Stock assessment of the Queensland east coast redthroat emperor *(Lethrinus miniatus)*

2020

Queensland Government

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Summary

Queensland's redthroat emperor *(Lethrinus miniatus)* is a line-caught fish forming a single population (stock) off Queensland's east coast. Redthroat emperor are sequential hermaphrodites of the protogyny variety (born female, many later changing sex to male) and aggregate to spawn between July and November. They can grow to more than 3 kg and live for more than 20 years.

Redthroat emperor occur along the tropical and subtropical coasts of eastern and western Australia, with the largest populations found on the Queensland east coast along the Great Barrier Reef between approximately 18° S and 24° S. An early tagging study suggested that redthroat emperor are very site-attached, and move only small distances within a reef, though recaptures indicate inter-reef movement. It has been hypothesised that there is some net northward migration, which may account for regional differences in age structure.

This assessment builds on a previous assessment that estimated the stock was at 70% of unfished biomass in 2004. This stock assessment includes updates to the input data and methods.

This stock assessment used an age-structured population model to 2019, with a yearly time step. It incorporated data spanning the period from 1945 to 2019 including commercial harvest (1988–2019), historical commercial harvest (1945–1981), recreational harvest (1995–2014), fisheries independent monitoring (1995–2009), and fishery dependent monitoring (2016–2019).

Over the last five years, 2015 to 2019, the Queensland total harvest averaged 281 tonnes (t) per year, including 142 t by the commercial sector, 76 t by the charter sector and 64 t by the recreational sector in recent years (Figure 1). The commercial and charter harvest are based on logbook reporting, whereas recreational and Indigenous harvest is estimated from surveys and interpolated between survey years.

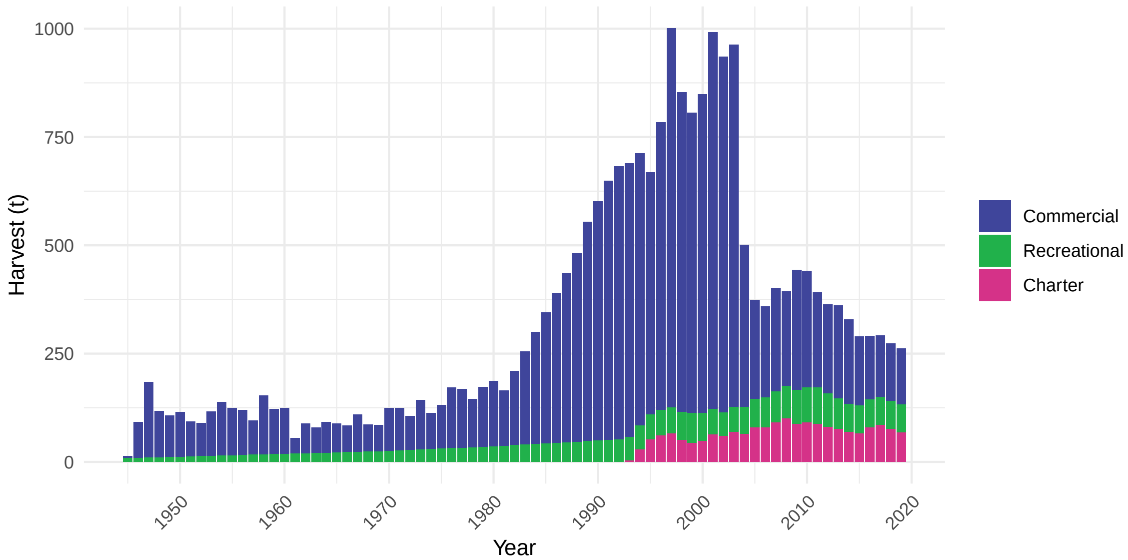

Figure 1: Annual estimated harvest (retained catch) from commercial, recreational (including Indigenous), and charter sectors between 1945 and 2019 for redthroat emperor

Both charter and commercial catch rates were standardised to estimate indices of redthroat emperor abundance through time. For charter catch rates (Figure 2), the unit of standardisation was number of redthroat emperor per 'operation-day', defined to be a single day of fishing by the charter vessel. Year, month, region, fishing operator and number of guests were included explanatory terms.

For commercial catch rates (Figure 3), the unit of standardisation was kilograms of redthroat emperor per 'operation-day', defined to be a single day of fishing by a primary vessel. Year, month, region, fishing operator, number of dories and number of crew were included explanatory terms.

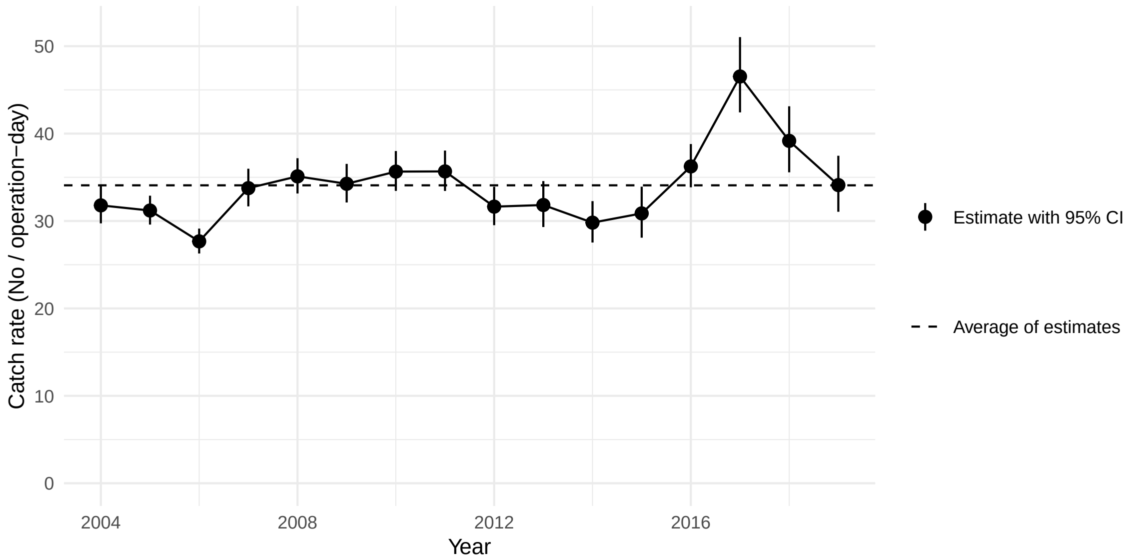

Figure 2: Annual standardised catch rates (95% confidence intervals) for charter line-caught redthroat emperor between 2005 and 2019

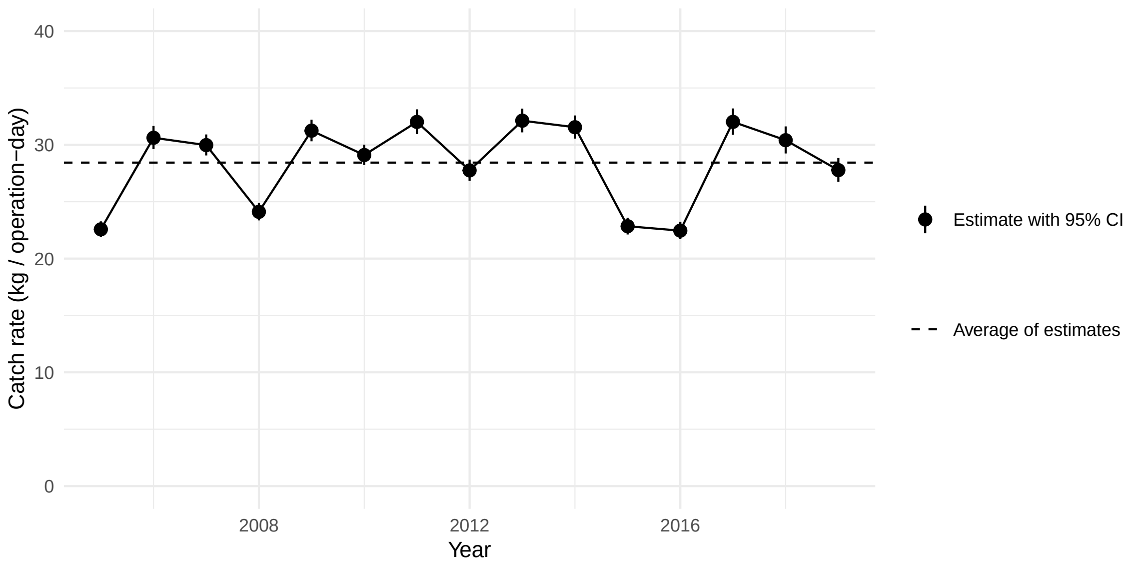

Figure 3: Annual standardised catch rates (95% confidence intervals) for commercial line-caught redthroat emperor between 2005 and 2019

Model results suggested that biomass declined between 1945 and 2012 to 54% unfished biomass. In 2019, the stock level was estimated to be 72% unfished biomass (Figure 4).

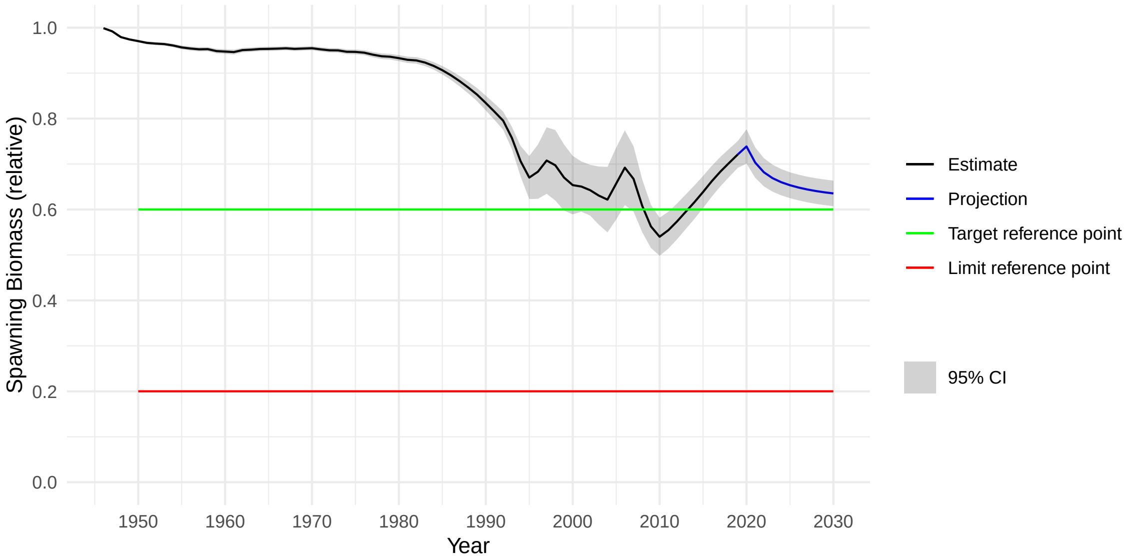

Figure 4: Predicted spawning biomass trajectory relative to virgin for redthroat emperor, from 1945 to 2030—refer to Section 5.6.5 for a description of the projection phase (2021–2030)

Maximum sustainable harvest was estimated at 897 t per year, and the harvest consistent with a biomass ratio of 60% (a proxy for maximum economic harvest) was estimated at 705 t (all sectors).

The stock assessment shows the state of the stock is at very healthy levels, and for this reason the recommended biological harvest in calendar year 2020 to achieve the Sustainable Fisheries Strategy longer term target of 60% unfished biomass may be up to 930 t (485–1709 t range across models). This recommended biological harvest would need to be reduced to 705 t over time.

Table 1: Current and target indicators for redthroat emperor

Parameter	Estimate
Current spawning biomass (relative to unfished)	72%
Maximum sustainable harvest	897 t
Maximum sustainable harvest biomass (relative to unfished)	41%
Current harvest (2019)	261 t
Equilibrium 60% biomass harvest	705 t
2020 harvest to achieve 60% biomass	930 t

Acknowledgements

The work was overseen by a project team committee that consisted of the authors and the following scientists and managers: Lachlan Barter, Sian Breen, Fay Helidioniotis, Sue Helmke, Ashley Lawson, Tyson Martin, Jason McGilvray, Michael O'Neill, Tom Roberts, Anthony Roelofs, James Webley and Sam Williams. The role of the committee was collaborative to share interpretation and decision making on data inputs, assessment methods and results.

Sincere thanks to Jemery Day for input on a range of technical and conceptual challenges, particularly in relation to the Stock Synthesis software.

Many thanks to George Leigh, who did the catch rates for this project. Dr Leigh's original literature review and stock assessment report on redthroat emperor in 2004 was referred to a great deal throughout the project. We also thank Alise Fox for report edits and review.

Researchers from the Effects of Line Fishing (ELF) Project, represented by Dr Bruce Mapstone and Dr Colin Simpfendorfer, provided length and age-frequency data from structured line surveys. The ELF Project field work ran every year from 1995 to 2005 and was undertaken by CRC Reef Research Centre with funding from the Australian Government's Fisheries Research and Development Corporation (FRDC, Project No. 97/124). Thank you to Dr Mapstone for providing an expanded update of this data and making time to discuss it.

Thanks to Bill Sawynok for providing an update on recaptured redthroat emperor movements.

The authors would also like to acknowledge and thank the many fishers and scientists who contributed to past research on redthroat emperor. They provided valuable information on the history of the fishery, and samples and measurements of fish as part of studies conducted by the Queensland Government, James Cook University, the University of Queensland and the Australian Government – through the Fisheries Research and Development Corporation (FRDC). Finally, we would like to thank Eddie Jebreen, in addition to members of the committee, for reviewing and providing comments on the draft report. The assessment was supported by the Queensland Department of Agriculture and Fisheries.

Glossary

CI	confidence interval
CRC Reef	Cooperative Research Centre for the Great Barrier Reef World Heritage Area
CRFFF	Coral Reef Fin Fish Fishery, currently referred to as Reef Line Fishery
DPI&F	Department of Primary Industries and Fisheries (now Department of Agriculture and Fisheries)
ELF	Effects of Line Fishing
fishing year	for redthroat emperor, fishing year is defined to be the same as calendar year
FL	fork length
fleet	a Stock Synthesis modelling term used to distinguish types of fishing activity: typically a fleet will have a unique curve that characterises the likelihood that fish of various sizes (or ages) will be caught by the fishing gear, or be observed at the survey
FRDC	Fisheries Research and Development Corporation
GBR	Great Barrier Reef
GBRMP	Great Barrier Reef Marine Park
ITQ	individual transferable quota
LTMP	Long Term Monitoring Program (managed by Fisheries Queensland)
NRIFS	the National Recreational and Indigenous Fishing Survey conducted by the Australian Department of Agriculture, Fisheries and Forestry
operation-day	a single day of fishing by a primary vessel, with year, month, region, number of dories and number of crew and combinations of these as example explanatory terms
QFB	Queensland Fish Board
RBH	recommended biological harvest
RFish	recreational fishing surveys conducted by Fisheries Queensland
RTE	redthroat emperor
SRFS	Statewide Recreational Fishing Survey
SS	Stock Synthesis
TL	total length

1 Introduction

1.1 Overview

Redthroat emperor are one of Queensland's most important commercial reef fish, with an annual harvest of approximately 280 tonnes in the Reef Line Fishery of the Great Barrier Reef (GBR). It is also a popular species targeted by charter fishers, and recreational line fishers able to travel offshore. It is known in Australia by a variety of local common names including sweetlip, sweetlip emperor, lipper, tricky snapper and tricky.

Redthroat emperor occur along the tropical and subtropical coasts of eastern and western Australia, with the largest populations found on the Queensland east coast along the GBR between approximately 18° S and 24° S (Figure 1.1). Research on the stock structure of redthroat emperor concluded that it was a single stock (Van Herwerden et al. 2003; Davies et al. 2005). However, studies on the population biology of redthroat emperor from the same locations have identified significant variation in a range of demographic parameters between regions of the GBR, which may be more relevant for management (Williams 2003; Williams et al. 2003). Therefore, although populations may be genetically homogenous across the GBR, productivity of redthroat emperor, and the response of populations to fishing, can vary significantly among regions of the GBR.

Redthroat emperor are typically associated with coral or rocky reefs, although they are also commonly encountered on shoal and rubble habitats between reefs (Newman et al. 1996). Along the GBR redthroat emperor are nearly exclusively found on mid and outer shelf reefs to a maximum depth of at least 128 m, and are rarely found on inshore reefs (Newman et al. 1996).

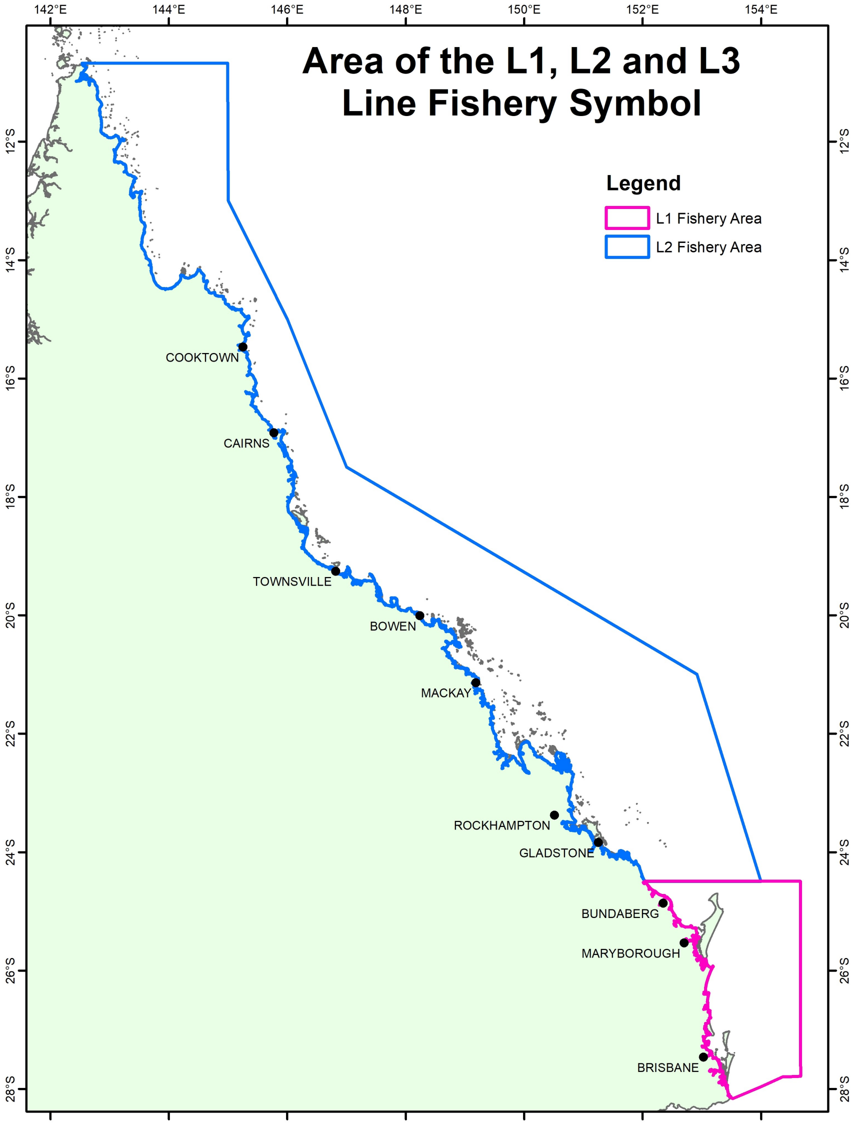

Figure 1.1: Commercial sector fishery zones of Queensland redthroat emperor. The L3 Fishery Area is the same as L2.

Movement patterns of redthroat emperor are not well known. An early tagging study suggested that redthroat emperor are very site-attached and move only small distances within a reef (<500 m) and not between reefs (Beinssen 1989). This study was limited to a period of only three weeks, and thus the results should be treated with some caution, as movements over greater distances may occur over longer periods. Recaptures of tagged redthroat emperor indicate that individuals are capable of moving among reefs, with one recaptured fish having moved about 215 km over a period of two years (W. Sawynok, Infofish, unpublished data). Williams (2003) hypothesised a net northward migration of redthroat emperor in order to account for regional differences in age structure of the population. Redthroat emperor can be solitary but often form large schools of similar sized individuals. More recently, Brodie et al. (2018) used telemetry data and redthroat emperor were determined to be an “occasional” mover. These were defined as site-attached individuals with a medium level of dispersal.

Redthroat emperor have been confirmed to be a sequential hermaphrodite, exhibiting protogyny, whereby individuals mature first as females before changing sex later in life (Bean et al. 2003; Williams 2003;

Sumpton et al. 2004). The mechanism that triggers sex change is not known, but the large overlap in sizes and ages of males and females (Williams 2003; Sumpton et al. 2004) suggests that it is most likely socially controlled rather than genetically predetermined (Vincent et al. 1998). The fact that some of the oldest fish in sampled populations have been female (Williams 2003; Sumpton et al. 2004) suggests that not all individuals change sex, and highlights the plasticity of sex change in redthroat emperor. Reported sex ratios for redthroat emperor populations vary among regions of the GBR, but all have been female biased, which is typical for an exploited protogyny-variant sequential hermaphrodite (Sadovy 1996).

The spawning season for redthroat emperor is relatively protracted and appears to be similar among regions of the GBR with peak spawning occurring between July and November (Williams 2003; Sumpton et al. 2004). The spawning behaviour of redthroat emperor is not known.

Redthroat emperor are a relatively large coral reef fish reaching a maximum size of approximately 600 mm fork length (FL) and a maximum weight of around 3 kg (Church 1985; Brown et al. 1998; Williams 2003; Williams et al. 2003). Reports of redthroat emperor reaching 900 mm FL and 9 kg in weight (Carpenter et al. 1989; Carpenter 2001) are likely to be other emperor species, such as *Lethrinus nebulosus*, *L. laticaudis*, *L. erythacanthus* and *L. xanthochilus*, that have been misidentified. It is often difficult to identify species of emperor due to similarities among species and varied colour patterns of individual species. Research on redthroat emperor reported a maximum age of 20 years using counts of validated annual increments in otoliths (Williams et al. 2005; Brown et al. 1998; Williams 2003; Williams et al. 2003).

Redthroat emperor can reach their maximum size at around 6 years of age, but there is a substantial amount of variability in size at age among individuals (Williams 2003). Patterns of growth for redthroat emperor have been found to vary significantly among locations on the GBR (Brown et al. 1998; Williams 2003; Williams et al. 2003). Generally, populations in the southern regions of the GBR reach a larger maximum size than populations in the northern region (Williams 2003; Williams et al. 2003).

There are four sectors in the coral reef finfish fishery: Indigenous, commercial, charter and recreational. Not much is known about the Indigenous fishery, though a survey in 2000 was carried out which yields a possible estimate of annual harvest.

Redthroat emperor has been an important species for the sectors of the Reef Line Fishery on the GBR (Mapstone et al. 1996; Higgs 2001; Slade et al. 2002). Redthroat emperor are caught year round by hook and line in all sectors, and occasionally by spear in the recreational, charter and Indigenous sectors. The majority of the commercial sector operates from 4–7 m dories working from 8–19 m primary vessels (Mapstone et al. 1996), and are usually retained whole on ice or filleted, skinned and frozen on board the primary vessel. Recreational and charter fishing occurs on vessels that take single- or multi-day trips to the east coast. All sectors operate throughout the distribution of redthroat emperor on the GBR although outer-shelf reefs are less accessible to recreational fishers than to commercial and charter fishers.

The majority of the commercial sector operates from 4–7 m dories working from 8–19 m primary vessels (Mapstone et al. 1996). There has been a recent shift to landing whole dead on ice fish but the majority of redthroat emperor is sold skinned and frozen on board the primary vessel. Recreational and charter fishing occurs on vessels that take single- or multi-day trips to the east coast.

Management of the Reef Line Fishery, of which redthroat emperor are a significant component, is the responsibility of Department of Agriculture and Fisheries. Minimum size restrictions and bag limits specifically relating to this species have been legislated since the *Fisheries Act 1957* (Table 1.1). Other historical management tools have included limited commercial entry, and gear specifications. Additional controls were introduced by the Fisheries (Coral Reef Fin Fish) Management Plan 2003, especially an annual total allowable commercial catch (TACC) and individual transferable catch quota (ITQ) system for the commercial sector (Table 1.1). ITQs came into effect in July 2004 and nine-day spawning closures in October, November and December 2004. Also, areas closed to fishing under the *Great Barrier Reef Marine Park Act 1975* were extended in July 2004 as a result of the Great Barrier Reef Marine Park Authority (GBRMPA) Representative Areas Program.

Table 1.1: History of redthroat emperor management. (Sources: DPI&F staff and Andersen et al. (2005)).

Year	Management	Legislation
1957	Minimum size limit 12 inches total length.	*Fisheries Act 1957*
1975	Inclusion of no-fishing zones in the Great Barrier Reef.	*Great Barrier Reef Marine Park Act 1975*
1976	Minimum size limit 300 mm total length.	*Fisheries Act 1976*
1984	Line fishery 'L' symbol introduced under the primary fishing boat policy. Limited entry for primary licences.	*Fishing Industry Organisation and Marketing Act 1982*
1987	Delegation of management responsibility for coral reef fish stocks in Commonwealth waters from the Commonwealth to Queensland. Restriction on the number of tender vessels.	Policy
1988	Restriction on sale of fish by recreational fishers to 50 kg of whole fish per permit, with a maximum of 12 permits to be sold to any individual annually. (Prior to 1988 there were no restrictions on the quantity of fish that a recreational fisher could sell.)	*Fishing Industry Organisation and Marketing Regulation*
1990	Ability of recreational fishers to sell catch stopped. Discussion paper for Coral Reef Fin Fish Fishery (CRFFF) released: A review of the reef line fishery and proposed management measures.	*Fishing Industry Organisation and Marketing Regulation*
1993	Minimum size limit 350 mm total length. Recreational possession limits of 10 redthroat emperor per fisher, and a combined total of 30 coral reef fish covering 26 species. Charter vessel possession limit arrangements— extended charters in excess of 48 hrs allowed double the prescribed possession limit. Restructure of commercial line fishery into regional endorsements—the existing L symbol was introduced into legislation with the numbers L1–L9 depicting different regions of operations. New format for landed fish—where a fish has been filleted there must be two fillets equal to one whole fish. Skin not to be removed from fillets by recreational fishers, except in the case of charter vessels in excess of 48 hrs where the majority of the skin may be removed provided a minimum is left for identification.	Fishing Industry Organisation and Marketing Regulation

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Table 1.1 – *Continued from previous page*

Year	Management	Legislation
1995	Reef Fisheries Management Advisory Committee (ReefMAC) established.	Fisheries Regulation under *Fisheries Act 1994*
1995	Refinement of management responsibilities for coral reef fish in Commonwealth waters.	Offshore Constitutional Settlement
1996	Discussion paper 2 for CRFFF released: Queensland tropical coral reef fish species.	
1997	Investment Warning for the CRFFF released 19 May 1997. Issues Paper released—Excess fishing capacity in the commercial sector of the tropical coral reef fish fishery—an approach for inclusion in a statutory Fisheries Management Plan.	
1998	Investment Warning was re-issued 3 September 1998.	
1999	Draft Management Plan and Regulatory Impact Statement (RIS) for CRFFF released.	
2002	Revised Draft Management Plan and RIS released 28 September 2002.	
2003/04	Fisheries (Coral Reef Fin Fish) Management Plan implemented. Minimum legal size increased to 380 mm total length in December 2003. Recreational in-possession limits reduced to 8 redthroat emperor per fisher, and a combined total of 20 coral reef fish. Anglers on charter boat trips of more than 72 hours have double the bag limit; trips of eight days or longer can retain up to 60 fish per fisher. Recreational fishers are limited to handline, rod and line (limit of 3 lines at a time with a maximum total of 6 hooks or lures), hand-held spear and spear gun (no SCUBA or hookah). Commercial fishers limited to a handline or rod and line. All commercial vessels must hold an RQ licence. RQ licence holders must hold appropriate line units (RTE units) to take redthroat emperor, which take the form of individual transferable quotas. The total yearly catch of redthroat emperor available for allocation is currently 700 t. New reporting requirements. Seasonal closures across the GBR for nine days around the new moon period in October, November and December each year.	*Fisheries (Coral Reef Fin Fish) Management Plan 2003*
2004	GBRMPA implemented new zoning arrangements for the Great Barrier Reef Marine Park. Under the rezoning approximately 33% of the marine park area is protected through closed green zones within which extractive uses are restricted.	*Great Barrier Reef Marine Park Zoning Plan 2003*
2007	All RQ fishers allowed to fillet RTE and the introduction of a minimum fillet size length of 16 cm.	*Filleting policy*
2020	Harvest strategy for the Reef Line Fishery implemented with decision rules for RTE based around the outputs of this assessment.	

In 2019, the Queensland Department of Agriculture and Fisheries commissioned an update to the stock assessment for redthroat emperor. This assessment aims to determine the status of the north eastern Australian (Queensland) biological stock. This report informs estimates of sustainable harvests to ensure the fishery operates at sustainable levels, for commercial, charter and recreational fishing, and support the harvest strategy defined in Queensland's Sustainable Fisheries Strategy 2017–2027.

The stock was previously assessed with data through to 2004 by Leigh et al. (2006). This assessment contains updates to data and methodology. Key updates include:

- Stock Synthesis software has been used to model the population and estimate parameters
- Charter catch rates have been included as an index of abundance
- Recent fishery dependent survey data (biological data which included length and age) have been included in the model

2 Methods

2.1 Data sources

Data sources included in this assessment were used to determine catch rates, age and length compositions, and create annual harvests. These were summarised and modelled by sector. Preparation of data was compiled by calendar year. The assessment period began in 1945 up until and including 2019 based on available information.

Data included in this assessment are detailed in Table 2.1, Figure 3.1 and are described in more detail in the following sections.

Table 2.1: Data used in the Queensland east coast redthroat emperor stock assessment

Data	Source	Years	References
Commercial	Logbook data managed by Fisheries Queensland	1988–2019	
	Historical Queensland Fish Board Data	1945–1980	Halliday et al. 2007
	Length data from fisheries dependent monitoring undertaken by Fisheries Queensland	July-December 2019	
	Observer program data collected by Fisheries Queensland from the commercial fishery	2011	
Charter	Logbook data collected by Fisheries Queensland	1988–2019	
Recreational	Recreational fishing surveys conducted by Fisheries Queensland (RFish, and the Statewide Recreational Fishing Survey)	1997, 1999, 2002, 2005, 2011, 2014	Higgs 1999; Higgs 2001; Higgs et al. 2007; McInnes 2008; Taylor et al. 2012
	Recreational fishing surveys conducted by the Australian Department of Agriculture, Fisheries and Forestry (the National Recreational and Indigenous Fishing Survey, NRIFS)	2000	Henry et al. 2003
	Boat ramp survey, conducted by Fisheries Queensland	2015–2019	Queensland 2017
Indigenous	Indigenous fishing survey conducted in 2000 by the Australian Department of Agriculture, Fisheries and Forestry (the National Recreational and Indigenous Fishing Survey, NRIFS)	2000	Henry et al. 2003
Fisheries independent Surveys	Biological monitoring (age and length from line survey) undertaken by the Effects of Line Fishing (ELF) project	1995–2005	Mapstone et al. 2004; Fisheries Queensland 2012
	Biological monitoring (age and length from line survey) undertaken by Fisheries Queensland	2006–2009	Fisheries Queensland 2012
Observer	Observer program data collected by Fisheries Queensland	2011	N/A

2.1.1 Commercial

2.1.1.1 Logbook data and quota reporting system

Commercial harvests of redthroat emperor were recorded in the Queensland logbook system. The logbook system consists of daily harvests (landed weight in kilograms) of all fish species from each individual fishing operator (license) since 1988. In addition to landed weight, logbooks also record the location of the catch (30 minute or 6 minute grid identifier), the number of boats (dories) that were fishing, and the number of crew.

Since financial year 2004–05, commercial harvest for redthroat emperor have also been available from the quota reporting system where fishers are required to report exact weights, rather than estimated weights (as reported in logbooks).

2.1.1.2 Historical Queensland Fish Board data

Fish sold were by law marketed through the Queensland Fish Board (QFB) until 1981. The data may underestimate the total catches, as fish destined for overseas or interstate were not required to be marketed through the QFB. There was also an unknown level of illegal marketing of fish in Queensland outside the QFB.

2.1.1.3 Fisheries dependent monitoring

The Fishery Monitoring program, part of Fisheries Queensland, collects fishery dependent data from commercial fishers. Data includes the date the fish was caught, catch location, species name and lengths. Some of the fish are also sexed. Data collected during 2019 was used in the redthroat emperor assessment.

2.1.1.4 Observer data

This observer data was used as to estimate the commercial discard proportion, and was similar to the discard fraction assumed by Leigh et al. (2006).

2.1.2 Charter

This provided the operator identifier, the date, the location fished, retained catch by species (including discards) and the number of guests on the trip.

2.1.3 Recreational

2.1.3.1 Recreational fishing surveys

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

Surveys conducted in 2000, 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 (Lawson 2015).

2.1.3.2 Boat ramp survey

Recreational data were collected by Fisheries Queensland in 18 different regions, extending from Aurukun to the Gold Coast. Staff trained in the survey protocol, and identifying fish, interviewed recreational fishers at boat ramps during a survey shift. The surveys recorded day and location fished, catch of key species (including discards) and length of retained key species (Northrop et al. 2018; Queensland 2017). The length data was used as input in the model, and discards were used to infer discard rates of redthroat emperor for the recreational sector.

2.1.4 Indigenous

The National Recreational and Indigenous Fishing Survey in 2000 attempted to redress the lack of Indigenous fishing information on a national scale by involving Indigenous communities in the gathering of fisheries statistics. Estimates of total harvest and discard for Indigenous communities followed similar procedures (Henry et al. 2003). Indigenous harvests were combined with recreational harvests for reporting purposes.

2.1.5 Fisheries independent line surveys (age and length compositions)

2.1.5.1 Effects of Line Fishing

The ELF project was a major research project run by CRC Reef Research Centre and partly funded by the FRDC. The ELF Project sampled 24 reefs in the GBR (four clusters each of six reefs) each year. Line fishing catch surveys were conducted in spring of each year. These line surveys were done via the charter of an active commercial fishing operation with a master fisherman and four dory-fishermen, accompanied for the surveys by four research staff. Fishing gear was standardised among fishers and over time to be comparable with standard contemporary gear used in the commercial Reef Line Fishery on the GBR. In addition to age and length data, where possible, the sex of each fish and its weight were also recorded. For more details see Mapstone et al. (2004).

2.1.5.2 Fisheries Queensland Long Term Monitoring Program

Following on from ELF, Fisheries Queensland continued to collect age and length composition data using a similar methodology as ELF (Fisheries Queensland 2012) at six reefs in regions where the most coral reef fin fish were landed: Cairns, Townsville, Mackay and the Swains.

Underwater visual surveys of demersal reef fish populations were carried out as part of the DPI&F Long Term Monitoring Program and ELF Project from 1999–2009. Very low numbers of redthroat emperor were recorded in these surveys, because it is generally a diver-averse species and difficult to survey by this method, and much of the population lives at depths greater than the 12 m limit of these surveys.

2.2 Harvest estimates

Commercial, charter, recreational and Indigenous harvest and data (where available) were analysed to reconstruct the history of harvest from 1945 until the end of 2019. Prior to 1945 redthroat emperor harvest is presumed to be small. This section describes how this data was combined to create the history of redthroat emperor harvest (Figure 3.2).

Commercial sector:

- was assumed zero in 1945, and increased linearly to the value from the Queensland Fish Board in 1945.
- equalled Queensland Fish Board records from 1945 through 1981.
- increased linearly from the last recorded Queensland Fish Board value in 1981 through to the first recorded Queensland logbook value in 1988.
- equalled logbook values from 1988 through calendar year 2004.
- equalled quota reporting values from calendar year 2005 through 2019.

Charter sector:

- estimates equalled Queensland charter logbook values from first records in 1992 through 2019.

Recreational:

- was assumed zero in 1945 and increased proportionally to Queensland population growth through to reach a rescaled RFish estimate in 1997.
- this rescaled estimate was calculated in the following way:
  - The RFish estimates from 1999 and 2002 were interpolated to obtain a candidate estimate for the year 2000.
  - The rescale factor was calculated as this candidate estimate divided by the NRIFS estimate for the year 2000.
  - This rescale factor was then used to rescale all RFish estimates, including the 1997 value which anchored the series that started from zero in 1953.
- estimates for 1999, 2002, and 2005 were set to equal the values from the rescaled RFish estimates.
- estimates for 2000, 2011 and 2014 were set to equal the values reported in the NRIFS (2000) and SRFS (2011 and 2014) surveys.
- estimates for 2015 through 2019 were set to equal the value reported in the 2014 SRFS survey.
- "missing" recreational harvests in 1998, 2001, 2003, 2004, 2006–2010 were set to values linearly interpolated between the above estimates.
- estimates for all years were converted from numbers to an estimated retained (landed) harvest using the mean redthroat emperor fish weight from the ELF data set (aggregate mean weight over all years, which were different before 2004 and after 2004 with the change in minimum legal size).

Indigenous harvest:

- equalled the NRIFS estimate from 2000 for all years from 1945 onwards.
- were added to the recreational harvest.

2.3 Abundance indices

Queensland logbook data on commercial and charter line catches (kg whole weight for commercial, and number of fish for charter) of redthroat emperor per fishing-operation-day were used as an index of legal-sized fish abundance. The indices were standardised by removing the effects of a number of factors not related to abundance. The methods below outline the concepts and procedures used to achieve this standardisation. In the following, the term "catch rate" refers to a standardised catch rate unless otherwise specified.

From the initial logbook data set, including all coral reef logbook records, a series of filters were applied to arrive at the final analysis data set. These filters involved a number of criteria relating to location, species, fishing method, fishing date and trip duration. The resulting data set had a maximum of one record per fisher per day. When particular species were caught by a fisher on a particular day, but no redthroat emperor were caught, a "zero catch" for redthroat emperor was inferred. More details on the data filtering process are given in Appendix A, Section A.4.

The statistical model used was a quasi-negative-binomial generalized linear model, where the variance was modelled as a quadratic function of the mean. The analysis was carried out using the software R (version 3.6.2, (R Core Team 2020)). The analyses used the 'glm' function, using the "quasi" family with a log link. Details of preliminary data filtering are given in Appendix A.

Once filtered, the data sets were grouped into regions for analysis (Figure 2.1):

- "North" - which includes Cairns North and Townsville
- "Central" - which includes Bowen, Storm Cay and Swains
- "South" - which is the Capricorn Bunker

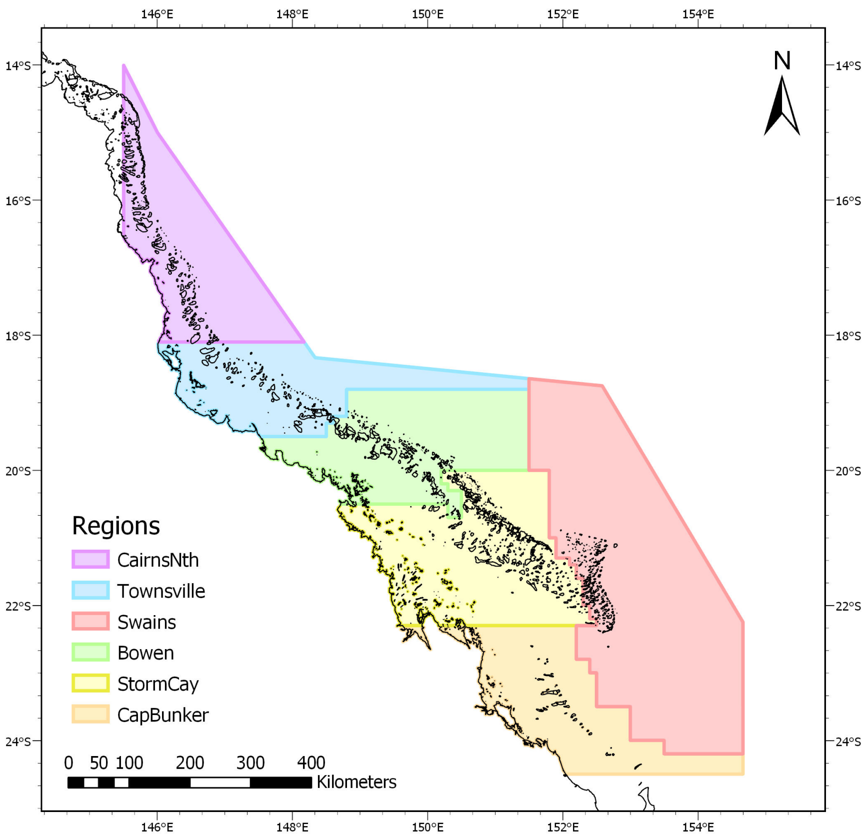

Figure 2.1: The regions used in the estimation of abundance indices for Queensland redthroat emperor

2.3.1 Charter sector

Variables that were accounted for in the charter catch rate model to model the number of redthroat emperor caught per fishing operator per day were:

- Region
- Year (region of the record combined with the year of the record)

- Sub-region
- Month
- Fisher (fisher license number)
- Number of guests

2.3.2 Commercial sector

Variables that were accounted for in the commercial catch rate model to model the weight of redthroat emperor caught per fisher operator per day were:

- Region
- Year (region of the record combined with the year of the record)
- Sub-region
- Month
- Fisher
- Number of dories including the primary vessel
- Number of crew

2.4 Discards and discard mortality

Discard data were available from the logbooks for the charter fishery, and estimated to be 27%.

Recreational discard rates from the boat ramp survey and diary surveys were estimated at 55%.

The observer survey results from 2011 gave an impression of commercial discards for redthroat emperor which showed a 12% discard rate. This may be an underestimation, as a study carried out by Welch et al. (2008) showed that discard rates were at a minimum 12%. Based on this evidence, a discard rate of 12% was assumed.

Discarded harvests were also subject to a fixed discard mortality of 20% across all sizes for all sectors (based on Brown et al. (2008)). The expected weight of the dead discards were added to the total reported harvest for the year as input into the model.

All harvest recommendations and MSY values calculated by the model were then reduced by the total amount of dead discards, which equated to multiplying the output from stock synthesis by approximately 0.95 to obtain the actual retained portion of the harvest.

2.5 Biological information

2.5.1 Fork length and total length

Leigh et al. (2006) fitted a linear regression model to fork length from the ELF data and Brown et al. (1998). The following conversion was applied to convert all lengths in the model to total length (TL).

$$TL_{mm} = 3.2 + 1.0732 * FL_{mm}$$

where TL_{mm} is total length (mm) and FL_{mm} is fork length (mm).

2.5.2 Average total weight

The minimum legal size was 35 cm TL before 2004. Using ELF data, this translated to an average weight of 1.169 kg, and was the figure used to convert between number and weight of fish before 2004.

After 2004, a minimum legal size of 38 cm was implemented, which translates to an average weight of 1.496 kg.

2.5.3 Maturity and fecundity

Maturity values in the model were age-based, following the result of an analysis by Leigh et al. (2006):

- 75% mature at age 1,
- 88% at age 2,
- 95% at age 3,
- 98% at age 4,
- 99% at at 5,
- fully mature from age 6.

No information is available on the fecundity for redthroat emperor or any other emperor. For this assessment we assumed that the number of eggs produced by a female redthroat emperor was proportional to its weight.

2.5.4 Weight and length

Length and weight data from the ELF program was used to calculate the weight-length relationship:

$$W = 1.21105 \times 10^{-4} \times TL^{2.42}$$

where W is whole weight (kg) and TL is total length (cm).

2.6 Population model

For the base model, a single sex (both sexes combined) population dynamic model was fitted to the data to determine the number of redthroat emperor in each year and each age group using the software package Stock Synthesis (SS; version SS-V3.30.14.0). A full technical description of SS is given in Methot et al. (2019).

2.6.1 Model assumptions

For the base model, assumptions for formulating inputs to the SS redthroat emperor model included:

- The fishery began from an unfished state in 1945.
- The fraction of fish that are female at birth is 50% and remains so throughout an individual's life.
- Growth occurs according to the von Bertalanffy growth curve.
- The weight and fecundity of redthroat emperor are parametric functions of their size.
- The proportion of mature fish depends on age and not size.
- The instantaneous natural mortality rate does not depend on age, size or sex.

The assumption that the sex ratio is 50% throughout life is in conflict with known biology, which indicates female to male sex change (protogyny sequential hermaphroditism). An alternate scenario which explicitly accounted for hermaphroditism was included and outlined in Section 3.3.

2.6.2 Model parameters

A variety of parameters were included in the model, with some of these fixed at specified values and others estimated. Uniform priors were used unless stated otherwise.

The natural logarithm of virgin spawning stock size ($\ln(R_0)$) was estimated within the model.

Stock recruitment steepness (h) was fixed at 0.5 as a base case. This value would be low for many species, but is plausible for the less productive Australian waters and serves a precautionary purpose in this assessment.

Parameters of the von Bertalanffy growth curve were estimated within the model, including coefficients of variation for both young and old fish.

Logistic length-based selectivity parameters were also estimated for the model fleets. Separate selectivity curves were estimated for each survey fleet (the LTMP and ELF line surveys). Separate selectivity curves were also estimated for each fishery fleet (charter, commercial and recreational) based on length data obtained from the fisheries dependent monitoring and boatramp survey programs. These were found to be very similar, and therefore were grouped and a single selectivity curve was estimated for all three fleets.

Recruitment deviations between 1992 and 2007 improved fits to composition data and abundance indices as variability in recruitment annually allowed for changes in the population on shorter time-scales than fishing mortality alone.

2.6.3 Model weightings

For the base case, data inputs were given equal weighting in the model. A Francis adjustment was applied to the age and length compositions within Stock Synthesis (Francis 2011). An automatic adjustment was made to the catch rate coefficient of variation and shown in the estimates tables.

2.6.4 Sensitivity tests and alternate scenarios

Several additional model runs were undertaken to determine sensitivity to fixed parameters, assumptions and model inputs. Methodology was loosely derived from Burch et al. (2018). The sensitivities were as follows:

- Natural mortality parameter at 0.25 and 0.35.
- Steepness was observed at 0.45 and 0.55.
- Two thirds of the catch were assumed between 1997 and 2004
- Double and half the weight of the CPUE.
- Double and half the weight on the lengths.
- Double and half the weight on the ages.
- Maturity was determined by length, which was 50% mature at 28 cm as in Williams et al. (2006)

The summary statistics presented for these were:

- The virgin spawning stock biomass SB_0
- The spawning stock biomass in 2019 SB_{2019}
- The current biomass ratio, i.e. SB_{2019}/SB_0
- The negative log-likelihood value $-lnL$
- Recommended biological harvest at 60% equilibrium biomass

In addition to the above scenarios, hermaphroditism was explicitly accounted for in a test scenario, and a poor recruitment scenario was also tested.

2.6.4.1 Hermaphroditism

A model which explicitly accounted for hermaphroditism of the species was built. All of the fish were assumed to be female at birth, with 60% changing to male over the period of the assumed maximum age of 20 years (Leigh et al. 2006). Much about the dynamics of sex change for redthroat emperor is still not known. Hermaphroditism is believed to be socially determined, potentially driven by fishing pressure in particular regions.

2.6.4.2 Poor Recruitment Scenario

For the base case, recruitment deviations were estimated up to and including 2007 as there was insufficient evidence to estimate recruitment further. From 2008 onwards an average level of recruitment was assumed. To explore this assumption, an alternative scenario of low recruitment between 2008 and 2019 was simulated. To examine the possibility of ongoing poor recruitment on current biomass estimates, lower than average recruitment was simulated from 2008–2019. The mean of the log recruitment deviations in the base case for the final five years (1998–2002) were used.

2.6.5 Forward projections

Stock Synthesis's forecast sub-model was used to provide forward projections of biomass and future harvest targets, following a 20:60:60 harvest control rule. This rule has a linear ramp in fishing mortality between 20% biomass, where fishing mortality is set at zero, and 60% biomass, where fishing mortality is set at the equilibrium level that achieves 60% biomass ("F_{B60}"). Below 20% biomass fishing mortality remains set at zero, and above 60% biomass fishing mortality remains set at F_{B60} (Figure 2.2). This rule is augmented with a "buffer" to offset model uncertainty. A buffer is a discount factor applied to the control rule to account for risk under uncertainty. For this assessment a buffer value of 0.87 has been chosen, following Commonwealth Harvest Strategy policy guidelines (Department of Agriculture and Water Resources 2018).

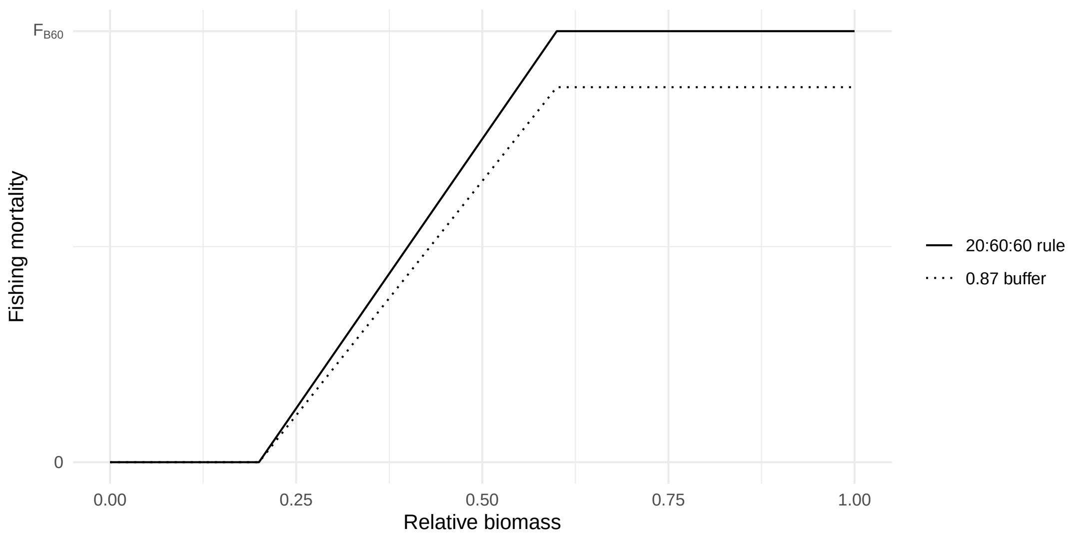

Figure 2.2: The 20:60:60 harvest control rule (solid line) with 0.87 buffer (dashed line)

3 Results

3.1 Model inputs

Figure 3.1 summarises the estimated data used as input to the model.

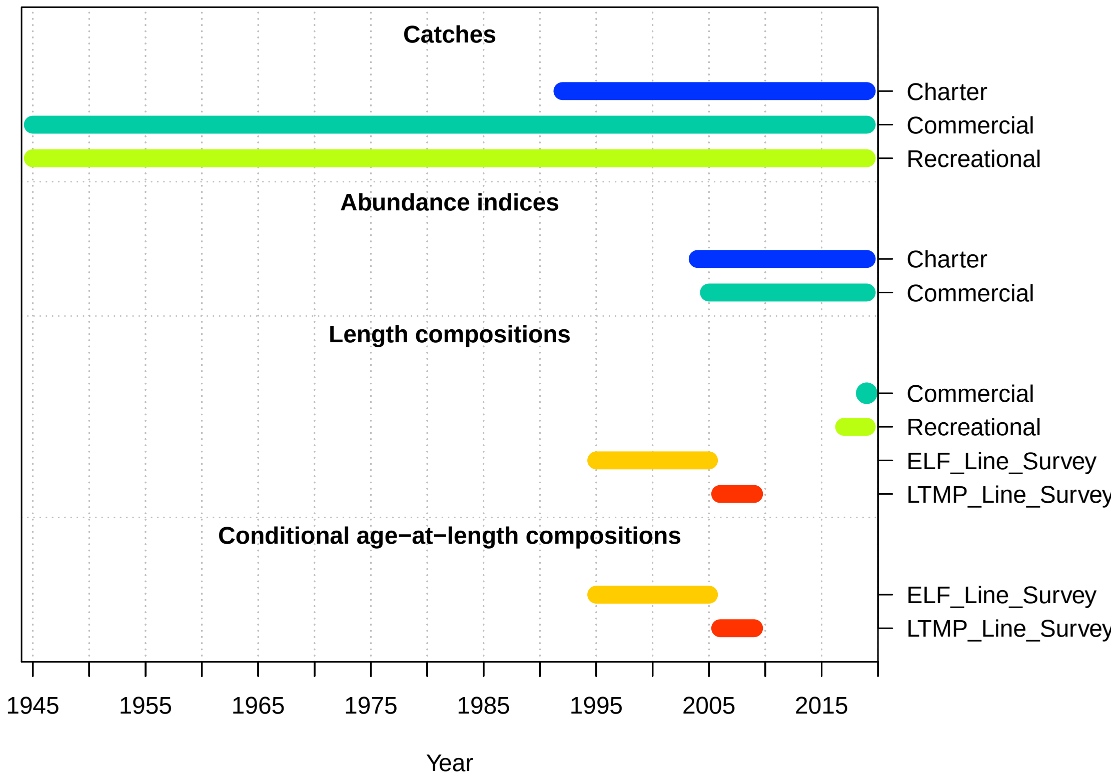

Figure 3.1: Data presence by year for each category of data type and Stock Synthesis fleet for redthroat emperor

3.1.1 Harvest estimates

Total harvest (landed catch) combined harvest from commercial, recreational, charter and Indigenous sectors (Figure 3.2). The majority of the total harvest can be attributed to the commercial sector. Prior to 1980, total harvest was relatively low. The harvest estimates indicate that up to 1000 tonnes of redthroat were landed annually in the early 2000s, before individual transferable quotas (ITQs) were introduced in 2004. Since this time, the estimated total harvest has reduced significantly.

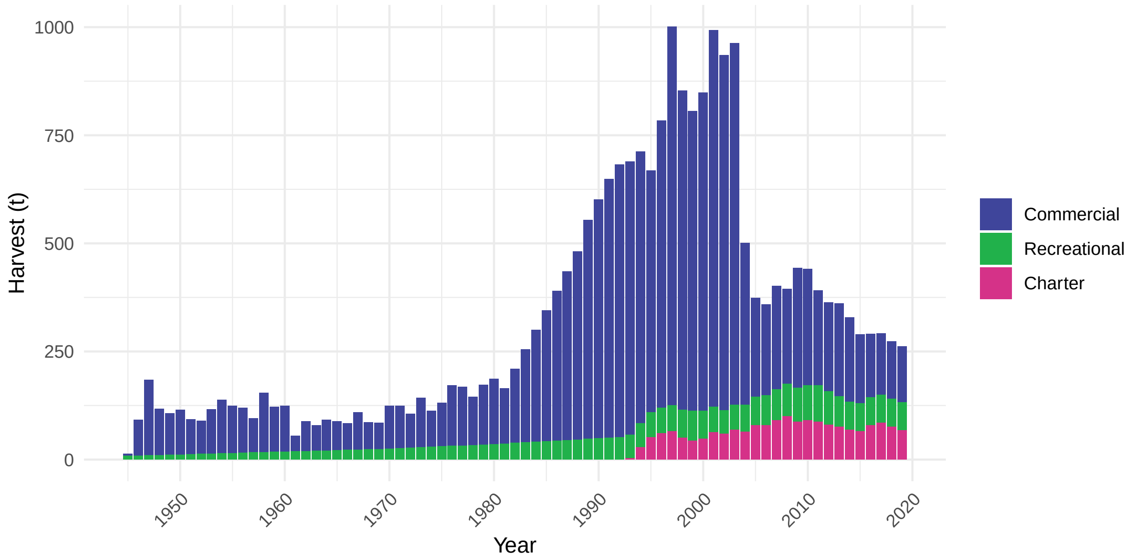

Figure 3.2: Annual estimated harvest (retained catch) from commercial, recreational (including Indigenous), and charter sectors between 1945 and 2019 for redthroat emperor

3.1.2 Standardised catch rates

The standardised charter catch rate averages about 34 fish per operation-day with a minimum of 27 kg per operation-day in 2006 and a maximum of 46 fish in 2016 (Figure 3.3).

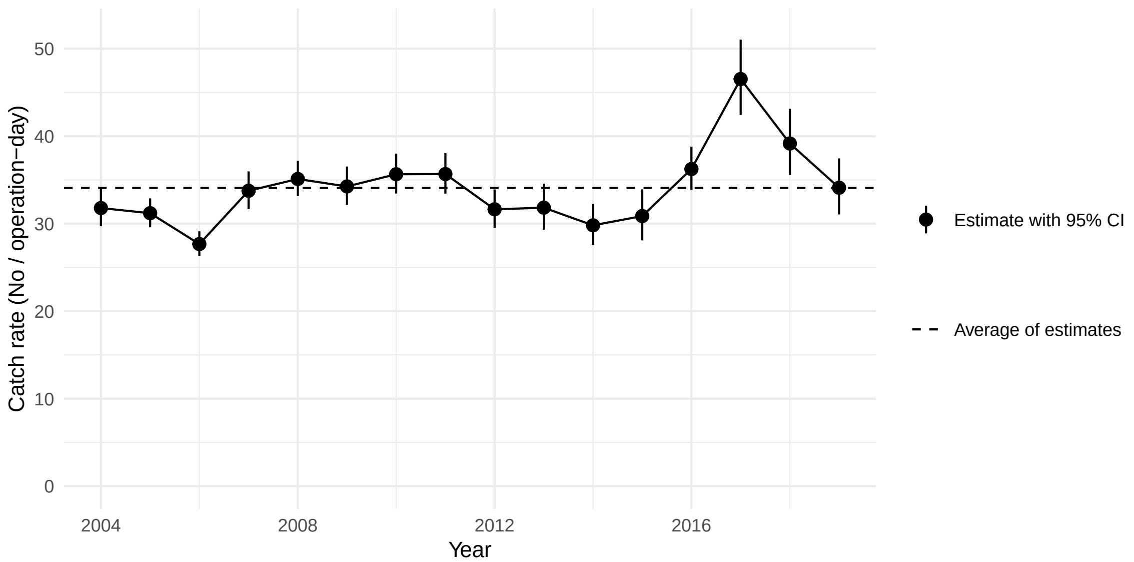

Figure 3.3: Annual standardised catch rates (95% confidence intervals) for charter line caught redthroat emperor between the years of 2005 and 2019

The standardised commercial catch rate averages about 28 kg per operation-day with a minimum of 27 kg per operation-day in 2005 and a maximum of 32 fish in a number of years throughout the series (Figure 3.4).

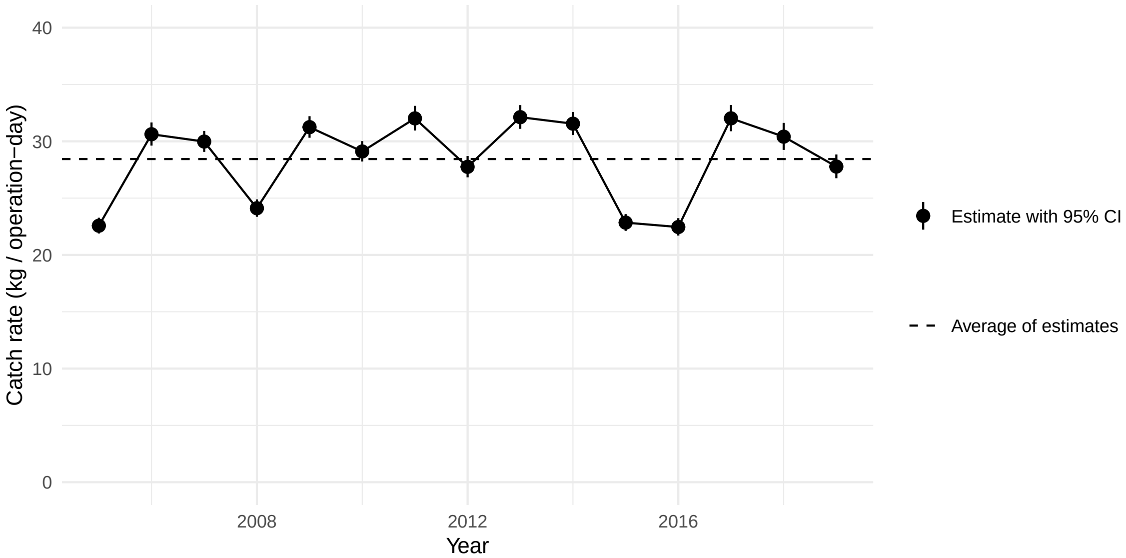

Figure 3.4: Annual standardised catch rates (95% confidence intervals) for commercial line caught redthroat emperor between the years of 2005 and 2019

3.1.3 Age composition

Fishery age composition data were input to the population model, as part of age-at-length compositions, for the ELF survey fleet (Figure 3.5) and the LTMP survey fleet (Figure 3.6). The data were right-skewed for most years in both regions. Sample sizes are in Appendix A, Table A.1.

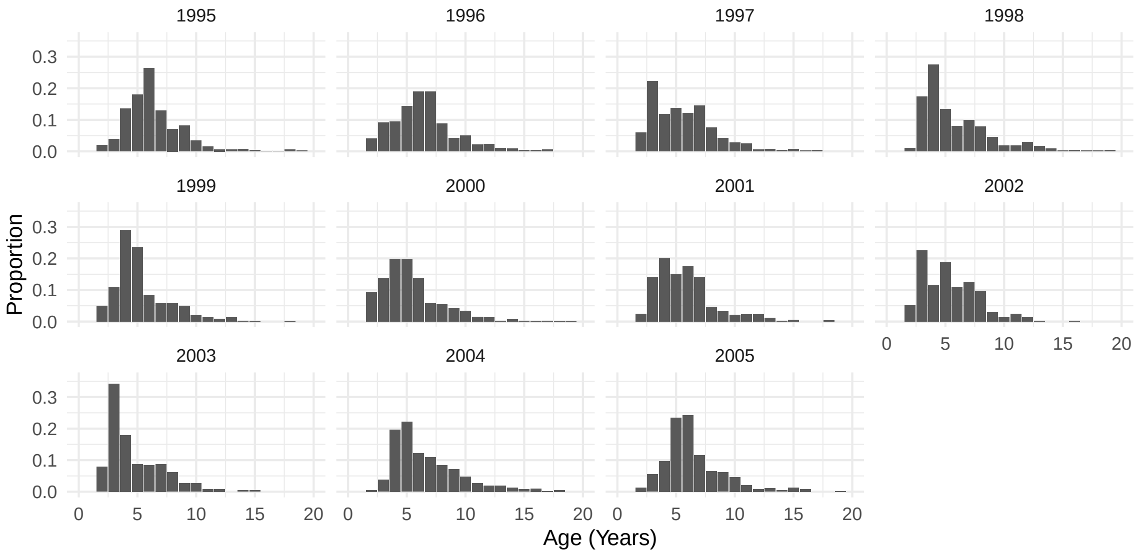

Figure 3.5: Annual age compositions of redthroat emperor for line caught fish between 1995 and 2004 by the ELF survey

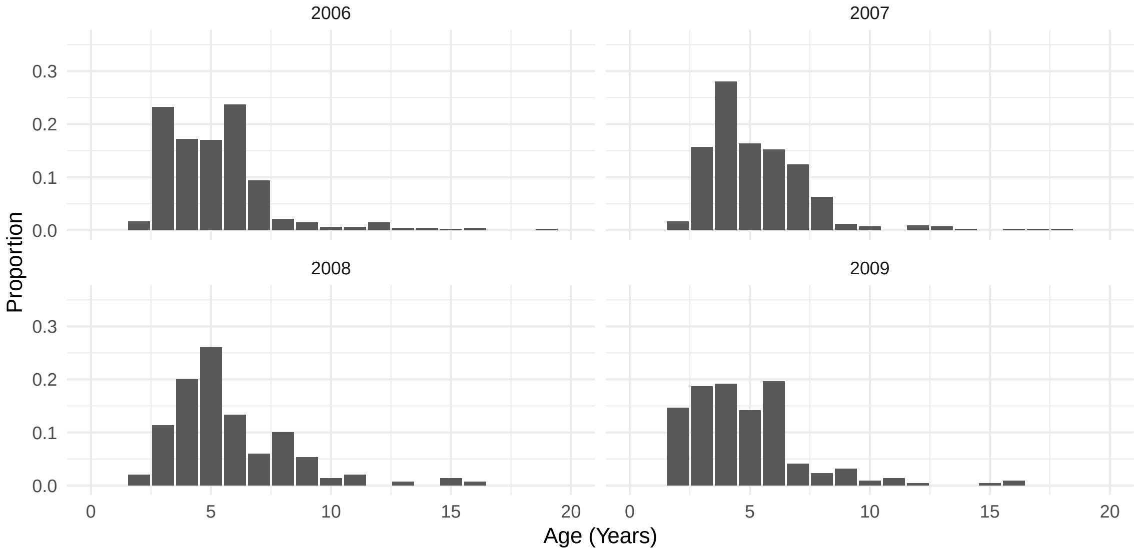

Figure 3.6: Annual age compositions of redthroat emperor for line caught fish between 2006 and 2009 for the LTMP survey

Conditional age-at-length composition data and fixed biological relationships are provided in Appendix A, Sections A.2 and A.3.

3.1.4 Length composition

Fishery length compositions were input to the population model for the commercial fleet (Figure 3.7), recreational fleet (Figure 3.8), ELF survey fleet (Figure 3.9) and the LTMP fleet (Figure 3.10).

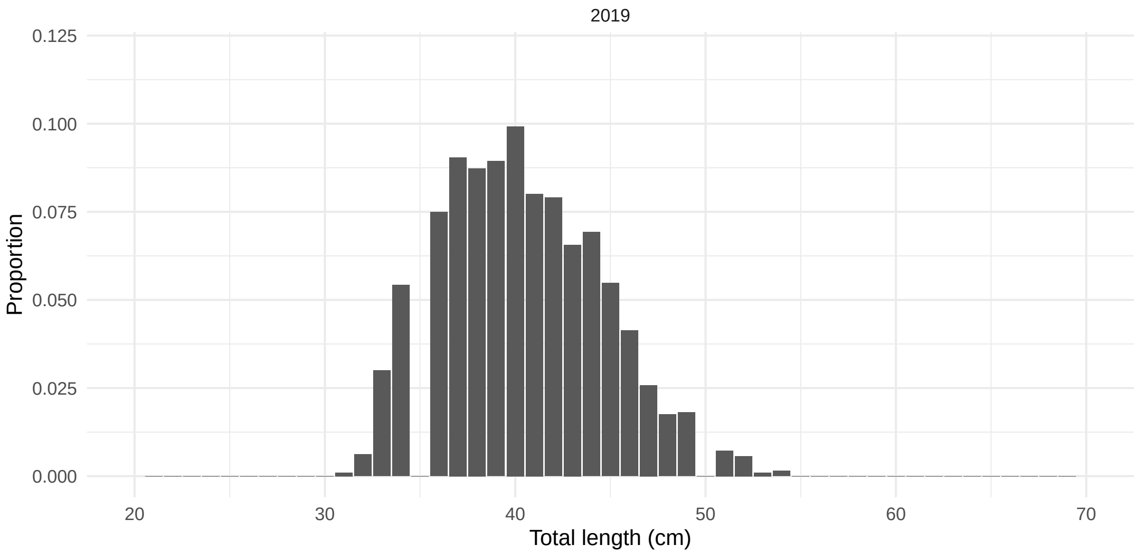

Figure 3.7: Annual length compositions of redthroat emperor for commercially caught line caught fish in 2019

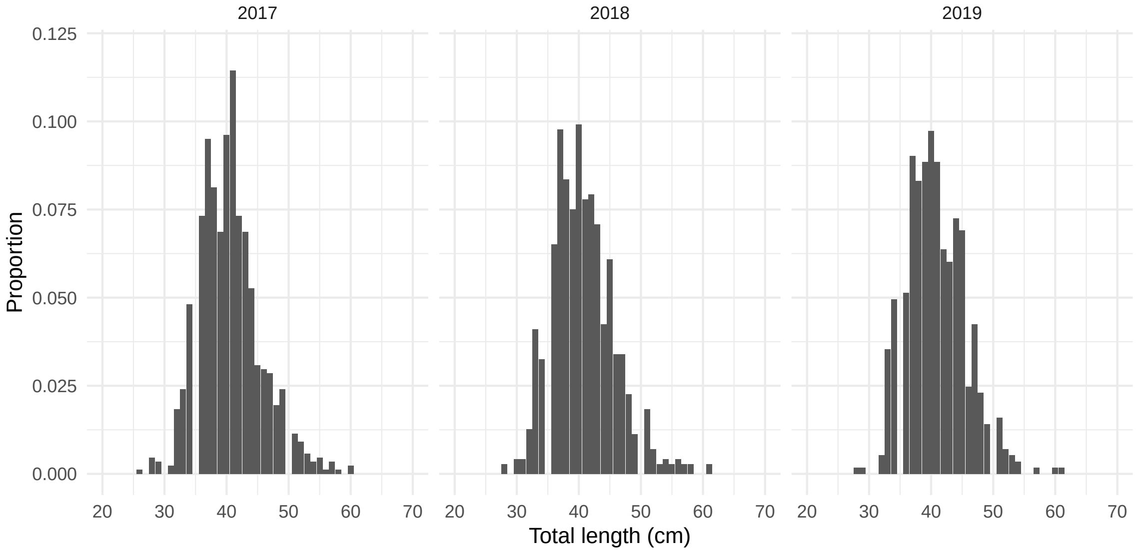

Figure 3.8: Annual length compositions of redthroat emperor for recreational line caught fish between 2017 and 2019

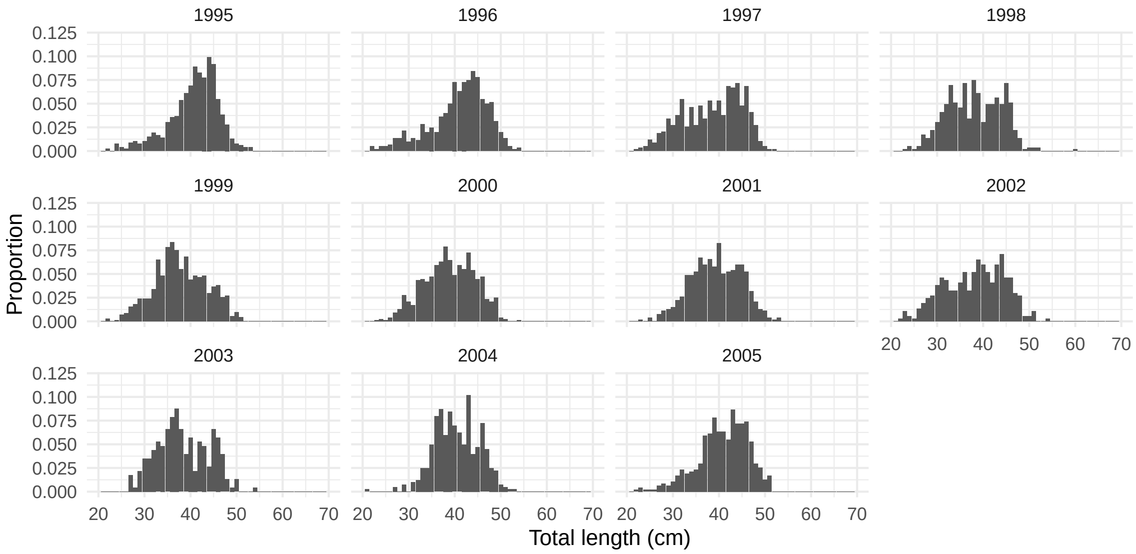

Figure 3.9: Annual length compositions of redthroat emperor for line caught fish between 1995 and 2005 in the ELF survey

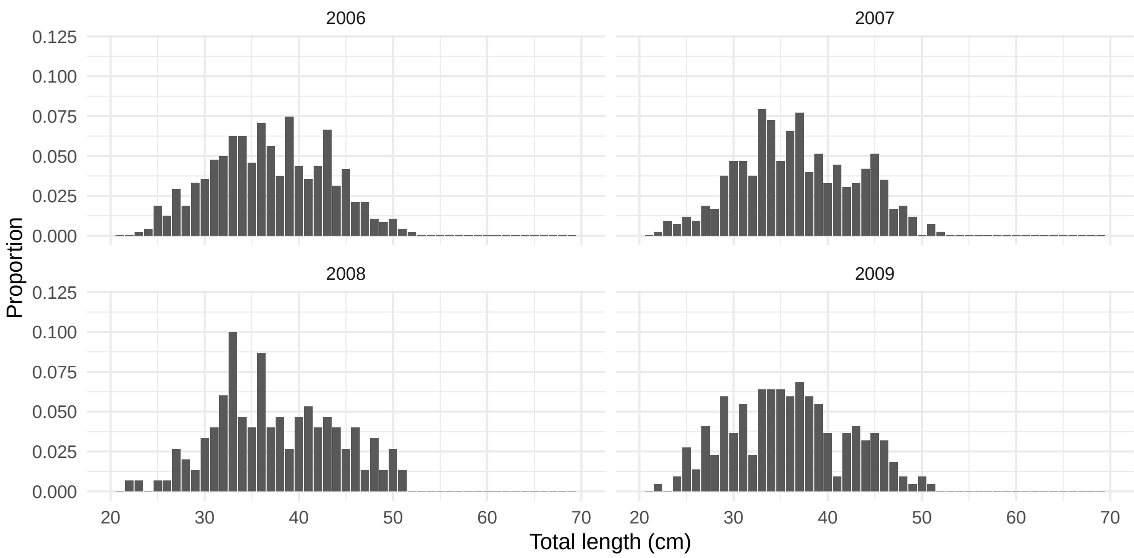

Figure 3.10: Annual length compositions of redthroat emperor for line caught fish between 2006 and 2009 in the LTMP survey

3.1.5 Discards

Mortality due to discarding was factored in by increasing the landed biomass input to the model. This amount was calculated as an increase of 5.5% for charter, 2.5% for commercial, and 11% for the recreational sector. This equated to increasing the overall harvest by a weighted average of 5%. The breakdown is given in Figure 3.11. All model output values involving harvest were therefore multiplied by 0.95 to show actual harvest estimates.

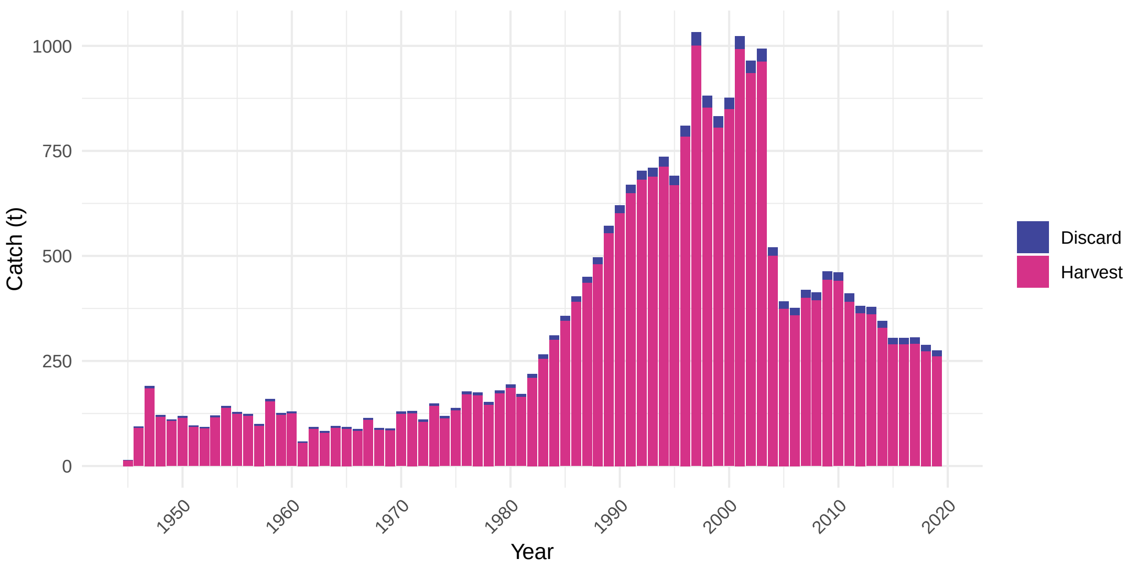

Figure 3.11: Estimated total catch of redthroat emperor, categorised by whether it was harvested or dead discards, from 1945 to 2019

3.1.6 Sensitivity and alternative scenarios

3.1.6.1 Hermaphroditism

For the hermaphroditism scenario, 100% of the biomass was assumed to be female at birth, with 60% changing to male throughout the lifetime of the fish (Figure 3.12).

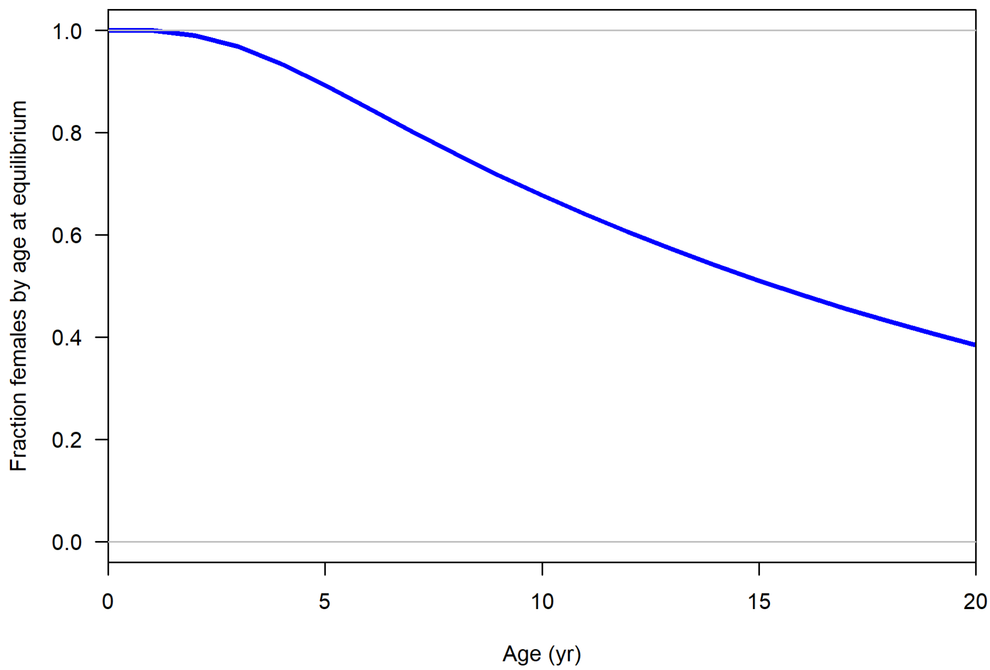

Figure 3.12: Fraction of females modelled by age. Redthroat emperor are born female and may change to male during their lifetime

3.1.6.2 Poor Recruitment Scenario

To simulate poor recruitment, the mean of the log recruitment deviations in the base case for the final five years of estimated recruitment (1998–2002) were used, resulting in a value of -0.258 (Figure 3.13). This value was replicated from 2008 to beyond 2020.

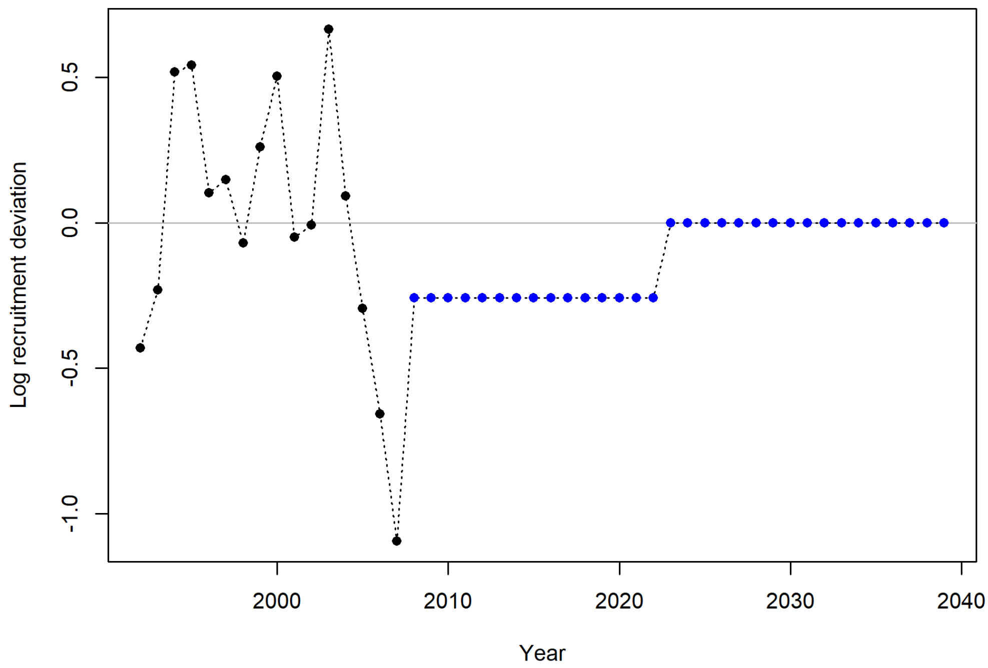

Figure 3.13: Poor recruitment scenario for redthroat emperor showing the time trajectory of log recruitment deviations estimates

3.2 Model outputs

3.2.1 Model parameters

Several parameters were estimated within the base case model (Table 3.1). The full list of estimated parameters for the base and sensitivity runs is given in Appendix B, Tables B.1 and B.2.

Table 3.1: Summary of parameter estimates for redthroat emperor from the base population model

Parameter	**Estimate**	**Standard deviation**
Total length at Age 3 (TL_3)	33.54	0.28
Total length at Maximum Age (TL_{inf})	62.02	1.98
von Bertalanffy growth parameter (κ)	0.09	0.01
logarithm of the number of recruits in 1945	8.77	0.05
Extra standard deviation in catchability for the Charter fishery	0.01	0.02
Extra standard deviation in catchability for the Commercial fishery	0.06	0.03
Fishery selectivity, asymptotic, parameter p1 - ascending inflection (cm)	42.38	0.16
Fishery selectivity, asymptotic, parameter p2 - ascending width (cm)	5.43	0.09
ELF line survey selectivity, asymptotic, parameter p1 - ascending inflection (cm)	47.15	1.08
ELF line survey selectivity, asymptotic, parameter p2 - ascending width (cm)	10.47	0.63
LTMP line survey selectivity, asymptotic, parameter p1 - ascending inflection (cm)	43.15	4.06
LTMP line survey selectivity, asymptotic, parameter p2 - ascending width (cm)	14.27	2.74

The sensitivity of the model to the assumption on steepness and mortality was explored through a likelihood profile (Appendix B, Section B.3.3).

3.2.2 Model fits

Good fits were achieved for all data sets, including abundance indices, conditional age-at-length compositions and length compositions (Appendix B, Section B.2).

3.2.3 Selectivity

Selectivity of redthroat emperor was estimated within the model (Table B.2, Figure 3.14). Recreational and commercial length data were very similar, so a “mirrored” selectivity function was used to represent the commercial, recreational and charter fleets, making their selectivity curves identical.

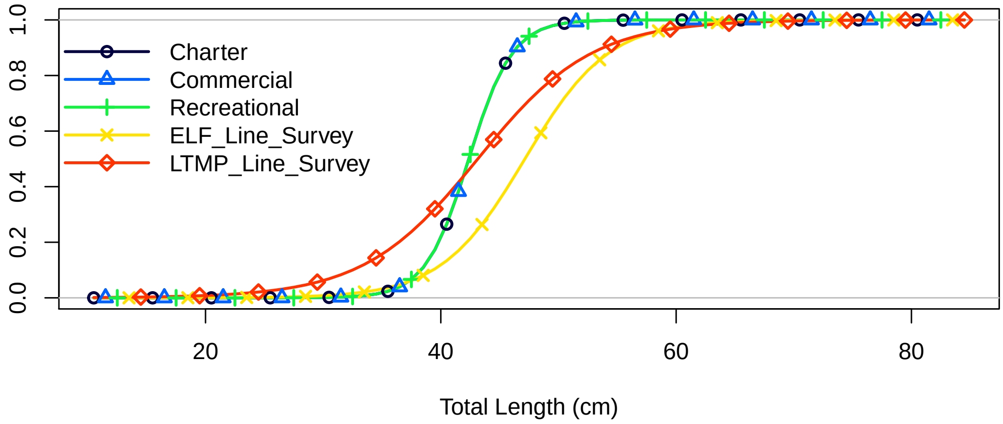

Figure 3.14: Model estimated length-based selectivity for redthroat emperor by fleet in 2019

3.2.4 Growth curve

The von Bertalanffy growth curve, including coefficients of variation of old and young fish, was estimated within the model (Table B.2, Figure 3.15).

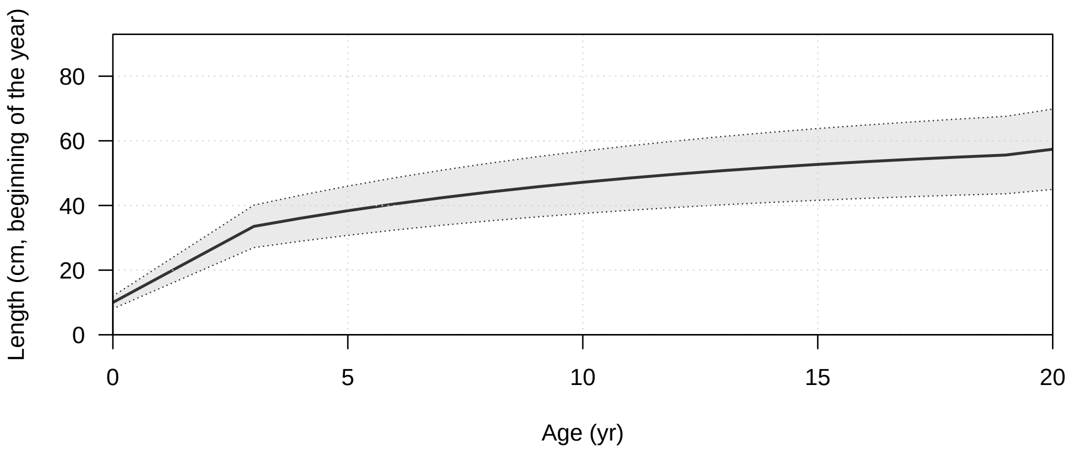

Figure 3.15: Model estimated growth of redthroat emperor (95% confidence intervals)

3.2.5 Biomass

The base case model predicted spawning stock biomass declined between 1945 and 2012 to 54% unfished biomass. In 2020, the stock level was estimated to be 72% unfished total biomass (Figure 3.16).

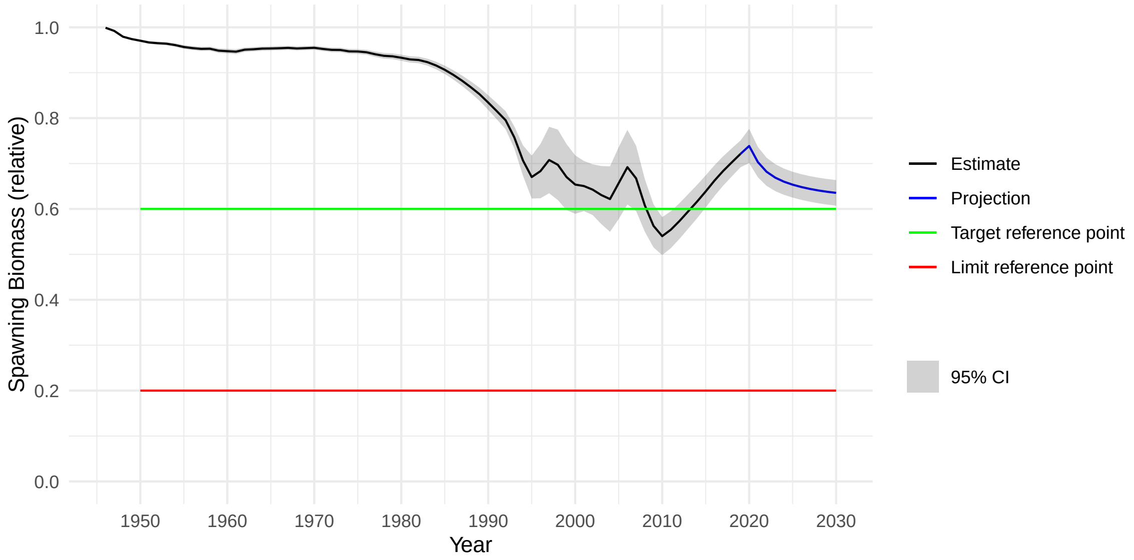

Figure 3.16: Predicted spawning biomass trajectory relative to virgin, from 1945 to 2030, for redthroat emperor

The relationship between the biomass estimate and fishing mortality are presented in a phase plot (Appendix B, Figure B.9).

The equilibrium yield informs on the productivity of the stock at different biomass levels (Figure 3.17). It is important to note that estimates of maximum sustainable harvest should be interpreted with caution, as steepness was fixed within the model, and it is a key driver of productivity.

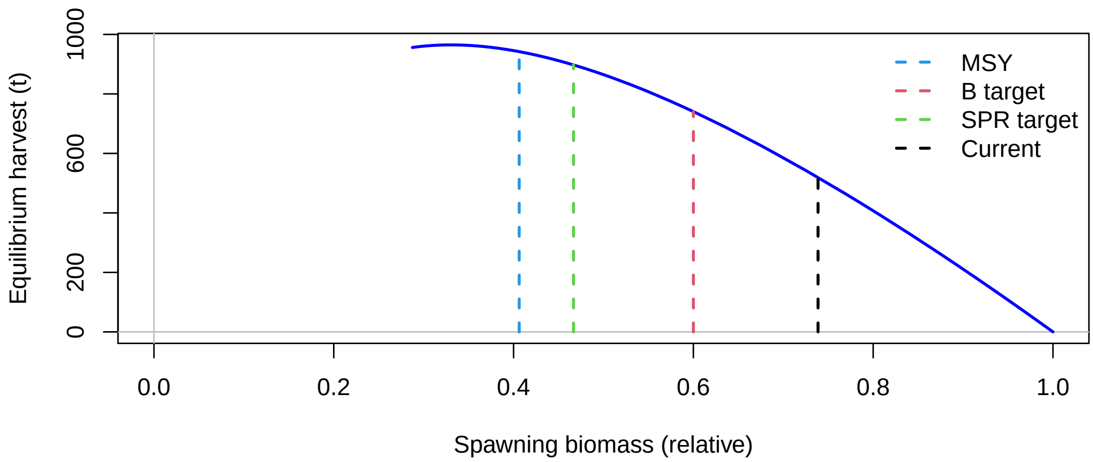

Figure 3.17: Equilibrium harvest curve for redthroat emperor

3.2.6 Harvest targets

Harvest targets have been calculated to maintain spawning biomass at the 60% target reference point for the base model, and a number of sensitivity test models, resulting in recommended biological harvests (RBHs) of 930 t (base), 485 t (low), and 1709 t (high). These RBHs are the first in a schedule of projected recommended harvests for the Harvest Strategy 2017–2027, using the 20:60:60 harvest control rule with a 0.87 buffer. The schedule is presented here for the base case Table 3.2, and in Appendix B for sensitivity runs (Table B.4).

Table 3.2: Estimated total harvests and biomass ratios of redthroat emperor for the base case to rebuild and maintain the stock at the target reference point of 60% unfished spawning biomass, following a 20:60:60 control rule with 0.87 buffer

Year	Harvest (t)	Biomass ratio
2020	931	0.74
2021	841	0.7
2022	783	0.68
2023	747	0.67
2024	726	0.66
2025	713	0.65
2026	706	0.65
2027	700	0.64

3.3 Sensitivities

Table 3.3 shows the differences between model runs. The assumption of the value for natural mortality $M = 0.3$ for the base case had a very large impact on the resulting biomass predictions. For this reason, the two model runs with natural mortality $M = 0.25$ and $M = 0.35$ respectively were used as the reported “low” and “high” scenarios throughout the assessment. Table 3.3 shows a number of other model runs which tested other sensitivities.

Table 3.3: Summary of the redthroat emperor results from the base case and the sensitivity tests – log-likelihood (-lnL) values that are comparable contain a “*” and lower values for the comparable likelihoods are indicative of a better fit

Model	$-LnL$	SB_0	SB_{2019}	SB_{2019}/SB_0	Harvest at 60% biomass ratio
Base case*	2506.84	10659	7687	0.72	705
Steepness 0.45*	2507.64	10872	7400	0.68	645
Steepness 0.55*	2506.28	10504	7879	0.75	758
Mortality 0.25*	2514	9619	5729	0.6	513
Mortality 0.35*	2503.19	12709	10310	0.81	1013
Two thirds catch	2504.47	9320	6624	0.71	613
Double CPUE weight	2458.92	10751	7821	0.73	713
Half CPUE weight	2530.07	10589	7599	0.72	700
Double length weight	4907.93	10306	7447	0.72	684
Half length weight	1302.59	10907	7884	0.72	721
Double age weight	2654.96	10651	7619	0.72	702
Half age weight	2429.05	10651	7738	0.73	707
Logistic maturity	2508.15	9480	6483	0.68	636
Hermaphroditism	1745.96	9909	6944	0.70	783
Poor recruitment	2527.53	10659	5441	0.50	705

4 Discussion

4.1 Stock status

Redthroat emperor were targeted by markedly more fishers between 1998 and 2004 when there were higher number of operators in the fishery. After the Reef Line Fishery restructured and moved to quota management in 2004, harvests dropped significantly due to a number of factors: licence numbers able to catch reef line species were reduced considerably, there was a Commonwealth buyout as a result of the Representative Area Program, and industry focused their catches on the higher value species coral trout (Little et al. 2009).

This assessment estimated an increase in biomass after 2007. The results also suggest that harvest levels during the late 1990s and early 2000s were higher than would be consistent with a 60% target reference point. Management reforms enacted in 2004 (whether the Representative Area Program rezoning or the influence of the total allowable commercial catch administered through individual transferable quotas, or both) appear to have reduced fishing mortality to above target levels.

4.2 Performance of the population model

A number of sensitivities were tested to better understand which assumptions and parameters are most influential on the model. Assumptions surrounding mortality were particularly influential. Likelihood profiles show that mathematically, a much higher natural mortality may be more apposite (Section B.3.3). However, this is likely due to the lack of much older fish in the samples available for modelling. Use of the mathematically determined mortality results from the likelihood profiles results in implausibly high biomass ratio estimates. The more biologically realistic value fixed at $M = 0.3$ was used for the base case.

Results from the “poor recruitment” scenario suggest that if recruitment were lower than average after 2007, the biomass ratio could be as low as 50%.

Model limitations of note include:

- The productivity parameter “steepness” (h) was fixed and a likelihood profile confirmed the data are not sufficiently informative to estimate it, the model was somewhat sensitive to this assumption (Section 3.3).
- Regional variation in biological characteristics has not been taken into account.
- By assuming a fixed sex ratio in modelling a species which exhibits sequential hermaphroditism, the base case may be misrepresenting the interaction between total mortality at age and fertilized egg production. This could result in underestimation of the productivity of the species (more likely if the hermaphroditism is socially controlled) or overestimation (more likely if hermaphroditism is environmentally influenced). While one sensitivity run did explore hermaphroditism directly, it was difficult to parameterise as little is known about the sex change of redthroat emperor (Leigh et al. 2006). The little that is known is complex - probably socially determined but through varying fishing intensities across regions - and further work is required.
- The extent of discarding in the commercial sector remains largely unknown, and the limited data that were available to support an estimate may not be reliable.

- The RBH estimates were somewhat sensitive to the choice of maturity. The base case model used maturity curve estimates from Leigh et al. (2006) which assumed 75% maturity at age 1, which is quite high. This is based on only nine fish in total for age 1. If a logistic maturity curve by length is assumed, the results suggest that a lower RBH would be estimated.

These limitations suggest a cautious interpretation of the current model outputs is needed, and further work will improve model performance (see Section 4.3.5).

4.3 Recommendations

4.3.1 Data

Commercial data utility would be improved by accurate effort measures with fishing time and accurate location recorded for each commercial operation. More data should be collected regarding number of discards, and the size composition of discarded fish from the commercial fishery. Electronic reporting systems may be valuable for achieving these objectives.

4.3.2 Monitoring

Uncertainty in the model outputs was attributed to the lack of age data available since 2009. It is recommended that the newly restarted Fisheries Queensland biological monitoring of redthroat emperor continue on an annual basis, and that the data it provides be included into the next assessment. Mortality estimates may be improved by obtaining more age and length samples of larger, older fish.

4.3.3 Research

More biological information about the proportion of redthroat emperor mature at age, particularly at early ages, is required.

4.3.4 Management

Maximum sustainable harvest was estimated at 897 t per year, and the harvest consistent with a biomass ratio of 60% (a proxy for maximum economic harvest) was estimated at 705 t (all sectors).

The stock assessment shows the state of the stock is at healthy levels, and for this reason the recommended biological harvest in calendar year 2020 to achieve the Sustainable Fisheries Strategy longer term target of 60% unfished biomass may be up to 930 t (485–1709 t range across models). This recommended biological harvest would need to be reduced to 705 t over time.

Management action in the early 2000s appears to have put stock levels on a sustainable track. The Sustainable Fisheries Strategy is a sensible way to maintain this as it is underpinned by a harvest control rule. This can buffer against model uncertainty and should remain responsive as modelling and data improve.

The recommended harvest is higher than the current actual harvest. This “undercatch” suggests that management could consider a true assessment of maximum economic yield (rather than using a 60% proxy), or could consider a higher target level.

4.3.5 Assessment

Limitations with the performance of the current model have been discussed in this document. Specific recommendations for a future redthroat emperor assessment include:

- Further investigation into maturity at age modelling.
- Collation of any data relating to much larger, older redthroat emperor to aid in more biologically realistic estimation of natural mortality.
- An investigation into the effect of cyclones on redthroat emperor availability (Tobin et al. 2010).
- A deeper investigation into the functioning of the hermaphroditism section of Stock Synthesis.
- The ELF and Fisheries Queensland independent line surveys yielded differing selectivity curves, possibly due to the differing gear that was employed. Further investigation of the different selectivity curves associated with the LTMP and ELF line surveys may be apposite.

4.4 Conclusions

This assessment has informed the status of the redthroat emperor population on the east coast of Queensland. It suggests that current harvest levels are in line with the target reference point under the Sustainable Fisheries Strategy, with no rebuilding required to buffer against uncertainty. The results provide recommended biological harvests using a 20:60:60 control rule. Some limitations of the assessment have been noted and recommendations made.

References

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A Model inputs

A.1 Age and length sample sizes

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

Table A.1: Raw sample sizes measured and aged input to the model for redthroat emperor

Year	Commercial Fishery (Length)	Recreational Fishery (Length)	ELF Survey (Length)	LTMP survey (Length)	ELF Survey (Age)	LTMP Survey (Age)
1995			786		786	
1996			604		604	
1997			586		586	
1998			589		589	
1999			704		704	
2000			760		760	
2001			534		534	
2002			367		367	
2003			228		228	
2004			402		402	
2005			473		473	
2006				482		482
2007				428		428
2008				150		150
2009				219		219
2017		874				
2018		706				
2019	1935	565				

A.2 Conditional age-at-length

Conditional age-at-length composition data were input to the population model for the ELF survey (Figure A.1) and the LTMP survey (Figure A.2).

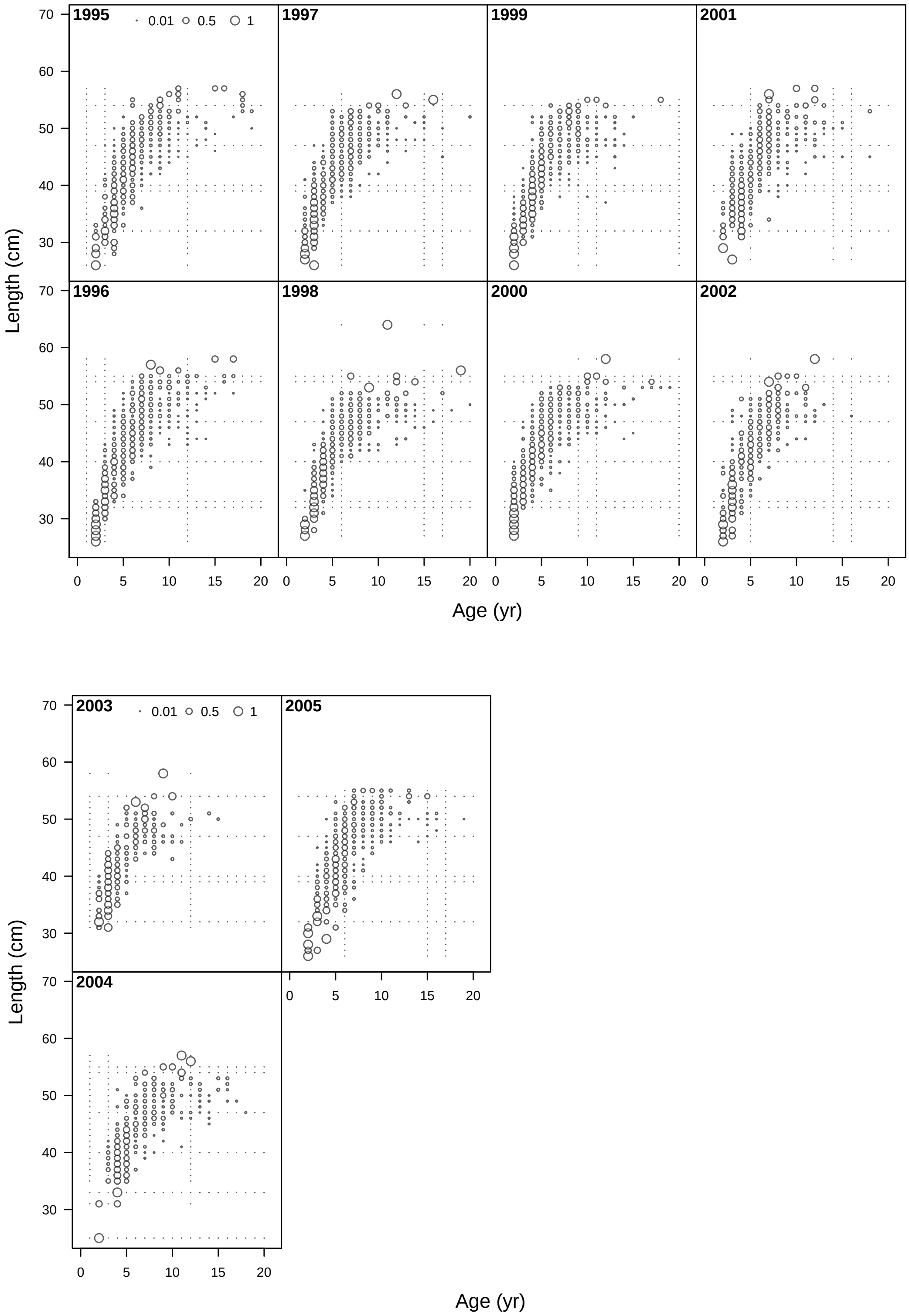

Figure A.1: Conditional age-at-length compositions for redthroat emperor between 1995 and 2005 in the ELF Survey. Circle size is proportional to relative sample size in each bin across rows (i.e. for a given length bin)

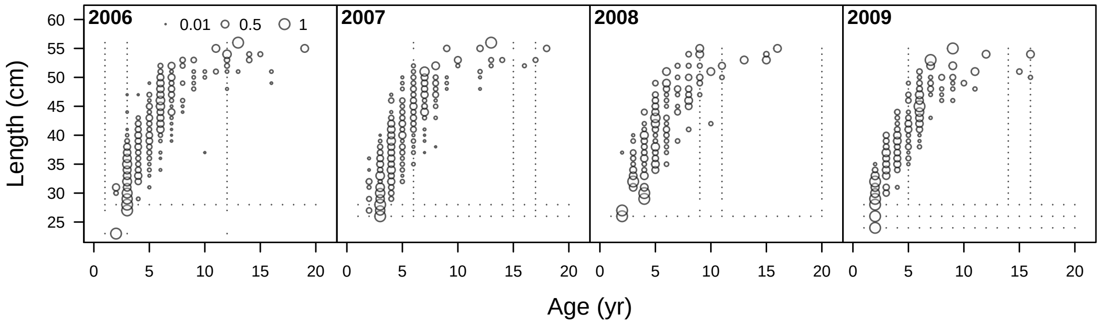

Figure A.2: Conditional age-at-length compositions of redthroat emperor between 2006 and 2009 for the LTMP survey. Circle size is proportional to relative sample size in each bin across rows (i.e. for a given length bin)

A.3 Biological data

A.3.1 Fecundity and maturity

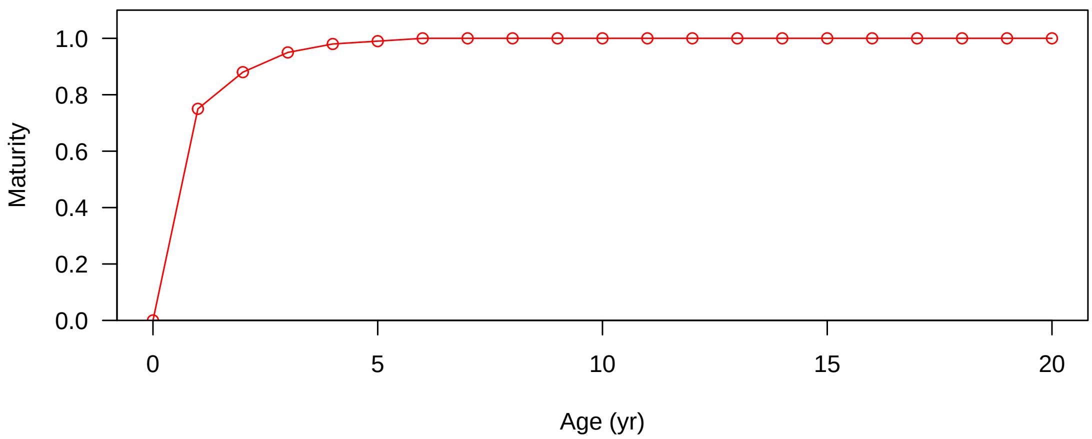

Figure A.3: Maturity at age for redthroat emperor

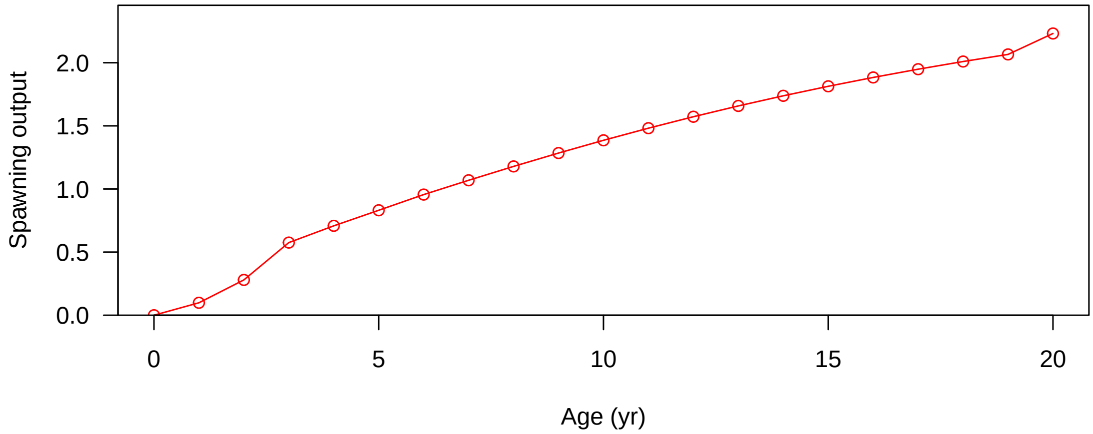

Figure A.4: Spawning output (maturity times fecundity) at age for redthroat emperor

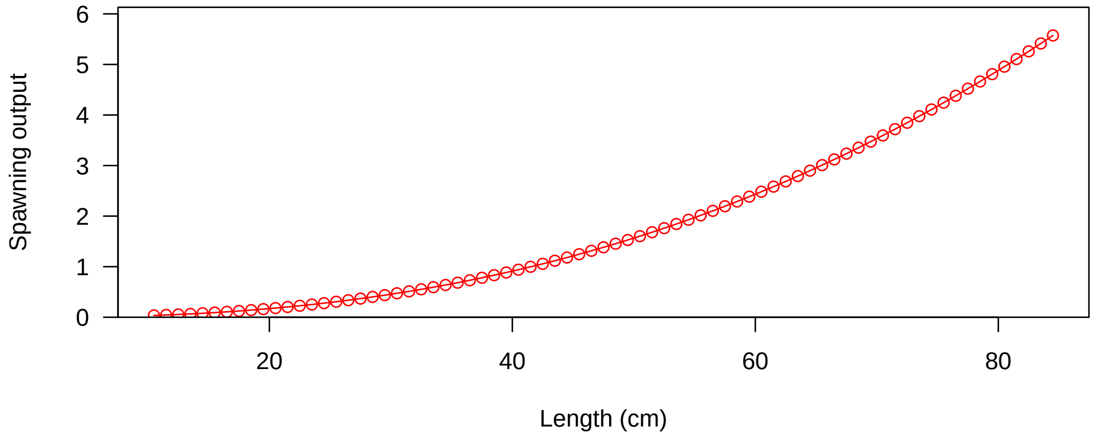

Figure A.5: Spawning output (maturity times fecundity) at length for redthroat emperor

A.3.2 Weight and length

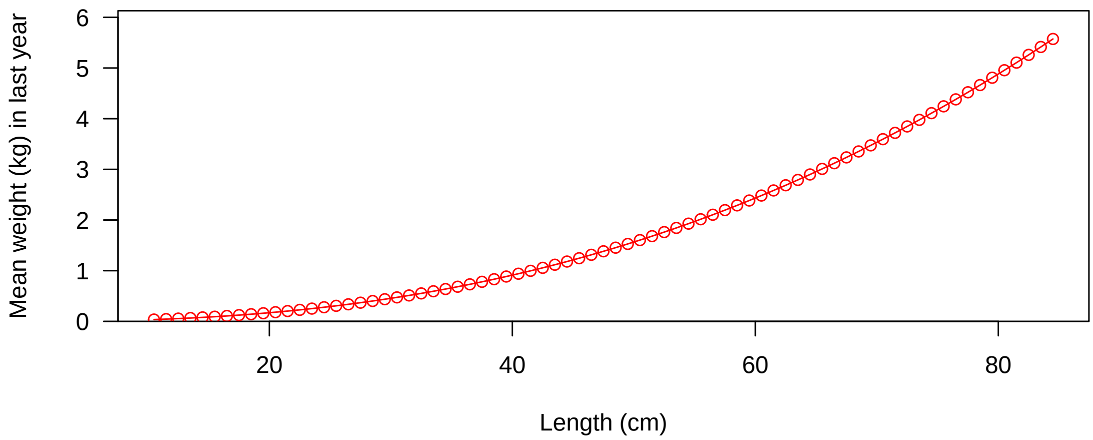

Figure A.6: Weight-length relationship for redthroat emperor

A.4 Catch rate data filtering

Commercial and charter vessel catch and effort data was extracted from the Queensland logbook database. From this initial set of records, the catch rate analysis data was defined through a series of filters, each of which excluded a number of records.

In the first filter, records were excluded if:

- The longitude was missing, or
- The longitude was less than 142.531° E (east of Cape York), or
- The fishing end date was greater than 31 Dec 2019, or
- The species was not redthroat emperor or emperor (unspecified) and either:
  - The log type code was CV (Charter Vessels) and the fishing method wasn't one of "Bait", "Bait and Lure", "Handline", "Line fishing", or
  - The log type code was LF (Line Fishery) and fishing method wasn't one of "Demersal longline", "Dropline (Demersal longline)", "Handline", "Line fishing", "Trolling", "Trotline (Demersal longline)", or
  - The log type code was MI (Mixed Fishery) and fishing method wasn't one of "Handline", "Line fishing"

In filter two, further exclusions were made:

- If the log type code was CV and the fishing method wasn't one of "Bait", "Bait and Lure", "Handline", "Line Combination", "Line fishing" or "Lure"
- If the log type code was LF or MI and the fishing method wasn't one of "Demersal longline", "Dropline (Demersal longline)", "Handline", "Line fishing" or "Trotline (Demersal longline)"

In filter three, further exclusions were made:

- If the log type code was CV and the fishing trip duration was longer than 10 days
- If the log type code was LF or MI and the fishing trip duration was longer than 31 days

The fourth filter involved cases where a fisher fished multiple locations on the same day. In this situation, the catch was summed over all records, and the location, number of guests (for charter) and number of dories and crew (for commercial) were set to the values for the location where the greatest amount of catch was taken.

At this point, the Charter and Commercial analyses differed, and took into account spatial factors. The spatial locations are based on the GBRMPA bioregions and a map with the spatial codes referenced below is given in (Great Barrier Reef Marine Park Authority 2001).

In a fifth (Charter) filter, records for the Charter analysis were excluded

- If they belonged to a fisher who only fished one year or less, and
- If:
  - the total catch of redthroat emperor and tusk fish was zero and
  - either the location was not FNQ or RG2-N or the catch of coral trout was zero and
  - either the location was FNQ or RA2-S or RG1 or RG2-N or the total catch of coral trout and spangled emperor was zero

In a fifth (Commercial) filter, records for the commercial analysis were excluded

- If they belonged to a fisher who only fished one year or less, and
- If:
  - the total catch of redthroat emperor was zero and
  - either the location was not one of FNQ, RG1, RG2-N, RA3-S, RG2-S, RA4-N, RHW-N, RA4-S, RHL, RHW-S, or RCB2, or the catch of wrasse was zero and
  - either the location was not one of RA3-N, RG2-N, RCB1, or RCB2, or the total catch of shark mackerel was zero and
  - either the location was not one of RCB1 or RCB2, or the total catch of tusk fish was zero

B Model outputs

B.1 Parameter estimates

Model parameters were estimated by Stock Synthesis, and parameter labels follow a Stock Synthesis specific naming convention (Table B.1).

Table B.1: Parameter label explanation for redthroat emperor

Stock Synthesis Parameter Label	Explanation
L_at_Amin	Total length at Age 3 (TL_3)
L_at_Amax	Total length at Maximum Age (TL_{inf})
VonBert_K	von Bertalanffy growth parameter (κ)
SR_LN(R0)	logarithm of the number of recruits in 1945
Q_extraSD_Charter	Extra standard deviation in catchability for the Charter fishery
Q_extraSD_Commercial	Extra standard deviation in catchability for the Commercial fishery
Size_inflection_Fishery	Fishery selectivity, asymptotic, parameter p1 - ascending inflection (cm)
Size_95%width_Fishery	Fishery selectivity, asymptotic, parameter p2 - ascending width (cm)
Size_inflection_ELF_Line_Survey	ELF line survey selectivity, asymptotic, parameter p1 - ascending inflection (cm)
Size_95%width_ELF_Line_Survey	ELF line survey selectivity, asymptotic, parameter p2 - ascending width (cm)
Size_inflection_LTMP_Line_Survey	LTMP line survey selectivity, asymptotic, parameter p1 - ascending inflection (cm)
Size_95%width_LTMP_Line_Survey	LTMP line survey selectivity, asymptotic, parameter p2 - ascending width (cm)

Table B.2: Stock synthesis parameter estimates for the base population model for redthroat emperor

Parameter	Estimate	Phase	Min	Max	Initial value	Standard deviation	Gradient
L_at_Amin_Fem_GP_1	33.54	2	-10	45	10	0.28	0.0002904
L_at_Amax_Fem_GP_1	62.02	3	40	90	70	1.98	0.0003342
VonBert_K_Fem_GP_1	0.09	3	0.05	0.5	0.15	0.01	0.0004029
SR_LN(R0)	8.77	1	3	31	8.87	0.05	0.0011794
Q_extraSD_Charter(1)	0.01	4	0	0.5	0	0.02	0.0000014
Q_extraSD_Commercial(2)	0.06	4	0	0.5	0	0.03	-0.0000045
Size_inflection_Fishery(1)	42.38	2	15	50	41.36	0.16	0.0006611
Size_95%width_Fishery(1)	5.43	3	0.01	60	4.7	0.09	-0.0003369
Size_inflection_ELF_Line_Survey(4)	47.15	2	15	50	35	1.08	-0.0000102
Size_95%width_ELF_Line_Survey(4)	10.47	3	0.01	60	6.67	0.63	0.0000544
Size_inflection_LTMP_Line_Survey(5)	43.15	2	15	50	35	4.06	-0.0000012
Size_95%width_LTMP_Line_Survey(5)	14.27	3	0.01	60	18.83	2.74	0.0000023

Likelihood components for the three model runs are given in Table B.3.

Table B.3: Likelihood components for the base model and sensitivity tests for redthroat emperor.

Indicator	Base	Low	High
Total NLL	2506.84	2513.99	2503.18
Survey NLL	-47.0918	-45.6927	-48.6804
Length NLL	2404.96	2405.13	2407.27
Age NLL	151.81	156.137	148.418

B.2 Goodness of fit

B.2.1 Abundance indices

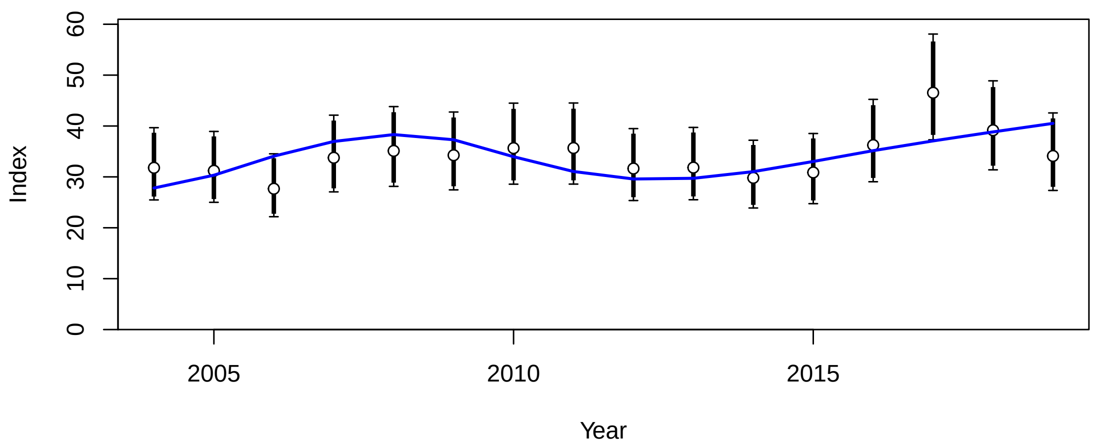

Figure B.1: Model predictions (blue line) to standardised charter catch rates (points) for redthroat emperor. Thick black bars represent the standard error input into the model, while the thin error bars represent additional error estimated by the model

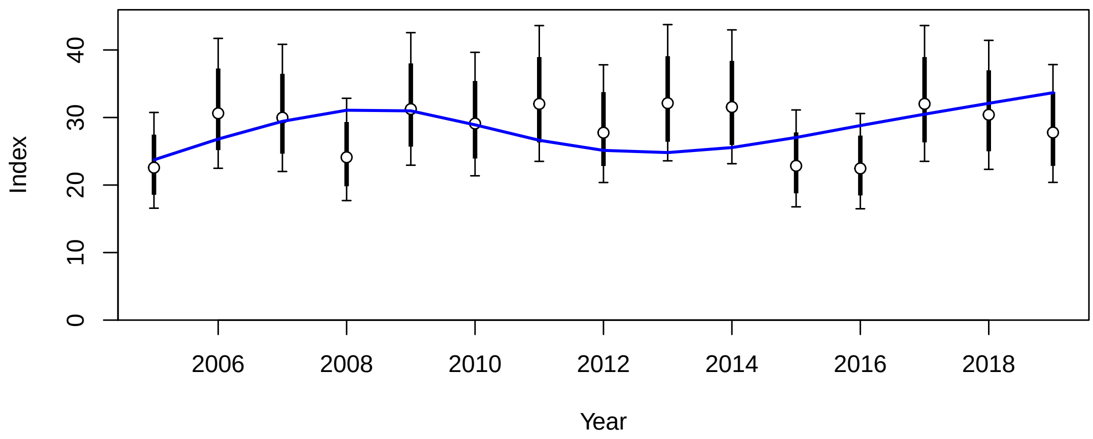

Figure B.2: Model predictions (blue line) to commercial catch rates for redthroat emperor. Thick black bars represent the standard error input into the model, while the thin error bars represent additional error estimated by the model

B.2.2 Length compositions

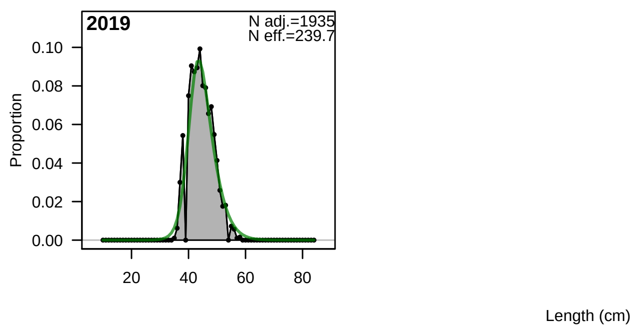

Figure B.3: Length structure for the commercial fleet for redthroat emperor. 'N adj.' is the input sample size after data-weighting adjustment. N eff. is the calculated effective sample size used in the Francis tuning method

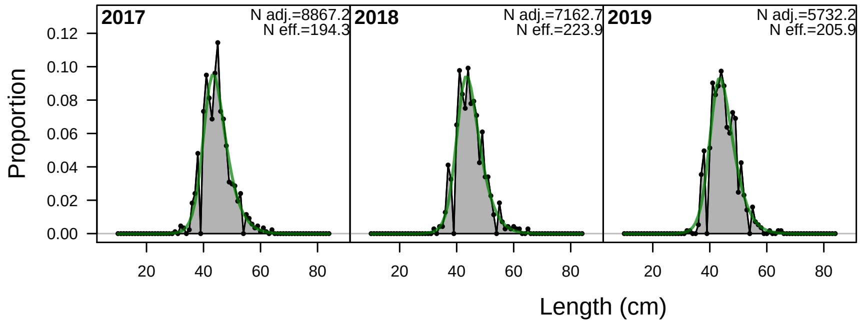

Figure B.4: Fits to length structures for the recreational fleet for redthroat emperor. 'N adj.' is the input sample size after data-weighting adjustment. N eff. is the calculated effective sample size used in the Francis tuning method

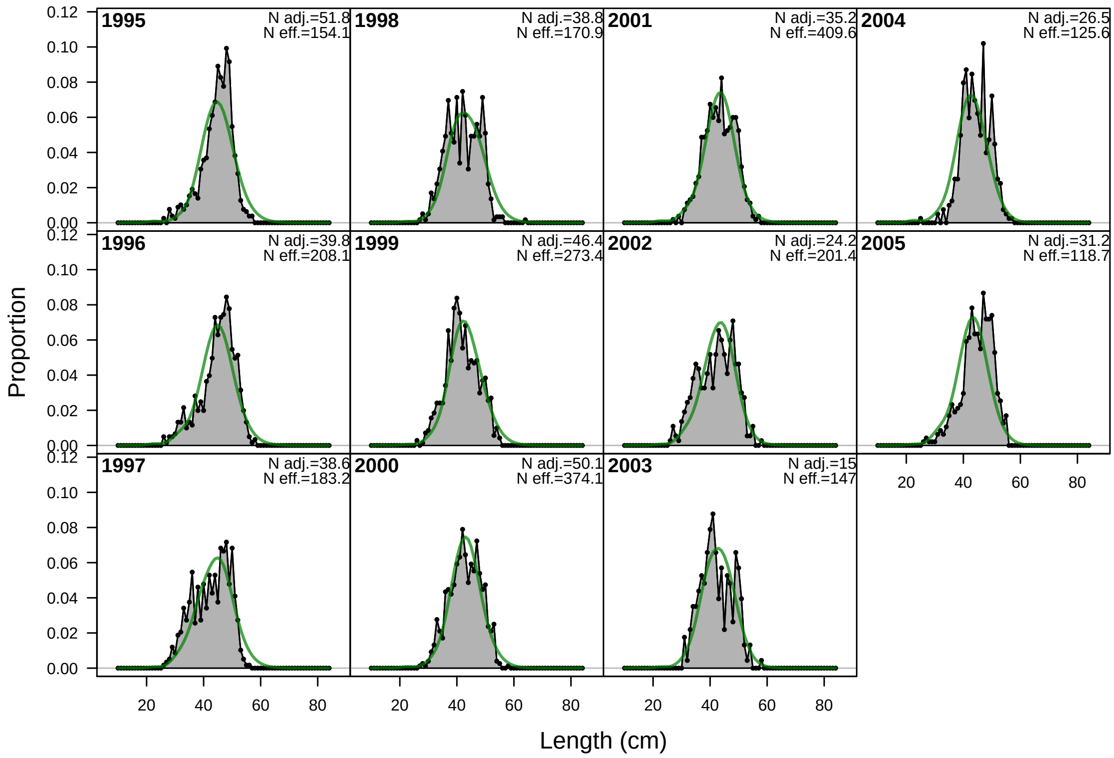

Figure B.5: Fits to length structures for the ELF survey for redthroat emperor. 'N adj.' is the input sample size after data-weighting adjustment. N eff. is the calculated effective sample size used in the Francis tuning method

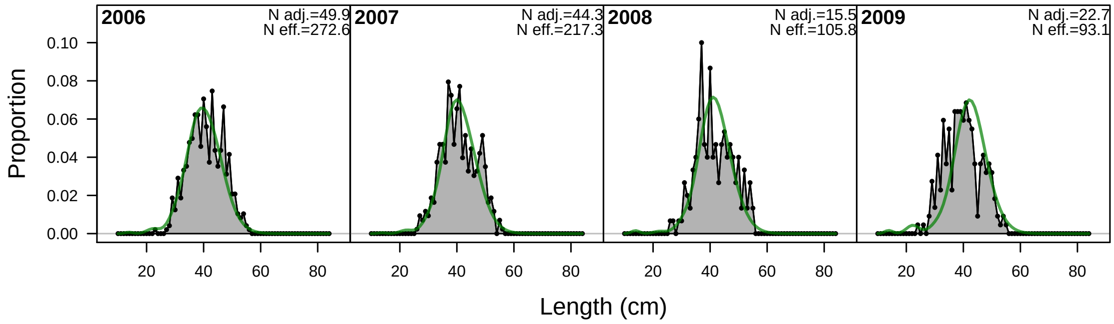

Figure B.6: Fits to length structures for the LTMP survey for redthroat emperor. 'N adj.' is the input sample size after data-weighting adjustment. N eff. is the calculated effective sample size used in the Francis tuning method

B.2.3 Conditional age-at-length compositions

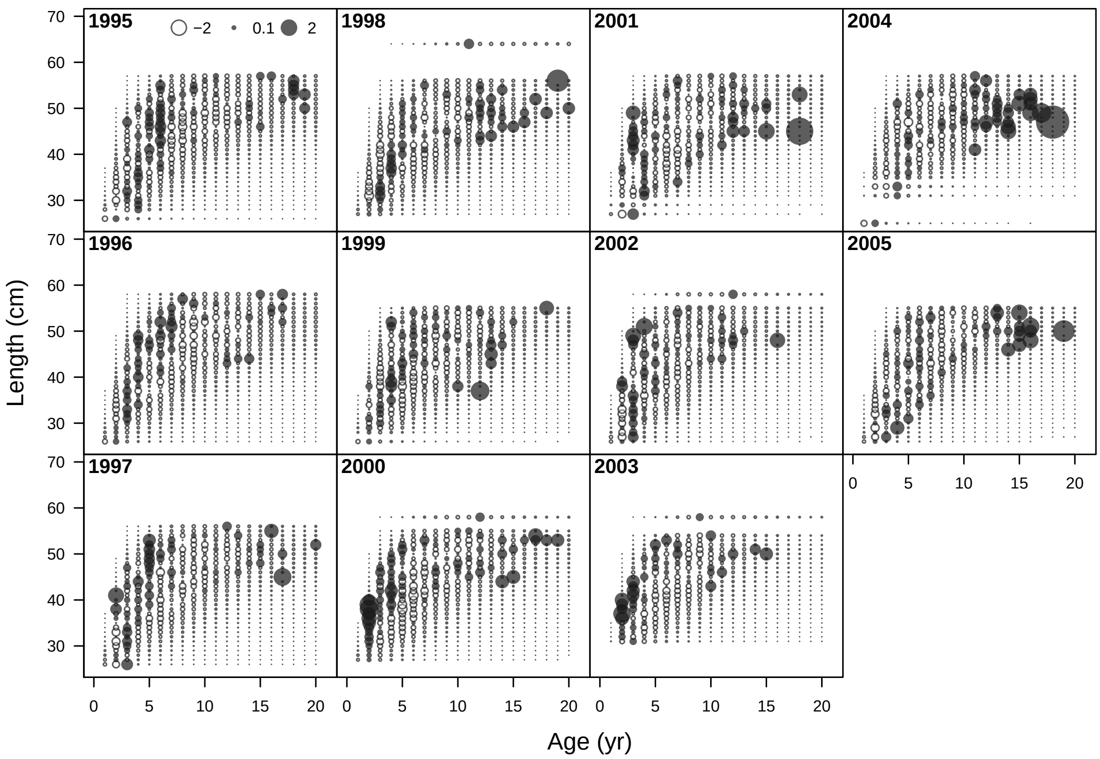

Figure B.7: Pearson residuals for age-at-length compositions for the ELF Survey for redthroat emperor

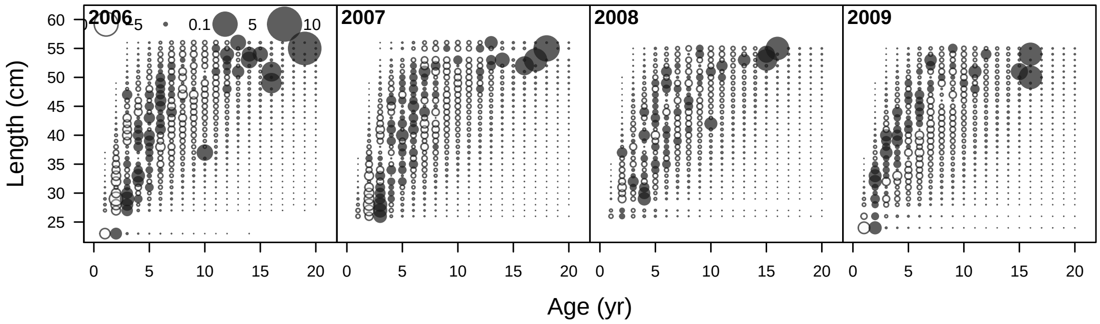

Figure B.8: Pearson residuals for age-at-length compositions for the LTMP survey for redthroat emperor

B.3 Other outputs

B.3.1 Phase plot

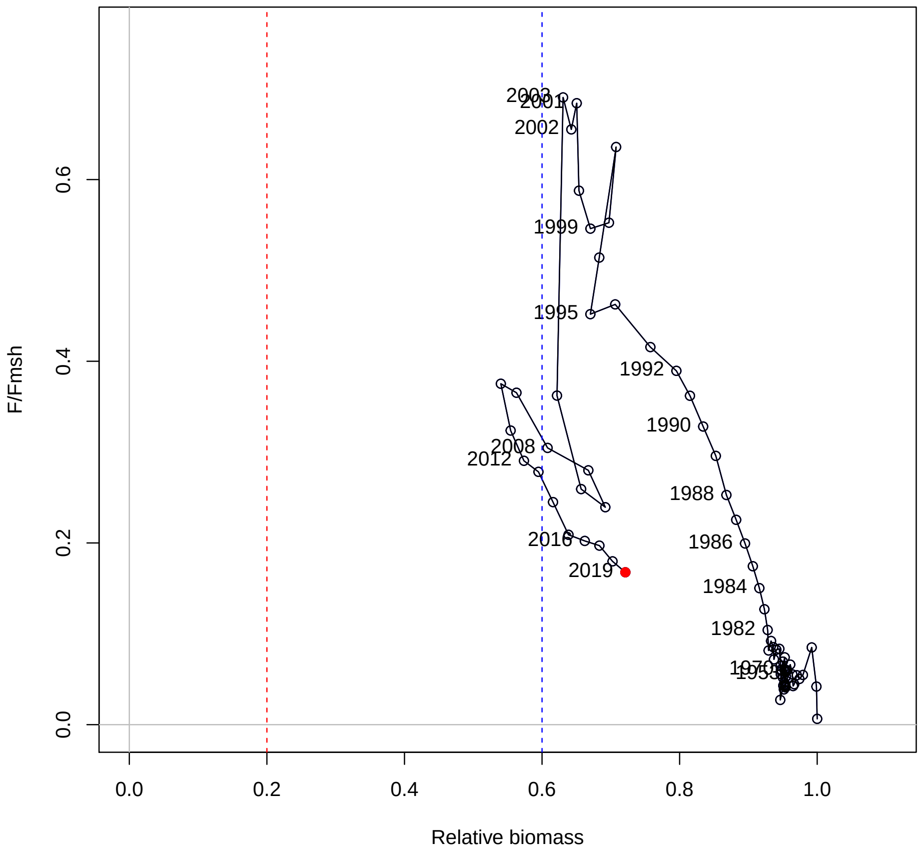

Figure B.9: Phase plot for redthroat emperor. The horizontal axis is the biomass ratio of Queensland redthroat emperor relative to unfished and the vertical axis is the fishing mortality relative to fishing mortality at maximum sustainable harvest. The red dashed vertical line is the limit reference point (20% relative biomass) and the blue dashed vertical line is the target reference point (60% relative biomass)

B.3.2 Sensitivity harvest targets

Table B.4: Estimated total harvests and depletion levels of redthroat emperor to rebuild or maintain the stock at the target reference point of 60% unfished spawning biomass, following a 20:60:60 control rule with 0.87 buffer. Values are given for two sensitivity tests: 'low mortality', and 'high mortality'

Year	Harvest low (t)	Biomass ratio low	Harvest high (t)	Biomass ratio high
2020	485	0.62	1709	0.83
2021	480	0.61	1384	0.75
2022	476	0.61	1209	0.71
2023	474	0.62	1121	0.69
2024	474	0.62	1079	0.67
2025	475	0.62	1056	0.66
2026	476	0.62	1039	0.65
2027	478	0.62	1025	0.65

B.3.3 Likelihood profile

Likelihood profiles can be used to determine whether parameters have been fixed at appropriate values. Integrated stock assessments use numerous data sources which may be in conflict with each other, but likelihood profiles provide a tool to determine these conflicts (Punt 2018). A likelihood profile was calculated to explore the assumption on steepness ($h = 0.5$).

In this case, the overall likelihood (combining likelihood contributions from all data sources) does not have an optimum value for steepness: the likelihood continues to improve as steepness approaches its theoretical maximum (Figure B.10). This confirms that there is insufficient information in the data to constrain this parameter, and that there is not some other value that is possible. This run was conducted with natural mortality fixed at its base case level ($M = 0.3$).

The likelihood profile below produces unfeasible estimates in natural mortality. This is discussed in more depth in Section 4.

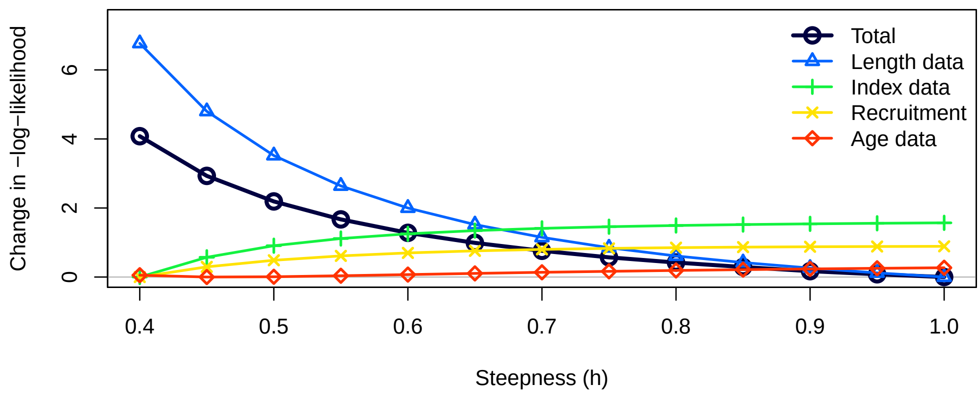

Figure B.10: Likelihood profile for steepness (h)

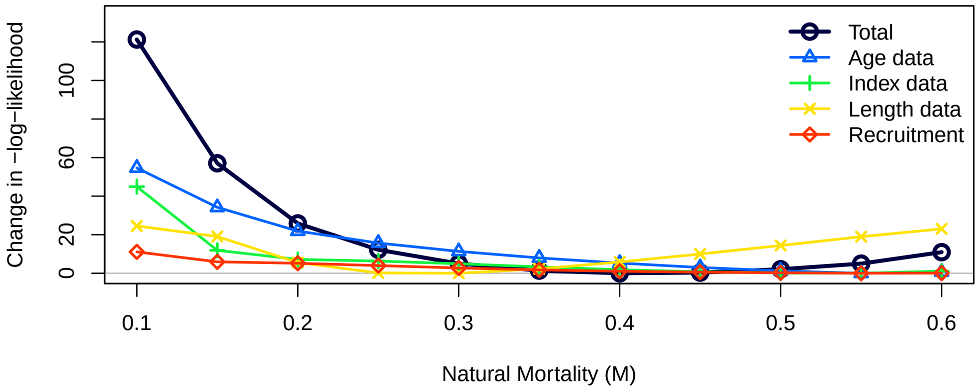

Figure B.11: Likelihood profile for natural mortality (M)