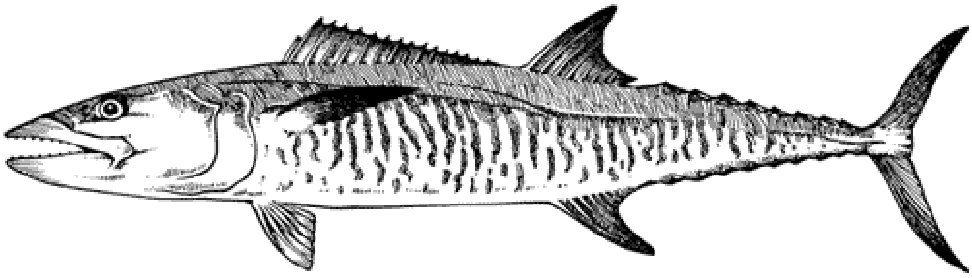

Torres Strait Finfish Fishery:

Spanish mackerel stock assessment, with data to June 2022

Year Two Report

AFMA Project Number: 2020/0815

December 2023

Queensland Government
Australian Government
Australian Fisheries Management Authority
Sea Sense

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Contents

Summary

This stock assessment indicates the Torres Strait Spanish mackerel spawning biomass was at 31 percent of unfished biomass in the 2022 fishing year.

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 in 2019 (Figure E.1, Appendix). All stock assessments were overseen by the Torres Strait Finfish Fishery Resource Assessment Group (TSFFRAG).

This stock assessment was conducted on financial (fishing) years. The convention for labelling fishing years was to refer to the year in which the fishing year ends. For example, fishing year 2022 in this assessment referred to the period July 2021 to June 2022. This was a change from previous Torres Strait assessment reports (which referenced the start year), to now be consistent with the labelling convention used by Fisheries Queensland.

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 2022. The key data inputs were: 1) estimated total harvests for all years, including all fishing sectors and foreign fishing, 2) catch rates from the Sunset fishing sector for 7 years between 1975 and 1983, and for 33 years since 1990, and 3) fish age frequencies from 13 years since 1975; see glossary for Sunset description.

The Torres Strait Spanish mackerel fishery commenced in 1941 (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 1980 and 1992, possibly harvesting in order of 100 t of Spanish mackerel per year. Net fishing for mackerel was and is illegal in the Torres Strait.

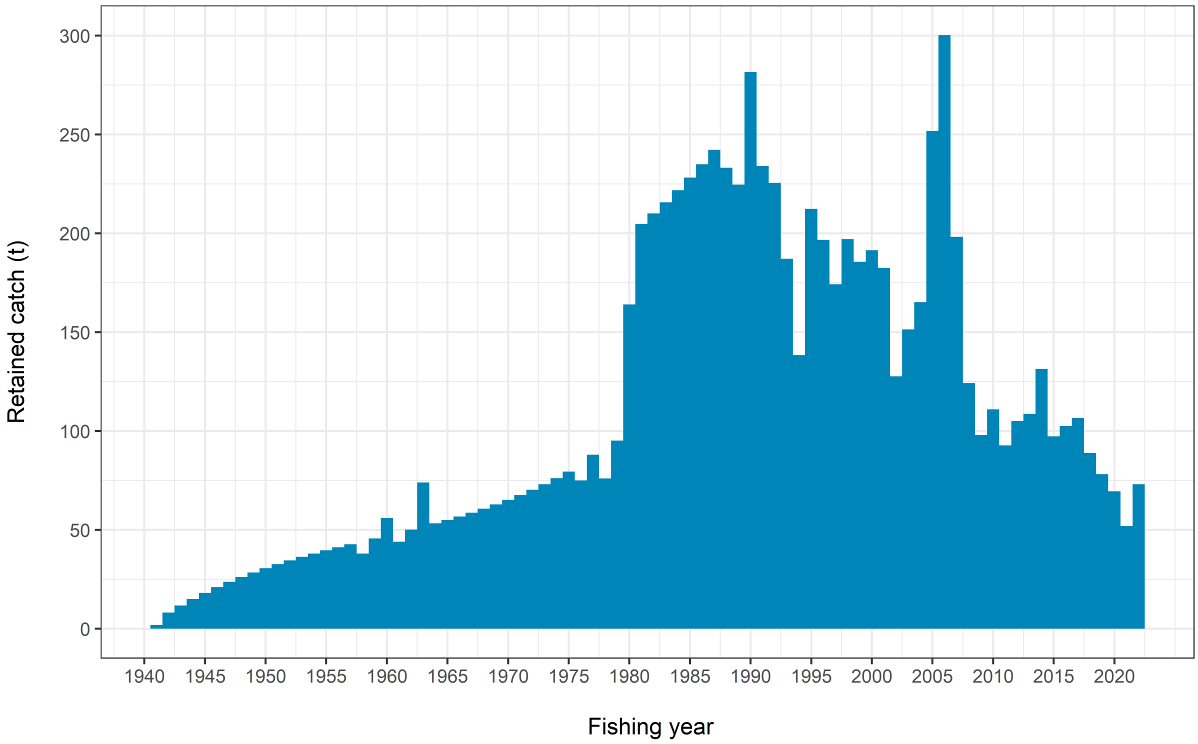

Figure 1: Annual estimated retained catch of Torres Strait Spanish mackerel between 1941 and 2022.

Spanish mackerel harvest peaked at 300 t in the 2006 fishing year, prior to fishery quota and allocation reforms. Since the fishery adjustments in 2008, harvests have declined to below 132 t per year. In 2022, 73 t of Spanish mackerel (73 percent commercial take) was harvested. Over the last five fishing years, up to 2022, the annual harvest averaged 72 t per year, with commercial fishing taking about 79 percent; commercial Sunset boats averaged 54 t per year and commercial traditional inhabitant boats (TIB) averaged 4 t.

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. Once standardised (mean number of Spanish mackerel harvested per Sunset operation day) the annual catch rates varied as follows (Figure 2):

- The longer time series of Sunset catch rates since 1990 showed a general decadal pattern of increase or decrease.
- Catch rate were depressed between 1997 and 2003.
- Consistent increases were observed from 2004 to 2010.
- Catch rates fell nearly 50 percent between 2010 and 2019.
- Catch rates since 2020 improved by about 62 percent.

Seperately recorded historical catch rates, by a key Sunset vessel, showed a decline in 1983 (Figure 3).

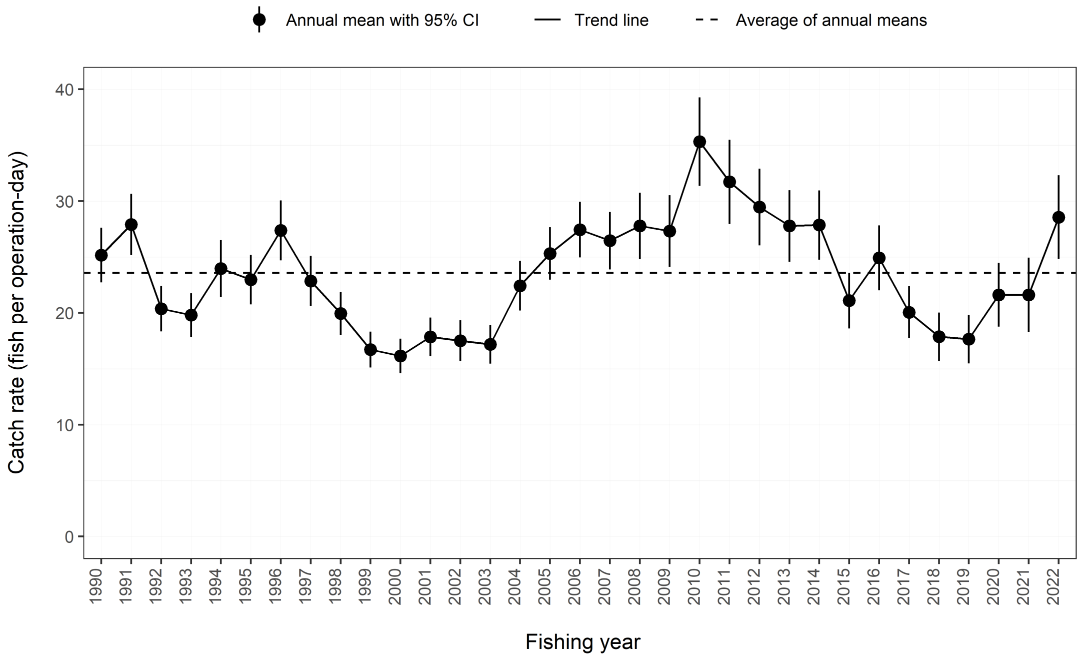

Figure 2: Annual standardised catch rates for Sunset-sector line-caught Torres Strait Spanish mackerel between the fishing years of 1990 and 2022.

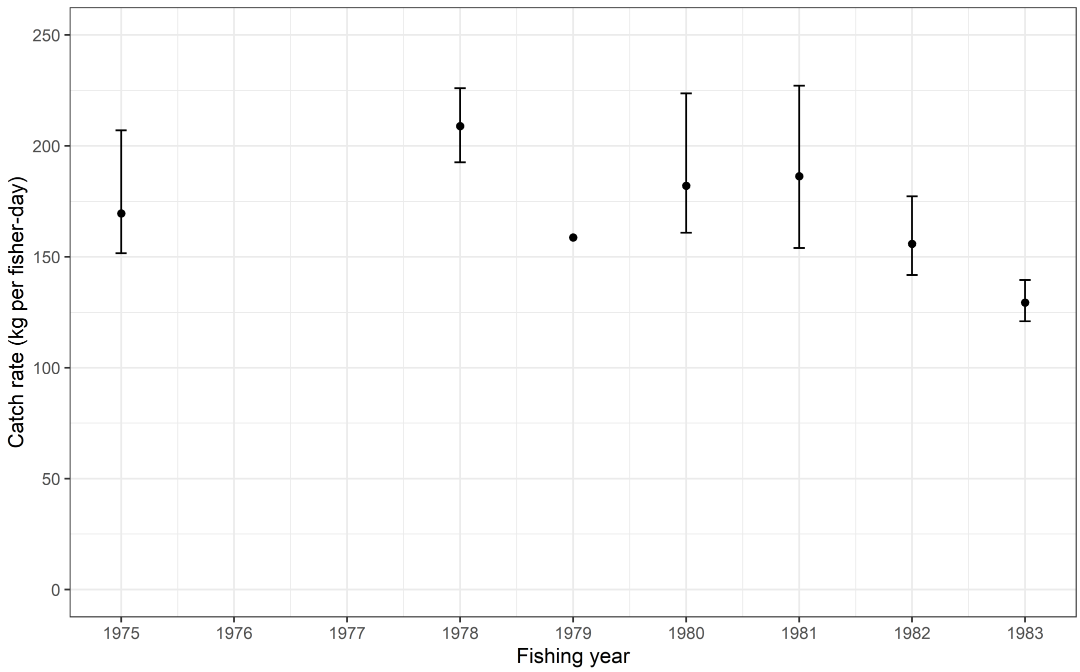

Figure 3: Pre 1983 annual catch rates of Torres Strait Spanish mackerel reported by a single Sunset line-fishing vessel. The mean was nominal kg of whole fish per fisher per day. The error bars show the reported range of trip means. The data was extracted from Figure 1 in McPherson (1986). No catch rate range was published for 1979. The coefficient of variation (relative standard deviation) calculated for these data was about 19 percent.

The stock assessment models, across analyses of different natural mortality and harvest, estimated the median spawning biomass of Spanish mackerel in 2022 at 31 percent of the estimated unfished spawning biomass at the start of the fishery in 1941 (Figure 4). The biomass estimate resulted from high harvests between 1981 and 2007, the downturn in Sunset catch rates 2010–2019 and the resulting patterns of recruitment variability signalled by the data.

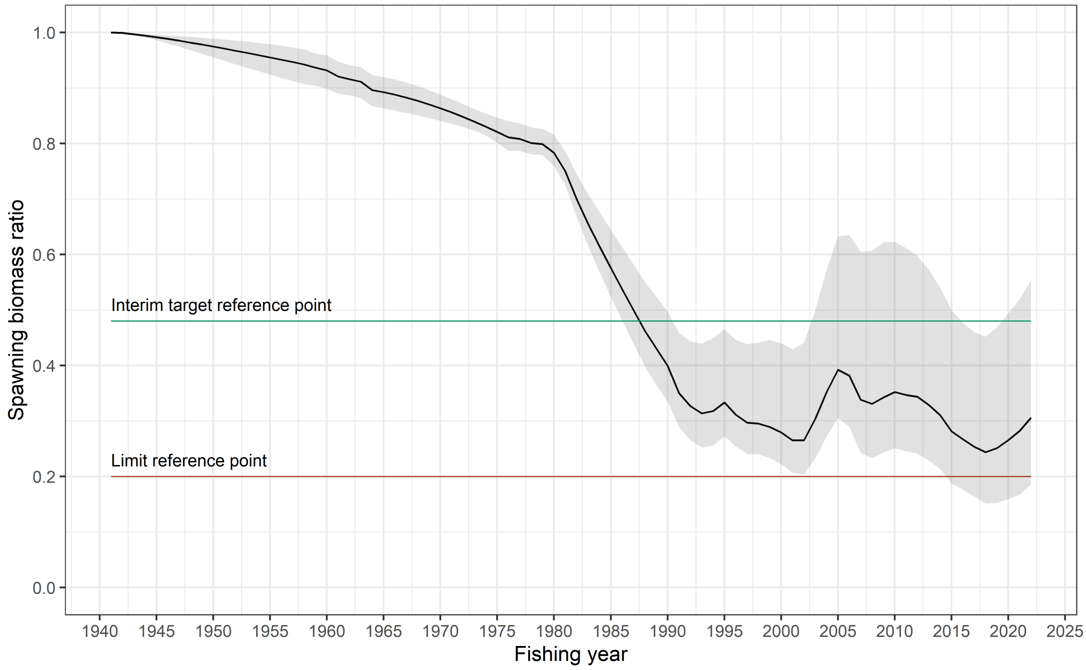

Figure 4: Estimated spawning biomass ratio for Torres Strait Spanish mackerel, from 1941 to 2022.

The 2023–2024 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 low risk of reducing the spawning stock to a level below the 20% biomass limit reference point.

The assessment completed comparisons between the custom-built population model and the packaged stock assessment software stock synthesis (SS). The SS estimate of median spawning biomass ratio in 2022 was also 31% compared against the custom model developed by the Department of Agriculture and Fisheries. SS diagnostics and results were consistent and satisfactory, supporting further adaptation of SS and the provision of a streamlined stock assessment from 2023 after TSFFRAG review.

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

Indicator	Median estimate
Biomass$^{\diamond}$ (relative to unfished) in 2021–2022	31% (19% to 55%)
Interim target$^{\odot}$ biomass (relative to unfished)	48%
Limit biomass reference point (relative to unfished)	20%
Biomass (relative to unfished) at MSY*	39%
Harvest taken in 2021–2022	73 t
$F_{MSY}^{\star}$ harvest for 2023–2024	136 t
$F_{40}^{\star}$ harvest for 2023–2024	132 t
$F_{48}^{\star}$ harvest for 2023–2024	102 t
$F_{50}^{\star}$ harvest for 2023–2024	95 t
$F_{60}^{\star}$ harvest for 2023–2024	67 t
Overfishing limit$^{\wedge}$	102 t
RBC† for 2023–2024 to achieve interim target biomass	95 t
RBC selected to achieve target biomass within	12 years

$^{\diamond}$ Biomass (B) was defined to be spawning egg production biomass, measured as a percentage of unfished estimates in 1941. The 95 percent confidence interval is 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 3.3 and Figure D.18.
$^{\wedge}$ 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 in 12 years.
† 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 authors proudly acknowledge First Nations (Aboriginal peoples and Torres Strait Islanders) and the Traditional Owners of the country on which we live and work.

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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).

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 similar as fish abundance declines.
IUU	Illegal, unreported and unregulated fishing. For example, foreign fishing.
Kai kai	Traditional islander take of fish for food.
kg or g	Weight measured in kilograms or grams.
MCMC	Markov chain Monte Carlo.
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 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, 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. They are operated by non-traditional inhabitants. https://www.pzja.gov.au/sunset-fishing-licence
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.
VMS	Vessel monitoring system provides AFMA information to monitor commercial vessel position, course and speed.
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 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 5).

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 1941–2022. Fishing years were equal to financial years. The labelling convention was changed in this report. For an example, labelling of the fishing year from 1 July 2021 to 30 June 2022 was 2022 or 2021–2022. 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 Strait Spanish mackerel, the initial reference year for original (unfished) population size was 1940–1941 (Begg et al. 2006).

The outputs from this assessment provided a range of values for potential interim target reference points, to support the continuing quota setting process used by TSFFRAG 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 1941 level.

Objectives of the year two 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 2022 and forecast the RBC for the 2023–2024 fishing year.
- Work in collaboration with AFMA and the TSFFRAG. This included producing results for TSFFRAG input and review, and creating a summary presentation for TSFFWG.
- Produce stock assessment results using both the DAF custom-built population model and the stock synthesis (SS) software (Methot et al. 2013). Both models will analyse all data inputs defined by TSFFRAG, covering uncertainty in natural mortality and historical harvests for RBC options. The results will be evaluated by TSFFRAG, to guide transition to SS, and streamline the stock assessment. In year one, the initial SS comparison was run on a single base case dataset, and produced similar results compared to the custom model.
- Commence the stock assessment streamlining. Computer code will be developed to complete analyses and publish results.

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 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).

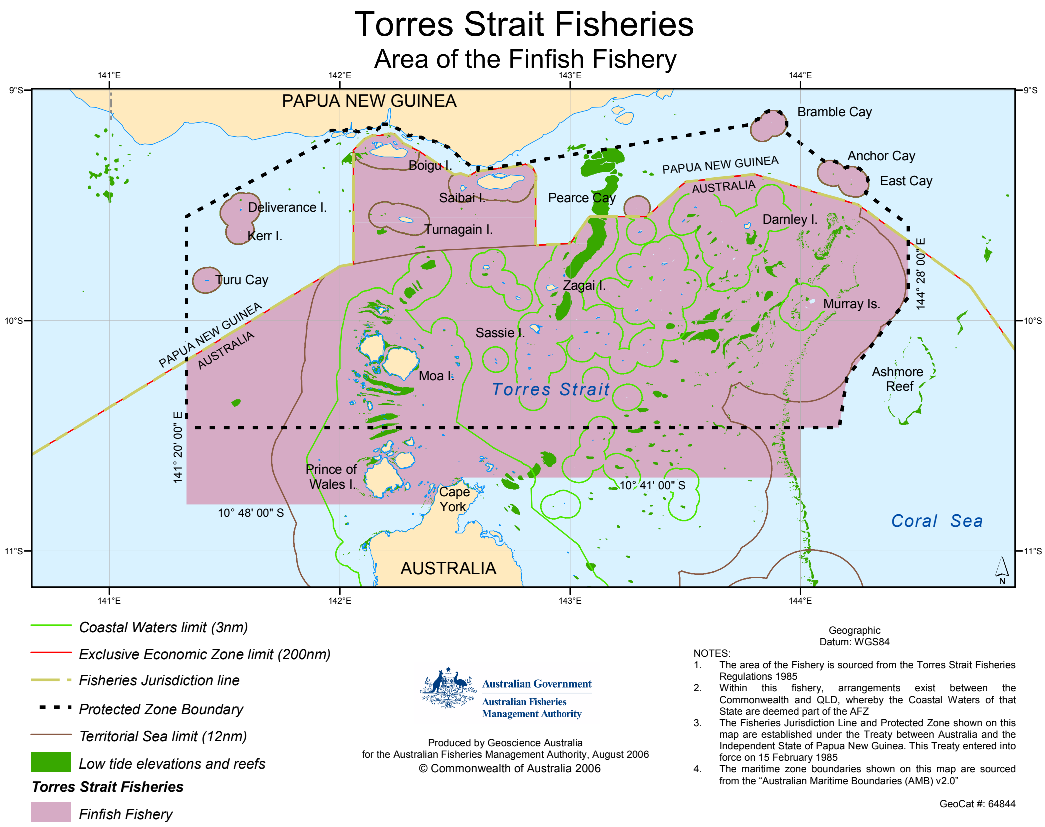

Figure 5: The management zones of Torres Strait finfish fishery; sourced from the PZJA website.

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 (described in Appendix B). They frequent offshore reefs, shoals and bays, and sometimes taken 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 others 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 5). These aggregrations 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 are assumed to reside in these surrounding waters, with published stock-structure research recommending that Torres Strait Spanish mackerel are a discrete population for fishery management (Buckworth et al. 2007).

In 2022, new genetic research confirmed this stock-structure recommendation, that Torres Strait waters appropriately formed the spatial boundary for stock assessment – Spanish mackerel in the Torres Strait were genetically separate from the Gulf of Carpentaria and Australia's east coast (Williams et al. 2022).

The Australian area of the Torres Strait protected zone is an important economic and traditional food source for all communities (Begg et al. 2006). Historically, all fishing sectors have harvested between 50 and 300 t of Spanish mackerel per year; estimated non-commercial harvests were small at around 20 t per year.

Access to the commercial fishery is 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, given future leasing amounts might be reviewed) (PZJA 2022b). All 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 5). Spanish mackerel catch shares are 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 are 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).

Past stock assessments of Spanish mackerel up to 2020–2021 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 that 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 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. 2020a; 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 two 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).
	1975–1983	Sunset historical catch rates from one fishing operation.
	1989–2022	Sunset harvests and catch rates from compulsory logbooks.
	1989–2017	TIB harvests from docket (doc) book records.
	2018–2022	CDR version TDB02 records for Sunset harvests and TIB harvests and catch rates.
Traditional harvest	1989–2022	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.
	2020–2022	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 1990 were from three sources:

1. Compulsory logbook (Log) records for Sunset operations 1990–2022,
2. Docket (Doc) book records for TIB landings 1990–2018, and

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

The CDR records provided information to verify fish catch weights from Sunset and TIB fishing operations. The CDR reports calculated annual harvest tonnages since 2019 (for the Sunset CDR summary, see Appendix C Table C.2). Annual harvests pre 2019 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 matched 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 describe 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 only. In total, these filters removed about 1–2% of catch rate data (see data selection report, Appendix C.5.3).
- The tallied number of tenders used each day by each fishing operation was derived 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 1990–1993. However, TSFFRAG considered a scenario with tender data for catch rate analysis, and represents a data input scenario in stock assessment.

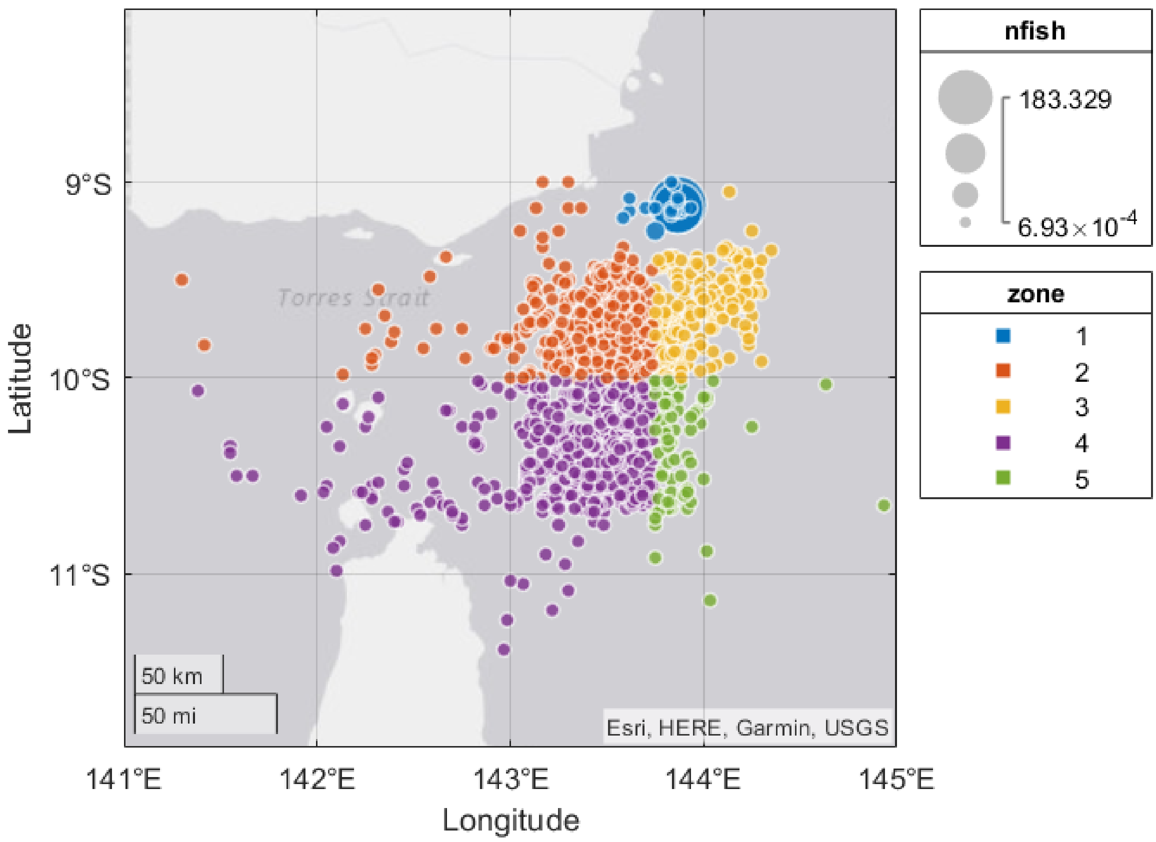

Figure 2.1: Map of the Torres Strait zones illustrated by colour (Bramble Cay zone 1 - blue, Ugar zone 2 - orange, east/anchor zone 3 - yellow, dugong zone 4 - purple, and southeast zone 5 - green). Map circles indicate the numbers of Spanish mackerel harvested by Sunset operations 1990–2021 at unique logbook latitude and longitude coordinates. Larger circles showed the main harvest locations, such as 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 numbers of 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 = 6828 logbook records) and 1.608 kg was the mean conversion for fillets to whole fish (O'Neill et al. 2018b).	$n = 0, w_{old} = 0,$ $c > 0$
$n = w_{new}/wt_y$		$n = 0$

The Torres Strait wind data was sourced 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 π/2 radians = East, 180 degrees or π radians = South, and 270 degrees or 3π/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):

$$s1cos = cos(2\pi d_y/T_y),\ s1sin = sin(2\pi d_y/T_y)$$
$$s2cos = cos(4\pi d_y/T_y),\ s2sin = sin(4\pi d_y/T_y)$$
$$s3cos = cos(6\pi d_y/T_y),\ s3sin = sin(6\pi d_y/T_y)$$

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 the same as for 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 C.6, Appendix C.5.1).

2.3 Catch rates

The standardisation of catch rates (mean catch of Spanish mackerel per operation-day) 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 new data were available since the 2014 calendar year (O'Neill et al. 2018a). No increase in fishing power was assumed 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 1990 to 2022 (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 for numbers of fish (values on the scale of the linear predictions were back transformed using the link function). 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 before 2019. Similar GLM and prediction methods were employed for TIB catch rates of Spanish mackerel as for Sunset.

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, like in the Sunset analysis, were not significant in the short time series of data. No fishing-power offset was applied.

The R equation form of the commercial TIB GLM was:

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

where the GLM type and variables were:

- *kg*: daily harvest per client-boat of Spanish mackerel (kg)
- *year*: fishing year 2019 to 2022 (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 client-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 weights 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 13 years. Sample details are in Table C.3 (Appendix C.3).

Since 2020, 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 sample numbers are maintained to be the same in each year 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 (as per the regions defined in the AFMA catch disposal records) 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 for the data since 2020 Table C.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 2020, monitoring was conducted only from Sunset fishing operations, who mostly fished around 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 noted that some years of fish data had different sampling aims, 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 (Table C.4) were inspected in each year where available (Buckworth et al. 2021).

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

Fishing 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
2021-22	7.30	2.18	6.98	1787	DAF – age and lengths
All years	7.47	2.50	7.00	981	Summary means

2.5 Population models

2.5.1 Custom-built

The population dynamic model calculated numbers of Spanish mackerel by year and age group. The 1941–2022 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 used 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 1990 was necessary to fit the cycles of annual harvests and catch rates. Statistically, this added 33 estimated parameters for the data in this assessment.

The calculations of the fishery reference points were by solving the equilibrium annual harvest rates (u = 1-exp(-F)). The harvest rates were estimated 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.

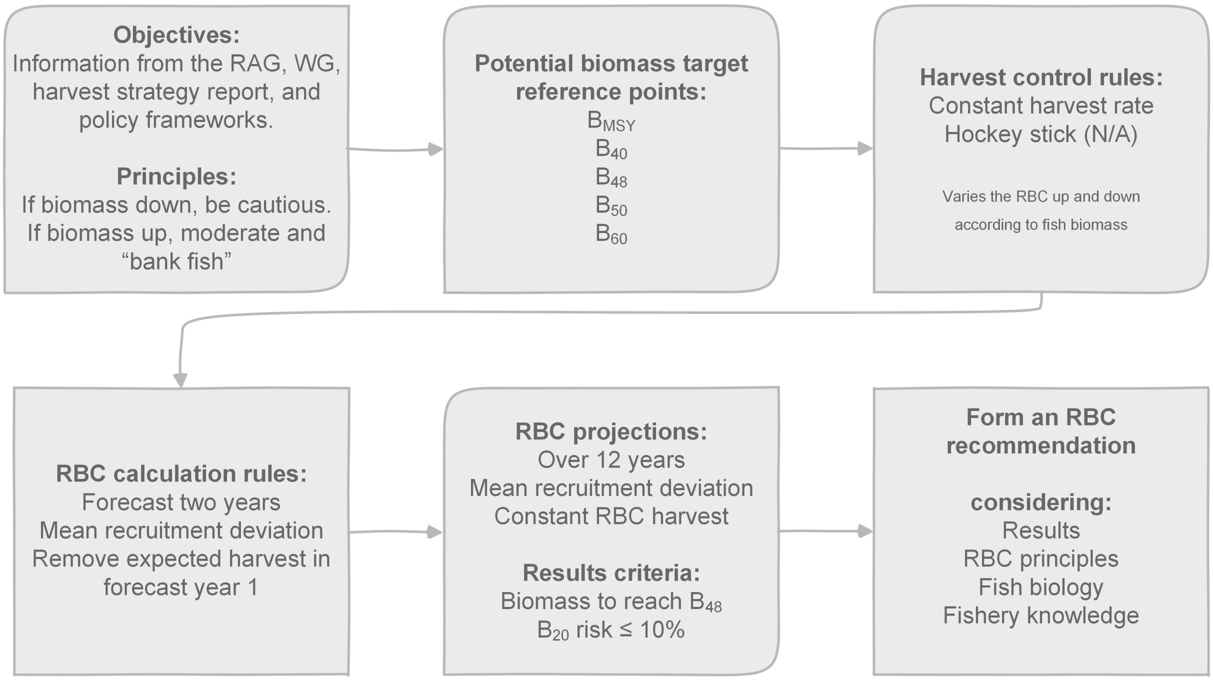

Figure 2.2: Flow chart of the considerations in RBC calculation and recommendations. Hockey-stick harvest control rules were not applied.

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 Australian offshore waters, 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 through differentiation to generate confidence intervals on estimates.

For the SS analyses, an annual age structured model was defined through the data inputs and model settings, requiring large 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, fish size, reproduction, and functions for fish recruitment, selectivity and catchability.

The SS software was operated through Rstudio/R using code 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 and jitters 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 long based on the amount of data (> 200 lines of code). The file also defined the number of years, genders and zones were combined as a single sex and area model, a single combined fleet and units kg of the harvest data.
- The ‘Control file’ specified the model to be fitted to the data (selectivity, recruitment, etc.) as well as how the data was to be statistically weighted. This file was about 300 lines of code including comments. Example settings included parameters for natural mortality, fish size, 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} were specified.

SS was written in AD Model Builder (ADMB). 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. 2022).

SS was setup with similar annual data inputs and biology as in the custom-built model. Scenarios were run as listed in Table 2.4. This was to enable comparisons between models. The SS software version used was SS 3.30.19.01.

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

- The fishery began from an unfished state in 1941.
- The fraction of fish that were female or male at birth was 50%. The model combined the sexes.
- Average fish fork length at age 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 1990 and stochastic with recruitment deviations thereafter.

Fecundity, as number of eggs, was specified as a function of average fish weight at age (Begg et al. 2006). The quadratic equation for Torres Strait female Spanish mackerel gonad weights, used in the custom model, did not fit the formula options in SS. Options for reformulating the gonad weight equation in SS will be reviewed.

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 1941.
- 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 removal of fish from the population due to causes not associated with fishing (examples include predation or old age).
- 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 1990. The log scale deviations were estimated to have a mean of zero.
- The designated level of recruitment variability (log sigmaR standard deviation) was fixed at 0.3 based on previous estimates.
- The catchability parameter (as simple closed form (float) q) was calculated in the model with no set priors.
- Data inputs were given approximate equal weighting in the SS model. A Francis adjustment was applied to the age compositions within SS (Francis 2011), to achieve a suitable effective sample size (and thus relative weighting).

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, a number of exploratory analyses were conducted (Table 2.4). Analyses were advised by TSFFRAG.

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 C.1).
- Three rates of fish natural mortality M (0.3, 0.35, 0.4 per year).

The exploratory assessments considered the influences of (Table 2.4):

- Including TIB standardised catch rates, which had a large confidence interval in 2022 (analysis 7).
- Halving the assumed IUU harvest (analysis 8).
- Changing the Sunset catch rate standardisation for the possible effects of tender data post 2003 (analysis 9, data is illustrated in Figure 3.3). Tender effects pre 2004 were assumed constant, as the earlier tender data was incomplete.
- Including only the Sunset catch rate index, standardised without tender data (analysis 10). This was labelled analysis 2 in the last stock assessment report (O'Neill et al. 2022). TIB and historic Sunset catch rates were excluded.
- Increasing model fits to Sunset catch rates. From the analyses, it appeared that Sunset catch rates in 2021 and 2022 signalled a greater increase in stock compared to the signal from the fish age data. Annual fish age data can contain important information from a number of years and inertia (slow to change). Using the custom model, select analyses were rerun by multiplying the corresponding age negative log likelihood component by an emphasis factor (<1) to test increasing the catch rate fit compared to the age data (Methot et al. 2022).

Median results, such as for the biomass ratio and RBC tonnages, across analyses 1–6 were inferred for reporting on the status of the fishery and stock. This was done to address and equally consider different hypotheses and uncertainties that might be present from changed data inputs or model settings. Use of a median statistic mitigated against possible skewness and variance between individual analyses. This simple type of model averaging or generalisation, for a range of plausible analyses, was adopted by TSFFRAG and followed the concepts by Millar et al. (2015). Klaer (2018) also stated:

- model structural uncertainty is normally greater than that estimated within any selected model scenario.
- Model averaging and ensemble models are gaining favour to more correctly account for stock assessment uncertainty (e.g., see Millar et al. 2015).

Table 2.4: Summary of the stock assessment analyses. Inclusions of natural mortality, harvest time series, and different catch rates for Sunset (1990–2022, standardised and always included but generated with or without tender data), standardised TIB catch rates (2019–2022) and nominal catch rates for historic Sunset fishing (1975–1983) were noted. "Yes" indicated the fitted data, and "No" indicated the data aspect was excluded from analysis. Steepness was estimated in all analyses. Different age data likelihood weights (lambdas) were explored in the custom model.

Analysis	Natural mortality M	Harvest series	Sunset with tender data	TIB used	Historic Sunset used	Lambdas†
1*	0.30	Polynomial, IUU	No	No	Yes	1.0, 0.7
2*	0.35	Polynomial, IUU	No	No	Yes	1.0, 0.7, 0.5
3*	0.40	Polynomial, IUU	No	No	Yes	1.0, 0.7
4*	0.30	Logistic, IUU	No	No	Yes	1.0, 0.7
5*	0.35	Logistic, IUU	No	No	Yes	1.0, 0.7
6*	0.40	Logistic, IUU	No	No	Yes	1.0, 0.7
7	0.35	Polynomial, IUU	No	Yes	Yes	1.0, 0.7
8	0.35	Polynomial, half IUU	No	No	Yes	1.0, 0.7
9	0.35	Polynomial, IUU	Yes	No	Yes	1.0, 0.7
10	0.35	Polynomial, IUU	No	No	No	1.0

Analyses 1–6: * indicates the RBC core stock assessments with lambda = 1.0. Other analyses > 6 were exploratory scenarios. Lambdas†: Analyses 1–9 were rerun in the custom model only using a different emphasis (lambda) data weighting of 0.7 on the age frequency negative log likelihood. An age data weighting of 0.5 was also explored, only in analysis 2, to further understand the effects of down weighting the age data negative log likelihood component. The default lambda data weights were otherwise 1.0 for no adjustments.

3 Results

3.1 Model inputs

Figure 3.1 summarised the time-series data available for input into stock assessment. The abundance index data were commercial (fishery dependent) catch rates of Spanish mackerel. Sunset catch rates 1975–1983 and 1989–2022 were the primary indices, fitted as a non-continuous times series. TIB catch rates were included in exploratory analyses (Table 2.4)

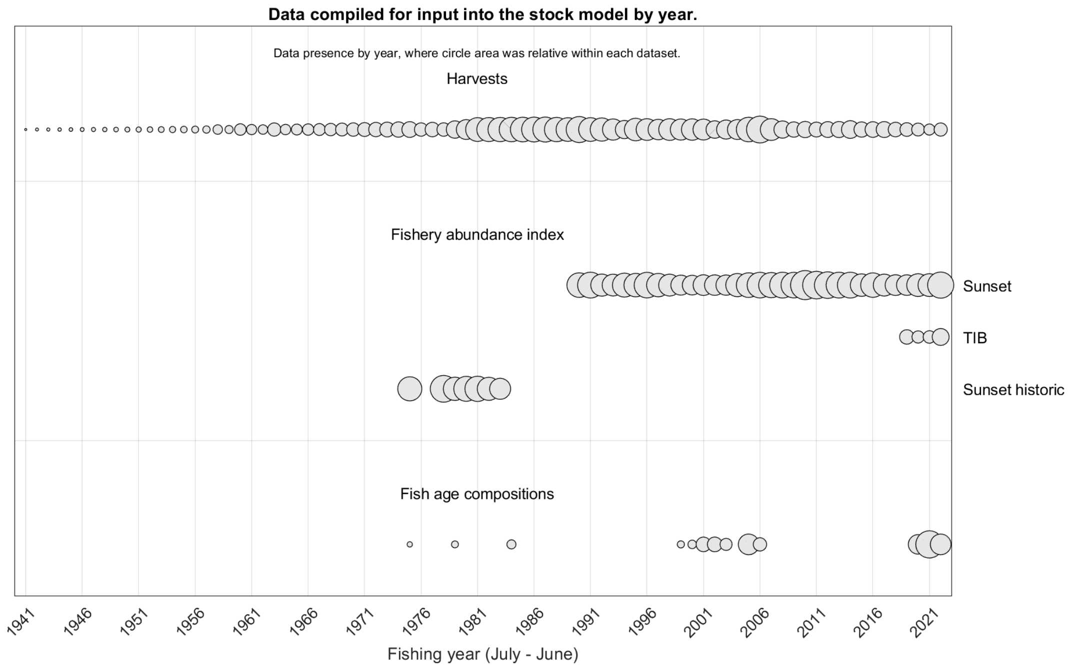

Figure 3.1: Data compiled for input into the model by year for each category of data type for the Spanish mackerel stock assessment.

3.1.1 Harvest

The annual estimates of Spanish mackerel harvest considered data from all fishing sectors (Appendix C.1). Historical gaps in this data resulted in different scenarios to estimate harvests (Figure 3.2). This was to examine different annual patterns of historical fishing. Data input into stock assessment combined harvests across all fishing sectors, given the sector similarities of line fishing and fish age-length data. There is no discard catch.

From 1941–1979 annual harvests built steadily to around 100 t per year (Figure 3.2). The two polynomial and logistic estimates varied by only 20–30 t in these years.

Estimated harvests increased between 1980–1989 (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 1980–1987, and then was tapered down annually to zero t by 1993. Half of the IUU estimate was considered for exploratory analysis only.

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 discussion by TSFFRAG and with input from several sources (Buckworth et al. 2021).

Since 1990, Sunset fishing dominated total harvests per year (Appendix C.1, Table C.1). Total harvests ranged 128–300 t per year between 1990 and 2007. 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 C.1, Figure C.2).

From 2008, 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 catch rates declined 2015–2020.

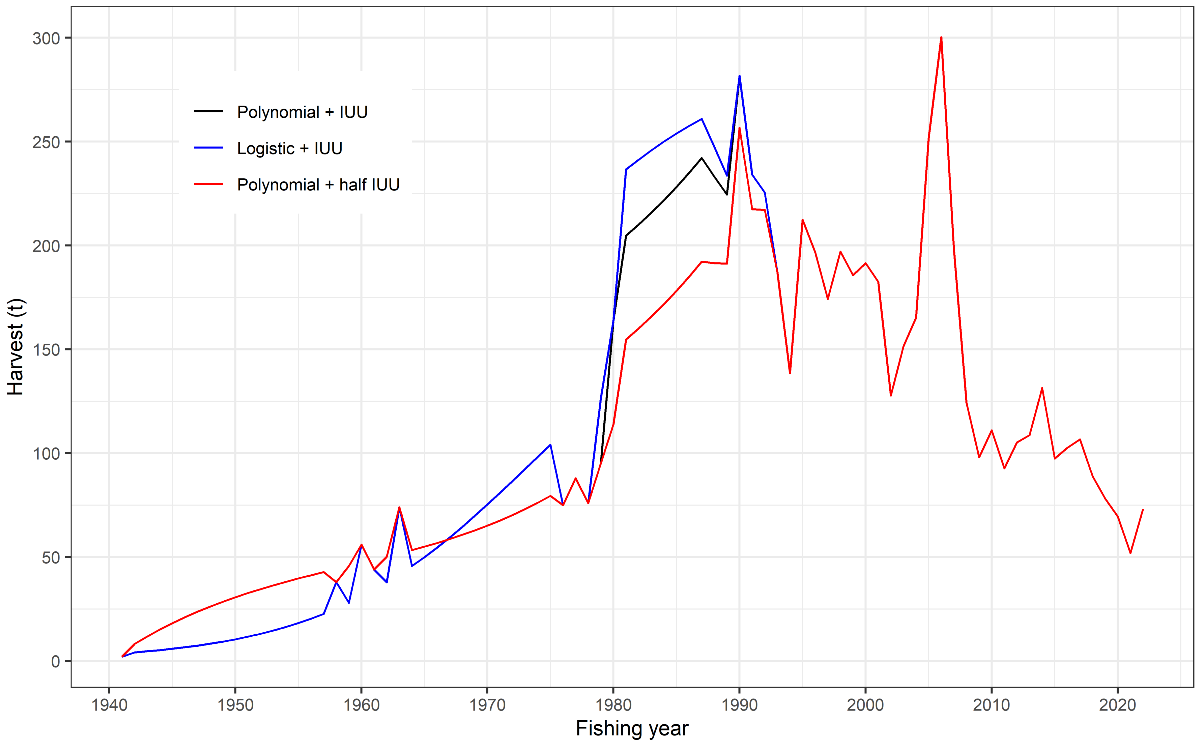

Figure 3.2: Estimated harvest (retained catch) taken by all fishing sectors since 1941 for Spanish mackerel. Three scenarios were considered prior to around 1990.

3.1.2 Catch rates

The Sunset standardised catch rate was important to inform on the annual proportional change in the exploitable Spanish mackerel population. This was the primary assumption in the stock assessment.

The assumption of proportionality was made only after employing a regression model. This was to standardise the variation in the data, that affected measuring trends in 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. Standardisation primarily accounted for efficiency changes in locations fished through time and between fishing operations (boats).

The nominal catch rate data (numbers of Spanish mackerel harvested per operation day) between 1990 and 2022 had skewed distributional properties. The catch rate nominal median = 15 fish per operation-day, mean = 24 fish and standard deviation = 26 fish (CV = 109%).Variance in catch rates was evident between fishing operations (Appendix Figure C.6), with some surprisingly large harvests above 100 Spanish mackerel per operation day.

The estimated Box-Cox λ parameter, for normalising and decreasing skewness properties in GLM residuals and data, had decreased to 0.15. The small λ, approaching zero and less than 0.33 for a cube-root transformation, suggested other GLM forms could also be tested. For example, a log transformation on the number of fish caught might normalise GLM residuals, or that a strong variance function with a log link such as the negative binomial distribution could be used (McCullagh et al. 1989).

Use of a log link function, either with over-dispersed Poisson or negative binomial variance properties, appeared appropriate to standardise catch rates. This was for consistency with past assessments, to maintain the same data assumptions and multiplicative effects, and to model appropriate likelihood weights between small and big catches per day; so that larger catches and trends in means (by a log link) are modelled, rather than medians (log transformation), to provide more insight on fish abundance (Leigh et al. 2014). The intention of the GLM analysis with log link was to leave the response data as is, in numbers of fish, and not to transform.

Figure 3.3 showed the Sunset standardised catch rate of Spanish mackerel for the fishing years from 1990. The following results were noted:

- Catch rates experienced temporal cycles, and statistical differences were detected between years (Table C.5, Appendix C.5.1). This started with a decrease between 1990–2000, then an increase to 2010, and a downturn to 2019. The catch rate increased significantly in 2020, levelled in 2021 and increased again in 2022. The scale (amplitude) in cycle from 2000 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 2010 and 2019. This trend was in all operators' data, particularly the declines in 2017–2019.
- 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 $\pm$ 2–4 fish. Statistically, these interval widths indicated annual differences in standardised catch rates could be detected.
- A box plot of the standardised residuals against fitted values was in Figure C.4 (Appendix C.5.1). The residual plot showed no lack of model fit, with relatively few large residuals ($\approx$ 5%) 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 37%, with a dispersion of 14.1 fish.
- Subset analysis of the 2004–2020 daily data (TSF01 logbook, using hours and tenders data per operation-day) produced catch rate indices that were similar and confirmed the later decline (Buckworth et al. 2021). Updated analysis by including daily tender data from 2004 produced similar results, but suggested higher standardised catch rates in 2012 and 2021 (blue line, non base case, in Figure 3.3).
- The inclusion of boat-operation, seasonal and fishing power terms were important in the standardisation of catch rates (Figure C.5, Appendix C.5.1). The 2017–2019, 2021 and 2022 years were associated with the better-catching fishing vessels, and therefore catch rates were standardised down to the benchmark average vessel (Figure C.7, Appendix C.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 C.6, Appendix C.5.1). Catch rates were higher from Bramble Cay (zone 1) compared to the other fishing zones. Only one fishing operation essentially fished in 2021, the highest catching (fishing power) boat (Figure C.6d), and the standardisation effect was large compared to the nominal catch rate (red line in Figure C.5).

In this stock assessment, TSFFRAG introduced additional historical Sunset catch rates 1975–1983 into the key RBC analyses (Table 2.4). The catch rates were nominal for one vessel that fished consistently in the Torres Strait for Spanish mackerel (McPherson 1986). The catch rates showed a decline in average fish weight landed per fisher day on an annual basis (Figure 3, in report summary). The decline was evident after 1980. This change coincided with IUU gill net fishing that entered Torres Strait waters (Buckworth et al. 2021).

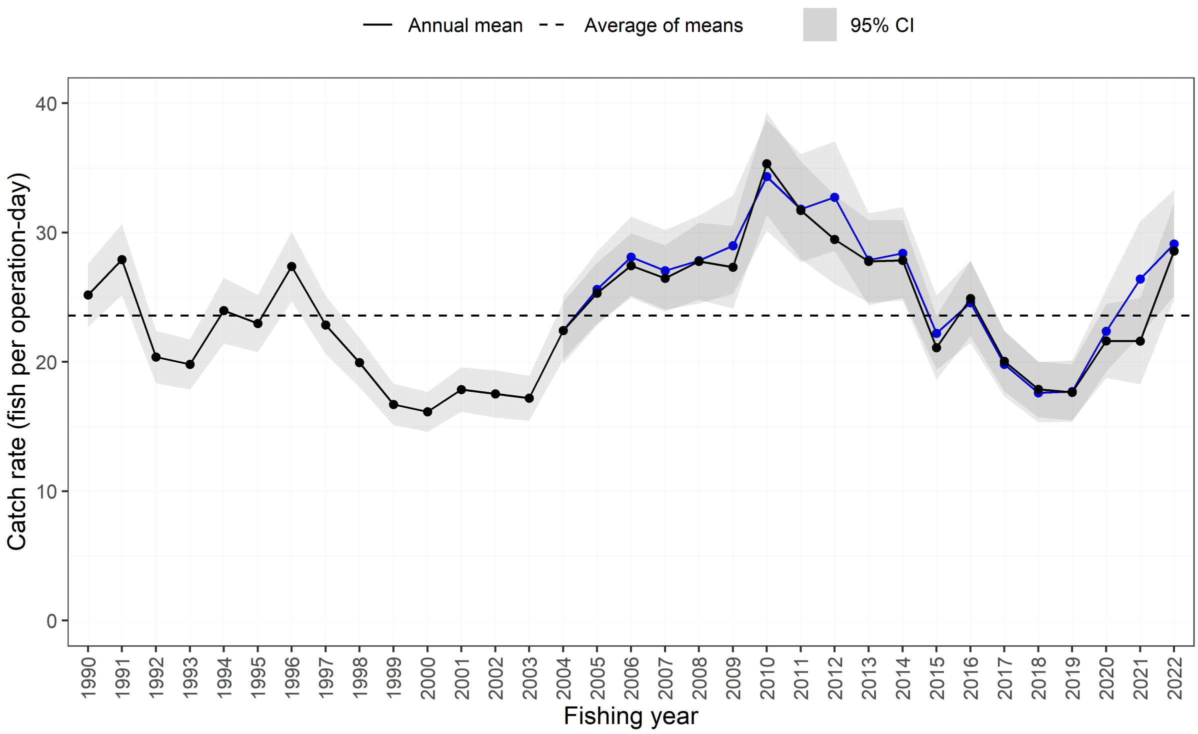

Figure 3.3: Spanish mackerel average catch rate (number of fish per Sunset operation-day) by fishing year. The base case standardisation (black line) included a fishing power (FP) offset, but excluded tender data which was incomplete over the time series. The blue line was the standardisation result for including tender data from 2004 (for stock assessment analysis scenario 9). Note the logbook version changed from 2003. The 95 percent confidence intervals (CI = 2 x standard error) on predictions typically extended 2–4 fish.

TIB-CDR reports on Spanish mackerel fishing varied between fishing years, with 104 client boat-days fished in 2019, 65 in 2020, 63 in 2021 and only 11 in 2022 (Table C.10, Appendix C.5.3). Generally, TIB fishing was not conducted around Bramble Cay waters.

Nominal catch rates varied with clients (Table C.10), and had skewed distributional properties. The nominal median was 34.5 kg per client boat-day, mean = 75.1 kg and standard deviation = 201.1 kg (CV = 268%). The skewness was highlighted by the estimated box-cox λ parameter, for normalising the residual properties of the data, being low at 0.04.

Limited standardisation was applied for the short 4 years of TIB-CDR catch rates. GLM methods were kept similar to the Sunset analysis. The standardised catch rates suggested a decline from 2019 to 2020 (Figure 3.4). The decline did not correlate with increased Sunset catch rates, who mostly fished at Bramble Cay (Figure 3.3). TIB catch rates in 2020 and 2021 were similar (Figure 3.4), as were the 2020 and 2021 Sunset catch rates. Statistical differences in catch rates between years were non-significant (Appendix C.5.2, Table C.7). Confidence in the 2022 mean catch rate, with few catch reports, was low (Figure 3.4).

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

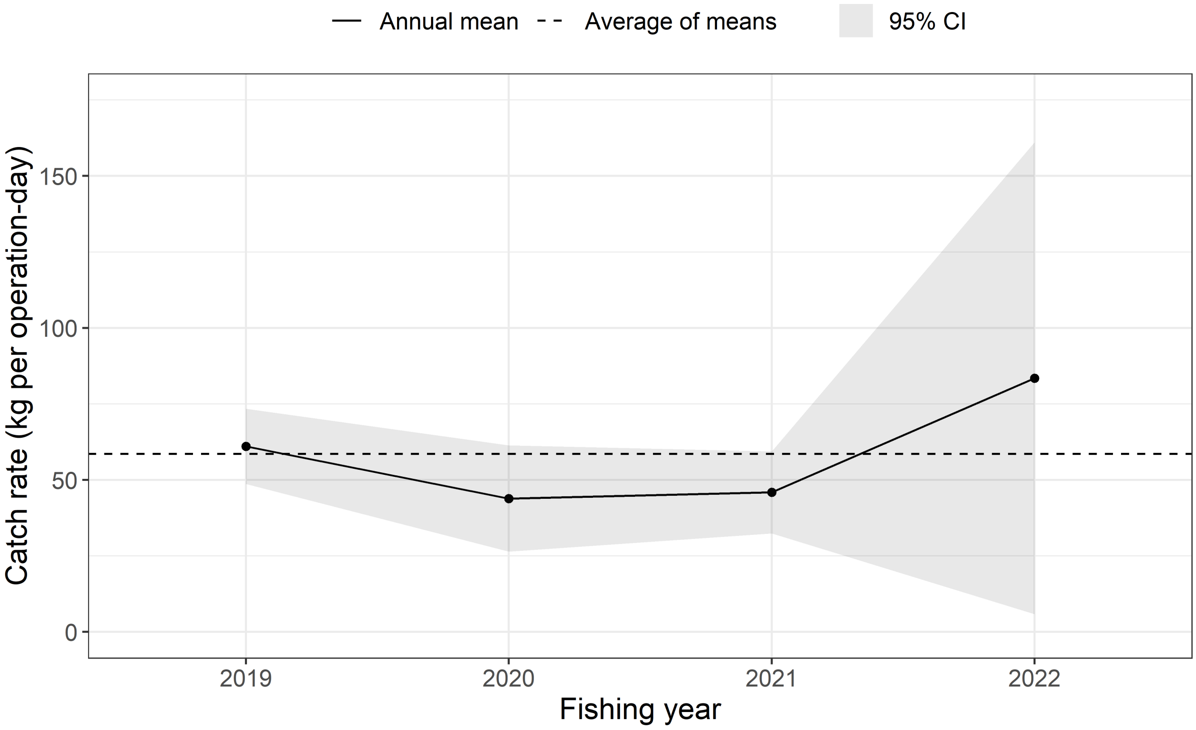

Figure 3.4: Standardised catch rates for commercial line-caught Spanish mackerel by the TIB sector.

3.1.3 Age composition

The Spanish mackerel age frequencies showed limited numbers of older fish in all years 1975–2022 (Figure 3.5). Sampled fish were mostly aged in the 2+ to 4+ cohort-age-groups.

Fish vulnerability and recruitment to the fishery was by 2–3 years of age. This was indicated by the 2+ or 3+ age groups varying between years in being the most frequent (Figure 3.5). This was also confirmed by the 2.5 year parameter estimate for age-at-95% vulnerability (Tables 3.1 and 3.2). Harvests of young 0+ and 1+ year old fish were few, as they had not entered the fishery (Figure 3.5).

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. 2020a).

Catch curve estimates, which simply measured the rate of decline in frequency by age in each year, suggested past levels of fishing mortality were near or exceeding natural mortality (M) 1975–2006 (Figure 3.6). Estimates of mortality 2020–2022 were less, as would be expected from reduced harvests since 2018 (Figure 3.2).

The rate of decline in age frequency from young to old fish might associate with: 1) past levels of fish mortality, 2) spatial and seasonal movements of older fish that might less regularly frequent the focused areas of fishing and/or less regularly interact with the choices of fishing gear (Appendix B), and 3) potential longevity was less compared to other Spanish mackerel stocks across northern Australia.

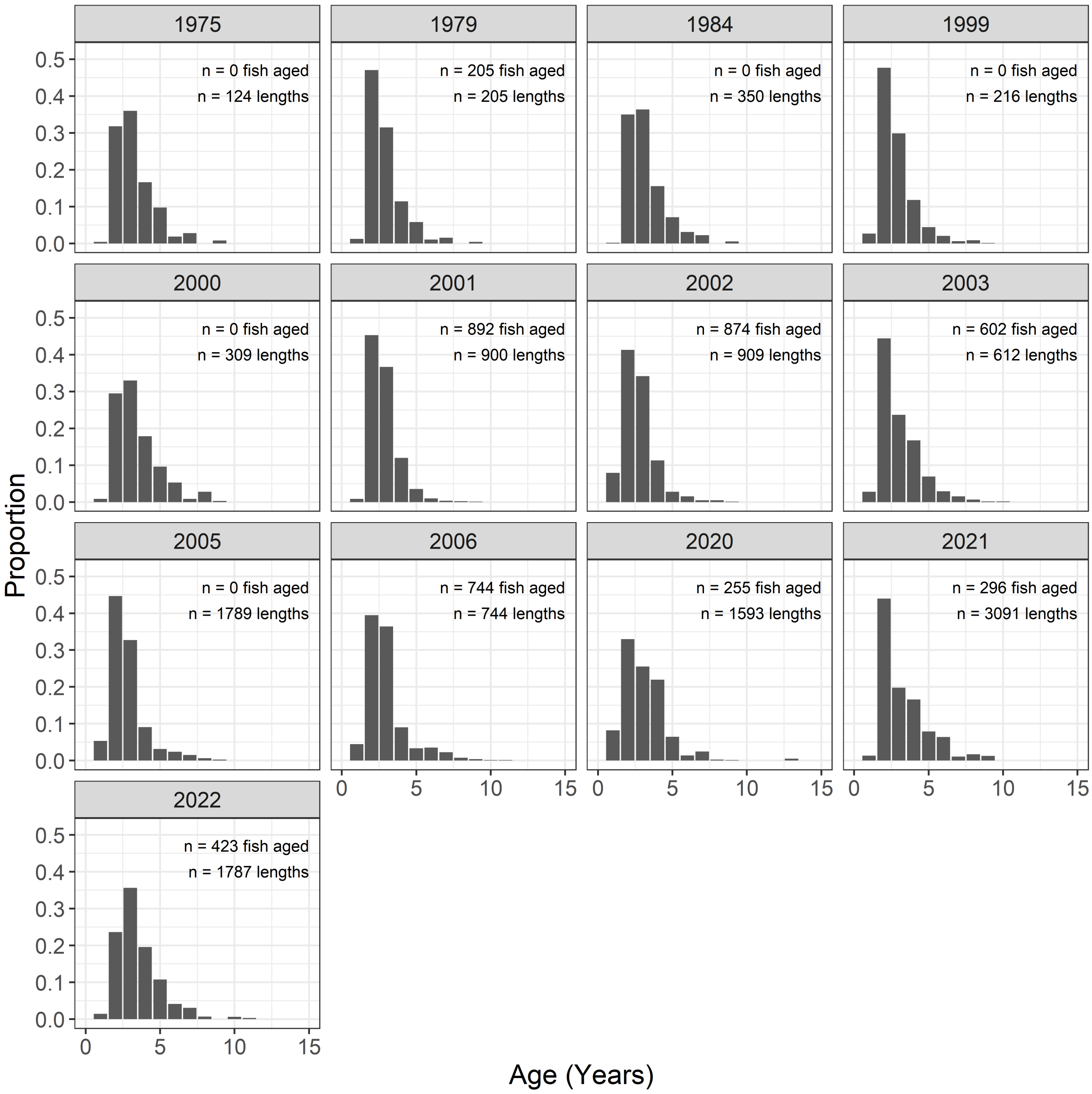

Figure 3.5: Annual age compositions of Spanish mackerel for the sampled years between 1975 and 2022 in the Torres Strait. n was the number of fish sampled.

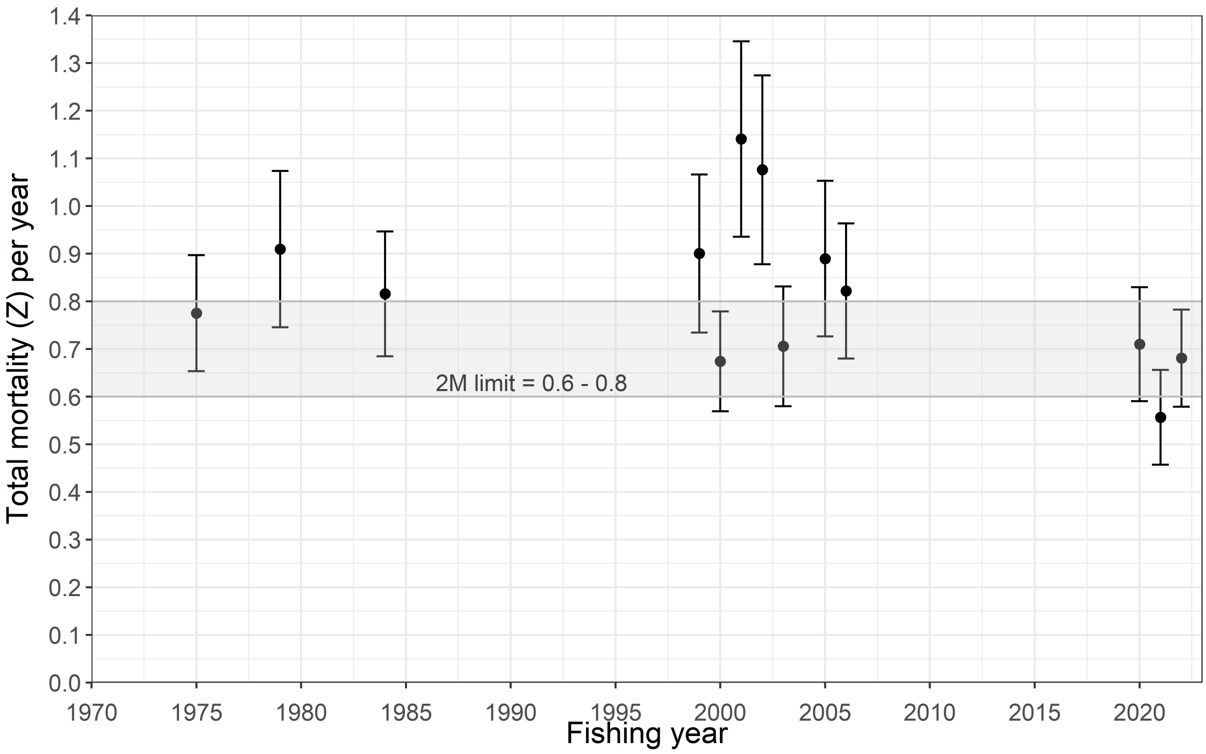

Figure 3.6: Catch curve estimates of total mortality (Z) by year. Error bars were 95 percent confidence intervals. The shading represents the two-times natural mortality (2M) range between 0.6 and 0.8. Estimates were from analysing the 3+ to 13+ age groups, using an over-dispersed Poisson GLM with log link function.

3.2 Model outputs

3.2.1 Analyses 1–6

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

All six analyses resulted in parameter convergence and sound fits to the input data in both the custom and SS models (Appendix D). Better model fits (smaller negative log-likelihood numbers) were associated with 0.35 or 0.4 natural mortality per year and lower steepness (Table 3.1 and Table 3.2). Parameter estimates were consistent with past stock assessments (Buckworth et al. 2021; O'Neill et al. 2022).

The values of recruitment steepness (*h*) 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 0.4 over the six analyses from the custom model (Table 3.1), and 0.47 from SS (Table 3.2)) .

Estimates of virgin recruitment (R_0) negatively correlated with steepness. Over past stock assessments, R_0 estimates have tended marginally smaller from the decline in Sunset catch rates after 2011 (Buckworth et al. 2021; O'Neill et al. 2022). The R_0 estimates herein were similar to the previous stock assessment, with a median of 149000 fish (Table 3.1). The standard deviation of annual log recruitment was 0.25–0.3 (Table 3.1).

Estimates of fish 50% and 95% age-at-vulnerability were consistent between analyses, with median age a_{50} = 1.84 years and age a_{95} = 2.56 years (Table 3.1). Spanish mackerel older than or equal to the 2+ age group were mostly vulnerable to fishing (Buckworth et al. 2021).

The following stock status estimates were for 2021–2022:

- All fishing mortality (F) indicators were sustainable (Appendix D.2). They were less than the instantaneous natural mortality rate of 0.3 per year, which equates to an annual death fraction of 0.26 per year (1-exp(-0.3)), and less than the median MSY harvest fraction of 0.23 in Table 3.3).
- The spawned egg production was at or below the level for MSY (39% median from the custom model and 35% median from SS). Egg production was above the limit reference point of 20%, but below the interim target reference point of 48% (Figure 3.7).
- The latest catch rate and fish age data estimated larger recruitment deviations after the down cycle 2009–2018 (Figure D.19, Appendix D.3).
- All analysis outputs were consistent and similar in terms of informing on potential management options (Table 3.1 and Table 3.2).

Table 3.1: Summary of parameter estimates from the custom analyses 1–6. 95 percent asymptotic 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	0.474 (0.432-0.519)	0.41 (0.369-0.457)	0.362 (0.327-0.405)	0.457 (0.419-0.498)	0.397 (0.364-0.434)	0.352 (0.32-0.391)
Unfished recruitment R0 / 10^6	0.109 (0.099-0.121)	0.144 (0.127-0.164)	0.187 (0.161-0.219)	0.118 (0.108-0.128)	0.154 (0.139-0.172)	0.2 (0.172-0.233)
Age at 50% vulnerabilty	1.837 (1.636-2.027)	1.842 (1.637-2.045)	1.847 (1.638-2.054)	1.84 (1.652-2.021)	1.845 (1.642-2.036)	1.849 (1.65-2.048)
Age at 95% vulnerability	2.555 (2.314-2.806)	2.56 (2.297-2.84)	2.563 (2.295-2.841)	2.559 (2.315-2.818)	2.564 (2.31-2.839)	2.567 (2.292-2.862)
Catch rate negLL	-33.726	-33.824	-32.662	-34.203	-34.233	-33.052
Fish age negLL	-201.817	-204.901	-208.227	-201.868	-205.013	-208.332
Fish age effective sample size	196 (10-260)	181 (8-255)	175 (9-248)	196 (12-263)	180 (10-262)	175 (8-257)
Spawning ratio S_{1990} / S_{1941}	0.412 (0.373-0.459)	0.447 (0.404-0.506)	0.482 (0.432-0.551)	0.38 (0.346-0.423)	0.415 (0.374-0.467)	0.45 (0.402-0.519)
Spawning ratio S_{2022} / S_{1941}	0.283 (0.144-0.481)	0.317 (0.144-0.547)	0.354 (0.167-0.596)	0.262 (0.132-0.461)	0.294 (0.137-0.517)	0.329 (0.127-0.591)

Table 3.2: Summary of parameter estimates from the SS analyses 1–6. 95 percent asymtotic 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	0.557 (0.518-0.595)	0.483 (0.446-0.519)	0.426 (0.391-0.461)	0.533 (0.498-0.568)	0.463 (0.43-0.496)	0.41 (0.378-0.441)
Unfished recruitment R0 / 10^6	0.115 (0.108-0.122)	0.152 (0.14-0.164)	0.198 (0.18-0.218)	0.124 (0.116-0.131)	0.163 (0.152-0.176)	0.213 (0.195-0.234)
Age at 50% vulnerabilty	1.818 (1.681-1.955)	1.838 (1.703-1.972)	1.859 (1.727-1.99)	1.822 (1.685-1.959)	1.841 (1.706-1.975)	1.861 (1.73-1.992)
Age at 95% vulnerability	2.527 (2.404-2.65)	2.55 (2.43-2.67)	2.575 (2.457-2.693)	2.533 (2.41-2.656)	2.554 (2.434-2.674)	2.578 (2.46-2.696)
Catch rate negLL	-90.91	-91.663	-92.058	-91.547	-92.316	-92.734
Fish age negLL	28.681	26.139	24.55	28.497	26.004	24.452
Fish age effective sample size	110 (11-348)	116 (13-425)	127 (15-525)	110 (11-352)	117 (13-430)	128 (15-531)
Spawning ratio S_{1990} / S_{1941}	0.35 (0.323-0.378)	0.39 (0.359-0.421)	0.43 (0.394-0.433)	0.32 (0.294-0.312)	0.358 (0.328-0.356)	0.397 (0.362-0.403)
Spawning ratio S_{2022} / S_{1941}	0.289 (0.24-0.338)	0.327 (0.268-0.385)	0.364 (0.295-0.433)	0.266 (0.221-0.312)	0.302 (0.247-0.356)	0.338 (0.273-0.403)

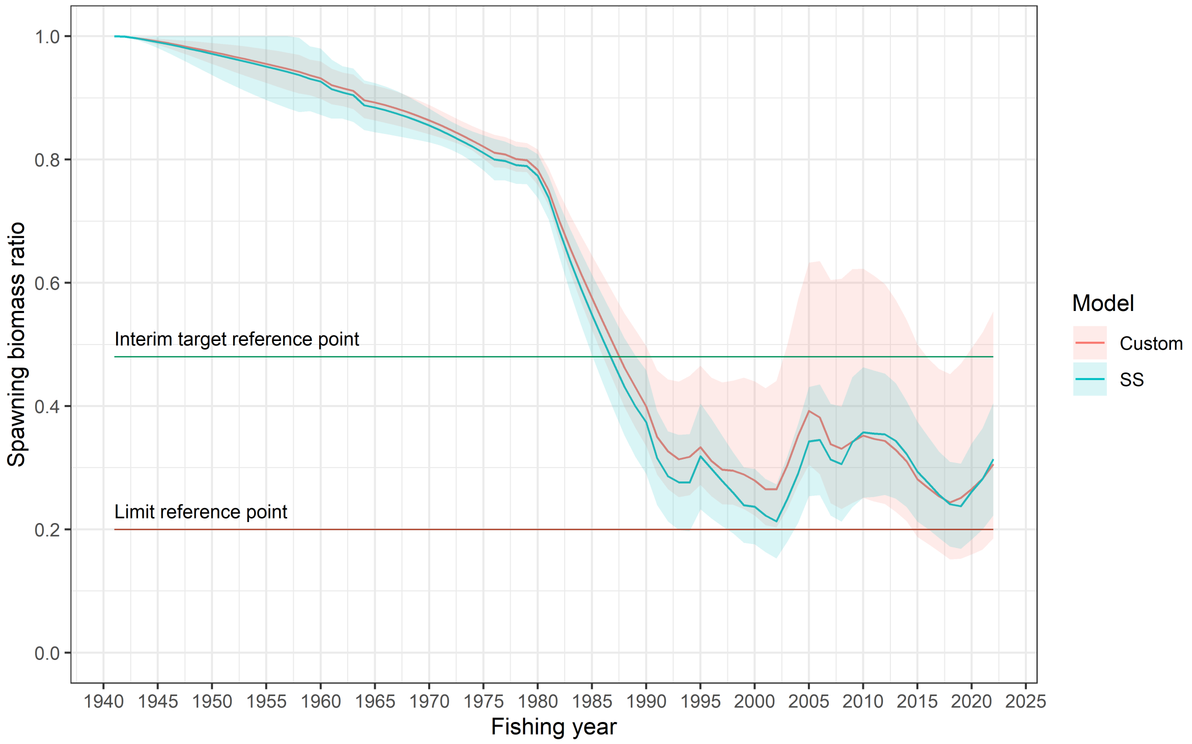

Figure 3.7: Estimated median spawning biomass ratio for Torres Strait Spanish mackerel, from 1941 to 2022. Results were from analyses 1 to 6, for each stock assessment model, with shaded lower and upper 95 percent confidence intervals.

The median RBC reference points for 2022 use are in Table 3.3. The TSFFRAG principles (Figure 2.2) and RBC options considered:

- Median estimates over the six analyses from the custom model.
- Forecast risk of less than 10% probability of spawning biomass falling below 20%. Risks were calculated over 6000 simulations (6 analyses x 1000 simulations each) and 12-year forecasts (3 times age at full maturity = 4 years).
- Forecasts generally reached a spawning biomass of 48% by the end of 12 years (Figure 3.8).
- Reference points 4 and 5 met the TSFFRAG principles (Table 3.3).
- 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 within the custom model.

Table 3.3: Custom model median–RBC estimates for five fishing-mortality (F) reference-points, for the 2023–2024 fishing year.

No.	Reference point◇	Risk⋆ (%)	RBC† (t)
1	F_{MSY}	12.7	137
2	F_{40}	12.2	132
3	F_{48}	10.3	102
4	F_{50}	9.9	95
5	F_{60}	8.9	67

◇ The median harvest rate factions of exploitable biomass (harvest rate u = 1 - exp(-F)), in order of the reference points 1 to 5, were 0.23, 0.22, 0.18, 0.17, 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 2023–2024.

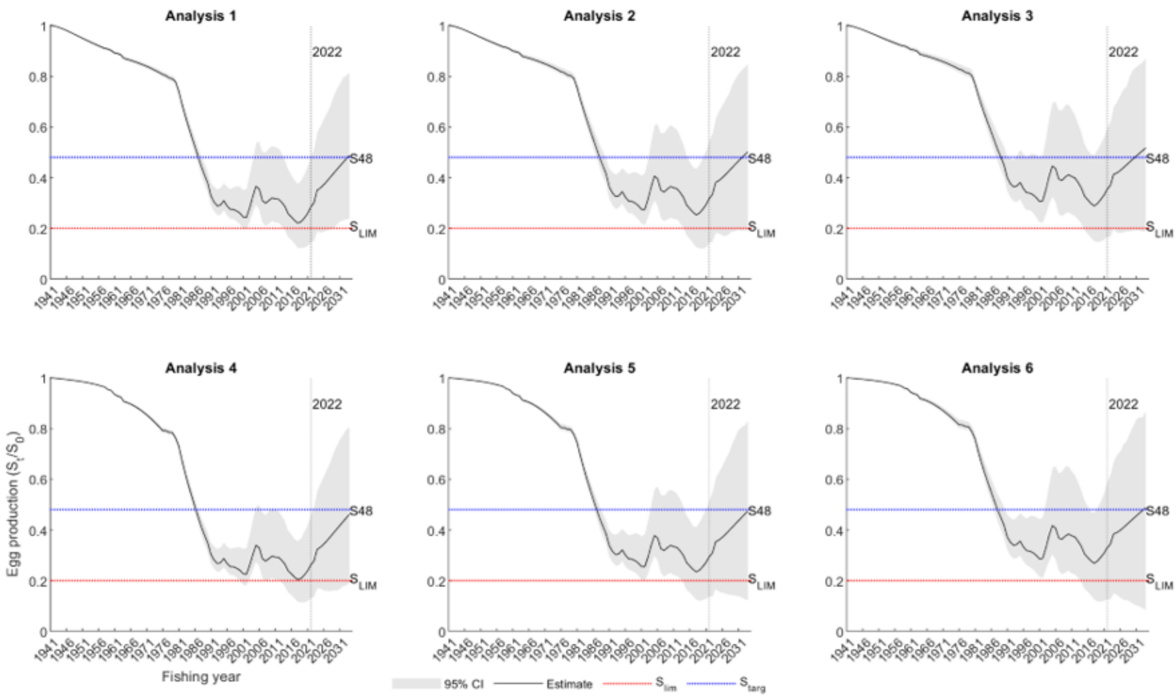

Figure 3.8: Spawning biomass (egg production) forecast for 95 t, RBC reference point no.4 F50, using the custom model.

3.2.2 Analyses 7–10

Additional analyses were run to explore model effects of different IUU harvest, catch rates and negative log-likelihood weights (Table 2.4, Method report section 2.5.3). These analyses were for TSFFRAG to gauge further modelling effects to be considered in future stock assessment.

The findings from the exploratory analyses, compared to analysis 2 in Figure 3.9, were:

- The additional analyses signalled no dramatic change in spawning biomass ratio (Figure 3.9).

- SS software, using ADMB optimisation, produced smaller confidence intervals, compared to the custom model simulations.
- Analysis 7 included TIB catch rates and showed no significant change in biomass ratio compared to analysis 2.
- Analysis 8 halved the level of IUU harvest. This increased the spawning biomass ratio by about 7%.
- Analyses 9 tested the use of Sunset catch rates which were standardised with tender data. The resulting spawning biomass ratios were about 3% higher.
- Analysis 10 used only the Sunset catch rates and excluded other catch rate sources, like in previous stock assessments ((O'Neill et al. 2022)), to produce similar results.
- Adjustment down of the age negative log-likelihood, using proportional weights of 0.7 or 0.5 to allow better fitting of catch rates, only increased biomass ratios marginally.
- Parameter estimates were similar as in analysis 2 (Table 3.1).

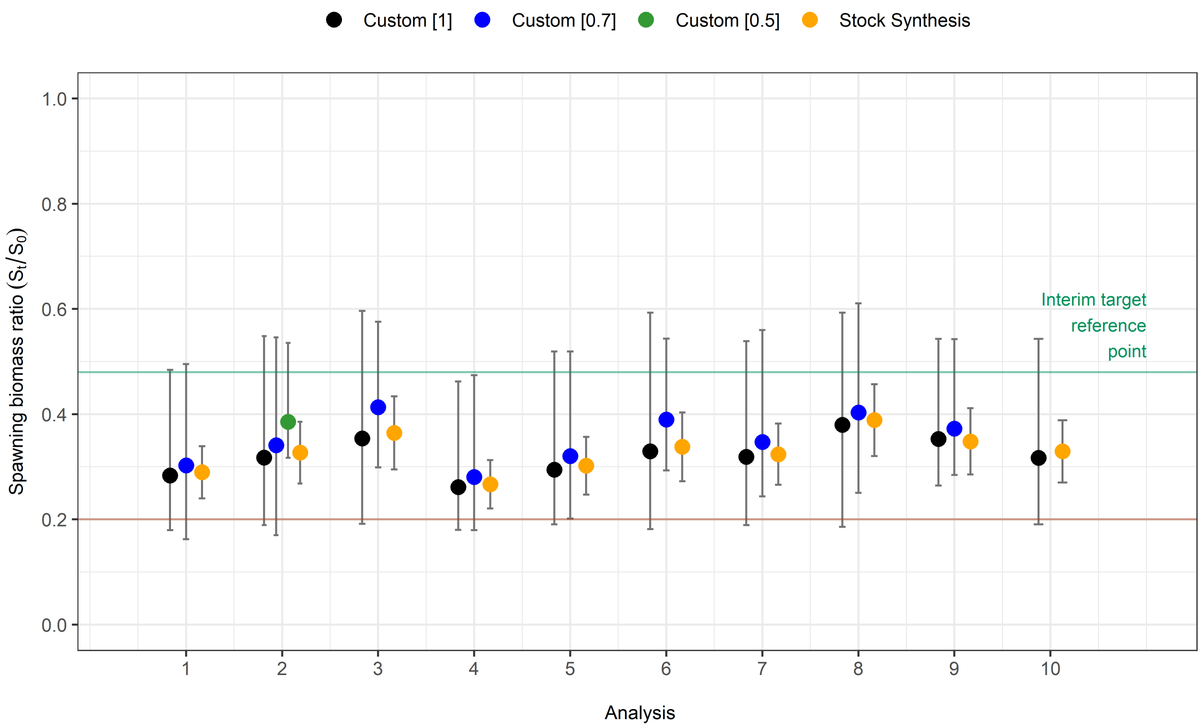

Figure 3.9: Estimated spawning biomass ratio for Torres Strait Spanish mackerel in 2022. Results compared estimates across analyses 1 to 10, from different stock assessments, with the error bars representing 95 percent confidence intervals.

3.2.3 Extra model comaprisons

Population quantities

Stock synthesis (SS) was run to compare with the custom model. In general, the results were alike and appear acceptable to consider the transition of the stock assessment into SS, after TSFFRAG final review and recommendation.

Parameter estimates from both models were similar (Table 3.1 and Table 3.2):

- Estimates for recruitment variation (σ_r, the standard deviation of annual log recruitment deviations 1990–2022) ranged 0.25 to 0.3 between analyses and models.
- Logistic age vulnerability parameters were aligned.
- SS estimates of virgin recruitment (R0) were higher, but only by about 8000 fish (5.7%).
- Steepness was larger in SS by about 0.07 compared to the custom model. In SS, steepness was a bounded (0.2,1) untransformed parameter, and the custom model used a biological transformation that required no bounding in estimation (Buckworth et al. 2021).
- SS calculated smaller standard errors on the estimated recruitment deviation parameters (Figure 3.10).
- Both models assumed no prior values on estimated parameters.

Both SS and custom models calculated asymptotic 95% confidence intervals. Confidence intervals on the SS biomass ratios were smaller (Figure 3.9). The methods of forming the parameter covariance matrix, was by differentiation in SS and MCMC simulation in the custom model. The effect of limited catch rate and age data before 1990, and not estimating earlier recruitment deviations before 1990, might impact on confidence interval widths differently in SS (read the recruitment variability discussion in Methot et al. 2022).

Confidence interval widths on the steepness parameters were about the same between models (Table 3.1 and Table 3.2). For unfished virgin recruitment (R0), confidence interval widths were about twice in the custom model at around ± 20 thousand fish (13%), compared to about ± 12 thousand fish (7%) in SS. Confidence intervals were also marginally larger around the vulnerability parameters in the custom model.

The SS spawning biomass predictions, as ratios, were comparable to the custom model (Figure 3.9 and Figure 3.11). Both models estimated near 31% in the last fishing year 2022.

The comparison of actual population numbers produced by SS, compared to the custom model, in general showed:

- Higher numbers of fish, but only by about 7% (Figure 3.12).
- Similar annual harvest rates (where u = 1-exp(-F), see Figure 3.13). The custom model calculated harvest rates by annual harvest (kg) divided by exploitable biomass (kg), and SS used a hybrid tuning method to approximate the Baranov continuous fishing mortality rate F (Methot et al. 2022; Methot et al. 2013).
- About 7% more recruits (Figure 3.14).
- Recruitment deviations differed more between models in the earlier years 1990–2000, and were in general similar post 2000 (Figure 3.10 and Figure 3.15).

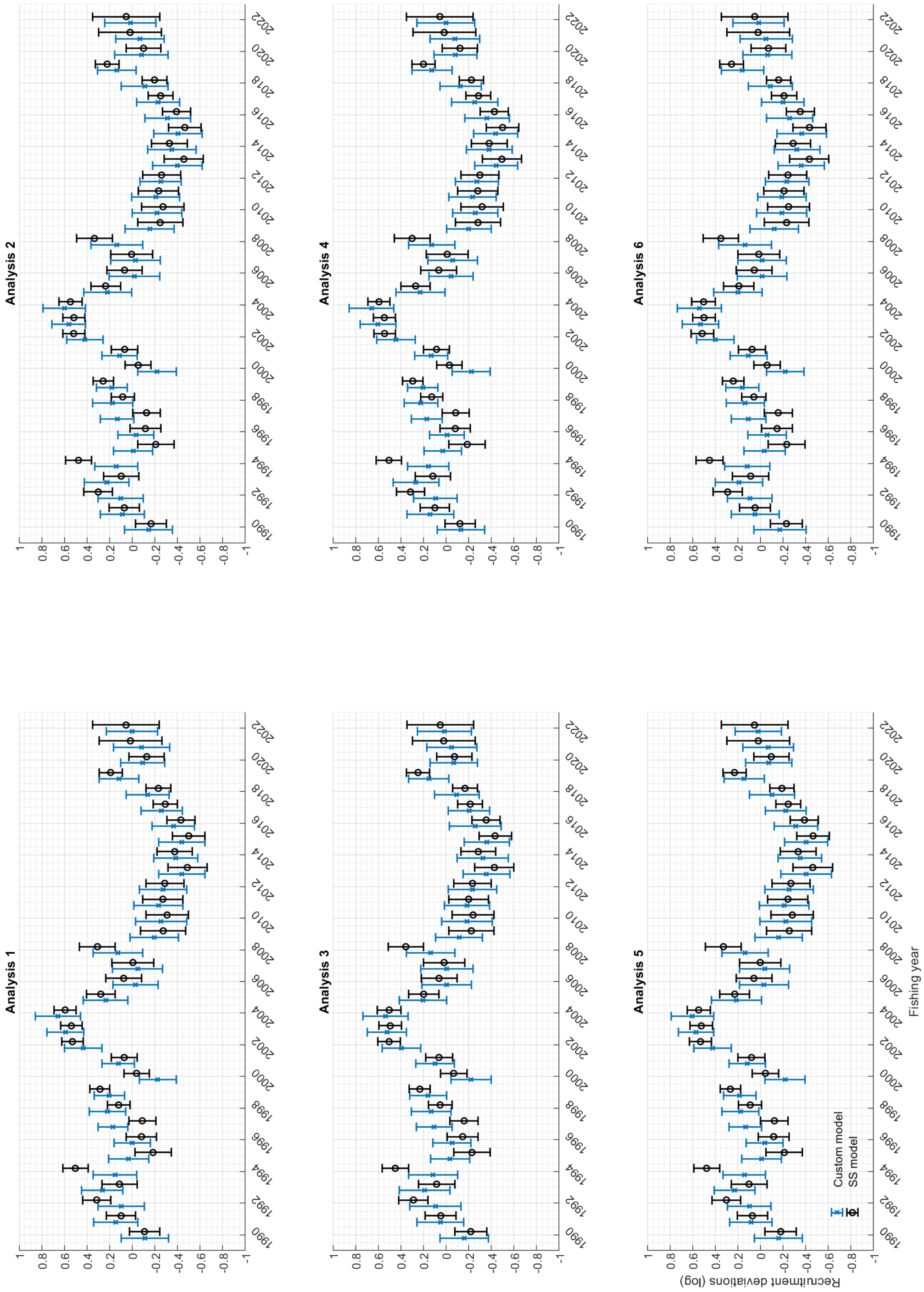

Figure 3.10: Error bar plot of the estimated log recruitment deviations ± 1 standard error by analysis, from 1990 to 2022, for both the custom and stock synthesis models. Blue points and error bars were from the custom model, and the black points and error bars were from SS.

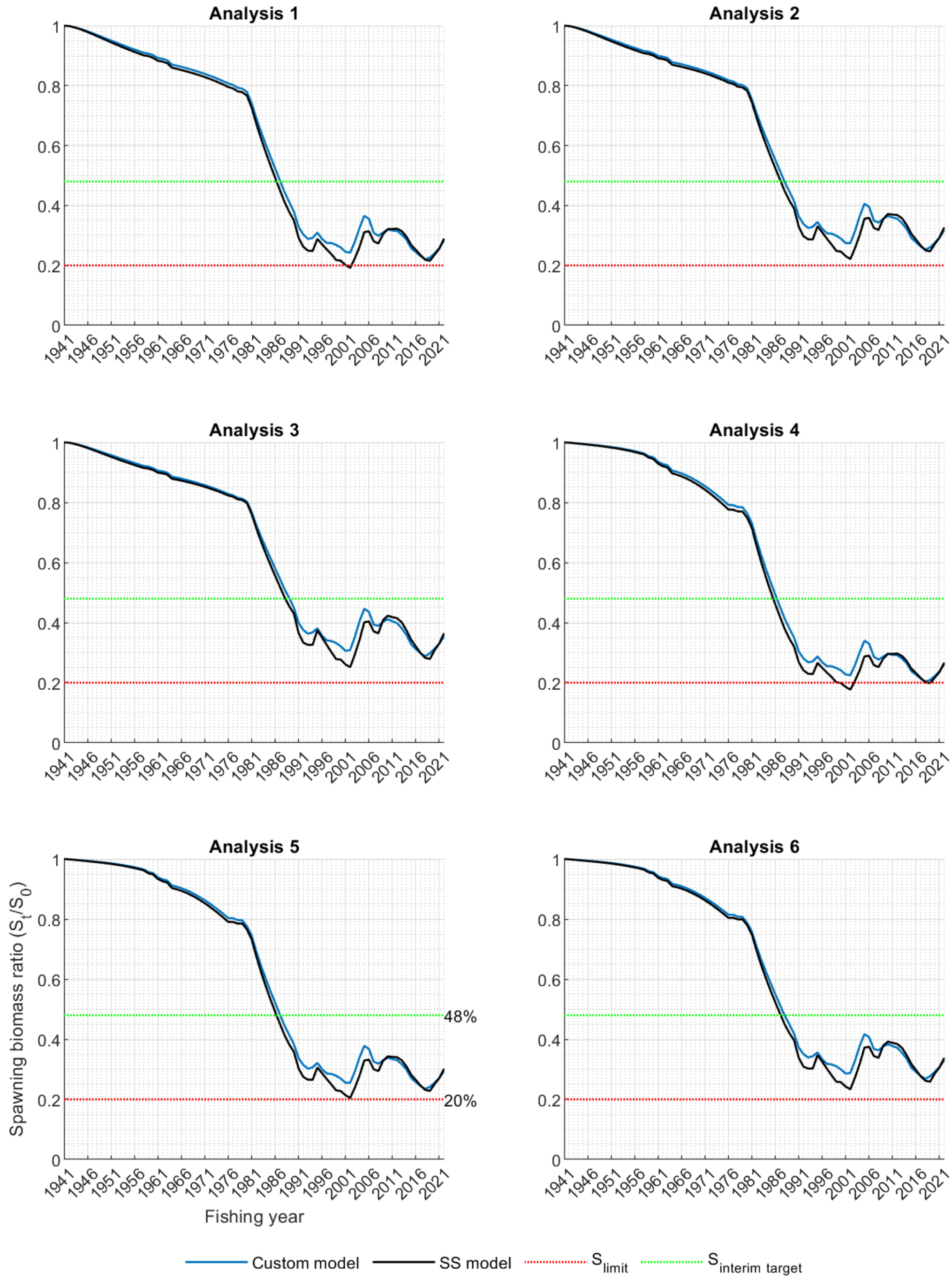

Figure 3.11: Predicted spawning stock biomass trajectory relative to unfished by analysis, from 1941 to 2022, for both the custom and stock synthesis models.

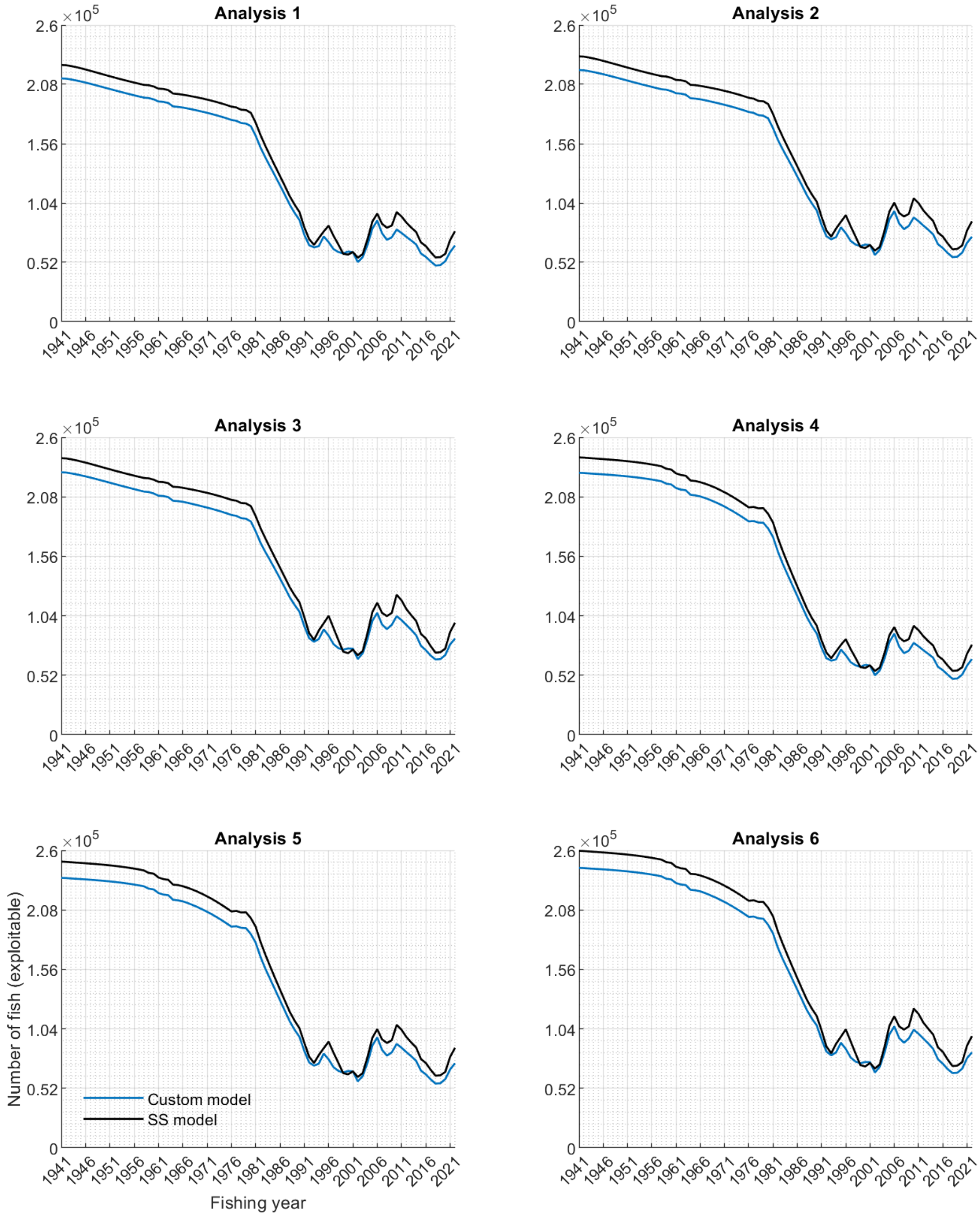

Figure 3.12: Predicted exploitable (vulnerable) numbers of fish by analysis, from 1941 to 2022, for both the custom and stock synthesis models. Blue lines were for the custom model, and the black lines were for SS.

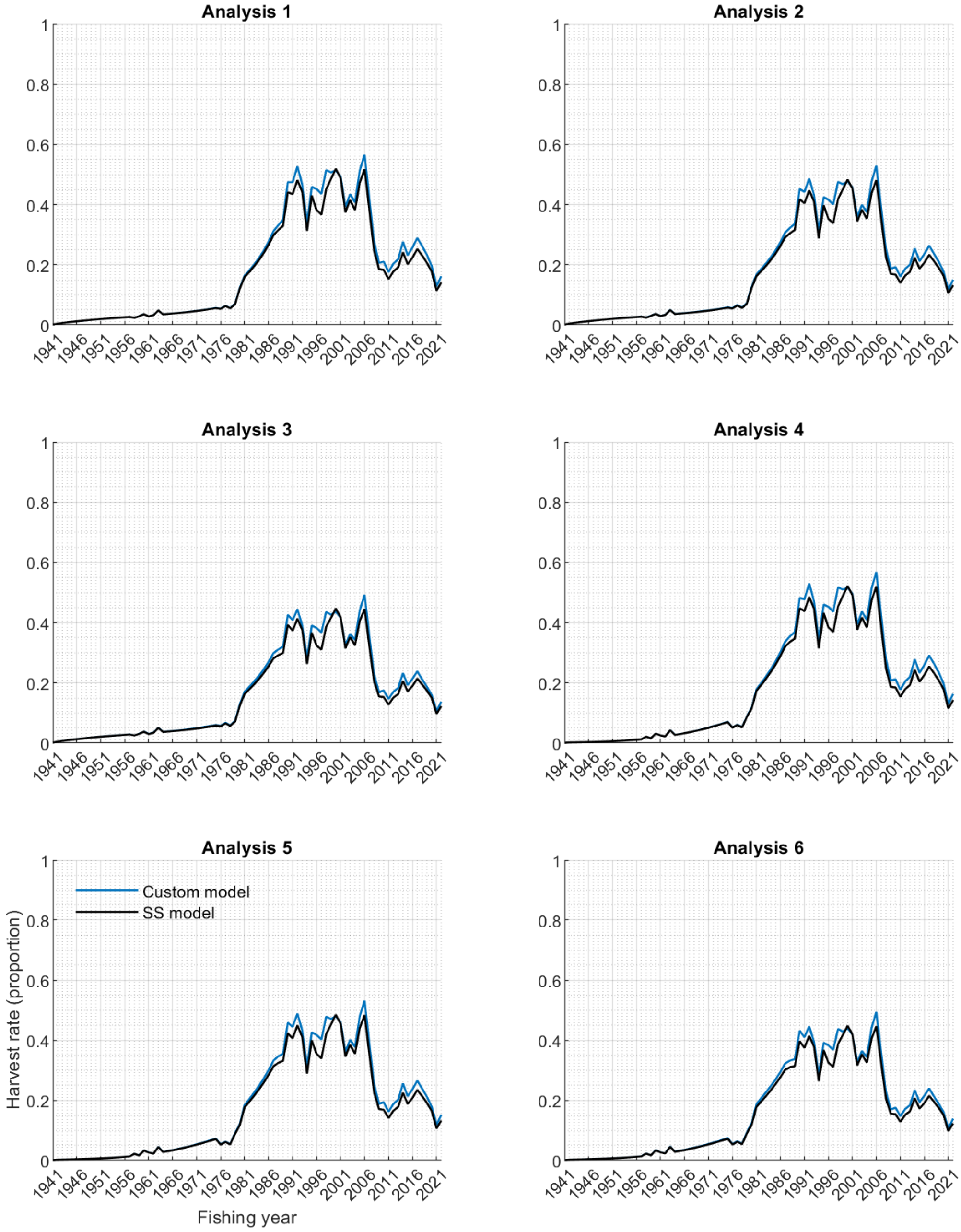

Figure 3.13: Predicted harvest rates (fraction of exploitable biomass) by analysis, from 1941 to 2022, for both the custom and stock synthesis models. Blue lines were for the custom model, and the black lines were for SS.

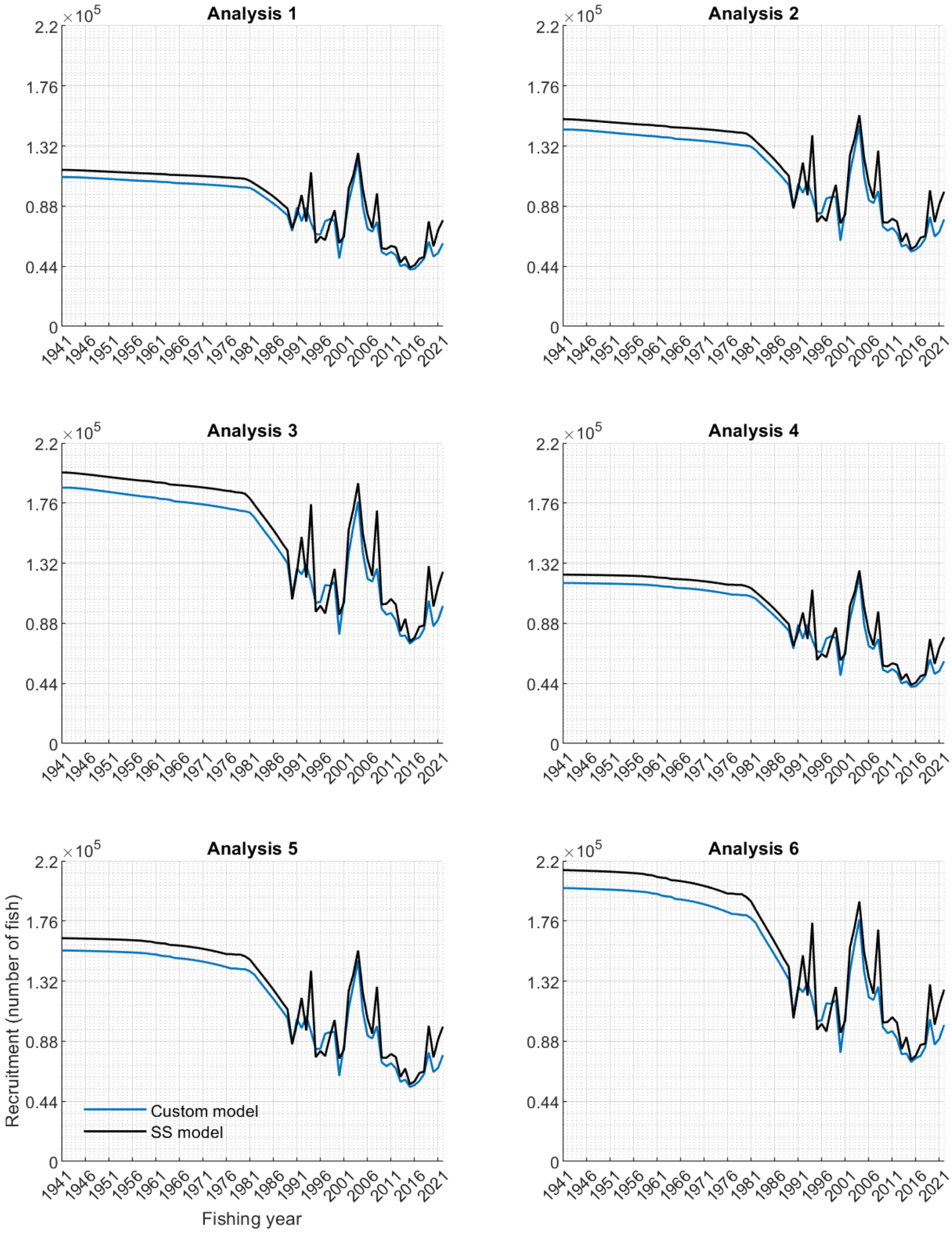

Figure 3.14: Predicted recruitment numbers of fish by analysis, from 1941 to 2022, for both the custom and stock synthesis models. Blue lines were for the custom model, and the black lines were for SS.

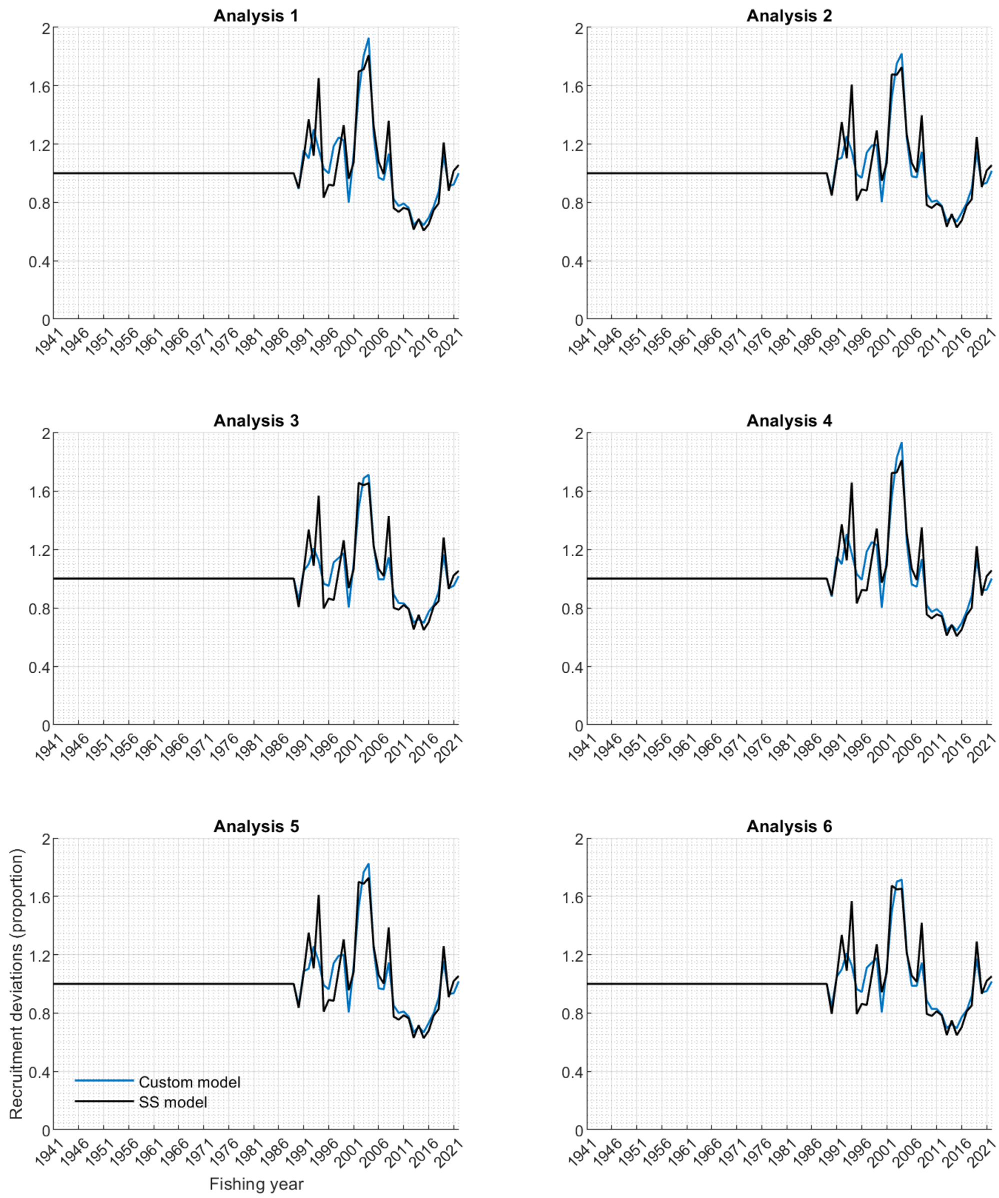

Figure 3.15: Predicted recruitment deviations by analysis, from 1941 to 2022, for both the custom and stock synthesis models. Blue lines were for the custom model, and the black lines were for SS.

RBC management quantities

This was the first examination of stock synthesis calculations of recommended biological catch (RBC) against the custom model. Together with the estimated spawning biomass ratio, which indicated stock status, RBC was the secondary output of importance for fishery management of TACC.

In stock synthesis, the specifications for RBC were set-up in the forecast file (Methot et al. 2022). Settings were looped through the different reference points (Table 3.4), using the same assumptions as in the custom model.

The calculations of RBC in SS used the Baranov catch equation (Methot et al. 2013; Methot et al. 2022). This was due to SS using a hybrid fishing mortality (F) method. The Baranov method of calculating harvest is common, but the measures and units of F in SS can sometimes be complex due to the many potential time, area and fleet dimensions of the SS software.

These complexities can alter the interpretation of F, but in application, SS searches for what it calls F_{mult} to solve to Baranov catch equation for different reference points (e.g. F_{48}) (Methot et al. 2022). The median F_{mult} solutions were footnoted in Table 3.4, and were consistent with the custom model (Table 3.3).

The resulting calculations of median RBC for each reference point across analyses was in Table 3.4. They were 28 t, 10 t, 9 t, 9 t and 8 t higher than the custom model calculations for each respective reference point (Table 3.3). The 7–11% difference between model RBCs generally related to the marginally higher recruitment (from the R0 and h parameters) estimated by SS (Table 3.1 and Table 3.2).

The estimate of B_{20} risk was lower in SS and not the same as the custom model (Table 3.3 and Table 3.4). This was due to the smaller standard errors on SS parameter estimates. The SS lower estimates of uncertainty appeared to be the main difference between the models outputs; essentially all the other aspects reviewed showed acceptable differences between SS and the custom model.

The appropriate estimation of uncertainty is important for RBC recommendations, as risk was defined in relation to the limit spawning biomass reference point (20%). Estimation of uncertainty less than it really is can turn into underestimated risk and over recommendation of RBC. More work is required to understand the uncertainty aspect in SS. Applying 2 standard deviations on spawning biomass ratios in risk calculations produced better values to distinguish RBC options (Table 3.4).

Table 3.4: Stock synthesis median–RBC estimates for five fishing-mortality (F) reference-points, for the 2023–2024 fishing year.

No.	Reference point◇	Risk[1] (%)	Risk[2] (%)	RBC† (t)
1	F_{MSY}	6.7	19.6	165
2	F_{40}	2.2	14	142
3	F_{48}	0.4	8.5	111
4	F_{50}	0.2	7.6	104
5	F_{60}	0.1	4.7	75

◇ The median harvest rate factions of exploitable biomass (harvest rate u = 1 - exp(-F)), in order of the reference points 1 to 5, were 0.25, 0.22, 0.17, 0.16, and 0.12.

[1] Calculated risk using 1 standard deviation.

[2] Calculated risk using 2 standard deviations.

† SS median 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 2023–2024.

4 Discussion

4.1 Stock status

Across analyses and models, estimated spawning biomass (egg production) of Spanish mackerel in fishing year 2022 was around 31% of estimates for the start of the fishery in 1941.

While the biomass ratio indicated how large the spawning stock was, the harvest rate estimates (fishing mortality F, defined in the Glossary) in 2022 and RBC forecast (Figure 3.8) provide a prediction of future stock direction under current 2022 fishing pressure and normal recruitment. In 2022 the median harvest rate fraction was 0.15, and this level of fishing corresponded to building higher biomass ratios than in 2022. The 0.15 harvest rate, was between the harvest rates for F_{50} and F_{60} (Table 3.3 and Table 3.4).

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 annual fishing licences to non-Traditional Inhabitants (Sunset operations). Over this time, commercial fishing pressure had eased compared to before 2008.

4.2 Model performance

This stock assessment used an age based model with an annual time step, with age-based selectivity common for all fishing sectors. Data inputs included total dead catch (harvest; there were no reports of discards), standardised catch rates, and fish-age compositions. Overall, the models performed well, achieving good fits to all data.

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

Assumptions on natural mortality (from analyses 1–6) gave results ranging around ± 4% on the final median spawning biomass ratio of 31%. Previous sensitivity testing in the custom model indicated rates of natural mortality up to 0.4 per year resulted in acceptable model fits to catch rates and parameter R0 estimates (Buckworth et al. 2021; O'Neill et al. 2022).

SS profiling also suggested the upper value of 0.4 for natural mortality was acceptable (Table 3.1 and Table 3.2), but higher rates of natural mortality correlated with lower steepness (Figure D.22). New methods for inversely relating fish maximum age (currently 13.5 years for Torres Strait Spanish mackerel) to natural mortality supported a rate near 0.4 per year (Hamel et al. 2022).

For this assessment, we estimated steepness and the stock recruitment relationship. Contrast in the data appeared to allow for this, together with testing three different fixed rates of natural mortality (M). The steepness estimates across analyses and stock models ranged 0.3–0.6. The steepness estimates aligned with values suggested by meta-analysis and biological methods for Spanish mackerel or related *Scomberomorus* fish species.

An important caveat in relation to steepness estimation is that for the data contrast to meaningfully inform the steepness parameter, it would need to have been caused by the population rising and declining in response to fluctuations in fishing pressure. This has not been definitively established, and there may be other causes (e.g. environmental or ecosystem-wide processes). Section 4.5.2 makes some recommendations in this regard.

The choice of alternative harvest history had a small influence on the estimated status of the fishery (analyses 1–6 and 8). From the custom model, the polynomial harvest scenario estimated a 2% higher final median spawning biomass, and 7 t higher median RBC than the logistic harvest scenario. These differences were similar for SS.

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 C.1 and Figure C.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.

Analysis 7 tested the use of TIB catch rate data. Inclusion of the data did not influence results (Figure 3.9). Future use of the TIB data is desirable in RBC analyses, but is dependent on complete and accurate catch rate reporting, and reduced variance (Figure 3.4).

Analysis 9 revealed a 3% higher biomass ratio (Figure 3.9), when catch rates were standardised using tender data (Figure 3.3). Given the tender data had a strong F statistic (Table C.6), and that such effort data was desirable in analysis, TSFFRAG should consider how to best include the tender data in future catch rate analyses. Model performance was improved by reducing the biomass confidence intervals in the custom model (comparing analyses 2 and 9, Figure 3.9).

Further model development in stock synthesis will assess potential improvements in estimates and performance. One aspect is that stock synthesis provides flexibility to consider and link growth dynamics for analysing each year's available fish age-length key and/or length frequency. The expected benefits of using this functionality are to improve the length, maturity and fecundity relationships at age for young fish in the 0+ and 1+ age groups. Few young fish have been aged (Figure 3.5), due to the spatial-temporal behaviours of fish and fishing selectivity (vulnerability).

In addition for stock synthesis, more customising of age-length data weights, testing of more pre-1990 recruitment deviations and increasing the standard deviations on Sunset catch rates might help broaden model performance and increase the current confidence interval widths (Figure 3.9).

4.3 Environmental influences

In 2009–2018, Torres Strait Spanish mackerel recruitment deviations were lower than expected (Figure D.19). This suggested that some years of fish abundance had not responded to reductions in the total fishery harvest (Figure 3.2). Given 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 hypothesised by TSFFRAG that environmental conditions may have contributed to this observed trend (AFMA 2019; AFMA 2020b).

As well as undertaking annual assessments, the 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 survive to 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 impact on catchability via behaviour of fishers. For example, windy weather makes fishing 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 C.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 around reef slopes and edges and the eggs were presumably pelagic; they have a large oil droplet and float (Munro 1942; 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 (Munro 1942). 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 have been found inshore, in coastal and estuarine areas which may include mangrove areas as well as near-shore reefs. The timing of spawning was such that the young juveniles can utilise the seasonal productivity of inshore waters. 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 previous decade was important for future management of the fishery. Recruitment variation was estimated in the stock assessment, capturing potential environmental effects, but the environmental influences (drivers) were not known (Buckworth et al. 2021).

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; analyses were constrained by a lack of proximate environmental data (such as flow rates of the Fly River in PNG). 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). However, new research is currently happening for environmental influences on neighbouring Australian east coast Spanish mackerel, with published results that might support Torres Strait discussions due in early 2026 (FRDC project number 2021-111; https://www.frdc.com.au/project/2021-111).

4.4 Spawning aggregations

A fish spawning aggregation is 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) is 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 does raise awareness for the management of Torres Strait Spanish mackerel, particularly for the small fishing ground of Bramble Cay. Harvests need to be monitored and managed to ideally maintain appropriate levels of fish egg production. Harvest quota-management is in place, and this was important to mitigate the risks of recruitment and catch rate declines such as those experienced 2009–2018. If management responses such as spatial and temporal closures are not used, then safe reference points, such as B_{MEY} or B_{48}–B_{60}, might be needed to limit RBC levels and vessel numbers. Annual harvests should not result from overly concentrated fishing-effort (high harvest rates) on spawning aggregations.

Historically for the last 10 years for the September to November spawning months at Bramble Cay, commercial line harvests represented about 50% 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. 2004b).

In 2012 a genetic tag-recapture study on Spanish mackerel in the 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 is 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

Median spawning biomass in 2022 was below the reference point of 48% of unfished spawning stock biomass, and 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 2022).

The TSFFRAG process aligns to harvest strategy aspects noted by Sloan et al. (2014) and Hutton et al. (2019). Methods used the principles in Figure 2.2. The procedure aimed to ensure a building population biomass (above B_{MSY} and at least to 40% biomass) 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).

In reporting against general fishery harvest strategy policies (e.g. Department of Agriculture and Fisheries 2021, Table 3 uncertainty tier system), the uncertainty category for this assessment was 0.91 based on a qualitative tier 1-2 assignment process using Ralston et al. (2011).

However, as multiple assessments have been conducted (Figure E.1), the actual uncertainty for the 2022 stock assessment can be calculated following the methods of Ralston et al. (2011). The calculated standard deviations (sd) of variation in biomass ratios from the custom models and the potential uncertainty statistics were:

- 0.109, for the between-analysis 1–6 sd in 2022. The sd was calculated using the median biomass ratio of 31% as the central tendency, rather than the mean as described in method 2 on page 220 in Ralston et al. (2011).
- 0.14, for the within-analysis sd, calculated as a mean sd across analyses 1–6.
- 0.16, for the between-stock-assessment sd, calculate by comparing biomass ratios from this stock assessment to past results in 2004, 2015, 2018, 2019, 2020 and 2021 as illustrated in Figure E.1.
- 0.24, was the combined sd, from the three variance components above.
- 0.97, was the calculated uncertainty statistic for the 0.45 P^* buffer in Ralston et al. (2011).
- 0.94, was the calculated uncertainty statistic for the 0.40 P^* buffer in Ralston et al. (2011).

The purpose of reporting the uncertainty statistics, here for management, was to quantify the scientific confidence for consideration in stock status reporting and RBC setting. The calculated factors were high and above 0.91, consistent for a tier 1 stock assessment (Department of Agriculture and Fisheries 2021).

Note that the uncertainty statistic was just one aspect for consideration, and can support other discussions on the reliability of data inputs and trends, and model structures (Table 4.1). There are always uncertainties in stock assessment modelling. Accounting for all these can be a substantial task, and not often fully done for most accepted stock assessments (Klaer 2018). A working table, for TSFFRAG, is described below to track and discuss options around some of the current stock assessment uncertainties (Table 4.1). The table was a qualitative guide, designed from the examples in Klaer (2018) and Klaer (2021), listing different aspects for management purposes and TSFFRAG action items.

Table 4.1: Summary of stock assessment uncertainties and the levels addressed. Yes = aspect has been investigated sufficiently in this or past stock assessments or data collection has been actioned; partly = aspect has been considered, sometimes well, but more data or analyses might be required in key RBC analyses; No = missing). For more information, please also consult FFRAG meeting records.

Aspect	Function	Extent considered	Comments
Spatial	Data	Yes	Fishery data were mostly from Bramble Cay. The assessment assumed these fish mixed throughout the Torres Strait. Spatial age-length sampling has been extended. More data from more areas will better inform the assessment in time. Recent genetics has confirmed the stock boundaries used (Williams et al. 2022).
Harvests	Data	Yes	Two estimates of historical fishery harvests have been used. They were similar and appear sufficient. But estimates for IUU were more uncertain. Sensitivity analysis number 8 (Figure 3.9) might suggest that more uncertainty could be built into RBC considerations with extra scenarios for different IUU (such as half and full 100 t) assumptions.
Shark depredation	Data	No	There were no data or reports of changing incidences. A method of data collection is required from fishers, and to be considered in an update to the TSF01 logbook . This was a lesser issue compared to the fisher perceptions/reports in adjacent Queensland waters.
Catch rates	Data	Yes	Different catch rates and model weightings have been examined. It is important to monitor the number of Sunset tenders used per operation day and commence use in analyses using an agreed GLM method. It is also desirable to improve the number of TIB catch rate reports through daily catch and effort logbooks. In SS, increased catch rate CVs should be tested to infer lesser trend and more uncertainty, to examine the influence on results, increase confidence intervals and address perceived overfitting comments. Review and cleaning of the fishing skipper and tender driver data is desirable.
Fishing power	Data	Yes	Catch rate analyses included annual changes in vessel operations and gear fishing powers. Updates to gear fishing power will be required in time, and use of the square root version was sufficient.
Hyperstability	Data	Partly	No hyperstability adjustment is considered in catch rates. But fishing power is. Reporting of zero catches and VMS locations by tenders is needed to mitigate this risk.
Age structures	Data	Yes	Monitoring has been spatially extended. Ongoing samples are important to measure recruitment variation and fish mortality. The SS method of using an annual length frequency matched with a conditional length-age key should be tested. Years with shared keys can be removed in SS.

Aspect	Function	Extent considered	Comments
Growth	Data	Partly	Improving growth estimates for young fish (e.g. like biphasic growth Figure 1b, Wilson et al. (2018). Selectivity in the fish age-length data bias maturity estimates up for 0+ and 1+ aged fish. Quantitatively, new growth models need to be estimated in and outside SS to better inform female maturity, but more data on young and large old fish are ideally needed.
Steepness	Model	Yes	Sensitivity to different steepness values have been examined. Note, current methods estimate this parameter and the report discussed this around literature.
Natural mortality	Model	Yes	Three different fixed values assessed a range of rates 0.3–0.4 per year. Marginally high values to 0.45 can be tested in SS. Rates of M were confounded with fishing mortality and do not allow estimation without informed priors.
Recruitment	Model	Yes	Stock assessment results were reliant on estimated recruitment deviations to fit trends in the data. However, recruitment deviations were only estimated for the later part of the full time series. While this is appropriate for the available data, much of the pre 1990 history was only informed by the harvest data and estimates about life history such as fish longevity, natural mortality, and steepness.
Depletion	Model	Partly	Dissect the depletion levels up to 1989. Work has been completed in the custom model, but it is desirable to expand in SS by testing the expansion of recruitment deviations.
Sensitivity tests	Model	Yes	Many scenarios have been conducted over the years. The settings for key RBC analyses are reviewed annually.
Diagnostics	Model	Yes	A full range of diagnostics have been implemented for SS, following Carvalho et al. (2021). See report appendix.
Bridging	Model	Yes	Analysis comparisons have been completed to facilitate stock assessment transition to SS.

4.5.2 Assessment and monitoring

The following considerations are provided, as were summarised from Begg et al. (2006) and the year one report (O'Neill et al. 2022), in order to further build and improve status indicators for Torres Strait Spanish mackerel:

- 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 daily reporting, clarification on Sunset number of tenders used, and complete reporting on Sunset and TIB hours fished per operation day is required to improve fishing effort and catch rate indicators.

  - The Sunset tender data was re-analysed in catch rate standardisation (Figure 3.3). In future analyses, it is recommended to assume constant tender use pre 2004 where the data was incomplete (or ideally conduct a retrospective survey to verify the data), and use the tender data thereafter to standardise catch rates. Methods for this need to be discussed by TSFFRAG. The number of tenders being used by each fishing operation is an important consideration to better monitor future stock trends, through standardised catch rates.
  - Knowing the number of fishing locations of the primary operation and dories, from VMS latitude and longitude coordinates, is important for improving the spatial resolution of data. This is to mitigate hyperstability from the way data might be recorded (O'Neill et al. 2018a). The effort signature VMS research and knowledge from current FRDC project 2021-111, when published, should be considered to improve measures of fishing effort for catch rate standardisation. In turn, this would enable better understanding of the spatial extent of aggregations. Ideally, catch and effort data needs to inform on the number, size and densities of aggregations.
  - Note and enable how to record zero catches for each fishing day, number of AM/PM sessions, and days when fishing was stopped due to capacity limitations (too many fish), in logbook TSF01.
- Monitor and estimate Spanish mackerel harvests taken by non-commercial sectors [for stock model assessment].
- Continue annual monitoring of fish age-length structures that are 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 1990 data and settings, and IUU estimates [for stock model assessments].
- Link key environmental data and report on trends that can support TSFFRAG discussions.
- Explore the robustness of the parameter estimation process and improve ability to characterise uncertainty by conducting Markov chain Monte Carlo estimation.
- Further explore the question of steepness estimability by considering other possible causes for the contrast in the data, as well as the impact of well-informed priors and meta-analysis derived fixed values on a wide range of model performance diagnostics.
- If it is determined that steepness (or other key parameter) cannot be sufficiently well determined by the available data, the TSFFRAG may want to consider a more formal decision analysis framework that carries residual uncertainty through to well-defined alternatives for the possible states of nature (i.e. biomass ratios), alternative recommendations (i.e. recommended biological catches) for those states of nature, and the risks associated with implementing latter in each case (see e.g. Punt et al. (1997)).

4.6 Conclusions

Across analyses, the median estimated spawning biomass of Torres Strait Spanish mackerel in 2022 was 31 percent of unfished estimates at the start of the fishery in 1941.

The recommended Spanish mackerel RBC for 2023–2024, inclusive of all fishing sectors in the Torres Strait, was 95 t based on the median forecast estimates.

The comparisons of the packaged stock assessment software stock synthesis (SS) produced an estimate of spawning biomass ratio that was similar to the custom model. Management RBC recommendations were marginally higher from SS. The positive correlation between models support transition of the stock assessment fully into using stock synthesis during year three of the project, with further testing and review of SS settings and estimates against the preferred data-input style for the age-length data (use of annual age frequency verse use of annual length frequency and age-length keys). The extended range of diagnostics reported, including the retrospective analyses, currently demonstrated stability in results.

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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). There was one new event for 2022.

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).
1984-1985	*AFV Winston* was sold by the Jarret family after fishing Torres Strait.	McPherson pers. comm. AFMA interview Oct 2020.

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Table A.1 – *Continued from previous page*

Year	Management	Source
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
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

Continued on next page

Table A.1 – *Continued from previous page*

Year	Management	Source
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
2022	The western line closure for commercial line fishing was redefined. This opened a new area for the finfish fishery north of the southernmost point of Buru Island. The intent was to provide more economic opportunity to fishers in Gudamaluilgal (top-western) communities.	AFMA and PZJA

Appendix B Commercial fishing methods

B.1 Sunset sector

- Operations generally used a primary vessel (a mother-ship of around 10 m length) towing several smaller 5–6 m dories/tenders with the primary accommodating their crew.
- Troll fishing may occur directly from the primary vessel with no accompanying dories.
- Mostly though, for a primary-tender operation, the primary vessel would anchor in a suitable sheltered position and each dory will move out to troll over GPS marks within site of the primary for the duration of a morning fishing session. Dories would return to the primary with the mornings harvest for processing ahead of a second afternoon fishing session, with processing of this additional catch occurring in the evening.
- A mackerel dory was generally powered by an inboard diesel motor and was fitted out with a driving section for a single fisher where foot operated tiller controls were located. The fisher can steer the dory through the troll while simultaneously setting and retrieving fishing lines.
- Trolling speed was generally 4 to 6 knots.
- Once a school of fish was located the dory will circle and troll over the school.
- Mainlines were typically 15–20 m in length and were made up of 1.2 mm spring steel wire (Bowden cable). Mainlines were attached to the dory by a short length of rope and a shock-rubber (a piece of large rubber O-ring used to seal pipelines).
- Trace for each line was about 5 m (3 arm lengths) of 1.2 mm Bowden cable.
- Fishers have advised that past operations generally used lighter trace (0.9 mm), but heavier 1.2 mm wire trace was common nowadays.
- A combination of up to three fishing lines might be trolled at once. Fishers would generally set lines with rigs trolled as follows:
  1. Shallow trolled line:
     - Normally set on an outrigger arm.
     - Rigged with a Halco "Kimberley" spoon lure (diamond profile 6 inch, 50 g).
     - If spoons were unavailable this line may sometimes be set using a 6 inch hard body plastic jig in a pink or white colour.
  2. Deep trolled line:
     - Approximately 9 m of 1.5 mm Bowden cable leads down to a paravane, then 15–20 m of mainline was attached behind this, with a final trace of 1.2 mm Bowden cable.
     - The paravane pushes the rig to about 7 m depth which can be adjusted according to conditions.
     - A normal rig on the deeper line was a weighted wog head jig with skirt including hair and fire-tail fibres. This was baited with a single dead garfish set on a two 10/0 gang hooks (noting this can be a 12/0 hook at times depending on availability).
  3. Long trolled line:
     - Set to troll the longest out behind the dory than the shallow and deep lines. This line was normally set with a wog-head jig baited with a garfish as per the deep line.
     - If fish were on the bite, this line would not be used, and the fisher might just work the shorter spoon and deep lines together. Three lines of unequal length were too many to deal with during a busy session.

- Notes on locations fished:
  - Operations do not actively scout or search for new fishing grounds as a proportion of their fishing effort. Fishing was normally on marks that were previously discovered.
  - Fishing generally occurred on established trolling marks over shallow water adjacent to the edge of reefs (though the depth might drop away to 15–45 m at times).
  - When trolling, if the dory drifted into more than 20 m depth, the fisher will generally reset and move back to shallower water.

B.2 TIB sector

- TIB fishing operations generally used similar trolling gear to the Sunset sector, although the boats and set-ups were more likely to vary.
- Most of the TIB operations used a general-purpose dory of around 4–6 m length with tiller steer outboards.
- TIB boats may have both a driver and a fisher or be crewed only by a single driver/fisher.
- Mother ships were not common.
- Only a couple of larger primary-tender operations have been active within the TIB sector and only in recent seasons (since 2022).
- TIB fishers may work a set route moving to fish from reef to reef in a loop leading away and then back towards their island community.
- Fishing methods can vary between boats, with some using multiple lines and some using single lines; some fishers may use outriggers while others do not.
- Some fishers work a combination of spoons and wog-head jigs baited with garfish.
- Some fishers have a preference to run baits until good patches of Spanish mackerel were located yielding good catch rates. Fishers may then switch to one spoon/one gar to save bait.
- Bait available to purchase in communities is expensive and might not be of the best quality, in comparison to the Sunset sector who bring their bait from the Queensland mainland or have it brought up on their barge resupply service.
- Tackle can be hard to find at times and is expensive in communities. Some fishers adapt found materials such as using car battery terminals as wog-heads and rope strands might be used for the jig skirting material.

B.3 Notes on big fish

- Fish of a greater maximum size than those currently sampled by the biological sampling program (148cm FL female, 121cm FL male) are reportedly present on the fishing grounds.
- In general fishers do not target large size class fish as they are harder to retrieve past sharks, harder to fillet and become a “two-person lift” once they have reached a certain size. This creates potential safety risks for the crew which are generally avoided.
- Smaller fish are easier to handle and process.
- TIB sector reports provided to the TSFFAG state that large size class fish are available at known locations within their sea country but are not targeted as they are culturally significant.
- It has been advised that the fishery in the past had greater overlap with areas of large fish prior to 2008, and implementation of 10 nm radial closures such as to the north-east of Ugar (Stephen’s Island) where up to 22% of the fishery used to be harvested. This area is now closed to the Sunset sector. Prior to the 10 nm closures a reasonable proportion of fish were taken in areas outside of Bramble Cay.

Appendix C Data and model inputs

C.1 Harvest estimates

Annual estimates of Spanish mackerel harvest used the data from Table (C.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 1941 (Begg et al. 2006).
- Pre 1990, 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 1990 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.
- The recreational harvest estimate was small from an initial survey (Webley et al. 2015). The best estimate was two tonnes. This was considered a minimum due to low survey participation. Uncertainty was considered above two tonnes, based on the upper confidence interval, and the assumed recreational harvest was randomised between two and five tonnes per year. A constant of 5 t per year was assumed for 2021 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 1990 years of total harvest in Table C.1. The approach, illustrated in Figure C.1, was similar to Begg et al. (2006).
- An assumed 100 t per year of IUU harvest was included for 1980–1987, 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). Half of IUU was considered for one exploratory analysis, to understand it's influence on biomass results pre 1993.

The polynomial and logistic models used Table C.1 combined totals between 1941 and 1994, without IUU. 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 1990 total harvests only.

The logistic estimates used a binomial GLM (with logit link function). The analysis data scaled the average annual 1990–1994 total harvest to 100%, to represent the full catch expansion of the fishery. The pre 1990 harvests were scaled to a fraction of the 1990–1994 average. The logistic model estimated the harvest fractions, and they were multiplied by the 1990–1994 average harvest to form the missing estimates. The logistic-shape by year aimed to create a different 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 C.1). Nominal Sunset effort was reduced since 2008 (Figure C.2).

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

Fish Year	Financial Year	TIB	Traditional	Sunset	Recreational	Charter	PNG	Total
1941	1940-41	0	2	0	0	0	0	2
1958	1957-58	0	2	34	2	0	0	38
1960	1959-60	0	2	52	2	0	0	56
1961	1960-61	0	2	40	2	0	0	44
1963	1962-63	0	2	70	2	0	0	74
1976	1975-76	3	2	68	2	0	0	75
1977	1976-77	3	2	81	2	0	0	88
1978	1977-78	3	2	69	2	0	0	76
1980	1979-80	3	2	57	2	0	0	64
1990	1989-90	3	10	215	4	0	0	232
1991	1990-91	4	10	182	5	0	0	201
1992	1991-92	1	10	194	4	0	0	209
1993	1992-93	2	10	173	2	0	0	187
1994	1993-94	3	10	121	4	0	0	138
1995	1994-95	5	10	192	5	0	0	212
1996	1995-96	2	10	182	3	0	0	197
1997	1996-97	3	10	157	4	0	0	174
1998	1997-98	4	10	181	2	0	0	197
1999	1998-99	4	10	167	5	0	0	186
2000	1999-00	9	10	168	5	0	0	192
2001	2000-01	5	10	164	4	0	0	183
2002	2001-02	8	10	108	2	0	0	128
2003	2002-03	7	10	129	5	0	0	151
2004	2003-04	13	10	137	5	0	0	165
2005	2004-05	14	10	225	3	0	0	252
2006	2005-06	10	10	277	3	0	0	300
2007	2006-07	14	10	171	3	0	0	198
2008	2007-08	7	10	105	2	0	0	124
2009	2008-09	6	10	77	5	0	0	98
2010	2009-10	8	10	89	4	0	0	111
2011	2010-11	8	10	71	4	0	0	93
2012	2011-12	2	10	89	4	0	0	105
2013	2012-13	3	10	91	5	0	0	109
2014	2013-14	1	10	116	4	0	0	131
2015	2014-15	2	10	81	4	0	0	97
2016	2015-16	2	10	86	5	0	0	103
2017	2016-17	3	10	90	4	0	0	107
2018	2017-18	2	10	75	2	0	0	89
2019	2018-19	6	10	65	4	0	0	86
2020	2019-20	2	10	54	3	0	0	70
2021	2020-21	4	15	29	5	0	0	52
2022	2021-22	6	15	47	5	0	0	73

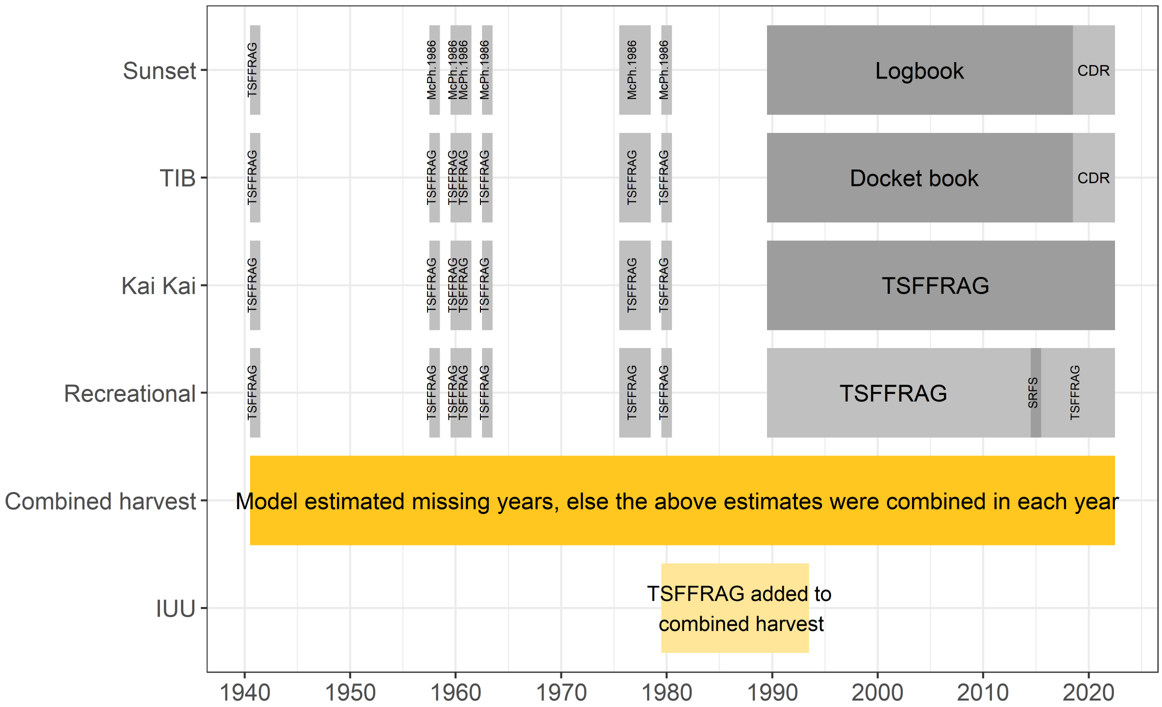

Figure C.1: Overview of the information and process used to reconstruct the history of Torres Strait Spanish mackerel harvest. The years of data (shaded grey) note the estimates from the harvest table above, where the labels: TSFFRAG - was the agreed estimate based on reports, publications and traditional knowledge; McPh.1986 - was the McPherson (1986) harvest data; and SRFS - was the state-wide recreational fishing survey by Fisheries Queensland for Torres Strait waters (Webley et al. 2015). Harvest estimation (shaded orange) was for the combined fishery in each year and not separately for each sector.

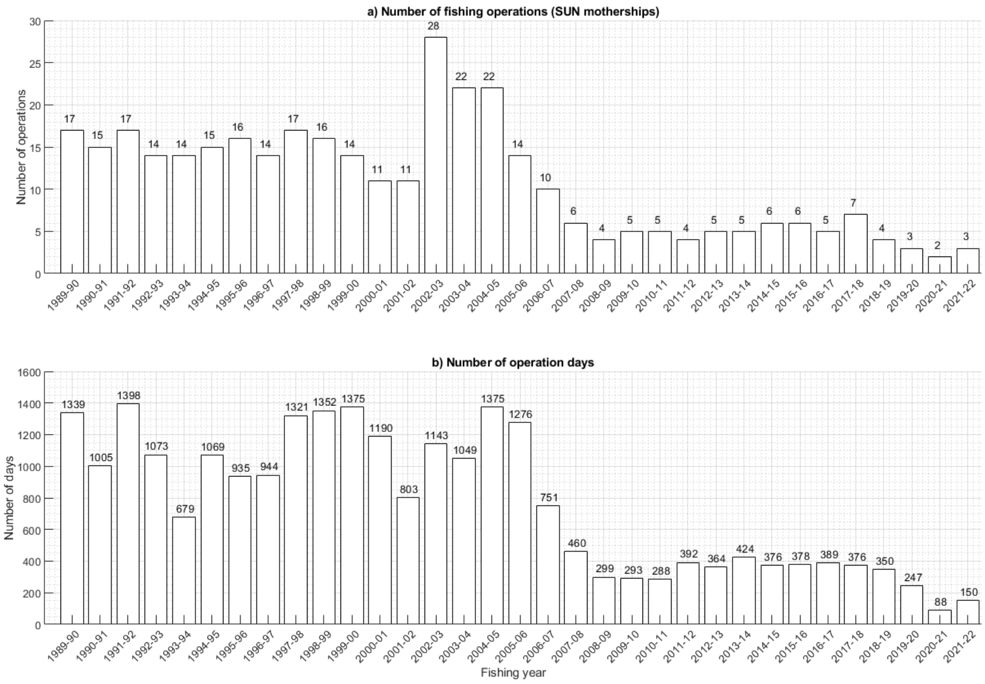

Figure C.2: Sunset logbook reports of total fishing effort by year for a) number of primary fishing operations, and b) number of days fished by the primary operations.

C.2 CDR Sunset report

- The TDB02 CDR collected landings information on Spanish mackerel catch weights.
- The CDR collected 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 2019 to compare measured average fish weight with the CDR. 7.65 kg was tabled from 2020.

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

Table C.2: Summary of Catch Disposal Records

Fishing year	Fish count (logbook)	Total whole fish weight (kg)	Average fish weight (kg)	Average fish weight measured (kg)
2019	8645	65362	7.56	7.65
2020	6427	54097	8.42	7.65
2021	4126	28813	6.98	7.45
2022	6856	47320	6.9	7.3

C.3 Age-length samples

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

Fishing Year	Number of fish aged	Number of fish lengths
1975	0	124
1979	205	205
1984	0	350
1999	0	216
2000	0	309
2001	892	900
2002	874	909
2003	602	612
2005	0	1789
2006	744	744
2020	255	1593
2021	296	3091
2022	423	1787

Fish length-composition data were not a direct input into the population model. Instead, annual length data (Figure C.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).

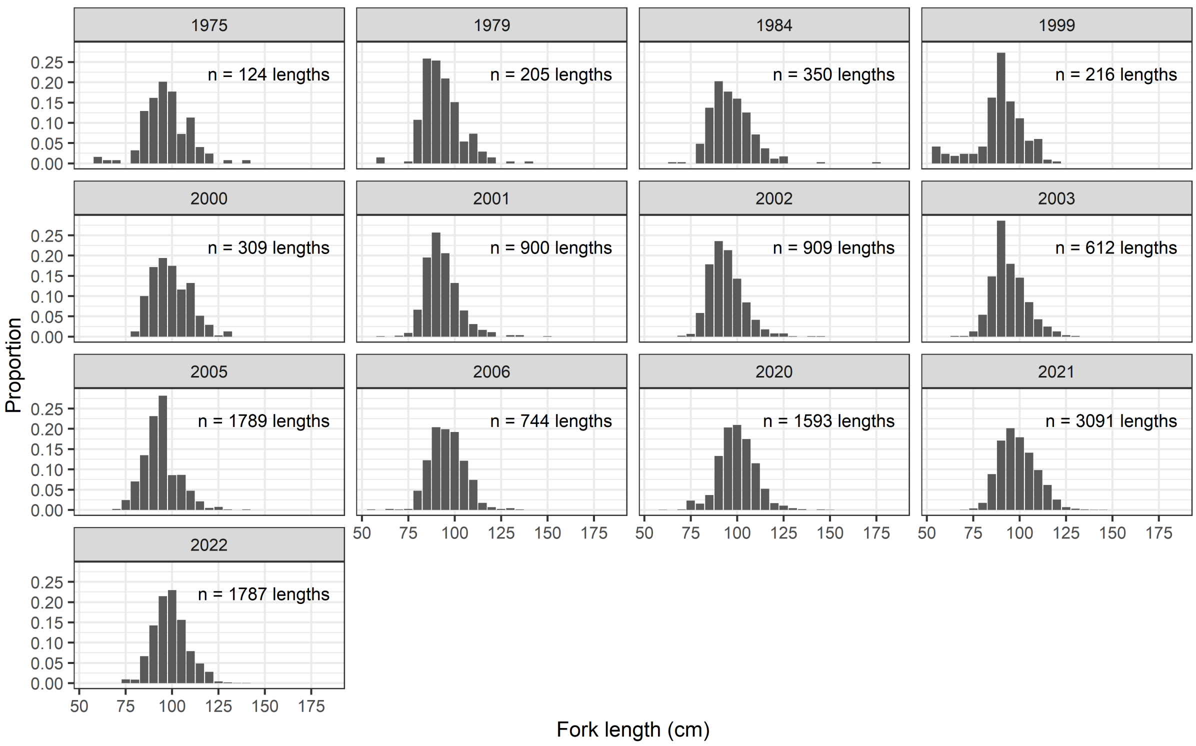

Figure C.3: Annual length compositions of Spanish mackerel harvested in the Torres Strait for sampled years between 1975 and 2022.

C.4 Ageing statistics

The fish ageing statistics showed no significant concerns on increment counts (Table C.4). Only the 2006 ageing had lower percent agreement for intermediate and wide otolith margins. These otoliths were few in number compared to those with new edges, as sampling was mostly during the spawning season.

Precision was measured as the percentage agreement between re-aged otoliths and edge types (new, intermediate and wide). IAPE was the index of average percent error in ageing across fish re-aged for increment count. Acceptable levels for Torres Strait Spanish mackerel ageing, for a pass criteria were: IAPE ≤ 6 and edge % correct $\geq$ for new 70%, intermediate 50% and wide 50% (Fisheries Queensland 2023).

Table C.4: Quality assurance fish ageing statistics. This was for selected otoliths by fishing year. IAPE was an index of average percent error (IAPE) of the otolith increment assignment between read 1 and read 2 when fish samples were aged twice. Fisheries Queensland's biological monitoring was from 2020 and James Cook University in 2006.

Ageing	2006	2020	2021	2022
number otoliths aged	740	256	301	400
number otoliths re-aged	740	200	200	199
% increment agreement	70	92	88.5	82.9
IAPE increment count	5.129	1.201	3.38	3.81
% agreement news	88	90.7	87	93
% agreement intermediates	45	73.5	83	59
% agreement wides	20	90.5	73	50
count news	507	130	102	246
count intermediates	101	44	58	78
count wides	132	25	37	70
count unreadable	0	1	3	6

C.5 Catch rates

C.5.1 Sunset diagnostics

Table C.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	24496	344934		
fishyear	32	361154	35.996	0.000
zone5	4	351066	108.860	0.000
boat	46	422042	119.043	0.000
s1cos	1	345099	11.724	0.001
s1sin	1	350958	427.822	0.000
s2cos	1	347255	164.824	0.000
s2sin	1	346085	81.742	0.000
s3cos	1	345024	6.406	0.011
s3sin	1	345009	5.326	0.021
lunar	1	347964	215.217	0.000
lunaradv	1	353843	632.690	0.000
windns	1	345094	11.373	0.001
windns2	1	345196	18.590	0.000
windew	1	344941	0.498	0.480
windew2	1	345517	41.371	0.000

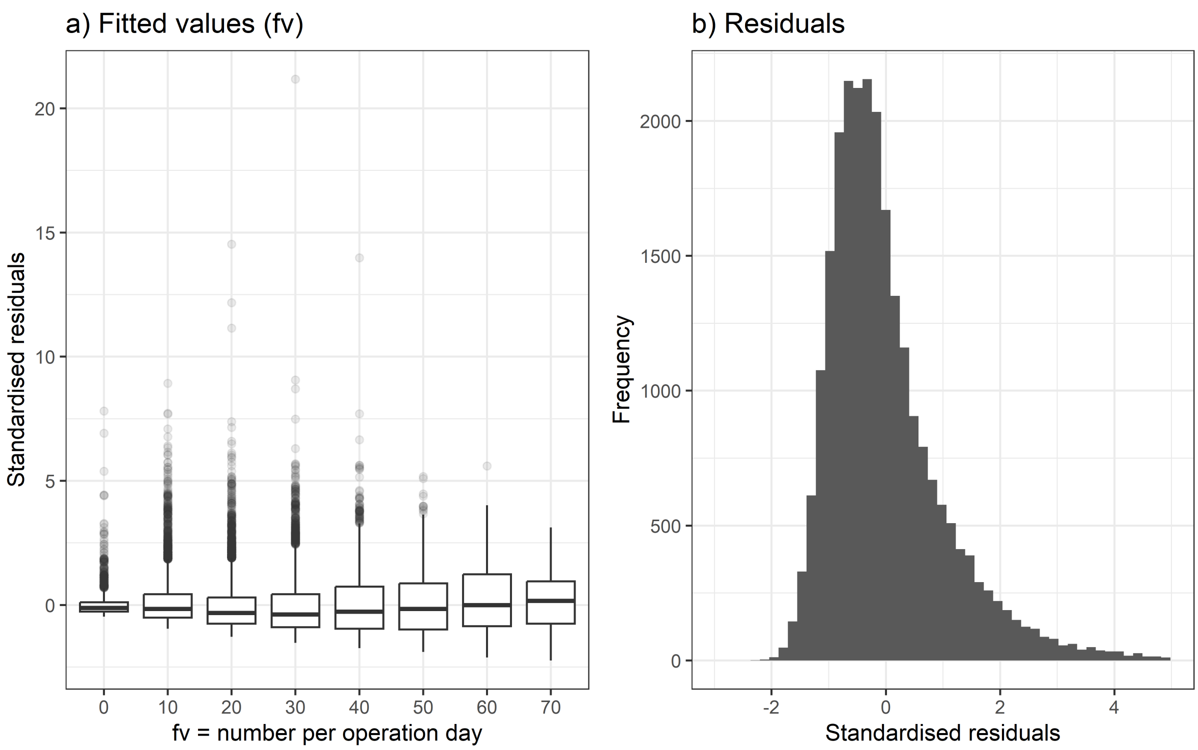

Figure C.4: Sunset catch rate residual plots for a) box plot of fitted values and residuals, and b) histogram of residuals. Fitted values > 70 fish were grouped. Residuals were standardised by the sqrt(variance * dispersion).

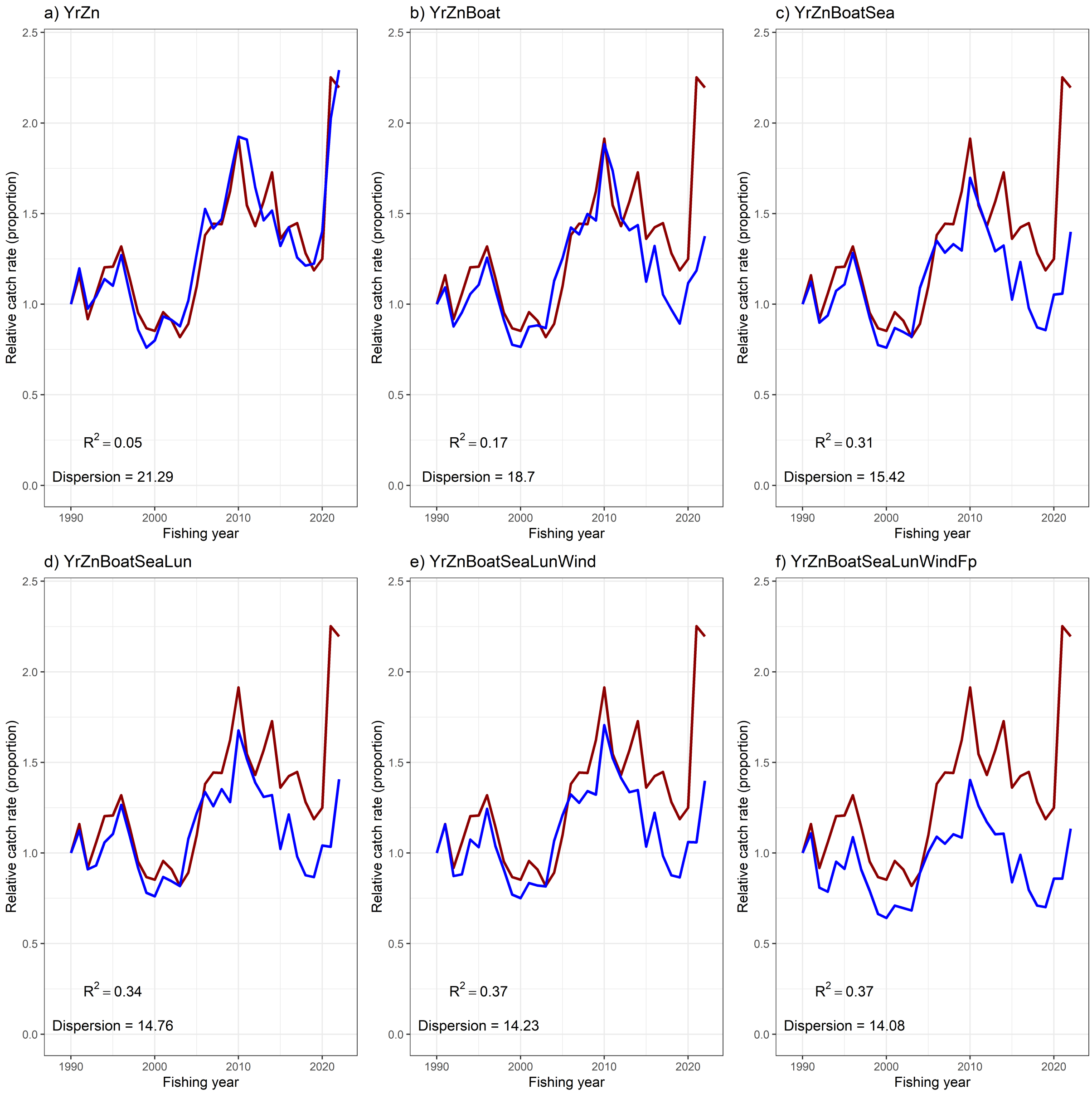

Figure C.5: Influence plot comparing the GLM effects on standardised catch rates against the nominal mean catch rate (red line). Sub-plot: a) compared a year (Yr) and zone (Zn) model; b) compared a Yr, Zn and Boat model; c) compared a Yr, Zn, Boat and Seasonality (Sea) model; d) compared a Yr, Zn, Boat, 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.

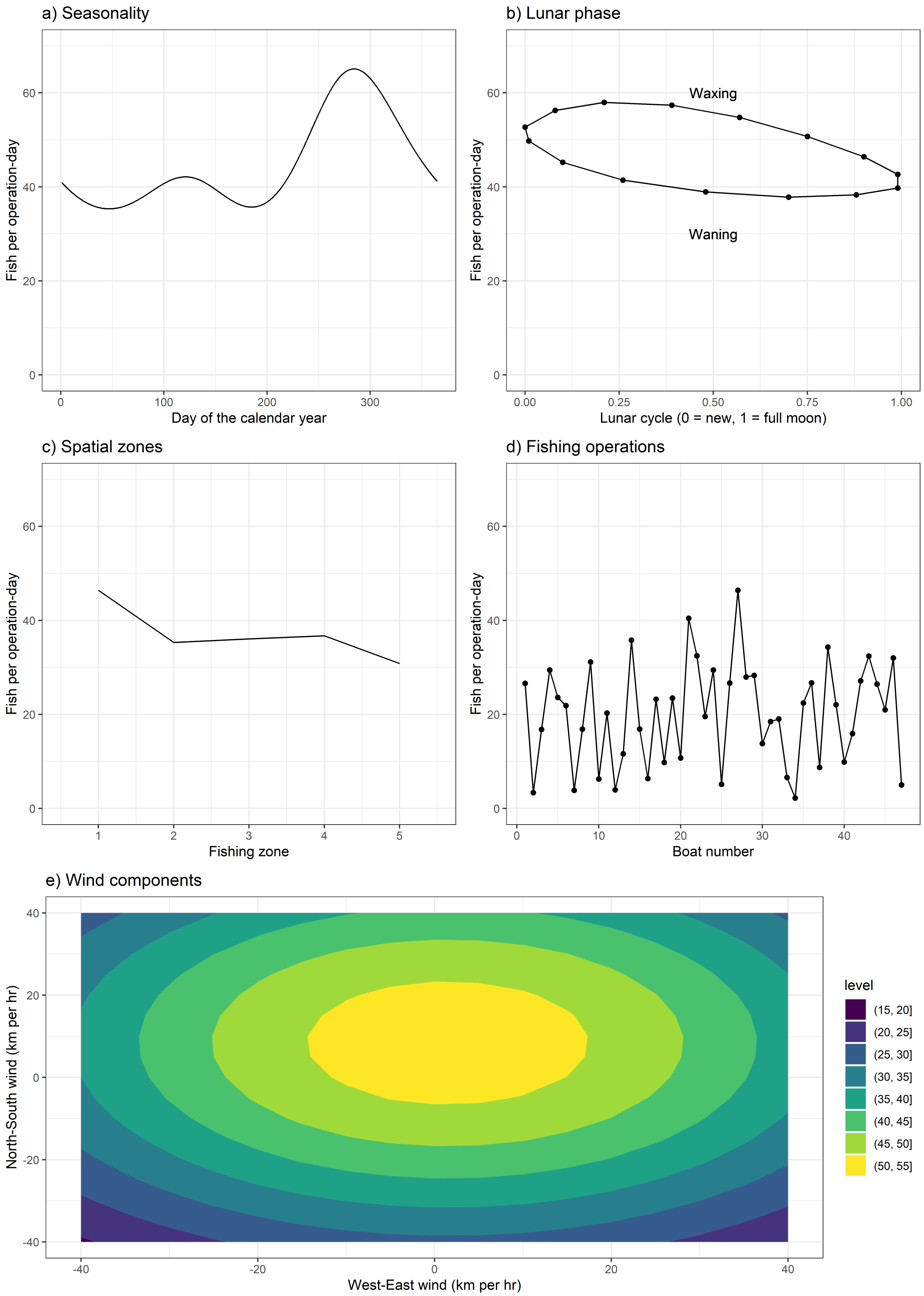

Figure C.6: Mean catch rate effects estimated by the Sunset GLM. Subplot a) by time-of-year, b) lunar cycle, c) zones fished (1 = Bramble Cay), d) differences between boats (fishing power effect, where the main 2021 and 2022 boat was the highest catching power), and e) the wind speed and direction.

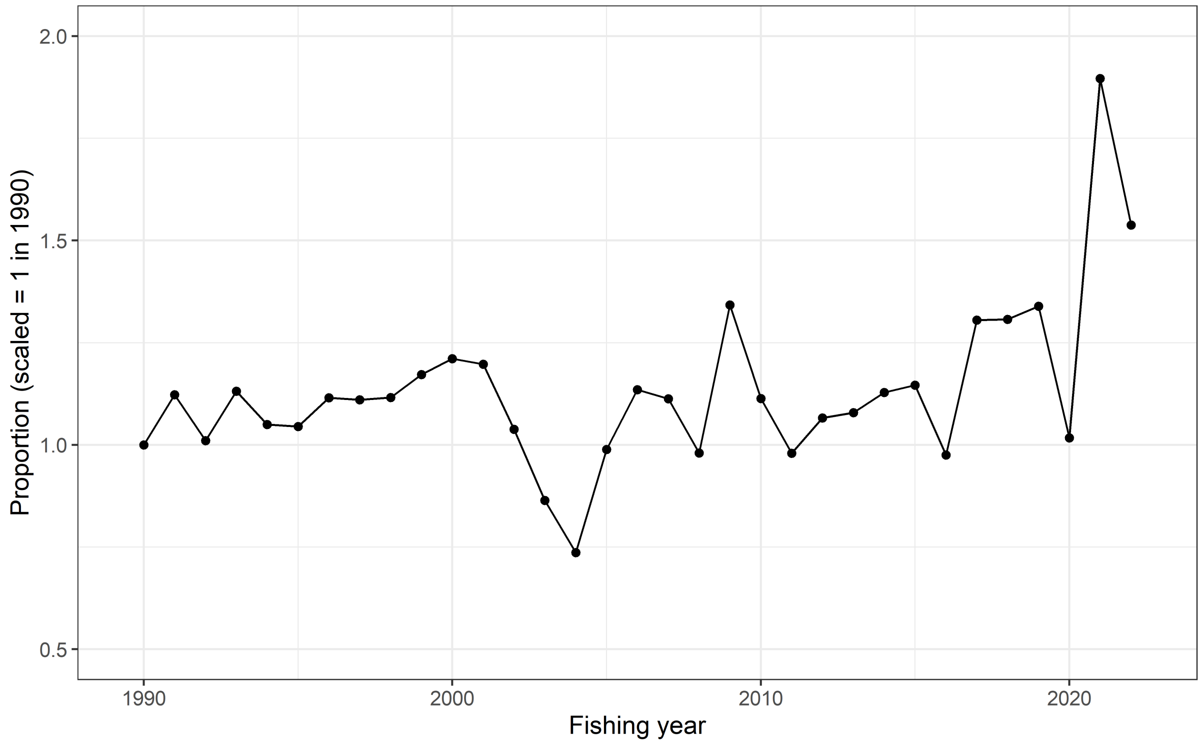

Figure C.7: Relative average Sunset-fleet fishing-power by year as estimated from the GLM boat factor.

Table C.6: Anaylsis of variance table for the Sunset commercial catch rate analysis using tender data. F statistics were derived from the R drop1 procedure.

term	Df	Deviance	F value	Pr(>F)
residual	24496	132080		
fishyear	18	137569	21.253	0.000
zone5	4	133866	31.122	0.000
boat	22	174686	134.970	0.000
s1cos	1	132139	4.095	0.043
s1sin	1	133212	78.924	0.000
s2cos	1	132544	32.327	0.000
s2sin	1	132453	25.991	0.000
s3cos	1	132118	2.634	0.105
s3sin	1	132425	24.061	0.000
lunar	1	133778	118.331	0.000
lunaradv	1	135617	246.501	0.000
windns	1	132218	9.620	0.002
windns2	1	132092	0.845	0.358
windew	1	132167	6.056	0.014
windew2	1	132449	25.703	0.000
logtenders	1	136105	280.523	0.000

C.5.2 TIB diagnostics

Table C.7: 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	187	6308		
fishyear	3	6468	1.580	0.196
client	34	10918	4.019	0.000
s1cos	1	6609	8.933	0.003
s1sin	1	6391	2.460	0.118
windew	1	6504	5.824	0.017
crew	1	6453	4.318	0.039

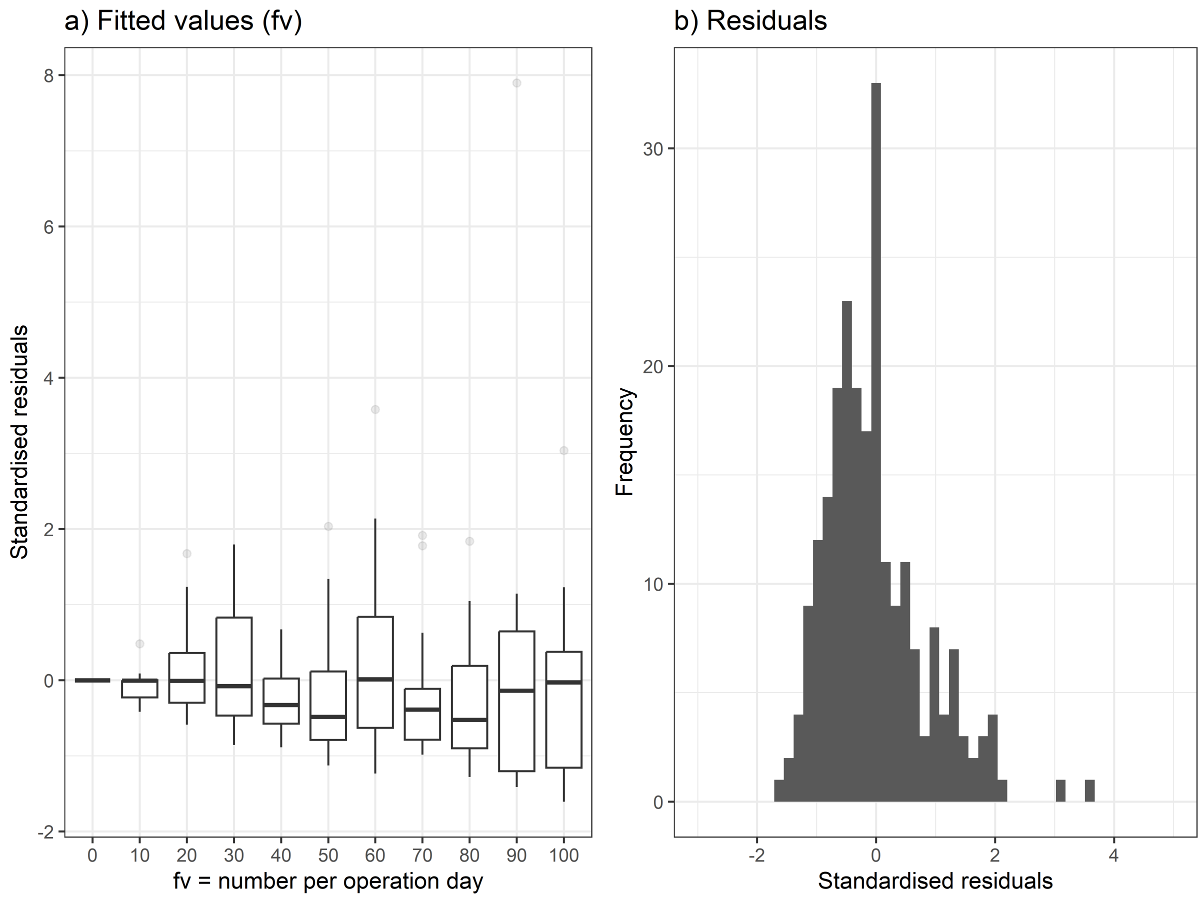

Figure C.8: TIB catch rate residual plots for a) box plot of fitted values and residuals, and b) histogram of residuals. Fitted values > 100 kg were grouped. Residuals were standardised by the sqrt(variance * dispersion).

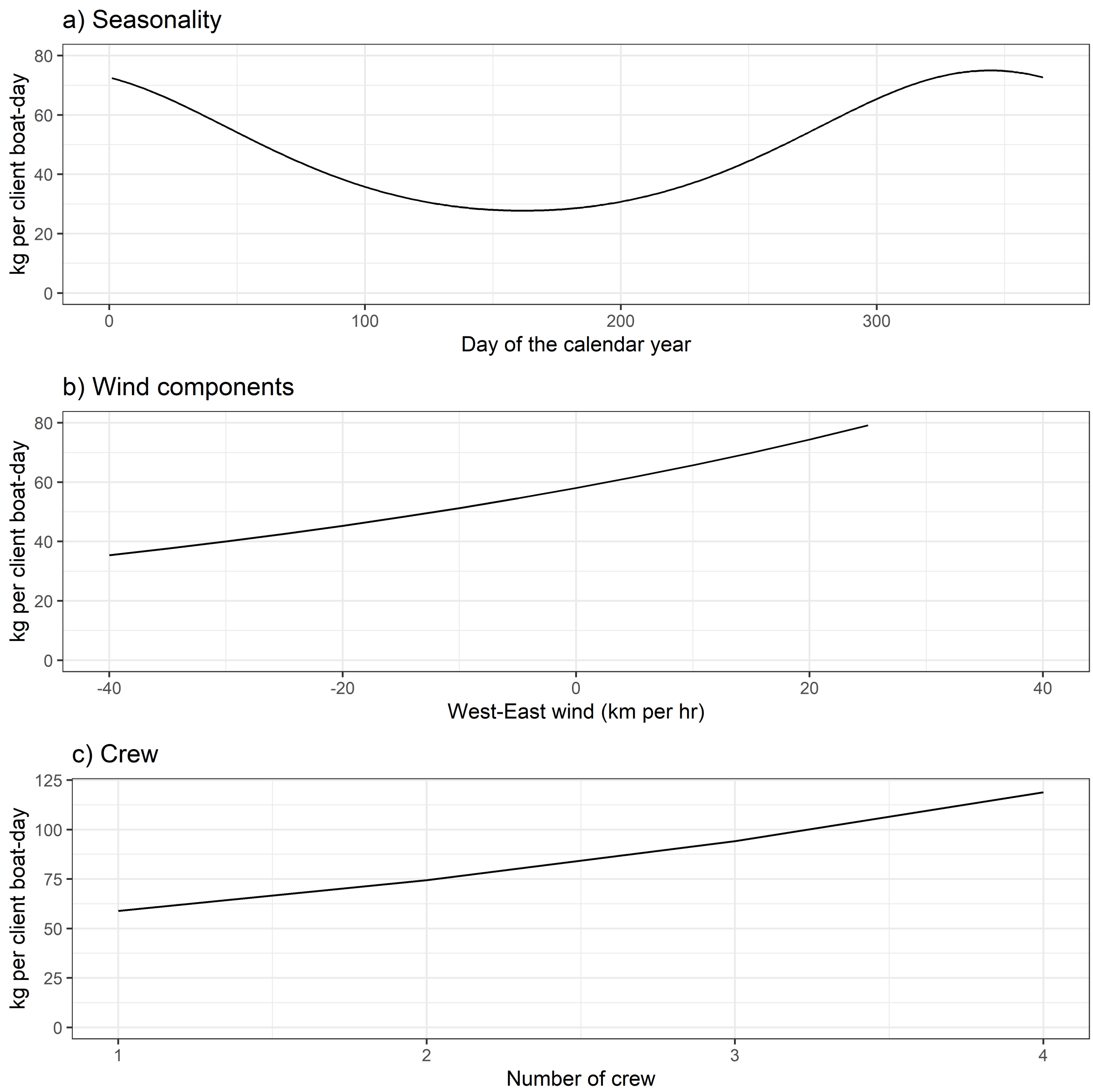

Figure C.9: Mean catch rate effects estimated by the TIB GLM. Subplot a) by time-of-year, b) the wind speed and direction and c) number of crew on the client boat.

C.5.3 Data selection for catch rates

A number of data selection rules for Sunset catch rates were assessed through past stock assessments and by TSFFRAG. The purpose was to check the key trends in catch rates, particularly for the decline post 2011. 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 - number of data), b) mean catch rates (Mn - number of fish) and c) number of boats (B). The data report was 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 C.8 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 2011.

Table C.9 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 C.10 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 time series was young, with some fisher clients just commencing reporting, and no significant differences detected. The data for 2022 was low in number and influenced by large catch reports that may not be daily.

Table C.8: 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
2022	150	150	150	102	102	46	46	46	55	55	3	3	3	1	1
Total	24951	24591	22108	16029	10920						68	47	26	12	6
N. removed	0	360	2843	8922	14031										
% removed		1	11	36	56										

Table C.9: 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	-1	-4	-4	0	0	0	0
T statistic	-1.79	-4.98	-7.51	-5.86	-0.42	-0.07	-0.09	0.02
Pr(>T)	0.08	0	0	0	0.67	0.95	0.93	0.99
Slope	1	0.97	0.88	0.88	1	1.01	1	0.99
T statistic	-1.31	-3.94	-8.81	-7.69	-0.08	0.68	-0.23	-0.53
Pr(>T)	0.2	0	0	0	0.94	0.5	0.82	0.6

Table C.10: 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	86	67	37	62	64	66	71	80	15	11	9	4	1
2020	65	32	28	8	1	38	49	51	67	129	20	10	7	2	1
2021	63	38	36	27	10	56	70	71	84	134	16	9	8	5	2
2022	11	9	9	9	3	531	416	416	416	1121	5	3	3	3	1
Total	243	169	159	111	51						37	14	11	5	2
N. removed	0	74	84	132	192										
% removed	0	30	35	54	79										
Mean difference							22	21	12	-194					
T statistic							0.71	0.66	0.35	-1.46					
Pr(>T)							0.53	0.56	0.75	0.24					
Slope							1.25	1.25	1.23	0.47					
T statistic							4.19	3.87	2.36	-30.48					
Pr(>T)							0.02	0.03	0.1	0					

Appendix D Model outputs

D.1 Diagnostics

D.1.1 Abundance indices

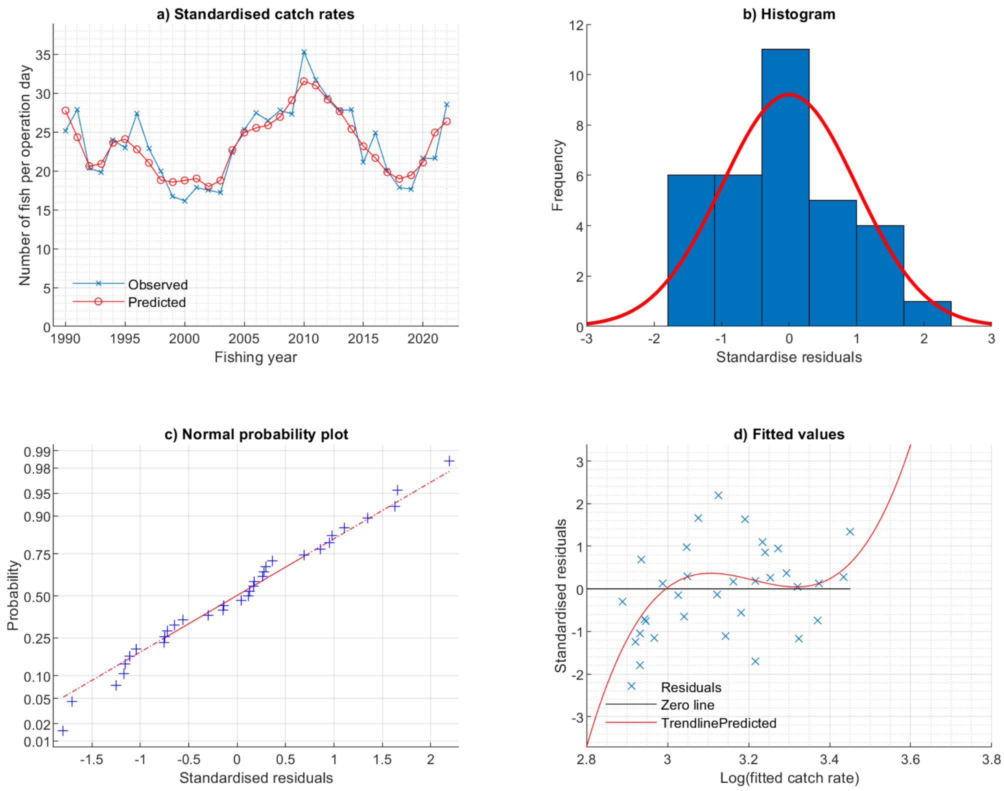

Figure D.1: Example custom model analysis 2 fit to catch rates. The level of fit was similar between analyses. There were no influential standardised-residuals, beyond the values of -2 and 2, that suggested any lack of fit.

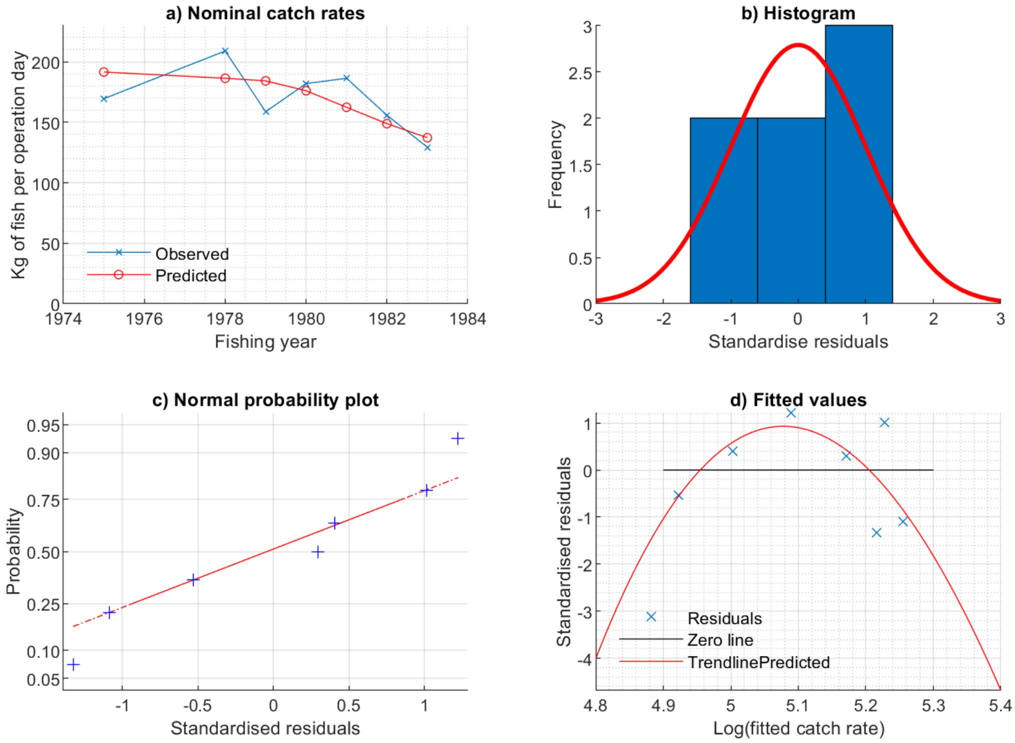

Figure D.2: Example custom model analysis 2 fit to the historical Sunset catch rates between 1975 and 1983. The level of fit was similar between analyses. There were no influential standardised-residuals, beyond the values of -2 and 2, that suggested any lack of fit.

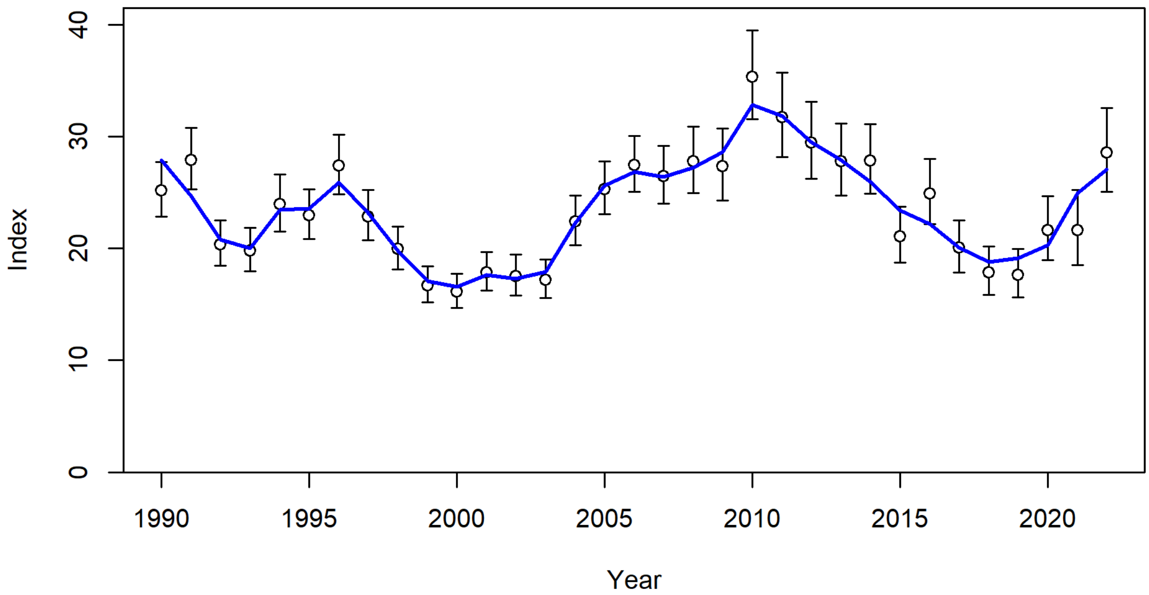

Figure D.3: Example stock synthesis analysis 2 fit to Sunset catch rates. The level of fit was similar between analyses, and to the custom model. There were no influential standardised-residuals, that suggested any lack of fit. The y-axis scale was numbers of fish per operation day.

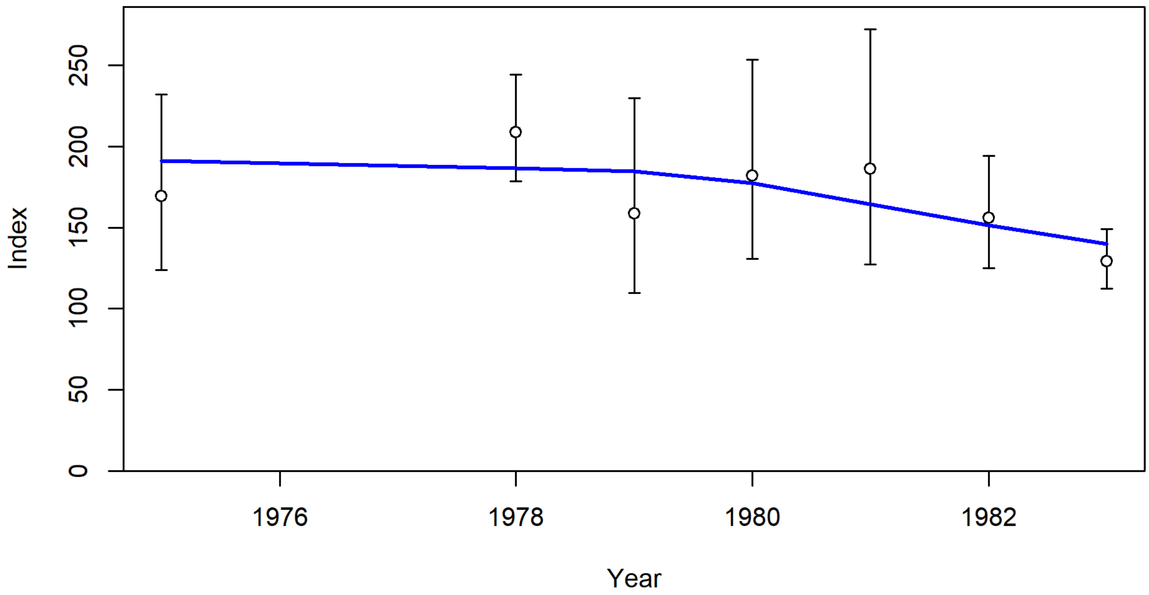

Figure D.4: Example stock synthesis analysis (SS) 2 fit to historic catch rates between 1975 and 1983. The level of fit was similar between analyses, and to the custom model. There were no influential standardised-residuals, that suggested any lack of fit. The y-axis scale was kg of fish per fisher-day. The error bars represented two standard deviations, calculated from the CVs used by SS.

D.1.2 Age compositions

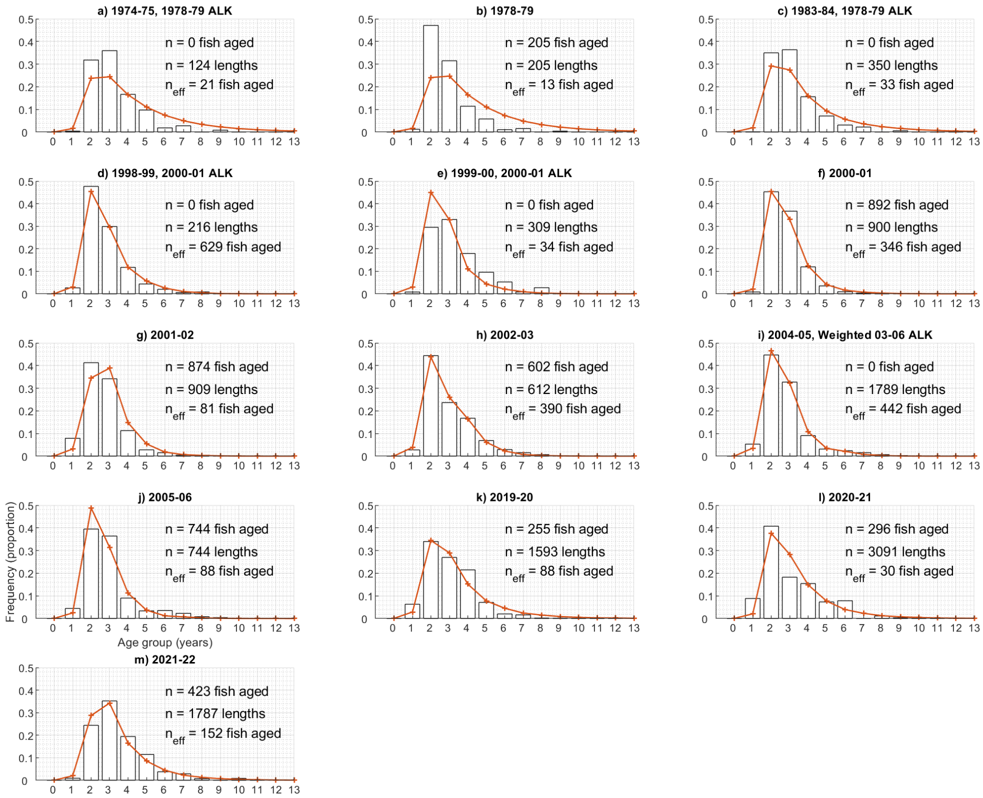

Figure D.5: Example custom model analysis 2 prediction of fish ages. The predicted model fits were similar for other analyses. n was the number of fish sampled. n_{eff} was the estimated effective number of fish sampled for the fit. ALK – age length key used.

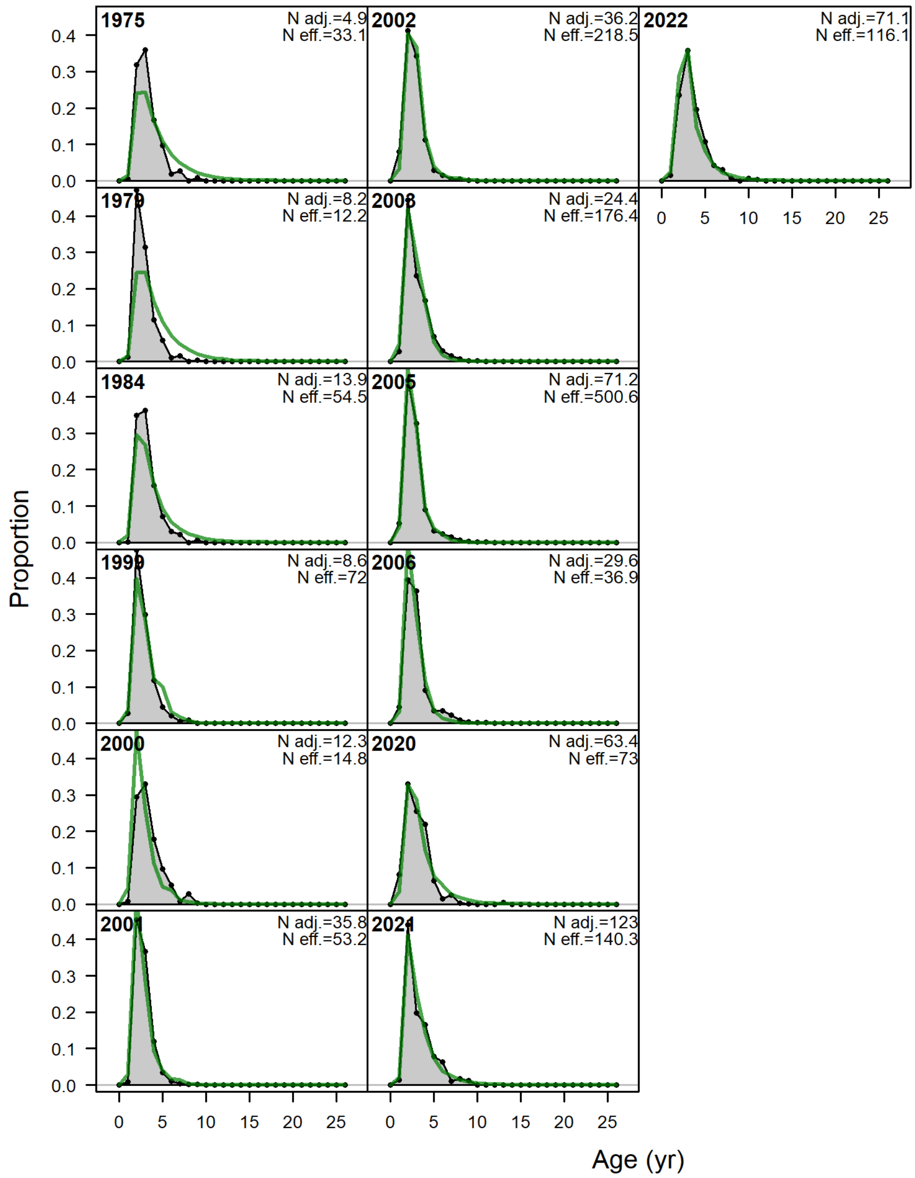

Figure D.6: Fits to age structures for the SS model analysis 2. Values are shown for the estimated effective number of fish sampled for the fit. The measures of effective sample numbers summarised the level of model fit (higher better and lower worse), but the methodology was different and not comparable to the custom model effective sample sizes.

D.1.3 SS cookbook

The appraisal of SS fitting was by implementing the ”cookbook” of diagnostic tests, using the *r4ss* and *ss3diags* R packages (Carvalho et al. 2021). For understanding diagnostics, the paper by Carvalho et al. (2021) is best used as a guide.

In summary, SS performance was evaluated as acceptable for model convergence, fits to the data, consistency in estimates and results, and 1–3 year forecasting. As the SS parameter estimates and negative log-likelihoods were not too dissimilar between analyses (Table 3.2), the cookbook diagnostics were only reported for analysis 2.

The following points described the diagnostics:

- No parameters were estimated at bounds (Table 3.2). Estimation was unconstrained.
- Optimisations achieved the final gradient (absolute value ≤ 0.0001) for each estimated parameter.
- The Hessian matrix for parameter derivatives was positive definite.
- There were no large variances evident in parameter estimates (Table 3.2 and Figure 3.10).
- Run-test results for catch rates indicated good model fits, with no evidence ($p \geq 0.05$) to suggest non-random or any large residuals (Figure D.3, Figure D.7 and Table D.1).
- Run-test results for the age frequency data also suggested good model fits with an overall RMSE less than 30% (Figure D.7 and Table D.1). The three early years of age data had strong frequencies of 2+ and 3+ aged fish. These frequencies were under fit, and no recruitment deviations were used for these years (Figure D.6). The residual for 1979 was outside of the 3 sigma limit (Figure D.7). A check on the 1979 samples, age-length key and how to better fit these early data is warranted.
- The minimum (better) values along the virgin recruitment R0 profile were similar, with little difference between the data components (Figure D.8). The fish age data tended to provide more contrast for estimating R0.
- The profile for natural mortality (M) suggested larger values were beter to fit the data (Figure D.9). The lack of curvature also indicated little infomation to estimate M, and supported the approach to consider different fixed values. The profile was constrained between the 0.3–0.4 M range considered by this assessment.
- The minimum values along the steepness profile were similar between the data components (Figure D.10). The catch rate data, with recruitment deviations, tended to dislike higher steepness values more than the age data. In general though, all data components seemed to be more informative about steepness than for natural mortality. See also the two dimensional profiling of h and M in the steppnes disscussion (Figure D.22).
- The results of the age structured production model (ASPM) diagnostics were in Figure D.11. The same work flow was used as in the cookbook (Carvalho et al. 2021). This involved comparing the SS analysis 2 results (the full model) to: 1) the ASPM where only the R0 parameter was estimated, the log recruitment deviations were all set to zero and the model was only fit to catch rates; and 2) the production model was rerun estimating R0 and the recruitment deviations (labelled ASPMdev). The diagnostic steps, of comparing simplified models with fixed parameters, were to assess if the annual harvests alone could explain trends in catch rates. In summary, the answer was no, but the models following the cookbook methods showed:
  - The catch rate fits were better by using recruitment deviations; models would under or over estimate without (Figure D.11a). The catch rate RMSE values were 21%, 5% and 6% for the ASPM, ASPMdev and full models respectively. The recruitment deviations also indirectly supported a better fit to historic catch rates (Figure D.11b), by better estimating R0.
  - The ASPMdev and full models lower RMSE, for the degrees of freedom used by estimating the recruitment deviations, might suggest SS was fitting too well to the catch rates.
  - Annual recruitment deviations were required not only to estimate the trends, but also for scaling of R0 and therefore the spawning calculations (Figure D.11c and D.11d). The ASPM model might be better specified and assessed, by deviating from the cookbook method, to estimate both R0 and steepness, and to fix the other parameters. More investigation of the current ASPM is required, which estimated high R0 and error. This R0 result was not consistent with the behaviour of deterministic models in earlier assessments, that showed comparable R0 and steepness values and biomass ratios (Figure E.1) (Begg et al. 2006; O'Neill et al. 2018a).
  - The ASPMdev model indicated that annual harvest and catch rates informed estimates of recruitment variability with similar confidence intervals compared to the full model (Figure

D.11e). The fish age data in the full model suggested different deviations in 2019 and 2020, but in general smaller confidence intervals were calculated.

  - The ASPM diagnostic re-enforced that catch rates were used as one of the primary assumptions in the stock assessment and to inform recruitment deviations.

- Retrospective diagnostics were implemented by removing (peeling) 1–7 of the most recent years of data from SS (Figures D.12, D.13, D.14, and D.15). There was small retrospective bias, within acceptable thresholds, for 1–2 year peels (Table D.1). The bias increased positively over 7 years (Table D.1). The positive bias (overestimation) was due to SS expecting random recruitment deviations. However, in retrospect the trends in the data did not occur this way, with the annual deviations being consistently negative between the years 2009–2018 (Figure D.19). Of note, the R0 estimates were consistent retrospectively (Figure D.15).
- Similarly, the 1–2 year forecast bias was acceptable (Table D.1). However, again for the years tested, having more negative recruitment deviations, the positive bias (overestimation) increased out to 7 years (Table D.1).
- The hind casting diagnostic further illustrated the prediction bias (Figure D.16). Four of the seven catch rate hind-casts were outside the GLM confidence interval, and three were inside. This result was summarised by the undesirable MASE score being > 1 in Table D.1. However, the 4 outside predictions were by only a few fish. Predictions were improved after 2018 when recruitment deviations normalised. The predictions of mean fish age were in the confidence interval zone (Figure D.16). As indicated above, the assessment was reliant on catch rates, and SS testing is warranted to increase the catch rate variance (beyond the GLM confidence interval) to broaden uncertainty in SS predictions.
- The jitter test, by changing the starting values, returned the same converged parameter estimates and negative log-likelihoods (Figure D.17). The test used a jitter fraction of ± 0.1 for 100 model reruns.

Table D.1: Summary statistics for runs tests, retrospective analaysis, retrospective forecasts and hindcast cross validation (HCxval) diagnostics for stock synthesis, where n was the number of data for the statistics.

Diagnostic	Quantity	Statistic	Value	n	Acceptance
Runs Test	cpue Sunset	p-value	0.991	33	>0.05
Runs Test	cpue historic	p-value	0.686	7	>0.05
Runs Test	Fish age	p-value	0.197	13	>0.05
Retrospective analysis	SSB 1-year peel	Mohn's Rho	-0.016	1	-0.22-0.30
Retrospective analysis	SSB 2-year peel	Mohn's Rho	0.078	2	-0.22-0.30
Retrospective analysis	SSB 7-year peel	Mohn's Rho	0.158	7	-0.22-0.30
Retrospective forecasts	SSB 1-year peel	Forecast bias	-0.016	1	-0.22-0.30
Retrospective forecasts	SSB 2-year peel	Forecast bias	0.120	2	-0.22-0.30
Retrospective forecasts	SSB 7-year peel	Forecast bias	0.235	7	-0.22-0.30
HCxval	cpue Sunset	MASE	1.263	7	<1
HCxval	Fish age	MASE	0.939	2	<1

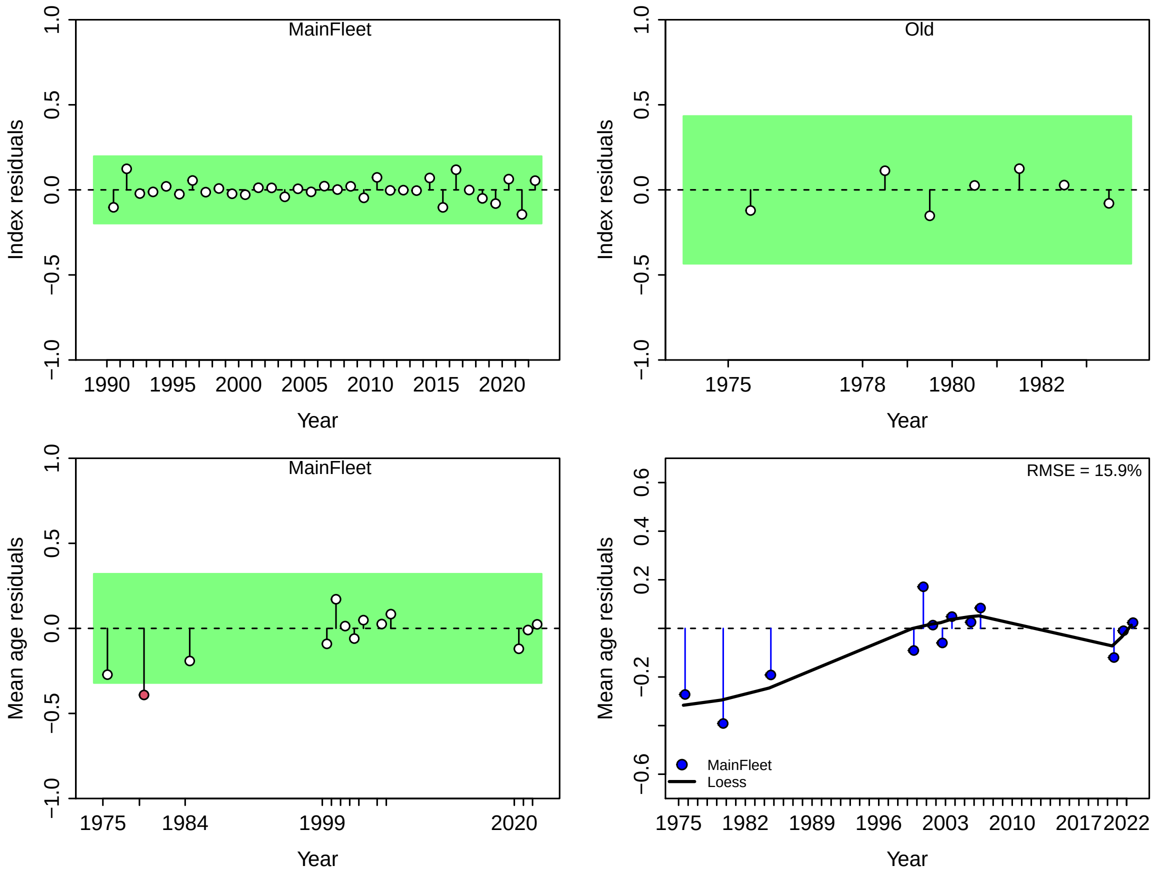

Figure D.7: Runs tests results illustrated for catch rates (in the top two sub-plots labelled ”MainFleet” for the Sunset sector and ”Old” for the early historical Sunset data) and age frequencies (in the bottom two sub-plots). Values in the green shading indicated no evidence of non-random or large residuals. The shaded area covered three standard deviations either side of zero, and any red points outside of the shading violated the three-sigma-limit for that data series.

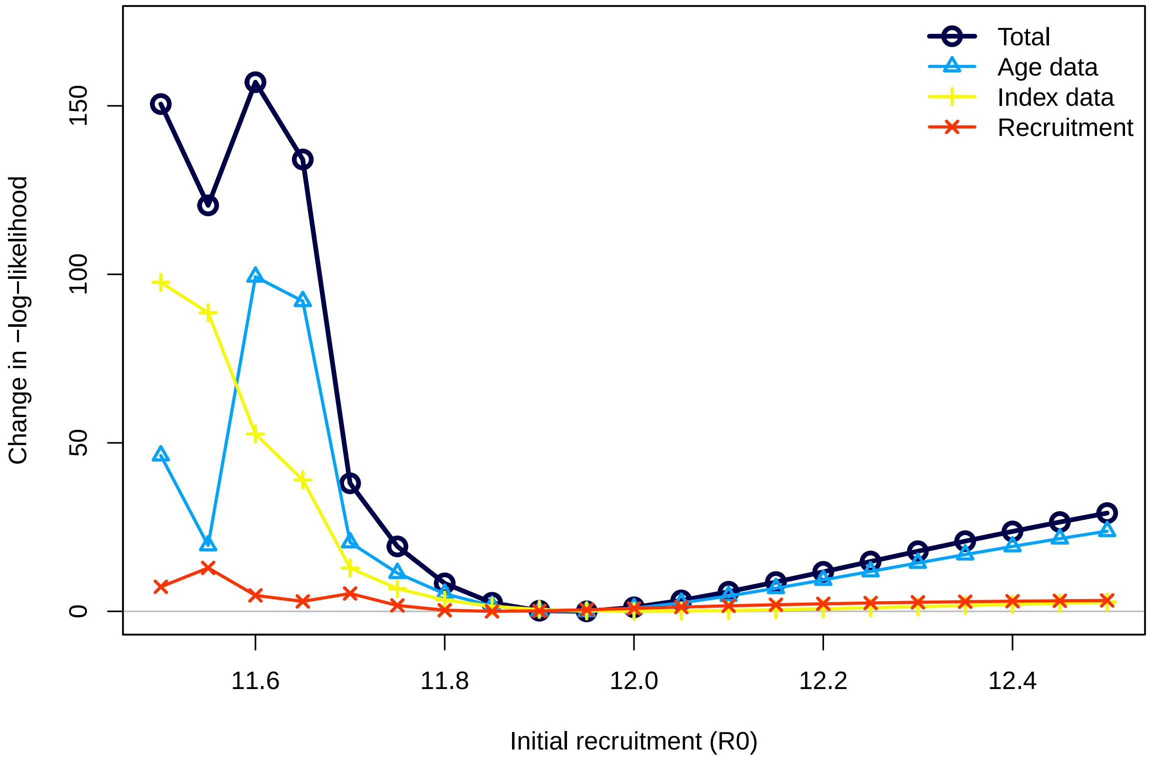

Figure D.8: Log-likelihood profile for virgin (initial) recruitment R0 for the various data components. For the x-axis, R0 was illustrated on the log scale. The blue line was for the fish age data, the yellow line was for the catch rate index data, and the red line was for the recruitment deviates. The black line was the combined profile for all data components. Results were for analysis 2.

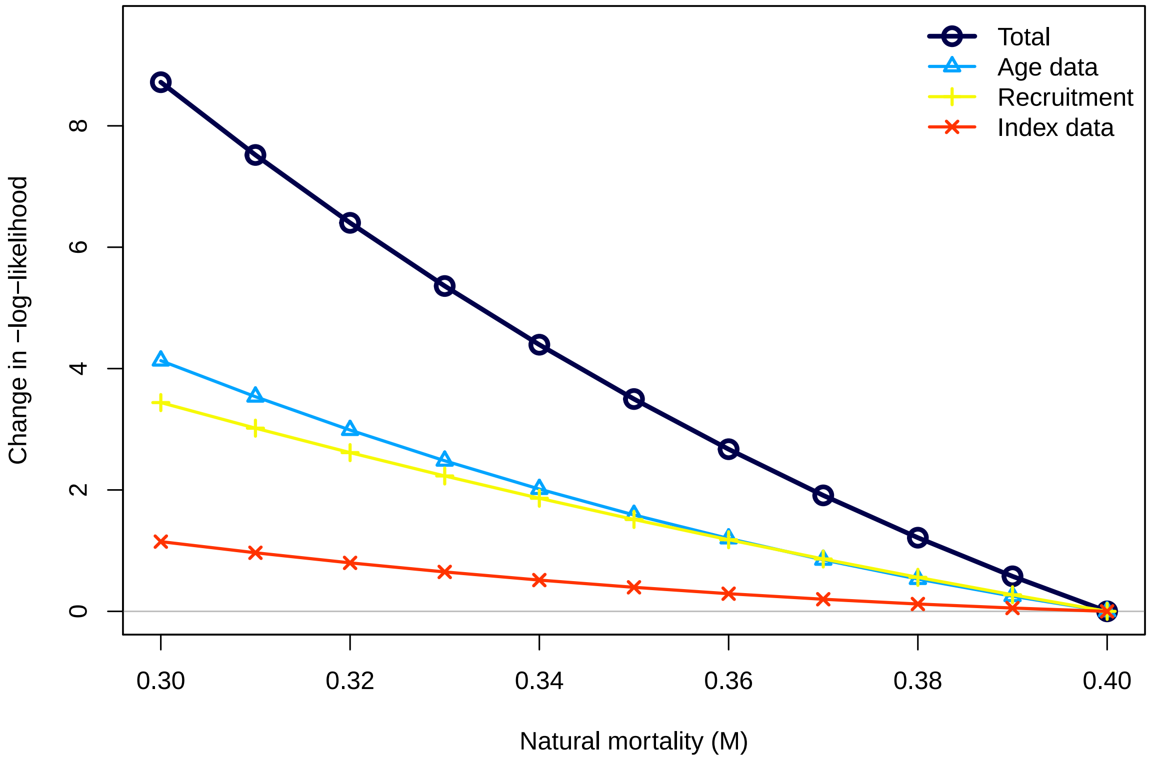

Figure D.9: Log-likelihood profile for natural mortality (M per year) for the various data components. The blue line was for the fish age data, the red line was for the catch rate index data, and the yellow line was for the recruitment deviates. The black line was the combined profile for all data components. Results were for analysis 2.

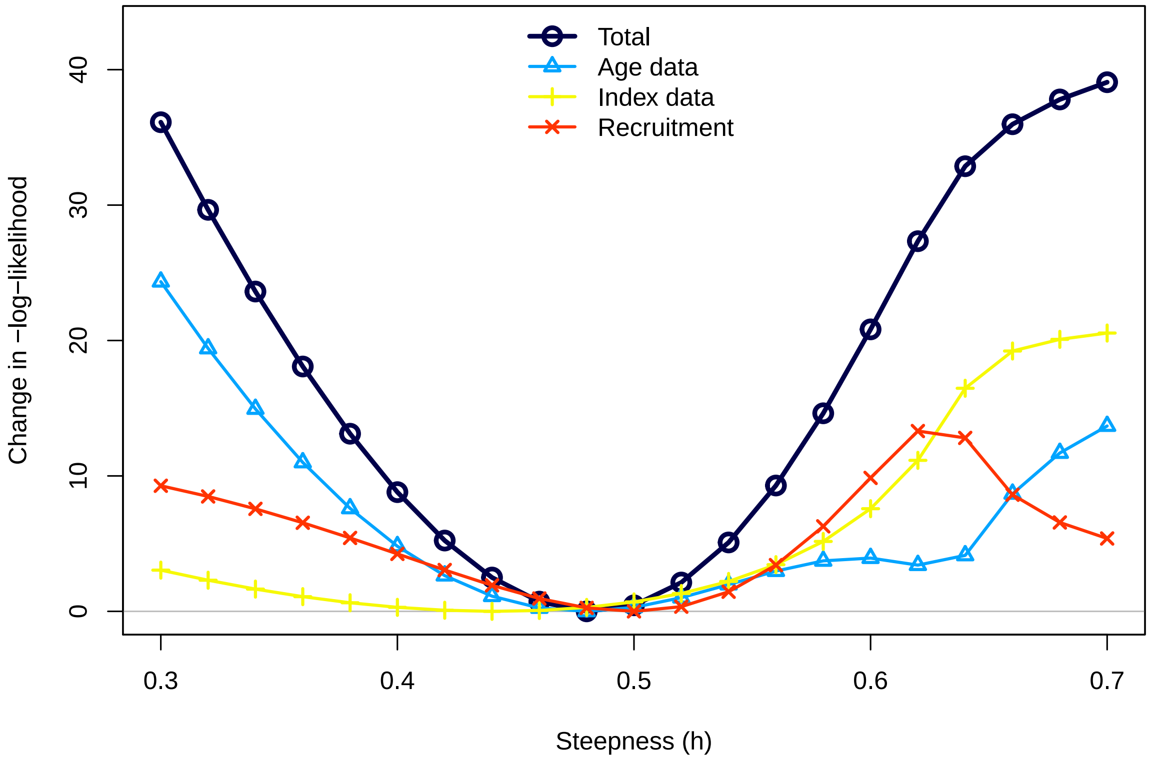

Figure D.10: Log-likelihood profile for steepness (h) for the various data components. The blue line was for the fish age data, the yellow line was for the catch rate index data, and the red line was for the recruitment deviates. The black line was the combined profile for all data components. Results were for analysis 2.

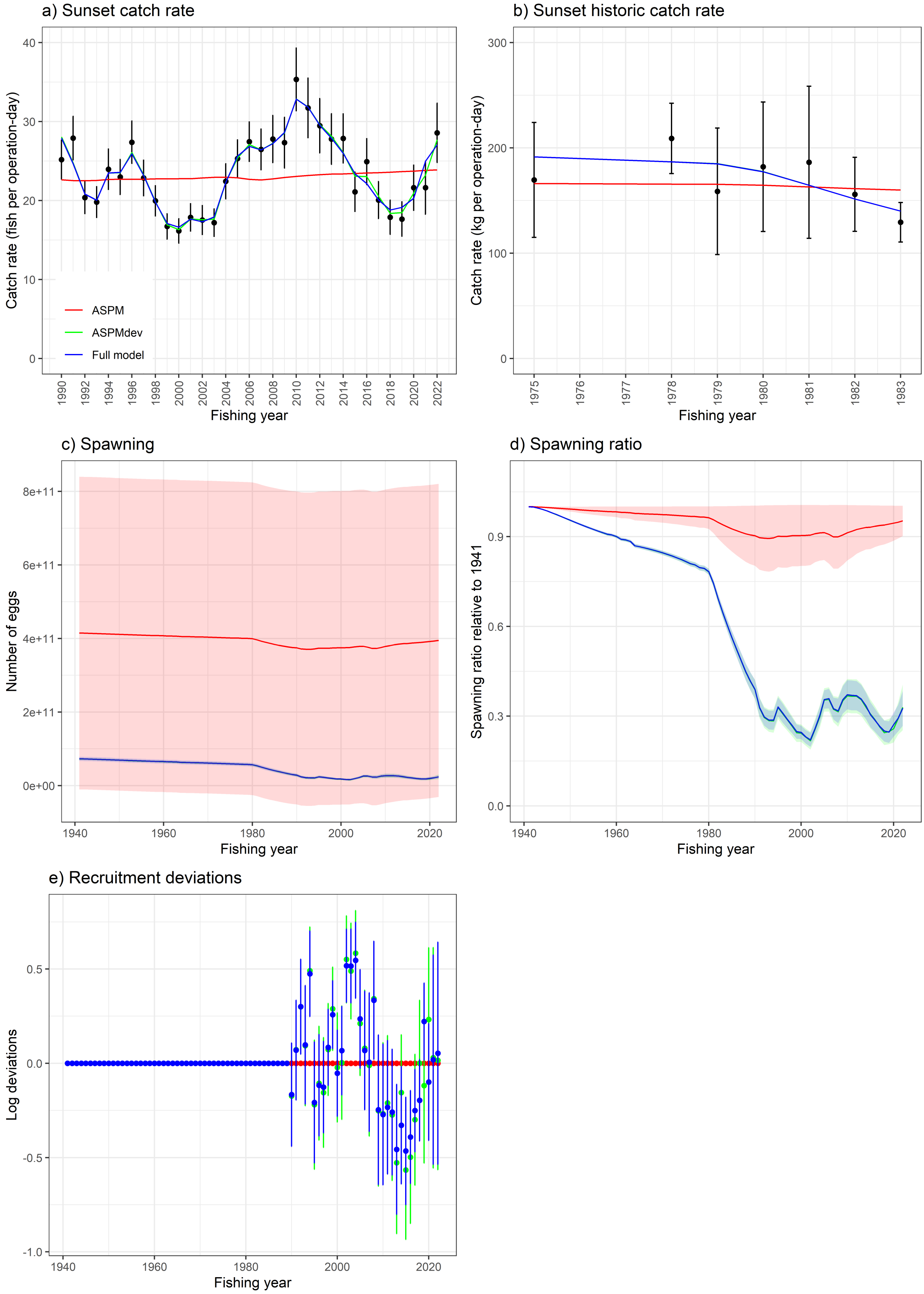

Figure D.11: Comparison of results between the full SS analysis 2 model (blue line) and the age-structured production model versions - ASPM without recruitment deviations (red line) and ASPMdev with recruitment deviations (green line).

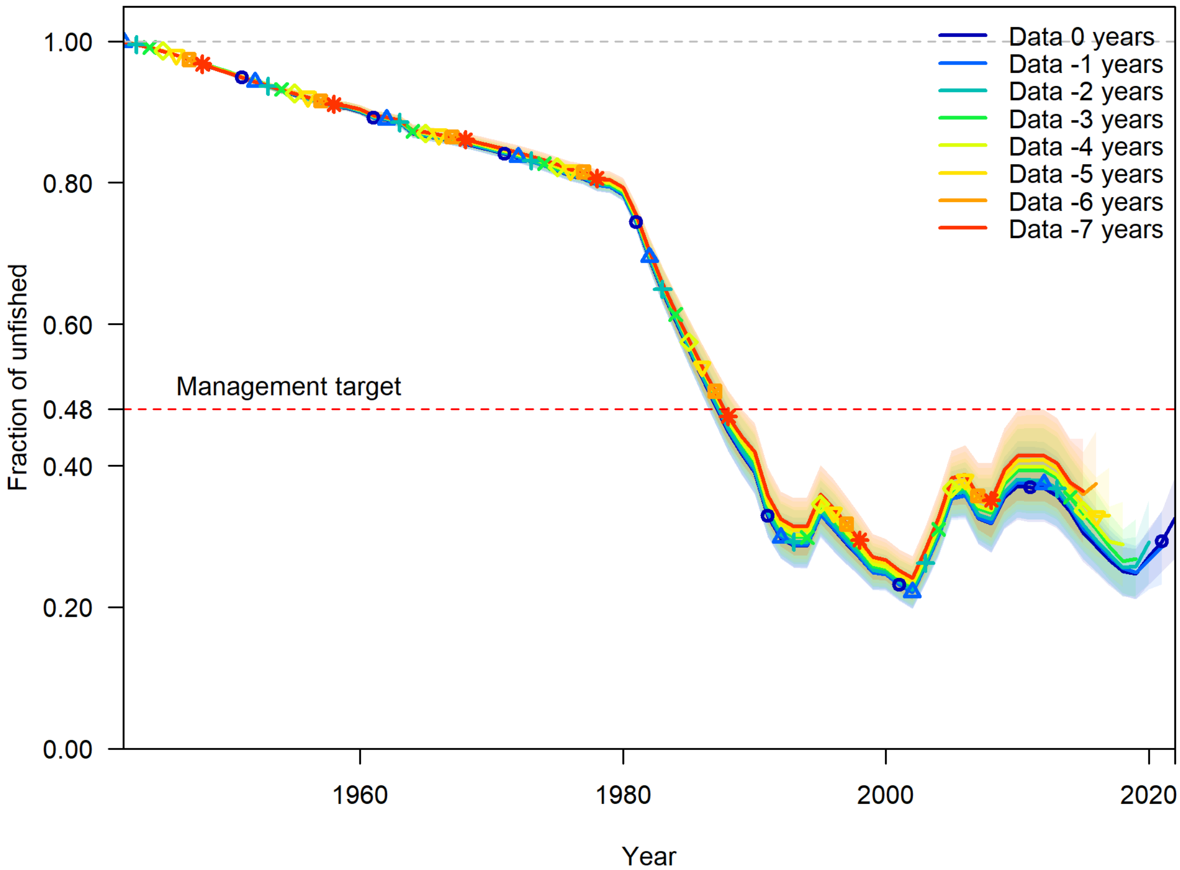

Figure D.12: Retropsective analysis for spawning biomass (egg production) ratios after removing 7 years of data, one year at a time sequentially.

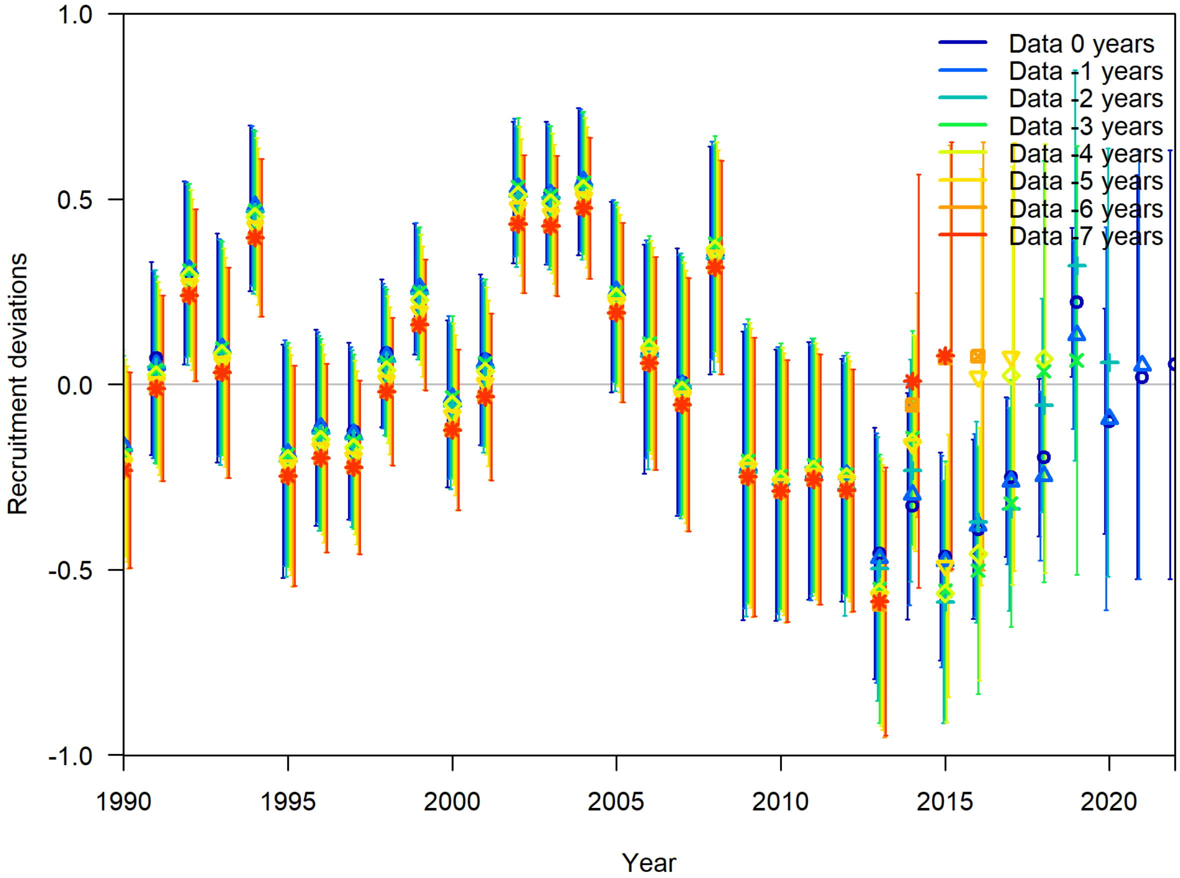

Figure D.13: Retropsective analysis for recruitment deviations after removing 7 years of data, one year at a time sequentially.

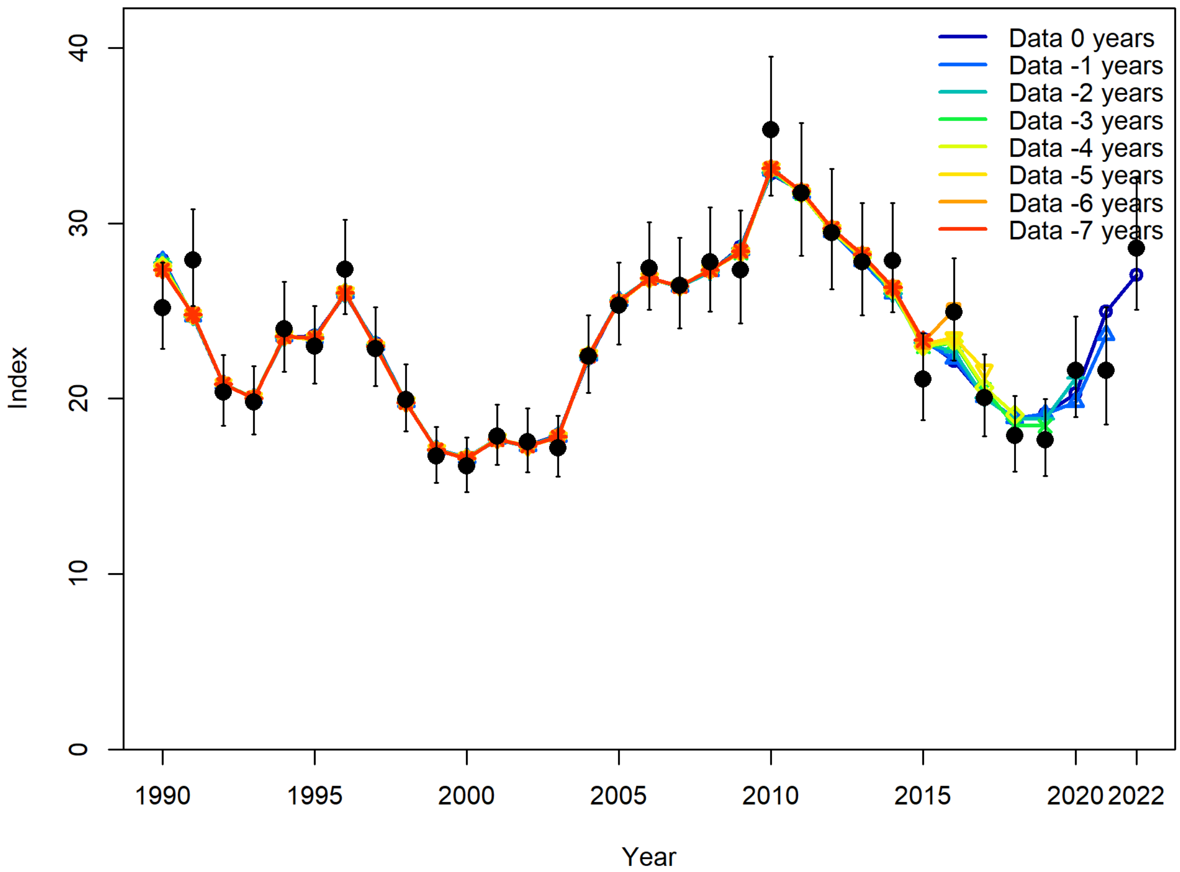

Figure D.14: Retropsective analysis for catch rate fits after removing 7 years of data, one year at a time sequentially.

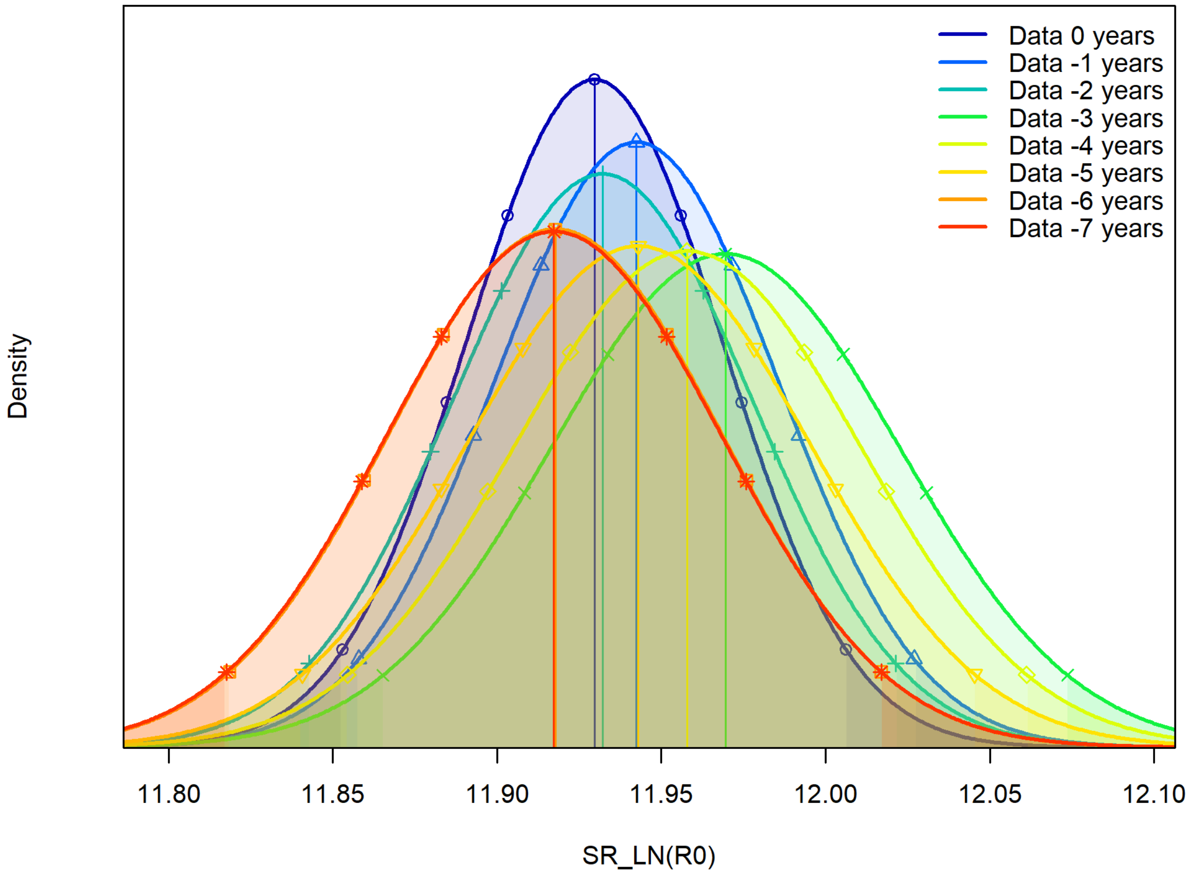

Figure D.15: Retrospective estimates for the virgin recruitment, the log R0 parameter.

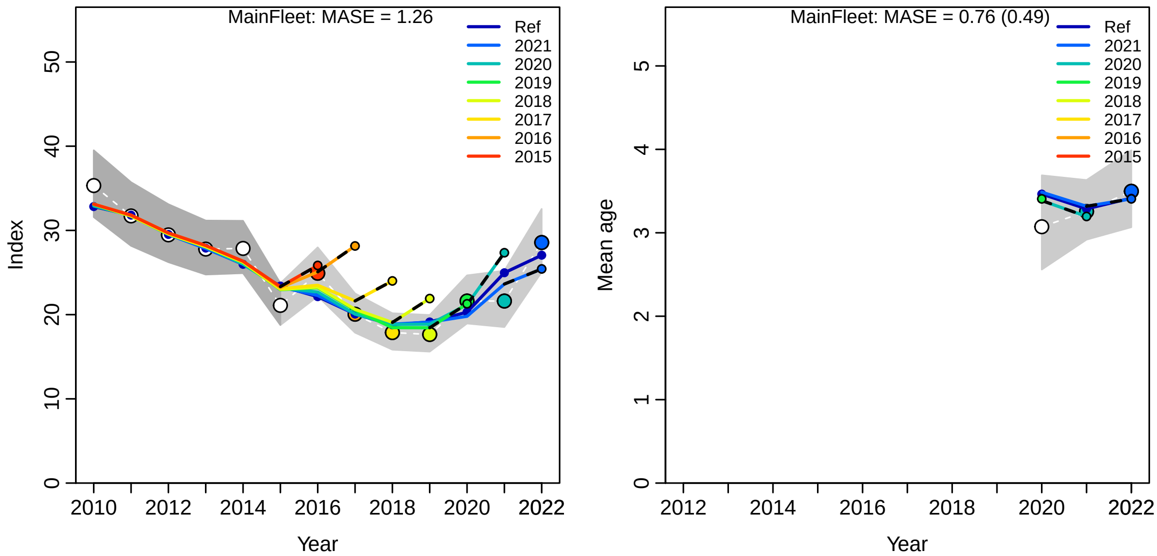

Figure D.16: Hindcast cross-validation (HCxval) for predicting Sunset catch rates (number of fish) and mean fish age (years). HCxval was performed from the full SS analysis 2 model and 7 hindcast runs. The mean absolute scaled error (MASE) score was listed in each subplot.

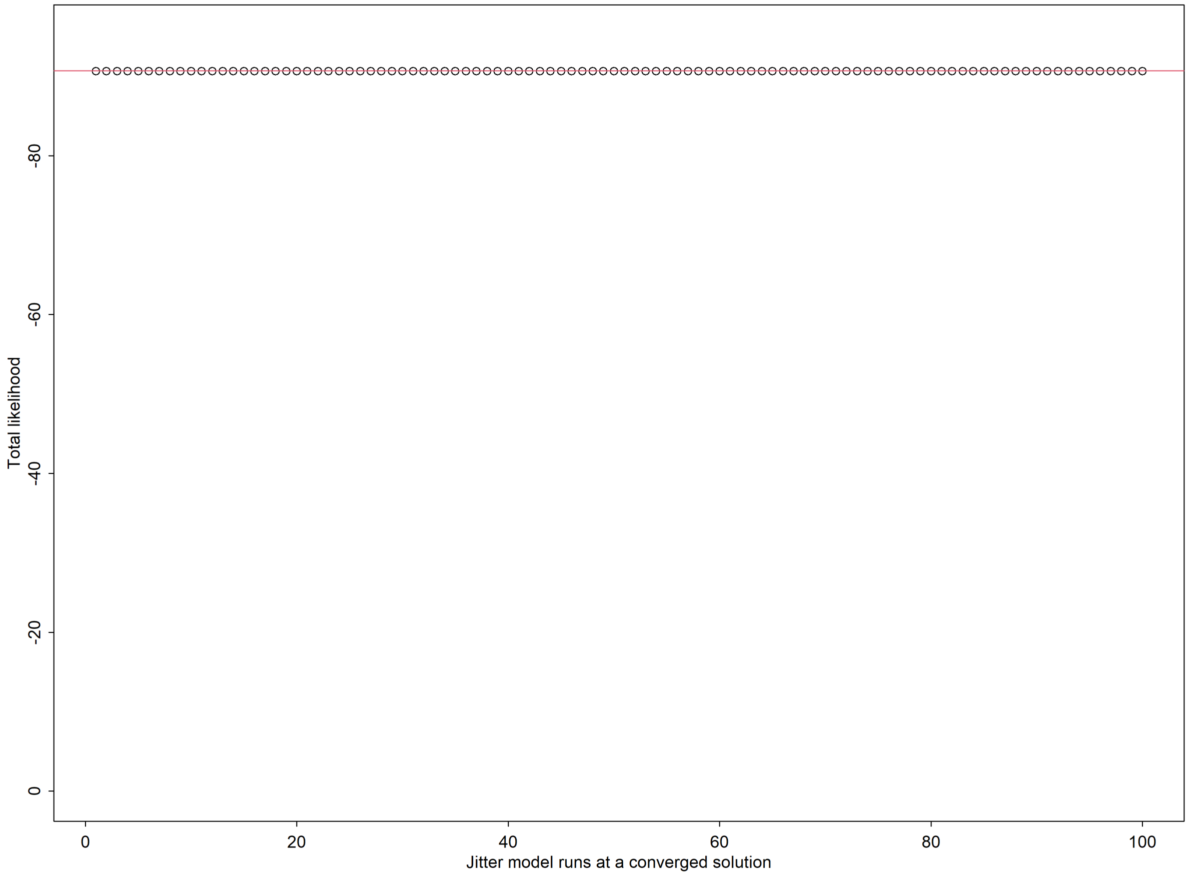

Figure D.17: The jitter diagnostic for the negative log-likelihood, with the red horizontal line for the base-case fit.

D.2 Harvest rates

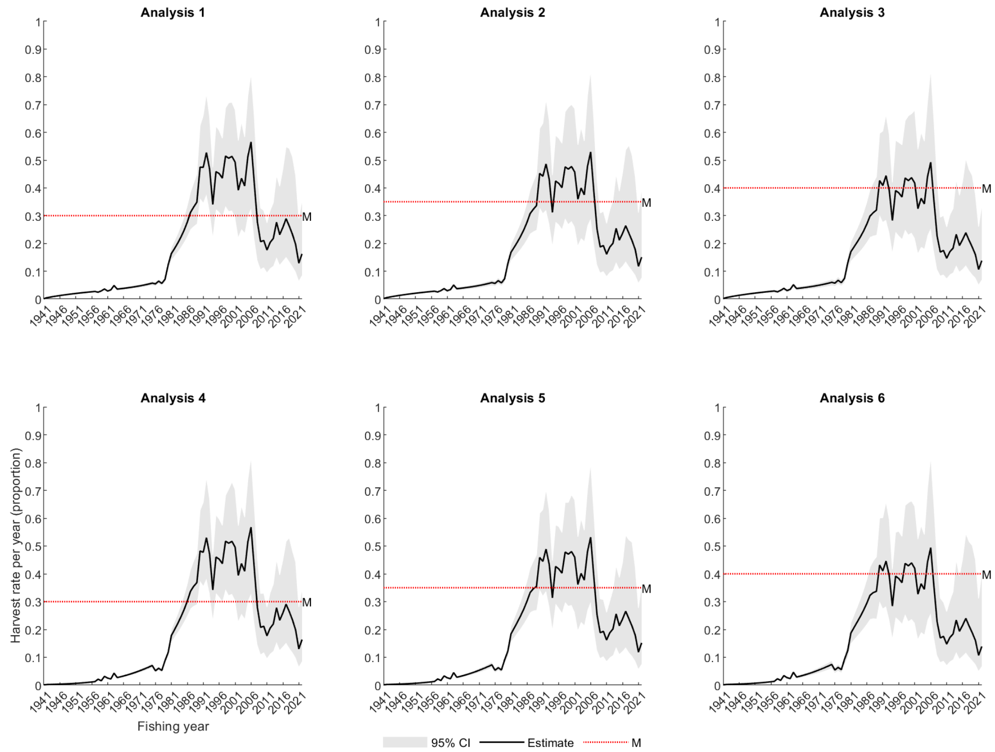

Figure D.18: Time series of harvest rates (fraction of exploitable biomass) from the custom model.

D.3 Recruitment deviations

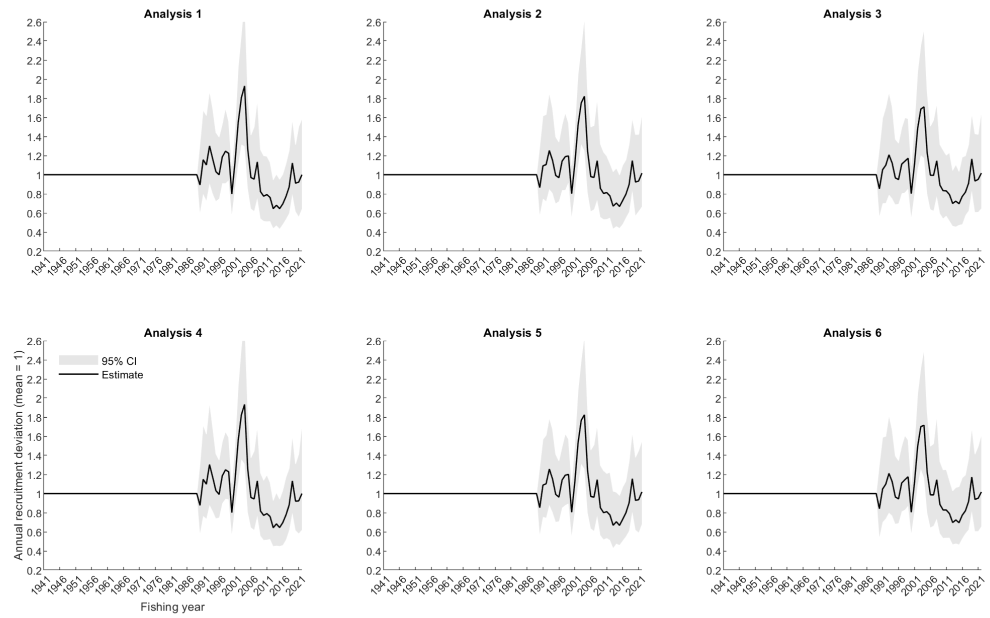

Figure D.19: Time series of recruitment deviations from the custom model. Estimates were similar across analyses and demonstrated consistency in results.

D.4 Steepness

The estimates of Torres Strait Spanish mackerel steepness, from the custom and SS stock assessment models, indicated a general range between 0.3 and 0.6. Some points of comparison:

- Scenario two from the most recent Torres Strait Spanish mackerel assessment estimated 0.47 (Stock Synthesis) and 0.40 (custom model) (O'Neill et al. 2022).
- The FishLife Thorson (2020) *Scomberomorus* life-history prediction is 0.46; the value used in the east coast Spanish mackerel asssessment (Tanimoto et al. 2021).
- The Spanish mackerel Gulf of Carpentaria stock model best fits of steepness around 0.55–0.60 (Bessell-Browne et al. 2020b).
- The Myers et al. (1999) meta-analysis median for Scombridae of 0.52.
- The estimation of steepness in earlier Torres Strait Spanish mackerel 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).

Torres Strait Spanish mackerel has experienced change both up and down in catch rates and harvests, and these data were consistent in signal with the age frequency data (see model diagnostic fits and data in Figure 3.2 and Figure 3.3, and Figure D.20; catch rates were not a one-way trip, for the contrast diagnostic described by Hilborn et al. (1992)). Together, the fishery harvest, catch rate and fish age data appeared to provide some contrast for informing the stock-recruitment relationship. The Torres Strait data included measures from the 1970's before harvests increased, during peak harvests, and for the harvest decline post 2010 (Figure 3.2, Figure 3.3 and Figure D.4).

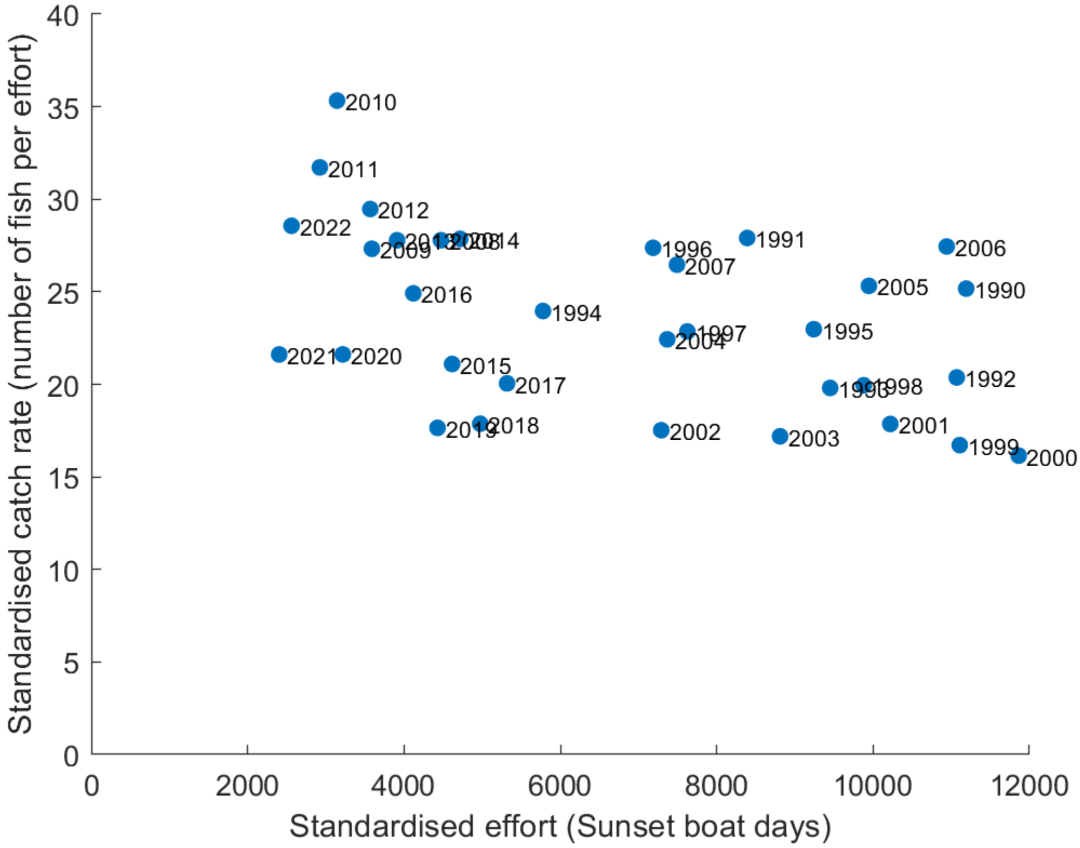

Figure D.20: Annual standardised catch rate verse effort for Torres Strait Spanish mackerel, showing a range of catch rates across different efforts between 1990 and 2022; this was not a one-way trip as described in Hilborn et al. (1992).

For SS analysis 2, plots of the log of recruits per spawning output (eggs) verse spawning were examined to compare estimated and fixed steepness at 0.7 (Figure D.21). As suggested by Walters et al. (2004a), the plots indicate the estimated survival rate of eggs to recruitment and the level of density dependence. For fixed steepness at 0.7, the standard deviation of recruitment deviations was reduced to 0.25; compared to 0.3 when estimating steepness.

Stock Synthesis results for analysis 2 data with fixed steepness at 0.7, reduced model performance and fits compared to estimating steepness at 0.48:

- The overall SS negative loglikelihood (-LL) increased significantly from -91.5184 to -43.1351.
- The catch rate -LL increased from -91.7693 to -64.
- The age data -LL increased from 25.407 to 48.0079

Profiling of steepness in Stock Synthesis analysis 2 suggested a high natural mortality rate would be required to match a steepness like 0.7 (Figure D.22). Such a value would be outside the natural mortality range of 0.25–0.45 per year that are generally believed for Spanish mackerel in Australia, as estimated from life-history relationships based on an assumed maximum fish age (Hoenig 1983; Then et al. 2015; Hamel et al. 2022, and see also "The Natural Mortality Tool: Empirical Estimators of Natural Mortality (M)" at https://connect.fisheries.noaa.gov/natural-mortality-tool/).

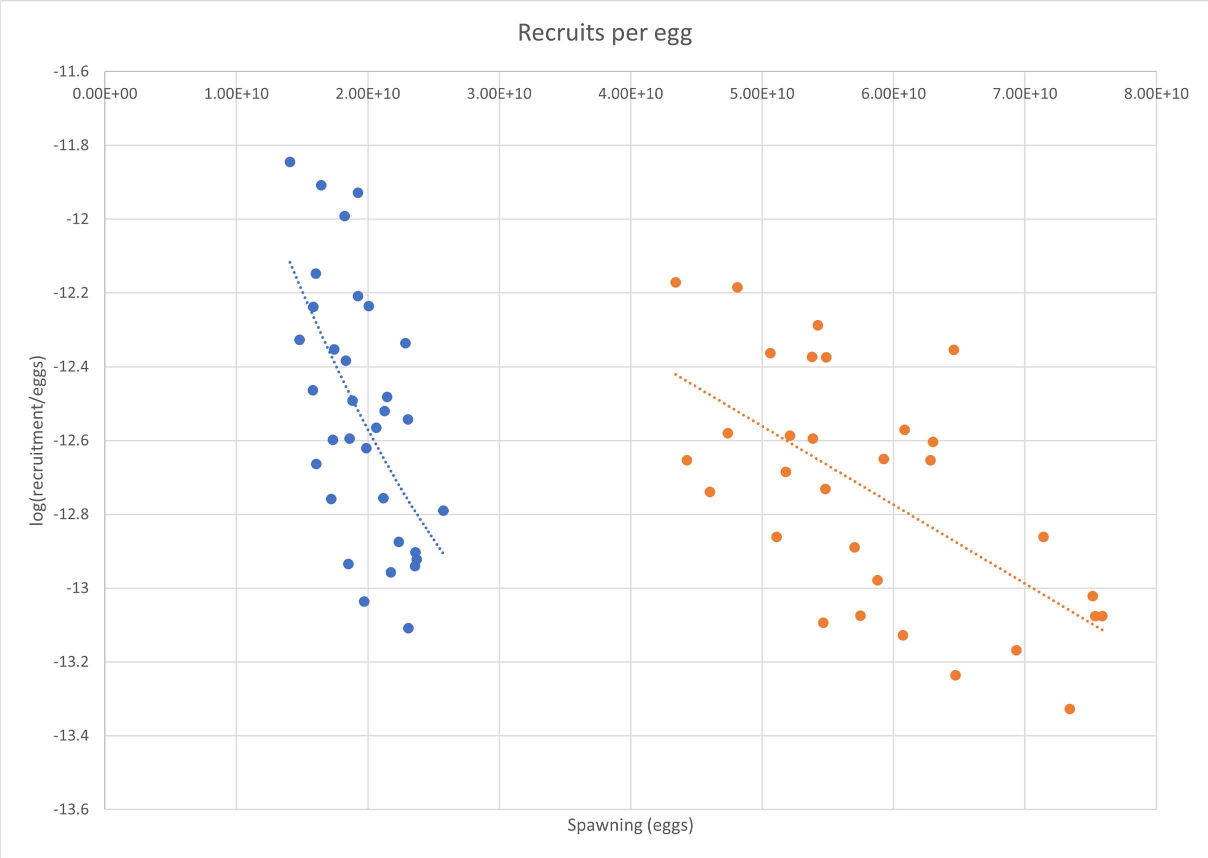

Figure D.21: The survival index log(R/S) showing compensation effects. The blue result with trend line was from SS analysis 2 for steepness estimate at 0.48, and the orange result for forcing higher steepness fixed at 0.7.

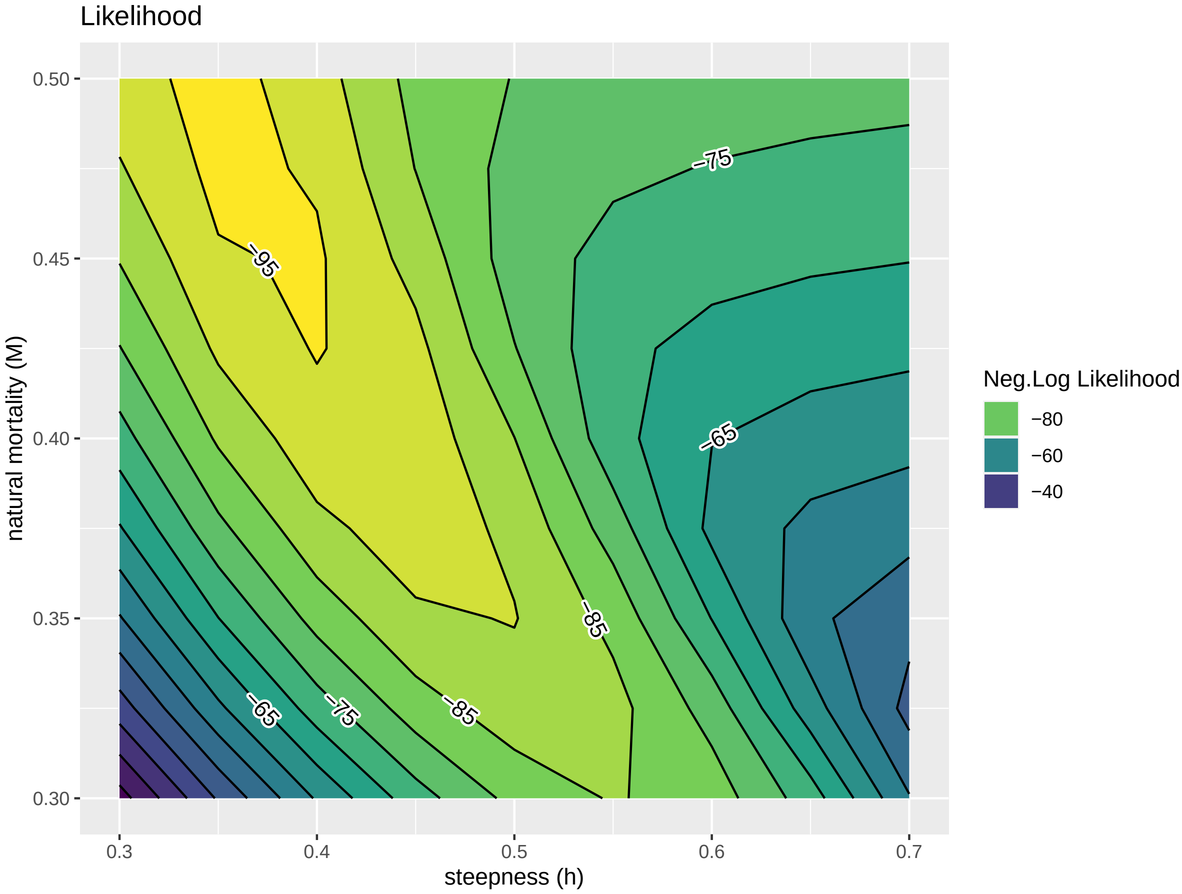

Figure D.22: Two-dimensional negative likelihood profiling of natural mortality and steepness, for SS analysis 2 data. The SS profiling procedure highlights the parameter correlation.

Appendix E Past assessments and history

E.1 Biomass and historical management plot

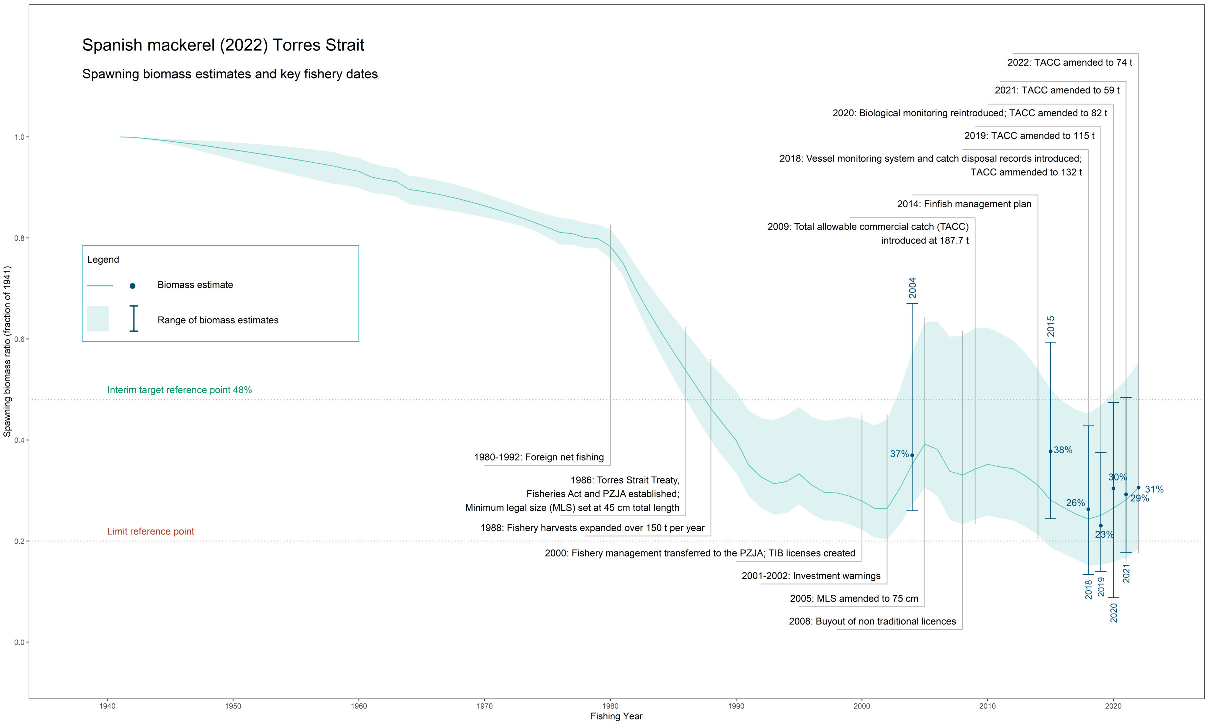

Figure E.1: Spanish mackerel biomass estimates by fishing year, with past stock assessment results and key fishery dates.