Stock assessment of the Australian east coast spotted mackerel (*Scomberomorus munroi*) fishery

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Queensland Government

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Executive summary

Australian east coast spotted mackerel, *Scomberomorus munroi*, is a pelagic fish species that forms a single genetic stock in New South Wales and Queensland waters. Spotted mackerel exhibit schooling behaviours that form prominent spawning and feeding aggregations between Cairns and Port Stephens. When present, their highly aggregated, near surface, and catchable behaviour makes them susceptible to overfishing.

Catches of spotted mackerel peaked around 700 t in the 2001–02 fishing year. Over 90% of this harvest was from Queensland waters. In 2013–14 harvest was approximately 45% recreational and 55% commercial, with 80% of the total harvest from Queensland waters.

Management changes were implemented in 2003, including a limit on ring netting and establishment of a total allowable commercial catch of 140 tonnes. Quota utilisation since then has averaged 53%, with lows of 20% and 31% harvested in 2007–08 and 2016–17 respectively, while the maximum quota utilisation of 80% was harvested in 2004–05.

The previous stock assessment for spotted mackerel included data up to 2002–03. The assessment suggested that the stock was being harvested near or exceeding sustainable levels. It suggested the biomass was in the range of 33–66% of virgin biomass. Total harvest at maximum sustainable yield (MSY) was estimated between 296–570 t and that a total harvest of less than 300 t was required to increase the biomass to MSY levels.

This stock assessment update includes annual estimates of spotted mackerel harvests up to 2016–17, along with commercial catch rates and fish age-length compositions for both commercial and recreational sectors. The assessment combined data in an annual age-structured population model tailored for the biology, management and fishing history of spotted mackerel. The age-structured population model analysed 252 scenarios based on different combinations of input data, including harvest histories, age structures, standardised catch rates and considered both high and low estimates of natural mortality.

The analyses indicated that before the limit on ring netting, fishing mortality was as high as two to three times natural mortality, and this resulted in reductions of stock size to approximately 25–40% of virgin biomass (in 1998–2004). Since the implementation of management changes fishing mortality has dropped to below limit reference points and the analyses predicted that spotted mackerel biomass has slowly increased.

Lower estimates of stock size averaging around 21% of virgin biomass were obtained from scenarios that included low levels of natural mortality (M=0.42) and no standardised catch rates. In contrast, higher estimates of stock size, averaging 41% of virgin biomass, were obtained from scenarios that included high levels of natural mortality (M=0.57) and standardised catch rates

Further detailed investigations were undertaken on a subset of eighteen of the scenarios. Of these eighteen analyses, nine provided successful model fits, with these all corresponding with the higher level of natural mortality (M=0.57). The results from the nine successful analyses suggest that the biomass of spotted mackerel in the 2016–17 fishing year ranged between 40–60%, and were therefore between trigger and target reference points. Other health parameters, including spawning egg production, recruitment and spawning per recruit were also within the trigger and target reference points.

The results suggest that the MSY harvest target is 215 t per year (including all sectors and jurisdictions). Assuming a stable level of recreational harvest of around 70 t (based on

2013–2014 Queensland statewide recreational fishing survey), total harvest (for years 2009–10 to 2016–17) has ranged between 114–207 t. This total harvest has been below the suggested MSY harvest level. Rebuilding of the stock to 60%, as outlined by the Sustainable Fisheries Strategy, requires a total harvest between sectors and jurisdictions of 80-120 t.

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1 Acknowledgements

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2 Scope

The assessment was conducted on the whole (genetic east coast) spotted mackerel stock across jurisdictional waters of New South Wales and Queensland. Estimates of fish population size and limits on annual fishing include data from commercial, charter and recreational fishing sectors in both jurisdictions.

Estimates of spotted mackerel recreational harvests included all retained fish and 50 per cent of non-retained fish. The reasons for including 50 per cent non-retained fish were a) significant release numbers were estimated by recreational fishing survey programs, b) anecdotal evidence of high mortality rates for non-retained fish, and c) use of 50 per cent survival/mortality rate, rather than a higher value, to offset risks of inflated recall bias in non-retained fish estimates.

The assessment covered the fishing years 1961–2017. 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 spotted 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.

Queensland’s *Sustainable Fisheries Strategy 2017–2027* (the Strategy) 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 spotted mackerel provide information on setting sustainable fishing and harvest limits to achieve the 2020 objectives under the Strategy: i.e. reach a fish population size of 40–50 per cent of the original unfished level. Results also provide insights on what is required by the fishery to meet the 2027 objective of 60 per cent fish population size described in the Strategy.

Estimated reference points of annual harvest tonnages were calculated for the whole east coast spotted 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.

3 Definitions

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_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 1961.
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.
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 extreme estimates that were not considered outliers.
B_{TRP}	Target biomass: the desired biomass of the population. The reference point refers to the target objective, e.g. the 60% biomass target by 2027 in the Queensland Sustainable Fisheries Strategy. It is referred to as B_{MEY} by the Australian Government where 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}.
Catchability q	The ability to catch fish. More formally 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.
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.
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 the average for the time period investigated. The elements of fishing power and catchability have the potential to bias abundance indices derived from nominal catch rates. Therefore, methods of standardisation are required based on the data at hand.
Fishing year	Months July–June. Also labelled as 'year' within. Fishing years were equal to financial years to group the seasonal and biological patterns of spotted mackerel. Labelling used the second year in the financial year string. For example, the financial year July 2015 to June 2016 was labelled as the 2016 fishing year.
Fishery	The stock assessment evaluated Australian east coast spotted mackerel. The assessment was conducted for the whole (genetic) stock across jurisdictions and

	included commercial, charter, recreational and research data from both New South Wales and Queensland. The fishery covers all fishing sectors: commercial, charter, recreational and traditional indigenous.
FRDC	Fisheries Research and Development Corporation, Australian Government, www.frdc.com.au
GLM	Generalised linear model. A flexible linear model that allows distributions that are not normal.
GLMM	Generalised linear mixed model is an extension of a GLM, where the linear predictor includes random effects.
LTMP	Now formally known as ‘Fishery Monitoring’ – Fisheries Queensland’s long-term monitoring program, Queensland Department of Agriculture and Fisheries.
MCMC	Monte Carlo Markov Chain: statistical computer simulation method for estimating population model parameters and their variance.
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.
NIRFS	National Recreational and Indigenous Fishing Survey.
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.
RFISH	Fisheries Queensland’s Recreational Fisheries Information System.
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.
SWRFS	Fishery Queensland’s State-Wide Recreational Fishing Survey.
Vulnerability	Probability of fish being exposed to fishing mortality. This varies for different sized fish. This is generally a result of fish being present in the fishing area (fishery) and is subject to their susceptibility of being caught by the fishing gear.

4 Introduction

Spotted mackerel (*Scomberomorus munroi*) are tropical–subtropical pelagic fish endemic to Australasian waters. Their distribution around Australia is between Coffs Harbour on the east coast and the Abrolhos Islands on the west coast north to southern regions of Papua New Guinea (Munro 1943; Collette and Russo 1984).

The species forms a single stock along eastern Australia, as determined through genetic, tag-recapture and otolith elemental data (Begg et al. 1997; Begg 1998; Begg and Sellin 1998; Begg et al. 1998; Cameron and Begg 2002). They are located in east coast waters of less than 100 m depth, forming highly aggregated schools near the surface.

Spotted mackerel movements are seasonally predictable as they migrate from spawning grounds in north Queensland (Qld) waters during winter and spring, to southern waters feeding on baitfish during summer and autumn (Begg 1998). Spawning generally occurs between Townsville and Mackay, producing pelagic eggs and sperm that mix and are dispersed through water currents (Begg 1998).

Growth occurs quickly in their early years, showing sex specific growth rates with female spotted mackerel growing faster and reaching larger sizes than males (Begg and Sellin 1998; Begg et al. 2005). Sexual maturity is generally reached by 2 years of age (Begg and Sellin 1998; Begg et al. 2005). Age studies on spotted mackerel indicate they can reach 10 years of age and measure up to approximately 1.1 m in length (Fisheries Queensland 2017).

Fishing pressure on east coast spotted mackerel commenced building from the early 1960s. Annual east coast harvests taken by commercial, charter and recreational fishers increased during the 1990s to 2002–03, with annual harvest peaking around 700 t in 2001–02. Over 90% of this harvest was from Queensland waters. Sustainability concerns and evidence of reduced recreational catch during the 1990s led to the completion of a stock assessment to determine the ongoing status of the stock (Begg et al. 2005).

Up until the early 2000s, fishing pressure was mostly unconstrained, with high-yielding commercial ring and gill net operations dominating harvests to fill commercial markets. The previous stock assessment indicated that ring-gill net operations were in order of 25+ times more powerful at harvesting schools of spotted mackerel than line fishing (Begg et al. 2005). In addition, the results suggested over fishing was occurring and the report recommended limits on fishery-wide harvests of less than 300 t.

Sustainability concerns, complaints and evidence of failed line fishing during the 1990s and early 2000s led to revised fishery management procedures in Queensland implemented in May 2003. These amendments aimed to improve the sustainability of the fishery, with important management changes including:

- Increase in the minimum legal size to 60 cm total length (up from 50 cm),
- Recreational possession limit of five spotted mackerel (down from 30),
- Commercial net in-possession limit of 15 spotted mackerel per licence,
- Commercial line in-possession limit of 150 spotted mackerel per licence, and
- Nominal annual commercial competitive quota of 140 t.

In 2008, management changes removed the commercial line in-possession limit of 150 and increased the net in-possession limit to 50 fish per licence when the reported commercial harvest for the year was less than 100 t. This was to promote the increased harvest of the 140 t quota by commercial line and net fishing, which did not happen.

Management intervention was actioned to limit the targeted fishing of spotted mackerel using nets, along with a total allowable commercial catch (TACC) set at 140 t per annum (Table 1). Since 2001–02, the majority of reported harvest has originated from line fishing. However, a fisheries regulation amendment (No. 5, 2008) changed the 15-fish incidental net in-possession limit per licence to 50 fish and allowed over-catching of the TACC (competitively fished with no individual allocations), although the TACC has never been reached since its introduction.

In 2017, the Qld Department of Agriculture and Fisheries commissioned the present stock assessment update for spotted mackerel. This update aimed to evaluate recent levels of harvest and mortality rates suggested by fish age-length information. The report informs estimates of sustainable harvests that will maintain the New South Wales (NSW) and Qld fishery, including both commercial, charter and recreational sectors.

5 Methods

5.1 Fishery data and history

5.1.1 Data sources

Fish harvest and effort data were analysed from the anticipated start of fishing in 1961 until the end of the 2016–17 financial year (June 2017). Commercial harvests of spotted mackerel were recorded in the Qld compulsory logbook system. This data consisted of daily harvests of all fish species from each individual fishing operation (licence) since 1988. Data on the NSW commercial harvest was collected by their compulsory logbook system, which began in 1985. Recreational catches of spotted mackerel (both retained and non-retained) were estimated from eight Qld state-wide surveys (between 1995 and 2014), along with two surveys in NSW. Detailed descriptions of this data can be found in O'Neill et al. (2018).

5.1.2 Management and research history

There have been various management changes within the spotted mackerel fishery since 1984 when limited entry for commercial fishers was introduced (Table 1). The most impactful changes were introduced in the early 2000s, which included a recreational in-possession limit of five fish, prohibition of the use of nets to target spotted mackerel commercially, and an annual TACC of 140 t (Table 1). These amendments aimed to improve the sustainability of the fishery and change sectoral dynamics through reduced total harvests that resulted in a reduction of harvest by net operators and an increase in harvest by line operators, reducing overall fishing pressure on the stock (Fisheries Amendment Regulation No. 5 2008, Table 1, Figure 2).

During the history of the fishery, numerous research projects improved understanding of the species biology and population spatial structure, and in turn informed management and understanding of the fishery (Table 2).

Table 1. History of spotted mackerel management in Queensland and New South Wales

Year	State	Management
1984	**Qld**	Limited entry for commercial net and line fisheries (i.e. vessel licences capped).
1990	**NSW**	Recreational in-possession limit of 5 spotted mackerel per fisher.
1990 (May 22)	**Qld**	Repeal of section 35 of the Fishery and Industry Organisation and Marketing Act making the sale of recreational harvests unlawful.
1994	**NSW**	Commercial in-possession limit of 10 fish introduced.
1995 (Dec 1)	**Qld**	Minimum legal size of 50 cm total length (TL). Recreational in-possession (bag) limit of 30 spotted mackerel per fisher.
1997 (Dec 19)	**Qld**	Declaration of Dugong Protection Areas and resultant netting area restrictions (commenced 12 January 1998).
2002 (Apr 8)	**Qld**	Investment warning for the commercial harvest of spotted mackerel.
2002 (Dec 6)	**Qld**	Minimum legal size of 60 cm TL. Recreational in-possession limit of 5 spotted mackerel per fisher. Annual TACC of 140 t (1 July – 30 June). Commercial line operators required to prior-report harvests before landed on shore. This was only for harvests greater than 15 spotted mackerel caught within a 24-hour period.

2002 (Dec 6)*	**Qld**	Prohibition on the use of nets to target spotted mackerel (but deferred until May 2003). Commercial line in-possession limit of 150 spotted mackerel per licence. Commercial net in-possession limit of 15 spotted mackerel per licence.
2003 (May 1)	**Qld**	No targeted netting for spotted mackerel allowed – end of the phase-in period.
2003 (Dec 19)	**Qld**	Commercial net limit of 15 spotted mackerel entered in legislation.
2008	**Qld**	Removed the commercial 150 spotted mackerel in-possession limit for line fishing. Increased the net in-possession limit to 50 fish per licence.
2010	**NSW**	Minimum legal size of 60 cm TL introduced.
Current regulation	**Qld**	Minimum legal size of 60 cm TL. Regulations include a commercial 140 t TACC. While the annual commercial harvest tally ≤ 100 t, a 50-fish net in-possession limit per licence applies and line fishing has no limit. When the harvest tally reaches 100 t, the net limit is reduced to 15 fish. Line fishing continues unlimited. If the harvest tally > TACC, then the in-possession limit for both line and net caught fish is 15 fish. Spotted mackerel fishing can continue. Recreational in-possession limit of 5 spotted mackerel per fisher.

*The netting limit was phased in until 1 May 2003. Therefore, from 6 December 2002 to 30 April 2003, fishers could continue to net for spotted mackerel with an in-possession limit of 150 fish. From the 1 May 2003, fishers could only take harvests of 15 fish or less by net and 150 in-possession by line. Due to a drafting oversight, the net limit of 15 fish was not legislated until 19 December 2003.

Table 2. History of spotted mackerel research

Year	Author	Research
1943	**Munro**	Taxonomic review of Australian *Scomberomorus* species, including spotted mackerel, describing nomenclature, distribution and morphological features. Identified spotted mackerel as *S. niphonius*, Japanese Spanish mackerel.
1980	**Collette and Russo**	Identified spotted mackerel as a separate species from *S. niphonius*.
1981	**Lewis**	Screened spotted mackerel from Australian waters for genetic polymorphisms, as part of a broader study of the ecological genetics of *Scombrids*.
1982	**Okera**	Macroscopically estimated the maturation stage of gonads from spotted mackerel sampled in the Arafura Sea and Gulf of Carpentaria.
1984	**Collette and Russo**	Described the morphology, systematics and distribution of 18 species of *Scomberomorus*, including spotted mackerel, to clarify relationships and systematic position within the Family Scombridae.
1996	**Begg**	Species coexistence, stock structure and fisheries management of spotted mackerel in Queensland east coast waters.
1997	**Begg et al.**	Movements and stock structure of spotted mackerel in Australian east coast waters.
1997	**Begg and Hopper**	Feeding patterns of spotted mackerel in Queensland east coast waters.
1998	**Begg**	Reproductive biology of spotted mackerel in Queensland east coast waters.
1998	**Begg and Sellin**	Age and growth of spotted mackerel in Queensland east coast waters.

1998	**Begg et al.**	Genetic variation and stock structure of spotted mackerel in northern Australian waters.
1998	**Cappo et al.**	Stock discrimination of spotted mackerel in Queensland east coast waters using otolith elemental analysis.
2002	**Cameron and Begg**	Fisheries biology and interaction in the northern Australian small mackerel fishery. Gill net drop-out in the spotted mackerel ring net fishery.
2003	**Ward and Rogers**	Review of current and future research needs for mackerel (*Scomberomorus*) in northern Australian waters.
2005	**Begg et al.**	Stock assessment of the Australian east coast spotted mackerel fishery.
2007	**Robertson et al.**	Identification of small juvenile Scombrids from northwest tropical Australia.

5.1.3 Commercial harvest trends

Data has been summarised across five regions along the Australian east coast. These five regions include Lockhart to Lucinda, Bowen and Mackay, Rockhampton and Fraser Coast, Sunshine Coast to Gold Coast and NSW, with the locations and boundaries of these regions illustrated in Figure 1. Average catch totals throughout the history of the compulsory commercial logbook period were approximately equal between the four northern regions of Qld. NSW had low yield up to 1998 but thereafter has continued to account for a significant portion of the total catch.

Qld’s commercial harvests are typically variable along the coast, with low harvests (< 2 t annually) recorded across vast areas, and small areas of targeted effort and increased harvest (up to 20 t annually) (Figure 1). These areas of increased harvest are generally located within one to two 30-nautical-mile grids within each region (Figure 1). In the northern most region (Lockhart to Lucinda), the majority of harvest is caught in the Mission Beach area (Figure 1). In the Bowen and Mackay region, the majority of harvest is caught in the Bowen area (Figure 1). In the Rockhampton and Fraser Coast region, the majority of harvest is taken around Fraser Island, while in the Sunshine Coast to Gold Coast region harvest predominantly occurs in Moreton Bay (Figure 1).

There was a steady increase in total commercial harvest from the late 1980s to a peak of nearly 400 t in the early 2000s (Figure 2). Management changes in the fishery resulted in reductions of the commercial harvest to ≤ 100 t following controls placed on net fishing in Qld in May 2003 (Figure 2). Since this time, total harvest has been predominantly line caught (Figure 2). Differences between harvests reported by Begg et al. (2005) and those in Figure 1, are due to improvements in data validation by Fisheries Queensland and methods to allocate portions of unspecified Qld mackerel catch to spotted mackerel catch based on reported catch through Qld and NSW commercial logbooks (Section 9.2).

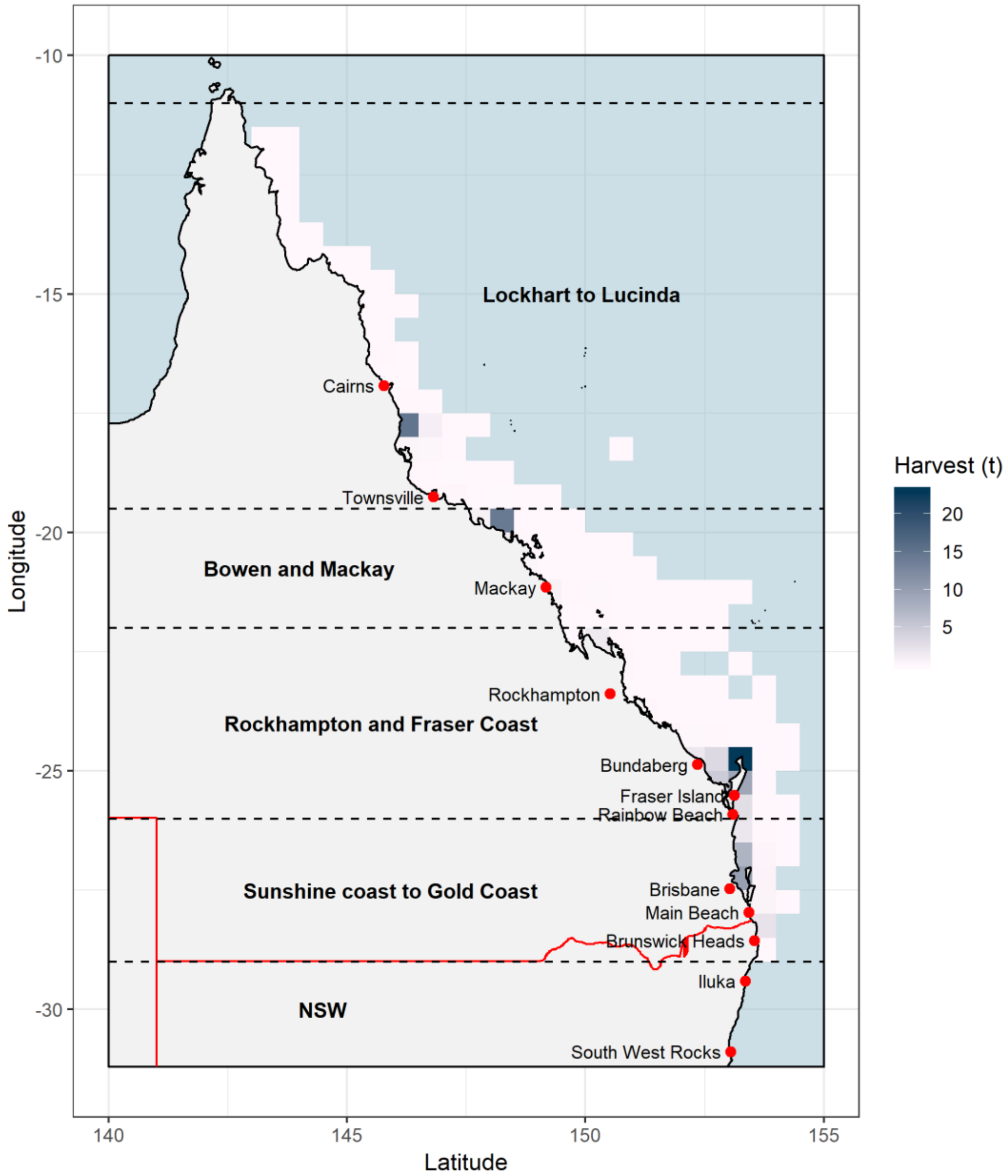

Figure 1. Map illustrating the location of the five regions used to summarise harvests with boundaries illustrated by the dashed horizontal lines. Average Queensland harvest (t) between 1988-98 and 2016-17 is also shown for each 30-nautical-mile grid square along the Qld east coast. Note that NSW harvest data are not included.

Regional patterns of commercial fishing along the east coast were reflective of spotted mackerel's seasonal movements and the impacts of management changes. The majority of harvest was originally from netting in the Bowen/Mackay and Rockhampton/Fraser Coast regions in the late 1990s and early 2000s (Figure 3). Since 2003, total harvests in all Qld regions have declined, and this is particularly evident in the Bowen/Mackay and Rockhampton/Fraser Coast regions, where ring netting dominated harvests prior to management intervention (Figure 3). Harvests in the northern most region (Lockhart to Lucinda), have been variable throughout the entire time series (Figure 3). Since 2013 NSW has taken a greater proportion of the total harvest than previously and this particularly evident in 2016-17 (Figure 3).

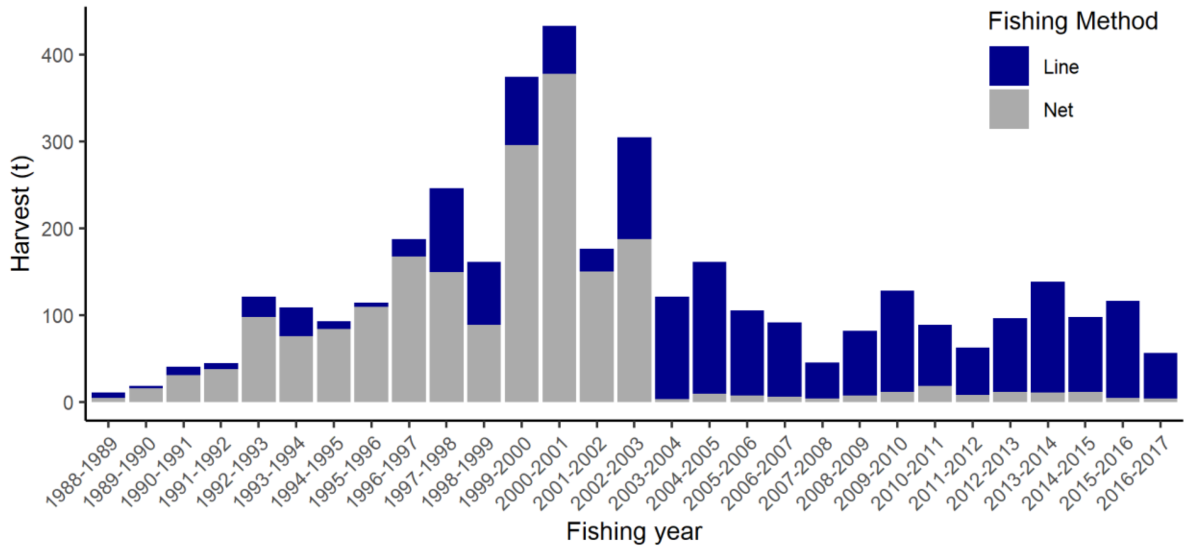

Figure 2. Reported annual commercial harvest (t) of spotted mackerel for both line and net fishing from Queensland and northern New South Wales east coast waters between the fishing years of 1988–89 to 2016–17.

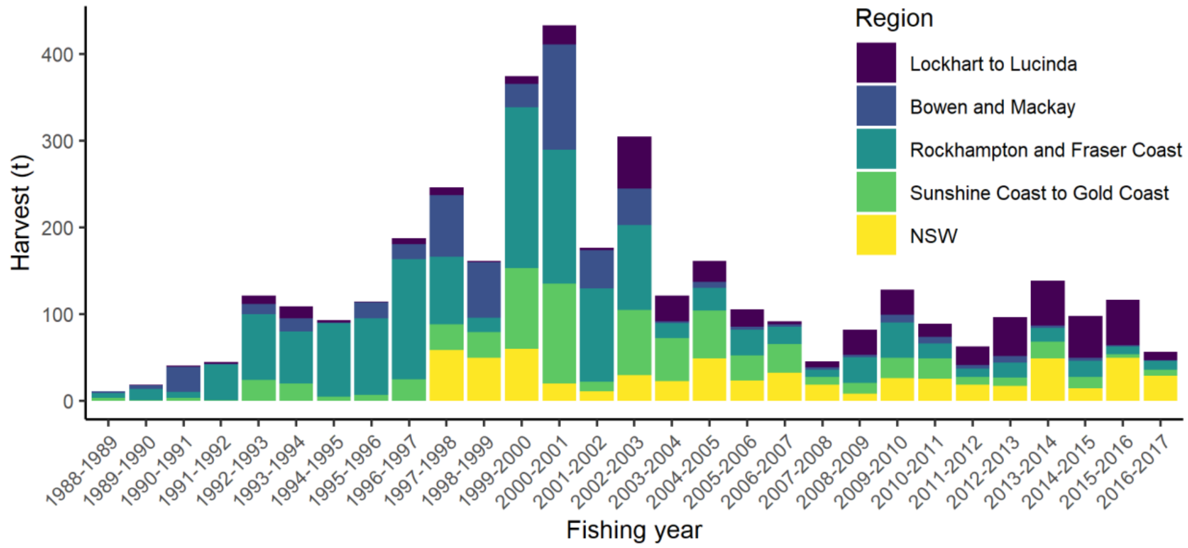

Figure 3. Annual regional commercial harvest (t) of spotted mackerel from Queensland and northern New South Wales east coast waters between the fishing years of 1988-89 to 2016-17.

The seasonal movement of the stock was evident in the monthly harvest patterns of each region (Figure 4). Proportions of catch in each region and month also varied before and after management intervention (Figure 4). Prior to management intervention (1988–2003), during the summer and autumn months (Dec-Apr), the majority of the harvest was taken in the Rockhampton and Fraser Coast region, which peaked in Dec and Jan (Figure 4). Additionally, during Dec-Apr harvests in the Sunshine Coast to Gold Coast region were also higher than other months of the year (Figure 4). NSW harvests were highest in Jan-Apr. In Jul-Aug harvests were mainly taken in the Lockhart to Lucinda region, and Bowen and Mackay region (Figure 4).

Following management changes (2004–2017), the average monthly harvest across all months declined (Figure 4). This decline was most apparent in the Rockhampton to Fraser

Coast region where ring netting was the predominant fishing method (Figure 4). The average harvest in the Bowen and Mackay region also declined, while the average catch in the Lockhart to Lucinda region increased (Figure 4). The average harvest in NSW increased in Mar, Apr and May post management changes (2004–2017) (Figure 4).

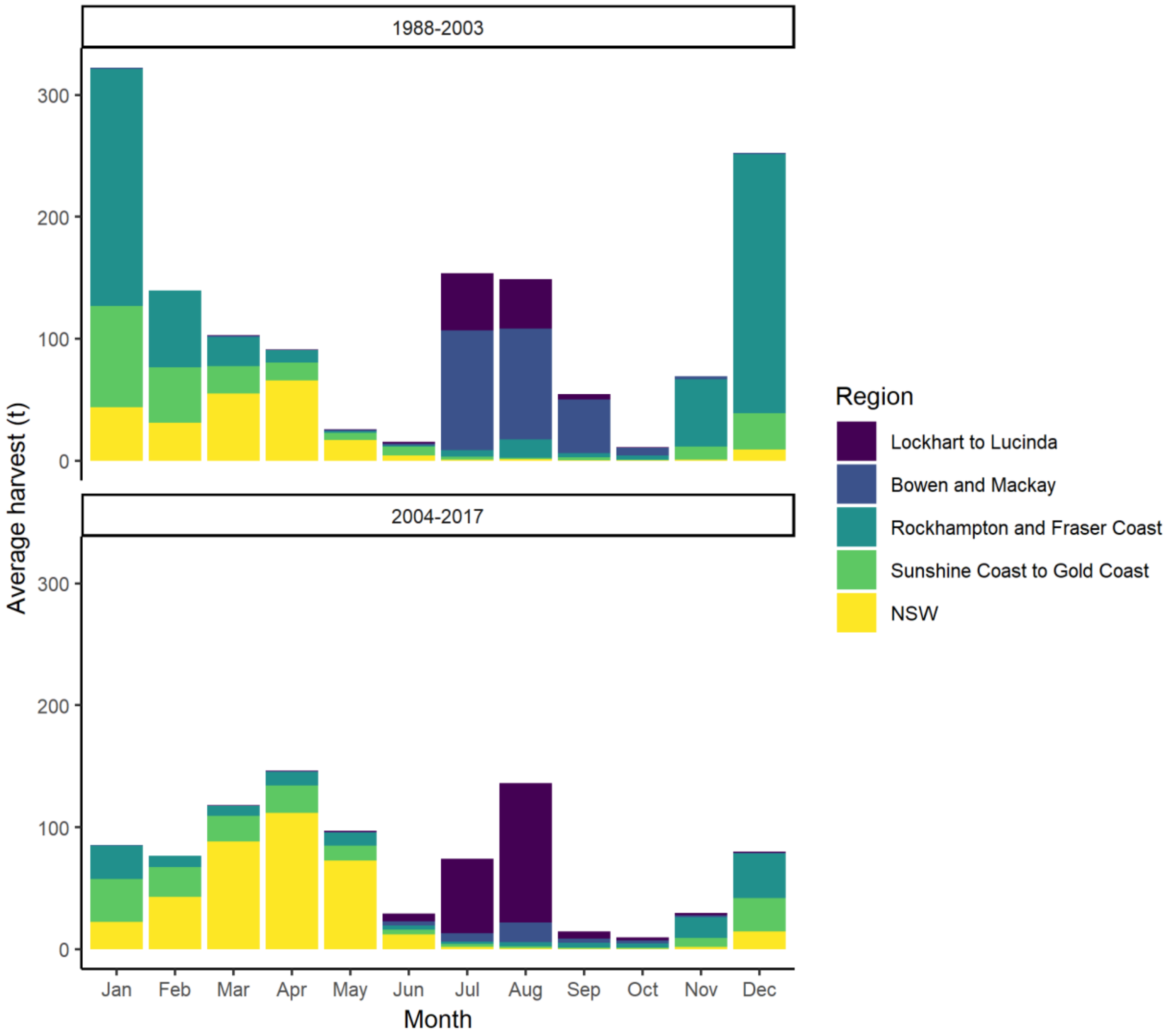

Figure 4. Average commercial harvest (t) of spotted mackerel by month–region, averaged over the years prior to major management intervention (1988-2003) and following the management changes (2004-2017).

5.1.4 Recreational harvest trends

Recreational harvest estimates of spotted mackerel were highest in 2001, with a total harvest of approximately 255 t that included 50% discard mortality of non-retained fish (Figure 5). This has reduced in recent years (2010-11 and 2013-14) and is currently estimated between 58–70 t (Figure 5a). This reduction in recreational harvest is consistent with the reduction in commercial catch over this period (Figure 2, Figure 5). The majority of recreational harvest is taken from Qld (Figure 5a).

The majority of spotted mackerel caught by recreational fishers were retained (Figure 5b) and this retained proportion of the catch has remained relatively consistent through time (Figure 5b).

Surveys conducted in 1995, 2001, 2011 and 2014 had more effective follow-up contact procedures with diarists resulting in less dropout of participants compared to the other survey years using RFISH methodology (Fisheries Queensland, pers. comm.). Therefore for surveys conducted in 1997, 1999, 2002 and 2005 using RFISH methodologies, estimates were adjusted using the ratio method and were calculated at 0.42 for retained and one for non-retained spotted mackerel (O'Neill and Leigh 2007). These adjustments made the estimates of fish catches more comparable between surveys.

When calculating total recreational harvests, half of the non-retained estimates of spotted mackerel were tallied into the retained estimate to account for suspected discard mortality (O'Neill et al. 2018). A portion of the unspecified mackerel catches were allocated to spotted mackerel by applying the proportion of spotted mackerel catch from other mackerel species and including this proportion of unspecified retained and non-retained totals from each survey.

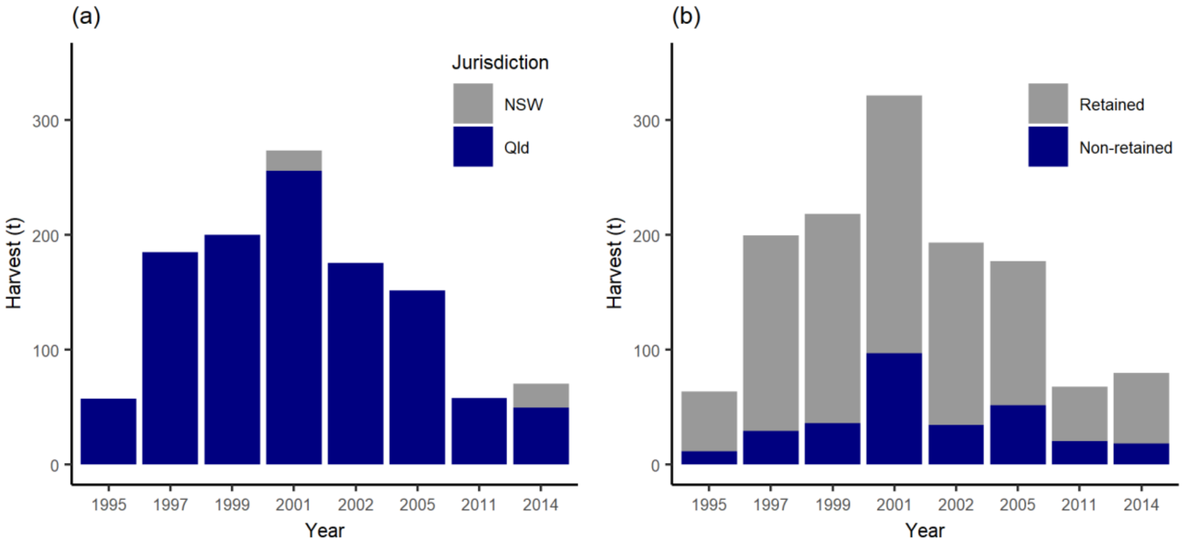

Figure 5. Estimated recreational harvest (t) since 1995 of spotted mackerel in (a) both Queensland and New South Wales, and (b) illustrating the proportion of the retained and non-retained harvest.

5.2 Fish age data

Annual fish age and length structures for spotted mackerel have been monitored using fishery-dependent techniques since 2005–06. Sampling is conducted for both recreational and commercial line caught fish from across the major spatial extent of the fishery from Cairns to the Gold Coast. Each year, the recreational and commercial harvest is representatively sampled for lengths, with a subsample of these fish sampled for otoliths (Fisheries Queensland 2010a,b). The collection of length data is in 10 mm length classes and a maximum of 20 otoliths are randomly sampled from each length class in each fishing year (Fisheries Queensland 2010c). The macrostructure of whole otoliths is then interpreted to estimate fish age (Fisheries Queensland 2010c,2018). From these ages, an annual age-length key (ALK) was calculated. Annual age frequencies were then determined using age-length key methodology for each fishing sector (commercial and recreational).

5.3 Standardised catch rates

Please refer to O'Neill et al. (2018) for detailed methodology used to standardise catch rates. Briefly, Qld logbook data on commercial line catches (kg whole weight) of spotted mackerel per fishing-operation-day were used as an index of legal sized fish abundance measured by fishing year and separated into four regions along the Qld east coast. The methods below outline the concepts and procedures used to standardise mean (average) catch rates. Hereon, the term 'catch rate' means standardised catch rate unless otherwise specified.

Various metrics of catchability were used to standardise mean catch rates of spotted mackerel. This data includes elements of fishing power, measuring each fishing operation's ability to catch fish (O'Neill and Leigh 2007) and the spatial-temporal patterns of exploitation associated with the aggregation patterns of this species (Walters 2003; Carruthers et al. 2010; Marriott et al. 2017).

Standardisation components for fish catchability *q* included:

- Spatially weighted average catch rates through time across each of the four regions. This aimed to reduce bias introduced by systematic changes in the spatial distribution of fishing (Carruthers et al. 2011).
- Lunar phases, wind speeds and wind direction on each day, which can influence fish catchability.
- The seasonality of catch rates were modelled using sinusoidal data to identify the time of year. This minimised the number of model parameters.
- Increased fishing power and effort from better fishing operations, gear, techniques, knowledge and increased fishing time.

Fisheries Queensland sourced wind direction and strength data from the Bureau of Meteorology (BOM, Australian Government). The wind data was collected from 76 representative coastal weather stations along Qld east coast. The recorded measures of wind speed (km hour^{-1}) and direction (degrees for where the wind blew from) were converted to an average daily reading based on recordings between 3am and 3pm, within each latitudinal band along the coast. Missing values were imputed from the next nearest available measurement. From this data the north-south (NS) and east-west (EW) wind components were calculated. Squared wind components were also included for each wind direction variable, resulting in a greater proportional weighting for higher wind speeds.

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 luminance measure (lunar) followed a sinusoidal pattern and was copied and advanced 7 days (≈ ¼ lunar cycle) into a new variable to quantify the cosine of the lunar data (O'Neill and Leigh 2006). The two variables were modelled together to estimate the variation of harvest according to the moon phase (i.e. contrasting waxing and waning patterns of the moon phase).

Fishing power values were log-offset in the statistical analyses to standardise commercial mean catch rates. For details of fishing power determinations see O'Neill et al. (2018).

Commercial line-fishing records were available on when, where and how many spotted mackerel were caught, but data on 'zero' catches and fishing effort were not available. This probability adjustment, in addition to data on changing fishing powers were required to standardise commercial mean catch rates as an index of fish abundance.

The models used to standardised mean catch rates of spotted mackerel were completed using the software R (version 3.5.1, R Core Team 2017). The analyses used a generalised linear model (GLM) and a generalised linear mixed model (GLMM). The analyses defined:

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

The probability model included all possible days that could be fished in each region, based on the total number of days spotted mackerel were caught in each of the four Qld regions and was divided by the total number of days in the month to calculate the response variable (p). The model used a quasi-Binomial distribution with a logit link to account for overdispersion. The model included an interaction between region (reg) and year (year), with additive effects of fishing method (method), number of fishers that caught spotted mackerel in the month (n_acn), 12 month seasonal variables (c12 and cs12), 6 month seasonal variables (c6 and cs6) and wind variables (wind EW, wind EW^2, wind NS and wind NS^2). The probability of catching model was specified as:

> p ~ reg * year + method + n_acn + c12 + cs12 + c6 + cs6 + wind EW + wind EW^2 + wind NS + wind NS^2

The catch rate model included every daily spotted mackerel harvest each by each individual fisher. When multiple locations were recorded for a single fisher in a day the first location was retained. The model used a Gaussian distribution with the response variable, harvest per fisher day, log transformed. The variables modelled included additive effects of fishing year, fishing month, region, 12-month seasonal variables (c12 and cs12), 4 month seasonal variables (c4 and cs4) and wind variables (wind EW, wind EW^2, wind NS and wind NS^2). Fisher was included in the model as a random effect. The catch rate was converted to a proportional value by dividing by the average catch rate over the entire time period (1989–90 to 2016–17). Low recorded harvests prevented catch rates from being calculated for the 1988-89 fishing year. Three catch rate models were calculated for varying levels of fishing power adjustment (none, half and full). The catch rate model was specified as:

> log(harvest) + log(FP) ~ year + region + month + c12 + cs12 + c4 + cs4 + wind EW + wind EW^2 + wind NS + wind NS^2 + random(fisher)

GLMs were calculated using the ‘glm’ function, while GLMMs were calculated using the ‘lmer’ function, both in the lme4 package (Bates et al. 2015). The prediction of standardised mean catch rates were determined using the effects package (Fox 2003).

To ensure comparability of means between different regions, predictions were normalised annually as proportions measured against the mean catch rate and 95% confidence intervals were calculated for all predictions.

In total, six different annual indices of fish abundance between 1989 and 2017 were calculated from the Qld commercial line data. The six results included the three catch rate models, with each of these included on their own and then multiplied by the probability model to assess the effects of possible hyper-stability.

The six annual indices combined predictions across regions. Each region's prediction was weighted by their total harvest summed over years 1989–2017. The region weightings were scaled proportionally and kept constant over 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).

5.4 Population dynamics model

A population dynamic model was fit to the data to determine the number of spotted mackerel in each year and each age group from the start of fishing in 1961 to the current year (2016–17). The model takes into account births, growth rates, reproduction and mortality, and how these change though time. This analysis was conducted using MATLAB, version R2018a. Refer to O'Neill et al. (2018) for details of model specifics.

When examining the age-length distributions for this species between sectors (both commercial line and recreational) there appeared to be minimal differences between the two, therefore, fish vulnerability was assumed consistent between the commercial line and recreational sectors in the model (Figure 8).

The model included one sector, with commercial line, commercial net, charter and recreational harvests grouped together. Recreational harvests were only available for a small subset of years, so these were estimated from a proxy measure of fishing effort.

Fish growth estimation was calculated outside the model using a von Bertalanffy growth curve for each sex, based on each age group and corresponding fish lengths and weights. In this relationship, L_∞ was the average maximum fish length (cm) or weight (kg), k was the growth rate parameter determining how quickly the maximum size was reached and a_0 was the theoretical age at which the fish had no length or weight. As the age data available was representative of the fishery, therefore, there were few measurements of the length and corresponding age of fish below the minimum legal size (60 cm). This meant there was little data for the model to fit the downward curve at small lengths and weights. To account for this, the a_0 variable was fixed to zero to account for the decline. The age based maturity of females was taken from the relationship determined by Begg et al. (2005) in the previous stock assessment. Two levels of natural mortality were included in the model, with these based on the equations developed by Hoeing (2005) and Then et al. (2015) based on a maximum age of 10 years old.

6 Results

6.1 Standardised catch rates

Catch rates for line caught spotted mackerel fluctuated around the average (red dotted line) between 1988–90 and 2002–03 (Figure 6). Since 2002–03, catch rates and their variability have declined, reaching their lowest point in the 2016–17 year, with this representing a 52% decline in the catch rate over the 14-year period (Figure 6). Over this period, there were two distinct periods of catch rate decline, interspersed by a period of steady and then slight increase in catch rates (Figure 6). The first decline in catch rate was observed between 2003–04 and 2007–08 (Figure 6). There was relatively steady catch rates between 2007–08 and 2011–12, before a slight increase in 2012–13 (Figure 6). The increased catch rate in 2012-13 was the first time catch rates had been above the long-term average in six years (Figure 6). Following this peak in catch rates, there was a decline to the 2016–17 year that was the lowest catch rate observed in the 30-year time series (Figure 6).

Fishing power adjustments shifted the relative change in catch rates both up and down through the time series (Figure 7). Between 1989–90 and 1999–00, the full fishing power adjustment was higher than the catch rate without adjustment (Figure 7). The catch rate with half fishing power adjustments were between the full and no fishing power adjustment catch rates (Figure 7). Since 1999-00, the opposite trends have been observed (Figure 7). Full fishing power adjustments resulted in a decrease in the catch rate when compared to catch rates without adjustments, again the half adjustments were between the two (Figure 7).

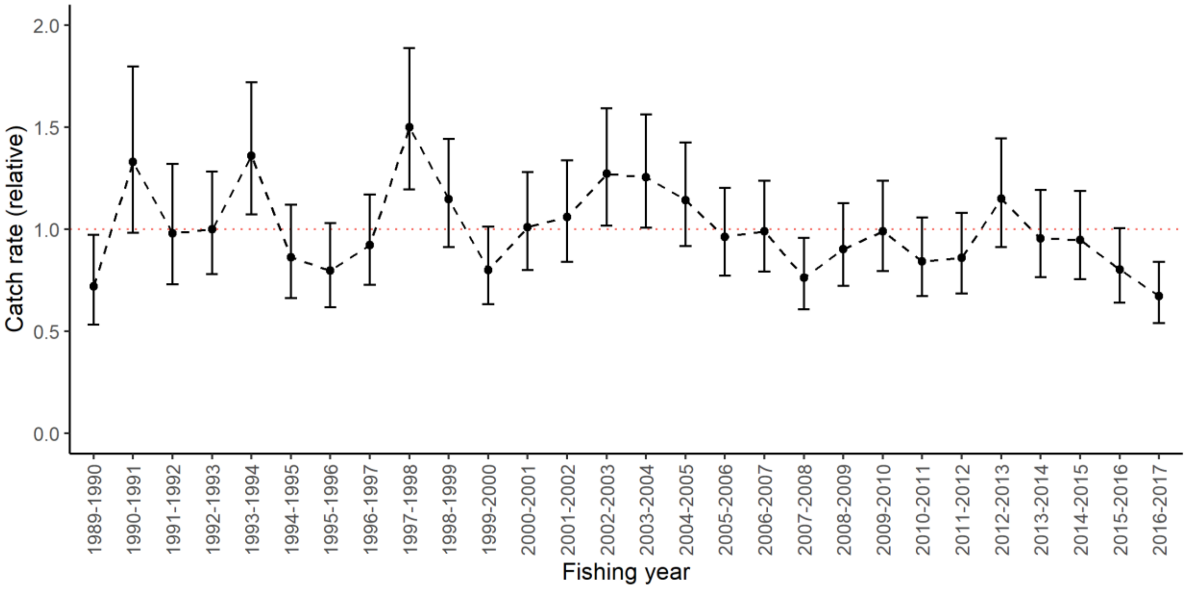

Figure 6. Standardised catch rates of commercial line harvested spotted mackerel, with no fishing power adjustments, between 1989–90 and 2016–17. The error bars represent 95% confidence intervals.

Including the probability adjustment with catch rates resulted in changes to the catch rates without probability adjustments (Figure 7). These differences are most apparent in the most recent years of the time series, particularly the decline in 2016-17 (Figure 7).

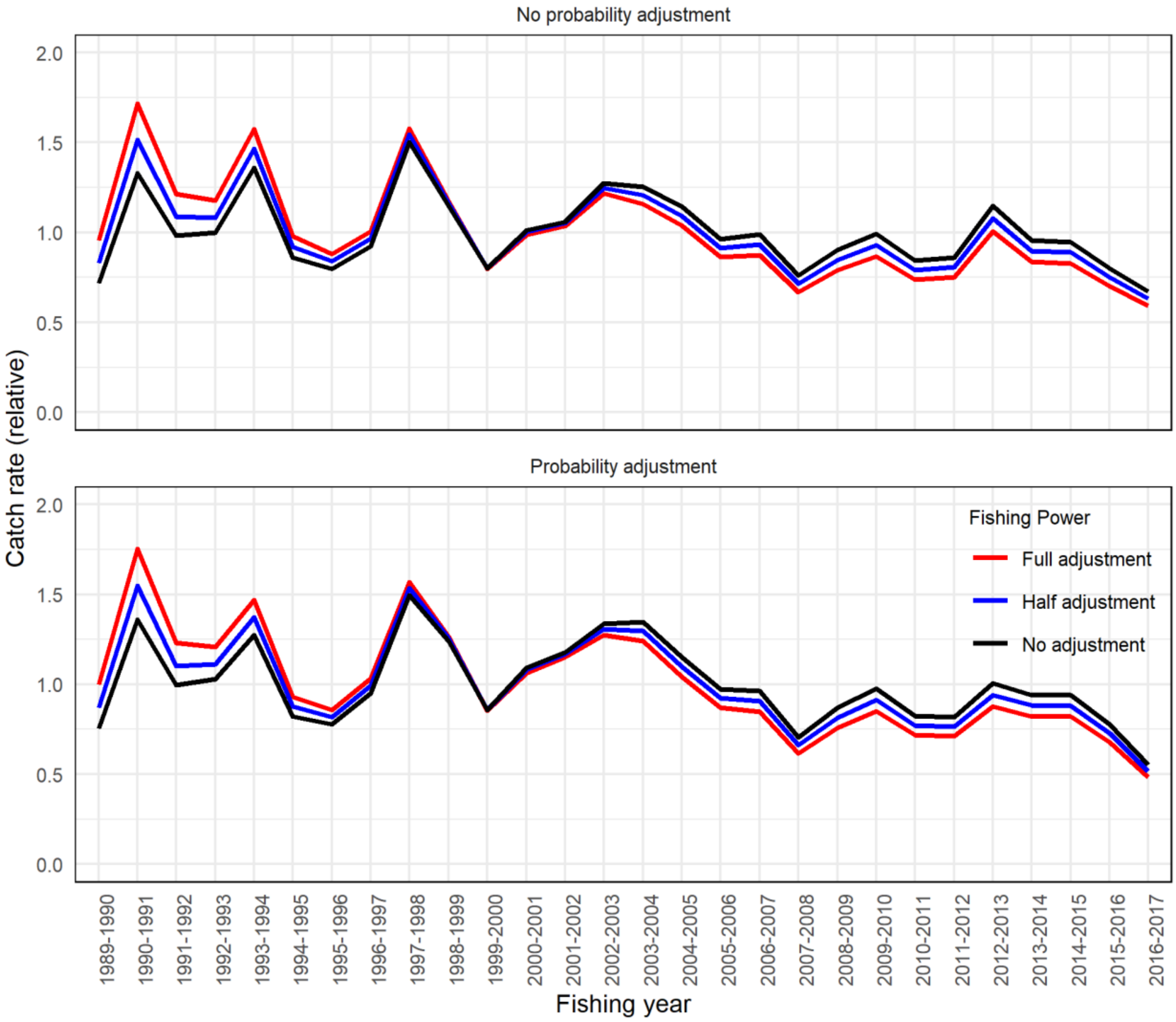

Figure 7. The six included standardised catch rates of commercial line harvested spotted mackerel between 1989–90 and 2016–17, including the three levels of fishing power offsets, no (black), half (navy blue) and full (red) adjustments and two levels of probability adjustment.

6.2 Fish age data

Routine, fishery-dependent biological monitoring of spotted mackerel commenced in the 2005–06 fishing year. This data demonstrates that on the east coast of Australia, spotted mackerel can live up to 10 years of age, with two to five year olds dominating the commercial and recreational catch (Figure 8). Spotted mackerel are considered to be fully recruited into the fishery by 2 years of age, with a relatively high proportion of 2 year olds often identifying years of strong recruitment (Figure 8).

Modelling of catch curves for individual years and fishing sectors revealed declines in the age frequencies of spotted mackerel from age group two to six. From this assessment, the slope of these models were averaged to give an estimate of total mortality (Z) through time (Figure 9). On average, there was more variance associated with the commercial data than the recreational estimates. Commercial line estimates were also generally higher than the recreational sector (Figure 9). Mean estimates were 0.89 ± 0.17 year^{-1} and 1.15 ± 0.36 year^{-1} for the recreational and commercial line sectors, respectively. In the years before 2006 when age sampling was not conducted routinely, estimates of total mortality were variable with differences observed between recreational and commercial estimates (Figure 9).

Since 2008, estimates consistently increased and reached the upper limit reference point of two times the natural mortality (Figure 9). This result suggested harvest rates of fish have increased and exceeded the target of reference point of ½ M, which is considered an appropriate target reference point for mackerel species (Welch et al. 2002).

Examination of catch curve model-residuals was unremarkable. They suggest no annual pattern of growing or weakening strength in fish recruitment. The cause of higher estimates of fish mortality since 2008 was unclear, but could indicate levels of unreported harvests, discard mortality or management changes from this time.

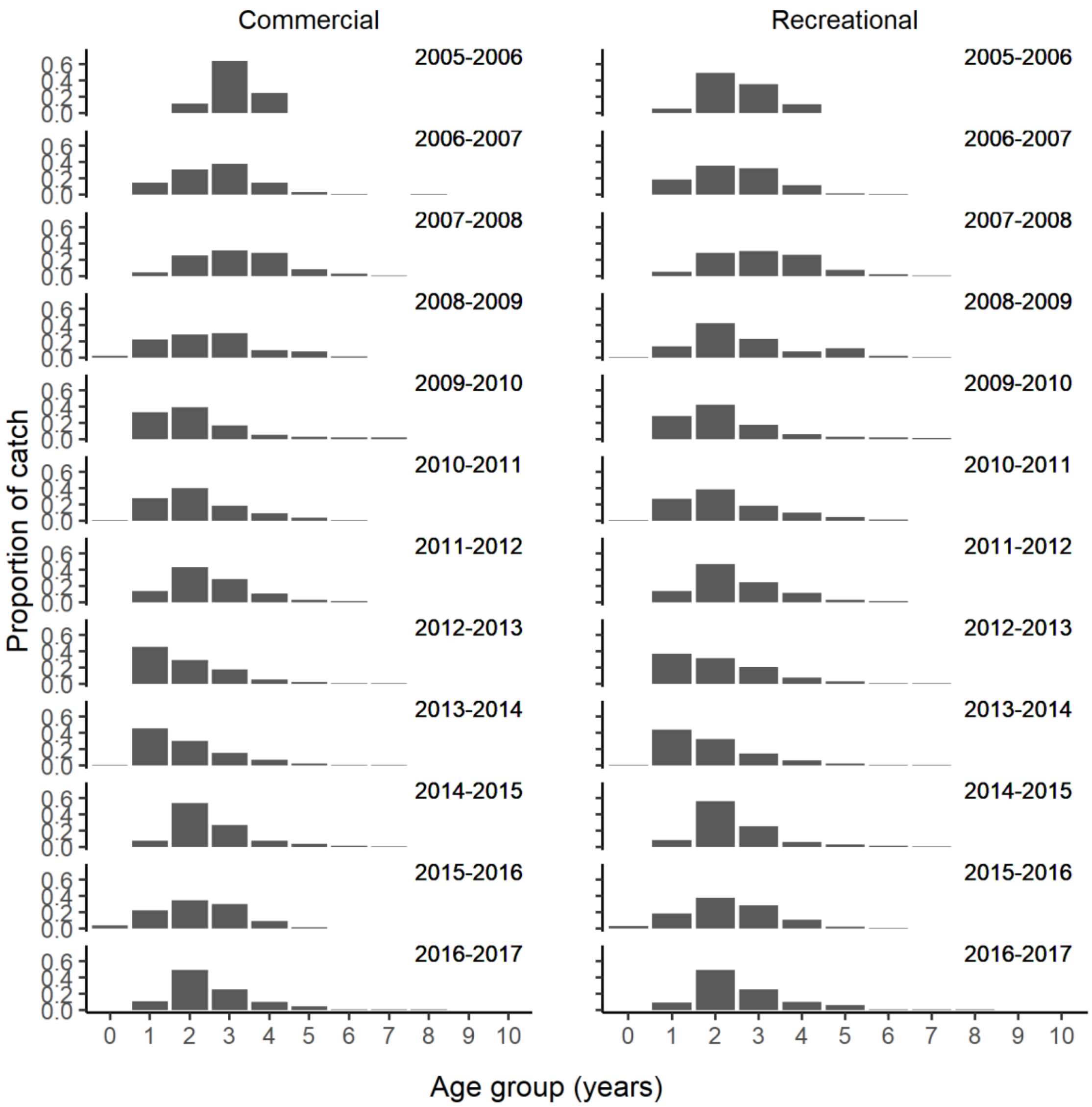

Figure 8. Annual age frequency distributions of spotted mackerel retained by the recreational and commercial line fishery between 2005-06 and 2016-17.

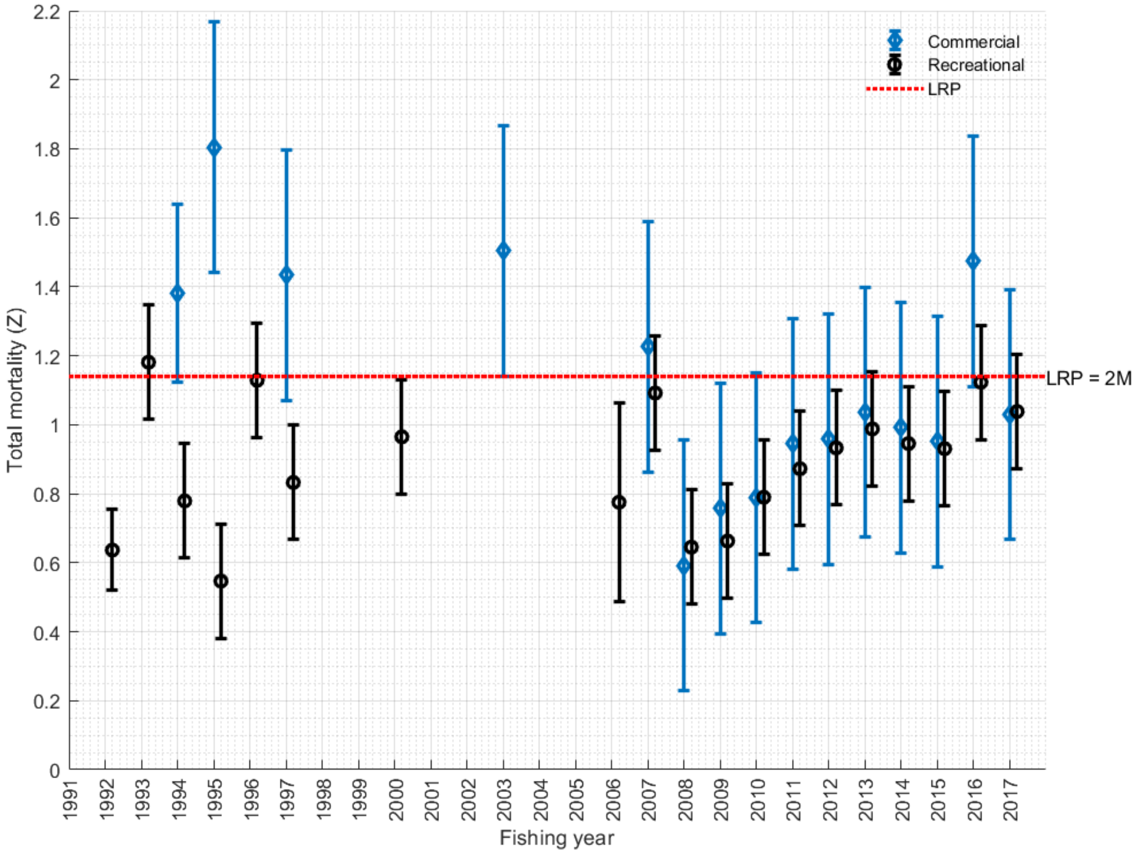

Figure 9. Linear catch curve measures of fish total mortality for each fishing year sampled. Error bars represent ± standard error. The limit reference point was twice natural mortality (M).

6.3 Population dynamics model

6.3.1 Data investigations

The stock model was run 252 times with different combinations of data to identify key results. The different combinations of parameters tested are detailed in Table 3. There were six time series of commercial catch rates, three measures of recreational fishing effort, two estimates of natural mortality and two methods of estimating the reproductive rate, with these resulting in 216 individual model combinations. In addition, 36 models were analysed with no catch rate included.

For each run, the results from the parameter values that maximise the model fit to the data were presented (maximum likelihood solutions; Figure 10). From the range of outputs, key states were selected for more detailed MCMC analysis and examination (Table 4).

The predicted stock status of spotted mackerel in 2016–17 are summarised in Figure 10. Across all data inputs, the spawning ratios ranged widely between 19–70%. Lower ratios resulted when not fitting to catch rate and only to fish age data, ranging from 19–25%. Assuming probability and fishing power standardised catch rates resulted in median ratios of 43%. We contend that the no hyper-stability (probability) and no fishing power adjustments produce hyper-stable catch rates and questionable results, with higher estimates. Results were similar between the varying levels of recreational and historical harvest during 1906–

88, although the recreational fish-harvest age frequencies predicted marginally lower spawning ratios compared to commercial age-frequencies (6% lower). Assumption of low natural mortality (M=0.42) predicted 13% lower spawning ratios compared to M=0.57.

Table 3. Data variables and settings for model inputs.

Data input	Number options	Explanation
Commercial Catch rate	6	Annual index of fish abundance 1990–2017. 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 7) and increased fishing power (0 = no increase; 0.5 = reduced; 1 = full increase; Figure 7).
Recreational Harvests	3	Recreational estimates of spotted mackerel harvest. The data were always used and recreational estimates included all kept fish plus 50% of non-retained fish assumed to have died. Analyses considered three variance estimates. They connect and add to total harvests.
Commercial and Charter Harvests	2	Commercial and charter logbook and recreational estimates of spotted mackerel harvest. There were two estimates for the fishing years 1961–1988, based on the 1989–2004 trend in total harvests. The two 1961–1988 estimates were 1) mean and 2) upper 95% confidence interval.
Fish age frequencies	3	Annual fish age structures of spotted mackerel harvests. Three combinations of data considered 1) commercial, 2) recreational and 3) both commercial and recreational.
Natural mortality (*M*)	2	Death rate due to natural causes (i.e. not fishing; logarithm scale). Two approaches were modelled: 1) fixed at 0.57 year^{-1} based on the Then et al. (2015) equation and a maximum age of 10.5 years and 3) fixed at 0.42 year^{-1} based on Pauly's schooling equation (Hoeing 2005).
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 lifetime at very low spawner abundance. The parameter estimation considered unrestrictive (0) likelihood-information for estimation.

Mean (equilibrium) predictions of harvest reference points for all fishing sectors and all waters ranged between 80–380 t (Figure 11). Lower levels of harvest (< 150 t) will build higher spawning egg production and exploitable biomass (towards $B_{0.6}$) (Figure 11). Higher annual harvests in order of or exceeding 220 t will limit rebuilding of the population to 60% levels within 5 years. Such levels of extended harvest will direct biomass and spawning egg production to around or less than B_{MSY} (Figure 11).

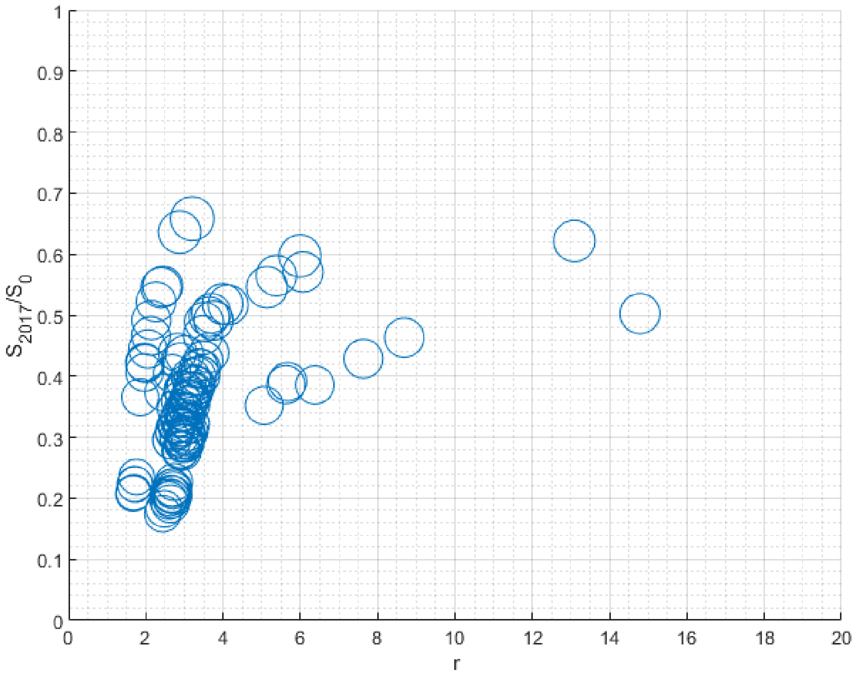

Figure 10. Scatter plot of the 252 estimates of reproductive rate r and spawning stock ratio in fishing year 2016-17.

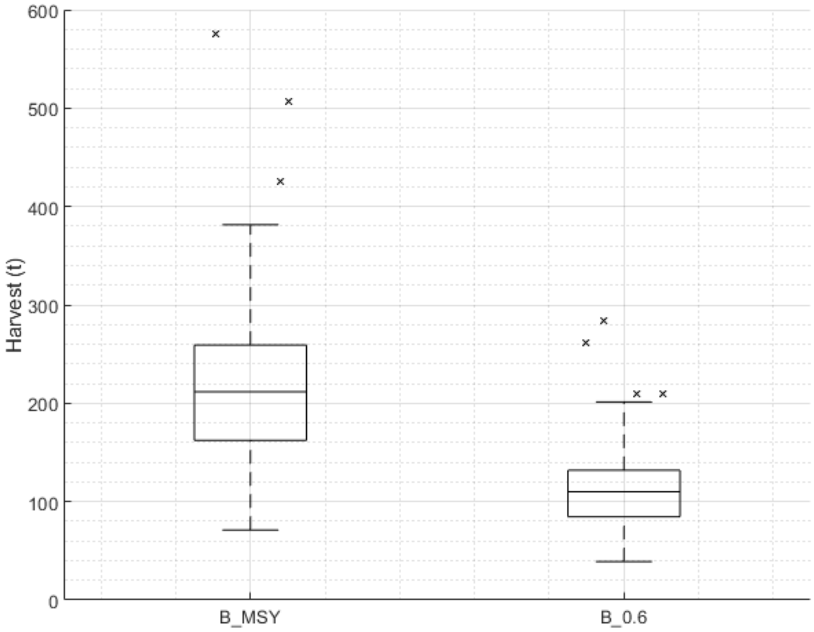

Figure 11. Box plot of the estimated equilibrium yields for spotted mackerel. The first box was for MSY at the exploitable biomass (B_{MSY}). The second box was the expected yield at higher exploitable biomass of 60% of virgin exploitable biomass ($B_{0.6}$). Each box illustrates the distribution of results around the median (horizontal line in the middle of the box). Outliers are plotted individually using the × symbol.

6.3.2 Simulations

In total 18 analyses were selected for Markov chain Conte Carlo (MCMC) simulations (Table 4). The analyses represented the extent of results identified in data investigations.

Initially, 15 analyses were selected, however, the MCMC traces revealed that the lower natural mortality settings (M=0.42) were less stable compared to M=0.57. Investigations revealed the MCMC iterations moved to artificially high selectivity parameters. Restrictions to discourage this increase in selectivity did not improve confidence in predictions. These analyses included runs 1, 2, 6, 7, 8, 9, 13 and 14, which are not summarised, but results for analyses 3–5, 10–12 and 15–18, which provided sound runs are summarised (Table 4). The lower M maximum likelihood results are not be discounted, but the broader estimated covariance matrix needed more MCMC simulations to interpret results.

The parameter estimates for each analysis are in section 9.6 (Figure 23). Estimates of virgin (new) fish recruitment (R_0 for age group 0 before fishing) ranged between 1–2 million fish per year and were correlated with measures of reproductive rate r (or steepness, ranging 0.4–0.7 million fish per year) (Figure 23). The estimates of fish age-at-vulnerability to fishing were consistent between analyses, with $a_{50\%}$ variable within age group 2 and $a_{95\%}$ variable within age group 3 (Figure 23).

All analyses resulted in model convergence and sound goodness of fit to the trends in data (Figure 22-Figure 25). One exception though was the sudden jump up in 2001–2003 catch rates. This was not predictable without altering the catchability parameter, as no fish age monitoring data were available to verify any cohort strengths (Figure 24). In addition, the model did not fit the reduction in catch rates in the three most recent years (2015–2017), fitting preferentially to age structures during this time, which did not suggest such a decline in fish abundance (Figure 24).

Table 4. Selected analyses and data inputs for MCMC simulation. See Table 3 for a description of data.

Analysis	**Commercial catch rate**			**Recreational effort**	**Natural mortality (M)**	**Reproductive rate (r)**	**Historical harvest**	**Successful MCMC**
	Scenario	Hyper-stability	Fishing power	Scenario			Scenario	
1	3	0	2	2	0.42	2.97	1	No
2	6	1	2	1	0.42	5.06	2	No
3	6	1	2	1	0.57	1.86	2	Yes
4	5	1	1	2	0.57	3.75	2	Yes
5	2	0	1	1	0.57	2.14	2	Yes
6	1	0	0	3	0.42	3.11	2	No
7	3	0	2	1	0.42	3.21	1	No
8	2	0	1	3	0.42	3.16	1	No
9	3	0	2	1	0.42	5.62	2	No
10	6	1	2	2	0.57	2.68	2	Yes
11	6	1	2	2	0.57	5.13	1	Yes
12	2	0	1	3	0.57	2.40	2	Yes
13	2	0	1	2	0.42	3.02	2	No
14	4	1	0	2	0.42	3.20	1	No
15	3	0	2	1	0.57	2.90	2	Yes
16	3	0	2	1	0.57	6.01	1	Yes
17	2	0	1	2	0.57	2.87	1	Yes
18	0	0	0	1	0.42	2.63	2	No

The MCMC predicted stock status ratios for spotted mackerel in the fishing year 2016–17 (labelled 2017) are in Figure 12. The spawning, exploitable biomass-recruitment estimates and spawning per recruit estimated were all above limit reference points (Figure 12). In general, the median MCMC spawning and biomass ratios ranged between 40–65%, with the median of six analyses exceeding the 60% target reference estimate (Figure 12).

Estimates of 2016–17 fishing mortality were all below the limit reference point. Maximum estimates since 2012–13 were elevated, nearing the limit reference point (Figure 13). Generally, there were very high levels of fishing mortality in the early 2000s when ring netting was the dominant fishing method (Figure 28-Figure 36). Following the introduction of limits on this method, fishing mortality dropped to levels between the target and limit reference points, rather than exceeding up to double the limit reference point F_{lim} (Figure 28-Figure 36).

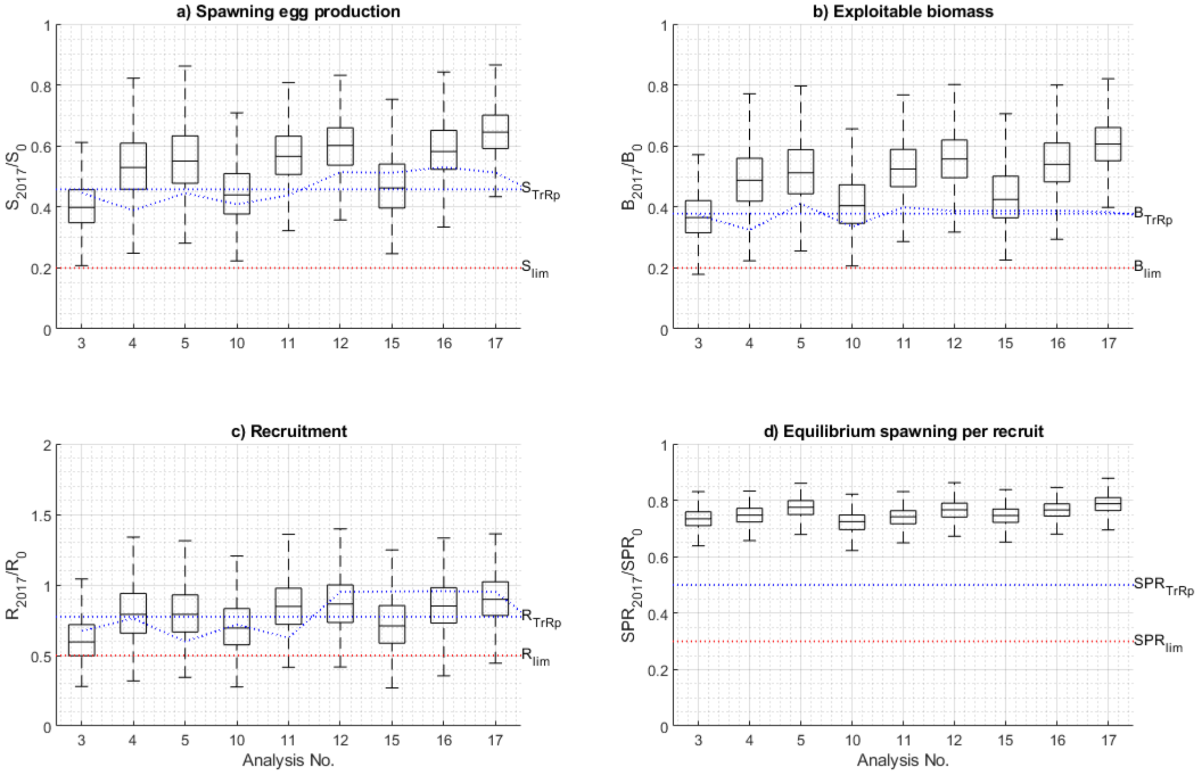

Figure 12. Estimated stock status ratios of spotted mackerel. The ratios compare the fishing year 2016–17 against 1961, for a) spawning egg production, b) exploitable biomass, c) recruitment of age group 0 fish and d) equilibrium spawning egg production per recruit based on the 2017 estimated fishing mortality F_{2017}. 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 blue dotted lines show the trigger reference points for B_{MSY} in subplots a–c and 50% reduction in spawning per recruit in subplot d. The trigger reference points are shown averaged over analyses (straight blue line) and individually for each analysis (irregular blue line).

Mean (equilibrium) predictions of target harvests for the 60% biomass target, for all fishing sectors and all waters ranged around 230 t, while equilibrium estimates for B_{MSY} were approximately 300 t (Figure 14). This level of harvest (<230 t) would gradually build higher spawning egg production and exploitable biomass (towards $B_{0.6}$). These assumed the higher rate of natural mortality and in addition, the stock model predicted higher catch rates for 2015 to 2017 compared to the data inputs. Accordingly, these should be interpreted as optimistic results, which may overestimate the size of the population.

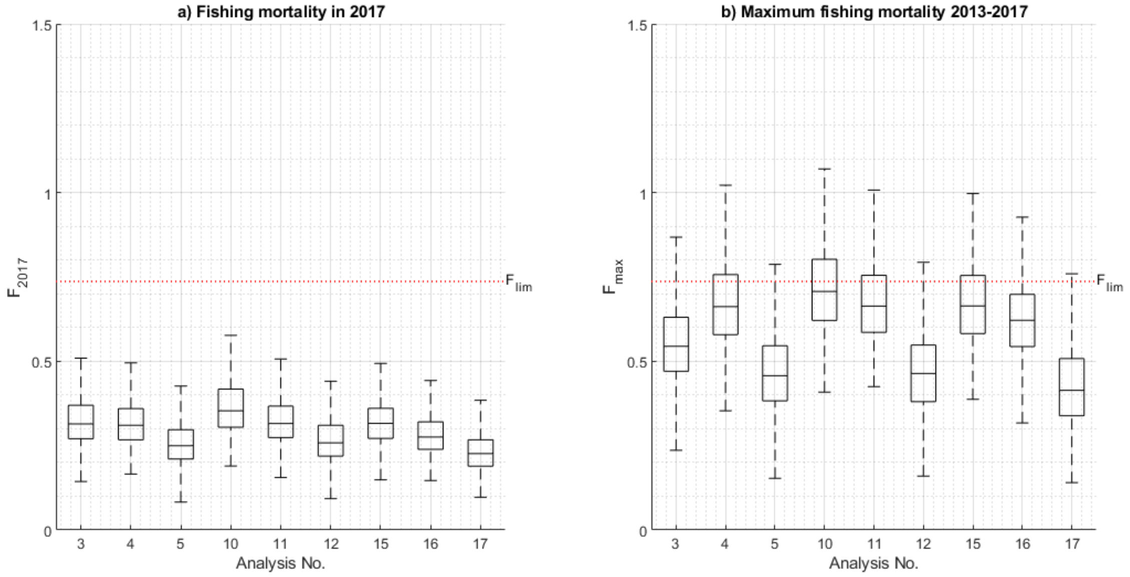

Figure 13. Estimated annual fishing mortality of spotted mackerel for (a) the 2017 fishing year (2016–17), and (b) the maximum between 2012–13 and 2016–17. The red dotted lines show the limit reference point.

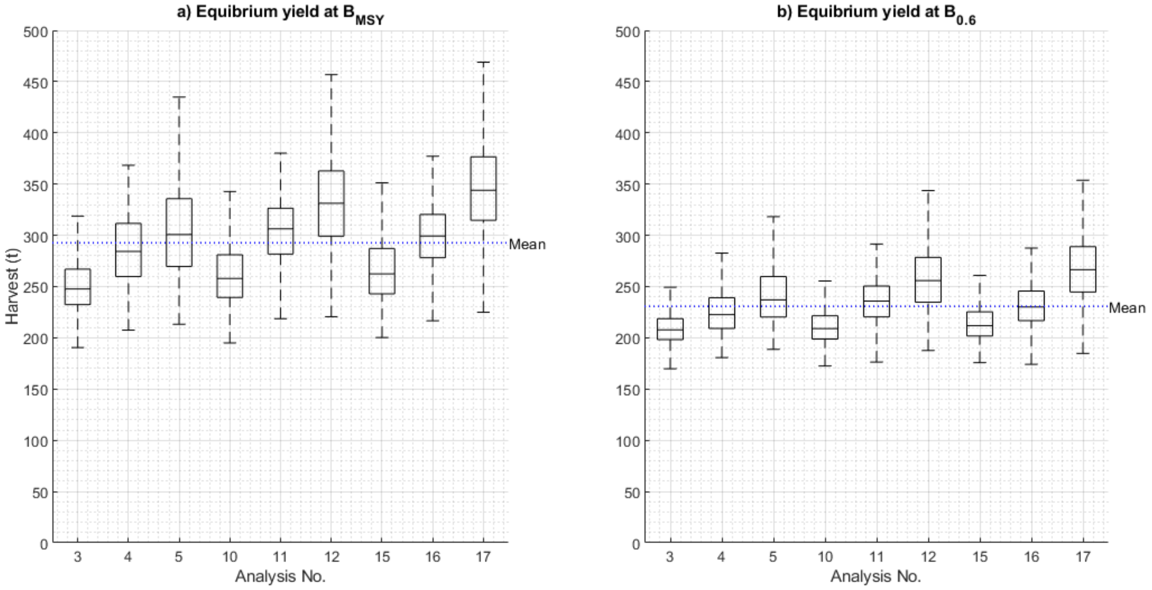

Figure 14. Estimated equilibrium yields of a) MSY biomass levels, and b) 60% biomass levels for spotted mackerel. The blue dotted lines represent the average across all analyses.

The phase plot illustrates the time series relationship between exploitable biomass and harvest rate (~ fishing pressure) (Figure 15). Since 1998, estimated harvest rates were above the MSY reference point. Biomass ratios declined from 60% in 1989 to the MSY reference point in 2003 (Figure 15). Since 2003 biomass ratios further declined to between the MSY (dashed orange line) and limit reference point (dashed red line) (Figure 15).

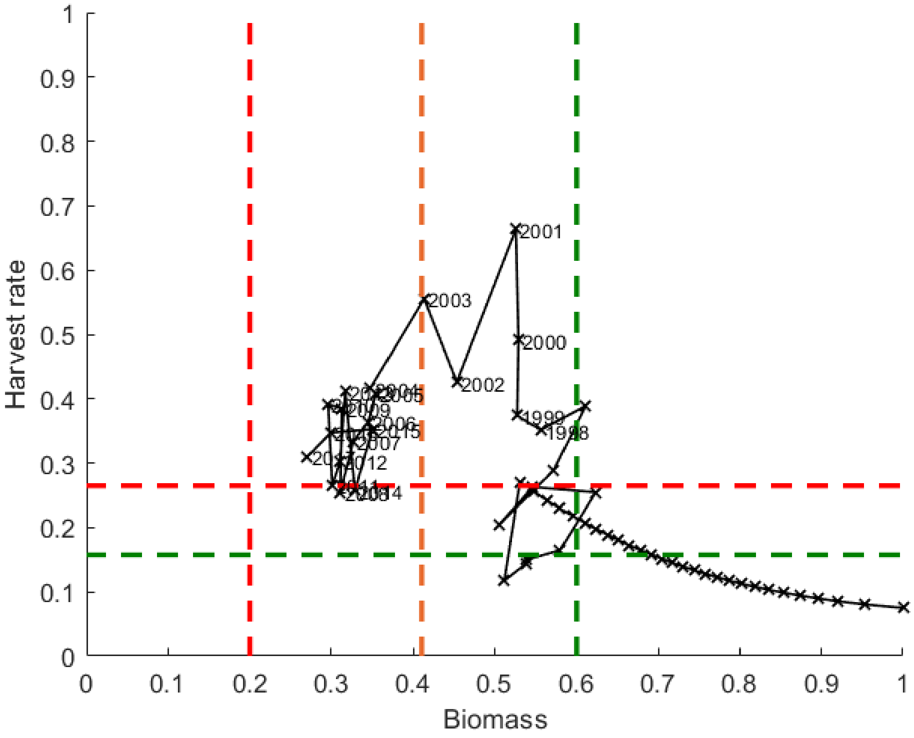

Figure 15. Analysis 3 'phase plot' for the relationship between harvest rate and exploitable biomass ratio (B_t/B_0). The green reference lines represent the harvest rate and biomass ratio of 60%, while the orange reference line represents the MSY exploitable biomass ratio. The red lines represent the limit reference point of 20% for both harvest rate and exploitable biomass ratio. Other analyses are illustrated in section 6.4 (Figure 37-Figure 44).

7 Discussion and conclusion

7.1 Stock status

The Qld spotted mackerel fishery has a complex management history. Regulatory changes have focussed on managing the competing fishing capacities of line (all sectors) and commercial net fishing on aggregations of this species. The predictable aggregation and movement of spotted mackerel attract fishers in the same regions and seasons each year. When present, their highly aggregated schools on the surface ensures easy catchability and makes them susceptible to overfishing. This behaviours also introduced problems of hyper-stability for stock assessments and management (Walters 2003; Campbell et al. 2012).

This hyper-stability means that catch rates can remain high, even when fish numbers in schools are decreasing (Walters 2003). Although corrections have been made when standardising catch rates through probability and fishing power adjustments, it is difficult to determine the full extent of its impact. Therefore, some precaution and understanding of results is required to classify fishery stock status.

In the late 1990s, ring netting expanded as it was an efficient method to commercially harvest spotted mackerel. In the early 2000s, reductions in line fishing catch rates prompted a stock assessment with subsequent management changes made to the fishery (Table 1) (Begg et al. 2005). A Queensland TACC of 140 t (introduced in late 2002), along with a range of limitations, including fishing with nets, has resulted in a marked reduction of total annual harvest.

The high harvests in the early 2000s resulted in declines of the spotted mackerel stock. This decline was apparent in the results presented here and in those presented by Begg et al. (2005). During this time, fishing mortality reached two to three times that of natural mortality, well above the limit reference point. Since 2010, there has been a gradual increase in the stock size with spawning stock biomass in 2016–17 averaging 20–40%, with varying estimates depending on data inputs.

When model scenarios were fitted to age structures without catch rates, similar to model seven in Begg et al. (2005), the stock status results were lower than when catch rates were included. This suggests lower sustainable harvests are more appropriate and that catch rates may be hyper-stable, not reflecting the true abundance of the population. Therefore, results calculated with catch rates, and including the higher natural mortality (M=0.57) should be interpreted with care. The results obtained from fits to age structures without including catch rates represent spawning stock biomass estimated around 30% (Figure 10), with 60% biomass targets requiring a harvest of approximately 110 t across all jurisdictions (NSW and Qld) and sectors (commercial, recreational and charter), including a 50% discard mortality of non-retained recreational harvests (Figure 11).

There has been anecdotal evidence of high grading in this fishery (Fisheries Queensland pers. comm.). High grading involves continuing to fish over the maximum allowed net in-possession catch of 50 fish. If fishers return smaller fish to the water dead to allow further fishing, this can result in under-reporting of fishing harvests and mortality. If this practice occurs frequently, it can also influence estimates of stock size and sustainable harvest. This anecdote suggests a conservative management approach should be applied. Investigations into the extent of these practices would aid confidence around future predictions of biomass and target harvests.

Recent evidence of some catch misreporting in the northern region around Mission Beach has also been revealed (Fisheries Queensland pers. comm.). This involved catches of school mackerel (*Scomberomorus queenslandicus*) on occasion being recorded as spotted mackerel. Spotted mackerel are considered more marketable and many consumers cannot discern the difference between them, particularly when filleted. This suggests that recorded harvests may be higher than the actual harvest of spotted mackerel, and this may have some influence on the results presented here. Further investigation into the extent of this misreporting may enable this to be accounted for in future assessments.

It is clear that the current Qld commercial quota of 140 t is well above the estimate of 110 t (average across models) for both jurisdictions (NSW and Qld) and sectors (commercial, recreational and charter) to reach 60% of virgin biomass. Therefore, if the commercial quota is fully utilised the current management strategies are not sufficient to grow the stock to 60% of virgin biomass by 2027, as prescribed by Queensland's Sustainable Fisheries Strategy.

Results from the present assessment suggest lower estimates of sustainable harvest compared to the 2005 stock assessment. Begg et al. (2005) concluded that target harvests for the whole east coast fishery were 200–282 t and that fulfilling the 140 t Queensland commercial quota together with the harvest of other sectors would exceed limit reference points. The new estimates clearly support this message. Target harvests are now between 100–230 t for the whole east coast fishery, including a recreational discard allowance. These lower harvest results take into consideration:

- The change to a 60% biomass target by 2027 under the Strategy,
- 16 years of additional data compared to that included by Begg et al. (2005),
- Declines in catch rates and harvest,
- Revised estimates of lower recreational harvest with acknowledgement of release discard mortality,
- Variable fish recruitment that was reduced in a number of years,
- Fish age data suggesting increases in fish mortality, and
- Hyper-stability influencing catch rates and not tracking fish abundance.

7.2 Environmental impacts

The transient nature of the stock, which forms aggregations along the coast moving north to spawn and south to feed, is most likely influenced by changes in environmental conditions. Changes in ocean currents, and therefore sea surface temperatures, along the east coast of Australia may influence the timing of the movement of spotted mackerel. Similar changes have been observed in other species, such as sardines, anchovy, mackerel, flounder and Spanish mackerel (Heath et al. 2012; Pinsky and Fogarty 2012; Jung et al. 2014). These observations of temperature influences on baitfish location and availability could have direct impacts on the feeding patterns of spotted mackerel, and therefore influence their availability to the fishery. These temperature changes may also influence the patterns and success of spotted mackerel recruitment, with temperature an important determinant of mortality and recruitment in the early life stages of various fish species (Houde 1987; Takasuka et al. 2007). Spawning location and timing of various fish species can also move with changes in sea surface temperatures (Frank et al. 1990; Drinkwater 2005; Rose 2005). The relationship between changing environmental conditions and spotted mackerel recruitment and prey availability warrants further investigation, particularly as periods of elevated sea surface temperatures are predicted to become more severe and frequent with climate change (Cai et al. 2014).

7.3 Recommendations

7.3.1 Data

It is recommended that improved mechanisms to report daily spotted 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. In particular, data accuracy would be improved by including accurate effort measures with the time spent fishing and locations recorded per boat-operation-day. Additional improved information of the location of fishing and the inclusion of data where no spotted mackerel were caught but were actively targeted.

Improved and more frequent measures of recreational fishing effort and harvest would also benefit future assessments. Regular on-site survey measures of vessel and angler numbers are recommended.

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

7.3.2 Monitoring

Continued monitoring of age and length structures, which are representative of the fishery, are vital for the ongoing assessment of the species. Due the hyper-stable nature of catch rates, there is a high model dependence on the age structures for both commercial and recreational fisheries. Without this data, the same level of confidence would not be achieved in future assessments.

7.3.3 Management

The most conservative biomass estimates range around 20–40% of virgin spawning stock biomass, with all model combinations and data inputs included. In order to grow the stock to the target state of 60% of virgin biomass by 2027, as specified in the Strategy, total harvests for all sectors need to be approximately 100–150 t (median 110 t). The population size of spotted mackerel is not large relative to other species and cannot support the fishing capacities of all net and line fishing.

The implementation of a harvest strategy, to initially grow the stock back to the 60% size and then maintain the population size over time is required. Indicators to include in a harvest strategy and monitor over time could include periodic biomass estimated from a detailed stock assessment (Smith et al. 2008; Wayte 2009). Using catch rates as an indicator must be done with caution due to the hyper-stable nature of this stock, particularly until improved fishing effort measures are recorded.

7.4 Conclusions

This study has informed the status of the east coast spotted mackerel stock, with harvests from both NSW and Qld. It suggests that fishing pressure was too high in the early 2000s that resulted in declines of stock biomass. Management intervention following this period has reduced harvests, but resulted in only a gradual increase in stock size. Ongoing harvests at reported reduced levels are anticipated to result in an increase in the stock size to 60% of virgin biomass in the next 5 years. This, however, is dependent on total catch of the entire stock remaining below 110 t. Due to the potential of hyper-stable catch rates, it is critical that biological monitoring of age structures continues to ensure the ongoing sustainability of the stock is closely monitored. Further investigation into potential misreporting in the fishery could benefit future assessments.

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9 Supplementary information

9.1 Commercial data

A clear increase in the total number of reported commercial days fished across the fishery was evident from the late 1980s to the peak in catch in the early 2000s (Figure 16). Following this period there was some decreased effort following the management intervention (Figure 16). The reported commercial fishing effort within each region appeared to be stable (Figure 16).

The annual number of commercial boats operating in the fishery varied with stable regional pattern (Figure 17). Few boats reported operations in 1995 and 1996 compared to other years.

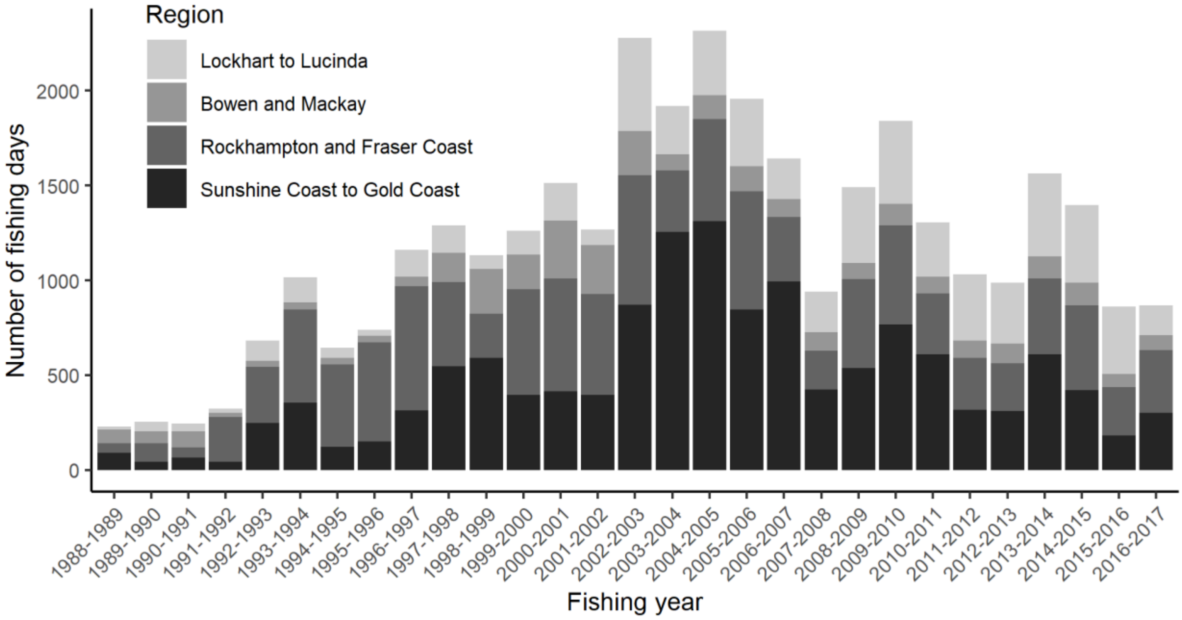

Figure 16. Total number of commercial days fished in the Queensland spotted mackerel fishery between the fishing years 1989 and 2017.

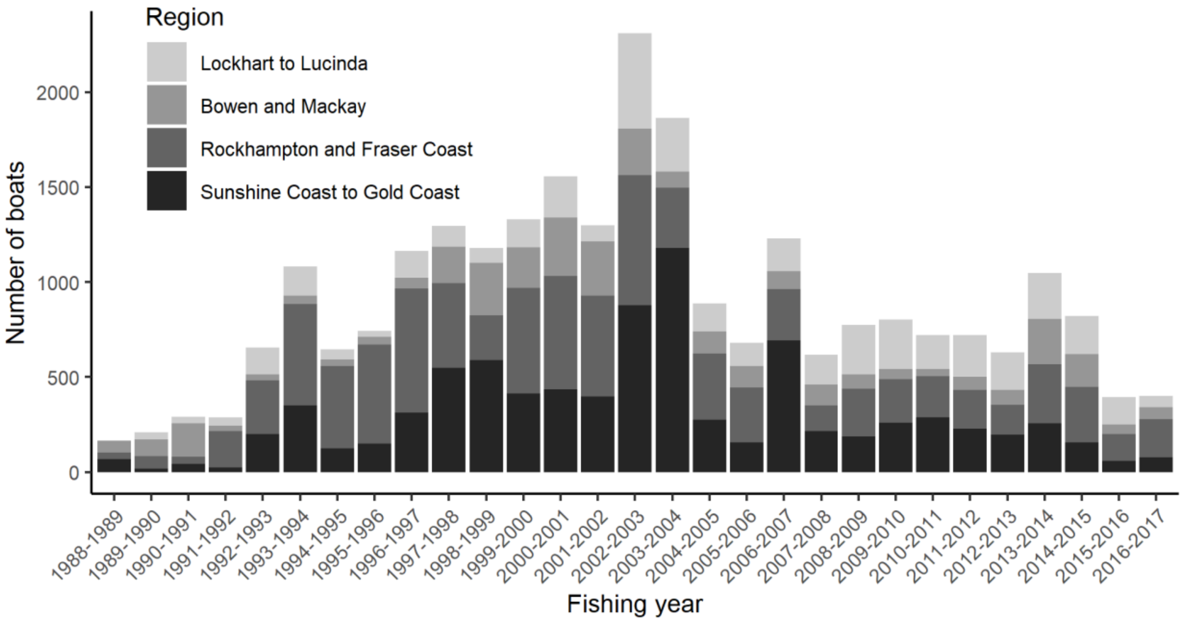

Figure 17. Total number of commercial boats operating in the Queensland spotted mackerel fishery between the fishing years of 1989 and 2017.

9.2 Allocating unknown commercial mackerel harvest to spotted mackerel

Proportions of unspecified (unknown mackerel species) harvests were allocated as spotted mackerel. The allocations were estimated pre and post 2003, using a binary regression model with logit link.

9.2.1 Pre-2003 model

The binary regression for 1989–2003 was:

$$\mathrm{logit(P)} = \mathrm{Constant} + \mathrm{Year} \times \mathrm{Gear} + \mathrm{Month} + \mathrm{log(Weight)} + \mathrm{Region}$$

The model included a two-way interaction term $\mathrm{Year} \times \mathrm{Gear}$. Adjustments were applied to the model predicted probabilities. Let α_1 be the predicted probability from the model, and β_1 be the prevalence (i.e. the actual probability from the data). Thus $\alpha_0 = 1 - \alpha_1$ and $\beta_0 = 1 - \beta_1$ denotes their respective complement. Also, let p_{10} be the false negative probability (i.e. the number of false negative divided by the total number of observations). Then, the following adjustment obtained the allocated proportions:

$$\widehat{\mathrm{P}} = \alpha_1 + \mathrm{p}_{10}\,\delta$$

where

$$\delta = \frac{\alpha_0}{\beta_0} - \frac{\alpha_1}{\beta_1}.$$

9.2.2 Post-2002 model

The binary regression for 2004–2017 was:

$$\mathrm{logit(P)} = \mathrm{Constant} + \mathrm{Year} \times \mathrm{Gear} \times \mathrm{log(Weight)} + \mathrm{Month} + \mathrm{Region}$$

The final model included a three-way interaction term $\mathrm{Year} \times \mathrm{Gear} \times \log(\mathrm{Weight})$. Allocated proportions were adjusted as above.

9.2.3 Combined

With the two analyses, predictions were improved compared to the results given by a single model. Without the adjustments, the model overestimates the actual catch in 8 of the 30 years. This occurs mainly between 2005 and 2016. However, the amount of overestimate is relatively small. Using this model, the probability of spotted mackerel catch being spotted mackerel for all unspecified mackerel catches is calculated. The probabilities were multiplied by the unspecified catches to obtain an estimated of further harvest of spotted mackerel. The total estimated harvest per fishing year is, therefore, given by the sum of the actual harvest (identified as being spotted mackerel) and the estimated harvest (of being spotted mackerel) derived from the unspecified mackerel harvests (Figure 18).

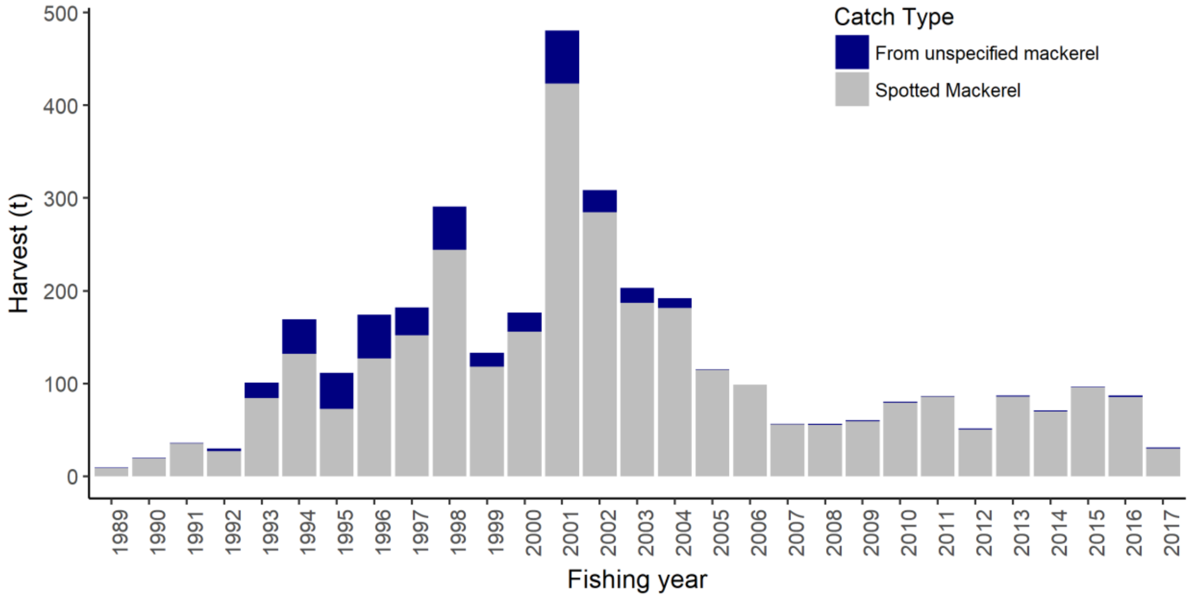

Figure 18. Unspecified mackerel catch that has been allocated to spotted mackerel between the fishing years of 1989 and 2017.

Table 5. Recorded harvest, unspecified mackerel harvest and the proportions allocated to the total spotted mackerel harvest in Qld.

Fishing year	Recorded spotted mackerel harvest	Unspecified mackerel harvest	Unspecified harvest allocated to spotted mackerel	Total harvest for spotted mackerel
1989	8.61	36.85	0.56	9.17
1990	19.51	7.62	0.22	19.72
1991	35.60	9.62	0.50	36.10
1992	27.37	35.64	2.59	29.96
1993	84.18	77.57	16.99	101.16
1994	131.90	102.17	37.20	169.10
1995	72.49	107.60	38.89	111.38
1996	127.28	122.30	47.16	174.45
1997	152.15	113.64	30.08	182.23
1998	244.30	142.54	46.62	290.91
1999	118.29	68.68	14.73	133.03
2000	155.72	84.34	20.88	176.59
2001	423.69	100.61	57.11	480.80
2002	284.73	76.13	23.98	308.72
2003	186.93	57.70	16.01	202.94
2004	181.29	47.02	10.46	191.75
2005	114.99	1.67	0.26	115.25
2006	98.71	0.86	0.22	98.92
2007	56.11	0.98	0.29	56.41
2008	55.27	7.39	1.57	56.84
2009	59.56	7.75	1.17	60.73
2010	79.23	8.00	1.41	80.64
2011	85.78	4.74	0.60	86.38
2012	50.38	13.01	1.05	51.44
2013	85.76	7.37	1.13	86.89
2014	69.86	6.03	1.08	70.95
2015	96.00	4.63	0.75	96.75
2016	85.34	7.63	1.93	87.28
2017	30.13	5.03	0.71	30.84

9.3 Model parameters and equations

Table 6. Equations for calculating the spotted mackerel population dynamics.

Population dynamics	**Equations**
Numbers of fish in the 1st year 1961 (*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 1961 (*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:	
$\exp\left(-Z_{t,a}\right) = \exp\left(-M\right) \prod_{\mathrm{f}} 1 - v_a u_{\mathrm{f},t}$	(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:	
$u_{\mathrm{f}=1,t} = C_{\mathrm{f}=1,t} \Big/ \sum_a B_{t,a}^1 \sqrt{1 - v_a u_{\mathrm{f}=2,t}}$	(8)
Midyear exploitable biomass – forms 1 and 2 are labelled in order by superscript ^{1} and ^{2}:	
$B_t^1 = \sum_a N_{t,a} \bar{w}_a v_a \exp\left(-0.5M\right)$	(9)
$B_t^2 = \sum_a N_{t,a} \bar{w}_a v_a \exp\left(-0.5M\right) \sqrt{\prod_{\mathrm{f}} 1 - u_{\mathrm{f},t}}$	(10)
Recreational harvest, fleet f=2, number of fish:	
$\hat{C}_{\mathrm{f}=2,t} = \sum_a \dfrac{v_a q_{\mathrm{f}=2} E_{\mathrm{f}=2,t}}{Z_{t,a}} N_{t,a} v_a \left(1 - \exp\left(-Z_{t,a}\right)\right)$; × w_a calculates harvest tonnes.	(11)
Catch rate, commercial fleet index:	
$c_{\mathrm{f},t} = q_{\mathrm{f}} B_t^2$. This was only calculated for commercial catch rates.	(12)

Table 7. Parameter definitions for the spotted 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.
$\text{Max}(a)$	10	Based on considering the maximum fish age recorded from the Queensland east coast (10 years).
w or *l*	$l_\infty, \kappa\ , a_0$	The estimated von Bertalanffy growth curve parameters (Haddon 2001).
m_a	-20.89x – 0.35	Maturity schedule determine by Begg et al. (2005) with a logistic regression from total length and macroscopically determined maturity data in the previous stock assessment of spotted mackerel in Queensland.
ϑ_a	$w_a \times \text{eggs kg}^{-1}$	Mature female egg production at age (number of eggs).
M	0.59 or 0.42	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 10 years. The age based estimator of Then et al. (2015) was 0.59 year^{-1} and 0.42 year^{-1} from Hoeing (2005) assuming a maximum fish age of 10 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 (R_0) 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. 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 8. 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: $\frac{n}{2}\left(\log(2\pi)+2\log(\sigma)+(\hat{\sigma}/\sigma)^2\right)$, or simplified as $n\left(\log\sigma+\frac{1}{2}(\hat{\sigma}/\sigma)^2\right)$, where $\sigma=\max(\hat{\sigma},\sigma_{\min})$, $\sigma_{\min}$ = 0.108, 0.19 and 0.19 respectively, and $\hat{\sigma}=\sqrt{\sum\left((\log(c_t)-\log(\hat{c}_t))^2\right)/n-1}$ 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, $\hat{T}=(\tilde{n}-1)/2\sum\hat{p}\log(\hat{p}/p)$, $T=\max(2,\hat{T})$ 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 $\cong$ 24% CV.	O'Neill et al. (2014)	(14)
Recruitment compensation r_{comp} $0.5\left(\frac{\xi-\log(6-1)}{\sigma}\right)^2\times\left(\xi>\log(19)\right)$, 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 : $\frac{n}{2}\left(\log(2\pi)+2\log(\sigma)+(\hat{\sigma}/\sigma)^2\right)$	O'Neill et al. (2014)	(16)

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.

9.4 Standardised catch rates

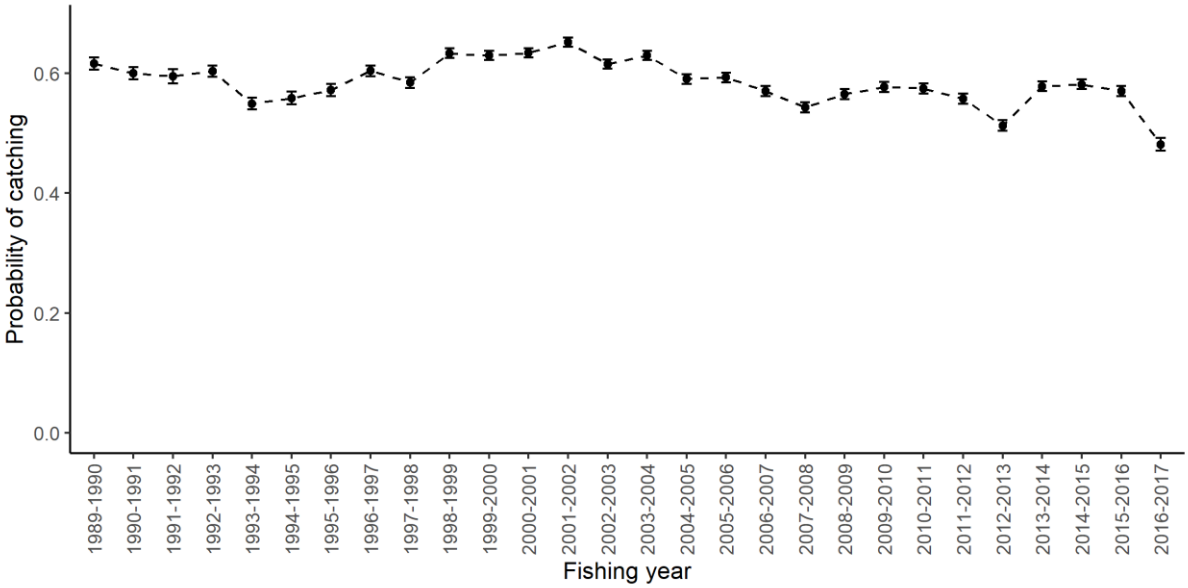

Figure 19. Probability of commercially harvesting for spotted mackerel between of 1989–90 and 2016–17.

9.5 Biological parameters

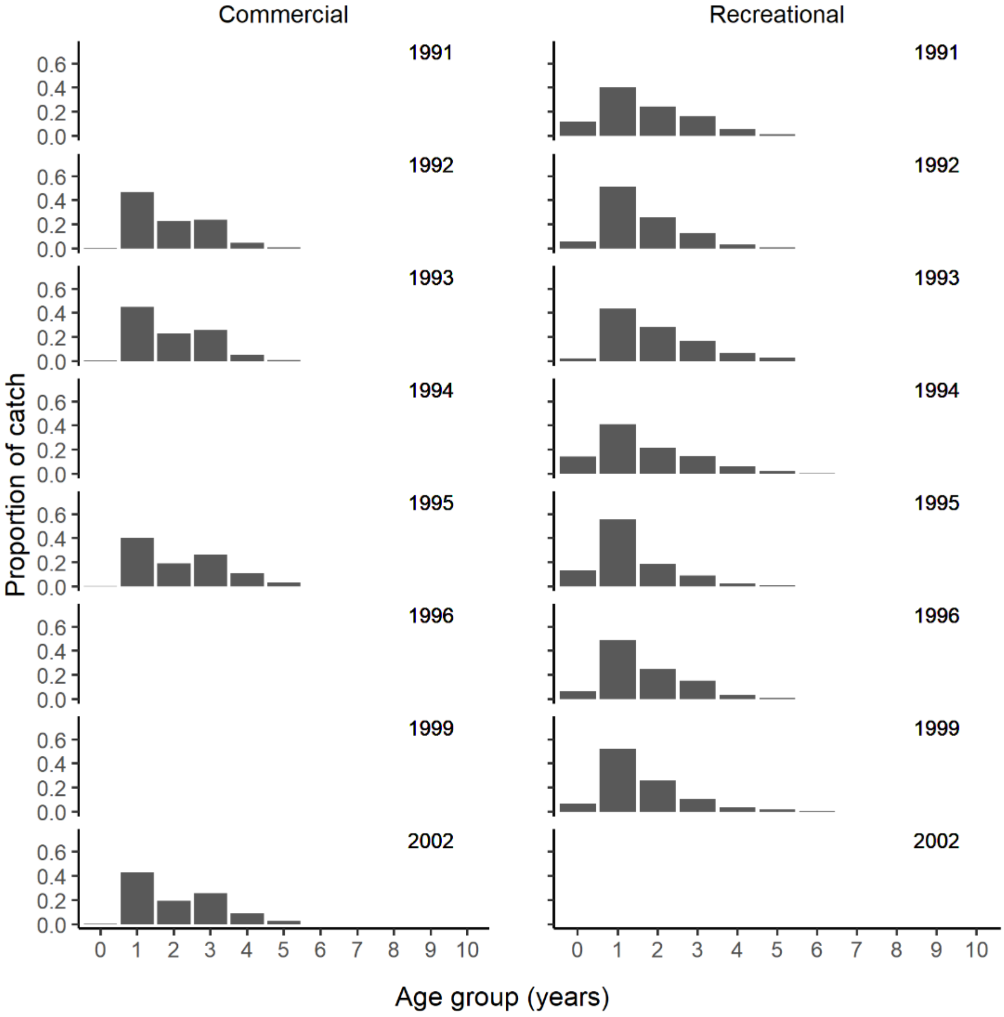

Figure 20. Fish age structure for both commercial line and recreational catches between the 2005-06 and 2016-17 financial years from historical research projects

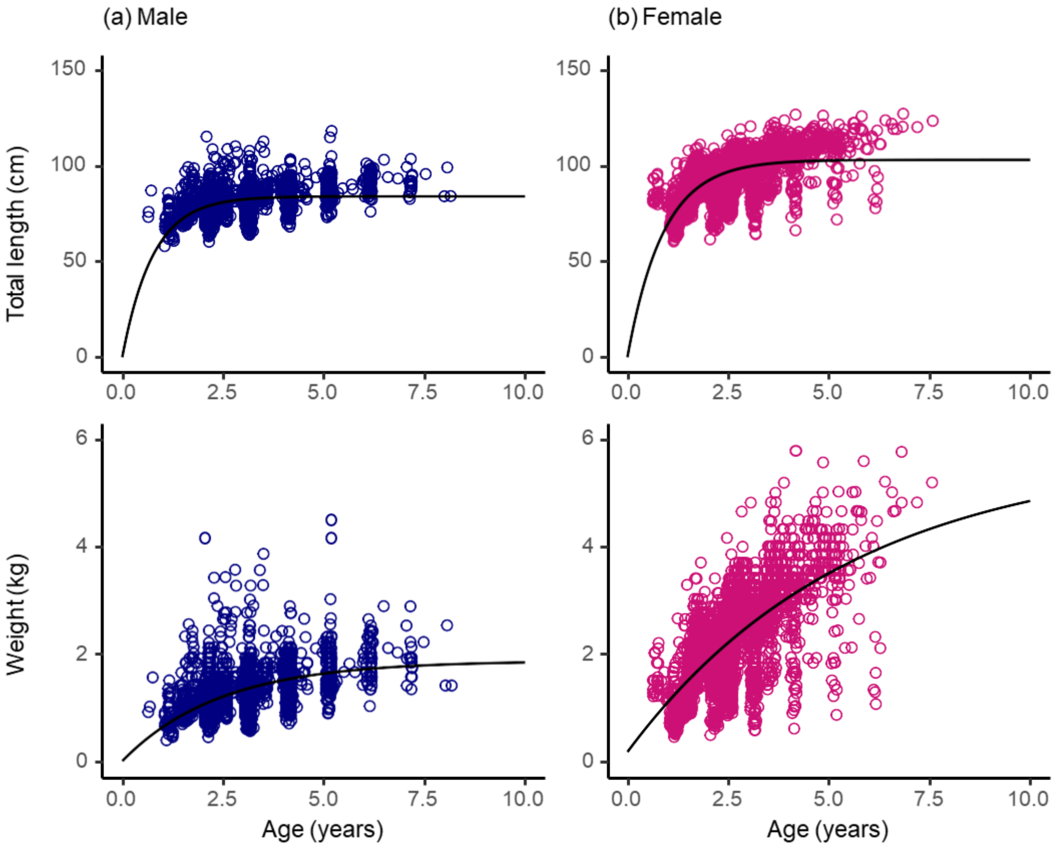

Figure 21. Von Bertalanffy growth curves for (a) male and (b) female spotted mackerel for both length-age and weight-age relationships. Recreational and commercial catch are aggregated for the purpose of this analysis, along with data collected between 2005 and 2017.

9.6 Stock model results and diagnostics

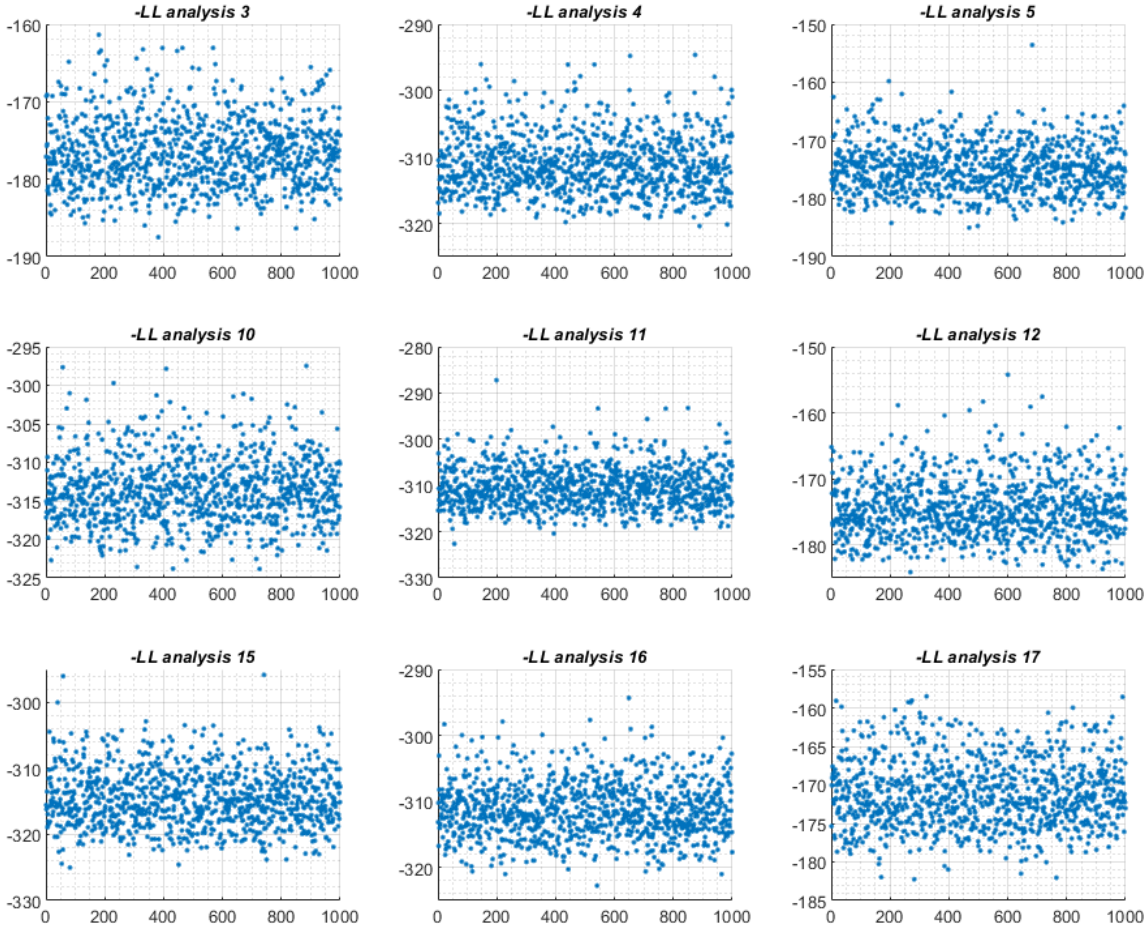

Figure 22. Serial plot of the negative log-likelihood (-LL, y-axis) values for retained parameter samples from the Markov chain Monte Carlo (MCMC) optimisations. 1000 data points were retained from 100000 simulations. Autocorrelations were low and acceptable.

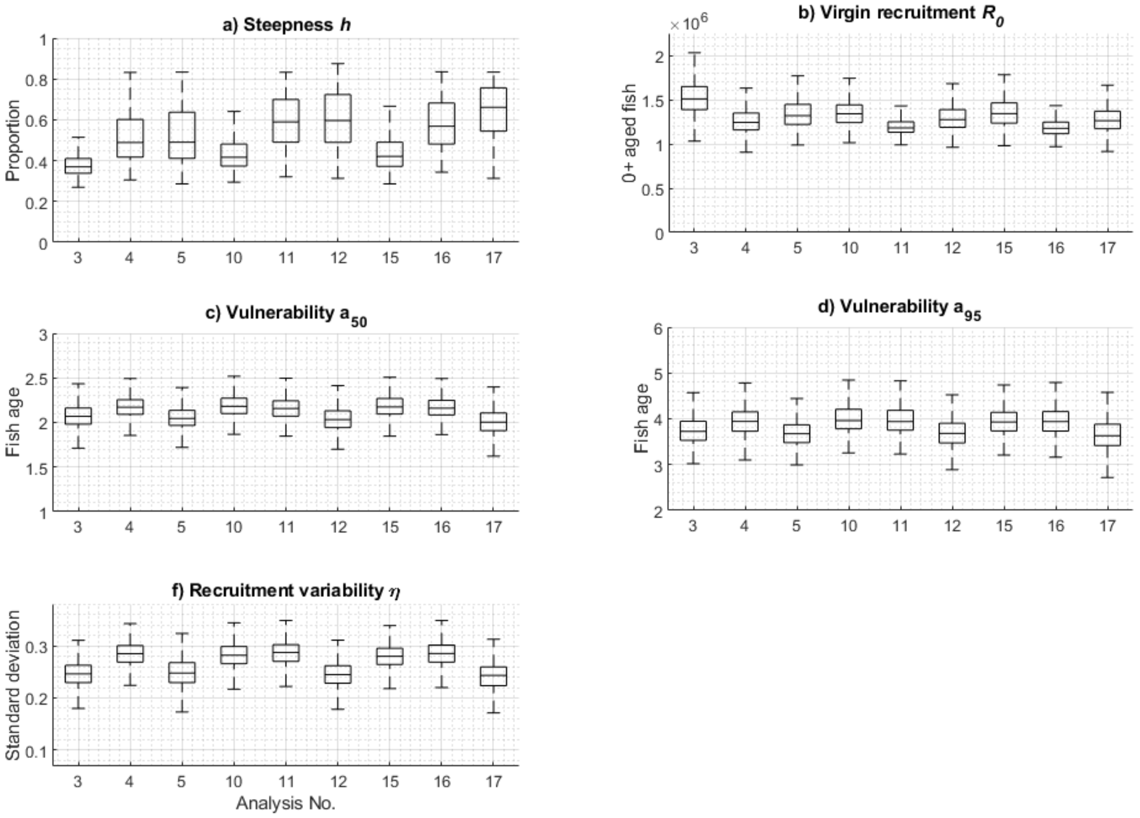

Figure 23. MCMC parameter estimates for the 10 analyses. Each box illustrates the distribution of estimates around the median (horizontal line in the middle of the box).

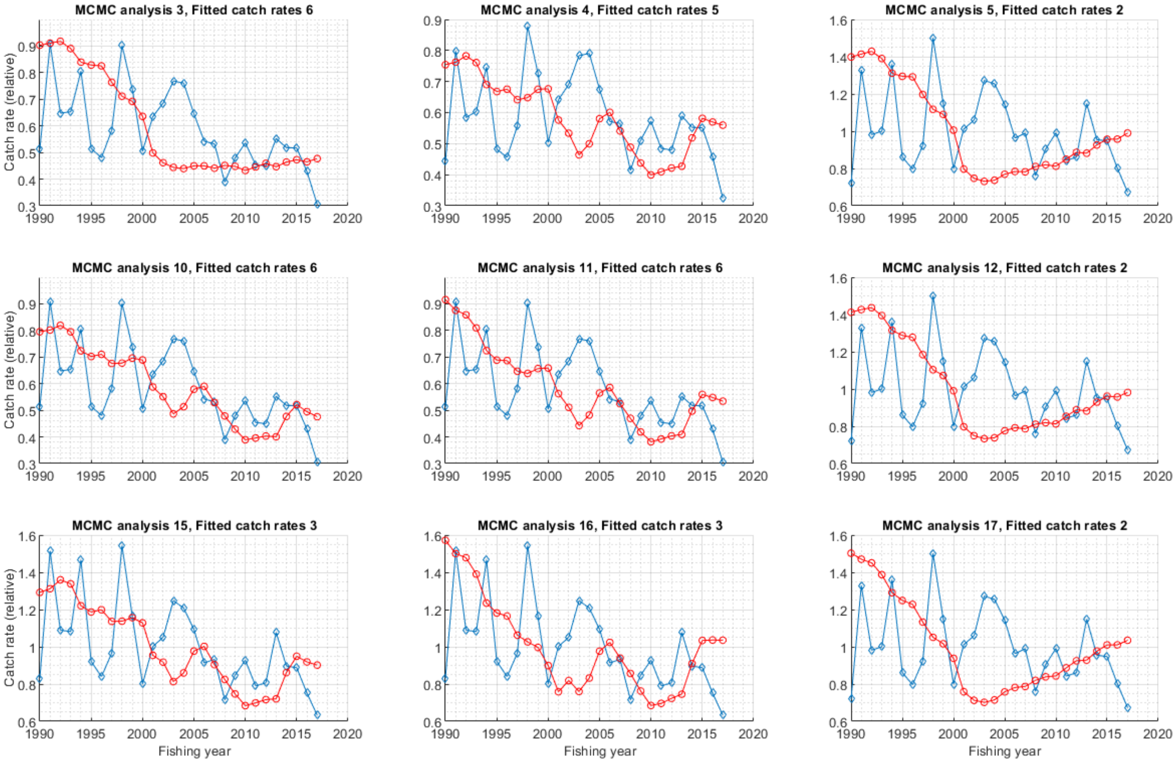

Figure 24. Stock model fitted values to the standardised commercial catch rates of spotted mackerel for each MCMC analysis. The blue line represents the calculated catch rate, while the red line represents the fitted catch rate within the model.

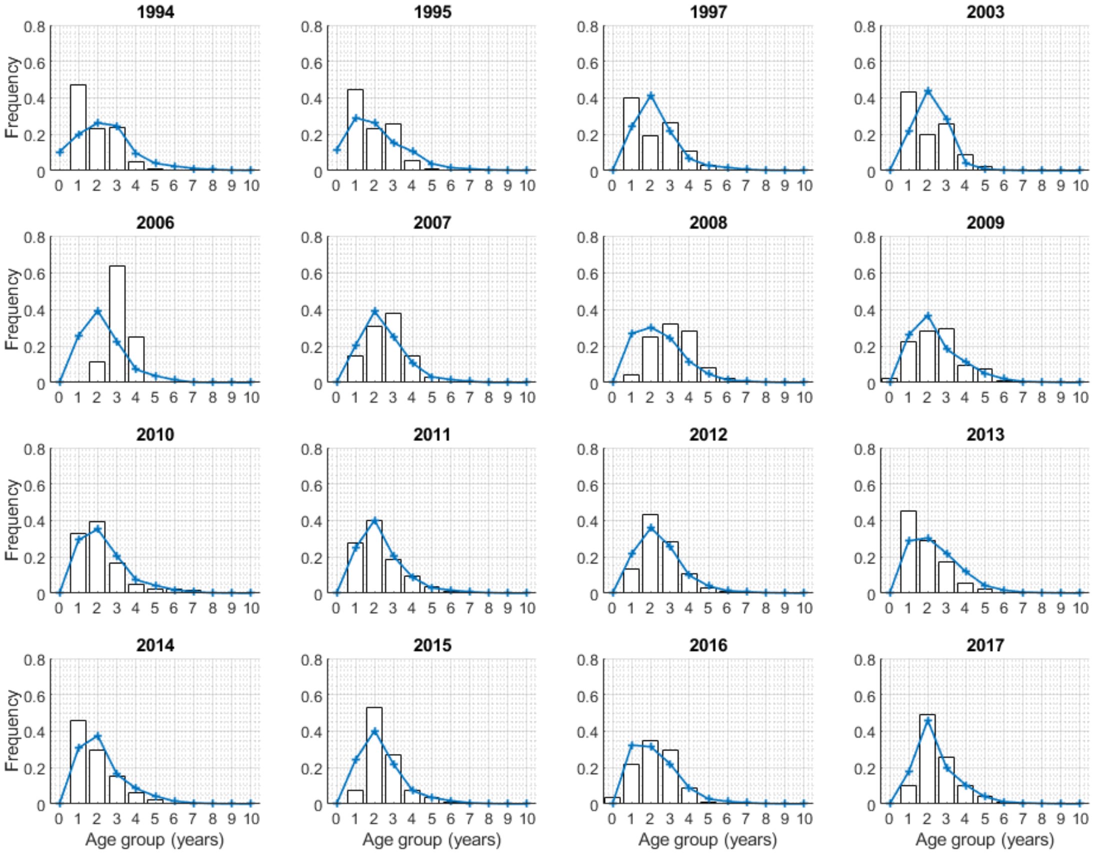

Figure 25. Stock model predictions of spotted mackerel ages harvested by commercial operations from Qld waters. Bars represent the measured values, while the blue line represents the model fit. The frequency of each observation is recorded as a proportion.

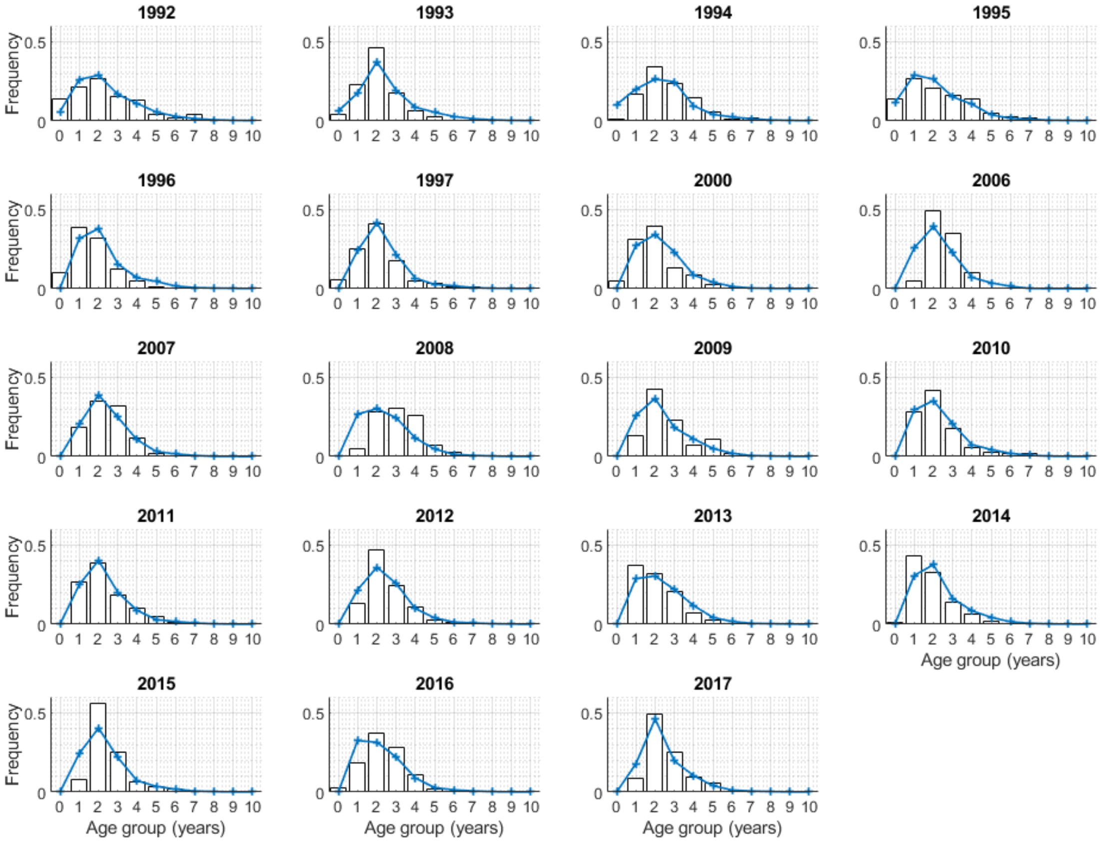

Figure 26. Stock model predictions of spotted mackerel ages harvested by recreational operations from Qld waters. Bars represent the measured values, while the blue line represents the model fit. The frequency of each observation is recorded as a proportion.

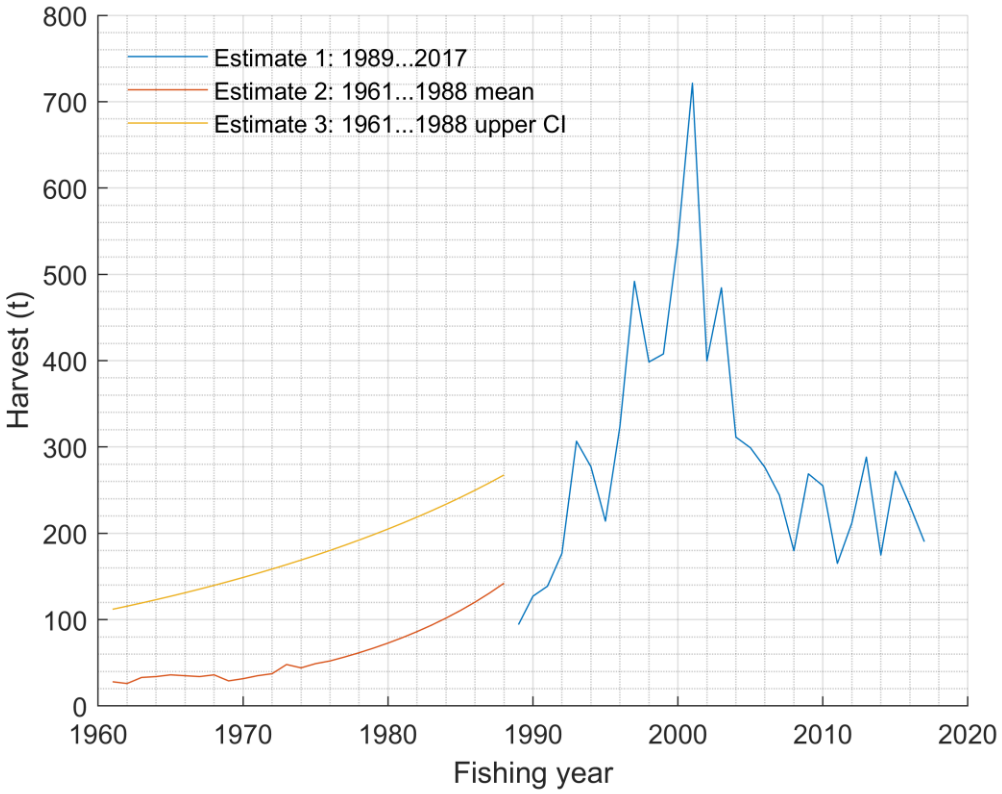

Figure 27. Estimated harvests of spotted mackerel with upper confidence interval prior to reporting of catch in commercial logbooks.

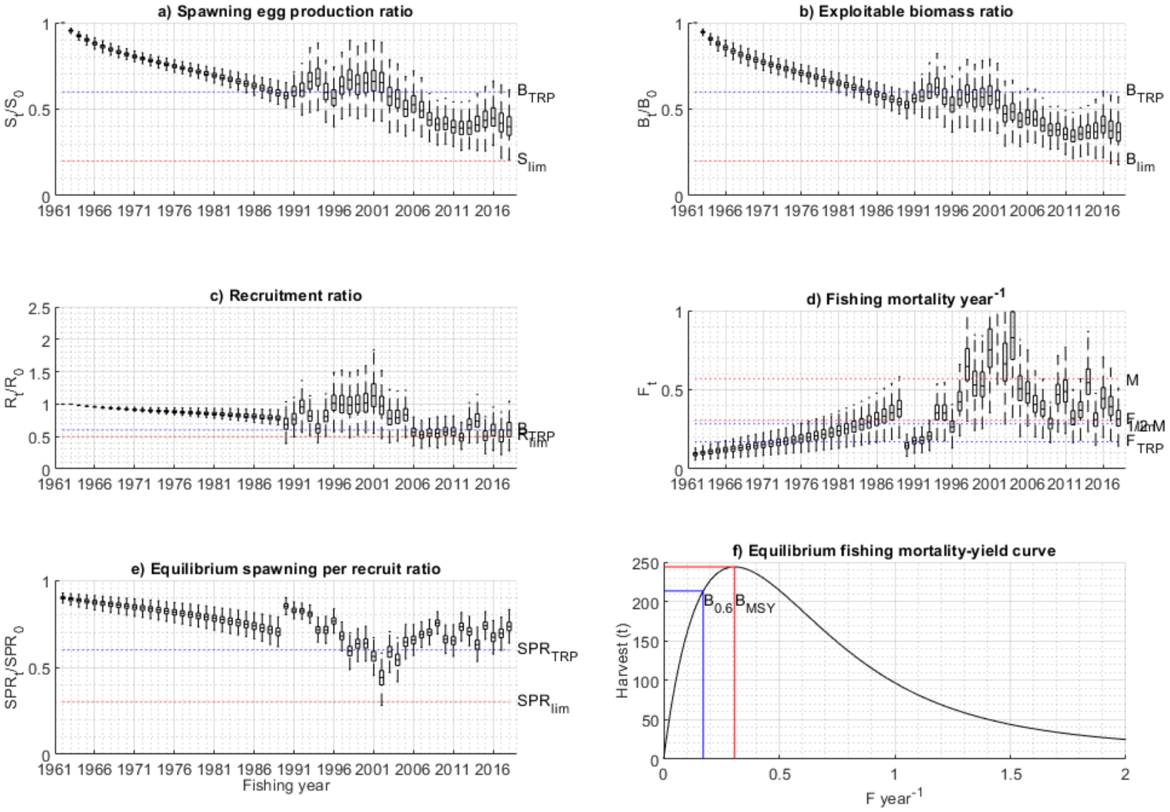

Figure 28. Predictions from analysis 3 for (a) spawning egg production, (b) exploitable biomass, (c) recruitment and (d) fishing mortality. Reference points are plotted for both BMSY and B0.6, with the dashed lines representing the limit reference point (red), target reference point (blue) and trigger reference points (magenta).

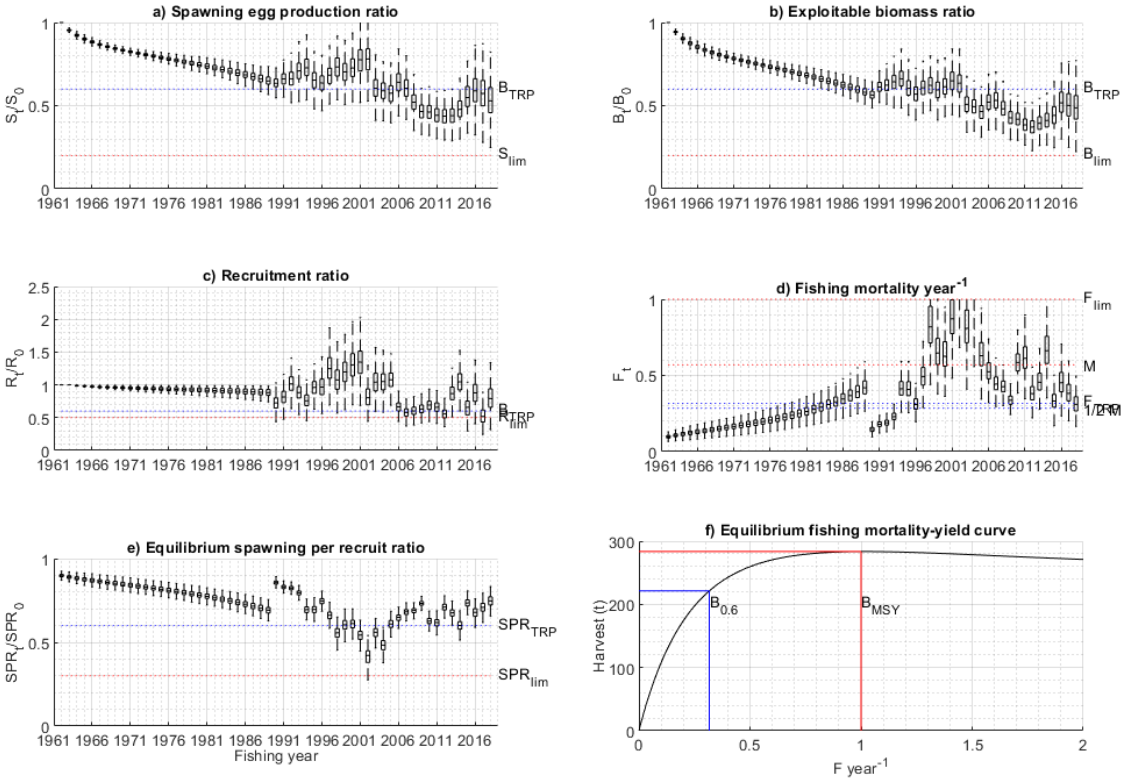

Figure 29. Predictions from analysis 4.

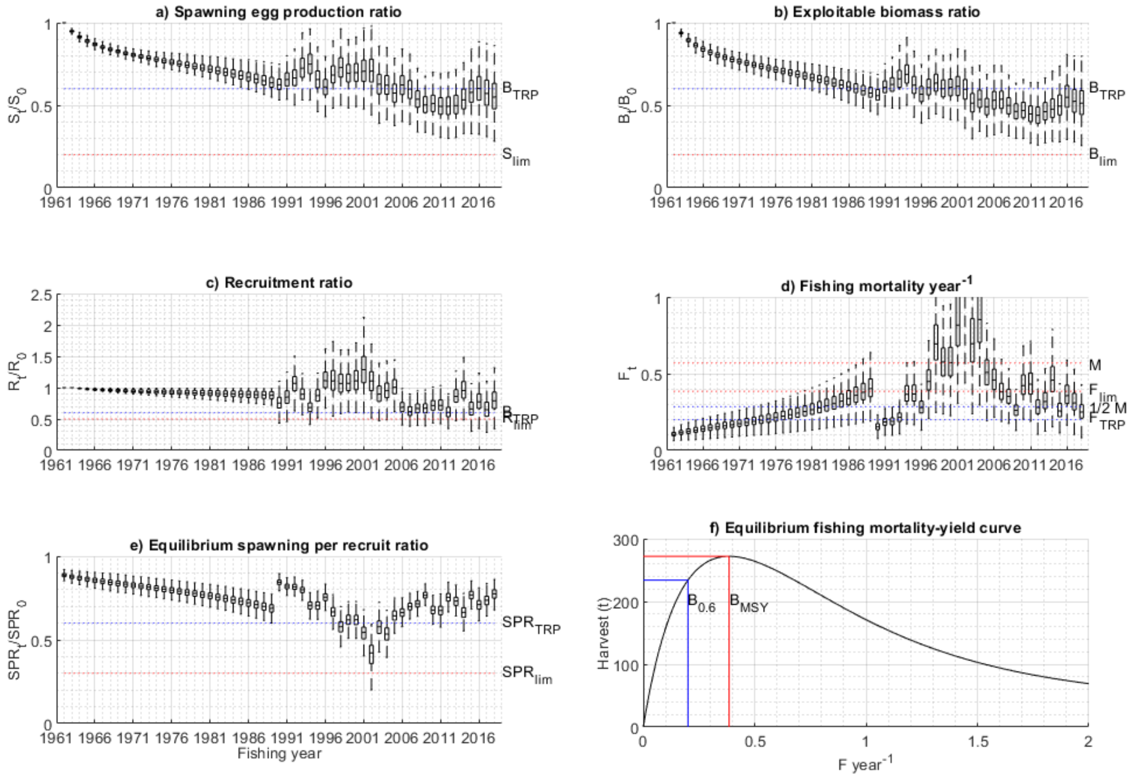

Figure 30. Predictions from analysis 5.

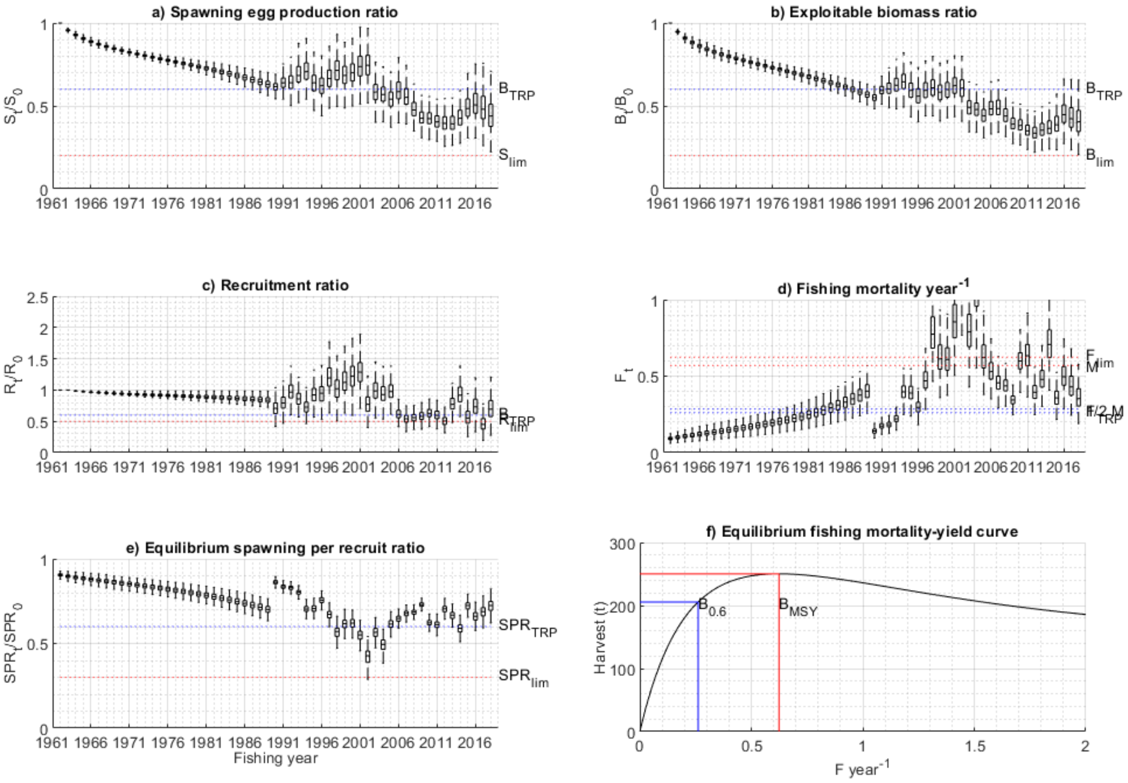

Figure 31. Predictions from analysis 10.

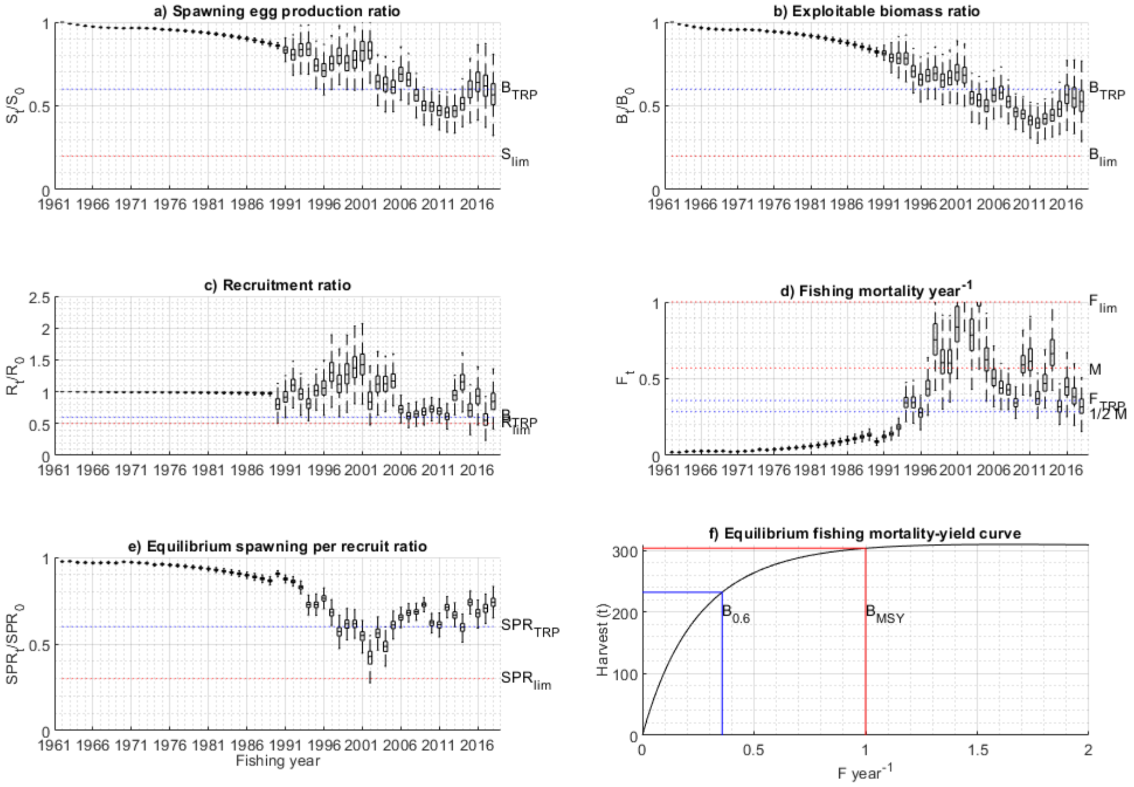

Figure 32. Predictions from analysis 11.

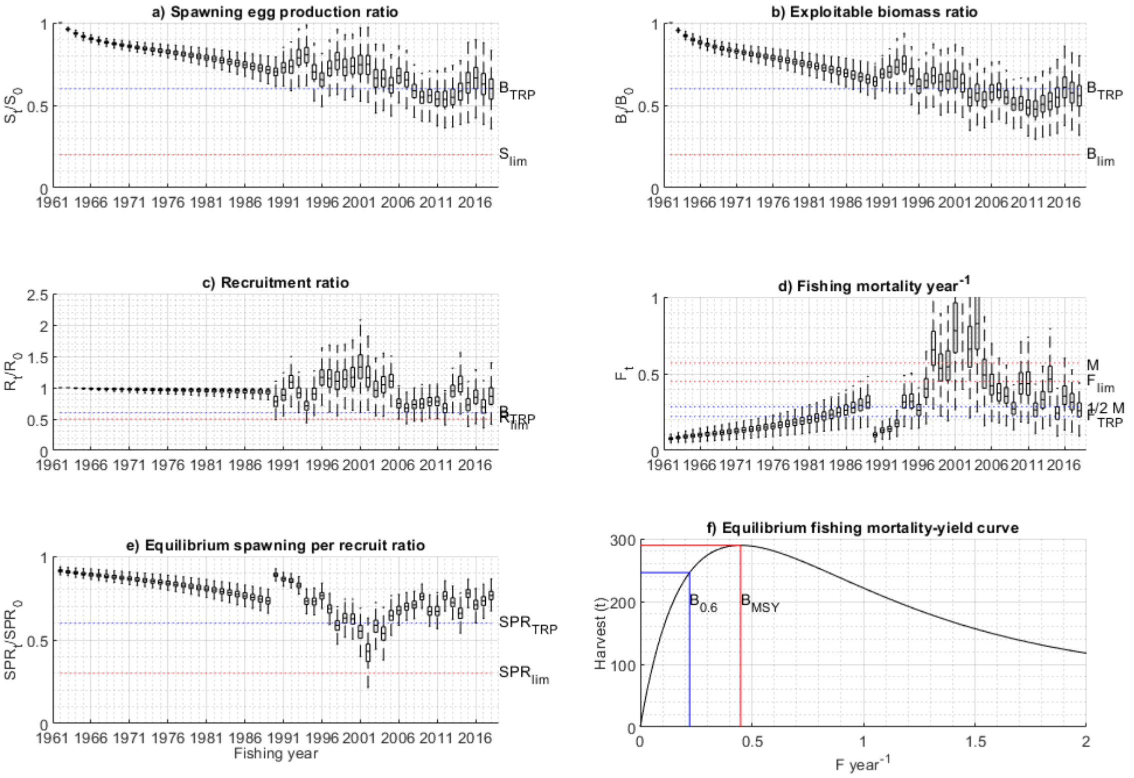

Figure 33. Predictions from analysis 12.

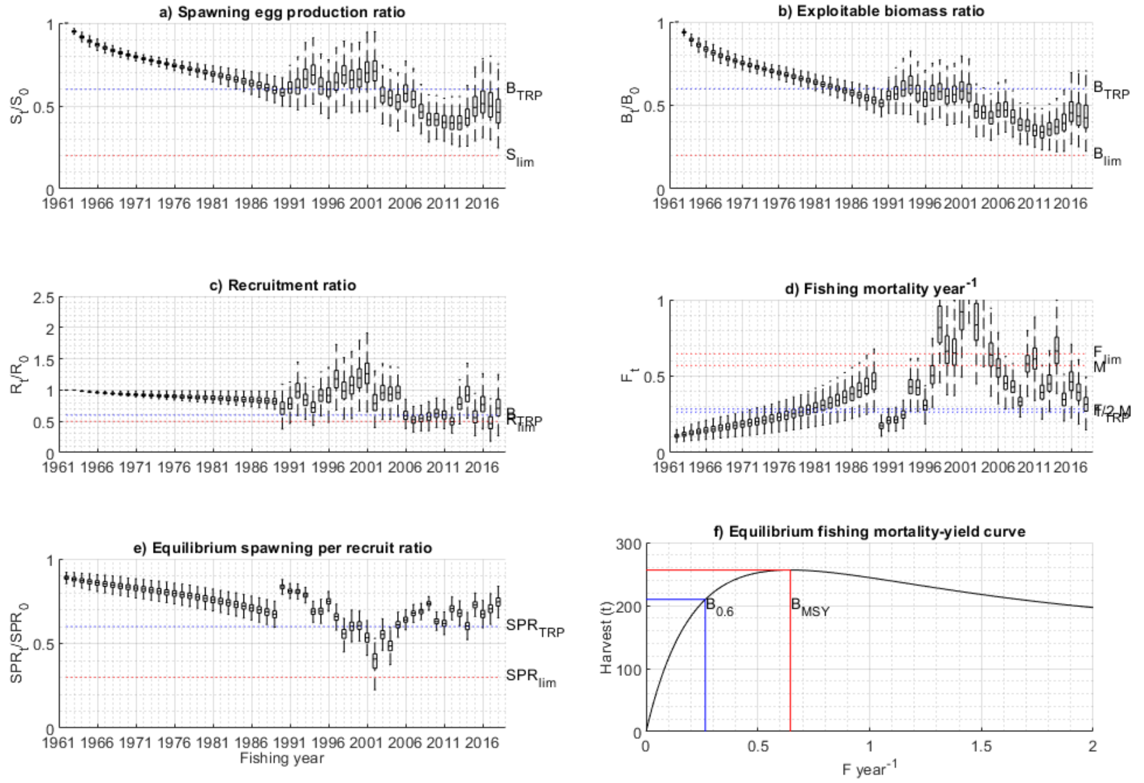

Figure 34. Predictions from analysis 15.

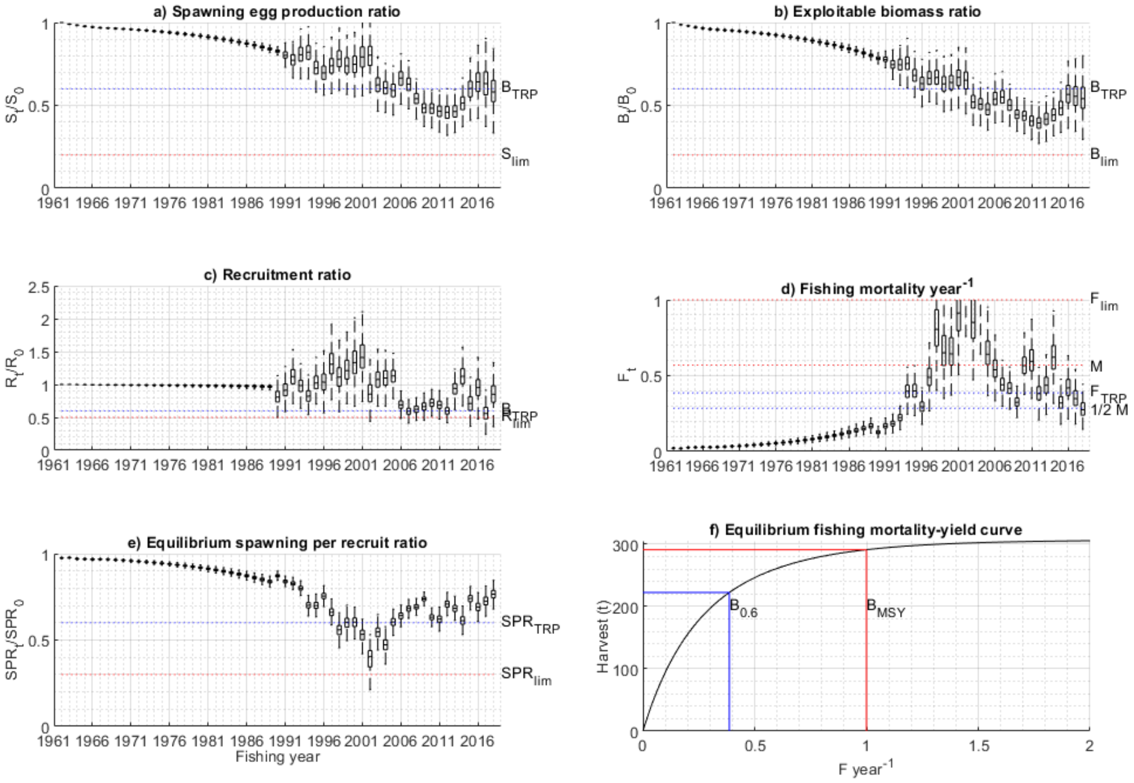

Figure 35. Predictions from analysis 16.

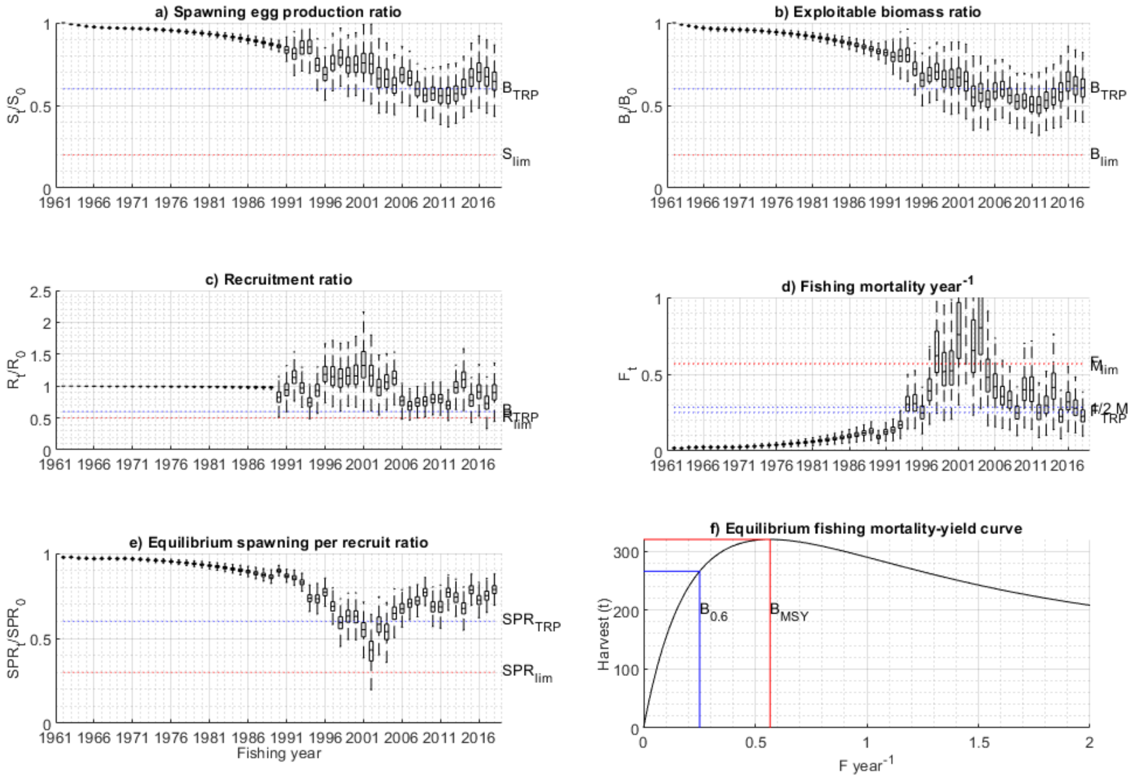

Figure 36. Predictions from analysis 17.

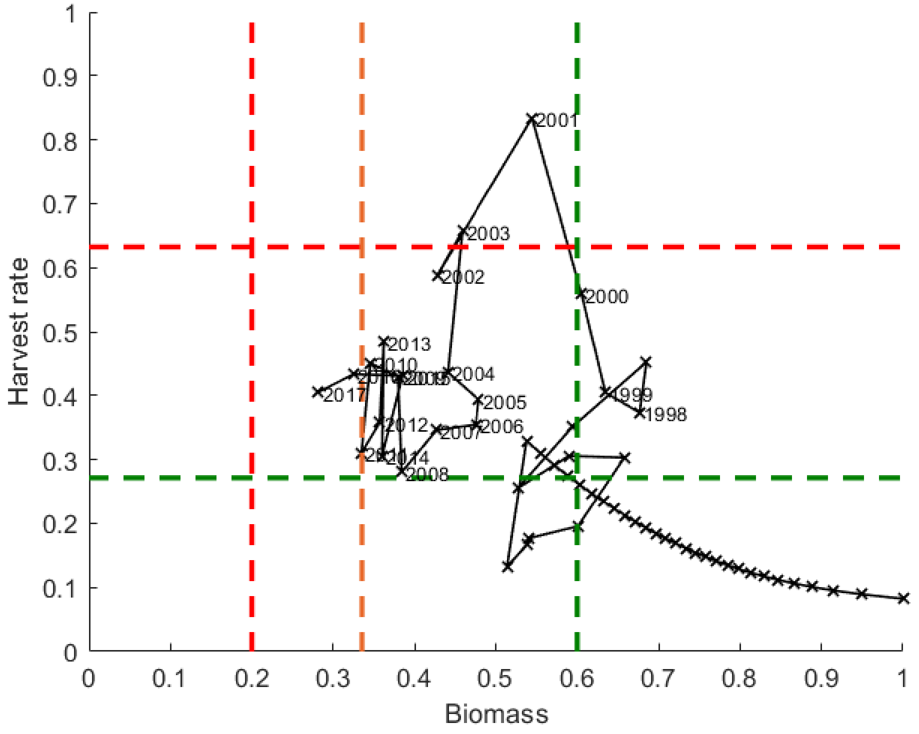

Figure 37. Phase plot of predicted model trajectory for the relationship between harvest rate and biomass for analysis 4.

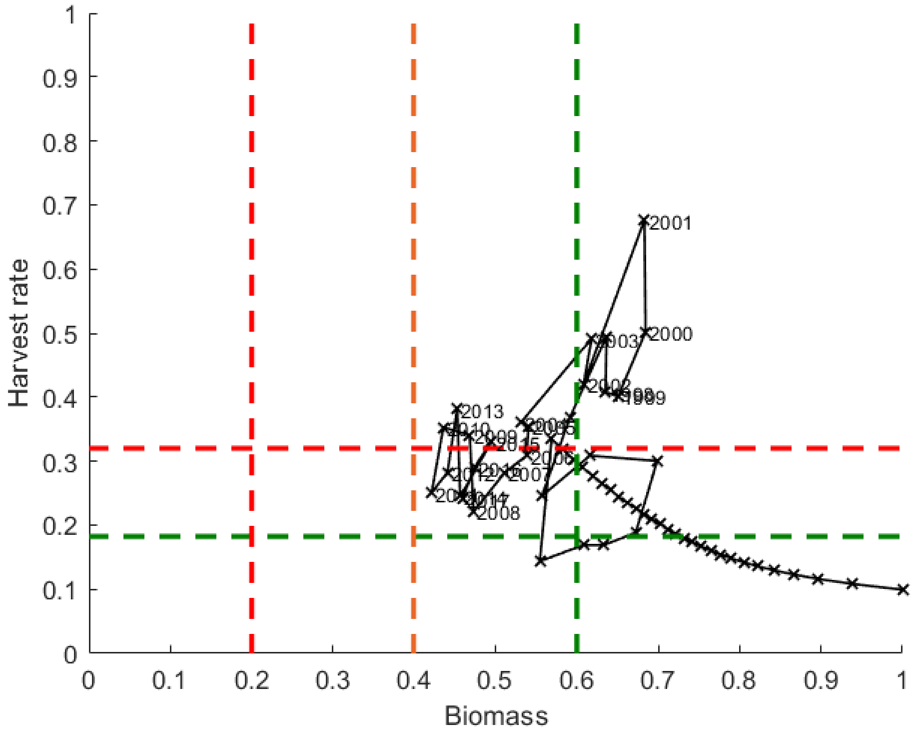

Figure 38. Phase plot of predicted model trajectory for the relationship between harvest rate and biomass for analysis 5.

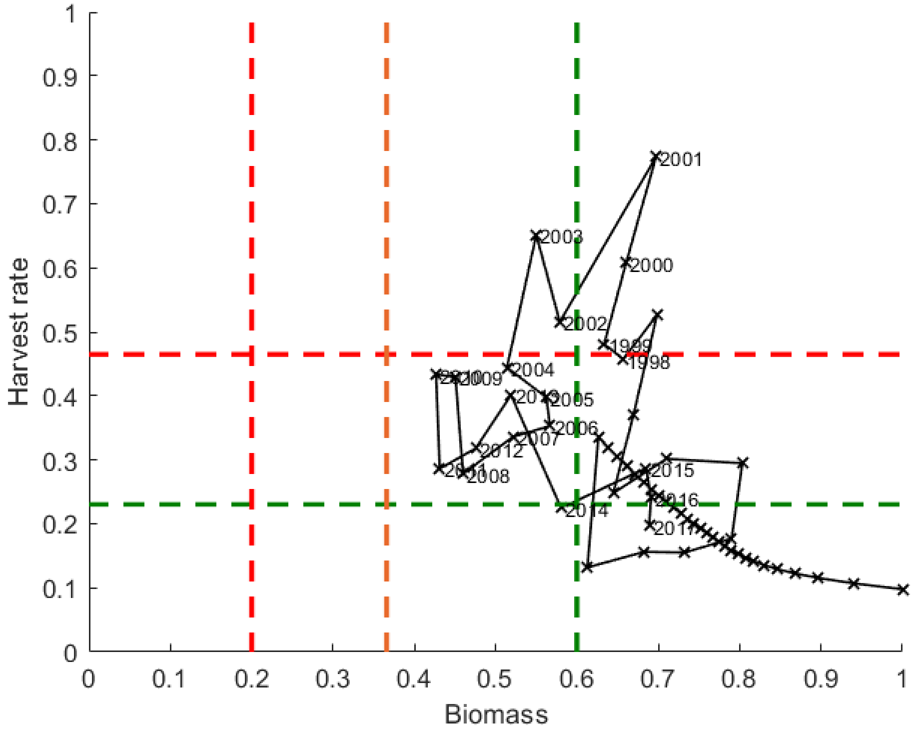

Figure 39. Phase plot of predicted model trajectory for the relationship between harvest rate and biomass for analysis 10.

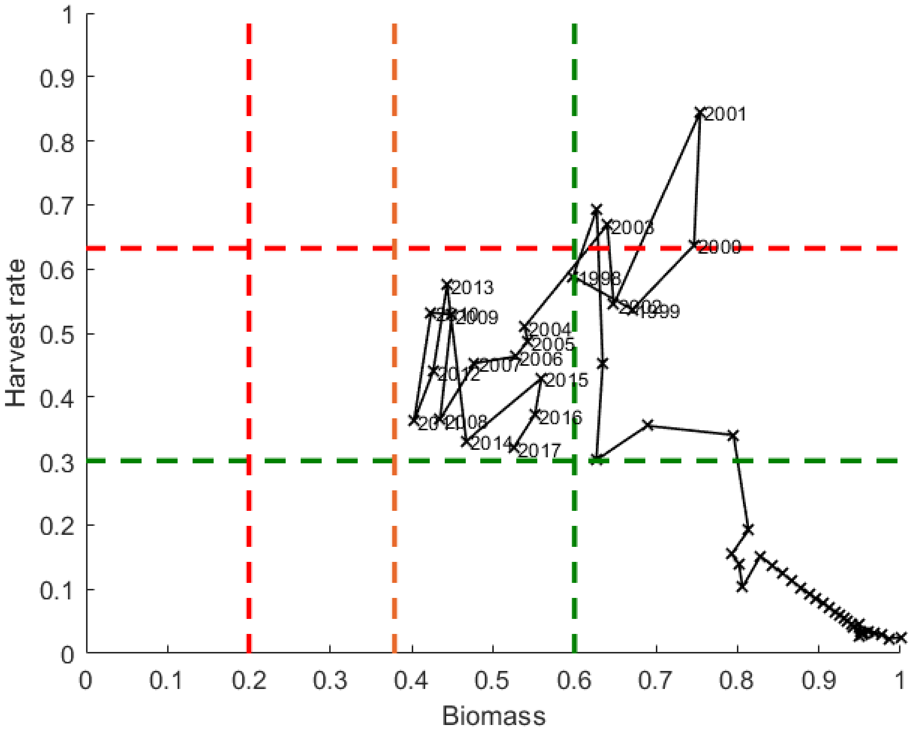

Figure 40. Phase plot of predicted model trajectory for the relationship between harvest rate and biomass for analysis 11.

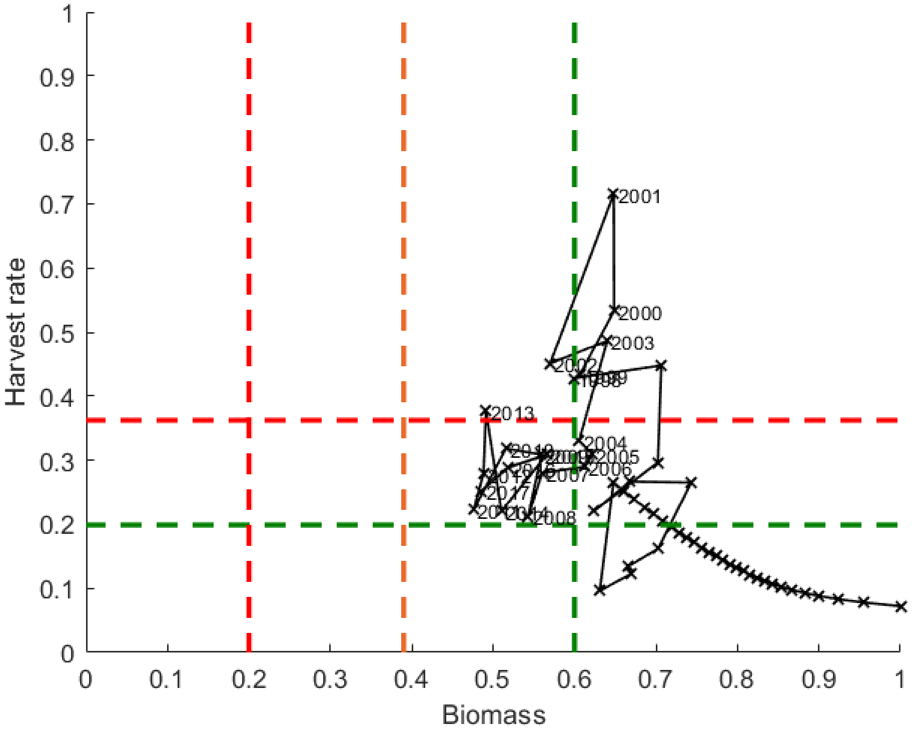

Figure 41. Phase plot of predicted model trajectory for the relationship between harvest rate and biomass for analysis 12.

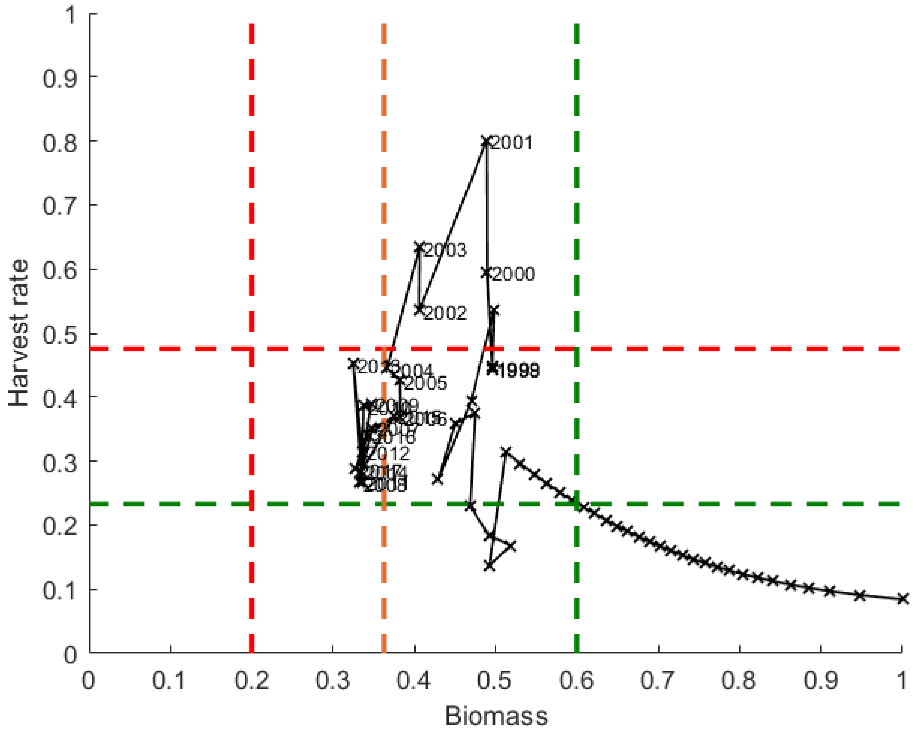

Figure 42. Phase plot of predicted model trajectory for the relationship between harvest rate and biomass for analysis 15.

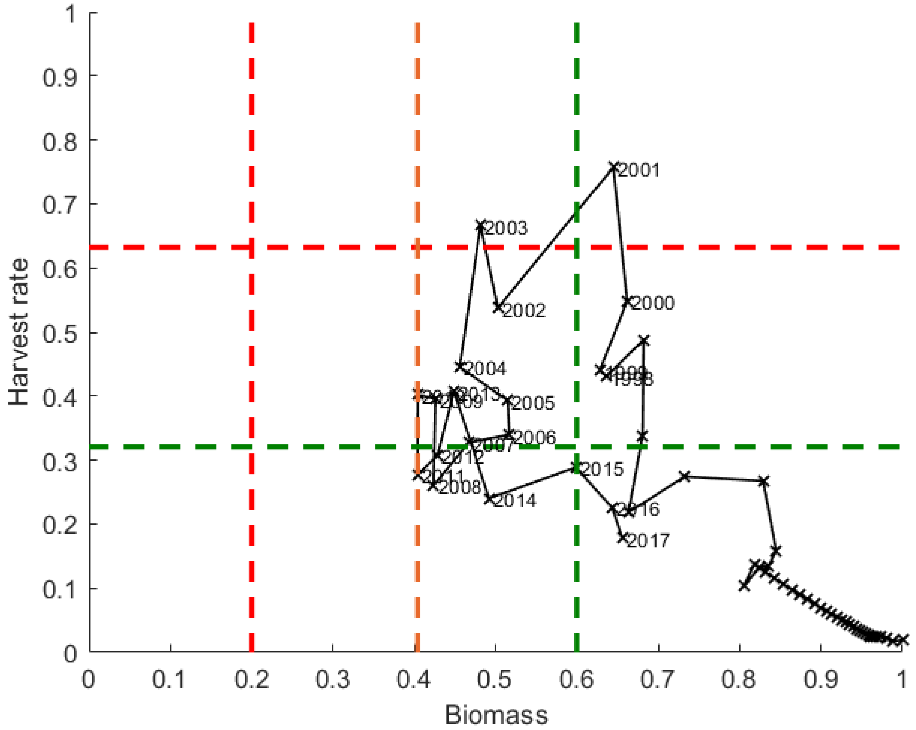

Figure 43. Phase plot of predicted model trajectory for the relationship between harvest rate and biomass for analysis 16.

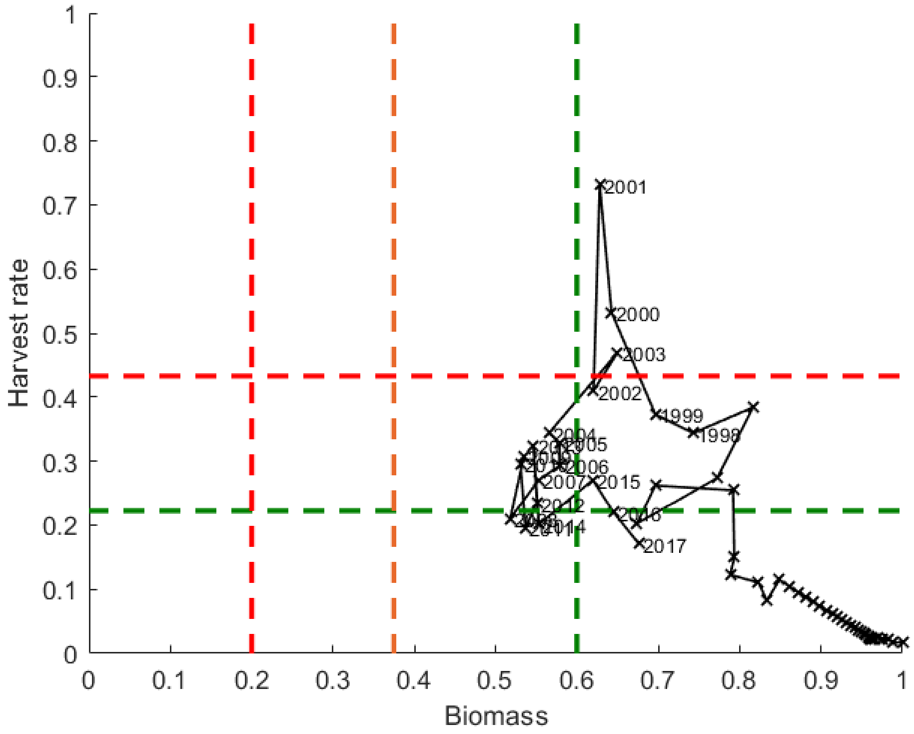

Figure 44. Phase plot of predicted model trajectory for the relationship between harvest rate and biomass for analysis 17.

Table 9. Estimated management quantities for the nine selected MCMC analyses. Median yields (tonnes) of east coast spotted 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% of virgin 1961 exploitable biomass, F_{MSY} – level of fishing mortality for attaining B_{MSY}, $F_{0.6}$ – level of fishing mortality for attaining $B_{0.6}$.

Analysis No.	F_{MSY} @ B_{MSY}	$F_{0.6}$ @ $B_{0.6}$
3	247 (216 : 313)	207 (187 : 244)
4	284 (232 : 340)	222 (195 : 260)
5	300 (243 : 386)	237 (203 : 294)
10	257 (218 : 322)	209 (186 :246)
11	306 (243 : 350)	235 (200 : 268)
12	331 (259 : 414)	255 (213 : 316)
15	262 (224 : 329)	211 (190 : 252)
16	299 (239 : 348)	230 (196 : 267)
17	343 (275 : 437)	266 (221 : 333)
Median yield (t)	299	230