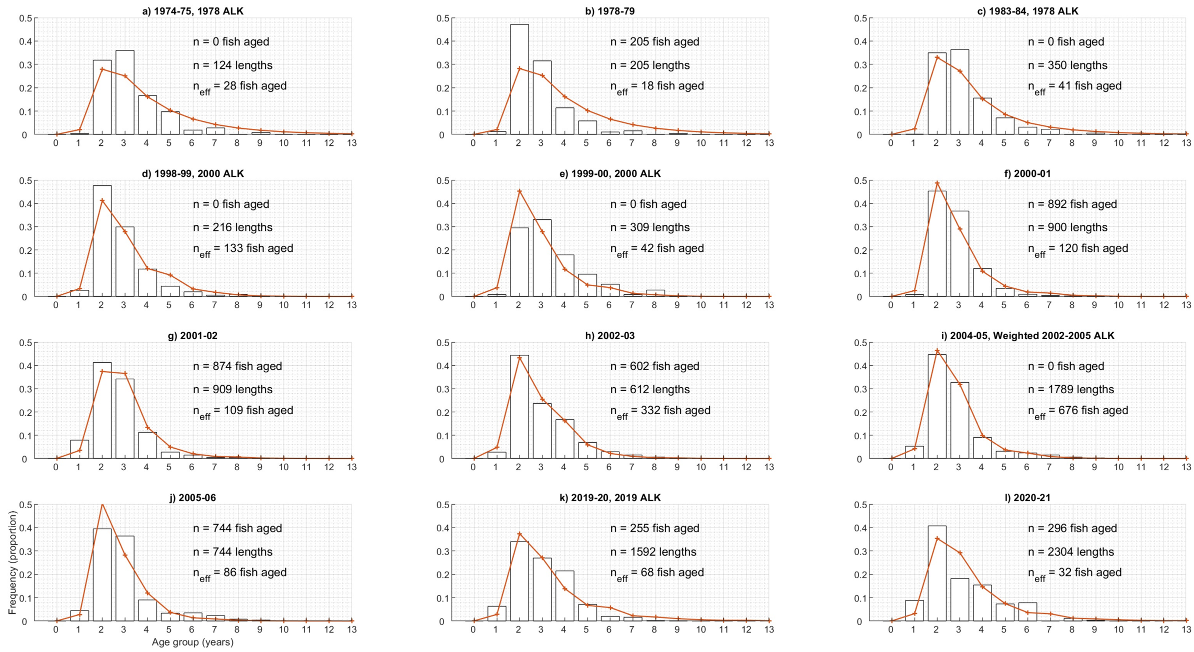

Figure C.3: Example custom model analysis 3 prediction of fish ages. The predicted model fits were similar for other analyses. Negative log likelihood = -180.9. n was the number of fish sampled. n_{eff} was the estimated effective number of fish sampled for the fit. ALK – age length key used.

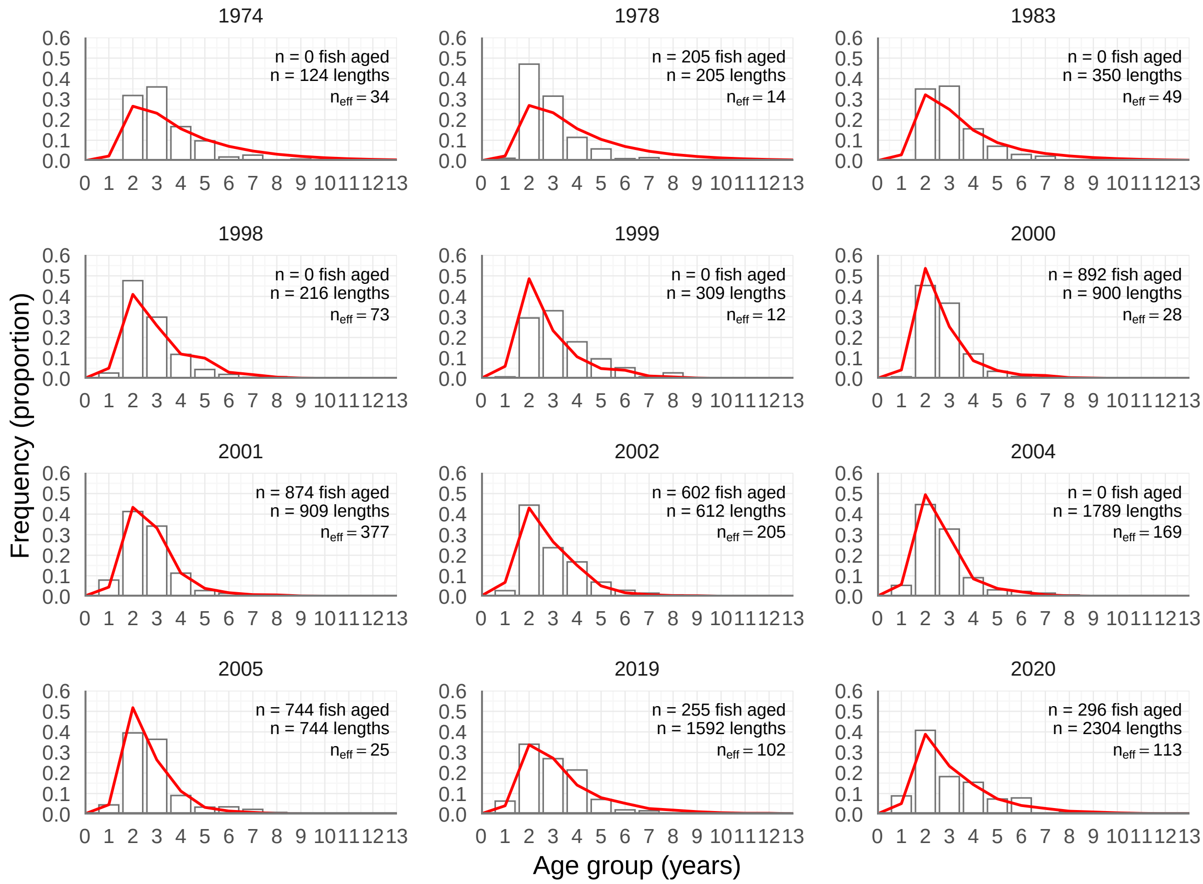

Figure C.4: Fits to age structures for the SS model. n was the number of fish sampled. n_{eff} was the estimated effective number of fish sampled for the fit. The measures of n_{eff} summarised the level of model fit (higher better and lower worse), but the methodology was different and not comparable to the custom model effective sample sizes.

C.2 Harvest rates

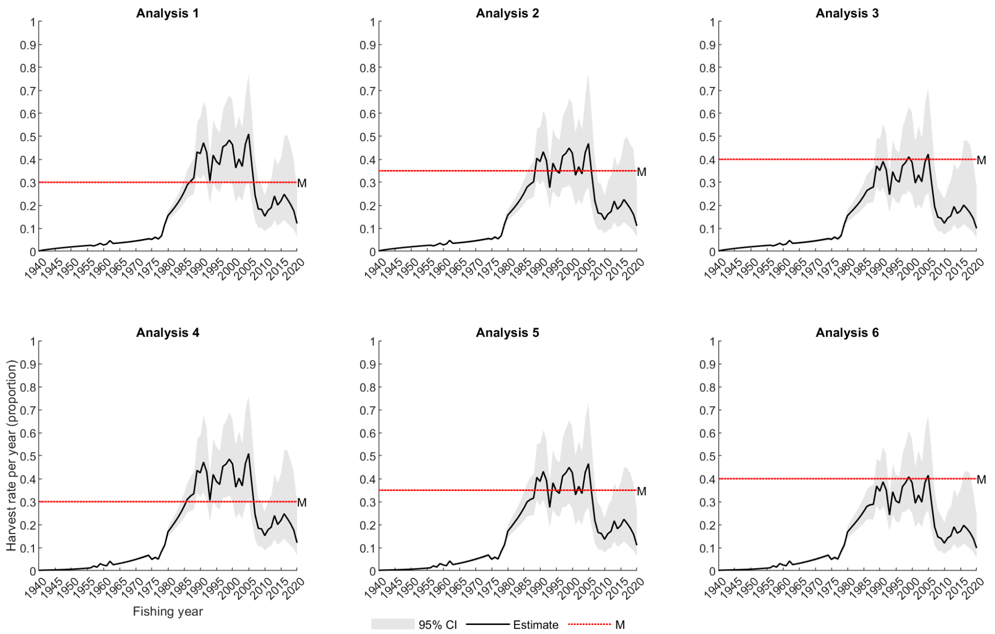

Figure C.5: Time series of harvest rates (fraction of exploitable biomass) from the custom model.

C.3 Recruitment deviations

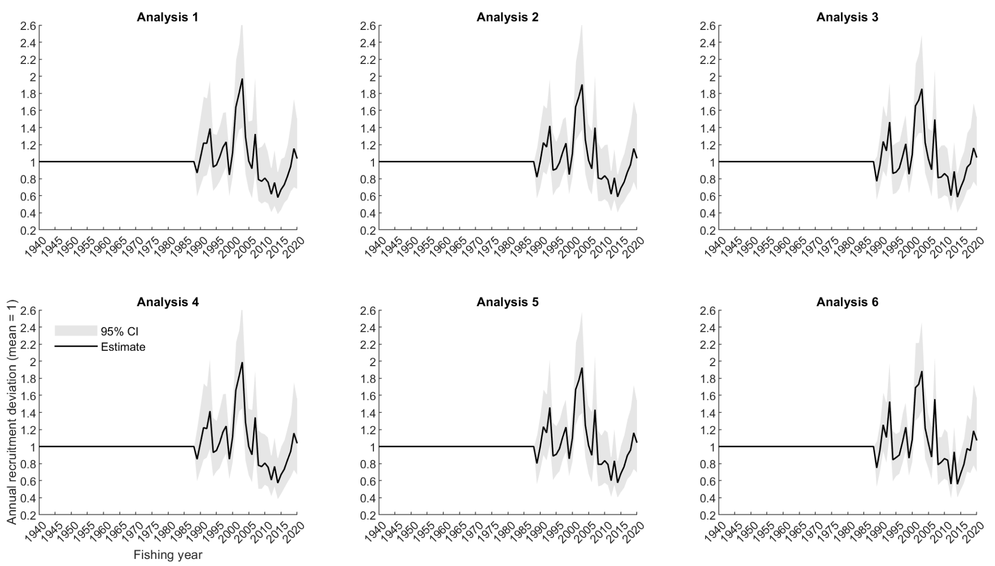

Figure C.6: Time series of recruitment deviations from the custom model. Estimates were similar across analyses and demonstrated consistency in results.

Appendix D Past assessments and history

D.1 Biomass and historical management plot

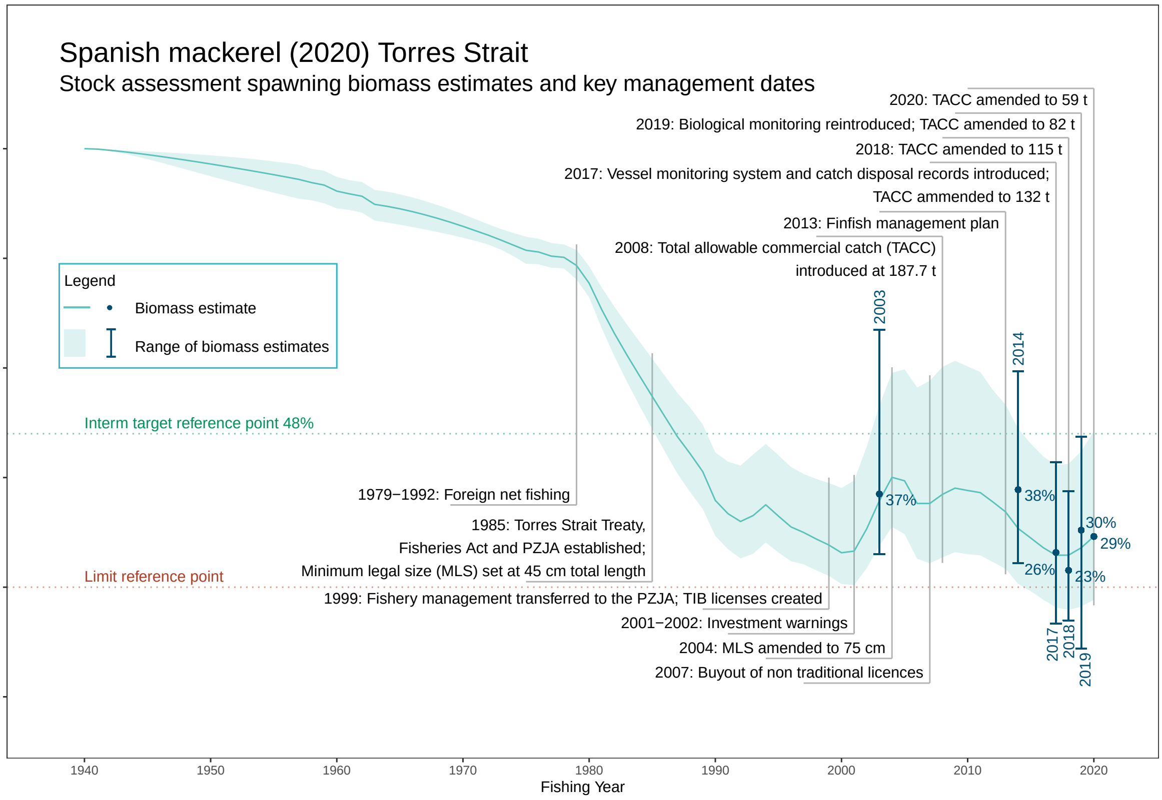

Figure D.1: Spanish mackerel biomass estimates by fishing year, with past stock assessment results and key fishery dates.