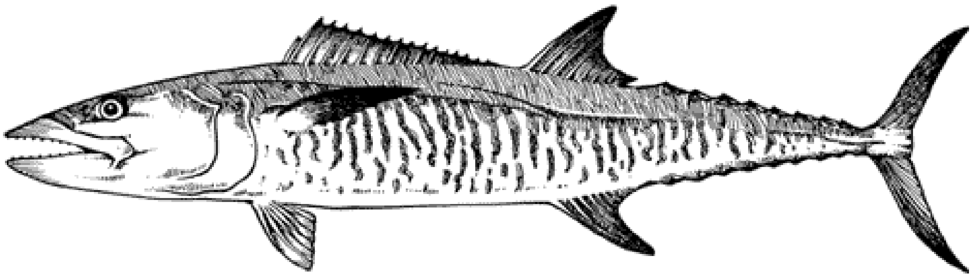

Torres Strait Finfish Fishery:

Spanish mackerel stock assessment, with data to June 2023

Year Three Report

AFMA Project Number: 2020/0815

2024-06-13

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 around 41 percent of unfished biomass in the 2023 fishing year. The uncertainty range (95 percent confidence interval) was between 21 percent and 61 percent.

Spanish mackerel, *Scomberomorus commerson*, sustain an important finfish line fishery within the Torres Strait and are considered 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 is the third and final report of the contract. The spawning biomass was estimated around 29 percent in 2021 and 31 percent in the 2022 report. New analyses in 2023 suggested higher spawning biomass around 41 percent.

All stock assessments and harvest recommendations were overseen by the Torres Strait Finfish Fishery Resource Assessment Group (TSFFRAG). This has seen increases in the spawning biomass from 23 percent to 41 percent between 2018 and 2023 (Figure 4.4, Appendix).

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, the most recent data and fishing year 2023 in this assessment referred to the period July 2022 to June 2023.

The stock assessment combined all data inputs into an annual age-structured population model and used stock synthesis (SS) software. This assessment analysed 12 new combinations of data. This was increased from the six analyses used the year two report.

The assessment incorporated data spanning from 1 July 1940 to 30 June 2023. 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 seven years between 1975 and 1983, and for 34 years since 1990, and 3) fish age–length frequencies from 13 years since 1979; see glossary for the Sunset-sector definition.

For the 12 new analyses, the three annual rates of natural mortality were unchanged (0.3, 0.35 and 0.4). The two-time series of annual total harvests were changed to consider different full and half estimates of foreign fishing (only full estimates were used previously). Alternate Sunset catch rates were introduced from 1990, to consider no influence or a proportional effect of coral trout fishing on Spanish mackerel catch rates (the consideration of coral trout fishing was new). The measures of likely variance on several stock synthesis data-inputs were also increased. All these changes increased the range of values (confidence intervals) that described the uncertainty surrounding biomass estimates.

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.

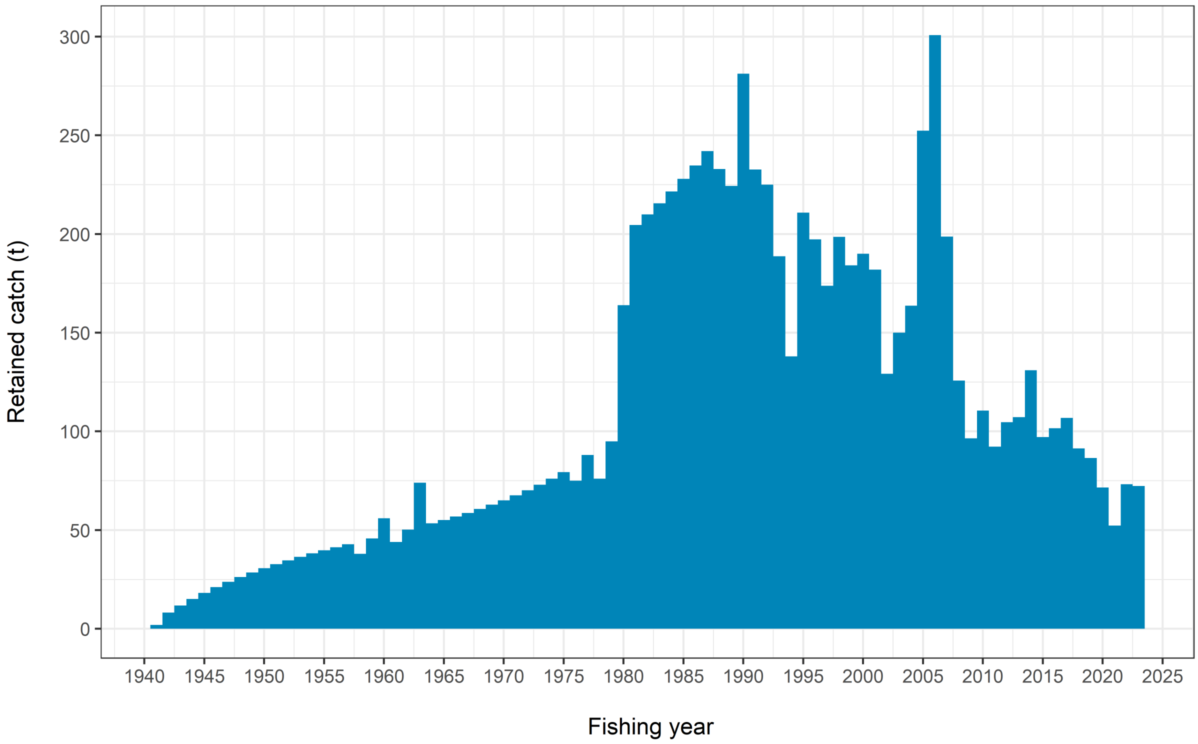

Figure 1: Annual estimated retained catch of Torres Strait Spanish mackerel between 1941 and 2023.

Spanish mackerel harvest peaked at about 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 2023, 72 t of Spanish mackerel (78 percent commercial take) was harvested. Over the last five fishing years, up to 2023, the annual harvest averaged 71 t per year, with commercial fishing taking at least 75 percent; commercial Sunset boats averaged 49 t per year and commercial traditional inhabitant boats (TIB) averaged 4 t.

Catch rates were standardised using generalised linear models (quasi-Poisson and log link, in R software). The models analysed daily catches, using explanatory data for the fishing year, zone, boat-operation, time-of-year, lunar cycle, wind strength, number of tenders used, proportion of the total catch weight being coral trout, and gear fishing power. Standardised annual catch rates (mean number of Spanish mackerel harvested per Sunset operation day per year) varied as follows (Figure 2):

- The 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 2019 improved between 37 and 69 percent, dependent on the coral trout affect in recent years.
- Catches of coral trout with Spanish mackerel were more prominent by key vessels in recent years, as illustrated by the adjustment difference.

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

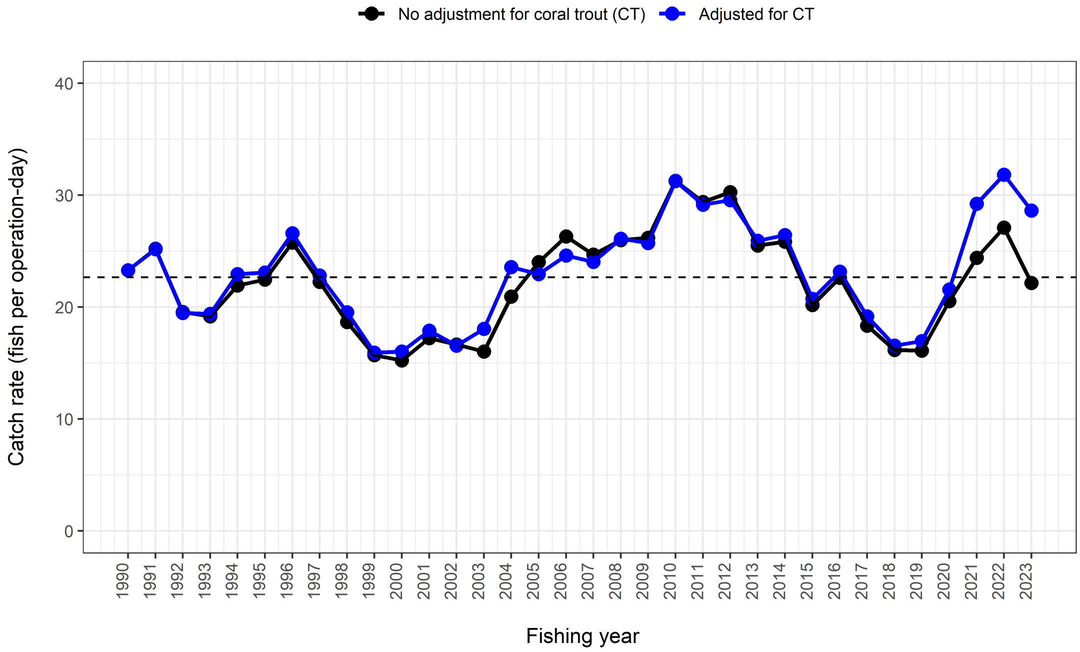

Figure 2: Annual standardised catch rates for Sunset-sector line-caught Torres Strait Spanish mackerel between the fishing years of 1990 and 2023. The generalised linear model coefficient of variation (relative standard errors) for these results was around seven percent, and 95 percent confidence intervals were approximately plus or minus three fish per operation day. Results are shown for no coral trout model adjustment (black line) and model adjusted (blue line).

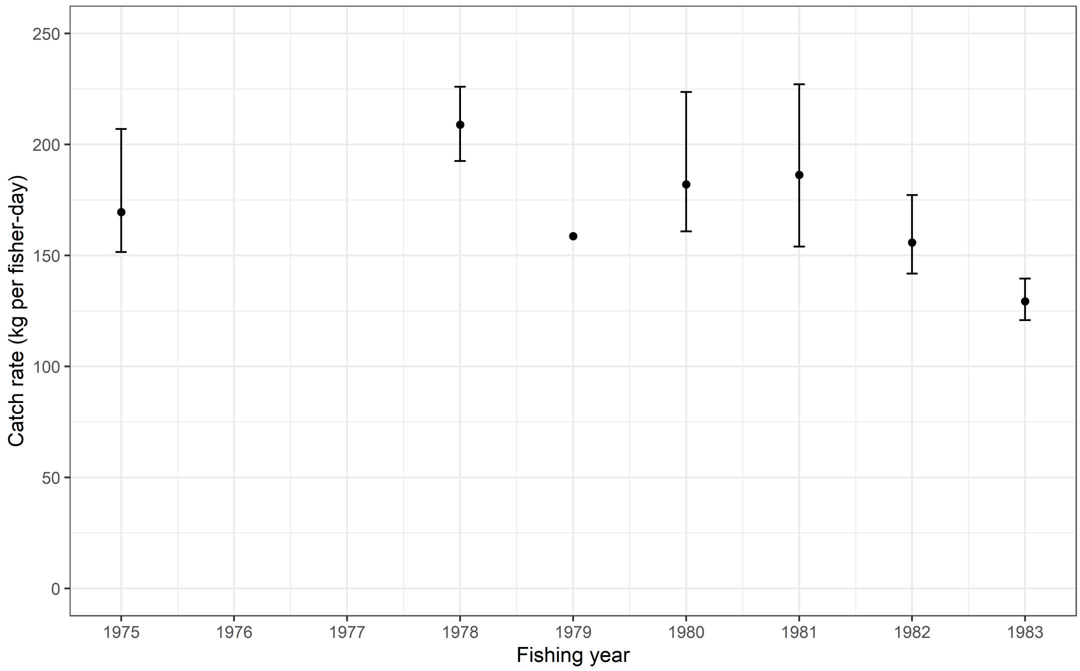

Figure 3: Historical annual catch rates of Torres Strait Spanish mackerel reported by a single Sunset line-fishing vessel. The mean was nominal kg of whole fish per fisher per day. The error bars show the reported range of trip means. The data was extracted from Figure 1 in McPherson (1986). No catch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

The stock assessment analyses, applying different natural mortality, harvest and catch rates, estimated the spawning biomass of Spanish mackerel in 2023 between 21 and 61 percent (Figure 4). The time series of biomass resulted from high harvests between 1981 and 2007, the downturn in Sunset catch rates 2010–2019 and upturn since 2019, and the resulting patterns of recruitment variability signalled by the data.

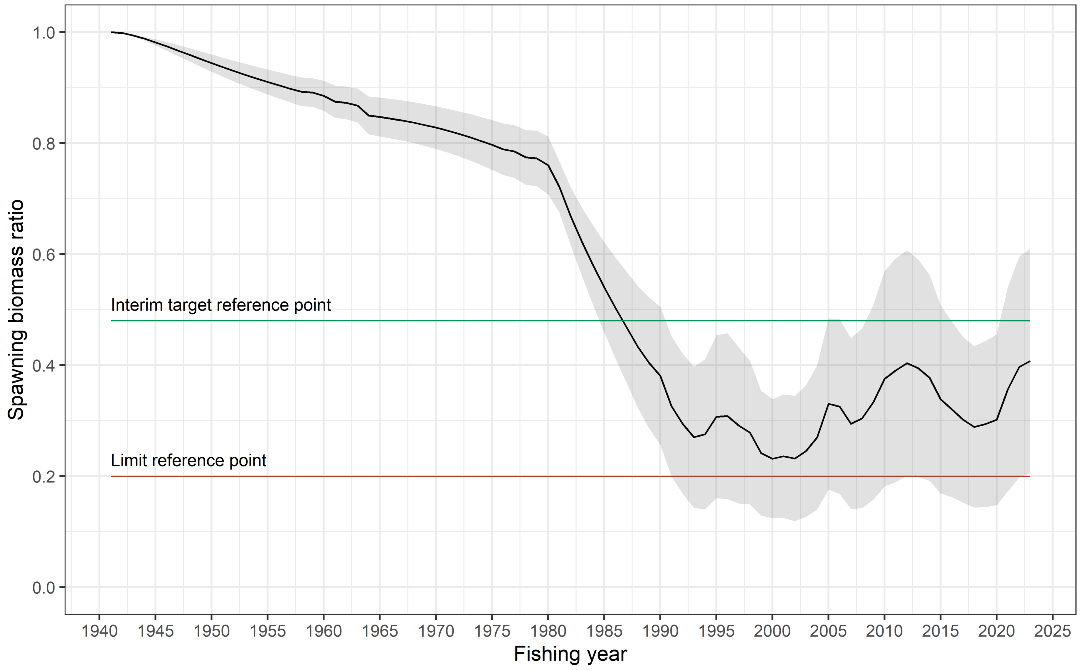

Figure 4: Estimated spawning biomass ratio for Torres Strait Spanish mackerel, from 1941 to 2023.

The 2024–2025 potential recommended-biological-catch (RBC) of Spanish mackerel for all fishing sectors in the Torres Strait was between 97 and 133 t based on the median forecasts (Table 1); 97 t was recommended by TSFFRAG. This RBC was forecast to build Spanish mackerel beyond the interim 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 97 t RBC aligned with stakeholder principles to continue to "bank fish" at this time, for a possible longer term 60% spawning biomass target.

The assessment was completed using the packaged stock assessment software stock synthesis (SS). SS diagnostics were satisfactory, but further adaptation is required. This is to refine the settings of likely variance on several SS data inputs, particularly the extra standard deviation applied on catch rates.

On 6–8 June 2023 the TSFFRAG reviewed the proposal for an SS-only assessment. Support was given to continue with only SS in 2023 (project reports one and two found similar results between SS and DAF's custom model). Additionally, TSFFRAG adopted 40% as a maximum sustainable harvest level, to compare with the potential target biomass reference points (48%, 50%, and 60%). The TSFFRAG agreed to remove maximum sustainable yield (MSY) from RBC options, given it's variability, uncertainty and association with overfishing.

Computer code for the stock assessment has been organised in R software to make the workflow run smoothly as one and take less time. The result is a streamlined process for the Torres Strait Spanish mackerel stock assessment. If utilised, this will enable more cost-effective assessments and allow annual or regular quantitative evidence to continue for quota setting and stock status classification. The potential to reduce future costs depends on two aspects: a) agreement on core methods and analyses for RBC setting, and b) to tailor report briefs and design (Discussion chapter 4.6).

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

Indicator	Median estimate
Biomass$^{\diamond}$ (relative to unfished) in 2022–2023	41% (21% to 61%)
Interim target$^{\odot}$ biomass (relative to unfished)	48%
Limit biomass reference point (relative to unfished)	20%
Harvest taken in 2022–2023	72 t
$F_{40}{}^{\star}$ harvest for 2024–2025	162 t
$F_{48}{}^{\star}$ harvest for 2024–2025	141 t
$F_{50}{}^{\star}$ harvest for 2024–2025	133 t
$F_{60}{}^{\star}$ harvest for 2024–2025	97 t
Overfishing limit$^{\wedge}$	133 t
RBC† for 2024–2025	97 t
RBC expected to achieve target biomass within	4 to 7 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 parentheses.
$^{\odot}$ 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 was the annual fishing mortality, applied to calculate the retained catch for all fishing sectors for the forecast year. Calculations applied F corresponding to 40%, 48%, 50% and 60% biomass.
$^{\wedge}$ Overfishing limit was the maximum retained catch that would result from fishing in the forecast year, consistent with achieving the target 48% 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 and less than 10% risk of triggering the limit biomass reference point.
Median: median estimate across analyses 1–12. 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 (than a mean) 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.

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

We express gratitude and thanks to the Traditional Inhabitant representatives and fishers who participated in TSFFRAG and TSFFWG committees, to provided stock assessment advice: Kenny Bedford, Benny Dau, Tenny Elisala, Quinten Hirakawa, Yen Loban, Paul Lowatta, Rocky Stephen, Gavin Mosby, Hilda Mosby, Harry Nona, John Tabo Jr and Terrence Whap.

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- Technical subgroups of TSFFRAG for advice on aspects of the assessment data and methodology. This team of people have included past and present Torres Strait Spanish mackerel stock assessment authors, Andrew Penney, Ashley Williams, Chris Boon, David Brewer, Eva Plaganyi, Selina Stoute, Trevor Hutton and Pia Bessell-Browne. Their support was greatly valued.
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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 to provide an index of abundance.
CDR	Catch disposal record. Verified landings on fish catch weights per primary operation.
CI	Confidence interval for an estimate.
CKMR	Close-kin mark-recapture is a method for estimating abundance from kinship relationships determined from genetic samples.
CT	Coral trout.
CV	Coefficient of variation, a statistical measure of variability that indicates the size of standard deviation relative to the estimate.
DAF	Department of Agriculture and Fisheries, Queensland.
Ensemble	A group of analyses interpreted together as a whole, rather than individually.
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 annual fishing mortality F, where u = 1-exp(F) and F = -log(1-u)
Hyperstability	When catch rates or age frequencies remain similar as fish abundance declines.
IUU	Illegal, unreported and unregulated fishing. For example, unlicensed foreign fishing in Australian waters.
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.
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	Tonnes, a 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 area 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 1941–2023. Fishing years were equal to financial years. For an example, labelling of the fishing year from 1 July 2022 to 30 June 2023 was 2023 or 2022–2023. 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 spawning season and Naigai season of lighter winds and calm seas.

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 RBC setting process used by TSFFRAG and AFMA work on harvest strategies. This covered different fishing rates (fishing mortality reference points) associated with fish spawning biomass between 40–60% of the 1941 level.

Objectives and directions for the year three 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 2023 and forecast the RBC for the 2024–2025 fishing year.
- Work in collaboration with AFMA and the TSFFRAG. This included applying new information or methods, producing results for TSFFRAG input and review, and creating a summary presentation for TSFFWG.
- Produce stock assessment results using only stock synthesis (SS) (Methot et al. 2013). SS will analyse all data inputs defined by TSFFRAG, covering key uncertainties for RBC options. In project years one and two, model comparisons were completed, and SS produced similar results compared to the DAF custom model.
- Establish a first streamlined SS stock assessment. Computer code was developed to complete analyses and publish results.
- Increase uncertainty in SS data inputs and outputs (Table 2).

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, August–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 for the Finfish Working Group (For TSFFWG, meeting 3, after the TSFFRAG technical review meeting 2, December).
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).

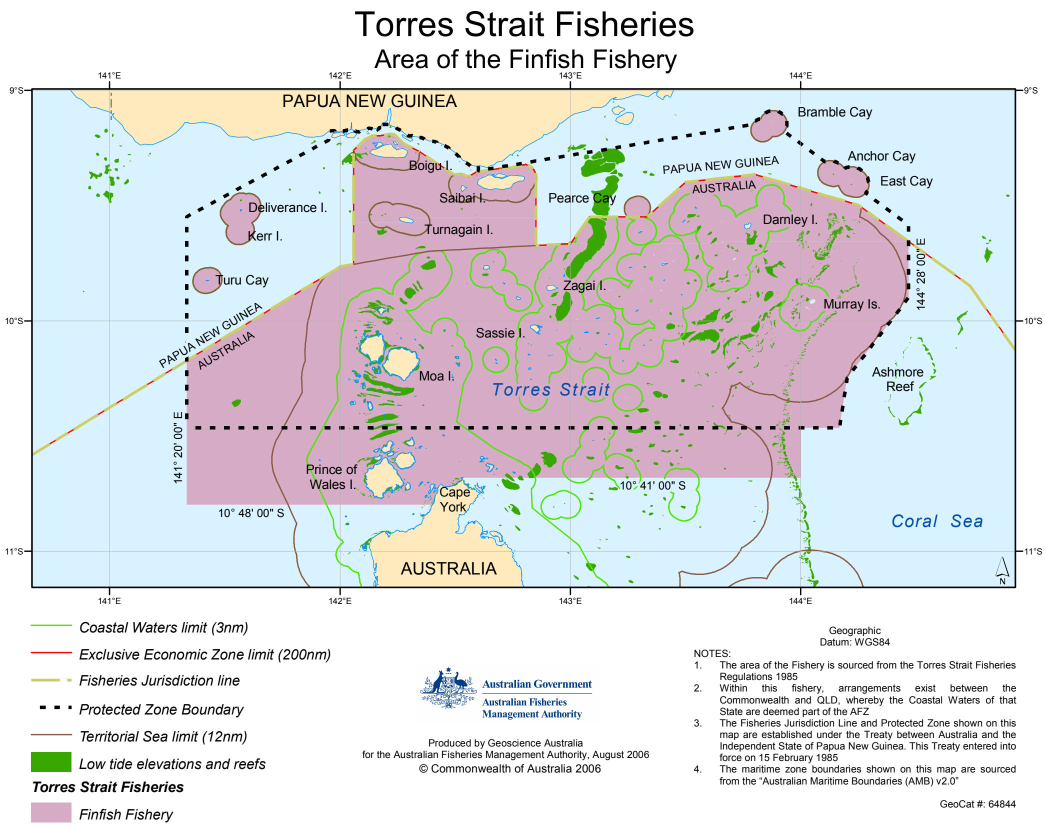


Figure 5: The management zones of Torres Strait finfish fishery; sourced from the PZJA website.

Table 2: TSFFRAG considerations and scopes given for this assessment, summarised from the June 2023 meeting approving the use of SS.

No.	Aspect	SS function	Questions	Comments	Recommendation
1	Catch rates	Input	How well do Sunset catch rates index exploitable abundance? How do we know either way? How close should SS follow this data? Do we have evidence that there is adequate movement of fish over the area? Can future CKMR work help to inform on the representativeness of catch rates?	Standardised catch rates is our best index of abundance. There is no other index to use. An index is required for a tier one stock assessment. Potential CKMR estimates aim to help verify annual point estimates of spawning abundance and better relate the catch rates estimates. Even though the Sunset fishery was in general focused around Bramble Cay, no data were available to suggest limited movements of fish (catch rates have been measured across 5 zones).	
2	Catch rates	Input	Why an over-dispersed Poisson GLM with log-link and not log-normal? Do we start using the tender data? Do we need a targeting factor for other species catches?	The meeting also discussed splitting the catch rate time series around 2004 in SS. This was not done, and is not recommended as good practice (Hoyle et al., 2024)	Use a log-link GLM and tender data. Check on colinearity between data covariates. Assess how small catches and possible changed targeting influence standard catch rates.
3	Catch rate CVs	Input	How can we reduce the SS fit?	Previous good fits were produced due to the recruitment deviations. Test increasing the CVs, to lessen the SS model's information from catch rates.	Use a spline smoother to inform SS on higher CVs. Compare this to the measure of dispersion from the GLM. Use the SS extra standard deviation (SD) setting.
4	Harvest	Input	What CVs do we set?	Test increasing the CV higher for the early data. This might help increase model uncertainty.	Keep polynomial estimates and change IUU (use both full and half IUU estimates). Increase CVs on early harvest estimates.
5	Spawning biomass (B)	Input	What spawning biomass units should we use?	Female tonnage whole fish weight or tonnage of eggs (gonad weight) or numbers of eggs.	Use Torres gonad weight data and combined stages 6 and 7 as appropriate.
6	Steepness (h)	Parameter	Do we estimate?	Consider changes in new SS set-up for year 3.	Continue to estimate and fix, but review and evaluate against the number of SS changes.
7	Natural mortality	Parameter	Do we keep the same fixed values?	Rates of M were not estimable. Three different fixed values were previously assessed: 0.3, 0.35 and 0.4 per year.	Use the same rates of M. In M profiling plots, add cut off thresholds.
8	Length-age data	Input	How do we best use the length-age data?	Essentially disaggregating annual age frequencies. Shared keys will be removed.	Change SS to use annual LF and only known age-length keys. Use days fished as LF sample size.
9	Growth	Parameter	How do we improve estimates of mean length for young fish?	Fish less than 2 years are not selected by the fishery, and few have been aged to support a growth curve for young fish.	In SS, look at a female and male model, that might help in growth curve estimation. Try and estimate growth inside SS; by this we recognise the interplay between growth and related age/size based vulnerability. Reduce the minimum bin below 50cm FL to better test early linear growth. Test growth type settings 1 and 2. Try estimating only 2 parameters first, not all. (e.g. fix l1 and estimate lmax and kappa; but iterate). If testing fixed Lmax, then inform this from mean FL from old ages. Increase CVs, such as 0.15, but test different values by fixing and estimating. If exploring growth outside of SS for a comparison, then check for fitting routines in "FishR". Note, fitting growth in SS is preferred, to better capture uncertainty.
10	Recruitment deviations	Parameter	Which years do we assess?	Stock assessment results were reliant on these.	Estimate rec-devs from 1990 to the end year minus 2. Test different sigmaR settings of 0.3 0.5 and 0.7. Ensure the bias ramp diagnostic is sound, and that the red and blue lines overlap in r4ss plots.
11	Estimates of SS uncertainty.	Output	How can we broaden confidence intervals on B ratios? How can they be increased for risk calculations?	SS confidence intervals were tight. Does changing data CVs or -LL weights help?	Options for this were covered above. E.g. increasing CVs on data inputs, growth and sigmaR. The grid approach was good to propagate uncertainty into biomass estimates; but profiling B0 and current stock status is another important diagnostic to add.
12	Recommended biological catches (RBC)	Input	How do we estimate RBCs for a constant F?	TSFFRAG reviewed the forecast file and settings. Use constant F, but have F equal to 0 for biomasses less than B20. See TSFFARG minutes and proposal to remove FMSY.	TSFFRAG confirmed the file settings were correct. Minor suggestions were put forward to change the number of forecast loops to 3 and the first forecast loop with stochastic recruitment to setting 3.
13	Cookbook	Diagnostics	To which base-case analysis do we apply and monitor the diagnostics?	Note, this was in the year two report for analysis 2. One analysis takes time to apply and has many outputs.	Only analysis 2.
14	Sensitivity tests	Input	What are the likely scenarios for the November 2023 meeting?	Having this early helps project streamlining, and to enable a draft report for TSFFRAG in Nov 2023. More information is required to design the scenarios table.	Number of analyses were expanded.
15	Report	Ouput	What do TSFFRAG want?	The level of detail in report two was high. One idea is that we separate out this detail into a "Supplementary Document" and leave the main report a bit lighter and more readable to publish. But one large report might be better for all readers?	Keep one report. Look to develop a 1 page fact sheet as advised by stakeholders. Email sent 7/7/2023 to Chris Boon about designing.
16	Dynamic B0 report	Output	What is this and do we want to report? What other SS outputs do we need to report?	This is a part of SS.	Ensure all biological settings are documented. Add dynamic B0 as extra information to support discussions. Add extra stepwise SS bridging results in future stock assessments.

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 that although they are a large species physically able to travel great distances, their general movement behaviour can favour 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 aggregations 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 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 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 licence primary-tender packages (called Sunset boats, given future leasing amounts might change) (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.1, 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 2019 were pessimistic on stock status and RBC (AFMA 2019b; 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 signals for only sustaining a small fishery. The assessment data suggested high harvests like 200–300 t per year were not sustainable in the long term.

Given the reductions in total fishery catch over the last decade, the assessment results were lower than anticipated 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. 2020; Tanimoto et al. 2021). This raised speculation that the broader regional environment may have negatively 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 three report, delivered updated stock assessment results for consideration in defining future harvest strategies, reviewing RBC settings and streamlining of the stock assessment processes.

The report informs fishery management agencies and stakeholders on new higher estimates of sustainable harvest that will build and maintain the fishery in the long term. The yearly collaboration of using this science, stakeholders, and harvest strategy decision making, through TSFFRAG and the TSFFWG, has seen increases in spawning biomass and catch rates, and identification of a strong cohort of Spanish mackerel (from fish age-length monitoring) in 2022 and 2023.

In addition, this final report outlined and discussed the streamlined assessment, summarising what it was, how to run, the components, and building of the report. This enables considerations for scheduling regular stock assessments while reducing the cost per assessment.

2 Methods

2.1 Data sources

A summary of the times series data collated for the stock assessment is in Table 2.1. There were two changes from the 2022 year two report:

- The 1974–1975 Sunset-sector fish length data, from the survey of fisheries resources - Torres Strait in 1974, was removed due to suspected duplication.
- The raw 2000 fish length and age data was located and used in the assessment. Only summarised length data was available previously.

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

Type	Years	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.
	1989–2023	Sunset harvests and catch rates from compulsory log-books.
	1989–2017	TIB harvests from docket (doc) book records.
	2018–2023	CDR version TDB02 records for Sunset harvests and TIB harvests and catch rates.
Traditional harvest	1989–2023	Estimated kai kai harvests (AFMA 2021b; AFMA 2023c). This considered traditional knowledge and survey data (Busilacchi et al. 2015).
IUU harvest	1980–1992	Estimated IUU harvest taken by Taiwanese drift nets (AFMA 2021b).
Recreational harvest	2014–2015	Survey estimates between 2 and 5 t (Webley et al. 2015; AFMA 2021b).
Fish age-length data	Removed	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.
	1999–2000	Length data only from the Sunset sector, sampled by a FRDC stock definition study. Fish aging only in 2000.
	2000–2003	Sunset at-sea catch sampling from Bramble Cay (Begg et al. 2006). Age and length data.
	2005-2006	Age-length data collected by James Cook University research (aging only in 2006). At-sea sampling from Sunset vessels fishing Bramble Cay.
	2020–2023	Annual age-length monitoring undertaken by Fisheries Queensland (Langstreth et al. 2020; Trappett et al. 2021).

2.2 Harvest data

AFMA supplied new 2023 commercial harvest data for all finfish. 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 2023 data was appended to last year's assessment files. The full data request for all years was not possible due an upgrade to the AFMA database.

The commercial Spanish mackerel harvests since 1990 were from three sources:

1. Compulsory logbook (Log) records for Sunset operations 1990–2023,
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. TSF-FRAG 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 estimated annual average fish weights to calculate annual harvest tonnages from the numbers of fish reported, rather than using 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, wind components and the proportion of coral trout in the day's total catch (kg) of all fish species.

Analyses of harvests at the primary vessel-operation-day unit matched the daily recording format. This avoided any correlations in catch rates between tenders on an operation day, 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 described 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.6.7).
- 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. There were missing records and inconsistencies in the numbers of tenders reported pre 2004 (O'Neill et al. 2023). Only tender data post 2003 were used in catch rate standardisation. Tender usage pre 2004 was assumed steady and similar to 2004, based on previous reports and TSFFRAG discussions (AFMA 2023b; AFMA 2023c).
- Total fish (all fish, kg) and coral trout (all trout species grouped, kg) catches were also tallied per operation-day. These data columns were merged with the known Spanish mackerel catch rates, to calculate the proportion of coral trout. This was to address a potential coral trout targeting-influence on Spanish mackerel catch rates. This method, for the time available, was suggested by TSFFRAG (AFMA 2023c). Where applicable, numbers of coral trout were converted to whole fish weights assuming 1.64 kg per fish (calculated from coral trout data, on 11/8/2023, by Clayton et al. (2023)). The coral trout product conversions for whole fish were 2.0 for fillets, 1.048 for gilled, 1.1 for gilled and gutted, and 1.4 for trunks.

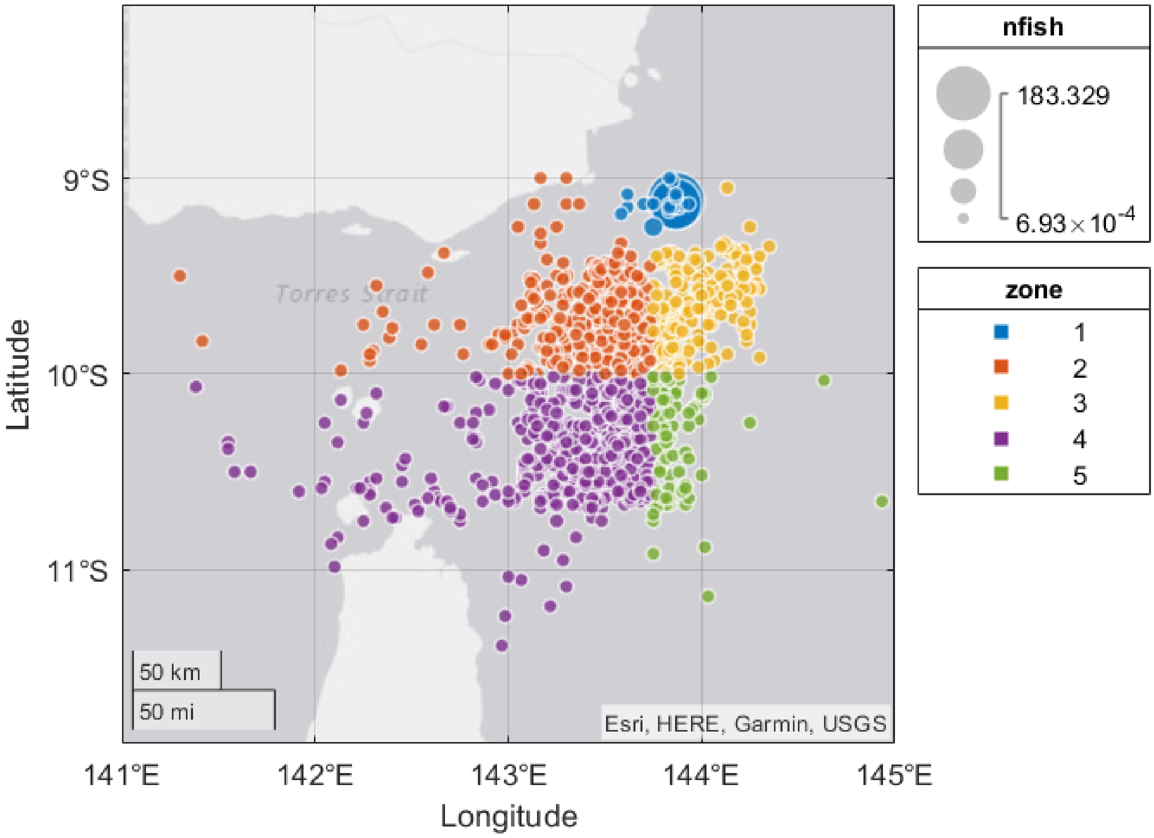


Figure 2.1: Map of the Torres Strait zones illustrated by colour (Bramble Cay zone 1 - blue, Ugar zone 2 - orange, east/anchor zone 3 - yellow, dugong zone 4 - purple, and southeast zone 5 - green). Map circles indicate the numbers of Spanish mackerel harvested by Sunset operations 1990–2021 at unique logbook latitude and longitude coordinates. Larger circles showed the main harvest locations, such as Bramble Cay. 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 $\pi/2$ radians = East, 180 degrees or π radians = South, and 270 degrees or $3\pi/2$ radians = West).

For an easier GLM alternative to wind components, a binary variable 'goodwind' was calculated for wind speeds less than 30 km per hour (about 16 knots). Wind speeds above 16 knots can produce moderate waves with white caps making fishing difficult (https://en.wikipedia.org/wiki/Beaufort_scale). The 30 km per hour cut off was also selected to allow for a sufficient number of data in the good wind = 1 and bad wind = 0 categories. Similar wind coding was used by Clayton et al. (2023).

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 ($\approx$ quarter lunar cycle) into a new variable (lunaradv) to quantify the cosine of the lunar data (O'Neill et al. 2006). The two variables were modelled together to estimate the variation in catch rate according to the moon phase (i.e. contrasting waxing and waning patterns of the moon).

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

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

The d_y numbers were the cumulative day of the year $(1 \cdots T_y)$, and T_y was the total number of days in the year (365 or 366 for a leap year). The reason for using both cosine and sine data together was 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.8, Appendix C.6.1).

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 dispersion are essential to assess the significance of model parameters and to calculate 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 2023). 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 considered main effects for different fishing years, zones, boats, seasonality, tenders, lunar cycle, good-wind, and the proportion of coral trout.

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:

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

where the GLM type and variables were:

- *nfish*: daily harvest per boat operation of Spanish mackerel (number)
- *year*: fishing year 1990 to 2023 (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)
- *goodwind*: wind strengths less than 30 km per hour (binary variate, 1 = TRUE and 0 = FALSE)
- *tenders*: number of tenders used (variate)
- *pCT*: proportion of coral trout in the daily harvest of all fish (variate)
- *fishingpower*: annual proportional change (variate; log transformed and offset)
- *GLM family and link function*: Quasi-poisson and log link

The GLM was run four times, alternating model terms in and out for tenders and pCT:

1. without tenders and without pCT, using all years of data 1990 to 2023 in the GLM.
2. with tenders and without pCT, using data from 2004 to 2023.
3. without tenders and with pCT, using all years of data.
4. with tenders and with pCT, using data from 2004.

Predicted catch rates from model runs 1 and 2 were standardised together to form the scenario that coral trout (CT) fishing did not influence Spanish mackerel catch rates in later years. Model runs 3 and 4 were used to form standardised catch rates for a coral trout scenario that did influence Spanish mackerel catch rates.

Predicted catch rates from the coupled models were standardised together at the common year of 2004, taking either:

- Predictions for 1990 to 2004 from model run 1 and splicing with predictions for 2004 to 2023 from model run 2 (for no CT), or
- Predictions for 1990 to 2004 from model run 3 and splicing with predictions for 2004 to 2023 from model run 4 (for CT).

The standardisations ensured a continuous time series 1990–2023, to best capture annual changes of tenders and coral trout in later years. Hoyle et al. (2024b) correctly stated and advised that splitting catch rates by time was counter-productive and should be avoided where possible.

From each 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 consistency with previous analyses and reports, consistent spatial averaging, and 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 common/statistical way of combining predicted values over levels of a factor (VSN International 2022). It assumed that fish in the Torres Strait spatially mix and aggregate around Bramble Cay.

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
- *goodwind*: mean equal to 0.87.
- *tenders*: 3 tenders, a common annual median in later years.
- *pCT*: 0, for catching no CT.
- *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, and the 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:

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

where the GLM type and variables were:

- *kg*: daily harvest per client-boat of Spanish mackerel (kg)
- *year*: fishing year 2019 to 2023 (factor)
- *client*: anonymous codes for different clients (factor)
- *s1*: two seasonality variables defined by cosine and sine functions (variates)
- *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 catch rate 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 (= 308, for early November)
- *crew*: mean number of crew (= 1.667 people).

2.4 Age-length compositions

Monitoring projects have sampled annual fish age and/or length compositions of Spanish mackerel in 13 years. Sample details were published in the year one and two reports, with associated references.

The fish ageing methods across years were similar (Begg et al. 2006; Hutton et al. 2019; Langstreth et al. 2020; Trappett et al. 2021). The methods used whole otoliths, and no aspects of the data appeared conspicuous. Age precision statistics were inspected in each year where available (Table C.4).

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

All whole-otolith ages were 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 (marginal increment) of the otolith was classified as new (narrow), 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.

Increment count represented the age at the time the fish was caught. Edge types can also depend on the time of year of capture. Increment ages were compared against edge types – distance between the inner edge of the outermost opaque zone and the periphery. This comparison allowed an estimate of the birth year, to assign each fish to the correct cohort (age group). This was needed for stock assessment.

For assigning an age group, to a biological/fishing year, it was considered that Spanish mackerel move from one cohort age to the next at the start of the fishing year on 1 July. Consideration of the otolith edge type was needed for this allocation, as the marginal opaque zone does not become visible in all fish at the same time. The opaque zone can vary by a number of months.

The monthly patterns in edge types were reviewed (J. Langstreth, biological monitoring project, 2023). From this, new adjustments (compared to previous stock assessments) were applied to allocate each fish into an age group. The new age group adjustment excluded October (see the dot point for wide edges below).

The new rule was more careful to not adjust increment counts when two or three months of growth could change the edge type category. This process aimed to group similar aged fish into their cohorts, using information on the month of capture, edge type determined during otolith reading and a nominal peak spawning date of 1 November. The new rules were:

- For new edge types, in months April–June, age group = increment count - 1;
- For intermediates, in months July–August, age group = increment count + 1;
- For wide edges, in months July–September, age group = increment count + 1; October is now excluded.
- Special case for 0 aged fish, in October, for intermediates, age group = increment count + 1;
- Else, age group = increment count.

The age-length data was reorganised in this assessment. It used annual length frequency from 13 years. These frequencies were matched with conditional age-at-length samples from 10 years. Where possible, the data were separated for female and male fish.

The length frequency data were in two-centimeter fork length (FL cm) bins from 0 to 170 cm (Figure C.3). The lengths were unadjusted, and based on the time of capture (mostly from October and November each year). The number of catches sampled for lengths formed the initial data weighting (effective sample sizes) in SS (Figure C.3). These numbers were increased by 1.5–2 times in SS, in applying the Francis method for adjusting sample sizes.

The conditional age-at-length samples were defined by age-groups and 2 cm FL bins, by sex. Use of conditional age-at-length increased the number of age observations. Initial sample sizes were based on the numbers of fish aged in each year (Figure 3.5). In SS, the Francis method scaled these down by 0.12–0.13. The conditional age-at-length data informed the relationship between FL and age to estimate growth parameters by sex and the variance of FL-at-age. The relationships by sex allowed SS to infer age-structures from the length frequencies, assuming no annual variation in fish growth (SS modeled a common conditional age-at-length key across years by sex).

Annual age group frequencies were calculated in 10 years for fish sexes combined (external to SS). This was to visualise cohort strengths and to estimate catch curve measures of total mortality (Z per year; Haddon 2011). In SS, these data were inputted and given a negative value for fleet to be included in model expected values, but not in contribution to model fitting. This provided another diagnostic to evaluate how well SS converted length to age through it's non-time-varying female and male growth curves.

Age frequencies before 2020 were tallied from direct fish ageing (the majority of fish sampled were aged). For 2020–2023, age frequencies were calculated by the annual length frequencies multiplied by the annual conditional age-at-length samples. For the current monitoring since 2020, this multiplication followed the way the age data were being collected through an age-at-length stratified program (Trappett et al. 2021).

Ageing error matrices were estimated for SS (Appendix C.5). Error was modelled using TMB code written for R by Dr Andre Punt. Methods considered Punt et al. (2008), Heifetz et al. (1999) and Burch et al. (2023). Error matrices assumed no bias with linear increased standard deviation with age. Three matrices were estimated for pre 2020, 2020 and post 2020, using twice read otoliths by five different people.

2.5 Biological relationships

2.5.1 Weight and length

The assessment expressed all length measurements as fork length (FL).

Mean fish weight (kg) at fork length (cm) for each sex was expressed by the formula:

$$W = aL^b \tag{2.4}$$

The parameters for female fish were: a = 6.61171184885004e-06 and b = 3.04037846719918. The parameters for male fish were: a = 9.88525584542126e-06 and b = 2.94861272363958.

The relationships were from re-analysing the Begg et al. (2006) data. For the female analysis, n = 469 and the residual standard deviation sd = 0.683 kg. For males, n = 408 and sd = 0.468 kg.

2.5.2 Female maturity

In most species, sexual maturity is attained by age rather than by size (Hancock 1992).

Foremost, to account for this phenomenon, first maturity at age was set at 2 years (Begg et al. 2006). All ages below 2 years had maturity set to zero.

Fractions mature (p) were further defined in SS by a length logistic equation (option type = 1) (Methot et al. 2023):

$$p = 1/(1 + exp(\alpha(FL - \beta))) \tag{2.5}$$

Parameters for this equation were based on Mackie et al. (2005), where the slope α = -0.128009163338326 and the 50% inflection of the maturity curve β = 80.9 cm FL.

2.5.3 Fecundity

Female Spanish mackerel gonad weight (kg), FL (cm), and maturity staging data (defined in Table 2.10, page 21, Begg et al. (2006)) were collected from the Torres Strait by:

- DAF monitoring in the 2001–2003 fishing years (Begg et al. 2006), and
- Geoff McPherson, during FRDC research, in the 1999 fishing year (Buckworth et al. 2007).

In total, for gonads with reproductive behaviour, 274 stage-6 (post-ovulatory) and 95 stage-7 (ripe) female fish were analysed and reviewed by TSFFRAG (AFMA 2023b; AFMA 2023c). A gonad-weight – fork-length relationship was use to define increased egg production with fish size. In SS, the relationship used the type-2 fecundity equation:

$$Eggs = aL^b \tag{2.6}$$

Parameters a and b were estimated from the data using an R linear model (lm):

$$\log(\text{GonadWeight}) \sim -1 + \text{stage} + \log(\text{flcm}) \tag{2.7}$$

where the linear model variables were:

- *GonadWeight*: female Spanish mackerel gonad weight (kg)
- *-1*: no mean intercept
- *stage*: intercept for each gonad stage (factor)
- *flcm*: fork length cm (variate)
- *LM family and link function*: Normal and identity link

From the linear model, parameters: a = exp(stage 6 intercept), and b = slope for log(flcm). Estimates were tabled in Appendix C.7.

2.5.4 Natural mortality

Natural mortality rate (M) was the annual rate of removal of fish from the population due to causes not associated with fishing (examples include deaths due to predation or old age).

The assessment assumed one constant rate. The same rate was applied for female and male fish.

Three values of 0.3, 0.35 and 0.4 were used, and considered a lifespan of about 13 years in the Torres Strait. The three values were used in previous assessments, and considered a plausible range and mid-point for this assessment. Profiling in the year 2 report suggested M was not estimable in SS (O'Neill et al. 2023), confirming the need to test different values.

Empirical methods for M were calculated using the "The Natural Mortality Tool: Empirical Estimators of Natural Mortality (M)". The tool is located online at https://connect.fisheries.noaa.gov/natural-mortality-tool/ , and has the methods of Then et al. (2015), Hamel (2015) and Hamel et al. (2022). The tool calculated M values 0.42 to 0.47 for an age of 13 years. These methods were based on knowing the maximum age from lightly fished or unfished stocks (Hoyle et al. 2024a).

Historically, Begg et al. (2006) considered empirical estimates of 0.37 and 0.28 per year, with an upper range to 0.44 in scenario testing.

In general, the annual natural mortality rates used for Spanish mackerel assessments in Australia have ranged 0.25–0.45 per year, as estimated from life-history relationships based on an assumed maximum fish age (Hoenig 1983; Then et al. 2015; Hamel et al. 2022).

2.6 Population models

2.6.1 Stock synthesis (SS)

SS is an age-structured population model platform that has been applied to a variety of fish stock assessments globally (Methot et al. 2013).

SS was used to analyse annual harvest, catch rate, fish age-length and biological data. SS estimated a time series of spawning biomass and management quantities for RBC. The software quantified uncertainty through differentiation to generate 95% confidence intervals on estimates; this was compared to outputs from MCMC simulations in analysis 2.

The age structured model by sex was defined through the annual data inputs and model settings. The input files detailed the biology and life history characteristics of the species such as longevity, natural mortality, fish size, reproduction, and functions for fish recruitment, selectivity and catchability.

The SS software was operated through Rstudio using R 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. It defined settings for outputs and jitters of parameters to test maximum likelihood solutions. The fishing mortality outputs were set to be actual rates per year, and not fractions of reference points. The depletion reports were set as a fraction of virgin stock.
- The 'Data file' specified the information on which the assessments were based, and the initial sample sizes and CVs for the data. The data were set-up for 83 years, two genders and a single area model, with different fleets, units of tonnes for the harvest data and units of numbers for Sunset catch rates.
- The 'Control file' specified the model to be fitted to the data (logistic selectivity, Beverton-Holt recruitment, etc.) as well as how the data was to be statistically weighted. Example settings included parameters for natural mortality, fish size, maturity, fecundity, recruitment distribution and selectivity.
- The 'Forecast file' specified the management reporting outputs. The file defined the reference points, type and years of forecasting. The target and limit biomass reference points between B_{60} and B_{20} were specified.

SS was written in AD Model Builder software (ADMB, Fournier et al. 2011). The r4ss package allowed for output plotting, statistics and diagnostics (Taylor et al. 2021).

Key methods for SS were published in peer reviewed journals and reports by NOAA in the USA (Methot et al. 2013; Methot et al. 2023).

SS scenarios were run as listed in Table 2.5. The SS software version used was SS 3.30.22.

The key assumptions for the assessment included:

- The Torres Strait fishery for Spanish mackerel forms a single stock.
- In general, fish moved and mixed over time.
- The fishery began from an unfished state in 1941.
- All legal sized fish caught were retained.
- The fraction of fish that were female or male at birth was 50%.
- Growth had two phases and was estimated in SS. Average fork length at age by sex occurred according to the von Bertalanffy growth curve for ages two years and above. Growth up to two years of age was linear with zero intercept. The growth curves, for SS age-length conversion, were the same across years with normally distributed error.
- The first age for female maturity was two years.
- Fish weight and fecundity were functions of fork length.
- The instantaneous natural mortality rate per year was constant and did not depend on age.
- Annual recruitment was a Beverton-Holt function of spawning stock size with recruitment deviations.
- Logistic length-based selectivity was the same for each sector or data source, and used to approximate age-based vulnerability patterns that might be present (Francis 2016).

Parameters were estimated within SS where possible (Table 2.3). No priors were used.

The catch rate extra SD parameter was calculated as a mean difference between GLM standard errors and the residual standard error from a Loess (spline) model. The Loess model on Sunset catch rates, in R, was a simple spline by year: loess(log(cpue) ~ year). The method followed Sporcic (2022). The Loess was suggested by TSFFRAG (AFMA 2023b); see Table 2.

Table 2.3: Key parameters in the population model.

Symbol	Description	Phase estimated or fixed
M	Natural mortality rate per year	Fixed at different values
Log R_0	Log virgin 0+ aged number of recruits in 1941	Estimated in phase 1
h	Steepness	Estimated in phase 5 or fixed
η	Simple type 2 year-specific log recruitment deviations	Estimated in phase 2
σ_R	Standard deviation of log recruitment deviations	Fixed
L_{50}	FL cm at 50% logistic vulnerability by sunset fishing. Other fleets were mirrored. For both sexes.	Estimated in phase 3
$L_{95\ \mathrm{width}}$	Difference in cm between 50% and 95% vulnerability	Estimated in phase 3
Extra SD	Sunset catch rate extra standard deviation	Fixed, mean difference between Loess and GLM
L_{min}	Mean length of fish by sex at 2 years (cm FL)	Two parameters estimated in phase 4
L_{max}	Mean length of fish by sex at maximum age (cm FL)	Two parameters estimated in phase 4
K	Von Bertalanffy growth coefficient per year by sex	Two parameters estimated in phase 4
CV_{young}	CV=f(LAA) by sex at 2 years of age	Two parameters estimated in phase 4
CV_{old}	CV=f(LAA) by sex at maximum age	Two parameters estimated in phase 4

Analyses, except number 17, assumed deterministic recruitment before 1990 and stochastic with recruitment deviations thereafter up to 2021. The last two years were deterministic as fish recruitment into the fishery generally takes around two years (data beyond 2023 would be required to inform these deviations).

The recruitment deviations were estimated as simple log scale parameters. The level of recruitment variability (log σ_R standard deviation) was fixed at 0.33 based on results and the suggested tuning from the r4ss σ_R information object (Methot et al. 2023). Larger values were tested. However, the SS manual cautioned that if σ_R was too large, then the bias-adjustment was too large, and the model may want to compensate by increasing steepness to keep the mean level of recent recruitments at the correct level (Methot et al. 2023).

Settings for the recruitment bias adjustments varied with the catch rates used, the number of recruitment deviations and the level of of recruitment variability (log σ_R standard deviation). Table 2.4 lists the settings, for the analyses defined in Table 2.5.

Table 2.4: Advanced settings for the recruitment bias adjustments (Methot et al. 2023).

Aspect	**No CT effect**	**No CT**	**No CT**	**No CT**	**Yes CT**	**RecDevStart**
Analyses	1–6, 16, Grid	13	14	15	7–12, Grid	17
σ_R	0.33	0.5	0.7	0.1	0.33	0.33
Last year with no bias adjustment	1959	1959	1959	1959	1959	1945
First year with full bias adjustment	1997	1997	1997	1997	1994	1974
Last year with full bias adjustment	2021	2021	2021	2021	2021	2021
First recent year with no bias adjustment	2023	2023	2023	2023	2023	2023
Max bias adjustment	0.63	0.76	0.83	0.18	0.63	0.40

The catchability parameters q, for model fitting to catch rates, were calculated as simple closed form (float). Catch rates pre and post 1989 were fitted separately.

Lambdas, the emphasis factors used to re-weight negative log-likelihoods, were not used and set equal to 1.

Francis adjustments were applied to the composition data within SS (Francis 2011), to achieve a suitable effective sample size and thus relative weighting against other data inputs. See comments in the age-length methods.

Reference points for the RBC followed the TSFFRAG endorsed methods in 2020 (AFMA 2020a; AFMA 2020b). This accounted for the 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 a harvest of 81 t in 2024 and average stock recruitment from the Beverton-Holt function (mean log recruitment deviation = 0; no deviation applied in the RBC calculation). The 81 t represented 57 t taken by Sunset (their full TACC allocation), plus 4 t TIB, plus 15 t traditional, plus 5 t recreational. The RBC setting process followed Figure 2.2.

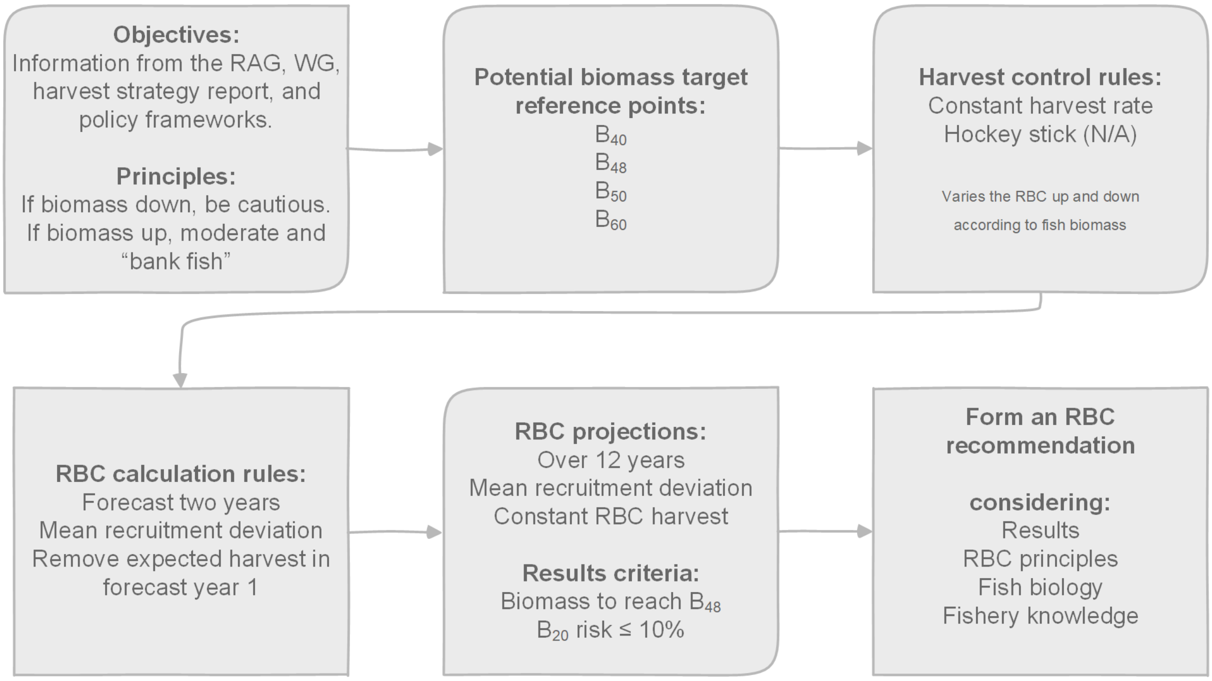


Figure 2.2: Flow chart of the considerations in RBC calculation and recommendations. Hockey-stick harvest control rules were not applied.

2.6.2 Analyses

The core stock assessments 1–12 analysed (Table 2.5):

- Two series of annual harvest, considering full and half IUU estimates of Taiwanese gill netting (Appendix C.1).
- Three rates of fish natural mortality M (0.3, 0.35, 0.4 per year).
- Two series of Sunset catch rates, with or without a proportional coral trout (CT) catchability effect.

Analysis 2 was extended with one million MCMC simulations, saving every 100th, to check maximum likelihood results.

The exploratory assessments 13–17 considered (Table 2.5):

- Increased σ_R to 0.5 for recruitment deviations (analysis 13).
- Increased σ_R to 0.7 (analysis 14).
- Reduced σ_R to 0.1 (analysis 15).
- Fixed steepness h at 0.7 (analysis 16).
- Fixed h at 0.7 and estimated recruitment deviations for all years 1941–2021 (analysis 17).

Analyses 13–17 were compared to analysis 2, using the middle M = 0.35 (Table 2.5). Analysis 2 was used for comparisons to be consistent with previous stock assessments.

Additionally, a grid of 36 analyses was explored by interacting analyses 1–12 with three levels of fixed steepness (0.5, 0.6, and 0.7). Results were compared to those from estimating steepness.

The exploratory and grid analyses were run to further inform on the importance of different σ_R settings for recruitment deviations, advantages or not of fixing steepness, and the ability to estimate recruitment deviations for all years. The results help tailor future model designs for stock assessment, to improve confidence intervals and risk calculations.

Ensemble median results across analyses 1–12, and separately for the grid, considered each analysis equally. A median statistic was used as a middle result to mitigate any skewness. 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).

Two standard deviations were used to calculate asymptotic 95% confidence intervals for ensemble results. The standard deviation over analyses, was the square-root of adding the within and between analysis variance components.

Table 2.5: Summary of the stock assessment analyses. Different inclusions of steepness, natural mortality, harvest time series, catch rates for Sunset (1990–2023, standardised with or without a proportional coral trout (CT) effect), standard deviation and start year for recruitment deviations are noted.

Analysis	h	M	Harvest	CT effect	σ_R	RecDevStart†
1*	Estimate	0.30	Full IUU	No	0.33	1990
2*	Estimate	0.35	Full IUU	No	0.33	1990
3*	Estimate	0.40	Full IUU	No	0.33	1990
4*	Estimate	0.30	Half IUU	No	0.33	1990
5*	Estimate	0.35	Half IUU	No	0.33	1990
6*	Estimate	0.40	Half IUU	No	0.33	1990
7*	Estimate	0.30	Full IUU	Yes	0.33	1990
8*	Estimate	0.35	Full IUU	Yes	0.33	1990
9*	Estimate	0.40	Full IUU	Yes	0.33	1990
10*	Estimate	0.30	Half IUU	Yes	0.33	1990
11*	Estimate	0.35	Half IUU	Yes	0.33	1990
12*	Estimate	0.40	Half IUU	Yes	0.33	1990
13	Estimate	0.35	Full IUU	No	0.50	1990
14	Estimate	0.35	Full IUU	No	0.70	1990
15	Estimate	0.35	Full IUU	No	0.10	1990
16	0.70	0.35	Full IUU	No	0.33	1990
17	0.70	0.35	Full IUU	No	0.33	1941
Grid	0.50, 0.60, 0.70	0.30, 0.35, 0.40	Full and half	No and Yes	0.33	1990

Analyses 1–12: * indicates the RBC stock assessments. Other analyses numbered > 12 or in the grid were exploratory.
RecDevStart†: First year for estimating recruitment deviations, up until 2021.
Grid: 36 analyses, interacting analyses 1–12 with three levels of fixed steepness (0.5, 0.6, and 0.7).

3 Results

3.1 Model inputs

Figure 3.1 summarised the time-series data available for input into stock assessment.

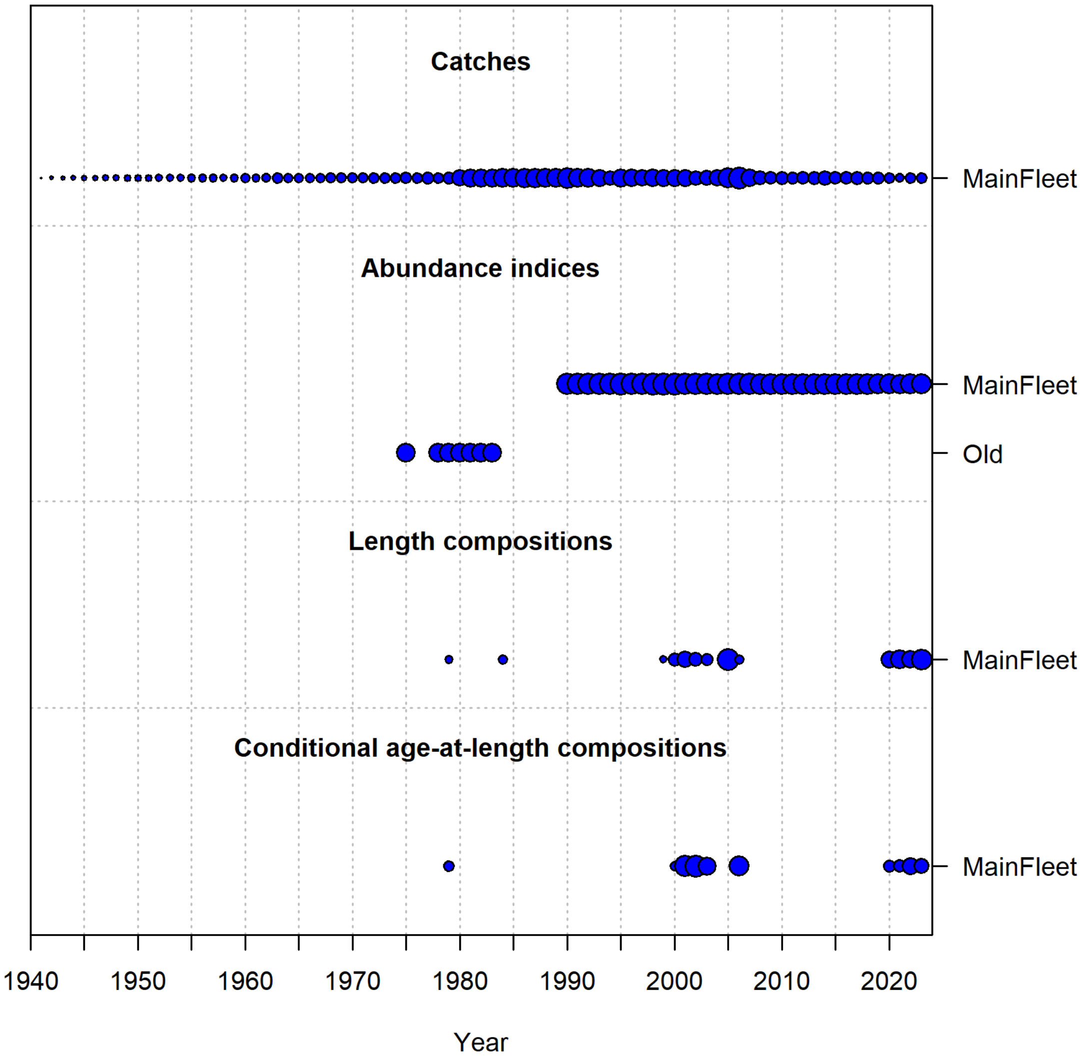


Figure 3.1: Data compiled for SS input by year and for each category of data type. Circle area was relative within a data type. The 'Old' label showed the historical Sunset catch rates, otherwise the data was summarise under the 'MainFleet' label used by SS.

3.1.1 Harvest

The annual estimates of Spanish mackerel harvest considered data from all fishing sectors (Appendix C.1). Historical uncertainty in IUU data resulted in different scenarios to estimate harvests (Figure

3.2). Data input into stock assessment combined harvests across all fishing sectors, given the sector similarities of line fishing, selectivity and that most data was Sunset. There was no discard catch.

From 1941–1979 annual harvests built steadily to around 100 t per year (Figure 3.2).

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 also considered, based on the year 2 results that half IUU could add important uncertainty into the assessment (O'Neill et al. 2023).

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 679–1398 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 entitlements to Torres Strait Islanders and reduced quotas. Catch rates also declined 2015–2020.

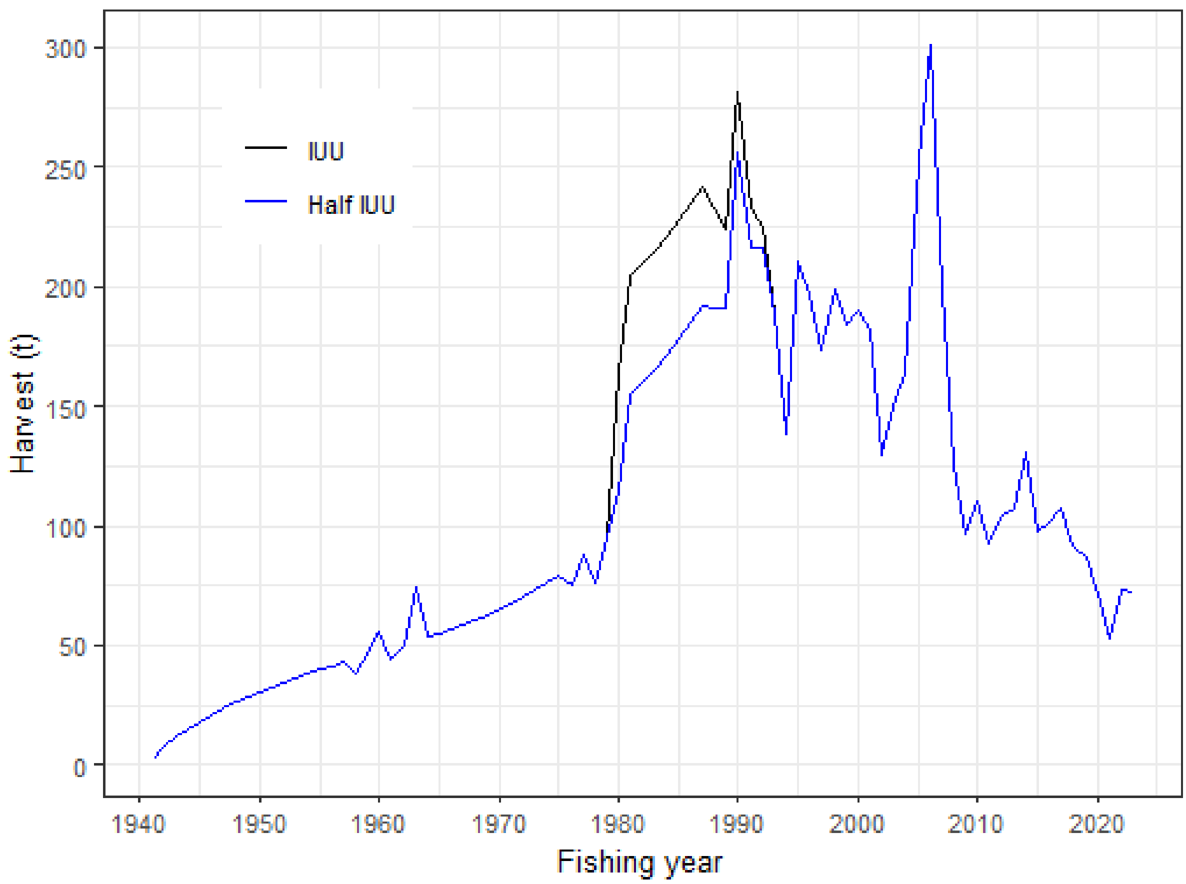


Figure 3.2: Estimated harvest (retained catch) taken by all fishing sectors since 1941 for Spanish mackerel. Two scenarios were considered for different IUU estimates between 1980 and 1993.

3.1.2 Catch rates

The Sunset standardised catch rates were used to index 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 measurement of trends in fish abundance and fishing efficiency (Hilborn et al. 1992). The intention here was 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, between fishing operations (boats) and multi-species targeting through time.

The nominal catch rate data (numbers of Spanish mackerel harvested per operation day) between 1990 and 2023 had skewed distributional properties. This was highlighted by comparing measures of the median = 15 fish per operation-day, geometric mean = 13 fish, arithmetic mean = 24 fish and standard deviation = 26 fish (CV = 110%). There were occasionally large harvests above 100 Spanish mackerel per operation day, with a different time series signal between nominal mean and geometric-mean catch rates in later years (Appendix C.6.5, Figure C.10).

The estimated Box-Cox λ parameter, for normalising and decreasing skewness in residuals and data, was 0.15. The small λ, about half of 0.33 for a cube-root transformation, suggested other GLM forms could be tested. For example, a log transformation on the number of fish caught would normalise residuals, or that a strong variance function with a log link could be used (McCullagh et al. 1989; Hoyle et al. 2024b).

Use of a log link function, with dispersion greater than the mean μ ($var(y) = \phi\mu$, McCullagh et al. (1989)), was used for consistency with past assessments. This maintained the same data assumptions and multiplicative effects. It also modelled appropriate likelihood weights between small and big catches per operation-day; so that trends in means were modelled rather than geometric-means (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 (Appendix C.6.5).

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

- A species targeting effect had become apparent 2021–2023, with small catches of Spanish mackerel taken with coral trout. Standardisation suggested higher catch rates of Spanish mackerel in 2021–2023 for lower catchability when coral trout fishing (see also Appendix C.6.5, Figure C.11). Both, with and without coral trout effects were consider in the stock assessment.
- Catch rates experienced temporal cycles, and statistical differences were detected between years (Tables C.6, C.7, C.8, C.9, Appendix C.6.1). This started with a decrease between 1990–2000, then an increase to 2010, and a downturn to 2019. The catch rate increased significantly up to 2022, and levelled off with a slight downturn in 2023. 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 generally seen in all operators' data, particularly the declines in 2017–2019.

- The CV on standardised catch rates was ≈ 7%, and 95% confidence intervals about ± 2–6 fish. Statistically, these interval widths indicated annual differences in standardised catch rates could be detected in the GLMs.
- For SS input, the annual catch rate CV was increased based on the Loess residual standard error. The Loess suggested higher CV at 14.96%, assuming an equivalent number of spline parameters = 4.47.
- A box plot of the standardised residuals against fitted values was in Figure C.6 (Appendix C.6.1). The residual plot was similar between GLM analyses and showed no lack of model fit, with relatively few large residuals (≈ 5%) exceeding -2 and +2. The box plot pattern was typical for Poisson type models applied to skewed data. The models percentage of mean deviance accounted for by the four GLMs (see methods) were: model 1) 36.7%, with a dispersion of 14.3 fish; model 2) 45.9%, with a dispersion of 14.7 fish; model 3) 40.3%, with a dispersion of 13.5 fish; and model 4) 50.3%, with a dispersion of 13.6 fish; adding the tender and CT data improved model 4 fits.
- The inclusion of boat-operation, seasonal and fishing power terms were important in the standardisation of catch rates (Figure C.7, Appendix C.6.1). The 2017–2019 and 2021–2022 years were associated with the better-catching fishing vessels, and therefore catch rates were standardised down to the benchmark average vessel (Figure C.9, Appendix C.6.1).
- In general, the GLMs predicted relationships of higher catch rates during August–November, on the early waxing moon phase and timed with weather of lighter good-winds (Figure C.8, Appendix C.6.1). Catch rates were higher from Bramble Cay (zone 1) compared to the other fishing zones.

In the previous stock assessment, TSFFRAG introduced historical Sunset catch rates 1975–1983 into the RBC analyses (O'Neill et al. 2023). 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).

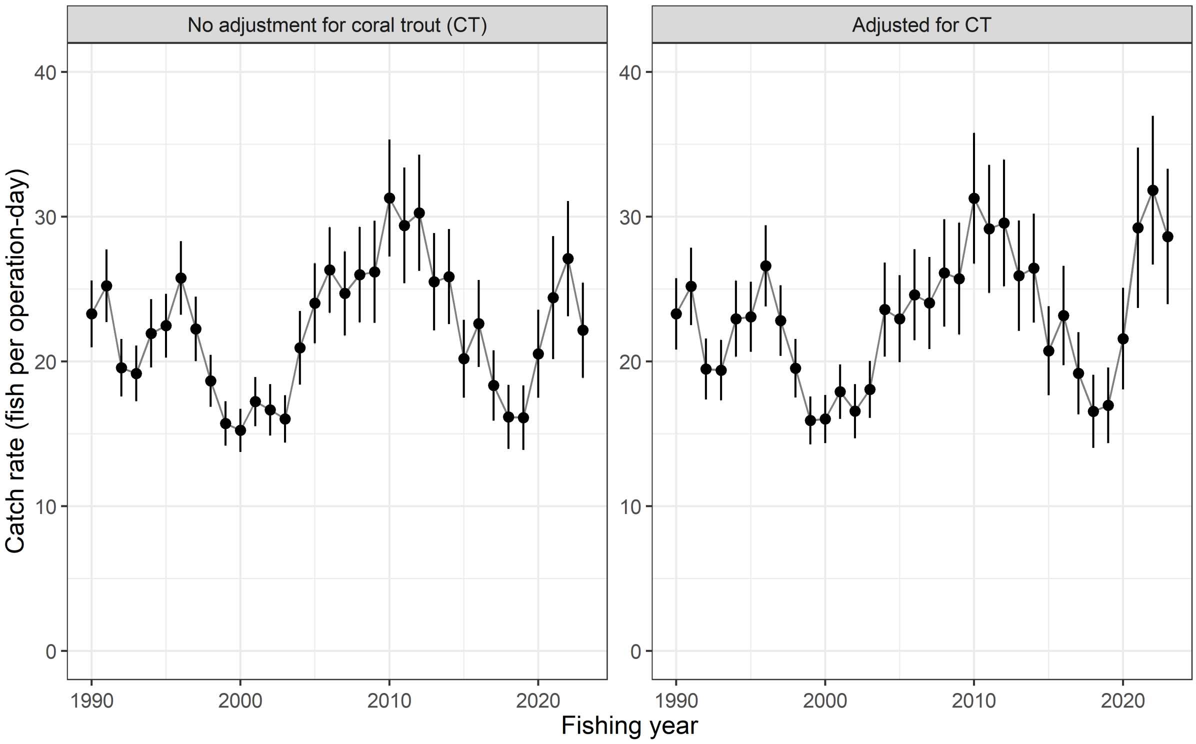


Figure 3.3: Spanish mackerel average catch rate (number of fish per Sunset operation-day) by fishing year. The first standardisation (left subplot) included a fishing power (FP) offset and tender data, but excluded effects of coral trout. The right subplot was the standardisation result for including coral trout. Asymtopic 95 percent confidence interval error bars are illustrated.

TIB-CDR reports on Spanish mackerel fishing varied between fishing years (Table C.13, Appendix C.6.7). Generally, TIB fishing was not conducted around Bramble Cay waters.

TIB nominal catch rates varied with clients (Table C.13), and had skewed distributional properties. The nominal median was 35.2 kg per client boat-day, mean = 86.4 kg and standard deviation = 271.9 kg (CV = 315%). 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 5 years of TIB-CDR catch rates. GLM methods were kept similar to the Sunset analysis. Statistical differences in catch rates between years were non-significant (Appendix C.6.6, Table C.10). Confidence in the 2022 and 2023 mean catch rates, with few catch reports, was low (Figure 3.4).

Appendix C.6.6 summarised the TIB catch rate diagnostics. Residuals were typical for the amount of data and skewness (Figure C.13). Seasonal trends were modelled simply for a single annual cyle, indicating higher catch rates associated with November and December (Figure C.14). Higher catch rates also associated with the number of boat crew (Figure C.14).

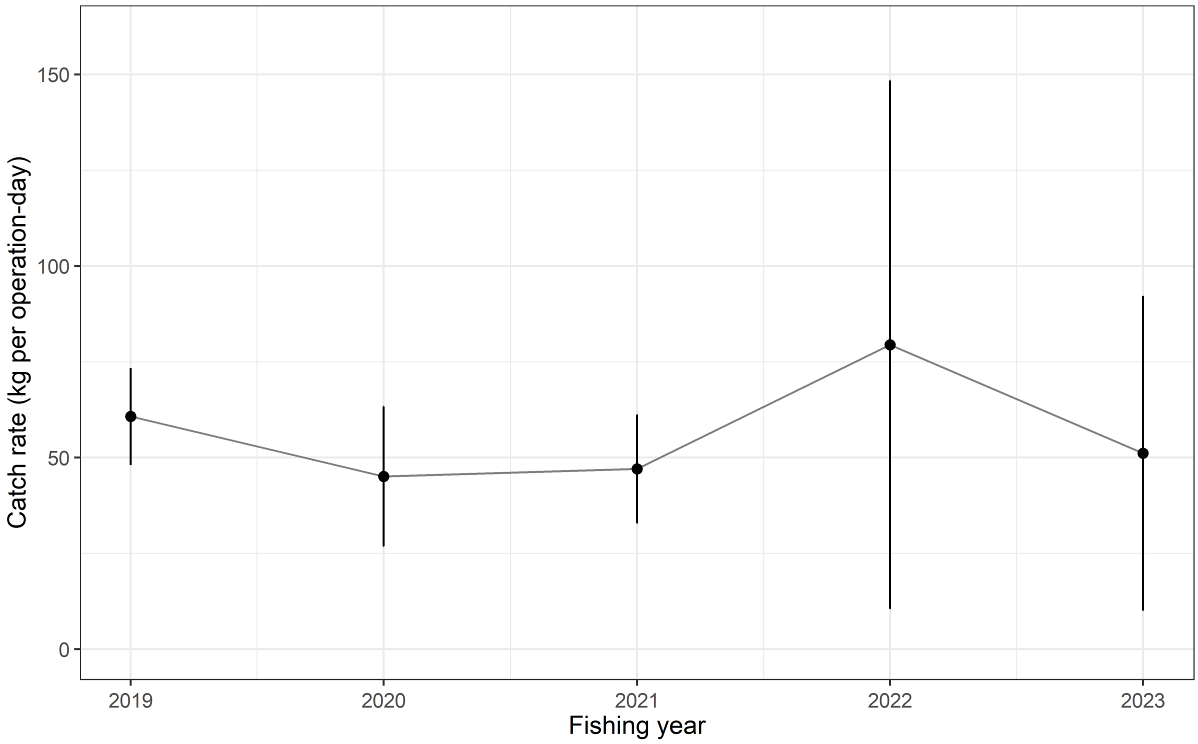


Figure 3.4: Standardised catch rates for commercial line-caught Spanish mackerel by the TIB sector.

3.1.3 Age composition

The Spanish mackerel age frequencies showed most fish were the 2+ to 4+ cohort-age-groups (Figure 3.5). A strong age-group of 2 year old fish was sampled in 2021, and their frequency can be seen as 3 year olds in 2022 and 4 year olds in 2023 (Figure 3.5).

Fish vulnerability and recruitment to the fishery was by 2–3 years of age (O'Neill et al. 2023). This was indicated by the 2+ or 3+ age groups varying in being the most frequent between years (Figure 3.5). Harvests of young 0+ and 1+ year old fish were few (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. 2020).

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) 1979–2006 (Figure 3.6). Estimates of total mortality 2020–2023 were less, as expected from reduced harvests since 2018 (Figure 3.2).

The rate of decline in age frequency from young to old fish considers: 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.

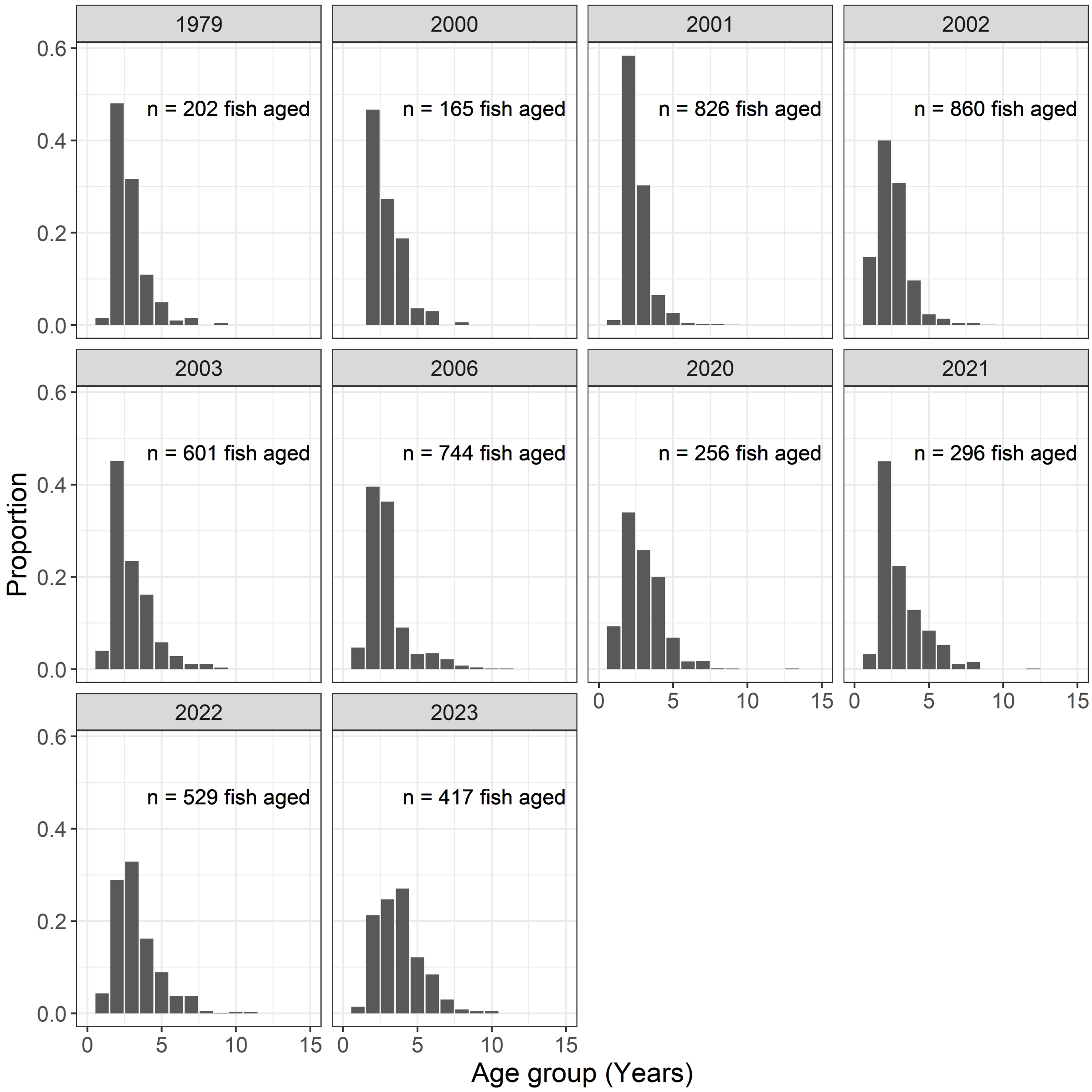


Figure 3.5: Annual age compositions of Spanish mackerel for the sampled years between 1979 and 2023 in the Torres Strait. n was the number of fish aged in the annual age-length keys. See the appendix for length frequencies.

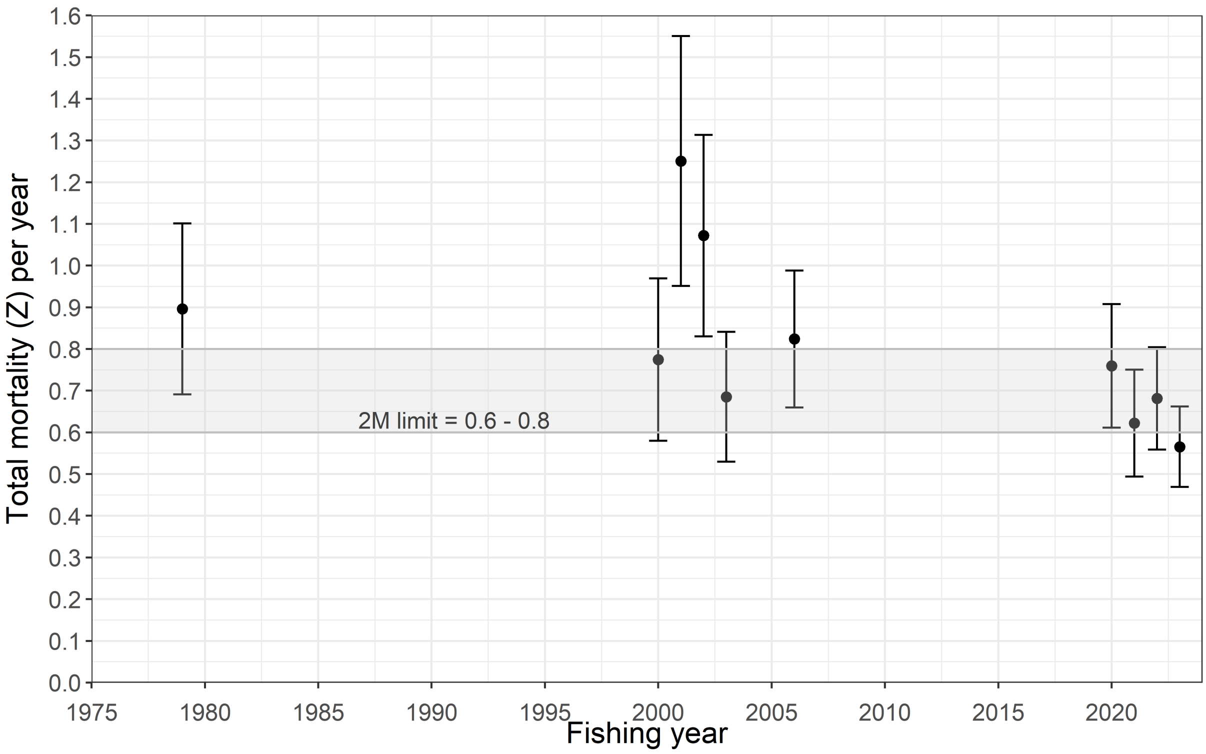


Figure 3.6: Catch curve estimates of annual total mortality (Z) by year. Error bars were 95 percent confidence intervals. The shading represents the two-times natural mortality (2M) range between 0.6 and 0.8. Estimates were from analysing the 3+ to 13+ age groups, using a quasi-Poisson GLM with log link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

3.2 Model outputs

3.2.1 Analyses 1–12

All analyses resulted in parameter convergence and satisfactory fits to data (Appendix D). Parameter estimates were consistent across analyses (Table 3.1 and Table 3.2). The investigative MCMC on analysis 2 produced similar parameter estimates (Appendix D.5), to the maximum likelihood estimates in Table 3.1 and Table 3.2.

The values of recruitment steepness (*h*) measured the expected proportion of virgin recruitment at 20% of virgin spawning biomass (egg production kg) (Myers et al. 1999; Begg et al. 2005; Begg et al. 2006). The median steepness was 0.67 over the 12 analyses (Table 3.1 and Table 3.2).

Estimates of virgin recruitment (R_0) negatively correlated with steepness. Over stock assessments, R_0 has tended smaller from the decline in Sunset catch rates after 2011 (Buckworth et al. 2021; O'Neill et al. 2022; O'Neill et al. 2023). The R_0 estimates herein were marginally smaller again, but with higher steepness compensating. The median R_0 was 133000 fish (Table 3.1 and Table 3.2).

Estimates of fish 50% and 95% length-at-vulnerability were consistent between analyses, with median fork lengths L_{50} = 78 cm and L_{95} = 84 cm (Table 3.1 and Table 3.2). Spanish mackerel older than or equal to the 2+ age group were vulnerable to fishing (Buckworth et al. 2021).

Growth parameters for recruited female and male fish are in Table 3.1 and Table 3.2, and illustrated in Figure D.9 (Appendix D.1.2).

The following stock status estimates were for 2023:

- 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 F_{40} of 0.18 (Table 3.3).
- The spawned egg production was around the reference level for 40%. Egg production was above the limit reference point of 20%, but below the interim target reference point of 48% (Figure 3.7).

Table 3.1: Summary of estimates from SS analyses 1–6. Standard errors are in parentheses.

Data	Analysis 1	Analysis 2	Analysis 3	Analysis 4	Analysis 5	Analysis 6
M	0.3	0.35	0.4	0.3	0.35	0.4
IUU	1	1	1	0.5	0.5	0.5
CT effect	0	0	0	0	0	0
R_0 millions fish	0.103 (0.006)	0.136 (0.009)	0.178 (0.015)	0.084 (0.006)	0.11 (0.01)	0.143 (0.017)
h	0.643 (0.067)	0.568 (0.07)	0.505 (0.073)	0.791 (0.131)	0.716 (0.158)	0.655 (0.195)
L_{50}	77.12 (2.753)	77.531 (2.662)	78.057 (2.691)	77.105 (2.803)	77.537 (2.725)	78.102 (2.784)
$L_{95\ \mathrm{width}}$	5.701 (2.44)	5.909 (2.315)	6.213 (2.308)	5.744 (2.486)	5.955 (2.371)	6.28 (2.387)
L_{minF}	87.342 (1.499)	87.732 (1.398)	88.032 (1.3)	87.197 (1.517)	87.622 (1.422)	87.95 (1.322)
L_{maxF}	129.245 (8.679)	130.379 (8.86)	131.68 (9.142)	129.15 (8.617)	130.305 (8.837)	131.653 (9.147)
K_{F}	0.264 (0.093)	0.249 (0.086)	0.236 (0.08)	0.267 (0.094)	0.251 (0.087)	0.237 (0.081)
$\mathrm{CV}_{\mathrm{youngF}}$	0.053 (0.008)	0.054 (0.007)	0.056 (0.007)	0.053 (0.008)	0.054 (0.008)	0.056 (0.007)
$\mathrm{CV}_{\mathrm{oldF}}$	0.072 (0.013)	0.071 (0.012)	0.071 (0.012)	0.072 (0.013)	0.071 (0.012)	0.07 (0.012)
L_{minM}	85.208 (1.503)	84.952 (1.561)	84.673 (1.676)	85.236 (1.502)	84.969 (1.576)	84.666 (1.717)
L_{maxM}	111.868 (4.149)	111.884 (3.954)	111.909 (3.815)	111.862 (4.166)	111.879 (3.969)	111.897 (3.826)
K_{M}	0.332 (0.103)	0.338 (0.102)	0.343 (0.101)	0.332 (0.103)	0.337 (0.102)	0.343 (0.102)
$\mathrm{CV}_{\mathrm{youngM}}$	0.068 (0.01)	0.068 (0.01)	0.068 (0.009)	0.068 (0.01)	0.068 (0.01)	0.069 (0.01)
$\mathrm{CV}_{\mathrm{oldM}}$	0.034 (0.009)	0.035 (0.009)	0.035 (0.008)	0.034 (0.009)	0.034 (0.009)	0.035 (0.008)

Subscript labels with F are female estimates.
Subscript labels with M are male estimates.
Full IUU = 1 and half IUU = 0.5.
No coral trout (CT) targeting in standardisation, labelled = 0.
Selectivity and growth parameter units were cm FL.

Table 3.2: Summary of estimates from the SS analyses 7–12. Standard errors are in parentheses.

Estimates	Analysis 7	Analysis 8	Analysis 9	Analysis 10	Analysis 11	Analysis 12
M	0.3	0.35	0.4	0.3	0.35	0.4
IUU	1	1	1	0.5	0.5	0.5
CT effect	1	1	1	1	1	1
R_0 millions fish	0.101 (0.006)	0.133 (0.009)	0.173 (0.015)	0.082 (0.006)	0.106 (0.011)	0.136 (0.02)
h	0.665 (0.071)	0.592 (0.077)	0.532 (0.082)	0.838 (0.154)	0.779 (0.207)	0.746 (0.315)
L_{50}	77.532 (2.62)	78.068 (2.625)	78.79 (2.689)	77.49 (2.665)	78.064 (2.694)	78.837 (2.792)
$L_{95\ \mathrm{width}}$	5.957 (2.279)	6.265 (2.254)	6.715 (2.295)	5.978 (2.32)	6.307 (2.316)	6.793 (2.385)
L_{minF}	87.92 (1.377)	88.222 (1.266)	88.494 (1.173)	87.793 (1.407)	88.129 (1.29)	88.421 (1.193)
L_{maxF}	130.468 (8.941)	131.875 (9.263)	133.551 (9.662)	130.288 (8.86)	131.773 (9.222)	133.511 (9.639)
K_{F}	0.245 (0.085)	0.231 (0.079)	0.217 (0.073)	0.248 (0.087)	0.233 (0.08)	0.218 (0.073)
$\mathrm{CV}_{\mathrm{youngF}}$	0.055 (0.007)	0.056 (0.007)	0.057 (0.007)	0.055 (0.007)	0.056 (0.007)	0.057 (0.007)
$\mathrm{CV}_{\mathrm{oldF}}$	0.071 (0.012)	0.071 (0.012)	0.069 (0.012)	0.071 (0.012)	0.07 (0.012)	0.069 (0.012)
L_{minM}	84.824 (1.585)	84.549 (1.681)	84.152 (1.871)	84.857 (1.593)	84.56 (1.708)	84.132 (1.928)
L_{maxM}	111.693 (3.905)	111.768 (3.789)	111.776 (3.648)	111.689 (3.923)	111.763 (3.804)	111.76 (3.658)
K_{M}	0.342 (0.103)	0.347 (0.102)	0.355 (0.103)	0.341 (0.103)	0.346 (0.103)	0.355 (0.104)
$\mathrm{CV}_{\mathrm{youngM}}$	0.067 (0.009)	0.068 (0.009)	0.069 (0.009)	0.068 (0.01)	0.068 (0.009)	0.069 (0.009)
$\mathrm{CV}_{\mathrm{oldM}}$	0.035 (0.009)	0.036 (0.008)	0.036 (0.008)	0.035 (0.009)	0.035 (0.009)	0.036 (0.008)

Subscript labels with F are female estimates.
Subscript labels with M are male estimates.
Full IUU = 1 and half IUU = 0.5.
Coral trout (CT) targeting effect standardised in catch rates, labelled = 1.
Selectivity and growth parameter units were cm FL.

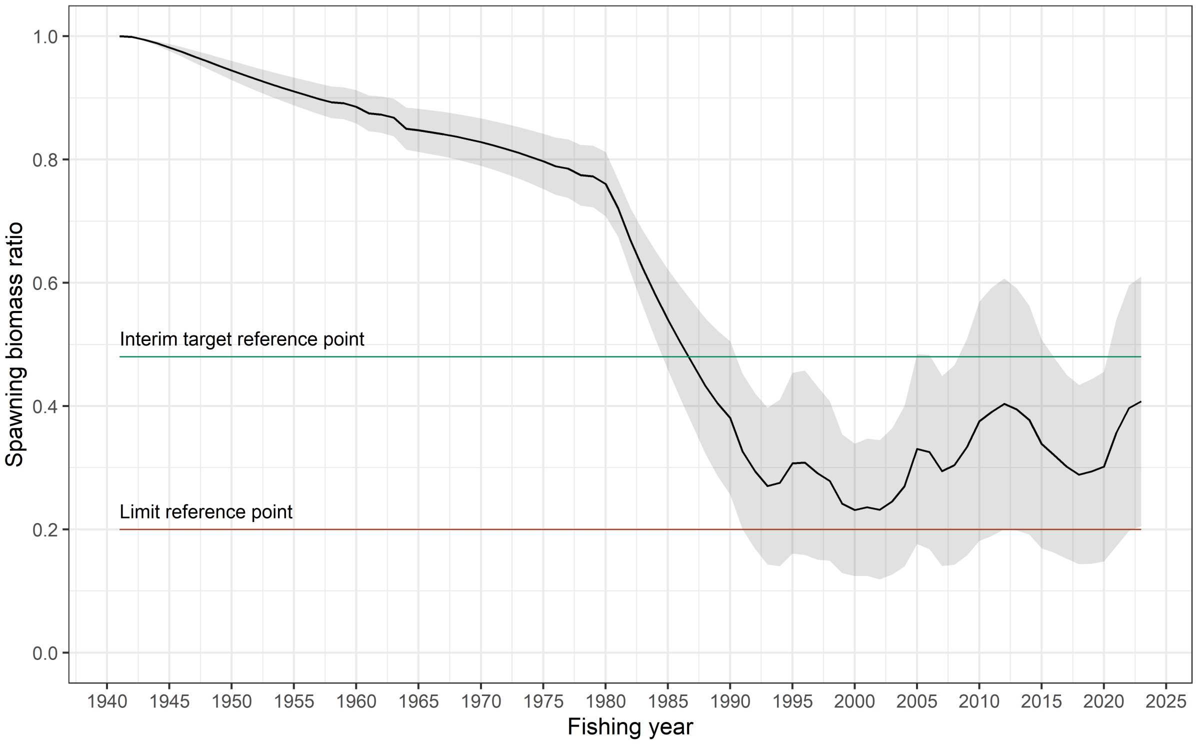


Figure 3.7: Estimated median spawning biomass ratio for Torres Strait Spanish mackerel, from 1941 to 2023. Results were from analyses 1 to 12, with shaded lower and upper 95 percent confidence intervals.

The median RBC reference points are in Table 3.3. The TSFFRAG principles (O'Neill et al. 2023) and RBC options considered:

- Median estimates over analyses 1–12.
- Forecast risk of less than 10% probability of the spawning biomass falling below 20%. Risks were calculated over analyses and 12-year forecasts (3 times age at full maturity = 4 years).
- Forecasts that generally reached a spawning biomass of 48% by the end of 12 years (Figure 3.8).
- Reference points for 50% and 60% biomass met the TSFFRAG principles (Table 3.3). F_{40} and F_{48} reference points did not.
- Forecast graphs suggested harvests up to 133 t per year should promote increases in Spanish mackerel towards 48% spawning biomass, with an acceptable risk level by 12 years (Figure 3.8).

Table 3.3: Median RBC estimates by fishing-mortality (F) reference-points, for the 2024–2025 fishing year.

No.	Reference point$^{\diamond}$	Risk* (%)	RBC† (t)
1	F_{40}	7.6 (11.5)	162
2	F_{48}	4 (5.3)	141
3	F_{50}	3.1 (5)	133
4	F_{60}	1.6 (5)	97

$^{\diamond}$ The annual fishing mortality rate (annF) for the reference points 1 to 4 were around 0.18, 0.14, 0.13, and 0.10.

* Probability (as a percent chance) of forecasts falling below the limit reference point of 20%. Forecasts were over 12 years and analyses. Forecasts assumed average recruitment (i.e. no deviation from the stock recruitment curve) and a constant RBC per year. TSFFRAG considered no more than 10% risk of triggering the limit biomass reference-point (AFMA 2021a). Upper 95% confidence interval in parenthesis.

† Median recommended biological catch (RBC) over the 12 analyses. This was the recommended maximum harvest to be taken by all fishing sectors in the forecast fishing-year of 2024–2025.

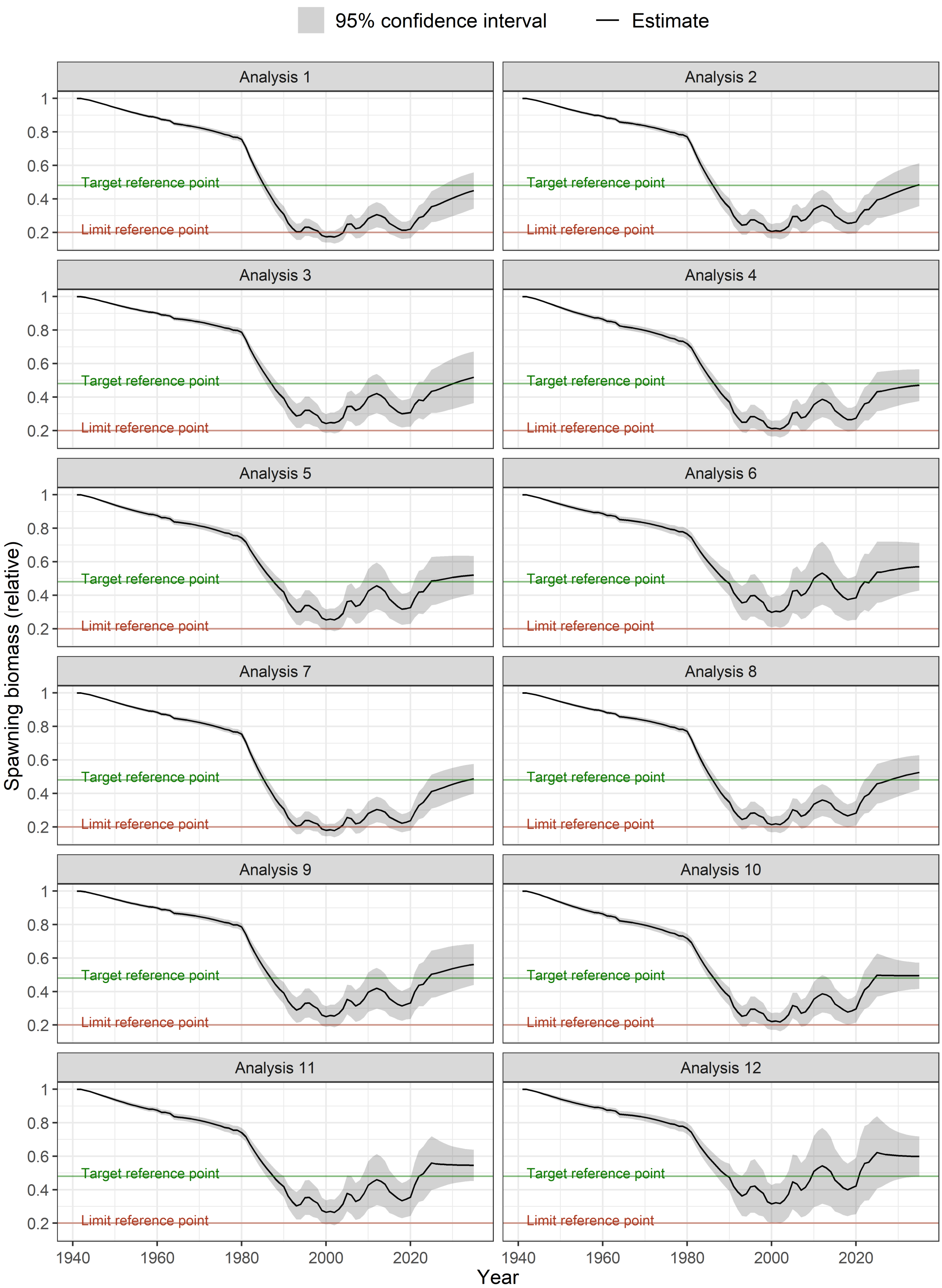


Figure 3.8: Spawning biomass (egg production) forecast for a constant RBC of 133 t, by analysis 1–12. The forecast was for RBC reference point F_{50}. The green line illustrated the interim target of B_{48}.

3.2.2 Analyses 13–17

Additional analyses were run to explore results of different σ_R settings for recruitment deviations, fixing higher steepness at 0.7, and estimating recruitment deviations for all years (Table 2.5, Method report section 2.6.2). These analyses were for TSFFRAG consideration, to tailor future model designs for stock assessment.

The findings from the exploratory analyses, compared to analysis 2.0 in Figure 3.9 and Figure 3.10, were:

- Analyses 13 and 14 used higher recruitment σ_R at 0.5 and 0.7 respectively. The results signalled no significant change in spawning biomass ratio or recruitment deviations. The analysis 2 setting of σ_R = 0.33 appeared sufficient and large enough to not limit parameter estimates. However, the larger σ_R did broaden the confidence interval.
- Analysis 15 used low σ_R at 0.1 and this changed estimates. The biomass ratio was higher. The annual pattern of recruitment deviations was unchanged, but their magnitude was reduced between -0.2 and 0.2 compared to Figure D.28 in appendix D.3. The R_0 estimate increased to 152239 fish and steepness reduced to 0.517. Data fits were reduced and the analysis did not fit the cyclic pattern in catch rates post 2000.
- Analysis 16 fixed higher steepness. This estimated a higher biomass ratio by only 3%. The estimated R_0 was about 9% lower at 124160 fish.
- Steepness was fixed in order to estimate recruitment deviations in all years. The analysis 17 biomass ratio was estimated higher at 0.43, but R_0 was lower at 109976 fish.
- In general, analyses 13–17 selectivity and growth parameter estimates were similar to analyses 1–12 (Table 3.1).

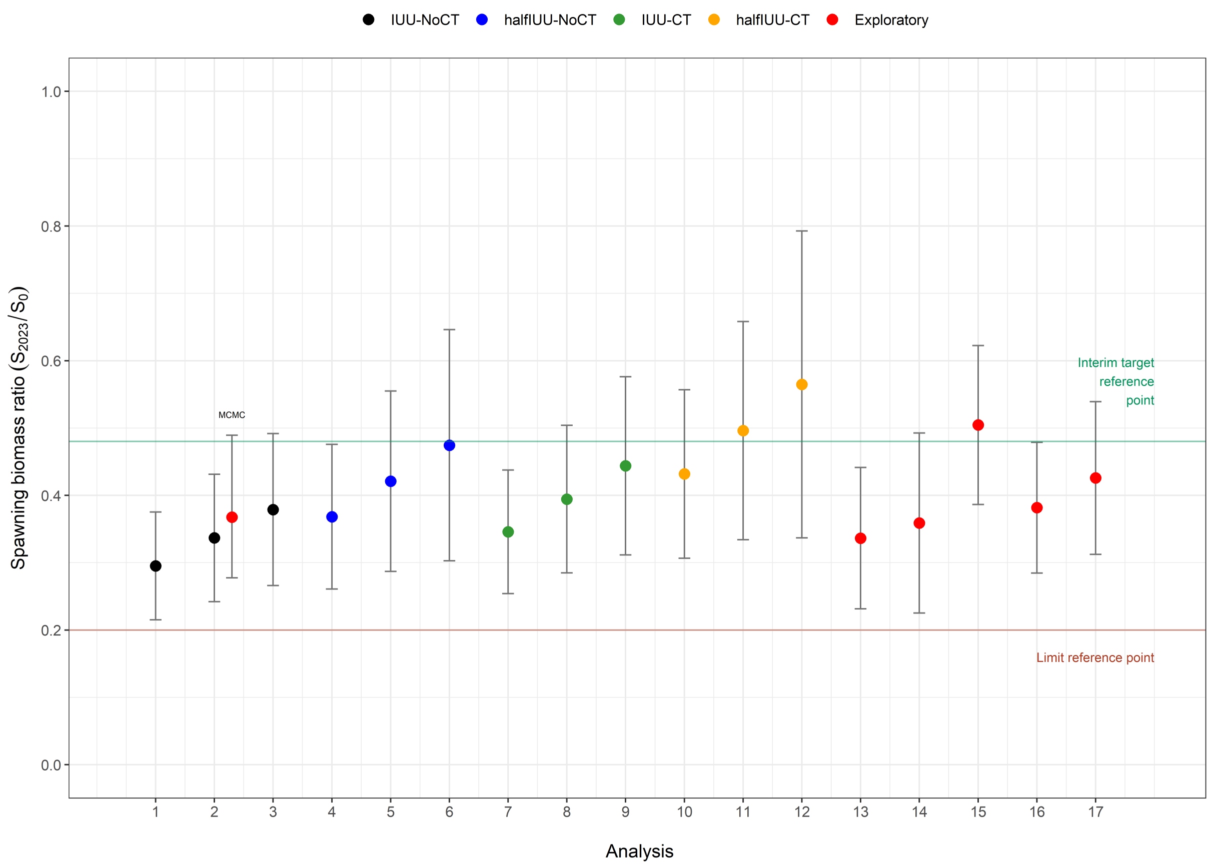


Figure 3.9: Estimated spawning biomass ratio for Torres Strait Spanish mackerel in 2023. The figure compared estimates across analyses, with error bars representing 95 percent confidence intervals. Two analysis–2 results are shown. The first was for the maximum likelihood best fit estimate (x-axis = 2.0, with a black data point) and the second was for the MCMC median estimate (x-axis = 2.3, with a red data point). All other analyses were maximum likelihood.

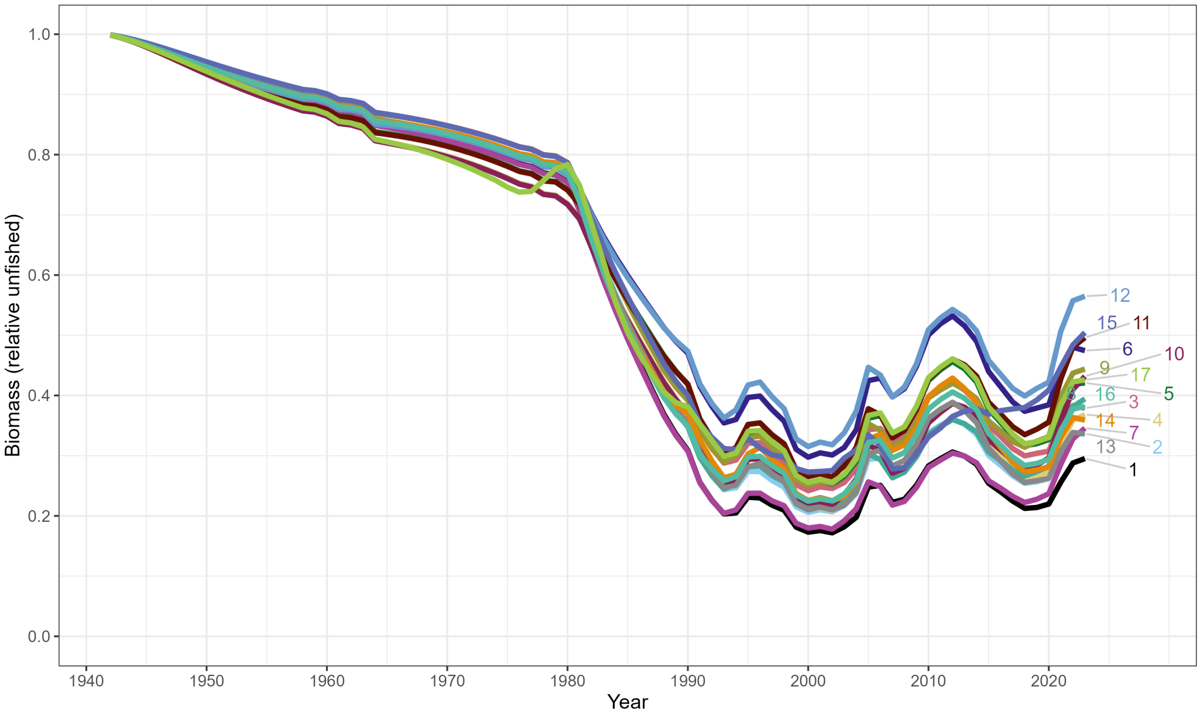


Figure 3.10: Estimated spawning biomass ratio for Torres Strait Spanish mackerel, from 1941 to 2023, by analysis.

3.2.3 The grid

A matrix of 36 analyses was explored by fixed steepness. Results were similar to analyses 1–12 (Figure 3.7).

The median spawning biomass ratio was estimated at 39% in 2023. The biomass ratio was above the limit reference point of 20%, but below the interim target reference point of 48% (Figure 3.11). The 2023 confidence interval width was less at ± 16.9% from the grid analyses. The 2023 confidence interval width from analyses 1–12, that estimated steepness, was ± 20.3%.

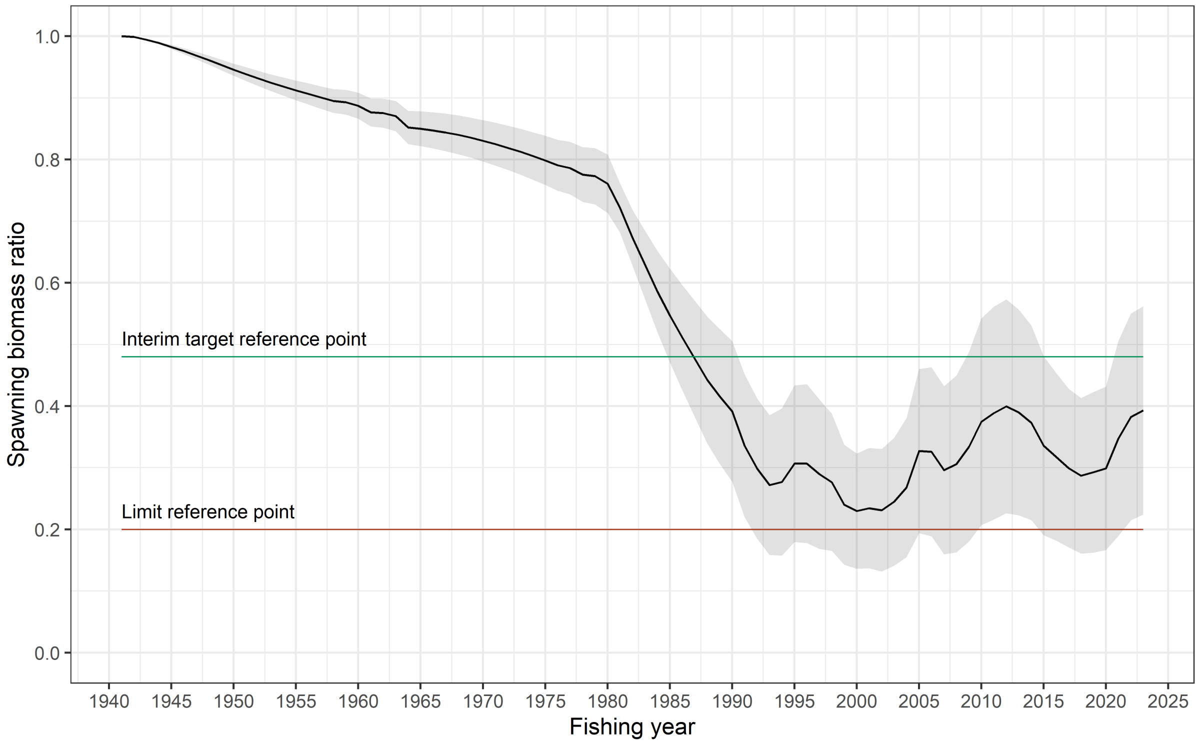


Figure 3.11: Estimated median spawning biomass ratio for Torres Strait Spanish mackerel, from 1941 to 2023. Results were from the grid analyses, with shaded lower and upper 95 percent confidence intervals.

The median RBC reference points from the grid are in Table 3.4. In general, they were 6–13 t lower compared to analyses 1–12 (Table 3.3).

Table 3.4: Median RBC estimates by fishing-mortality (F) reference-points, for the 2024–2025 fishing year. Estimates were from the grid analyses.

No.	Reference point	RBC[†] (t)
1	F_{40}	149
2	F_{48}	132
3	F_{50}	124
4	F_{60}	91

[†] Median recommended biological catch (RBC) over the grid analyses. This was the recommended maximum harvest to be taken by all fishing sectors in the forecast fishing-year of 2024–2025.

4 Discussion

4.1 Stock status

The results for Torres Strait Spanish mackerel indicated that recent harvests were sustainable. Across analyses, estimated spawning biomass (egg production) of Spanish mackerel in fishing year 2023 was around 41% of estimates for the start of the fishery in 1941.

While the biomass ratio indicated how the spawning stock was positioned in relation to reference points, the harvest rate estimates (fishing mortality F, defined in the Glossary) in 2023 and RBC forecast (Figure 3.8) provide a prediction of future stock direction under current 2023 fishing pressure and expected average recruitment. In 2023 the median harvest rate fraction was 0.09, and this level of fishing corresponded to building higher biomass ratios than in 2023. The 0.09 harvest rate was approximately the harvest rate for F_{60} (Table 3.3).

4.2 Model performance

A number of analyses were run to understand which data and parameters were influential in results (Section 2.6.2). The results highlighted future considerations for the RBC ensemble-design and add to the findings of past research (see past stock assessment reports and TSFFRAG meeting records online).

Different values of natural mortality (M) produced results ranging around ± 7% between the spawning biomass ratios in 2023. Past analyses indicated rates of natural mortality up to 0.4 per year resulted in acceptable model fits to catch rates and parameter R_0 estimates (Buckworth et al. 2021; O'Neill et al. 2022).

Higher natural mortality could be tested in SS up to 0.45 (see method section 2.5.4). However, this might be problematic in underestimating fishing mortality (F), particularly if matching fixed values of high steepness (h). SS profiling did indicate lesser likelihood with high natural mortality, noting that natural mortality can negatively correlate with steepness. Future assessments could explore whether M changes with size, such as setting M inversely proportional to fish length (Lorenzen 2022; Hoyle et al. 2024a).

The choice of IUU harvest history influenced the estimated spawning biomass ratio. Use of half IUU increased biomass estimates by about 9% in 2023. The change in IUU contributed important uncertainty in confidence intervals. It is not recommended to reduce analyses on different IUU scenarios.

Analyses 13 and 14 tested increased σ_R. This allowance, for higher recruitment variation, did not influence estimates and only increased confidence intervals marginally. Reducing σ_R in analysis 15 aimed to understand the effect of small recruitment deviations predicting a 16% higher biomass ratio.

The grid analyses, fixing steepness between 0.5 and 0.7, produced similar median biomass ratios as to analyses 1–12. Confidence intervals were marginally smaller. If fixed steepness and the grid approach is favoured, then further testing is needed. Consideration is needed on how h and M correlate (to better design the grid or to use likelihood weightings in the ensemble) and to estimate recruitment deviations in all years to avoid smaller confidence intervals.

Further model development in stock synthesis will assess potential improvements in estimates and performance. One aspect is that stock synthesis can link growth dynamics for analysing fish age-length keys and/or length frequencies. The 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). However, verifying model predicted age frequencies against ghost fleet (externally calculated) age frequencies is an important diagnostic. This was satisfactory, this time, but deviations like in 2023 (Appendix D.1.2, Figure D.10) might warrant more analyses using direct annual age frequencies.

In addition for stock synthesis, more customising of data weights, testing of recruitment deviations for all years, and changing standard deviations on Sunset catch rates might help broaden model performance and increase the confidence interval widths.

4.3 Steepness

The purpose of this discussion was to explain the use of stock-recruitment relationships and steepness. These aspects were important, given their use to calculate reference points and RBC options.

In summary, the assessment compared estimated and fixed steepness in the stock recruitment relationship, using an ensemble – a group of results viewed as a whole rather than individually (Millar et al. 2015). Contrast in the data allowed comparison, together with testing three different fixed rates of natural mortality (M). Methods were overseen by TSFFRAG, but new considerations are always required, with new data and given the literature and views on steepness were broad.

4.3.1 Introduction

The stock assessment used a Beverton-Holt function (Haddon 2001), with variation, to specify the spawning stock-recruitment relationship. The relationship defined the linkage between annual spawning stock size (female egg production summed over the whole population) and the consequent recruitment of new young fish (called 0+ aged fish) produced by that spawning. The function combines and simplifies the different life history stages between birth and age-at-recruitment (Hilborn et al. 1992).

The Beverton-Holt function contains two parameters: 1) average virgin recruitment for numbers of new 0+ aged fish (labelled R_0), and 2) steepness (labelled h). The steepness parameter defines the behaviour of the stock-recruitment relationship and is sometimes described as the measure of population resilience or productivity when the spawning stock is declining or depleted.

Mathematically, the steepness parameter defines how strongly the population responds (through increased survival rate of eggs, larvae and juveniles) when the spawning level is low at 20% of virgin spawning biomass (Haddon 2001). The function can use values between 0.2 and 1.0. For example, values of 0.4 or 0.7 would mean the stock could produce on average 40% or 70% of R_0, respectively, when the spawning stock had been reduced to 20% (Figure 4.1); see also the maths for recruitment compensation described by Goodyear (1977), Myers et al. (1999) and Begg et al. (2005).

Biologically, steepness defines how decreased competition between individual larvae and juveniles increases their survival rates when the spawning stock size decreases (Hilborn et al. 1992). The spawning-recruitment relationship incorporates density-dependent survival rates, reflecting population competition for critical resources (Haddon 2001). The relationship infers lower survival of eggs and juveniles when the stock is large, and higher survival when stock level is low. Such behaviour is called recruitment compensation (Goodyear 1977).

For fishery management, steepness can influence rebuild times, where higher steepness might indicate fewer years to achieve a target biomass level. Higher values of steepness are also associated with lower biomass ratios for maximum sustainable yield (B_{MSY}/B_0) and higher levels of fishing mortality F_{MSY} (Hillary et al. 2020), which can be difficult to translate into effort control rules when the steepness value is subject to uncertainty. This is a reason to limit fishing mortality below natural mortality, to be more certain of maintaining healthy stock sizes (Hilborn et al. 2021); and to use biomass proxies for MSY instead (Punt et al. 2014; Sainsbury 2008).

The concepts of spawning and recruitment are not just about how many thousands of eggs are produced per spawner, so that parental abundance is immaterial, or how fast fish grow (Walters et al. 2004). Steepness is determined by the response of the survival rate of eggs, larvae and juveniles to changes in parental abundance. Recruitment can compensate for fishing only if survival rates improve when spawning declines (Hilborn et al. 2021).

Meta-analyses show that the steepness values used in stock assessments can vary between species and stocks, possibly according to different productivities of fish habitats, even within the same fish family (Punt et al. 2005; Myers et al. 1999; Thorson 2020). In addition, a range of stock assessment methods can add variability to the range of steepness values seen in analyses. Often, a range of steepness values need to be tested.

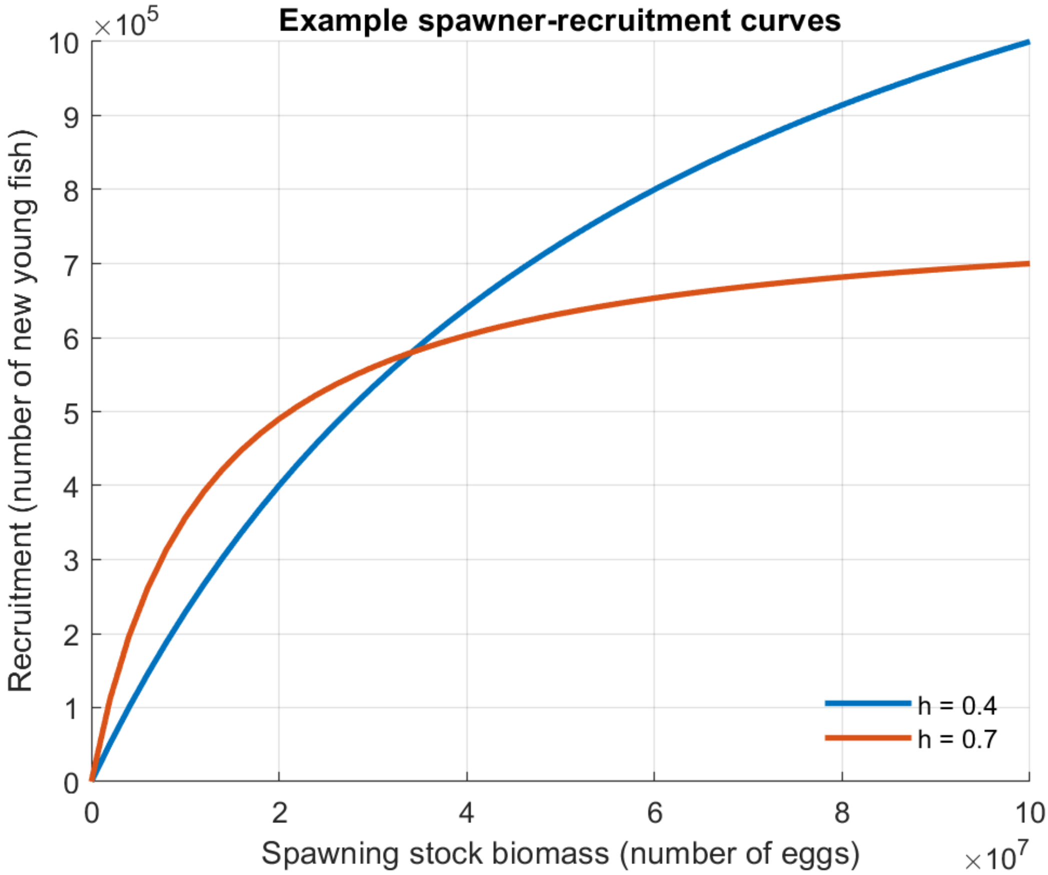


Figure 4.1: Illustration only of hypothetical Beverton-Holt functions for two values of steepness (h). Virgin recruitment R_0 (numbers of fish) was scaled differently to 1.0 million for h = 0.4 and R_0 = 0.7 million for h = 0.7, to draw attention to the often-encountered negative correlation between these two parameters. In this hypothetical, higher h inferred stronger recruitment compensation and that the potential average size of R_0 might be limited more by available habitat, food and therefore density-dependence, than h = 0.4. However, also note that potential recruitment at low spawning stock (less than 20%) was higher for h = 0.7. The general illustration also assumed the same natural mortality rate (M) per year, but it's parameter correlation with different values of h and R_0 might imply other higher or lower shaped curves.

4.3.2 Difficulties

It should be noted that the central tendency (average or median) of steepness is difficult to identify. It is a stochastic process as a part of annual recruitment deviations. Typically, in behaviour and estimation, steepness correlates negatively with natural mortality M and virgin recruitment R_0; as illustrated in Figure 4.1. As a consequence, steepness values can differ between judgements by the scientists and objective estimation within a population model.

In general, assuming lower steepness will result in smaller overall losses of yield through stock re-building, compared to assuming higher steepness than the true value, suggesting that lower steepness might be a more robust assumption in terms of yield (Zhu et al. 2012; Maunder et al. 2015). Hilborn et al. (2021) state that only modest gains in fishery value can be expected for high steepness species by fishing them hard and assuming no effect of spawning abundance on recruitment, unless spawning abundance is severely reduced.

Hillary et al. (2020) summarised the general difficulties of estimating steepness. For southern bluefin tuna (a member of the Scombridae fish family, like Spanish mackerel), they described their difficulties as:

- The “one-way trip” in spawning stock dynamics, making decoupling resilience from abundance difficult.
- The need for the spawning stock to have historically demonstrated recovery from low levels.
- The need-to-have informative abundance data (relative or absolute).
- The need-to-know other life-history characters, such as the natural mortality rate, reasonably well.

For southern bluefin tuna assessment, steepness uncertainty was captured pragmatically by modelling a grid of four fixed values 0.55, 0.63, 0.72, and 0.80 (CCSBT 2020). They conclude that it was best not to prefer any single steepness value over another. Lower values than 0.55 were not used in their current model assumptions. Interestingly, they also gridded fixed values of other key parameters including the natural mortality rate, and estimated R_0, which explained their tight confidence intervals on each analysis (CCSBT 2020).

Simulation research, testing the estimation of steepness on 12 overseas groundfish assessments, by Lee et al. (2012), suggested:

- Assessments might misjudge their ability to estimate steepness.
- Only three species of the select 12 had information on the magnitude of steepness.
- Across the simulation cases, steepness was estimated with mixed precision and bias.

The Lee et al. (2012) study was valuable and requires extension. Due to the 12 examples being low in number and non-random, they could not generalise their results outside of the case studies. Also, they did not ask the question of performance when compared to fixing steepness. Overall, they conclude that reliable estimation of steepness was attainable with good model structure and contrast in data to inform the model about spawning biomass (Lee et al. 2012). No diagnostics were explained to define these attributes, but the plausibility of a model from: 1) model convergence, 2) fit to the data, 3) model consistency, and 4) prediction skill would be properties for consideration (Carvalho et al. 2021).

To date, for Torres Strait Spanish mackerel steepness, stock assessments have considered values between 0.3 and 0.8. Torres Strait Spanish mackerel, being a small stock compared to the Australian east coast, has experienced change both up and down in catch rates and harvests, and these data were surprisingly consistent in signal with the age frequency data (O’Neill et al. 2023); 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 provided some contrast for informing the stock assessment and to see changes in the spawning dynamics. Walters et al. (2004) say that it is not always true that we must over exploit to establish stock recruitment relationships, and that information to define or limit the steepness can be available at higher stock sizes. The Torres Strait data included measures from the 1970’s before harvests increased, during peak harvests, and for the harvest decline post 2010 (Figure 1, Figure 2 and Figure 3). Nevertheless, we have treated any single estimate of steepness with caution.

4.3.3 Comments

The information presented described how estimates of steepness were used for linking spawning and recruitment. However, they do not discount the uncertainties and difficulties in estimating steepness.

Changes to model assumptions or structures, such as to error settings or the recruitment deviations or natural mortality, or to the historical levels of harvest, might alter inferences of steepness in the Beverton-Holt function. Therefore, the steepness discussion or values used should not be viewed as fixed, but to change and evolve with future learning, new data and new stock model adaptations; such as testing with the Ricker function and with different density dependent assumptions (Haddon 2001).

Nevertheless, the current harvest strategy and use of the stock assessment by estimating steepness appears to measure higher uncertainty in biomass and support building the fishery stock after declines in recruitment (Figure D.28), at least defensively following stakeholder principles to "bank fish". If fixed values of steepness were to be used in future, like the grid approach tested herein or used for southern bluefin tuna (CCSBT 2020), then a range of values should be used.

Herein, we increased standard errors (extra-SD) on catch rates. This lessened and flattened the model fits to catch rates compared to previous assessments, which inferred higher steepness. However, this flattening or lack-of-fit might have been excessive. Future analyses should consider different values of extra-SD from 0 to the Loess estimate and in between.

Caution should be applied before accepting any single steepness values. The use of a range of steepness values, matched appropriately with assumed natural mortality rates, supports the continued use of an ensemble approach.

4.4 Environmental influences

In 2009–2018, Torres Strait Spanish mackerel recruitment deviations were lower than expected (Figure D.28). 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, and that similar catch rate declines had occurred in other fisheries (TSFFRAG presentation by D. Brewer), it was hypothesised by TSFFRAG that environmental conditions may have contributed to this observed trend (AFMA 2019b; AFMA 2020b).

As well as undertaking annual assessments, the stock assessment for 2019 discussed the impact of environmental drivers on Torres Strait Spanish mackerel (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 over 2–3 years 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.

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.

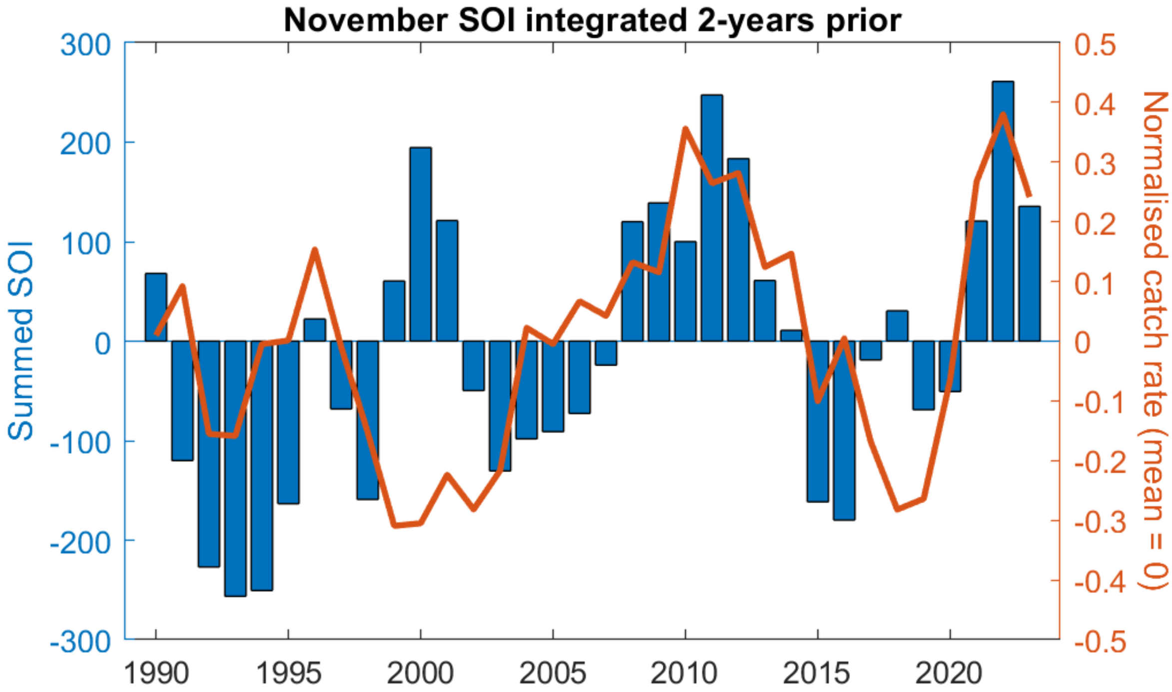
In Great Barrier Reef (GBR) shelf waters, larvae of *S. commerson* were found only in oceanic conditions of the lagoon (Jenkins et al. 1985). Juveniles have been found inshore, in coastal and estuarine areas which may include mangrove areas as well as near-shore reefs. The timing of spawning was such 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, compensation, and growth, as well as duration, of all life history stages of Spanish mackerel, as well as for 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).

Of relevance for RBC decisions, is for TSFFRAG and TSFFWG to monitor patterns in annual climate reports (AFMA 2023a). In 2023, the PZJA agreed that a standing agenda item “Climate and ecosystem update” be introduced to all RAG and Working Group agendas where total allowable catch and effort limits are to be considered. Interestingly, integrated-SOI associations were apparent against standardised catch rates in later years after 2005 (Figure 4.2). Strong or persistent ± SOI (potentially outside of a threshold range) might be a consideration for TSFFRAG ”to watch”. The Southern Oscillation Index, or SOI, gives an indication of the development and intensity of El Nino or La Nina events in the Pacific Ocean (www.bom.gov.au).



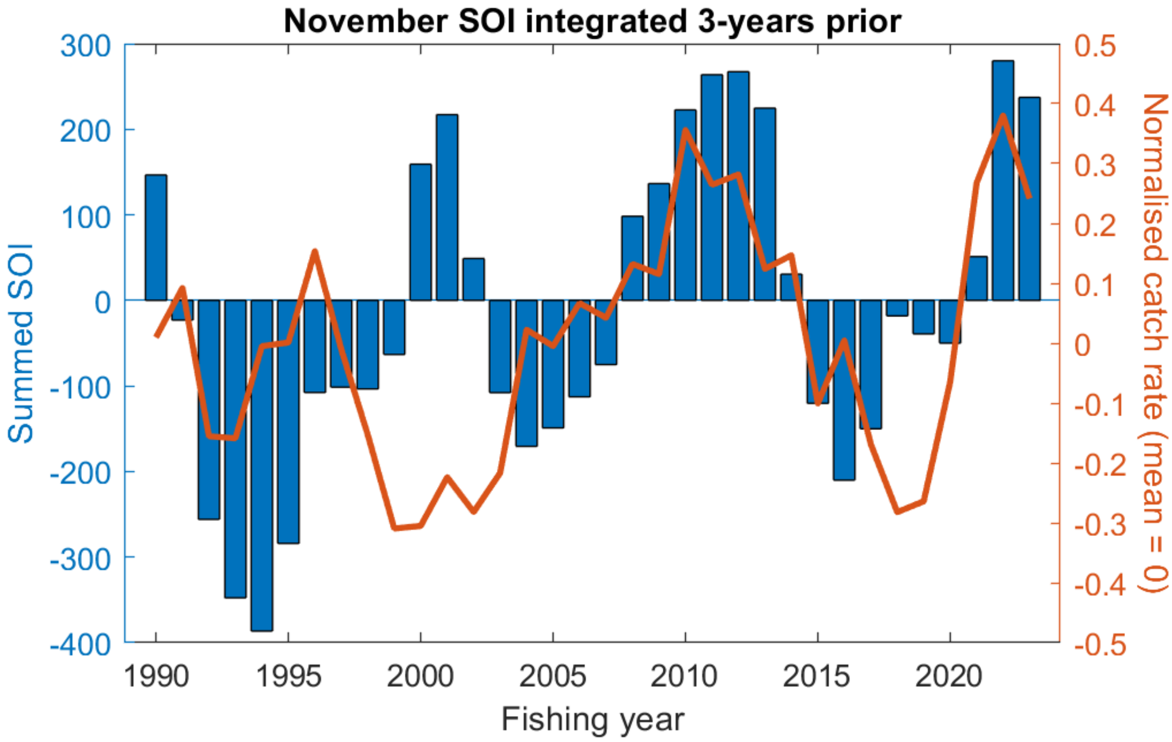


Figure 4.2: Comparison of November integrated SOI values (monthly SOI summed over 2 or 3 years prior) with annual standardised catch rates (from the Sunset data and model with coral trout targeting). SOI values were summed to correspond with the 2–3 years survival needed to enter the fishery.

4.5 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 best practice reference points (Sainsbury 2008), 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.

For the last 10 years for the September to November spawning months at Bramble Cay, commercial line harvests represented about 48% of the annual harvest. Typical Bramble Cay harvests were 15–93 (25th – 75th percentiles, mean = 70) Spanish mackerel per day across fishing operations (maximum was 965). The accumulation of these daily harvests of fish over time during the spawning season can be substantial when many vessels operate. With Spanish mackerel aggregated to spawn and a general focus of fishing effort around Bramble Cay, harvest rates (fishing mortality) could easily exceed those estimated annually for the complete stock area. The catchability of Spanish mackerel at Bramble Cay during the spawning season will likely be higher than other areas and times. Density dependence in catchability and risk of increased fishing mortality on spawning fish is important to manage (Walters et al. 2004).

In 2012 a genetic tag-recapture study on Spanish mackerel in 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 mark-recapture 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.

4.6 Streamlining

4.6.1 Overview

In stock assessment, streamlining refers to integrating multiple analysis tasks into an easier, systematic and repeatable process. This involves organising the computer code into sections to ensure a smooth and efficient workflow, thereby reducing the time required for execution. Streamlining aims to create a cohesive and structured process, akin to following a detailed action plan or recipe.

This was the result for the project: all the assessment steps were joined together in R code from data access to analysis and stock assessment, and to generate the final report with basic accessibility aspects included.

The successful output was a streamlined process for the Torres Strait Spanish mackerel stock assessment. This means that, for an agreed core set of analysis scenarios (like in Table 2.5), fewer days are required to produce the results for TSFFRAG. If utilised, this will enable more cost-effective assessments.

This outcome would allow for annual or regular quantitative evidence to continue to be used in quota setting and stock status classification. It could also be advanced to provide timely and contemporary information for web-dashboard reporting or summary fact sheets (like for SAFS or ABARES reporting; this would represent future benefit and investment beyond this project).

Previous and current reporting have been detailed documents of the stock assessments. This was to support reviews, the transition to SS, and for the AFMA contract requirement. Current project reports were built in R Studio, using an Rtex file with LaTeX scripting, executable R code, Rdata and matching BibTeX bibliography.

In this way, the report was produced with consistent formatting and familiarity for readers. There is potential for AFMA and TSFFRAG to agree on and design more concise reporting to reduce costs, in a way still allowing information to be published and cited.

As mentioned, the streamlining was setup in RStudio and R software packages. The code was version-controlled using Git on DAF's secure IT network system. This enabled reproducibility principles, to improve accessibility, transparency, consistency, and history-tracking of all code changes.

4.6.2 Features and steps

The stock assessment of Torres Strait Spanish mackerel had many features to support the current RBC methods. To do so, the streamlining used nine stages (Figure 4.3):

1. **Specify global settings.** The stock assessment was run from "MasterCode.R". This file was structured in sections. In RStudio, the file outline (table of contents listing each section) was used for navigation. The start of the stock assessment specified the global settings:
   (a) Identified the stock assessor.
   (b) Set the year of the stock assessment to the last fishing year.
   (c) Loaded R packages.
   (d) Created working directories for sourcing data and saving results.
2. **Data acquisition and treatment.** Data were sourced, analysed, and formatted into data frames (tables) for SS input and the Rtex report:
   (a) Source file 1, "ts_1_data_harvest_catchrate.R", was for the catch and effort data. For example, all the AFMA logbook and CDR data, BOM winds, fishing power offsets and product form kg conversions were loaded. The code joined all the data into a boat-day format separately for the Sunset and TIB fishing sectors. GLM catch rate tables were made for each sector. A data report was produced to check numbers for consistency between assessments or for new data supplied.
   (b) Source file 2, "ts_2_glm_sunset_catch_rates.R", analysed the Sunset catch rates. GLMs were run, standardised residual diagnostics stored, influence effects calculated, and the predictions of standardised catch rates and standard errors formed.
   (c) Source file 3, "ts_3_glm_tib_catch_rates.R", was similar in function to step 2b, but for the TIB standardised catch rates.
   (d) Source file 4, "ts_4_agelength.R", compiled all the fish age length data by sector, year and sex. This included annual fish length and age frequencies, and age-length keys, including sample sizes.
   (e) The analysis table (design matrix) of SS scenarios was loaded from "sa_spm_data_ts.xlsx".
3. **Import data and assessment specifications into SS.** The four SS files (starter, data, control, and forecast) were created:
   (a) SS settings, data variables and parameters common to all analyses were fixed.
   (b) Settings, data and parameters different for each analysis were changed.
   (c) The source file "UpdateSSfiles_LF_CAAL.R", made the four SS files.
   (d) The SS files were read into R as list objects using ss_read functions in the r4ss package.
4. **Run SS.** For each analysis:
   (a) The Francis weights and recruitment deviation options were tuned. This required the stock assessor's insight.
   (b) Set the spawning biomass target reference point. The code started with 48%.
   (c) Run, evaluate, and store the SS and r4ss outputs.
   (d) If the analysis MCMC flags were "true", then also do MCMC to compare with the maximum likelihood estimates (MLE was the default method).
   (e) Loop over 4b and 4c for other target reference points. Store SS outputs.
   (f) Loop oversteps 3 and 4 for different analyses.
5. **Generate diagnostics.** For selected analyses (analysis 2 was used herein), run the cookbook (Appendix D.1.3) for extra model diagnostics.
   (a) R_0, M and h profiling.
   (b) Runs test.
   (c) ASPM diagnostic.
   (d) Retrospectives.
   (e) Hindcasting.
   (f) Jittering.

(g) Collate all diagnostic results.

6. **Calculate RBCs.** Calculate median RBC for each target reference point, across core analyses.
7. **Forecasts for alternative RBCs.** Forecast the median RBC options.
   (a) For all core analyses, project each median RBC as constant catch over future years.
   (b) An expected catch was used in the first year of the 12-year projection.
   (c) Store yearly biomass forecasts and standard deviations.
   (d) Calculate the risk of biomass forecasts falling below 20%, across years and analyses for each median RBC.
8. **Assemble Results.** Collate and tidy all key results into dataframe tables or graphs for use in the Rtex report.
9. **Build the Rtex report.**
   (a) Modify content as needed for the stock assessment year.
   (b) Check accessibility aspects.
   (c) The report is built in RStudio. The Rtex file is processed by ”Knitr”, a package for dynamic report generation, that integrates R and LaTeX code.
   (d) Optional, use Overleaf for the review process.

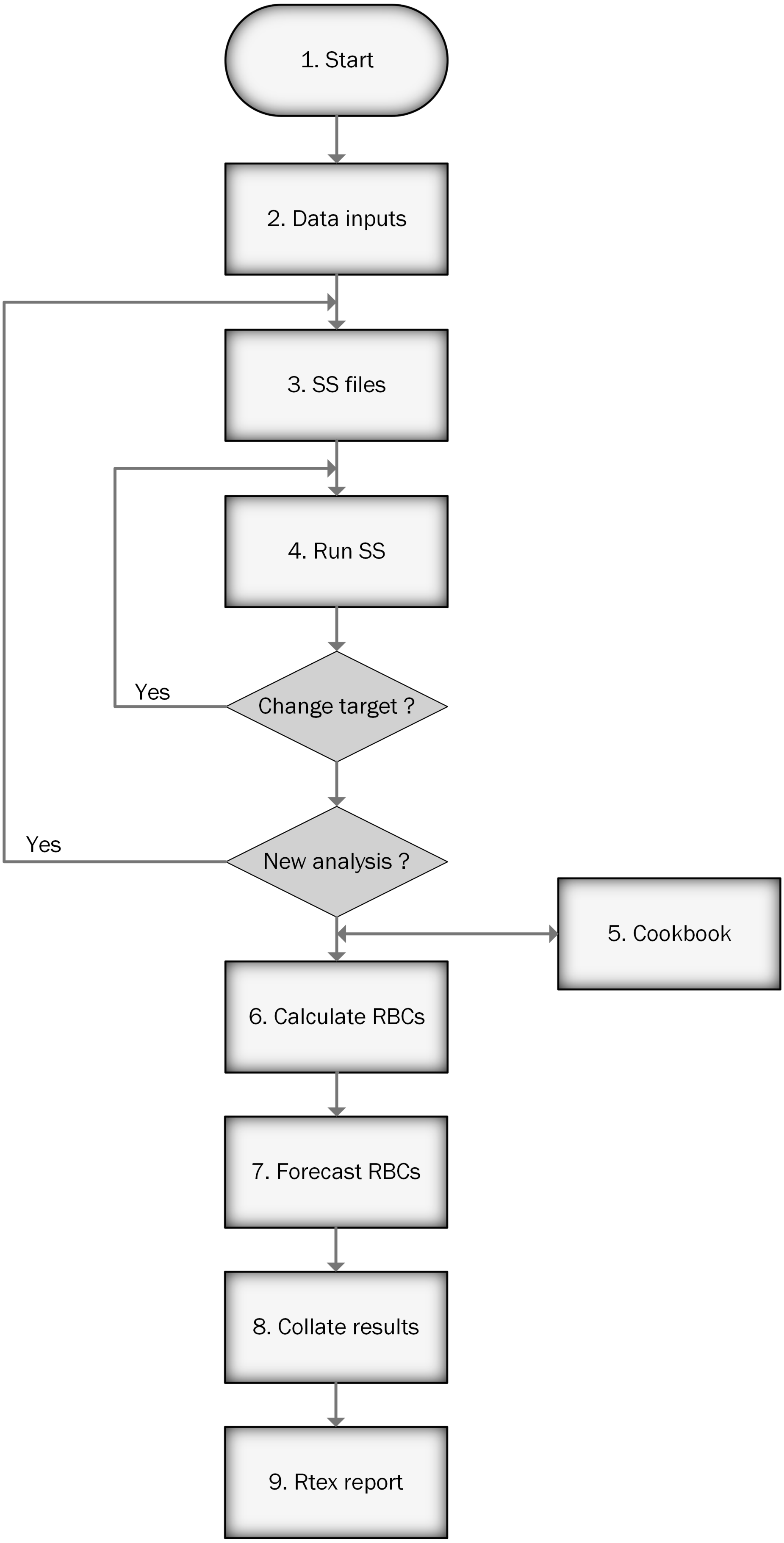


Figure 4.3: The steps in the stock assessment.

4.6.3 Comments

DAF is using SS as part of standardising software-methods for many finfish stock assessments across Queensland. This stock assessment, and the streamlining, is compatible. It has actioned the TSSAC letter advocating the use of ”open-sourced stock assessment models” (to Dr Michael O'Neill on 21 April 2021) and formed part of the national approach in stock assessments (Dichmont et al. 2018). The Torres Strait work has continued to develop and contribute to key methods for mackerel (*Scomberomorus* species) stock assessments in Australia.

An expected outcome from the project is for managers and stakeholders to better understand that annual or regular stock assessments of Torres Strait Spanish mackerel can be cost effective. The potential to reduce future costs depends on two aspects: a) settle on core methods and analyses for RBC setting, and b) make the Rtex report brief or report key results through TSFFRAG minutes, with detailed SS outputs stored for extra appraisals.

These aspects (changing analyses and lengthy reports) accounted for a large amount of time per year in the current project. If reduced, regular stock assessments and use of the streamlining would reduce the cost per assessment, including the ability for minor refinements and the use of any new information. Review at, say, 3–5 yearly intervals, would ensure that core methods and analyses remained appropriate to PZJA requirements.

Another cost consideration was the AFMA logbook and CDR data. Consistent and clean data supply is critical. AFMA database extractions still needs to be streamlined and AFMA data team inclusion is necessary in the process (noted in the project proposal). This aspect was different compared to Queensland stock assessments, which were automated to use direct database links to pull data in real-time. If rapid access to the data was setup, then this would allow for earlier stock assessment updates as required by fishery management and reduce the AFMA staff time and costs in data supply. One hurdle in the current Rtex/LaTeX setup was to meet accessibility conditions, required for the report to be published on the AFMA website. An accessible document means that people with different abilities can read the document. This was addressed by:

- Setting the document properties (metadata), to enable readers to know the PDF file content. This included specifying the author: e.g., Queensland Government - not person or department, title: user-friendly title, subject: use of document, and keywords: possible search terms (keywords in title, acronyms, common terms etc.).
- Writing alternate text (alt text) for all figures and tables.
- Using a PDF compliance accessibility checker.
- Publishing on the DAF eResearch archive: eRA is a digital repository of reports, journal articles, book chapters, conference papers, theses and data created by departmental staff during their research.

However, there was a limitation. In using Rtex/LaTeX, alt text could only be included on imported figures (graphs made and saved outside of the Rtex file). The original setup with plotting code in the Rtex file had to be switched off. The benefit of using dynamic plotting within the Rtex verse alt text needs further consideration to improve the streamlining and reducing costs.

The aspects above covered the main considerations in future stock assessment. Previous assessment timelines have taken 3–4 months or more per year. A settled streamlined system, with the aspects addressed, will reduce this time. This will also allow more timely results to be delivered into fishery-management decision making.

The system can be managed by one person, ideally under AFMA and TSFFRAG direction. The system enables different staff to be able to run and produce repeatable stock assessments. The benefits of the SS streamlined stock assessment for the Torres Strait are:

- Version controlled.
- Fit for purpose to AFMA data and Fisheries Queensland monitoring data.
- Data formatting and filtering checked and applies TSFFRAG agreed rules.
- Freeware R coding used, generating text files for SS.
- SS model fitting by maximum likelihood and MCMC.
- Key SS parameters estimated to capture their uncertainty.
- Different data scenarios run.
- Forecasts capable for F based reference points and constant catches.
- RBC results can be produced for different reference points.
- LaTeX reporting and semi-automated.
- SS results were comparable to the custom DAF model (O'Neill et al. 2023).

In 2024, advice is pending from AFMA and Fisheries Queensland regarding an ongoing stock assessment and monitoring schedule. Advice here, understanding the future streamlining needs and addressing the aspects above will influence decisions on annual or multi-year RBC/TACC going forward.

For Torres Strait Spanish mackerel, less frequent stock assessments and use of the streamlining might increase the cost per assessment, with reduced activity in addressing necessary changes and keeping data, code and methods in good condition. Fewer stock assessments might also lessen the frequency of harvest advice and evaluations against target performance indicators.

4.7 Evolution of the stock assessment

The Torres Strait Spanish mackerel fishery of 2023 was very different to that assessed by Begg et al. (2006). The management has changed substantially from input to output control, and with allocation of the fishery to the traditional sector. The annual harvest level and number of commercial boats in the fishery are now smaller. The assessments of the fishery have grown, investigating additional sources of information, incorporating new techniques and a new software platform (Figure 4.4).

The assessment process has grown in complexity and sophistication, yet has also been streamlined, to enable more rapid and less expensive assessments. However, what we know of the biology of Spanish mackerel, and fishing operations directed at them, were nevertheless much the same, and the assessment presented here was fundamentally based on a similar form of statistical age-structured model as used by Begg et al. (2006).

Since the contemporary series of assessments began with the work of O'Neill et al. (2018b), evolution of the assessments has been characterised by careful evaluation and treatment of input data.

The harvest history of the fishery was a fundamental input to the assessments. Compulsory logbooks provide this information for the Sunset sector since they were introduced in 1988. Begg et al. (2006) sourced several other pieces of information that were required to build the harvest history since the fishery began in 1941. The contemporary assessment series has built on this base, also using information from McPherson (1986) and from expert input.

An advantage of the Resource Assessment Group and Working Group process was that it promoted dialogue between stakeholders, managers, and the assessment team. All scenarios considered in the assessments were based on TSFFRAG discussion and agreement.

TSFFRAG discussions around 2018 highlighted concerns that Illegal, Unreported and Unregulated (IUU) fishing might have impacted Spanish mackerel stocks in the Torres Strait fishery, through the 1980s and into the 1990s. Subsequent investigations by Buckworth et al. (2021) prompted the inclusion of a catch series for IUU in later assessments.

By their very nature, IUU fishing catches are rarely known. We have adopted the approach of using alternative scenarios that include different magnitudes of catches. This illustrates the capturing of uncertainties in the assessments, ensuring that uncertainty around inputs is also captured in the uncertainties expressed in outputs.

An alternative model form relying only on the harvest time series (Catch-MSY, Haddon et al. 2018) was also applied (Buckworth et al. 2021), confirming the biomass trends from the age-structured model. Lower levels of biomass results in the range for the age-structured models were associated with including IUU harvests.

Logbook data might not, in some circumstances, always provide accurate catch details. The investment warnings of 2001–2002, made prior to management changes, might have prompted inflated catches being declared in Sunset sector logbook data. We investigated the effect of this uncertainty on assessment outputs, known as the 'Paper Fish' problem, concluding that it was not influential on assessment results (see section C.1).

Intuitively, catch rates were related to abundance and so were used as the basis of indices of abundance provided to the models. As described in method sections 2.2 and 2.3 above, there has always been a careful selection process to include only that data which was representative of the fishery.

Catch rates might be influenced by many different factors, and these should be accounted for (Hilborn et al. 1992). It has been standard practice since the assessment by Begg et al. (2006) to develop indices of abundance using general linear models (GLM) or general linear mixed effects models (GLMM). This has served to take account of a range of factors which drive variation in catch rates (see section 2.3).

Downturns in Sunset sector catch rates between 2010 and 2019 led the TSFFRAG to question whether environmental drivers, not otherwise captured in assessments, were impacting catch rates, or the abundance of Torres Strait Spanish mackerel. This could occur via changes to fish behaviour, or to recruitment, growth, mortality, or reproduction. Sea surface temperature has proven to be quite influential on catch rates of Spanish mackerel in Western Australia (pers. comm., Paul Lewis, Department of Primary Industries and Regional Development, WA) and elsewhere (e.g. in Vietnam, Nguyen et al. 2017, and Taiwan, Chen et al. 2021).

In an exploration, catch rates and recruitment deviations from the assessments were analysed against sea surface temperature (SST), ENSO and rainfall (Buckworth et al. 2021). We could not find any strong relationships. However, this initial investigation was limited by availability of data sourced close to the fishery. Further investigation would probably provide better understanding of the influences of environment on catch rates for Torres Strait Spanish mackerel and would be in the spirit of investigating uncertainties in the fishery.

In the current assessment (up to and including 2023 data), we noted that increasing emphasis on coral trout fishing in recent years might be distorting the apparent catch rates of Spanish mackerel. Alternate Sunset catch rates were introduced from 1990, to consider no influence or a proportional effect of coral trout on Spanish mackerel catch rates. The fishery continues to evolve, and the assessment process must update accordingly.

A recent innovation, published by O'Neill et al. (2022), was the inclusion of a catch rates series published by McPherson (1986). This has enabled the inclusion of abundance information for the period 1974–1982.

Given the improving series of data on TIB catch rates and with the anticipation that TIB catches will grow into the future, the use of an additional index of abundance based on TIB catch rates was introduced in 2018–2019. It was valuable that this source of data has been captured as the relative importance of the sector grows.

An issue with catch rates is that they might be hyperstable, i.e. as abundance declines, catch rates remain disproportionately high. This is difficult to account for and alternative forms of information are thus desirable. Not subject to hyperstability, age and length frequency data can provide such an additional source of information for assessments. Begg et al. (2006) included age and length data for three years 2001—2003. We were able to acquire several years' worth of additional data by investigating archived information and acquiring data from historical projects (Buckworth et al. 2021; O'Neill et al. 2022).

The value of such data was clear to the TSFFRAG and fishery managers and a monitoring program to provide age and length frequency and other data was introduced in 2019 (Langstreth et al. 2020). This growing stream of quality data means that the current assessment was able to exclude one year's data considered not sufficiently representative.

The assessments have had the ongoing benefit of TSFFRAG and TSFFWG dialogues that provide the insights of stakeholders and managers as well as other assessment scientists. The scrutiny has been actively sought and the assessment has benefited from an expert review session in 2023.

Practices for modelling have evolved, and so have the ways of which adjustments to the model parameter inputs have been made. For example, using age structured dynamics to infer length-based parameters and different approaches to consider the recruitment steepness parameter, h. While steepness was estimated in the series of scenarios by O'Neill et al. (2018b), the current assessment estimates steepness but also explored alternative scenarios which apply fixed values in a wide range (see section 4.3).

Assessment not only captures knowledge of the fishery, but also highlights areas where improved knowledge would be of benefit. Given the difficulties associated with building an index of abundance based on catch rates, building alternative information streams is desirable.

Mark-recapture approaches could provide information on abundance and harvest rates, as well as movements. This could be a based on a 'traditional' physical tagging approach, or Genetag (Buckworth et al. 2012). However, the feasibility of the elegant Close Kin Mark Recapture (CKMR) approach was recently established for the Torres Strait Spanish mackerel fishery (Williams et al. 2022). CKMR uses genetic information as an analogue of physical tagging and would use genetic information collected in the monitoring program.

The importance of dialogue was also shown by the evolution of the communication of outputs supporting decisions by the TSFFRAG and the management of the fishery on RBC recommendations. Thus, the current assessment attempts to capture the uncertainty within the assessment process and so provide stakeholders and managers with information to make their decisions with uncertainty being explicit (e.g. Figure 3.8).

DAF is using stock synthesis (SS) as part of the modernisation of many finfish stock assessments across Queensland and its implementation in the Torres Strait Spanish mackerel fishery assessments responds to a TSSAC advocacy of 'open-sourced stock assessment models'. It forms part of the national approach in stock assessments (Dichmont et al. 2018). Implementation of the assessment models in the SS modelling platform has been via a careful transition using comparative analyses.

The current project provided, in the year one report (O'Neill et al. 2022), an updated assessment in the bespoke model developed since O'Neill et al. (2018b), and an initial implementation in SS. This was followed, in year two, with full implementation in both platforms (O'Neill et al. 2023), with almost identical results. This provided the confidence to proceed, with TSFFRAG support, in this last year with a full implementation in SS, alone. The transition provided many advantages (O'Neill et al. 2022).

The efforts undertaken in this assessment to streamline the assessment process, including the transition to SS, reduces the work and the cost required to undertake regular assessment - vital to a well managed fishery.

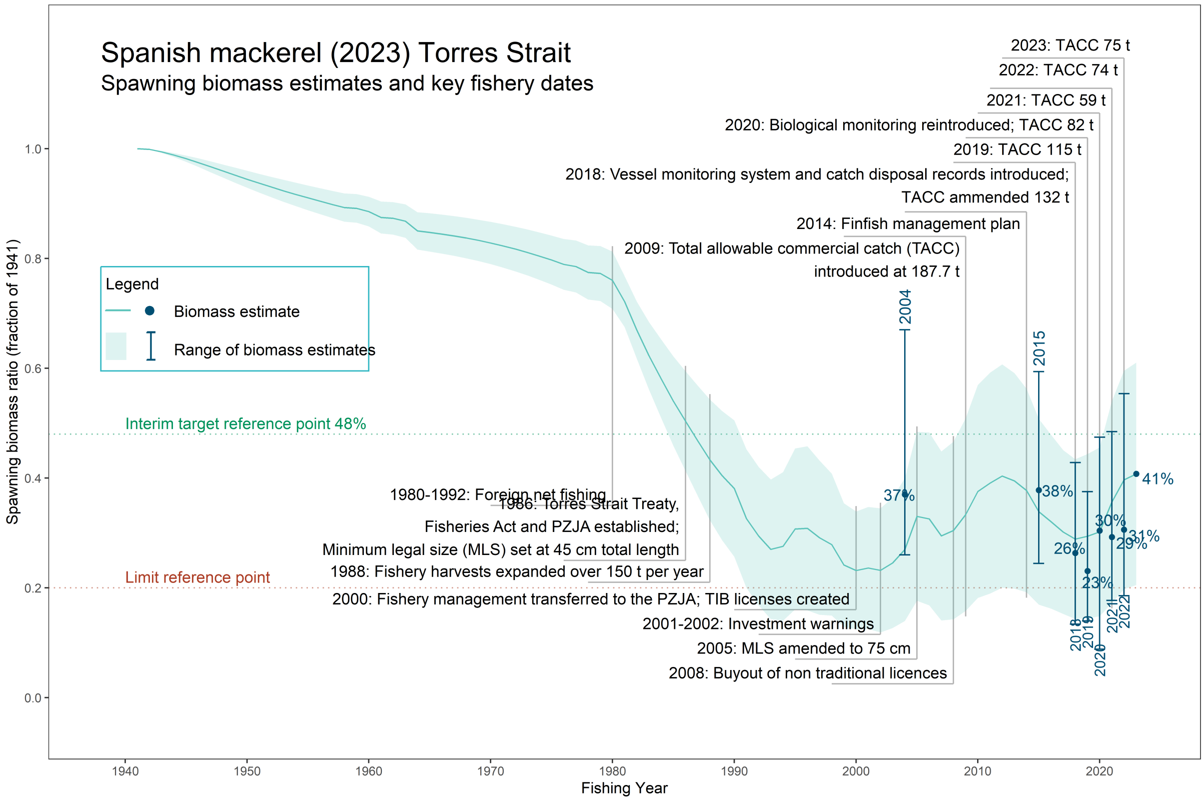


Figure 4.4: Spanish mackerel biomass estimates by fishing year, from the new core analyses, with past stock assessment results and key fishery dates.

4.8 Recommendations

4.8.1 Management

Median spawning biomass in 2023 was below the reference point of 48% of unfished spawning stock biomass (Table 1). The assessment, following TSFFRAG process, recommended RBC options between 95 t and 133 t (AFMA 2023d).

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 (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 4.4), the actual uncertainty for the 2023 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:

- 0.182, for the between-analysis 1–12 sd in 2023. The sd was calculated using the median biomass ratio of 41% as the central tendency, rather than the mean as described in method 2 on page 220 in Ralston et al. (2011).
- 0.06, for the within-analysis sd, calculated as a mean sd across analyses 1–12.
- 0.21, for the between-stock-assessment sd, calculate by comparing biomass ratios from this stock assessment to past results in 2004, 2015, and 2018–2022 as illustrated in Figure 4.4.
- 0.28, was the combined sd, from the three variance components above.
- 0.96, was the calculated uncertainty statistic for the 0.45 P^* buffer in Ralston et al. (2011).
- 0.93, 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 and Table 2). 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), but more samples to confirm the southern boundary (Lockhart River to Cape York) are being processed by FRDC, QDAF and CSIRO.
Harvests	Data	Yes	Two estimates of historical fishery harvests have been used. They appear sufficient. Estimates for IUU were more uncertain. Extra scenarios for different IUU (half and full 100 t) used.
Shark depredation	Data	No	There were no data or reports of changing incidences. A method of data collection has been drafted in the new TSF01 logbook.
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 species targeting. It is also desirable to improve the number of TIB catch rate reports through daily catch and effort logbooks. In SS, increased catch rate variation (extra SD) was used and this lessened the fitted trend, but addressed perceived over fitting comments in previous assessments; more testing is required. 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 the nth Qld square root version was used.
Hyperstability	Data	Partly	No direct adjustments have been considered, but fishing power is included in catch rates. Reporting of zero catches and VMS locations by tenders is needed to mitigate this risk. The extra SD effect might magnify this risk in SS.
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 was used. Years with shared keys were removed in SS. Age data are valuable given the difficulty of accounting for hyperstability.

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. New growth models need to be estimated both 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 has 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. Previous assessments have found higher values of M not suitable.
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. Punt, A. E., pers. comm. remarked that some USA assessments estimate recruitment deviations right back for all years.
Depletion	Model	Yes	Dissect the strong biomass depletion up to 1989. Work has been completed in the custom model, but it is desirable to further test in SS by the expansion of recruitment deviations to all years with different steepness values. Analysis 17, herein, did not produce different results (Figure 3.10)
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	Model comparisons have been completed to facilitate stock assessment transition to SS. Future changes in SS should be bridged.

4.8.2 Assessment and monitoring

The following considerations are still provided to further build and improve status indicators for Torres Strait Spanish mackerel (Begg et al. 2006; O'Neill et al. 2022; O'Neill et al. 2023):

- 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 Sunset trip harvests and average fish weights using unload/sale receipts.
- Clarifications are still required on Sunset number of tenders used per operation-day, species targeted, and on the number of hours fished per AM and PM session.
- Complete reporting on TIB catch and hours fished per operation day is required to improve fishing effort and catch rate indicators.
- The Sunset tender data was used in catch rate standardisation from 2004. Tender use was assumed constant pre 2004, where the data was incomplete (ideally, a retrospective fisher survey could update and verify the tender data). Methods for joining results (pre and post 2004) into a single continuous time series need to be confirmed 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.
- Monitor the frequency of small catches and their association with different species targeting.
- 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].
  - Measuring abundance or fishing mortality to reduce the reliance of the assessment on historical data would reduce uncertainty. This could be achieved through CKMR, other tagging methods, surveys, or by placing greater emphasis on length and age data gathered over time.
* In association with fish monitoring, continue 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]. Otolith microchemistry studies can support this to infer finer spatial dynamics that are in the temporal scale of fishery management.
* 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].
* Report on environmental data and annual trends that can support TSFFRAG discussions.

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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 were no new events for 2023.

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

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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), with the primary accommodating their crew, towing several smaller 5–6 m dories/tenders.
- 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 morning's 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 Fisher 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 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 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

Estimates of Spanish mackerel harvest used the data from Table (C.1). TSFFRAG documented aspects of this data (AFMA 2020a; AFMA 2021b), with the following assumptions:

- 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 were assumed complete.
- TIB harvests before 1990 were estimated from Islander traditional knowledge (AFMA 2020a; AFMA 2021b).
- Traditional 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 estimate was two tonnes. Uncertainty was considered above two tonnes, up to the upper confidence interval of five tonnes. A constant of 5 t per year was assumed for 2021 onwards (AFMA 2021b). Further notes are below.
- Papua New Guinea fishing operations have not leased or reported any harvest.
- The polynomial model was used 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 model. 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 also considered in this year's RBC analyses, to capture it's influence on biomass results pre 1993.

The polynomial model 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.

Previous logistic estimates were not used given similarity to the polynomial (O'Neill et al. 2023).

Overall, the Islander traditional, 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).

TSFFRAG 2023 method change in recreational catch

An initial recreational fishing survey, including the Torres Strait (Webley et al. 2015), estimated that the recreational harvest of Spanish mackerel was small. The estimate was two tonnes in 2014. This estimate was considered a minimum due to low survey participation. The 2 t estimate was unlikely to include charter fishing (particularly for clients on charter boats arriving from the mainland). Uncertainty is considered above two tonnes, based on the upper confidence interval at five tonnes. A constant of 5 t per year was agreed to and assumed for 2021 onwards (AFMA 2021b).

From the TSFFRAG meeting number 14, August 2023, changes were made to keep the recreational harvest estimate constant prior to 2014, remove randomness between two and five tonnes and consider a ramp up of harvest to five tonnes in 2021 (Table C.1). For this, recreational harvest was set at a constant of 3.5 tonnes per year between 1990 and 2014, then increased by 0.25 t per year to equal five tonnes in 2020-2023. The 3.5 tonne years of recreational harvest captured the mid-point of uncertainty between 2 and 5 tonnes. The annual recreational harvest estimates also aimed to include charter fishing. Charter fishing is currently not specified as a direct allocation sector and a future consideration. The TSFFRAG meeting 14 reviewed Queensland charter logbooks for Torres Strait Spanish mackerel and the data indicated annual landings up to 2.69 t in 2008, with limited charter records since 2008 (AFMA 2023c).

The Australian Bureau of Statistics census data (for the Torres and Torres Strait Island government areas, https://abs.gov.au/census/find-census-data/search-by-area) indicated the annual population number of people in the Torres Strait, and fraction of Islander to Non-Islander people, was steady between 2011, 2016 and 2021. No Torres Strait recreational vessel data were available online to review trends. However, Queensland wide registration data indicate a small 1–2% growth in recreational vessels per year (https://www.data.qld.gov.au/organization/transport-and-main-roads; searching in vessel datasets). These data might suggest little change in Torres Strait recreational fishing pressure.

High Sunset harvest

The high 2005 and 2006 Sunset harvest was questioned in TSFFRAG meeting 14 (AFMA 2023c). Discussion notes were provided in PowerPoint during meeting 15 (AFMA 2023d)

In 2019 TSFFRAG noted concerns raised on the impacts of high catches flagged as possible "paper fish" (potential over-reporting of catch prior to the government funded 2007 buyout of TVH licences). These years harvest might be falsely inflated and could influence the outcomes of the stock assessment model (AFMA 2019b).

Heatmaps from the October 2019 TSFFRAG PowerPoint (note the fish year labels were in the old format) raised questions on two vessel's high number of fishing days (AFMA 2019a).

In 2019, exploratory model runs were performed and lowered the harvest values of the apparent years of paper-fish. The harvest values were reduced down to a catch-rate level comparable with previous years (AFMA 2019b). The RAG noted that reducing the values of these points had little effect on the outcomes of the model and that reducing these catch values might make the model more conservative (estimating a smaller population size) and would act to adjust the RBC downwards by a few tonnes (AFMA 2019b).

TSFFRAG 6 concluded at that time, as an issue, paper fish was not substantially influential on the model outcomes. TSFFRAG supported this approach to leave these data unadjusted and that there would need to be a clear justification to remove or alter these values in future (AFMA 2019b).

From estimates, Sunset harvests were high at 225 and 277 t in 2005 and 2006 respectively (Table C.1). The number of boat operation days were also high in 2005 and 2006, and similar to previous high years like 1998–2000 (Figure C.2).

The effort per boat in 2005 and 2006, calculated by dividing boat operation days (Figure C.2b) by the number of boats (Figure Figure C.2a), were like other years. However, the nominal catch rates in 2005 and 2006 were higher at around 23 and 29 fish respectively, compared to lower catch rates in previous years when effort was high. For example, catch rates 1998–2000 were about 18–20 fish (Table C.11, using mean Mn all N.).

The higher reported catch rates tend to explain the 2005 and 2006 harvests. Calculations were presented at TSFFRAG meeting 15 to demonstrate the case.

For this SS assessment, an increased harvest CV was used at 0.1 in 2005 and 2006, compared to the default CV of 0.05. No harvest adjustments were made.

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	0.00	0	0	2.0
1958	1957-58	0	2	34.0	2.00	0	0	38.0
1960	1959-60	0	2	52.0	2.00	0	0	56.0
1961	1960-61	0	2	40.0	2.00	0	0	44.0
1963	1962-63	0	2	70.0	2.00	0	0	74.0
1976	1975-76	3	2	68.0	2.00	0	0	75.0
1977	1976-77	3	2	81.0	2.00	0	0	88.0
1978	1977-78	3	2	69.0	2.00	0	0	76.0
1980	1979-80	3	2	57.0	2.00	0	0	64.0
1990	1989-90	3	10	214.7	3.50	0	0	231.2
1991	1990-91	4	10	181.8	3.50	0	0	199.3
1992	1991-92	1	10	193.8	3.50	0	0	208.3
1993	1992-93	2	10	173.2	3.50	0	0	188.7
1994	1993-94	3	10	121.5	3.50	0	0	138.0
1995	1994-95	5	10	192.3	3.50	0	0	210.8
1996	1995-96	2	10	181.7	3.50	0	0	197.2
1997	1996-97	3	10	157.2	3.50	0	0	173.7
1998	1997-98	4	10	181.1	3.50	0	0	198.6
1999	1998-99	4	10	166.7	3.50	0	0	184.2
2000	1999-00	9	10	167.5	3.50	0	0	190.0
2001	2000-01	5	10	163.5	3.50	0	0	182.0
2002	2001-02	8	10	107.7	3.50	0	0	129.2
2003	2002-03	7	10	129.5	3.50	0	0	150.0
2004	2003-04	13	10	137.2	3.50	0	0	163.7
2005	2004-05	14	10	224.8	3.50	0	0	252.3
2006	2005-06	10	10	277.3	3.50	0	0	300.8
2007	2006-07	14	10	171.2	3.50	0	0	198.7
2008	2007-08	7	10	105.2	3.50	0	0	125.7
2009	2008-09	6	10	77.0	3.50	0	0	96.5
2010	2009-10	8	10	89.0	3.50	0	0	110.5
2011	2010-11	8	10	70.7	3.50	0	0	92.2
2012	2011-12	2	10	89.2	3.50	0	0	104.7
2013	2012-13	3	10	90.7	3.50	0	0	107.2
2014	2013-14	1	10	116.4	3.50	0	0	130.9
2015	2014-15	2	10	81.4	3.75	0	0	97.1
2016	2015-16	2	10	85.6	4.00	0	0	101.6
2017	2016-17	3	10	89.6	4.25	0	0	106.9
2018	2017-18	2	10	74.6	4.50	0	0	91.4
2019	2018-19	6	10	65.4	4.75	0	0	86.5
2020	2019-20	2	10	54.1	5.00	0	0	71.6
2021	2020-21	4	15	28.8	5.00	0	0	52.3
2022	2021-22	6	15	47.3	5.00	0	0	73.2
2023	2022-23	3	15	49.0	5.00	0	0	72.3

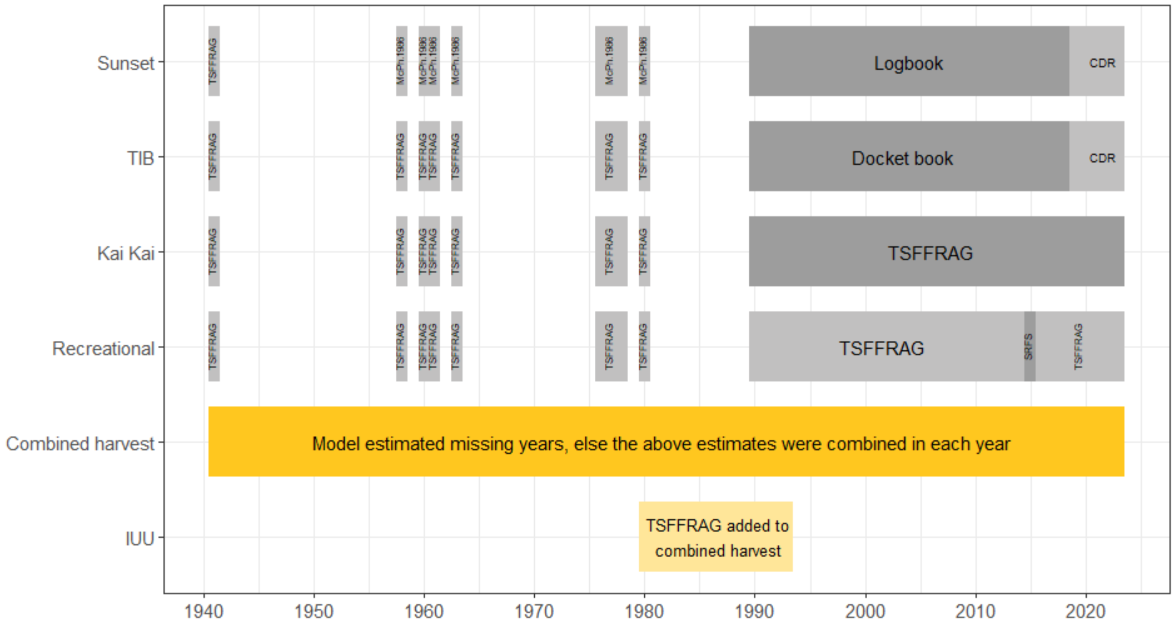

Figure C.1: Overview of the information and process used to reconstruct the history of Torres Strait Spanish mackerel harvest. The years of data (shaded grey) note the estimates from the harvest table above, where the labels: TSFFRAG - was the agreed estimate based on reports, publications and traditional 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.

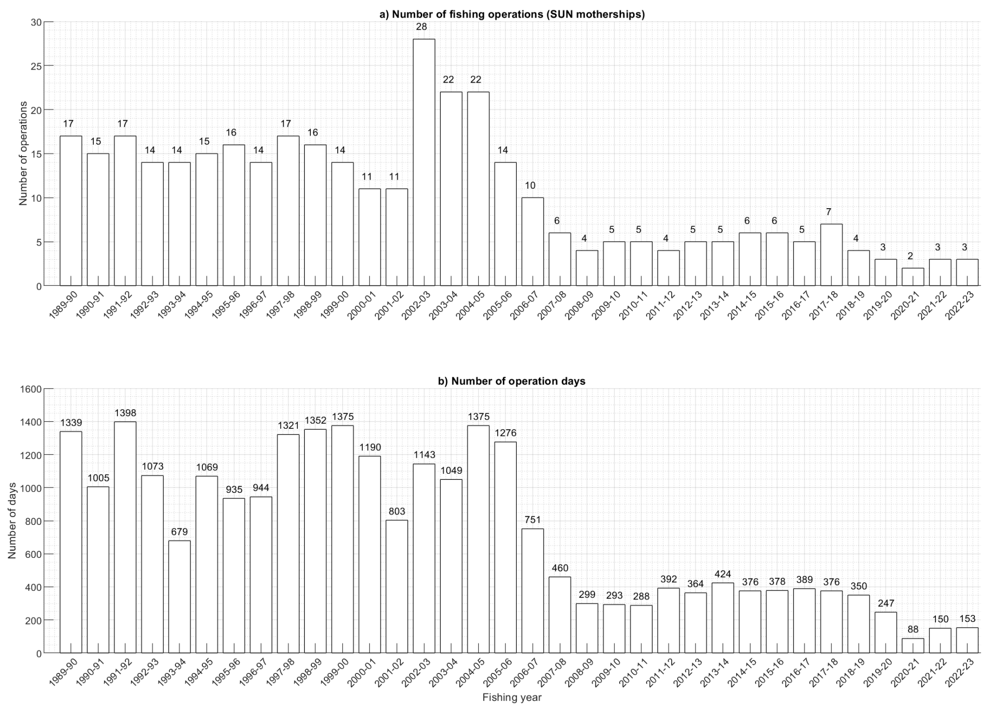

Figure C.2: Sunset logbook reports of total fishing effort by year for a) number of primary fishing operations (Sunset motherships), and b) number of days fished by the primary operations.

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/commercial-fisheries-management/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	47339	6.9	7.28
2023	7132	49016	6.87	7.61

C.3 Age-length samples

Fish length-compositions and effective sample sizes (number of catches sampled) were entered into the SS model (Figure C.3). The length frequencies were also used to construct annual age compositions through the application of annual age-at-length keys (Langstreth et al. 2020; Trappett et al. 2021).

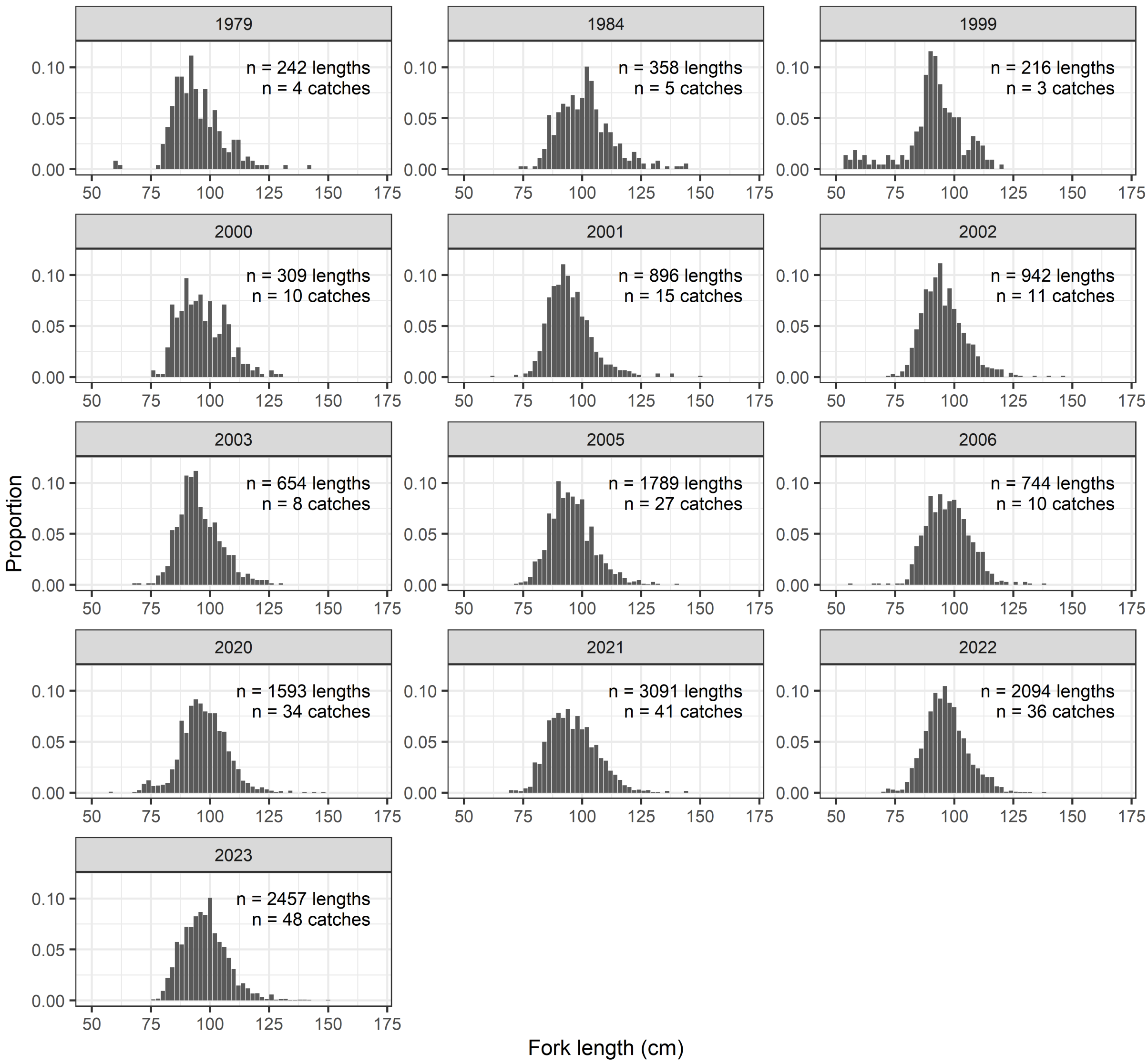

Figure C.3: Annual fork-length compositions of Spanish mackerel commercially harvested in the Torres Strait for sampled years between 1979 and 2023.

Table C.3: Mean fish weight (kg) by year and data source.

Fishing year	Mean	Standard deviation	Number of fish	Data source
1978-79	7.14	2.61	242	DAF – age and lengths
1983-84	8.07	3.41	358	DAF – lengths only from tagging
1998-99	6.83	2.42	216	DAF – lengths only
1999-00	8.62	2.72	309	DAF – lengths only
2000-01	6.90	2.37	896	DAF – age and lengths
2001-02	7.08	2.31	942	DAF – age and lengths
2002-03	7.07	2.19	654	DAF – age and lengths
2004-05	7.22	2.19	1789	AFMA – lengths only
2005-06	7.62	2.26	744	JCU – age and lengths
2019-20	7.65	2.44	1593	DAF – age and lengths
2020-21	7.45	2.32	3091	DAF – age and lengths
2021-22	7.30	2.18	2094	DAF – age and lengths
2022-23	7.61	2.97	2457	DAF – age and lengths
All years	7.43	2.49	1183	Summary means

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 for 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 $\leq$ 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. Statistics were sourced from the DAF fish ageing website (fishfas, Fish Ageing 5.1.0.116).

Ageing	2006	2020	2021	2022	2023
number otoliths aged	740	256	301	400	504
number otoliths re-aged	740	200	200	199	200
% increment agreement	70	92	88.5	82.9	88.3
IAPE increment count	5.129	1.201	3.38	3.81	2.28
% agreement news	88	90.7	87	93	94
% agreement intermediates	45	73.5	83	59	73
% agreement wides	20	90.5	73	50	62
count news	507	130	102	246	325
count intermediates	101	44	58	78	106
count wides	132	25	37	70	69
count unreadable	0	1	3	6	4

C.5 Ageing error

Ageing error matrices were estimated for SS.

Error was modelled using TMB code written for R by Dr Andre Punt. Methods followed Punt et al. (2008), Heifetz et al. (1999) and Burch et al. (2023).

Error matrices assumed no bias with linear standard deviation (type 7 error) with age (Burch et al. 2023). Three matrices were estimated for pre 2020, 2020 and post 2020. The rereads of otoliths were from five different people, equating to five paired (twice read otolith) comparisons. Multiple reads were generally from the same person. Third reads on a minor number of otoliths were excluded; data were few and non-random.

The three matrices grouped: a) early fish ageing projects before 2020 that appeared similar in approach and had different readers, b) first year of the current biological monitoring program, that utilised an experienced otolith reader, and c) post 2020 monitoring with a different otolith reader. More data groupings might be possible, but initial testing of different stratification (of years or readers) did not achieve convergence in more complex models.

The range of ages modelled were 0 to 13 years. The number of data (reread ages) analysed was 3137. For analysis, ages were annual increment counts.

The linear type 7 error-model had two parameters (minimum and maximum standard deviation) to estimate for each group. In total, six parameters were estimated for pre 2020, 2020 and post 2020 (Table C.5). Figure C.4 illustrated the results of standard deviations by age.

The fitted model maximum gradient was $-6.0183573 \times 10^{-4}$. Burch et al. (2023) suggested acceptable convergence values between 0 and ± 0.001. The model effective sample size was 203 fish. All read ages were within model 95% confidence intervals. Observed and estimated (fitted) ages were similar, with the suggestion that some one year olds were more likely two years old (Figure C.5).

For the data, the type 2 error-model (Punt et al. 2008; Heifetz et al. 1999; Burch et al. 2023) could not be estimated for all readers, but could across readers. The type-2 model relates the standard deviation in the Michaelis-Menton equation (Burch et al. 2023). This logistic shaped option with age had three parameters to estimate for each analyses group or paired rereads of otoliths. The pooled (across readers) result was not used, as the level of error differed with time/readers.

In discussion of standard deviation models in the TMB code, linear was preferred and understood by monitoring staff. This model was estimable. Adding more complexity, as demonstrated in some models by Burch et al. (2023), resulted in non-convergence. Further work could research the use of hierarchical GLMs (Lee et al. 2006; VSN International 2022), where more detailed dispersion models could be estimated.

Table C.5: Parameter estimates (standard deviations in years, with their model standard error SE) for linear ageing error. The estimates were minimums (min, for one year old fish) and maximums (max, for 13 year old fish), describing a linear increase in standard deviation of random age-reading error with fish age (years).

Parameter	Estimate	SE
Pre 2020 min	0.2557	0.01
Pre 2020 max	0.8062	0.0636
2020 min	0.2287	0.0243
2020 max	0.2987	0.0768
Post 2020 min	0.2618	0.018
Post 2020 max	0.4453	0.0768

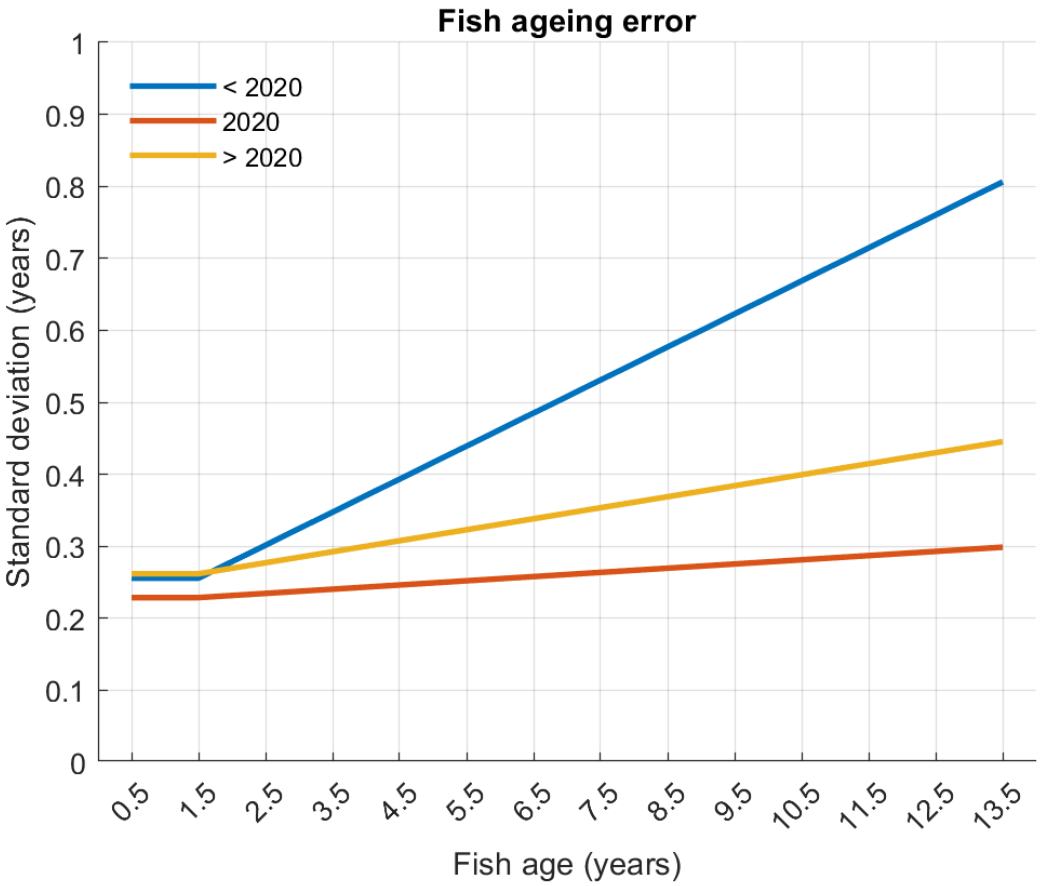

Figure C.4: Linear increase in standard deviation of random age-reading error with fish age by time period.

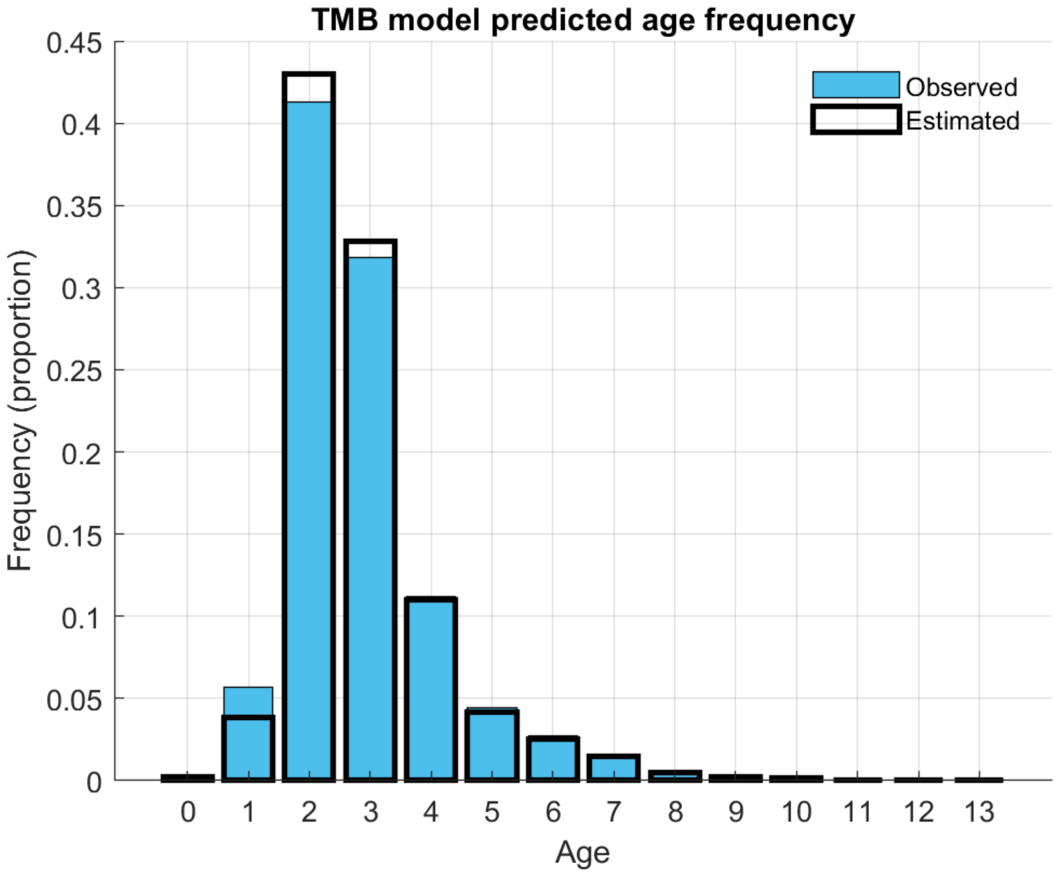

Figure C.5: Comparison of observed and estimated ages over all readers/years.

C.6 Catch rates

C.6.1 Sunset diagnostics 1

The GLM was run without tenders and without coral trout pCT, using all years of data 1990 to 2023.

Table C.6: 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	24651	352804		
fishyear	33	368594	33.433	0.000
zone5	4	359240	112.423	0.000
boat	46	429913	117.123	0.000
s1cos	1	353945	79.715	0.000
s1sin	1	358730	414.009	0.000
s2cos	1	355116	161.508	0.000
s2sin	1	353701	62.654	0.000
s3cos	1	352901	6.761	0.009
s3sin	1	352834	2.068	0.150
lunar	1	355894	215.865	0.000
lunaradv	1	362248	659.861	0.000
goodwind	1	353522	50.109	0.000

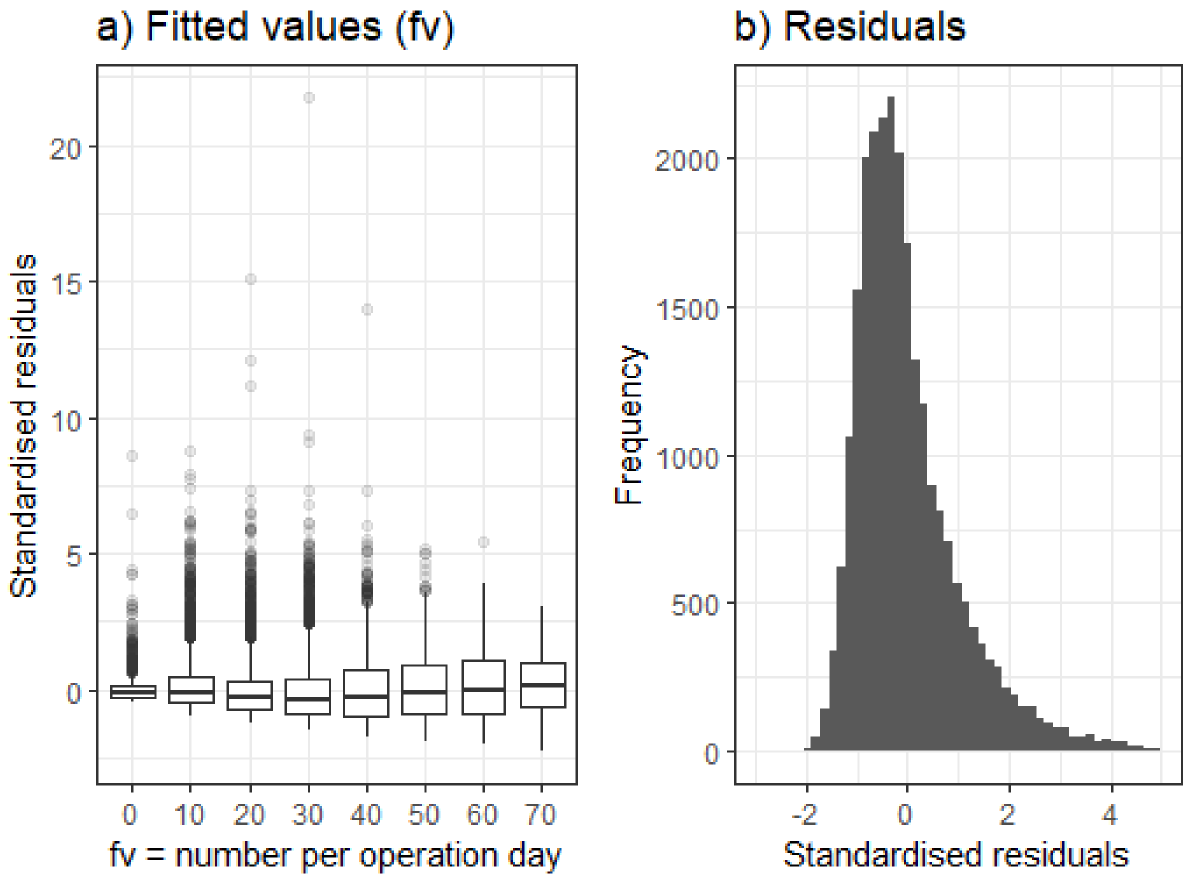

Figure C.6: Sunset catch rate residual plots for a) box plot of fitted values and residuals, and b) histogram of residuals. Fitted values > 70 fish were grouped. Residuals were standardised by the sqrt(variance * dispersion).

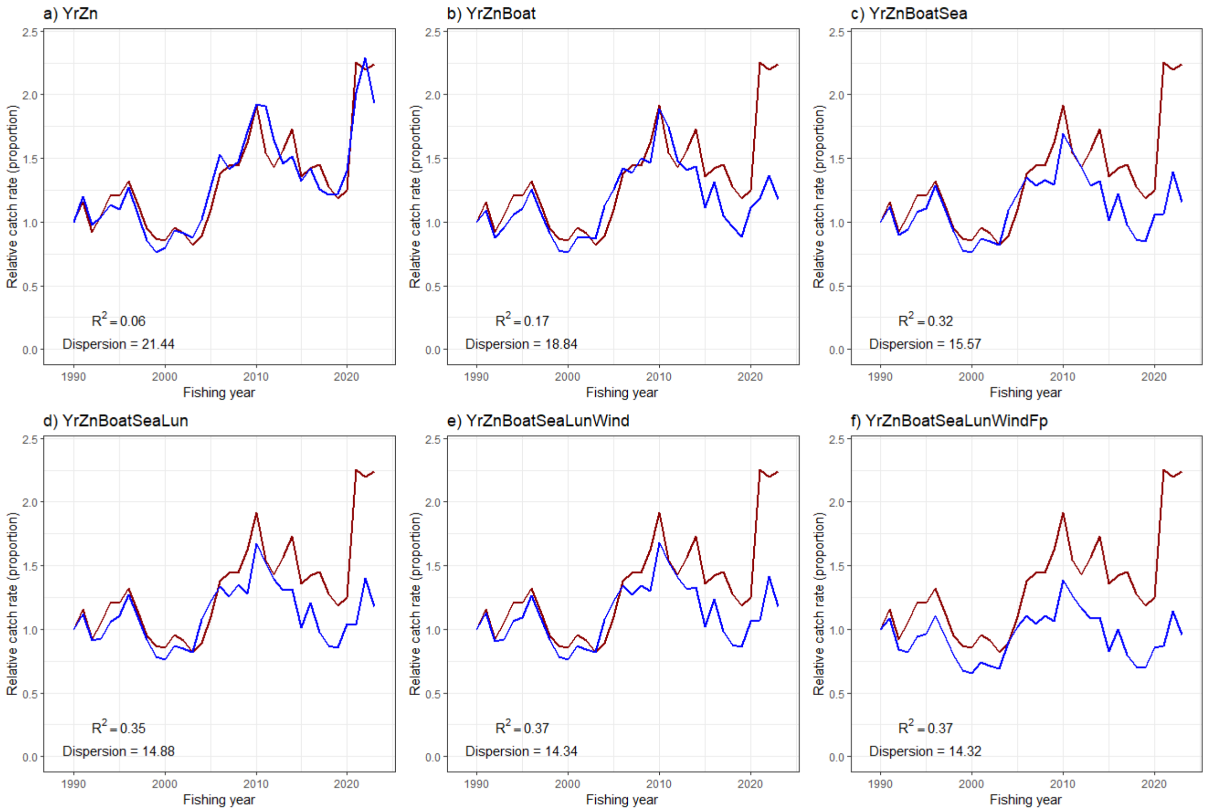

Figure C.7: Influence plot comparing the GLM effects on standardised catch rates against the nominal mean catch rate (red line). Sub-plot: a) compared a year (Yr) and zone (Zn) model; b) compared a Yr, Zn and Boat model; c) compared a Yr, Zn, Boat and Seasonality (Sea) model; d) compared a Yr, Zn, Boat, 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.

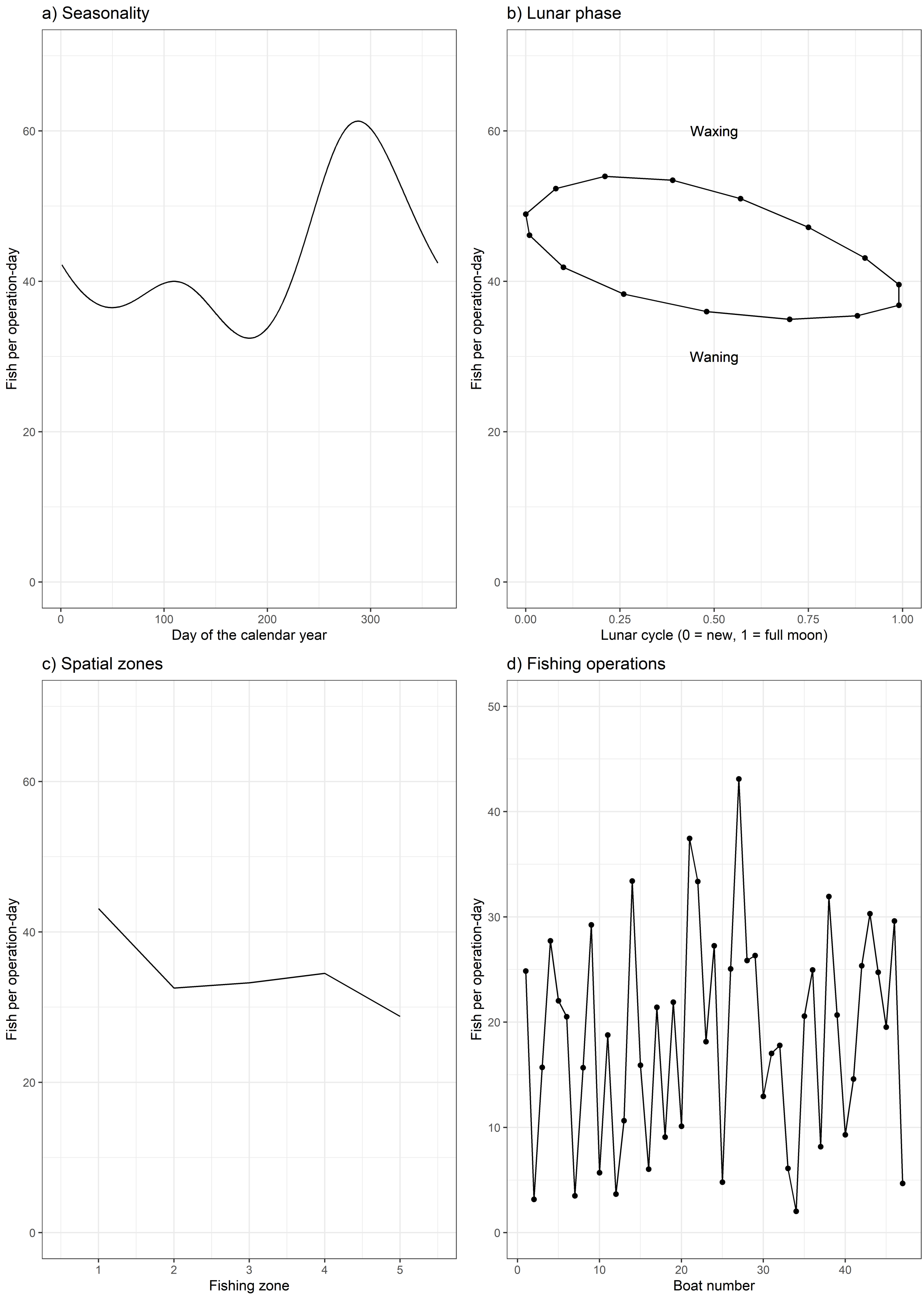

Figure C.8: Mean catch rate effects estimated by the Sunset GLM. Subplot a) by time-of-year, b) lunar cycle, c) zones fished (1 = Bramble Cay), and d) differences between boats (fishing power effect, where the main 2023 boat had the highest catching power).

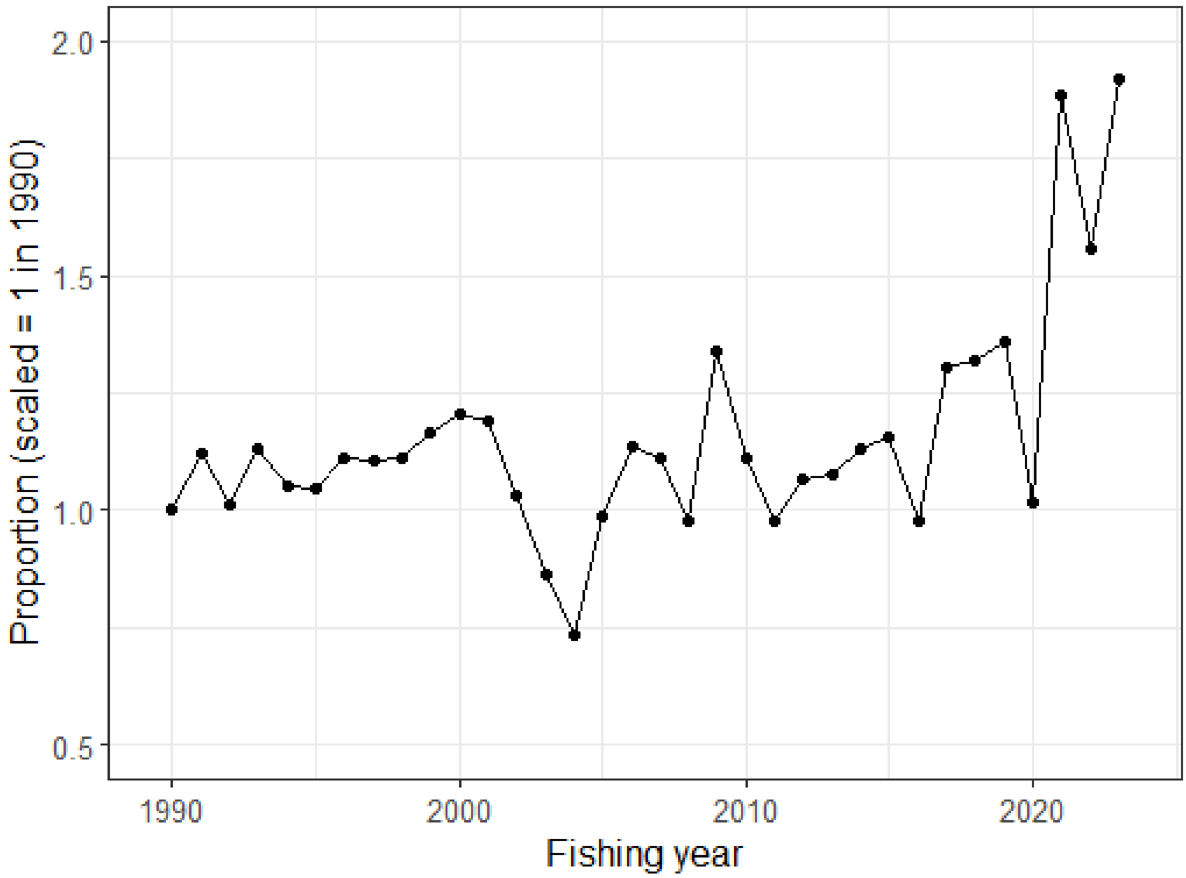

Figure C.9: Relative average Sunset-fleet fishing-power by year as estimated from the GLM boat factor.

C.6.2 Sunset diagnostics 2

The GLM was run with tenders and without coral trout pCT, using data from 2004 to 2023.

Table C.7: 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	9360	137988		
fishyear	19	143882	21.044	0.000
zone5	4	139985	33.859	0.000
boat	22	181329	133.633	0.000
s1cos	1	138326	22.899	0.000
s1sin	1	139459	99.778	0.000
s2cos	1	138388	27.157	0.000
s2sin	1	138327	22.986	0.000
s3cos	1	138035	3.204	0.074
s3sin	1	138251	17.850	0.000
lunar	1	139656	113.131	0.000
lunaradv	1	141923	266.925	0.000
goodwind	1	138044	3.773	0.052
logtenders	1	142151	282.410	0.000

C.6.3 Sunset diagnostics 3

The GLM was run without tenders and with coral trout pCT, using all years of data.

Table C.8: 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	24650	332277		
fishyear	33	346833	32.722	0.000
zone5	4	337051	88.530	0.000
boat	46	386721	87.802	0.000
s1cos	1	332975	51.790	0.000
s1sin	1	335281	222.814	0.000
s2cos	1	335064	206.750	0.000
s2sin	1	333555	94.754	0.000
s3cos	1	332421	10.628	0.001
s3sin	1	332299	1.606	0.205
lunar	1	335298	224.071	0.000
lunaradv	1	341514	685.265	0.000
goodwind	1	333024	55.421	0.000
pCT	1	352804	1522.806	0.000

C.6.4 Sunset diagnostics 4

The GLM was run with tenders and with coral trout pCT, using data from 2004 to 2023.

Table C.9: 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	9359	126823		
fishyear	19	132479	21.966	0.000
zone5	4	128245	26.222	0.000
boat	22	139528	42.618	0.000
s1cos	1	126927	7.655	0.006
s1sin	1	127247	31.292	0.000
s2cos	1	127389	41.749	0.000
s2sin	1	127507	50.453	0.000
s3cos	1	126909	6.304	0.012
s3sin	1	127063	17.723	0.000
lunar	1	128482	122.387	0.000
lunaradv	1	130825	295.284	0.000
goodwind	1	126881	4.295	0.038
logtenders	1	130579	277.136	0.000
pCT	1	137988	823.917	0.000

C.6.5 Log link or log transform?

The Sunset GLM type and model terms were reviewed in TSFFRAG meeting 13 (AFMA 2023b). The meeting supported the current GLM method, but discussed: "Why an over-dispersed Poisson GLM with log-link and not a log-transformed-response normal linear model (LM)". The following attributes were noted:

- The data consisted of counts of fish (> 0) harvested per operation day.
- The data was used as reported and not transformed into kg. Counts can be a better index of abundance than kg.
- Numbers of fish are used in calculating spawning biomass. SS can use catch rates in number or weight.
- Count data can be analysed as an over-dispersed Poisson-like process (McCullagh et al. 1989).
- Different mean-variance relationships are GLM options, given the Box-Cox lambda diagnostic was small.
- The dispersion function can quantify the rate that arises due to fish aggregating (schooling).
- GLM is an alternative, more flexible, option to transforming data.
- A GLM decouples the link function and error distribution, and models the mean of the response.
- A log transformed normal-model analyses the trend in the mean of the transformed response (trend in geometric-mean).
- Log link function is common in GLMs and gives multiplicative effects. The log-normal is also multiplicative.
- A GLM with log-link function recognises that larger catches contribute more in averaging than small. The definition of average catch rate matches maximum likelihood theory.
- For log transforming the data:
  - Fishery scientists often use log-normal models.
  - In doing so, small and large catches are given more equal weights (for normality).
  - A temporal change in the frequency of small catches might influence this method more compared to log-link.
  - Defining catch rates as the geometric mean might create a different trend-hypothesis to be tested.
  - You can bias correct, but this might not always be the same trend as log-link.
  - Residual plots often look normal just due to all the data being strongly compressed by a log transformation.

Different trends were apparent in recent years between mean and geometric-mean catch rates for Torres Strait Spanish mackerel (Figure C.10). This was a result of a small Sunset fleet and a broadening in the catch distribution with more smaller and larger catches in later years (Figure C.10).

Since 2020, there was one main Sunset operation, which had begun to diversify and harvest coral trout in the second half of the fishing season from January to June, after mostly filling their Spanish mackerel leased-quota in the first half of the season. Their late season catches of Spanish mackerel were generally associated with coral trout harvests (Figure C.11).

To account for this change in species targeting (read section 5.3, in Hoyle et al. (2024b)), a proportional coral trout targeting term was recommended by TSFFRAG and used in the GLM. The result was significant, but also highlighted a difference in interpretation of the small catches between log-link or log transformation models (Figure C.12). The was because the GLM likelihood was in units of numbers of fish (the log-link transformed the model not data) and the LM was on the log scale of transformed data. The monitoring of small catches of Spanish mackerel with coral trout, and their use by either model adjustment like herein or exclusion, is important. Further checking of methods is required by TSFFRAG, against the paper by Hoyle et al. (2024b).

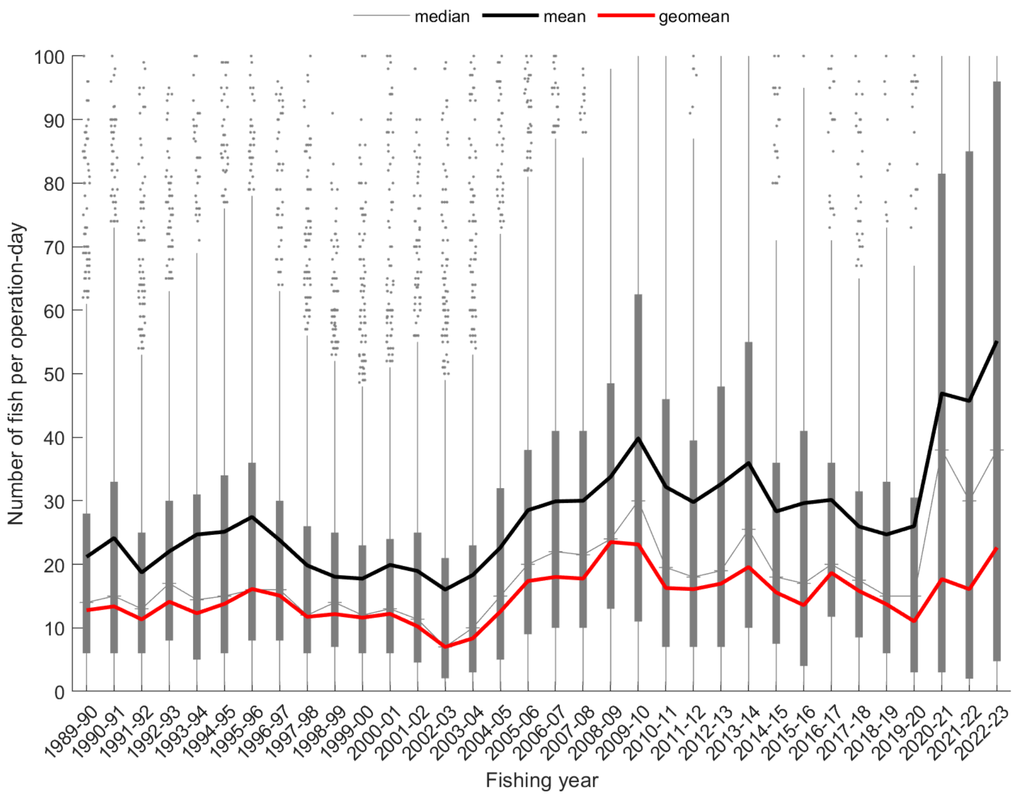

Figure C.10: Boxplot of the annual distribution of nominal Sunset daily catch rates.

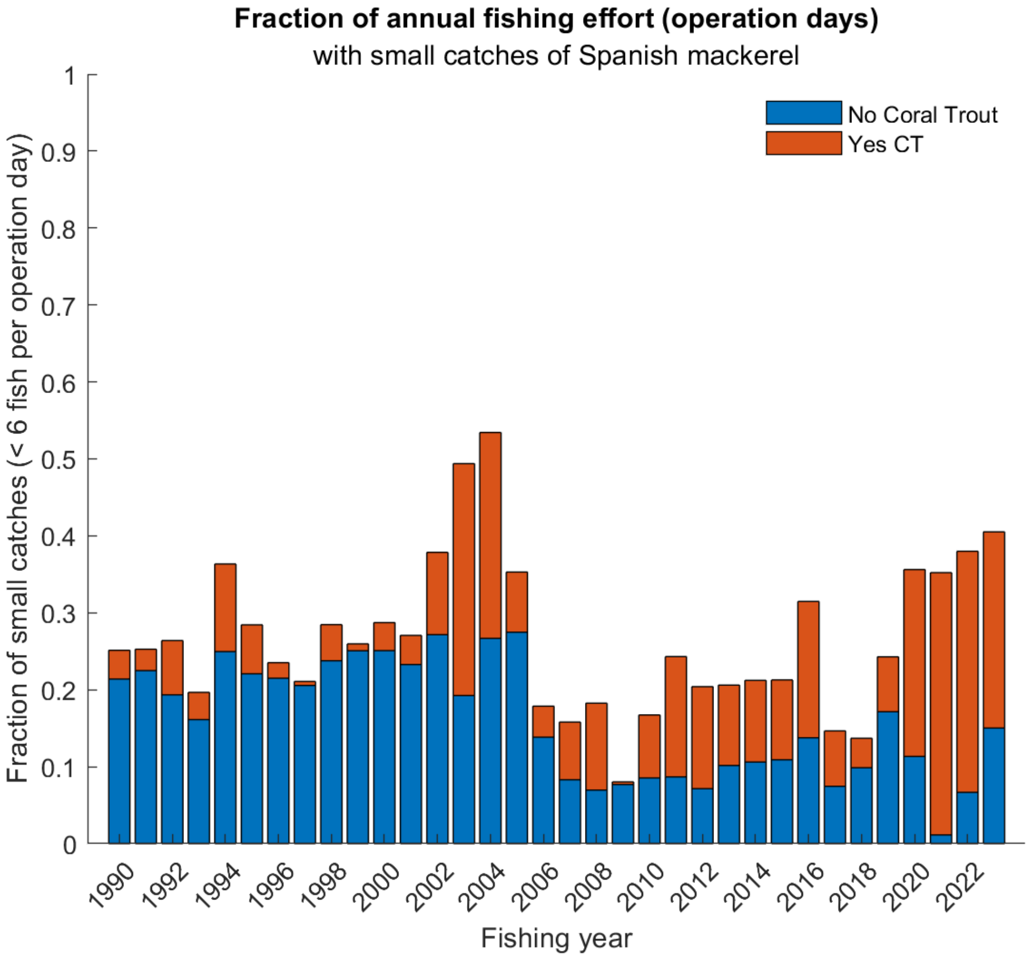

Figure C.11: Stacked bar graph of the proportion of annual fishing effort with small catches of Spanish mackerel, when coral trout were (yes CT) or were not (no CT) caught.

Figure C.12: Comparison of standardised catch rates from quasi-Poisson log-link GLMs and log-transformed-response normal LMs, with and without the effects of coral trout (CT). For simplicity, tenders effects were excluded. Results align to model-term descriptions 1 and 3 in methods.

C.6.6 TIB diagnostics

Table C.10: 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	194	6553		
fishyear	4	6688	0.999	0.409
client	34	11347	4.174	0.000
s1cos	1	6693	4.133	0.043
s1sin	1	6813	7.683	0.006
crew	1	6713	4.726	0.031

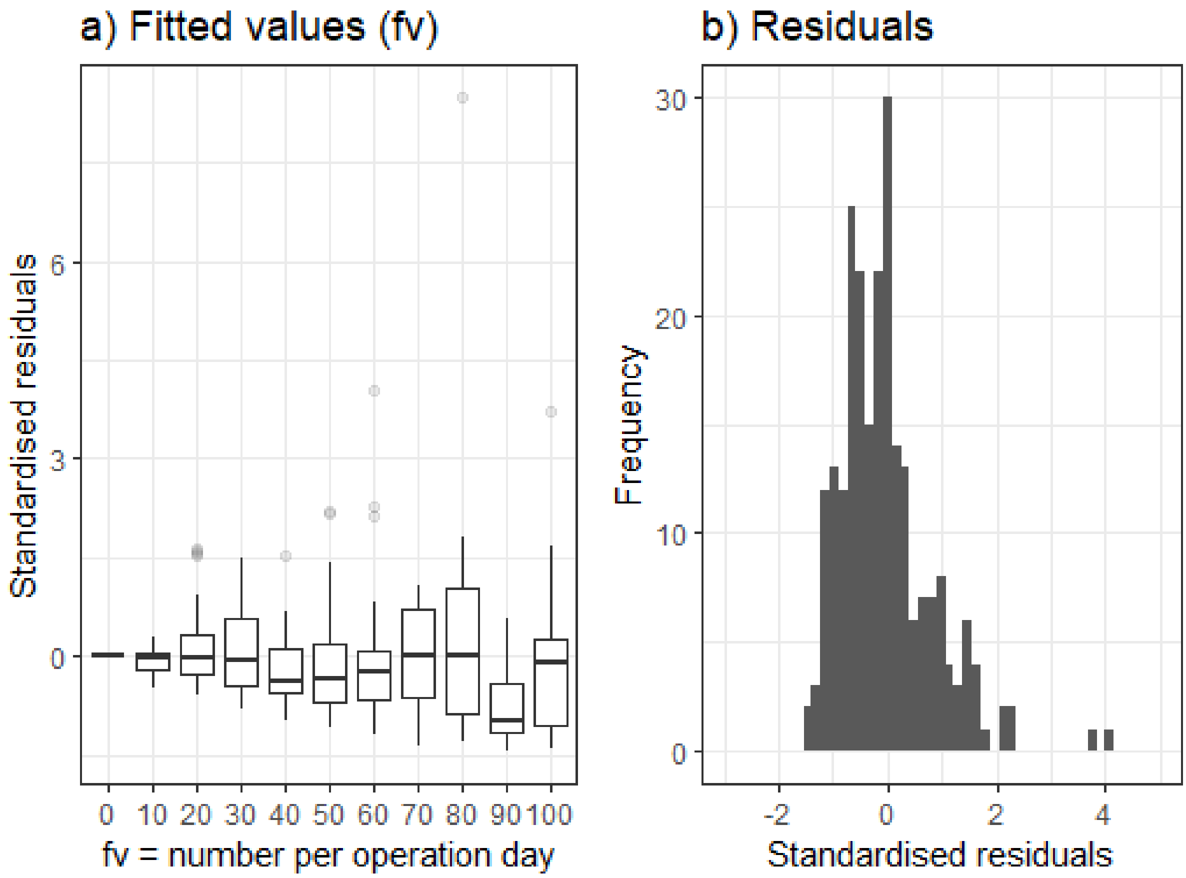

Figure C.13: TIB catch rate residual plots for a) box plot of fitted values and residuals, and b) histogram of residuals. Fitted values > 100 kg were grouped. Residuals were standardised by the sqrt(variance * dispersion).

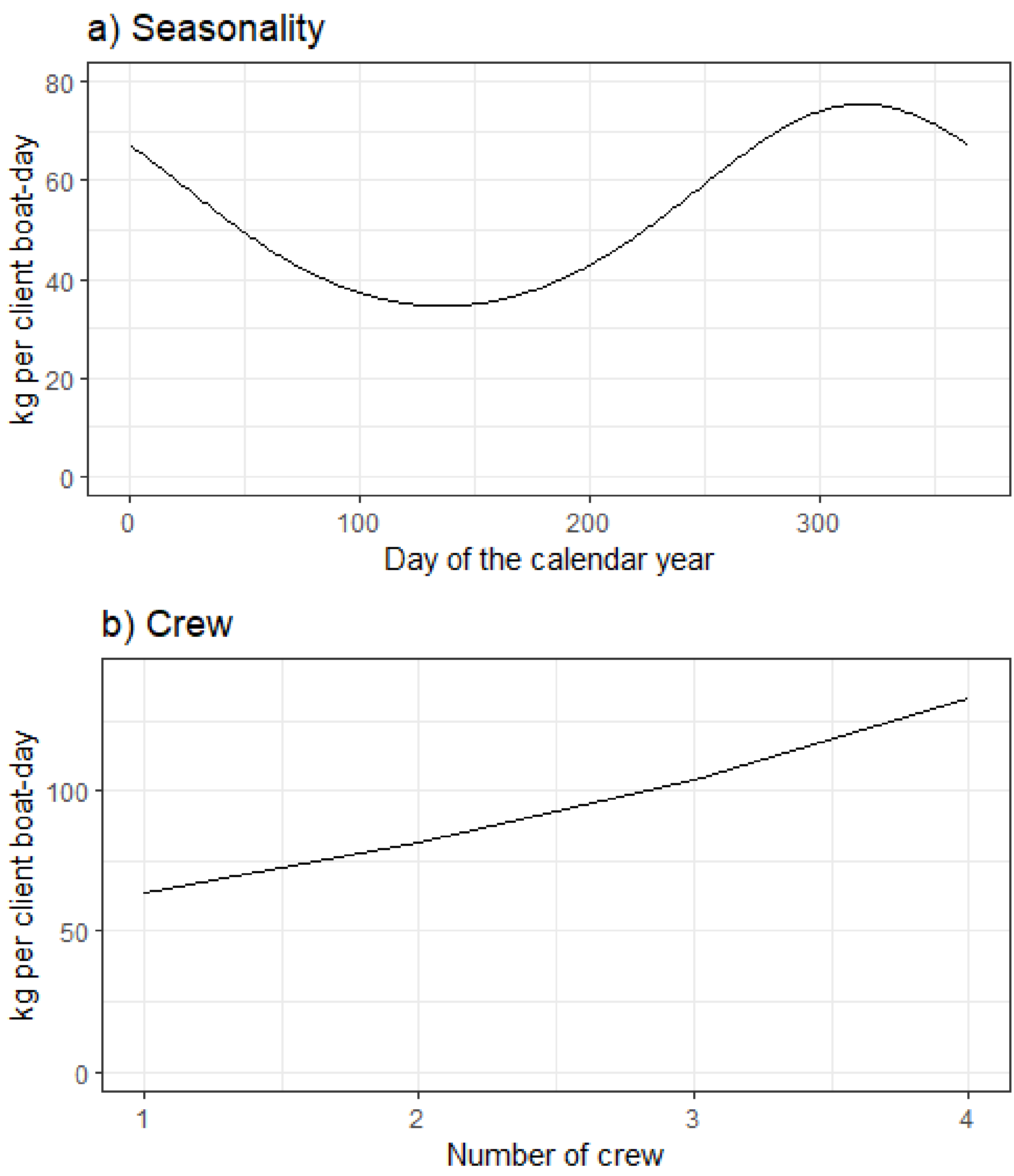

Figure C.14: Mean catch rate effects estimated by the TIB GLM. Subplot a) by time-of-year, b) the wind speed and direction and c) number of crew on the client boat.

C.6.7 Data selection for catch rates

Historically, 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 nominal 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 trends. 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 Spanish mackerel boats and their available daily logbook data. 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 future thresholds if removing data.

Table C.11 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 61% of the data were removed respectively. However, all rules confirmed a decline in catch rates and boats post 2011.

Table C.12 summarised the statistical differences between data rules. The paired T tests on annual catch rates between all data and the used data were 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. Retaining data therefore provided the potential for capturing nuance in the full data set without altering the trend.

Table C.13 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 29% of data. The TIB catch rate data time series was young, with some fisher clients just commencing reporting, and no significant differences mostly detected between filters. The data for 2022 and 2023 were low in number and influenced by large catch reports that may not be daily.

Table C.11: 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	544	20	20	20	22	24	17	17	15	9	4
1999	1352	1352	1231	981	520	18	18	18	18	19	16	16	13	8	4
2000	1375	1375	1203	999	568	18	18	19	19	17	14	14	11	7	4
2001	1190	1190	1081	866	436	20	20	21	23	17	11	11	10	7	4
2002	803	803	734	640	382	19	19	20	21	16	11	11	9	7	4
2003	1143	1065	945	671	457	16	17	19	24	20	28	16	12	7	4
2004	1049	1031	858	484	410	18	19	21	29	26	22	14	9	5	4
2005	1375	1357	1174	734	450	23	23	25	30	31	22	17	12	7	4
2006	1276	1265	1208	833	332	29	29	30	30	32	14	13	11	7	4
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
2023	153	153	153	119	119	47	47	47	50	50	3	3	3	1	1
Total	25104	24774	22261	16148	9850						68	47	26	12	5
N. removed	0	360	2843	8956	15254										
% removed		1	11	36	61										

Table C.12: 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	-3	0	0	0	0
T statistic	-1.79	-4.92	-7.69	-4.93	0	-0.07	-0.04	-0.03
Pr(>T)	0.08	0	0	0	1	0.94	0.97	0.98
Slope	1	0.97	0.88	0.89	1	1.01	1	0.99
T statistic	-1.27	-3.78	-8.74	-6.68	0.42	0.78	-0.08	-0.69
Pr(>T)	0.21	0	0	0	0.67	0.44	0.94	0.49

Table C.13: 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	Mn. all N	Mn. N used	Mn. filter95	Mn. filter75	B. total	B. N used	B. filter95	B. filter75
2019	104	90	86	50	62	64	66	81	15	11	9	3
2020	65	32	26	8	38	49	51	67	20	10	6	2
2021	63	38	35	25	56	70	72	86	16	9	7	4
2022	11	11	11	6	534	534	534	932	4	4	4	3
2023	7	7	7	5	475	475	475	646	3	3	3	2
Total	250	178	165	94					36	15	11	5
N. removed	0	72	85	156								
% removed	0	29	34	62								
Mean difference						-5	-7	-129				
T statistic						-1.82	-1.98	-1.78				
Pr(>T)						0.14	0.12	0.15				
Slope						1	1	0.63				
T statistic						-0.26	-0.28	-9.81				
Pr(>T)						0.81	0.8	0				

C.7 Fecundity

The fecundity relationship used gonad weight data (Table C.14 and Figure C.15). Accounting for the egg maturity stage was significant. A reduced combined intercept model, by removing the egg-stage factor, underestimated the power b parameter at 3.45 with a smaller adjusted R squared of 0.39.

More data was available from stage 6 gonads, and this intercept was used in SS; as advised by TSF-FRAG (AFMA 2023c).

Table C.14: Parameter estimates for the log-transformed female gonad weight model.

Parameter	Estimate	Std. Error	T statistic	Pr
Stage 6 intercept	-18.1033	0.9899	-18.29	0.000
Stage 7 intercept	-17.7428	0.9827	-18.05	0.000
Log(FL cm)	3.7019	0.2144	17.27	0.000
Adjusted R squared	0.8657			
Residual standard error	0.4061			
Residual D.F.	366			
Parameter a	1.37352543388325E-08			
Parameter b	3.7019			

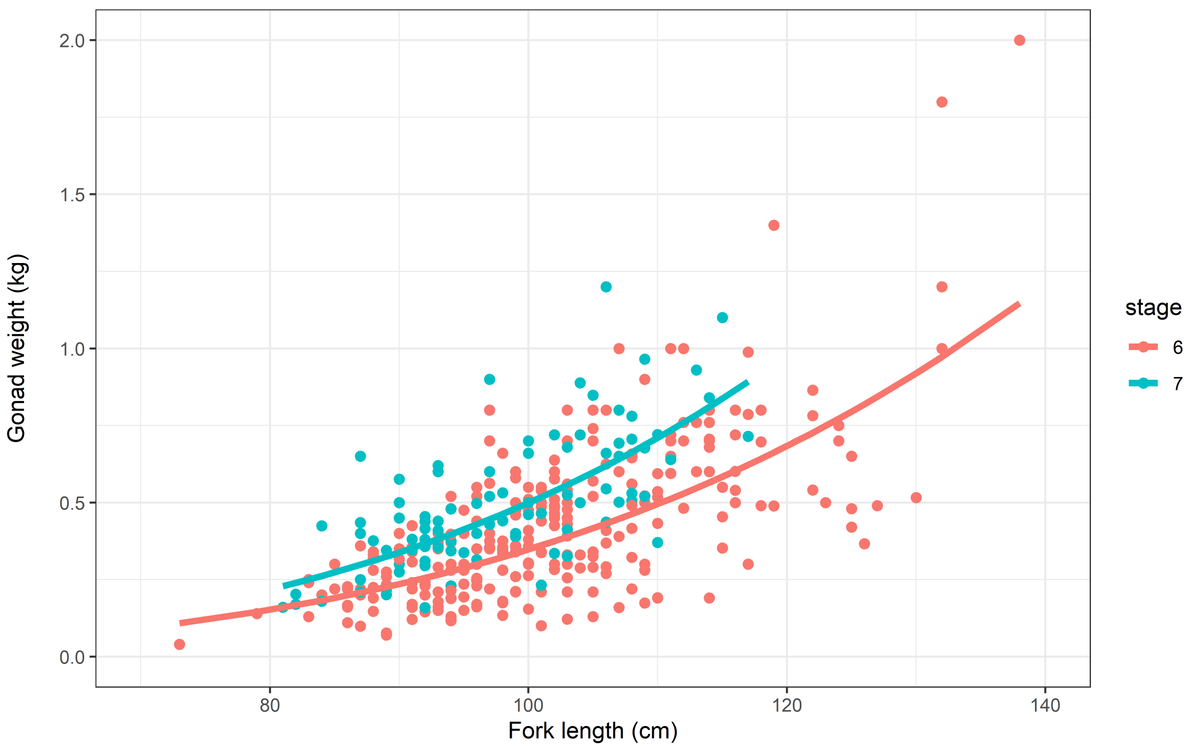

Figure C.15: SS type-2 fecundity, relating female fish length (cm) to gonad weight (kg).

Appendix D Model outputs

D.1 Diagnostics

D.1.1 Abundance indices

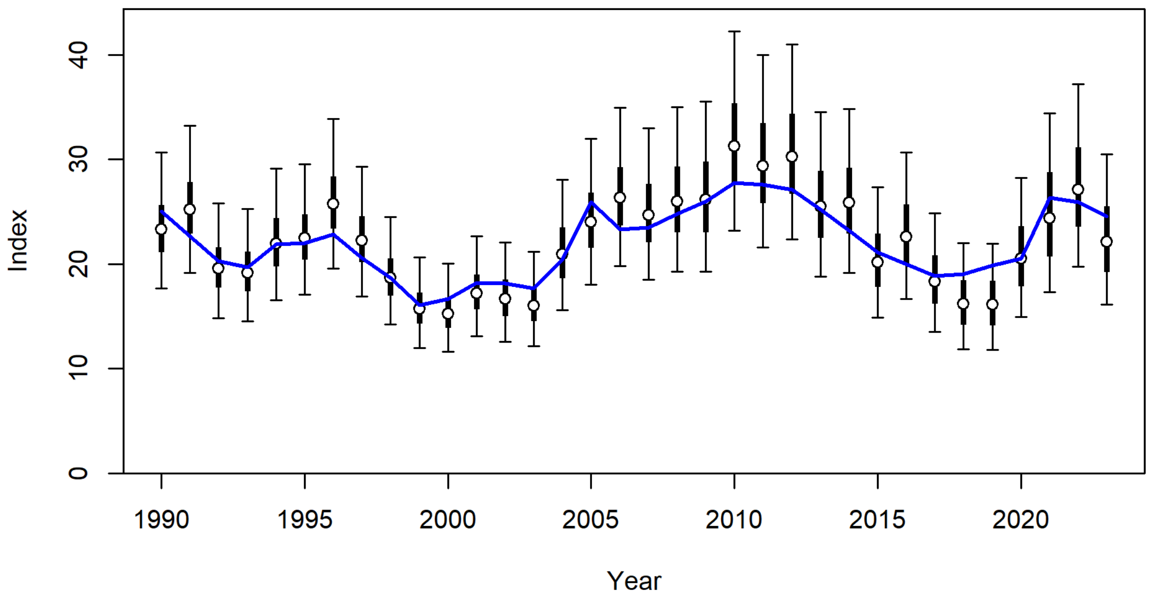

Figure D.1: SS analysis 2 fit to Sunset catch rates. The level of fit was similar between analyses. The y-axis scale was numbers of fish per operation day. The 95% uncertainity intervals consisted of two components, the GLM error by the bold error bar and the extra deviation (derived from Loess) by the thin error bar.

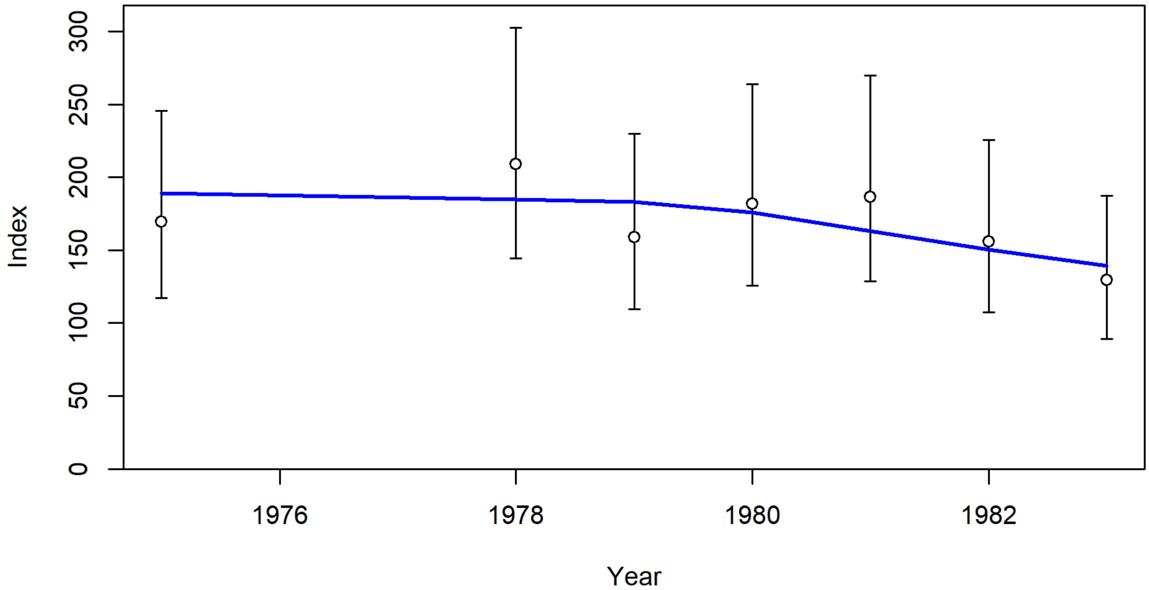

Figure D.2: Stock synthesis analysis 2 fit to historic catch rates between 1975 and 1983. The level of fit was similar between analyses. The y-axis scale was kg of fish per fisher-day. The 95% uncertainity intervals represented two standard deviations, calculated from the CVs used by SS.

D.1.2 Age-length compositions

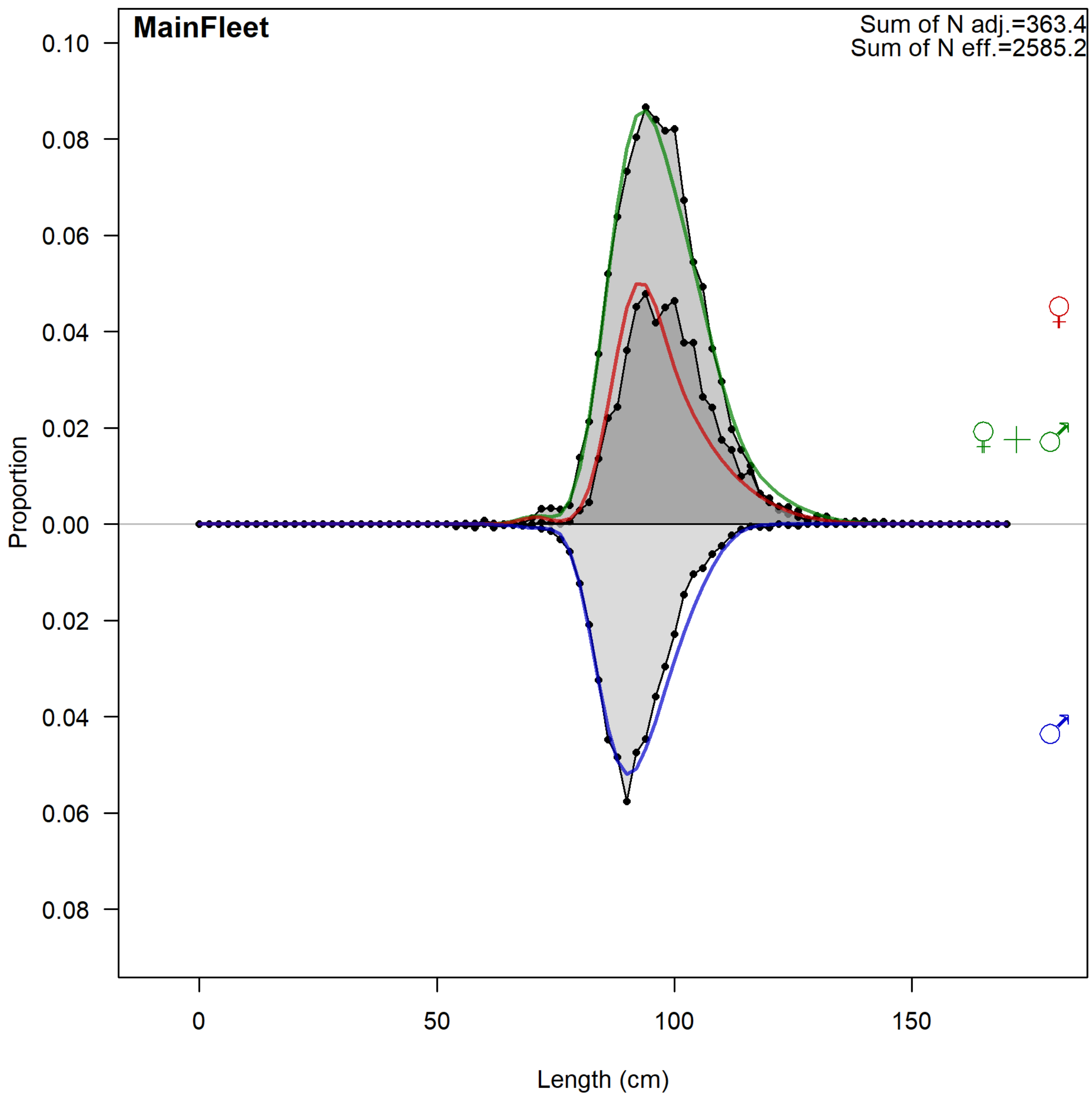

Figure D.3: Fitted length compositions from analysis 2, aggregated across time by sex.

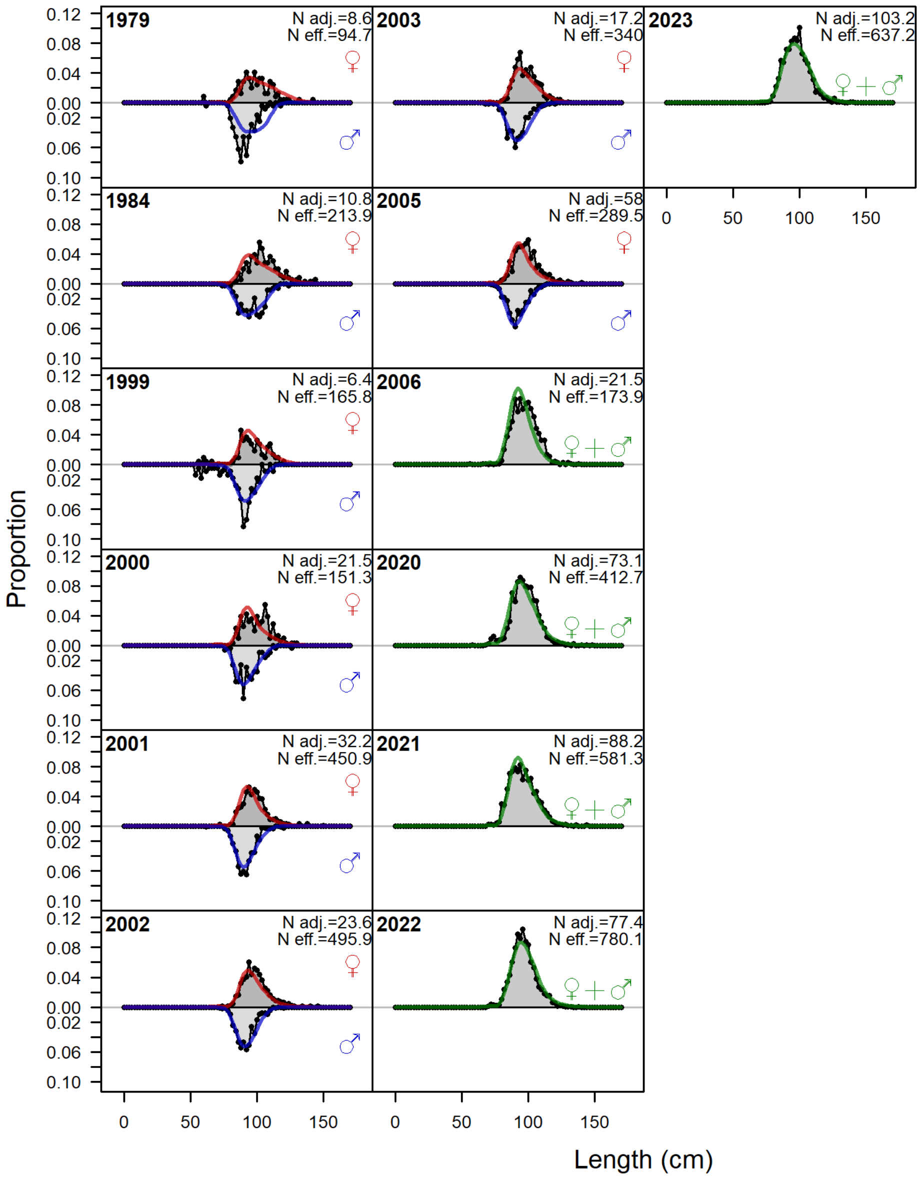

Figure D.4: Length composition fits by year and sex, from analysis 2. Adjusted 'N adj' is the input sample size after data-weighting adjustment. N eff. was not used and is the calculated effective sample size used in the McAllister-Ianelli tuning method.

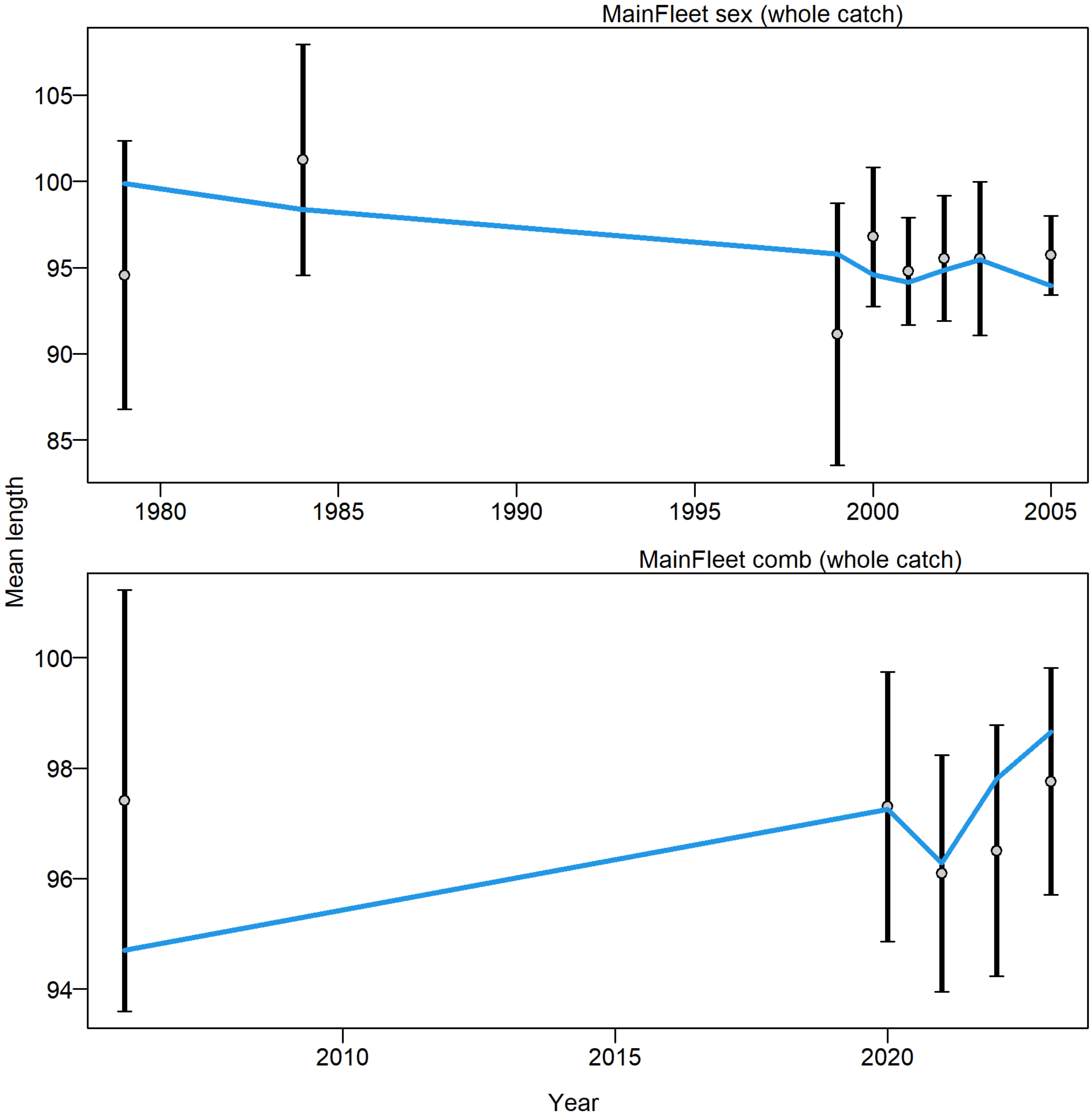

Figure D.5: Mean length with 95% confidence intervals based on current sample sizes, from analysis 2.

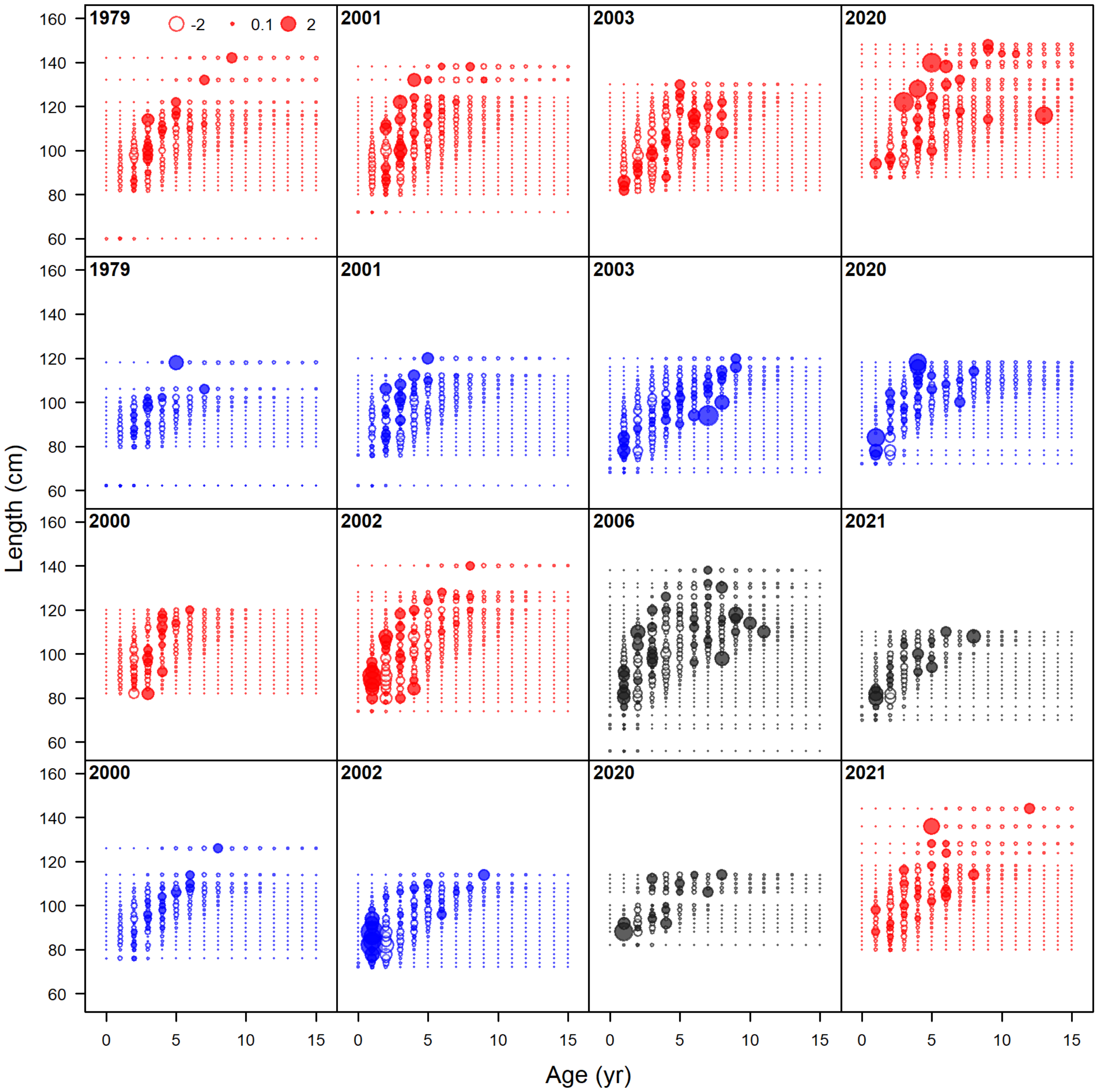

Figure D.6: Pearson residuals for the analysis 2 fit to conditional age-length data - graph 1.

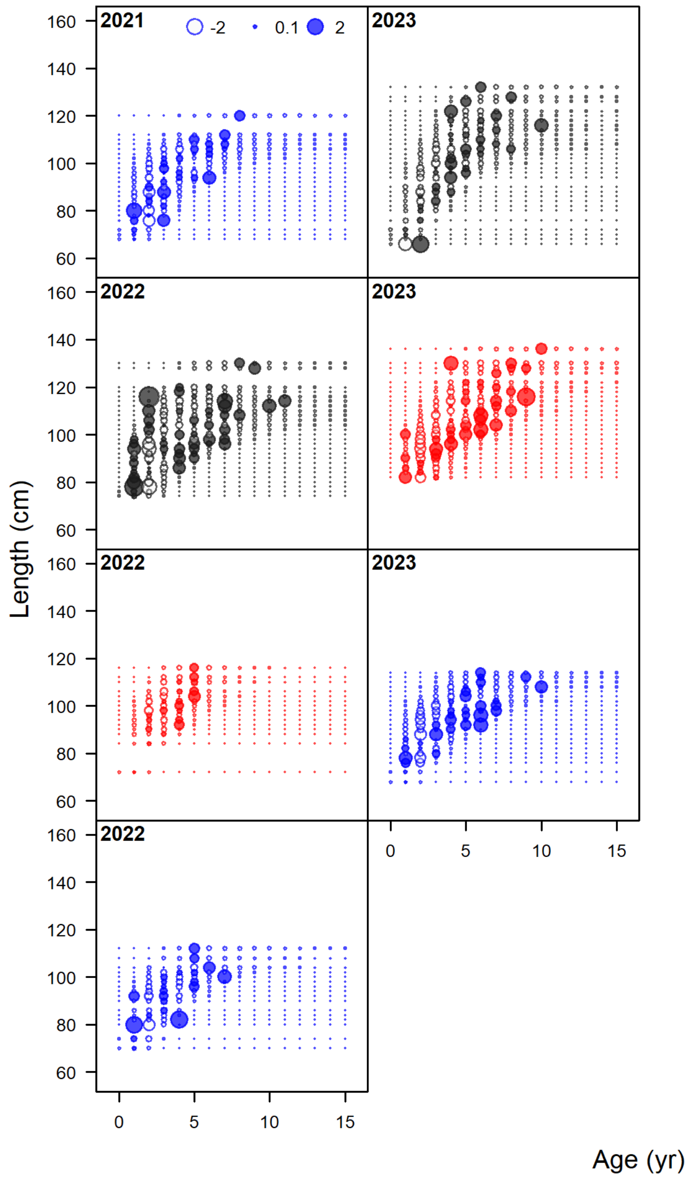

Figure D.7: Pearson residuals for the analysis 2 fit to conditional age-length data, continued - graph 2.

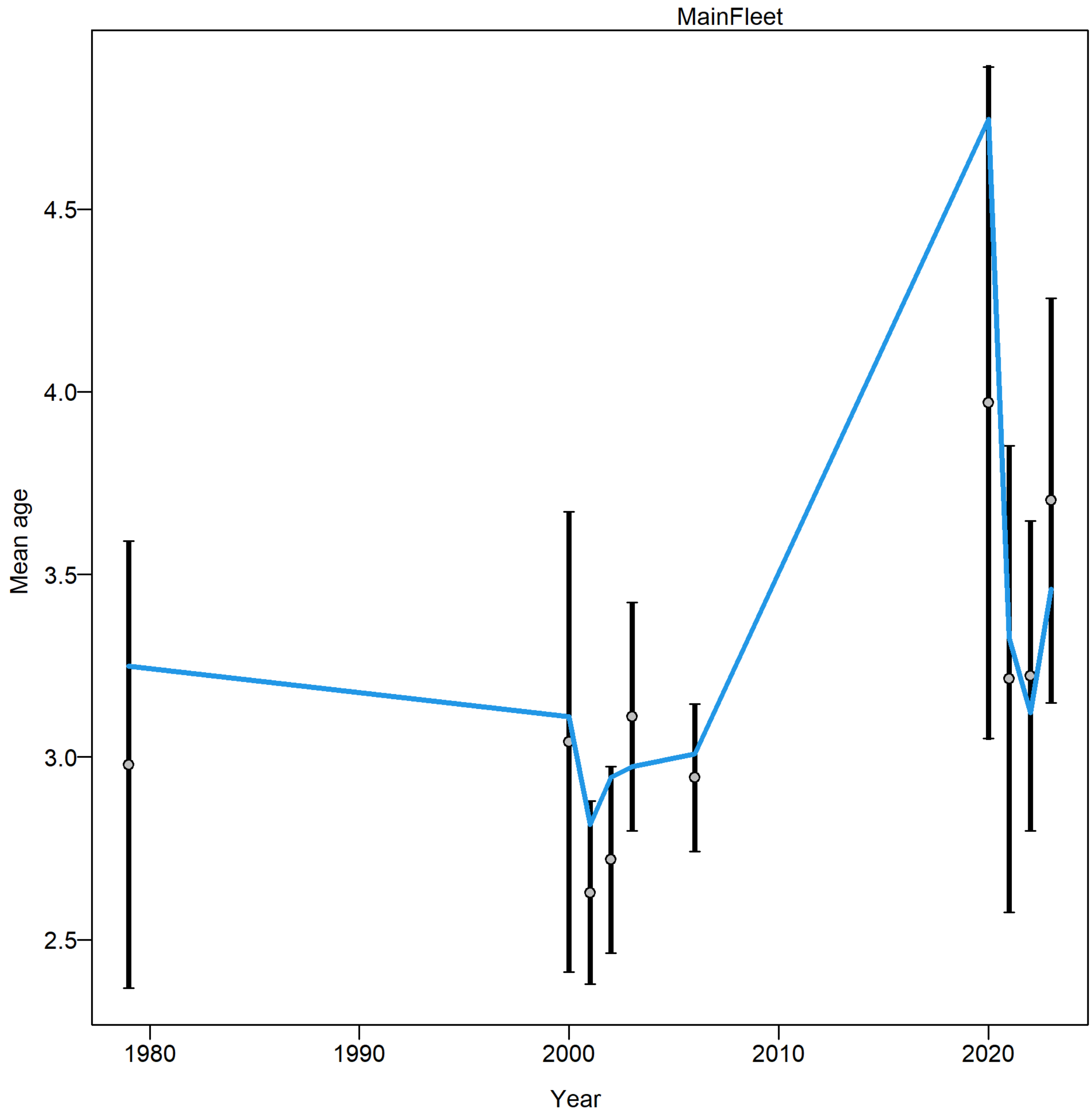

Figure D.8: Mean age from conditional data aggregated across length bins for analysis 2 with 95% confidence intervals.

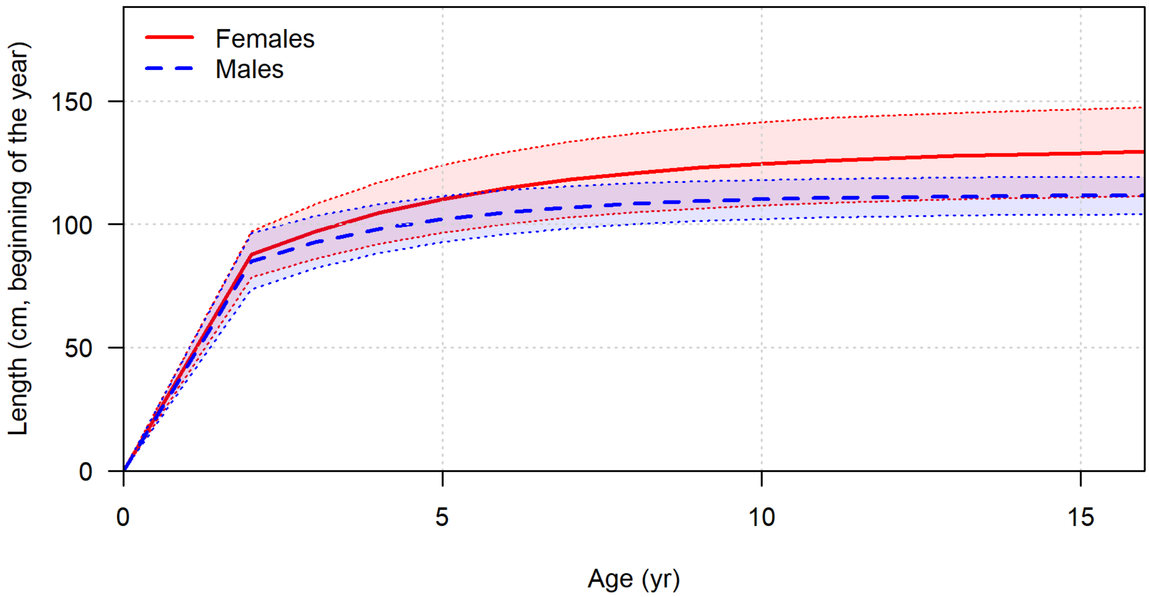

Figure D.9: Mean fork length at age by sex from analysis 2. Shaded areas indicate the 95% distribution of length at age around the estimated growth curve.

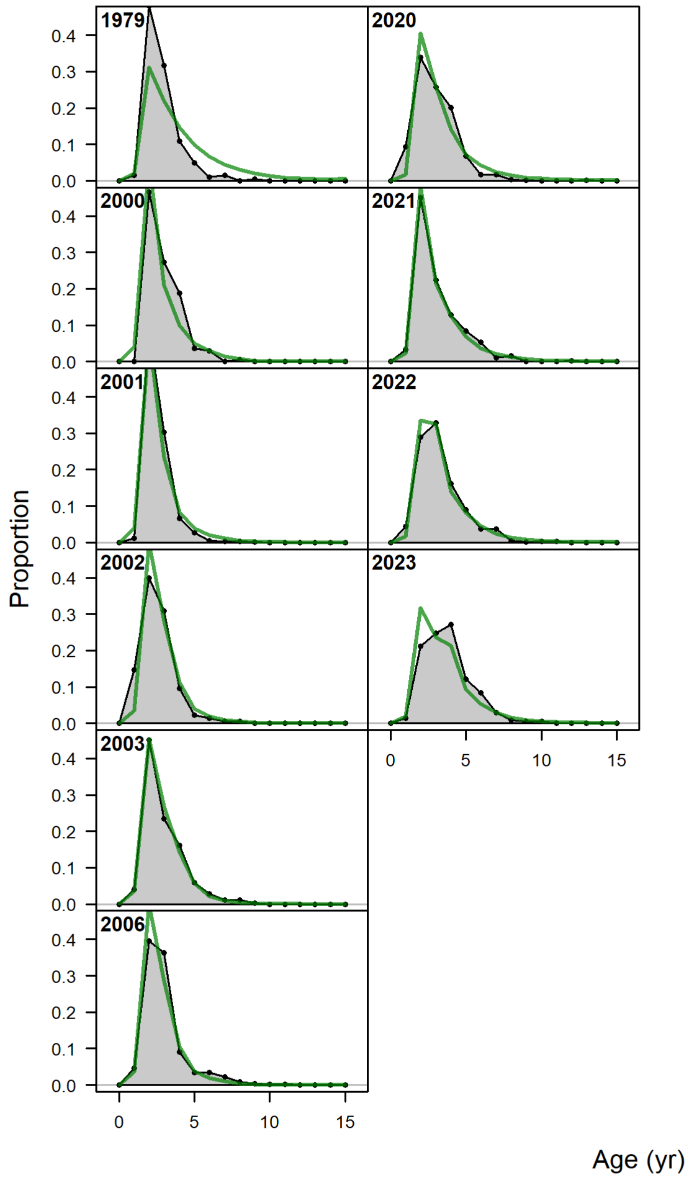

Figure D.10: Inferred age structures from the SS model analysis 2, Sunset ghost fleet setting. The figure represents how well SS converted length frequencies using it's growth curves compared to age-frequencies estimated outside of SS.

D.1.3 SS cookbook

Details on SS fitting are further described using "cookbook" diagnostics. The tests were calculated using the *r4ss* and *ss3diags* R packages (Carvalho et al. 2021). The paper by Carvalho et al. (2021) is best used as a guide to navigate the diagnostics.

For interpretation of diagnostics, in was important to re-note that the Torres Strait Spanish mackerel data were characterised by consistent use of line-trolling methods, with no apparent shifts in gear size or age selectivity over time, with fishing mortality largely on fish aged ≥ two years old. There has been no management influences affecting at-sea daily fishing behaviours, other than annual changes in the number of fishing vessels/trips/effort.

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 were not too dissimilar between analyses (Table 3.1 and Table 3.2), the cookbook diagnostics were only reported for analysis 2.

For all analyses:

- No parameters were estimated at bounds. Estimation was unconstrained.
- Optimisations achieved the final gradient (absolute value $\leq$ 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 3.1, Table 3.2, and Figure D.28).

Run-test results for Sunset catch rates indicated acceptable fit with no larger residuals, but with evidence to suggest they were non-random (Figure D.1, Figure D.11 and Table D.1). From the figures, as a result of adding extra standard deviation in SS and this down weighted catch rates in the log-likelihood, the model systematically under fit the highs and lows in catch rates post 2000. This behaviour allowed the model to favour higher steepness and a flatter fit. Extra standard deviation was not estimable, with attempts suggesting these should be ≤ 0 to improve the catch rate fit.

Run-test results for the length data suggested good model fits with an overall RMSE less than 30% (Figure D.11 and Table D.1).

Runs test for the historic catch rates passed (Figure D.11 and Table D.1).

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. Runs tests were acceptable if values were greater than 0.05. Retrospective values were acceptable if between -0.22 and 0.30. Hindcast values were acceptable if less than 1.

Diagnostic	Quantity	Statistic	Value	n	Acceptance
Runs Test	cpue Sunset	p-value	0.041	32	>0.05
Runs Test	cpue historic	p-value	0.686	7	>0.05
Runs Test	Fish length	p-value	0.093	13	>0.05
Retrospective analysis	SSB -1 year peel	Mohn’s Rho	0.031	1	-0.22-0.30
Retrospective analysis	SSB -2 year peel	Mohn’s Rho	0.025	2	-0.22-0.30
Retrospective analysis	SSB 7-year peel	Mohn’s Rho	0.155	7	-0.22-0.30
Retrospective forecasts	SSB -1 year peel	Forecast bias	0.121	1	-0.22-0.30
Retrospective forecasts	SSB -2 year peel	Forecast bias	0.076	2	-0.22-0.30
Retrospective forecasts	SSB 7-year peel	Forecast bias	0.227	7	-0.22-0.30
HCxval	cpue Sunset	MASE	1.699	7	<1
HCxval	Fish length	MASE	0.944	3	<1

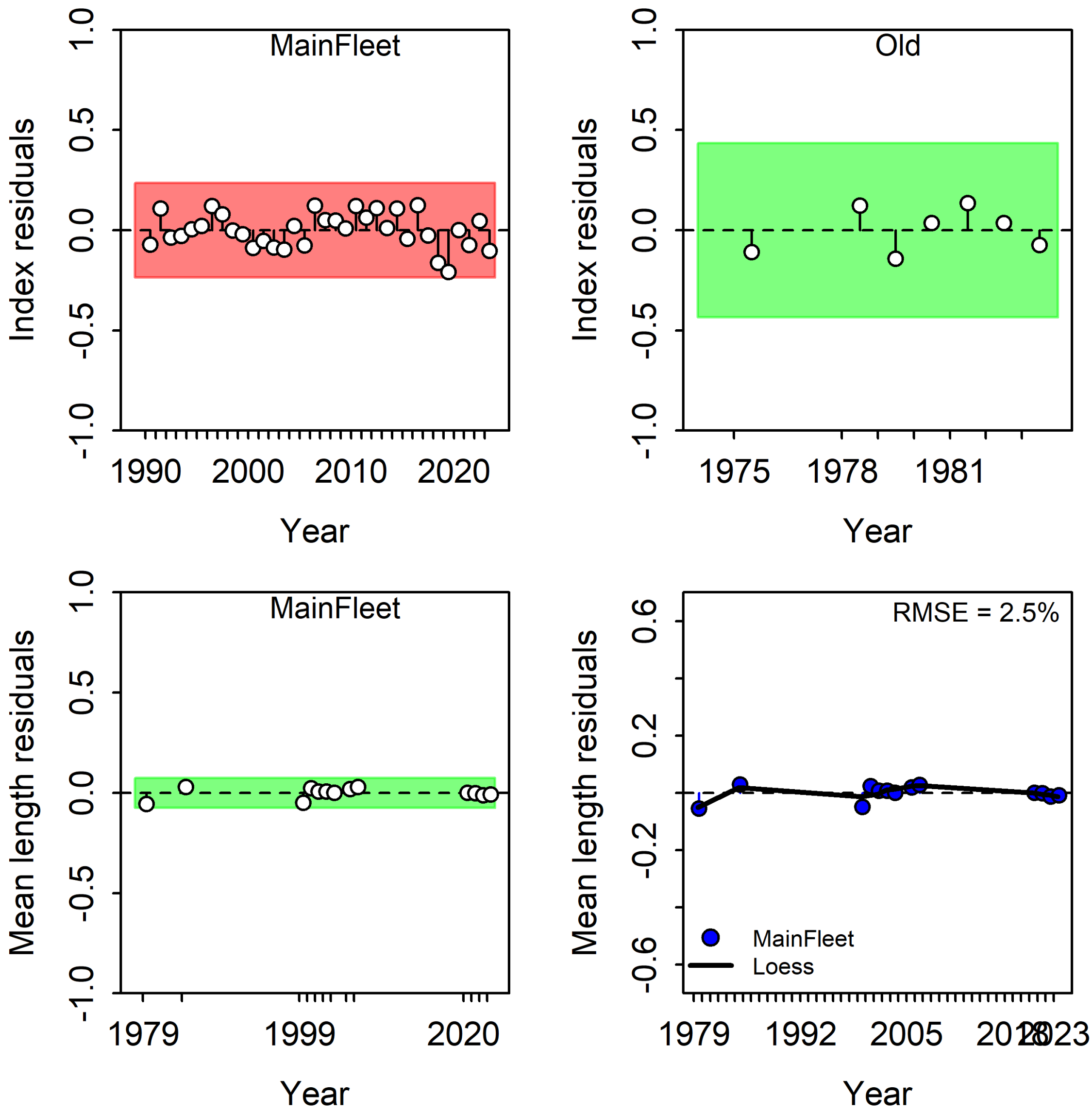

Figure D.11: Runs tests results illustrated for catch rates (in the top two sub-plots labelled "MainFleet" for the Sunset sector and "Old" for the early historical Sunset data) and length frequencies (in the bottom two sub-plots). Values in the green shading indicated no evidence of non-random or large residuals. Red shading suggested evidence for non-random 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.

The minimum (better) values along the virgin recruitment R_0 profile were similar, with little difference between the data components (Figure D.12). The fish age data tended to provide more contrast for estimating R_0.

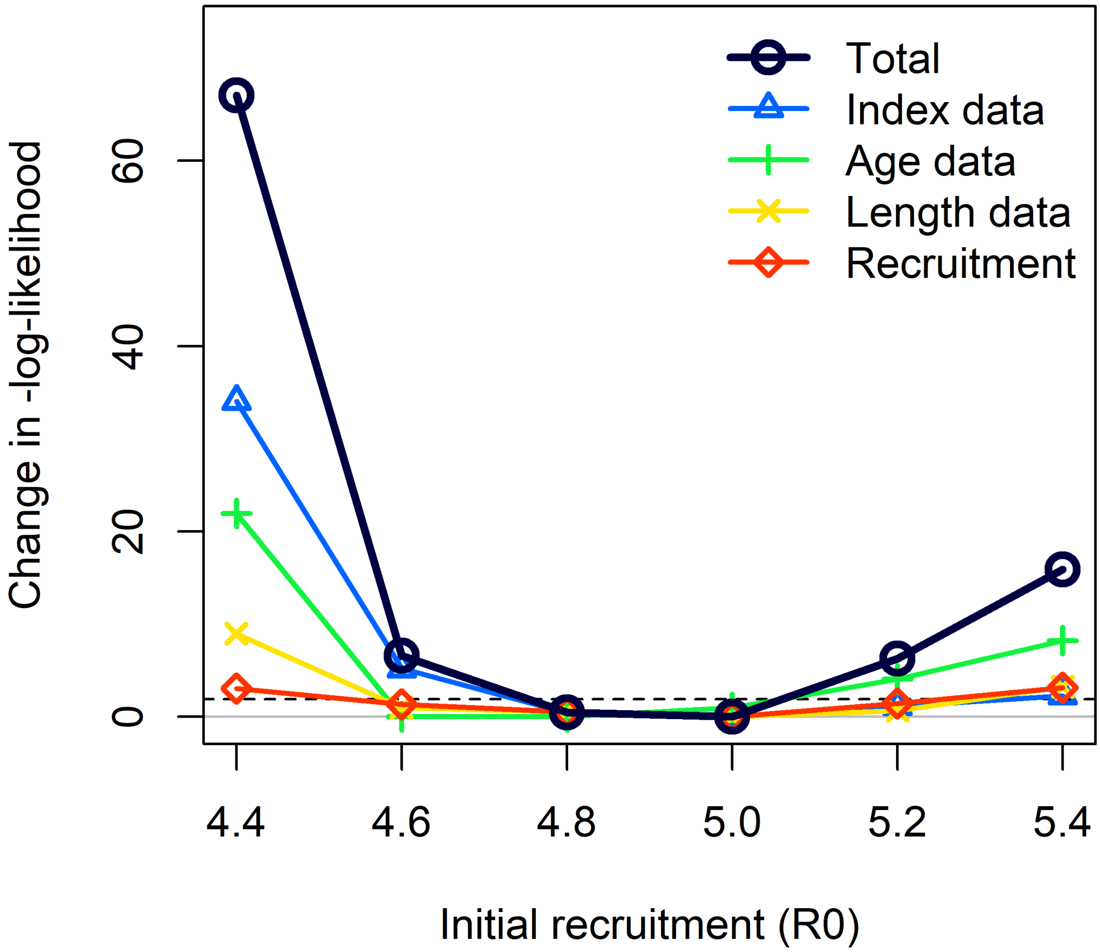

Figure D.12: Log-likelihood profile for virgin (initial) recruitment R_0 for the various data components. For the x-axis, R_0 was illustrated on the log scale. The black line was the combined profile for all data components. Results were for analysis 2. The dashed cutoff line indicated the 95% confidence interval for significant differences between -log-likelihoods.

The profiles for natural mortality (M) suggested larger values might better fit the age data (Figure D.13 and Figure D.14). However, the length data showed curvature for M below 0.4. In general though, across data, likelihood differences for M between 0.3 to 0.42 were not that significant. This indicated minimal information to estimate M, and supported the approach to consider different fixed values.

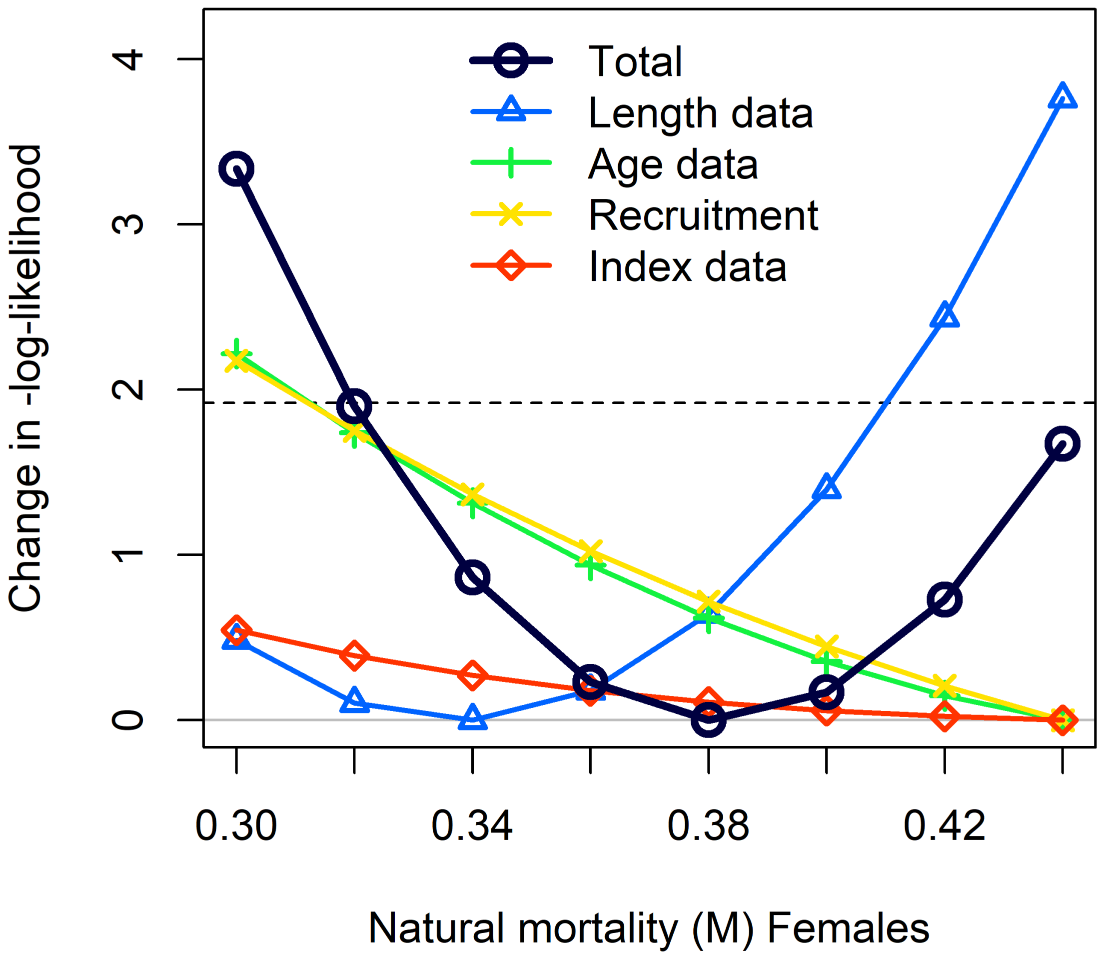

Figure D.13: Log-likelihood profile for natural mortality (M per year) for the various female data components. The black line was the combined profile for all data components. Results were for analysis 2. The dashed cutoff line indicated the 95% confidence interval for significant differences between -log-likelihoods.

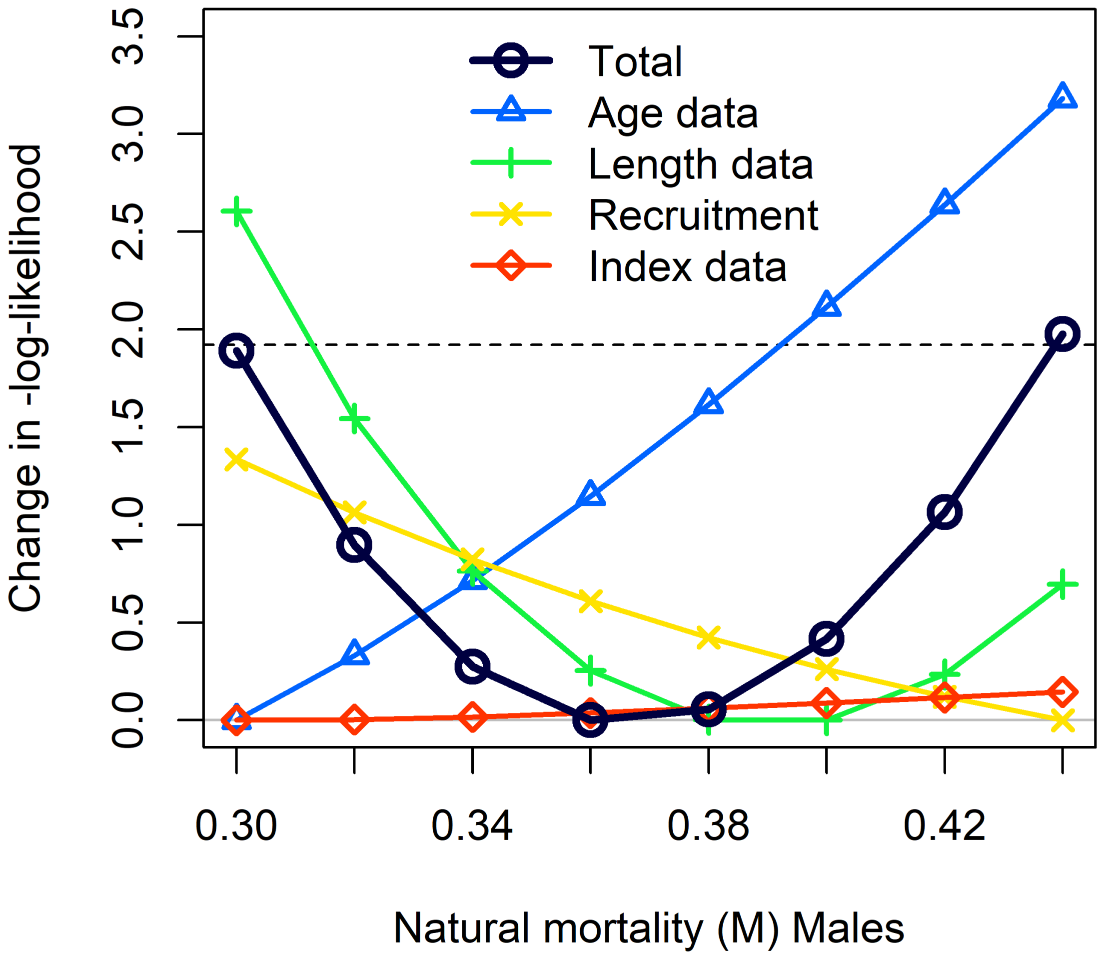

Figure D.14: Log-likelihood profile for natural mortality (M per year) for the various male data components. The black line was the combined profile for all data components. Results were for analysis 2. The dashed cutoff line indicated the 95% confidence interval for significant differences between -log-likelihoods.

The minimum values along the steepness profile ranged between 0.4 and 0.8 (Figure D.15). In general, different data weightings or structuring (use of length frequencies or age frequencies) might inform differently about steepness.

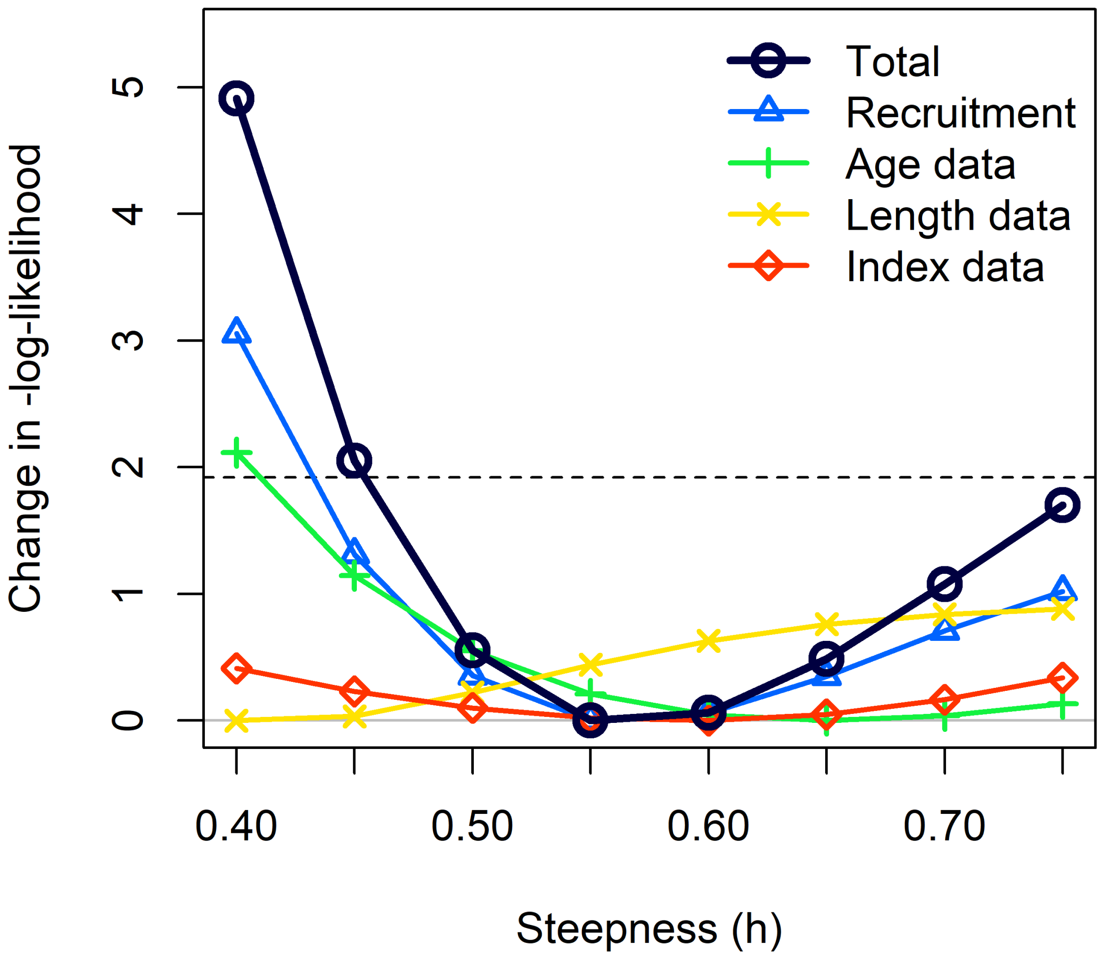

Figure D.15: Log-likelihood profile for steepness (h) for the various data components. The black line was the combined profile for all data components. Results were for analysis 2. The dashed cutoff line indicated the 95% confidence interval for significant differences between -log-likelihoods.

Age structured production models (ASPM) were reviewed, following the cookbook work flow (Carvalho et al. 2021). This involved comparing the SS analysis 2 results (the full model) to: 1) the ASPM where only the R_0 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 R_0 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 showed:

- The catch rate fits were better by using recruitment deviations; otherwise the model would fit no trend (Figure D.16). The recruitment deviations also supported a better fit to historic catch rates (Figure D.17), by better estimating R_0.

- The ASPMdev model indicated that annual harvest and catch rates informed estimates of recruitment variability with similar estimates compared to the full model (Figure D.18). The fish age-length data in the full model suggested different deviations in 2020 and 2021, but in general smaller confidence intervals were calculated.
- Annual recruitment deviations were required not only to estimate the trends, but also for scaling of R_0 and therefore the spawning calculations (Figure D.19 and D.20). The ASPM model might be better specified and assessed, by deviating from the cookbook method, to estimate both R_0 and steepness, and to fix the other parameters. More investigation of the current ASPM is required, which estimated high R_0 and error. This R_0 result was not consistent with the behaviour of deterministic models in earlier assessments, that showed more comparable R_0 and steepness values, and biomass ratios as to analyses 1–12 herein (Figure 4.4) (Begg et al. 2006; O'Neill et al. 2018a).
- The ASPM diagnostic reinforced that catch rates were one of the primary assumptions in the stock assessment and to inform recruitment deviations. Secondly, that the age-length data gave important information to estimate the scale of R_0.

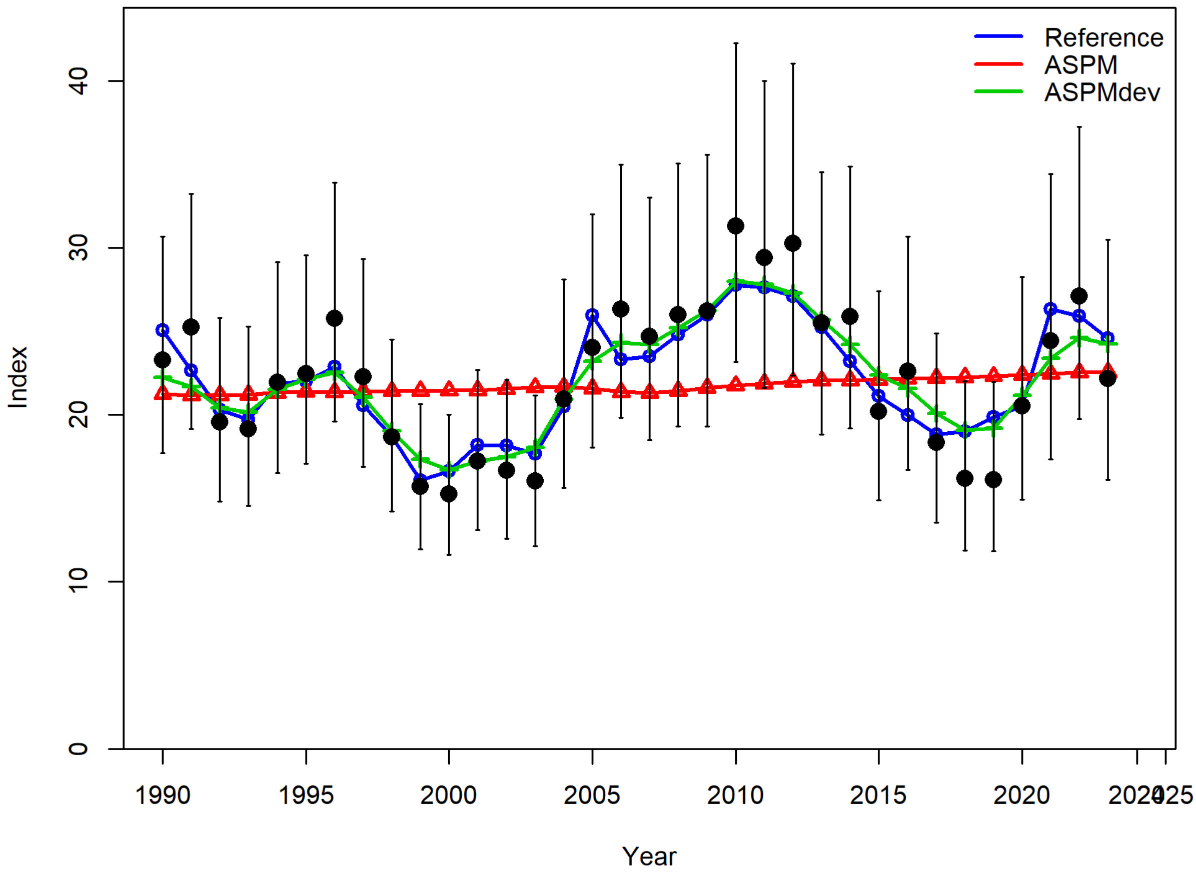

Figure D.16: Comparison of results between the full SS analysis 2 model (blue line) and the age-structured production model versions - ASPM without recruitment deviations (red line) and ASPMdev with recruitment deviations (green line). The figure compares fits to Sunset catch rates.

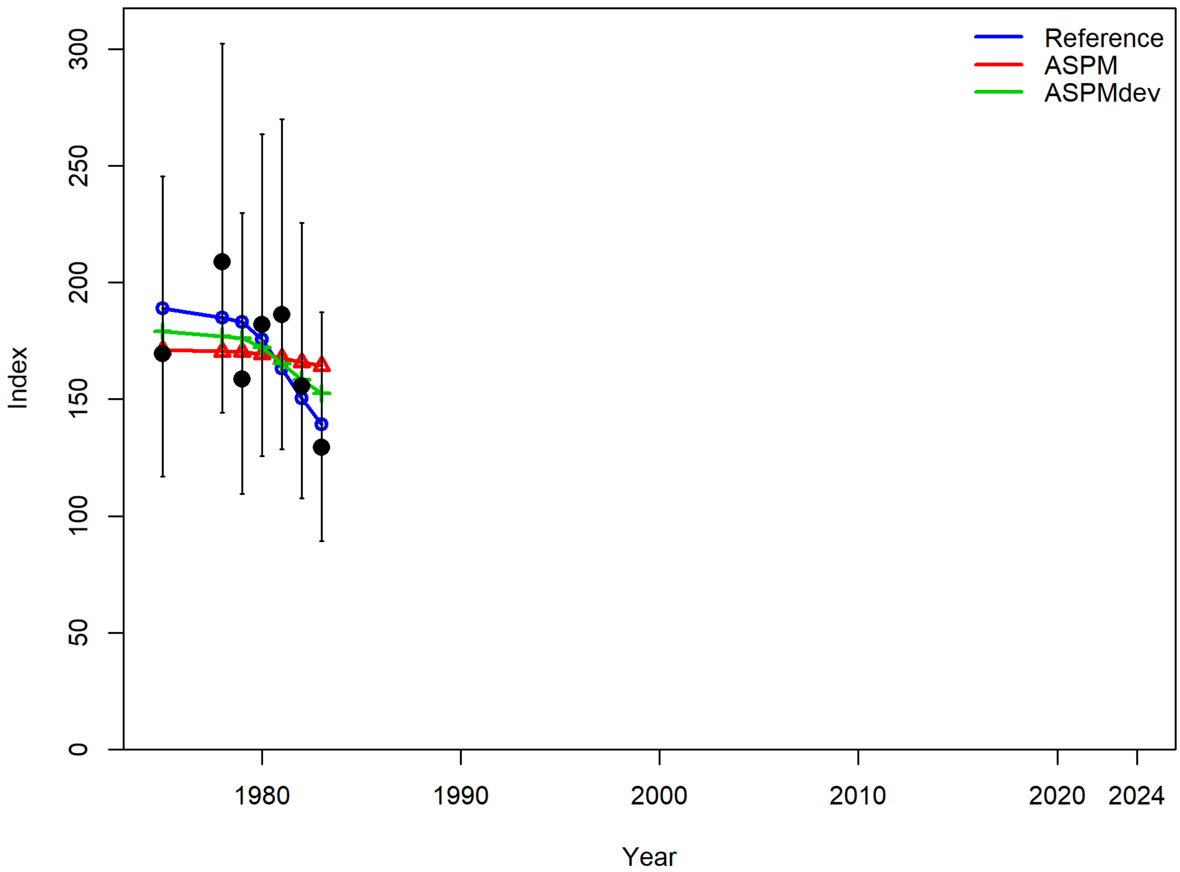

Figure D.17: Comparison of results between the full SS analysis 2 model (blue line) and the age-structured production model versions - ASPM without recruitment deviations (red line) and ASPMdev with recruitment deviations (green line). The figure compares fits to the historic catch rates.

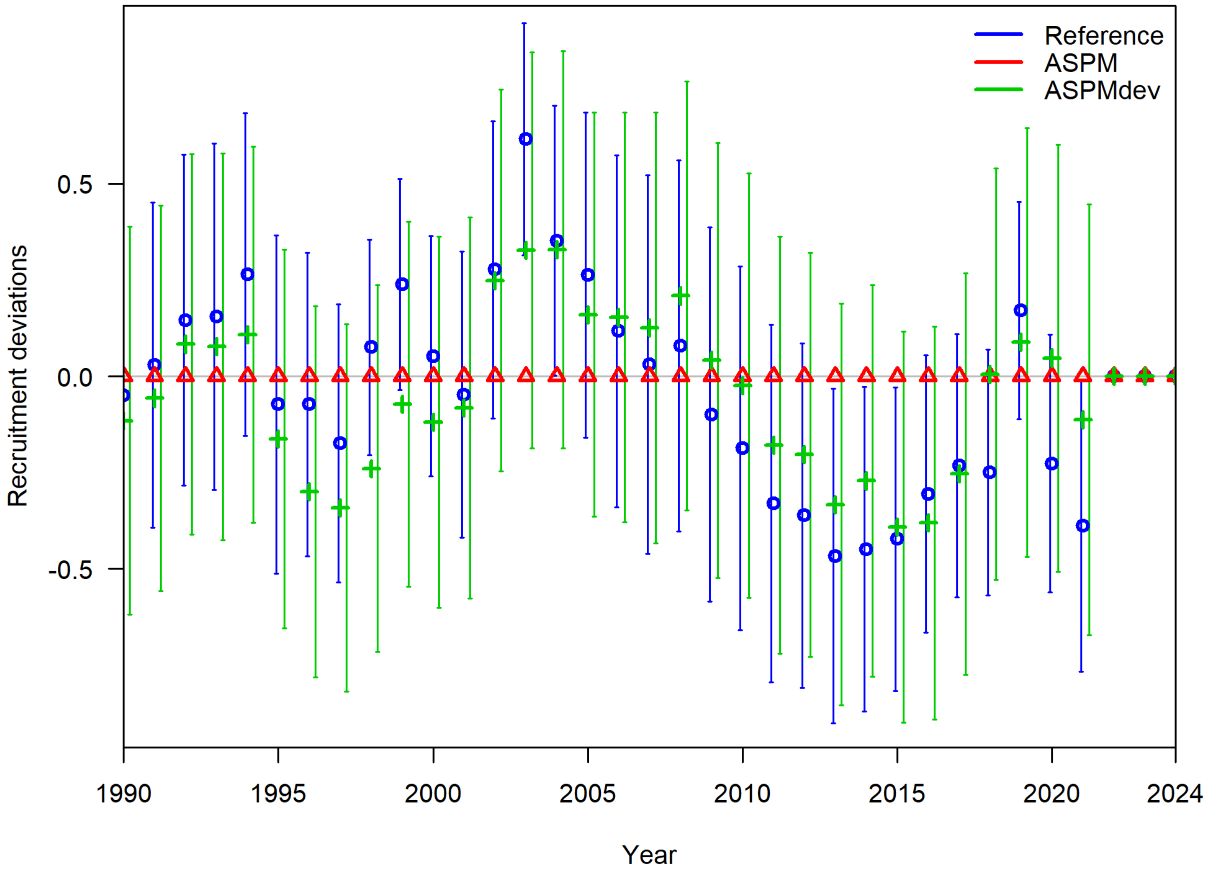

Figure D.18: Comparison of results between the full SS analysis 2 model (blue line) and the age-structured production model versions - ASPM without recruitment deviations (red line) and ASPMdev with recruitment deviations (green line). The figure compares estimates of recruitment deviations.

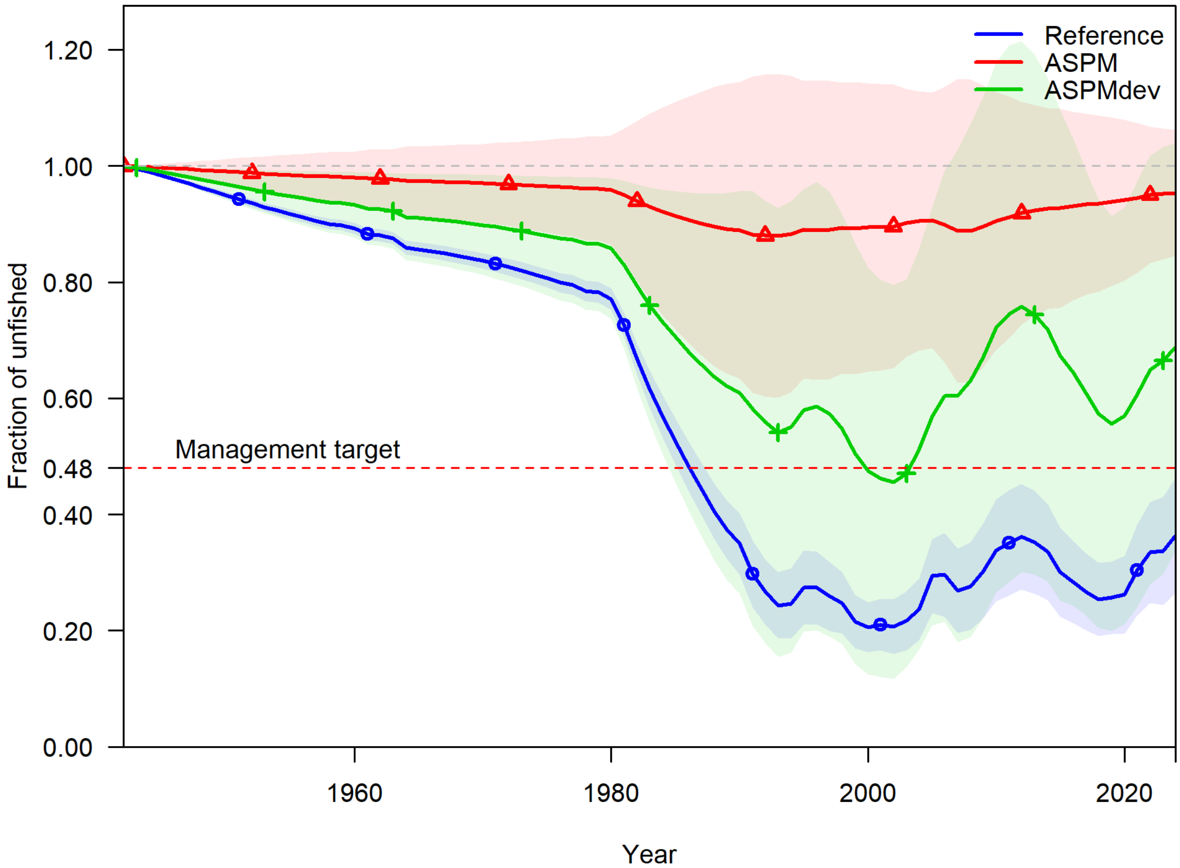

Figure D.19: Comparison of results between the full SS analysis 2 model (blue line) and the age-structured production model versions - ASPM without recruitment deviations (red line) and ASPMdev with recruitment deviations (green line). The figure compares spawning biomass ratios.

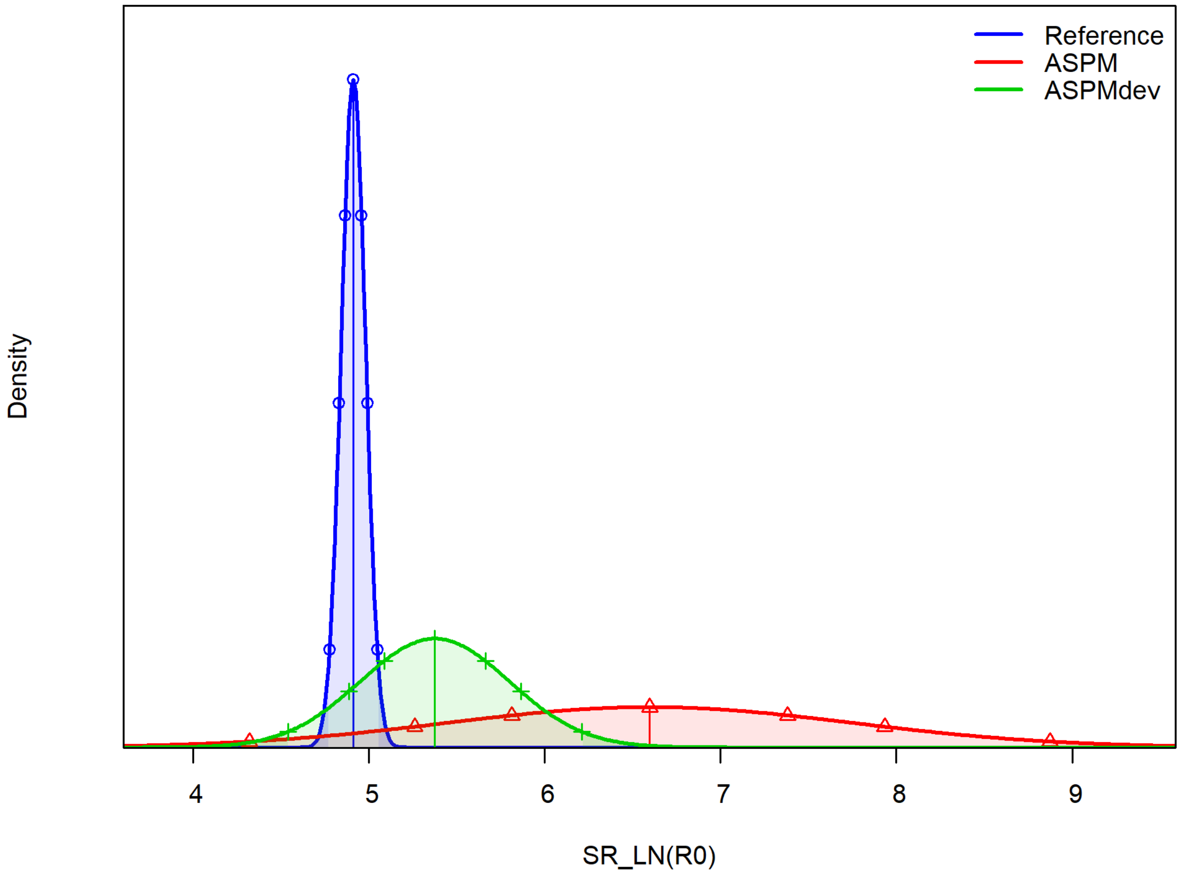

Figure D.20: Comparison of R_0 densities between the full SS analysis 2 model (blue) and the age-structured production model versions - ASPM without recruitment deviations (red) and ASPMdev with recruitment deviations (green). The figure compares the estimates on the log R_0 scale.

Retrospective diagnostics were implemented by removing (peeling) 1–7 of the most recent years of data from SS (Figures D.21, D.22, D.23, and D.24). 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 more often negative between the years 2009–2018 (Figure D.28). Of note, the R_0 estimates were in general consistent retrospectively (Figure D.24).

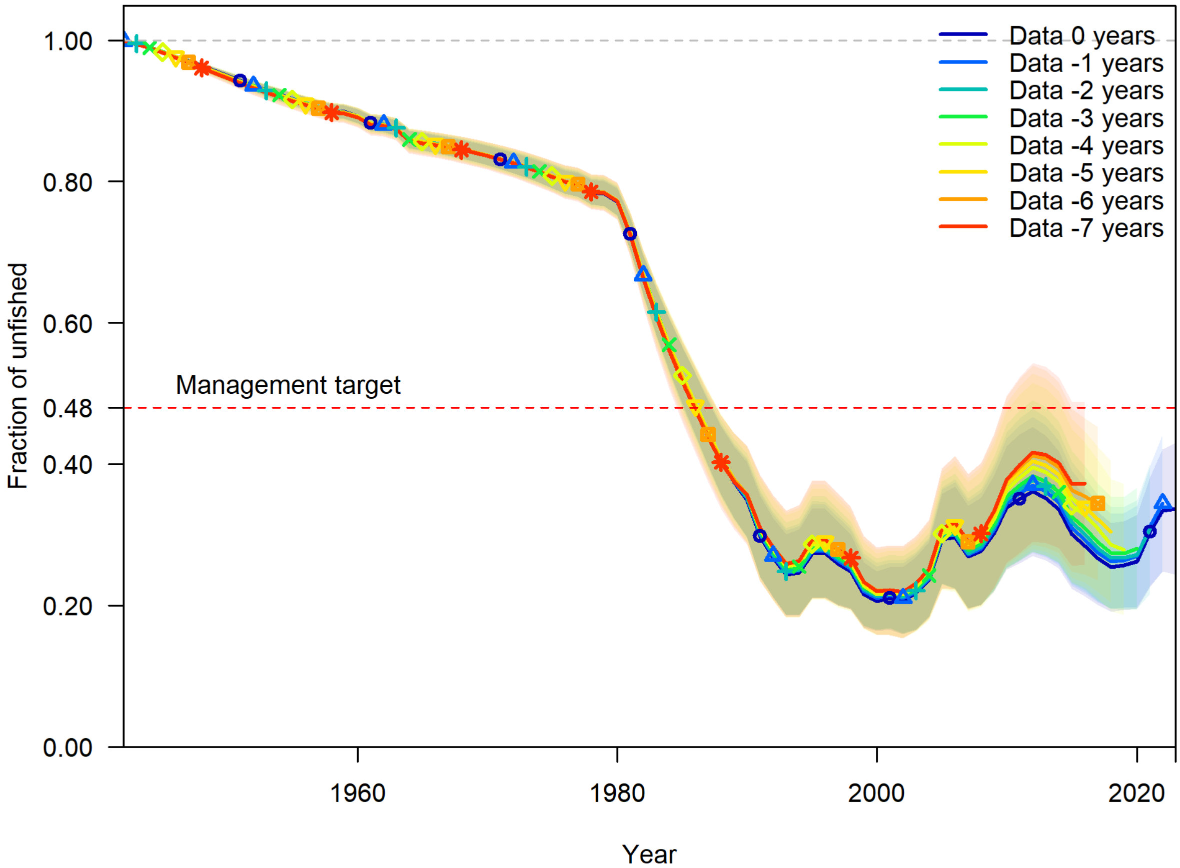

Figure D.21: Retropsective analysis for spawning biomass (egg production) ratios after removing 7 years of data, one year at a time sequentially.

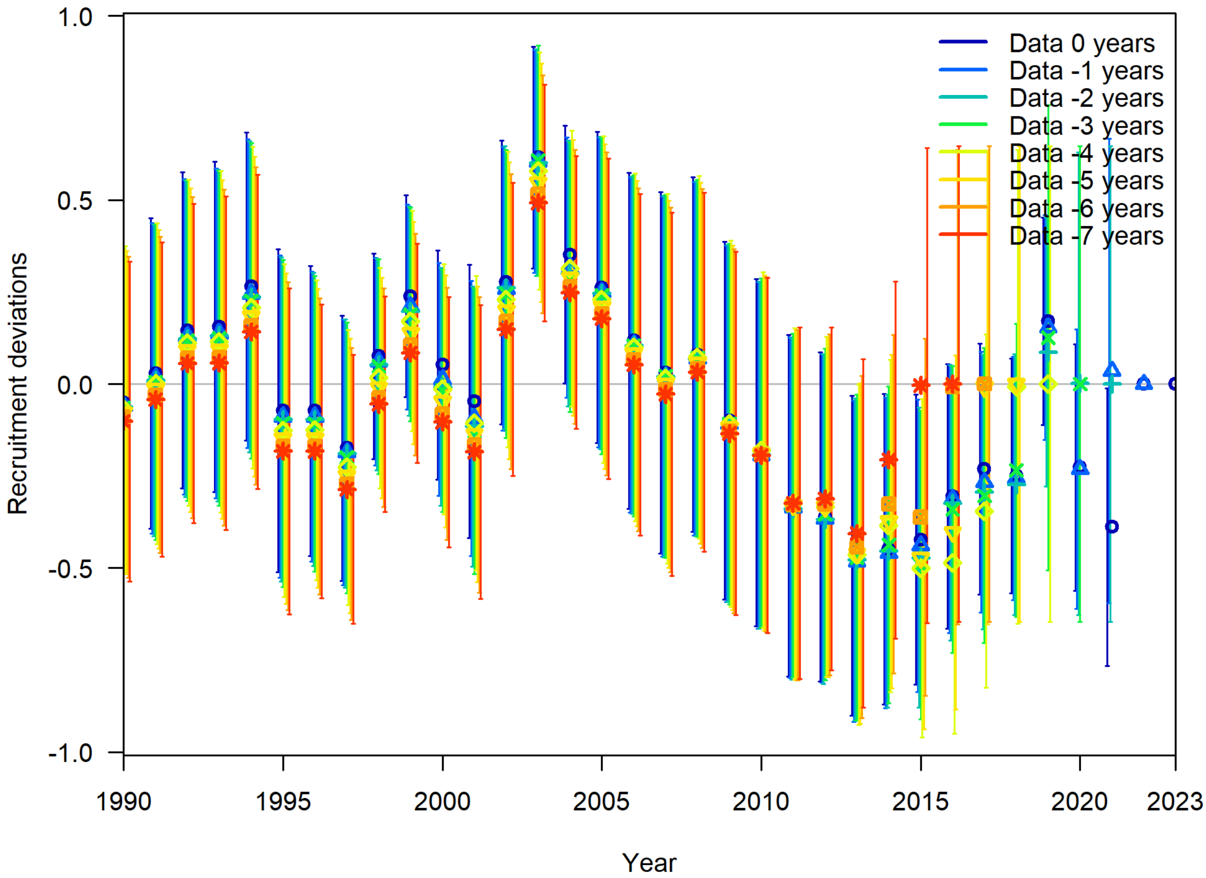

Figure D.22: Retropsective analysis for recruitment deviations after removing 7 years of data, one year at a time sequentially.

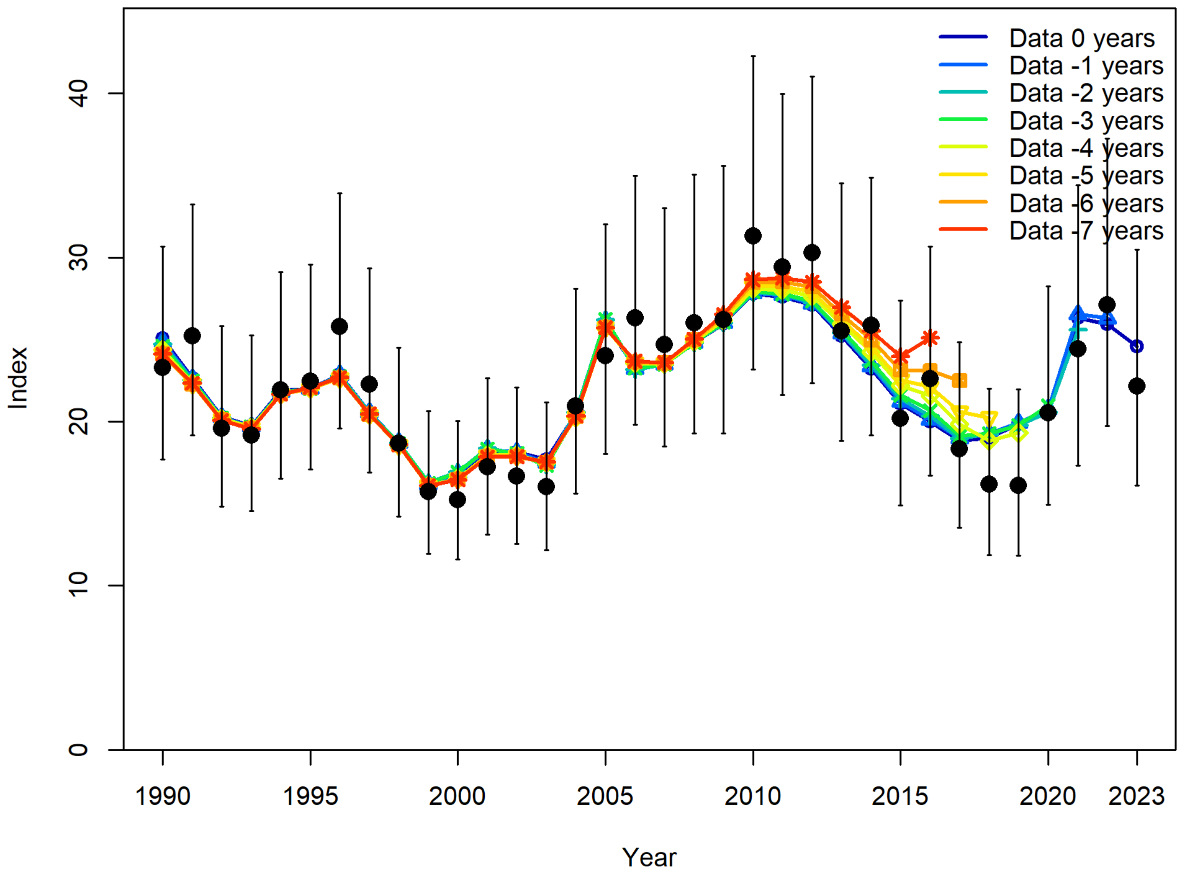

Figure D.23: Retropsective analysis for catch rate fits after removing 7 years of data, one year at a time sequentially.

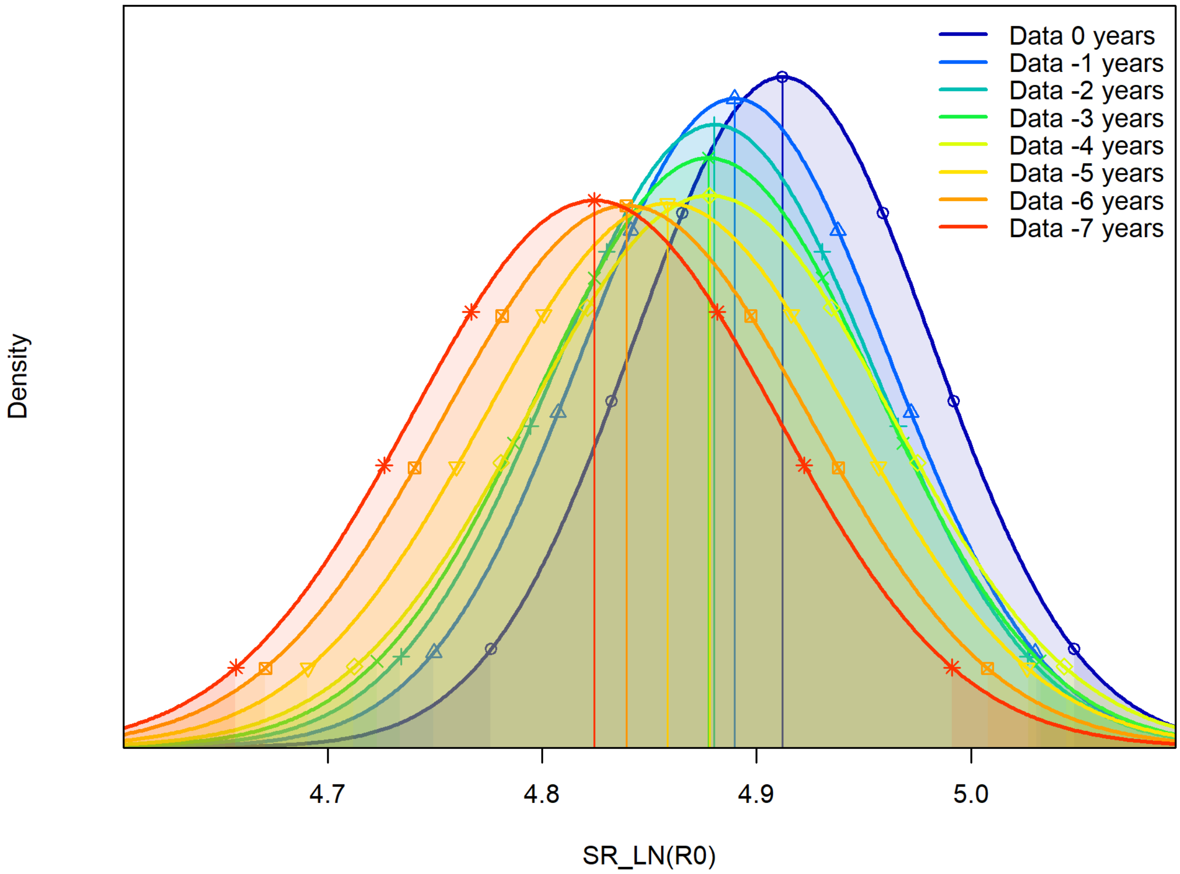

Figure D.24: Retrospective estimates for the virgin recruitment, the log R_0 parameter.

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.25). Three of the seven catch rate hind-casts were outside the confidence interval, and four were inside. This result was summarised by the MASE score being >1 in Table D.1. However, the three predictions outside were by only a few fish. Predictions were improved after 2018 when recruitment deviations normalised. The predictions of mean fish length were in the confidence interval zone (Figure D.25).

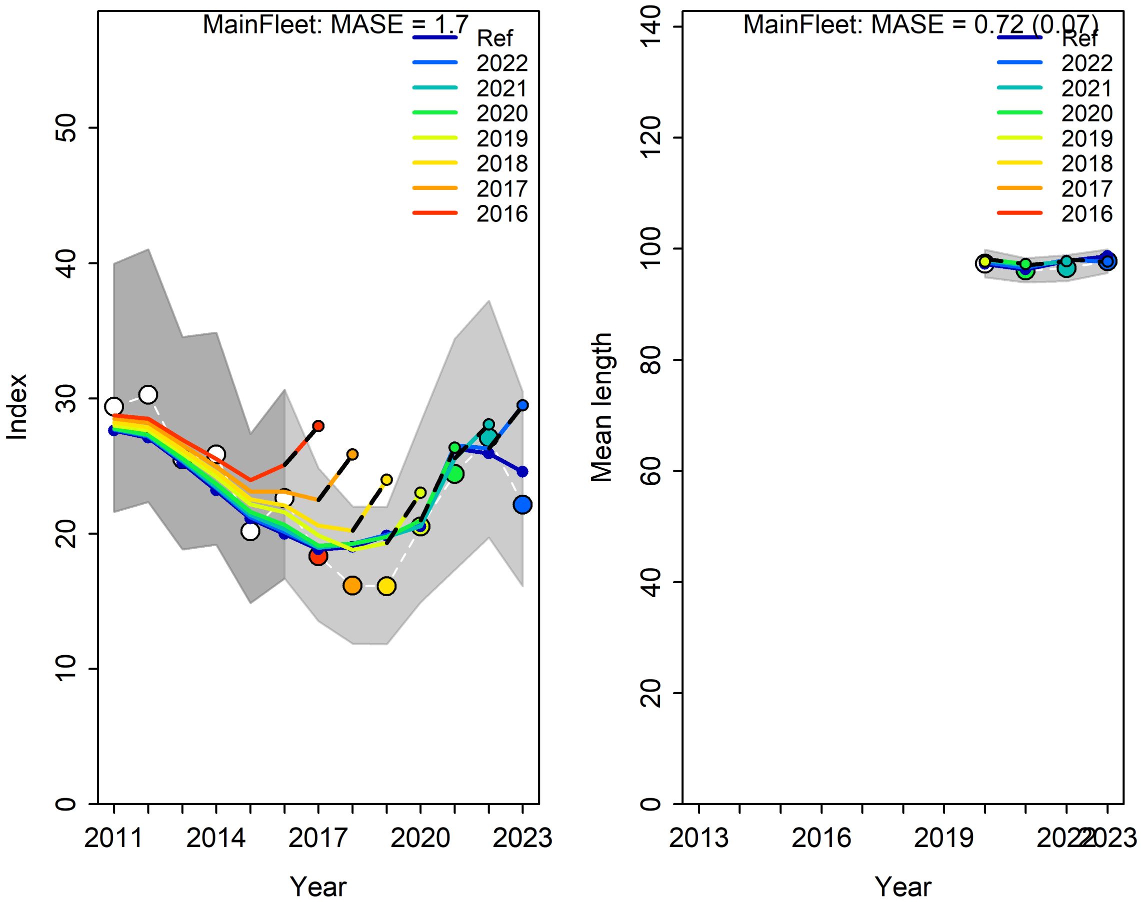

Figure D.25: Hindcast cross-validation (HCxval) for predicting Sunset catch rates (number of fish) and mean fish age (years). HCxval was performed from the full SS analysis 2 model and 7 hindcast runs. The mean absolute scaled error (MASE) score was listed in each subplot.

The jitter test, by changing the starting values, returned the same converged parameter estimates and negative log-likelihoods (Figure D.26). The test used a jitter fraction of ± 0.1.

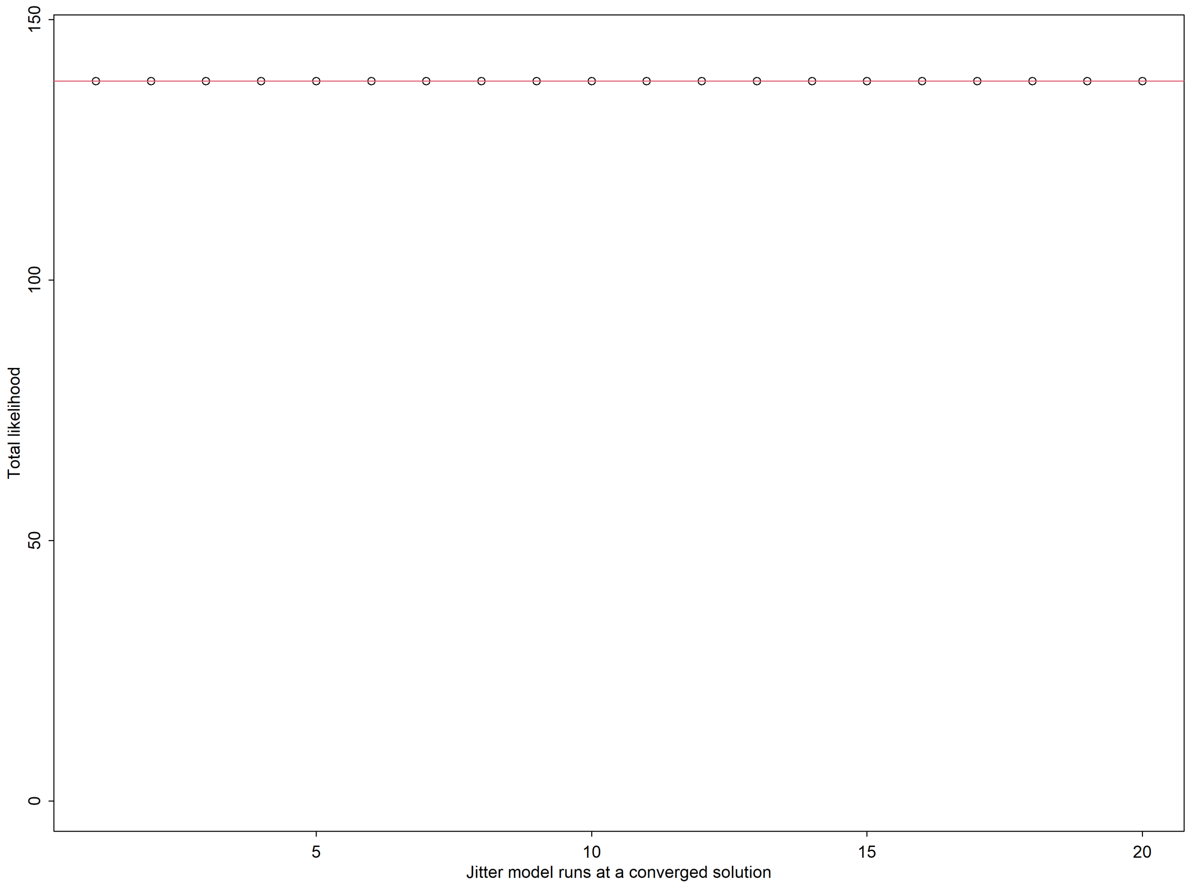

Figure D.26: The jitter diagnostic for the negative log-likelihood, with the red horizontal line for the base-case fit.

D.2 Harvest rates

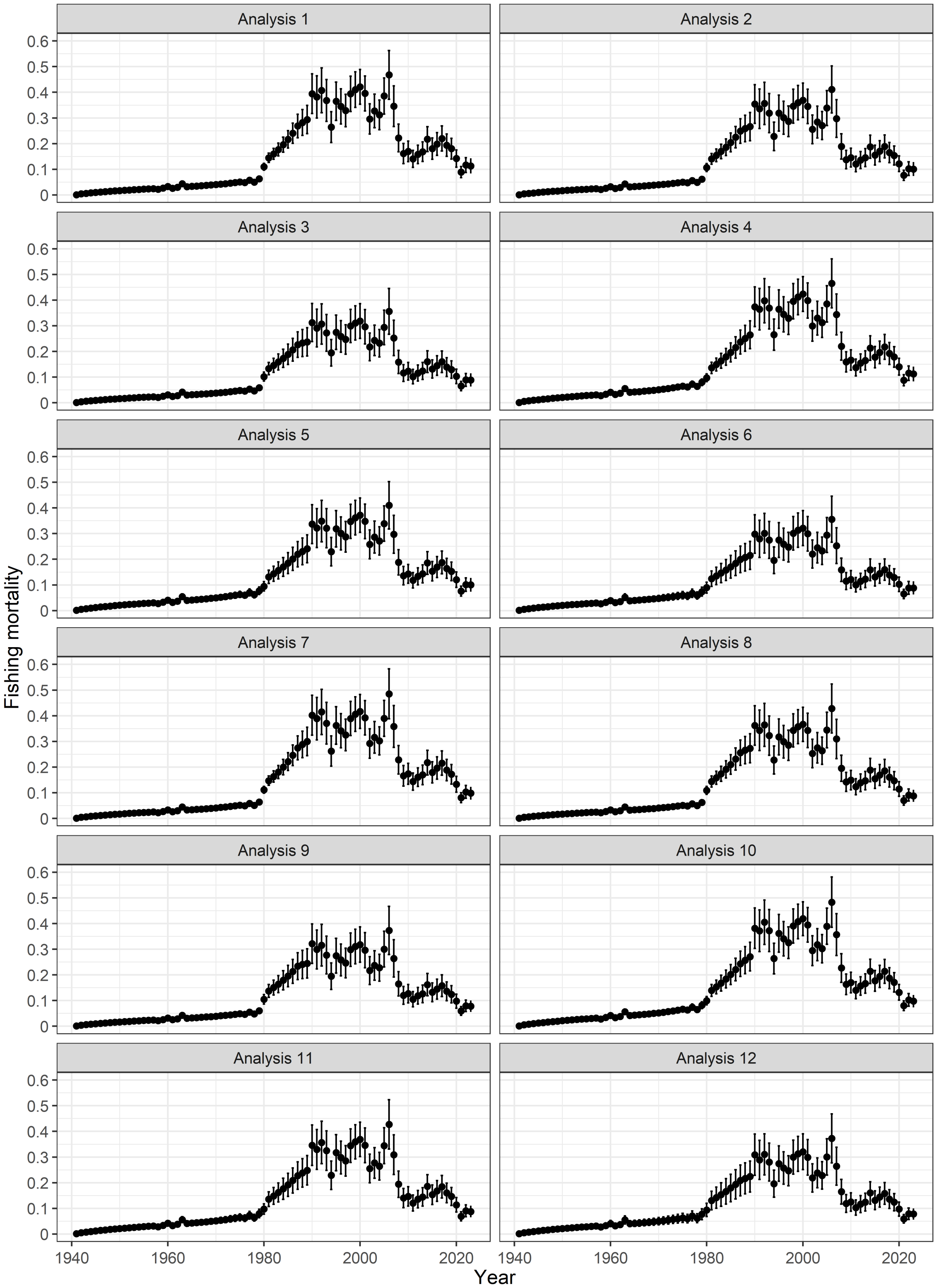

Figure D.27: Time series of instantaneous fishing mortality (F) per year by analysis.

D.3 Recruitment deviations

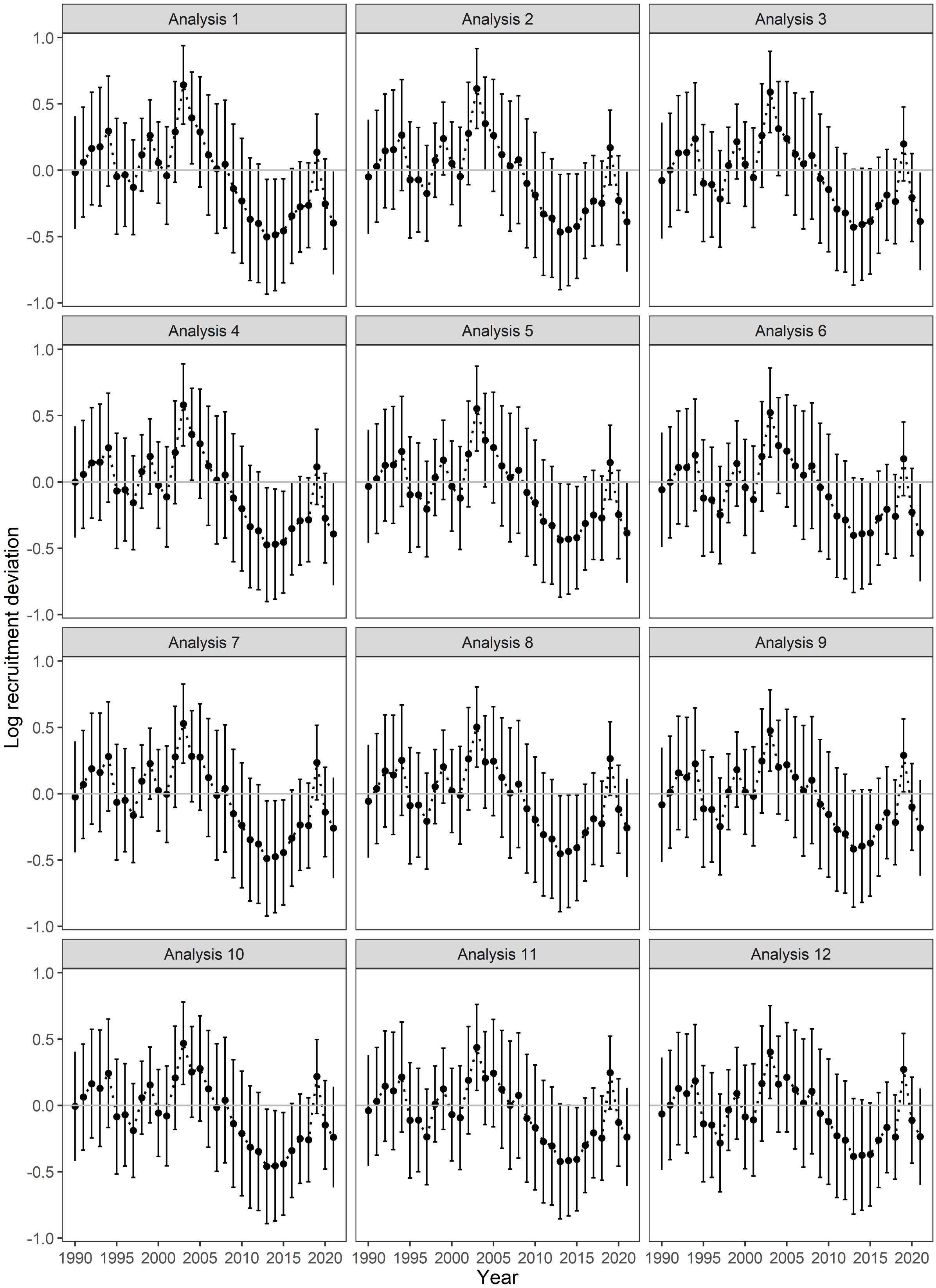

Figure D.28: Time series of log recruitment deviations. Estimates were consistent across analyses.

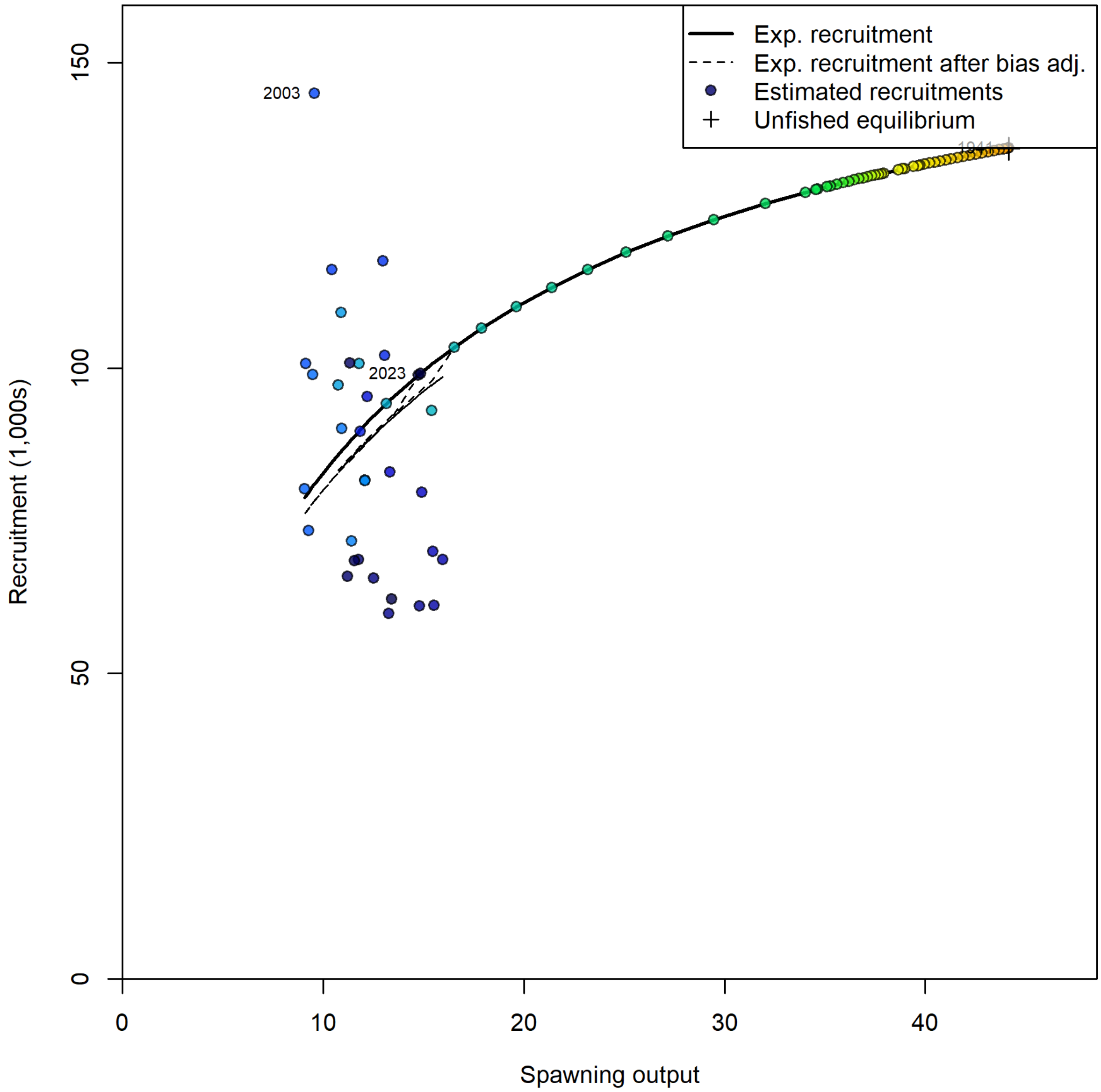

Figure D.29: Stock recruitment curve from analysis 2. The curve labels the first, last, and years with log deviations > 0.5. Point colors indicate year, with warmer colors indicating earlier years and cooler colors in showing later years.

D.4 Dynamic B_0

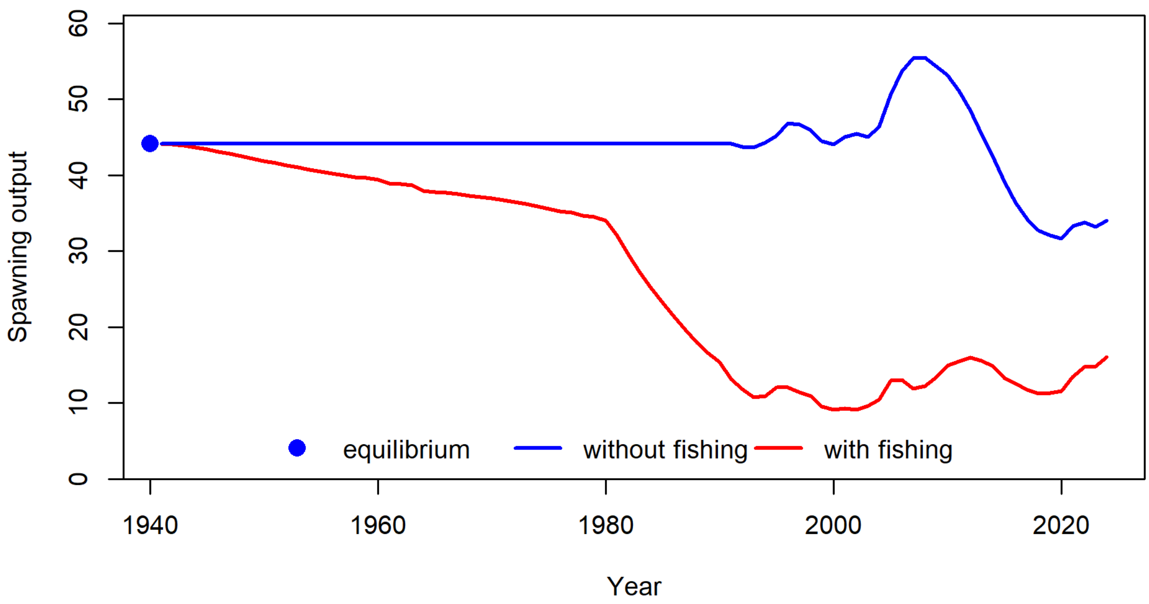

Figure D.30: Dynamic B_0 plot from analysis 2. The lower line shows the time series of estimated spawning output in the presence of fishing mortality. The upper line shows the time series that could occur under the same dynamics (including deviations in recruitment), but without fishing. The point at the left represents the unfished equilibrium.

D.5 MCMC on analysis 2

For the key parameters, the medians of the MCMC posterior distributions were similar to the maximum likelihood estimates (labelled optimised in Figure D.31). Skewness was evident in some distributions, suggesting MCMC runs might help propagate slightly more uncertainty and wider confidence within an analysis. More simulations might produce better normality in trace plots (Figure D.32). Traces related to steepness greater than 0.8 and log(R_0) being small were divergent and questionable.

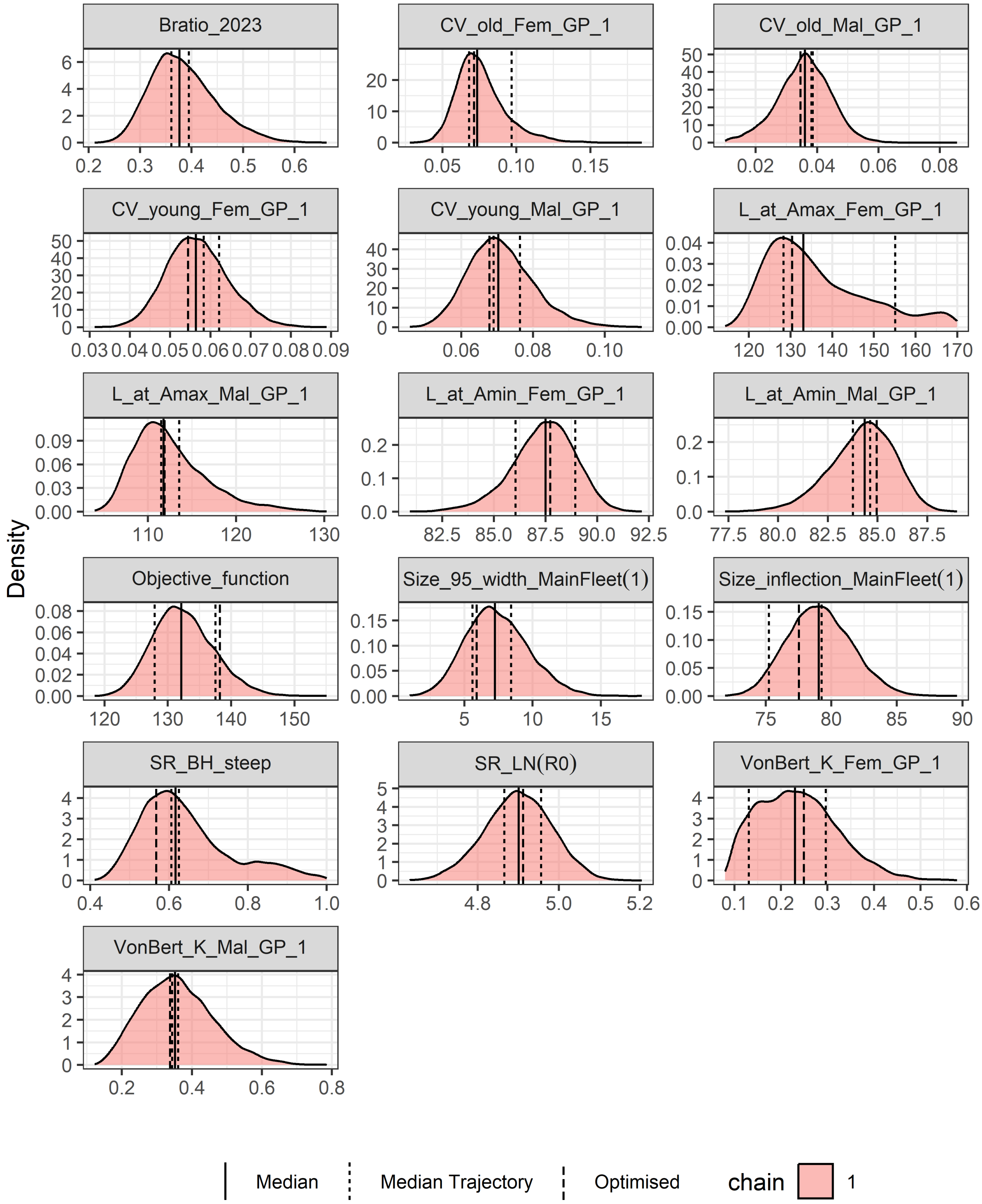

Figure D.31: MCMC probability distributions for key parameters, from analysis 2.

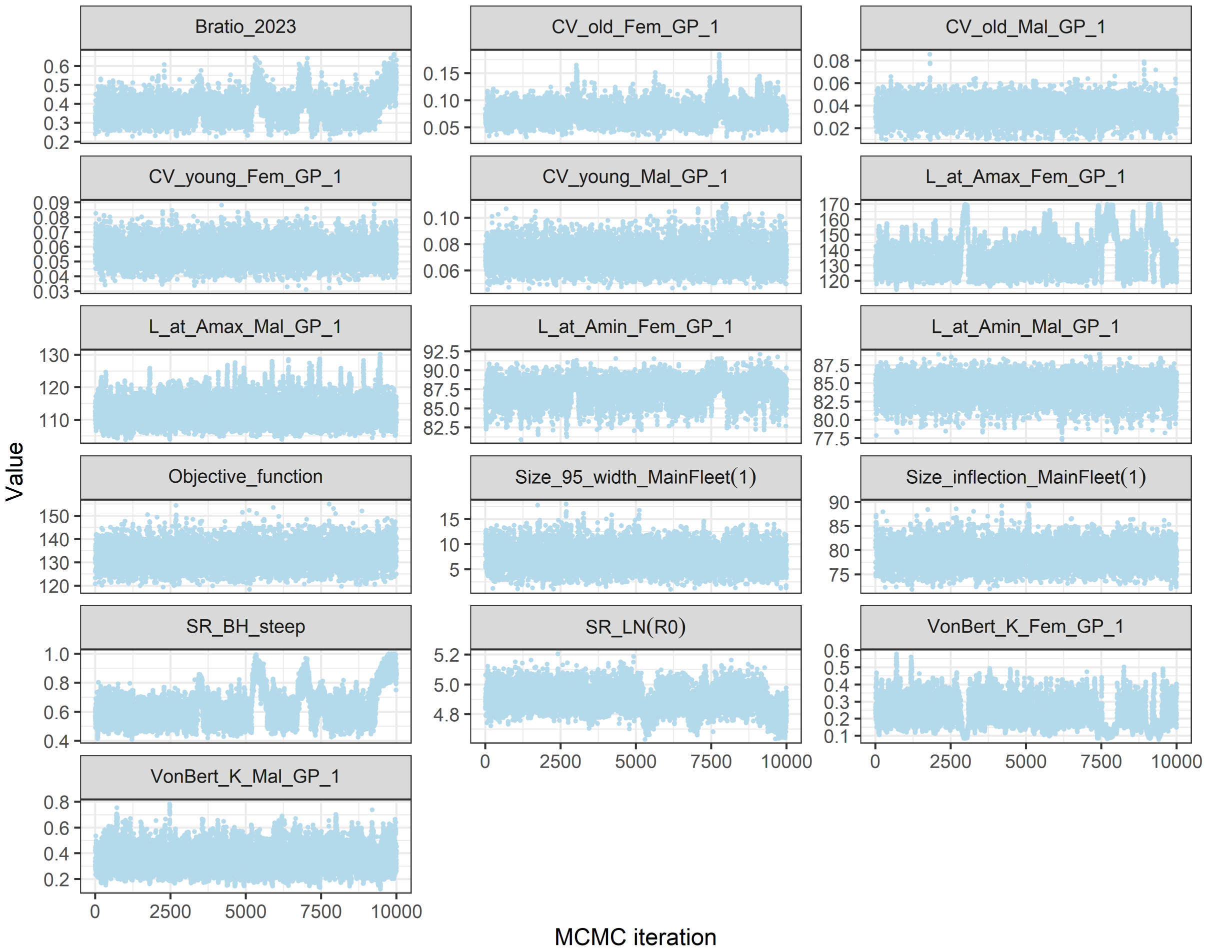

Figure D.32: MCMC trace plots for key parameters, from analysis 2.

The results of MCMC simulations of recruitment deviations (Figure D.33) were similar to the maximum likelihood estimates (analysis 2, in Figure D.28). The posterior distributions and trace plots, in general, were normal in appearance (Figure D.34 and Figure D.35).

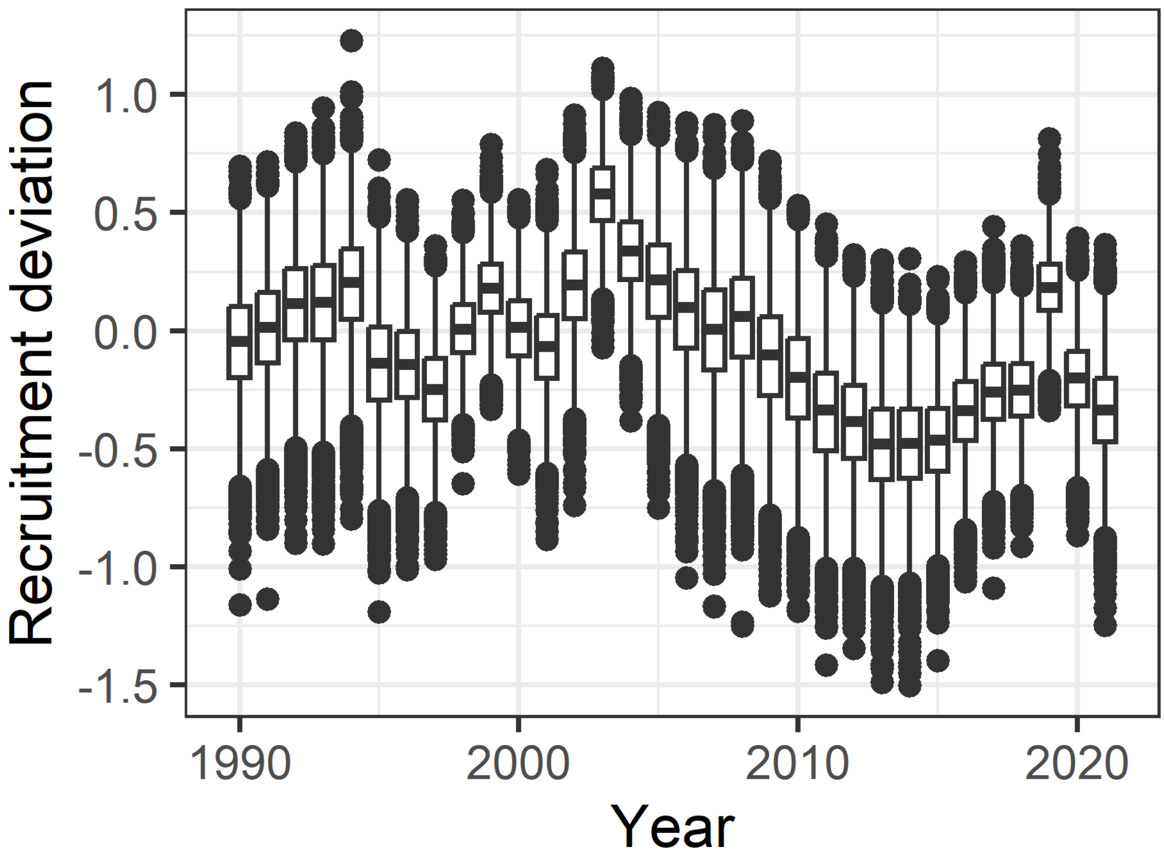

Figure D.33: Box plot of recruitment deviations, from MCMC analysis 2.

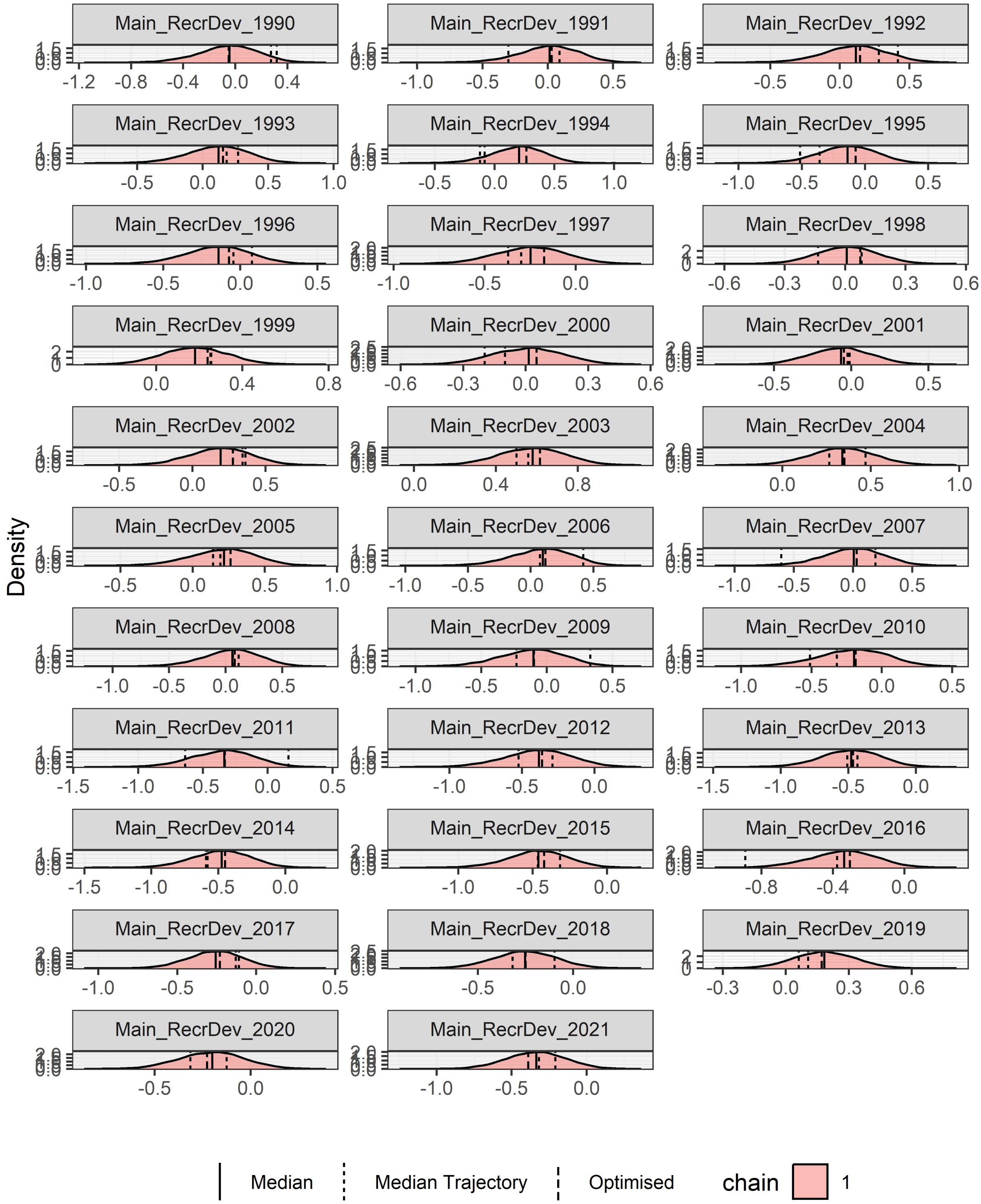

Figure D.34: MCMC probability distributions for the recruitment deviations, from analysis 2.

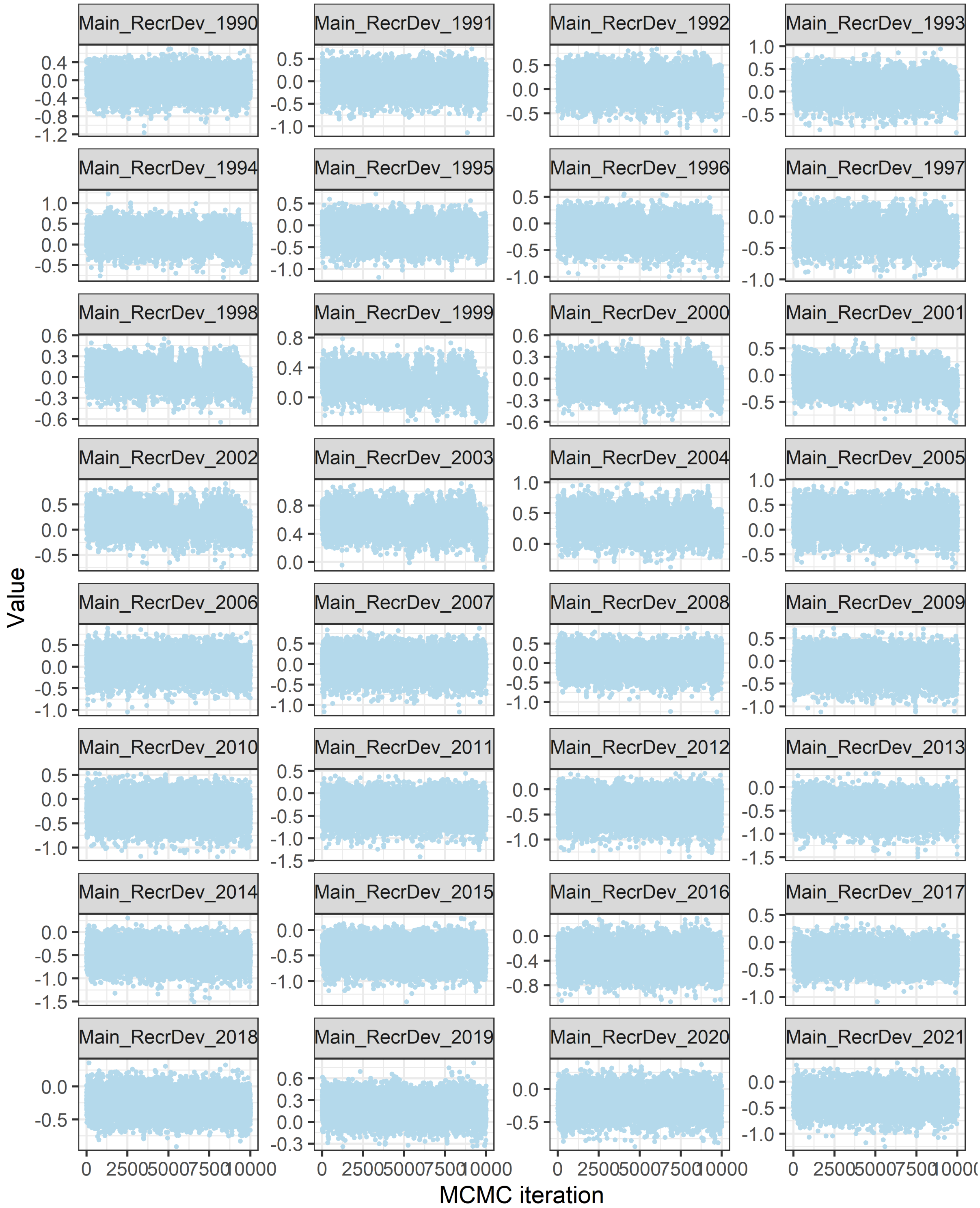

Figure D.35: MCMC trace plots for the recruitment deviations, from analysis 2.