Stock assessment of Australian east coast Spanish mackerel (*Scomberomorus commerson*)

2021

Queensland Government

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Summary

Australian east coast Spanish mackerel (*Scomberomorus commerson*) are large offshore pelagic fish. They form a single genetic stock between Cape York Peninsula in north Queensland and Newcastle on the New South Wales mid-coast. In these waters the species has been recorded to live for up to 26 years, grow to over 30 kg in weight and mature between two and four years of age.

During springtime, east coast Spanish mackerel school to form one of the most notable and predictable spawning aggregations of fish on the Great Barrier Reef. The spawning aggregation occurs in waters north of Townsville, typically over a two lunar month period. Spanish mackerel can have strong reef fidelity during the spawning season.

Following the last stock assessment, in 2016, some stakeholders raised concerns about the perceived reduced size of the spawning aggregation and under catch of the Queensland commercial quota. This assessment updates the estimates of spawning stock biomass ratio (population indicator for female egg production relative to the start of the fishery in 1911). This is the seventh stock assessment on the east coast stock since 2000.

This stock assessment implemented an annual time-step, two-sex, age-structured population model within Stock Synthesis software. The model incorporated data from 1911 to 2020, including annual estimated commercial, charter and recreational harvest (including recreational released fish mortality), commercial standardised catch rates, fish age-length frequencies, and key long-term fishery information on fishing power changes and catch rates. The assessment was conducted at the whole stock level, including data from across jurisdictions and fishing sectors.

Over the last five years, 2016 to 2020, the total Spanish mackerel harvest by all fishing sectors averaged 515 tonnes (t) per year (Figure 1). This was approximately half the annual harvest compared to 1973–2004. The annual allocated Queensland commercial quota was initially set to 619 t in 2004–05, then revised to 578 t since 2016–17.

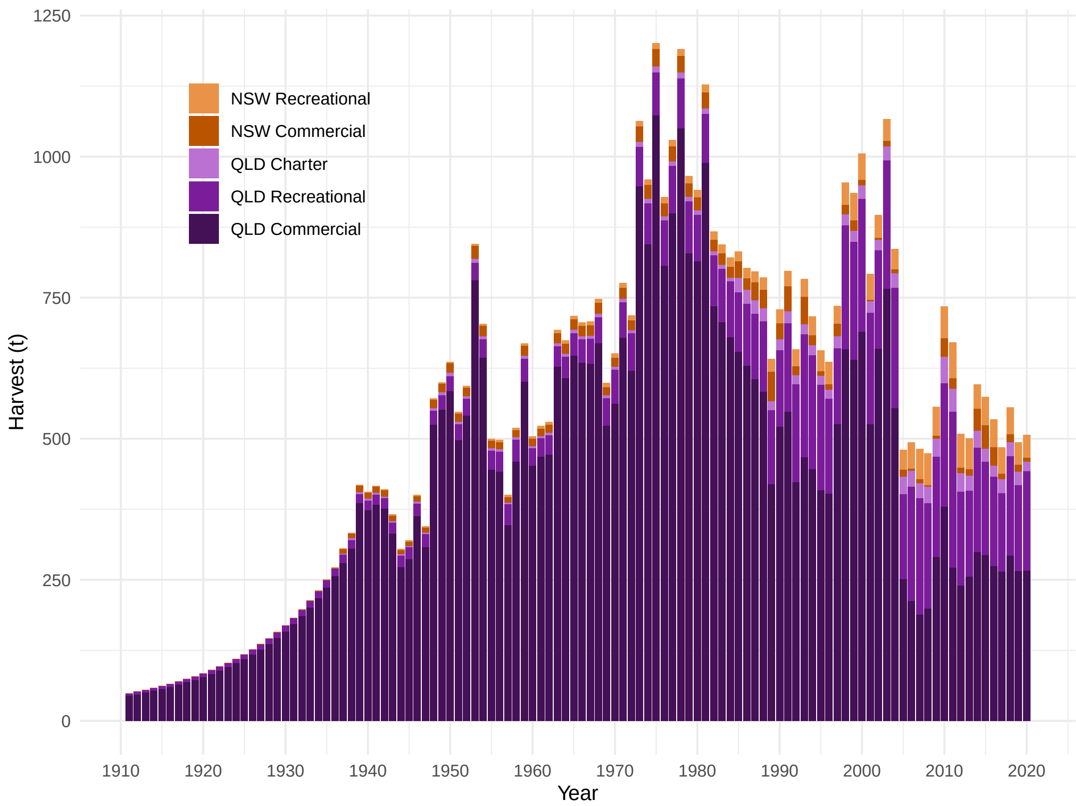

Figure 1: Annual estimated harvest from commercial, recreational and charter sectors between 1911 and 2020 for Spanish mackerel

Queensland commercial catch rates in 1989–2020 were standardised to estimate an index of legal-sized Spanish mackerel abundance through time (Figure 2). The catch rate index informed proportionally on the annual change in abundance of legal-sized fish relative to 1990. This was a primary assumption for the stock assessment. Catch rates were standardised through two-component statistical analyses (binomial generalized linear model for the probability of catching Spanish mackerel, multiplied by the linear mixed model for when catch rates were taken).

The catch rates were influenced by two main factors: annual increases in fishing power due to improved fishing gears and technologies, and the probability model showing fewer days when Spanish mackerel were caught. The selected base case results, in Figure 2, indicate 2016–2020 catch rates were 25–38% below what they were in 1990. The standardised commercial catch rates in 2017 and 2020 were record lows in Queensland.

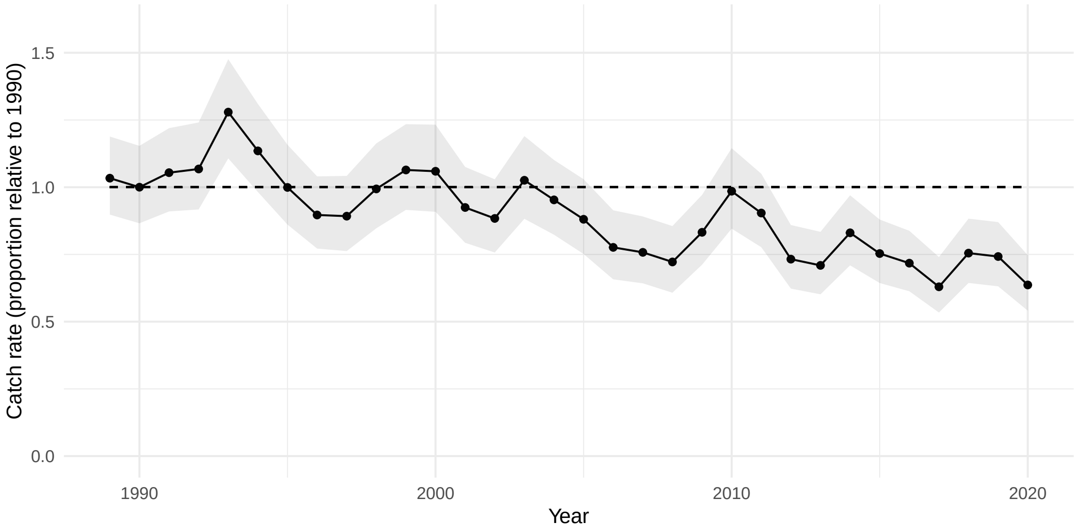

Figure 2: Annual standardised catch rates (95% confidence intervals) for Queensland commercial line-caught Spanish mackerel between the years of 1988 and 2020—dashed line indicates catch rate in 1990

Eight model scenarios were run, covering a range of assumptions. Spawning biomass ratios were relatively similar among all model runs (ranged between 14% and 27% of unfished spawning biomass in 2020), except one at 57%. The base case data and analysis, selected by the overseeing project team, recognised potential influences of annual changes in fishing power and hyperstability (aggregation effects of fish and fishers). The analysis suggested that spawning biomass had declined (Figure 3) as a result the high harvests during the 1970s, early 1980s and early 2000s (Figure 1). In 2020, base case analysis estimated spawning biomass at 17% (±4%) of the unfished biomass (Figure 3).

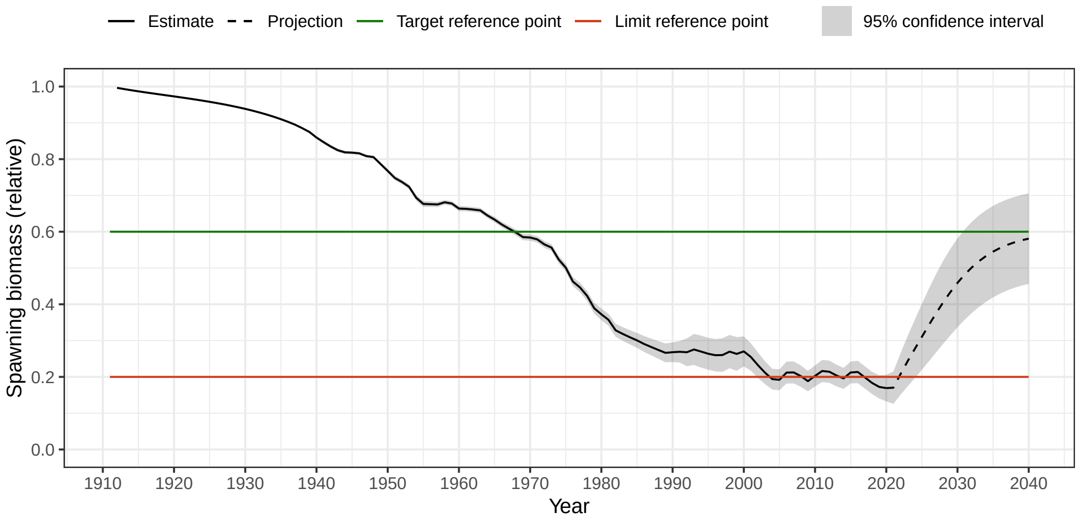

Figure 3: Estimated and predicted biomass trajectory relative to unfished for Spanish mackerel from 1911 to 2040

Estimates of recommended biological catch, including all waters, sectors and discard mortality, vary with datasets and model assumptions of fish natural mortality and spawning productivity (steepness resilience parameter). The draft harvest strategy policy for spawning biomass ratios below 20% recommends zero harvest.

There is presently substantial unfished Queensland commercial quota (267 t fished, 311 t unfished). The current Queensland total allowable commercial catch quota is 578 t. If this were to be largely utilised, together with current or increased charter, recreational and New South Wales commercial harvests, then the biomass of the Spanish mackerel population may further deplete.

Estimated reference points of annual harvest include all fishing sectors: commercial, charter and recreational across Queensland and New South Wales. They also include a discard morality component required in fishery management allocations. As part of this, potential harvest strategies need to consider risks from target fishing of spawning aggregations, potentially including time-area closures or bounds on localised fishing pressure. The report provides a number of recommendations to support future stock assessment and management procedures.

Table 1: Current and target indicators for the base case analysis

Parameter	**Estimate**
Current (2020) biomass (relative to unfished)	17%
Current (2020) harvest	507 t (90.5% QLD, 9.5% NSW)
Sustainable harvest at biomass target (60%)	557 t
Recommended biological catch (2021) to achieve target	0 t

Acknowledgements

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In addition to their roles on the committee, we would like to thank Carlie Heaven and Ashley Lawson for assistance with the Queensland commercial harvest data and the acquisition of weather data from the Bureau of Meteorology; John Stewart for the provision of, and assistance with, the New South Wales commercial and recreational harvest data; Tyson Martin for the provision of, and assistance with, the Queensland boat ramp survey data; Jason McGilvray for the assistance with the biological age and length monitoring data; and Daniella Teixeira and Rachel Janes for the provision of, and assistance with, the Queensland recreational statewide survey data. We thank Robyn Lovett for providing constructive inputs throughout the project as an independent stock assessment scientist.

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The authors acknowledge the fishers and scientists who have contributed to past research on Spanish mackerel. We thank Sarah Buckley for her research into historical fishing information, which enabled the calculation of decadal catch rates and fishing power changes.

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Glossary

ACN	Authority chain number
AFMA	Australian Fisheries Management Authority
age	Age within this report refers to age group unless otherwise stated
B	Biomass, total weight of a population or of a component of a population. This assessment refers to spawning biomass, measured by spawning egg production
B_{limit}, B_{20}	Biomass limit reference point, the point below which the risk to the population is regarded as unacceptable under the DAF Sustainable Fisheries Strategy
B_{MSY}	Biomass at maximum sustainable yield
B_{target}, B_{60}	Target biomass, the desired biomass of the population. The reference point refers to the target objective. For example the Queensland Sustainable Fisheries Strategy 60% biomass target and a proxy for biomass at maximum economic yield (MEY).
B_0	Mean equilibrium virgin unfished biomass, average biomass level if fishing had not occurred. Virgin state corresponds to the first year assessed in 1911.
Catch rate	Index of fish abundance, referred to as average (mean) catch rates standardised (adjusted) to a constant vessel and fishing power through time. All references to catch rates were standardised unless specified to be different.
Catchability, q	The ability to catch fish. More formally, it is defined as the probability of catching a fish with a single unit of standardised fishing effort. Catchability is the interaction of the fishing gear and a fish's behaviour, whereas fishing power is a property of the fishing effort, gear and practices.
CKMR	Close-kin mark-recapture
EC	East coast
F_{B60}, F_{btg}	Fishing mortality that achieves 60% spawning biomass
Fishery	This stock assessment evaluated Australian east coast Spanish mackerel. The assessment was conducted on the whole (genetic) stock across jurisdictions and included commercial, charter, recreational and research data from both New South Wales and Queensland. The fishery covers all fishing sectors: commercial, charter and recreational.
Fishing power	Measures 'a' or 'a group' of fishing operations' effectiveness in catching fish. More generally, fishing power refers to a measure of deviation in actual fishing effort from the standard unit of effort. For example, the standard unit of effort used to calculate catch rates may be scaled to an average fishing operation in 1990. The elements of fishing power and catchability have the potential to bias abundance indices derived from nominal catch rates. Therefore, methods of standardisation are required based on the data at hand.
Fishing year	1 July to 30 June. Also labelled as 'year' within. Fishing years were equal to financial years to group the seasonal and biological patterns of Spanish mackerel. Labelling used the second year in the financial year string. For example the financial year July 2019 to June 2020 was labelled as 2020 fishing year.
FL	Fork length
fleet	A Stock Synthesis modelling term used to distinguish types of fishing activity. Typically a fleet will have a unique curve that characterises the likelihood that fish of various sizes (or ages) will be caught by the fishing gear, or observed by the survey.
FRDC	Fisheries Research and Development Corporation
GBRMPA	The Great Barrier Reef Marine Park Authority
GLM	Generalised linear model
h	Beverton-Holt steepness parameter
ITQ	Individual transferable quota
JL	Jaw length
LMM	Linear mixed model
M	Natural mortality

MLS	Minimum legal size
MSY	Maximum sustainable yield, the maximum level at which the species can be routinely exploited without long-term depletion
NRIFS	The National Recreational and Indigenous Fishing Survey conducted by the Australian Department of Agriculture, Fisheries and Forestry
NSW	New South Wales
Overfished	A fish population with a biomass below the biomass limit reference point (B_{limit})
Overfishing	The condition where a population is experiencing too much fishing and the removal rate is unsustainable, that is, fishing mortality is higher than fishing mortality at maximum sustainable yield. F measured the level of fish harvested by different fishing sectors.
QLD	Queensland
R_0	Virgin recruitment
RAP	The Representative Areas Program
RBC	Recommended biological catch, the estimated total annual catch that can be taken by fishing, while achieving the management objectives for the fishery
Reference point	An indicator of the level of fishing, harvest or size of a fish population, used as a benchmark for interpreting the results of an assessment
REML	Restricted maximum likelihood (type of linear mixed model), statistical method used to standardise catch rates
RFish	Recreational fishing surveys conducted by Fisheries Queensland
SM	Fishery symbol used to access the commercial east coast Spanish mackerel fishery
SRFS	The Statewide Recreational Fishing Survey conducted by the Queensland Department of Agriculture and Fisheries
SS	Stock Synthesis
t	Tonnes
TACC	Total allowable commercial catch
TL	Total length
VMS	Vessel monitoring system
Vulnerability	Probability of fish to being exposed to fishing mortality. This varies for different sized/aged fish. This is generally a result of fish being present in the fishing area (fishery) and their susceptibility to being caught by the fishing gear.
WW	Whole weight

1 Introduction

Spanish mackerel, *Scomberomorus commerson*, are large pelagic fish. In Australian east coast waters, they are recognised as a high-quality eating and powerful sports fish, and are an important target species for all fishing sectors. Spanish mackerel are mainly caught from offshore reefs, shoals and bays, and sometimes from ocean beaches and headlands. Catches are primarily taken by line fishing techniques, with some harvest by the growing popularity in spear fishing. Net fishing for east coast Spanish mackerel is prohibited.

East coast Spanish mackerel have been observed to live up to 26 years and can weigh in excess of 30 kg. They reach sexual maturity above the minimum legal size limit of 75 cm between two and four years of age. East coast Spanish mackerel form a single genetic stock in ocean waters between Cape York Peninsula and northern New South Wales (Buckworth et al. 2007).

Movement patterns are varied and depend on spawning and feeding behaviours, water temperatures, and currents. Some fish can remain localised, whereas some fish move along the east coast (Buckworth et al. 2007). Spanish mackerel generally aggregate more in northern tropical waters during winter and spring for feeding and spawning, and some fish move to southern waters during summer and autumn to extend their feeding range. Seasonal and spatial patterns of fishing follow the predictable locations of schooling fish.

Tobin et al. (2013) and Tobin et al. (2014) characterised east coast Spanish mackerel as an obligate transient aggregator, meaning their spawning–schooling behaviour was generally restricted to specific reef locations. Fish acoustic-tag monitoring identified some fish as having strong reef fidelity during the spawning season (Tobin et al. 2014). This predictable schooling and aggregation behaviour signified that east coast Spanish mackerel were vulnerable to overexploitation.

Commercial fishing of Spanish mackerel commenced in 1911, with fishing operations targeting spawning aggregations on the Great Barrier Reef (Thurstan et al. 2016; Buckley et al. 2017). The reported commercial fleet increased in size from one operation in 1911 to twenty in 1936. This increased to 36 fishing operations in 1937 and to 115 by 1950. Between 1934 and 1947 estimated commercial landings per fishing operation ranged up to 540 Spanish mackerel (about 4 t) for a two day fishing trip, with at least 300 t of Spanish mackerel taken commercially in 1938 (Thurstan et al. 2016).

Since 1938 commercial harvests of Spanish mackerel steadily built to produce around 1000 t per year during the 1970s and reduced to around 500–700 t between 1998 and 2004 (Campbell et al. 2012). Prior to 2005 the fishery was less regulated (Table 1.1). Since 2005 commercial harvests decreased to around 300 t per year after the Queensland commercial quota system was implemented.

In Queensland waters, access to the commercial east coast Spanish mackerel fishery is restricted to holders of an ‘SM’ fishery symbol. This symbol is linked to individual quota holdings, established on 1 July 2004, and as of April 2021 there were 240 licensed operations (each ‘SM’ licence symbol identifies the primary line-fishing operation) (Department of Agriculture and Fisheries 2021).

Of these licences which includes the primary fishing vessel (mothership), about 200 were each permitted to use between 1 and 5 additional smaller boats called dories or dinghies. The total number of licensed fishing boats tallies around 600, including about 400 dories. Of the 240 licences, 187 held individual transferable quotas (ITQ) sharing the current annual 578.013 t total quota (Queensland total allowable commercial catch: TACC). In total 53 licences held no quota and were not permitted to harvest Spanish mackerel for commercial purposes.

The commercial fishing sector in New South Wales waters is small compared to Queensland. Spanish mackerel generally only school and feed in New South Wales waters during summer and autumn. Harvests of Spanish mackerel were first reported in 1937 at 8 t (Campbell et al. 2012; O'Neill et al. 2018). Annual harvests built steadily to 52 t in 1989. Harvests reduced to below 13 t per year between 2000 and 2009, returned back to 40 t in 2015, and has since dropped to 6 t in 2018 (Langstreth et al. 2018). Since the 1970s the number of commercial fishing operations harvesting Spanish mackerel from New South Wales waters was approximately 50 vessels per year.

Information on fishing efforts and harvests from the non-commercial fishing sectors varied in time and quality. Historical fishing by charter and recreational operations were not well known or frequently reported. In Queensland there were 322 active licensed charter operations in April 2021 (Department of Agriculture and Fisheries 2021), with many setup for offshore fishing. Measures of recreational fishing in Queensland have been surveyed periodically since 1997 suggesting 14 000–33 000 boat-days per year have been expended catching east coast Spanish mackerel (Higgs 2001; Henry et al. 2003; Higgs et al. 2007; McInnes 2008; Taylor et al. 2012; Webley et al. 2015; Teixeira et al. 2021).

For all fishery sectors, additional rules apply to limit fishing pressures such as the current 75 cm minimum total fish length for all kept Spanish mackerel and recreational in possession fish bag-limits (Table 1.1).

Table 1.1: History of east coast Spanish mackerel management in Queensland and New South Wales

Year	Management	Legislation
Queensland		
18 April 1957	Introduced a minimum legal size (MLS) of 18 inches (45.72 cm) for Spanish mackerel. This provision commenced on 1 January 1958	*Fisheries Act 1957*
16 Dec 1976	MLS amended to 45 cm for Spanish mackerel	*Fisheries Act 1976*
1 Jan 1988	Commercial logbook database began	
22 May 1990	Recreational fishers prohibited from selling any of their catch	
25 Jun 1993	MLS increased to 75 cm for Spanish mackerel and introduction of recreational in-possession limit of 10 fish	*Fishing Industry Organisation and Marketing Regulation 1991*
15 July 1994	Amendment to allow twice the in-possession limit for Spanish mackerel, as part of the reef fish provisions, if taken during an extended fishing charter (extended fishing charters occur over a continuous duration of 48 hours or more)	*Fishing Industry Organisation and Marketing Regulation 1991*
21 Feb 2003	Investment Warning for Spanish mackerel issued	

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Table 1.1 – *Continued from previous page*

Year	Management	Legislation
12 Sep 2003	Amendment to set a recreational in-possession limit of three fish. The amendments also introduced a total allowable catch of 619 520 units (1 unit equals 1 kg) and an individual transferable quota management system for the commercial sector. These amendments took effect on 1 July 2004.	*Fisheries Regulation 1995*
1 July 2004	The Great Barrier Reef Marine Park Authority (GBRMPA) revised the reef zonings and expanded the Representative Areas Program (RAP). The zoning process gave consideration for the importance of Spanish mackerel fishing and five key reefs remained open to fishing (Tobin et al. 2014).	*Great Barrier Reef Marine Park Zoning Plan 2003*
28 May 2019	Recreational boat limits set to two times the possession limit to a total of six Spanish mackerel per boat (these boat limits do not apply to charter fishers)	*Fisheries Declaration 2019*
	The total allowable commercial catch (TACC) stands at 578 013 kg following cancellation of units and the 2014 surrender of units bought by the former Australian Government Department of Environment, Water, Heritage and the Arts as part of the structural adjustment package for the Representative Area Program for the Great Barrier Reef introduced in July 2004.	
New South Wales		
1 Jul 1998	Bag limit of five introduced (comprised all of Spanish mackerel or all of spotted mackerel or partly of each)	*Fisheries And Oyster Farms Act 1935 – Regulation*
3 Sep 2007	The minimum legal length of Spanish mackerel of 75 cm total length was introduced in NSW	*Fisheries Management (General) Amendment (Prohibited Size Fish and Bag Limits) Regulation 2007 under the Fisheries Management Act 1994*

A number of stock assessments have evaluated fishing pressures on east coast Spanish mackerel (O'Neill et al. 2000; Hoyle 2002; Welch et al. 2002; Hoyle 2003; Campbell et al. 2012; O'Neill et al. 2018). For results up to the 2016 fishing year, estimated Spanish mackerel spawning population sizes were 30–50% of 1911 levels depending on the data analysed (O'Neill et al. 2018). This report also concluded that fishing pressure was too high to allow the population to increase in size, or to improve/increase catch rates. Recommendations were noted to reduce fishing pressure on Spanish mackerel to increase fish abundance, catch rates and protection of spawning aggregations.

Tobin et al. (2014) described the decline of historically important Spanish mackerel spawning aggregations from waters east of Cairns, as well as a reduction in the size and frequency of spawning aggregations in waters out from Lucinda. The data were further examined by Buckley et al. (2017), who concluded a significant reduction in the number of Spanish mackerel spawning aggregations and a long term decline in commercial catch-rates in the Lucinda region. Logbook data show about 40% of the Queensland commercial harvest was generally taken from the Lucinda region during the well-known September–November spawning season. Significant proportions of harvest were also taken recreationally and by charter operations from the broader Cairns–Townsville region.

In 2020 the Queensland Department of Agriculture and Fisheries commissioned an updated stock assessment for east coast Spanish mackerel. This stock assessment evaluates historical trends in data for the east coast of Australia, estimates spawning population biomass and predicts target harvest reference points for the stock. The report informs fishery management agencies and stakeholders on estimates of sustainable harvest that will build and maintain the fishery in the long term.

2 Methods

2.1 Data sources

Data sources included in this assessment (Table 2.1) were used to determine fish catch rates, age and length compositions, and annual harvests. Data sets were compiled by fishing year[1] (July–June) and all references to year should be assumed to be fishing year, unless stated otherwise. The assessment period began in 1911 up until and including 2020 based on available information.

Table 2.1: Data used in the Spanish mackerel stock assessment

Type	Year	Source
QLD commercial	1989–2020	Logbook data collected by Fisheries Queensland
	1937–1981	Historical Queensland Fish Board Data (O'Neill et al. 2018; Campbell et al. 2012)
QLD recreational	1997, 1999, 2002, 2005	RFish recreational fishing surveys conducted by Fisheries Queensland (Higgs 2001; Higgs et al. 2007; McInnes 2008)
	2011, 2014, 2020	Statewide Recreational Fishing Survey conducted by Fisheries Queensland (Taylor et al. 2012; Webley et al. 2015; Teixeira et al. 2021).
	2001	Recreational fishing surveys conducted by the Australian Department of Agriculture, Fisheries and Forestry (the National Recreational and Indigenous Fishing Survey, NRIFS) (Henry et al. 2003).
	2016–2020	Boat ramp survey, conducted by Fisheries Queensland
QLD charter	1997–2020	Logbook data collected by Fisheries Queensland
NSW commercial	1985–2020	Logbook data collected by New South Wales Department of Primary Industries, Fisheries
NSW recreational	2001, 2014, 2018	New South Wales survey using similar methodology to the NRIFS (West et al. 2015; Murphy et al. 2020)
Historical surveys	1941–2013	Historical fishing information (decadal catch rates and fishing power changes) collected by Buckley et al. (2017)
Biological data	2005–2020	Biological monitoring (age and length) undertaken by Fisheries Queensland
Lunar	1989–2020	Continuous daily luminous scale of 0 (new moon) to 1 (full moon) (O'Neill et al. 2014)
Wind	1989–2020	Weather data collected by Bureau of Meteorology

2.1.1 Regions

One degree latitude bands were used to stratify data for analyses, from 12° S (Lockhart, QLD) to 34° S (Port Stephens, NSW) (Figure 2.1). Region names are added to the map for reference. All report commentary refers to east coast fish and does not include adjacent Torres Strait or Gulf of Carpentaria fish stocks.

[1] Fishing year naming convention is to reference the calendar year during which the fishing year ended, that is, fishing year 2020 is July 2019 to June 2020.

In general, approximately 90% of historical annual harvests of east coast Spanish mackerel were taken from Queensland waters compared to New South Wales, with approximately half of Queensland commercial harvest taken from the key spawning region of Lucinda (latitude band 19).

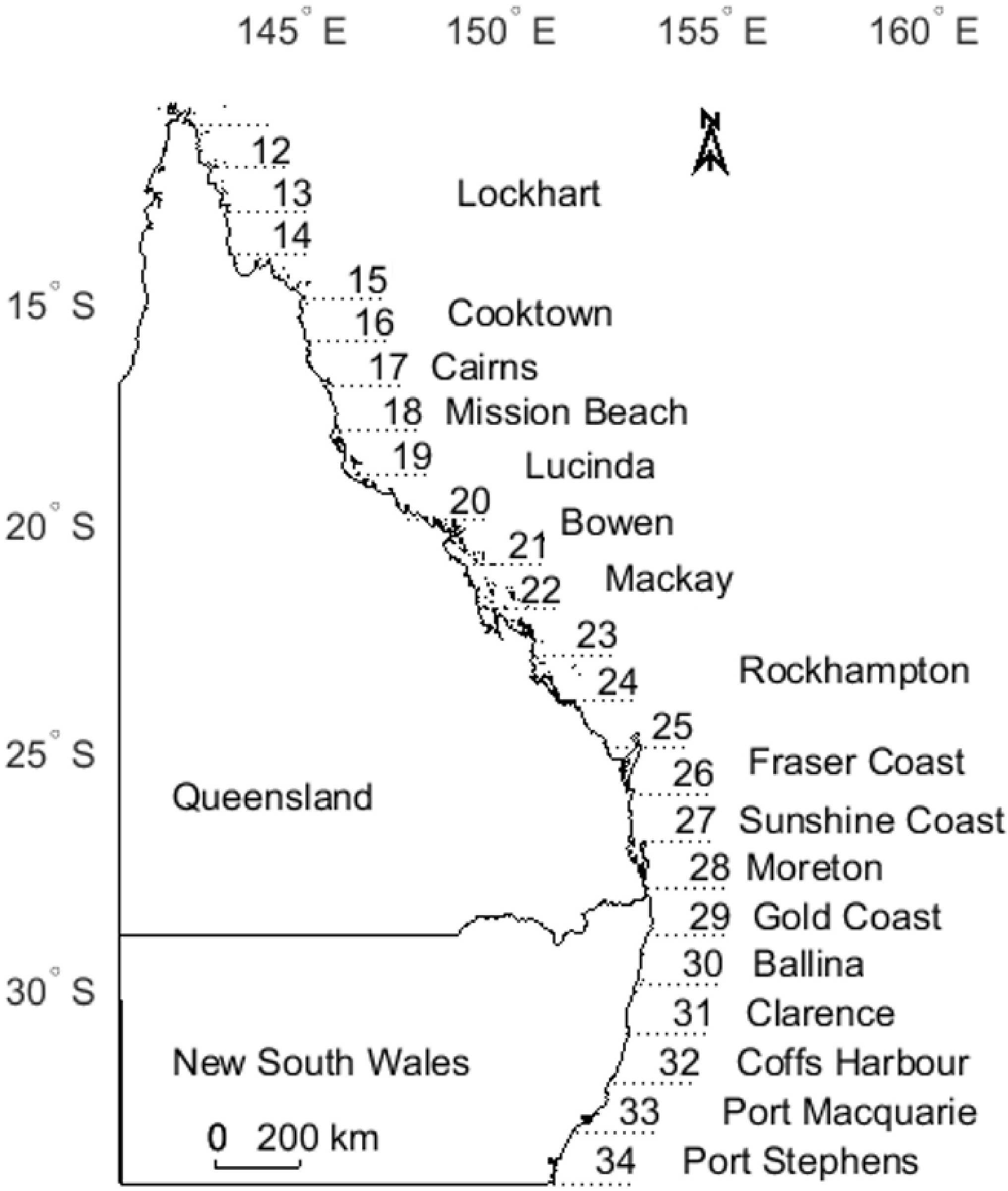

Figure 2.1: Spatial stratification for the catch rate standardisation analysis

2.1.2 Commercial

The Queensland Fish Board data documented monthly and annual commercial landings of Spanish mackerel for 45 years from 1937 to 1981. The harvest tonnages were originally published in annual reports of the various fish boards responsible for marketing and distributing fish in Queensland. The data were digitised in the early 2000s. No fishing effort data were available to complement the fish landings data. For the stock modelling, it was assumed the fish board tonnages of Spanish mackerel were relatively complete and taken from along Queensland's east coast (Campbell et al. 2012).

Between 1989 and 2020, Queensland commercial harvests of Spanish mackerel were recorded through the compulsory logbook system. The data consisted of the daily fish harvest (in kilograms) by species from each fishing operation. The spatial resolution of where fish were harvested was based on 30×30 minute latitudinal and longitudinal grids, which were grouped into one degree latitude bands.

Commercial harvest (in kilograms) of Spanish mackerel from New South Wales waters was recorded through compulsory logbook systems from 1985 to 2020. From 1985 to 2009 monthly harvests by species were reported per fishing operation. The procedure changed to daily reports in 2010. The spatial resolution of where fish were harvested was based on one degree latitude bands.

2.1.3 Recreational

All recreational surveys provided estimates of the number of fish harvested and discarded per trip, and combined this with demographic information to estimate annual totals for each species (or species group) at state and regional scales. See the references listed in Table 2.1 for more detail.

The statewide methods used telephone surveys of random households to estimate recreational fishing participation, catch and effort. Logbook records of fish catches and fishing effort were maintained by a sample of fishing households. Fishing data were demographically weighted to estimate total catches of fish and fishing effort by factors such as key species, seasons and coastal regions.

Surveys conducted in 2001, 2011, 2014 and 2020 had more effective follow-up contact procedures with survey participants, resulting in less dropout of participants compared to the other survey years using RFish methodology (Lawson 2015).

In 2001, 2014 and 2018 statewide surveys of recreational fishing were completed for New South Wales waters. The survey methods were equivalent to those used in Queensland.

Through boat ramp surveys, recreational data were collected by Fisheries Queensland in 18 different regions, extending from Aurukun to the Gold Coast. Fifteen of these regions were along the Queensland east coast, with Cooktown being the northern most region. Staff trained in the survey protocol, and identifying fish, interviewed recreational fishers at boat ramps during a survey shift. The surveys recorded day and location fished, catch of key species (including discards) and length of retained key species (Northrop et al. 2018; Fisheries Queensland 2017). These data were used to inform recreational discarding behaviour.

2.1.4 Charter

Harvests of Spanish mackerel taken by Queensland charter vessels were recorded through the logbook system from 1997 to 2020. This provided the operator identifier, the date, the location fished, retained catch by species (recorded by weight) and the number of guests on the trip.

2.1.5 Historical

Commercial mean decadal relative catch rates from Thurstan et al. (2016), from 1941 to 2013, were evaluated in the stock assessment. Given the sample size of data and verification testing completed in separate published papers (including the previous stock assessment by O'Neill et al. (2018)), the dataset was incorporated at the decadal time-scale.

2.1.6 Age and length compositions

Fish age-length compositions of Spanish mackerel were sampled over a number of years by fishery monitoring and research programs. The details of sampling were documented by Sumpton et al. (2004), Tobin et al. (2004), Campbell et al. (2012) O'Neill et al. (2018), and Fisheries Queensland (2021).

The monitoring program has been conducted since 2000. In 2000–2002 sampling was focused solely on Spanish mackerel that were commercially fished in the Lucinda area during the spawning season in October/November (Sumpton et al. 2004). From 2005, sampling was increased to be temporally and spatially expansive covering both commercial and recreational harvests of Spanish mackerel in Queensland (Tobin et al. 2004; Campbell et al. 2012). Sampling of age data (otoliths collection) has been in operation since fishing year 2002 (Sumpton et al. 2004). Opportunistic collection of age data from New South Wales (2009–2020) has been included.

2.2 Harvest estimates

Commercial, charter and recreational harvest and data were analysed to reconstruct the history of harvest from 1911 (prior to which east coast Spanish mackerel harvest is presumed to be small) until the end of 2020. This section describes how these data were combined to create the history of Spanish mackerel harvest. All harvest is retained (landed) unless stated otherwise. Figure 2.2 shows a graphical overview of the methods used to reconstruct the harvest history for this assessment.

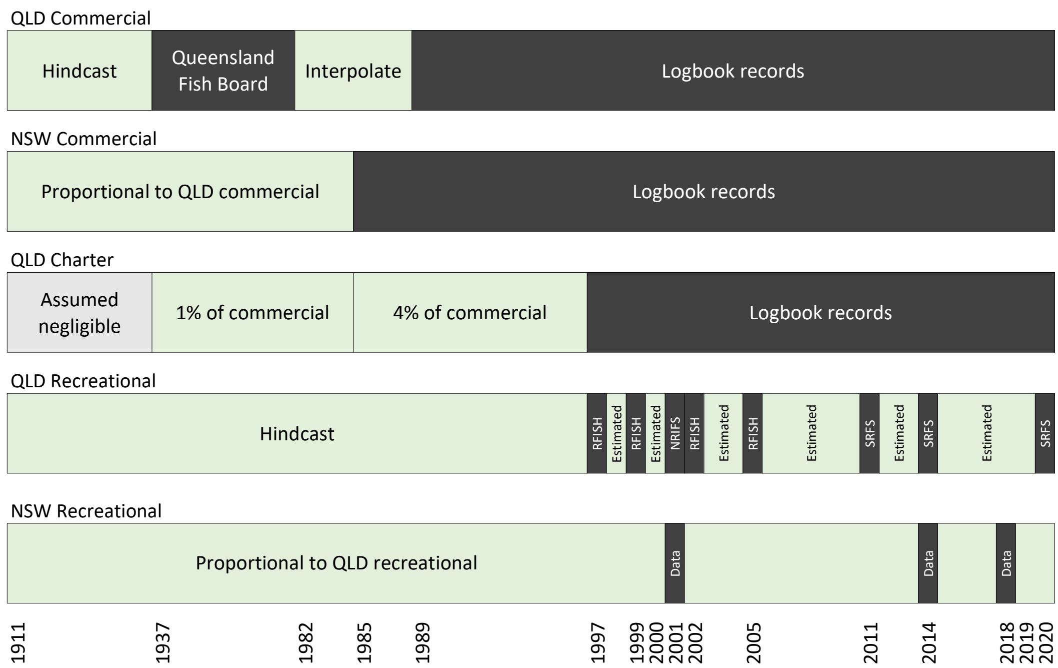

Figure 2.2: Overview of the methods used to estimate harvests

2.2.1 Commercial harvest

Queensland commercial sector harvest:

- equalled logbook values from 1989 through 2020.
- were linearly interpolated from 1982 to 1988, using coefficients based on the best fit of available harvests in each year 1973–1996 (from O'Neill et al. (2018) and Campbell et al. (2012)).
- equalled Queensland Fish Board records from 1937 to 1981.
- were hindcasted from 1911 to 1937. The preceding year's Queensland commercial harvest C_{t-1} starting from 1937, was calculated back in time to 1911 by reducing the annual tonnage by the power of 0.985 ($C_{t-1} = C_t^{0.985}$)(Campbell et al. 2012; O'Neill et al. 2018).

New South Wales commercial harvest:

- equalled New South Wales logbook values from 1985 to 2020.
- prior to 1985 was estimated based on the geometric mean of the proportion of New South Wales to Queensland commercial harvest between 1985 and 2009 (Campbell et al. 2012; O'Neill et al. 2018). For these years the proportion was 2.7%, showing the magnitude of commercial New South Wales harvests was small compared to those from Queensland waters.

2.2.2 Charter harvest

As per the previous assessment (O'Neill et al. 2018), Queensland charter sector harvest:

- estimates equalled Queensland charter logbook values from first records in 1997 through to 2020.
- estimates were assumed to be equivalent to 4% of the commercial take from 1985 until 1996.
- estimates were assumed to be equivalent to 1% of the commercial take from 1937 until 1984.
- was assumed to be negligible prior to 1937.

2.2.3 Recreational harvest

Queensland recreational catches (numbers of kept and released fish) of Spanish mackerel were estimated using data from eight statewide surveys (telephone-logbook surveys) (Table 2.1), and annual changes in fishing power, boat registrations and catch rates.

Estimates from the RFish surveys in 1997, 1999, 2002 and 2005 had higher participant drop out. This may bias the mean catch rates and fishing effort upwards and result in an overestimate of recreational fish catches. To account for this bias, a simple ratio method from Leigh et al. (2017) was applied to reduce RFish catch estimates to better align with the 2001, 2011, 2014 and 2020 surveys:

$$c_{2001}/(\frac{2}{3}c_{1999} + \frac{1}{3}c_{2002}). \tag{2.1}$$

The RFish catch adjustments were calculated at 0.340 for harvested and 0.256 for released Spanish mackerel. The assumption in this scaling was that the RFish estimates were overstated by the same fraction in all survey years in which the RFish methodology was employed.

Released survey estimates of Spanish mackerel were tallied into the recreational harvest. A 50% discard mortality rate was assumed on released fish. No research has quantified discard mortality rates of Spanish mackerel, but observations by scientists and fishers suggest that discard mortality is high. The decision to included discard mortality on released fish was based on information from the Department of Fisheries, Western Australia. Anecdotal evidence there suggested high post-discard mortality due to stress of capture (Western Australian Government 2016). A rate higher than 50% was not considered as the addition of spurious harvest may risk overestimating sustainable harvest. Survey released-fish estimates can be biased upwards due to the time lag and poor memory recall of fish numbers by anglers (Lyle 1999; Connelly et al. 2011).

All of the Queensland recreational surveys (other than the 2011 survey) had records of "unspecified mackerel". For each survey, the ratio of known Spanish mackerel to total identified mackerel (i.e. Spanish, grey, school, shark and spotted mackerel combined) was applied to the total number of unspecified mackerel, and these were added to the Spanish mackerel catch. This method was applied to kept and released fish separately. In the 1997 RFish survey all mackerel were unspecified, so a conservative ratio of 12% was applied, which was the minimum of all RFish unspecified mackerel ratios.

Estimates of kept and released fish were predicted for years with no survey information. This was required for the population modelling in order to estimate time-series trends of Spanish mackerel. The methods were based on Bessell-Browne et al. (2018) and Lovett et al. (2020), with the following calculations:

1. Catches prior to 1997 were hindcast from the mean of the known 1997, 1999, 2001 and 2002 survey estimates. Hindcasting was scaled proportional to:
   - the trend in boat registrations (effort pre-1991 $\sim$ Poisson GLM back in time based on 1991–2008 data),
   - fishing power scenario (years prior to 1951 were set equal to the 1951 fishing power estimate), and
   - catch rates (decadal pre-1989 and standardised annual rates post-1988).

   The proportional trend was relative to the scale = 1 in 1997.
2. Catches after 1997 were estimated by annual commercial catch rates multiplied by mean fishing effort. Mean effort was calculated from the known survey catches divided by their annual standardised catch rate.

Queensland recreational harvest:

- estimates for 1997, 1999, 2002, and 2005 were set to equal the values from the rescaled RFish estimates and the methods described above.
- estimates for 2001, 2011, 2014 and 2020 were set to equal the values calculated using the NRIFS (2001) and SRFS (2011, 2014 and 2020) surveys and the methods described above.
- were hindcasted from 1911 to 1997 using calculation 1, above.
- estimates for between survey years, 1998, 2001, 2003–2004, 2006–2010, 2012–2013 and 2015–2019, were calculated using calculation 2, above.

New South Wales recreational harvest:

- was equal to the Queensland recreational harvest rescaled by the ratio of New South Wales to Queensland recreational catch, over the years for which NSW data were available. This ratio was 0.23.

The harvest from the recreational surveys was reported in numbers of fish. These numbers were converted into total weight of fish, using the average fish weight. The average fish weight was calculated separately for kept and released fish. For kept fish between 2005 and 2020 the average fish weights were calculated each year using the monitoring length data. Prior to 2005, the average fish weight was defined as the average of all fish caught recreationally from 2005 to 2020 (without grouping by year). This average weight for all years is 7.80 kg.

For released fish, the boat ramp survey data showed that approximately 33% of reported Spanish mackerel were released between 2016 to 2020, and that only 2.3% of sampled fishers were at, or over, the bag limit. The statewide recreational fishing survey data indicated that 29% of caught Spanish mackerel were released, and 51% of those were released because they were "too small" (according to either fisher preference or MLS) and a further 6% were released for being below MLS. This suggests that fish were being released due to being undersized. Thus, the average weight of a released fish was defined as the weight of a fish 1 cm below the minimum legal size of 75 cm. This translates to 2.11 kg (for a 74 cm fish). This weight was considered to be a mid-point that accounts for undersize and oversize fish being released.

2.3 Abundance indices

Relative trends in legal-sized Spanish mackerel abundance were inferred from Queensland commercial logbook data. The logbook data provided commercial line catch rates (kg whole weight) of Spanish mackerel per fishing-operation day.

The catch rate index informed proportionally on the annual change in abundance of legal-sized Spanish mackerel. This was a primary assumption for the stock assessment. The assumption of proportionality was made only after catch rates were standardised for factors affecting fish catchability and fishing efficiency (Hilborn et al. 1992).

O'Neill et al. (2018) described why catch rates were standardised and the critical factors. This was to address the issues of hyperstability and missing fishing effort data (zero catches not reported, and no data on the number of locations, gears and hours fished per fishing operation day). The main factors considered to lessen these issues were:

- annual changes in fishing power to examine how increased fishing effort and improved gears and technologies affect catch rates.
- a probability model to overcome the non-reporting of zero catches. Walters (2003) suggested presence-absence data may aid in dealing with suspect hyperstability. This was applied in the previous stock assessment and the approach was endorsed at the time by the scientific advisory committee (Campbell et al. 2012; O'Neill et al. 2018).

From the initial logbook data, a series of filters were applied to obtain the Spanish mackerel data for catch rate standardisation. The filters used criteria relating to species, location, fishing method, fishing date and trip duration. The filtering process is detailed in Appendix A.4.

The catch rate information was analysed in relation to two components/models defining mean catch rates $E(c)$:

$$E(c) = p(c)E(c|c > 0), \qquad (2.2)$$

where the first component ($p(c)$) measured the availability and capture of fish according to the probability and the second component ($E(c|c > 0)$) was for where a weight of fish was caught and retained (i.e. $c > 0$).

The models used to standardise catch rates of Spanish mackerel were completed using the software GenStat (VSN International 2020). The analyses used generalised linear (GLM) and linear mixed (LMM) models. The LMM used the 'REML' (restricted maximum likelihood) algorithm allowing for model terms that can contain both fixed and random effects. The variables modelled included effects of:

- fishing year ($year$),
- latitude band ($latband$),
- seasonal variables ($s1 - s6$),
- wind component variables ($windew, windns$),
- lunar phase variables ($lunar, lunar\_adv$),
- number of fishing operations ($nACN$), and
- fishing operations (ACN).

The analyses were defined based on:

1. A probability model (GLM for predicting $p(c)$) for catching Spanish mackerel by the commercial fleet.
2. A catch rate model (for harvests > 0; $E(c|c > 0)$) incorporating annual changes (offsets) in fishing power to examine how increased fishing effort and improved gear technologies affect catch rates. In analysis, the fishing power offset was a logarithm value.

The probability model, a binomial GLM with logit link function, was specified as:

$$\begin{aligned} log\left(\frac{p(c)}{1-p(c)}\right) =& year * latband + latband.s1 + latband.s2 + latband.s3 + latband.s4 + \\ & latband.nACN + windew + windew^2 + windns + windns^2 \end{aligned} \tag{2.3}$$

where the data were structured per month, using average monthly wind components, and the model was run for both additive and interaction effects between year and latband (the interaction form was noted in the above equation).

The catch rate LMM model, for when Spanish mackerel were caught, was specified as:

$$\begin{aligned} log(catch\_offset) =& year * latband + latband.s1 + latband.s2 + latband.s3 + latband.s4 + latband.s5 + latband.s6 + \\ & latband.lunar + latband.lunar\_adv + windew + windew^2 + windns + windns^2 + random(ACN) \end{aligned} \tag{2.4}$$

where the data were structure per fishing-operation day, $log(catch\_offset)$ was calculated as $log(catch) - log(fp)$, fp was the annual proportional fishing power to be log offset, and the ACN fishing operation factor was treated as random variable.

The annual proportional fishing powers were estimated per year and region in the previous stock assessment (Figure 14 in O'Neill et al. (2018), reproduced in Appendix A.7). No new data were available, and the 2015–2020 fishing powers were assumed equal and unchanged. Two fishing power offsets were considered: 1) based on the actual data provided by fishers (full fishing power), and 2) a square root estimate (about half fishing power effect).

The square root scenario recognised potential fishing power increases, but this was a constrained effect to account for possible overestimation. This was in consideration that each fishing gear effect, which was suggested by fishers, may not truly be independent full add-ons to fishing power. The fishing power data represented increased use in global positioning systems, colour depth sounders, down riggers and baiting technique (Appendix Table 14 and Figures 38–29 in O'Neill et al. (2018)).

In total four different annual indices of fish abundance for 1989–2020 were calculated from the Queensland commercial line data. The four results evaluated the effects of possible hyperstability (either no adjustment—i.e. constant probability of catching Spanish mackerel—or adjusted for $p(c)$) and increased fishing power offset (labelled 'half' for a reduced square root increase, or 'full' for a full increase as suggested by the data). Catch rates with half fishing power with probability adjustment (for hyperstability) were selected as a base case for the model and others were used in sensitivity analyses.

The prediction of standardised mean catch rates of Spanish mackerel was formed using GenStat's 'PREDICT' and 'VPREDICT' procedures for the GLM and LMM models respectively (VSN International 2020). Mean catch rates (log_prediction$_{y,a}$) were predicted from the model terms fishing year $(y) \times$ latitude band area (a), keeping all other model terms constant. Logarithm predictions were biased corrected and back transformed:

$$c_{y,a} = \exp(\text{log\_prediction}_{y,a} + \frac{\sigma^2}{2} + \text{log\_offset}_{2020} \pm 1.96 \times \text{log\_prediction\_se}_{y,a}), \tag{2.5}$$

where $c_{y,a}$ is the catch rate for year y at latitude band area a, σ^2 was the residual model variance, log_prediction_se$_{y,a}$ was the prediction standard error, and the ± component is upper and lower 95% confidence intervals. The term log_offset$_{2020}$ corresponded to the fishing power setting in year 2020 and the se label was the standard error.

Final predictions were normalised annually as proportions measured against the fishing year 1990. Ninety-five percent confidence intervals were calculated for all predictions.

The seasonality of Spanish mackerel catch rates was modelled using sinusoidal data to identify the time of year. In total six trigonometric covariates were considered, which together modelled an average seasonal pattern of catch rates (Marriott et al. 2014): $s_1 = \cos(2\pi d_y/T_y)$, $s_2 = \sin(2\pi d_y/T_y)$, $s_3 = \cos(4\pi d_y/T_y)$, $s_4 = \sin(4\pi d_y/T_y)$, $s_5 = \cos(6\pi d_y/T_y)$, $s_6 = \sin(6\pi d_y/T_y)$, where d_y was the cumulative day of the year and T_y was the total number of days in the year (365 or 366).

The wind direction and strength data were from representative coastal weather stations along Queensland east coast and spatially referenced to one-degree latitude bands. The recorded measures of wind speed (km hour^{-1}) and direction (degrees for where the wind blew from) were converted to daily components between 3 am and 3 pm. The north-south ($windns$) and east-west ($windew$) wind components were:

$$windns = \text{km hour}^{-1} \times \cos(\text{radians(degrees)}), \text{ and}$$

$$windew = \text{km hour}^{-1} \times \sin(\text{radians(degrees)}). \tag{2.6}$$

The wind components were used to standardise Spanish mackerel catch rates for different wind directions and strengths. The component functions considered the wind directions as degrees measured clockwise from true north such that:

- 0° or 0 radians = North,
- 90° or $\pi/2$ radians = East,
- 180° or π radians = South, and
- 270° or $3\pi/2$ radians = West.

Two lunar variables estimated the variation in Spanish mackerel catch rates according to the moon phase (i.e. contrasting waxing and waning patterns of the moon phase). The lunar phase (luminance) was a calculated measure of the moon cycle with values ranging between 0 (new moon) and 1 (full moon) for each day of the year (Courtney et al. 2002; Begg et al. 2006; O'Neill et al. 2006). The luminance measure ($lunar$) followed a sinusoidal pattern and was copied and advanced 7 days ($\sim \frac{1}{4}$ lunar cycle) into a new variable ($lunar\_adv$) to quantify the cosine of the lunar data (O'Neill et al. 2006).

2.4 Biological information

2.4.1 Fork length and total length

All length measurements were provided in either fork length (FL), total length (TL) or jaw length (JL) and the population model was run using FL.

The following conversions by Mackie et al. (2003) and Fisheries Queensland (unpublished) were applied where necessary:

$$TL = 42.74 + (1.06 \times FL) \tag{2.7}$$

$$FL = (TL - 42.74)/1.06 \tag{2.8}$$

$$FL = 2193.05 - 2488.95 \times (0.99376283^{JL}) \tag{2.9}$$

where TL is total length (mm), FL is fork length (mm) and JL is jaw length (mm).

2.4.2 Fecundity and maturity

Model inputs of fecundity and maturity of Spanish mackerel were taken from relationships determined by Sumpton et al. (2004):

$$\text{eggs} = 76539 \times \text{kilogram of fish.} \tag{2.10}$$

Maturity values in the model were length-based, following a logistic function with coefficients obtained from Mackie et al. (2005) and Begg et al. (2006):

$$mat = \frac{exp(-10.349 + 0.0128FL)}{1 + exp(-10.349 + 0.0128FL)}$$

where mat is maturity and FL is fork length (cm). The age-dependent maturity was calculated from length-dependent maturity within Stock Synthesis using age-length transition matrix (Methot et al. 2013). The first mature age was set as two years of age.

2.4.3 Weight and length

The weight-length relationship was taken from Mackie et al. (2003):

$$WW = 3.40 \times 10^{-9} \times FL^{3.12} \tag{2.11}$$

where WW is whole weight (kg) and FL is fork length (mm).

2.5 Population model

A population model was fitted to the data to determine the number of Spanish mackerel in each year and each age group using the software package Stock Synthesis (SS; version 3.30.16.00). A full technical description of SS is given in Methot et al. (2020).

Biological monitoring data indicated a growth difference between the sexes with females growing larger than males. The population model was therefore set up as a two-sex model.

2.5.1 Model assumptions

The main assumptions underlying the model included:

- The Australian east coast stock is reproductively isolated.
- The standardised catch rate index inform proportionally on the annual change in abundance of legal-sized Spanish mackerel.
- The fishery began from an unfished state in 1911.
- The fraction of fish that are female at birth is 50% and fish do not change sex during their life.
- Growth occurs according to the von Bertalanffy growth curve.
- The weight and fecundity of Spanish mackerel are parametric functions of their size.
- The first mature age is at 2+ years, after which the proportion of mature fish depends on size.
- The proportion of fish vulnerable to fishing depends on their size, not age, fishing sector nor time.
- The instantaneous natural mortality rate does not depend on size, age, year or sex.
- Deterministic annual recruitment is a Beverton-Holt function of stock size.

2.5.2 Model parameters

A variety of parameters were included in the model, with some of these fixed at specified values and others estimated. No prior distributions were used for the estimated parameters, unless stated otherwise.

Table 2.2: Parameters fixed or estimated in the model

Parameter	Value	Prior / Reference
Beverton-Holt unfished recruitment (logarithm of the number of recruits in 1911)	Estimated	No prior
Beverton-Holt stock recruitment steepness (h)	0.45	Thorson (2020)
Fork length at age 1 (FL_1) (male and female)	Estimated	No prior
Fork length at maximum age (FL_{inf}) (male and female)	Estimated	No prior
von Bertalanffy growth parameter (κ) (male and female)	Estimated	No prior
Coefficient of variation in length at age 1 (male and female)	Estimated	No prior
Coefficient of variation in length at maximum age (male and female)	Estimated	No prior
Natural mortality (NatM, M)	Estimated	Then et al. (2015)
Commercial selectivity inflection (cm)	Estimated	No prior
Commercial selectivity width (cm)	Estimated	No prior
Standard deviation of natural log recruitment (σ_R)	0.35	O'Neill et al. (2018)

Natural mortality (M) was estimated in the model, initially with a log-normal prior. This prior had a (natural scale) median value of 0.29 and standard deviation of 0.1. This prior was based on the meta-analytical approach from Then et al. (2015). The prior is defined as a log-normal distribution with a median value (corresponding to the mean in log-space) equal to $4.899 \times A_{max}^{-0.916}$ and logscale standard deviation equal to 0.1. While the oldest fish in the dataset provided was 26 years old, the maximum age was considered to be 22 years old (the second oldest fish) for the calculation of the prior. This placed the natural mortality at 0.29, which was in between the two scenarios considered in O'Neill et al. (2018) in which M was fixed to 0.25 and 0.33. Once model optimization became stable, M was attempted to be estimated without a prior.

Beverton-Holt stock recruitment steepness (h) was fixed at a value of 0.45, based on the meta-analysis of Thorson (2020). Table 4 of Thorson (2020) lists a steepness value of h=0.69 for the Scombridae family, however Figure 3 of the same paper indicates great variation in steepness at the genus level (*Scomberomorus*). The R package "*FishLife*" was used to extract the steepness value for the *Scomberomorus* genus (h=0.45) from the meta-analysis described in the paper. Different levels of h were tested as sensitivity analyses.

Standard deviation of natural log recruitment (σ_R) was fixed at 0.35, based on the recruitment variability estimated in the previous assessment (O'Neill et al. 2018). Recruitment deviations between 1989 and 2018 improved fits to composition data and abundance indices as variability in recruitment annually allowed for changes in the population on shorter time-scales than fishing mortality alone.

2.5.3 Model weightings

All data inputs were given equal weighting in the model, however, Francis weighting of age and length data within Stock Synthesis was completed (Francis 2011).

2.5.4 Sensitivity tests and scenarios

Several additional model runs were undertaken to determine sensitivity to fixed parameters, assumptions and model inputs (Table 2.3).

Four catch rate scenarios were explored (as described in Section 2.3): two which included a probability adjustment to prevent hyperstability and two which did not. These catch rate scenarios also affected the recreational harvest reconstruction.

Table 2.3: Scenarios tested to determine sensitivity to parameters, assumptions and model inputs

Scenario	Steepness	Natural mortality	Probability adjustment	Fishing power
1 (Base)	0.45	Estimated	Yes	Half
2	0.35	Estimated	Yes	Half
3	0.55	Estimated	Yes	Half
4	0.55	Estimated	No	Half
5	Estimated	0.33	No	Half
6	0.65	Estimated	No	Half
7	0.45	Estimated	Yes	Full
8	0.45	Estimated	No	Full

The values of steepness (h) that were explored in this assessment were chosen to align with range of estimated values in O'Neill et al. (2018).

In addition to the scenarios presented in Table 2.3, two additional scenarios were explored to address the issue of shark depredation using the base case catch rates and steepness fixed at 0.45 and 0.55. Full details of this scenario are presented in Appendix F.

2.5.5 Forward projections

Stock Synthesis's forecast sub-model was used to provide forward projections of biomass and future harvest targets, following a 20:60:60 harvest control rule. This rule (also known as a hockey stick rule), has a linear ramp in fishing mortality between 20% spawning biomass, where fishing mortality is set at zero, and 60% exploitable biomass, where fishing mortality is set at the equilibrium level that achieves 60% biomass (F_{B60}). Below 20% spawning biomass fishing mortality remains set at zero, and above 60% spawning biomass fishing mortality remains set at F_{B60} (Figure 2.3). This shifting rate of fishing mortality starts out small, which enables the stock to recover much more quickly and means that harvests are impacted for a shorter period. This assessment did not include a discount factor to account for uncertainty in recommended target estimates as the Fisheries Queensland Spanish Mackerel Fishery Working Group and fishery management will evaluate whether to apply discount factors to recommended biological catch.

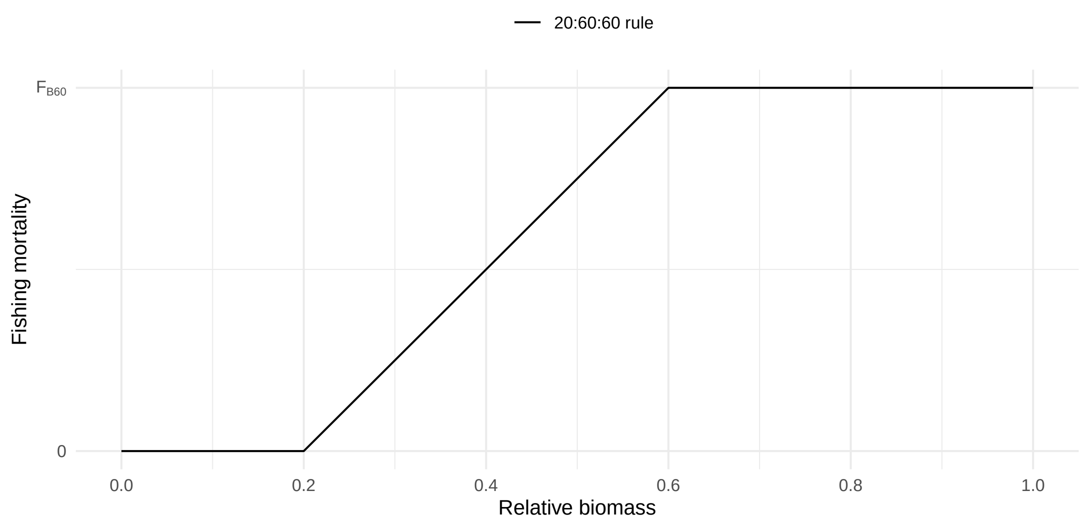

Figure 2.3: The 20:60:60 harvest control rule

3 Results

3.1 Model inputs

Figure 3.1 summarises the assembled data sets input to the model. Note that standardised catch rates and decadal catch rates were included as abundance indices in Stock Synthesis, and they were denoted as “Fleet” and “Survey”, respectively.

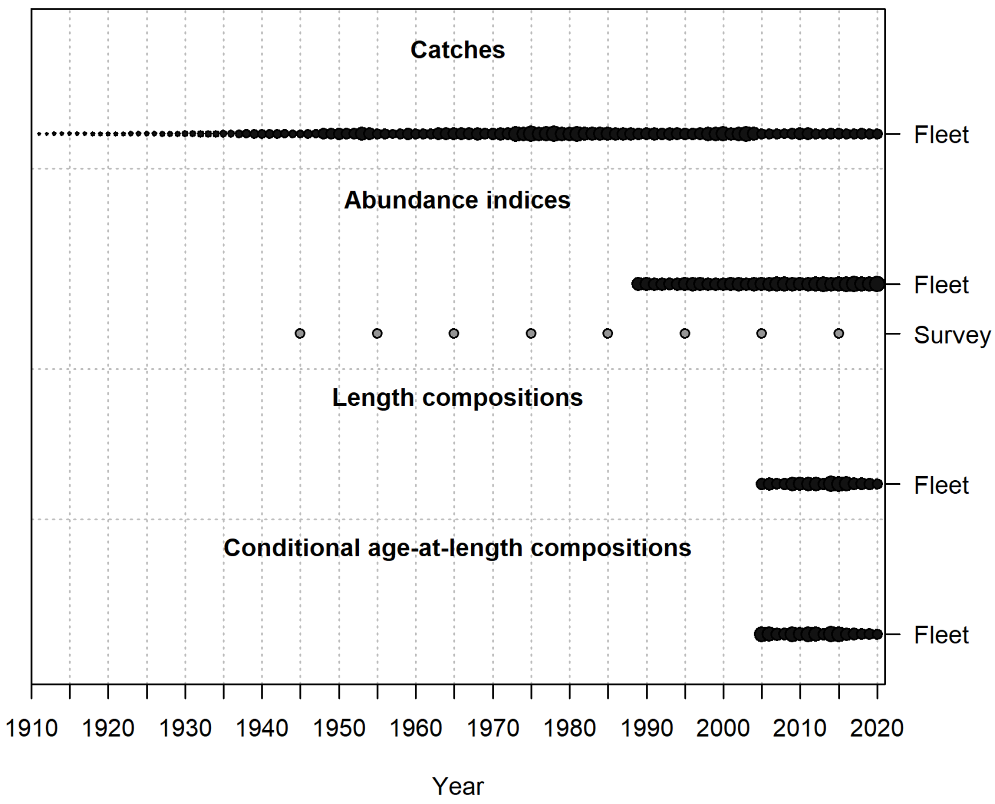

Figure 3.1: Data presence by year for each category of data type for east coast Spanish mackerel

3.1.1 Harvest estimates

Total combined harvest from commercial, recreational (including assumed discard mortality) and charter sectors in Queensland and New South Wales is shown in Figure 3.2. Harvest shares for each sector in years when recreational fishing surveys were conducted are shown in Table 3.1.

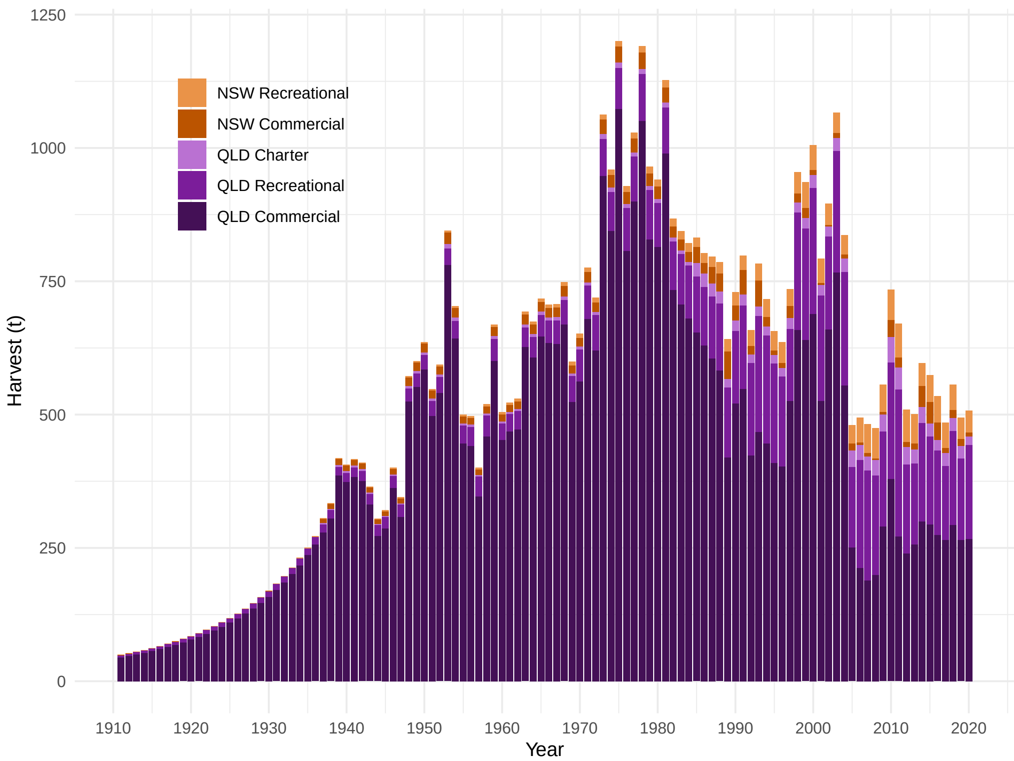

Figure 3.2: Annual estimated harvest from commercial, recreational and charter sectors between 1911 and 2020 for Spanish mackerel

Table 3.1: Harvest shares per sector (including "QLD discard mortality") expressed in kilograms with annual percentages

Sector	2001	2014	2020
QLD Commercial	525 945 (66.4%)	299 872 (50.3%)	266 565 (52.5%)
QLD Charter	20 207 (2.6%)	30 041 (5.0%)	16 650 (3.3%)
NSW Commercial	3 384 (0.4%)	39 703 (6.7%)	7495 (1.5%)
NSW Recreational	45 535 (5.7%)	42 522 (7.1%)	40 626 (8.0%)
QLD Recreational	189 577 (23.9%)	164 229 (27.5%)	166 272 (32.8%)
QLD discard mortality	7748 (1.0%)	20 037 (3.4%)	9778 (1.9%)

The harvest estimates peaked over the periods 1973–1981 and 1998–2004 with a mean harvest of 993 t. The majority of the total harvest was attributed to the commercial sector until early 2000s, before the commercial line harvest quota (total allowable commercial catch: TACC) was introduced in 2005. Since then, the estimated total harvest has reduced to around 500–600 t per year (except in 2010 and 2011).

In Queensland waters, annual commercial harvests of Spanish mackerel ranged around 400–780 t between the years 1989 and 2004. These harvests declined greatly to range around 200–380 t since the introduction of the TACC. Most commercially harvested fish were taken from offshore waters north of Bowen (North and Townsville regions in Figure 3.3). The TACC was considerably under filled for all years 2005–2020 (Figure 3.3).

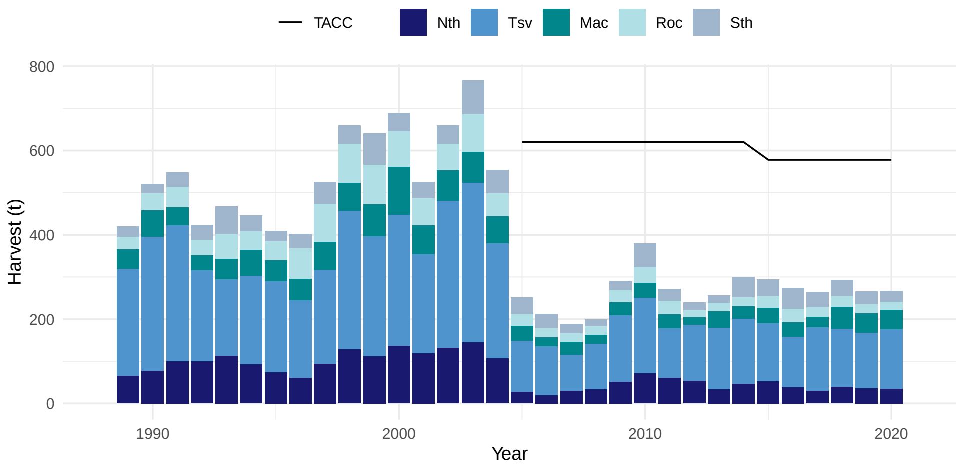

Figure 3.3: Total harvests of Spanish mackerel by fishing year as reported by commercial line fishing operations in Queensland waters—the graph coloured areas were: North (Nth) latitudes 12–17, Townsville (Tsv) latitudes 18–20, Mackay (Mac) latitudes 20–22, Rockhampton (Roc) latitudes 23–25 and South (Sth) latitudes 25–29

Figure 3.4 shows the Queensland recreational harvest reconstruction in more detail.

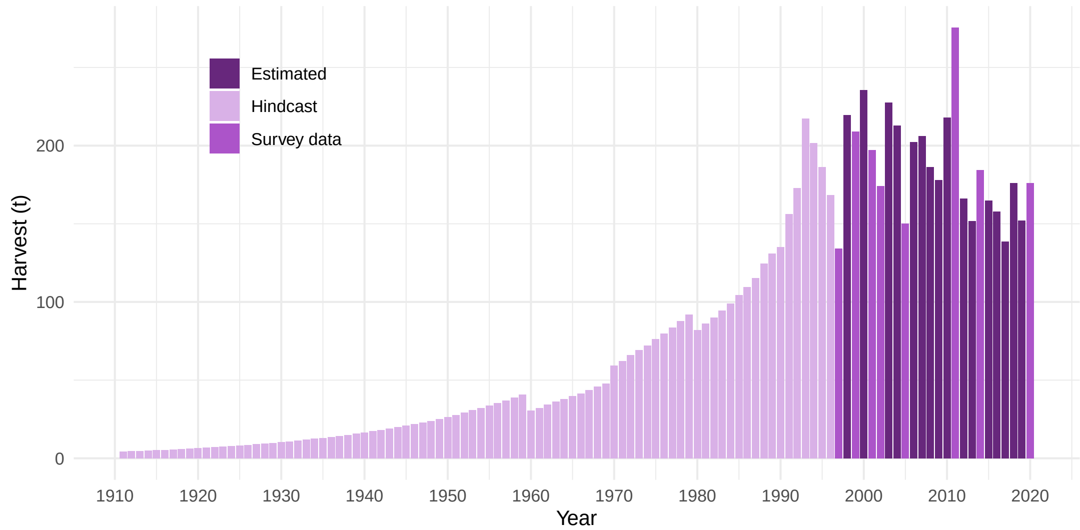

Figure 3.4: Annual estimated harvest from the recreational sector between 1911 and 2020 for Spanish mackerel

3.1.2 Standardised catch rates

The analyses described in Section 2.3 resulted in four catch rate scenarios (Figure 3.5). Model diagnostics were satisfactory (Tables C.1, C.2, Figures C.1 and C.2).

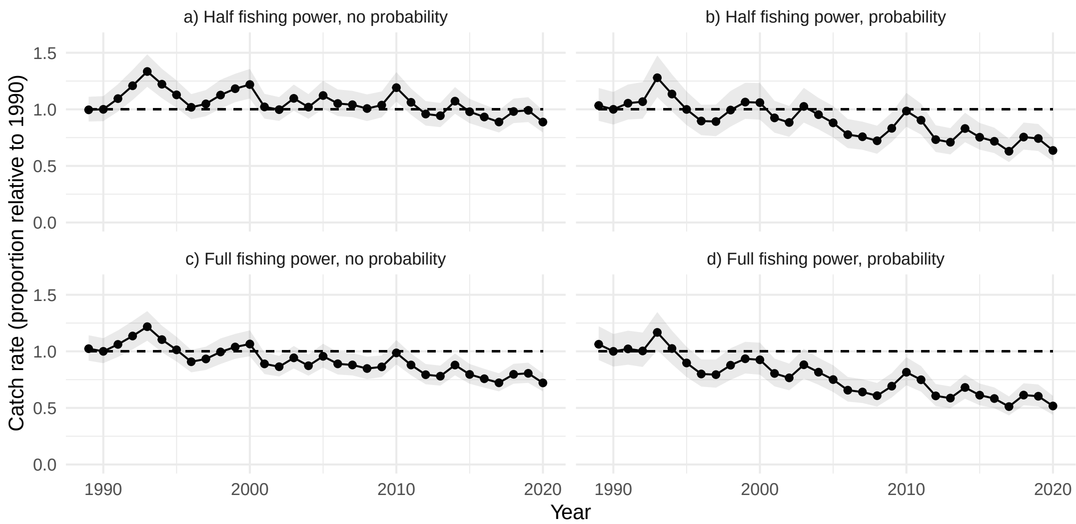

Figure 3.5: Annual standardised catch rates (95% confidence intervals) for Queensland commercial line-caught Spanish mackerel between the years of 1989 and 2020, for four scenarios

Figure 3.5b shows the base case that was selected. The base case assumed half fishing power and included the probability model (Figure C.3). Discussions within the project team agreed that half fishing power was considered appropriate to account for fishing power and that probability adjustment was important to account for the hyperstability nature of the fishery. This base case shows a mid-range scenario, as opposed to a more stable (Figure 3.5a) or declining outcome (Figure 3.5d). The base case scenario shows a downward trend over the whole time series, ending with a catch rate of about 60% of that at the start of the time series.

Scenarios 4–6 explored the effect of using the higher standardised catch rates (half fishing power without probability model) (Figure 3.5a). The trend in this optimistic catch rate is quite flat but still with an overall slightly downward trend. Standardised catch rates with full fishing power—with and without probability adjustment—was tested in Scenarios 7 and 8, respectively.

Figure 3.6 shows the historical decadal catch rates that were input into the model. Only one data point per decade was entered into the model.

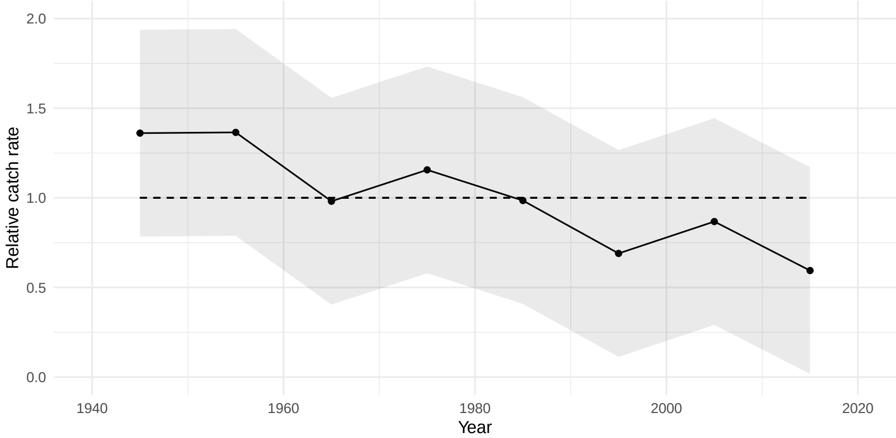

Figure 3.6: Historical decadal catch rates (relative to average) for commercial line-caught Spanish mackerel between the years of 1945 and 2015—shade indicates 95% confidence intervals

3.1.3 Age-at-length

The age data were input as conditional age-at-length in the population model (Figures A.1–A.2). Age composition of Spanish mackerel analysed by the monitoring team is provided in Appendix D.

3.1.4 Length composition

Fishery sex-based length compositions were input to the population model (Figures 3.7–3.9).

Figure 3.7: Annual length compositions of female Spanish mackerel for fish caught between 2005 and 2020 in Queensland in all sectors combined

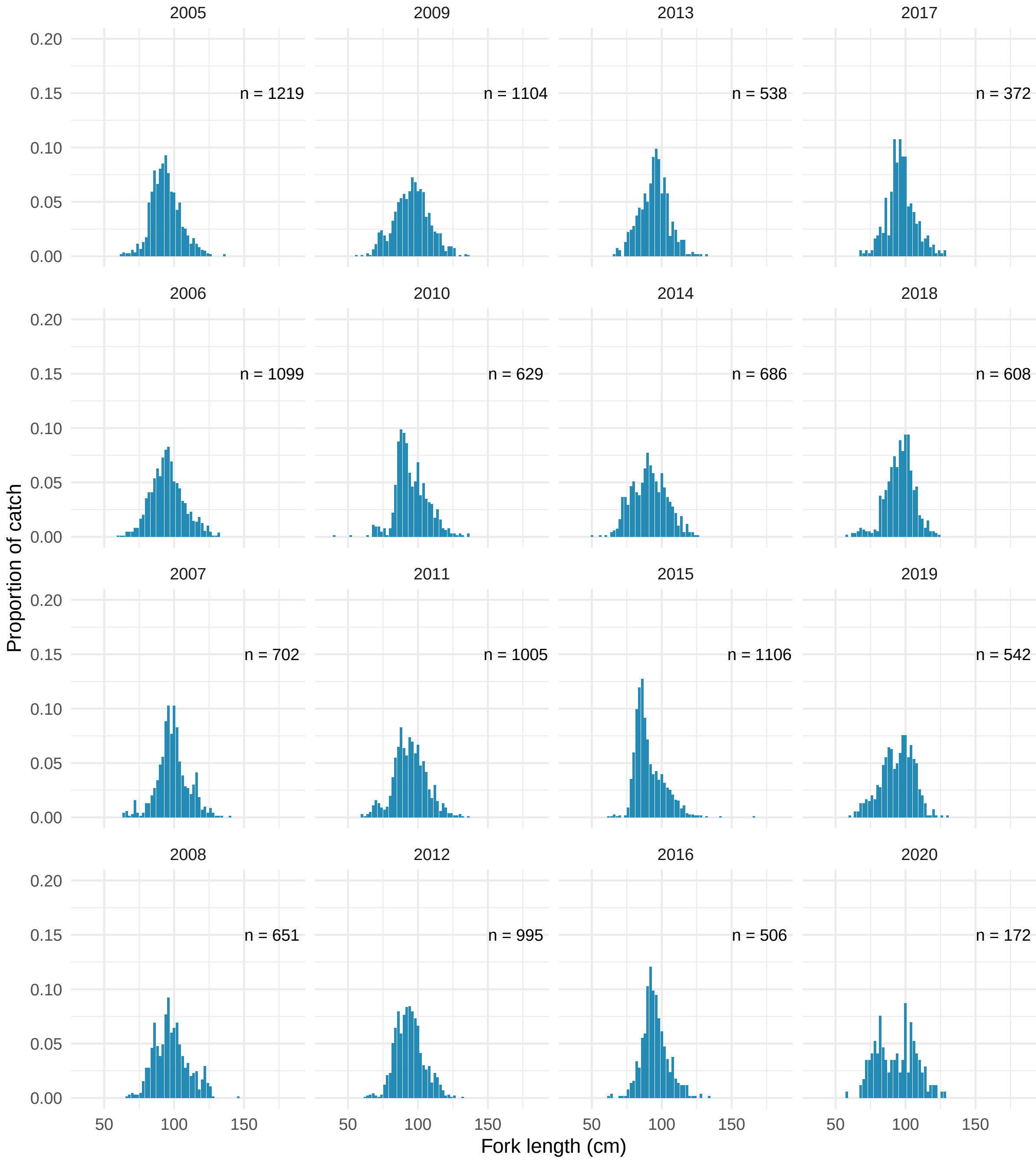

Figure 3.8: Annual length compositions of male Spanish mackerel for fish caught between 2005 and 2020 in Queensland in all sectors combined

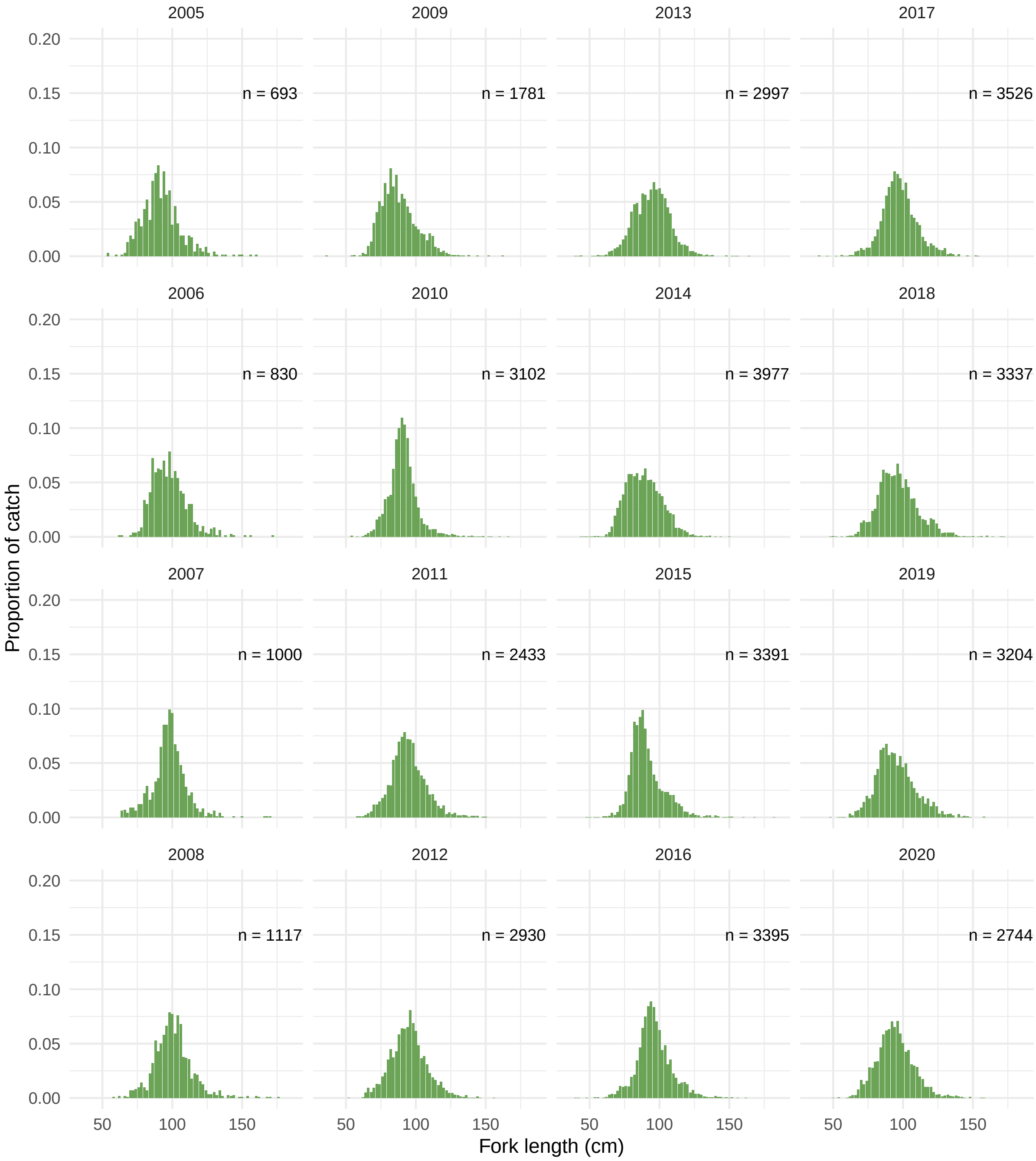

Figure 3.9: Annual length compositions of unknown-sex Spanish mackerel for fish caught between 2005 and 2020 in Queensland in all sectors combined

3.2 Model outputs

3.2.1 Model parameters

Parameters estimated for the base case population model is shown in Table 3.2. No prior was used for natural mortality once the model had stabilised.

Table 3.2: Summary of parameter estimates for Spanish mackerel from the base population model

Parameter	Estimate	Standard deviation
Natural mortality per year	0.27	0.01
Fork length at age 1 (FL_1) female (cm)	66.9	1.39
Fork length at maximum age (FL_{inf}) female (cm)	130.19	2.38
von Bertalanffy growth parameter (κ) female	0.29	0.03
Coefficient of variation in length at age 1 female	0.07	0.01
Coefficient of variation in length at maximum age female	0.07	0.01
Fork length at age 1 (FL_1) male (cm)	65.97	1.28
Fork length at maximum age (FL_{inf}) (cm) male	114.18	1.29
von Bertalanffy growth parameter (κ) male	0.35	0.03
Coefficient of variation in length at age 1 male	0.08	0.01
Coefficient of variation in length at maximum age male	0.04	0.003
Beverton-Holt unfished recruitment (logarithm of the number of recruits in 1911)	13.3	0.05
Commercial selectivity inflection (cm)	81.28	0.9
Commercial selectivity width (cm)	11.46	1.34

3.2.2 Model fits

Good fits were achieved for all data sets including abundance indices, length compositions and conditional age-at-length (Appendices B.1).

3.2.3 Selectivity

Selectivity of Spanish mackerel in the east coast stock/fishery was estimated within the model. Estimated parameters suggest that 50% of Spanish mackerel are selected at 81 cm fork length, while 95% are selected at 93 cm (Table 3.2, Figure 3.10). These estimates suggest that Spanish mackerel are caught larger than the minimum legal size of 75 cm total length, which corresponds to approximately 67 cm fork length (Figure 3.10).

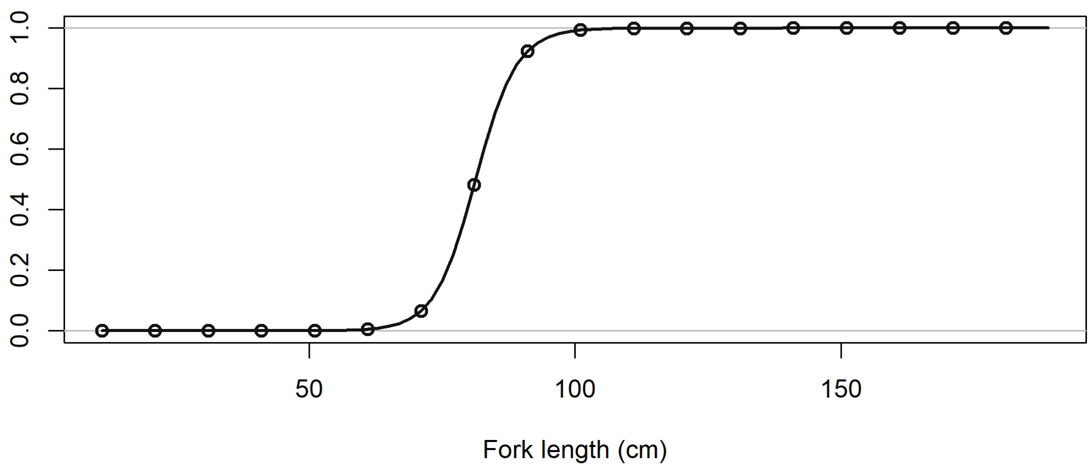

Figure 3.10: Model estimated length-based selectivity for Spanish mackerel in 2020

3.2.4 Growth curve

The von Bertalanffy growth curve, including coefficients of variation of old and young fish, was estimated within the model for both males and females (Table 3.2, Figure 3.11).

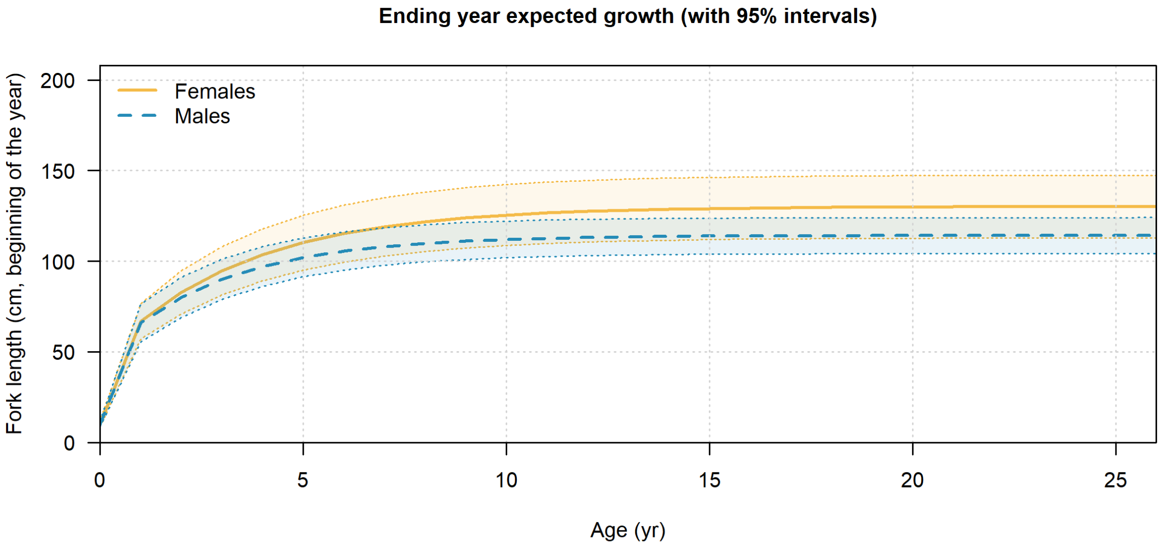

Figure 3.11: Model estimated growth curve for Spanish mackerel by sex in 2020

3.2.5 Biomass

The model predicted that the spawning stock biomass declined between the virgin state in 1911 to around 60% of unfished biomass in late 1960s. The spawning biomass sharply declined in 1970s and 1980s, reaching spawning biomass down below 30% of unfished biomass by 1990. Biomass level was relatively stable in 1990s at around 26% of unfished state, but further declined in early 2000s by 8–9%. The spawning biomass ratio has been around limit reference point B_{20} since 2005. In 2020, the stock level was estimated to be 17% unfished spawning biomass (Figure 3.12).

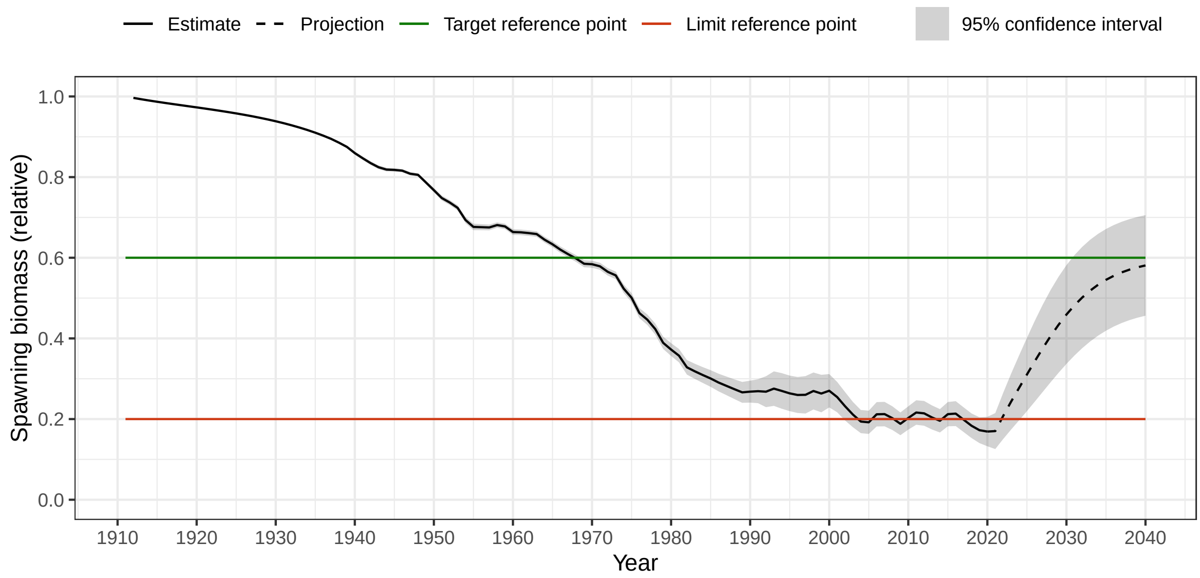

Figure 3.12: Predicted spawning biomass trajectory relative to virgin for Spanish mackerel, from 1911 to 2040

The relationship between the biomass estimate and fishing mortality are presented in a phase plot (Appendix B.2.1, Figure B.6).

The equilibrium yield curve informs on the productivity of the stock at different biomass levels (Figure 3.13).

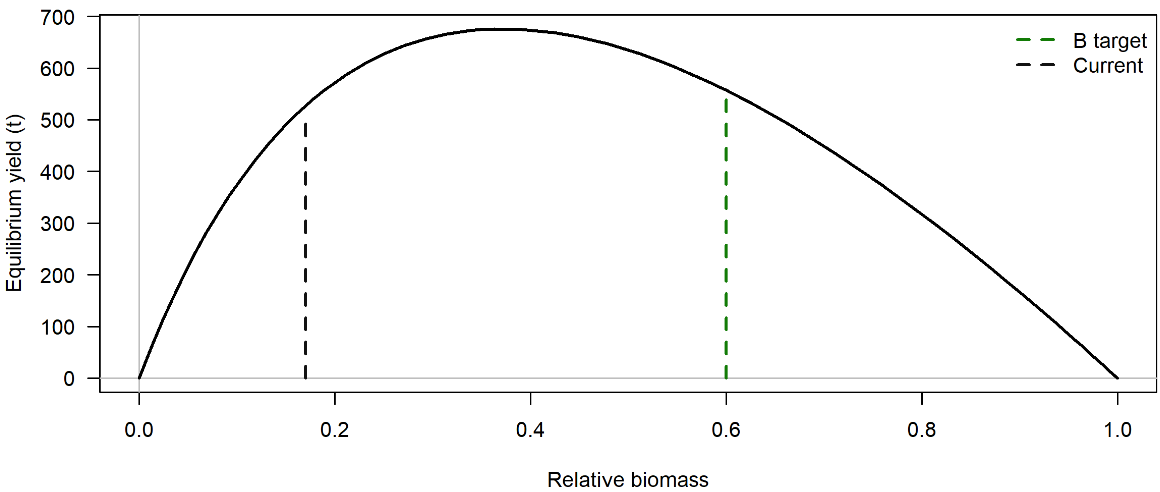

Figure 3.13: Equilibrium yield curve for Spanish mackerel

3.2.6 Harvest targets

Recommended biological catches (RBCs) to move the stocks to the desired level B_{60} are shown in Table 3.3. Note that RBCs are for all sectors and jurisdictions combined (including discard mortality).

Because the current biomass is less than B_{20}, the recommended limit is zero for the first year of rebuilding, rising to 283 t in 2030 and 515 t in 2040.

Table 3.3: Estimated total harvests and biomass ratios of Spanish mackerel for the base case to rebuild and maintain the stock at the target reference point of 60% unfished spawning biomass, following a 20:60:60 control rule

Year	RBCs (t)	Biomass ratio
2021	0	0.17
2022	4	0.21
2023	26	0.24
2024	53	0.28
2025	84	0.31
2026	120	0.34
2027	160	0.38
2028	201	0.41
2029	243	0.43
2030	283	0.46
2031	322	0.48
2032	357	0.5
2033	389	0.52
2034	417	0.53
2035	441	0.55
2036	462	0.56
2037	479	0.56
2038	493	0.57
2039	505	0.58
2040	515	0.58

3.2.7 Sensitivity

The eight scenarios presented in Section 2.5.4 all had parameters that were estimated cleanly (none hit their bounds), and final parameter gradients were small implying no convergence problems.

Table 3.4 shows the differences between model scenarios. Apart from scenario 6, spawning biomass ratio and sustainable harvest at B_{60} are relatively similar among different model runs, which indicate that the model results are, in general, not greatly sensitive to the parameter values that were fixed.

Table 3.4: Summary of the Spanish mackerel results from the base case and the sensitivity tests
Log-likelihood ($-\ln L$) values are not comparable as different Francis weighting was applied to individual scenario; biomass is presented as a ratio relative to an unfished state, and annual harvest values are in tonnes.

Scenario	h	M	Prob	FP	$-\ln L$	B_{2020}/B_0	Harvest at B_{60}
1	0.45	Est	Y	0.5	389.547	0.169	557
2	0.35	Est	Y	0.5	381.06	0.202	552
3	0.55	Est	Y	0.5	394.127	0.145	543
4	0.55	Est	N	0.5	349.142	0.205	543
5	Est	0.33	N	0.5	346.412	0.269	564
6	0.65	Est	N	0.5	370.121	0.574	759
7	0.45	Est	Y	1	370.851	0.144	564
8	0.45	Est	N	1	385.279	0.193	560

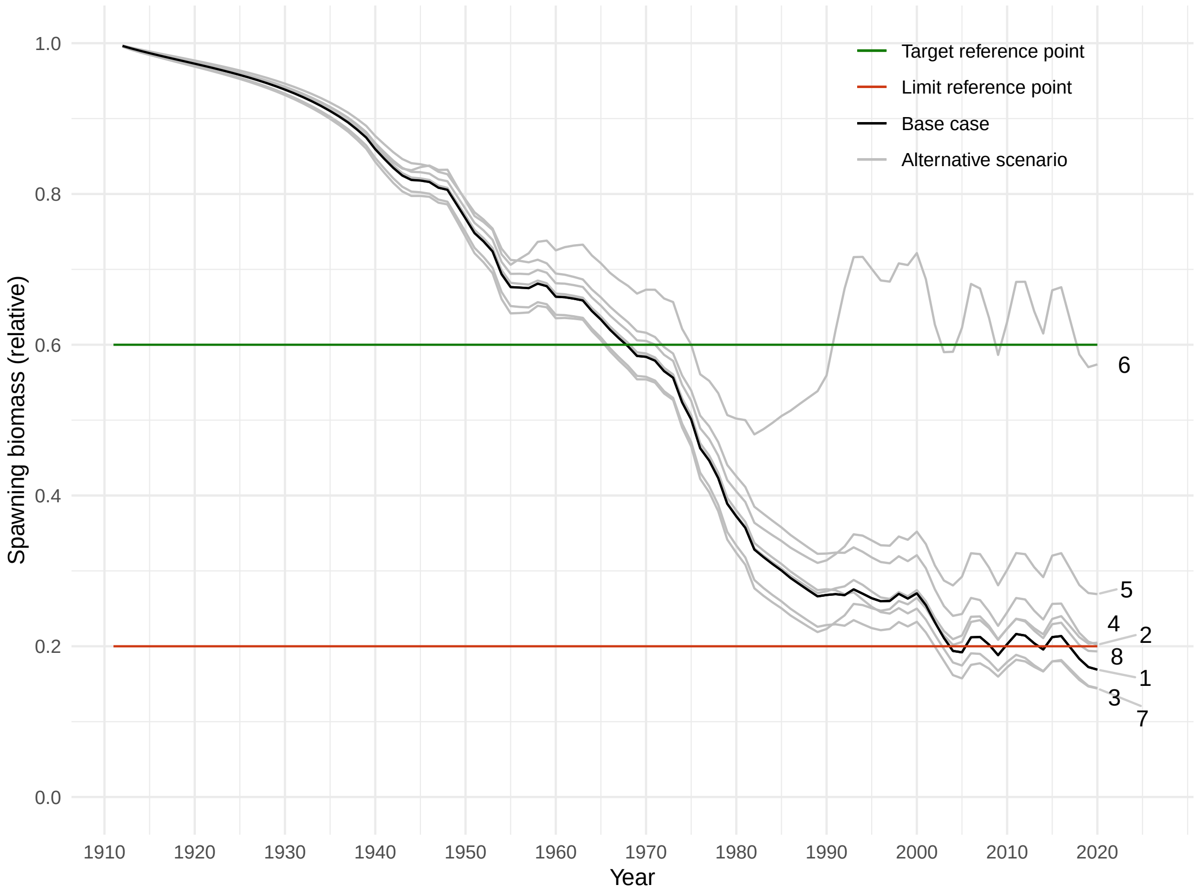

Figure 3.14: Predicted spawning biomass trajectory relative to virgin for Spanish mackerel, from 1911 to 2020 for all eight sensitivity tests—scenarios are summarised in Table 3.4

4 Discussion

4.1 Stock status

Results suggest there has been a long-term decline in the Spanish mackerel spawning population along the Australian east coast. The estimated large 1970s and early 2000s harvests (≥ 900 t) had strong depleting effects (see the slope of biomass decline during these years; Figure 3.12). The large harvests in 1998–2004 were just prior to new quota management. In these years there were on average an extra 24–69 commercial operations per year fishing, when the estimated Spanish mackerel spawning population size was around 30% in the base case. The drive to fish in the 1998–2004 years was a significant effect on the 2020 spawning biomass results. The results of the base case scenario suggest the spawning stock might be as low as 17% (±4%), which is below the limit reference point of 20%.

The numbers of spawning Spanish mackerel of the Lucinda region (latitude band 19) are believed to contribute substantially to the stock's overall reproduction level during the spawning months in spring (O'Neill et al. 2018; Buckley et al. 2017; Tobin et al. 2014). Levels of fish harvest remain significant in latitude 19, and the decreasing standardised catch rates suggest the Spanish mackerel spawning aggregation was reduced (Figure C.5). The low recruitment deviations, on new spawned fish, for 2014–2016 also contribute to the low spawning biomass result (Figure B.7)

4.2 Stock assessment uncertainties

Stock assessment scenario testing, using different data and model settings, can be effective to identify a range of possible results. Broader uncertainties can be found to identify best-case and worst-case solutions. Herein, the stock assessment model was run 8 times, with different settings of data inputs, model steepness and natural mortality (Table 2.3). This was to identify key assumptions, variations and uncertainties in the 2020 results. The key aspects that varied in analyses were four different time series of commercial catch rates, four settings of the reproductive rate steepness and different estimates of natural mortality.

For each model run the results for finding the parameter values that maximise the model fit to the data were presented (maximum likelihood solutions and asymptotic errors). From the range of results, two key states were noted:

- low spawning biomass ratios ranging 14–27% in 2020 (scenarios 1–5, 7 and 8; which were similar to the estimates in group 4 low spawning biomass results and settings (i.e. half fishing power with probability catch rate) in Figure 27 of O'Neill et al. (2018)), and
- high spawning biomass ratios 57% in 2020 (scenario 6; which was similar to the group 2 high spawning biomass results in Figure 27 of O'Neill et al. (2018)).

The highest 2020 spawning biomass result (B_{2020}/B_0) of 57% was associated with catch rates that were less standardised for fishing power and hyperstability considerations, matched with a resilient (high) reproductive rate steepness ($h = 0.65$), high natural mortality for reduced longevity (generally less than 10 years of age) and fishing mortality effect, and higher potential recruitment (virgin R_0) levels. Some of these aspects are questionable and for such a result to be likely, many schools of fish would be present to support harvests, catch rates, and a potential total fishery MSY of over 1000 t per year. However, the potential Queensland TACC of 578 t was only roughly half caught for many years since 2005.

In addition, there are a number of other aspects that might associate to the low biomass ratios:

- Spanish mackerel were aged to be longer lived up to 26 years. This was older than in the Gulf of Carpentaria and the Torres Strait, where both of these stocks of fish have been in decline towards limit reference points (O'Neill et al. 2021; Bessell-Browne et al. 2020).
- There has been a steady decline in catch rates of Spanish mackerel in stocks across northern Australia (O'Neill et al. 2021; Bessell-Browne et al. 2020).
- Recent environmental conditions might limit spawning success and survival rates or fish catchability, however no environmental data were readily available to test hypotheses (Section 4.3.1).
- Trends in catch rates generally suggested a lower resilient steepness parameter (h).

4.3 Unmodelled influences

There are a number of possible drivers of the Australian east coast Spanish mackerel population that have not been identified or fully understood. The following points should be taken into consideration when interpreting results. They give emphasis to ensure safe levels of harvest rates are enforced when fishing aggregations of Spanish mackerel.

4.3.1 Environmental influences

Little is known about the environmental drivers on stock size of Spanish mackerel. Particularly, we don't know the specific environmental conditions or cycles that affect Spanish mackerel survival, success of spawning to produce new young for the year, or the abundance of bait fish populations on which mackerel feed. Welch et al. (2014) indicated that spring sea surface temperature could potentially be a key environmental variable for Spanish mackerel, affecting recruitment by influencing the timing of spawning, egg production and larval survival, and potentially affecting growth and catchability. Long-term and ongoing declines in the primary productivity of waters off the east coast of Queensland (Richardson et al. 2020, FRDC Research Project Number 2019/013, in press) may be negatively impacting growth and survival of larval Spanish mackerel, or negatively impacting the abundance of bait fish on which juvenile and adult mackerel feed.

Declining trends in population size have been reported in Spanish mackerel stock in the Gulf of Carpentaria (Bessell-Browne et al. 2020) and other mackerel species in Queensland (Bessell-Browne et al. 2018; Lovett et al. 2019). Bessell-Browne et al. (2020) indicated that numerous warm water events in recent years might have influenced the recruitment and spawning location and timing of Spanish mackerel stock in northern Australia. The relationship between changing environmental conditions and Spanish mackerel recruitment and prey availability merits direct investigation, as these relationships have important implications for potential rates of recovery of the east coast Spanish mackerel stock. In particular, periods of elevated sea surface temperatures are predicted to become more severe and frequent with climate change (Cai et al. 2014; Wang et al. 2020), and are already implicated in significant environmental cascades, in which warmer conditions enhance water column stratification, limiting upwelling of nutrients and the primary productivity blooms on which higher organisms depend (Richardson et al. 2020).

In the Torres Strait, Spanish mackerel catch rates fell near 50% between 2009 and 2018 (O'Neill et al. 2021). Reductions in fish quota followed the downturn in catch rates. This may suggest an environmental influence on fish recruitment and/or survival. Levels of harvest alone could not explain the downturn, which has also been seen in other Spanish mackerel fisheries across northern Australia (Bessell-Browne et al. 2020).

4.3.2 Hyperstability

The predictable aggregation and movement of Spanish mackerel attract fishers in the same regions and seasons each year. When present, aggregated schools of Spanish mackerel on the surface ensures high catchability and makes them susceptible to overfishing. This behaviour also introduces the problem of hyperstability for stock assessments and management (Walters 2003; Campbell et al. 2012). This hyperstability means that catch rates can remain high, even when fish numbers in schools are decreasing (Walters 2003). Although corrections have been made when standardising catch rates through probability and fishing power adjustments, it is difficult to determine the full extent of its impact as seen in the variation in catch rate results when comparing different levels of adjustments (Figure 3.5).

4.4 Recommendations

4.4.1 Data

Early fish age monitoring data from the late 1970s and late 1990s were available from research projects by McPherson (1992) and McPherson (1993). However the sampling was spatially restricted to the spawning aggregation north of Townsville and not across the east coast. It is recommended that the methodology and suitability of these data be reviewed and standardised for consideration in the next assessment of this stock similar to methods used by AFMA Research Project Number: 2019/0831, in the Torres Strait.

The age-length data from 2000 to 2004 were also excluded as they were not representative of the entire east coast. It is recommended that these data be investigated and if possible, standardised for use in future assessments.

It is also recommended that the re-weighting/re-scaling of the age and length data is investigated for the next assessment. The regional stratification used to sample monitoring data is allocated proportionally to commercial catch. In practice, sampling can not always be stratified as intended, so data can be re-weighted to reflect this regional distribution. This assessment did not include re-weighting of monitoring data, however this should be considered in future assessments.

The quality of commercial data would be improved by accurate effort measures with fishing time and accurate location recorded for each commercial operation. More data should be collected regarding targeting species, zero catches and number of dories and hours fished each operation day. Electronic reporting systems and vessel monitoring system information may be valuable for achieving these objectives.

4.4.2 Monitoring and research

Continued annual monitoring of fish age and length structures, by fishing sector with spatial references, is required to support stock assessment and ensure accurate reference points for harvest strategies.

Information on trends in annual fish recruitment, from the fish age frequencies, improved our understanding of potential impacts of environmental variation on the population and would help to confirm the model predictions of poor recruitment in recent years.

Monitoring of the fished status of the Spanish mackerel spawning aggregation is important for determining the overall stock health. Fine scale details on fishing locations are required to understand potential localised fishing mortality, numbers of aggregations and densities of Spanish mackerel (O'Neill et al. 2018).

Shark depredation is increasingly being noted by many offshore line fishers in Queensland (Major 2020) yet its impact on Spanish mackerel harvests and catch rates are unknown. While a pilot depredation scenario was hypothesized and considered in Appendix F, more research is needed to quantify shark depredation affect on east coast Spanish mackerel fishery.

4.4.3 Management

The results of the assessment recommends that:

- action needs to be taken to rebuild the stock towards the Sustainable Fisheries Strategy biomass target of 60%.
- once the stock recovers to the target spawning biomass level, the annual sustainable harvest of Spanish mackerel be capped at the level for 60% spawning biomass for all fishing sectors and east coast waters combined (minus any discard mortality) (Table 3.3).

4.4.4 Assessment

Specific recommendations for a future Spanish mackerel assessment include:

- exploration of alternative recreational harvest reconstruction methods, such as the methodology developed by Holden et al. (2020),
- incorporating historical length and age data collected in late 1970s and 1990s in the model,
- review on monitoring data between 2000 and 2004 and re-examine their utility,
- investigation on the improvement of population modelling in Stock Synthesis for the steepness parameter and it's uncertainty, and consideration of age-based maturity.
- specific analysis on the spawning aggregation data.
- investigation on the effect of shark depredation rates.

Separate to the recommendations listed above, independent survey research is required to resolve stock assessment uncertainties on spawning biomass levels and the potential number of schools of fish to harvest. Suggested methods include extensive fish genetic tag-recapture or new close-kin mark-recapture (CKMR) research. CKMR has been applied to southern bluefin tuna, transforming its stock assessment and forming an ongoing key fishery independent index of fish abundance (Bravington et al. 2016; Davies et al. 2020). A successful and well executed CKMR study could provide estimates to verify levels of spawning biomass, natural mortality and potential fishery yields.

4.5 Conclusions

This assessment was commissioned to establish the status of Spanish mackerel on Australia's east coast and inform the *Sustainable Fisheries Strategy*. The most plausible scenarios suggested biomass is currently between 14 and 27% of unfished levels, and most likely at 17% and that the stock is in need of rebuilding. The results provide annual recommended biological catches (RBCs) using a 20:60:60 control rule. These RBCs aim to rebuild the spawning biomass towards the 60% level, consistent with the 2027 biomass targets set in the Queensland Government's *Sustainable Fisheries Strategy*. To achieve this, management procedures should review and consider options for input and output controls as noted by

Walters et al. (2004). This is to safe guard against excess fishing pressure and to mitigate effects on the breeding population leading to reduced production of fish eggs and recruitment.

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Appendix A Model inputs

A.1 Age and length sample sizes

These sample sizes are input to the model and form a starting point for data set weighting.

Table A.1: Sample size of fish measured and aged for input to the model for Spanish mackerel

Year	Length	Age
2005	3026	1366
2006	3028	1307
2007	2256	941
2008	2281	907
2009	3845	1341
2010	4465	1099
2011	4282	1443
2012	4968	1253
2013	4069	775
2014	5588	1520
2015	5723	1393
2016	4517	954
2017	4169	887
2018	4305	730
2019	3895	728
2020	3286	655

A.2 Conditional age-at-length

Conditional age-at-length composition data were input to the population model (Figures A.1–A.2).

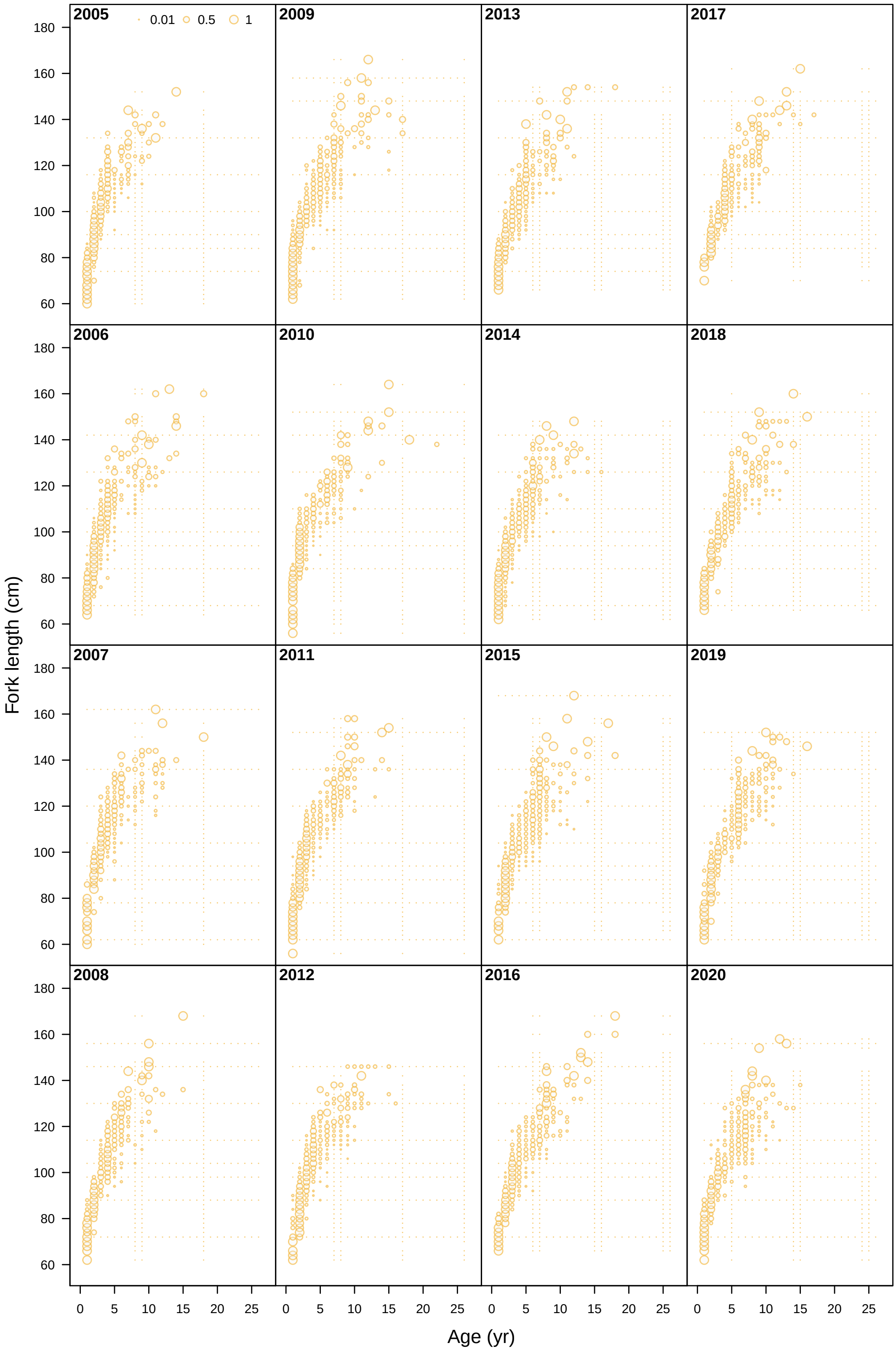

Figure A.1: Conditional age-at-length compositions of female Spanish mackerel between 2005 and 2020 —circle size is proportional to relative sample size in each bin across rows (i.e. for a given length bin)

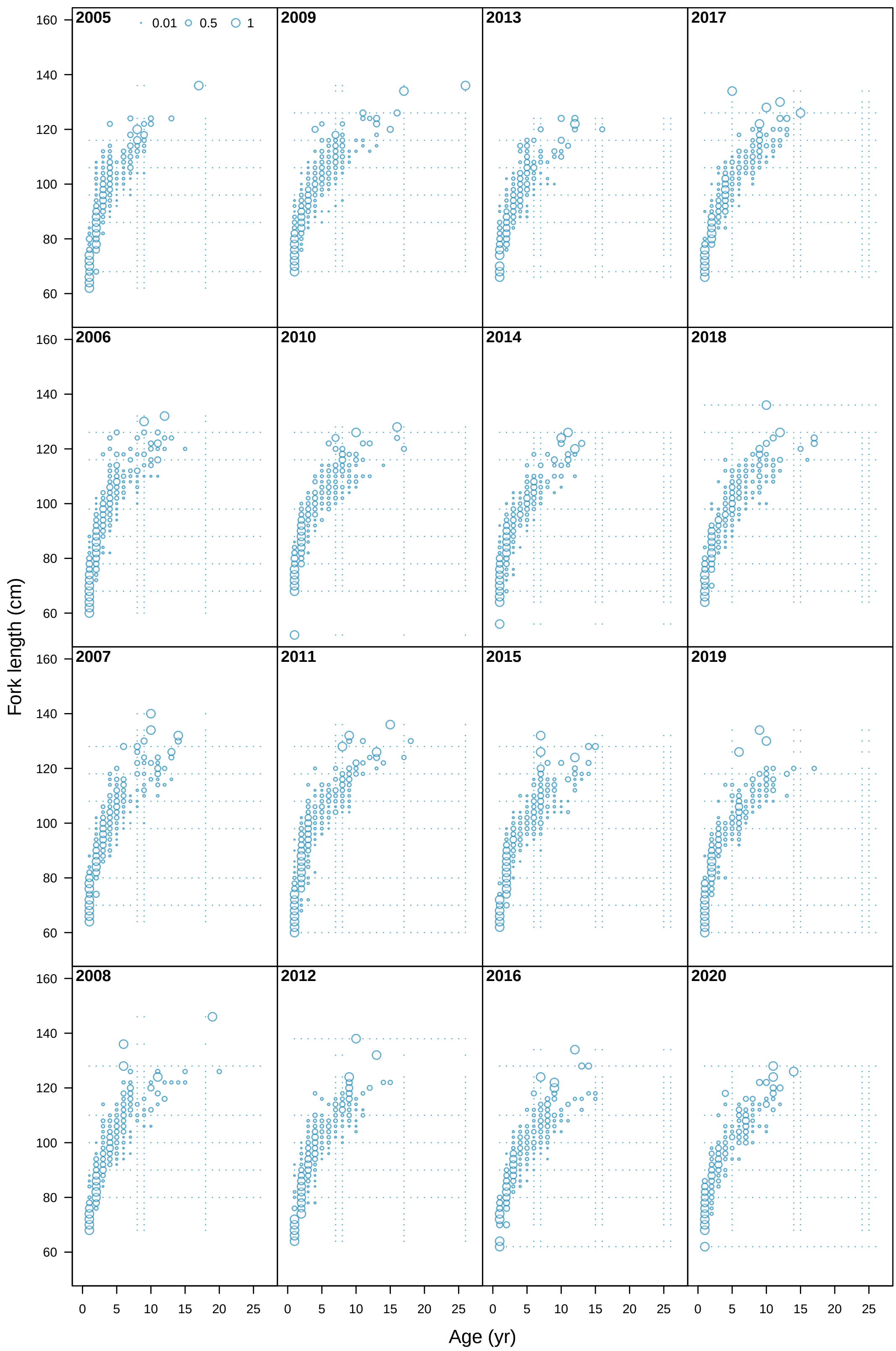

Figure A.2: Conditional age-at-length compositions of male Spanish mackerel between 2005 and 2020—circle size is proportional to relative sample size in each bin across rows (i.e. for a given length bin)

A.3 Biological data

A.3.1 Fecundity and maturity

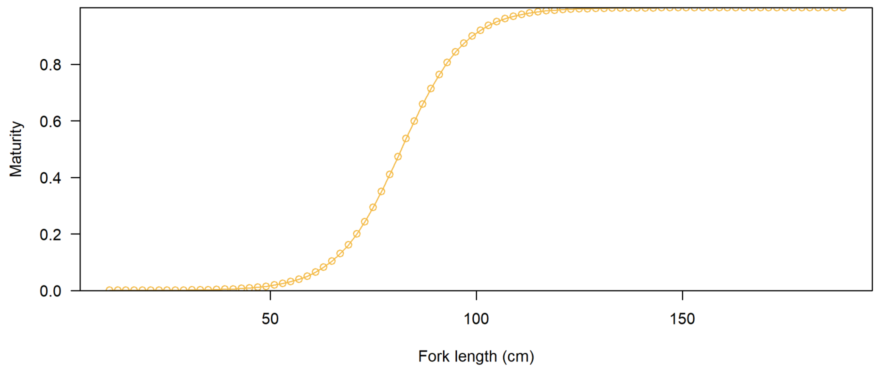

Figure A.3: Maturity at length for female Spanish mackerel

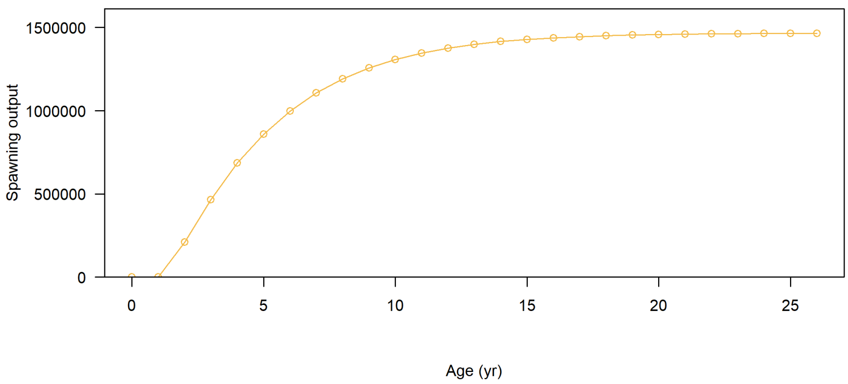

Figure A.4: Spawning output (maturity times fecundity) at age for Spanish mackerel

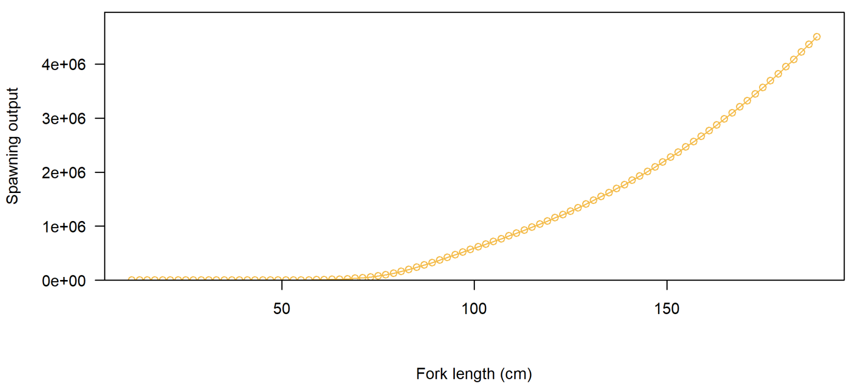

Figure A.5: Spawning output (maturity times fecundity) at length for Spanish mackerel

A.3.2 Weight and length

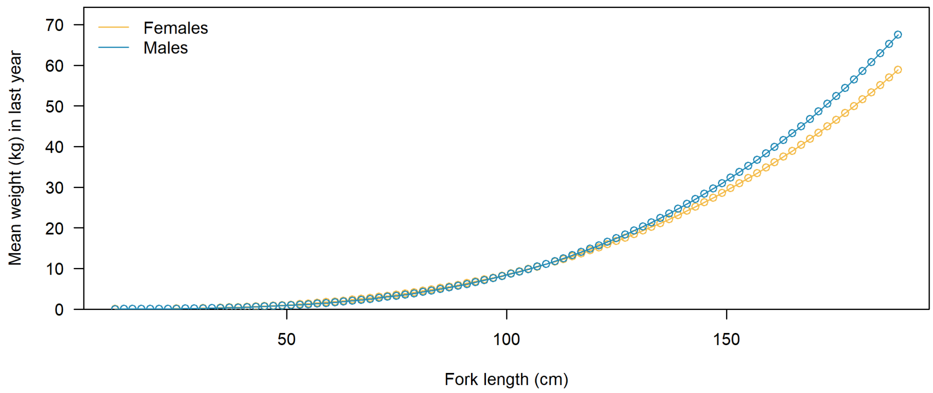

Figure A.6: Weight-length relationship for Spanish mackerel

A.3.3 Fishing power offsets

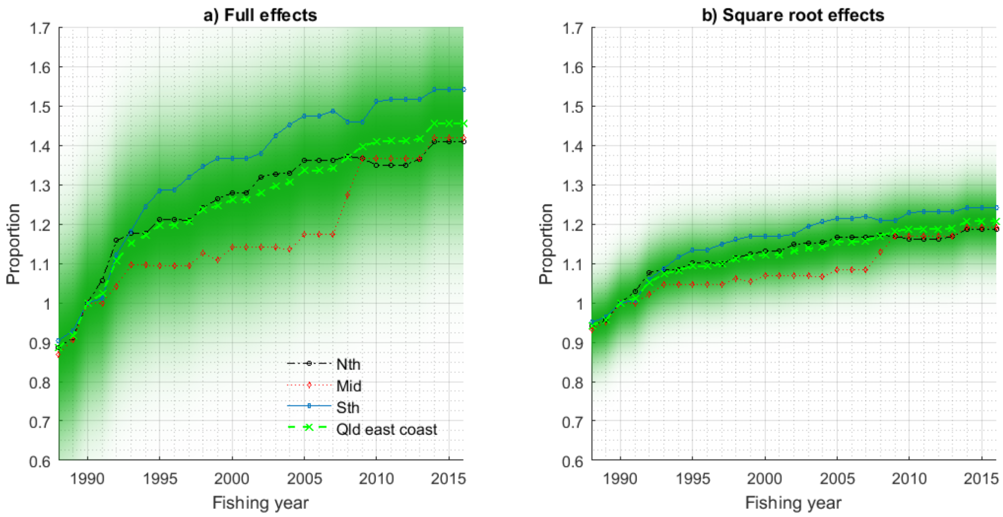

Figure A.7: The annual fishing power offsets that were estimated per year and region in the previous stock assessment (O'Neill et al. 2018)

A.4 Abundance indices

Commercial catch data were extracted from the Queensland logbook database. From the initial set of records, the catch rate data were defined through a series of filters.

For the probability model (first component of the standardisation model), the following filters were applied:

- Spanish mackerel (CAAB Code 37441007) catches per latitude band and day.
- Where multiple latitudes were recorded on a single day, the catch was summed over all records, and the location was set to mean of latitude derived and mean of longitude derived.
- Date between 1 July 1988 and 30 June 2020.

- Location was east coast (between 11.00° S and 28.50° S, ≥ 142.5° E).
- Location excluded records in the far north latitude band 11 (due to lack of available data).

For the catch rate model (second component of the standardisation model), the following filters were applied:

- Line fishers that had at least three years of catching Spanish mackerel.
- Line fishing methods included “Trolling”, “Handline”, and “Line fishing”.
- Where multiple locations were fished on a single day, the catch was summed over all records, and the location was set to mean of latitude and mean of longitude.
- Date between 1 July 1988 and 30 June 2020.
- Duration of the fishing trip was a single day.
- Location was east coast (between 11.00° S and 28.50° S, ≥ 142.5° E).
- Where kilograms of Spanish mackerel caught was greater than zero.

Appendix B Model outputs

B.1 Goodness of fit

B.1.1 Abundance indices

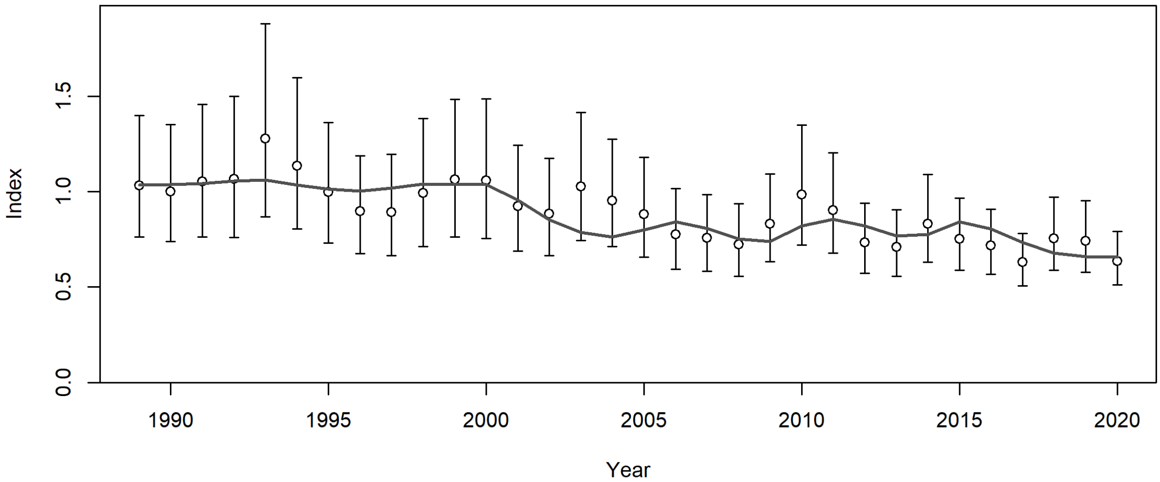

Figure B.1: Model predictions (grey line) to commercial catch rates for Spanish mackerel for base case scenario

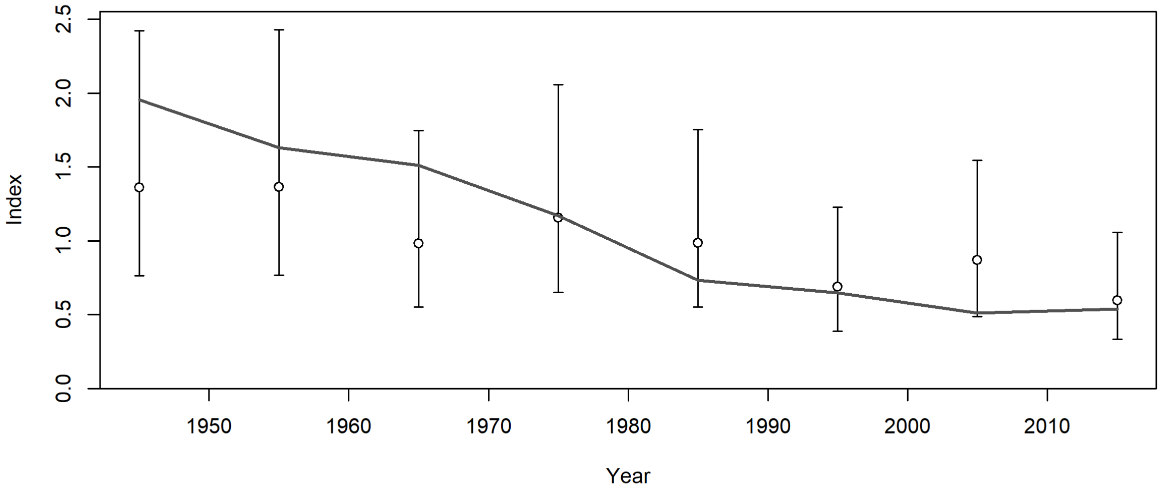

Figure B.2: Model predictions (grey line) to historical decadal catch rates for Spanish mackerel for the base case scenario

B.1.2 Length compositions

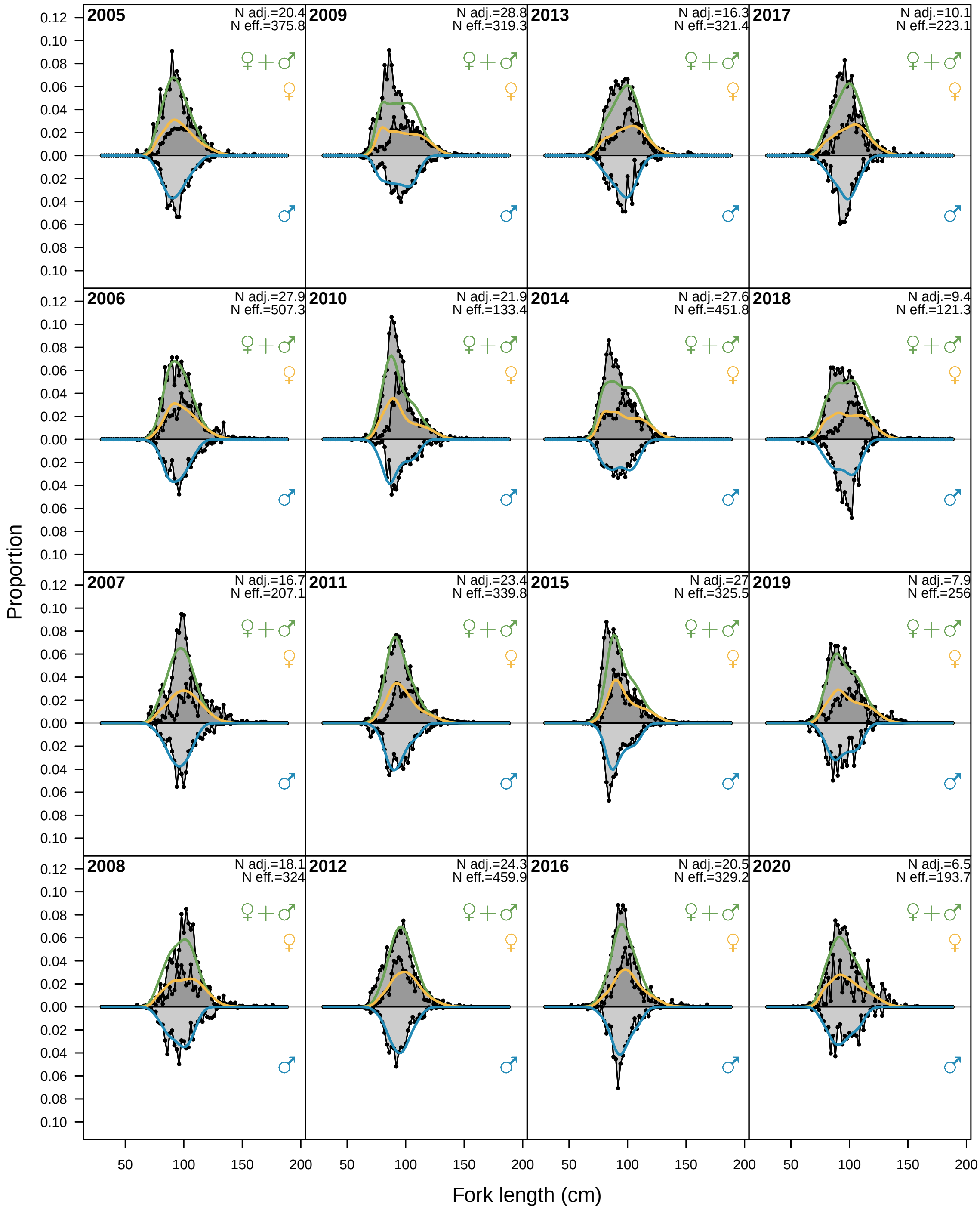

Figure B.3: Length structure for the commercial fleet for Spanish mackerel for each sex for the base case scenario

'N adj.' is the input sample size after data-weighting adjustment. 'N eff.' is the calculated effective sample size used in the McAllister-Iannelli tuning method. Shaded areas are actual data and coloured lines indicate fitted values.

B.1.3 Conditional age-at-length compositions

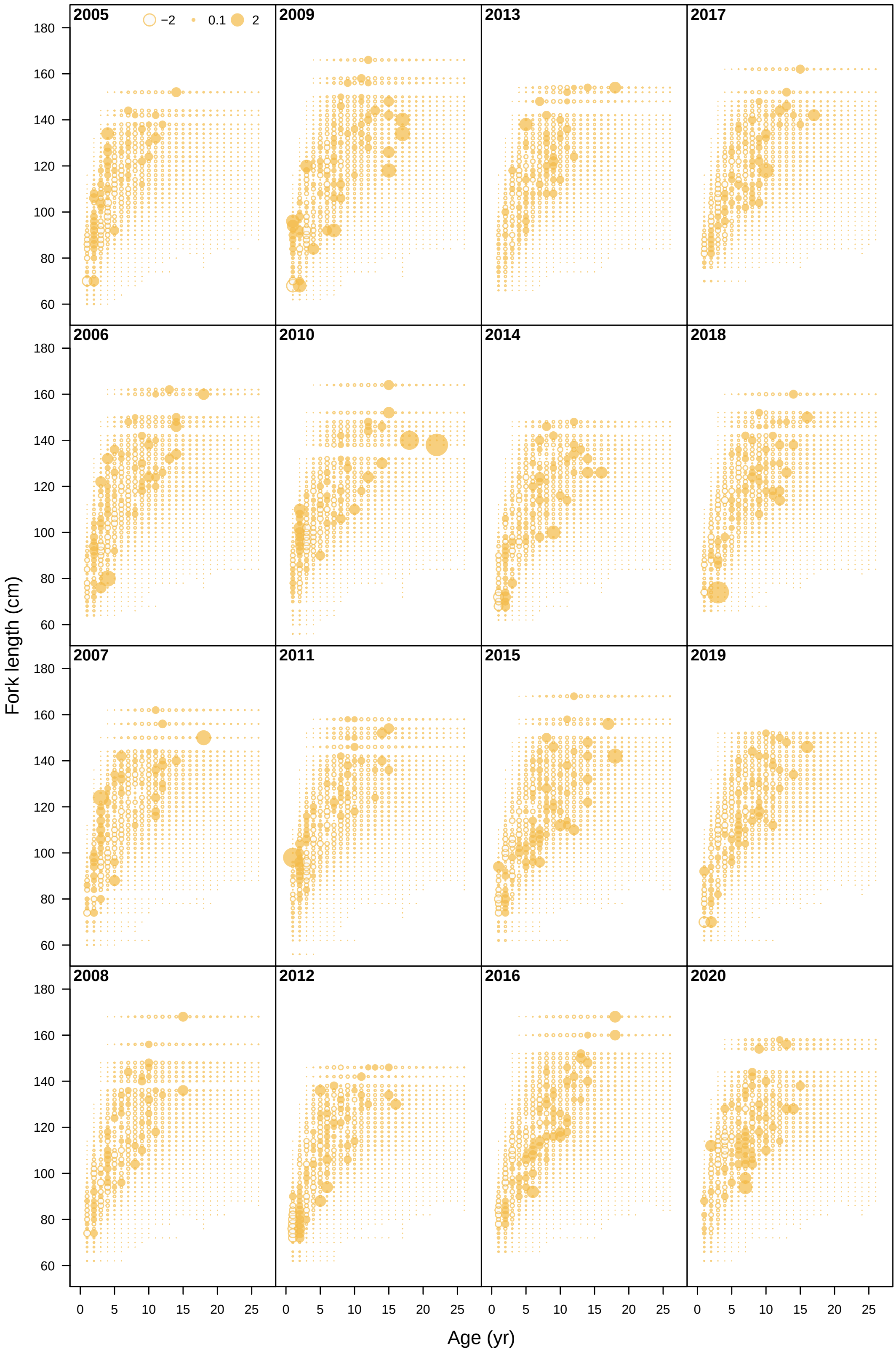

Figure B.4: Pearson residuals for age-at-length compositions for the commercial fleet for female Spanish mackerel for the base case scenario

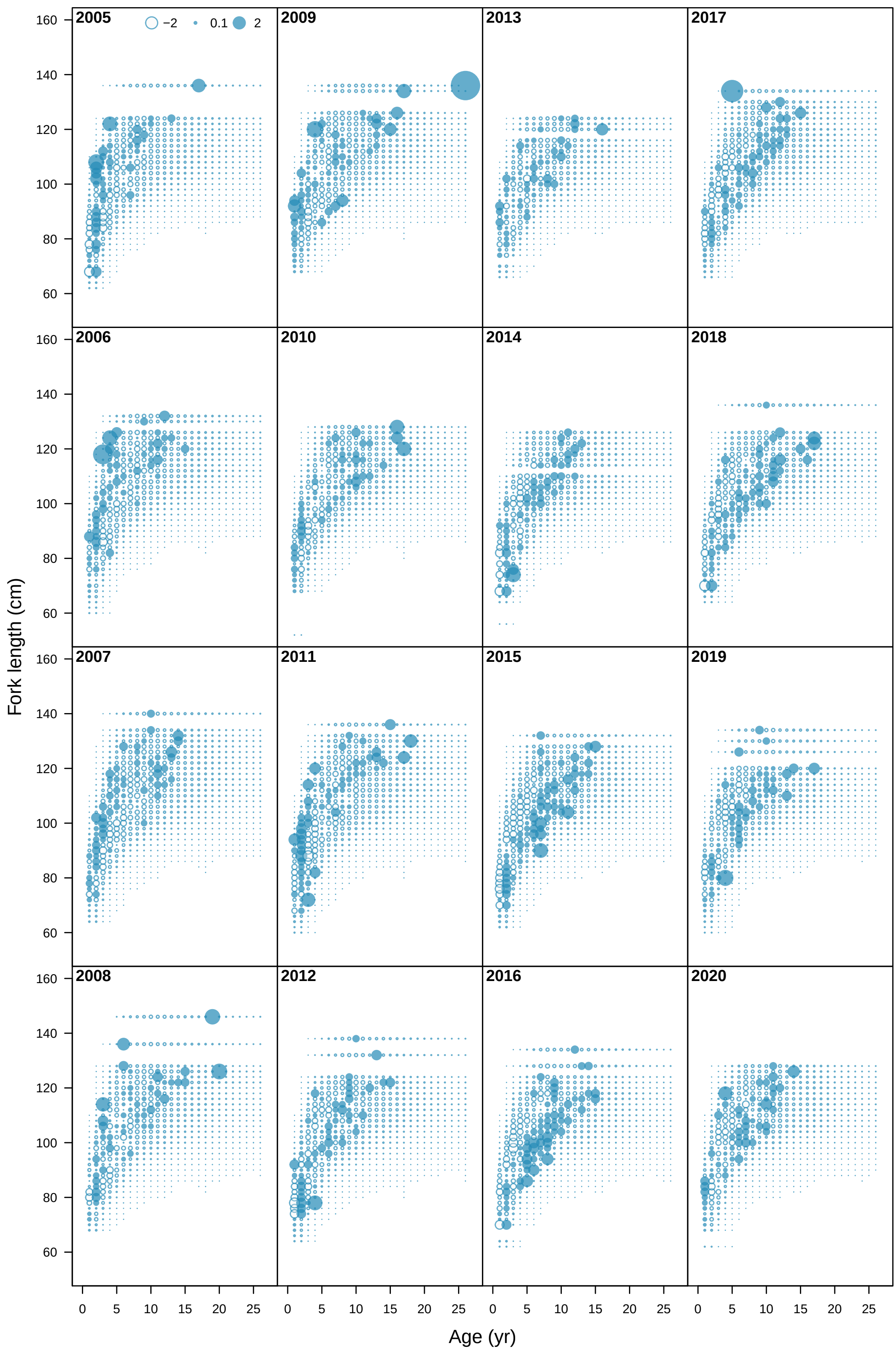

Figure B.5: Pearson residuals for age-at-length compositions for the commercial fleet for male Spanish mackerel for the base case scenario

B.2 Other outputs

B.2.1 Phase plot

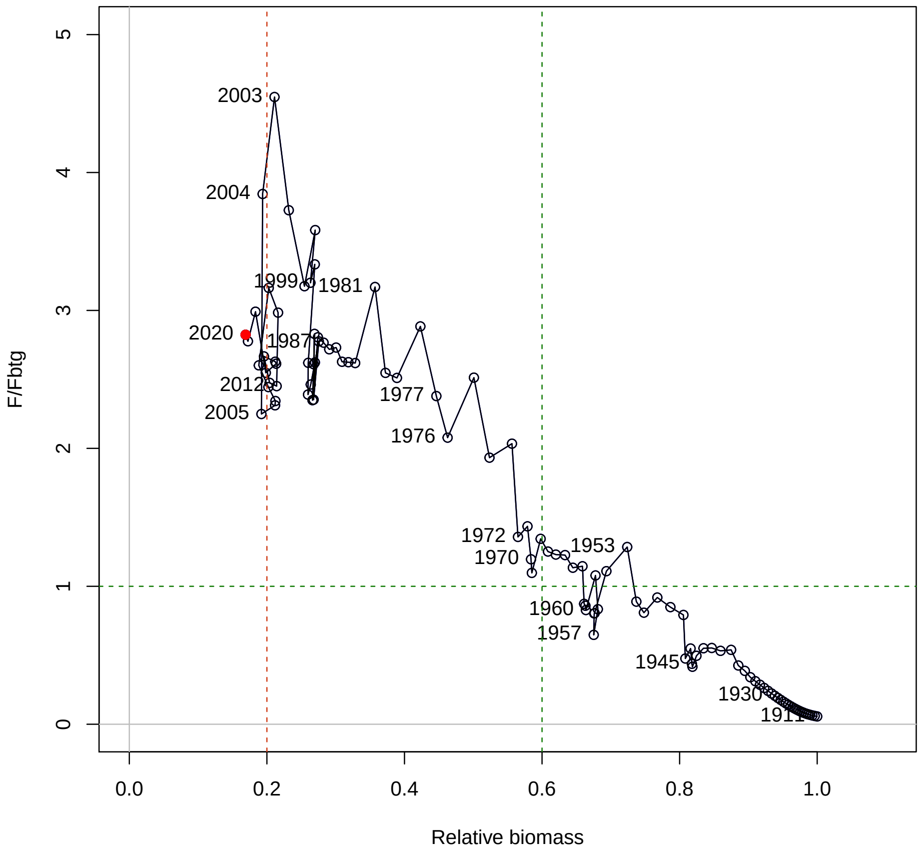

Figure B.6: Phase plot for Spanish mackerel for the base case scenario

The horizontal axis is the biomass ratio of Queensland Spanish mackerel relative to unfished and the vertical axis is the fishing mortality relative to the fishing mortality which would produce the *Sustainable Fisheries Strategy* biomass target of 60%. The red dashed vertical line is the limit reference point (20% relative biomass) and the green dashed vertical line is the target reference point (60% relative biomass).

B.2.2 Recruitment deviations

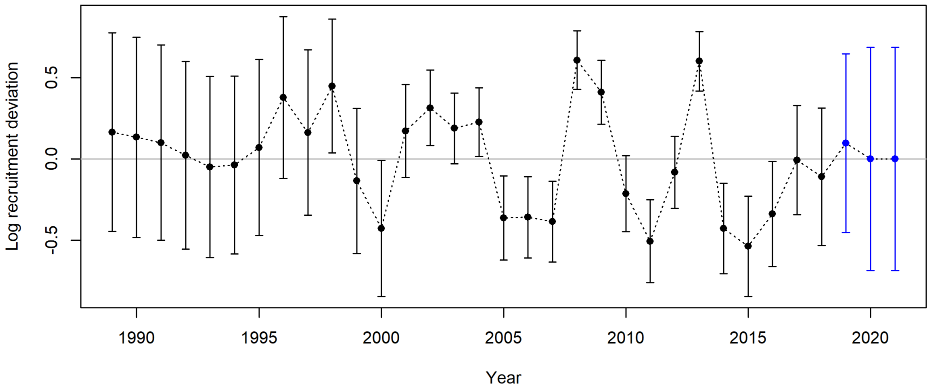

Figure B.7: Recruitment deviations with 95% confidence intervals for Spanish mackerel for the base case scenario

B.2.3 Harvest rate

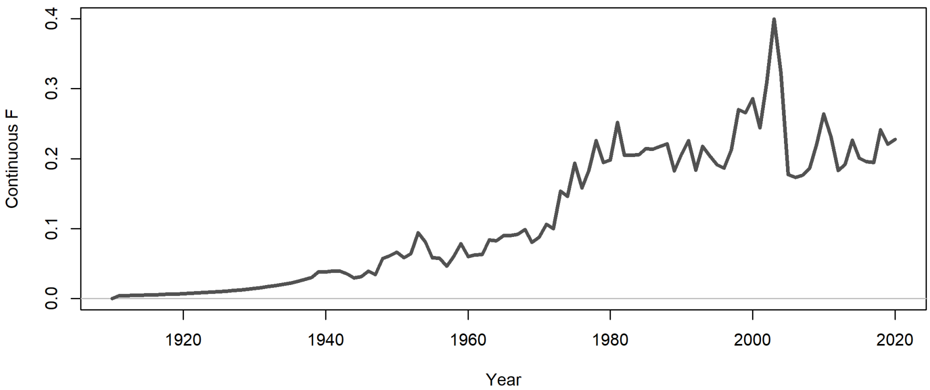

Figure B.8: Harvest rate for Spanish mackerel for the base case scenario

B.2.4 Likelihood profiles

Section 3.2.8 of Bessell-Browne et al. (2020) describes the importance and interpretation of likelihood profiles in stock assessments analysis.

The likelihood profile shows that two optima—one global and one local—exist within the appropriate range of virgin recruitment values. Depending on the initial values and priors used to configure the parameters, the model tended towards one of the two optima. Figure B.9 and Figure B.10 showed that, of the two optima, the lower virgin recruitment ($\ln(R_0) = 13.25$ for base case and $\ln(R_0) = 13.0$ for scenario 4) was more likely as the associated change in log likelihood was closer to zero.

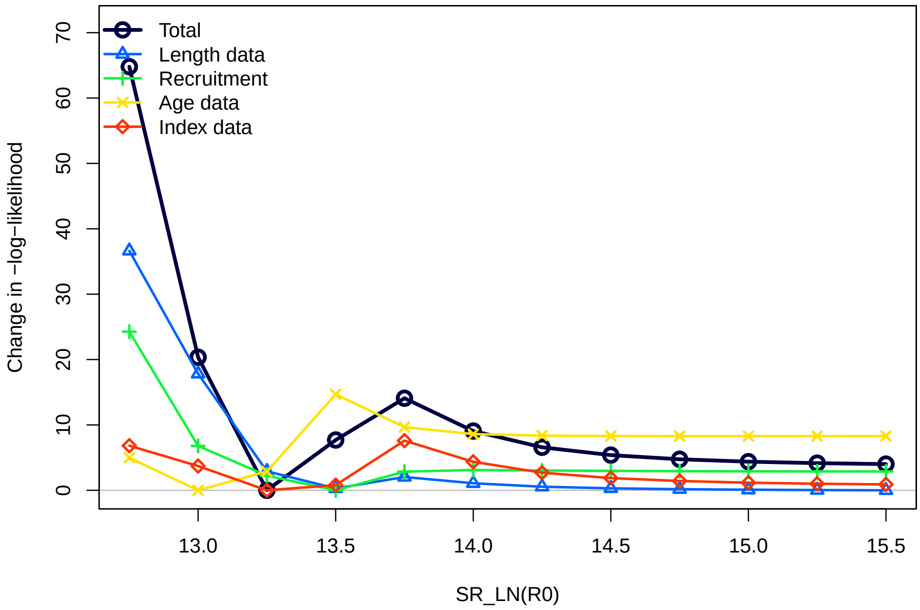

Figure B.9: Likelihood profile for SR_LN(R0) (virgin recruitment) for the base case scenario with steepness (h) fixed at 0.45

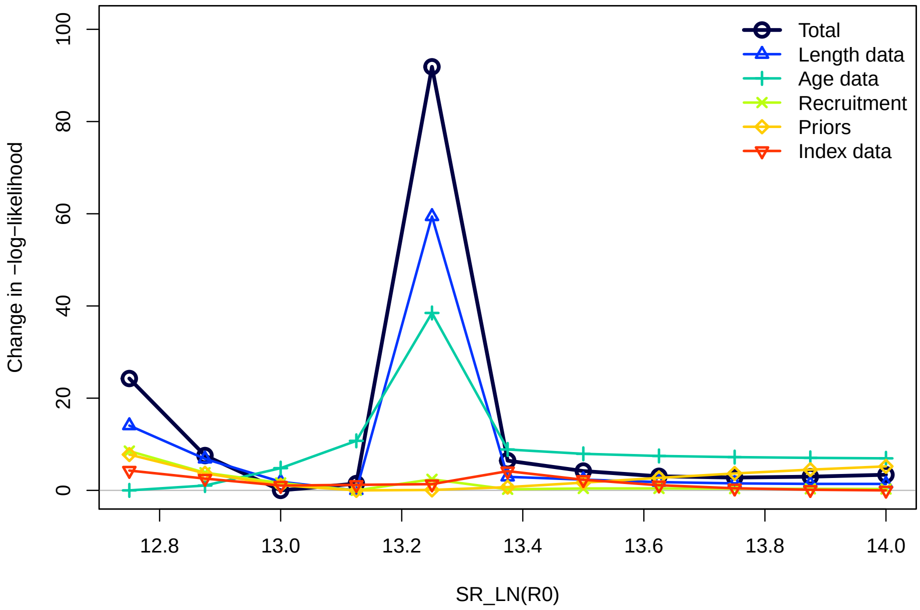

Figure B.10: Likelihood profile for SR_LN(R0) (virgin recruitment) for scenario 4 with steepness (h) fixed at 0.55

B.2.5 Spawning output vs recruitment

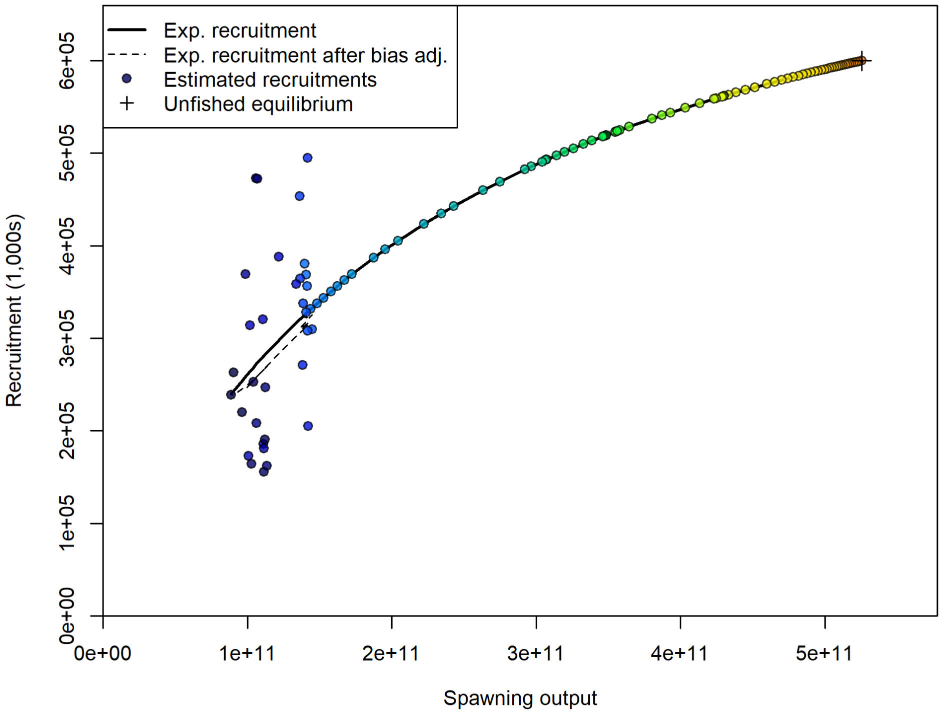

Figure B.11: Stock-recruit curve; point colors indicate year, with warmer colors indicating earlier years and cooler colors in showing later years

Appendix C Additional catch rate outputs and diagnostic plots

Additional outputs from catch rate standardisation, including model summary statistics, diagnostic plots, predicted probability *p(c)* of commercially catching Spanish mackerel (overall and by latitude bands), and fishing power effect estimated from REML analysis are shown below to support discussion of the report.

Table C.1: Summary statistics for the binomial generalised linear model of Queensland commercial line fishing days

Regression analysis

Response variate:	ndaysS - when a Spanish mackerel was caught
Binomial totals:	Ndays - number of calendar days in a month
Distribution:	Binomial
Link function:	Logit
Fitted terms:	Constant + fishyear + latband + fishyear.latband + s1.latband + s2.latband + s3.latband + s4.latband + nACN.latband + windew + windns (FACTORIAL limit for expansion of formula = 2)
Submodels:	POL(windew; 2) POL(windns; 2)

Summary of analysis

Source	d.f.	deviance	mean deviance	deviance ratio	approx F pr.
Regression	595	64596.	108.565	46.77	<.001
Residual	5548	12877.	2.321		
Total	6143	77473.	12.612		

Percentage mean deviance accounted for 81.6
Percentage deviance accounted for 83.4
Adjusted r-squared statistic (based on deviance) 0.816
R-squared statistic (based on deviance) 0.834
Akaike information criterion cannot be estimated.
Schwarz Bayes information criterion cannot be estimated.

Wald tests for dropping terms

Term	Wald statistic	d.f.	F statistic	F pr.
fishyear.latband	1176.6	465	2.53	<0.001
latband.s1	466.3	16	29.15	<0.001
latband.s2	359.3	16	22.45	<0.001
latband.s3	108.1	16	6.75	<0.001
latband.s4	42.8	16	2.67	<0.001
latband.nACN	2563.5	16	160.22	<0.001
windns	45.6	1	45.57	<0.001
windns2	0.5	1	0.51	0.473
windew	4.2	1	4.17	0.041
windew2	0.1	1	0.09	0.764

Table C.2: Summary statistics for the linear mixed model of Queensland commercial line fishing days

REML variance components analysis

Fixed model:	Constant + fishyear + latband2* + fishyear.latband2 + latband2 .s1 + latband2.s2 + latband2.s3 + latband2.s4 + latband2.s5 + latband2.s6 + latband2.lunar + latband2.lunar_adv + windew + windew2 + windns + windns2
Random model:	acn
Number of units:	191128

Full fishing power					**Square-root fishing power (half fishing power)**			
Estimated variance components					**Estimated variance components**			
Random term	component	s.e.			Random term	component	s.e.	
acn	0.3601	0.0193			acn	0.3607	0.0193	
Residual variance model					**Residual variance model**			
Term	Sigma2	s.e.			Term	Sigma2	s.e.	
Residual	0.837	0.0027			Residual	0.836	0.0027	
Deviance: -2*Log-Likelihood					**Deviance: -2*Log-Likelihood**			
Deviance	d.f.				Deviance	d.f.		
163330.79	190482				163264.46	190482		
Dropping individual terms from full fixed model					**Dropping individual terms from full fixed model**			
Fixed term	Wald statistic	n.d.f.	F statistic	F pr	Wald statistic	n.d.f.	F statistic	F pr
fishyear.latband2	5251.97	465	11.29	<0.001	5106.46	465	10.98	<0.001
latband2.s1	2616.86	16	163.55	<0.001	2622.06	16	163.88	<0.001
latband2.s2	2033.09	16	127.07	<0.001	1987.14	16	124.2	<0.001
latband2.s3	178.75	16	11.17	<0.001	178.42	16	11.15	<0.001
latband2.s4	511.51	16	31.97	<0.001	516.54	16	32.28	<0.001
latband2.s5	477.82	16	29.86	<0.001	477	16	29.81	<0.001
latband2.s6	69.16	16	4.32	<0.001	67.4	16	4.21	<0.001
latband2.lunar	254.06	16	15.88	<0.001	254.68	16	15.92	<0.001
latband2.lunar_adv	521.76	16	32.61	<0.001	522.38	16	32.65	<0.001
windew	6.87	1	6.87	0.009	6.64	1	6.64	0.01
windew2	28.71	1	28.71	<0.001	28.69	1	28.69	<0.001
windns	230.98	1	230.98	<0.001	230.64	1	230.64	<0.001
windns2	14.89	1	14.89	<0.001	14.81	1	14.81	<0.001

* latband2 grouped the most southern (lat11 and lat12) and northern latbands (lat28 and 29) together.

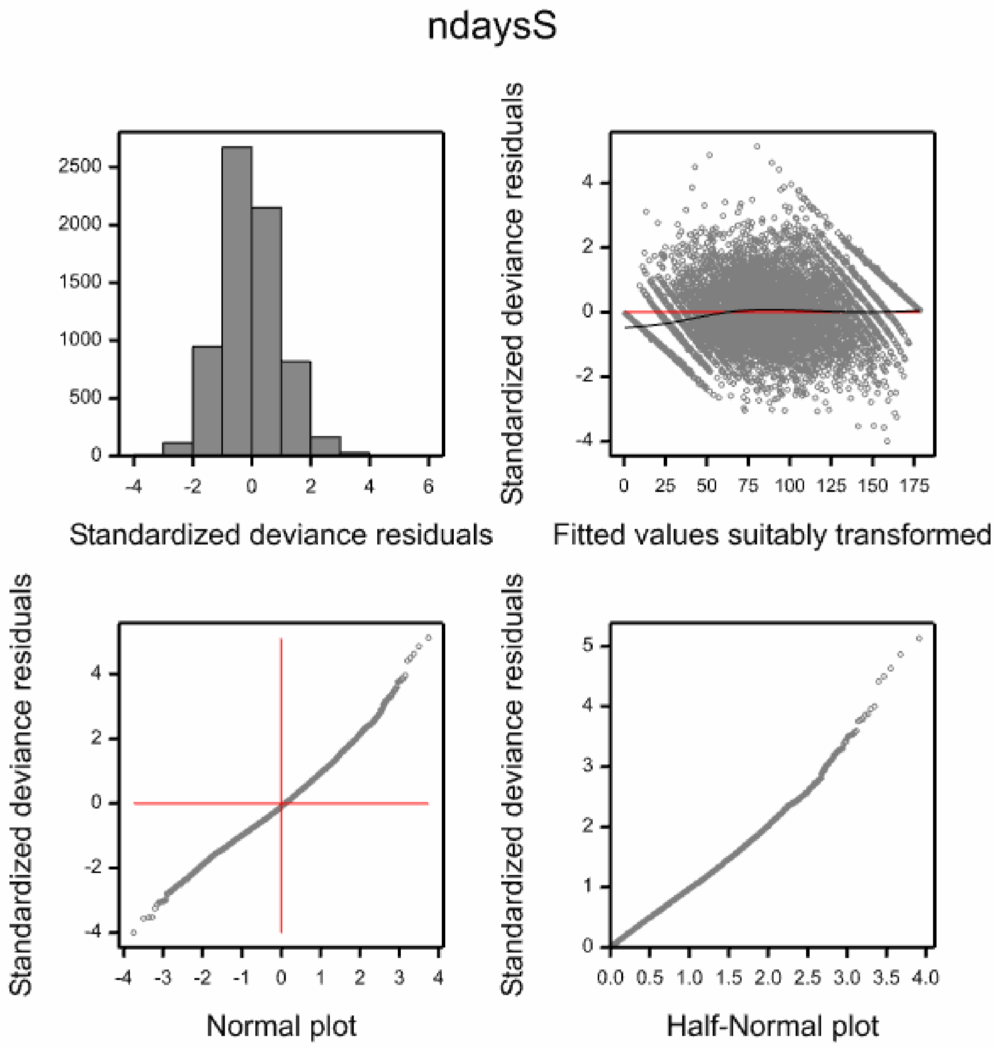

Figure C.1: Residual diagnostic plots for the binomial model analysis

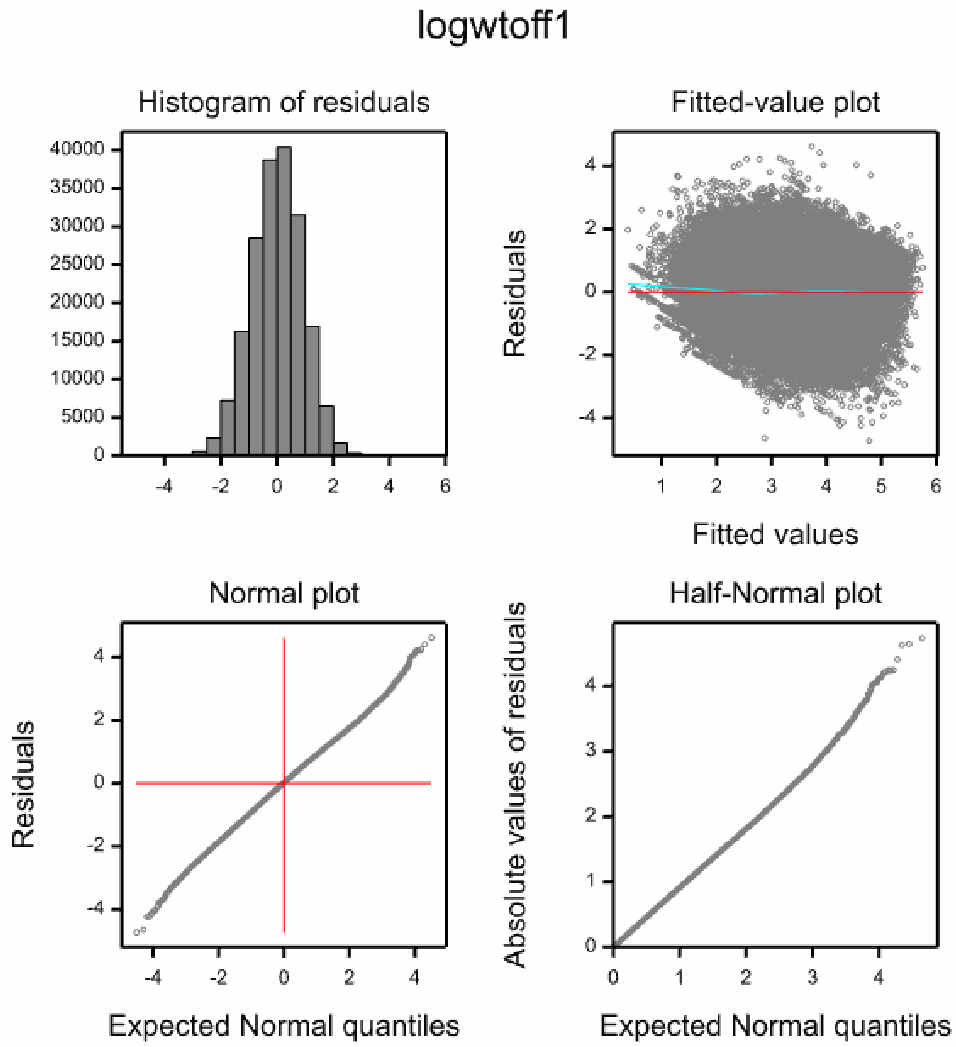

Figure C.2: Residual diagnostic plots for the linear mixed model assuming half fishing power increase (base case)

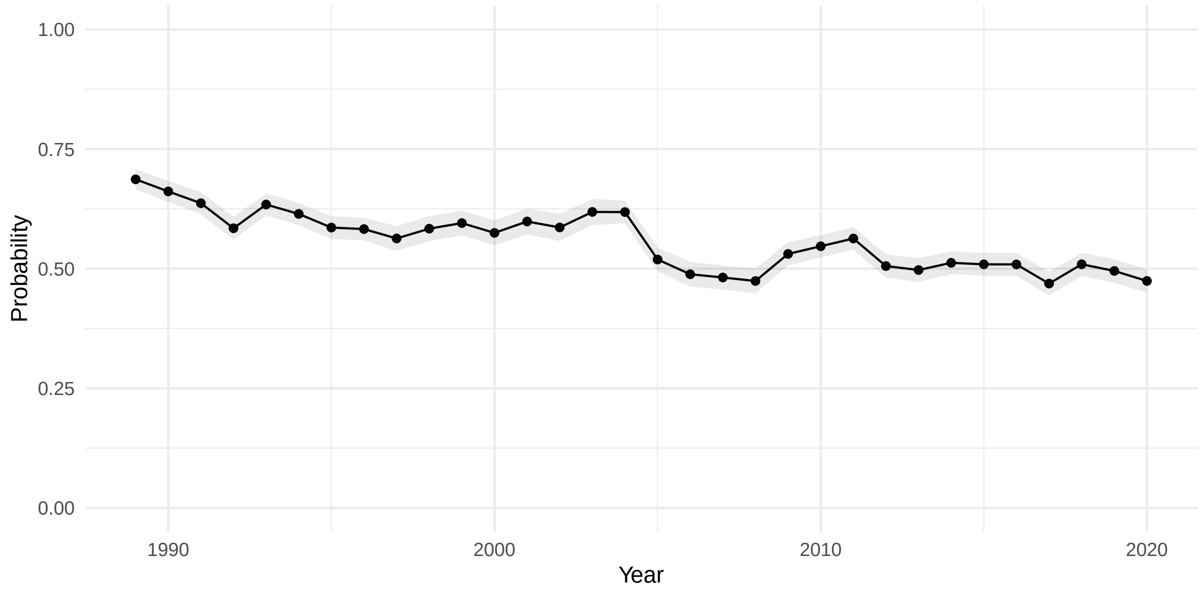

Figure C.3: Probability of commercially harvesting Spanish mackerel by fishing year—the error bars represent ± 2 standard errors on mean predictions

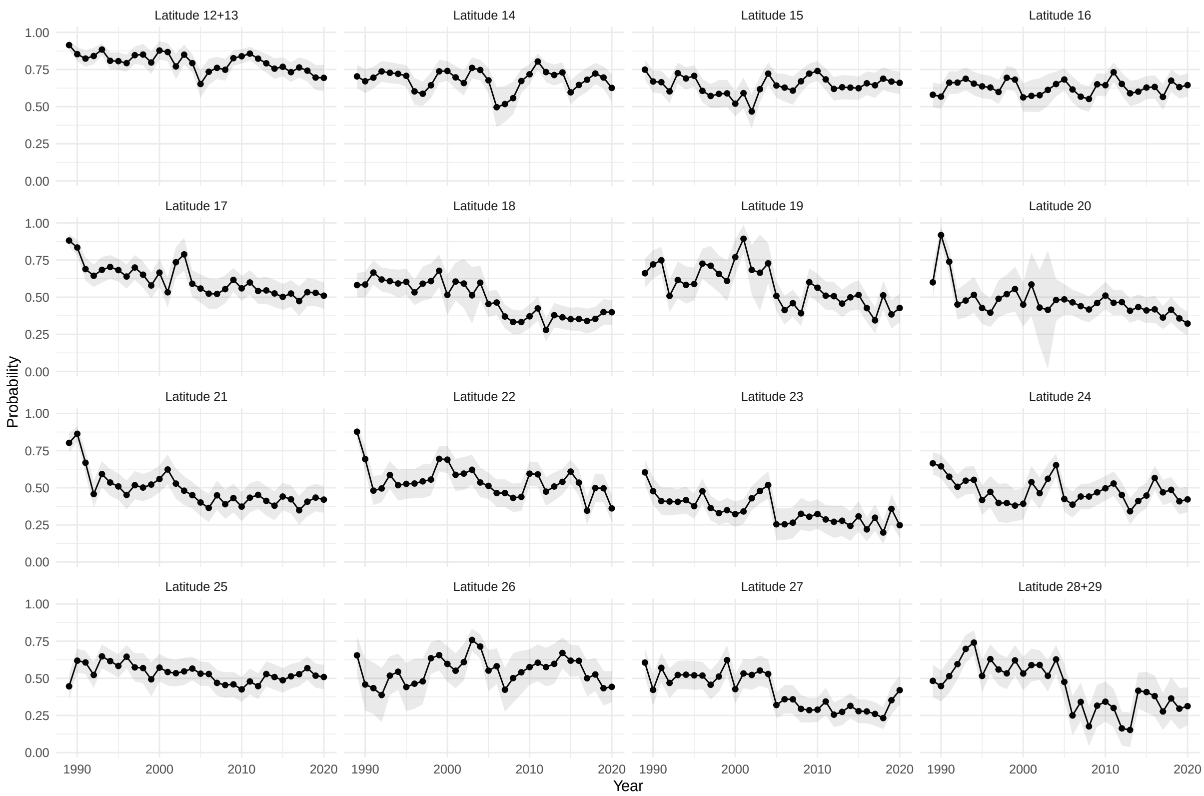

Figure C.4: Probability of commercially harvesting Spanish mackerel by latitude and fishing year—the error bars represent ± 2 standard errors on mean predictions

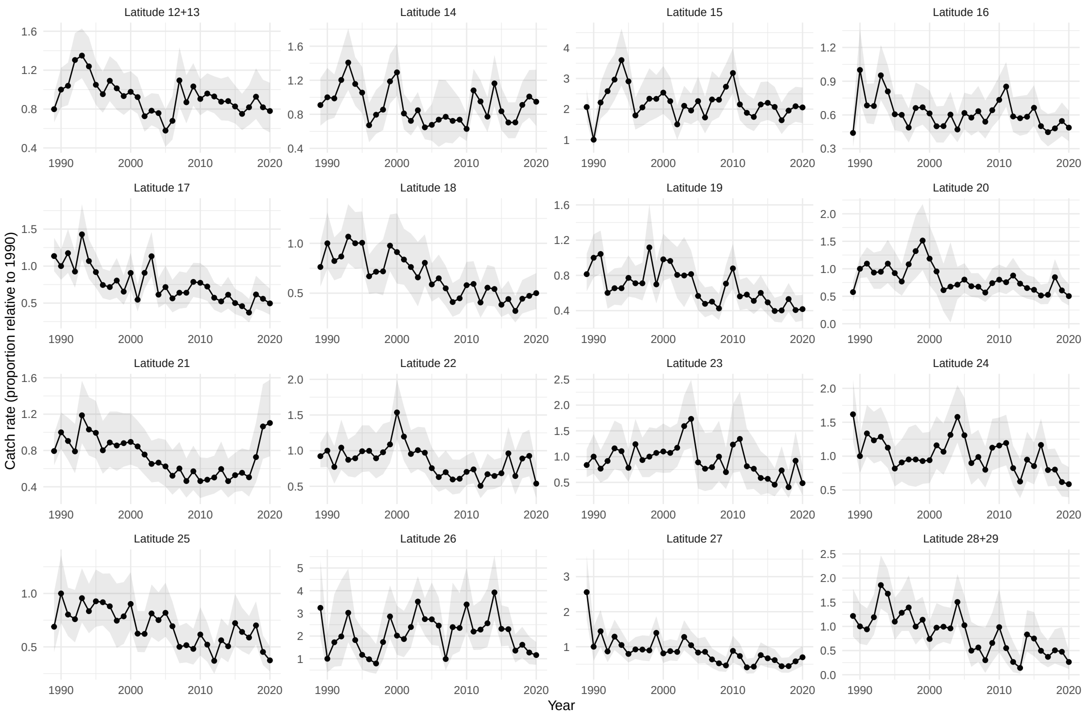

Figure C.5: Standardised mean catch rates of Spanish mackerel by latitude band and fishing year for the half fishing power with probability adjustment (with 95% confidence interval bands)—catch rates were scaled proportionally, with year 1990 = 1

Figure C.6 shows vessel-operation's mean catch efficiency for the base case model (half fishing power). The commercial sector's mean fishing power for Spanish mackerel was estimated to be about 27% higher in 2020 compared to 1989.

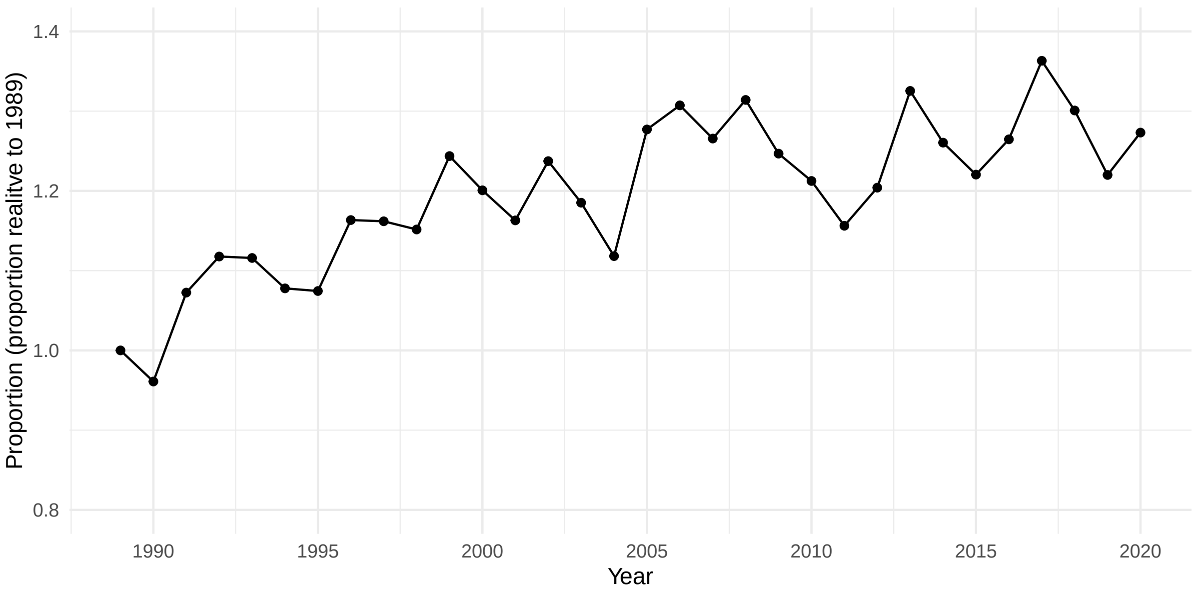

Figure C.6: Estimated Queensland commercial sector mean fishing power as calculated from the vessel-acn random-model parameters in REML

Appendix D Age compositions

Monitoring of annual fish age-length structures of Spanish mackerel, across east coast Queensland waters, has been continuous since 2005 (Figure D.1). The fish age data showed Spanish mackerel live up to 26 years of age. Most of the fish sampled were aged in the 1+ to 8+ cohort age-groups. Few older fish were present.

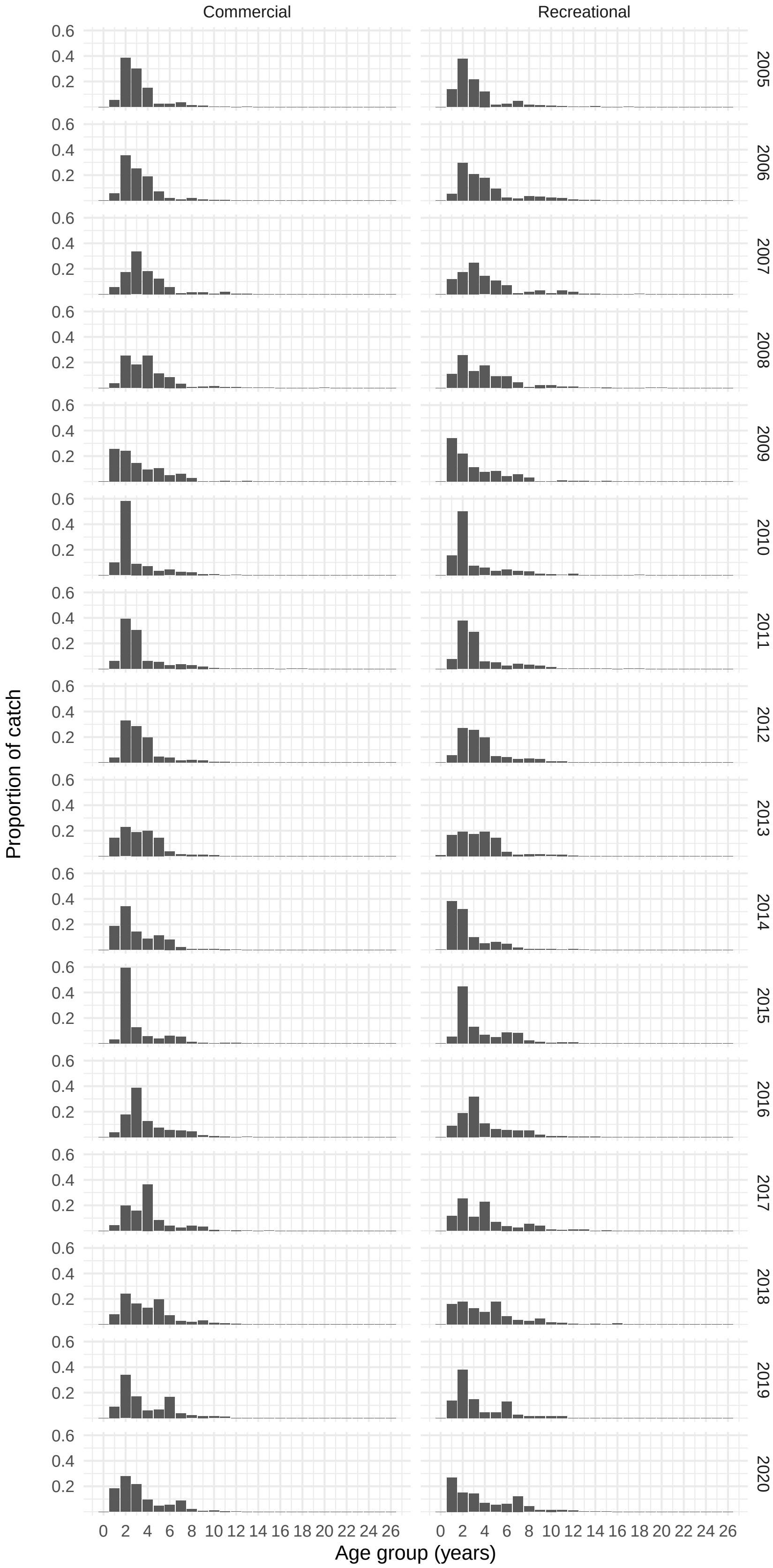

Figure D.1: Annual age compositions of Spanish mackerel for line-caught fish between 2005 and 2020

Zero-plus and one-plus year old Spanish mackerel were not fully vulnerable to fishing. Their frequency varied between years, but do indicate strengths of recruitment of young fish and their changed vulnerability from year to year. The data suggested pulses of recruitment resulting from spawning events in 2008 and 2013. This can be seen from the frequency of 1+ year old fish in 2009 flowing through to be 5+ year old fish in 2013 (Figure D.1). Similarly and more recently, 1+ year old fish in 2014 flowed through to be 3+ year old fish in 2016 (Figure D.1). The patterns of recruitment were evident in the data from both the commercial and recreational fishing sectors.

For each fishing sector and year, the declines in the age frequency of Spanish mackerel from 2+ years were modelled using a simple catch-curve (Figure D.2; log-linear Poisson model). The slope estimates were averaged over years to provide a rough measure of annual fish total mortality Z; smoothing out annual recruitment variation. The mean estimates were 0.40 year^{-1} and 0.48 year^{-1} from the recreational and commercial fishing data respectively (s.e. 0.019 and 0.027). On average, estimates of fish mortality from the commercial sector's data were higher, likely due to the difference in size and therefore age of fish targeted by each sector. The commercial estimate was near the limit reference point of 2 $\times$ natural mortality (M); assuming M = 0.27 year^{-1}); 1.5 $\times$ M was considered a sustainable target reference point for pelagic fish such as Spanish mackerel (Welch et al. 2002).

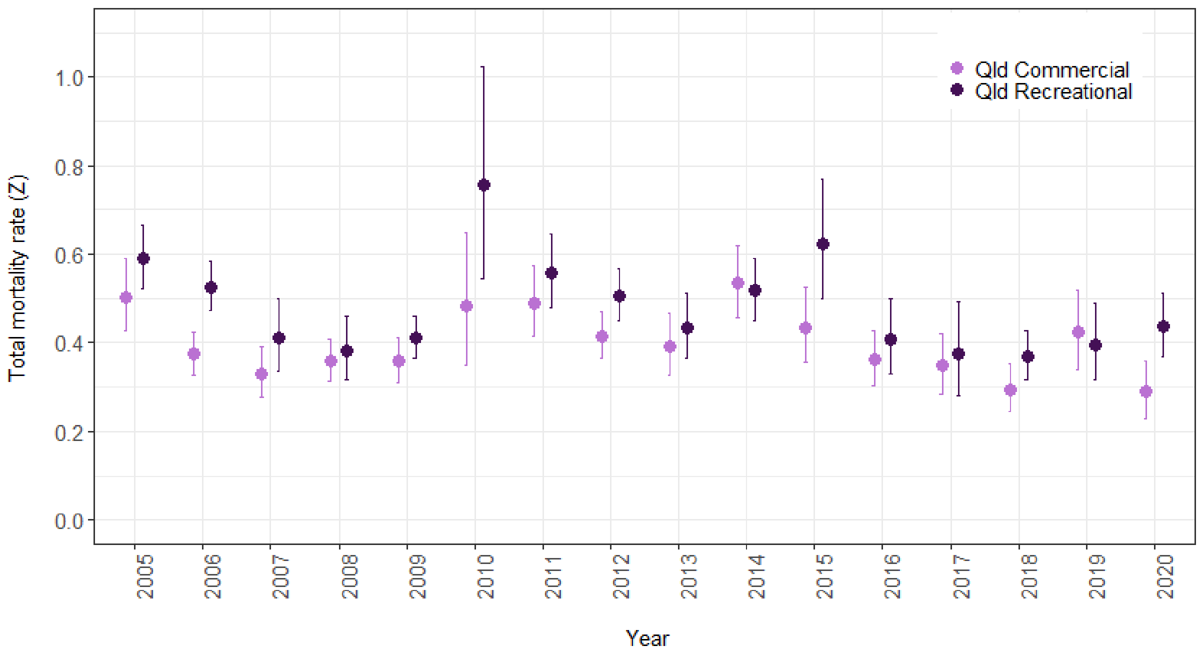

Figure D.2: Annual total mortality estimate (Z) of east coast Spanish mackerel for commercial and recreational sectors

Appendix E Results of sensitivity tests and scenarios

This chapter presents the outputs of the model and goodness-of-fit plots for scenarios 2 to 8.

E.1 Scenario 2

Scenario 2 was identical to the base case except steepness, h, was fixed at 0.35 instead of 0.45.

Table E.1: Stock Synthesis parameter estimates for the scenario 2 population model for Spanish mackerel

Parameter	Estimate	Phase	Min	Max	Initial value	Standard deviation
Natural mortality	0.33	3	0.01	0.5	0.29	0.01
Length at age 1 (FL_1) female	66.75	1	30	90	72	1.41
Length at maximum age (FL_{inf}) female	130.2	1	100	180	140	2.4
von Bertalanffy growth parameter (κ) female	0.29	1	0.1	0.4	0.22	0.03
Coefficient of variation in length at age 1 female	0.08	4	0.01	0.3	0.12	0.01
Coefficient of variation in length at maximum age female	0.07	4	0.01	0.2	0.14	0.01
Length at age 1 (FL_1) male	65.92	1	30	85	70	1.3
Length at maximum age (FL_{inf}) male	114.27	1	100	200	120	1.33
von Bertalanffy growth parameter (κ) male	0.34	1	0.1	0.45	0.21	0.03
Coefficient of variation in length at age 1 male	0.08	4	0.01	0.3	0.13	0.01
Coefficient of variation in length at maximum age male	0.04	4	0.01	0.2	0.12	0
Beverton-Holt unfished recruitment (logarithm of the number of recruits in 1911)	13.82	1	10	14.25	13.79	0.05
Commercial selectivity inflection (cm)	81.57	2	30	120	60	0.93
Commercial selectivity width (cm)	11.56	2	0	20	0.5	1.34

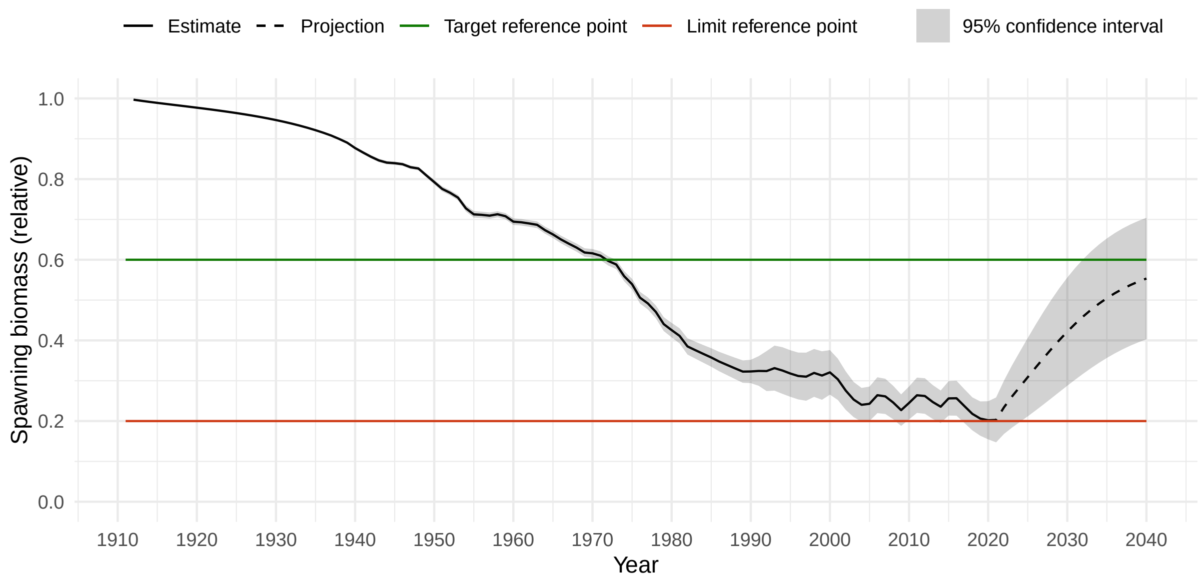

Figure E.1: Predicted spawning biomass trajectory relative to virgin for Spanish mackerel, from 1911 to 2040, for scenario 2

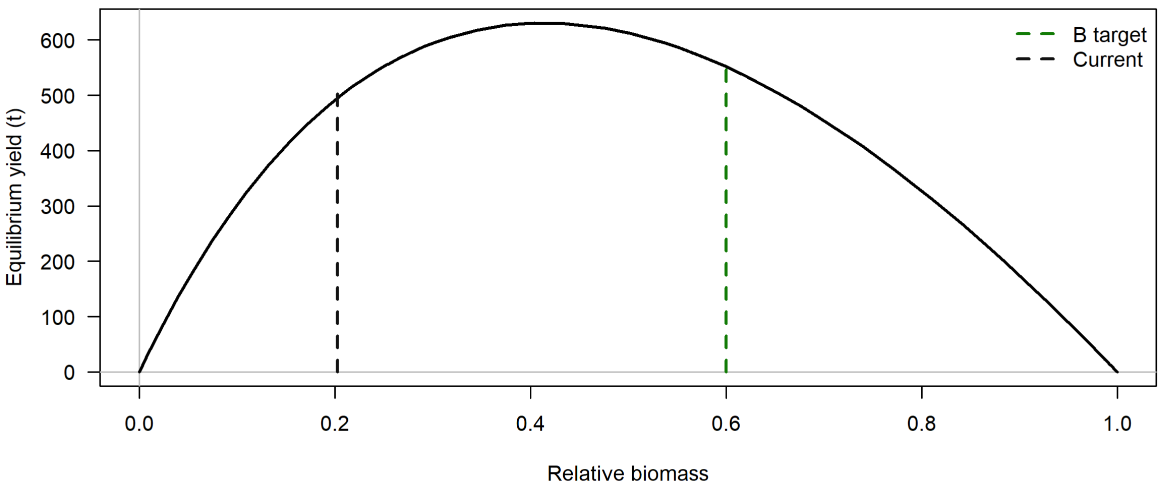

Figure E.2: Equilibrium yield curve for Spanish mackerel for scenario 2

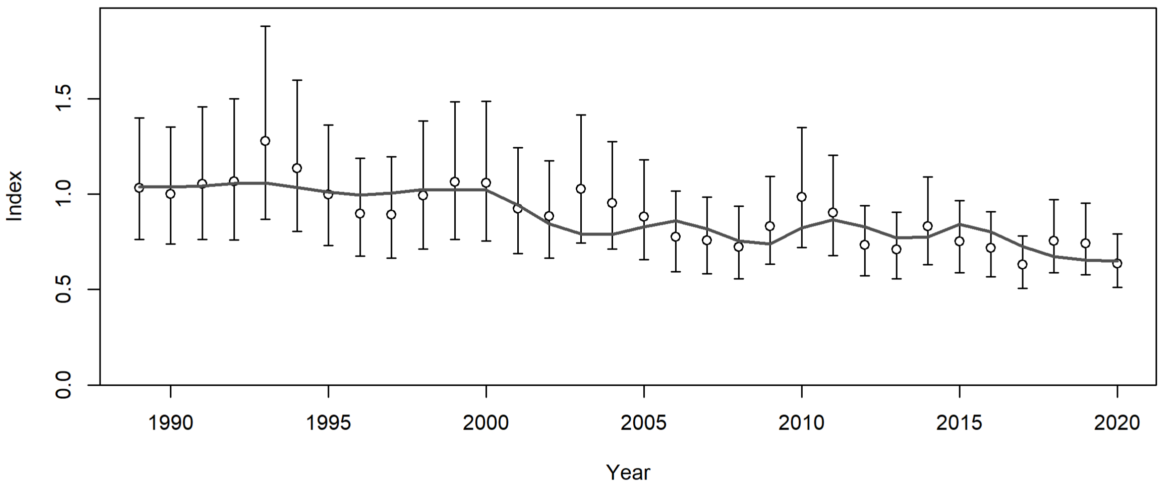

Figure E.3: Model predictions (grey line) to commercial catch rates for Spanish mackerel for scenario 2

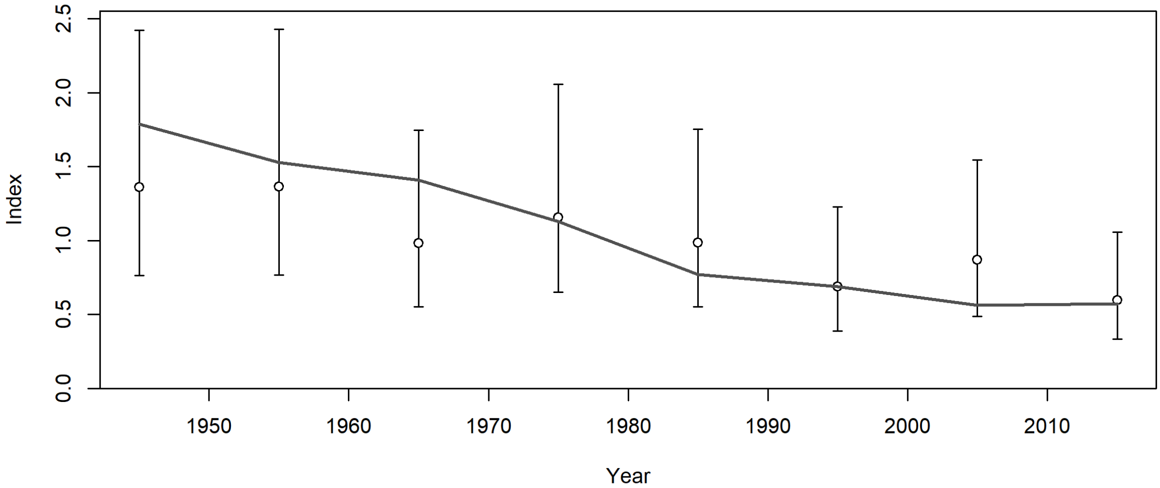

Figure E.4: Model predictions (grey line) to historical decadal catch rates for Spanish mackerel for scenario 2

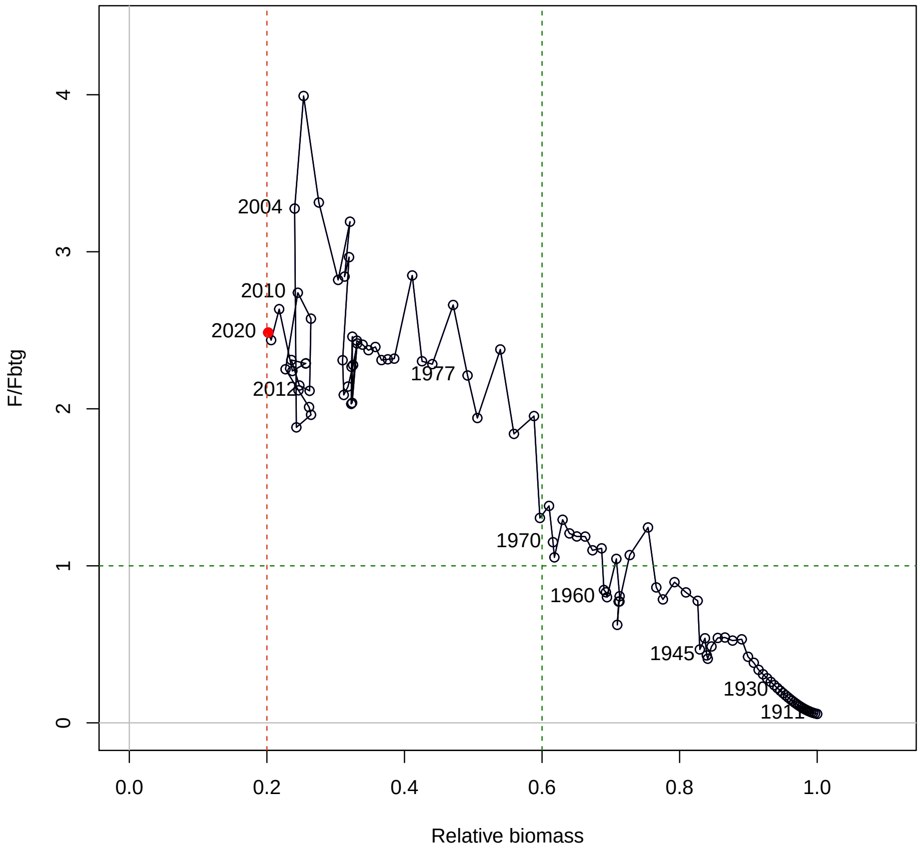

Figure E.5: Phase plot for Spanish mackerel for scenario 2

The horizontal axis is the biomass ratio of Queensland Spanish mackerel relative to unfished and the vertical axis is the fishing mortality relative to the fishing mortality which would produce the *Sustainable Fisheries Strategy* biomass target of 60%. The red dashed vertical line is the limit reference point (20% relative biomass) and the green dashed vertical line is the target reference point (60% relative biomass)

E.2 Scenario 3

Scenario 3 was identical to the base case except steepness, h, was fixed at 0.55 instead of 0.45.

Table E.2: Stock Synthesis parameter estimates for the scenario 3 population model for Spanish mackerel

Parameter	Estimate	Phase	Min	Max	Initial value	Standard deviation
Natural mortality	0.23	2	0.01	0.5	0.29	0.01
Length at age 1 (FL_1) female	67	3	30	90	72	1.38
Length at maximum age (FL_{inf}) female	130.16	3	100	180	140	2.38
von Bertalanffy growth parameter (κ) female	0.29	3	0.1	0.4	0.22	0.03
Coefficient of variation in length at age 1 female	0.07	5	0.01	0.3	0.12	0.01
Coefficient of variation in length at maximum age female	0.07	5	0.01	0.2	0.14	0.01
Length at age 1 (FL_1) male	65.99	3	30	85	70	1.27
Length at maximum age (FL_{inf}) male	114.08	3	100	200	120	1.27
von Bertalanffy growth parameter (κ) male	0.35	3	0.1	0.45	0.21	0.03
Coefficient of variation in length at age 1 male	0.08	5	0.01	0.3	0.13	0.01
Coefficient of variation in length at maximum age male	0.04	5	0.01	0.2	0.12	0
Beverton-Holt unfished recruitment (logarithm of the number of recruits in 1911)	12.93	1	12.5	13.25	12.97	0.04
Commercial selectivity inflection (cm)	81.03	4	30	120	60	0.88
Commercial selectivity width (cm)	11.36	4	0	20	0.5	1.35

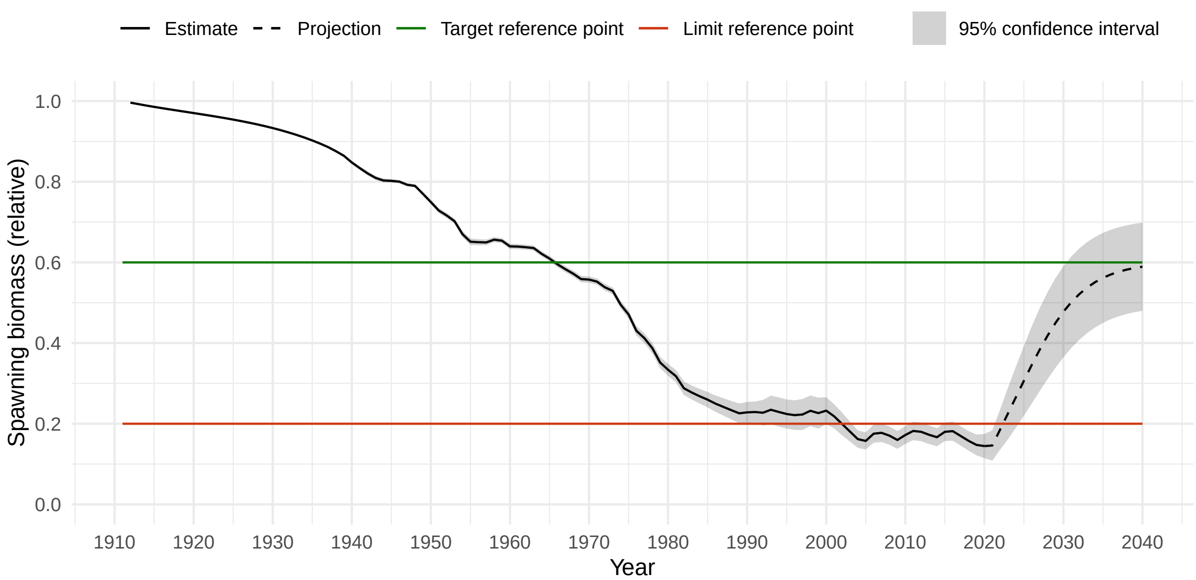

Figure E.6: Predicted spawning biomass trajectory relative to virgin for Spanish mackerel, from 1911 to 2040, for scenario 3

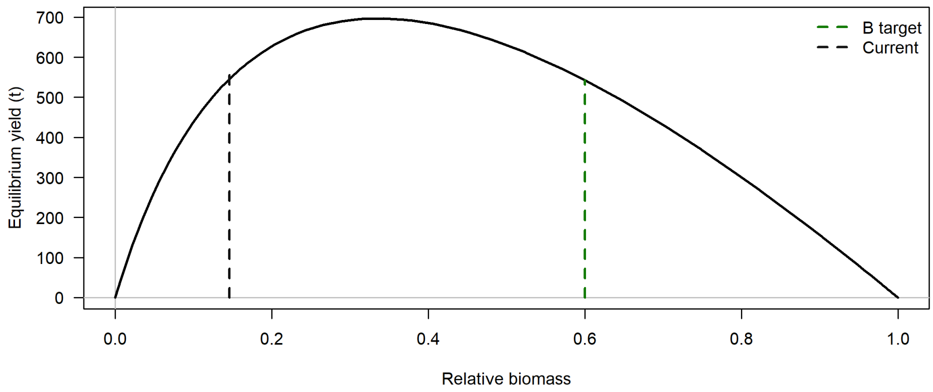

Figure E.7: Equilibrium yield curve for Spanish mackerel for scenario 3

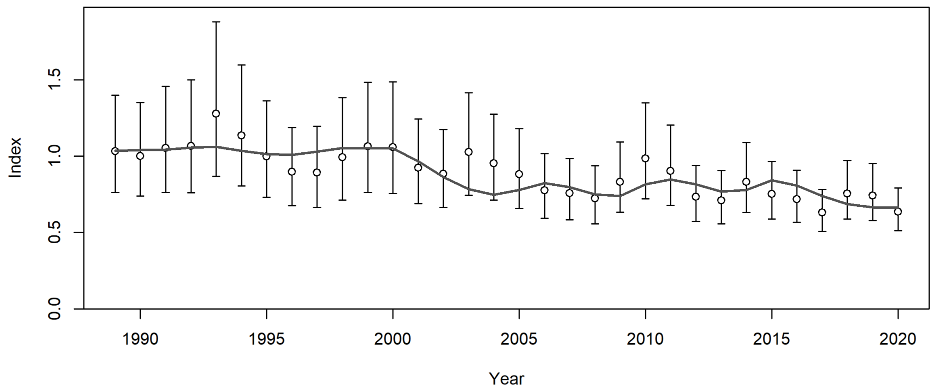

Figure E.8: Model predictions (grey line) to commercial catch rates for Spanish mackerel for scenario 3

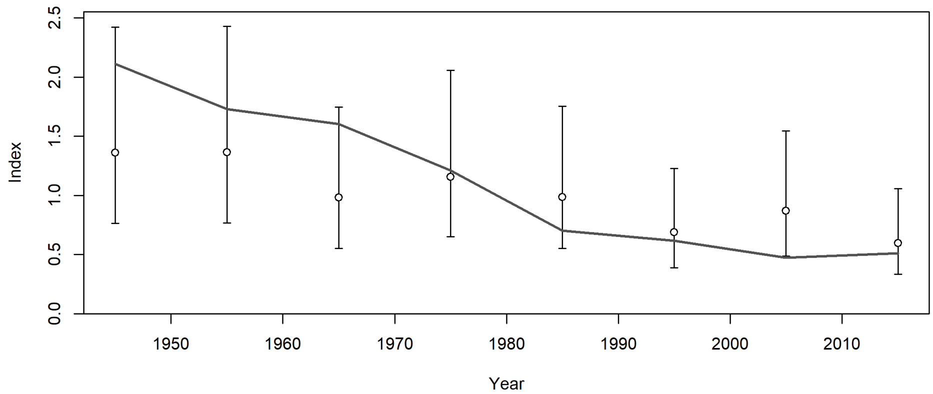

Figure E.9: Model predictions (grey line) to historical decadal catch rates for Spanish mackerel for scenario 3

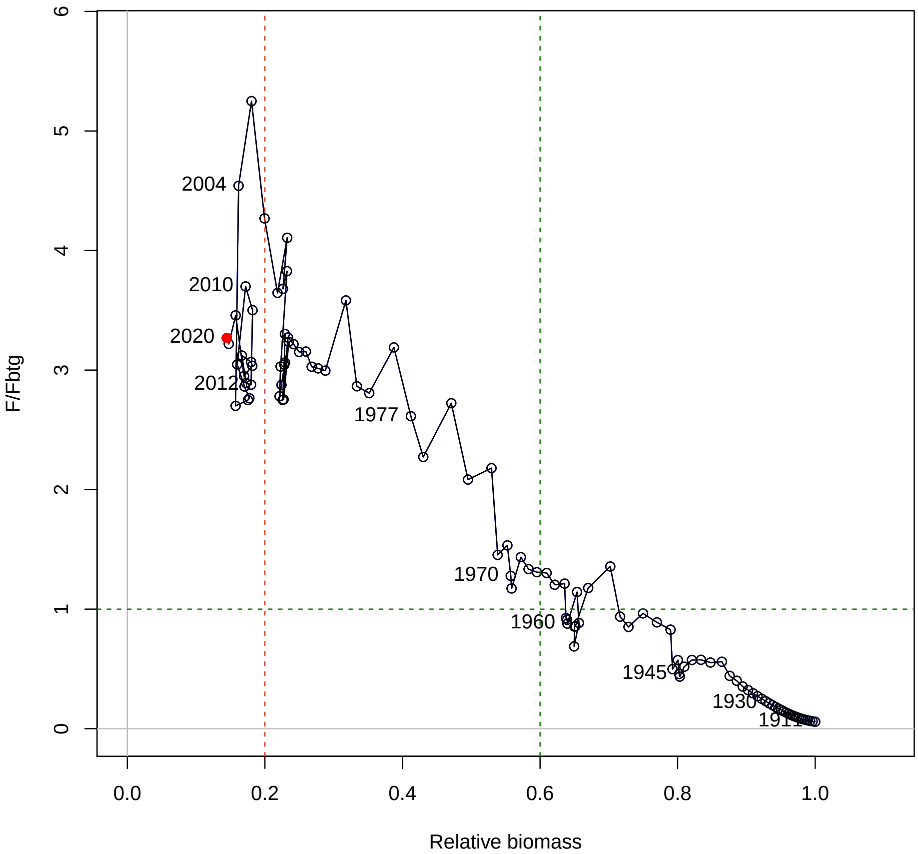

Figure E.10: Phase plot for Spanish mackerel for scenario 3

The horizontal axis is the biomass ratio of Queensland Spanish mackerel relative to unfished and the vertical axis is the fishing mortality relative to the fishing mortality which would produce the *Sustainable Fisheries Strategy* biomass target of 60%. The red dashed vertical line is the limit reference point (20% relative biomass) and the green dashed vertical line is the target reference point (60% relative biomass)

E.3 Scenario 4

Scenario 4 was identical to the base case except the catch rate modelling did not include a probability model (i.e. the higher catch rate scenario was used), and steepness, h, was fixed at 0.55.

Table E.3: Stock Synthesis parameter estimates for the scenario 4 population model for Spanish mackerel

Parameter	Estimate	Phase	Min	Max	Initial value	Standard deviation
Natural mortality	0.26	2	0.01	0.5	0.29	0.01
Length at age 1 (FL_1) female	67.21	3	30	90	72	1.43
Length at maximum age (FL_{inf}) female	130.7	3	100	180	140	2.51
von Bertalanffy growth parameter (κ) female	0.28	3	0.1	0.4	0.22	0.03
Coefficient of variation in length at age 1 female	0.07	5	0.01	0.3	0.12	0.01
Coefficient of variation in length at maximum age female	0.07	5	0.01	0.2	0.14	0.01
Length at age 1 (FL_1) male	66.14	3	30	85	70	1.33
Length at maximum age (FL_{inf}) male	114.34	3	100	200	120	1.37
von Bertalanffy growth parameter (κ) male	0.34	3	0.1	0.45	0.21	0.03
Coefficient of variation in length at age 1 male	0.08	5	0.01	0.3	0.13	0.01
Coefficient of variation in length at maximum age male	0.04	5	0.01	0.2	0.12	0
Beverton-Holt unfished recruitment (logarithm of the number of recruits in 1911)	13.04	1	10	14.2	13	0.04
Commercial selectivity inflection (cm)	81.41	4	30	120	60	0.9
Commercial selectivity width (cm)	11.65	4	0	20	0.5	1.37

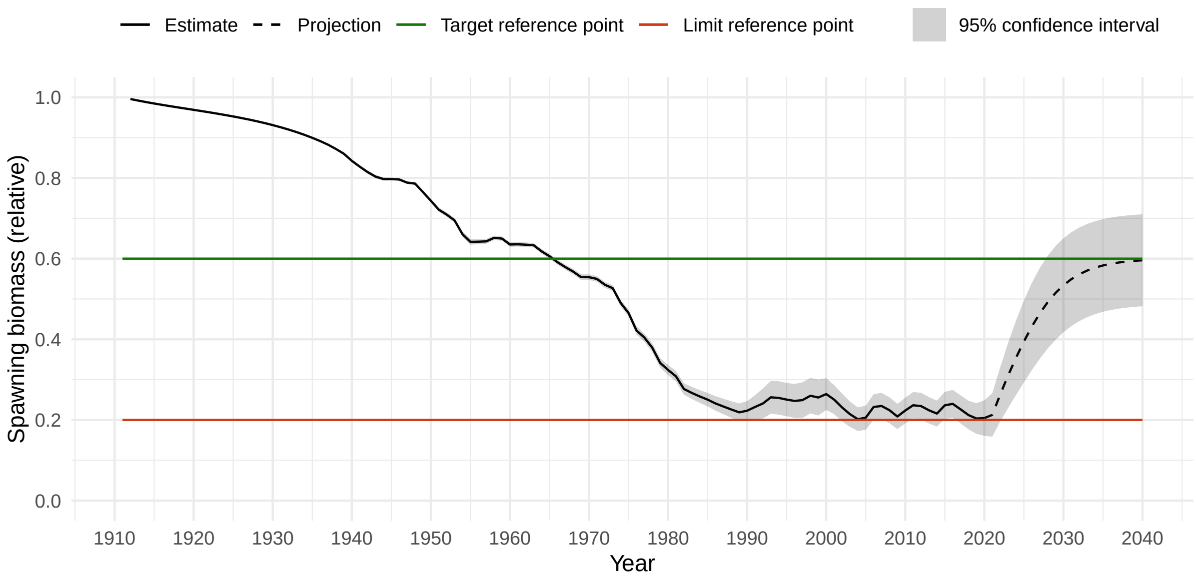

Figure E.11: Predicted spawning biomass trajectory relative to virgin for Spanish mackerel, from 1911 to 2040, for scenario 4

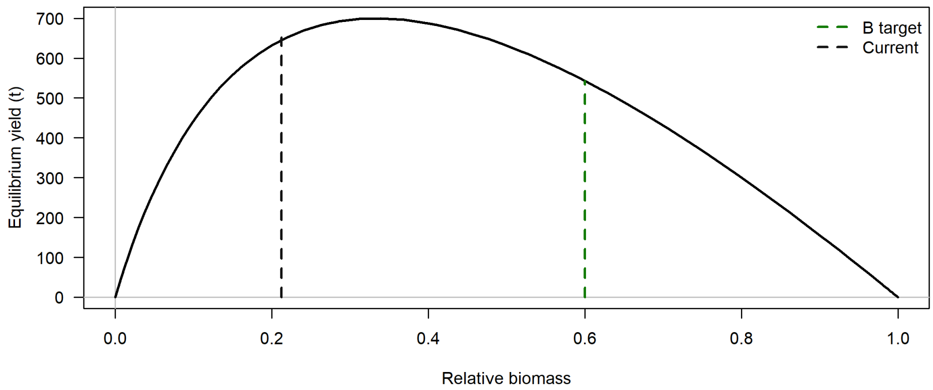

Figure E.12: Equilibrium yield curve for Spanish mackerel for scenario 4

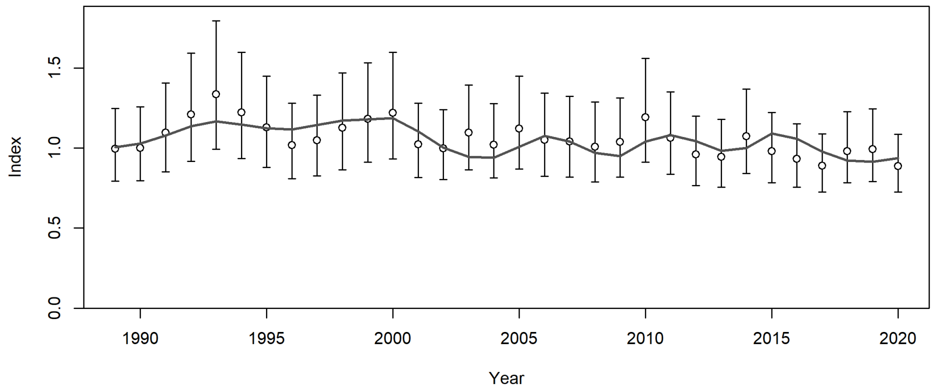

Figure E.13: Model predictions (grey line) to commercial catch rates for Spanish mackerel for scenario 4

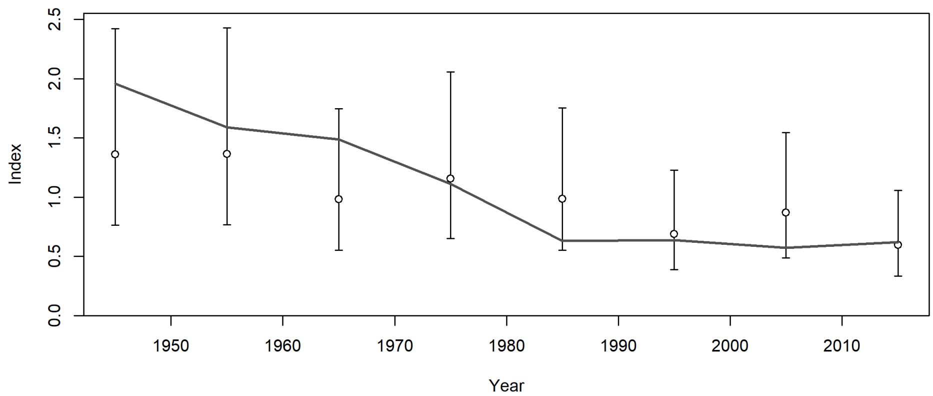

Figure E.14: Model predictions (grey line) to historical decadal catch rates for Spanish mackerel for scenario 4

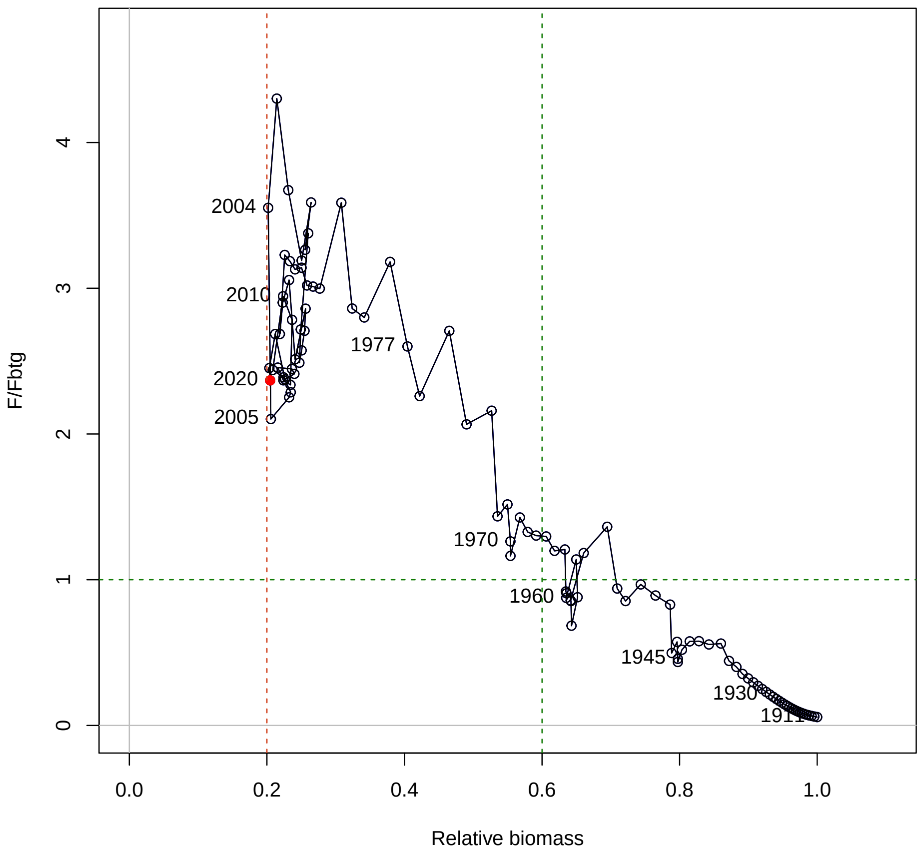

Figure E.15: Phase plot for Spanish mackerel for scenario 4

The horizontal axis is the biomass ratio of Queensland Spanish mackerel relative to unfished and the vertical axis is the fishing mortality relative to the fishing mortality which would produce the *Sustainable Fisheries Strategy* biomass target of 60%. The red dashed vertical line is the limit reference point (20% relative biomass) and the green dashed vertical line is the target reference point (60% relative biomass)

E.4 Scenario 5

Scenario 5 used the same input data as scenario 4, but estimating steepness h instead of fixing at 0.55. Natural mortality (M) was fixed at 0.33.

Table E.4: Stock Synthesis parameter estimates for the scenario 5 population model for Spanish mackerel

Parameter	Estimate	Phase	Min	Max	Initial value	Standard deviation
Length at age 1 (FL_1) female	66.86	3	30	90	72	1.46
Length at maximum age (FL_{inf}) female	130.39	3	100	180	140	2.48
von Bertalanffy growth parameter (κ) female	0.29	3	0.1	0.4	0.22	0.03
Coefficient of variation in length at age 1 female	0.07	5	0.01	0.3	0.12	0.01
Coefficient of variation in length at maximum age female	0.07	5	0.01	0.2	0.14	0.01
Length at age 1 (FL_1) male	66.06	3	30	85	70	1.34
Length at maximum age (FL_{inf}) male	114.42	3	100	200	120	1.38
von Bertalanffy growth parameter (κ) male	0.34	3	0.1	0.45	0.21	0.03
Coefficient of variation in length at age 1 male	0.08	5	0.01	0.3	0.13	0.01
Coefficient of variation in length at maximum age male	0.04	5	0.01	0.2	0.12	0
Beverton-Holt unfished recruitment (logarithm of the number of recruits in 1911)	13.66	1	10	15	13	0.07
Steepness (h) of Beverton-Holt function	0.39	2	0.2	1	0.55	0.02
Commercial selectivity inflection (cm)	81.61	4	30	120	60	0.92
Commercial selectivity width (cm)	11.65	4	0	20	0.5	1.36

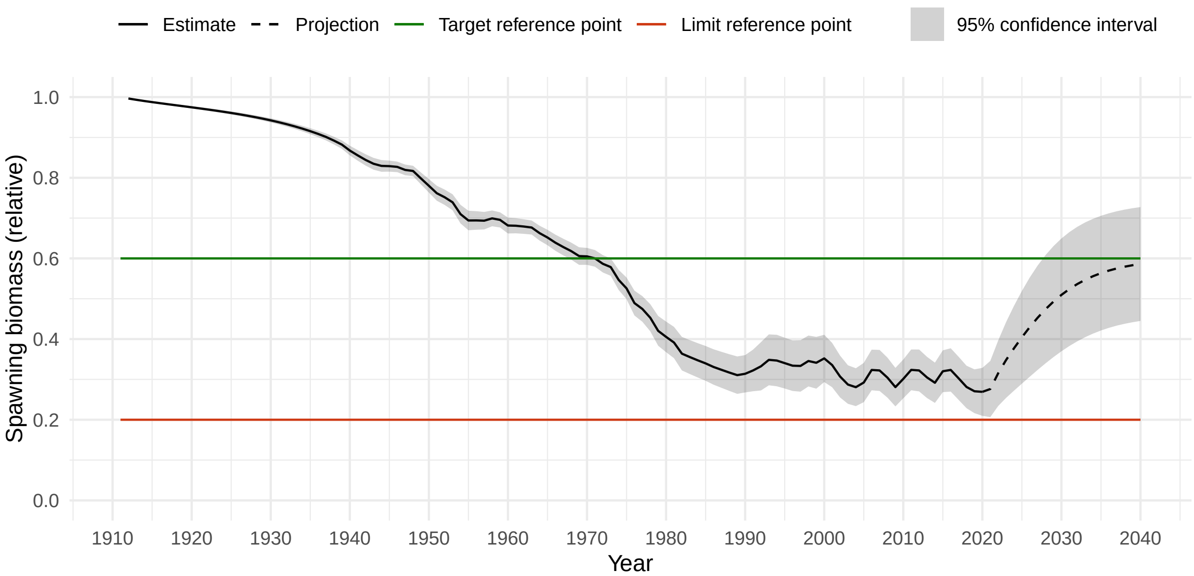

Figure E.16: Predicted spawning biomass trajectory relative to virgin for Spanish mackerel, from 1911 to 2040, for scenario 5

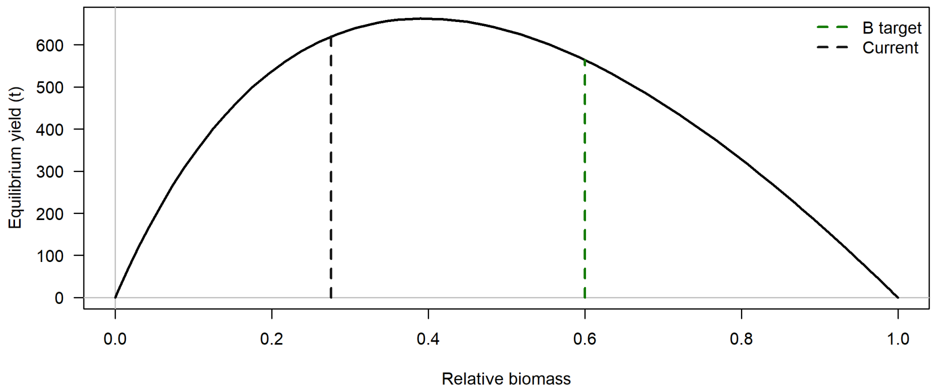

Figure E.17: Equilibrium yield curve for Spanish mackerel for scenario 5

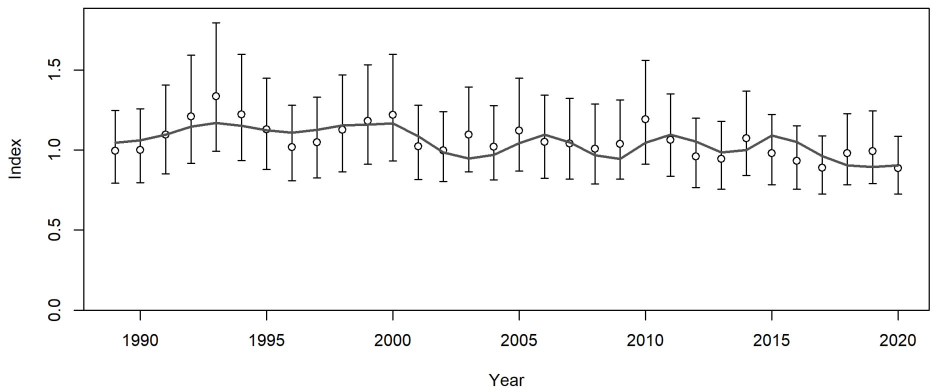

Figure E.18: Model predictions (grey line) to commercial catch rates for Spanish mackerel for scenario 5

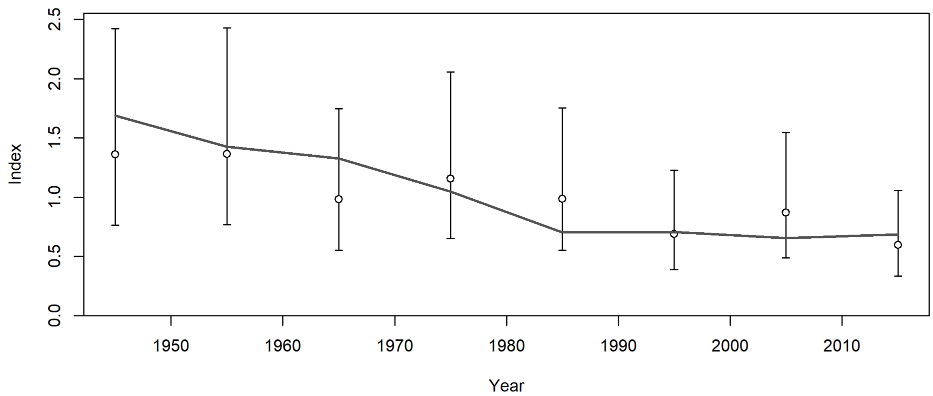

Figure E.19: Model predictions (grey line) to historical decadal catch rates for Spanish mackerel for scenario 5

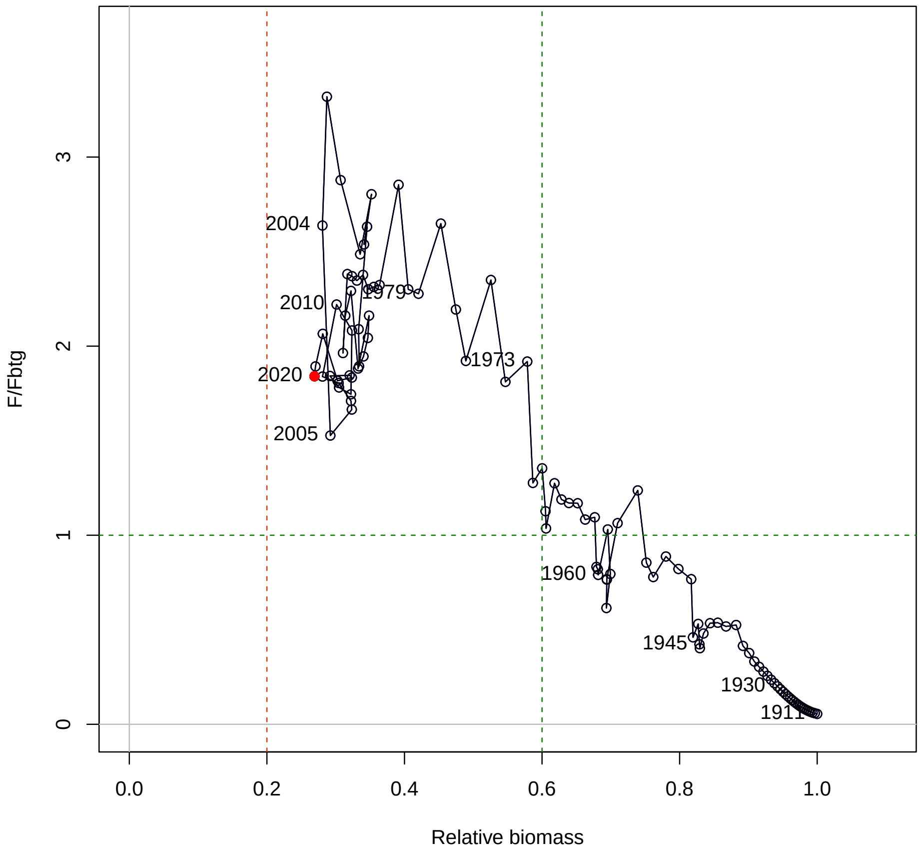

Figure E.20: Phase plot for Spanish mackerel for scenario 5

The horizontal axis is the biomass ratio of Queensland Spanish mackerel relative to unfished and the vertical axis is the fishing mortality relative to the fishing mortality which would produce the *Sustainable Fisheries Strategy* biomass target of 60%. The red dashed vertical line is the limit reference point (20% relative biomass) and the green dashed vertical line is the target reference point (60% relative biomass)

E.5 Scenario 6

Scenario 6 used the same input data as the base case except a probability adjustment was not included in the catch rate analysis, and steepness h was fixed at 0.65.

Table E.5: Stock Synthesis parameter estimates for the scenario 6 population model for Spanish mackerel

Parameter	Estimate	Phase	Min	Max	Initial value	Standard deviation
Natural mortality	0.37	3	0.01	0.5	0.29	0.02
Length at age 1 (FL_1) female	66.74	2	30	90	72	1.44
Length at maximum age (FL_{inf}) female	130.32	2	100	180	140	2.44
von Bertalanffy growth parameter (κ) female	0.29	2	0.1	0.4	0.22	0.03
Coefficient of variation in length at age 1 female	0.08	4	0.01	0.3	0.12	0.01
Coefficient of variation in length at maximum age female	0.07	4	0.01	0.2	0.14	0.01
Length at age 1 (FL_1) male	65.9	2	30	85	70	1.32
Length at maximum age (FL_{inf}) male	114.36	2	100	200	120	1.36
von Bertalanffy growth parameter (κ) male	0.34	2	0.1	0.45	0.21	0.03
Coefficient of variation in length at age 1 male	0.08	4	0.01	0.3	0.13	0.01
Coefficient of variation in length at maximum age male	0.04	4	0.01	0.2	0.12	0
Beverton-Holt unfished recruitment (logarithm of the number of recruits in 1911)	13.6	1	10	15	13	0.18
Commercial selectivity inflection (cm)	81.57	3	30	120	60	0.93
Commercial selectivity width (cm)	11.54	3	0	20	0.5	1.33

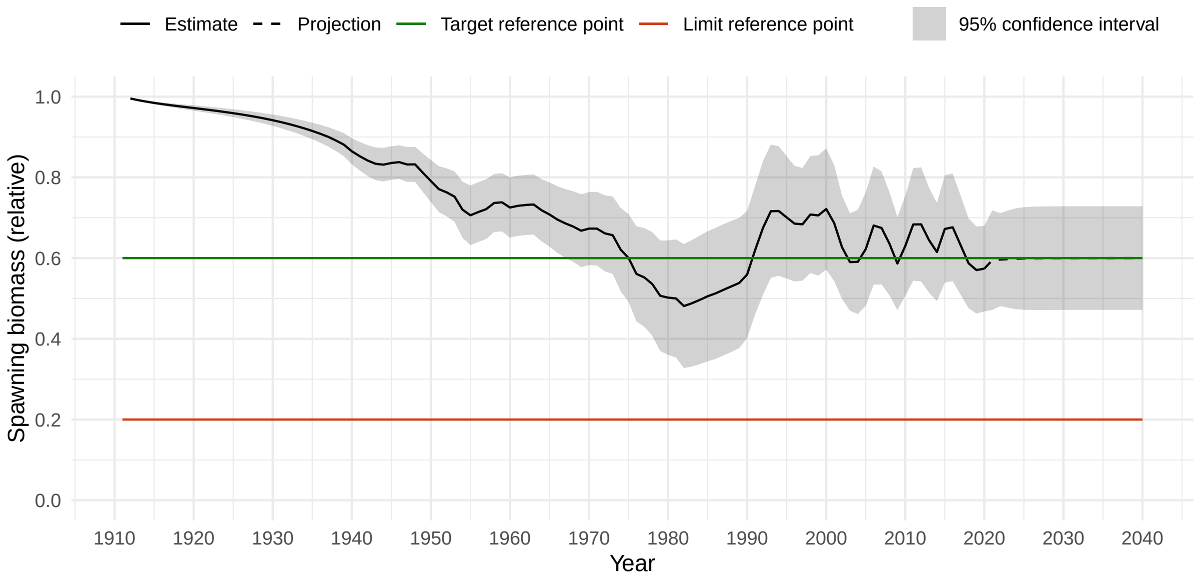

Figure E.21: Predicted spawning biomass trajectory relative to virgin for Spanish mackerel, from 1911 to 2040, for scenario 6

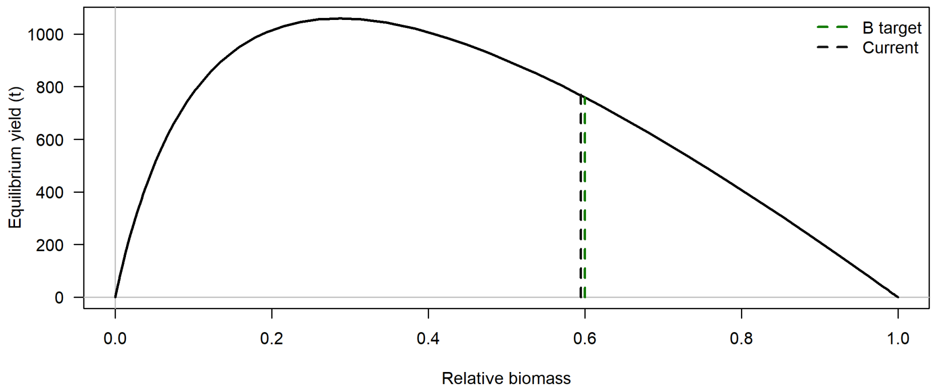

Figure E.22: Equilibrium yield curve for Spanish mackerel for scenario 6

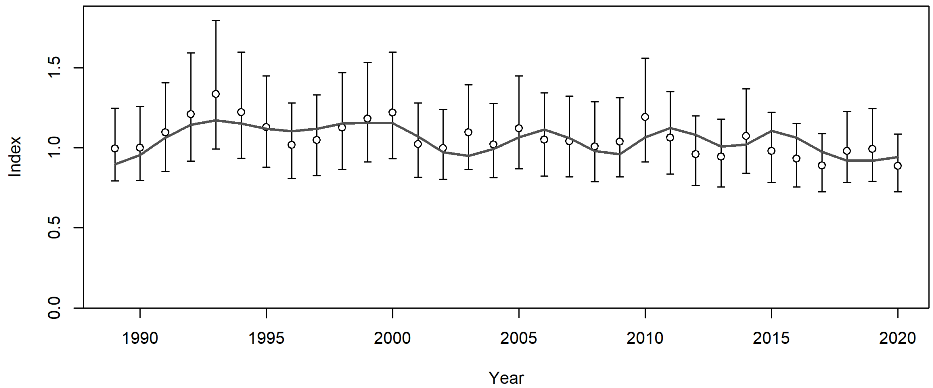

Figure E.23: Model predictions (grey line) to commercial catch rates for Spanish mackerel for scenario 6

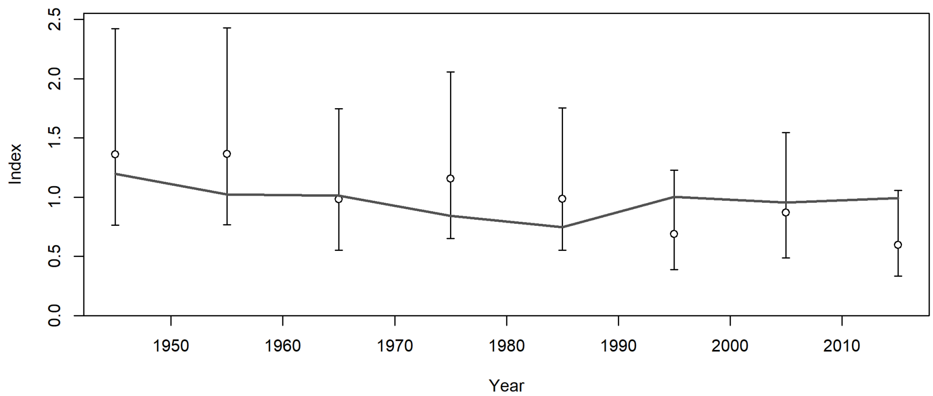

Figure E.24: Model predictions (grey line) to historical decadal catch rates for Spanish mackerel for scenario 6

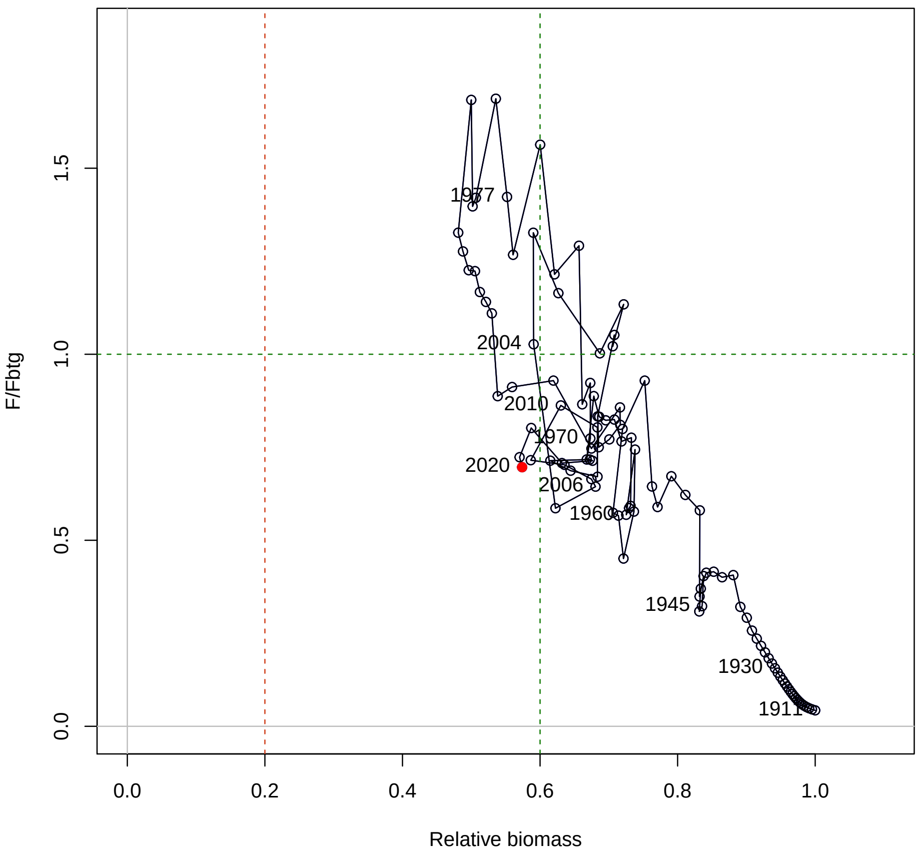

Figure E.25: Phase plot for Spanish mackerel for scenario 6

The horizontal axis is the biomass ratio of Queensland Spanish mackerel relative to unfished and the vertical axis is the fishing mortality relative to the fishing mortality which would produce the *Sustainable Fisheries Strategy* biomass target of 60%. The red dashed vertical line is the limit reference point (20% relative biomass) and the green dashed vertical line is the target reference point (60% relative biomass)

E.6 Scenario 7

Scenario 7 used the same input data as the base case except catch rates were calculated used full fishing power instead of half.

Table E.6: Stock Synthesis parameter estimates for the scenario 7 population model for Spanish mackerel

Parameter	Estimate	Phase	Min	Max	Initial value	Standard deviation
Natural mortality	0.26	3	0.01	0.5	0.29	0.01
Length at age 1 (FL_1) female	67.12	2	30	90	72	1.42
Length at maximum age (FL_{inf}) female	130.56	2	100	180	140	2.47
von Bertalanffy growth parameter (κ) female	0.28	2	0.1	0.4	0.22	0.03
Coefficient of variation in length at age 1 female	0.07	4	0.01	0.3	0.12	0.01
Coefficient of variation in length at maximum age female	0.07	4	0.01	0.2	0.14	0.01
Length at age 1 (FL_1) male	66.14	2	30	85	70	1.31
Length at maximum age (FL_{inf}) male	114.41	2	100	200	120	1.35
von Bertalanffy growth parameter (κ) male	0.34	2	0.1	0.45	0.21	0.03
Coefficient of variation in length at age 1 male	0.08	4	0.01	0.3	0.13	0.01
Coefficient of variation in length at maximum age male	0.04	4	0.01	0.2	0.12	0
Beverton-Holt unfished recruitment (logarithm of the number of recruits in 1911)	13.28	1	10	13.75	13.3	0.05
Commercial selectivity inflection (cm)	81.35	2	30	120	60	0.88
Commercial selectivity width (cm)	11.58	2	0	20	0.5	1.33

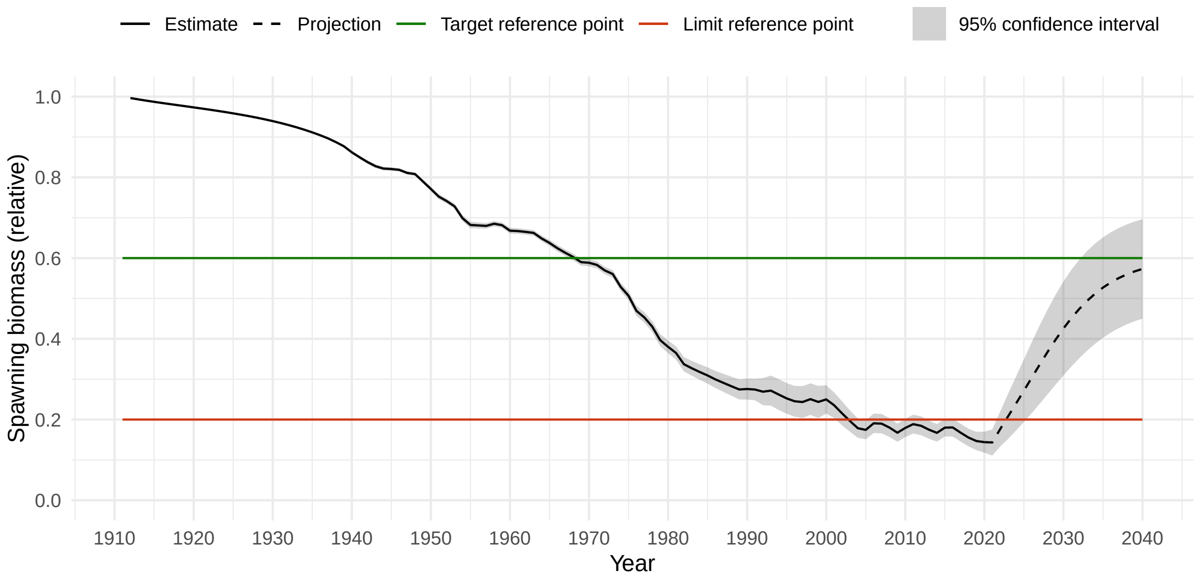

Figure E.26: Predicted spawning biomass trajectory relative to virgin for Spanish mackerel, from 1911 to 2040, for scenario 7

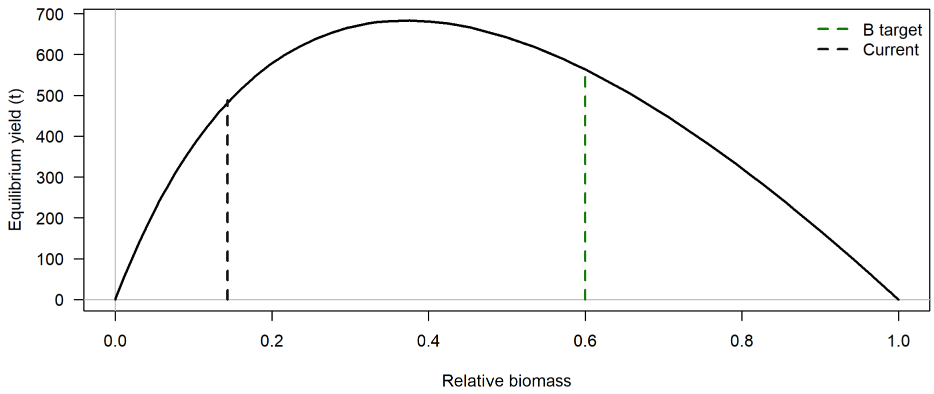

Figure E.27: Equilibrium yield curve for Spanish mackerel for scenario 7

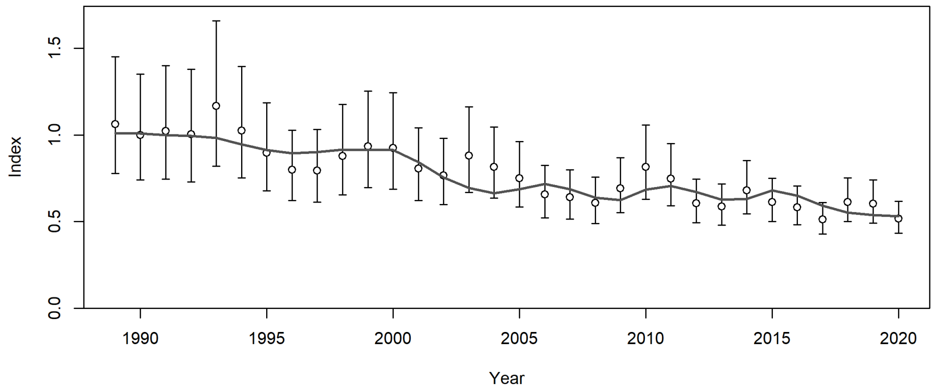

Figure E.28: Model predictions (grey line) to commercial catch rates for Spanish mackerel for scenario 7

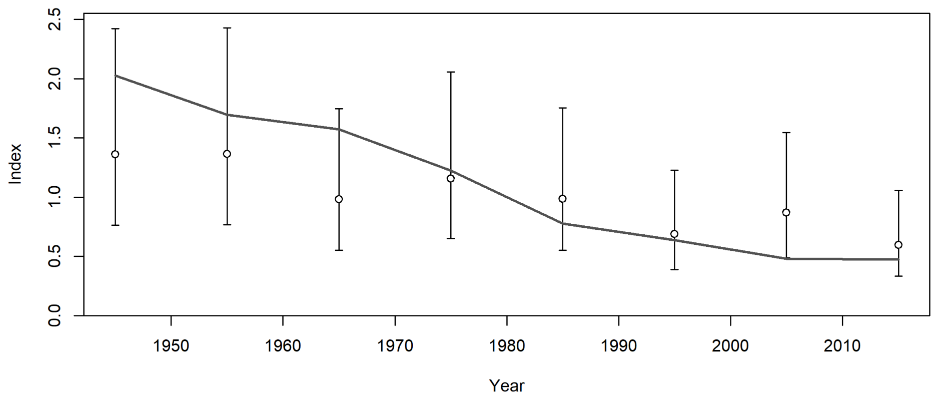

Figure E.29: Model predictions (grey line) to historical decadal catch rates for Spanish mackerel for scenario 7

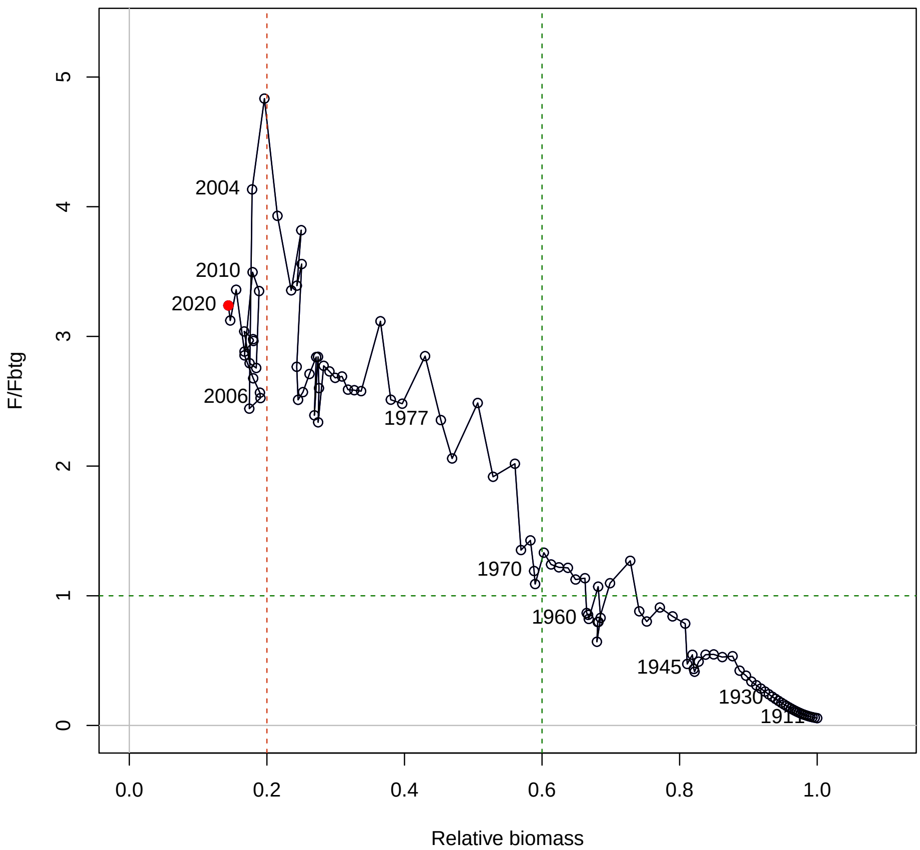

Figure E.30: Phase plot for Spanish mackerel for scenario 7

The horizontal axis is the biomass ratio of Queensland Spanish mackerel relative to unfished and the vertical axis is the fishing mortality relative to the fishing mortality which would produce the *Sustainable Fisheries Strategy* biomass target of 60%. The red dashed vertical line is the limit reference point (20% relative biomass) and the green dashed vertical line is the target reference point (60% relative biomass)

E.7 Scenario 8

Scenario 8 used the same input data as the base case except catch rates were calculated used full fishing power instead of half, and no probability adjustment was used.

Table E.7: Stock Synthesis parameter estimates for the scenario 8 population model for Spanish mackerel

Parameter	Estimate	Phase	Min	Max	Initial value	Standard deviation
Natural mortality	0.28	1	0.01	0.5	0.28	0.01
Length at age 1 (FL_1) female	67.01	2	30	90	67.01	1.38
Length at maximum age (FL_{inf}) female	130.38	2	100	180	130.38	2.38
von Bertalanffy growth parameter (κ) female	0.29	2	0.1	0.4	0.29	0.03
Coefficient of variation in length at age 1 female	0.07	4	0.01	0.3	0.07	0.01
Coefficient of variation in length at maximum age female	0.07	4	0.01	0.2	0.07	0.01
Length at age 1 (FL_1) male	66.05	2	30	85	66.05	1.28
Length at maximum age (FL_{inf}) male	114.28	2	100	200	114.28	1.3
von Bertalanffy growth parameter (κ) male	0.34	2	0.1	0.45	0.34	0.03
Coefficient of variation in length at age 1 male	0.08	4	0.01	0.3	0.08	0.01
Coefficient of variation in length at maximum age male	0.04	4	0.01	0.2	0.04	0
Beverton-Holt unfished recruitment (logarithm of the number of recruits in 1911)	13.33	3	10	15	13.33	0.05
Commercial selectivity inflection (cm)	81.34	2	30	120	81.34	0.89
Commercial selectivity width (cm)	11.58	2	0	20	11.58	1.33

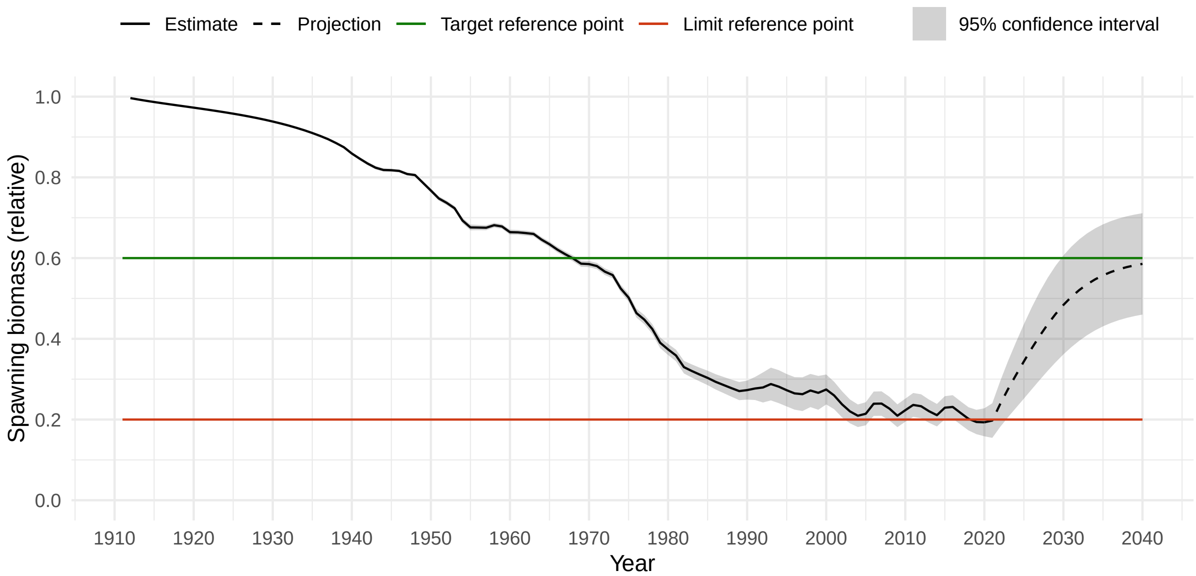

Figure E.31: Predicted spawning biomass trajectory relative to virgin for Spanish mackerel, from 1911 to 2040, for scenario 8

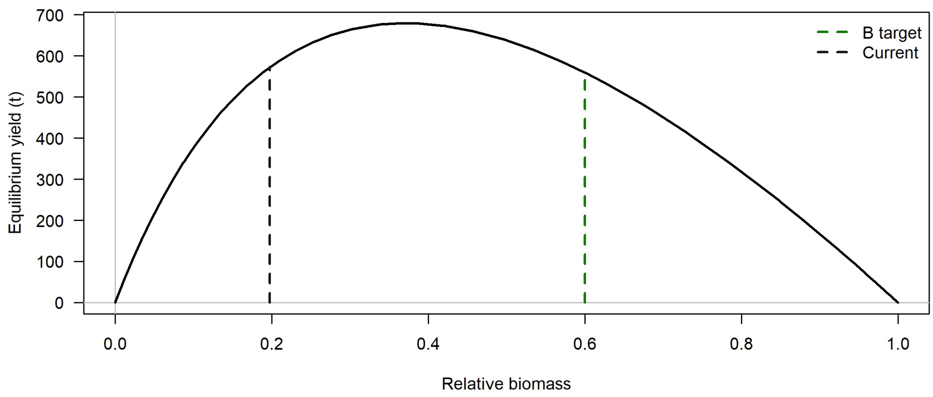

Figure E.32: Equilibrium yield curve for Spanish mackerel for scenario 8

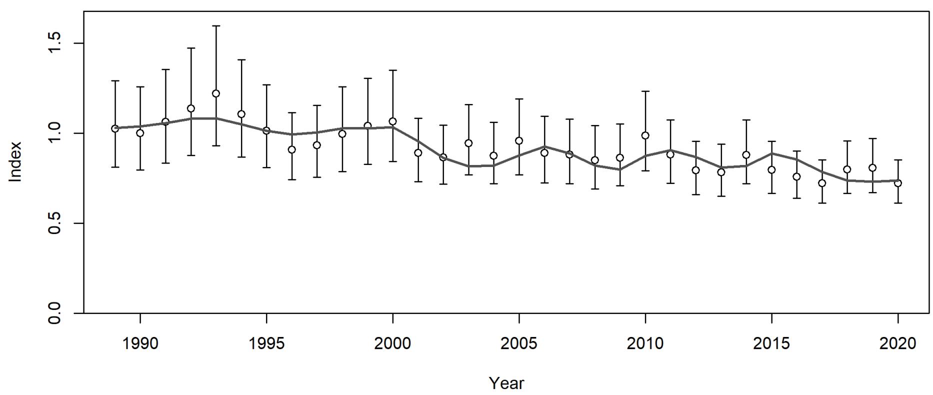

Figure E.33: Model predictions (grey line) to commercial catch rates for Spanish mackerel for scenario 8

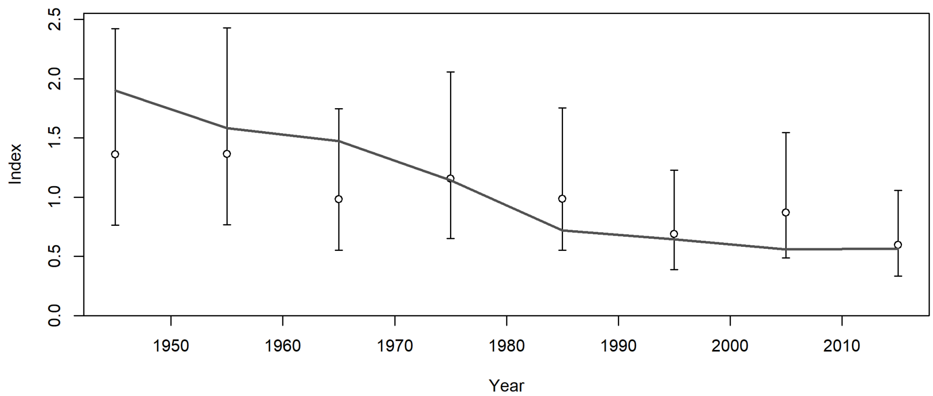

Figure E.34: Model predictions (grey line) to historical decadal catch rates for Spanish mackerel for scenario 8

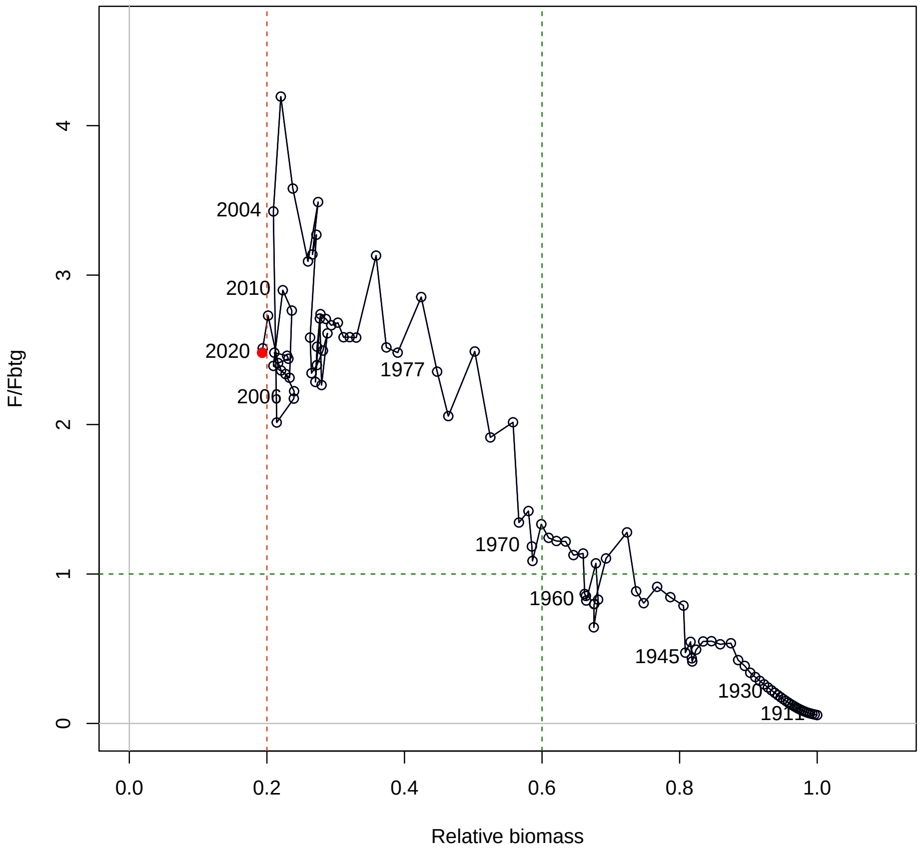

Figure E.35: Phase plot for Spanish mackerel for scenario 8

The horizontal axis is the biomass ratio of Queensland Spanish mackerel relative to unfished and the vertical axis is the fishing mortality relative to the fishing mortality which would produce the *Sustainable Fisheries Strategy* biomass target of 60%. The red dashed vertical line is the limit reference point (20% relative biomass) and the green dashed vertical line is the target reference point (60% relative biomass)

Appendix F Shark depredation

F.1 Background and methods

Depredation, when a shark preys on a fisher's catch before landing, is increasingly being described by many offshore line fishers in Queensland (Major 2020). Some offshore line fishers report shark depredation as increasing each year (pers. comm. Queensland rocky reef working group). To capture this phenomenon in stock assessment, a scenario was developed to hypothesise that the rate of depredation may have increased.

In these scenarios, shark depredation was assumed to increase from 2009, when fishery management introduced Queensland commercial quota for east coast shark harvest and the requirement to hold a commercial shark fishing 'S' symbol. Queensland commercial east coast shark catch decreased following the management changes in 2009 (Queensland annual total east coast shark quota was 600 t per financial year; mean annual shark harvest pre-quota, 2000–2009, was 1190 t; mean annual shark harvest, 2010–2020, was 338 t), and there was a belief among some fishers that these changes have directly resulted in higher numbers of shark and higher depredation rates.

In addition, to support the notion of increased shark depredation in offshore line fisheries, annual nominal levels of otter trawling have roughly halved since 2009, with a decline in bycatch discarding on which sharks may scavenge and feed (Wang et al. 2020; Hill et al. 2000). With less discarded trawl bycatch, one could speculate that sharks may alter their scavenging patterns as needed to rob more from offshore line fishing catches.

The change in shark depredation (decrease in landed Spanish mackerel harvest) since 2009 was hypothesised using the following equation:

$$d = (1 - r)^t \tag{F.1}$$

where d was the relative annual shark offset effect for reduced Spanish mackerel harvest since 2009, r was the hypothesised annual rate effect = 0.01842347, t was the cumulative years since 2009, and d was equal to 1 prior to 2009. The assumed reduction in Spanish mackerel catch due to shark depredation was 0.2 in 2020. The annual rate r was estimated to match $d = 1 - 0.2$ after 12 years in 2020.

The value of 0.2 related to the fraction of fish lost during the catching process (discard effects were accounted separately). This was a maximum value from Mitchell et al. (2018): "Gilman et al. (2008) conducted a large-scale study of depredation in 12 commercial pelagic longline fisheries from eight countries worldwide, with the highest rate of shark depredation (20%) recorded in the Australian fishery."

Lesser rates might be more realistic, but the high rate was used to assess a maximal effect in stock assessment. In the recent national Spanish mackerel research meeting (online in March 2021), Western Australian researchers measured smaller depredation effects around 3–5% and 8–10% varying with fishing grounds (pers. comm.); the WA research is ongoing. Shark depredation was not an issue in New South Wales waters (pers. comm.).

The shark depredation effect was applied two-fold: 1) in the combined log annual shark + log fishing power offset for non-zero catch rate analysis and standardisation, and 2) total annual harvests were inflated for lost fish by dividing harvest only estimates by the shark offset (Rabearisoa et al. 2018). The recreational harvest estimates were recalculated on the new catch rate results from step 1. These steps altered the data inputs into Stock Synthesis, to form the shark depredation scenario.

For the 2020 stock assessment results, interpretation and use, a 20% shark allocation is required in TACC allocation, unless mitigation measures are used to reduce the assumed effects. Overall, the shark analysis scenario aimed to provide an example test to compare different results against the base case stock assessment. In addition, a higher level of steepness parameter (h = 0.55) was tested to check the sensitivity of h on shark depredation effect adjustment.

F.2 Results

Standardised catch rate adjusted for shark depredation effect is given in Figure F.1. The summary of stock assessment results is provided in Table F.1, with full results in Section F.2.1 and F.2.2.

Notable points in results were:

- Standardised catch rates post 2009 were higher for the assumed 20% shark depredation adjustment (Figure F.1).
- Natural mortality and virgin recruitment (log($R0$) are similar, but slightly higher with shark depredation adjustment.
- Estimated spawning biomasses in 2020 were about 6% higher compared to assuming no shark effects, likely due to higher catch rate used as an index of abundance.

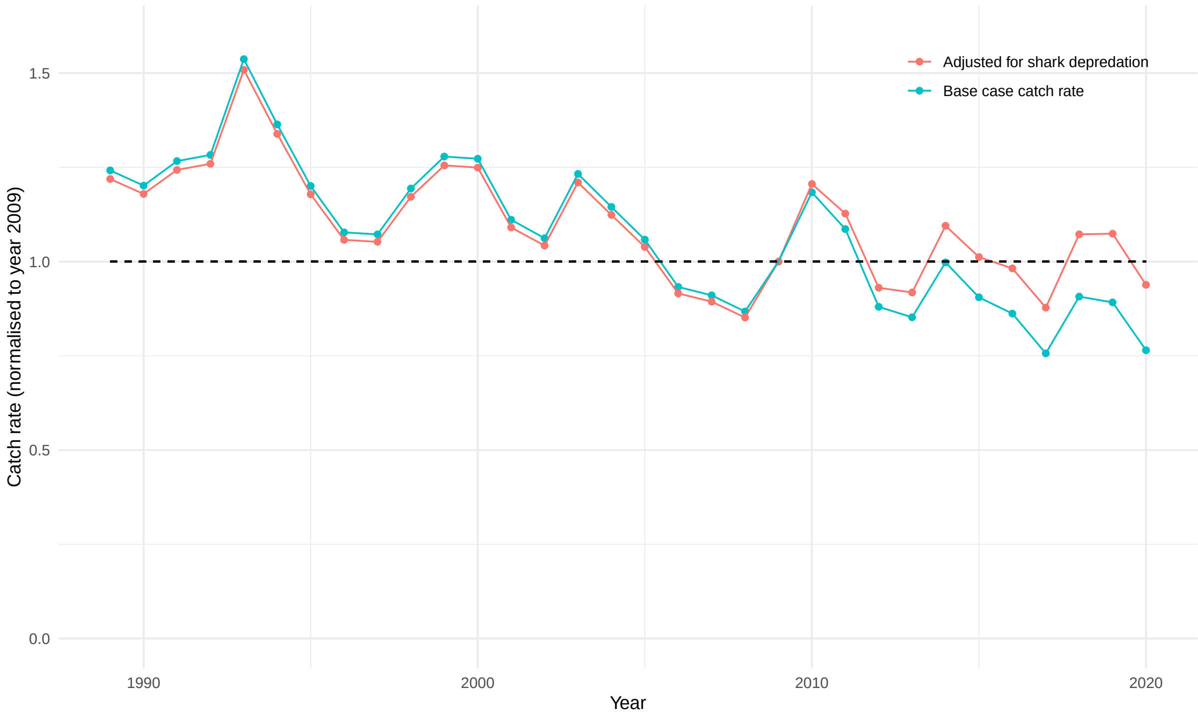

Figure F.1: Comparison of standardised catch rate with and without shark depredation effect, normalised to 2009.

Table F.1: Comparison of stock assessment results with and without shark depredation effect

parameters/indicators	Results for no depredation	Results adjusted for depredation
Scenario=1		
Steepness h (fixed)	0.45	0.45
Natural mortality M	0.27	0.28
log(R_0)	13.3	13.37
Spawning ratio B_{2020}/B_0	0.17	0.23
Sustainable harvest at B_{60}	557 t	573 t
Scenario=3		
Steepness h (fixed)	0.55	0.55
Natural mortality M	0.23	0.24
log(R_0)	12.93	12.99
Spawning ratio B_{2020}/B_0	0.14	0.20
Sustainable harvest at B_{60}	543 t	556 t

F.2.1 Steepness fixed at 0.45

Table F.2: Stock Synthesis parameter estimates for the shark depredation scenario population model where steepness was fixed at 0.45 for Spanish mackerel

Parameter	Estimate	Phase	Min	Max	Initial value	Standard deviation
Natural mortality	0.28	3	0.01	0.5	0.29	0.01
Length at age 1 (FL_1) female	66.82	1	30	90	72	1.4
Length at maximum age (FL_{inf}) female	130.21	1	100	180	140	2.39
von Bertalanffy growth parameter (κ) female	0.29	1	0.1	0.4	0.22	0.03
Coefficient of variation in length at age 1 female	0.07	4	0.01	0.3	0.12	0.01
Coefficient of variation in length at maximum age female	0.07	4	0.01	0.2	0.14	0.01
Length at age 1 (FL_1) male	65.93	1	30	85	70	1.28
Length at maximum age (FL_{inf}) male	114.23	1	100	200	120	1.3
von Bertalanffy growth parameter (κ) male	0.35	1	0.1	0.45	0.21	0.03
Coefficient of variation in length at age 1 male	0.08	4	0.01	0.3	0.13	0.01
Coefficient of variation in length at maximum age male	0.04	4	0.01	0.2	0.12	0
Beverton-Holt unfished recruitment (logarithm of the number of recruits in 1911)	13.37	1	10	13.75	13.3	0.05
Commercial selectivity inflection (cm)	81.44	2	30	120	60	0.91
Commercial selectivity width (cm)	11.52	2	0	20	0.5	1.35

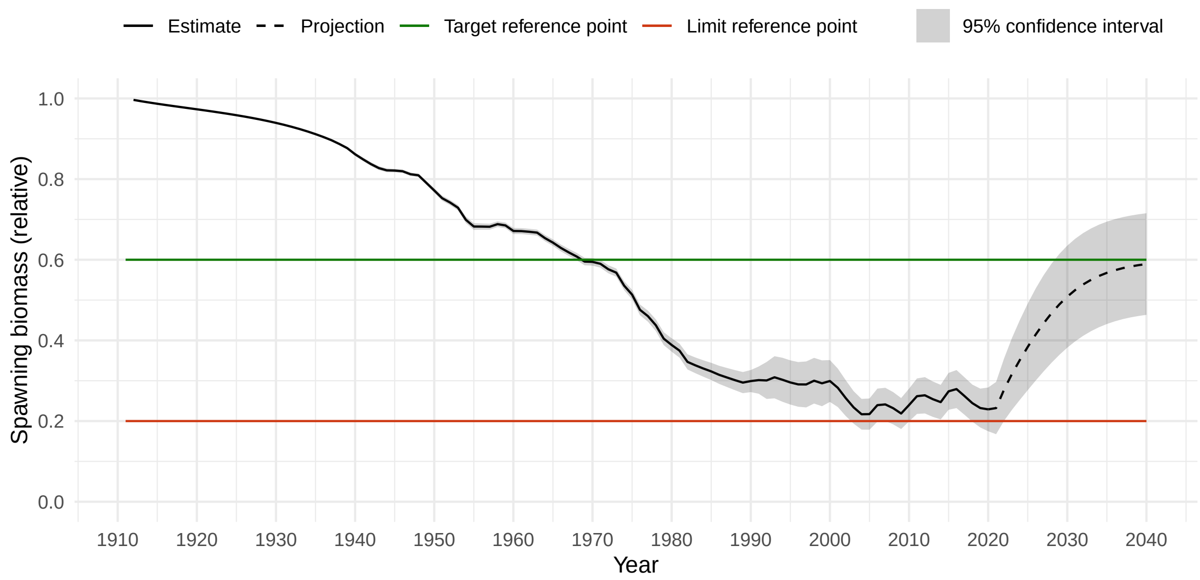

Figure F.2: Predicted spawning biomass trajectory relative to virgin for Spanish mackerel, from 1911 to 2040, for shark depredation scenario where steepness was fixed at 0.45

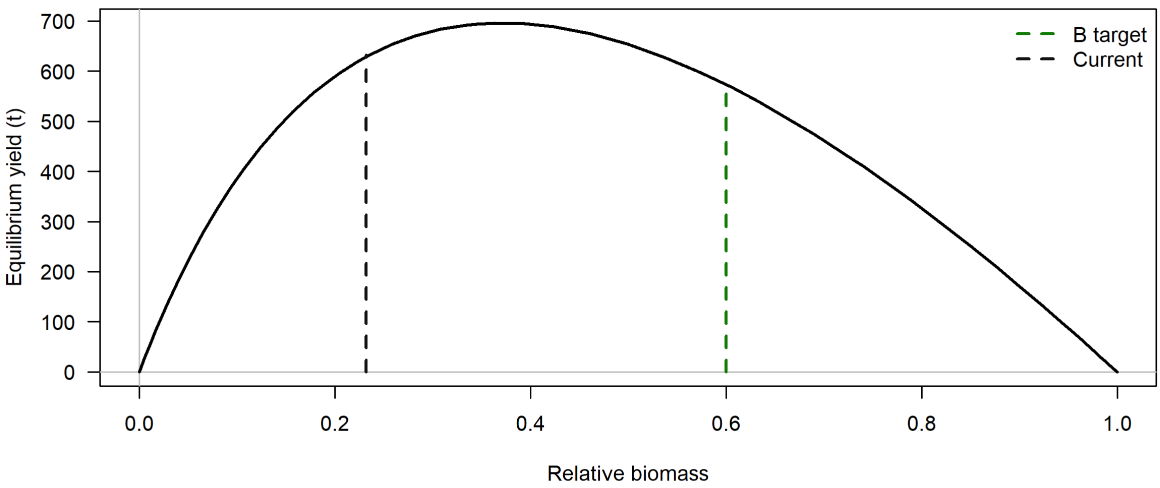

Figure F.3: Equilibrium yield curve for Spanish mackerel for shark depredation scenario where steepness was fixed at 0.45

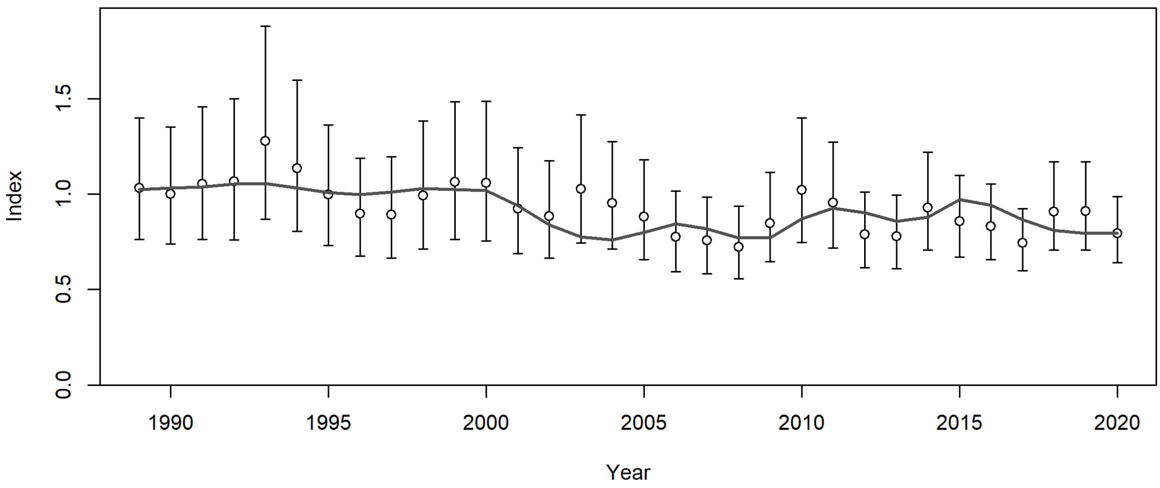

Figure F.4: Model predictions (grey line) to commercial catch rates for Spanish mackerel for shark depredation scenario where steepness was fixed at 0.45

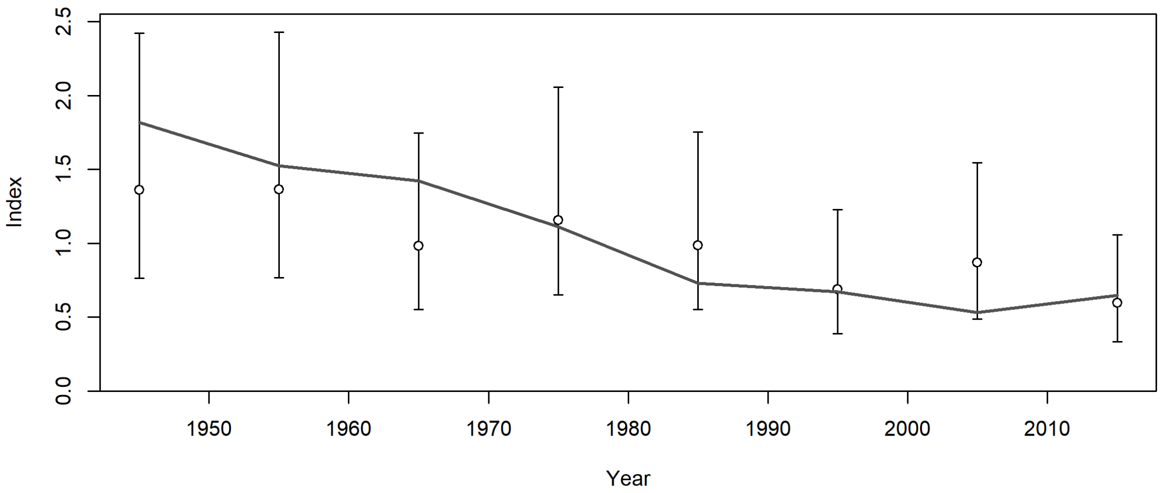

Figure F.5: Model predictions (grey line) to historical decadal catch rates for Spanish mackerel for shark depredation scenario where steepness was fixed at 0.45

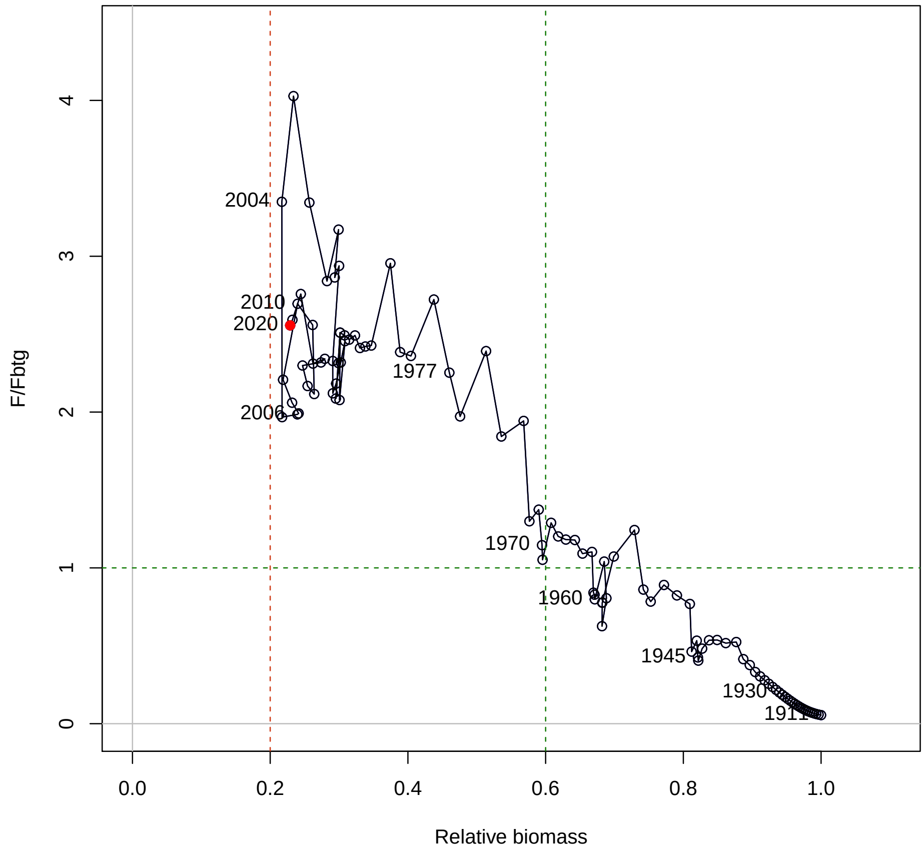

Figure F.6: Phase plot for Spanish mackerel for shark depredation scenario where steepness was fixed at 0.45

The horizontal axis is the biomass ratio of Queensland Spanish mackerel relative to unfished and the vertical axis is the fishing mortality relative to the fishing mortality which would produce the *Sustainable Fisheries Strategy* biomass target of 60%. The red dashed vertical line is the limit reference point (20% relative biomass) and the green dashed vertical line is the target reference point (60% relative biomass)

F.2.2 Steepness fixed at 0.55

Table F.3: Stock Synthesis parameter estimates for the shark depredation scenario population model for Spanish mackerel where steepness was fixed at 0.55

Parameter	Estimate	Phase	Min	Max	Initial value	Standard deviation
Natural mortality	0.24	3	0.01	0.5	0.29	0.01
Length at age 1 (FL_1) female	66.96	1	30	90	72	1.39
Length at maximum age (FL_{inf}) female	130.27	1	100	180	140	2.4
von Bertalanffy growth parameter (κ) female	0.29	1	0.1	0.4	0.22	0.03
Coefficient of variation in length at age 1 female	0.07	4	0.01	0.3	0.12	0.01
Coefficient of variation in length at maximum age female	0.07	4	0.01	0.2	0.14	0.01
Length at age 1 (FL_1) male	65.99	1	30	85	70	1.29
Length at maximum age (FL_{inf}) male	114.2	1	100	200	120	1.31
von Bertalanffy growth parameter (κ) male	0.35	1	0.1	0.45	0.21	0.03
Coefficient of variation in length at age 1 male	0.08	4	0.01	0.3	0.13	0.01
Coefficient of variation in length at maximum age male	0.04	4	0.01	0.2	0.12	0
Beverton-Holt unfished recruitment (logarithm of the number of recruits in 1911)	12.99	1	10	13.75	13.3	0.05
Commercial selectivity inflection (cm)	81.23	2	30	120	60	0.89
Commercial selectivity width (cm)	11.47	2	0	20	0.5	1.35

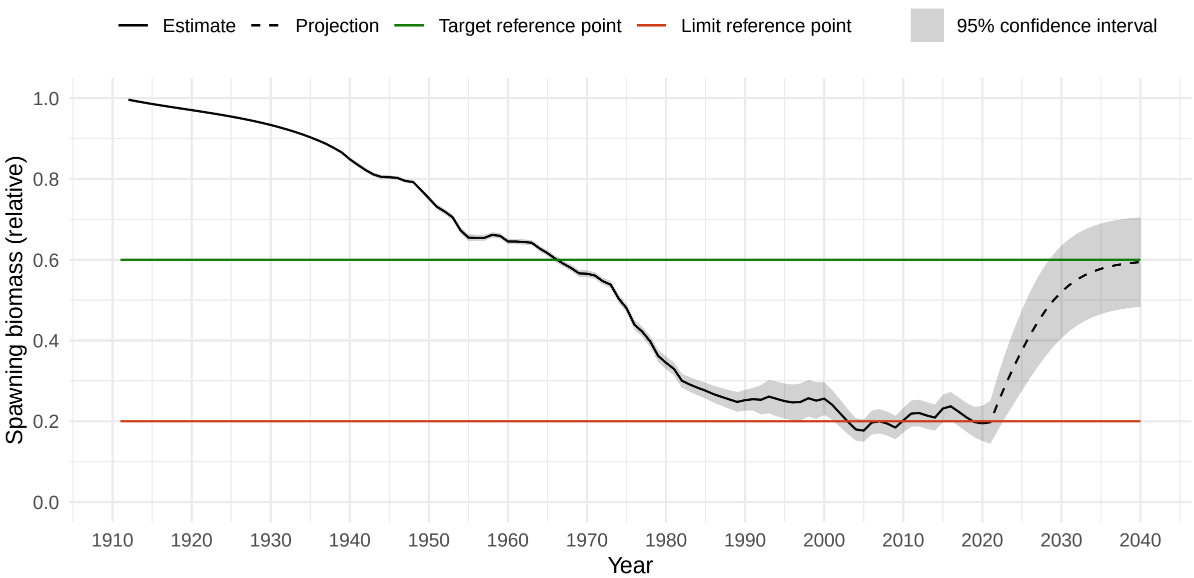

Figure F.7: Predicted spawning biomass trajectory relative to virgin for Spanish mackerel, from 1911 to 2040, for shark depredation scenario where steepness was fixed at 0.55

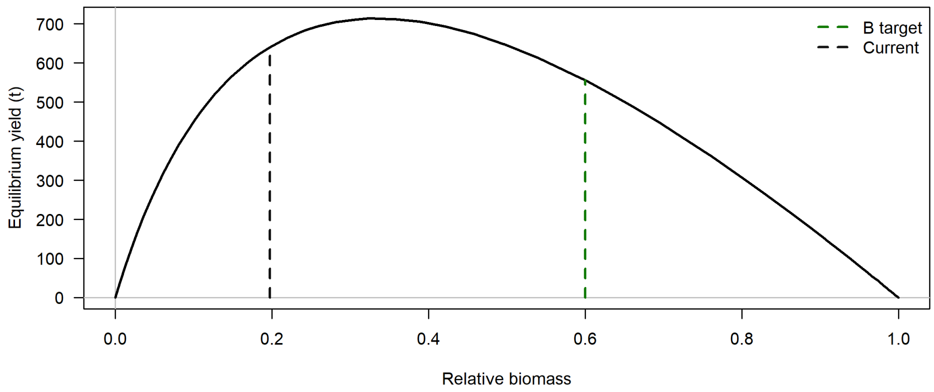

Figure F.8: Equilibrium yield curve for Spanish mackerel for shark depredation scenario where steepness was fixed at 0.55

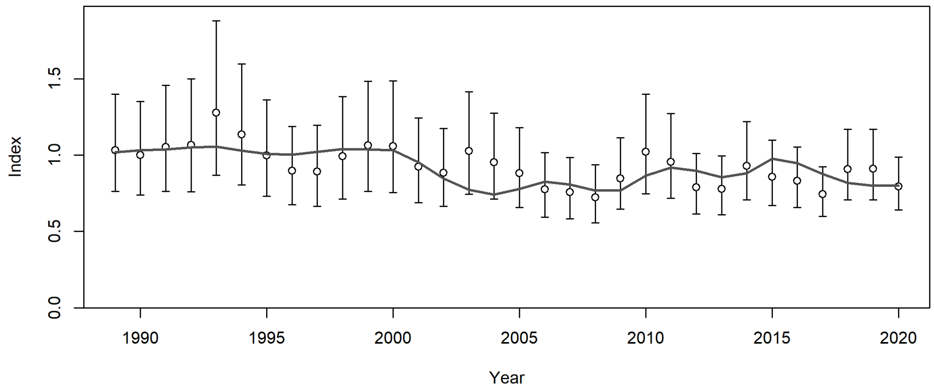

Figure F.9: Model predictions (grey line) to commercial catch rates for Spanish mackerel for shark depredation scenario where steepness was fixed at 0.55

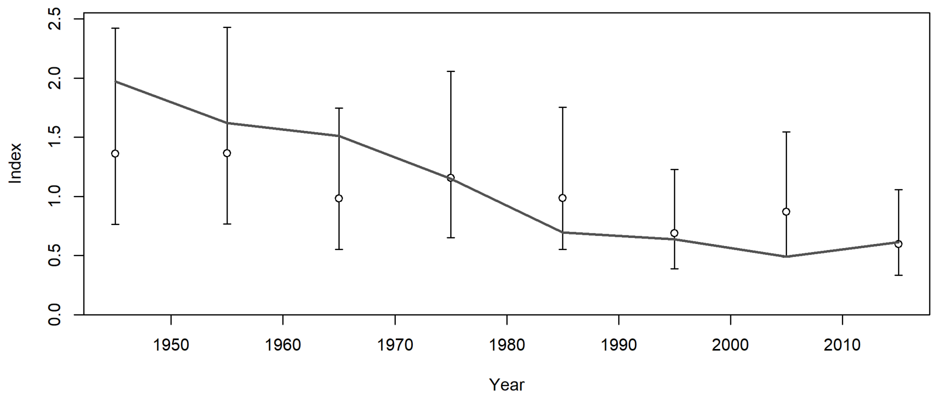

Figure F.10: Model predictions (grey line) to historical decadal catch rates for Spanish mackerel for shark depredation scenario where steepness was fixed at 0.55

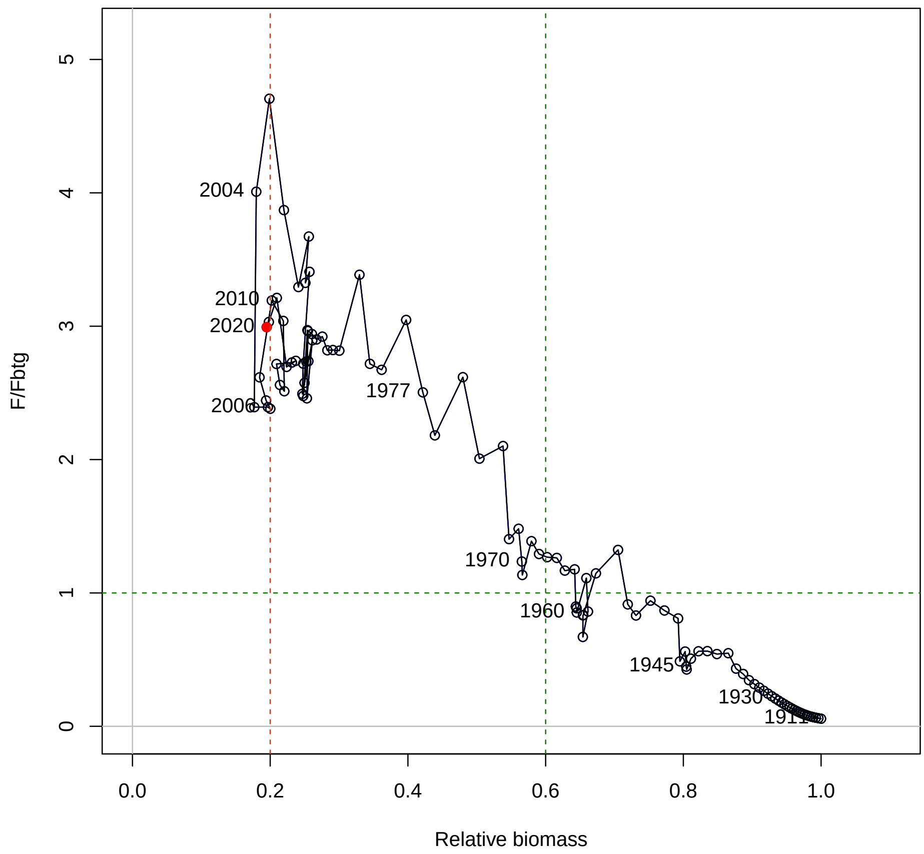

Figure F.11: Phase plot for Spanish mackerel for shark depredation scenario where steepness was fixed at 0.55

The horizontal axis is the biomass ratio of Queensland Spanish mackerel relative to unfished and the vertical axis is the fishing mortality relative to the fishing mortality which would produce the *Sustainable Fisheries Strategy* biomass target of 60%. The red dashed vertical line is the limit reference point (20% relative biomass) and the green dashed vertical line is the target reference point (60% relative biomass)