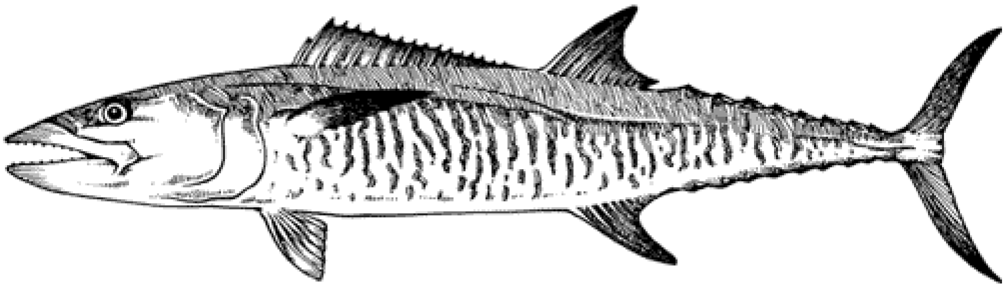

Scomberomorus commerson

Stock assessment of Australian east coast Spanish mackerel

Predictions of stock status and reference points.

Queensland
Government

This publication has been compiled by M. F. O'Neill of Agri-Science Queensland, Department of Agriculture and Fisheries, J. Langstreth of Fisheries Queensland, Department of Agriculture and Fisheries and S. M. Buckley, The University of Queensland and J. Stewart, Department of Primary Industries, New South Wales.

Summary

Australia’s east coast Spanish mackerel, *Scomberomorus commerson*, are large offshore pelagic fish. The species can live for up to 26 years, weigh in excess of 30 kg and mature between two and four years of age. Based on current research, east coast Spanish mackerel form a single genetic stock in ocean waters between Cape York Peninsula and northern New South Wales.

The fishery for east coast Spanish mackerel commenced in the early 1900s. Annual east coast harvests taken by commercial, charter and recreational fishing steadily built to peak at 1000–1300 tonnes (t) per year during the 1970’s and 1000–1150 t per year between 1998 and 2003. The estimated annual Spanish mackerel harvest since 2005 reduced to 500–760 t per year after Queensland commercial quota commenced in 2004; the quota limit was first set at 619.5 t.

Since 2005, the harvest shares in the fishery have been about 47 per cent commercial, 47 per cent recreational and 6 per cent charter from Queensland and New South Wales east coast waters. The modern fishery fully exploits Spanish mackerel with most fishers harvesting fish using line-fishing techniques. Net fishing is not permitted. Commonly, harvests of Spanish mackerel have been during their spawning season between September and November.

During September to November each year, Spanish mackerel school to form one of the most notable and predictable spawning aggregations of fish on the Great Barrier Reef. The aggregation occurs in reef waters north of Townsville where Spanish mackerel gather to breed mostly over a two lunar month period. Research has identified that Spanish mackerel usually have strong reef fidelity during the spawning season.

In 2016 the Queensland Department of Agriculture and Fisheries commissioned an update to the stock assessment for east coast Spanish mackerel following concerns about the perceived reduced size of the spawning aggregation, the fact that only about half of the Spanish mackerel commercial quota was caught, variable catch rates and the perceived increase in recreational fishing pressure.

The stock assessment was conducted at the whole stock level across jurisdictions and included commercial, charter, recreational and research data from both New South Wales and Queensland. The data included estimates of Spanish mackerel harvest from logbook systems and recreational fishing surveys, catch rates from commercial logbooks and historical surveys of long-term commercial fishers, and annual fish age-length compositions. The assessment combined the data in an annual age-structured population model tailored for the biology and management history of Spanish mackerel.

In total 227 population model analyses were run for different combinations of data. The analyses considered different hyper stability and fishing power adjustments to catch rates, levels of recreational fishing effort and levels of fish natural mortality and reproductive rate. The results over all analyses suggest that fish population size estimates in the year 2016 were between 30–50 per cent of original biomass estimates at the start of the fishery in 1911. The results indicate that the fishery in 2016 was at the biomass level for maximum sustainable yield (best estimate around 40 per cent biomass).

Estimates of recommended sustainable annual harvest of Spanish mackerel for all fishing sectors and east-coast waters ranged between 400–800 t based on the 2016 population estimates. The tonnage estimates varied with population model analyses because of the different combinations of data analysed.

The annual harvests in the last decade were similar to the recommended sustainable levels of 400–800 t, but there was no evidence to suggest any building of population size or improving catch rates. Measures of fishing pressure were above the level required to build higher fish population size such as 50–60 per cent biomass (the long-term target in the Queensland Sustainable Fisheries Strategy 2017-2027).

There is presently substantial unfished commercial quota. The current Queensland total allowable commercial catch quota is 574.6 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 decline. Such high harvests would reduce average catch rates longer-term. Overfishing will result if each fishing sector's current allocated capacity is regularly exercised.

The results suggest annual harvests of around 550 t (across all sectors) will build the biomass towards the 60 per cent level, consistent with the 2027 management targets set in the Queensland Government's Sustainable Fisheries Strategy. If there is a desire to operate the fishery closer towards 60 per cent biomass for better economic yield and quality of fishing (higher catch rates), then fishing pressure will need to reduce for a period of time to build the fish population to a higher biomass.

Estimated reference points of annual harvest tonnages include all fishing sectors: commercial, charter and recreational across New South Wales and Queensland. These can inform on the development of a harvest strategy for Spanish mackerel. As part of this, potential harvest strategies need to consider risks from target fishing of spawning aggregations, including potentially time-area closures or bounds on localised fish harvest rates. The report provides a number of recommendations to support future stock assessment and management procedures.

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Acknowledgments

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Scope

Results encompass Australian east coast Spanish mackerel. The assessment was conducted on the whole (genetic east coast) Spanish mackerel stock across jurisdictional waters of New South Wales and Queensland. Estimates of fish population size and limits on annual fishing cover the entire fishery of New South Wales and Queensland.

The assessment encompassed all east coast Spanish mackerel harvests by the commercial, charter and recreational fishing sectors across New South Wales and Queensland. Harvests of Spanish mackerel taken by indigenous fishing were likely to be small compared to the other sectors and were estimated within the recreational fishing surveys. The recreational data was combined across New South Wales and Queensland.

Estimates of Spanish mackerel recreational harvests included all kept fish and 50 per cent of released fish. The reasons for including 50 per cent released fish were a) significant release numbers were estimated by recreational fishing survey programs, b) anecdotal evidence of high released fish mortality (Western Australian Government, 2016), and c) use of 50 per cent survival/mortality rate, rather than a higher value, to offset risks of inflated recall bias in released fish estimates.

The assessment covered the fishing years 1911–2016. Each fishing year grouped information between the months July–June and was labelled as ‘year’ within this report. Fishing years were equal to financial years to group the seasonal and biological patterns of Spanish mackerel. For example, the labelling of fishing year July 2015 to June 2016 was ‘2016’. The definition of fishing year encompassed the seasonal patterns of fishing and the biological patterns of fish recruitment, growth and spawning.

The Queensland Sustainable Fisheries Strategy (SFS) 2017–2027 sets out clear target objectives to be achieved by 2020 and 2027 (https://www.daf.qld.gov.au/fisheries/sustainable-fisheries-strategy). The outputs from this assessment of Spanish mackerel provide information on setting sustainable fishing and harvest limits to achieve the 2020 objectives under the SFS: i.e. reach a fish population size of 40–50 per cent of the original unfished level. For Spanish mackerel, the original population size level was defined as year 1911. Results also provide insights on what is required by the fishery to meet the 2027 SFS objective of 60 per cent fish population size.

Estimated reference points of annual harvest tonnages were calculated for the whole east coast Spanish mackerel stock. The reference point tonnages include all fishing sectors: commercial, charter and recreational across New South Wales and Queensland. Use of the reference point tonnages in management procedures need to consider the uncertainties in estimates and how many fish should be allocated to different fishing sectors and jurisdictions. Recreational fish discard mortality was accounted for in the stock assessment and a discard allocation needs to be factored into quota setting.

Definitions

Fishery	The 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. See the spatial area in Figure 1. The fishery covers all fishing sectors: commercial, charter, recreational and traditional indigenous.
Fishing year	Months July to 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 2015 to June 2016 was labelled as 2016 fishing year.
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.
REML	Restricted Maximum Likelihood (type of linear mixed model); statistical method used to standardise catch rates.
Catchability q	Is 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.
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.
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.
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.
B	Biomass, total weight of a population or of a component of a population. For example, the weight of exploitable biomass is the combined weight of vulnerable sized fish. It can be measured differently in terms of all fish, exploitable fish or spawning fish.
B_{LIM}	Biomass limit reference point (or B_{LRP}): the point below which the risk to the population is regarded as unacceptable.
B_{MSY}	Biomass at maximum sustainable yield: average exploitable biomass corresponding to maximum sustainable yield.
B_{TRP}	Target biomass: the desired biomass of the population. The reference point refers to the target objective. For example the Queensland Sustainable Fisheries Strategy 60 per cent biomass target. It is referred to as B_{MEY} by Australian Government. B_{MEY} is the biomass at maximum economic yield (MEY).

B_{TrRP}	Trigger biomass: values below a TrRP are not desirable and changes to management are actioned. This reference point usually refers to B_{MSY}.
B_0	Mean equilibrium virgin unfished biomass: average biomass level if fishing had not occurred. Virgin state was subscript labelled as 0, which corresponded to the first year assessed in 1911.
MEY	Maximum Economic Yield: the sustainable catch or effort level for a fishery that allows net economic returns to be maximised (the value of the largest positive difference between total revenues and total costs of fishing, which equals the maximum profit).
MSY	Maximum Sustainable Yield: the maximum average annual catch that can be removed from a population over an indefinite period under historical environmental conditions.
Overfished	A fish population with a biomass below the biomass limit reference point (B_{LIM} or B_{LRP}).
Overfishing	The condition where a population is experiencing too much fishing and the removal rate is unsustainable (fishing mortality $F > F_{MSY}$). F measured the level of fish harvested by different fishing sectors.
FRDC	Fisheries Research and Development Corporation, Australian Government www.frdc.com.au
LTMP	Now formally known as 'Fishery Monitoring' – Fisheries Queensland's long-term monitoring program, Queensland Department of Agriculture and Fisheries.
NIRFS	National Recreational and Indigenous Fishing Survey.
RFISH	Recreational Fisheries Information System.
SWRFS	State-Wide Recreational Fishing Survey.
Box plot	Illustrates the distribution of results around the median (horizontal line in the box showing the middle of the results). The bottom and top of each box are the 25th and 75th percentiles. The whisker lines extend to cover the most extreme estimates that were not considered outliers.
MCMC	Monte Carlo Markov Chain: statistical computer simulation method for estimating population model parameters and their variance.

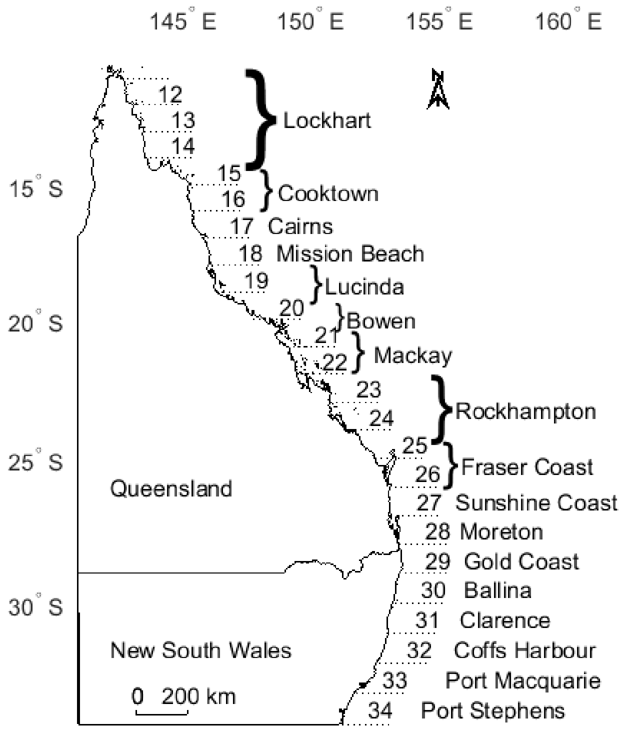

Figure 1. Map of Australian east coast waters and spatial stratifications for Spanish mackerel. One degree latitude bands were used to stratify data for analyses, with region labels marked for spatial reference. All report commentary refers to east coast fish and does not include adjacent Torres Strait or Gulf of Carpentaria fish stocks. In general, 80–95 per cent of historical annual harvests of east coast Spanish mackerel were taken from Queensland waters compared to New South Wales, with 30–40 per cent taken from the key spawning region of Lucinda (latitude band 19). All dotted-line borders cut at either ½ or 1 degree latitudes.

Introduction

Australia’s east coast Spanish mackerel, *Scomberomorus commerson*, are large pelagic fish. They are caught primarily from offshore reefs, shoals and bays, and sometimes from specific ocean beaches and headlands. The species can live for up to 26 years and weigh in excess of 30 kg. Spanish mackerel reach sexual maturity above the minimum legal size limit of 75 cm at between two and four years of age.

Spanish mackerel are recognised as a high-quality eating and powerful sports fish, primarily caught using line fishing techniques. Some large specimens, but not often, can have ciguatera toxin which may cause a lingering foodborne illness. Spanish mackerel caught from Platypus Bay, western side of Fraser Island, are declared no-take due to their ciguatera risk (Queensland Government, 2008). The Sydney Fish Market prefers to sell fish sizes of less than 10 kg per Spanish mackerel to reduce the chance of ciguatera poisoning (read the ‘Seafood and the food-safety golden rules’, Fisheries Research and Development Corporation web site: www.frdc.com.au).

Based on current research, 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). Their 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). Locations of schooling fish are seasonally predictable, more in northern waters during winter and spring for feeding and spawning and in southern waters during summer and autumn to extend their feeding range. The genetic populations of fish north of 15 °S, Cooktown to the Cape, have not been evaluated (Lockhart region, Figure 1). The historical levels of harvest from the remote Lockhart region were small and assumed a part of the east coast fishery; not Torres Strait, although some mixing of fish through the northern part of the Lockhart region is possible.

Fishing for east coast Spanish mackerel is conducted by three sectors in New South Wales and Queensland: 1) *commercial* operations which harvest and sell fish for profit and public utilisation, 2) commercial *charter* operations that take paying recreational anglers to catch fish and 3) *recreational* anglers who catch fish for their own personal pleasure, sport and consumption (this includes *indigenous* fishing). Spanish mackerel are an important economic and food source to these fishing sectors.

Commercial fishing of Spanish mackerel commenced in 1911 and targeted spawning aggregations on the Great Barrier Reef (Thurstan et al., 2016a; Buckley et al., 2017). The reported commercial fleet increased in size from one operation in 1911 to 20 in 1936. This jumped 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., 2016a).

Since 1938 the commercial fishery steadily built to produce around 1000 t per year during the 1970s (Campbell et al., 2012). Data herein show commercial harvests reduced to around 700 t between 1998 and 2004. Since 2005 commercial harvests decreased further to around 300 t per year after the Queensland commercial quota system was implemented. Prior to 2005 the fishery in general was less regulated (Table 11, chronicle of fishery management; Appendix). Many commercial fishing operations were licensed to operate, with up to 550 primary commercial vessels operating between 1998 and 2003.

In Queensland waters, access to the commercial 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 May through to June 2017 there were 239 licensed operations (each ‘SM’ license symbol identifies the primary line-fishing operation). Of these licences which includes the primary fishing vessel (mothership), 201 were each permitted to use between one and five additional smaller boats called dories or dinghies. The total number of licenced fishing boats tallied 601, including 400 dories. Of the 239 licences, 206 held individual transferable quotas (ITQ) sharing the current annual 574.631 t total quota (total allowable commercial catch: TACC); 33 held no quota and were not permitted to harvest Spanish mackerel for commercial purposes.

The commercial fishing sector in New South Wales waters was 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). Annual harvests built steadily to 52 t in 1989. Harvests reduced to below 13 t per year between 2000 and 2009 and returned back to 40 t in 2015. Since the 1970's the number of commercial fishing operations harvesting Spanish mackerel from New South Wales waters varied around 50 vessels per year.

Information on fishing efforts and harvests from the remaining 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 338 licenced charter operations during 2017, with many setup for offshore fishing. Measures of recreational fishing in Queensland have been surveyed periodically since 1997 suggesting 15 000–40 000 boat-days per year have been expended catching Spanish mackerel.

For the fishing sectors, additional fishing rules apply such as the current 75 cm minimum total fish length for all kept Spanish mackerel and recreational in possession fish bag-limits: three Spanish mackerel per person in Queensland waters and five mackerel (Spanish plus spotted) in New South Wales (Table 11, Appendix).

A number of stock assessments have evaluated fishing pressures on east coast Spanish mackerel (O'Neill and McPherson, 2000; Hoyle, 2002; Welch et al., 2002; Hoyle, 2003; Campbell et al., 2012). For results up to the year 2009, estimated Spanish mackerel population sizes were either 39 per cent or 51 per cent of virgin levels depending on the data analysed (Campbell et al., 2012). Suggested annual harvests for the fishery (all sectors and east coast waters) were 715–985 t (Campbell et al., 2012). Government fishery status reports have monitored recent harvest data and classified east coast Spanish mackerel fishing as sustainable (http://www.fish.gov.au/report/67-Spanish-Mackerel-2016).

Tobin et al. (2014) summarised from past stock assessments that the Spanish mackerel east coast population was either fully-fished or overfished relative to maximum sustainable levels. These inferences were based on a number of factors and concerns including that:

a) only about half of the Spanish mackerel TACC had been filled in recent years

b) a belief that recreational harvests of Spanish mackerel had increased

c) long-term fishers' information suggested that the size of spawning aggregations and their reproductive capacity had diminished over time.

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 necessary reef locations. Fish acoustic-tag monitoring identified some fish as having strong reef fidelity during the spawning season (Tobin et al., 2014). The predictable schooling and aggregation behaviour signified that east coast Spanish mackerel were vulnerable to fishing exploitation during spawning. 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 the Lucinda region. The data was 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 per cent 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 2016 the Queensland Department of Agriculture and Fisheries commissioned research to update the stock assessment for east coast Spanish mackerel. This stock assessment aimed to evaluate historical trends in data for the whole east coast and regionally, estimate population stock status and predict limit and target harvest reference points. The report informs fishery management agencies and stakeholders on estimates of sustainable harvest that will build and maintain the fishery in the long term.

Methods

Fishing data

The Spanish mackerel harvest and fishing effort data were compiled from the start of the fishery in 1911 (defined by Thurstan et al., 2016a) to the end of June 2016. The data were obtained from a number of sources: Queensland commercial fish board, charter and commercial logbooks systems in New South Wales and Queensland, State-wide recreational fishing surveys in New South Wales and Queensland and historical surveys of Queensland long-term fishers. The data were imported into a Microsoft Access database and stored in a secure directory to ensure confidentiality, integrity and back up of the data.

Commercial and charter fishing

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 was 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; as per Campbell et al. (2012)

Between 1988 and 2016, Queensland commercial harvests of Spanish mackerel were recorded through the compulsory logbook system. The data consisted of the daily fish harvest 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. The data was supplied through data request number DR2703. The commercial fishery ('SM' line fishing endorsement) has operated under quota regulation since 2005. Compulsory prior notices of commercial Spanish mackerel landings per vessel trip before unloading in port and processor dockets for fish weight were recorded in the quota system (https://www.business.qld.gov.au/industries/farms-fishing-forestry/fisheries/monitoring-reporting/requirements/catch-reporting). The data supported verification of overall logbook tonnages.

No data was available on total Queensland commercial harvests of Spanish mackerel between 1982 and 1988 or prior to 1937. For each fishing year 1982–1988, annual total harvests were linearly interpolated using coefficients based on the best fit of available harvests in each year 1973–1996 (Campbell et al., 2012). Total annual harvests prior to 1937 were hind casted. 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 ($C_{t-1} = C_t^{0.985}$). This power value was set to represent the historical levels of commercial fishing described by Thurstan et al. (2016a) and the number of years 1911–1936, in order to reasonably match the harvest levels reported from 1937 onwards.

Harvests of Spanish mackerel taken by Queensland charter vessels were recorded through the logbook system 1997–2016. From 1985 until 1996 total annual charter vessel harvests were assumed to be equivalent to 4 per cent of the commercial take and 1 per cent for the years 1937–1984 (Campbell et al., 2012). Charter harvests were assumed as being negligible prior to 1937.

Commercial tonnages of Spanish mackerel from New South Wales waters were recorded through compulsory logbook systems 1985–2016. 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. Commercial data from the previous stock assessment (Campbell et al., 2012) were updated to 2016. Harvests prior to 1985 were estimated based on the geometric mean of the ratio of New South Wales to Queensland commercial harvest between 1985 and 2009 (Campbell et al., 2012). For these years the ratio was 2.7 per cent, showing the magnitude of commercial New South Wales harvests was small compared to those from Queensland waters.

Recreational fishing

Recreational catches (numbers of harvested-kept and released fish) of Spanish mackerel were estimated from eight State-wide surveys. A reference list for the surveys is contained in the results section of the report (Table 7).

The State-wide methods used telephone surveys of random households to estimates participation rates in fishing. Diary records of fish catches and fishing effort were maintained by a sample of fishing households. Diary records of fish catch and effort were expanded by telephone household-data to estimate total catches of fish and fishing effort by key species, seasons, coastal regions, inshore/offshore/estuary waters and boat/shore fishing platforms.

Recreational fishing data and expanded survey estimates of fish catches and fishing effort were provided by Fisheries Queensland (data request number: DR2753) and the New South Wales Department of Primary Industries. For a general brief about the State-wide and Regional Recreational Fishing Survey Program, visit https://www.daf.qld.gov.au/fisheries/monitoring-our-fisheries/recreational-fisheries/statewide-and-regional-recreational-fishing-survey.

The methods for processing the recreational data for stock assessment was structured separately for a) collating and estimating annual harvests and b) estimating annual proxies for fishing effort. The effort proxies were used in the stock assessment population model to estimate Spanish mackerel harvests.

a) Spanish mackerel harvests

Surveys conducted in 1995, 2001, 2011 and 2014 had more effective follow-up contact procedures with diarists resulting in less drop out of participants compared to the other survey years using Recreational Fisheries Information System (RFISH) methodology (Fisheries Queensland, pers. comm.). For the surveys called RFISH in 1997, 1999, 2002 and 2005, the higher drop out was interpreted to inflate 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 and O'Neill (2017) was applied to reduce RFISH catch estimates to better align with the 2001, 2011 and 2014 surveys:

$$c_{2001} \Big/ \left(\frac{2}{3} c_{1999} + \frac{1}{3} c_{2002} \right).$$

The RFISH catch adjustments were calculated at 0.5876 for harvested and 0.4781 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. Leigh and O'Neill (2017) believed this assumption to be reasonable. The RFISH catch adjustments made the estimates of fish catches more comparable between surveys. If this was not done, then RFISH harvest estimates of Spanish mackerel would expand to 400–500 t per survey year. This magnitude of estimated recreational harvest seemed unreasonable compared to non RFISH surveys and commercial tonnages.

In 2001 and 2014 state-wide surveys of recreational fishing were completed for New South Wales waters. For the stock assessment modelling, recreational estimates of the NSW Spanish mackerel harvest needed to be calculated for each year where a recreational estimate existed for Queensland (eight surveys). For the six missing surveys not matching Queensland, New South Wales Spanish mackerel catches were calculated using a mean State (NSW:Qld) ratio estimator of 0.13 for harvested fish and 0.04 for released fish. The ratio estimator was calculated comparing State estimates from the 2001 and 2014 survey years.

Released estimates of Spanish mackerel were tallied into the harvest component for modelling. A 50 per cent discard mortality rate was assumed for this sector of the fishery. Further reasoning behind the 50 per cent mortality rate is explained in the results section of the report.

For input into the population modelling, final estimates of Spanish mackerel harvests (numbers of kept fish plus the 50 per cent of released fish that were assumed to have died) for the eight years were combined across States.

b) *Effort proxies*

Proxies of recreational fishing effort were predicted for years with no survey information. This was required for the modelling in order to estimate population time-series trends of Spanish mackerel. This involved joining historical information on annual vessel registrations and survey estimates of fishing participation, effort and fishing power. The proxy effort approach was suggested in the review of Queensland snapper stock assessment and used in stock assessments for pearl perch and blue swimmer crab (Campbell et al., 2009; Sumpton et al., 2015; Sumpton et al., 2016). In total six proxies were calculated based on three levels of fishing power, the pattern of increase in Queensland vessel registrations and a decrease or increase in fishing effort post 1996 based on survey estimates. The proxies intended to evaluate different patterns of fishing effort that could be associated with Spanish mackerel fishing across east-coast offshore waters, with the elements of zero catch effort and fishing power increase included. These elements aimed to map the recreational fleet’s capacity to catch fish (these elements and considerations of data hyper stability are outlined in the method section for catch rates).

The Queensland State-wide recreational surveys in 2001, 2011 and 2014 and the New South Wales surveys in 2001 and 2014 calculated boat-day estimates of total fishing effort. The totals represented all east coast boat fishing in oceanic waters using line or spear fishing gear, with northern open waters in Moreton Bay classified as oceanic and Moreton Bay waters south of Peel Island were not. For only Queensland east coast waters, estimates of boat-days of fishing effort where Spanish mackerel were successfully caught was available. The two sets of estimates respectively were used to imply a decrease or increase in fishing effort post 1996.

Figure 13c illustrates the overall effort decrease in oceanic boat fishing. An over dispersed Poisson generalised linear model with log link was fitted to estimate the slope of decline across States ($n = 5$; t statistic = 30.762; $p < 0.001$). Figure 13d illustrates the increase in fishing effort for Spanish mackerel. With only three data points, the proportion increase in effort between 2001 and the mean of 2011 and 2014 was calculated at 2.55 per cent year^{-1} over 13 years. The effort values in years 2015 and 2016 were set equal to 2014. The rate of decrease or increase was applied post 1996.

Prior to 1996 fishing effort was implied from the Queensland vessel registration boat count data (Figure 13b). The data years 1991–2006 were modelled using an over dispersed Poisson generalised linear model with log link ($n = 16$; t statistic = 141.52; $p <0.001$). The model was used to predict the effort proxy for years 1937–1990.

The final effort proxies were normalised on a proportional scale and a log-normal error standard deviation of 0.09 imposed for modelling input based on the data.

Historical surveys

Long-term Spanish mackerel fishing information was evaluated in the stock assessment. The information was collected from surveys of commercial and recreational fishers and provided important perspectives and observations on the east coast Spanish mackerel fishery over time. The information supplied to the stock assessment (by Dr S. Buckley) included: a) copy of the survey forms; b) breakdown on sample sizes of the data; c) calculated mean decadal catch rates of Spanish mackerel and standard errors (from Figure 13 in Thurstan et al. (2016a); no fishing power adjustments), and; d) annual uptake rates of fishing gear technology and gear effects to allow calculation of changes in annual fishing power.

The information filled knowledge gaps on past trends, which was important for analysing changes in the fishery since 1911. The historical information on fishing power and catch rates was an important data input into the stock assessment. The value of such information was recognised through funding to collect historical ‘fisher knowledge’ data on Spanish mackerel and snapper (Thurstan et al., 2016a).

The influence of the historical information on stock assessment was evaluated by comparing results ‘with’ and ‘without’ the data. As this new information was available for east coast Spanish mackerel, it was prudent to assess the data. This aspect of the stock assessment was a clear difference to the previous assessment (Campbell et al., 2012). Use of the historical data was shown to be beneficial to map early trends in the fishery.

Commercial, charter and recreational fishers of Spanish mackerel along Queensland’s east coast were interviewed between November 2013 and February 2015 to obtain data on: a) long-term decadal changes in catch rates of Spanish mackerel, and; b) fishing power technologies and their effects upon fish catches. The data were collected and supplied by Dr Sarah Buckley, from The University of Queensland, as part of PhD and FRDC research (Buckley, 2016; Thurstan et al., 2016a).

The interviews were conducted with fishers who had targeted Spanish mackerel for 10 years or longer. Interviews and data collection from each fisher averaged two hours, with a range of one to five hours. Fisher contacts were identified from industry representatives, businesses, websites, fishing articles and clubs, interviewee referral, boat ramp surveys and a south-east Queensland fishing conference. Fishing locations from Cooktown to Tweed Heads, along the distribution of Spanish mackerel, were sampled.

Data used in this stock assessment considered fishers’ annual uptake of different fishing gears and technologies, their effects on catch rates and recall of catch rates by decade (number of Spanish mackerel fisher-hour^{-1}). The data covered the years 1941–2013 (Figure 2). In total 221 fishers provided information on fishing technologies and catch rates (Table 1). Follow up interviews with 41 commercial and 23 recreational fishers provided estimates of technology effects on catch rates (Buckley, 2016; Thurstan et al., 2016a). Data on technology effects were averaged across all fishers. See Buckley (2016) and Thurstan et al. (2016a) for more detail about the data and for survey and questionnaire methods.

Use of the data to estimate changes in fishing power is described below under the section for ‘standardised catch rates’. The decadal mean catch rates (from commercial fishing) supplied from Thurstan et al. (2016a) were spatially averaged across the north (north of Bowen to Cooktown), middle (Bowen to Bundaberg) and south (south of Bundaberg to Tweed Heads) geographic regions using the proportion weightings (based on commercial logbook harvests) of 0.746, 0.188 and 0.066 respectively. No fishing power adjustments were applied to the decadal means given the recall nature of the survey information and no raw data for the means were available.

The reliability of fisher recall on fish catch rates over time was assessed in separate published papers by comparing individual logbook records with the survey information (Thurstan et al., 2016a; Thurstan et al., 2016b; Buckley et al., 2017). Comparisons of catch rates were tested using generalised linear models, percentage differences and percentile ranks of the distributions of recalled survey and recorded catch rates (to determine whether the variability of recalled catch fell within the distribution of recorded catches for each fisher).

Thurstan et al 2016a and 2016b concluded that: a) good and poor catches were recalled with reasonable accuracy, matching variability in recorded catch with no significant change observed over time; b) typical recalled catches were overestimated as time elapsed (by 0.65 per cent year^{-1}), but were more comparable to mean than median recorded values (Thurstan et al., 2016a; Thurstan et al., 2016b). Buckley et al. (2017) compared recalled and recorded catch rates of Spanish mackerel from two groups of 10 and 4 commercial fishers operating on the Great Barrier Reef. The comparison of fishers' recalled catch rates (good, average, and poor) were observed within the distribution of recorded logbook catches and thus considered fishers' perceptions of Spanish mackerel catch trends reliable (Buckley et al., 2017).

Commercial mean decadal catch rates from Thurstan et al. (2016a) were evaluated in the stock assessment. Given the sample size of data (Table 1 and Figure 2) and verification testing completed in separate published papers, this was accepted at the decadal time-scale.

Table 1. Number of fisher interviews by fishing sector and geographic region. The middle region boundaries were defined at Bowen and Bundaberg. Only 4 per cent (n=9) of interviews were obtained from the charter fishing sector.

Description	Commercial	Recreational
Overall	48% (n=106)	48% (n=106)
Region: North	50% (n=56)	37% (n=40)
Middle	27% (n=30)	25% (n=27)
South	23% (n=26)	37% (n=40)

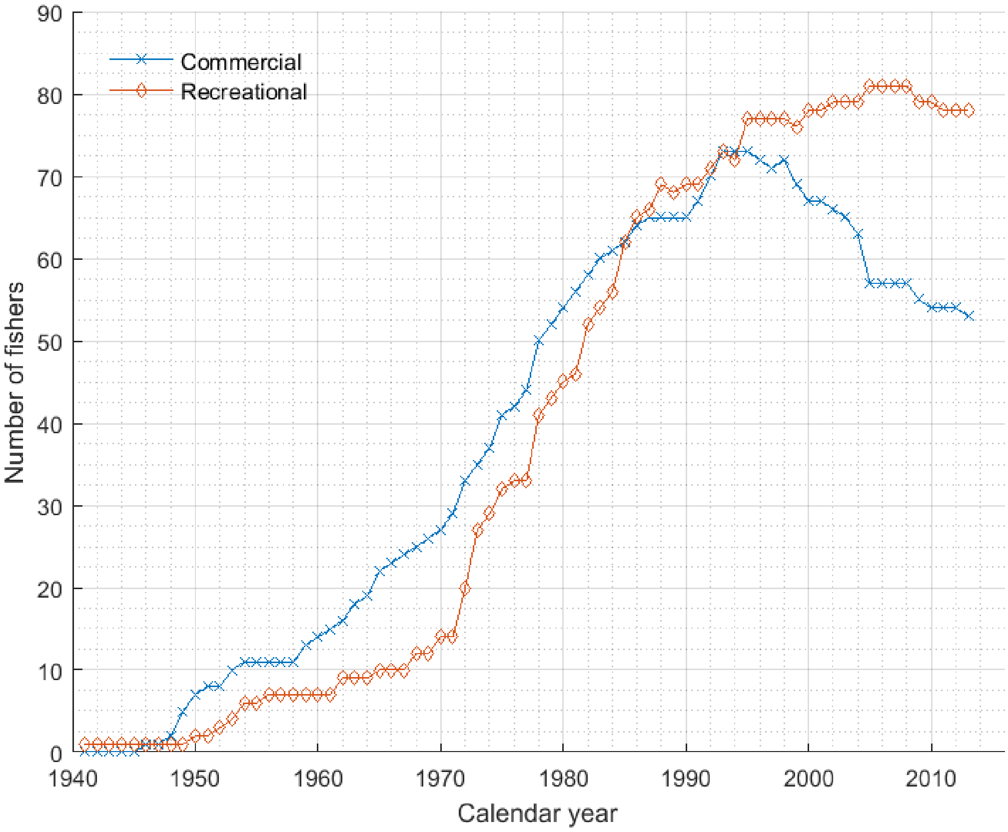

Figure 2. The number of surveyed fishers providing data per calendar year.

Fish age data

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 and O'Neill (2004), Tobin and Mapleston (2004) and Campbell et al. (2012).

For the early fishing years of data 1977–1979, monitoring focused on the fish-spawning grounds located between Cairns and Townsville (the Lucinda region, Figure 1). Sampling in these years was from the commercial fishing sector. The annual fish age-structures were believed to be an unbiased sample of commercially harvested Spanish mackerel for the Lucinda region (Sumpton and O'Neill, 2004). The annual age-structures were calculated by the scientists at the time, where fish were measured for age-length separately in each year. The 1977–1979 fish age-structured data were carried forward from the previous stock assessment by Campbell et al. (2012); no raw data were available.

In 2000–2002 sampling was re-established and focused solely on Spanish mackerel that were commercially fished in reef waters north of Townsville during the months of October and November. From 2003 sampling was increased to be temporally and spatially expansive covering both commercial and recreational harvests of Spanish mackerel in Queensland (Tobin and Mapleston, 2004; Campbell et al., 2012). Sampling effort was spatially stratified where target numbers of commercial catches of Spanish mackerel to sample (measure) were set at the start of each year based on historic harvests from the last three years. These targets were used only as a general guide. Sampling was flexible and opportunistic to adapt when changed spatial patterns in harvest arose.

For each fishing year since 2002, fish otoliths were used to estimate fish age from a subset of the total number of fish sampled (Campbell et al., 2012). Otolith collection was stratified by 1 cm length classes. A maximum of 20 fish were collected in each length class from the northern sample regions (Mission Beach to Mackay) and from the southern sample regions (Rockhampton to Gold Coast) per year. The otolith collection over all sample regions was a maximum of 40 fish otoliths in each 1 cm length class.

The calculation of fish annual age-structures was by combining each year’s fish age-length key and the fish length frequency. The algorithm used adjusted fish lengths (fork length cm adjusted to the nominal birthdate of 1 November) and a corresponding age-length key for each year. Fish lengths were grouped into 2 cm length classes. The methodology followed standard Fishery Monitoring practice and final fish age-structures represented age groups, assembling fish into their birth cohorts.

For reporting and analysis, final fish age-structures were stratified by fishing sector and aggregated across sample regions (Figure 3). Two different region weightings were compared using data 2005–2016: 1) a fixed mean annual harvest for each sample region, and; 2) a varying annual harvest for each sample region. The resulting fish age structures by year were effectively the same. For this stock assessment, the latter method for spatial weighting was used to be consistent with current Fishery Monitoring protocols and Campbell et al. (2012).

There were some years and regions where fish samples were limited and considered not representative. No fish age data were available for the years 2000 and 2001. Commercial and recreational fish age-structured patterns in 2002 and for recreational in 2004 were irregular compared to other years. These data were inconsistent and excluded from stock assessment analyses. These data need to be re-examined in future work.

Maps defining the sample regions (Figure 3) and sample sizes (Figure 4 and Table 16 in Appendix) for fish age-length monitoring are reported.

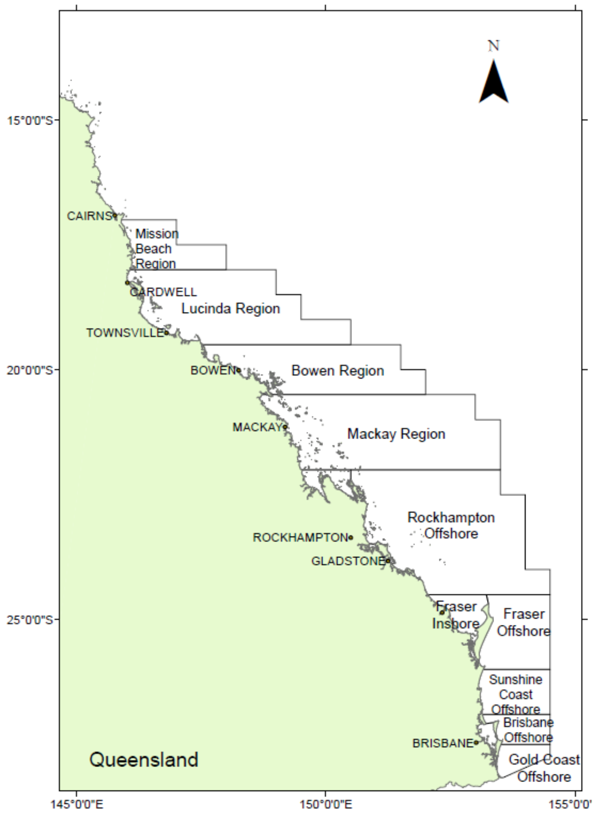

Figure 3. Map of the Spanish mackerel sample regions for fish age-length monitoring.

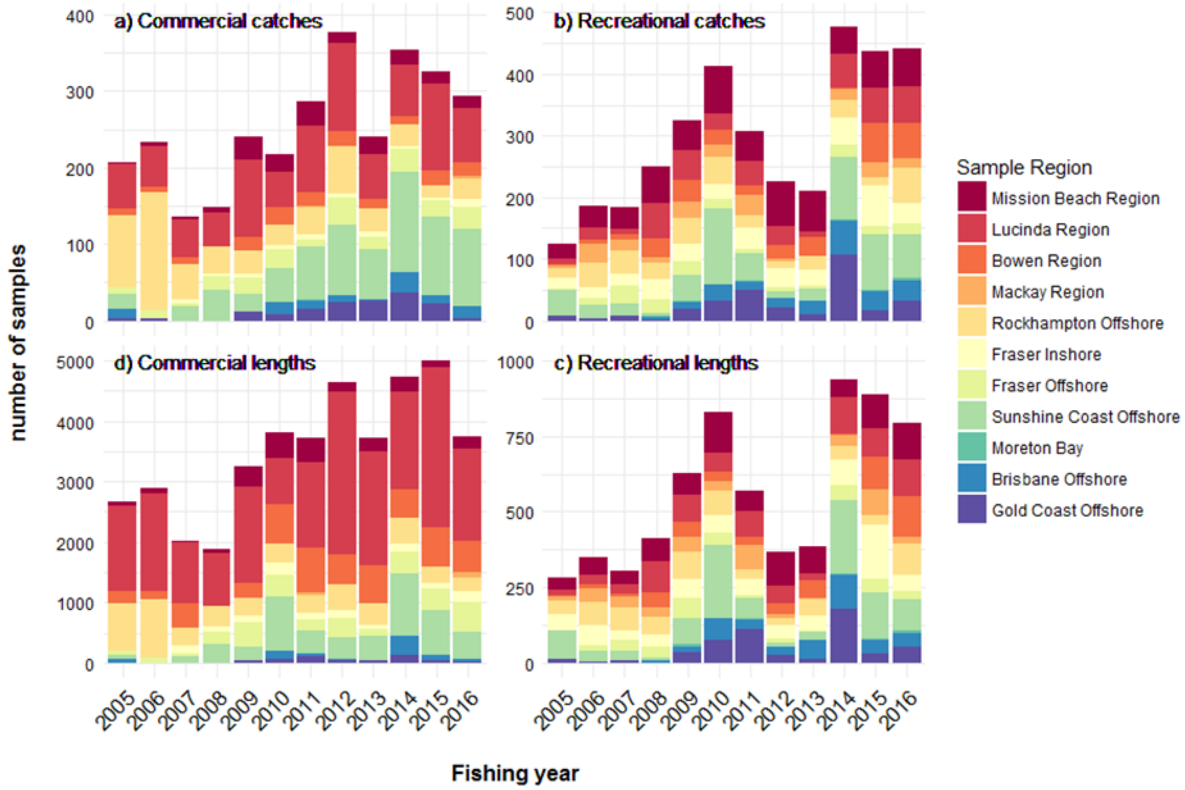

Figure 4. Number of commercial and recreational catches and lengths of Spanish mackerel sampled in each of the east coast sample regions (Figure 3) between 2005 and 2016. A catch typically represented a set of fish caught by one fisher on one fishing trip in a sample region. Infrequently sampling also captured larger combined catches of fish.

Standardisation of mean catch rates

Queensland logbook data on commercial line harvests was documented as weight of whole Spanish mackerel (kg) per fishing-operation-day. The data were used as an index of legal sized fish abundance measured by fishing years and one degree latitude bands.

The methods below outline the concepts and procedures used to standardise mean (average) catch rates. Of note, the standardisation methods considered newly available fishing gear and technology (fishing power) data.

The methods list details on missing fishing effort data (e.g. hours fished) and hyper stability concerns. This was noted in order to describe assumptions and limitations of certain results. These issues were considered when interpreting results.

In this document the term ‘catch rate’ was standardised unless otherwise specified.

Why standardised?

The standardisation of catch rates (mean catch of Spanish mackerel per unit of standardised effort) was calculated using statistical models. The resulting catch rates formed the indicator of legal sized fish abundance (exploitable fish lengths ≥ minimum legal size). They were standardised as trends in nominal catch rates over time may be biased by temporal and spatial changes in fishing effort and fish catchability. The data used for catch rates were ‘fishery dependent’ and were reported by commercial fishers through compulsory logbooks.

The standardisation of mean catch rates was important to generate an improved time-series indicator. Standardisation improved the consistency and comparability of means and reduced the biases or variation in data. This resulted in mean catch rates measuring and tracking changes in the state of fishing, the population size of legal fish and the performance of management more accurately.

The basic concepts, assumptions and science on the use of catch rate data as an index of fish abundance have been demonstrated in numerous texts such as Hilborn and Walters (1992) and Quinn and Deriso (1999). They were built on the assumption that changes in catch rates c can be proportionally related to change in abundance N, if catchability q is standardised and can be assumed to be constant: $c \propto qN$.

Based on stock assessments in Queensland (Department of Agriculture and Fisheries, 2016), a number of issues or features of evaluating catch rate data are listed in Table 2. These apply to Spanish mackerel and highlight the data requirements for effective catch rate standardisation. The issues stem from poor data recording processes, the type of fishing practice and the behavioural characteristics of the fished species.

For Spanish mackerel, the complexities of catch rate standardisation can be described by linking features from Table 2. Many fish form aggregations for various purposes such as spawning, feeding, travelling and protection. Spanish mackerel form seasonal breeding aggregations. The location and timing of these aggregations are predictable. Fishers gain experience and knowledge of these aggregation patterns and can increase their fishing capacity and reduce costs by targeting these aggregations. Overtime fishing operators improve their fishing methods, behaviour and knowledge leading to catch rate data that can overestimate abundance (Robins et al., 1998; O'Neill et al., 2003). Issues of high data variance associated with aggregation patterns of fish and missing data on fishing efforts (e.g. number of locations and hours fished on a day) may also cover up signals in catch rate data (Hilborn and Walters, 1992; O'Neill et al., 2011).

The aggregation behaviour of fish and data reporting processes of fishing can cause catch rate data to be hyper stable (Hilborn and Walters, 1992; Harley et al., 2001). Hyper stable data can lead to underestimation of declines in fish abundance and consequently overestimation of fishery performance and status.

Hyper stability is the main bias in catch rates of Spanish mackerel (Campbell et al., 2012), where observed fish catch rates can remain generally stable as fish abundance declines. This is because of the schooling behaviour of this pelagic fish species. In order for catch rates to be a reliable index of fish abundance, data collections should be distributed and quantified consistently over the spatial range of the fish population through time. However, as many fishers know where fish can be found (predictable aggregations; Tobin et al., 2014), this results in non-random fishing, which is typically concentrated on locations with higher numbers of fish aggregated.

Catch rates measured from fish aggregations, if measured simply as the number or weight of fish per day of fishing, generally will not decline much until the aggregations are substantially depleted (example depicted Figure 5). Consequently, mean catch rates have to account, as best as possible, for daily effort records on each fishing operation’s target species, skippers, gear, travel time, search time and efficiency at finding schools of fish, GPS of locations and the number of fish-schools fished, active fishing time and zero catches (Table 2). Hyper stability bias can be reduced or even circumvented by using these additional units of fishing effort effectively (O'Neill, 2015).

The daily catch rate data for Spanish mackerel that were sourced from commercial logbooks contain no records of detailed fishing effort. The example in Figure 5 illustrates the feature of hyper stability caused without appropriate data on fishing effort. Without the detailed effort information, trends in catch rates were hyper stable and only indexed changing densities of fish schools when found and caught, not the frequency of schools or population abundance. To explore these issues, a number of analyses were completed to produce differing catch rate predictions of legal sized fish abundance. The data were required to be interpreted carefully and considerations accounted for different fishing practices and powers through time.

Table 2. The confounding features of fishery dependent catch rate data.

Fishing behaviour – capacity to chase fish:

- Efficient at finding fish at local scale.
- Vessels can travel large distances; at sea and from different ports to expand the spatial range of exploitation.
- Fisher knowledge of spatially or temporally predictable fish aggregation behaviour.
- Improved knowledge and information sharing between fishers that leads to non-random spatial fishing.
- Increased fishing power from using better vessels, gear, techniques and improved knowledge.
- Aggregation of effort at high catch times and areas.
- Seasonality of market demand and price for product.
- Paucity of data from low catch areas.

Fish biology – aggregation patterns:

- The dynamics of schooling and movement.
- Type of concentration profile: the density of animals distributed spatially in time (Hilborn and Walters, 1992).
- Vulnerability to fishing due to environmental drivers and fish behaviour.

Commercial logbooks – data reporting templates:

- Limited catch validation via linking catch, disposal and quota reporting systems.
- No data codes to link fishing trips over multiple days.
- No consistent daily recording of each fishing operation’s target species, vessels/skippers, gear, travel time, search time and efficiency, locations fished, active fishing time and zero catches.
- Units of effort (time spent fishing and searching etc) by fishers not recorded.
- Details of locations fished not recorded.
- Fish age data and validation are generally collected separately and not linked to the catch-abundance data.

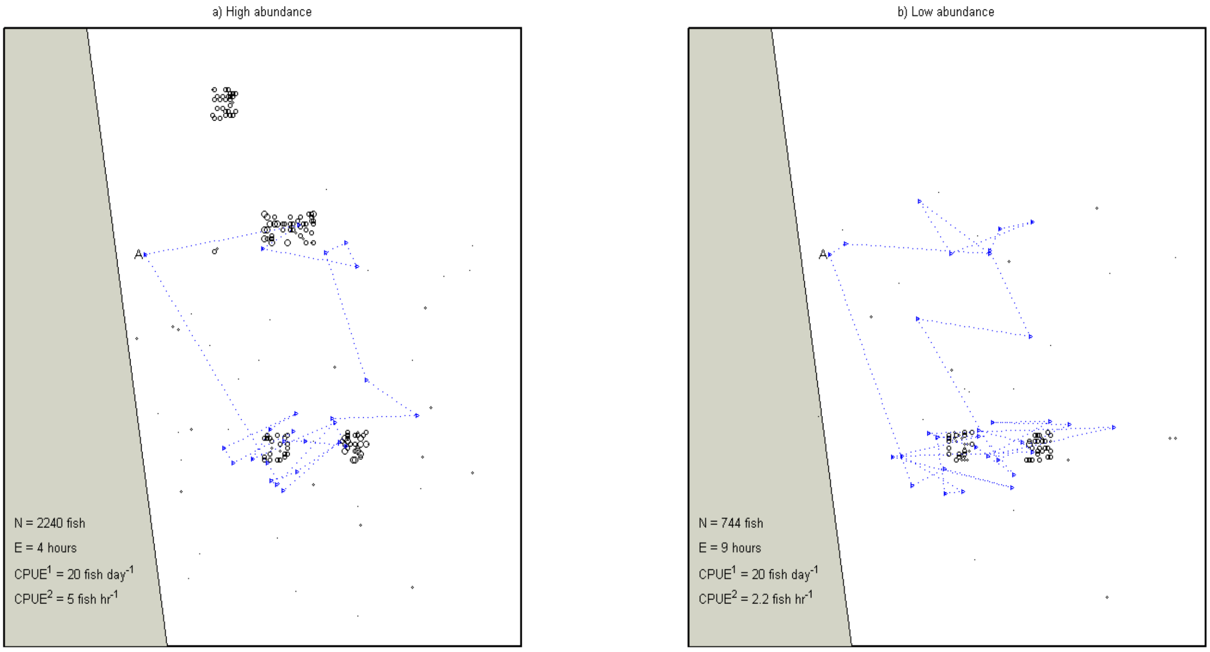

Figure 5. Example: Comparison of how limited effort data can confound catch rate (catch per unit effort (CPUE) differences between a) high, and; b) low abundance. At high abundance the vessel searched and fished over a four hour day yielding 20 fish at a rate of 5 per hour. At low abundance the vessel had searched and fished over nine hours to yield the same daily catch at a rate of 2.2 per hour. The daily catch rate (CPUE^1), as would be recorded in commercial logbook, indicated no change in abundance (hyper stable). In this hypothetical example abundance had declined by 66 per cent and catch rate per hour (CPUE^2) declined by 56 per cent (part-hyper stable). Here the drop in abundance and cpue were not 100 per cent proportional as the fishing pattern was non-random. Legend: N = exploitable population size, E = fishing effort, CPUE^1 = daily catch rate, CPUE^2 = catch per hour, vessel track = blue lines and symbols, fish = black circles and A = start of fishing track which progressed east and then south, before returning to A.

How did we standardise?

As discussed above there was a clear need to standardise catch rates given the issues of hyper stability and missing effort data.

Different standardisation analyses were explored to cover scenarios of:

- Annual changes in fishing power to examine how increased fishing effort and improved gears and technologies affect catch rates.
- Consider a probability model to overcome the non-reporting of zero catches. Walters (2003) suggested presence-absence data may aid in dealing with suspect hyper stability. 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).

What were the data?

Aspects of the harvest data were described above. The following explains the associated fish catchability data used to standardise mean catch rates of Spanish mackerel. The catchability data constitute elements of fishing power, measuring each fishing operation's ability to catch fish (O'Neill and Leigh, 2006) and the spatial-temporal patterns of exploitation associated with aggregation patterns of fish (Walters, 2003; Carruthers et al., 2010; Carruthers et al., 2011; Marriott et al., 2017).

Standardisation components for fish catchability *q* covered:

- Spatially weighted average catch rates consistently in time across east coast latitudes. This aimed to reduce bias introduced by systematic changes in the spatial distribution of fishing (Carruthers et al., 2011). Spanish mackerel are a pelagic fish that schools seasonally by latitude along Australia's east coast offshore waters (generally < 50m depth). Fish generally swim and school to the south during summer-autumn and to the north during winter-spring.
- Lunar phases, wind speeds and direction on each day can influence fish catchability and time fished.
- Increased fishing power and effort from better fishing operations, gear, techniques, knowledge and increased fishing time.
- The fishing fleet's structure was standardised explicitly with REML model parameters scaling each vessel-operation's mean catching efficiency, from low to high based on a normal distribution. Increases in the fleet mean (distribution) from year to year indicate more fishing proportionally by the higher catching operators (Figure 41, Appendix).

The seasonality of Spanish mackerel catch rates was modelled using sinusoidal data (labelled 'DayYear') to identify the time of year. The data were calculated and used to minimise the number of model parameters with the purpose to reduce temporal confounding with the latitudinal and vessel parameters compared to using more parameters to model the explicit monthly or weekly factorisations of the data. In total six trigonometric covariates were considered, which together modelled an average monthly pattern of catch (Marriott et al., 2013): $s_1 = \cos\left(2\pi d_y / T_y\right)$, $s_2 = \sin\left(2\pi d_y / T_y\right)$, $s_3 = \cos\left(4\pi d_y / T_y\right)$, $s_4 = \sin\left(4\pi d_y / T_y\right)$, $s_5 = \cos\left(6\pi d_y / T_y\right)$, $s_6 = \sin\left(6\pi d_y / T_y\right)$,where d_y was the cumulative day of the year and T_y was the total number of days in the year (365 or 366); Figure 6. The reason for using both sine and cosine functions together was similar to modelling lunar phases, where the functions together identify the seasonal patterns of catch rates corresponding to autumn, winter, spring and summer periods.

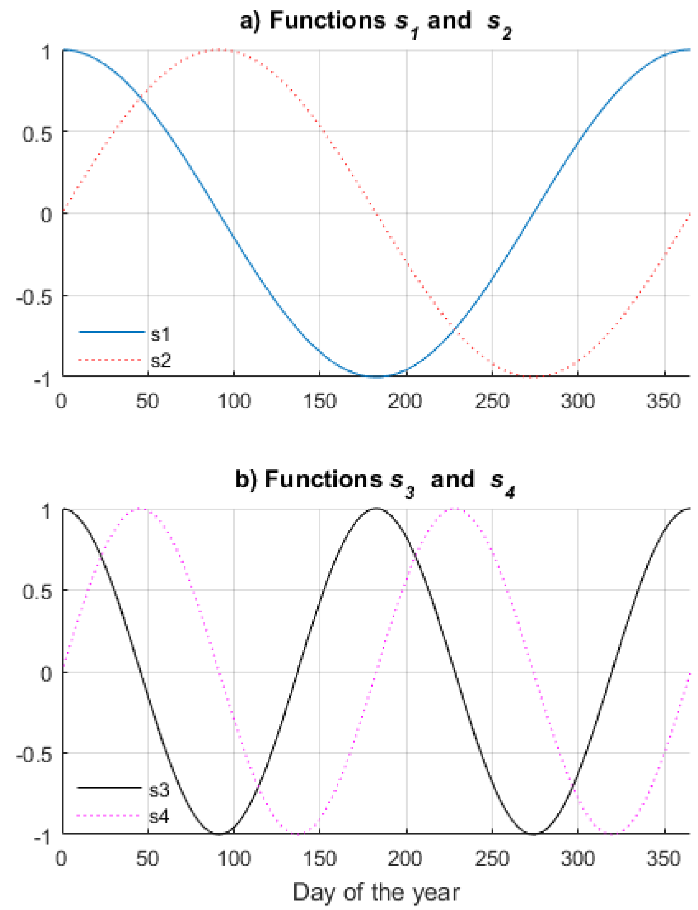

Figure 6. Illustration of the sinusoidal DayYear data for a) the annual cycle, and; b) the 6-monthly cycle. For the x-axis day of the year, 1 = 1st January and 365 = 31st December and the y-axis is the function value. For more information on the relationship between unit circles and the sine and cosine function, see https://en.wikipedia.org/wiki/Trigonometric_functions.

In concurrence with the catch rate data, wind direction and strength data were sourced by Fisheries Queensland from the Bureau of Meteorology (BOM, Australian Government; www.bom.gov.au). The wind data were from 76 representative coastal weather stations along Queensland east coast and spatially referenced to latitude bands. The recorded measures of wind speed (km hour^{-1}) and direction (degrees for where the wind blew from) in each latitude band were converted to an average daily reading based on recordings between 3 am and 3 pm. From this data the north-south (NS) and east-west (EW) wind components were calculated:

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

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

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 (http://www.wmo.int/pages/prog/www/IMOP/CIMO-Guide.html); 0 degrees = North, 90 degrees or π/2 radians = East, 180 degrees or π radians = South, and 270 degrees or 3π/2 radians = West.

Two lunar variables were modelled together to estimate the variation of Spanish mackerel harvest according to the moon phase (i.e. contrasting waxing and waning patterns of the moon 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 and Leigh, 2006). The data were sourced from the Department of Agriculture and Fisheries, Queensland Government. The luminance measure (lunar) followed a sinusoidal pattern and was copied and advanced 7 days (≈ ¼ lunar cycle) into a new variable (lunar_adv) to quantify the cosine of the lunar data (O'Neill and Leigh, 2006); Figure 7.

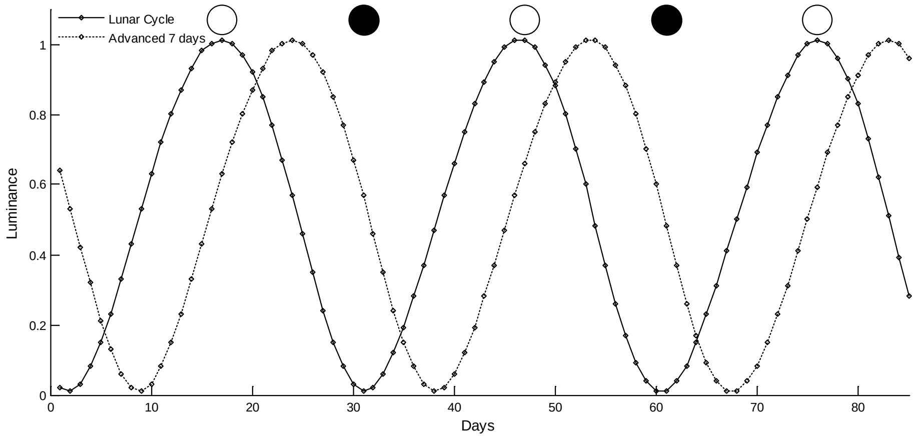

Figure 7. The lunar phase cycle (solid line) illustrated over 85 days. The dashed line illustrates the lunar cycle advanced by seven days. Together these lines were used to model catch rates allowing for new moon, waxing moon, full moon and waning moon effects.

Proportion changes in annual fishing power were calculated relative to the 1990 fishing year assuming constant conditions of fish abundance. The fishing power values were log-offset in the statistical analyses to standardise commercial mean catch rates. Fishing power values were also calculated to adjust the proxy effort for recreational fishing.

To calculate fishing power, linear predictors on the logarithm scale were formed using the historical survey fishing-technology data (design matrix **X**) and fishers' estimated effects (parameter vector **β**):

$$\mathbf{f} = \exp\left(\sum \boldsymbol{\beta}\mathbf{X} - \sum \boldsymbol{\beta}\mathbf{X}_{1990}\right),$$

where f was the vector of annual proportional measures of fishing power relative to the 1990 year, design matrix X was the survey data on proportional use of different technologies by year, parameter vector β was the logarithm catchability coefficients (mean technology effects estimated by fishers'), exp was the exponential function and Σ were summation symbols over the values in each year. For more information on this theory see O'Neill and Leigh (2006) and O'Neill and Leigh (2007).

Measures of uncertainty in annual changes in fishing power were calculated from 1000 simulations of different parameter vectors **β,** based on normal distributions of each parameter effect with their logarithm mean and standard deviation.

What were the analyses?

Spanish mackerel are pelagic fish that generally swim and school seasonally with latitude along Australia's east coast. They can be caught by many commercial fishers dependent on their fishing ability and practices. Commercial line-fishing records were available and included data on when, where and how many Spanish mackerel were caught. However data on 'zero' catches and fishing effort were not available or consistently identifiable. This information, in addition to data on changing fishing powers, were required to standardise commercial mean catch rates as an index of fish abundance.

In an attempt to lessen the issues of hyper stability and missing data, the expectation for mean catch rates *E(c)* was followed:

$$E(c) = p(c)E(c|c > 0),$$

where the capture of fish occurred according to the probability $p(c)$, the probability of not catching according to 1- $p(c)$ and the right hand expectation was for where a number or weight of fish were caught and retained (i.e. *c* > 0).

For analysing fish that were caught $E(c|c > 0)$, the standard catch-biomass relationship held from Hilborn and Walters (1992):

$$c_{ivayml} = q_{vayml} E_{iv} B_{iayml},$$

where c was the harvest of fish taken on day *i* by fishing operation *v* in latitude band area *a*, during fishing year *y*, month *m* and lunar cycle *l*; q_{vayml} was the measure of fish catchability including fishing power; E_{iv} was the fishing effort on the day fished (no information was available on the number of hours fished, travelled or searched; therefore analysis units was harvest per operation-day = 1); and B_{iayml} was the exploitable population abundance or biomass of Spanish mackerel available on the day ($B > 0$).

The logarithm of the catch-biomass equation for $E(c|c > 0)$ forms additive terms in a linear model and can be used to standardise mean catch rates (Hilborn and Walters, 1992; Robins et al., 1998; O'Neill and Leigh, 2006). The linear models formed the basis of developing indices of fish abundance (Table 3).

Catch rate indices were produced by using different log-scale offset schedules for annual changes in fishing power (i.e. effectively adjusting the *qE* component in the catch-biomass relationship). In addition, a probability component for catching fish *p(c)* was investigated to complete the predictions for *E(c)*. Together the fishing power and probability elements help overcome some level of hyper stability produced by the limited data on fishing-effort. This approach built upon the method used by Campbell et al. (2012). Extra information (Table 2) to cover more aspects of fishing effort are still required to ensure hyper stability is adequately accounted in catch rates; noted in report recommendations.

The models used to standardised mean catch rates of Spanish mackerel were completed using the software GenStat (VSN International, 2017). The analyses used generalised linear (GLM) and linear mixed (LMM) models. The LMM used the ‘REML’ algorithm allowing for model terms that can contain both fixed and random effects. The analyses were defined based on:

1. A probability model (GLM for predicting *p(c)*) for adjusting for zero catch days.
2. A catch rate model (for harvests > 0; $E(c|c > 0)$) incorporating annual changes in fishing power to examine how increased fishing effort and improved technologies affect catch rates.

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, 2017). For example, mean catch rates were predicted from the model terms fishing year *y* × latitude band area *a*, keeping all other model terms constant. Logarithm predictions were biased corrected and back transformed $c_{y,a} = \exp\left(\text{log\_prediction}_{y,a} + \frac{\sigma^2}{2} + \text{log\_offset}_{2016} \pm 1.96 \times \text{log\_prediction\_se}_{y,a}\right)$, with the ± component for calculating upper and lower 95 per cent confidence intervals. The log_offset$_{2016}$ corresponded to the fishing power setting in year 2016 and the se label was the standard error.

In total six different annual indices of fish abundance 1989–2016 were calculated from the Queensland commercial line data. The six results were evaluated individually through the fish population dynamics model to assess the effects of possible hyper stability (labelled 0 = no adjustment, i.e. constant probability; 1 = adjusted for *p(c)*) and increased fishing power offset (labelled 0 = no increase; 0.5 for a reduced square root increase; 1 = full increase as suggested by the data; implemented through the LMM for $E\left(c\middle|c>0\right)$).

To ensure comparability of means between different latitudes, predictions were normalised annually as proportions measured against the fishing year 1990. Standard errors or 95 per cent confidence intervals were calculated for all predictions.

The six annual indices combined predictions across latitude bands. Each latitude's prediction was weighted by their total harvest summed over years 1989–2016, resulting in 39 per cent weight for latitude band 19, the key spawning region. The latitude weightings *w* were scaled proportionally which satisfied $\sum w_a = 1$ and was kept constant over years. The proportional latitude weights were tested to be similar comparing summations from either the first 10 years 1989–2008 or over all years. The spatial prediction methodology, of not changing weights through time, adhered to the concepts of Walters (2003), Carruthers et al. (2010), Carruthers et al. (2011) and Leigh et al. (2014).

Table 3. GenStat code used to analyse commercial harvests of Spanish mackerel.

Queensland binary (presence of Spanish mackerel) : generalised linear model for *p(c)* 1989 to 2016

```
MODEL [DISTRIBUTION=binomial; LINK=logit; DISPERSION=1] ndaysSpanish; NBINOMIAL=Ndays
FITINDIV [PRINT=model,summ,accum,estimates;CONSTANT=est;FPROB=yes; TPROB=yes; FACT=2; \
selection=%variance,%ss,adjustedr2,r2,%meandeviance,%deviance,aic,sic;] \
fishyear*latband+latband.s1+latband.s2+latband.s3+latband.s4+\
pol(windew;2)+pol(windns;2)+latband.nACN
RWALD
```

For each fishing year, month and latitude band, the number of calendar days where mackerel were caught was modelled against the number of days in the month (e.g. ndaysSpanish =15 and Ndays =30 in November). Average monthly wind components were used.

Queensland Linear mixed model for $E\left(c\middle|c>0\right)$ 1989 to 2016

```
calculate logwtoff=logwt-logfp

VCOMPONENTS [FIXED= fishyear*latband2+\
latband2.s1+latband2.s2+latband2.s3+latband2.s4+latband2.s5+latband2.s6+\
latband2.lunar+latband2.lunar_adv+\
windew+windew^2+windns+windns^2; FACTORIAL=2]\
RANDOM=acn;  INITIAL=1; CONSTRAINTS=positive
REML [PRINT=model,components,effects,deviance,waldTests;\
 PSE=allestimates; MVINCLUDE=*; method=ai;] logwtoff
```

New South Wales linear mixed model for $E\left(c\middle|c>0\right)$ 2010 to 2016

```
calculate logwtoff=logwt-logfp

VCOMPONENTS [FIXED= fishyear*area+\
s1+s2+s3+s4+fishingmethod; FACTORIAL=2]\
RANDOM=boat;  INITIAL=1; CONSTRAINTS=positive
REML [PRINT=model,components,effects,deviance,waldTests;\
 PSE=allestimates; MVINCLUDE=*; method=ai;] logwtoff
```

Note: The importance of individual model terms was assessed formally using F statistics by dropping individual terms from the full model. nACN = number of fishing operations. acn or boat = factor variable identifying fishing operations

Population dynamics model

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

- yearly (*t*) time categories from the fishing year 1911 to 2016, and
- age-group (*a*) from 0+ to the maximum age.

The model accounted for the processes of fish births, growth, reproduction and mortality in every fishing year. The model was run in two phases: (i) historical estimation of the Spanish mackerel stock from the fishing years 1911–2016 and (ii) simulations of model values and errors to evaluate reference points.

The fishery for Spanish mackerel commenced around 1911 (Thurstan et al., 2016a) and it was unrealistic to start the model in later years assuming an unexploited state (virgin population). Fishing harvest and effort data were estimated to run the model for 1911–2016.

Visual inspection of the fish age-length distributions derived from the fish samples taken from the commercial and recreational sectors suggested similar vulnerabilities to fishing. The fish vulnerability assumptions were tested in the model to be equal between commercial and recreational fishing sectors. Therefore analyses were simplified to have equal vulnerabilities across sectors.

The population model allowed for two separate fishing sectors: commercial-charter (fleet f = 1) and recreational (fleet f =2). Sector-specific harvest rates ($u_{\mathrm{f},t}$) were calculated. Harvest rates by fleet 1 were calculated from the estimated harvest tonnages of Spanish mackerel taken by the commercial and charter fishing sectors. For the recreational fishing sector fleet 2, estimates of harvest were not available for many years. Recreational harvest rates of Spanish mackerel were estimated from a proxy measure of fishing effort (*E*; see data methods for recreational fishing). The formulas for this followed:

- $u_{\mathrm{f},t} = 1 - \exp\left(-q_f E_{\mathrm{f},t}\right)$, where the catchability q_f was a parameter to be estimated based on when $C_{\mathrm{f},t}$ was measured for the recreational fishing sector (f = 2; NSW and Qld waters combined).
- The model predictions of total Spanish mackerel recreational (f=2) harvests $\hat{C}_{\mathrm{f},t}$ was conditioned on the effort proxy *E*. This prediction was used in the negative log-likelihood for recreational harvests and the estimation of q_f, where f= 2.

The estimation of fish growth was completed outside of the stock model. Focus of the modelling was to predict temporal trends in the population and there was limited benefit in further increasing the complexity of the model. An externally estimated von Bertalanffy growth curve for each fish sex *s* based on age-group and fish length-weight data were used; where l_∞ was the average maximum fish total-length (cm) or w_∞ weight (kg), κ was the growth rate parameter that determined how quickly maximum size was attained and a_0 was the theoretical age at which the expected length or weight was zero – the value was typically negative and needed so that the function best represents the growth of exploitable (legal) sized fish, as data on small undersized fish were less vulnerable to fishing and under sampled. The calculated mean fish age–weight schedules were averaged over sexes.

Female fish age-based maturity was calculated using the female growth curve, where fish length at age was assumed to follow a normal distribution with different mean at age and constant variance. For a given fish age *a*, the normal distribution calculated the proportions of fish $p_{s,a}(l)$ at length *l*, such that $\sum_l p_{s,a}(l) = 1$.

Model parameters (Table 5) were estimated by calibrating the model to standardised fish catch rates and age composition data (Table 6). Effective sample sizes for scaling multinomial negative log-likelihoods were calculated within the model in order to give realistic weighting to the age structure data. Normal negative log-likelihoods were used for other data or calibration settings.

The model estimation process was conducted in Matlab® (MathWorks, 2017) and consisted of a maximum likelihood (ML) step followed by Markov Chain Monte Carlo sampling (MCMC). The flow of the estimation process is summarised in Figure 8. The maximum likelihood step used Matlab global optimisation (MathWorks, 2017), followed by a customised simulated annealing program to find and check the parameter solutions and estimate the parameter covariance matrix. The maximum likelihood step was effective for identifying optimal estimates for the negative log-likelihood (combined NLL fitting functions). The simulated annealing was started from a NLL scaling factor of 100 and then reduced to 10, 1, 0.1 and finally 0.01. For each scaling factor, the annealing process was run for 10 000 iterations of each parameter. The covariance matrix was built up by measuring the differences in the negative log-likelihood with each parameter jump.

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

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

The age-model biomass equilibrium limit reference point for maximum sustainable yield (B_{MSY}) and a target reference point proxy for maximum economic yield ($B_{MEY} \approx 0.6B_0$) were calculated (Queensland Government, 2017). The Australian Government's current proxy for B_{MEY}/B_{MSY} was 1.2 (Australian Government, 2007). The origin of this proxy was not clear (Dr Sean Pascoe, CSIRO, personal communication at the Fisheries Queensland harvest strategy workshop 4 to 5 August 2015), but likely based on the symmetric surplus production theory of $B_{MSY} \approx 0.5B_0$ (Zhou et al., 2013; Pascoe et al., 2014). This corresponds to $B_{MEY}/B_{MSY} = 1.5$ for the non-symmetric age-model dynamics used herein. The 1.5 ratio aligns more closely to the general default recommendations from Zhou et al. (2013) and Pascoe et al. (2014), of 1.3–1.4 times B_{MSY}. Similarly, it might be expected that optimal effort levels are most likely to fall between 55 per cent and 65 per cent of those at MSY (Pascoe et al., 2014).

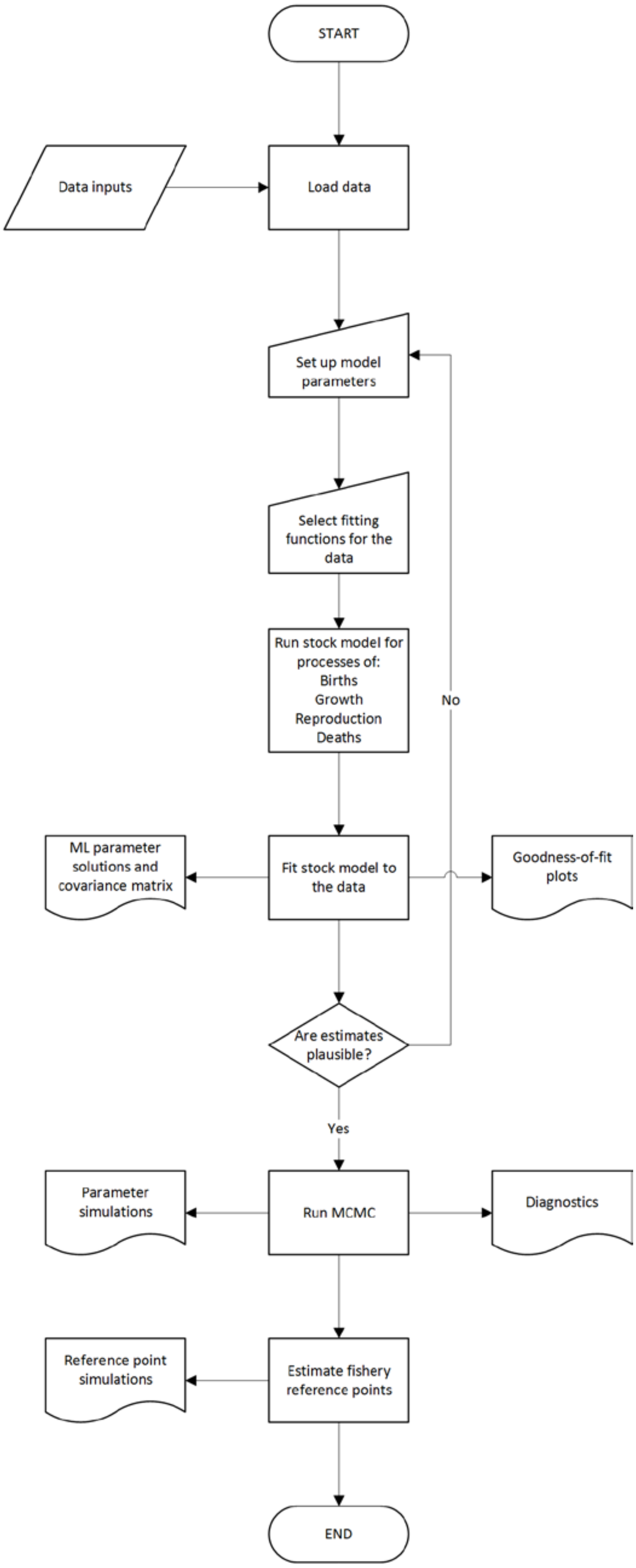

Figure 8. Flow of operations for the stock model from loading the data to evaluating model predictions.

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

Population dynamics	Equations
Numbers of fish in the 1st year 1911 (t=1): $N_{t,a} = R_t \exp\left(-Ma\right)$, where age groups a start at 0.	(1)
Numbers of fish after the 1st year 1911 (t>1): $N_{t,a} = \begin{cases} R_t & \text{for} \quad a = 0 \\ N_{t-1,a-1} \exp\left(-Z_{t-1,a-1}\right) & \text{for} \quad a = 1 \ldots \max\left(a\right) \end{cases}$	(2)
Recruitment number of fish – Beverton-Holt formulation: $R_t = \dfrac{S_{t-1}}{\alpha + \beta S_{t-1}} \exp\left(\eta_t\right)$	(3)
Spawning index – annual egg production: $S_t = \sum_a 0.5 N_{t,a} m_a \vartheta_a$ for female fish.	(4)
Fish survival: $\exp\left(-Z_{t,a}\right) = \exp\left(-M\right) \prod_{\text{f}} 1 - v_a u_{\text{f},t}$	(5)
Mean fish weight kg in each age-group cohort: $w_a = w_\infty \left(1 - \exp\left(-\kappa \left(a - a_0\right)\right)\right)$	(6)
Fish vulnerability to fishing: $v_a = \dfrac{1}{1 + \exp\left(-\log\left(19\right) \dfrac{\left(a - a_{50}\right)}{\left(a_{95} - a_{50}\right)}\right)}$	(7)
Harvest rate for commercial and charter fishing, fleet f=1: $u_{\text{f}=1,t} = C_{\text{f}=1,t} \Big/ \sum_a B^1_{t,a} \sqrt{1 - v_a u_{\text{f}=2,t}}$	(8)
Midyear exploitable biomass – forms 1 and 2 are labelled in order by superscript ^{1} and ^{2}: $B^1_t = \sum_a N_{t,a} \bar{w}_a v_a \exp\left(-0.5M\right)$	(9)
$B^2_t = \sum_a N_{t,a} \bar{w}_a v_a \exp\left(-0.5M\right) \sqrt{\prod_{\text{f}} 1 - u_{\text{f},t}}$	(10)
Recreational harvest, fleet f=2, number of fish: $\hat{C}_{\text{f}=2,t} = \sum_a \dfrac{v_a q_{\text{f}=2} E_{\text{f}=2,t}}{Z_{t,a}} N_{t,a} v_a \left(1 - \exp\left(-Z_{t,a}\right)\right)$; × w_a calculates harvest tonnes.	(11)
Catch rate, commercial fleet index: $c_{\text{f},t} = q_{\text{f}} B^2_t$. This was only calculated for commercial catch rates.	(12)

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

Parameter	Equations and values	Notes
Assumed		Parameters inputted (fixed) into the model. They were estimated based on data outside of the model dynamics.
$\mathrm{Max}(a)$	26	Based on considering the maximum fish age recorded from the Queensland east coast (26 years).
w or *l*	$l_\infty, \kappa\ , a_0$	The estimated von Bertalanffy growth curve parameters (Haddon, 2001).
m_a	$m_l = \dfrac{\exp(\varsigma)}{1+\exp(\varsigma)}$ $\varsigma = -10.349 + 0.0128 \times l$	Logistic maturity schedule $p(\mathrm{mature}\|l_a)$ by fork length (cm) for female fish (sex *s* = 1). The schedule was estimated using binomial regression and logit link (Mackie et al., 2005; Begg et al., 2006). The length-dependent maturity was converted to age dependent maturity.
ϑ_a	$w_a \times \mathrm{eggs\ kg}^{-1}$	Mature female egg production at age (number of eggs).
M		One parameter for instantaneous natural mortality year^{-1} (death rate of fish due to natural causes such as old age, predation, competition or other non-fishing reasons). This was fixed or estimated according to the negative log-likelihood equation. The prior distribution allowed for a fish lifespan of about 26 years. Empirical estimates for Spanish mackerel in east-coast waters have ranged from 0.26 to 0.34 year^{-1} (Campbell et al., 2012). The age based estimator of Then et al. (2015) was 0.25 year^{-1} assuming a maximum fish age of 26 years from east coast waters.
Estimated		Parameters estimated by the model.
Υ and ξ	$\alpha = S_0(1-h)/(4hR_0)$ $\beta = (5h-1)/(4hR_0)$ $R_0 = \exp(\Upsilon) \times 10^6$ $h = r_{comp}/(4 + r_{comp})$ $r_{comp} = 1 + \exp(\xi)$	Two parameters for the Beverton-Holt spawner-recruitment function, that define *α* and *β* (Haddon, 2001). Virgin recruitment (*R₀*) was estimated on the log scale for the first model year. One estimated value of steepness (*h*) was assumed for the stock. S_0 was calculated as the overall virgin egg production in the first model year. The r_{comp} parameter was the recruitment compensation ratio (Goodyear, 1977), based on the log scale coefficient ξ .
a_{50} and a_{95}		Two parameters for logistic vulnerability (Haddon, 2001). a_{50} was the fish age (years) at 50% vulnerability to fishing and a_{95} at 95%.
ζ	$\boldsymbol{\eta} = \boldsymbol{\zeta}\mathbf{e}$	Recruitment parameters to ensure log deviations sum to zero with standard deviation *σ*, equation 15 Table 6. ζ were the estimated parameters known as barycentric or simplex coordinates, distributed $NID(0,\sigma)$ with number nparRresid = number of recruitment years – 1 (Möbius, 1827; Sklyarenko, 2011). **e** was the coordinate basis matrix to scale the distance of residuals (vertices of the simplex) from zero (O'Neill et al., 2011).

```
e = zeros(nparRresid,
nparRresid+1);
for i = 1:nparRresid
    hh = sqrt(0.5 * i ./ (i + 1));
    e(i, 1:i) = -hh ./ i; e(i, i + 1) = hh;
end; e= e ./ hh;
```

Parameter	Equations and values	Notes
q_{f}		Fish catchability parameter measuring the proportion of the exploitable stock taken by one unit of standardised fishing effort. For commercial fishing, the parameter was derived as a closed-form median estimate of standardised catch rates divided by the midyear biomass form 2 (Haddon, 2001). *q* was an estimated parameter for recreational fishing.

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

***-LL* functions for:**	**Theory description**	**Equations**
Log standardised catch rates, log decadal catch rates and log recreational harvests for each fishing sector: $\frac{n}{2}\left(\log\left(2\pi\right)+2\log\left(\sigma\right)+\left(\hat{\sigma}/\sigma\right)^2\right)$, or simplified as $n\left(\log\sigma+\frac{1}{2}\left(\hat{\sigma}/\sigma\right)^2\right)$, where $\sigma=\max\left(\hat{\sigma},\sigma_{\min}\right)$, $\sigma_{\min}$ = 0.108, 0.19 and 0.19 respectively, and $\hat{\sigma}=\sqrt{\sum\left(\left(\log\left(c_t\right)-\log\left(\hat{c}_t\right)\right)^2\right)/n-1}$ and n was the number of annual data.	Normal distribution (Haddon, 2001)	(12)
Fish age *a* composition data for each fishing sector: $-\sum\left(-\log\left(T^{\frac{(\tilde{n}-1)}{2}}\right)-\frac{1}{2}(\tilde{n}-1)\frac{T}{\hat{T}}\right)$, or simplified as $-\sum\frac{1}{2}(\tilde{n}-1)\left(log(T)-\frac{T}{\hat{T}}\right)$, Where $\tilde{n}$ was the total number of categories *a* with proportion-frequency > 0, $\hat{T}=(\tilde{n}-1)/2\sum\hat{p}\log(\hat{p}/p)$, $T=\max\left(2,\hat{T}\right)$ specified sample size bounds, $\hat{p}$ were the observed proportions > 0 and p were predicted.	Effective sample size (*T*) in multinomial likelihoods (Leigh, 2011; O'Neill et al., 2011; Leigh et al., 2014; Leigh, 2016)	(13)
Instantaneous natural mortality *M* year^{-1}: $0.5\left(\frac{M-0.25}{\sigma}\right)^2$, where $\sigma=0.06$ defined the prior distribution ≅ 24% CV.	O'Neill et al. (2014)	(14)
Recruitment compensation r_{comp} $0.5\left(\frac{\xi-\log\left(6-1\right)}{\sigma}\right)^2\times\left(\xi>\log\left(19\right)\right)$, Where the condition statement was used for free estimation with *σ* = 1.2 and only triggered when steepness was exceedingly large *h* > 0.8; the condition statement was always on for setting a prior distribution with *σ* = 0.6		(15)
Annual log recruitment deviates η **:** $\frac{n}{2}\left(\log\left(2\pi\right)+2\log\left(\sigma\right)+\left(\hat{\sigma}/\sigma\right)^2\right)$ Where $\sigma=\min\left(\max\left(\hat{\sigma},\sigma_{\min}\right),\sigma_{\max}\right)$, $\sigma_{\min}=0.1$ and $\sigma_{\max}=0.2$ specified bounds, $\hat{\sigma}=\sqrt{\sum\eta^2/n-1}$ and n was the number of recruitment years modelled with variance.	O'Neill et al. (2014)	(16)

Results and discussion

Model inputs - data

Fishing harvests and effort

Harvests of Spanish mackerel and fishing efforts were analysed for the fishing years up to 2016. The results were summarised by fishing years (i.e. financial years, where for example the 2015/2016 fishing year was labelled as 2016). Note that the term 'harvest' referred to fish caught and killed. Estimates of recreational harvests used in analyses included both kept fish and released fish assumed to have suffered discard mortality. All Spanish mackerel landed by the commercial and charter fishing were assumed to be retained and reported.

From Queensland waters (Figure 9), annual commercial line harvests of Spanish mackerel ranged 415–776 tonnes (t) between the years 1989 and 2004. Harvests declined greatly to range 234–390 t between 2005 and 2016. Most fish (mean 68 per cent ± standard deviation 5.7 per cent) were harvested from offshore waters north of Bowen (≤ 19.5°S; Figure 1). This spatial percentage fell to its lowest annual value of 58 per cent in 2016. The commercial line harvest quota (total allowable commercial catch: TACC) was considerably under filled for all years 2005–2016 (Figure 9). Logbook tonnages of Spanish mackerel from 2005–2016 were verified against separate quota system reports, showing on average a small -8 per cent difference in logbook reports (Figure 32 and Figure 33, Appendix).

Nominal reports of Queensland commercial line-fishing effort for Spanish mackerel increased between 1989 and 2004 (Figure 10). Effort levels peaked at 545 vessel-operations in 1998, and 14 673 operation days and 23 722 boat days (including the reported number of dories used in the fishing operations) in 2003. After 2004, when quota procedures were implemented, the nominal numbers of vessel-operations and operation days fell about 60 per cent, and boat days by 50 per cent. Also from 2004, the Great Barrier Reef marine park zones were expanded but most of the key reefs for Spanish mackerel remained open to fishing (Tobin et al., 2014) and the TACC was not adjusted for any reduced fishing area. The use of multiple vessels (dories: 1 to 5 in addition to the primary vessel) per operation was prevalent in waters north of Rockhampton (≤ 22°S degrees; Figure 1). Normally this style of fishing is considered less suitable in southern waters as vessels have to operate and travel in more exposed seas.

Cumulative patterns of commercial annual line harvest illustrate many small catches, with the bulk of annual commercial harvests in Queensland waters taken by less than 70 fishing operations (Figure 11). Further examination of the cumulative patterns was conducted focusing on harvests between the 20th and 80th percentiles. This percentile range can be seen in Figure 11b (y-axis). This range was examined to see if there was any contraction in fishing over time, based on unique fishing dates when mackerel were harvested and removing the influence of overly high or low harvests. The data for each latitude indicate:

- There was no general change in the timing of the primary fishing season; i.e. for each latitude the length of fishing seasons were no longer or shorter (test for annual change in each latitude was not significant: d.f. =19, F statistic = 0.84, *p* = 0.656). The time between the dates corresponding to the 20th and 80th percentiles of the cumulative distributions in each latitude were not meaningfully different between years.
- In recent years the number of calendar days fished where a Spanish mackerel was successfully caught, between the 20th and 80th percentiles of cumulative harvest, were less in many latitudes (latitudes 11, 12, 17, 18, 20–25 and 29; Figure 12). It was unclear from the data if this information

suggested a contraction in the number schools of fish of commercial size and density, or if this was a result of changed fishing practices and a reduce number of fishing operations, or both. There was no clear reduction in the number of calendar days fished in latitudes 13–16, 19, and 26–27. Aspects of this information were examined in the catch rate probability analysis, to standardise for the reduced number of fishing operations since quota management started in 2005.

Commercial net records of Spanish mackerel harvest from Queensland waters reduced to less than 1 t per year after 2004. For the years prior 1989 –2004, reported net harvests ranged up to 20 t per year. On average 56 per cent of net harvests were taken from north of Bowen and the remaining 44 per cent to the south.

Queensland line-fishing charter vessels reported annual Spanish mackerel harvests up to 54 t per year for 80–150 operations. The mean charter harvest per year since 2000 was 35 t and ranged 19–54 t.

Commercial line harvests of Spanish mackerel from northern New South Wales (NSW) waters varied annually up to about 52 t for 40–60 operations. The NSW mean commercial harvest per year since 2000 was 15 t and ranged 3–40 t.

Spanish mackerel reports from NSW charter line fishing were sparse and considered negligible compared to other fishing sectors. Data have only been reported from four licences, tallying 134 fish between 2010 and 2016.

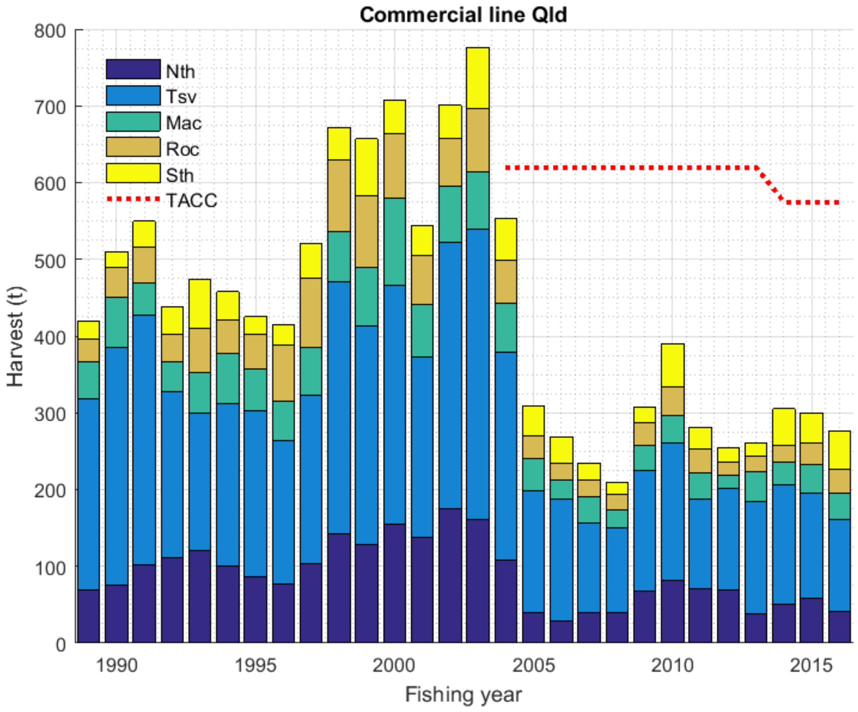

Figure 9. Total harvests of Spanish mackerel by fishing year as reported by commercial line fishing operations in Queensland waters. The graph coloured areas were: North (Nth) latitudes 12–17, Townsville (Tsv) 18–20, Mackay (Mac) 20–22, Rockhampton (Roc) 23–25 and South (Sth) 25–29. See Figure 1 for the map of latitudes.

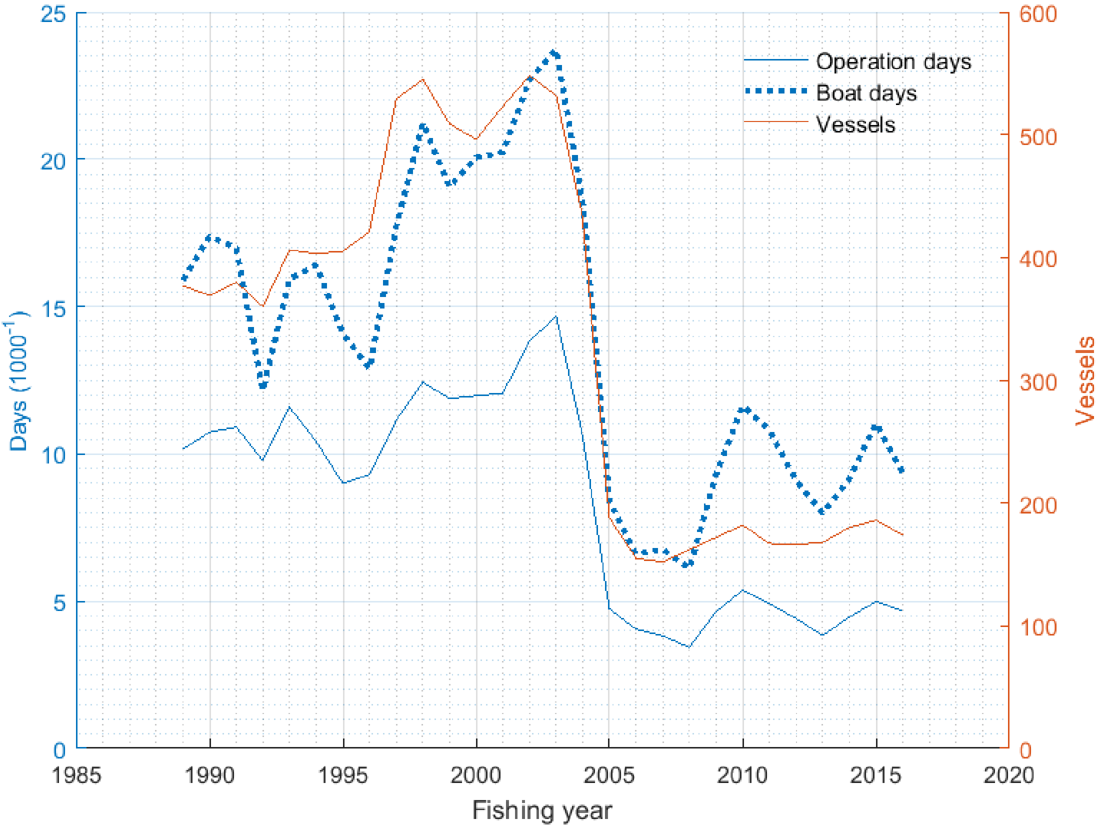

Figure 10. Nominal fishing effort by commercial Spanish mackerel line operations in Queensland waters. The figure summarises tallied operation days, boat days by operations using their primary vessel and dories together, and number of operations (vessels; red colour) by fishing year. The nominal data represents successful mackerel effort (harvest > 0).

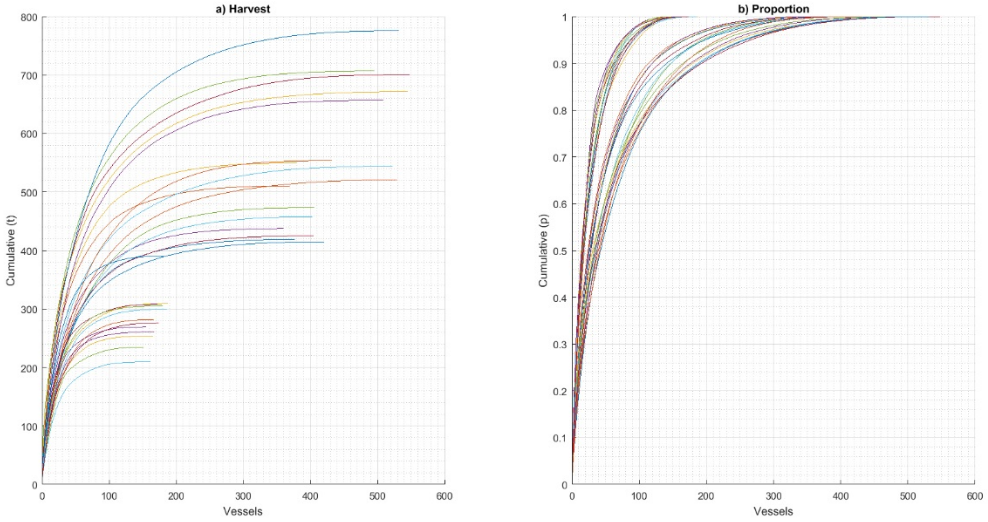

Figure 11. Cumulative harvests of Spanish mackerel by fishing year. Each line represents different years 1989–2016. The data were for commercial line fishing operations in Queensland waters and scaled increasing by a) harvest tonnes (t) and b) proportion.

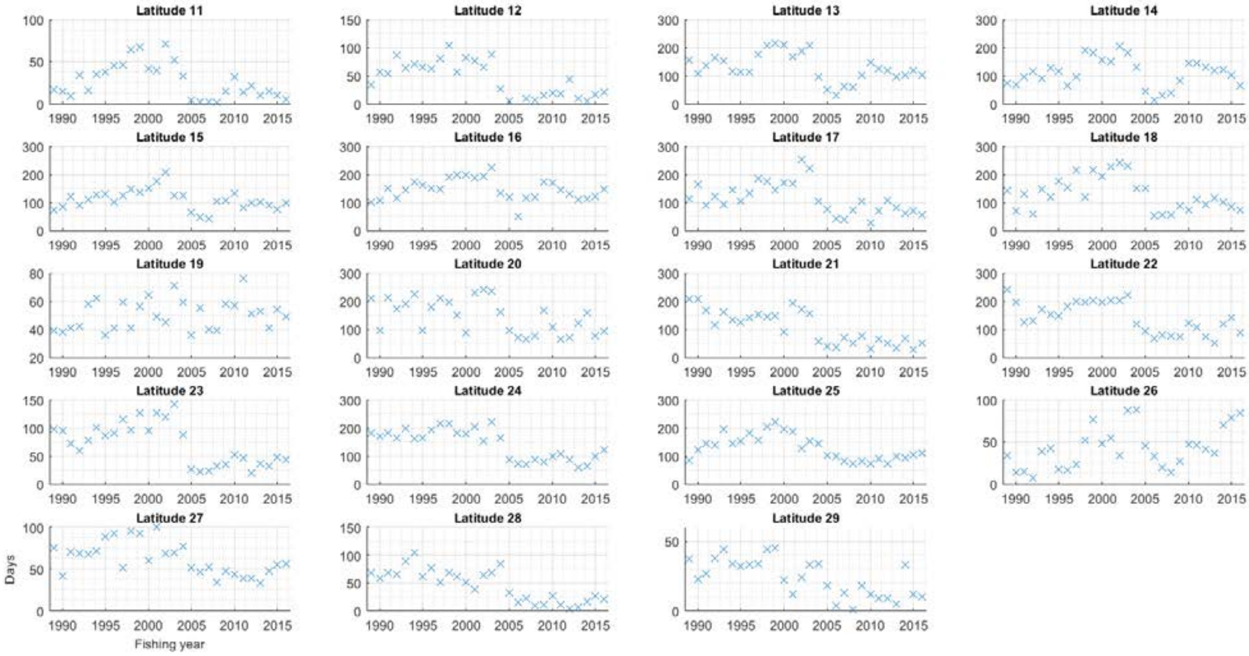

Figure 12. The number of unique calendar days fished by commercial line fishers to take 60 per cent (between 0.2 and 0.8 probabilities of the cumulative distribution) of the total harvest in each latitude band from Queensland waters. Focus was on within latitude changes – note the y-axis scale changes between latitude.

Survey estimates of recreational line harvests of Spanish mackerel were available for only eight years (Figure 13 and Table 7). The numbers of Spanish mackerel harvested (kept) were about 35-40 thousand fish per year since 1997. The estimates suggest that the combined recreational harvests from both New South Wales and Queensland waters were similar to the Queensland commercial fishing sector since 2004 (around 250–300 t; comparing Figure 9).

Model inputs included an additional 3-10 thousand Spanish mackerel per year as recreational harvest. This was to account for released fish suffering discard mortality (50 per cent of fish assumed to die after release; Table 7). No formal research has quantified discard mortality rates of Spanish mackerel, but observations by scientists and fishers suggest that this is high.

The decision to included discard mortality on released fish was based on information from The Department of Fisheries, Western Australia. They have proposed to abolish the Spanish mackerel minimum legal size of 90 cm total length because of anecdotal evidence of high post-discard mortality due to stress of capture and the little protection it provides for spawning egg production (Western Australian Government, 2016).

The rate of 50 per cent was chosen to incorporate the effects of discard mortality. A higher rate was not considered in the population modelling as the addition of spurious harvest would 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 and Brown, 2011).

For population modelling, prediction of recreational harvests or fishing effort for non-survey years was required. Based on the suggestion by Dr Francis (independent review of stock assessment: Campbell et al., 2009), a history of recreational Spanish mackerel harvests was predicted by the population model based on a constructed history of fishing effort (Figure 13). This involved joining historical information on vessel registrations, survey estimates of fishing participation and effort (Webley et al., 2015) and fishing power (Thurstan et al., 2016a).

In total six proxies of recreational fishing effort were constructed (Figure 13e and f). The proxies were based on three levels of fishing power, the pattern of exponential increase in vessel licences (Figure 13b) and a decrease or increase in fishing effort post 1996 based on survey estimates (Figure 13c and d). In Queensland participation rates in recreational fishing declined post 1996 (Fisheries Queensland data; and https://www.daf.qld.gov.au/fisheries/monitoring-our-fisheries/recreational-fisheries/statewide-and-regional-recreational-fishing-survey/key-findings).

For Figure 13e, comparing the difference between the two years of 1990 and 2016, fishing effort was assumed to have increased by 9 per cent, 33 per cent and 63 per cent respectively for values of no, reduced (square root) and full (actual estimate) fishing power increase. For Figure 13f, the change in fishing efforts between 1990 and 2016 were higher at 51 per cent, 85 per cent and 126 per cent respectively for the three different fishing powers.

The annual estimates of fishing power for the recreational fishing sector are illustrated in Figure 14. The estimates suggested fishing power increased by about 50 per cent between 1990 and 2016 and 100 per cent between 1940 and 2016 (Figure 14a). The reduced (square root) estimates were less at 20 per cent and 38 per cent respectively for the same time periods (Figure 14b). The fishing power estimates were based on information in Figure 39 and Table 14 (Appendix).

In comparing the ratio of estimates of recreational fish harvest and effort in years 2001, 2011 and 2014 (Figure 13), the following two situations could be inferred roughly:

- Harvests were measured to be steady (Figure 13a) and overall ocean boat fishing effort had fallen since 2001 (Figure 13c), suggesting an increase in catch rates.
- Alternatively, Figure 13d suggested that the boat effort that was focussed on trying to harvest Spanish mackerel had increased from 2001 to 2014, which could be interpreted as a decrease in catch rates.

The second situation was consistent with commercial data and suggested that with stable harvest and focussed effort increasing, catch rates had declined.

In the fish population modelling the recreational fishing effort proxies (NSW and Qld combined) were assumed to be a proportional index of the trend in overall effort trying to catch Spanish mackerel, rather than absolute values. Other constructs could be suggested, but we have used available data that provides a contrast of results for management insight. For the proxies, the ratio of fishing effort for successful to unsuccessful (zero) harvests were assumed constant through time, with no data to suggest a change.

Figure 15 compared harvest estimates by fishing year and sector, showing the strong build of the commercial harvest during the 1970s and decline to 2010s. The estimated recreational harvests were illustrated for available years, which since 2010 were of similar magnitude to the commercial harvest.

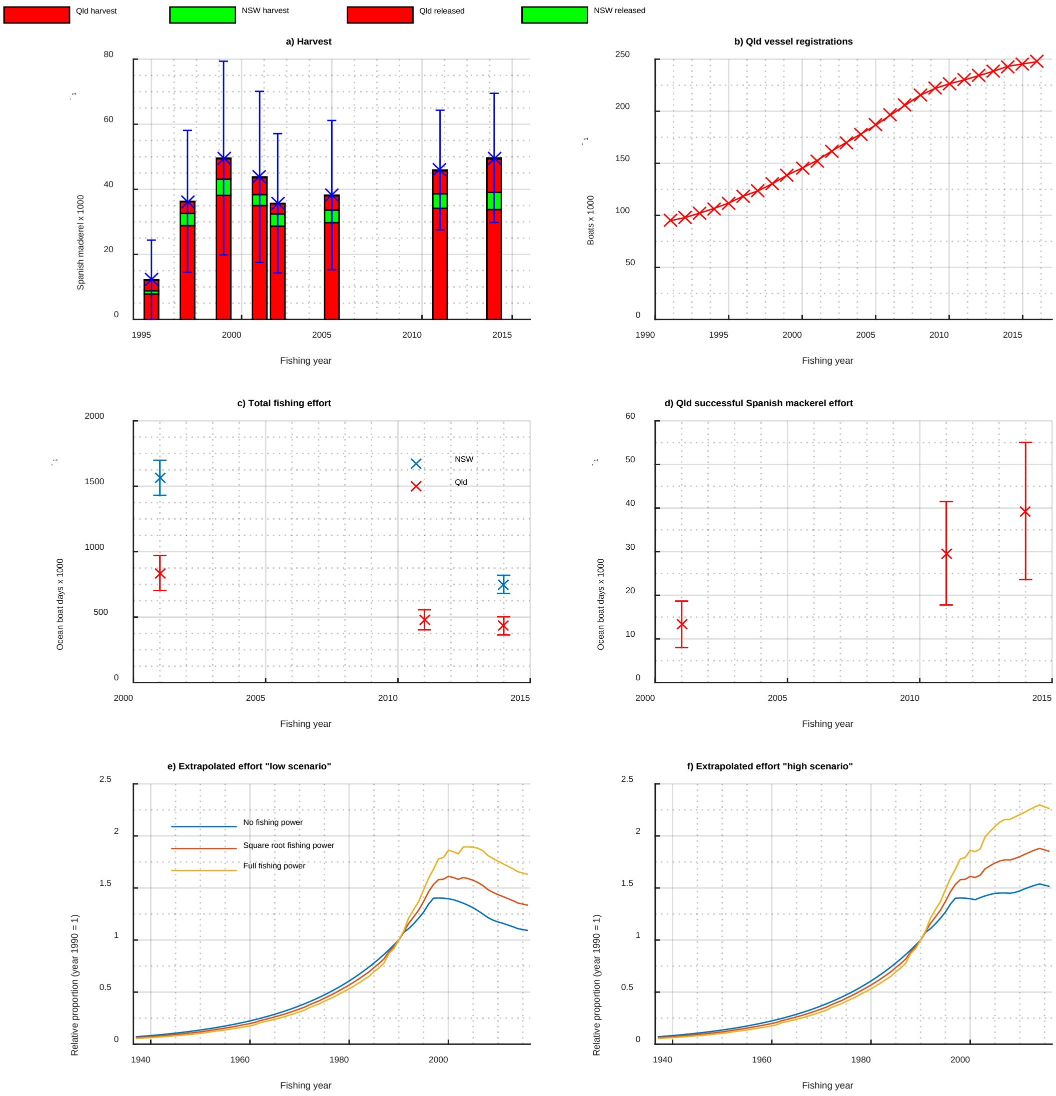

Figure 13. Annual estimates of Spanish mackerel harvest (total fish harvest in subplot a) and fishing effort (subplots b to f) by recreational anglers. Notes on data: 1) In subplot a, harvests from NSW waters were estimated to be 13 per cent (± 8 per cent; two standard errors) of harvests from Queensland waters and estimates of released fish assumed 50 per cent mortality with the NSW released component being small at 4 per cent ± 2 per cent of Queensland releases. Also refer to Table 7; 2) Subplot c represents all offshore ocean boat fishing effort for all fish catches including zeros; and 3) Subplot d represents only the 'successful' ocean boat fishing effort where Spanish mackerel was harvested or released, i.e. zero catches excluded. The extrapolated long-term trend of ocean boat fishing effort for Spanish mackerel in subplot e was calculated from data in subplots b and c and subplot f used data from subplots b and d. The fishing power values were from Figure 14. Error bars represent ± two standard errors. Data sources: Fisheries Queensland (Department of Agriculture and Fisheries), Cameron and Begg (2002), West et al. (2015), and the Department of Transport, Queensland.

Table 7. Revised estimates of Spanish mackerel harvests (caught and kept) and released from New South Wales and Queensland State waters. The tallied harvest numbers were for kept fish. The tallied released numbers were for discard-mortality fish (assumed rate of 50 per cent). Relative standard errors on estimates were 30–50 per cent between 1995 and 2005 and 15–30 per cent for 2011 and 2014. See Methods section on how the estimates were constructed.

Fishing year	Survey data source	Harvest Qld	Harvest NSW	Released Qld	Released NSW
1995	FRDC: Cameron and Begg (2002)	7816	1016	3234	129
1997	RFISH: Higgs (1998)	28838	3749	3586	143
1999	RFISH: Higgs (2001)	38159	4961	6234	249
2001	NRIFS: Henry and Lyle (2003)	35000	3385	5209	221
2002	RFISH: Higgs et al. (2007)	28683	3729	3158	126
2005	RFISH: McInnes (2008)	29749	3867	4425	177
2011	SWRFS: Taylor et al. (2012)	34185	4444	7027	281
2014	SWRFS: Webley et al. (2015)	33782	5283	10266	312

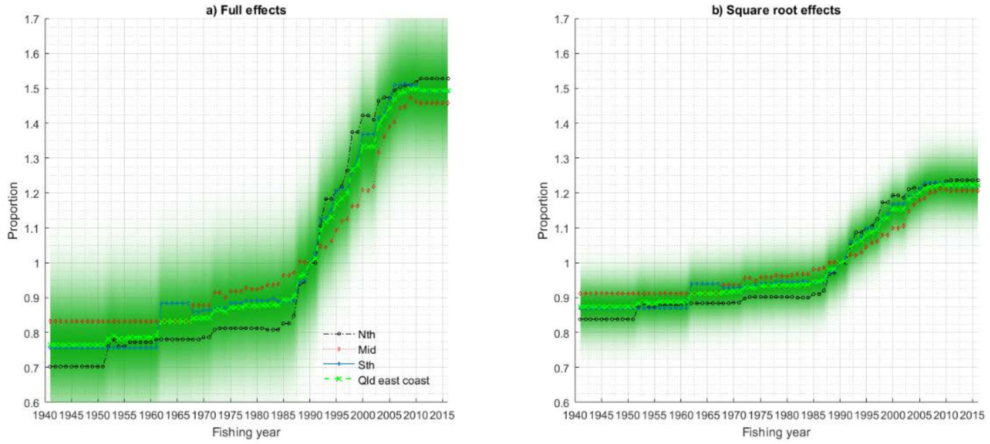

Figure 14. Annual fishing power increases in the Queensland east coast Spanish mackerel recreational sector. The proportional change in fishing power (i.e. catch improvements from using better fishing gear and technology) represents the difference relative to the 1990 fishing year, which was set equal to 1 on the vertical y-axis. The values were calculated for each fishing region and overall for east-coast waters, where in subplot a) the treatment effects for GPS, colour sounders, down riggers, live baiting, rod and braid line fishing were applied fully from Table 14 and in subplot b) the effects were lessened to consider that each treatment was conditional on one another (i.e. not independent). The semitransparent green shading tapers gradually to indicate normal distributed uncertainty around the means, with each subplot standard deviation equal to 0.12 and 0.06.

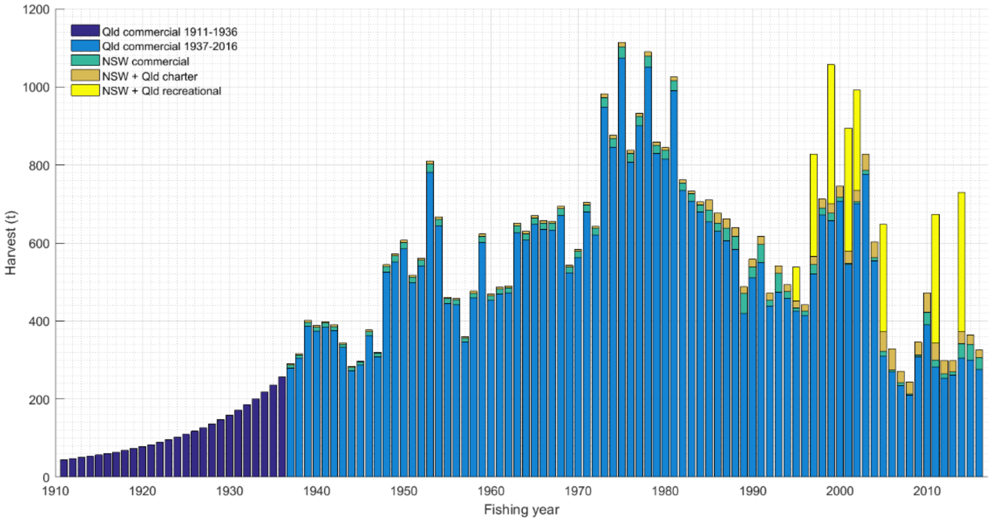

Figure 15. Annual estimates of Spanish mackerel harvest (tonnes) by fishing sector. Queensland commercial harvests for the years 1911–1936 were extrapolated to correspond with the beginning of the fishery; 1937 to 1981 harvests were sourced from Queensland Fish Board reports; commercial harvest logbook records starting in 1989; harvests between 1981 and 1989 were linearly interpolated using data between 1973 and 1996. For the figure only, the recreational harvest assumed a mean fish weight of 7.2 kg.

Catch rates

Relative trends in Spanish mackerel abundance were inferred from Queensland commercial logbook standardised catch rates. The catch rate index informed proportionally on the annual magnitude of change in abundance of legal sized fish. This was a primary assumption for the stock assessment.

The assumption of proportionality was made only after employing a regression model (Hilborn and Walters, 1992), which standardised for factors affecting fish catchability and fishing efficiency (i.e. accounted for certain biases or variation in the data). The result aimed to generate a time series of standardised catch rates that was representative of trends in the fished (exploited) population. If a catch rate measure was calculated on only raw catch and effort data, then this would produce a false outcome unless sources of variability were identified and corrected. This error can occur due to efficiency changes in fishing effort, gear, locations fished through time and differences between fishing operations.

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

$$E(c) = p(c)E(c|c>0),$$

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

The results for predicting the probability *p(c)* of commercially catching Spanish mackerel are shown in Figure 16 and Figure 17. The analyses were conducted to produce *E*(*c*), in order to adjust for zero catch days and lessen suspected hyper stability in $E(c|c>0)$. The predictions represent the proportion of days per month when Spanish mackerel were harvested. They were standardised for the number of fishing operations, seasonality and wind strengths and directions. Model fit and diagnostics were acceptable (Appendix: Table 12, Figure 34, Figure 35 and Figure 36).

For Queensland east coast waters, the predicted probabilities declined about 12 per cent post 2004 (Figure 16). By latitude, probabilities declined post 2004 in latitude bands 17 (≈ -15 per cent Cairns), 18 (≈ -30 per cent Mission Beach), 19 (≈ -10–20 per cent Lucinda), 21 (≈ -15 per cent Bowen), 23 (≈ -10 per cent Rockhampton), 27 (≈ -20 per cent Sunshine Coast) and 29 (≈ -20 per cent Gold Coast) (Figure 17). No overall declines were predicted in other latitudes, except a clear -20 per cent drop in probability for the years 2012–2013 in latitude band 28 (Moreton). Latitude band 19 covered the key spawning area for Spanish mackerel off Lucinda. Latitudes 17–18 covered waters east of Mission Beach and Cairns, which were considered former spawning areas (Buckley et al., 2017).

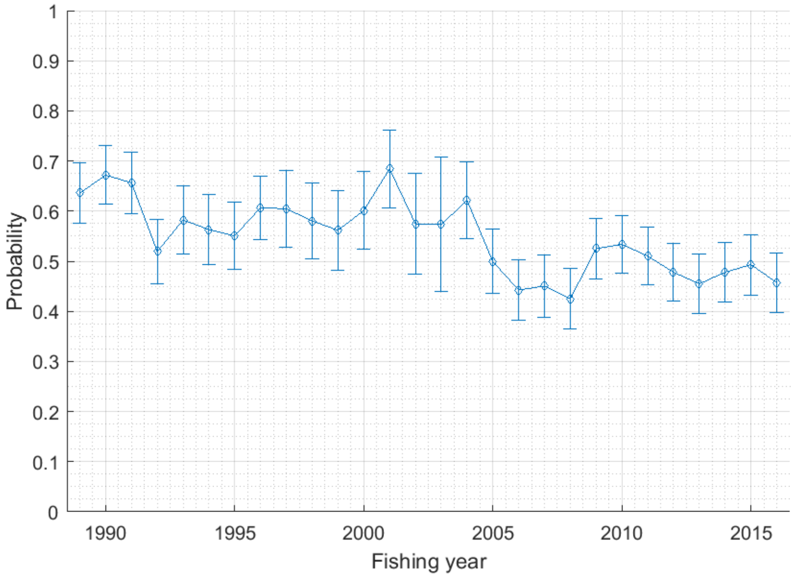

Figure 16. Probability of commercially harvesting Spanish mackerel by fishing year. The error bars represent ± 2 standard errors on mean predictions.

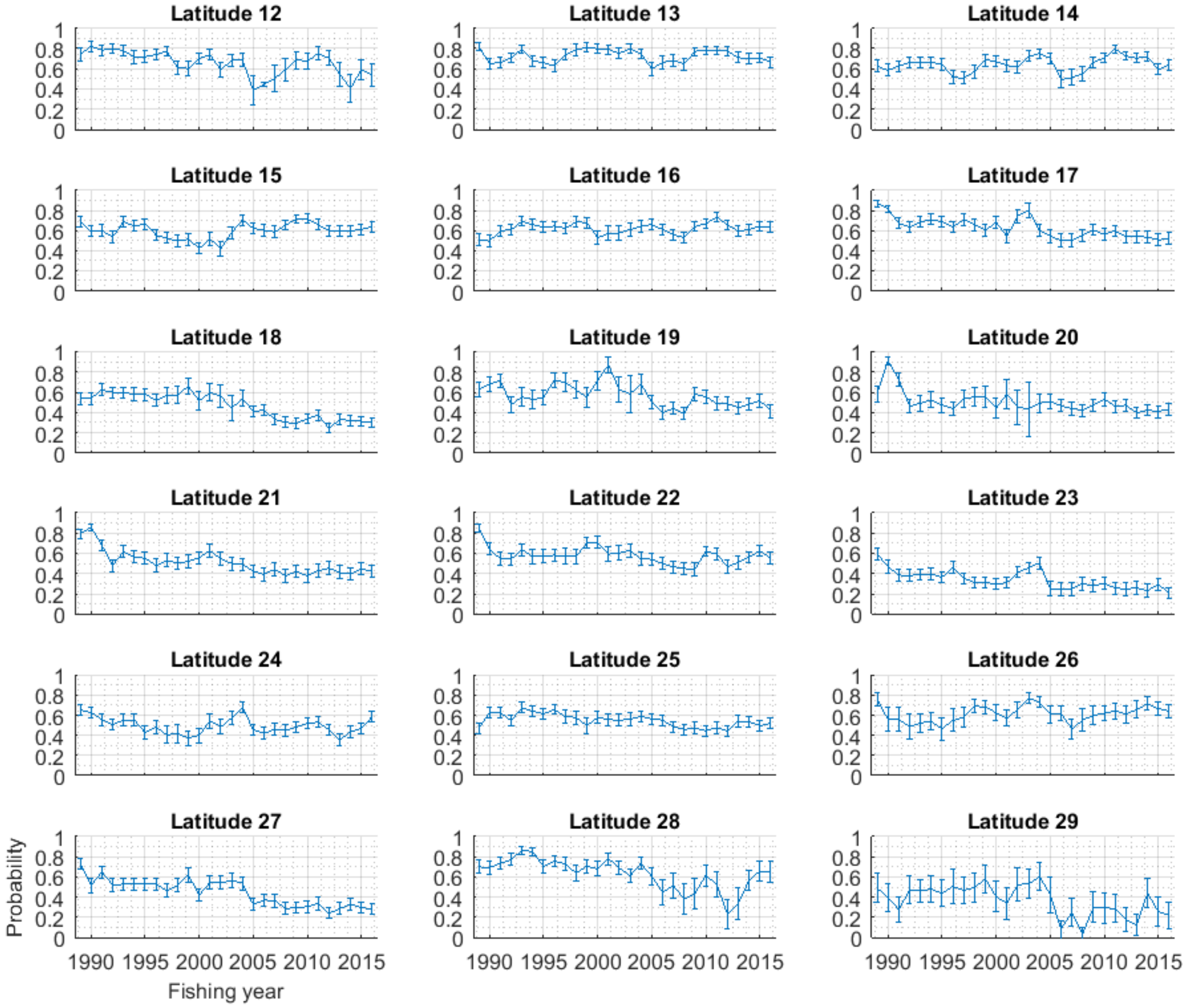

Figure 17. Probability of commercially harvesting Spanish mackerel by latitude and fishing year. The error bars represent ± 2 standard errors on mean predictions.

The analysis and prediction component for when commercial Spanish mackerel were caught $E\left(c|c>0\right)$, incorporated annual changes in fishing power to standardise the impacts of increased fishing effort and improved technologies. Similar to the probability results, the focus was on the standardised year and year × latitude trends. Model fits and diagnostics were all satisfactory (Appendix: Table 13 and Figure 37).

Three schedules of annual increases in fishing power were incorporated into $E\left(c|c>0\right)$: 1) no change in fishing power, 2) reduced (square root) and 3) full (actual) effects as estimated from the fisher knowledge data. The combination of increased use of global positioning systems, colour depth sounders, down riggers and live baiting (Figure 38; Appendix) and their effects (Table 14; Appendix) resulted in increases of commercial fishing power (Figure 18). The full estimated increases were about 42 per cent between 1990 and 2016 for waters north of Bundaberg (north and middle zones; Figure 18). The full estimate was greater in the south: nearly 54 per cent (Figure 18). Across all waters the full increase in fishing power was about 46 per cent between 1990 and 2016. The rate of increase was greatest between 1990 and 2000, but slowed in the last 10 years due to mostly unchanged fishing gears. The alternate reduced (square root) schedule of fishing power was calculated to account for possible overestimation and was estimated to increase 21 per cent between

1990 and 2016. Even though the reduced scenario was generated to cover risk of overestimation, other fishing power variables that were not surveyed may be important for increased fishing power (e.g. increasing fisher experience through time or other variables in Table 14 Appendix). Therefore, the 'full effects' schedule should not be discounted.

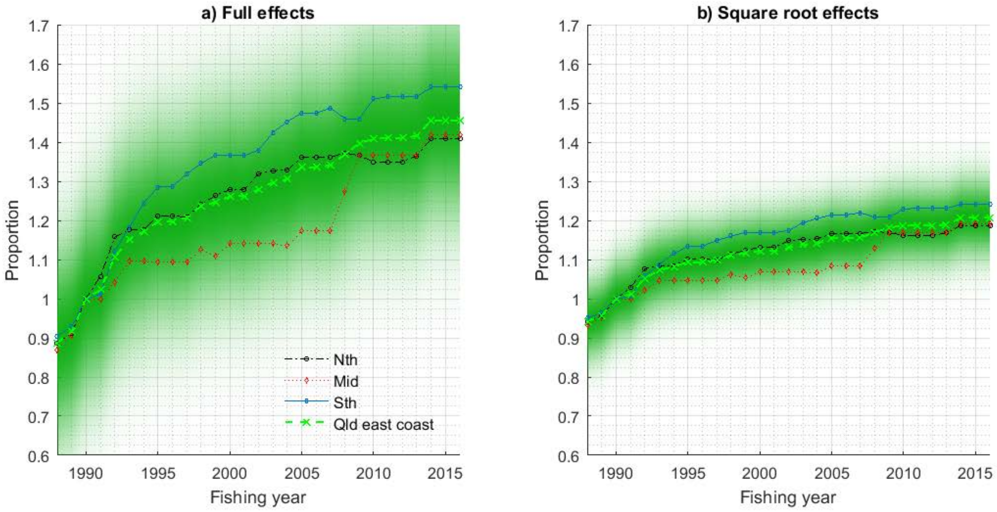

Figure 18. Annual fishing power increases in the Queensland east-coast Spanish mackerel commercial-line sector. The proportion change in fishing power (i.e. catch improvements from better fishing gears and technologies) represents the difference from the 1990 fishing year, which was set equal to 1 on the vertical y-axis. The values were calculated for each fishing region and overall for east-coast waters, where in subplot a) the full treatment effects for GPS, colour sounders, down riggers and live baiting were applied from Table 14 and in subplot b) the treatment effects were lessened to represent a scenario for conditional effects and inflated bias. The semitransparent green shading tapers gradually to indicate normally distributed uncertainty around the means, with each subplot standard deviation equal to 0.17 and 0.07.

In total six predictions of annual standardised catch rates were generated to cover three levels of fishing power and inclusion or not of the probability adjustment *p(c)* (Figure 19). For no adjustments, catch rates were generally steady across Queensland east coast waters with spikes in 1998–2000 and 2010 (Figure 19a). Catch rates decreased in 2015–2016 and were below average. Inclusion of increases in fishing power and probability adjustment pushed catch rates down (Figure 19b to f), with full adjustments suggesting catch rates declined by about 50 per cent between 1990 and 2016 (Figure 19f).

Latitudinal predictions were influenced in the same manner by the fishing power and probability adjustments (Figure 20 and Figure 21). Declines in catch rates were predicted over many regions. For example, decline in the 2015–2016 catch rates for the key spawning latitude 19 (Lucinda region) was estimated. Focusing on the Lucinda results, estimated declines between the fishing years 1990 and 2016 were about -15 per cent for no fishing power, -30 per cent for reduced fishing power adjustment and -45 per cent for full fishing power adjustment were predicted (Figure 20, latitude 19). The estimated declines for the Lucinda region were greater when including the probability adjustment, i.e., about -50 per cent for no fishing power, -60 per cent for reduced fishing power adjustment and -65 per cent for full fishing power adjustment when comparing the fishing years 1990 and 2016 (Figure 21, latitude 19). The only increasing trend in catch rates was identified for Fraser Island waters in latitude 26 (Figure 20 and Figure 21).

In summary the Spanish mackerel catch rate data (non zero kg of fish per operation-day) had high variance and was skewed with a nominal median = 26 kg operation-day^{-1}, mean = 57 kg and standard deviation = 87 kg (CV = 153 per cent). Harvests were reported as kg whole-fish weight as numbers of fish are not recorded. It should be noted that reporting both number and weight of fish harvested would better measure fish abundance. Significant variation in catch rates between years and locations was evident (illustrated in Figure 40, Appendix). Broader distributions of daily harvests were evident since quota management began in 2005; shown by the boxplot distance between the 25th and 75th percentiles (Figure 40). In general, catch rates were higher in the Lucinda (median = 35 kg and mean = 81 kg) and Fraser coast (median = 47 kg and mean = 74 kg) regions; suggesting larger schools of fish than in other areas.

Average catch rates of Spanish mackerel were estimated to increase on the early waxing moon phase in the Lucinda region, latitude 19 (Figure 42, Appendix). Latitude 19 was identified to have the strongest lunar effect, with lesser effects elsewhere. Latitude 19 catch rates were estimated to be about 25 per cent higher early in the waxing moon phase compared to after the full moon (waning phase). A similar pattern was identified for Spanish mackerel in the Torres Strait (Bramble Cay), with 33 per cent higher catch rate early in the waxing moon phase compared to after the full moon (waning phase) (O'Neill and Tobin, 2018).

The long-term decadal commercial catch rates of Spanish mackerel were also examined as an index of fish abundance (Figure 22b). The time series from the 1940s to the 2010s indicated a 56 per cent reduction in catch rates. The decadal means were aligned to the commercial-logbook standardised catch rates from the 1990s to 2010s, illustrating a rough agreement in the long-term trend. However, for the recent decades, the fisher interview information suggested higher catch rates in the 2000s and lower catch rates in the 1990s compared to the standardised catch rates. The differences between historic fisher information and commercial-logbook were due to the amount of data and different sampling procedures (sample of fishers verse compulsory logbook reports). The historic fisher data only provided information to the assessment on the overall long-term magnitude of change in catch rates. Analysis of broader Cairns–Lucinda (latitudes 17–19) data sets covering historical archives, fisher interviews, logbooks and fishing power data suggested a 70–90 per cent decline in catch rates between 1934 and 2011 (Buckley et al., 2017).

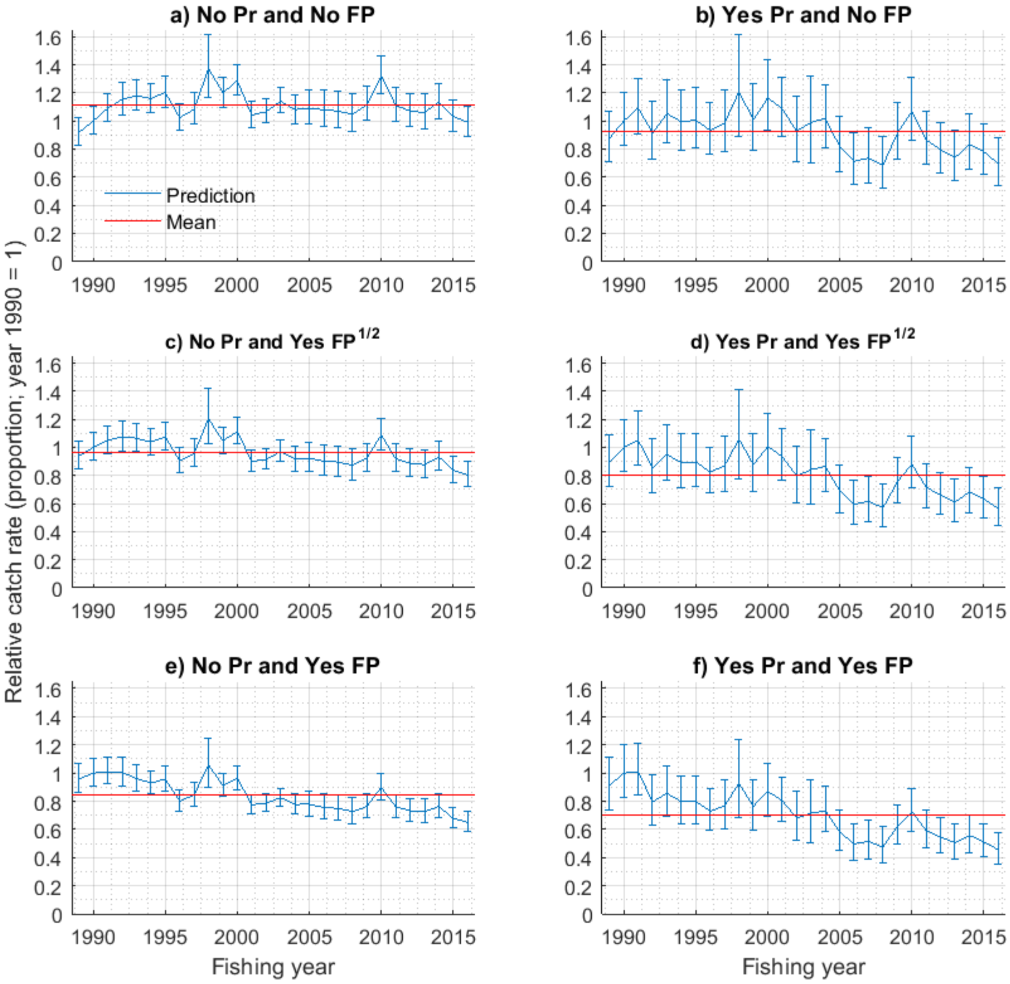

Figure 19. Standardised mean catch rates of Spanish mackerel by fishing year. Catch rates were scaled proportionally, with year 1990 =1. Results compared standardisations with and without probability (Pr) and fishing power (FP) adjustments; 95 per cent confidence interval error bars shown.

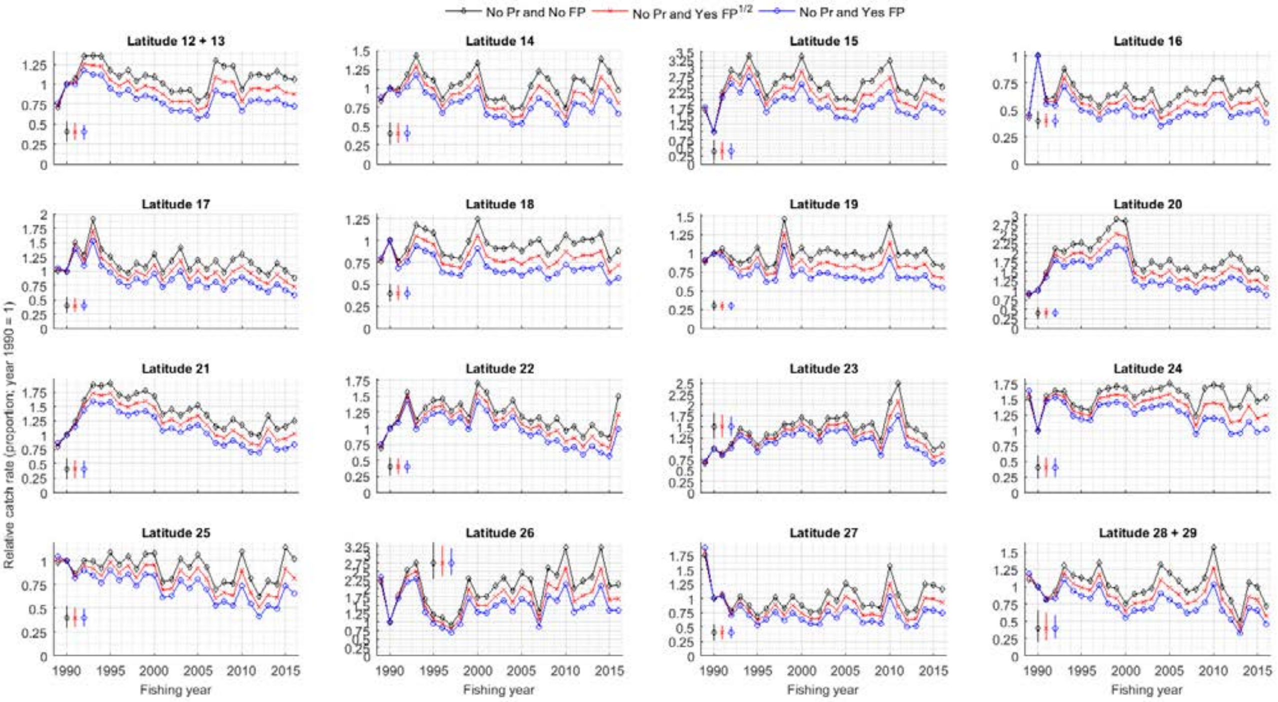

Figure 20. Standardised mean catch rates of Spanish mackerel by latitude band and fishing year. Catch rates were scaled proportionally, with year 1990 =1. Results were presented to compare three fishing powers (FP) and no probability (Pr) adjustment. Average 95 per cent confidence interval widths were shown.

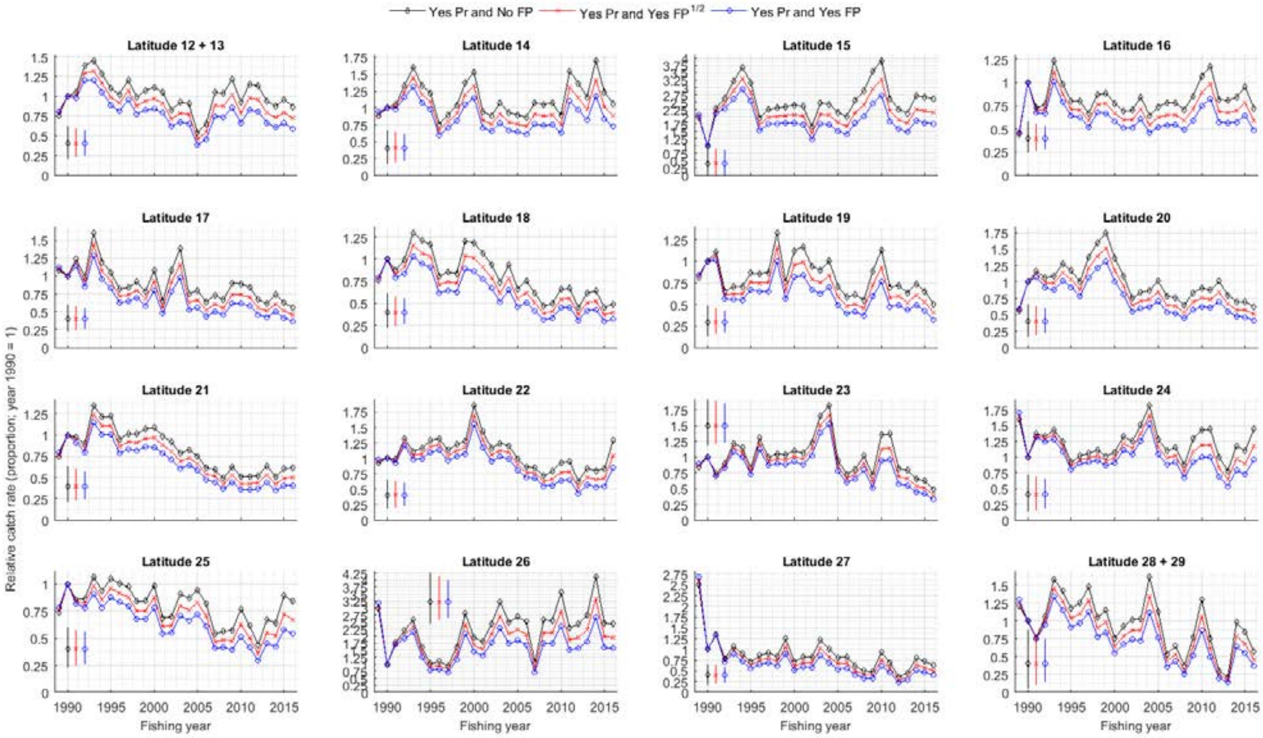

Figure 21. Standardised mean catch rates of Spanish mackerel by latitude band and fishing year. Catch rates were scaled proportionally, with year 1990 =1. Results were presented to compare three fishing powers (FP) and the probability (Pr) adjustment. Average 95 per cent confidence interval widths were shown.

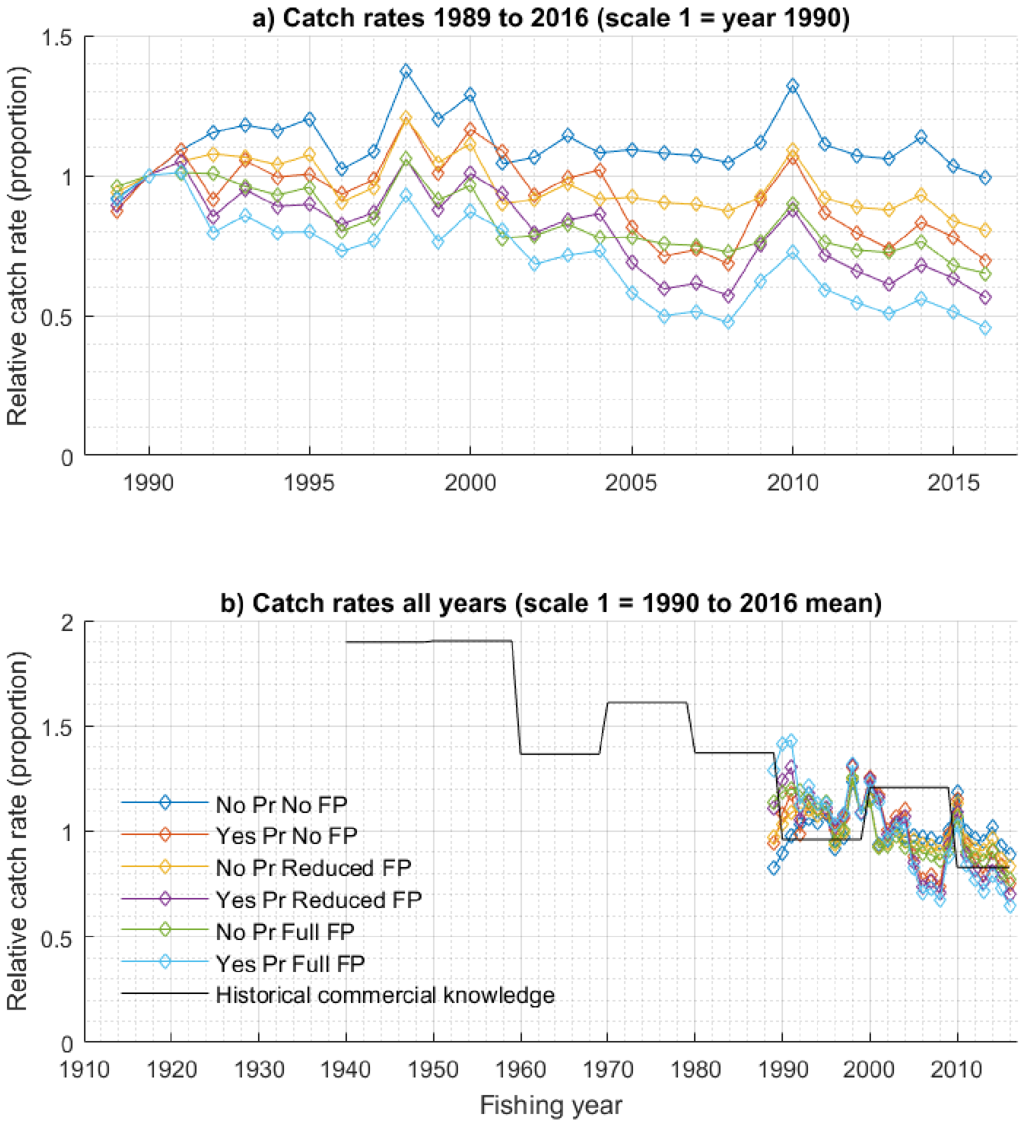

Figure 22. Overlay of standardised catch rates for a) the six commercial time series 1989–2016 and b) with decadal catch rates calculated using data sourced from historical surveys of commercial fishers 1940–2016. The mean relative standard error on decadal catch rates was 0.17.

Commercial catch rate of Spanish mackerel from New South Wales waters was analysed and standardised separately to Queensland. This was due to different logbook reporting procedures, which changed in 2010 from monthly to daily harvest reports. Analyses focused on the daily reporting data for fishing years from 2010 to 2016 and on where a weight of Spanish mackerel was caught and retained (i.e. c > 0; $E\left(c \middle| c>0\right)$). The full effects fishing power was assumed in the analysis. Fishing power had little effect as there was minimal change between 2010 and 2016 (Figure 18). Results from 2010–2016 were compared against Queensland catch rates. The catch rate data from New South Wales represents the southern spatial extent of east coast Spanish mackerel.

Like Queensland, the New South Wales commercial catch rate was reported in kilograms of Spanish mackerel harvested per operation day. The catch rate data had high variance and was skewed with a nominal median = 22 kg operation-day^{-1}, mean = 34 kg and standard deviation = 36 kg (CV = 107 per cent). Seasonally, catch rates were high from February to April.

For New South Wales waters, annual trends in mean catch rates were influenced most by the fishing in logbook zone 1 (Figure 23a). On average 44 per cent of Spanish mackerel were harvested zone 1 (NSW border – Ballina latitude 30), 24 per cent from zone 2 (Clarence, latitude 31) and 32 per cent from zone 3 (Coffs Harbour, latitude 32). In detail Figure 23 results show:

- Catch rates were highest in 2010, with a similar high point in Queensland (Figure 19, Figure 20 and Figure 21).
- In Ballina zone 1, catch rates were lowest in 2016. The 2016 estimate was 46 per cent of 2010 and 74 per cent of the mean between 2011 and 2015. The drop in catch rates was also evident in Queensland (Figure 20 and Figure 21, latitudes 28 + 29). Ballina zone 1 mean catch rates were generally 20–25 per cent higher than the other zones.
- Catch rates for the Clarence River zone 2 and Coffs Harbour zone 3 were variable, with broader error bars and showed no annual trend.
- The spatially averaged New South Wales catch rate, combining zones, show improved catch rates in 2010 and 2015, with no significant difference between other years.
- Variance components analysis (Table 15) and residual plots (Figure 43) are shown in the ‘catch rate diagnostics’ Appendix.

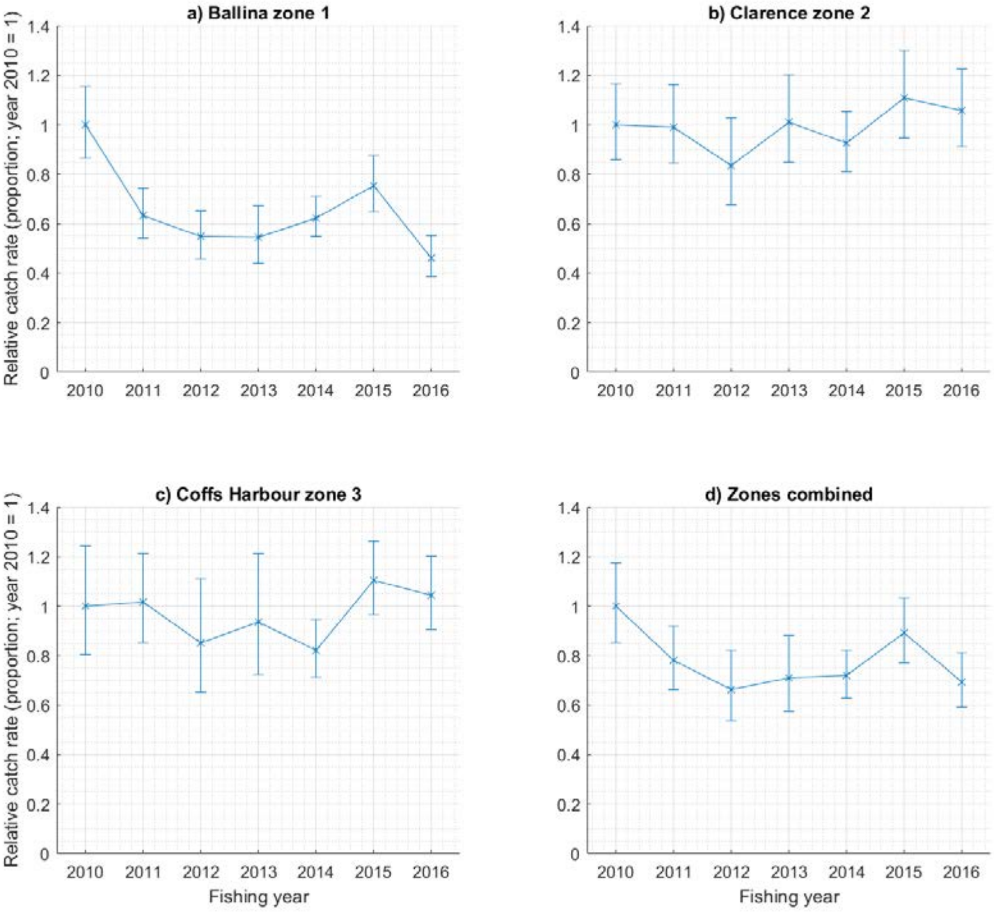

Figure 23. Standardised catch rates of Spanish mackerel by fishing year from a) fishing zone 1 for the Ballina region, b) zone 2 Clarence River region, c) zone 3 Coffs Harbour region and d) zones averaged for New South Wales waters. Catch rates were scaled proportionally in each subplot with year 2010 = 1 and 95 per cent confidence interval error bars shown.

Fish age-length compositions

Monitoring of annual fish age-length structures of Spanish mackerel in Queensland has been continuous since the year 2005 (Figure 24). The fish age data showed Spanish mackerel live up to 26 years of age (Figure 24). Most of the fish sampled were aged in the 1+ to 6+ cohort age-groups. Few older fish were present.

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 in 2008 and 2013. This can be seen from the frequency of 1+ old fish in 2009 flowing through to be 5+ year old fish in 2013 (Figure 24). Similarly and more recently, 1+ old fish in 2014 flowed through to be 3+ year old fish in 2016 (Figure 24). 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 25; 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 0.42 year^{-1} and 0.49 year^{-1} from the recreational and commercial fishing data respectively (± 0.025; 2 × s.e.). On average, estimates of fish mortality from the commercial sector's data was higher. The commercial estimate was near the limit reference point of 2 × natural mortality M ($Z_{LIM} = 0.5$, $p>0.1$; assuming $M = 0.25$ year^{-1}); 1.5 × M was considered a sustainable target reference point for pelagic fish such as Spanish mackerel (Welch et al., 2002).

Calculated long-term mean (equilibrium) spawning-per-recruit using the estimates of Z and M above suggest that the fraction of egg production will be about 40–50 per cent of unfished virgin levels. These estimates were below the suggested trigger reference point of 50 per cent, but were above the limit reference point of 30 per cent (Sainsbury, 2008). Collectively the spawner-per-recruit estimates and reference points suggest Spanish mackerel were fully exploited.

Frequency distributions and samples of the Spanish mackerel fork lengths are shown in the Appendix (Figure 44).

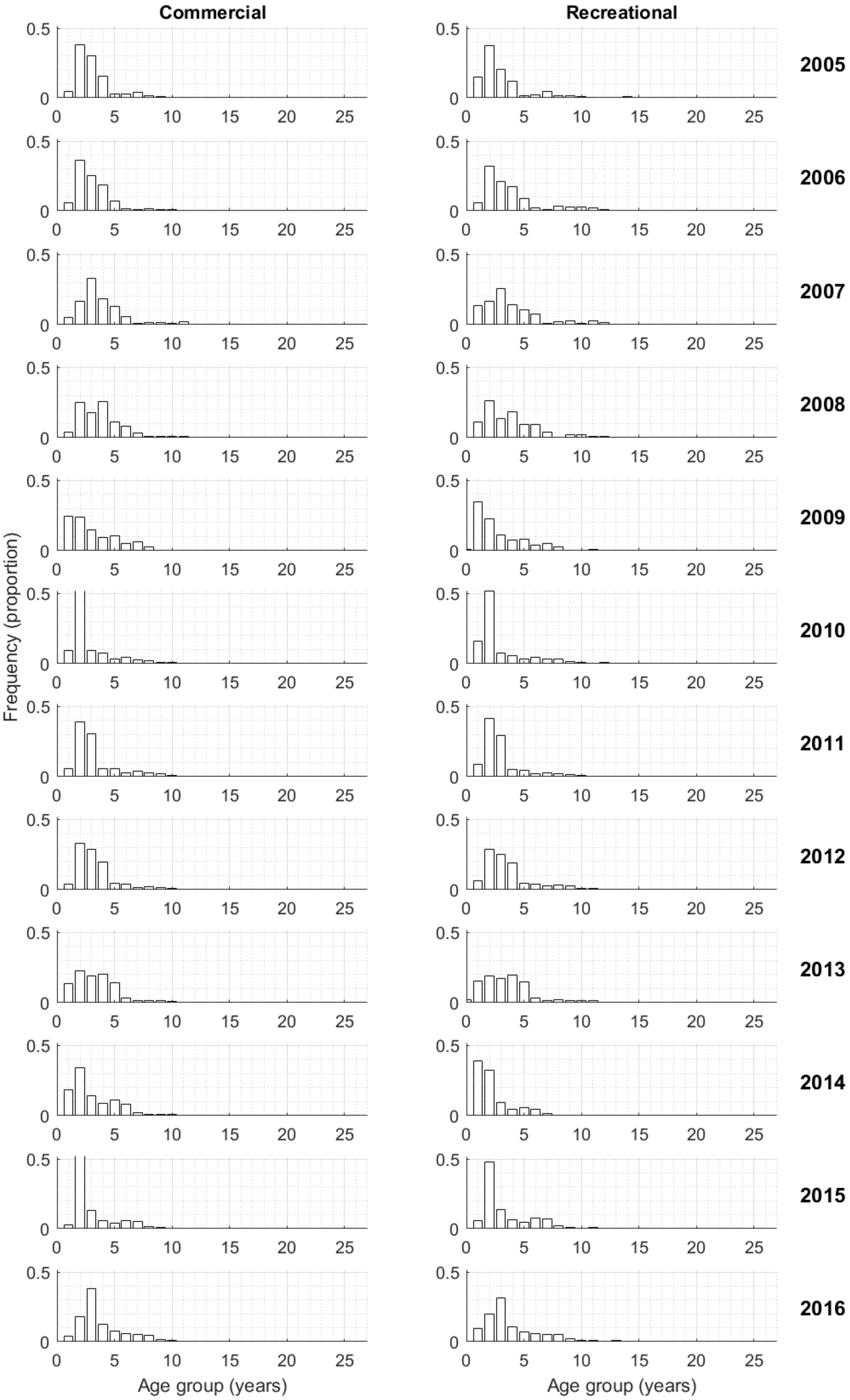

Figure 24. Age frequency of Spanish mackerel harvested by the commercial and recreational sectors between the fishing years 2005 and 2016.

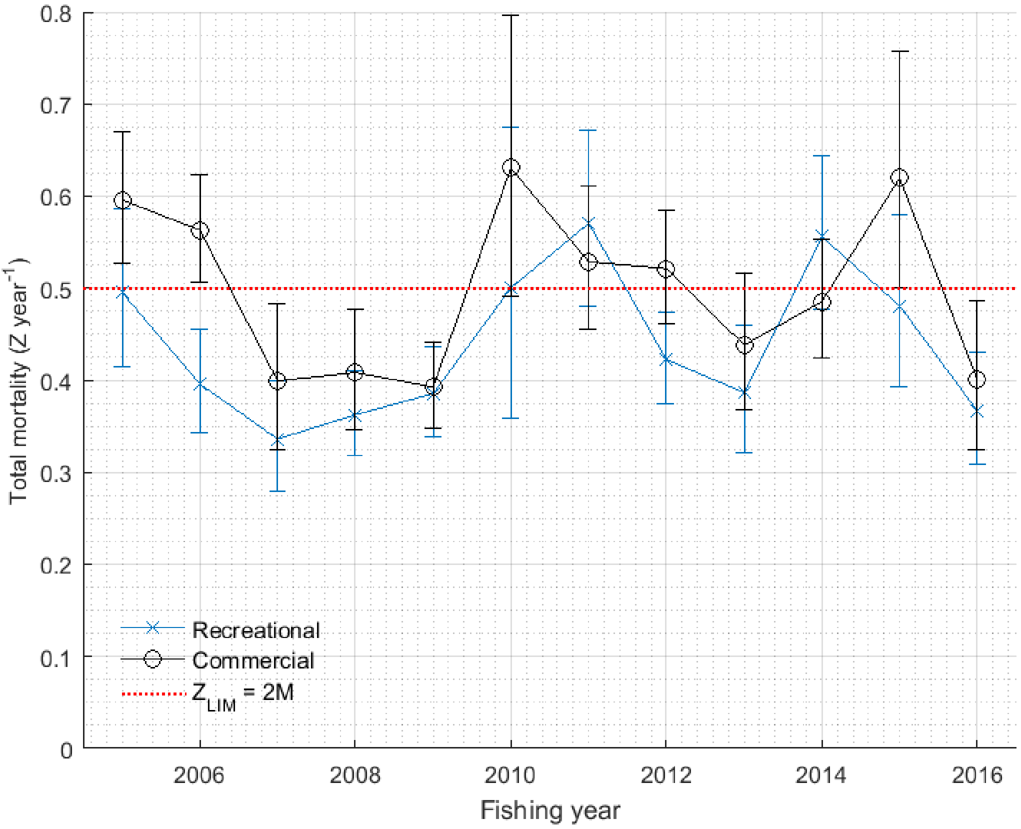

Figure 25. Annual total mortality (Z) of Spanish mackerel estimated for each fishing sector and year. The total mortality catch-curve measures were estimated from an over-dispersed Poisson log-linear model. Error bars were 95 per cent confidence intervals.

Model outputs – stock predictions from the data

Investigations of data

The stock model was run many times with different settings of data to identify key results for fishery management. Table 8 lists the variables and data settings. There were six different time series of commercial catch rates, six measures of recreational fishing effort, three approaches for estimating natural mortality and two methods of estimating the reproductive rate. A total of 216 analyses were completed. For each, the results for finding the parameter values that maximise the model fit to the data were presented (maximum likelihood solutions; Figure 26). From the range of outputs, key states were selected for more detailed MCMC analysis and examination (Table 9).

Readers should note that further data variables can be analysed. For example, different levels of commercial and recreational harvests. Involving more variables would expand the number of analyses to near or over one thousand. This would be unreasonable to interpret. Variations in harvests were tested in the previous stock assessment (Campbell et al., 2012), showing that predicted biomass ratios for the last year assessed were not sensitive and MSY values increased and decreased proportionally with the levels of assumed harvest. It was not sensible to remove the historical catch rate information from the investigative analyses, as the data fit with the sequence of other model inputs. The influence of removing the historical catch rates was examined in a MCMC analysis.

Results are summarised in Figure 26, Figure 27 and Figure 28. The following inferences were noted:

- Results from 39 analyses were deemed not sensible (spawning ratios $S_{2016}/S_0 > 0.7$; Figure 26). They were not considered for further analysis given the estimated rates of fishing mortality were small, population sizes were unrealistically high, reproductive rates hit upper bounds and MSY values were greater than historical harvests. The high spawning ratios were associated with high estimated natural mortality around 0.4–0.45 year^{-1}, and low estimates of recreational fishing (effort schedules 1, 2 and 3; Figure 13e) and catchability. These results suggest the fishery can sustain high fishing pressure and large harvests, but at quite low catch rates.
- The remaining 177 (82 per cent of analyses) investigations were grouped into five key states (Figure 27). From each state, two analyses were selected for MCMC simulation representing the group mean and the best negative log-likelihood – best prediction of the data (Table 9).
- The above 177 analyses estimated spawning ratios of 20–65 per cent (S_{2016}/S_0). Lower spawning ratios (groups 3 and 4, Figure 27) were generally associated with declining catch rates, signifying lower than expected reproductive rates ($r < 4$ or steepness $h < 50$ per cent).
- Myers et al. (1999) suggest reproductive rates will vary with species dependent on their natural mortality and age-at-maturity, with annual replacement spawners generally having r ranging 1–7 per spawner per year. Using this expectation, the reproductive rate r for a Spanish mackerel over its lifetime could range 3–20 replacement spawners per spawner. Myers et al. (1999) published reproductive rates r for the fish family Scombridae (mackerel and tuna like species) being 2–10. The previous stock assessment assessed reproductive rates around r=4.5, with lower values identified and noted (Campbell et al., 2012).
- Stock status results and harvest reference points (Figure 28) were sensitive to the reproductive rate r. MCMC analyses explored this uncertainty, with estimates of $r < 4$ considered conservative.
- In general many of the spawning ratios S_{2016}/S_0 in Figure 27 were around and below 0.4. This signifies that surplus production (fish spawning, recruitment and growth) produced by Spanish

mackerel over mortality was reduced and fish were being harvested around maximum sustainable levels.

- Other results were that estimates of lower values of natural mortality *M* were associated with declining time series of catch rates that included fishing power and hyper stability adjustment. Higher estimated *M* was associated with high estimates of MSY (Figure 28). Similar uncertainty around natural mortality was discussed in previous stock assessments (Welch et al., 2002; Campbell et al., 2012). Lower values of *M* are recommended for precautionary management inferences, with report results for Spanish mackerel focused on assessing *M* at values of 0.25 and 0.33 year^{-1}.

Table 8. Data variables and settings for model inputs.

Data input	Number options	Explanation
Commercial Catch rate	6	Annual index of fish abundance 1989–2016 (Figure 19). Six results of commercial standardised catch rates were evaluated individually to assess the effects of possible hyper stability (0 = no probability adjustment, i.e. constant; 1 = adjusted, Figure 16) and increased fishing power (0 = no increase; 0.5 = reduced; 1 = full increase; Figure 18).
Historical Catch rate	2	Decadal index of fish abundance 1940–2010 (Figure 22b). The data were calculated from historical surveys of commercial fisher information. The data were always used in the investigative analyses and provided context before 1989. Compared to other data inputs, the overall influence was limited due to only seven decadal data points. The more detailed MCMC analyses considered the presence and absence of this data.
Harvests	1	Commercial logbook and recreational survey estimates of Spanish mackerel harvest. The data were always used and recreational estimates included all harvested fish plus 50 per cent of released fish assumed to have died. No variants were tested.
Recreational effort	6	Annual measures of fishing effort 1911–2016 (Figure 13e and f). Six scenarios were evaluated individually to assess the effects of possible increased fishing power and decrease (0) or increase (1) in fishing effort in later years.
Natural mortality (*M*)	2	Death rate due to natural causes (i.e. not fishing; logarithm scale). Three approaches were modelled: 1) estimated, 2) fixed at 0.25 year^{-1} based on the Then et al. (2015) equation and a maximum age of 26 years and 3) fixed at 0.33 year^{-1} based on the previous stock assessment using Pauly's schooling equation, which was equivalent to a maximum age of 19 years in the Then et al. (2015) equation.
Reproductive rate (*r*)	2	Model parameter measuring the maximum lifetime reproductive rate (Myers et al., 1999). The value represents the mean number of spawners produced per spawner over its life time at very low spawner abundance. The parameter estimation considered unrestrictive (0) and restrictive prior (1) likelihood-information for estimation.

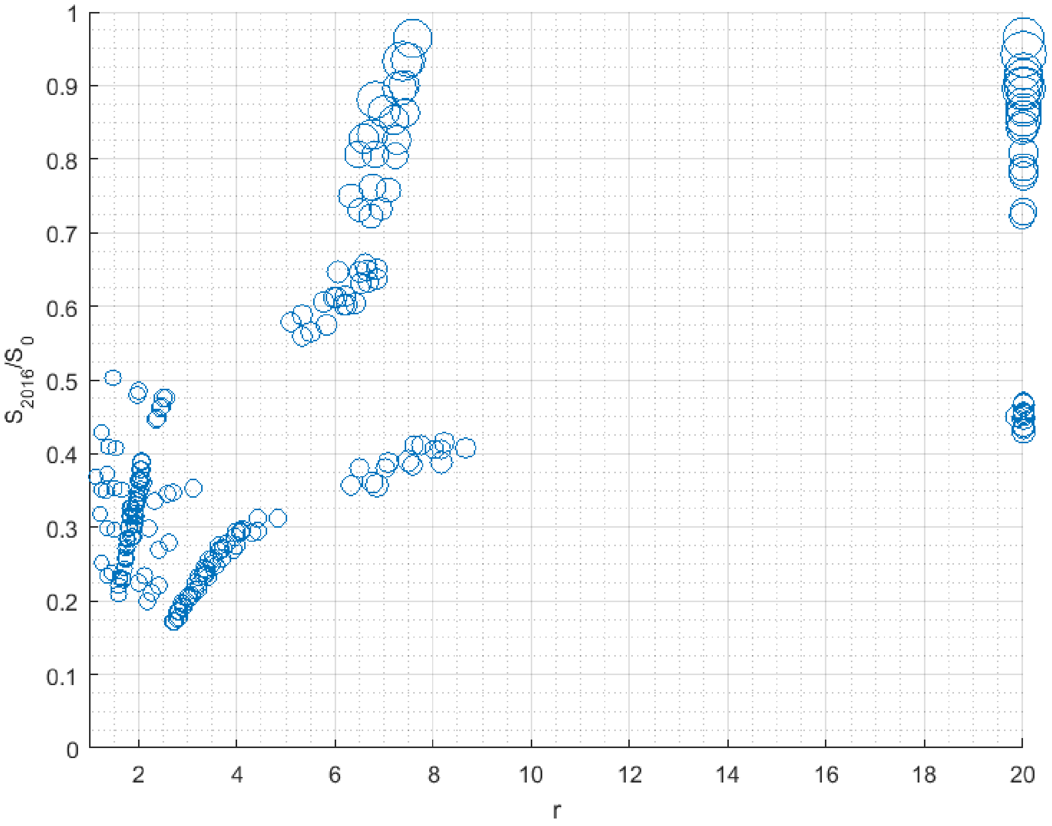

Figure 26. Scatter plot of the 216 estimates of reproductive rate r and spawning stock ratio in fishing year 2016, with circle areas scaled by equilibrium MSY. The smaller circles for S_{2016}/S_0 < 0.7 represent MSY between 500t and 1500t. Larger circles for S_{2016}/S_0 > 0.7 represent MSY 1500–5000t.

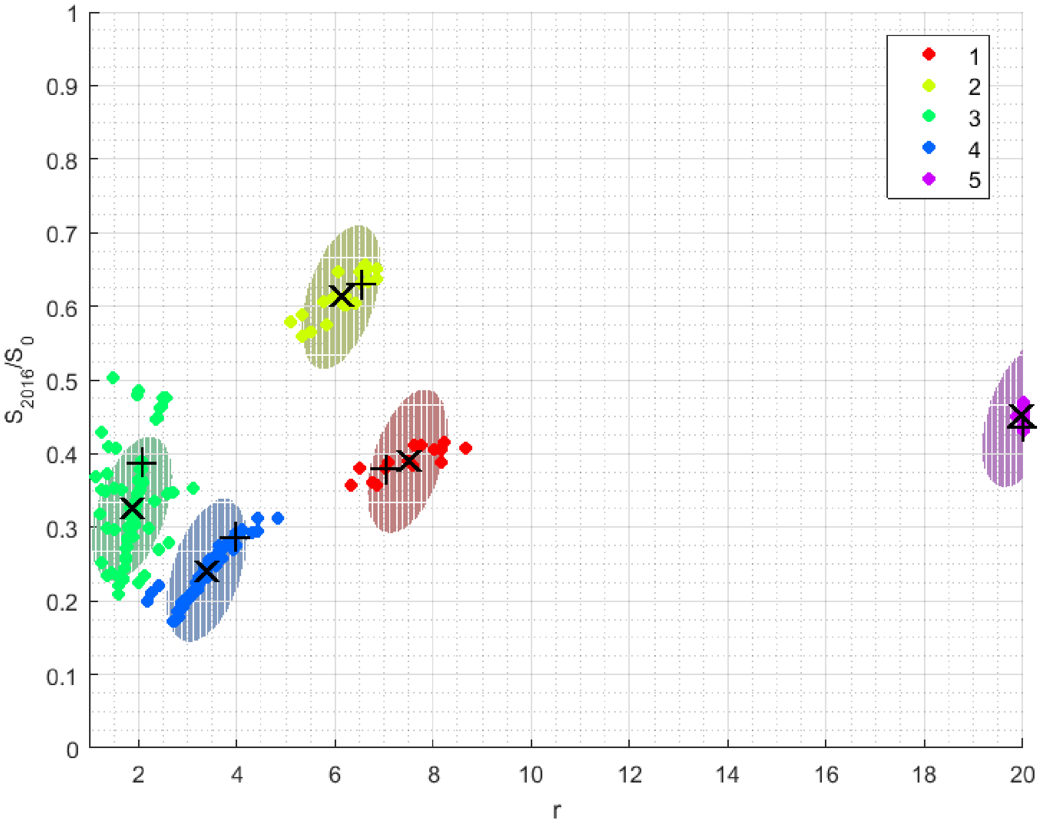

Figure 27. Gaussian mixture model (GMM) clustering of 177 estimates of reproductive rate r and spawning stock ratio. Results from 39 (18 per cent) analyses were excluded for S_{2016}/S_0 > 0.7. Five clusters (groups) were identified for MCMC analysis. The clusters assumed shared-full covariance's allowing for correlated data. The '×' symbol was the mean and the '+' symbol is the best maximum likelihood result for each group.

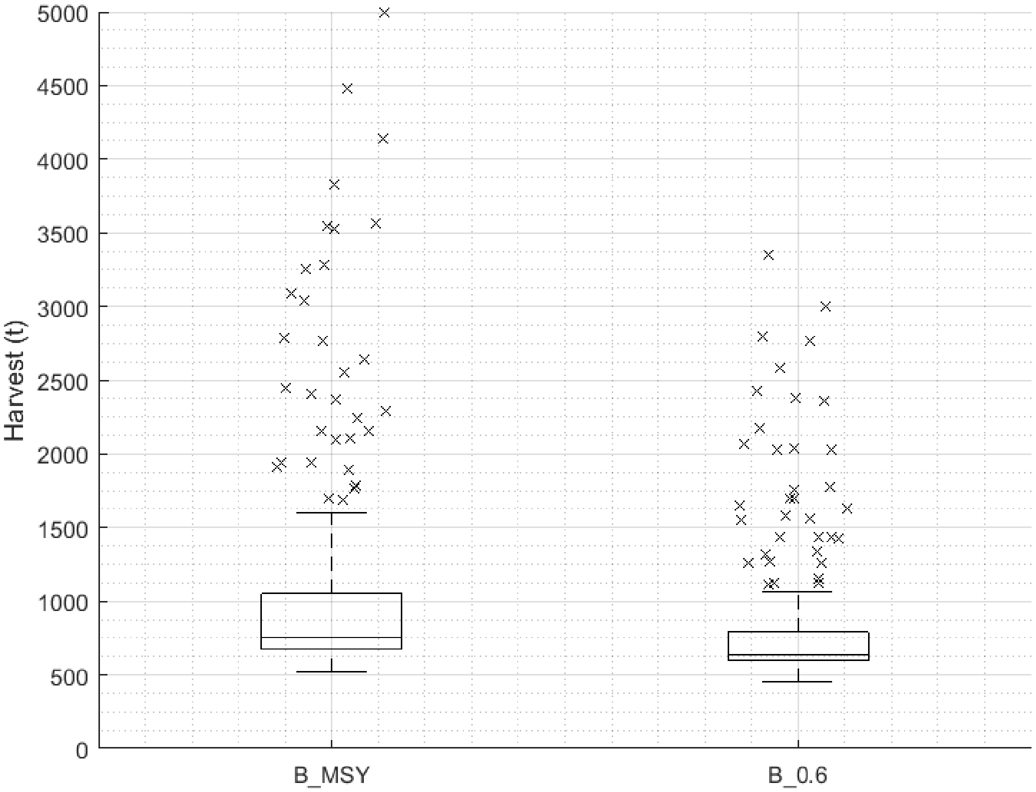

Figure 28. Box plot of the estimated equilibrium yields for Spanish mackerel. The first box was for MSY at the exploitable biomass B_{MSY}. The second box was the expected yield at higher exploitable biomass of 60 per cent of virgin exploitable biomass $B_{0.6}$. Each box illustrates the distribution of results around the median (horizontal line in the middle of the box). Outliers are plotted individually using the 'x' symbol.

Simulations

In total 11 stock analyses were conducted in detail using MCMC simulations (Table 9). The analyses were selected to represent the different groups of results identified in Figure 27. Explanations of results were based on the settings in Table 9. Only one hyper stability adjusted catch rate series was selected (Table 9). More analyses could have been run for each group, but the selections were adequate to describe results from each group. Estimated natural mortality *M* values of 0.25 and 0.33 year^{-1} were used (Table 9), with no lower values considered based on the learnings from the data and analyses.

The parameter estimates for each analysis were plotted in Figure 45 (Appendix – stock model diagnostics). Estimates of new fish recruitment (R_0 for 0+ aged fish) were correlated with measures of reproductive rate *r* (or steepness) and generally ranged 0.4–1 million fish per year. Annual recruitment variability was predicted at about 34 per cent. The estimates of fish age-at-vulnerability to fishing were consistent between analyses, with $a_{50\%}$ about 1½ years and $a_{95\%}$ from about 2.1 years. Fish catchability by fishing sector was estimated appropriately with each analysis and the assumed data. All analyses result in model convergence and sound goodness of fit to the data inputs (Figure 46 to Figure 52, Appendix – stock model diagnostics).

The following predictions for Spanish mackerel were produced for the model analyses and their parameters:

- Figure 29 summarised the predicted stock status ratios for Spanish mackerel in the year 2016. The spawning, exploitable biomass and recruitment estimates were above limit reference points. In general the spawning and biomass ratios were around 30–50 per cent, with four analyses near or exceeding trigger reference points. Estimates of 2016 fishing mortality from seven analyses suggest equilibrium spawning-per-recruit measures were at trigger reference points.
- More detailed time-series predictions are shown in Figure 53 to Figure 63 (Appendix – stock model diagnostics). The population trends showed clear declines after the large harvests (≥ 900 t) taken in the 1970s and early 2000s (Figure 15 and Figure 50). Spawning egg production had not improved across the years 1980–2016.
- In general the recent estimates of fishing mortality were above the levels required to build higher spawning egg production and exploitable biomass (Figure 30). Over the last five years the analyses suggested fishing mortality varied up to the limit reference point F_{MSY}. Fishing mortalities closer to the target reference point (blue line) are better to build higher spawning egg production and exploitable biomass (Figure 30).
- Mean (equilibrium) predictions of target harvests for all fishing sectors and all waters ranged 600–800 t (Figure 31). This level of harvest would gradually build higher spawning egg production and exploitable biomass (towards $B_{0.6}$). Clearer specifications on target levels and building times are required to narrow harvest predictions. If the 2016 fish population size was considered in predictions, then target harvests would be lower (tabulated in Table 17, Appendix).
- Higher annual harvests in order of or exceeding 1000 t will prevent any building of the Spanish mackerel population. Such levels of extended harvest will direct biomass and spawning egg production to around or less than B_{MSY} and erode catch rates (Figure 31).

Table 9. Selected analyses and data inputs for MCMC simulation. Selected analyses 1–5 represent the mean of each group from Figure 27 and analyses 6–10 were the best likelihood (MLL) solutions. Analysis 11 was an extra analysis for investigating the removal of historical catch rate data. See Table 8 for a description of data.

	Analysis	**Group**	**Commercial catch rate**		**Recreational effort**		**Natural mortality (*M*)**	**Prior Reproductive rate (*r*)**	**Historical catch rate**
			Hyper stability	Fishing power	Scenario	Fishing power			
Mean	1	1	0	0.5	0	0	0.25	1	1
	2	2	0	0.5	1	1	0.33	1	1
	3	3	0	1	1	1	0.33	0	1
	4	4	1	0.5	1	0.5	0.25	1	1
	5	5	0	0	1	0	0.25	0	1
MLL	6	1	0	0.5	1	1	0.25	1	1
	7	2	0	0	1	1	0.33	1	1
	8	3	0	0.5	1	1	0.33	0	1
	9	4	0	1	1	1	0.25	0	1
	10	5	0	0.5	1	1	0.25	0	1
Extra	11		0	0.5	0	0	0.25	1	0

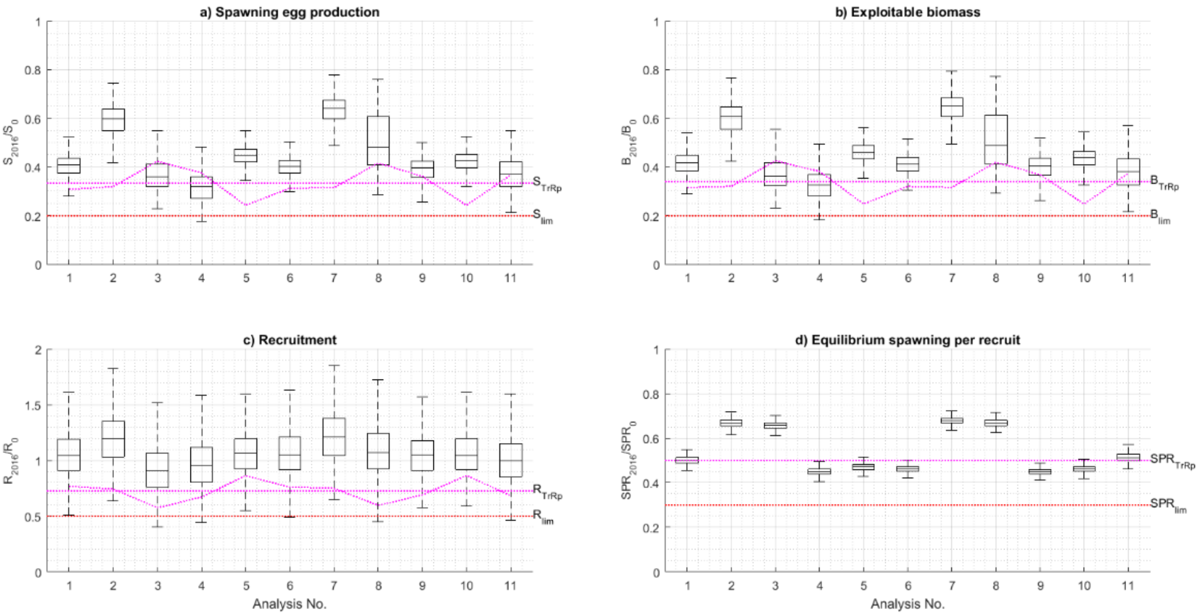

Figure 29. Estimated stock status ratios of Spanish mackerel based on the model settings in Table 9. The ratios compare the fishing year 2016 against 1911 (the first year of fishing data), for a) spawning egg production, b) exploitable biomass, c) recruitment of 0+ aged fish and d) equilibrium spawning egg production per recruit based on the 2016 estimated fishing mortality F_{2016}. Each box plot illustrates the distribution of results for each analysis around the median (horizontal line in the middle of the box). The red dotted lines show the lower limit reference points and the higher magenta coloured dotted lines show the trigger reference points for B_{MSY} in subplots a–c and 50 per cent reduction in spawning per recruit in subplot d. The trigger reference points are shown averaged over analyses (straight magenta line) and individually for each analysis (irregular magenta line)

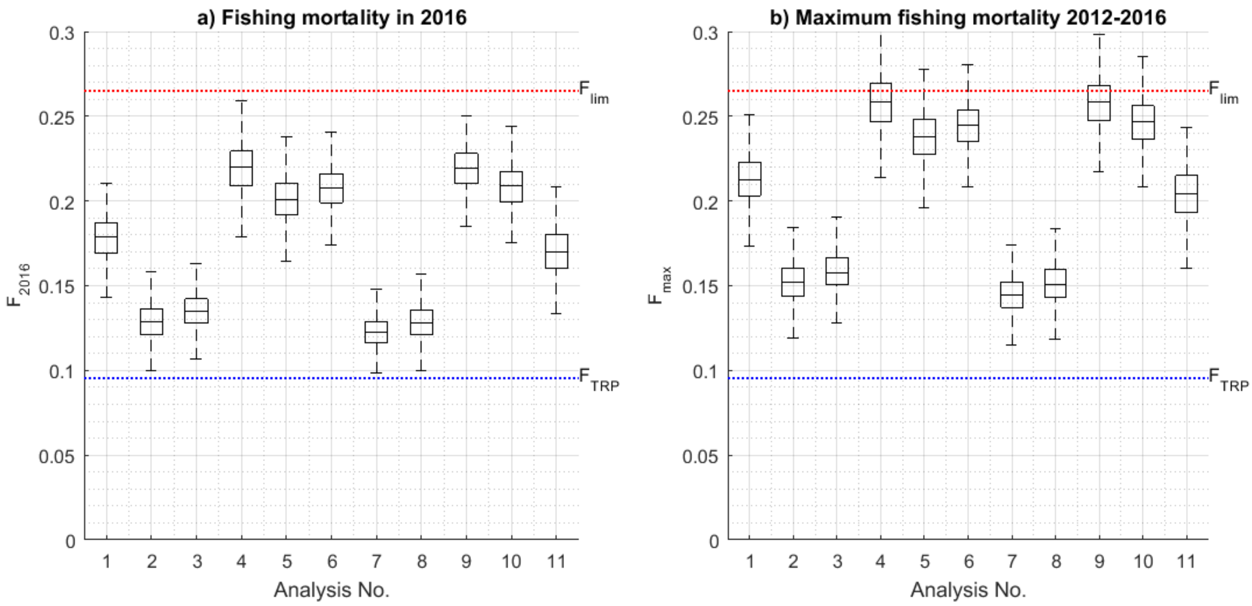

Figure 30. Estimated fishing mortality (F year^{-1}) on Spanish mackerel in a) fishing year 2016 and b) maximum from the last five years 2012–2016. As in Figure 29, each box plot illustrates the distribution of results for each analysis around the median (box horizontal line). The red dashed lines show the limit reference points for B_{MSY} and the blue coloured dash lines show the target reference points for $B_{0.6}$. The reference points were averaged over analyses.

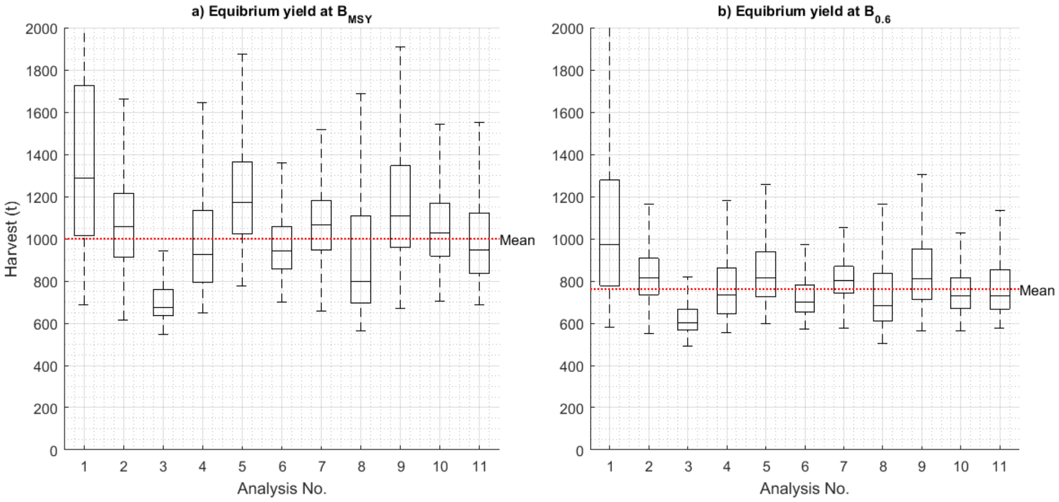

Figure 31. Estimated equilibrium harvests of Spanish mackerel for attaining a) B_{MSY} and b) $B_{0.6}$. Each box plot illustrates the distribution of results for each analysis around the median (box horizontal line). Table 17 lists the reference point tonnages for each analysis (see stock model appendix).

Concluding discussion

Stock status

Reference points

The assessment of Spanish mackerel considered a range of results, which were discussed by the ‘project team’ committee.

The results were considered alongside the guidelines described by the Australian Government (2007), Sloan *et al.* (2014) and Flood *et al*. (2014):

- Limit reference points (LRP or LIM): indicator values below a LRP are not acceptable and relate to recruitment overfishing. Stock status ratios for a LRP generally default to about 20 per cent of unfished biomasses (spawning, exploitable or total). The Australian Government (2007) states that there should be no more than 10 per cent chance of the stock falling below the 20 per cent LRP. Measures of fishing pressure (fishing mortality F) for the LRP relate to > F_{MSY} or more F > natural mortality M (Begg et al., 2005)
- Trigger reference point (TrRP): indicator values below a TrRP are not desirable and is a point at which important changes in management are designed and actioned. In essence, this is also a LRP (Caddy and Mahon, 1995). Stock status ratios for the TrRP are generally about 40 per cent of unfished biomasses or B_{MSY}.
- Target reference points (TRP): indicator values that are desirable and safe and at which stakeholders and management should aim for the public good. They generally relate to desired economic and social objectives; e.g. a level of catch rate that is profitable and provides a quality fishing experience in terms of the number of successful fishing trips, fish caught and their size. The population biomass size of $B_{60\%}$ (also labelled as $B_{0.6}$) was used to judge this state. This reference point was described in the recent Green paper on fisheries management reform in Queensland, July 2016, and the subsequent Sustainable Fisheries Strategy 2017–2027 (Queensland Government, 2017). Measures of fishing pressure for the $B_{60\%}$ TrRP relate to $F_{0.6}$.

> The F target reference point of ½ *M* outlined by Begg et al. (2005) for Spanish mackerel also roughly relates to $F_{0.6}$. For comparison, target spawning-per-recruit $SPR_{50\%}$ reference points relate to the ½ *M* levels. The ½ *M* target reference point was suggested to be appropriate for Spanish and spotted mackerel given the species early vulnerability of age groups to fishing and to ensure management procedures recommend a safe long term sustainable harvest (p 92, Begg et al., 2005).

The use of reference points to gauge the status of a fished population and manage fishing pressures can be regarded as 'best practice management' (Sainsbury, 2008). A clear benefit is that reference points allow key management issues and target operational-objectives to be addressed through management procedures that may include harvest control rules. The choice of where to place a reference point is a balance of the risk of overfishing against social and economic considerations of fishing. Changes and trends in the size of a fish population can occur before a reference point is activated and it is important not to believe that declines or improvements change suddenly at certain thresholds; especially if hyper stability is suspected. There can be significant risk even on the safe side of a reference point, especially as the limit is approached (Sainsbury, 2008).

In general terms of risks and reference points, the 20 per cent LRP stated above is common but not considered best practice compared to using a 30 per cent LRP which better safeguards against the risk of overfishing on low reproductive populations (Sainsbury, 2008). For Spanish mackerel, estimates of reproductive rate varied, with two out of five groups of results suggesting lower than expected spawning-recruitment steepness (see discussion point under report section 'Investigations of data' and Figure 27). A higher 25–30 per cent LRP should be considered to adequately manage against multiple risks of: reducing the number of older fish and consequent effect on the success of fish spawning; hyper stability and general predictability of where fish aggregations are to be exploited; increased fishing power; data limitations; and possible reliance on a small number of necessary spawning reef-locations (Tobin et al., 2014; Buckley et al., 2017).

In terms of the biomass $B_{60\%}$ target reference point for Spanish mackerel, the model dynamics calculated $B_{60\%}/B_{MSY}$ ratios of 1.5–1.7. These ratios were not too different from the maximum economic yield (MEY) biomass B_{MEY}/B_{MSY} ratios of 1.2–1.5 suggested by Zhou et al. (2013) and Pascoe et al. (2014), which considered a range of cost : revenue ratios and $B_{MSY} = B_{50\%}$. For Spanish mackerel, B_{MSY} was about 35–40 per cent of unfished biomass and aligns with the trigger reference point (TrRP).

Findings

The stock assessment analyses of east coast Spanish mackerel suggest that spawning and exploitable biomass population estimates in the year 2016 were around 30–50 per cent of estimates in 1911. These estimates overlap the trigger reference points for B_{MSY} (Table 10).

In general estimates of fishing pressure (fishing mortality) in the last five years were above the target levels required to build higher spawning egg production and exploitable biomass such as 60 per cent (Figure 30) (Queensland Government, 2017). Some estimates of fishing mortality in the last five years were in order of the trigger reference point F_{MSY}. The higher estimated levels of fishing mortality F were typically associated with M at 0.25 $year^{-1}$, rather than M=0.33 (Figure 30).While these fishing mortality estimates do not suggest overfishing of Spanish mackerel in 2016, they support inferences that fishing pressure is near a point equivalent to fully-fished or fully-exploited. Given the overlap of some fishing mortality estimates with F_{LIM} and high available fishing capacity of the sectors, this was judged at the TrRP trigger reference point level (Table 10).

The indicator of standardised catch rates since 1990 showed evidence of possible population declines in Spanish mackerel. The level of decline was dependent on the catch rate adjustment applied for hyper stability and annual increases in fishing power. The stronger declines in standardised catch rates suggest Spanish mackerel were not resilient to extended periods of large harvests such as those taken during the 1970s and late 1990s and early 2000s (Figure 50).

Table 10. Classification of the Spanish mackerel fishery relative to limit LRP (red), trigger TrRP (yellow) and target TRP (green) reference points for three key lines of evidence. Fishing pressure includes measures of fishing effort and mortality. The colour and '×' symbol indicates an activated reference point.

Evidence	**LRP**	**TrRP**	**TRP**
Stock assessment population predictions		×	
Fishing pressure		×	
Standardised catch rates		×	

Based on the guidelines described above and the results from the stock model, the Spanish mackerel fishery can be described as having reached trigger reference point levels. This judgement depends on the data and reference points used to represent the state of the fishery.

The fishery was not in a target reference area based on the available lines of evidence (Table 10). Target levels of fishing mortality for $B_{60\%}$ were exceeded. All lines of evidence indicate that trigger reference levels (coloured yellow in Table 10) may be activated suggesting that effective management intervention across the entire stock is required to direct Spanish mackerel abundance and catch rates to a more positive state if desired. Doing so would build resilience into the spawning success of Spanish mackerel.

Sustainable harvests

The median result over MCMC analyses suggested a sustainable annual harvests of around 550 t (across all sectors) based on the Spanish mackerel population size in 2016 (Table 17, Appendix). This level of harvest will build the biomass towards the 60 per cent level, consistent with the 2027 target set in the Queensland Government's Sustainable Fisheries Strategy. Lower more sustainable harvests of 400–800 t were estimated, than compared to equilibrium measures, when considering the target fishing mortality of $F_{0.6}$ with the fish population size in 2016 (Table 17, Appendix).

Long term (equilibrium – recommended tonnage that could be taken year after year) predictions of target harvests for all fishing sectors and all waters ranged 600–800 t (median = 632 t, for $B_{0.6}$ in Figure 28).

Higher annual equilibrium MSY harvests in order of or exceeding 1000 t will prevent any building of the Spanish mackerel population. Such levels of extended harvest will direct biomass and spawning egg production to around or less than $B_{MSY.}$ Higher mean harvests may erode catch rates long term.

A 400–800 t bound on Spanish mackerel annual harvest for all sectors and waters across New South Wales and Queensland's east coast should be considered until improvements in data collection and population indicators are observed. The decision level will depend on setting and implementing a target objective and time frame. Future management should always consider benchmarking target reference points for fishing to ensure healthy population biomass (above B_{MSY}) and catch rates of Spanish mackerel in order to achieve and better balance sustainability, economic and social objectives. The $B_{60\%}$ biomass reference point is one suitable target for this purpose.

Data and use in management

The development of stock assessment methods and reporting of fish status indicators is crucial for management of east coast Spanish mackerel. It is vital for underpinning management procedures that involve setting annual quotas on commercial harvest and seek to reach stock sustainability goals such as outlined in the Queensland Sustainable Fisheries Strategy 2017–2027.

For east coast Spanish mackerel, standardised fish annual catch rates and age structures formed the important indicators to monitor changes in fish population size and survival. Currently, limitations on these data exist because nominal records of catch rates are not proportional to fish population abundance (hyper stable; discussed in method’s section for standardised catch rates) and annual fish age structures are influenced by changing fishing locations and operations (Sumpton and O'Neill, 2004; Tobin and Mapleston, 2004; Campbell et al., 2012).

Methods herein of analysis, estimation and scenario modelling aimed to overcome these limitations and better represent the uncertainty surrounding data and model predictions. Further, improvements in data collection and monitoring are noted below in recommendations to address hyper stability issues in catch rates; see also (O'Neill, 2015).

Advice remains on how best to use the fish age-abundance information to service management procedures and quota management in coming years. Until new data or improved reporting procedures are developed, two approaches can be followed: 1) empirical indicator based assessment and management focused on the fish age-abundance data, or 2) model based assessment and management using the methods herein.

Indicator based management relies on using the standardised fish catch rate and/or age structure results in harvest control rules. This approach has been used in other Queensland fisheries such as coral trout, spanner crab and stout whiting (Little et al., 2015; Campbell et al., 2016; O'Neill and Leigh, 2016). This approach has also been evaluated and discussed against national and overseas examples (O'Neill, 2015).

The advantage and view point of using empirical indicator approaches is that they are quicker to process and avoid having to deal with missing sectoral fishing data or assumptions needed in model-based stock assessments. Reference points still need to be benchmarked. If the indicator suggests an important change relative to the reference points, then a harvest control rule should be actioned by management.

For model-based assessment, the results can be used in a similar way with harvest control rules. The advantage of this approach is that the results and reference points generally have clear biological meaning. The approach is reliant on many data sources and the model can synthesise their meanings and signals into one clear indicator. In some cases, like Spanish mackerel, many model results can be produced and this can be difficult to interpret (Campbell et al., 2012).

Given the model-based stock assessment for Spanish mackerel is established, with standardised catch rates, use of this process is suitable for underpinning management procedures. For quota setting, consideration is required for selecting results that mitigate risk of underestimating fishing mortality and overestimating fish population size (Walters and Martell, 2004; Rhodes and Warren-Rhodes, 2005). For this, the hyper stability and fishing power adjustment scenarios are suitable.

Use of conservative reference points are also needed to ensure that results from either simple or complex analyses are interpreted cautiously to avoid overfishing and help promote more profitable and successful fishing. This precaution is a necessity for Spanish mackerel given concerns of hyper stability and increased catchability of fish from spawning aggregations (Sadovy and Domeier, 2005; de Mitcheson, 2016).

Insight from the Spanish mackerel stock assessment suggests that success of future fishery management relies on better regulating the fishing effort. If significant levels of fishing effort are available and not appropriately limited or known, then the fishery may not be able to be managed to achieve some kind of optimum. Johannes (1998) noted this for fisheries with spawning aggregations and suggested the first aim of management was to simply ensure enough protection on spawning aggregations was in place to maintain their viability; see also (Erisman et al., 2017)

The fish spawning aggregation

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

During September–November each year, Australian east coast Spanish mackerel school to form one of the most notable and predictable spawning aggregations of fish on the Great Barrier Reef. The aggregation of Spanish mackerel occurs in reef waters north of Townsville where they gather to breed mostly over a period of two lunar months.

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

Since 1989 when commercial harvest monitoring commenced, key Spanish mackerel spawning aggregation and fishing sites have only been known for the Lucinda region (Tobin et al., 2014). This region covers the main fishing grounds located using commercial logbook grid-sites. Rib Reef is one grid area that was recognised as a key spawning and fishing ground, along with a number of other important reefs. As an overall spawning area, past research and monitoring has focused on the 30×30 minute logbook grids of J19, J20, K19 and K20; located in latitude ‘19’ and labelled as latitude ‘18’ in Tobin et al. (2014), covering the one degree latitude between 18.0°S and 19.0°S. Historically the grids of J19 and K20 on average produced most fish (57 per cent and 20 per cent respectively) in the commercial harvests within latitude 19 during the months of October and November. The following reefs (logbook 6×6 minute grid-site), with marine park zoning and fishing gear limits listed, are recognised for Spanish mackerel spawning:

- Bramble reef (J19-17; J19-18; J19-22; J19-23); Habitat Protection Zone, three fishing lines per person.
- Rib reef (J19-24; J20-4); Habitat Protection Zone.

- Kelso reef (J19-25; K19-21); Marine National Park Zone, no fishing allowed.
- John Brewer reef (K20-6); Conservation Park Zone; one bottom fishing line per person or trolling with three lines per person. Only one dory detached from a commercial fishing vessel.
- Lodestone reef (K20-7; K20-12); Habitat Protection Zone.
- Helix reef (K20-8; K20-9); Marine National Park Zone, no fishing allowed.
- Keeper reef (K20-13); Habitat Protection Zone.

Spawning Spanish mackerel located outside of latitude 19 were assumed to contribute to the stock's overall reproduction level during the spawning period. However the volumes of fish were considered less (Tobin et al., 2014).

What do the data say for latitude 19?

The data from latitude 19 and analysis results suggest the Spanish mackerel spawning aggregation was fully exploited:

- Predictions on overall spawning egg production were around 30–50 per cent of original virgin levels in 1911 (Figure 29). Prediction uncertainty overlapped with trigger reference points.
- Levels of fishing harvest remain significant in latitude 19 (Figure 9).
- The probability of harvesting Spanish mackerel between 1989 and 2016 in latitude 19 had declined from 60–80 per cent of fishing days to 40–50 per cent (Figure 17). The decline was more notable in latitude 18.
- Standardised (hyper stability and fishing power adjusted) catch rates measured reduced fish abundance in later years, particularly in 2015–2016 (Figure 20 and Figure 21).

What do the latitude 19 harvest levels indicate?

Since 2004 during October and November, latitude 19 commercial line harvests were generally 40–250 (median = 133 and mean = 177) Spanish mackerel per day across fishing operations (maximum was 931 fish in 2007). The accumulation of these daily harvests of fish overtime, together with harvests from other fishing sectors, during the spawning season can be substantial when many vessels operate. With Spanish mackerel aggregated to spawn and a general focus of fishing effort around key reefs in latitude 19, harvest rates (fishing mortality) could easily exceed those estimated for the whole stock area in Figure 30. The catchability of Spanish mackerel in latitude 19 during the spawning season will likely be higher than other areas and times. Density dependence in catchability and risk of increased fishing mortality on spawning fish is important to manage (Walters and Martell, 2004).

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

The confidence intervals (uncertainty) around the genetic estimates were wide due to sampling and technical challenges. Only 6+ fishing trips were able to be sampled effectively and measured the potential harvest rates at those times and areas. Irrespective of the uncertainty, the results help interpret fish harvest rates and their sustainability. For the Northern Territory, results indicate that commercial fishing operations can have significant fishing power and may at times take large proportions of exploitable fish from a location (7 per cent to 55 per cent, Table 23 in: Buckworth et al., 2012). This is also possibly true for Spanish mackerel in latitude 19 during the spawning season and on other aggregations.

What benefits do closed areas have for protecting spawning Spanish mackerel in latitude 19?

In 2004 the Great Barrier Reef Marine Park Authority revised the reef zonings and expanded the Representative Areas Program: RAP (http://www.gbrmpa.gov.au/zoning-permits-and-plans/rap). Of the key reefs for Spanish mackerel spawning within latitude 19 (listed above), only two were classified as no-fishing zones (http://www.gbrmpa.gov.au/zoning-permits-and-plans/zoning/zoning-maps). The zoning process gave consideration for the importance of Spanish mackerel fishing and five key reefs remained open to fishing (Tobin et al., 2014). A number of other fishing and no-fishing reefs were also positioned to the east and north-east of the key reefs for Spanish mackerel spawning (J19 and K20). Based on commercial logbook records since 1989, these other reefs were historically less important for Spanish mackerel fishing compared to the key reefs. However earlier data may suggest these other reefs were more important for Spanish mackerel fishing and spawning before increased exploitation (Buckley et al., 2017).

In 2014 research was published describing the movement patterns of Spanish mackerel between reefs during the spawning season in latitude 19 (Tobin et al., 2014). The research explained some possible benefits (and not) from spatial or temporal closures and provided information for spatial management of Spanish mackerel.

Through the spawning seasons of the 2009 and 2010 fishing years, the research tagged 105 Spanish mackerel with acoustic transmitters (Tobin et al., 2014). The movements of 67 Spanish mackerel on 13 reefs were recorded using acoustic receivers. Of these fish about 20 per cent moved between reefs, suggesting aggregating Spanish mackerel spend a significant amount of time around certain reefs. The proportion of tagged fish remaining around a reef after a lunar cycle was low. On some reefs fewer Spanish mackerel were detected during the night than day. This may suggest some fish have a night-time pattern of movement away and back to the reef.

More recent FRDC research (project number 2014-022) conducted plankton net surveys of Spanish mackerel egg spawn around Rib, John Brewer and Helix reefs. The test samples caught few Spanish mackerel eggs and may suggest actual spawning or egg advection at that time was away from reef edges and slopes (pers. comm. Dr Richard Saunders).

The research results implied that fine spatial or temporal scale closures on their own would not sufficiently protect Spanish mackerel for spawning. This inference was supported by Tobin et al. (2014) who calculated minimal reductions in overall harvest for five and nine day closures to fishing. Broader lunar month closures were suggested to be more effective based on the data (Tobin et al., 2014). This would encompass the spatial complexities of Spanish mackerel spawning. The calculated impact of reduced Spanish mackerel harvest from latitude 19 was about 33 per cent from a one lunar-month closure (October or November) and about 66 per cent for a two lunar-month closure (October and November) (Tobin et al., 2014); assuming fish that were protected were not caught on opening of the closure. Latitude 19 catch rates of Spanish mackerel were estimated to be about 25 per cent higher early in the waxing moon phase compared to after the full moon (Figure 42, Appendix).

For an objective to increase protection of all spawning fish, the lunar month closure concept had merit to reduce harvest rates, but would carry economic and social ramifications for some fishers (Tobin et al., 2014). Meaningful limits of the number of fishing operations and boats would allow reduced fishing pressure and provide alternative management options with less restrictive closures.

Tobin et al. (2014) and Buckley et al. (2017) signalled that the spawning aggregation of Spanish mackerel within latitude 19, and north to Cairns and south to Townsville, had diminished in time. These statements align with the TrRP signals from some of the fish population model predictions. For latitude 19, Tobin et al. (2013) consider the spawning aggregation of Spanish mackerel as vulnerable to overfishing due to their high catchability and transient aggregating behaviour.

Monitoring of the fished status of the Spanish mackerel spawning aggregation is important for determining the overall stock status. Current nominal commercial logbook data have limitations and suffer from hyper stability. Improvements in data collection, for monitoring catch rates, are required if fishing and the health of the spawning aggregation is to be effectively monitored. Given an important degree of reef fidelity was evident for Spanish mackerel (Tobin et al., 2014), fine scale details on fishing locations are required to understand the potential fishing mortality and aggregation densities of Spanish mackerel.

Recommendations

The Queensland Department of Agriculture and Fisheries commissioned an update to the stock assessment for east coast Spanish mackerel. This was to evaluate fish population status, suggest appropriate harvests associated with limit and target reference points and comment on required improvements to data collection. The Queensland Government has stated clear aims to build and maintain fisheries long term. Target reference points are 40–50 per cent of virgin exploitable biomass by 2020 and 60 per cent by 2027 (Queensland Government, 2017). For Spanish mackerel the results for both exploitable biomass and spawning egg production were around 30–50 per cent of early estimates in 1911 (Figure 29). Results can be viewed against the Government’s target reference points.

[*Management*] *Reduce fishing pressure on Spanish mackerel to increase fish abundance, catch rates and ensure resilience of the spawning aggregation.*

Setting regulations to reduce effective fishing pressure is recommended to achieve target operational-objectives for the fishery. Regulations on limiting harvest rates (i.e. input controls on fishing pressure / numbers of fishers or boats / catchability) are important considerations (Walters and Martell, 2004). High post-release mortality of Spanish mackerel means that changes in size limits may not be beneficial. A combination of effective limitations on fishing effort, annual quota using a low stock size estimate and time-area closures is recommended to improve fishery performance. A decision tree for these generic management options was discussed by Walters and Martell (2004). The following management options should be considered as part of any new harvest strategy to be developed under the Queensland Sustainable Fisheries Strategy 2017–2027 or in New South Wales:

- It is recommended that the annual sustainable harvest of Spanish mackerel be capped between 400 and 800 t for all fishing sectors and east coast waters combined (Figure 31 and Table 17). The selected level will depend on the agreed building time to achieve the target population size. An allocation component is also required for discard mortality, given the large number of released fish reported through the recreational fishing surveys (SWRFS). Future levels of harvest should be adjusted appropriately according to information and used in a harvest control rule. Allowance of a large amount of harvest and fishing effort in latitude 19 risks overfishing the spawning aggregation.

- Management by commercial quota (TACC) alone may not be effective. The basic problem is that modern fisheries are able to technically improve their catchability and optimise targeting of fish aggregations (Walters and Martell, 2004). Even if overall harvests were capped by management, safe guards against over estimating fish abundance and excess localised fishing pressures are required to mitigate depensatory effects - decrease in the breeding population (mature individuals) leads to reduced production of fish eggs and recruitment. Current management settings and sector allocations allow for overfishing if allocations are mostly utilised.
- In order to achieve a target biomass of $B_{60\%}$ by 2027, it is recommended that the fishery actively explores options to reduce effective/directed fishing efforts. Pascoe et al. (2014) commented that optimal effort levels for maximum economic yield (MEY) were most likely between 55 per cent and 65 per cent of those at MSY. At present the biomass sits at 30–50 per cent and is subject to harvest rates that will not support an increase in biomass. Under status quo fishing, there is potential that the fishery will not achieve the 2027 targets outlined in the Queensland Sustainable Fisheries Strategy 2017 - 2027. Longer term, it is suggested that a 40–50 per cent reduction in fishing mortality ($F_{2016} \rightarrow F_{60\%}$) will be required to achieve the $B_{60\%}$ objective.
- Consideration will need to be given to the risks of fishing spawning aggregations. Literature suggests the spawning population is reliant on necessary reef waters through latitude 19 (Tobin et al., 2014). Compared to the Lucinda region (latitude 19), no such comparable spawning aggregations along the east coast are currently identified. Of similar significance was the historically important spawning aggregations east of Cairns, which have declined (Tobin et al., 2014; Buckley et al., 2017). Improved time-area closures or bounds on localised fish harvest rates are recommended in order to manage the risk of depensatory effects. This tactical management option under output controls was noted by Walters and Martell (2004).

[*Monitoring*] *Commercial and charter logbooks; see discussion of hyper stability issues around* (Table 2)

It is recommended that improved mechanisms to report daily Spanish mackerel harvest and fishing effort per operation be identified and implemented. This should include the potential use of electronic reporting systems which are of particular use in the determination of harvest rates and standardised catch rates. The accuracy of the data used in the assessment would be improved with the following information:

- Trip and daily harvest numbers of fish per operation, with fish weights calculated from unload/sale receipts. Numbers of Spanish mackerel are easier and more accurate to record and better for use in catch rate measures of fish abundance. Accurate tallies of fish numbers and weight will help imply age-size structures of fish and measures of fishing mortality.
- Number of fish caught for each dory-day and skipper/fisher identification. Fishing power, abilities and practices can change significantly between different skippers.
- Number of dories used and hours fished each operation day; indication if effort was targeted or not.
- Number of and fishing locations of the primary operation and dories per day; plus utilising VMS/GPS latitude and longitude coordinates in future data recording.

- Recording of zero catches.
- Identification of days when fishing was stopped due to capacity limitations (too many fish).

For monitoring, the current best-available fish abundance (catch rate) indicator was hyper stability and fishing power adjusted.

[*Monitoring and research*] *Collect time-series data on commercial, charter and recreational fishing power*

The impact of improved technology in fisheries is an important consideration for standardising indicators of fish abundance (catch rates) and fishing effort. Some technologies were included in this assessment, but there were others that have not due to lack of information. In many fisheries there were advances in technology in addition to the ones assessed in this report. The challenge was to adequately model these, as fishing power will continue to increase as a response to ongoing technological advancement. Field survey approaches may be required to collect fishing power information from the recreational fishing sector. The collection of fishing power data from the commercial and charter sectors are recommended through compulsory logbook gear sheets. Further research is required to quantify the catchability effects of different fishing gears and technologies; repeated field based experiments may be needed.

[*Monitoring and research*] *Establish improved long-term measures of recreational fishing effort and harvest.*

This data is an important requirement for assessment of a number of Queensland's fisheries, including Spanish mackerel. Identification of and improved access to proxy effort data in government and non-government vessel databases is desirable. Use of recreational vessels for pursuits other than recreational fishing need to be separated so that changes in fishing effort can be better understood and incorporated into stock assessments (i.e. obtain regular and reliable estimates of vessel and angler numbers operating within the fishery). Regular on-site survey measures of vessel and angler numbers are recommended. Development of new camera monitoring technologies may be an innovative research solution.

Understanding and interpreting recreational fishing data continues to be a challenge, particularly for Spanish mackerel where mixed signals of declined total measures of fishing effort conflict with the increased trend from successful measures of fishing effort or boat registrations. It is critical to better quantify changes in recreational fishing effort in order to improve assessment predictions in the future. This needs to consider adjustments for patterns of alternative uses of boats (for reasons other than fishing) and improved survey methodology.

The importance of regular monitoring and estimates of Spanish mackerel harvests taken by non-commercial sectors through SWRFS should not be overlooked. This is an ongoing priority and methodological improvements should always be pursued.

[*Monitoring*] *Validate records of daily fishing effort and harvest in the commercial and charter logbooks.*

Improving validation of line and net harvest data is a priority for fisheries management across all commercial and charter fisheries. For Spanish mackerel, information on hours fished and more precise fishing location information (through VMS/GPS) will improve the ability to model changing dynamics of the fishery and produce better indices of abundance.

[*Monitoring*] *Continue annual long term monitoring of fish age-length structures.*

Record information to assess independence of samples and that they are spatially representative of the stock population (Sumpton and O'Neill, 2004; O'Neill et al., 2011). Biases caused by changes in the spatial patterns of fishing data should be identified and corrected to standardise annual fish age frequencies. To calculate annual age frequencies of fish, the prediction methodology of not changing spatial weights through time should be followed as for standardising mean catch rates. This will reduce annual variance caused from changes in the spatial patterns of fishing and sampling. Fishery dependent confounding factors need to be mitigated or considered in sampling data (Table 2). Continued annual sampling of Spanish mackerel age-length structures across the spatial stock-range is critical for the stock assessment.

Currently monitoring of Spanish mackerel length structures occurs from the Mission Beach Region southwards to the Gold Coast. Spatial expansion of sampling should consider including the Cairns, Lockhart, Cooktown and New South Wales regions. Expanded sampling to the northern and southern extents of the stock range would help confirm frequencies of older fish, fish mortality rates and genetic mixings of fish north of Cairns (see research recommendation below). Feasibility and costs/benefits of expanded sampling should be evaluated, even if just to improve annual fish age-length keys.

[*Research*] *Collect fine scale spatially representative genetic fish samples to further examine stock assumptions and boundaries.*

Linkages between north Queensland and Torres Strait Spanish mackerel were not clear. Buckworth et al. (2007) report distinct management/stock units for Spanish mackerel: a) Queensland east coast, b) Torres Strait and c) Northern Territory and Western Australian waters. Genetic results suggest Spanish mackerel typically exist as localised assemblages (i.e. larger stock areas generally consist of a mix of smaller spatial population groups) with the spatial spawning patterns of female fish generally less mobile compared to males (Buckworth et al., 2007). The genetic results also suggest Torres Strait Spanish mackerel were a mixture of surrounding populations (Buckworth et al., 2007). Otolith isotopes suggest some similarity between Torres Strait and Gulf of Carpentaria Spanish mackerel (Newman et al., 2009). No stock structure data has been evaluated from north east Queensland (north of 15°S) or Papua New Guinea waters. Management of Spanish mackerel adjacent to the Torres Strait may impact on the viability of the Torres Strait fishery (Buckworth et al. 2007).

This stock structure uncertainty does not undermine the management and assessment of east coast Spanish mackerel as a single unit. At this time it would be detrimental to combine north-east coast data with the Torres Strait because of the risks of over estimating sustainable levels of Spanish mackerel harvest in the Torres Strait. The stock structure uncertainty highlights that finer spatial scaled sampling is required to further understand Spanish mackerel between the Torres Strait and surrounding waters.

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Appendices –supplementary information

Fishery management

Table 11. Chronicle of fishery management for east coast Spanish mackerel.

Date	Fisheries Management measures - Queensland
18 April 1957	*Fisheries Act 1957* implemented a minimum legal size (MLS) of 18 inches for Spanish mackerel. This provision commenced on 1 January 1958.
16 Dec. 1976	*Fisheries Act 1976* implemented a MLS of 45 cm for Spanish mackerel.
1 Jan. 1988	Commercial logbook database began.
22 May 1990	Recreational fishers prohibited from selling any of their catch.
25 Jun. 1993	*Fishing Industry Organisation and Marketing Regulation 1991* implemented a MLS of 75 cm for Spanish mackerel and recreational in-possession limit of 10 fish.
15 July 1994	*Fishing Industry Organisation and Marketing Regulation 1991* amended 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).
21 Feb 2003	Investment Warning for Spanish mackerel issued.
12 Sep. 2003	*Fisheries Regulation 1995* amended 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. The current commercial Total Allowable Catch stands at 574,631 units (1 unit equals 1 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 2004.
	Fisheries Management measures – New South Wales
1 Jul 1998	*FISHERIES AND OYSTER FARMS ACT 1935 – REGULATION.* (Relating to size limits, bag limits and prohibited species) 5 comprised wholly of narrow barred or Spanish mackerel or wholly of spotted mackerel or partly or each Bag limit of 5 introduced
3 Sep 2007	*Fisheries Management (General) Amendment (Prohibited Size Fish and Bag Limits) Regulation 2007 under the Fisheries Management Act 1994.* The minimum legal length of Spanish Mackerel of 75 cm total length was introduced in NSW.

Catch rate diagnostics

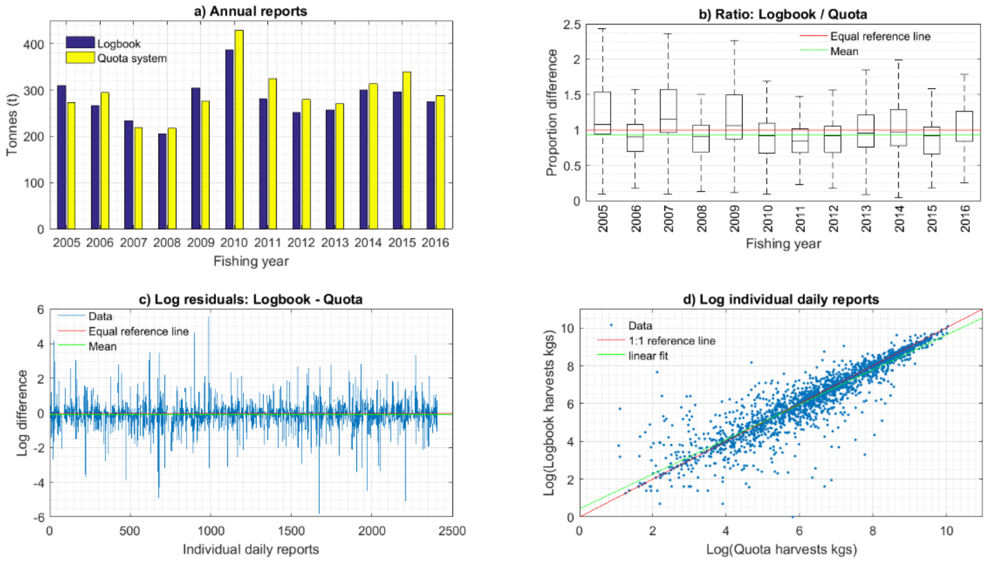

Figure 32. Differences in reported Spanish mackerel harvests between Queensland logbook and quota systems, with logbook tonnages only marginally under by 8 per cent.

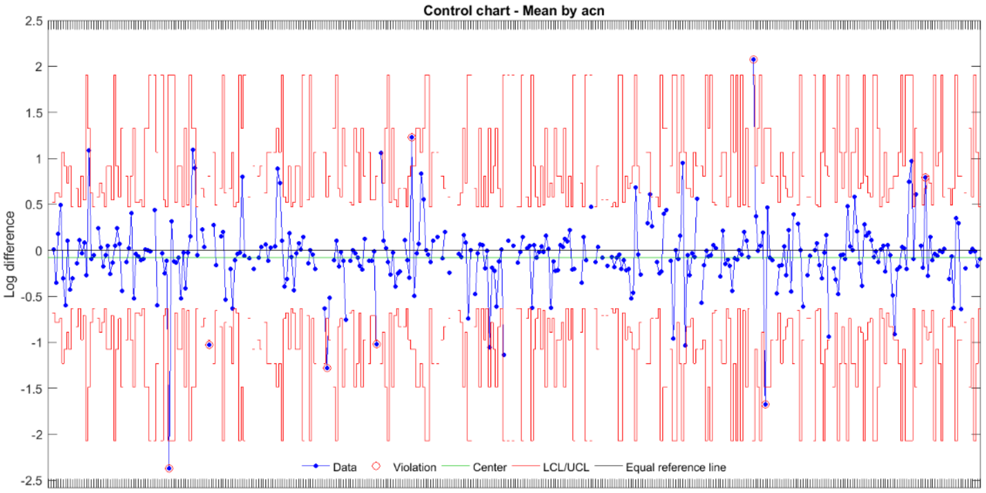

Figure 33. Shewhart control chart for the mean difference (log scale) between Queensland logbook and quota reports by fishing operation (acn: authority-chain-number). The chart plots the mean differences by acn, a center line (CL) at the average of the means, and upper and lower control limits (UCL, LCL) at three standard errors from the center line. Out of control measurements were marked as violations and drawn with a red circle. The figure illustrates the number of fishing operations reporting harvests accurately or not.

Table 12. Summary of analysis statistics for the binomial p(c) 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 + s1m.latband + s2m.latband +
        s3m.latband + s4m.latband + windew + windew^2 + windns + windns^2 + nACN.latband
(FACTORIAL limit for expansion of formula = 2)

Summary of analysis

                                          mean          deviance          approx
Source          d.f.    deviance        deviance        ratio       chi pr
Regression       633     73987.          116.884         116.88     <.001
Residual        5630     13907.            2.470
Total           6263     87895.           14.034

Percentage mean deviance accounted for 82.4
Percentage deviance accounted for 84.2
Adjusted r-squared statistic (based on deviance) 0.824
R-squared statistic (based on deviance) 0.842
Akaike information criterion is estimated to be 15175.
Schwarz Bayes information criterion is estimated to be 19450.

Wald tests for dropping terms

        Model Term        Wald statistic  d.f.     chi. pr.
        fishyear.latband       3018        493      <0.001
        latband.s1m            1164         18      <0.001
        latband.s2m             840         18      <0.001
        latband.s3m             260         18      <0.001
        latband.s4m             107         18      <0.001
        windew                   11          1      <0.001
        windew^2                 54          1      <0.001
        windns                   10          1       0.002
        windns^2                 17          1      <0.001
        latband.nACN           6385         18      <0.001
```

nACN – number of fishing operations; s1m … s4m were the sinusoidal seasonality parameters.

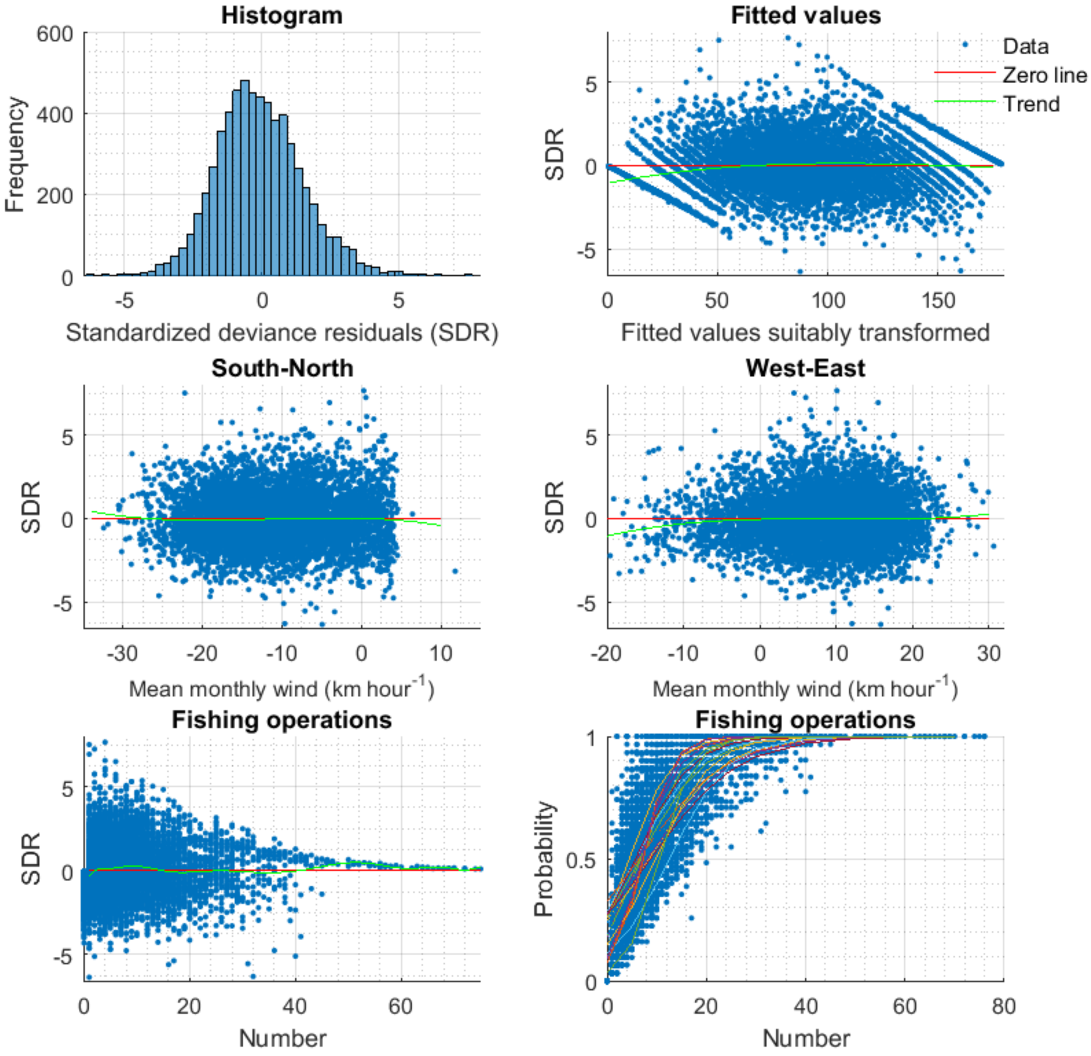

__Figure 34. Residual and fitted diagnostic plots for the binomial model analysis.__

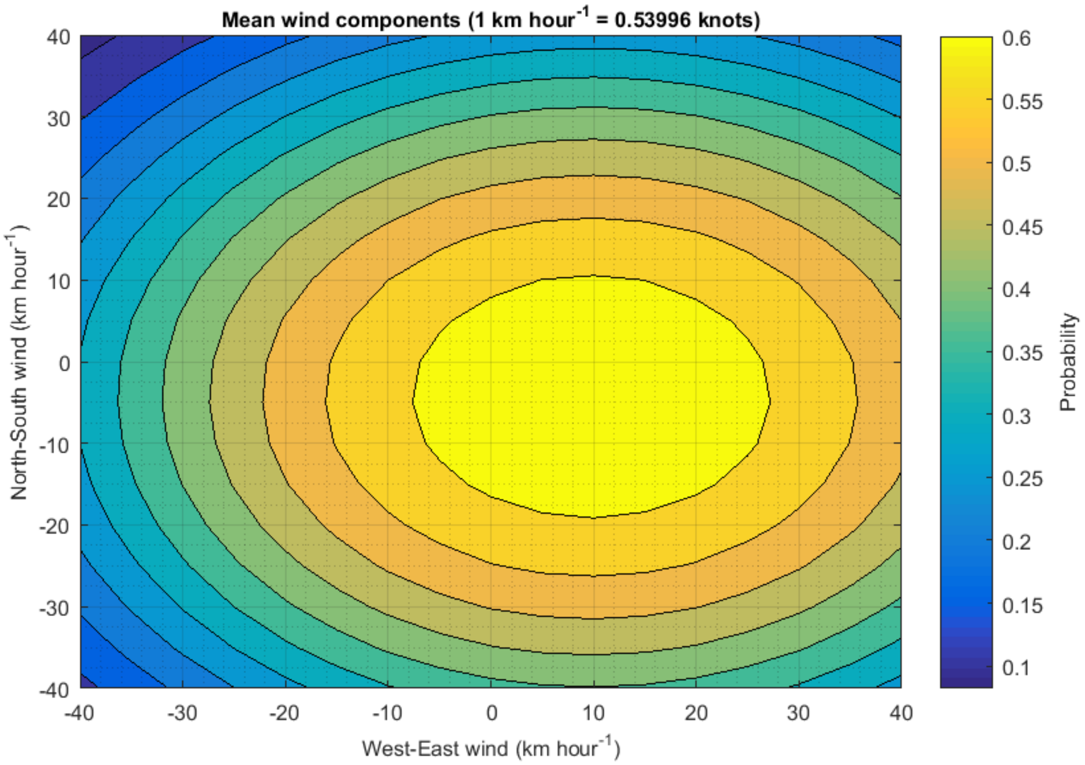

Figure 35. Monthly probability of harvesting Spanish mackerel according to monthly average wind speed and direction. The predictions were averaged across latitudes from the binomial model analysis.

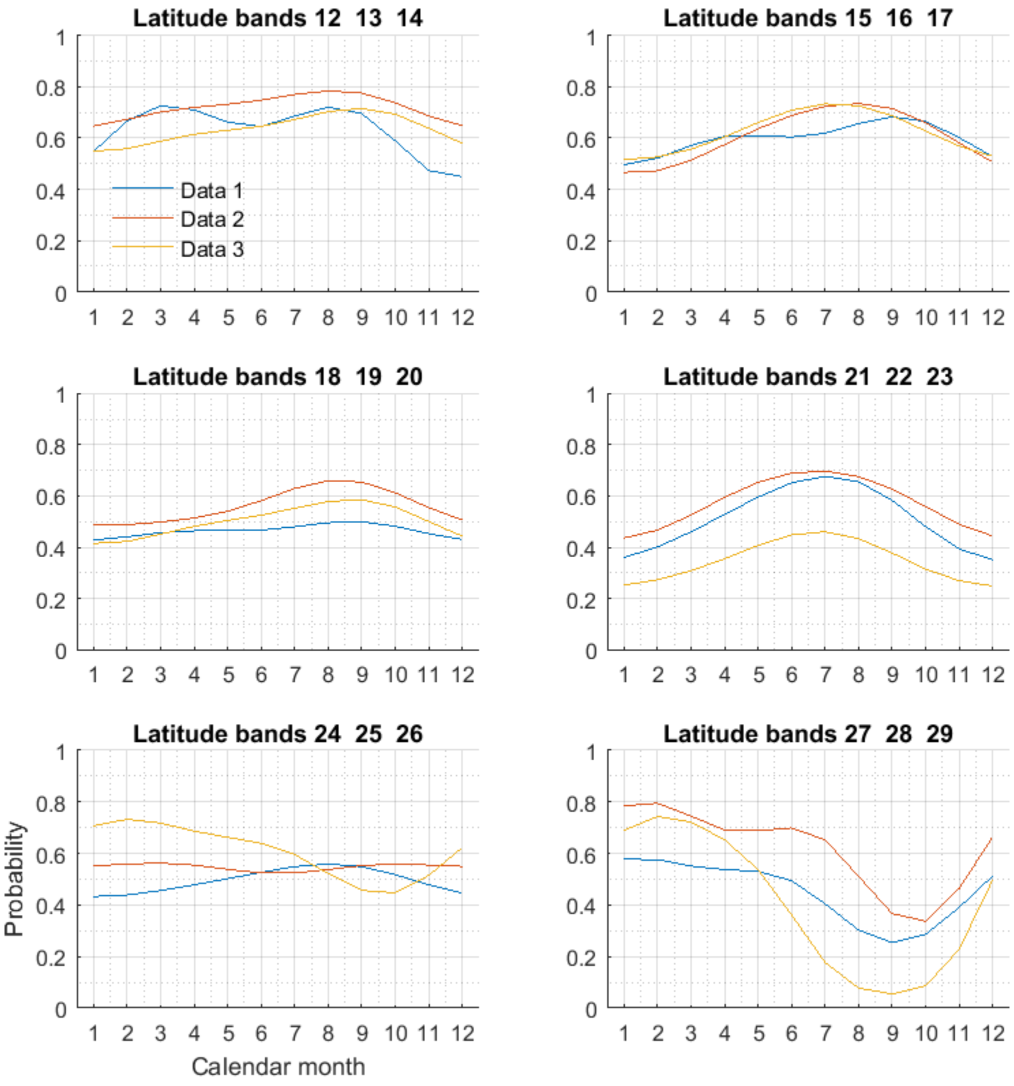

Figure 36. Monthly probability of harvesting Spanish mackerel according to latitude and time of year. The predictions were from the binomial model analysis. The lines for data 1, data 2 and data 3 corresponded in order of the latitude bands titled.

Table 13. Summary of analysis statistics for the three linear mixed models of Queensland commercial line harvests (c>0). All F-statistics were significant (p<0.001) and assessed by dropping terms from the full fixed model. The degrees of freedom (n.d.f) were the same across analyses. See Table 3 for methods and model components.

No fishing power			**Square-root fishing power**			**Full fishing power**		
Estimated variance components			Estimated variance components			Estimated variance components		
Random term:	Component	s.e.	Random term:	Component	s.e.	Random term:	Component	s.e.
ACN	0.3716	0.0199	ACN	0.3708	0.0199	ACN	0.3702	0.0199
Residual:	Sigma2	s.e.	Residual:	Sigma2	s.e.	Residual:	Sigma2	s.e.
	0.844	0.0028		0.844	0.0028		0.844	0.0028
Deviance:	-2*Log-Likelihood		Deviance:	-2*Log-Likelihood		Deviance:	-2*Log-Likelihood	
	152854.31			152876.2			152936	
	Deviance	d.f.		Deviance	d.f.		Deviance	d.f.
		176372			176372			176372
Fixed term	**n.d.f.**	**F stat**		**F stat**			**F stat**	
fishyear.latband2	405	10.99		11.25			11.62	
latband2.s1	16	130.82		130.59			130.34	
latband2.s2	16	111.03		114.11			117.42	
latband2.s3	16	11.28		11.29			11.3	
latband2.s4	16	32		31.75			31.49	
latband2.s5	16	24.83		24.87			24.92	
latband2.s6	16	5.1		5.22			5.38	
latband2.lunar	16	15.42		15.38			15.34	
latband2.lunar_adv	16	25.5		25.47			25.45	
windew	1	29.15		29.73			30.31	
windew^2	1	65.43		65.76			66.08	
windns	1	75.14		75.55			75.93	
windns^2	1	20.74		20.63			20.52	

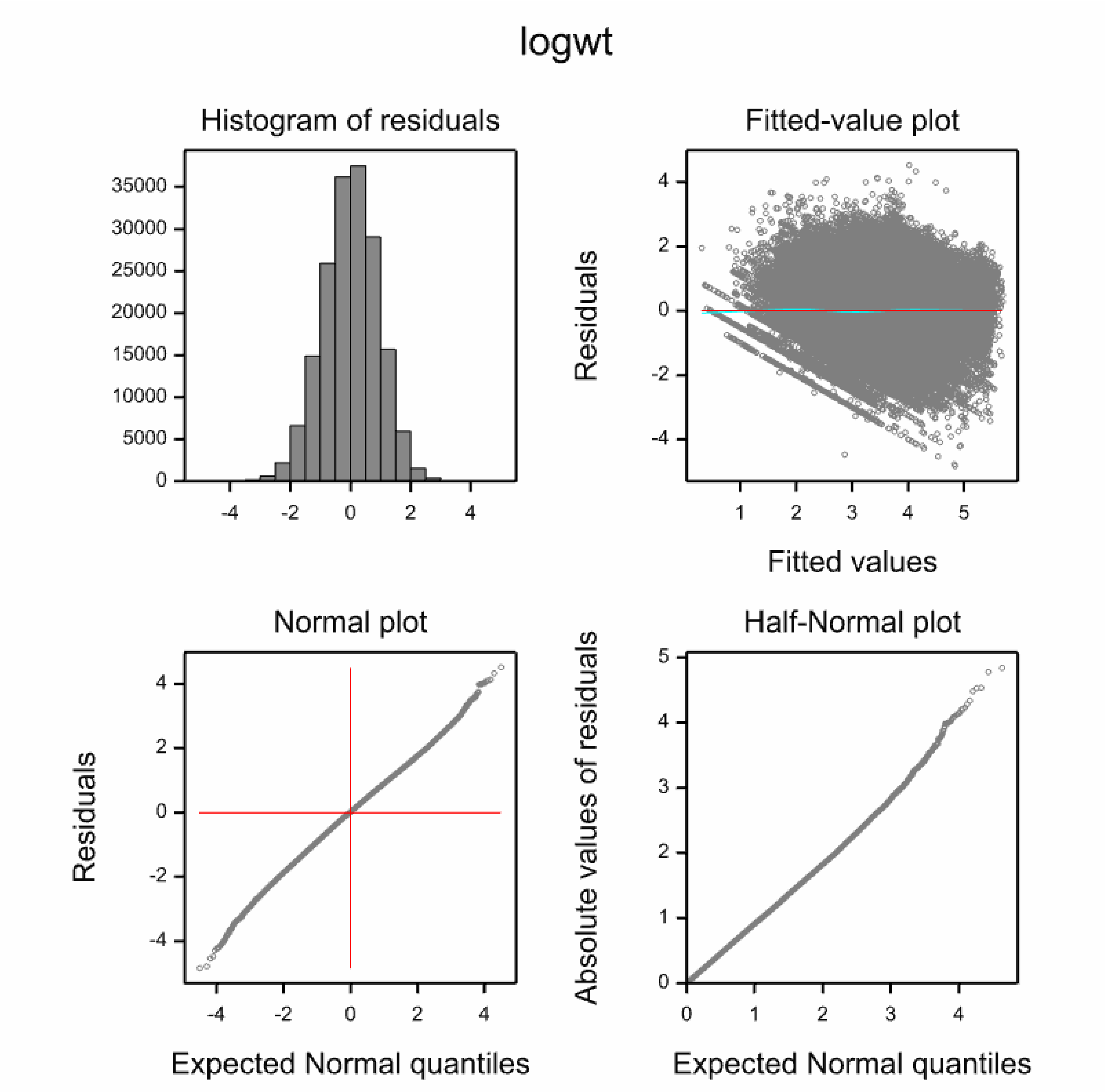

Figure 37. Residual diagnostic plots for the linear mixed model assuming no fishing power increase. The plots were similar for analyses with fishing power.

Table 14. List of add-on fishing power (FP) data used for the standardisation of catch-rates and recreational fishing effort. The mean proportional catch improvements suggested by fishers were listed under the 'treatment effect' column with the sector application superscripted (c = commercial and r = recreational; std = standard deviation in parentheses). The information was sourced from Thurstan et al. (2016a). FP aspects above the dotted line relate to finding fish verse catching fish below the dotted line.

Aspect	Data	Treatment effect	Comments and elements of fishing power (FP)
Vessel size	Length in metres (m)	Not used	Length is static for each vessel in time. Thus, the FP information is correlated with the logbook vessel-code data. Data on primary commercial vessels indicated no change through time (mean length = 10 ± 3 m).
Engine power	Horse power (HP)	Not used	Average engine power by decade. Higher HP can relate to faster speed in order to minimise time spent travelling between ports, fishing grounds and locating areas of highest catches. Economic and weather factors can restrict this behaviour. The data was considered limited with unclear FP effect and vessels were sufficiently powered since the 1980s. There was an increase in mean HP 1990–2016, but this was non-significant when comparing confidence intervals (Figure 38a).
Engine type	2 or 4 stoke	Not used	The adoption of 4-stroke engines (per cent of vessels) by year was strong (Figure 38b). 4-stroke engines use less fuel, but no evidence was available to suggest they drive higher catches (FP). If so, the effect possibly relates to slow-troll fishing methods (popular for Spanish mackerel in SE Qld waters). Adoption of 4-stroke engines may correlate with higher FP vessels (measured through logbook vessel code data).
Refrigeration	Percentage use (%)	Not used	Adoption (per cent of vessels) by year. Relates to the capacity to keep fish cold and in a high quality state. May also allow vessels to conduct longer and more distant fishing trips and stay 'on' the fish schools. Difficult to attribute the data and may correlate with other variables such as vessel codes, fishing grids and vessel size. The use on commercial vessels had not change greatly 1988–2016 and mainly used in north east-coast waters (≈ 80 per cent) and less in central (10–20 per cent) and southern (< 10 per cent) waters.
Distance fished from shore	Nautical miles (nm)	Not used	Average distance fished from shore by decade. Relates to the spatial expansion of fishing. Information is correlated with the spatial-grid terms in the logbook data.
Depth fished	Sea water depth (m)	Not used	Average depth fished by decade. Generally < 50m. Information is correlated with the spatial-grid terms in the logbook data.
Dories	Number of boats per fishing operation	Not used 85% (std=21%)	Data on the number of dories were available through commercial logbook data and generally static in time. The data were correlated with fishing operation codes and not used. The estimated effect for operations using multiple dories, compared to none, was -10 per cent and nonsensible when analysed with the fishing operation codes.
Global Positioning System (GPS)	Percentage use (%)	$42\%^{cr}$ (std=24%)	Adoption (per cent of vessels) by year (Figure 38c). Used to minimise search time spent locating fishing areas and marking locations of fish. GPS data are often displayed using colour depth contour mapping software.
Colour depth sounders	Percentage use (%)	$27\%^{cr}$ (std=17%)	Adoption (per cent of vessels) by year (Figure 38d). Used to locate schools of fish (mackerel and bait) at depth.
Down riggers	Percentage use (%)	$21\%^{cr}$ (std=15%)	Adoption (per cent of vessels) by year (Figure 38e). By using a downrigger, in combination with a sounder, you can present your bait or lure at the depth where fish are likely to be schooling. Simpler/cheaper versions of down-rigging include paravanes.
Fishing rods	Percentage use (%)	$17\%^{r}$ (std=13%)	Adoption (per cent of vessels) by year. Allows the use of light fishing lines and traces, compared to heavy hand/winch lines, to increase bite/strike and catch rates. The adoption rate has not changed over the years 1988–2016. This nullified the annual FP effect, but there were clear region preferences for hand/winch lines in the north (≈ 90 per cent) and mid (60–80 per cent) east-coasts verse using a rod in the south (> 80 per cent).
Fishing braid lines	Percentage use (%)	$8\%^{r}$ (std=8%)	The data suggest no adoption by the commercial sector.
Fishing reels	Percentage use (%)	Not used	For rod fishing, overhead reels were preferred (60–85 per cent) compared to using Alvey or spinning reels. The adoption rate had not changed over the years 1988–2016 and was not used in FP.
Live bait	Percentage use (%)	$26\%^{cr}$ (std=16%)	Adoption (per cent of vessels) by year (Figure 38f). Use of live bait over dead-bait or lures can improve catches in some areas.

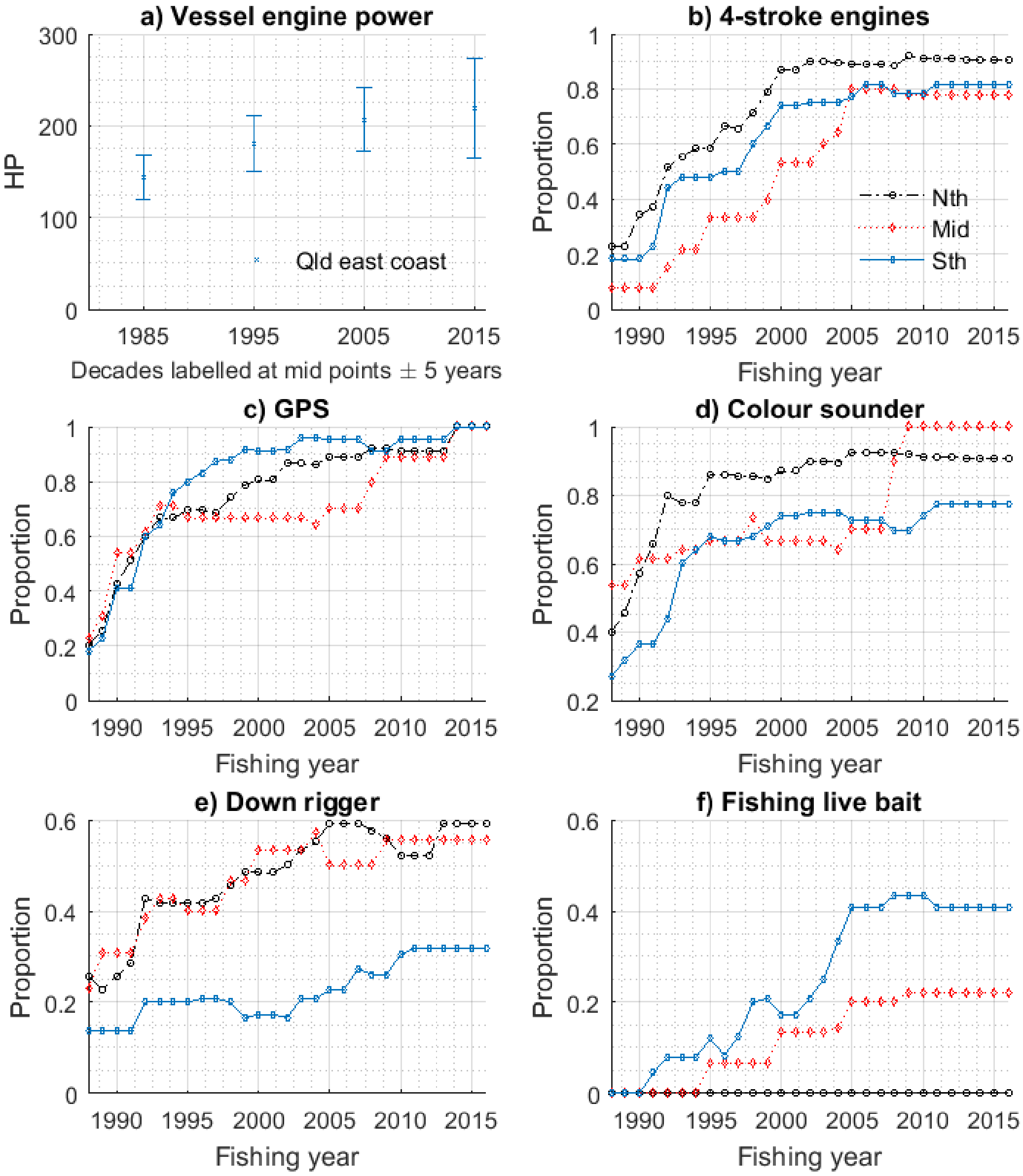

Figure 38. Mean attributes of vessels fishing in the Queensland east-coast Spanish mackerel commercial-line sector. Figure subplots show a) engine horse power by decade with 95 per cent confidence intervals, b) proportion of vessels with 4-stroke engines by fishing year and east-coast region, c) global positioning systems, d) colour depth sounders, e) down riggers and f) fishing live bait. Data up to the year 2013 were sourced from Thurstan et al. (2016a) and 2014–2016 values were imputed.

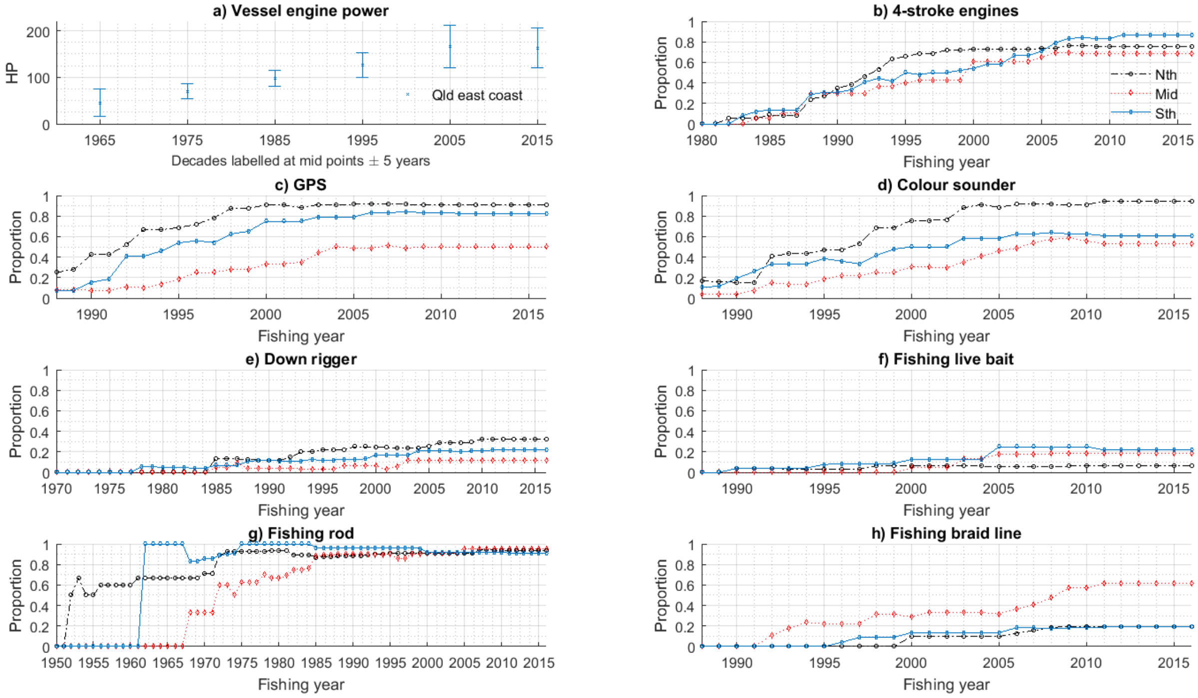

Figure 39. Mean attributes of vessels fishing in the Queensland east-coast Spanish mackerel recreational fishing sector. Figure subplots show a) engine horse power by decade with 95 per cent confidence intervals, b) proportion of vessels with 4-stroke engines by fishing year and east-coast region, c) global positioning systems, d) colour depth sounders, e) down riggers, f) fishing live bait, g) using fishing rods and g) using braided fishing line. Data up to the year 2013 were sourced from Thurstan et al. (2016a) and 2014–2016 values were imputed.

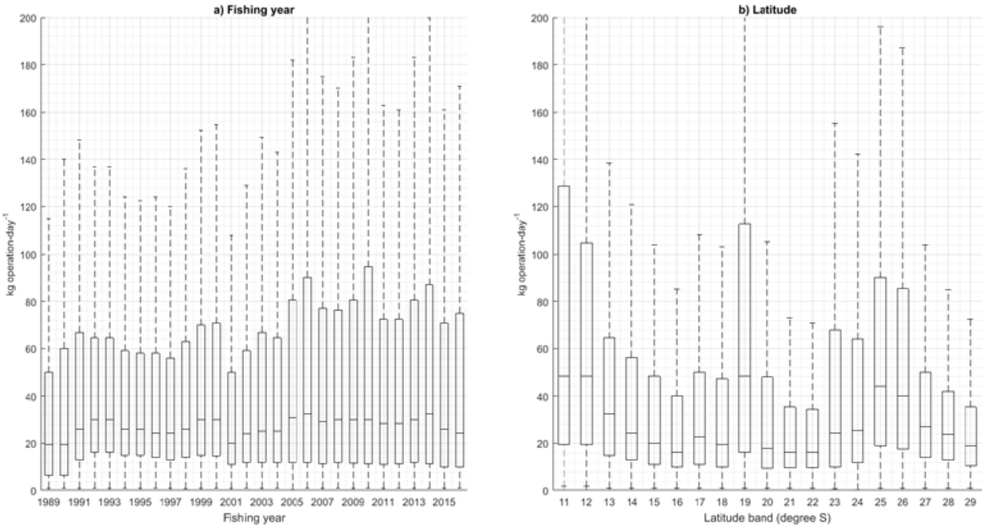

Figure 40. Boxplot of Spanish mackerel harvests reported per operation-day (nominal catch rates) by commercial line fishing in Queensland waters for a) by fishing year and b) by latitude. Each box plot illustrates the distribution of catch rates around the median (horizontal line in the middle of the box). Outlier catch rates were not shown but extended up 5 t.

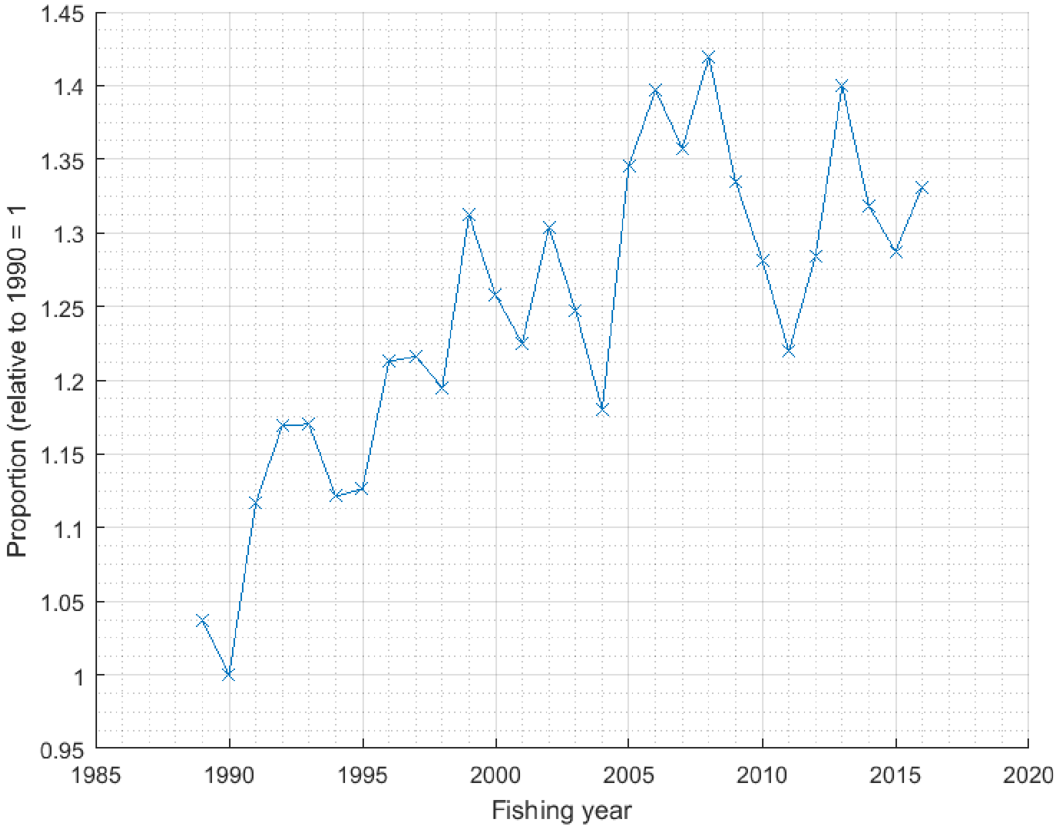

Figure 41. Estimated Queensland commercial line-sector 'fleet' mean fishing power as calculated from the vessel-acn random-model parameters in REML. The parameters estimates and variance components were stable across the different REML analyses (Table 13). The sector's mean fishing power for Spanish mackerel was estimated to be about 33 per cent higher in 2016 compared to 1990; and near 42 per cent higher in 2008.

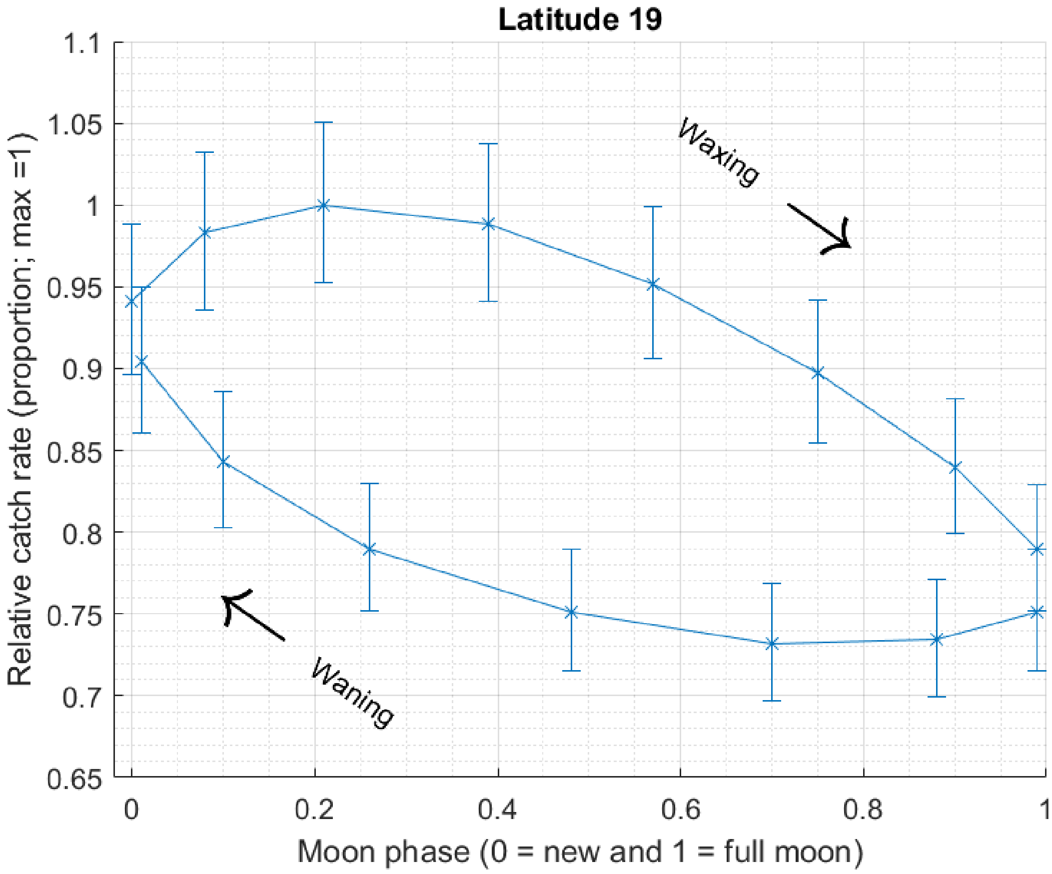

Figure 42. Predicted proportional change in mean catch rate of Spanish mackerel with moon phase for latitude 19. The plot was scaled relative to the maximum catch rate (=1). Error bars represent 95 per cent confidence intervals.

Table 15. Summary of analysis statistics for the linear mixed model analysis of commercial line catch rates from New South Wales. * F-statistics were significant at p<0.05 and assessed by dropping terms from the full fixed model.

Full fishing power

Response variate: logwt1 - log kg offset for log fishing power

Fixed model: Constant + fishyear + area + fishyear.area + s1 + s2 + s3 + s4 + metheffgroup

Random model: Fishing operation

Number of units: 3987

Estimated variance components

Random term: Component s.e.

Fishing operation 0.0908 0.0197

Residual: Sigma2 s.e.

0.647 0.0147

Deviance: -2*Log-Likelihood

2507.67

Deviance d.f.

3957

"2-level factor for each method, 1=handline, 2=trolling"; nunits defined the amount of fishing effort – effort quantity; number of hooks for handline and number of lures/bait for trolling.

```
calculate metheffgroup = (method.eq.1) * (nunits.gt.6) +\
                         (method.eq.2) * (nunits.gt.2) +\
                         (method.eq.2) *2
```

groups [redefine=yes] metheffgroup "convert to type factor"

Fixed terms	**n.d.f.**	**F stat**
fishyear.zone	12	5.53*
latband2.s1	1	2.5
latband2.s2	1	3.87*
latband2.s3	1	0.08
latband2.s4	1	13.36*
metheffgroup	3	6.27*

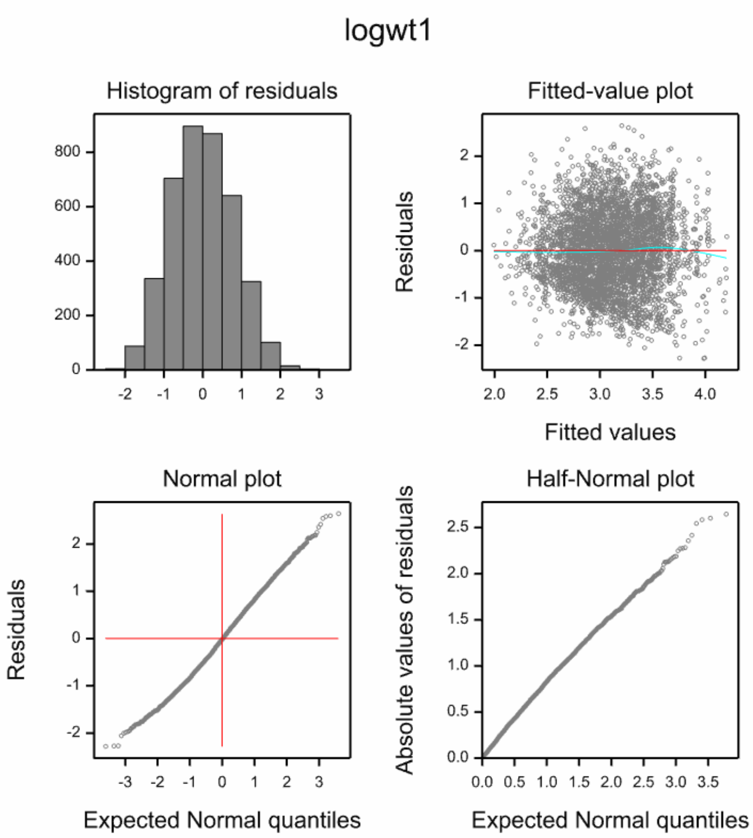

Figure 43. Residual diagnostic plots for the New South Wales catch rate linear mixed model.

Fish age-length monitoring

Table 16. Summary of number of Queensland samples of Spanish mackerel collected by Fishery Monitoring from the recreational and commercial sectors between 2005 and 2016. Catches refer to the number of fishing trips sampled. Fish lengths refer to a calculated (scaled) number of fish lengths to account for catch subsampling.

Fishing year	Sector	Catches	Fish lengths	Fish aged
2005	Recreational	125	283	257
	Commercial	206	2672	1075
2006	Recreational	186	351	288
	Commercial	234	2885	1011
2007	Recreational	183	305	178
	Commercial	136	2016	759
2008	Recreational	249	411	220
	Commercial	149	1878	690
2009	Recreational	325	628	507
	Commercial	241	3245	836
2010	Recreational	413	830	448
	Commercial	218	3803	639
2011	Recreational	307	570	266
	Commercial	287	3729	1160
2012	Recreational	226	367	227
	Commercial	377	4645	897
2013	Recreational	210	385	211
	Commercial	240	3723	522
2014	Recreational	476	938	446
	Commercial	354	4728	1028
2015	Recreational	438	890	403
	Commercial	325	5000	926
2016	Recreational	449	803	323
	Commercial	292	3734	559

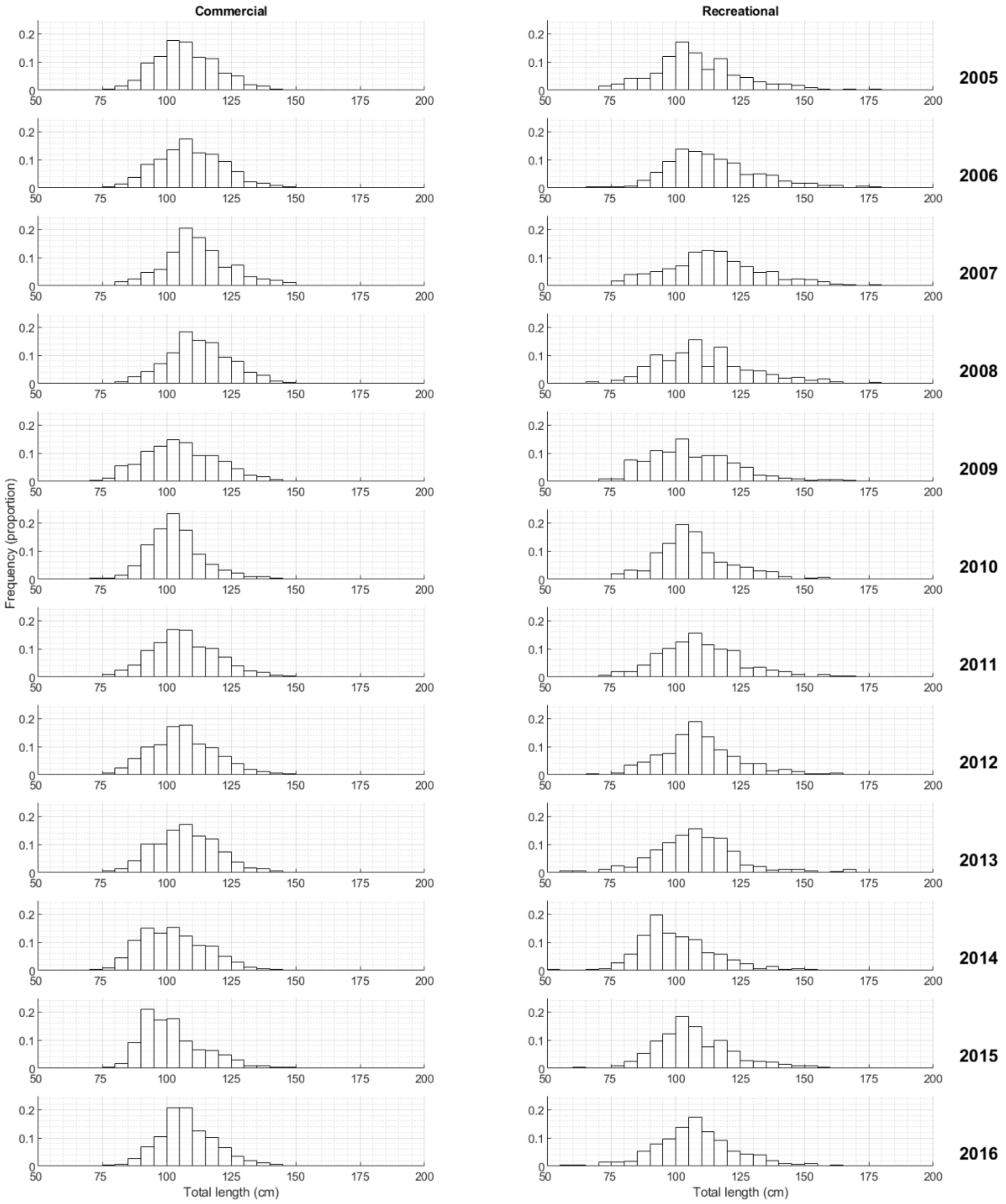

Figure 44. Total-length frequency of Spanish mackerel harvested by the Queensland commercial and recreational fishing sectors. Minimum legal total-length was 75 cm.

Stock model diagnostics

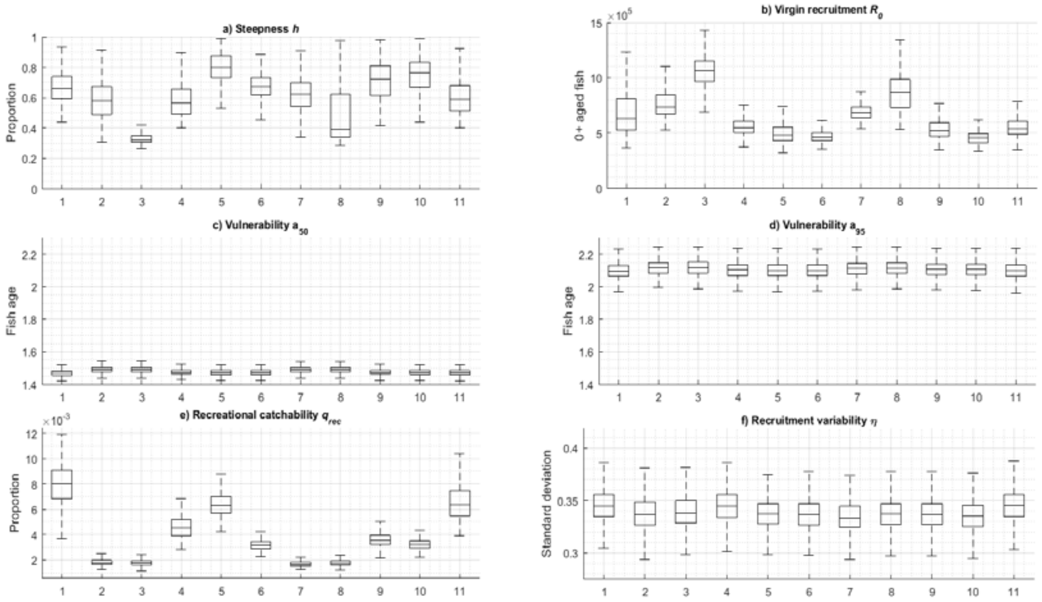

Figure 45. MCMC parameter estimates for the 11 analyses. Each box illustrates the distribution of estimates around the median (horizontal line in the middle of the box).

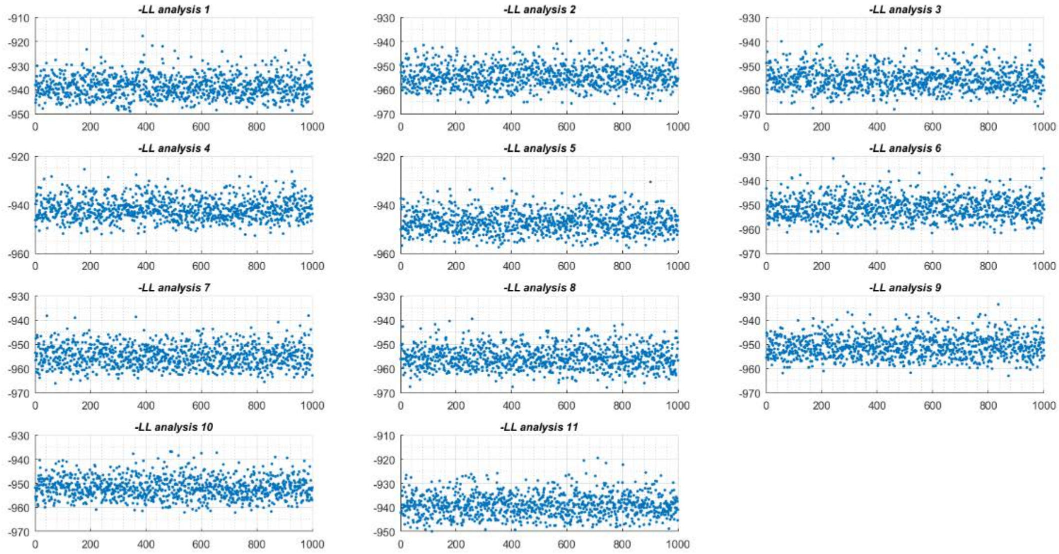

Figure 46. Serial plot of the negative log-likelihood (-LL, y-axis) values for the retained parameter samples from the Markov chain Monte Carlo (MCMC) optimisations. n = 1000 data points saved (x-axis) from 100 000 simulations. Autocorrelations was low and acceptable and the heildel test was non-significant and passed stationary for all parameters p>0.1.

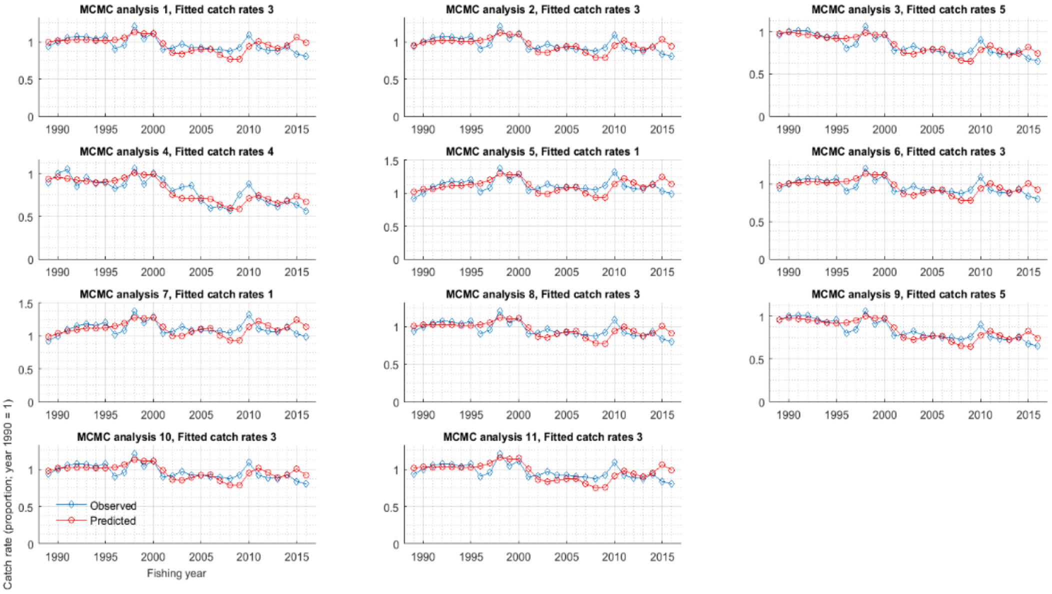

Figure 47. Stock model fitted values to the standardised commercial catch rates of Spanish mackerel for each MCMC analysis.

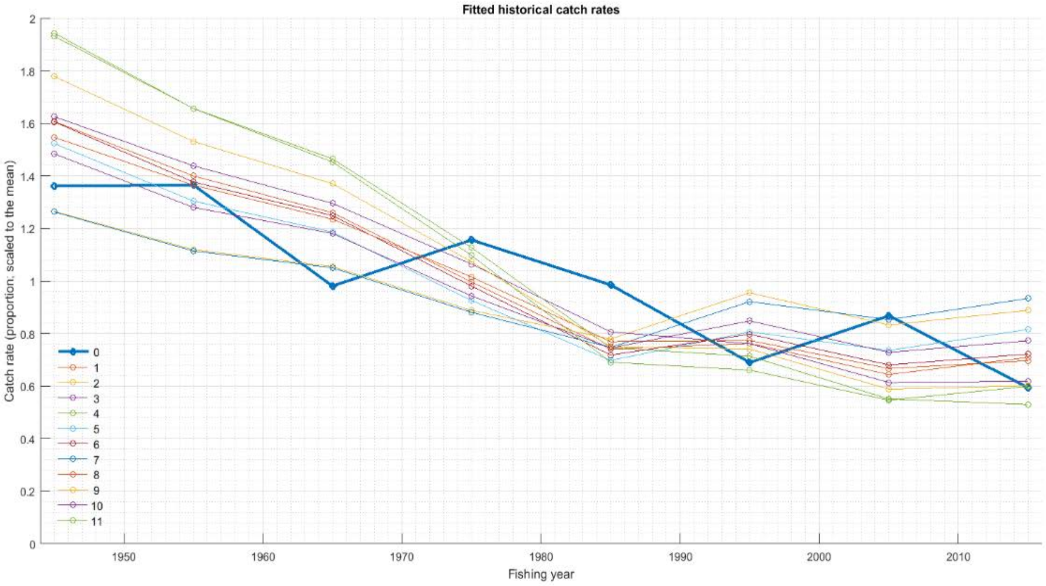

Figure 48. Stock model fitted values to the standardised historical catch rates of Spanish mackerel. The legend number 0 is the data and numbers 1 to 11 indicate the MCMC analysis.

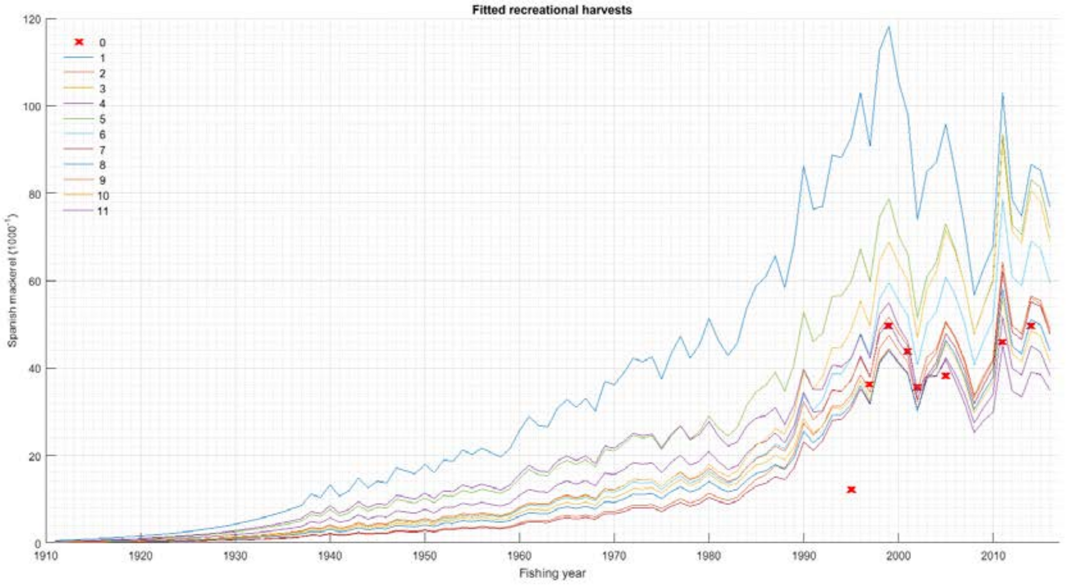

Figure 49. Stock model fitted values to the recreational harvest numbers of Spanish mackerel. The legend number 0 is the data and numbers 1 to 11 indicate the MCMC analysis.

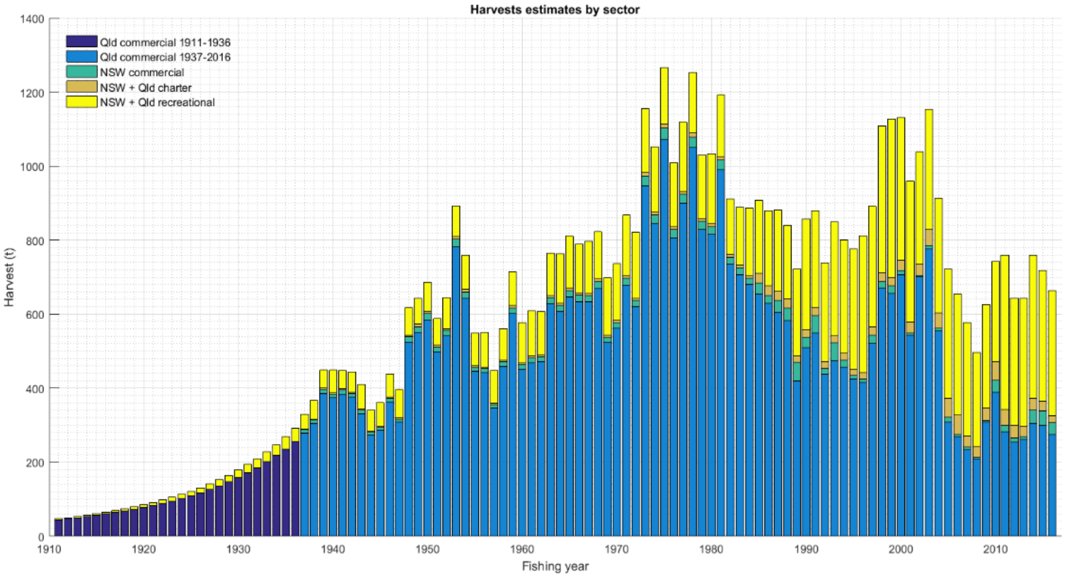

Figure 50. Estimated harvests of Spanish mackerel by fishing sector.

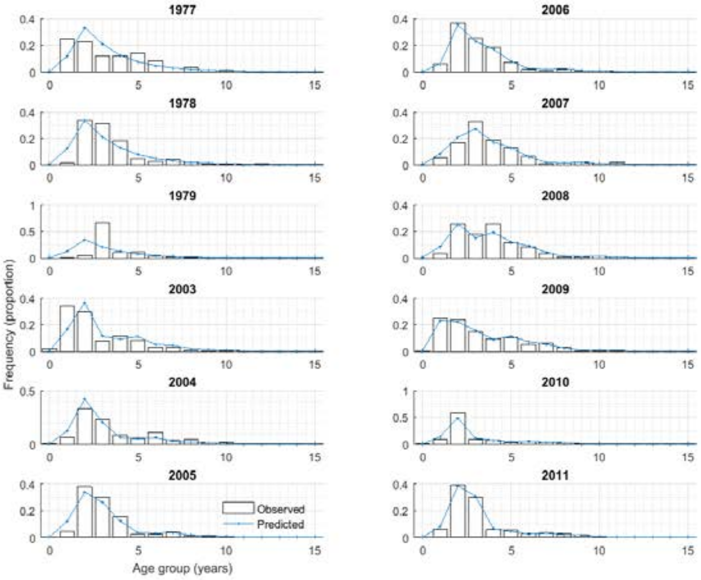

Figure 51. Stock model predictions of Spanish mackerel ages harvested by commercial operations from Qld waters.

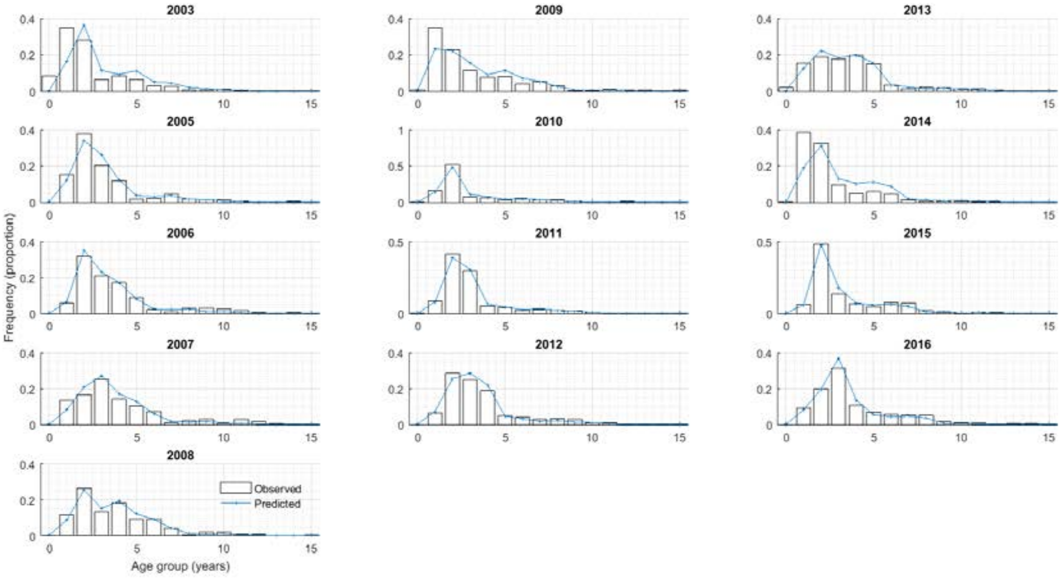

Figure 52. Stock model predictions of Spanish mackerel ages harvested by recreational anglers from Qld waters.

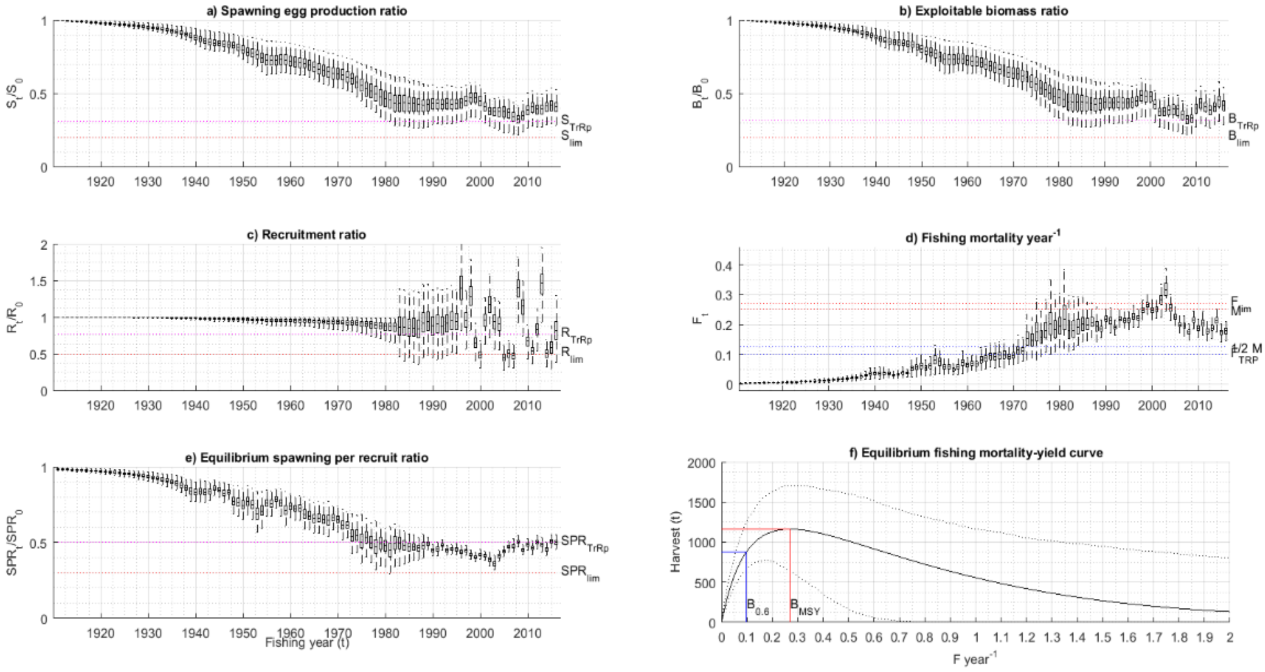

Figure 53. Predictions from analysis 1 for a) spawning egg production, b) exploitable biomass, c) recruitment of 0+ aged fish, d) fishing mortality, e) equilibrium spawning egg production per recruit based on each year's estimated fishing mortality and f) best fit equilibrium yield curve indicating points for B_{MSY} and $B_{0.6}$ with the dashed lines mapping 2.5 per cent and 75 per cent credible error region. The red dashed lines show the limit reference points and the magenta coloured dash lines show the trigger reference points.

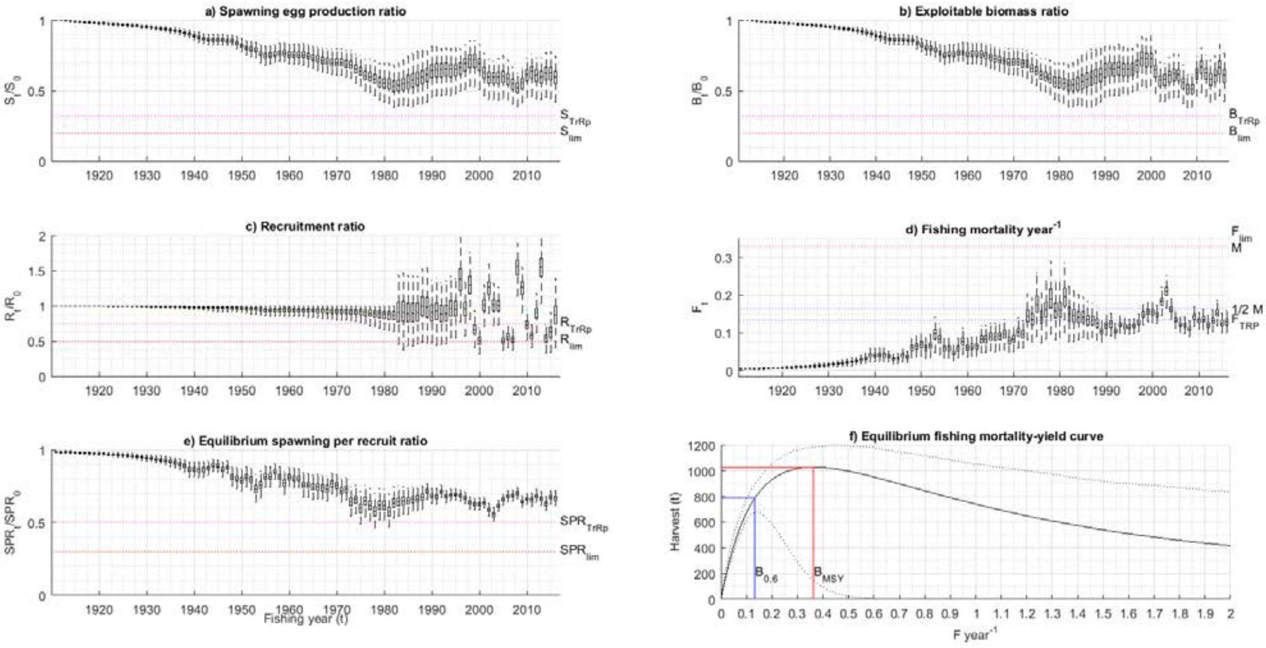

Figure 54. Predictions from analysis 2.

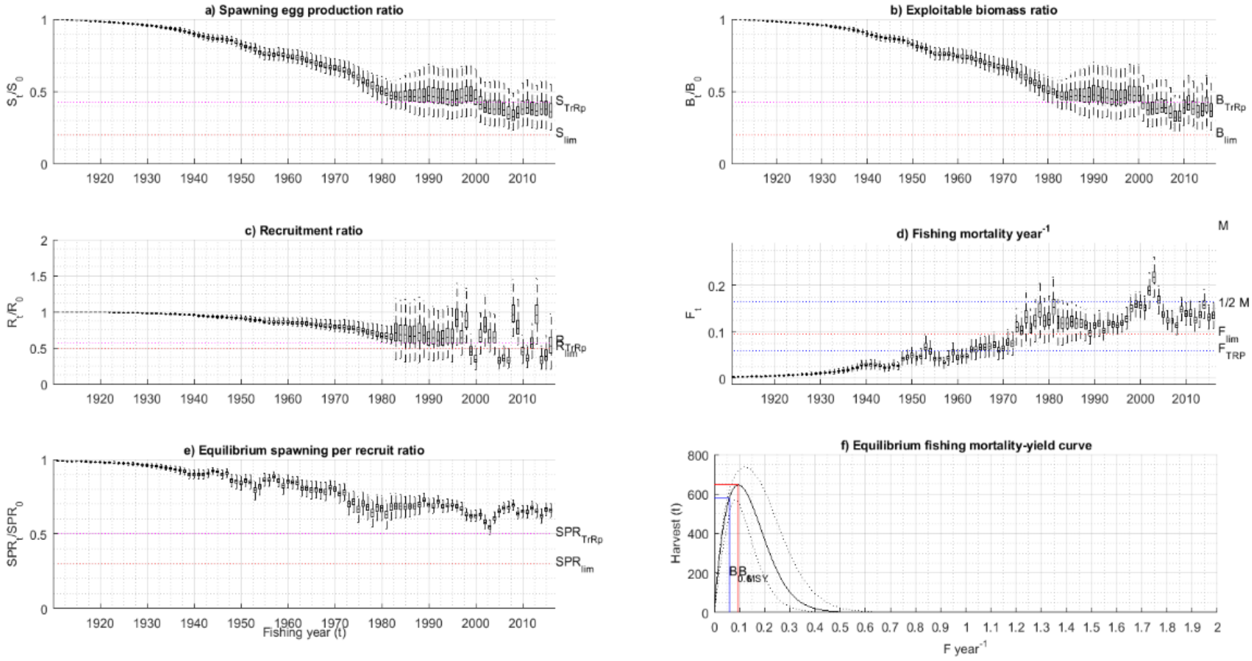

Figure 55. Predictions from analysis 3.

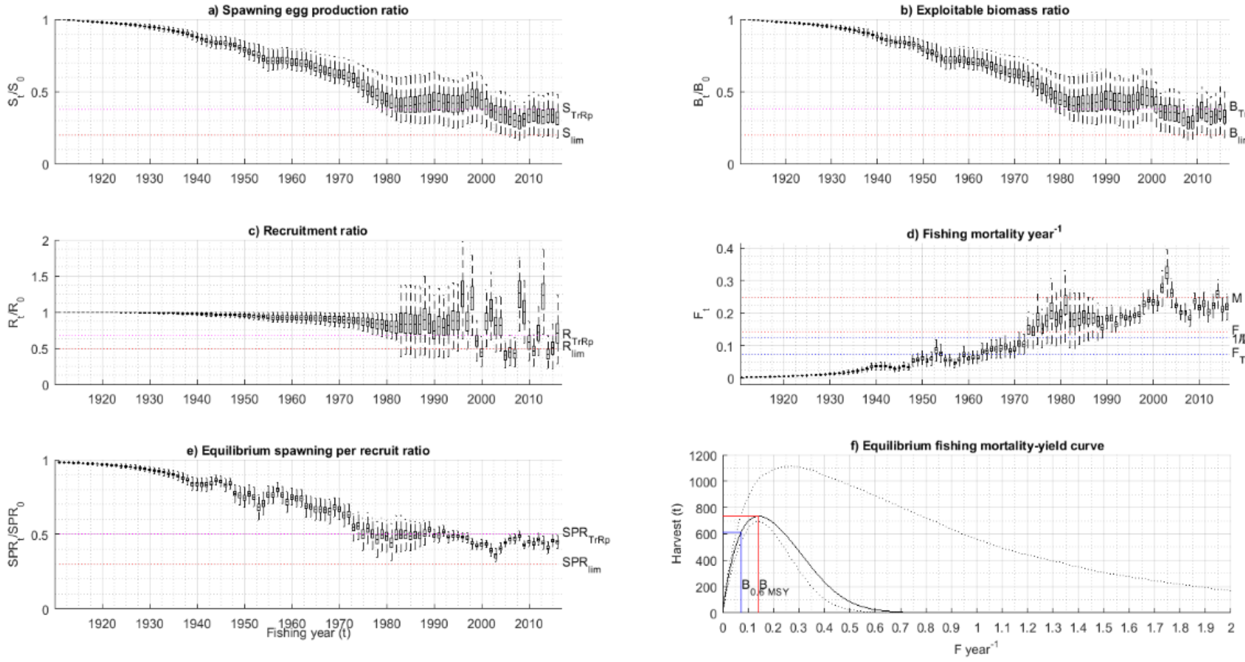

Figure 56. Predictions from analysis 4.

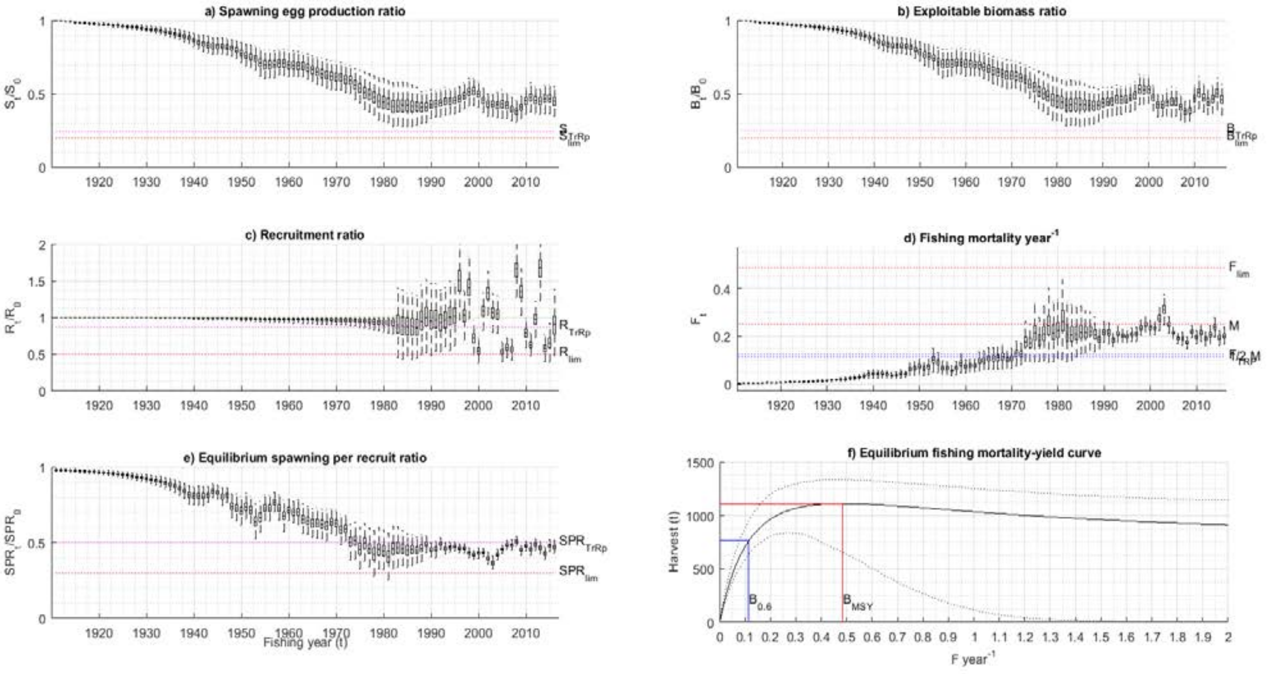
a) Spawning egg production ratio
b) Exploitable biomass ratio
c) Recruitment ratio
d) Fishing mortality year^{-1}
e) Equilibrium spawning per recruit ratio
f) Equilibrium fishing mortality-yield curve

Figure 57. Predictions from analysis 5.

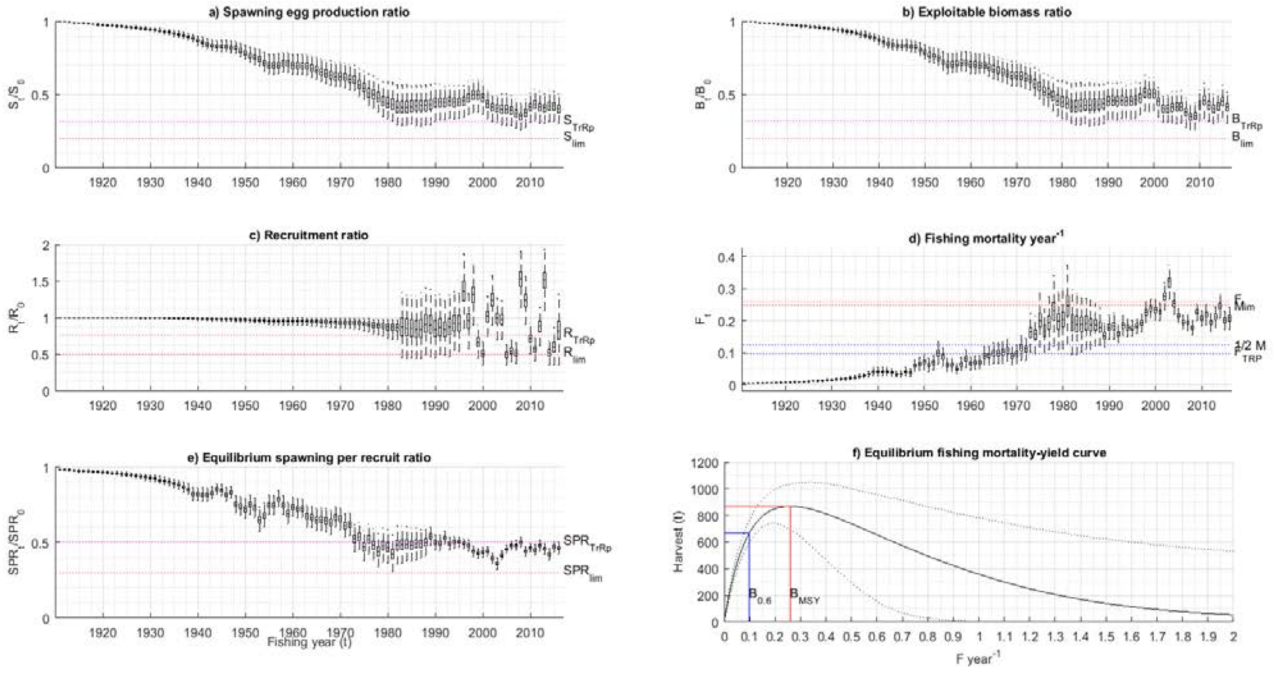
a) Spawning egg production ratio
b) Exploitable biomass ratio
c) Recruitment ratio
d) Fishing mortality year^{-1}
e) Equilibrium spawning per recruit ratio
f) Equilibrium fishing mortality-yield curve

Figure 58. Predictions from analysis 6.

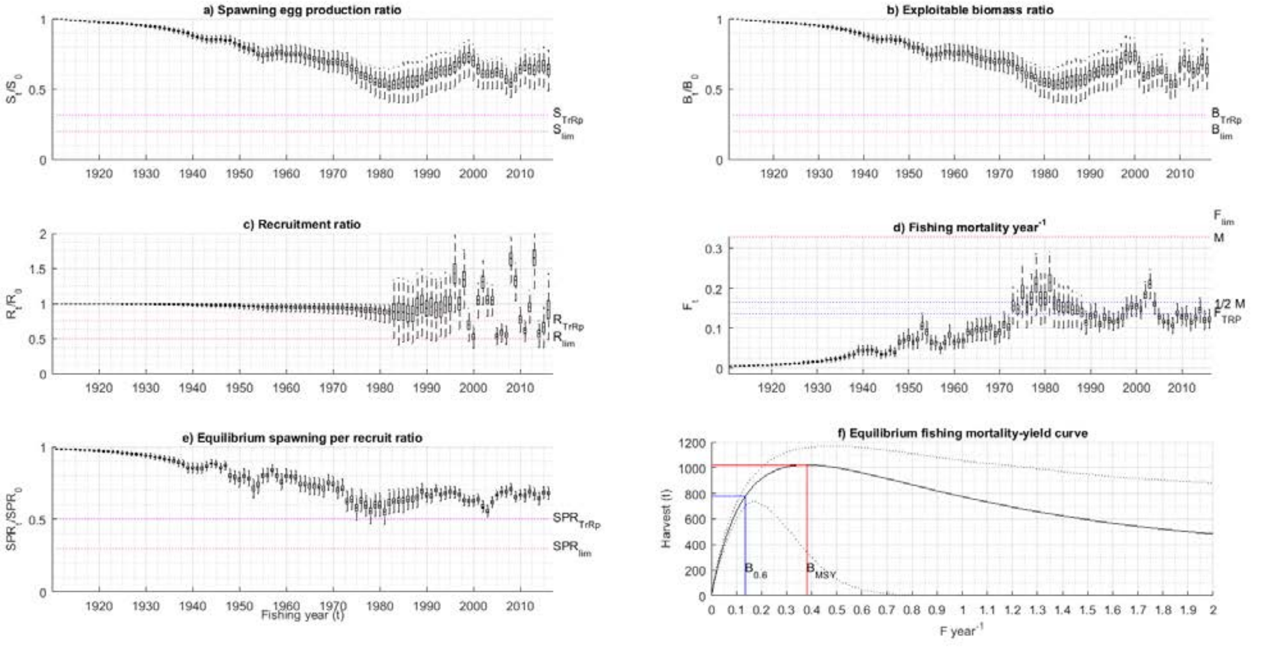

Figure 59. Predictions from analysis 7.

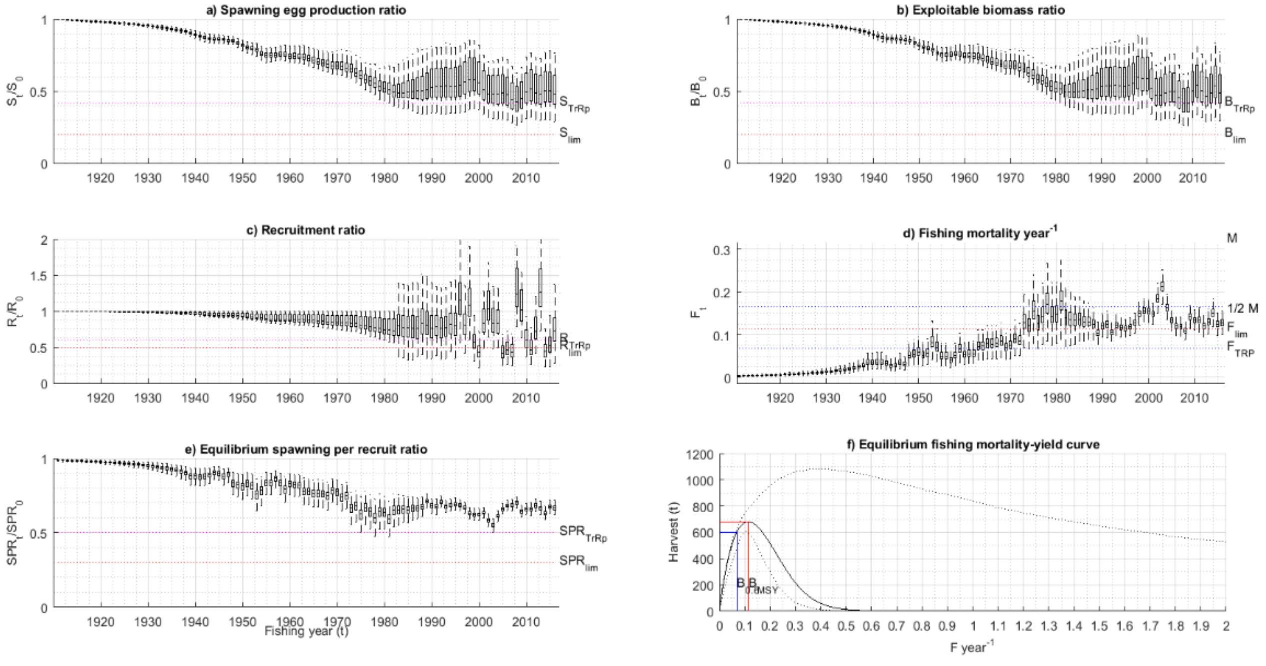

Figure 60. Predictions from analysis 8.

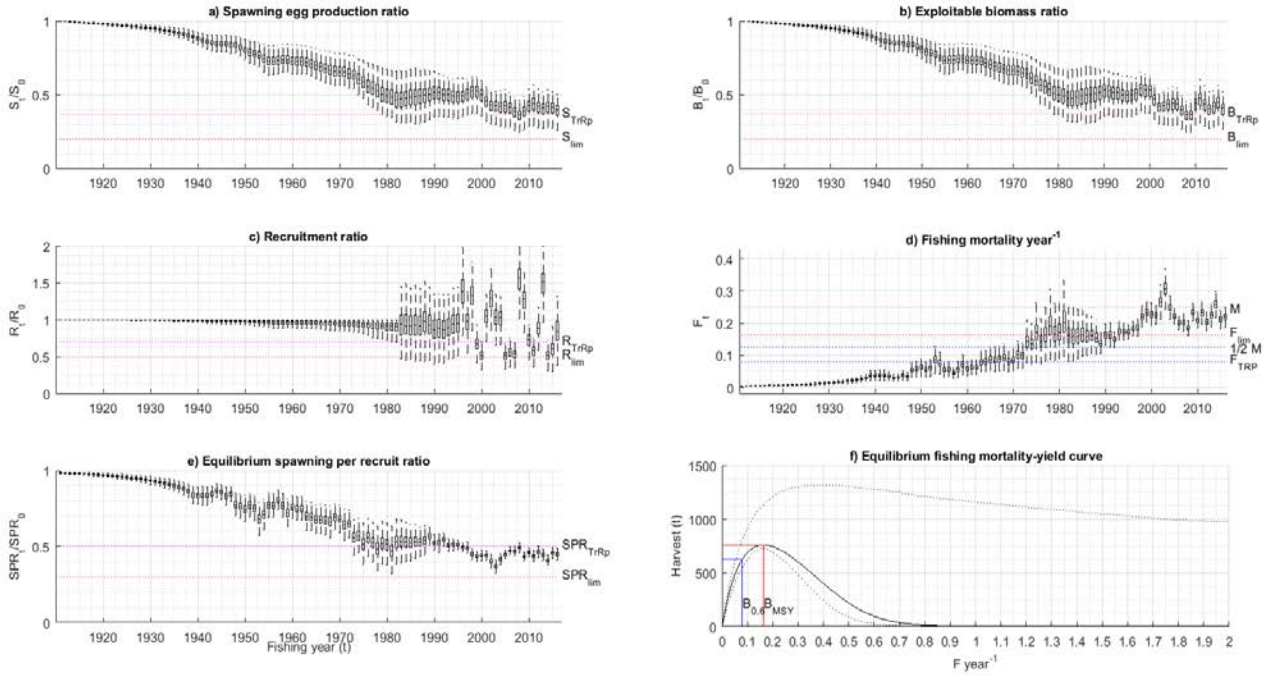

Figure 61. Predictions from analysis 9.

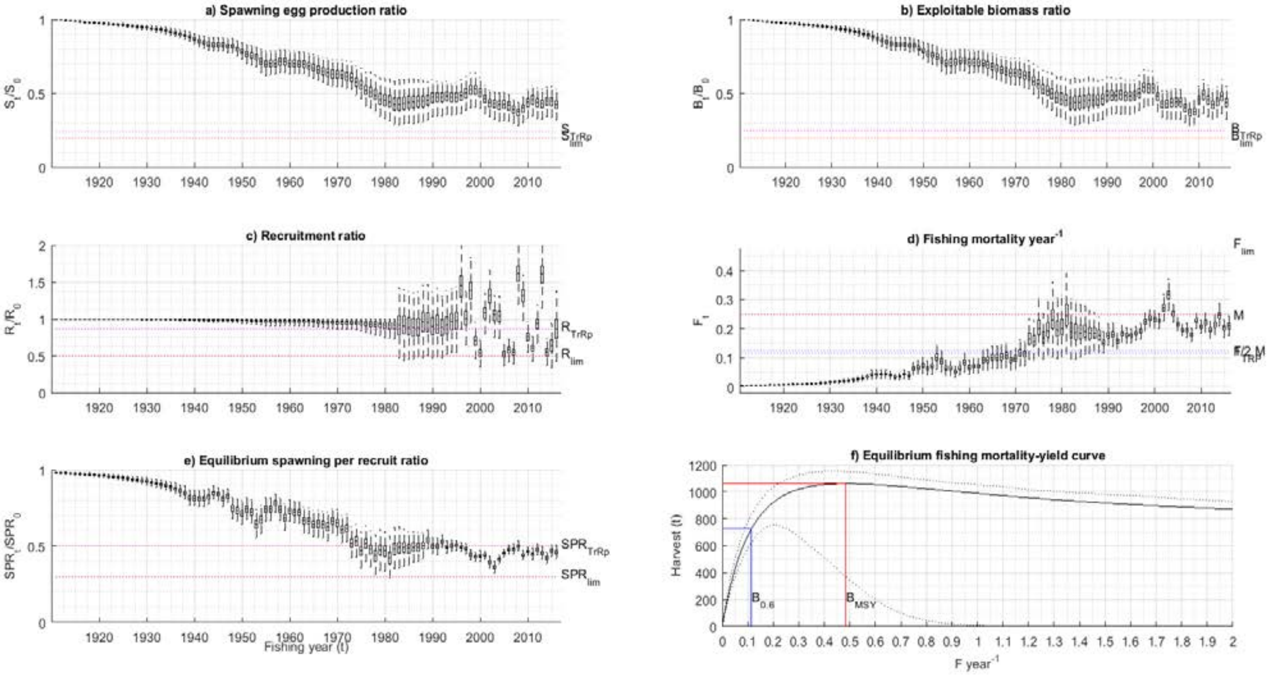

Figure 62. Predictions from analysis 10.

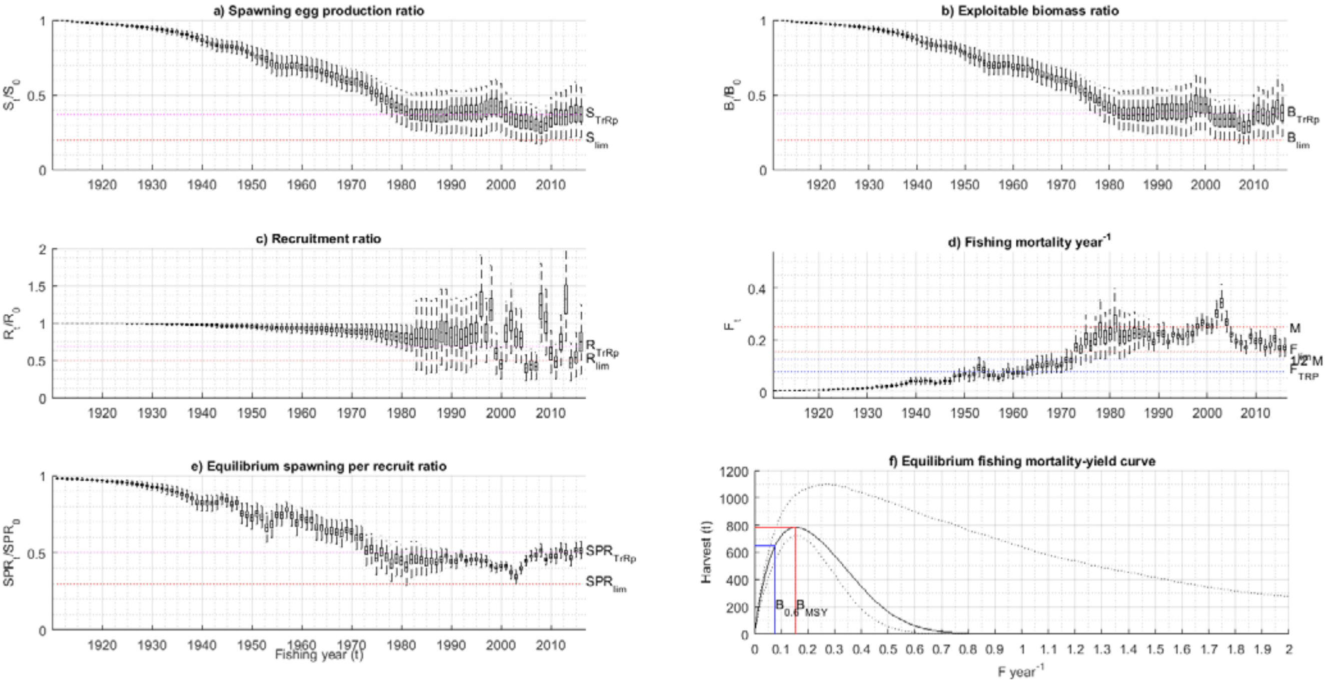

Figure 63. Predictions from analysis 11.

Table 17. Estimated management quantities for the 11 selected MCMC analyses. Median yields (tonnes) of east coast Spanish mackerel were tabulated along with the 25th and 75th percentiles in parenthesis. Definitions: B_{MSY} – exploitable biomass for maximum sustainable yield (MSY), $B_{0.6}$ – 60 per cent of virgin 1911 exploitable biomass, B_{2016} – year 2016 exploitable biomass, F_{MSY} – level of fishing mortality for attaining B_{MSY}, $F_{0.6}$ – level of fishing mortality for attaining $B_{0.6}$. The equilibrium B_{MSY} and $B_{0.6}$ column values were illustrated in Figure 31.

Analysis No.	**F_{MSY} @ B_{MSY}**	**$F_{0.6}$ @ $B_{0.6}$**	**$F_{0.6}$ @ B_{2016}**
1	1286 (1014 : 1727)	971 (778 : 1278)	679 (521 : 928)
2	1059 (912 : 1217)	815 (734 : 907)	837 (690 : 967)
3	675 (635 : 760)	600 (567 : 668)	370 (308 : 455)
4	927 (793 : 1135)	732 (646 : 862)	406 (307 : 528)
5	1174 (1022 : 1363)	813 (724 : 940)	625 (548 : 735)
6	941 (856 : 1058)	702 (652 : 780)	486 (429 : 556)
7	1067 (946 : 1181)	801 (742 : 868)	876 (762 : 980)
8	796 (697 : 1109)	682 (613 : 835)	551 (422 : 862)
9	1109 (958 : 1345)	811 (712 : 950)	552 (457 : 670)
10	1029 (919 : 1170)	731 (669 : 815)	535 (472 : 616)
11	945 (835 : 1122)	730 (667 : 855)	481 (381 : 595)
Median yield (t)	1029	732	551