Stock assessment of king threadfin (*Polydactylus macrochir*) in Queensland, Australia

2020

Queensland Government

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Summary

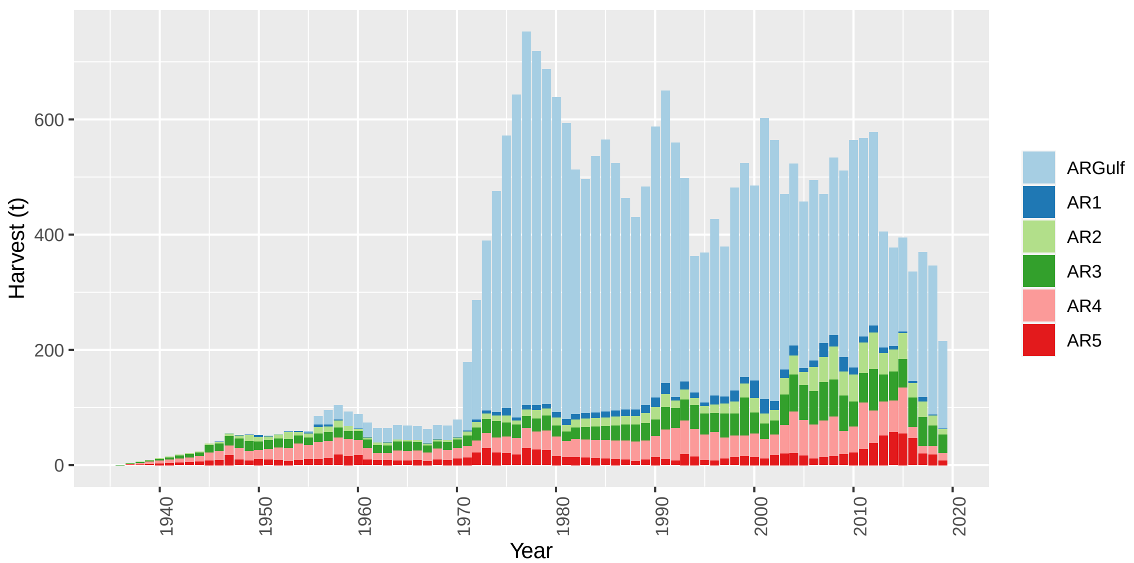
King threadfin is a large, predatory fish species that can grow to 150 cm total length and 30 kg in weight. It is found in foreshore areas of turbid coastal waters, estuaries, tidal rivers and mangrove creeks across northern Australia and southern Papua New Guinea. In Australia, its distribution extends from the Ashburton River in Western Australia across northern Australia to the Brisbane River in South East Queensland. It feeds mainly on prawns, other crustacea, and small fish.

King threadfin is a protandrous hermaphrodite, beginning as male, reaching sexual maturity at around 60–80 cm total length and 2–4 years of age, and changing to female around 70–100 cm total length at 4–8 years of age. It lives to at least 20 years of age.

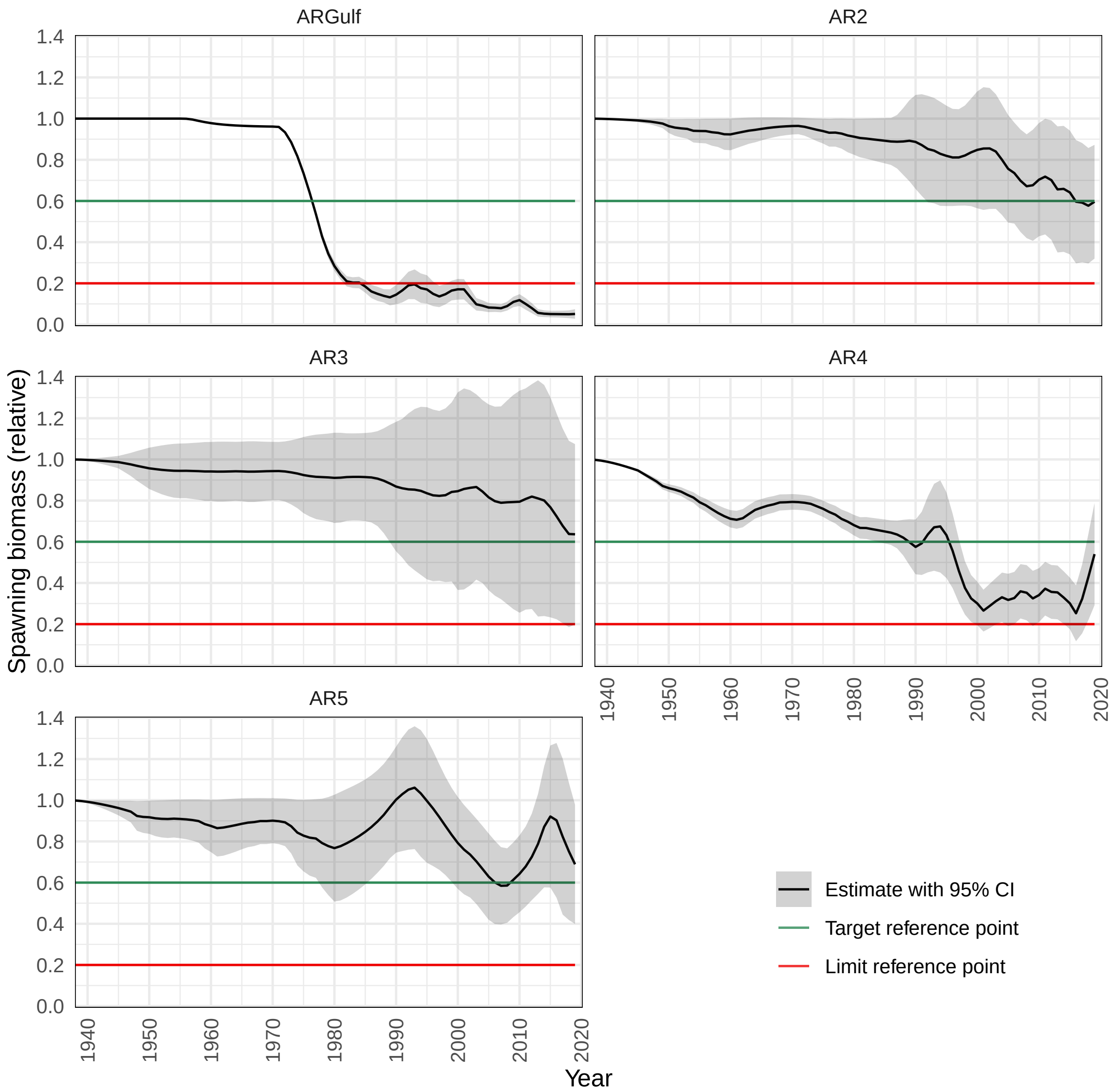
Over the last five years, 2015 to 2019, harvest in Queensland averaged 203 tonnes per year in the Gulf of Carpentaria and 129 t/yr on the East Coast. In the Gulf, 92% of the harvest was taken by the commercial sector and 8% by the recreational sector. East Coast harvest was 87% commercial and 13% recreational.

This is the first stock assessment of king threadfin conducted in Queensland since 2002. It uses an age-structured model with an annual time step and incorporates data from 1945 to 2019, including harvest sizes, standardised catch rates from commercial gillnetting daily logbook records, and length and age information. It assesses five separate Assessment Regions which are assumed to be self-contained stocks, coded ARGulf (Gulf of Carpentaria) and AR2–AR5 down the East Coast. An additional East Coast region AR1 in the far north was not assessed due to small harvests, lack of age and length data, and withdrawal of fishing effort to protect dugongs.

Model analyses suggest that spawning biomass in 2019 was around 5% of the unfished level in ARGulf and around 60% in each of the East Coast Assessment Regions. Region AR4, around the Fitzroy River estuary near the city of Rockhampton, was estimated to have fallen to about 25% prior to the introduction of a Net Free Zone in late 2015, but to have recovered since then.



Estimated harvest by Assessment Region, 1937–2019



Predicted spawning biomass trajectory relative to unfished, from 1940 to 2020, for king threadfin in each region

This report estimates harvest levels to support Queensland's Sustainable Fisheries Strategy 2017–2027 and ensure that the fishery operates at sustainable levels.

On the East Coast, recommended annual harvests (commercial and recreational sectors combined) range from 34 t in AR5 (Fraser Coast to Moreton Bay) to 91 t in AR3 (around Mackay). These harvests are approximately equal to the equilibrium harvests under the Sustainable Fisheries Strategy.

In ARGulf, the model outputs and harvest control rule recommend that no harvest be taken for three years, to allow the stock to rebuild to above 20% of unfished levels. After that, the harvest can gradually resume, reaching over 200 t/yr in the twelfth year of rebuilding.

Current and target indicators for king threadfin, under the Sustainable Fisheries Strategy target of 60% of unfished spawning biomass

Indicators	ARGulf	AR2	AR3	AR4	AR5
2019 spawning biomass (% of unfished)	5%	60%	64%	54%	69%
Maximum sustainable yield (MSY)	355 t	65 t	125 t	47 t	50 t
Biomass at MSY (% of unfished)	26%	25%	27%	26%	26%
2019 harvest	152 t	10 t	32 t	13 t	8 t
Equilibrium 60% biomass harvest	229 t	44 t	89 t	33 t	34 t
Recommended initial future harvest	0 t	45 t	91 t	35 t	34 t

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In addition to the role of the Project Team, we would like to thank Carlie Heaven for the extraction and supply of the Queensland commercial harvest data, and Jennifer Larkin, Daniella Teixeira and James Webley for the supply and extraction of Queensland recreational survey data.

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The authors would also like to acknowledge and thank the many fishers and scientists who have contributed to past and current research on king threadfin. This assessment was funded by the Department of Agriculture and Fisheries.

Glossary

Age class	Age of a fish at the time it was caught, measured in whole years
Age group	Age that a fish would have attained at the end of a calendar year, measured in whole years. This is one year more than the conventional age used in population models; e.g. age group 3 denotes fish between 2 and 3 years old, which we refer to as age 2 (commonly also referred to as age 2+).
CFISH	Commercial fisheries information system, which is the compulsory commercial logbook database managed by Fisheries Queensland
CI	Confidence interval
CPUE	Catch per unit effort
CZCRC	Coastal Zone Cooperative Research Centre
DAF	Department of Agriculture and Fisheries
ECIFFF	East Coast Inshore Fin Fish Fishery
Fisher-day	A day of fishing by a fishing operator, which corresponds to a single daily logbook record (commercial) or a single fishing diary page (recreational)
FL	Fork length, measured from the tip of fish's nose to the fork in its tail
Fleet	A population modelling term used to distinguish types of fishing activity: typically a fleet will have its own selectivity curve which characterises the probability of capture of animals of various sizes (or ages)
FRDC	Australian Government's Fisheries Research and Development Corporation
GLM	Generalised linear model
ID	Identifier
MLS	Minimum legal size
MSY	Maximum sustainable yield
NRIFS	National Recreational and Indigenous Fishing Survey, funded by the FRDC (2000–01)
QFB	Queensland Fish Board, marketing authority until 1981
RFish	Recreational fishing surveys conducted by Fisheries Queensland (1997, 1999, 2002, 2005)
SFS	Queensland's Sustainable Fisheries Strategy, 2017–2027
SS	Stock Synthesis software for fishery stock assessment
Stock	A distinct population that breeds only within itself
SWRFS	Statewide Recreational Fishing Surveys conducted by Fisheries Queensland (2010–11, 2013–14, 2019–20)
TACC	Total allowable commercial catch
TL	Total length, measured from the tip of fish's nose to the end of its tail lying freely in its normal position
TRaCK	Tropical Rivers and Coastal Knowledge research consortium

1 Introduction

1.1 Distribution and biology

King threadfin (*Polydactylus macrochir*) (Günther 1867), also known as king salmon and Burnett salmon, is a large, predatory fish species that can grow to 150 cm total length (TL) and 30 kg in weight (Roelofs 2003). It is found in foreshore areas of turbid coastal waters, estuaries, tidal rivers and mangrove creeks across northern Australia and southern Papua New Guinea (Motomura et al. 2000). In Australia, its distribution extends from the Ashburton River in Western Australia across northern Australia to the Brisbane River in South East Queensland (Motomura et al. 2000). It spawns in inshore coastal waters (Garrett et al. 1997). It feeds mainly on prawns (family Penaeidae), other crustacea, and small fish (Salini et al. 1998).

King threadfin is a protandrous hermaphrodite, beginning as male, reaching sexual maturity at around 60–80 cm TL and 2–4 years of age, and changing to female around 70–100 cm TL at 4–8 years of age (Garrett and Williams 2002; Roelofs 2003). It lives to at least 20 years of age.

Habitat and nutrition for king threadfin are provided largely by river systems. Inspection of commercial logbook data indicates that populations of king threadfin flourish where flows of nutrients are provided by large drainage basins. A map of the major drainage basins in Queensland is shown in Figure 1.1. It shows that many large basins drain to the southern half of the Gulf of Carpentaria (west coast of Queensland), most notably the Nicholson, Leichhardt, Flinders, Norman, Gilbert, Staaten and Mitchell basins. On the East Coast, the major basins are the Normanby, Herbert, Burdekin, Fitzroy, Burnett, Mary and Brisbane. The remaining East Coast basins are small, although some northern ones, such as the Tully basin north of the Herbert, receive very high amounts of rainfall. The Burdekin basin is an exception in that it is very large but does not produce many king threadfin, perhaps because its lower reaches have been extensively altered by the Burdekin Falls Dam (completed in 1987) and other water management measures.

1.2 Stock structure

The stock structure of king threadfin was investigated by Welch et al. (2010) in a project which gave rise to articles on spatial demography (Moore et al. 2011) and concerns of overexploitation of king threadfin (Moore et al. 2017). The project used techniques of genetics, otolith microchemistry and parasite identification to find that threadfins form regional stocks. Most of the analysis for Queensland stocks was conducted on fish from only three locations in the Gulf of Carpentaria (Albert, Flinders and Kendall Rivers) and two on the East Coast (Townsville and the Fitzroy River). There were no major differences between the samples from the Gulf. Moore et al. (2011) examined fish from the Fitzroy, Mary and Brisbane Rivers, and found no major differences in demography between the Mary and Brisbane Rivers.

Tagging data show that some king threadfin move hundreds of kilometres. In the Gulf, one fish moved 600 km from Weipa in the northern Gulf of Carpentaria to the Flinders River beyond Karumba in the southern Gulf (Infofish 2014b). On the Queensland East Coast, one fish moved 200 km from Shoalwater Bay to the Fitzroy River estuary (Infofish 2014a), and another moved 250 km from the Fitzroy River almost to Bundaberg (Infofish 2014a).

A common view holds that king threadfin forms multitudinous stocks of spatial extents less than 100 km (see, e.g., Welch et al. 2010, pp. 148–150). That hypothesis is not supported by available data from Queensland.

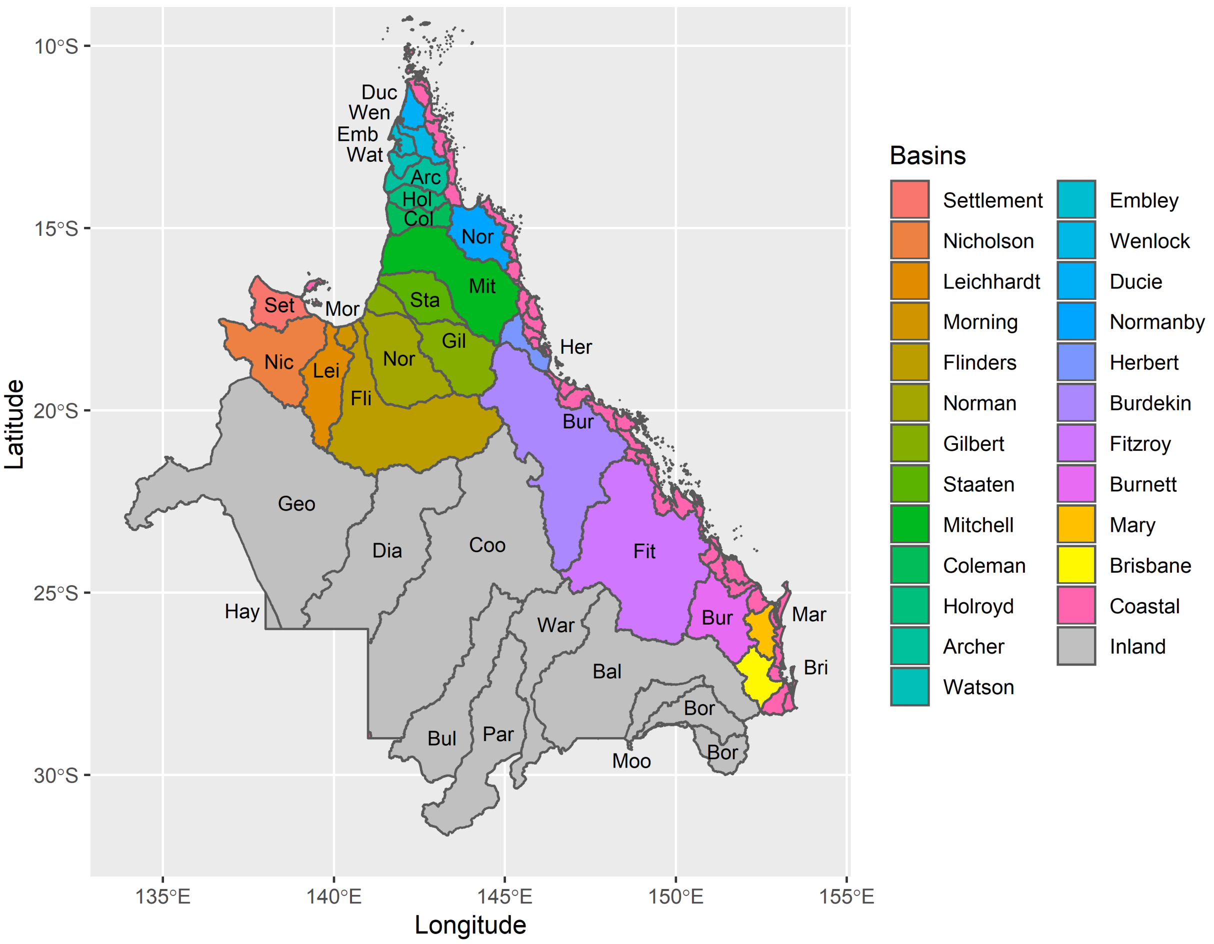

Figure 1.1: Drainage basins in Queensland
Source: Queensland Government mapping data

1.3 The fishery

King threadfin is targeted by commercial gillnet fishers and recreational line fishers in Queensland, in the Gulf Of Carpentaria Inshore Fin Fish Fishery and the East Coast Inshore Fin Fish Fishery. The majority of the harvest is commercial. Estimated total annual harvest has varied between 250 t and 600 t between 1980 and 2019. The estimated recreational component has not exceeded 100 t in any year. A stock assessment of king threadfin was attempted by Welch et al. (2002) but its authors did not consider the results realistic.

In the commercial sector, some of the king threadfin catch is taken by "bridling" in gillnets. In bridling, king threadfin are not caught around the body as in traditional gillnetting, but around the corners of their mouths. This method of fishing implies that there is no practical upper limit to the size of king threadfin that can be caught in gillnets. A major advance in gillnetting technology was the introduction of monofilament nets, whose strands are generally invisible to fish and which became widely used in about 1976 (Darcey 1990, pp. 208–210).

The East Coast fishery has recently been divided into five Management Regions labelled MR1 to MR5 from north to south (Figure 1.2), with boundaries at 15 °S, 19 °S, 22 °S and 24.5 °S. This figure also shows the Assessment Regions used to delineate the presumed separate stocks of king threadfin in the assessment, which correspond fairly closely, but not exactly, to the Management Regions.

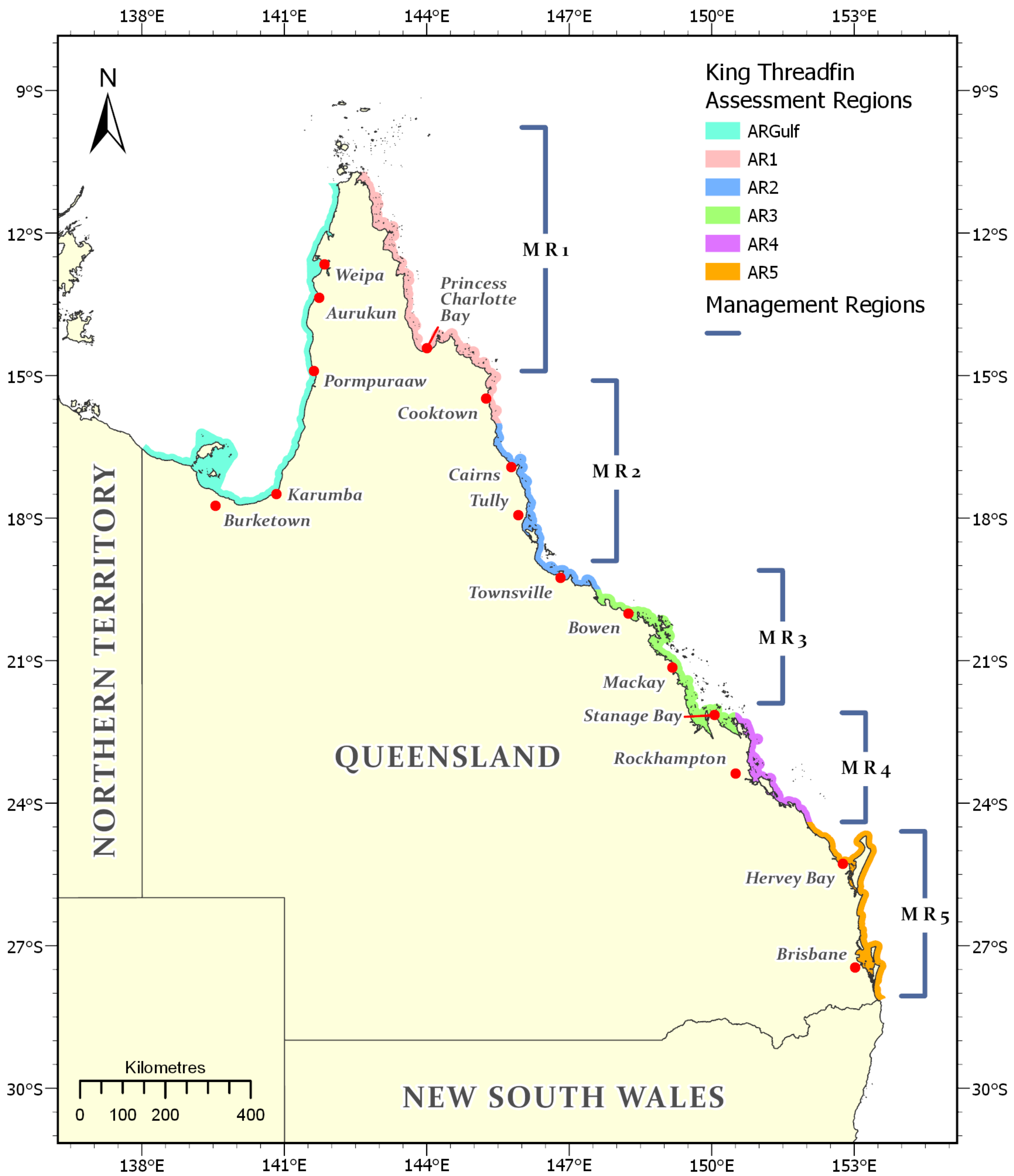

Figure 1.2: Map of the king threadfin fishery, showing Management Regions MR1–MR5 (defined on 0.5 degree latitude bands) and Assessment Regions ARGulf and AR1–AR5

1.4 Related species

The major Queensland species related to king threadfin is blue threadfin (*Eleutheronema tetradactylum*), also known as Cooktown salmon. It belongs to the same family Polynemidae but has shorter, thicker and more numerous pectoral filaments, doesn't grow as large and tends to be caught further from shore (Figure 1.3).

Figure 1.3: King threadfin *Polydactylus macrochir* (top) and blue threadfin *Eleutheronema tetradactylum* (bottom)

Fishers appear able to accurately distinguish the two threadfin species. Nevertheless, some recreational surveys contained combined categories comprising both species (see "Methods" below). Other species known as "salmon" are also easily distinguished, including saratogas (*Scleropages* spp., family Osteoglossidae), "beach salmon" or steelback (*Leptobrama muelleri*, Leptobramidae), and eastern Australian salmon (*Arripis trutta*, Arripidae) which occurs in south-eastern Australia but is not recorded in significant numbers in Queensland recreational fishing surveys.

1.5 Management history

Various management measures have been applied to threadfins in Queensland since the late 19th century (Table 1.1). A minimum legal size (MLS), of 12 inches (30.5 cm) total length, was first imposed in 1914. The first metric MLS was 40 cm TL in 1976. The MLS was increased to 60 cm TL in 1999 in the Gulf of Carpentaria and in 2009 on the East Coast. The East Coast MLS was increased to 65 cm TL in 2019. A recreational in-possession limit of 5 king threadfin was introduced in 1999 in the Gulf, and 2009 on the East Coast.

Various spatial restrictions on commercial netting in South East Queensland took effect between 1995 and 2015. Perhaps the biggest change was the introduction of Net Free Zones around Cairns, Mackay and the Fitzroy River in November 2015. Dugong Protection Areas have also had a major effect, especially in Princess Charlotte Bay (AR1).

Seasonal closures around the spawning of barramundi *Lates calcarifer* were introduced in 1981 (Quinn 1984; Darcey 1990, p. 144). These fishery closures certainly reduce the fishing effort on threadfins in the Gulf, and may also do so on the East Coast. Currently the Gulf of Carpentaria is closed to all net fishing from 7 October to 31 January each year. The East Coast remains open to net fishing but targeting of wild barramundi is not allowed between 1 November and 31 January. Historically, barramundi has been the primary target species for commercial and recreational fishers in Queensland tropical inshore waters, but in recent years its commercial importance has declined due to competition from aquacultured and imported barramundi. Queensland aquaculture production of barramundi increased from 1204 t in 2003–04 to 2950 t in 2018–19, while the market price (whole fish) of the aquacultured product increased only slightly from $8.36/kg to $9.09/kg (Lobegeiger and Wingfield 2006; Schofield 2020).

The size of the commercial harvest and the amount of recreational fishing effort on king threadfin in Queensland are not currently limited. Numbers of commercial fishers, and hence the amount of net that can be in the water at any one time, are limited by the number of licences available, gear restrictions, and various spatial and temporal closures. Recreational in-possession limits apply to fish held by a fisher at any one time, and there is no practical limit to the total number of fishers or their fishing effort.

Table 1.1: Management measures applied to threadfins and “salmons” in Queensland waters
“Bag limit” refers to in-possession limit for recreational fishers only.

Date	Fishery management measure
1877–1974	Numerous measures relating to fishing gear and practices; e.g. mesh size, net length, allowed species, closed seasons, powers of inspectors
3 Dec 1914	Minimum legal size for salmon 12 in. (30.5 cm) TL (*The Fish and Oyster Act of 1914*)
1926–1933	Minimum legal sizes for salmon 13 in. (33.0 cm) TL (Amendments 1926, 1929 and 1933 by Order in Council to *The Fish and Oyster Act of 1914*)
18 Apr 1957	Restate minimum legal sizes for salmon 13 in. (33.0 cm) TL. (*Fisheries Act 1957*)
1959–1964	Minimum legal sizes for threadfins 16 in. (40.6 cm) TL, said to be giant threadfin *Eleutheronema tetradactylum* and striped threadfin *Polynemus sheridani* (Subordinate Legislation to *Fisheries Act 1957*)
16 Dec 1976	Minimum legal sizes 40 cm TL for threadfins, specified as Burnett salmon *Polydactylus sheridani* and Cooktown salmon *Eleutheronema tetradactylum* (*Fisheries Act 1976*)
1 Nov 1981	Seasonal net fishing closure in Gulf of Carpentaria (currently set as 7 October to 31 January), and seasonal prohibition of targeting of wild barramundi on the East Coast (currently set as 1 November to 31 January) (Quinn 1984; Darcey 1990, p. 144)
	Minimum gillnet mesh size 150 mm in Gulf of Carpentaria and East Coast north of Cape Flattery (approx. 15 °S)
1989	Minimum gillnet mesh size 150 mm in rivers and creeks
	Maximum gillnet mesh size 245 mm, Gulf and East Coast
	Closure to net fishing of Mulgrave River, Russell River, Johnstone River, Haughton River, Plantation Creek, Burdekin River, Prosperpine River, Pioneer River, Cawarral Creek
	Opening of Barratta Creek to net fishing
1 Jul 1993	Restate minimum legal sizes from 1976. (*Fishing Industry Organization and Marketing Amendment Regulation No. 3*, Subordinate Legislation 1993 No. 235)

1 Dec 1995	Closure to commercial net fishing of most of Moreton Bay foreshore and waterways in the City of Brisbane (Brighton to Manly); Great Sandy Strait, all foreshore south of Double Island Point and all of Moreton Bay at weekends
	Restate minimum legal sizes set in 1976. (*Fisheries Regulation 1995*, 1995 No. 325)
6 Mar 1998	Specification of Dugong Protection Areas, with restrictions on fishing, by insertion of Sections 257 to 278 into Schedule 2 of *Fisheries Regulation 1995*
7 May 1999	Regulations for the Gulf of Carpentaria: Minimum legal sizes 60 cm TL for king threadfin, 40 cm TL for blue threadfin. Bag limits 5 for king threadfin, 20 for blue.
	Minimum mesh sizes 162.5 mm, maximum 245 mm. Maximum net length 120 m in a river or creek, 600 m on a foreshore or offshore; maximum combined length of multiple nets for one fisher 360 m in a river or creek, 600 m on a foreshore. (*Fisheries (Gulf of Carpentaria Inshore Fin Fish) Management Plan 1999*, 1999 No. 55)
2 Jul 1999	Declaration of Dugong Protection Areas (*Nature Conservation (Dugong) Conservation Plan 1999*, 1999 No. 155)
5 Nov 2004	Declaration of Princess Charlotte Bay as a Special Management Area for dugong protection (*Marine Parks (Great Barrier Reef Coast) Zoning Plan 2004*, 2004 No. 240, Part 3, Division 4)
1 Apr 2008	Restate king threadfin bag limit 5, minimum legal size 60 cm TL; blue threadfin (Cooktown salmon) bag limit 20 in Gulf of Carpentaria only, restate minimum legal size 40 cm TL set in 1976; entry for “Burnett salmon” *Polydactylus sheridani* (*Fisheries Regulation 2008*, 2008 No. 83)
13 Jun 2008	Restate king threadfin bag limit 5 in the Gulf only; minimum legal sizes 60 cm TL in the Gulf, 40 cm TL on the East Coast. (*Fisheries Amendment Regulation (No. 2)*, 2008 No. 156)
20 Oct 2008	Closure of 16% of the area of Moreton Bay Marine Park to all fishing and a further 8% to net fishing; this Marine Park is not confined to Moreton Bay itself and includes ocean beaches. (*Marine Parks (Moreton Bay) Zoning Plan 2008*, 2008 No. 343)
1 Mar 2009	King threadfin bag limit 5 and minimum legal size 60 cm TL on East Coast. Restate that these also apply in the Gulf. Blue threadfin bag limits 20 in the Gulf, 10 on the East Coast, restate minimum legal size 40 cm TL set in 1976. (*Fisheries Amendment Regulation (No. 5)*, 2008 No. 448)
22 May 2009	Restate bag and size limits set on 1 Mar 2009. (*Fisheries Legislation Amendment Regulation (No. 2)*, 2009 No. 61)
1 Nov 2015	Net Free Zones declared around Cairns (Trinity Bay – Cairns), Mackay (St Helens Beach – Cape Hillsborough – North of Mackay) and the Fitzroy River (Yeppoon – Keppel Bay – Fitzroy River – Capricorn Coast) (*Fisheries and Another Regulation Amendment Regulation (No. 1)*, 2015 No. 125)
28 May 2019	King threadfin minimum legal size increased to 65 cm TL on East Coast; restate bag limits and MLS’s of blue threadfin and Gulf king threadfin from 2009. (*Fishery Declaration 2019*, 2019 No. 76)

2 Methods

2.1 Data sources

Data included in the assessment are listed in Table 2.1. Commercial harvest and effort data come from the CFISH compulsory logbook database, which provides daily harvests (kg) by each fisher. Location is provided mostly to six-nautical-mile resolution, but has only thirty-nautical-mile resolution in many records up to about the year 2000. This database also includes some charter data.

Table 2.1: Data inputs for the assessment

Data	Years	Source	References
Commercial logbook	1988–2019	Compulsory commercial logbook database (CFISH)	
Charter logbook	1996–2019	Charter logbook database, compulsory only for vessels that fish offshore (CFISH)	
Gulf logbook	1981–1989	Collated commercial production returns from the Gulf of Carpentaria	Quinn (1987)
RFish surveys	1997, 1999, 2002, 2005	RFish recreational telephone and diary surveys conducted by Fisheries Queensland	Higgs (1999), Higgs (2001), Higgs et al. (2007), McInnes (2008)
NRIFS surveys	2000	National Recreational and Indigenous Fishing Survey, recreational telephone and diary survey	Henry and Lyle (2003)
SWRFS surveys	2011, 2014, 2019	Statewide Recreational Fishing Surveys, telephone and diary surveys conducted by Fisheries Queensland	Taylor et al. (2012), Webley et al. (2015)
Boat Ramp Surveys	2015–2019	Length data from recreational sampling conducted by Fisheries Queensland	Fisheries Queensland (2017)
CZCRC data	2000–2005	Length and age data collected by Coastal Zone Cooperative Research Centre	Halliday and Robins (2007)
TRaCK data	2008–2011	Length and age data collected by Tropical Resources and Coastal Knowledge (TRaCK) consortium	Halliday et al. (2012)
Fishery Monitoring	2000–2006, 2015–2019	Length data 2000–2006; length and age data 2015–2019	
Historical commercial harvest	1946–1981	Queensland Fish Board (QFB) annual returns	Halliday and Robins (2007)
Lunar phase	1950–2086	Publicly available astronomical data	

Charter CFISH logbooks have been compulsory for offshore charter fishing since 1996, but much of the fishing for king threadfin is conducted inshore, in locations where operators are not required to keep logbooks. Therefore our charter harvest estimates will be underestimates. Charter logbook data usually record numbers of fish rather than weights, and include released fish.

The Gulf logbook predated CFISH and was collated from commercial fishers' monthly production returns, which proved their activity in order to retain their licences to fish in the Gulf of Carpentaria. It provided monthly harvests. Location was recorded as one of four Areas A–D (Quinn 1987) (Figure 2.1). No finer spatial resolution was available for this data set. It did, however, record whether the catch was taken in a river or off a foreshore, which the CFISH database did not. We assigned Areas A and B to the Mapoon and Aurukun Catch Rate Regions respectively in the northern Gulf, and Areas C and D to the Karumba and Mornington Catch Rate Regions in the southern Gulf (see Figure 2.2 for Catch Rate Regions). In this assessment the Gulf logbook is used as a source of harvest size only, not abundance.

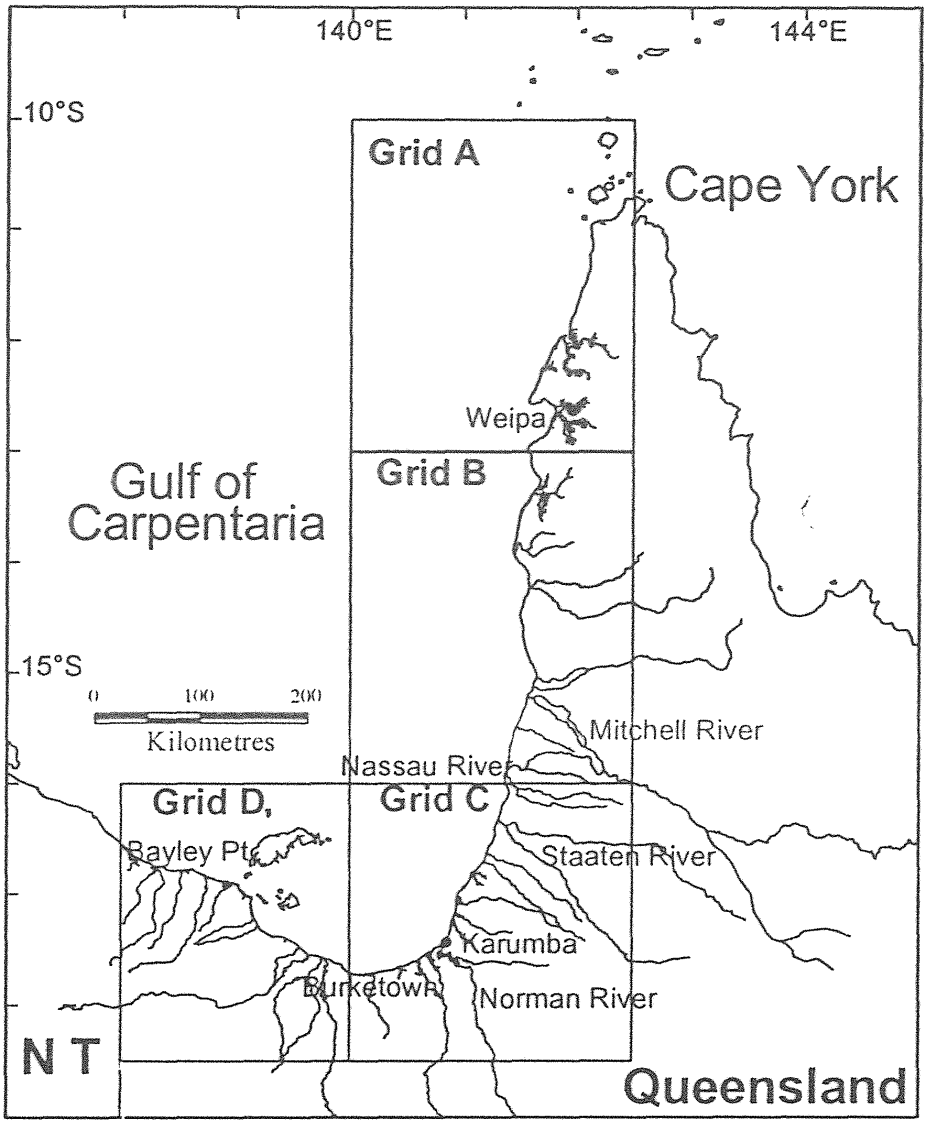

Figure 2.1: Spatial resolution of the Gulf logbook, 1981–1989, with Areas A, B, C and D
Source: Garrett et al. (1997)

Recreational surveys began with a telephone survey of randomly chosen residents, then assigned diaries to selected respondents to record their catches for one year. Catches, including releases, were recorded as numbers of fish, and participants generally recorded the precise names of the places where they fished. The surveys were aimed at calculating total numbers of fish caught over a year, and were not intended to provide abundance estimates.

The recreational surveys were conducted using RFish methodology from 1997 to 2005. Due to the methodology employed, it is believed that these surveys frequently overestimated recreational harvest (Lawson 2015). This assessment uses them only to provide a trend; i.e. not an absolute measure of harvest. Data from these surveys are still very useful because the period 1997–2005 corresponded to a big decline in recreational fishing activity for most fish species in Queensland.

The National Recreational and Indigenous Fishing Survey (2000), and the Statewide Recreational Fishing Surveys (2011–2019) used methodology which is believed to be the most accurate available. They 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).

Fisheries Queensland's Boat Ramp Survey program for recreational fishing began in 2015. It recorded numbers of fish caught by respondents at Queensland boat ramps at times when survey staff were present. The staff recorded the species, sexes and lengths of the fish retained, and the respondents' estimates of numbers of fish released.

For this assessment the Boat Ramp Survey program provided length data and species-composition information. It also provided a short time series of catch rates from AR4, which we used as a check on model results (see Section 2.4.2 and Appendix D).

Monitoring of king threadfin began in 2015. This Fishery Monitoring program provides fork length, total length, age and sex data from fishery-dependent commercial catches. The spatial resolution was finer than the Catch Rate Regions but coarser than the CFISH database, in order to maintain confidentiality of fishers' exact fishing locations. As with the recreational telephone–diary surveys, the Monitoring program is not designed to measure abundance of fish.

Data similar to the Monitoring data but from earlier years were provided by research projects. Research data from the 1980s and 1990s exist in paper form, but electronic entry had not been completed in time for inclusion in this assessment.

Historical commercial harvest sizes (kg) were provided by annual returns from the Queensland Fish Board (QFB), which was the compulsory marketing authority until 1981. This database did not provide a measure of fishing effort, so could not be used as an abundance index. Harvest sizes were allocated by receiving station or "district", which provided some information on the location of catches. Fish marketed interstate were not required to go through the QFB (Quinn 1984); nor were fish from the Gulf of Carpentaria, although they were in fact recorded by the QFB in some years (Dunstan 1959, pp. 17, 20). Also some product, e.g. taken by smaller, part-time operators, bypassed the QFB (Dunstan 1959).

Lunar data comprised relative luminosity (full moon = 1) on each day.

2.2 Regions

Fishery management advice was required for each of the Management Regions (see Figure 1.2). Published biological studies (e.g. Welch et al. 2010) indicated that the Management Regions might be much larger than the spatial extent of the stocks of king threadfin, and that fishing intensity within a Management Region might vary substantially. Therefore, catch rates were analysed on smaller Catch Rate Regions based on the sampling regions used by the Fisheries Queensland Fishery Monitoring team (Figure 2.2).

This assessment uses Assessment Regions labelled ARGulf and AR1 to AR5, which followed assumed stock boundaries which are similar to, but not identical to, the Management Region boundaries (Table 2.2). This similarity was not expected at the outset of the assessment, and came about only through detailed inspection of Fishery Monitoring data.

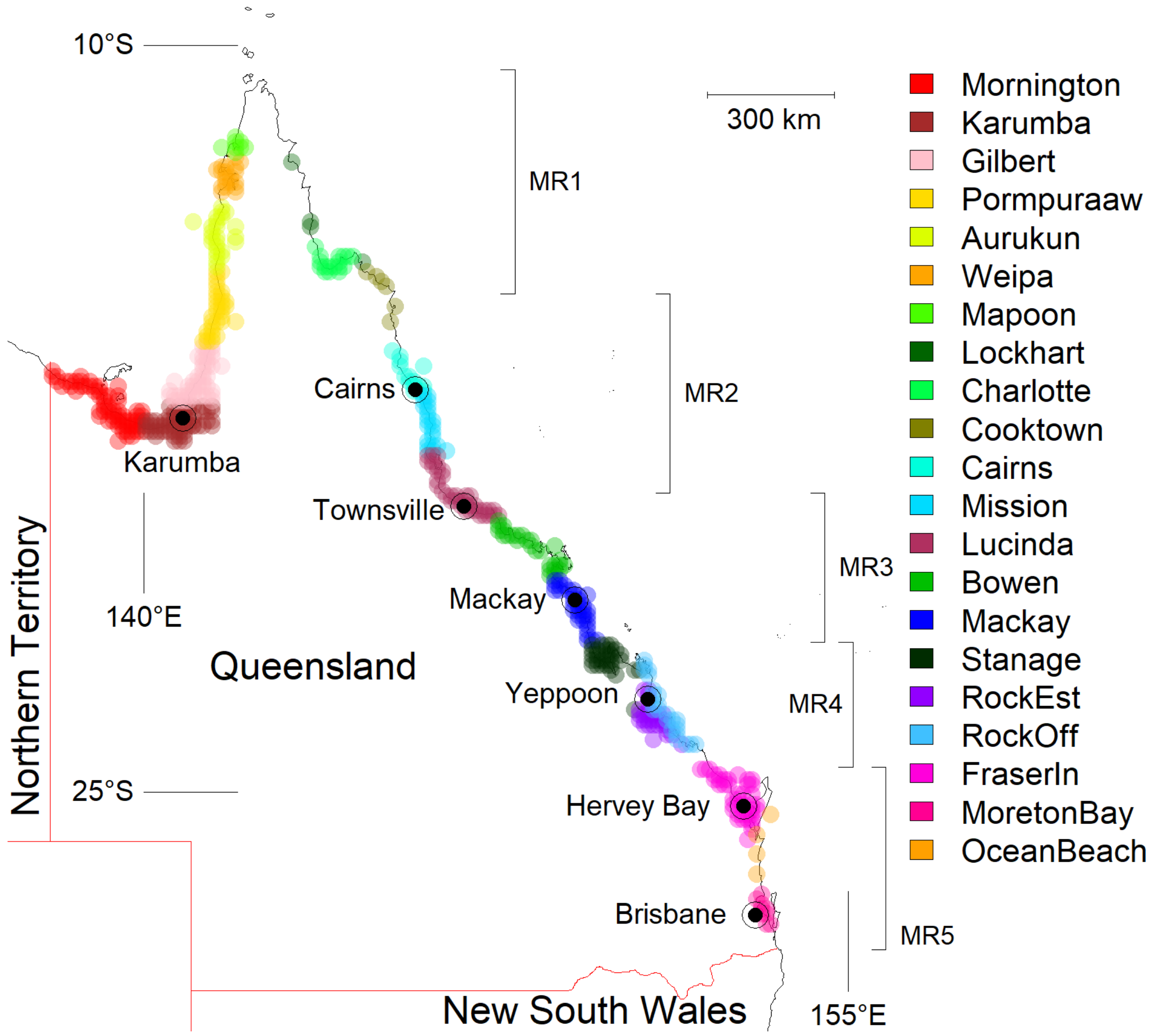

Figure 2.2: Map of fishery regions, showing Management Regions MR1–MR5 and smaller Catch Rate Regions (coloured dots)

Abbreviated Catch Rate Regions are Princess Charlotte Bay "Charlotte", Rockhampton Estuarine "RockEst", Rockhampton Offshore "RockOff" and Fraser Inshore "FraserIn". The Ocean Beach Region consists of surf zones, in which king threadfin is very uncommon.

Table 2.2: Regional structure of the assessment, with Catch Rate Regions, Assessment Regions and Management Regions

Catch Rate Region	Assess. Region	Manage. Region	Comment
Mornington	ARGulf	MRGulf	Southwestern Gulf
Karumba	ARGulf	MRGulf	
Gilbert	ARGulf	MRGulf	Limit of model's southern Gulf "fleet", in which both small fish and old fish are caught
Pormpuraaw	ARGulf	MRGulf	Beginning of model's northern Gulf "fleet", in which fish are young but large for their age
Aurukun	ARGulf	MRGulf	
Weipa	ARGulf	MRGulf	
Mapoon	ARGulf	MRGulf	Northeastern Gulf
Lockhart	AR1	MR1	East Coast of Cape York
Charlotte	AR1	MR1	Princess Charlotte Bay
Cooktown	AR1	MR1–2	Split between MR1 and MR2 at 15 °S; extends south to 16 °S
Cairns	AR2	MR2	
Mission	AR2	MR2	Mission Beach
Lucinda	AR2	MR2	Includes Townsville city and extends south to 19.5 °S, whereas AR2 extends only to 19 °S
Bowen	AR3	MR3	
Mackay	AR3	MR3	
Stanage	AR3	MR4	Major difference between ARs and MRs; AR3 extends east to 150.6 °E, whereas MR4 begins at 22 °S and about 149.5 °E
RockEst	AR4	MR4	Rockhampton Estuarine
RockOff	AR4	MR4	Rockhampton Offshore; extends south to 24.4 °S; MR4 to 24.5 °S
FraserIn	AR5	MR5	Fraser Inshore
MoretonBay	AR5	MR5	
OceanBeach	AR5	MR5	Surf zone, not preferred habitat of king threadfin

On the basis of the Fishery Monitoring data, the Stanage Catch Rate Region, which is in MR4, was assigned to AR3. The data showed that king threadfin in the Stanage Catch Rate Region grow to much the same size as in the Mackay Region, and that this size was a good deal smaller than in the Rockhampton Estuarine and Rockhampton Offshore Regions. The reassignment is also consistent with a natural boundary at Cape Townshend at the eastern extremity of the Stanage Catch Rate Region.

The only other notable difference between Management Regions and Assessment Regions was the assignment of all of the Cooktown Catch Rate Region, the southern half of which is in MR2, to AR1. The catch of king threadfin in the Cooktown Region turned out to be negligible, so this assignment made no practical difference. The city of Townsville is in the MR3 but AR2 (Lucinda Catch Rate Region) but this also made little difference as few king threadfin are caught around Townsville.

AR1 was not assessed, because the harvests from it were small and it had no age or length data. Most of the harvest was taken in the Princess Charlotte Bay Catch Rate Region, corresponding to the Normanby drainage basin (Figure 1.1). The commercial harvest from this Catch Rate Region is being phased out over time, as it was declared a Special Management Area in 2004 to protect dugongs (Table 1.1; GBRMPA 2020). Commercial fishers are not allowed to trade permits to fish in this area, and therefore fishing effort will cease by natural attrition as fishers retire.

2.3 Harvest estimates

2.3.1 East Coast commercial harvest

Data sources for the Queensland East Coast comprised

- Queensland Fish Board annual catch data for the period 1946 to 1981, and
- CFISH logbook records for the period 1988 to 2019.

QFB data were split into region by allocating each QFB District to its nearest Catch Rate Region. King threadfin had been recorded as “Salmon Burnett”, “King” and “Salmon”. While “Salmon Burnett” and “King” were king threadfin only, the majority of catches were reported as “Salmon”, which were mixed king and blue threadfin. The proportion of king threadfin from the first four years of commercial logbook data (1988–1991) was applied to the QFB “Salmon” catch records. The proportion was calculated regionally, by Catch Rate Region, as there were regional differences in species composition of the threadfin harvest (Figure 2.3). Because few data were available in Moreton Bay, the king threadfin proportion was calculated by combining Fraser Inshore and Moreton Bay.

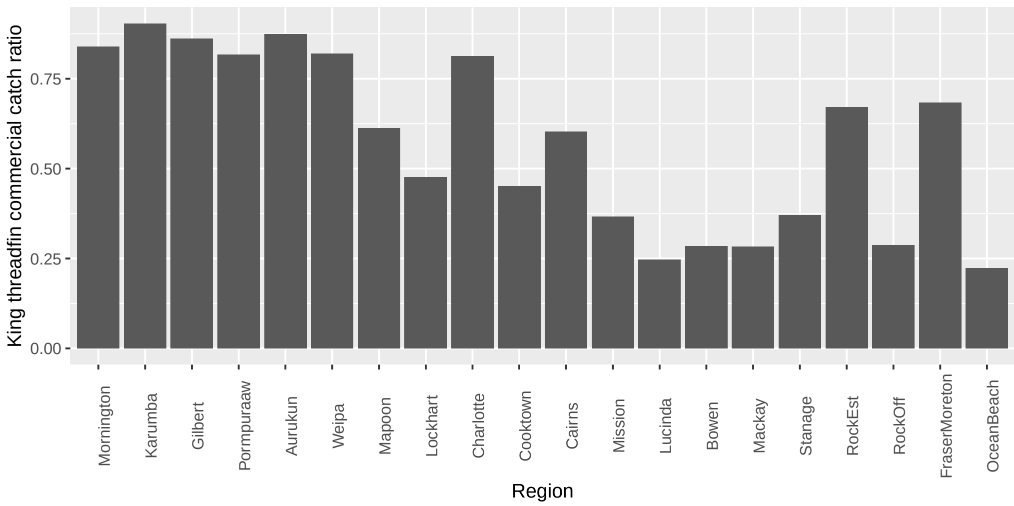

Figure 2.3: King threadfin catch proportion in each Catch Rate Region, based on king and blue threadfin harvest reported in the period 1988–1991
Catch Rate Regions have been calculated from location data in the CFISH database.

Regional time series of king threadfin harvest were constructed as follows:

- Assume zero up to 1936, and increase linearly to the value of the first year of QFB data (1946 in the majority of Catch Rate Regions; 1949 in Princess Charlotte Bay and Cairns, 1947 in Mission).
- Set to QFB figures from 1946 to 1981.
- Interpolate linearly from the mean catch of the last two years of the QFB (1980 and 1981) through to the mean catch of the first two years of CFISH data (1988 and 1989).
- Set to logbook values for calendar years 1988 to 2019.

2.3.2 Gulf commercial harvest

Few QFB data were available for the Gulf Catch Rate Regions. Therefore they were not used to reconstruct historical harvest in the Gulf. No source of harvest size in the Gulf of Carpentaria was available prior to the Gulf logbook introduced in 1981.

An alternative to reconstructing the historical harvest size was to reconstruct the historical fishing effort of net fisheries in the Gulf using oral histories, and use a few point-in-time references for barramundi catch (see Campbell et al. 2017). Similar methods and assumptions were applied to estimate a time series of king threadfin harvest in the Gulf of Carpentaria. There are a few point-in-time reference years:

- Dunstan (1959) reported the total Gulf catch for 1955 as 22 389 lb and that approximately 200 000 lb of headed and gutted fish (of which 70% was barramundi) was exported from the Gulf in 1957. We assumed that 25% of those remaining catches were king threadfin and applied a conversion factor of 1.1 from headed-and-gutted fish to whole fish weight. This equates to 2792.6 kg and 24 947.5 kg of king threadfin catch in 1955 and 1957, respectively.
- Campbell et al. (2017) assumed no expansion of the Gulf net fishery between 1957 and 1970, but thereafter a rapid increase in the effort and catch of barramundi, peaking in 1977. The peak of the Gulf fishery in 1977–78 is described in some detail by Gulf commercial fisher Bill Kehoe (Darcey 1990, p. 142).
- Quinn (1987) records that 306 master fishermen applied to enter the Gulf barramundi fishery in 1980, and 191 of those eligible obtained endorsement for 1981. This indicated that 115 more fishermen were potentially catching king threadfin during the late 1970s compared to 1981.

Our reference estimate of the king threadfin harvest series used the fishing effort data from the barramundi assessment; this became our "high" harvest scenario (see below). The simplest estimate of the peak catch in 1977 is an inflation of the 1981 Gulf logbook catch by the fisher ratio (306/191 = 1.6); however, those who left the fishery (possibly because they were not eligible for endorsement) were considered to be less committed to the Gulf inshore net fishery than those who were successfully endorsed in 1981. Therefore, half of the increase fraction (1.3) was applied to the 1981 Gulf logbook catch of 512 997 kg. Another point to consider is that the CPUE was probably higher in 1970s when the stock was nearer to virgin state than it was in the 1980s. A decrease in CPUE of 3% per year was assumed from 1970 to 1977 (when fishing activity was lower), and 5% per year from 1977 to 1981. Therefore, the peak king threadfin catch in 1977 was calculated as 512 997 $\times$ 1.3 (fisher factor) $\times$ 1.2 (CPUE factor) = 800 275 kg.

In summary, the following rules were used in the reference estimate of commercial harvest in the Gulf:

- Set to 2792.6 kg in 1955, 24 947.5 kg in 1957, and interpolate linearly between those two years.
- Set constant from 1957 to 1970.
- Increase linearly from 1970 to the estimated peak catch in 1977.
- Decrease linearly from 1977 to the first recorded Gulf logbook value in 1981.
- Set to the sum of Gulf logbook records from 1981 to 1988.
- Set to the sum of Gulf logbook records and CFISH commercial records in 1989.
- Set to the sum of CFISH commercial records from 1990 to 2019.

After discussion with the Project Team, largely about the feasibility of transporting and marketing harvests of the projected size, the above reference estimate was used as a high scenario. Other scenarios were defined as constant harvest from 1977 to 1981 (low scenario) and the average of the high and low scenarios (middle scenario). The middle scenario was used as the base case for the population model, for reporting the results and the sensitivity to different values of the model parameters. The validity of concerns about transport and marketing remains unclear, as substantial fractions of king threadfin catches in the 1970s could have been discarded dead and not required transport or marketing.

2.3.3 Recreational harvest

Data sources for recreational harvest comprise

- RFish data in 1997, 1999, 2002 and 2005,
- The National Recreational and Indigenous Fishing Survey (NRIFS) in 2000, and
- Statewide Recreational Fishing Survey (SWRFS) in 2011, 2014, and 2019.

The NRIFS also measured catch taken by coastal Indigenous communities, which in Queensland was about 11.6% of the corresponding recreational catch of king threadfin. The Indigenous harvest was not included in this assessment. We recommend that it be included in future assessments.

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 regional scales. King threadfin was reported to either individual species level ("King threadfin") and species group level ("Threadfin salmon", "Threadfin & Australian salmon" or "Threadfin salmons—unspecified"). The latter records were assumed to comprise only king threadfin and blue threadfin. Species identification in recreational surveys, although less of a problem for king threadfin than for many other Queensland fish species, has generally improved over time. When species composition is lacking in earlier surveys, it can be inferred from later ones.

Harvests were calculated by Management Region instead of Assessment Region, as the calculations were undertaken before the Assessment Regions had been finalised. We acknowledge that it would have been preferable to define them by Assessment Region, but the difference was very small, comprising only one surveyed king threadfin caught at Stanage Bay in 2011 which had a survey weighting factor of 178 (i.e. considered equivalent to 178 fish caught by the whole Queensland population). One blue threadfin was also caught in Stanage Bay in 2011 (weighting 632) and one in 2014 (weighting 227). No threadfins from the Queensland East Coast north of Cairns were recorded in either survey. As little difference found between Management Region and Assessment Region, the regions will be denoted as AR hereafter.

When king and blue threadfin were not distinguished, the species composition was inferred from the Boat Ramp Survey data. Separate proportions were calculated for the northern (ARGulf and AR1–3) and southern (AR4–5) Assessment Regions (Table 2.3). Due to the limited resolution of location, we reconstructed recreational harvest only to the level of Assessment Region (ARGulf and AR1–5).

Table 2.3: Species fraction estimated from Boat Ramp Survey program data (2015–2019)

Location	King threadfin	Blue threadfin	Species fraction	Assessment Regions
North	126	845	0.13	ARGulf, AR1, AR2, AR3
South	453	320	0.59	AR4, AR5

For NRIFS and SWRFS (except in 2019), the surveys were recorded in 19 fishing regions (Figure 2.4). The "Central Coast catchment" region is very big and we split its estimates into AR2, AR3 and AR4 in the following way:

- The 2011 and 2014 surveys contained finer location information called "Fishing Location". This field was used to identify the appropriate Assessment Region.
- The regional harvest proportions from 2011 and 2014 combined were used to allocate the catches to Assessment Regions when detailed location information was not available.

- Species compositions from Table 2.3 were applied to northern (AR2–3) and southern (AR4) regions.

Because the fishing regions in the 2019 SWRFS survey did not align with previous surveys, the estimates from the 2019 regions were proportionately allocated to previous years' survey regions and then grouped into the six Assessment Regions.

For RFish, harvests were allocated into the six Assessment Regions based on latitude and longitude recorded in the survey. Approximately 20% of RFish records in 1997, 1999 and 2002 had no location information. These records were allocated to the six Assessment Regions based on regional proportions of threadfin species observed in the NRIFS data in 2000.

After all recreational survey estimates were grouped into the Assessment Regions, species-group level estimates were multiplied by species fractions to estimate king threadfin harvest. As the species composition identified in recreational sector clearly varied with latitude, two separate species fractions (north and south) were estimated from Boat Ramp Survey data and applied to the respective Assessment Regions (Table 2.3).

RFish estimates were used only for trend, not as absolute harvest estimates. The following steps were taken to convert them to harvest estimates:

- The statewide RFish estimates from 1999 and 2002 were interpolated linearly 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 the RFish estimates in each year and region.

Once king threadfin harvest estimates were obtained for each Assessment Region in each survey year, extrapolations to earlier years and interpolations to intermediate years in which surveys were not carried out were made as follows:

- In the ARGulf: Set to zero in 1969, and increase linearly to reach the rescaled RFish estimate in 1997.
- For East Coast Assessment Regions: Begin in 1945 and set harvest proportional to Queensland human population, to reach the rescaled RFish estimate in 1997.
- Set to the rescaled RFish estimates in 1999, 2002, and 2005.
- Set to the NRIFS and SWRFS estimates in 2000, 2011, 2014 and 2019.
- Interpolate linearly between survey years to produce estimates for 1998, 2001, 2003–2004, 2006–2010, 2012–2013 and 2015–2018.
- Convert from numbers to estimated retained (landed) harvest using the mean king threadfin weight calculated from the Boat Ramp Survey length-frequency data and the length–weight relationship (Section 2.6.3), aggregated over all years and regions.

Time series of recreational harvests were not constructed for AR1 due to very small sample sizes in the recreational surveys.

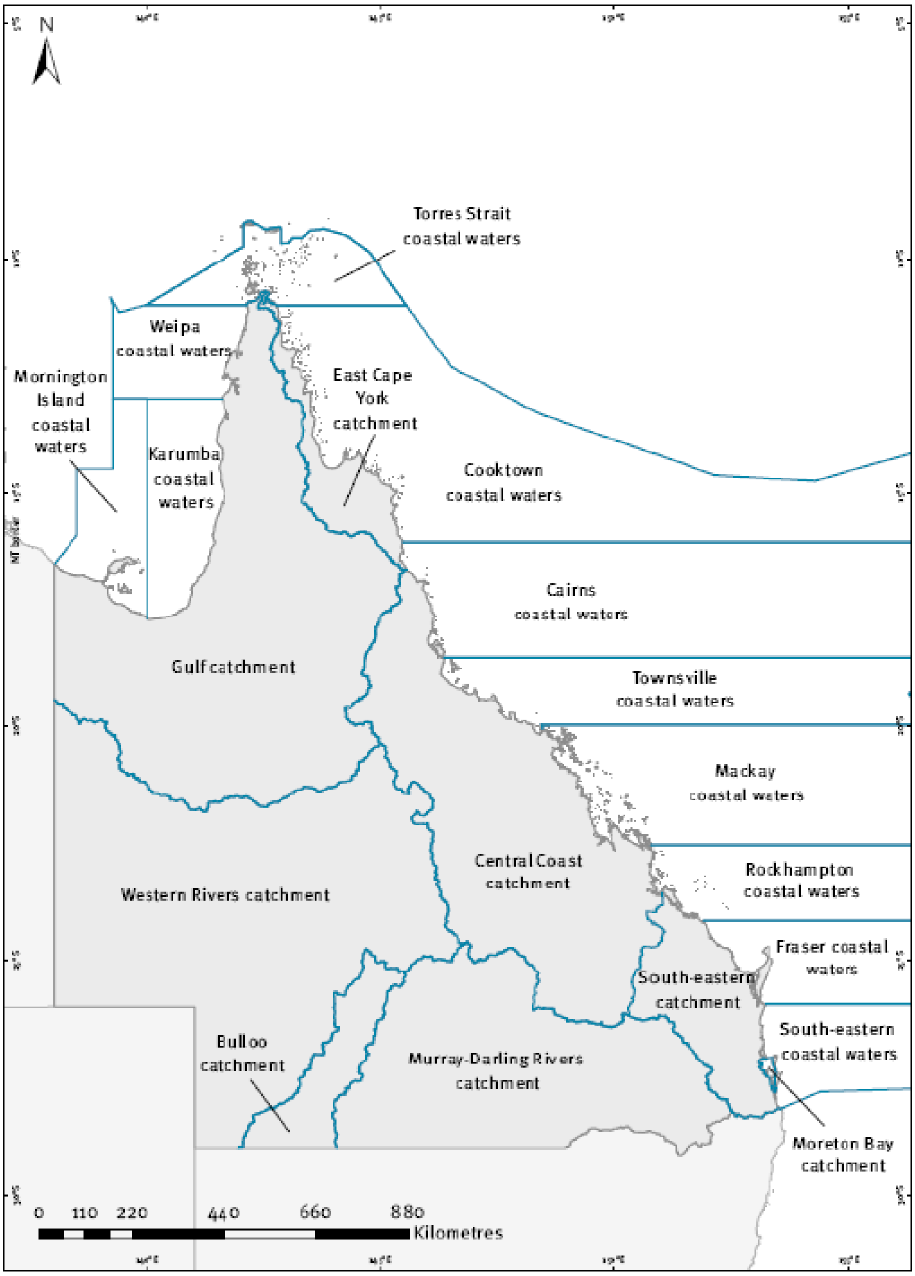

Figure 2.4: Fishing regions used in the NRIFS (2000) and SWRFS (2011, 2014) recreational surveys
Source: Taylor et al. (2012)

2.4 Abundance

2.4.1 Commercial catch rates

The time series of abundance for input to the population model came from commercial gillnetting catch rates from logbook data. Separate series were derived for each of the Catch Rate Regions (Figure 2.2), because literature (e.g. Welch et al. 2010) indicated that king threadfin form small stocks and that fishing pressure in one Catch Rate Region could be markedly different from that in a neighbouring Catch Rate Region (see Section 1.1 above).

Logbook data were collated to produce one record per fisher-day, with each fisher-day including just one location (the one in which the most fish were caught) and a separate field for each relevant species group. Zero catches of king threadfin were included when species groups commonly associated with king threadfin were caught (Table 2.4). These associated species groups were decided on the basis of the average catch of king threadfin over records in which a particular other species was caught. Details of this methodology are given in Leigh et al. (2017).

Table 2.4: Associated species used as indicators of zero catches of king threadfin in the catch rate analysis of commercial logbook data

Catch Rate Region	Assessment Region	Associated species
Mornington	ARGulf	Other threadfins, jewfish, grunter
Karumba	ARGulf	
Gilbert	ARGulf	
Pormpuraaw	ARGulf	
Aurukun	ARGulf	
Weipa	ARGulf	
Mapoon	ARGulf	
Lockhart	AR1	Other threadfins, grunter
Charlotte	AR1	
Cooktown	AR1	
Cairns	AR2	
Mission	AR2	
Lucinda	AR2	None
Bowen	AR3	
Mackay	AR3	Barramundi, jewfish, grunter
Stanage	AR3	
RockEst	AR4	
RockOff	AR4	Barramundi, jewfish
FraserIn	AR5	
MoretonBay	AR5	
OceanBeach	AR5	

Five separate catch rate analyses were conducted: one for the Gulf of Carpentaria; one for the Princess Charlotte Bay, Cairns and Mission Catch Rate Regions; one for Lucinda and Bowen; one for Mackay, Stanage and Rockhampton Estuarine; and one for Rockhampton Offshore, Fraser Inshore and Moreton Bay. The grouping of Catch Rate Regions was done on the basis of common seasonal patterns in the king threadfin catch. It simplified the analysis by allowing the interaction between Month and Catch Rate

Region to be omitted. Also, it was expected that the associated species would vary by latitude, and this structure allowed the associated species to be defined separately for each analysis.

The analysis used the quasi-negative-binomial generalised linear model (GLM), which is similar to the quasi-Poisson model used for tailor (Leigh et al. 2017, Section 3.2). The extension from quasi-Poisson to quasi-negative-binomial allows the variance of the residuals from the GLM to be more closely controlled so that data are weighted optimally and random "noise" in the resulting abundance estimates is minimised (Leigh in prep.).

The quasi-Poisson variance formula is

$$V(y) = \sigma\mu, \tag{2.1}$$

where V denotes variance, y is the dependent variable (catch in a fisher-day), σ is the dispersion parameter and μ is the mean or expectation of y. The quasi-negative-binomial model extends this to

$$V(y) = \sigma\left(\mu + \mu^2\big/\phi\right), \tag{2.2}$$

where ϕ is the negative-binomial shape parameter. The limit $\phi \to \infty$ recovers the quasi-Poisson model.

Explanatory variables included in all the GLMs were Region-year, fisher ID, mesh size, net length, and calendar month. In addition, lunar phase was included for the Cairns–Mission and Mackay–Stanage–RockEst GLMs; the precise terms fitted are described in Section A.2, Appendix A. Lunar phase was not statistically significant in the other analyses. All explanatory variables other than lunar phase were defined as categorical variables or "factors". The Region-year term was the combination of Catch Rate Region and calendar year. Mesh size and net length were converted from continuous variables to categorical ones because the relationships between these variables and catch rates were complex. For example, a shorter net often catches more fish than a longer one, perhaps because many high-catch locations are not suitable for long nets, or because a short net is more transportable and can be easily moved to a new location if it is not catching much.

Wind could be included when the assessment is updated. The CFISH commercial logbook data does not include a field to distinguish foreshore netting from river netting, so it was not possible to include this effect. Such a field was recorded in the earlier Gulf logbook.

The catch-rate GLMs used the log link function. This link function produces multiplicative effects: e.g. catch rates in location A may always be twice those in location B, irrespective of the levels of year, time of year and fisher skill level, which cause the abundance in both those locations to go up and down. The Region-year coefficients from the GLMs were used as Region-specific indices of abundance.

2.4.2 Recreational catch rates

A preliminary analysis of recreational catch rates from the Boat Ramp Survey data set was undertaken for AR4 only, the Region with the most data. These catch rates were used only as a check of the model results, as the time series was short and the continual changing of the fishers whose catches were sampled prevented the estimation of any trends in their average skill level. Despite the limitations, we believed that any sharp increase in abundance after the introduction of the Net Free Zone in this Region should be visible in the Boat Ramp Survey catch rates. The analysis is described in section D.1, Appendix D.

2.5 Length and age data

Length data were input to the population model in one-centimetre length bins. Age data were input as conditional age-at-length samples, to follow the method of generation of the data, as the selection of fish for ageing was based on their lengths. The ages used in the model were defined as the Fishery Monitoring "age group" minus one year, so that new recruits were assigned age zero.

Any fish smaller than 1.5 cm below the prevailing minimum legal size were excluded from the model input data, as the model assumed that only legal-sized fish (with a small margin for error) were retained by fishers.

2.6 Biological relationships

2.6.1 Fork length and total length

The assessment's population model expressed all measurements as fork length (FL). Minimum legal sizes were set in total length (TL), so had to be converted to fork length. Also, in the Fishery Monitoring data set, a few measurements made only in TL were converted to FL.

Length data collected by the Department of Agriculture and Fisheries (DAF) Fishery Monitoring team were used to estimate the relationship between FL and TL for three different regional combinations:

ARGulf: $\mathrm{FL} = -1.011 + 0.83481 \times \mathrm{TL}$

AR2, AR3: $\mathrm{FL} = -0.360 + 0.83528 \times \mathrm{TL}$

AR4, AR5: $\mathrm{FL} = -2.042 + 0.84691 \times \mathrm{TL}$

where FL denotes fork length (cm) and TL denotes total length (cm).

2.6.2 Maturity and fecundity

Maturity fractions in the population model were age-based, based on the study by Moore et al. (2011):

- 0% mature at ages 0, 1 and 2
- 25% at age 3
- 50% at age 4
- fully mature from age 5.

Fecundity of mature fish was assumed to be proportional to body weight.

2.6.3 Weight and length

McPherson (1997) estimated the length–weight relationship for king threadfin in the Gulf of Carpentaria:

$$W = 2.37 \times 10^{-5} \times \mathrm{FL}^{2.81}$$

where W denotes fish weight (kg) and FL is fork length (cm). In the absence of an East Coast equation, the same equation was used to calculate weights from fork length for all regions.

2.7 Population model

2.7.1 Description

Each Assessment Region was run separately through the software Stock Synthesis (SS) (Methot and Wetzel 2013), version 3.30.14. This is an annual, age-structured population model with multiple fishing "fleets" that can target fish of different size ranges. The model operated on calendar years. Stock Synthesis is widely used and understood, and can produce forecasts into the future from various control rules. The associated R package "r4ss" (Taylor et al. 2019) automatically produces standard plots and summaries of the outputs. Stock Synthesis itself is programmed in the software AD Model Builder (Fournier et al. 2011). The source code of SS was made publicly available in March 2020, thereby promoting its use outside the USA.

For use with king threadfin, SS has the limitation that, when assessing multiple regions simultaneously, it mixes larvae from all of the regions, thereby allowing lightly fished regions to seed recruits into heavily fished regions. We believed that it was important not to allow this, as literature indicated that king threadfin stocks were localised (Welch et al. 2010). Therefore we ran the model separately on each Assessment Region.

The separation of regions had the consequence that some population parameters were estimated separately for each Assessment Region, whereas, due to larger sample sizes, common estimates covering all Regions would have been subject to smaller observational error. These parameters included the natural mortality rate M and the parameter for recruitment compensation (Goodyear 1977) which SS parameterises as "steepness" h (Mace and Doonan 1988). We achieved consistent estimates of these parameters across Assessment Regions by varying the Region-specific value of either M or the catchability-increase parameter q_{inc} (see below) to make the results compatible with other Regions.

A major feature of the king-threadfin fishery is that standardised catch rates from commercial logbook data show major increases over the period 1989 to present, which must be due to increases in catchability (q) and could not be due to increased abundance. Fishers have learnt to target king threadfin by various net-setting techniques (fishery managers, personal communications). Another factor is that catchability of king threadfin appears to change with environmental conditions. For example, commercial logbook catch rates suddenly increase after floods, but Fishery Monitoring data show that the fish that appear are too old to have been born in response to the flood.

Catchability increase was handled by including a model parameter denoted q_{inc} which was a constant annual increase in $\log q$.

We did not attempt to model the environmental events. The population model fitted the input data as best it could by means of "recruitment deviations", whereby the number of fish born in a year can vary greatly between years. It is not likely that recruitment deviations are truly the major source of variation in perceived abundance of king threadfin.

It is important to note that different commercial fleets in the model were defined by different age and length ranges that were targeted in different locations. They do not necessarily imply different groups of fishers; a fisher can participate in more than one fleet.

In ARGulf the fleets were defined as southern Gulf (fleet 1, Mornington–Karumba–Gilbert Catch Rate Regions) and northern Gulf (fleet 2, Pormpuraaw–Aurukun), because the fish in the north were substantially larger than those of the same age in the south. Also Fishery Monitoring data showed that the northern fish were present only at ages 1, 2 and 3, with a few of age 4. The model assumption was that the southern Gulf was both a nursery area (with many small fish) and a spawning destination for middle-aged and old fish, many of which swam back from the northern Gulf to breed. We omitted the northern data from age 4 and imposed age-based selectivity of fleet 2 on ages 1, 2 and 3 only.

In AR2 the fleets were Mission–Lucinda (fleet 1) and Cairns (fleet 2), as the Cairns fish were bigger. There was no great difference in the ages present between the two fleet areas, and the Cairns Catch Rate Region contained a healthy proportion of female fish. Communications from fishers to the Fishery

Monitoring team indicated that they considered Mission a nursery area. The model assumption was that fish were able to swim between Mission and Cairns.

In AR5 the fleets were Fraser Inshore (fleet 1) and Moreton Bay (fleet 2). Moreton Bay fish were bigger, possibly because commercial fishers could not fish locations in the Brisbane River where smaller fish may reside. Fraser Inshore appeared to be a major nursery area.

A recreational fleet, with its own length-based selectivity function, was feasible only in AR4, as insufficient numbers of fish to estimate this function were sampled by Boat Ramp Surveys in the other Assessment Regions. In this Region, the fleets were commercial (fleet 1, gillnetting) and recreational (fleet 2, line fishing). For AR3 we used only one fleet.

Fishery discards were handled by inserting a retention function into the model. This function was defined from the minimum legal size that prevailed in each year. Actual data on discards were not available so were not used. This treatment of discards assumes that only fish below minimum legal size were discarded. We do not know what fraction of legal-sized fish may have been discarded in the past; for example, if fishers were targeting barramundi and may not have had space on the boat for threadfins.

The mortality rate of discarded king threadfin was set to 70%, on advice from Project Team members that this species does not survive well when released.

A representative standardised catch-rate time series was chosen for each fleet in each Assessment Region. This generally came from the Catch Rate Region with the greatest total catch of king threadfin, and so had the greatest precision in the catch rates. These regions are listed in Table 2.5.

Table 2.5: Catch Rate Regions chosen as representative for each fleet in each Assessment Region
No usable catch-rate time series were available for AR4 Recreational or AR5 MoretonBay.

Assessment Region	Fleet	Catch rate
ARGulf	South	Karumba
ARGulf	North	Pormpuraaw
AR2	Mission	Mission
AR2	Cairns	Cairns
AR3	–	Mackay
AR4	Commercial	RockEst
AR4	Recreational	–
AR5	FraserIn	FraserIn
AR5	MoretonBay	–

The stock–recruitment relationship was the Beverton-Holt one (Beverton and Holt 1957), which is conveniently parameterised as

$$R = R_0 \frac{rS}{S_0 + (r-1)S} \tag{2.3}$$

where R is the deterministic, year-specific number of recruits of age zero, R_0 is the deterministic recruitment for an unfished population, r is the recruitment compensation ratio (Goodyear 1977) ($r > 1$), S is the year-specific spawning stock size, and S_0 is the spawning stock size for an unfished population. When parameterised in terms of steepness h instead of r, this equation becomes ($0.2 < h \leq 1$)

$$R = R_0 \frac{4hS}{(1-h)S_0 + (5h-1)S}. \tag{2.4}$$

When random, annual recruitment deviations are included, R is multiplied by

$$\exp\left(\eta - \sigma_R^2 \big/ 2\right) \tag{2.5}$$

where η is the year-specific recruitment deviation and follows a normal distribution with mean zero and variance σ_R^2. The subtraction of $\sigma_R^2 \big/ 2$ is for bias correction, to prevent the expected biomass in the presence of recruitment deviations from becoming greater than the deterministic unfished biomass.

Selectivity of fish by fishers was length-based and followed a two-parameter logistic function. The fishing methods in use were considered not to de-select big king threadfin (see Section 1.3).

Only a single sex was used in the model. This setting is equivalent to assuming that sex change is socially controlled: if large, female fish are removed by fishing, the age and length at sex change will shift towards younger, smaller fish. Evidence for such a shift in the south-eastern Gulf of Carpentaria was documented by Moore et al. (2017).

2.7.2 Model assumptions

The following list summarises the major assumptions made in the population modelling:

- Each Assessment Region is a single stock and there is minimal mixing of fish between Assessment Regions.
- Fish swim freely and mix instantaneously across an Assessment Region, so that the different fleets compete for the same fish rather than targeting different sub-populations. In truth, the time scale of mixing is likely to be several years.
- The different fishing fleets compete with each other for the same fish, even though in ARGulf, AR2 and AR5 they fish different locations within an Assessment Region.
- The lack of old fish in the northern Gulf is due to the fish swimming back to the southern Gulf, not dying at a young age in the northern Gulf.
- Recruitment deviations are the dominant cause of variation in abundance of king threadfin. In truth, the dominant cause was likely to be changes in fish behaviour and catchability due to environmental causes, but currently it is not feasible to model that.
- The instantaneous natural mortality rate M does not depend on age or year.
- The value of M is similar across different Assessment Regions. This assumption could be used to tune the values of the catchability-increase parameters q_{inc}, which were expected to be difficult or impossible to estimate inside the model, due to lack of specific data for them.
- Log-catchability increased linearly over time (1989–2019) for each fleet in each Assessment Region, according to a fleet-specific or Region-specific q_{inc} parameter.
- Values of q_{inc} should not vary greatly between Assessment Regions, and the Regions showing the greatest increase in catch rates should also have the highest values of q_{inc}.
- Within each Assessment Region, catch rates are proportional to abundance, after adjusting for catchability increase over time.
- All legal-sized king threadfin caught by fishers are retained. Fish are returned to the water only when they are below minimum legal size.
- Selectivity of king threadfin by fishing depends on length, not age, except for the northern fleet in ARGulf.
- Notwithstanding the length-based nature of selectivity, pure age-based modelling, without the use of SS's "platoons" feature, was sufficient for this assessment. We regarded other uncertainties, such as the rate of increase in catchability (q_{inc} parameter), as having a much greater effect on the results than this one.

2.7.3 Model parameters

Model parameters are listed in Table 2.6. We attempted to estimate the five von Bertalanffy growth parameters (including two standard deviations) in all Assessment Regions, but were unable to obtain sensible estimates in AR5. Therefore we estimated these parameters outside the model for this Region. We also attempted to estimated the steepness h in all Regions, but in all cases it hit the upper bound of 0.75. To be precautionary, we set it to 0.75 in order to enforce some dependence of recruitment number of spawning stock size. We also carried out sensitivity testing on steepness. Years in which recruitment deviations were estimated were chosen partly to ensure that the series of recruitment deviations did not begin or end suddenly with a large value, as such an occurrence would have made the results depend on the choice of recruitment-deviation years to an unacceptable degree.

Table 2.6: Parameters included in the population model

Symbol	Description	Estimate or fix
M	Instantaneous natural mortality rate	Fix in ARGulf, estimate in AR2–AR5
L_{min}	Mean length of fish at minimum age	Estimate except in AR5
L_{max}	Mean length of fish at maximum age	Estimate except in AR5
K	Von Bertalanffy growth coefficient	Estimate except in AR5
SD_{young}	Standard deviation of length of fish at minimum age	Estimate except in AR5
SD_{old}	Standard deviation of length of fish at maximum age	Estimate except in AR5
$\ln R_0$	Log of number of recruits when unfished	Estimate
h	Steepness	Estimate if less than 0.75; otherwise fix to 0.75
σ_R	Standard deviation of log recruitment deviations	Estimate in ARGulf; Fix to 0.3 in AR2–AR5
$\ln q$	Log of catchability	Estimate
q_{inc}	Annual increase in $\ln q$	Estimate in ARGulf, fix in AR2–AR5
L_{50}	Fleet-specific length at 50% selectivity by fishing	Estimate
$L_{95\text{ width}}$	Fleet-specific difference in lengths at 50% and 95% selectivity	Estimate unless very small (< 2 cm)
$L_{50\text{ ret}}$	Year-specific length at 50% retention by fishers	Fix to minimum legal size
$L_{95\text{ ret width}}$	Year-specific difference in lengths at 50% and 95% retention	Fix to 2 cm
η	Year-specific recruitment deviations: 1985–2017 in ARGulf; 1984–2017 in AR2, AR3 and AR4; 1974–2017 in AR5	Estimate

2.7.4 Model weightings

All likelihood components were fully weighted ($\lambda = 1$).

Age and length data were manually weighted. The method of Francis (2011) was used as a rough guide. We found that this method worked poorly and often recommended impossibly small or large weightings, so educated guesses were necessary much of the time. Poor performance of this method was also noted by O'Neill et al. (2014).

2.7.5 Sensitivity tests

The major sensitivity of the results was to the catchability-increase parameter q_{inc}, which generally could not be estimated accurately due to lack of measurements on it. We conducted likelihood profile studies on this parameter, in order to study a range of values and compare the corresponding likelihood values.

Setting of the q_{inc} parameter was aided by the model assumption that the natural mortality rate M should not vary much between Assessment Regions, and to a lesser degree that the value of q_{inc} should not vary greatly between regions. We often preferred a q_{inc} value that was compatible with levels of M or q_{inc} in other Regions, over a value that provided a better likelihood value.

In ARGulf, this sensitivity testing took the form of testing different values of M instead of q_{inc}. The two Gulf fleets had different values of q_{inc} and it was important that they both be estimated in the model rather than fixed outside it. The effect was much the same, as higher values of q_{inc} increased the effect of fishing and produced correspondingly lower values of M.

In addition to varying q_{inc}, we also tested different values of the steepness h, and, for ARGulf, different histories of harvest size (high, middle and low) (see Section 2.3.2).

2.7.6 Forward projections

Model results were projected forward 20 years, to 2039. A 20:60:60 harvest control rule was employed, consistent with the Sustainable Fisheries Strategy (Department of Agriculture and Fisheries 2017). This control rule assumed that the fishery was closed when the spawning biomasss fell below 20% of the unfished level (B_{20}). Above B_{20}, the instantaneous fishing mortality rate F increased proportional to $B - B_{20}$, reaching the level F_{60} at B_{60}; i.e., the level of steady-state fishing at spawning biomass 60% of unfished (B_{60}). For $B > B_{60}$ the fishing mortality was held constant at F_{60}. We did not use any precautionary buffer on fishing mortality.

3 Results

3.1 Model inputs

Figure 3.1 shows the years in which model inputs were available. It is notable that age and length data generally become available only in more recent years. The most valuable additional data would have been age data from the Gulf of Carpentaria in the early 1970s or before, but these are not known to exist.

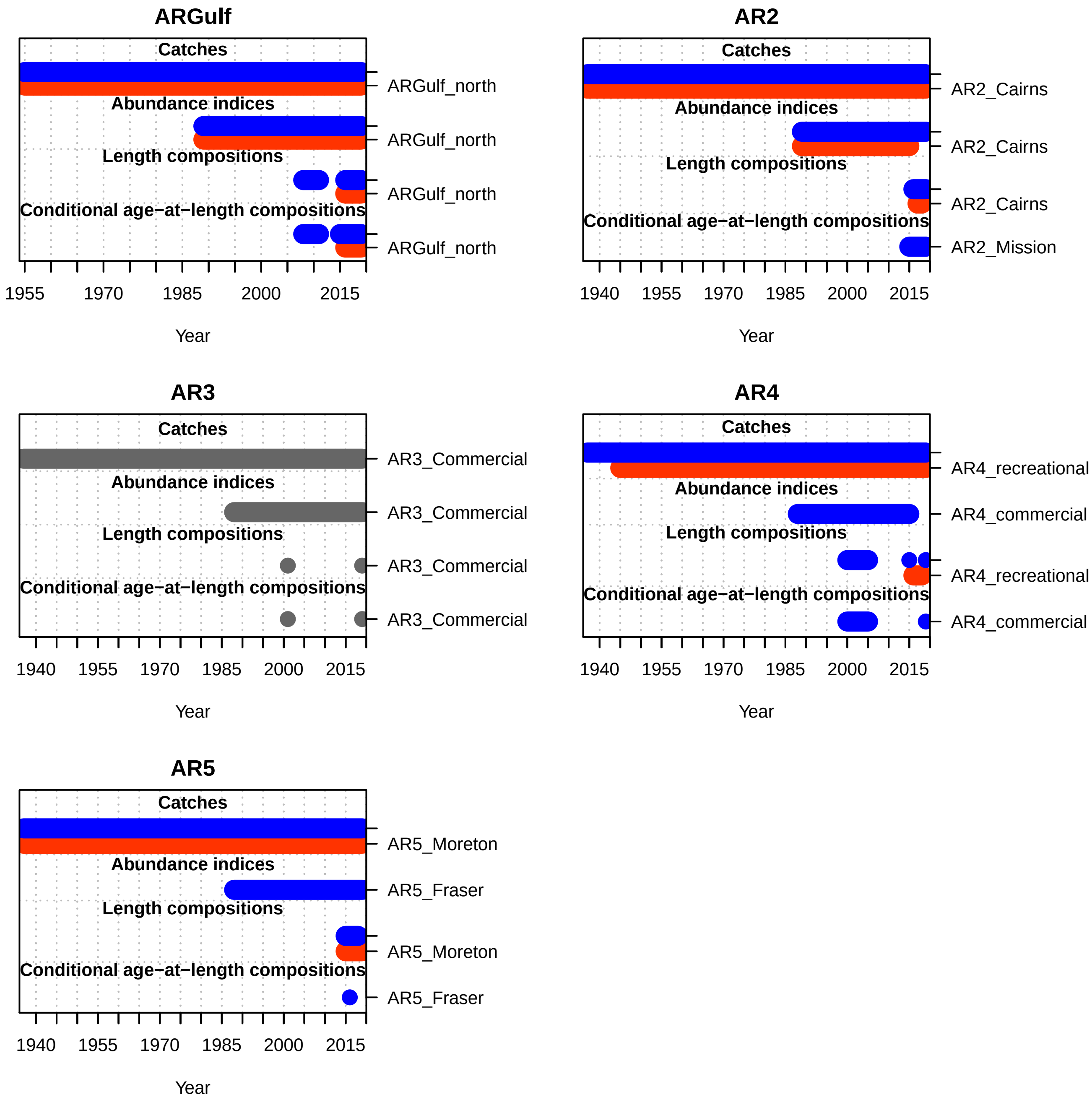

Figure 3.1: Data presence by year for each region and Stock Synthesis fleet for king threadfin

3.1.1 Harvest estimates

Time series of king threadfin harvests are shown by fishing sectors (Figure 3.2) and by Assessment Regions (Figure 3.3 and Figure A.1 in Appendix A). The overall harvests were mainly contributed by the commercial sector, with the majority from ARGulf. The estimates indicate that the total harvest in ARGulf increased rapidly in the early 1970s, reaching a peak in late 1970s (about 650 tonnes per year in our middle-harvest scenario), then gradually declined, ranging between 150 and 250 t/yr between 2013 and 2019. On the East Coast, total harvest increased gradually, reaching peaks in the early 2010s. Since 2015, when the Cairns, Mackay and Fitzroy-estuary Net Free Zones were introduced, a sharp decline in East Coast king threadfin harvest has taken place: approximately 240 tonnes was landed annually in the early 2010s, but this fell to approximately 60 tonnes in 2019.

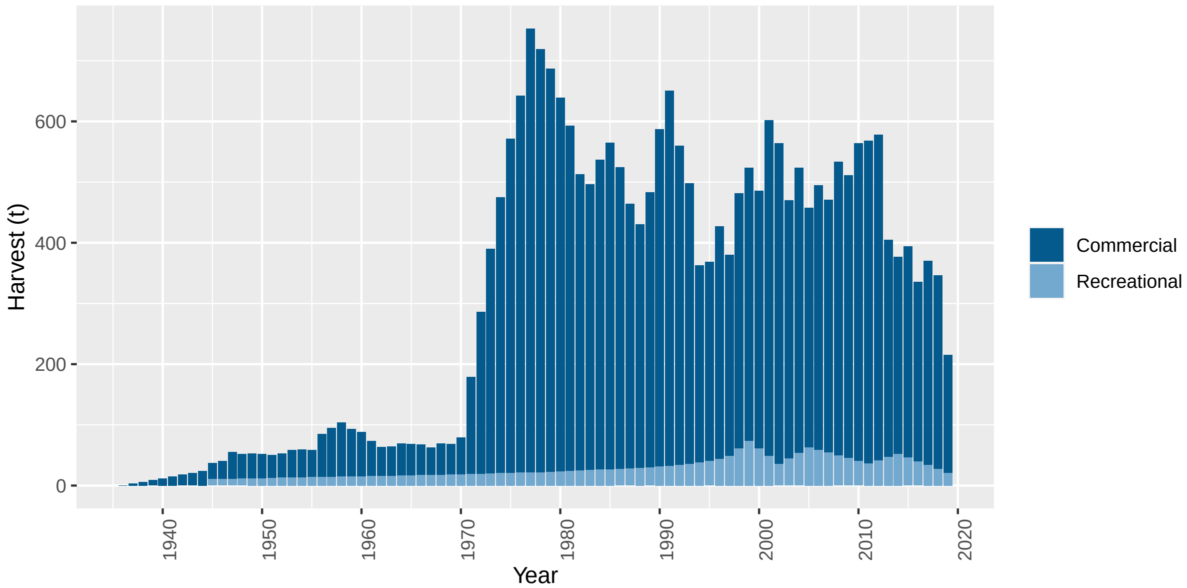

Figure 3.2: Estimated harvest (retained catch) by sector, 1937–2019, medium ARGulf harvest scenario

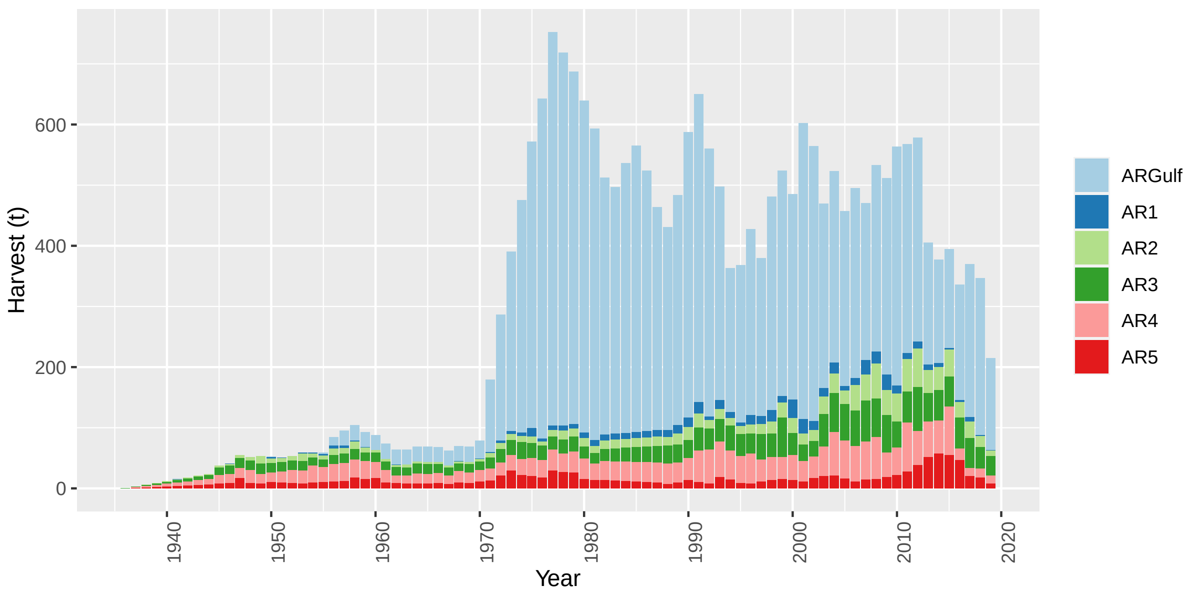

Figure 3.3: Estimated harvest by Assessment Region, 1937–2019, medium ARGulf harvest scenario

3.1.2 Standardised catch rates

Standardised catch rates (Figures 3.4–3.8) vary greatly over time. We believe that much of this variation comes from environmental drivers such as floods (which promote high catch rates) and droughts (low catch rates).

The continual increase in catchability, and hence the need for the catchability increase parameter q_{inc} in the population model, is shown most clearly in AR3 (Figure 3.6). It is also apparent in the northern Gulf (Figure 3.4) and in AR4 (Figure 3.7).

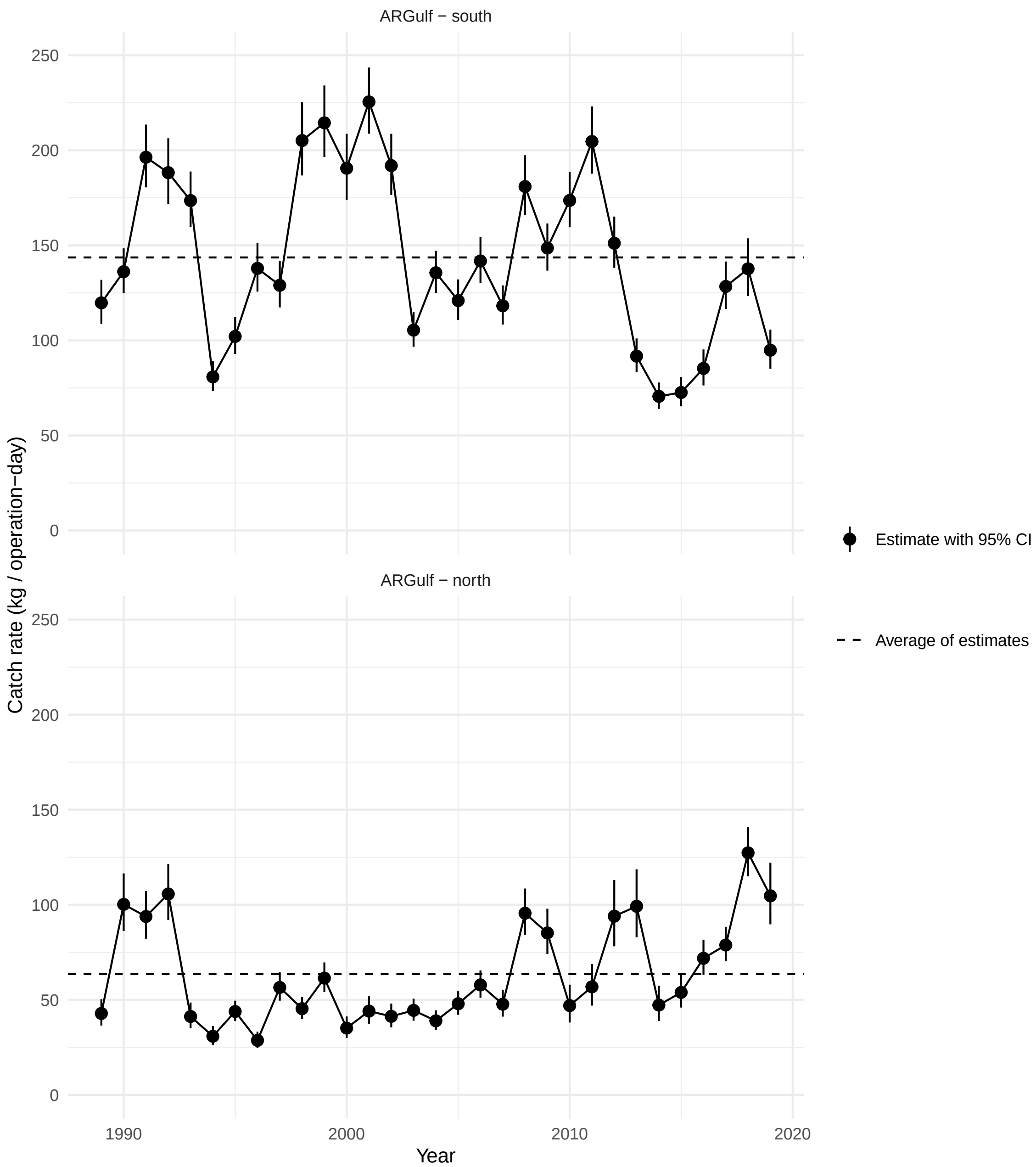

Figure 3.4: Annual standardised catch rates (95% confidence intervals) for king threadfin in ARGulf

Catch rates based on very small amounts of data, e.g. due to the presence of Net Free Zones after 2015, were excluded from the model and are not shown. Catch rates from the Moreton Bay Catch Rate Region (fleet 2 of AR5) were also not used, as king threadfin in commercially harvestable numbers came into this region only after the major flood in 2011 and more recently the abundance has dwindled, probably due to natural causes.

Catch-rate time series that were not used in the model are shown in Appendix C.

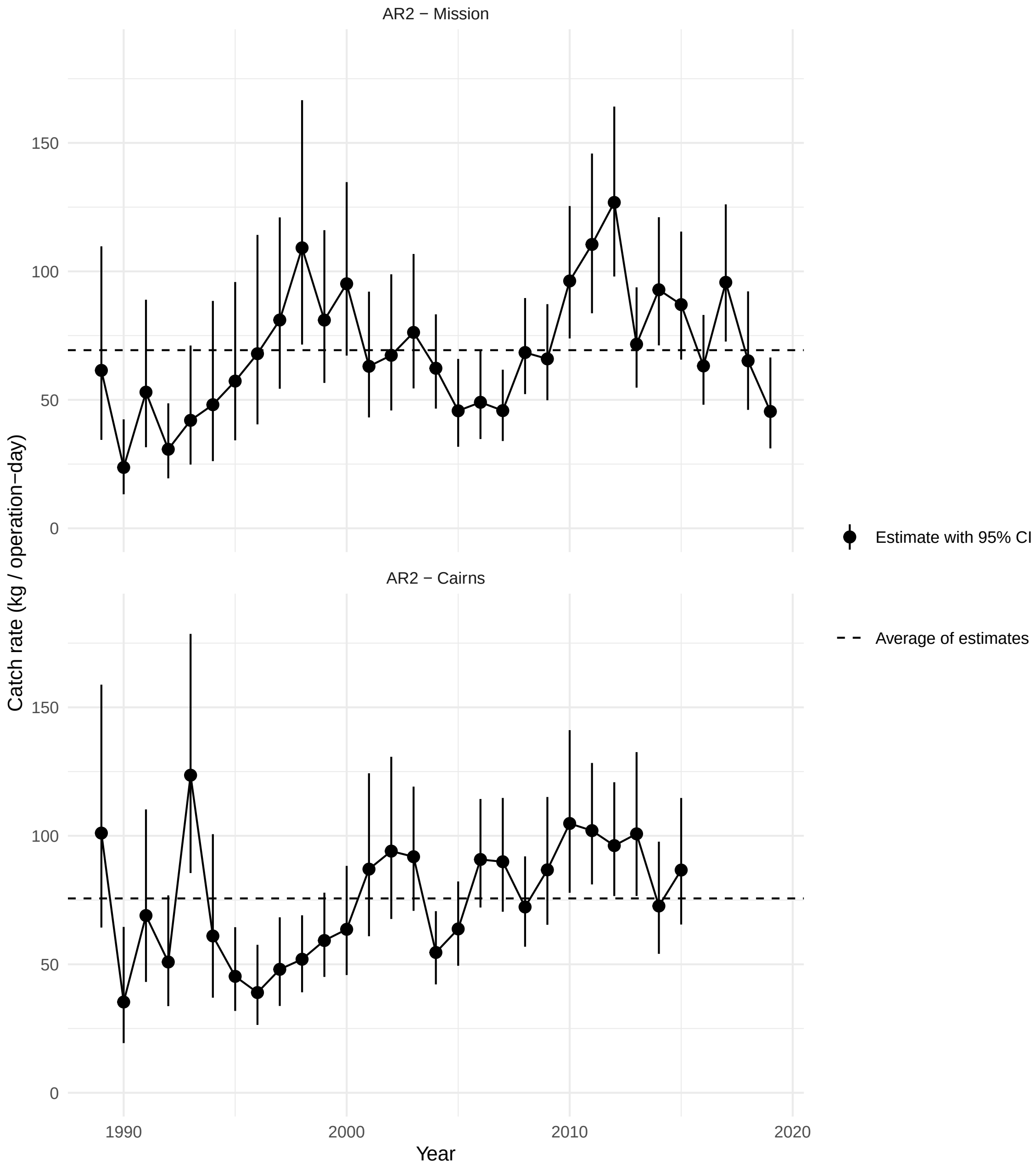

Figure 3.5: Annual standardised catch rates (95% confidence intervals) for king threadfin in AR2

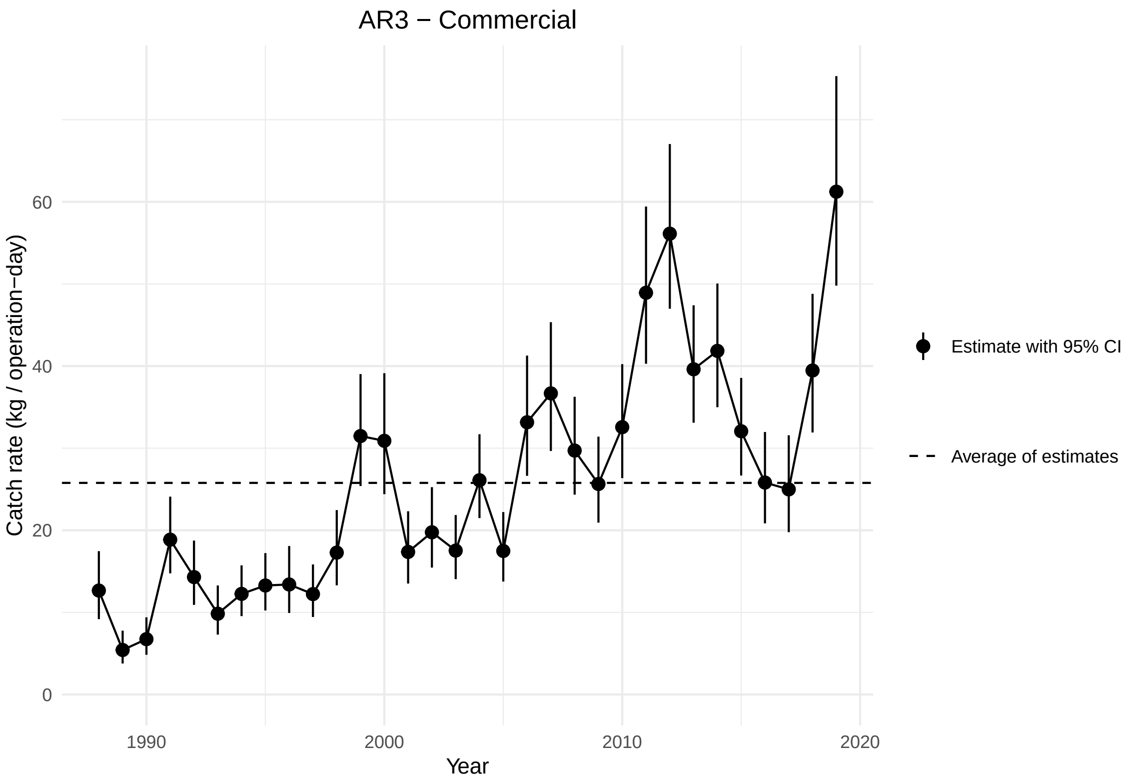

Figure 3.6: Annual standardised catch rates (95% confidence intervals) for king threadfin in AR3

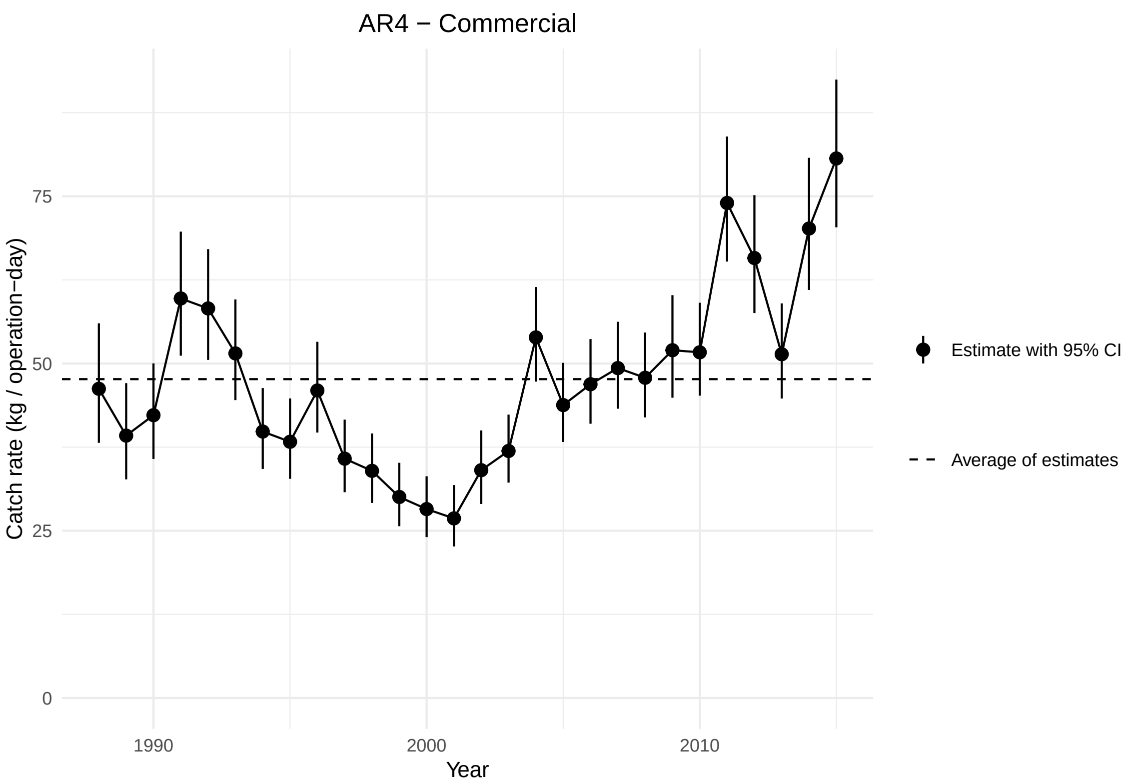

Figure 3.7: Annual standardised catch rates (95% confidence intervals) for king threadfin in AR4

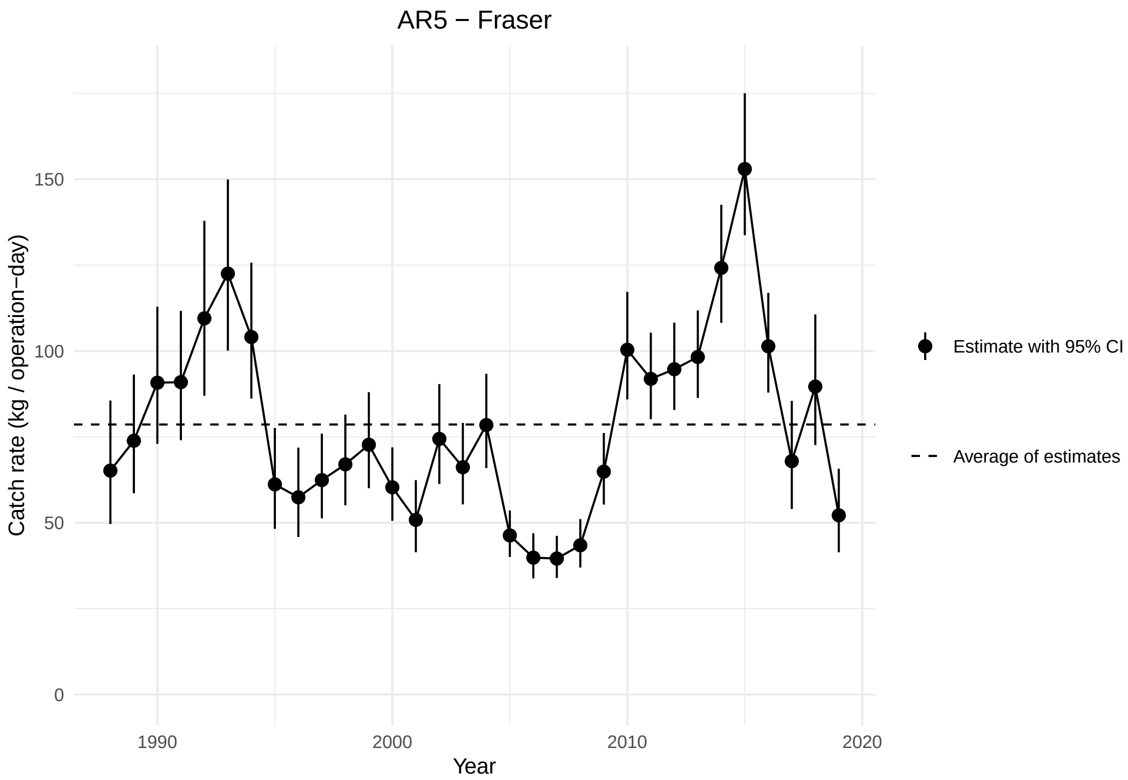

Figure 3.8: Annual standardised catch rates (95% confidence intervals) for king threadfin in AR5

3.1.3 Length composition

The length data input to the model are plotted in Figures 3.9–3.17. The length bins in the model ranged from 29.5 to 129.5 cm fork length. Fish below 29.5 cm FL were combined into the bottom bin, and fish above 129.5 cm were combined into the top bin.

In ARGulf the south includes both smaller and larger fish than the north. The model assumptions are that the larger fish of young age classes swim north and so become vulnerable to the northern fleet, but swim back again as they age, so that the northern fleet targets only the younger age classes. For these assumptions we caution that some northern commercial fishers' catches were not sampled, and the sampling in the north is less comprehensive than in the south.

In AR2 the fish from the Cairns Catch Rate Region are generally bigger than those from Mission. The model assumption is that Mission is a nursery area, from which many fish swim to Cairns as they grow bigger.

In AR4 the Fishery Monitoring samples from the commercial sector (2015–2019) do not have sufficient sample size for inclusion in the model, due to the Net Free Zone there. Fortunately, data from earlier research projects were available for this Assessment Region. AR4 is also the only Assessment Region in which sample sizes from the Boat Ramp Surveys were sufficient to define a recreational fleet.

Sample sizes for the length and age data are listed in Appendix A, Section A.3.

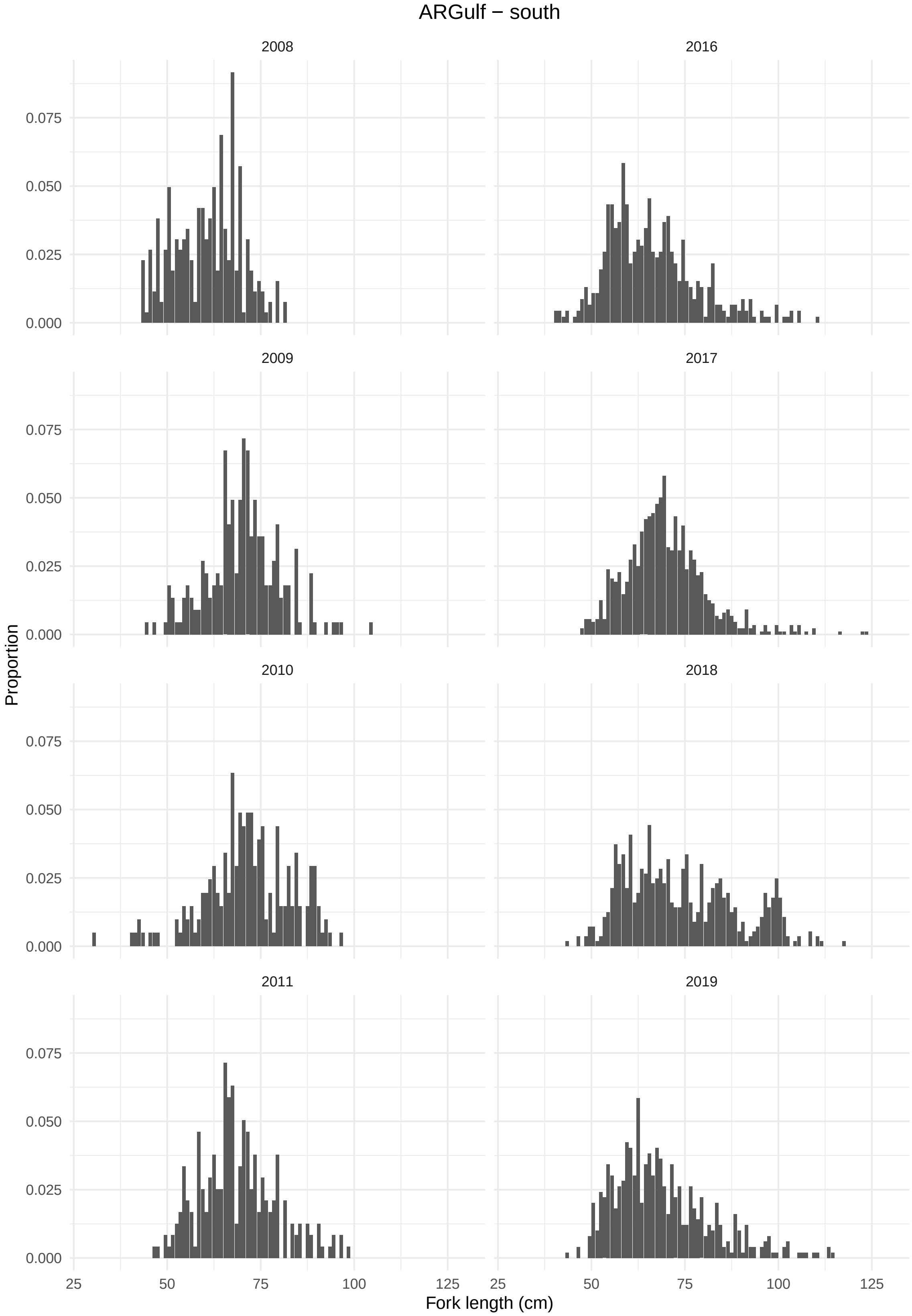

Figure 3.9: Annual length compositions of king threadfin in Gulf south

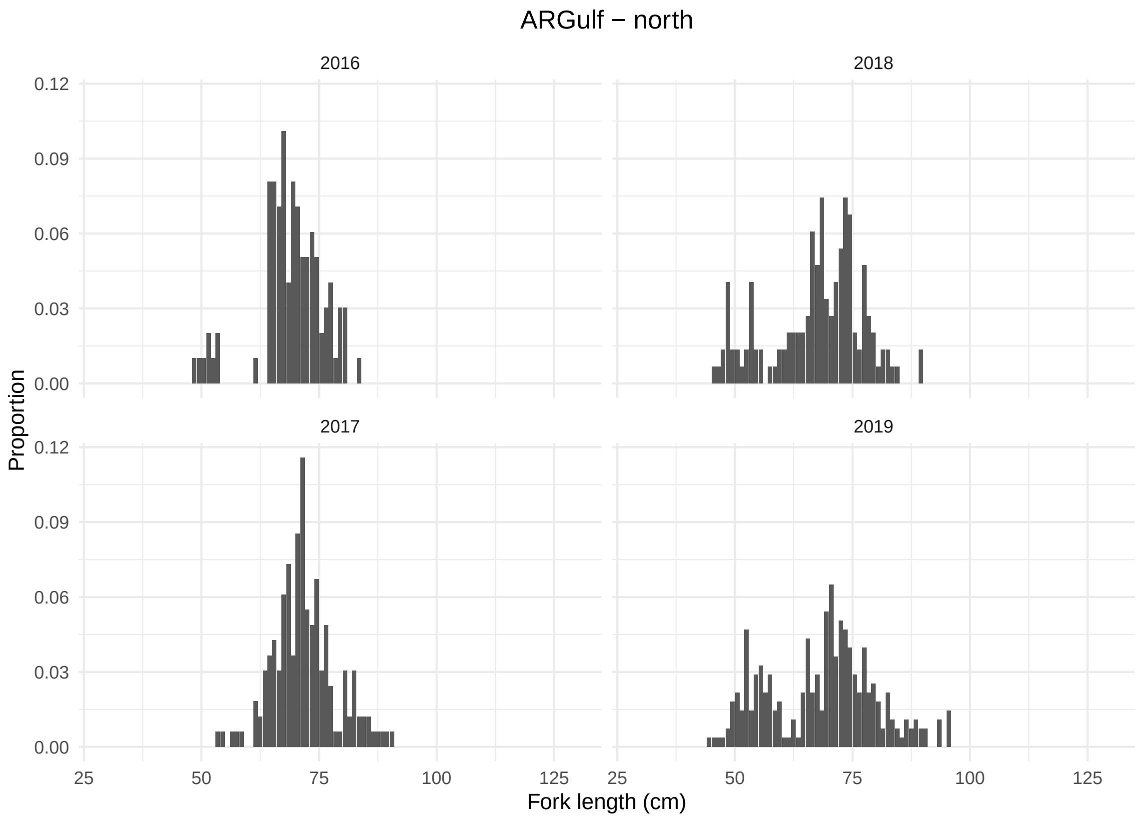

Figure 3.10: Annual length compositions of king threadfin in Gulf north

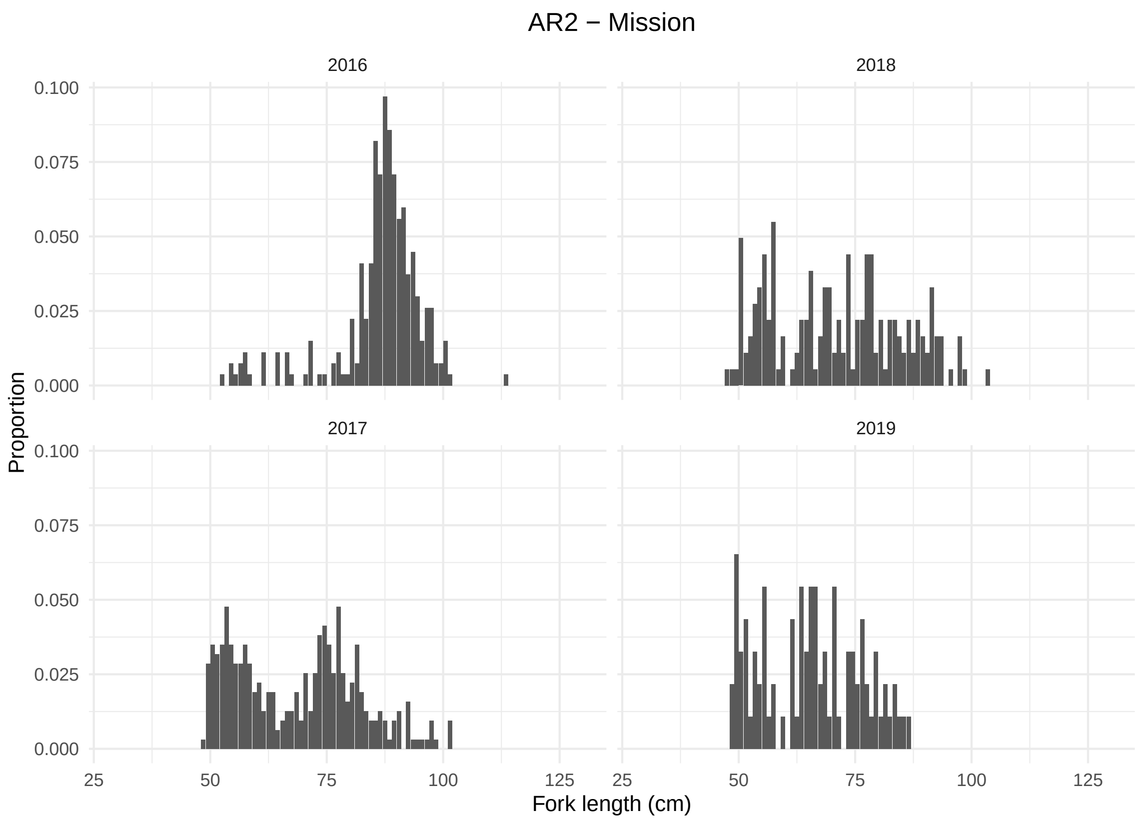

Figure 3.11: Annual length compositions of king threadfin in AR2 Mission

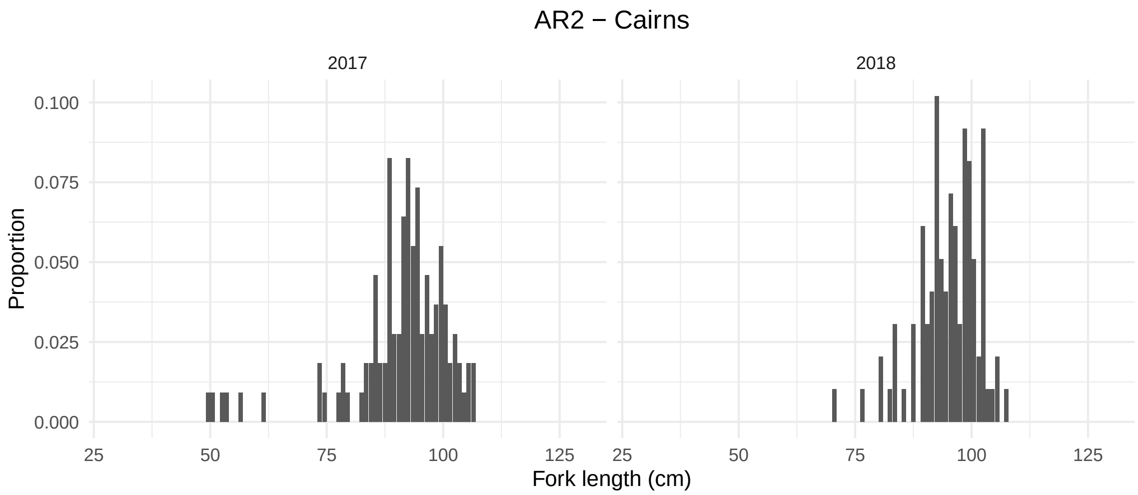

Figure 3.12: Annual length compositions of king threadfin in AR2 Cairns

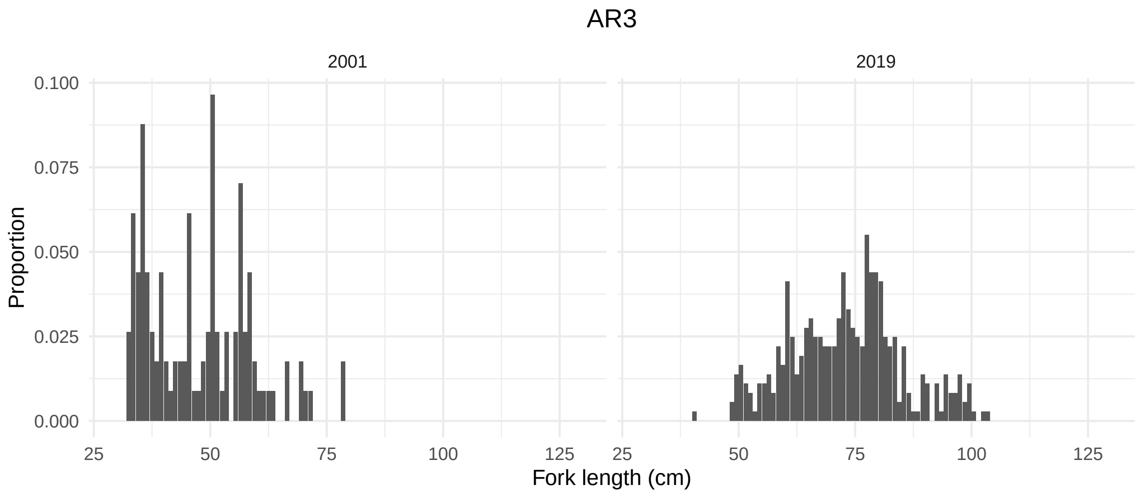

Figure 3.13: Annual length compositions of king threadfin in AR3

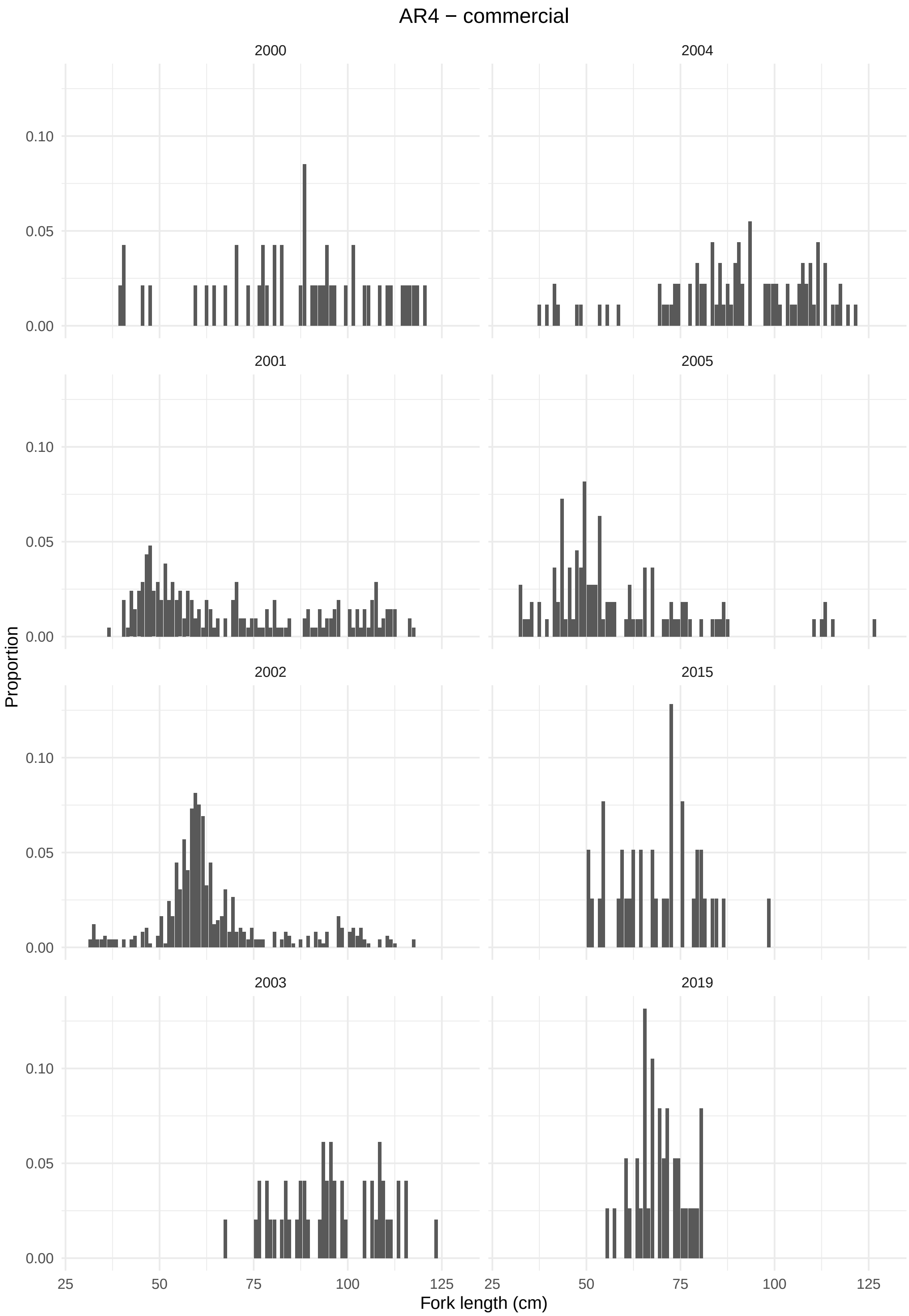

Figure 3.14: Annual length compositions of king threadfin in AR4, commercial

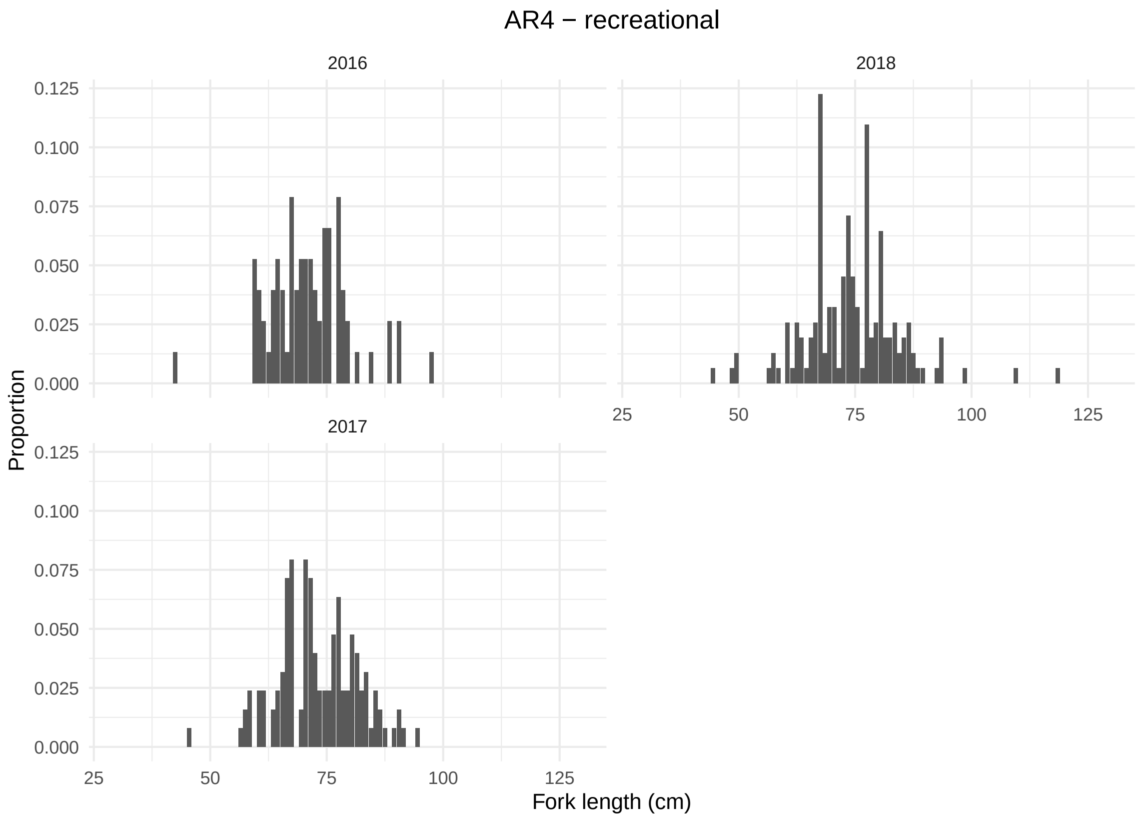

Figure 3.15: Annual length compositions of king threadfin in AR4, recreational

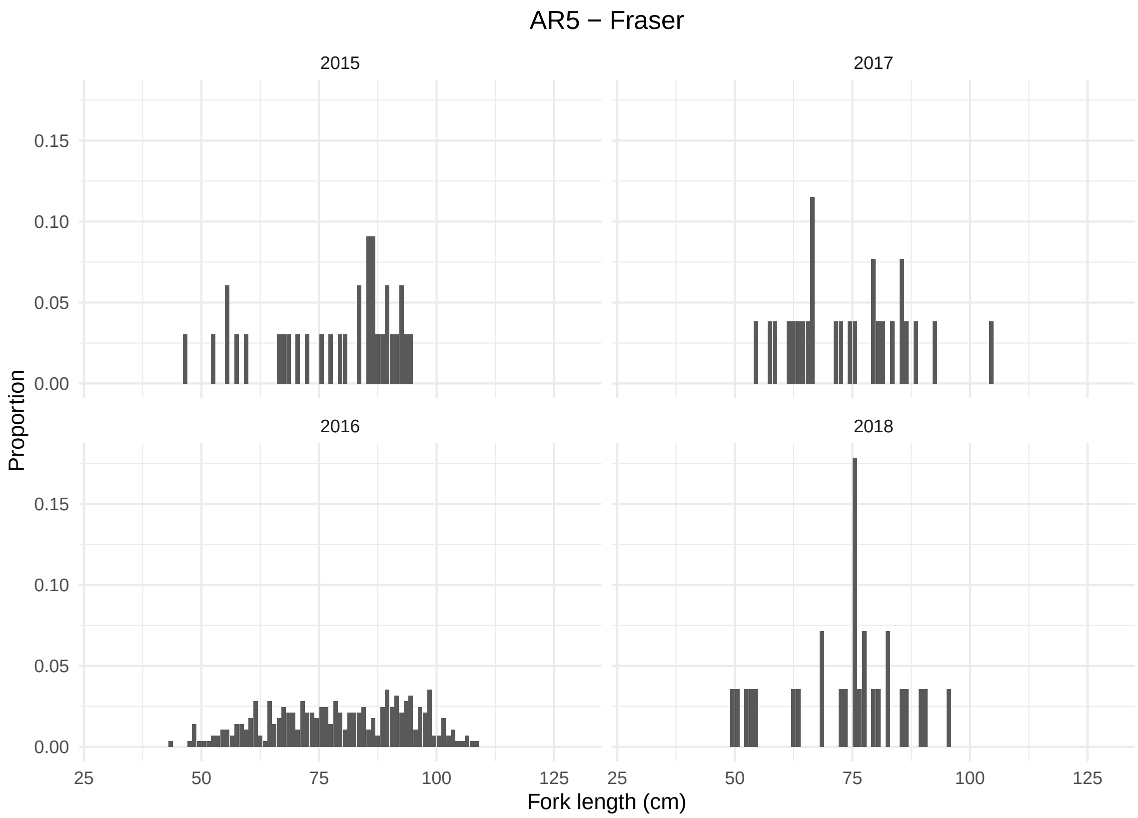

Figure 3.16: Annual length compositions of king threadfin in AR5 Fraser

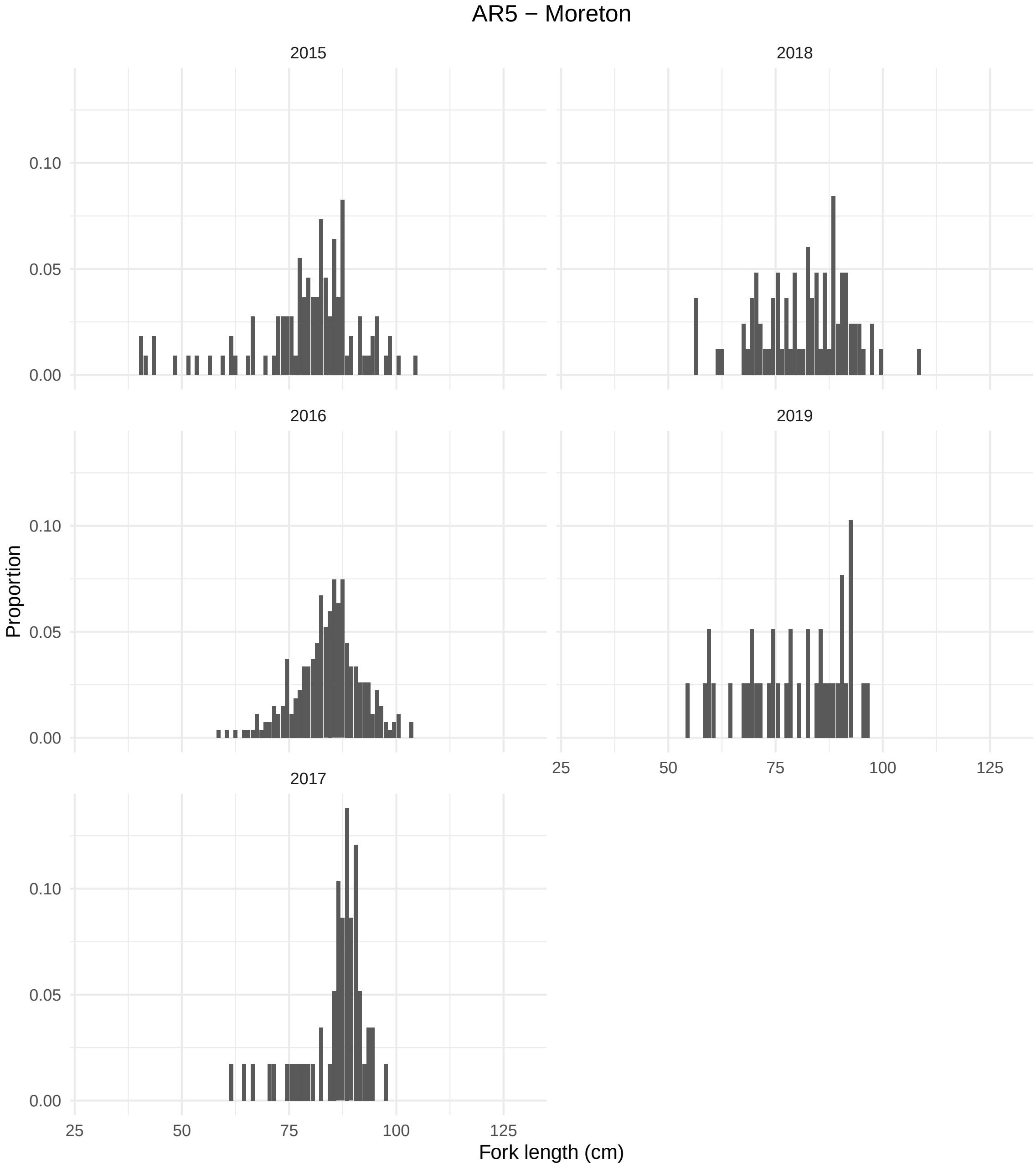

Figure 3.17: Annual length compositions of king threadfin in AR5 Moreton

3.1.4 Age composition

As noted in Section 2.5, the age data input to the population model were conditional age-at-length. The age data plotted here (Figures 3.18–3.23) are informational summaries to show the range of ages of the sampled fish; the data plotted were not entered directly into the model. The maximum age used in both the model and the plots was 8 in ARGulf, 11 in AR2, 10 in AR3, 16 in AR4, and 12 in AR5. Ages greater than these limits were combined into the bin with the greatest age, which became a “plus group”.

For AR2, AR4 and AR5, the data for both fleets were combined to increase the sample sizes. Because fishing selectivity in Assessment Regions other than ARGulf is assumed to be purely length-based, it makes no difference to which fleet age-at-length data are allocated, provided only that fish of those lengths are actually caught by that fleet. Sample sizes are provided in Appendix A, Table A.1.

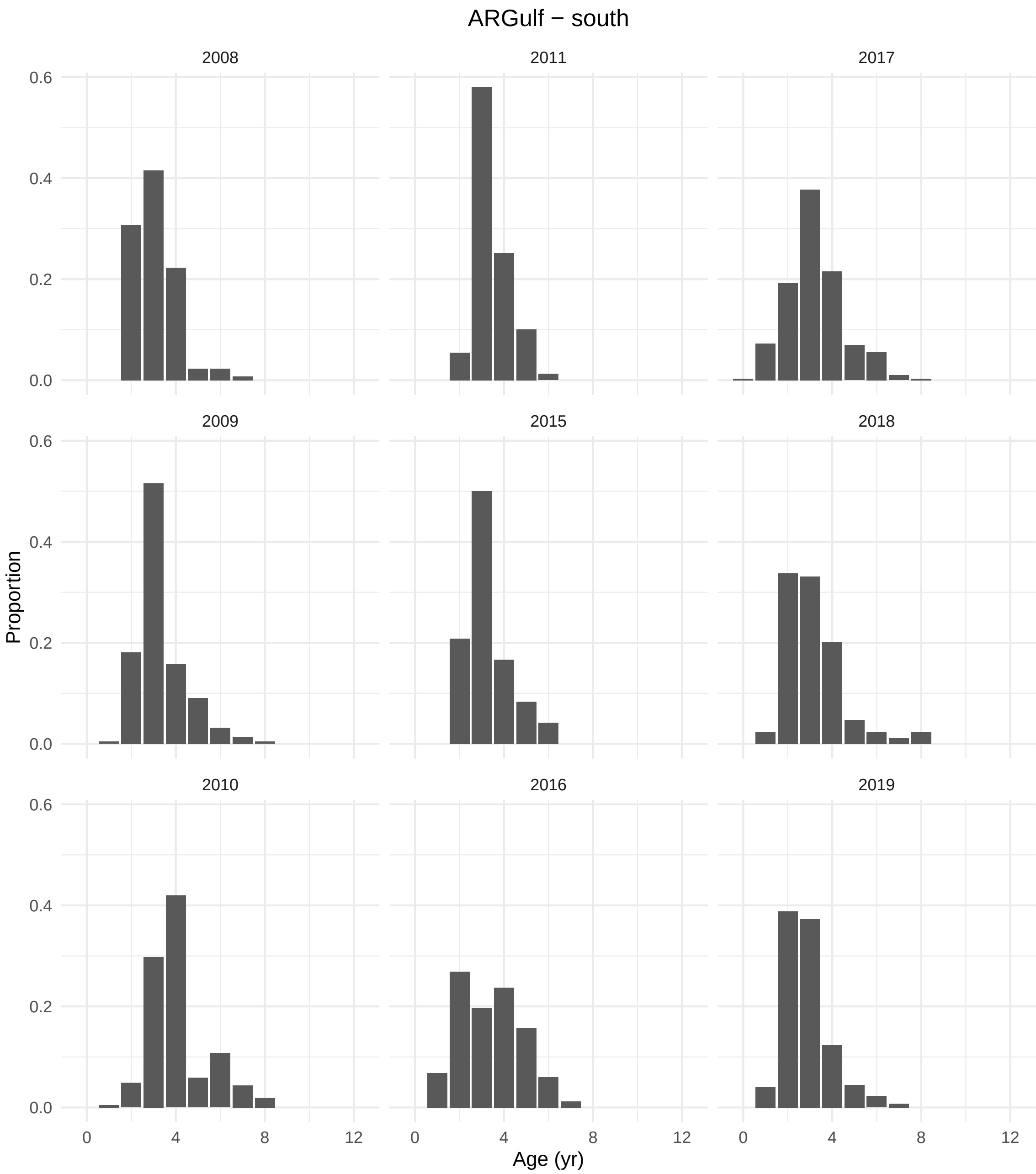

Figure 3.18: Annual age composition of king threadfin in ARGulf south

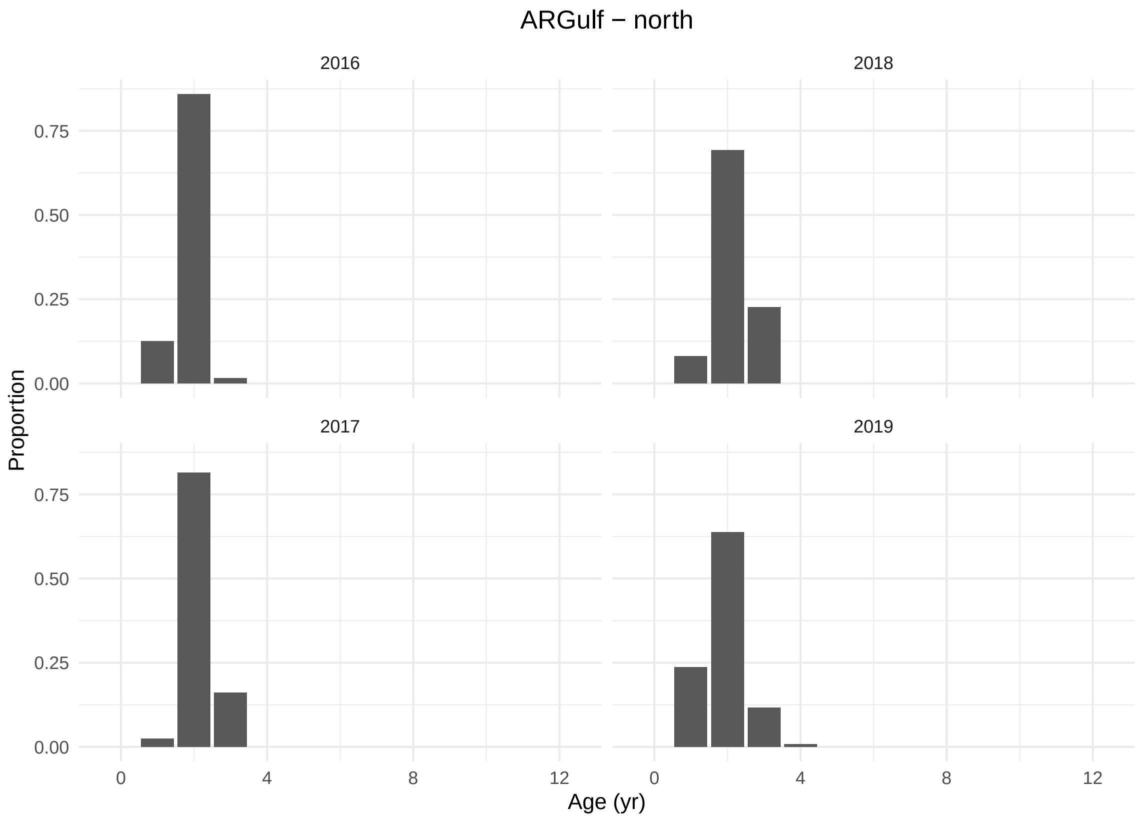

Figure 3.19: Annual age composition of king threadfin in ARGulf north

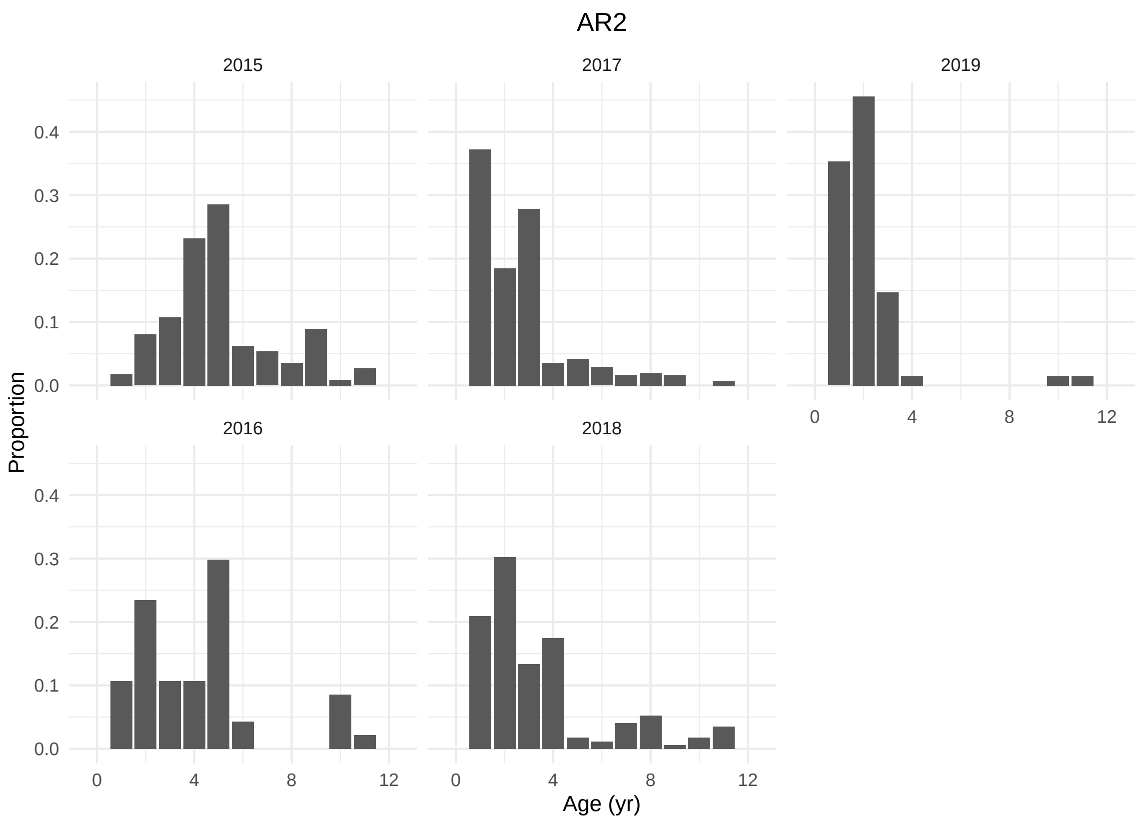

Figure 3.20: Annual age composition of king threadfin in AR2

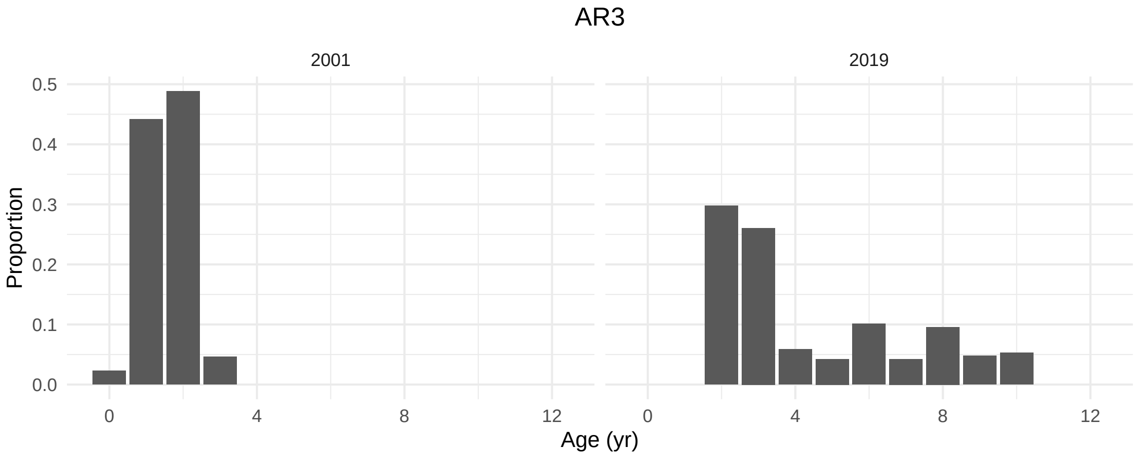

Figure 3.21: Annual age composition of king threadfin in AR3

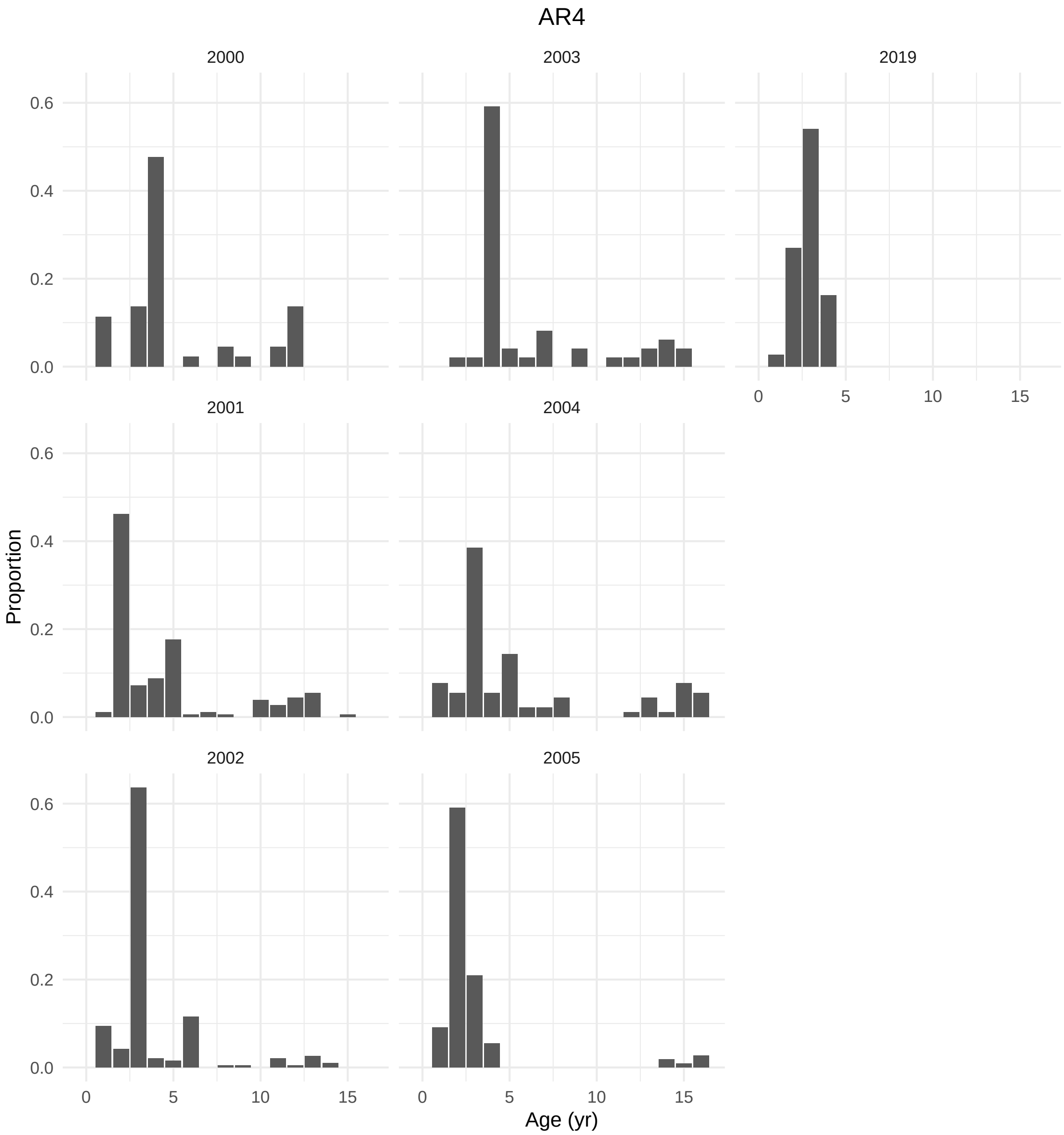

Figure 3.22: Annual age composition of king threadfin in AR4

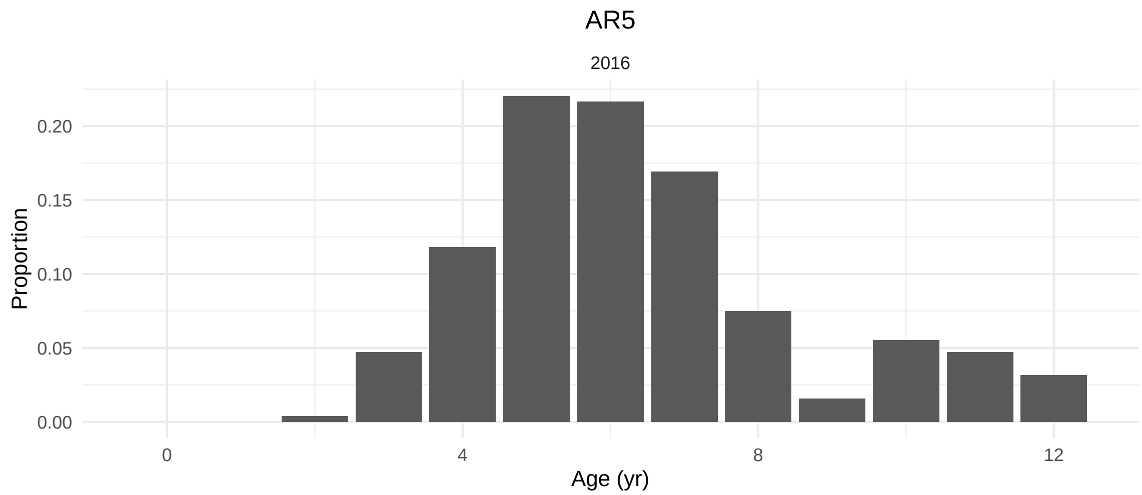

Figure 3.23: Annual age composition of king threadfin in AR5

3.1.5 Sensitivity and alternative scenarios

Alternative scenarios of the historical harvest size in ARGulf are plotted in Figure 3.24. The high scenario was calculated by projecting the 1981 harvest backwards, assuming an increased number of fishers and increased abundance due to the stock's not having been fished down so much. The low scenario assumes constant harvest from 1977 (the stated peak year in historical accounts) to 1981. The medium scenario is halfway in-between the high and low ones.

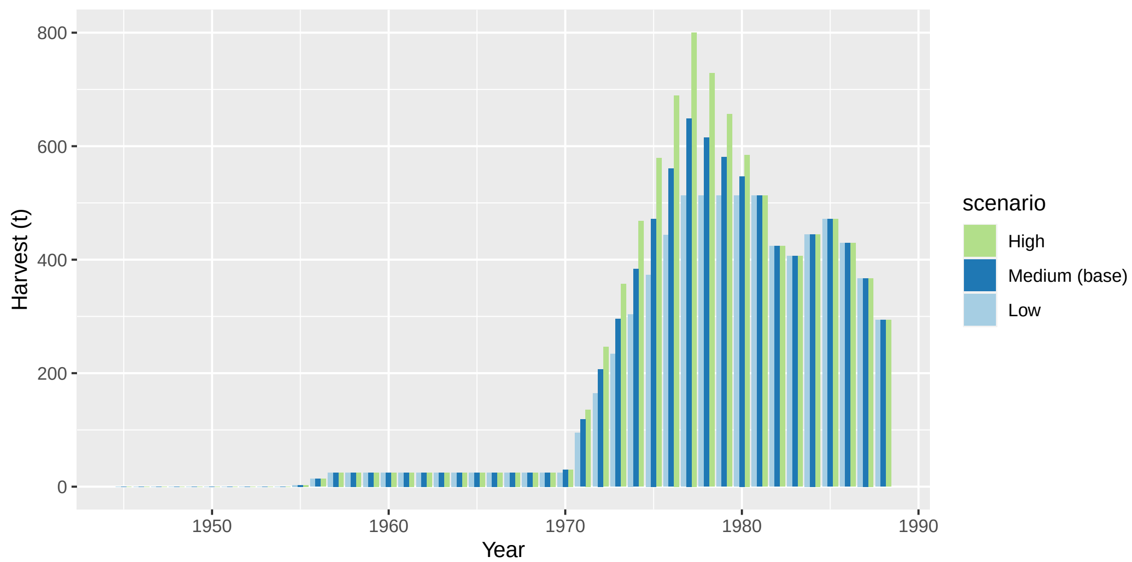

Figure 3.24: Historical harvest scenarios for ARGulf

3.2 Model outputs

3.2.1 Model parameters

Parameters were estimated separately for each Assessment Region (Tables 3.1–3.5). In ARGulf, because there were two q_{inc} parameters (one for each fleet), the instantaneous natural mortality rate M was fixed and the q_{inc} parameters were estimated. In the East Coast Regions, each of which had only one q_{inc} parameter, we saw it as more logical to fix q_{inc} and estimate M.

We emphasise that our selection of q_{inc} values was made scientifically, based on the requirement to have similar values of the natural mortality rate M across all of the Assessment Regions.

The steepness h was also fixed in all Regions, because estimates converged to a greater value than that when we allowed the model to estimate it. Such high values imply that recruitment depends very little on spawning stock size, which is not biologically reasonable or precautionary: very heavy fishing would not affect the number of recruits that come in to the population in a particular year.

Other parameters were fixed when model estimates of them were not sensible. Examples are the standard deviation σ_R of the log recruitment deviations for the East Coast Regions (estimates were very high, above 0.4), some of the $L_{95\text{ width}}$ parameters (estimates hit the lower bound of 2 cm), and the growth parameters in AR5.

The standard error of the $\ln R_0$ parameter in ARGulf (Table 3.1) is low at 0.03, which may lead to a question of whether the uncertainty in it has been adequately accounted for. The biomass ratio B/B_0 from the 1990s to present, however, does show a high amount of uncertainty (see Figure 3.27 below, and Table B.7 in Appendix B), with the high and low estimates differing by a factor of about three. Therefore we believe that the uncertainty has been adequately sampled and the estimate of $\ln R_0$ is mainly due to the harvest size history and the model's need to maintain a positive biomass in all years.

Table 3.1: Summary of parameter estimates for king threadfin

Symbol	Description	Value	S.E.
M	Instantaneous natural mortality rate (yr^{-1})	0.325	Fixed
L_{min}	Mean length of fish at minimum age (cm FL)	37.55	1.59
L_{max}	Mean length of fish at maximum age (cm FL)	82.15	Fixed
K	Von Bertalanffy growth coefficient (yr^{-1})	0.2723	0.0626
SD_{young}	Standard deviation of length at minimum age (cm FL)	9.04	0.7
SD_{old}	Standard deviation of length at maximum age (cm FL)	19.56	2.95
$\ln R_0$	Log of number of recruits when unfished	13.0712	0.0302
h	Steepness	0.75	Fixed
σ_R	Standard deviation of log recruitment deviations	0.3486	0.0636
$\ln q_1$	Log of catchability (south)	-7.3423	0.2151
$\ln q_2$	Log of catchability (north)	-6.6082	0.289
$q_{\text{inc }1}$	Annual increase in $\ln q$ (south) (yr^{-1})	0.02913	0.0097
$q_{\text{inc }2}$	Annual increase in $\ln q$ (north) (yr^{-1})	0.0499	0.00649
$L_{50\ 1}$	Length at 50% selectivity (south) (cm FL)	61.08	1.97
$L_{95\text{ width }1}$	Difference in lengths at 50% and 95% selectivity (south) (cm)	12.75	2.45
$L_{50\ 2}$	Length at 50% selectivity (north) (cm FL)	70.96	3.29
$L_{95\text{ width }2}$	Difference in lengths at 50% and 95% selectivity (north) (cm)	16.03	3.01

Table 3.2: Summary of parameter estimates for king threadfin in AR2

Symbol	Description	Value	S.E.
M	Instantaneous natural mortality rate (yr^{-1})	0.3106	0.0677
L_{min}	Mean length of fish at minimum age (cm FL)	49.58	1.35
L_{max}	Mean length of fish at maximum age (cm FL)	102.17	1.6
K	Von Bertalanffy growth coefficient (yr^{-1})	0.5086	0.0419
SD_{young}	Standard deviation of length at minimum age (cm FL)	7.28	0.58
SD_{old}	Standard deviation of length at maximum age (cm FL)	5.46	0.57
$\ln R_0$	Log of number of recruits when unfished	10.9441	0.7629
h	Steepness	0.75	Fixed
σ_R	Standard deviation of log recruitment deviations	0.3	Fixed
$\ln q_1$	Log of catchability (Mission)	-8.5655	0.5787
$\ln q_2$	Log of catchability (Cairns)	-7.9161	0.6117
q_{inc}	Annual increase in $\ln q$ (yr^{-1})	0.035	Fixed
$L_{50\ 1}$	Length at 50% selectivity (Mission) (cm FL)	49.42	2.86
$L_{95\text{ width }1}$	Difference in lengths at 50% and 95% sel. (Mission) (cm)	2	Fixed
$L_{50\ 2}$	Length at 50% selectivity (Cairns) (cm FL)	86.66	7.9
$L_{95\text{ width }2}$	Difference in lengths at 50% and 95% selectivity (Cairns) (cm)	19.57	9.15

Table 3.3: Summary of parameter estimates for king threadfin in AR3

Symbol	Description	Value	S.E.
M	Instantaneous natural mortality rate (yr^{-1})	0.2956	0.1103
L_{min}	Mean length of fish at minimum age (cm FL)	36.21	1.44
L_{max}	Mean length of fish at maximum age (cm FL)	83.76	3.01
K	Von Bertalanffy growth coefficient (yr^{-1})	0.6287	0.0948
SD_{young}	Standard deviation of length at minimum age (cm FL)	3.26	0.79
SD_{old}	Standard deviation of length at maximum age (cm FL)	6.37	0.95
$\ln R_0$	Log of number of recruits when unfished	12.2853	1.6371
h	Steepness	0.75	Fixed
σ_R	Standard deviation of log recruitment deviations	0.3	Fixed
$\ln q$	Log of catchability	-10.1402	1.3886
q_{inc}	Annual increase in $\ln q$ (yr^{-1})	0.0625	Fixed
L_{50}	Length at 50% selectivity (cm FL)	32.23	6.31
$L_{95\text{ width}}$	Difference in lengths at 50% and 95% selectivity (cm)	2	Fixed

Table 3.4: Summary of parameter estimates for king threadfin in AR4

Symbol	Description	Value	S.E.
M	Instantaneous natural mortality rate (yr^{-1})	0.3191	0.0316
L_{min}	Mean length of fish at minimum age (cm FL)	29.95	1.89
L_{max}	Mean length of fish at maximum age (cm FL)	109.64	1.94
K	Von Bertalanffy growth coefficient (yr^{-1})	0.3156	0.0188
SD_{young}	Standard deviation of length at minimum age (cm FL)	9.64	1.17
SD_{old}	Standard deviation of length at maximum age (cm FL)	8.24	1.2
$\ln R_0$	Log of number of recruits when unfished	11.0263	0.2131
h	Steepness	0.75	Fixed
σ_R	Standard deviation of log recruitment deviations	0.3	Fixed
$\ln q$	Log of catchability (commercial)	-8.1082	0.1812
q_{inc}	Annual increase in $\ln q$ (commercial) (yr^{-1})	0.035	Fixed
$L_{50\ 1}$	Length at 50% selectivity (commercial) (cm FL)	49	2.96
$L_{95\ \text{width}\ 1}$	Difference in lengths at 50% and 95% sel. (commercial) (cm)	12.63	3.71
$L_{50\ 2}$	Length at 50% selectivity (recreational) (cm FL)	60.98	1.17
$L_{95\ \text{width}\ 2}$	Difference in lengths at 50% and 95% sel. (recreational) (cm)	7.23	1.49

Table 3.5: Summary of parameter estimates for king threadfin in AR5

Symbol	Description	Value	S.E.
M	Instantaneous natural mortality rate (yr^{-1})	0.2952	0.0424
L_{min}	Mean length of fish at minimum age (cm FL)	38.86	Fixed
L_{max}	Mean length of fish at maximum age (cm FL)	101.91	Fixed
K	Von Bertalanffy growth coefficient (yr^{-1})	0.2145	Fixed
SD_{young}	Standard deviation of length at minimum age (cm FL)	8.98	Fixed
SD_{old}	Standard deviation of length at maximum age (cm FL)	8.98	Fixed
$\ln R_0$	Log of number of recruits when unfished	11.1436	0.7218
h	Steepness	0.75	Fixed
σ_R	Standard deviation of log recruitment deviations	0.3	Fixed
$\ln q$	Log of catchability (Fraser)	-8.4462	0.5824
q_{inc}	Annual increase in $\ln q$ (yr^{-1}) (Fraser)	0.020	Fixed
$L_{50\ 1}$	Length at 50% selectivity (Fraser) (cm FL)	53.6	3.51
$L_{95\ \text{width}\ 1}$	Difference in lengths at 50% and 95% sel. (Fraser) (cm)	14.12	9.21
$L_{50\ 2}$	Length at 50% selectivity (Moreton) (cm FL)	71.62	1.66
$L_{95\ \text{width}\ 2}$	Difference in lengths at 50% and 95% sel. (Moreton) (cm)	14.95	1.89

3.2.2 Growth curves

Von Bertalanffy growth curves, including parameters for the standard deviation about the mean length for both old and young fish, were estimated within the model in AR2, AR3 and AR4, and outside the model in ARGulf and AR5 (Tables 3.2–3.4, Figure 3.25). In ARGulf and AR5 we were unable to obtain sensible results when we attempted to estimate the growth curve inside the model.

The results show a high level of variation between Assessment Regions. The L_{max} asymptotic length estimate is above 100 cm fork length in AR2, AR4 (the highest at 110 cm FL) and AR5, but much smaller in ARGulf and AR3, at 69 cm and 84 cm FL respectively. The ARGulf estimate is subject to some uncertainty because the estimated fishing mortality there is high. The AR3 estimate does appear to indicate that king threadfin from this Assessment Region are smaller than in other Regions, and that this Region must constitute a separate stock. There is also a high level of variation in the lengths of individual fish at a given age, especially in ARGulf.

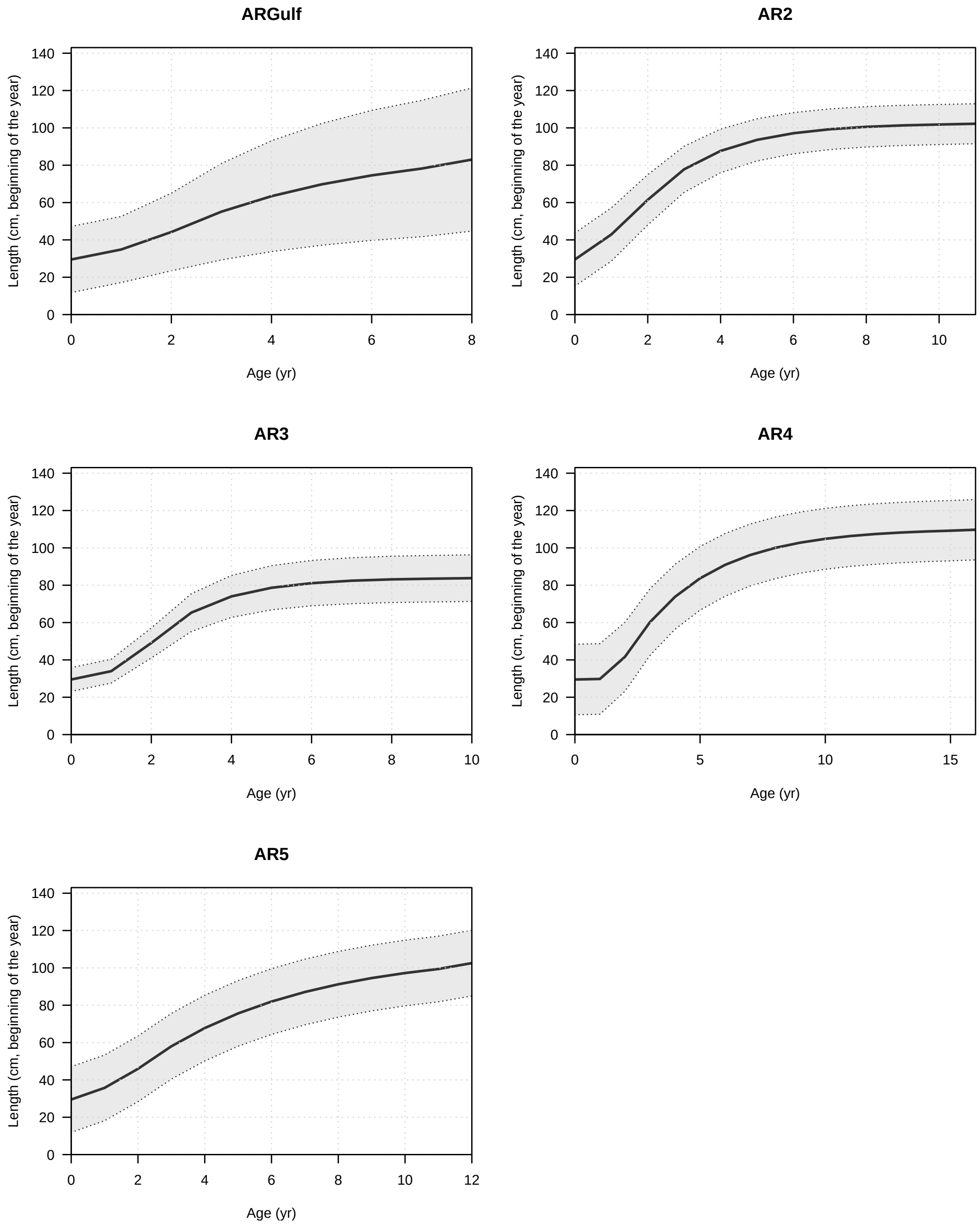

Figure 3.25: Estimated growth of king threadfin (95% confidence intervals) for each region

3.2.3 Selectivity

Parameters for length-based selectivity to fishing were estimated within the model (Tables 3.1–3.5, Figure 3.26). From a modelling viewpoint the selectivity functions represent the relative proportion of king threadfin of a given length that can be caught by the fishing gear deployed by a fleet (ranging from zero to 100%), but in practice they also reflect availability of fish of different lengths to fleets that operate in different locations. For example, in AR5 the Fraser fleet catches smaller fish than the Moreton fleet; this may happen because the Fraser Inshore Catch Rate Region is a nursery area with a high proportion of small fish, or because fishers in the Moreton Bay Catch Rate Region do not have access to the rivers where smaller king threadfin may live. We do not infer any major difference in fishing gear between the two fleets.

In AR4 there is a clear difference in selectivity parameters between the commercial and recreational fleets, which probably is indeed due to the different fishing methods used: line fishing appears to catch bigger fish than gillnetting does.

For AR3 and the Mission fleet of AR2, the estimation of the selectivity function was confounded by the minimum legal size. Because the sampling of fish was fishery dependent, fish below the minimum legal size were rarely observed, even though they may have been caught. The model is unable to tell whether the L_{50} parameter (the length at which 50% of king threadfin are vulnerable to gillnetting) is approximately equal to the MLS, or substantially less than it. This uncertainty makes relatively little difference to the results of the assessment. The major effect is on the number of fish that are not retained due to being under the MLS. In the other region–fleet combinations, the L_{50} estimate was greater than the MLS and confounding was not apparent.

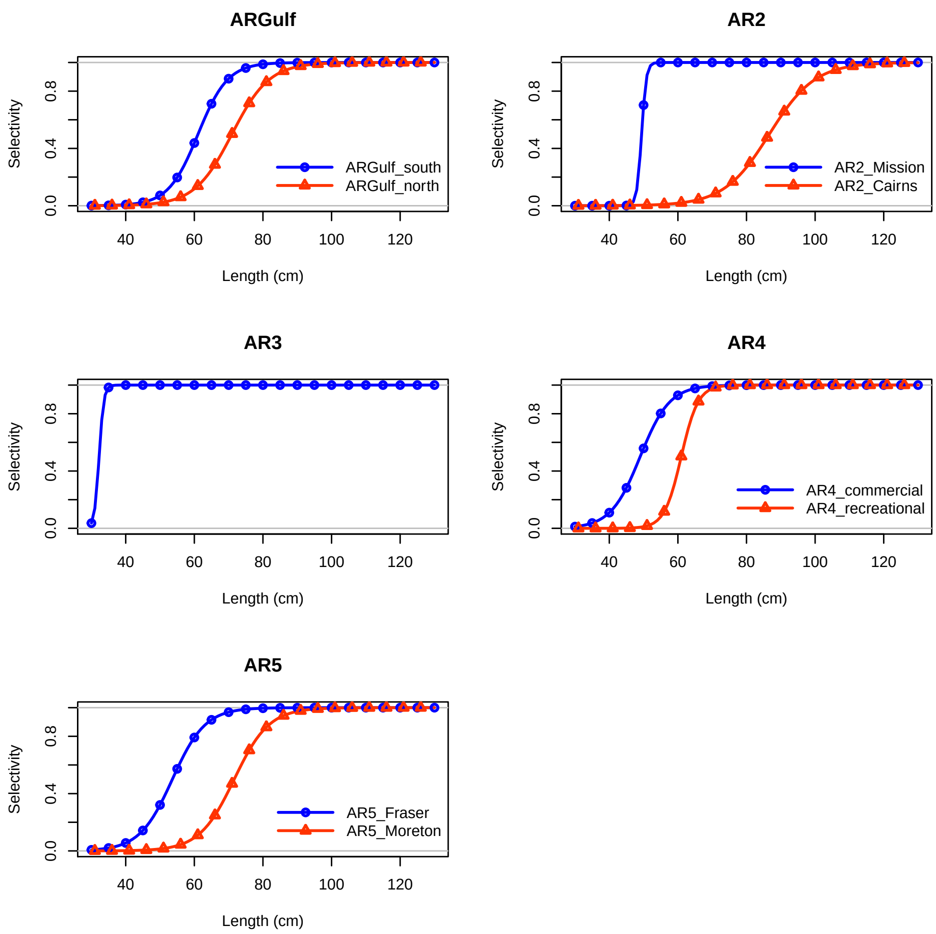

Figure 3.26: Model estimated length-based selectivity by fleet in 2019 for each region

3.2.4 Biomass and equilibrium yield

Time series of estimated spawning biomass ratio, relative to the unfished state, are shown in Figure 3.27. AR2, AR3 and AR5 appear to have been above the target reference point B_{60} (60% of unfished spawning biomass) for most of their history.

AR4 is estimated at currently about B_{60} but, according to the model, it was approaching the limit reference point B_{20} before the Net Free Zone was introduced in late 2015. The Net Free Zone may have had a major beneficial effect, although the results for this Region are uncertain due to a lack of recent Fishery Monitoring data and lack of clarity over whether historical harvests were large enough to reduce the population to B_{20}. The results are supported by the standardised Boat Ramp Survey catch rates for AR4, which show a steep increase from 2015–16 to 2017–18 (Figure D.1, section D.2, Appendix D).

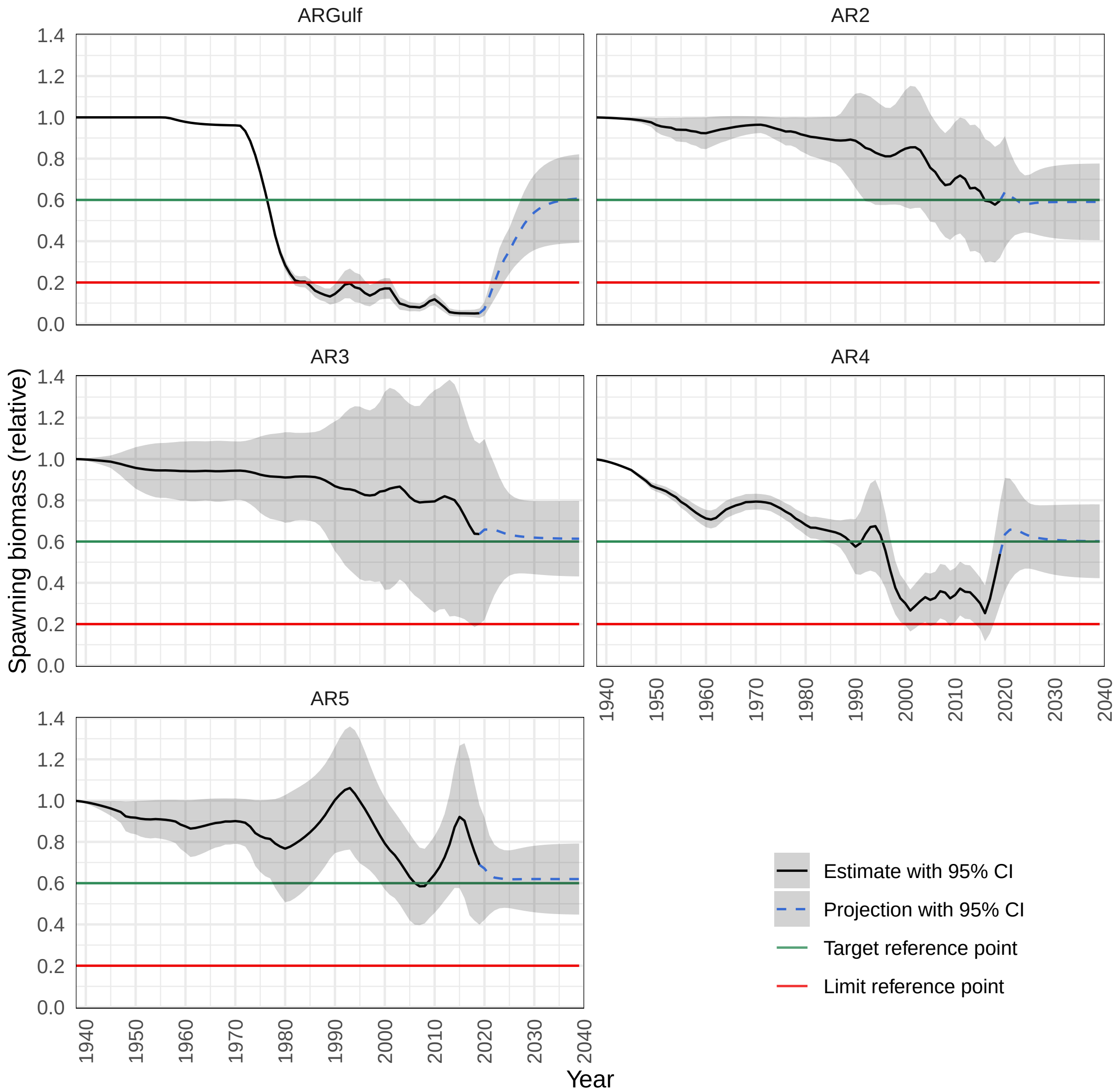

Figure 3.27: Estimated spawning biomass trajectory relative to unfished, from 1940 to 2040, for king threadfin in each region

The ARGulf stock is estimated as currently at 5% of spawning biomass, with the major depletion occurring in the 1970s. In recent years the harvest has fallen (Figure 3.3) but catch rates in the southern Gulf, where the majority of the ARGulf harvest is taken, have shown little sign of increasing (Figure 3.4) even though catchability is assumed to have increased.

In addition to the population model results, evidence for substantial disturbance to the biology of king threadfin in ARGulf comes from

- the reduced lifespan there compared to the East Coast: age 9 in ARGulf, versus age 19 on the East Coast
- the reduced age of sex change in ARGulf: combining ages 1, 2 and 3, 36.3% of king threadfin in ARGulf were female, versus only 14.5% in AR2 (the only other region with a substantial number of fish sexed)
- the very small proportion of female fish observed in northern ARGulf, indicating that little breeding occurs there.

We note that the sampling in the north of ARGulf was less extensive than in the south, with only a few fishers' catches sampled, but the bias was generally towards fish caught further offshore, which should have been larger and should have had an increased chance of being female had there been many female fish in the north.

Upper confidence limits above 100% (B_{100}) in AR2, AR3 and AR5 in some years come from the model's random recruitment deviations, whereby a period of high recruitment can push the biomass above 100%.

Model estimates of annual maximum sustainable yield (MSY) were 355 t in ARGulf, 65 t in AR2, 125 t in AR3, 47 t in AR4 and 50 t in AR5 (Figure 3.28). These equilibrium yields could be taken at spawning biomass ratios (% of unfished) between 25% and 27%. These ratios are much less than the target of 60% of unfished biomass (B_{60}) specified by the Sustainable Fisheries Strategy.

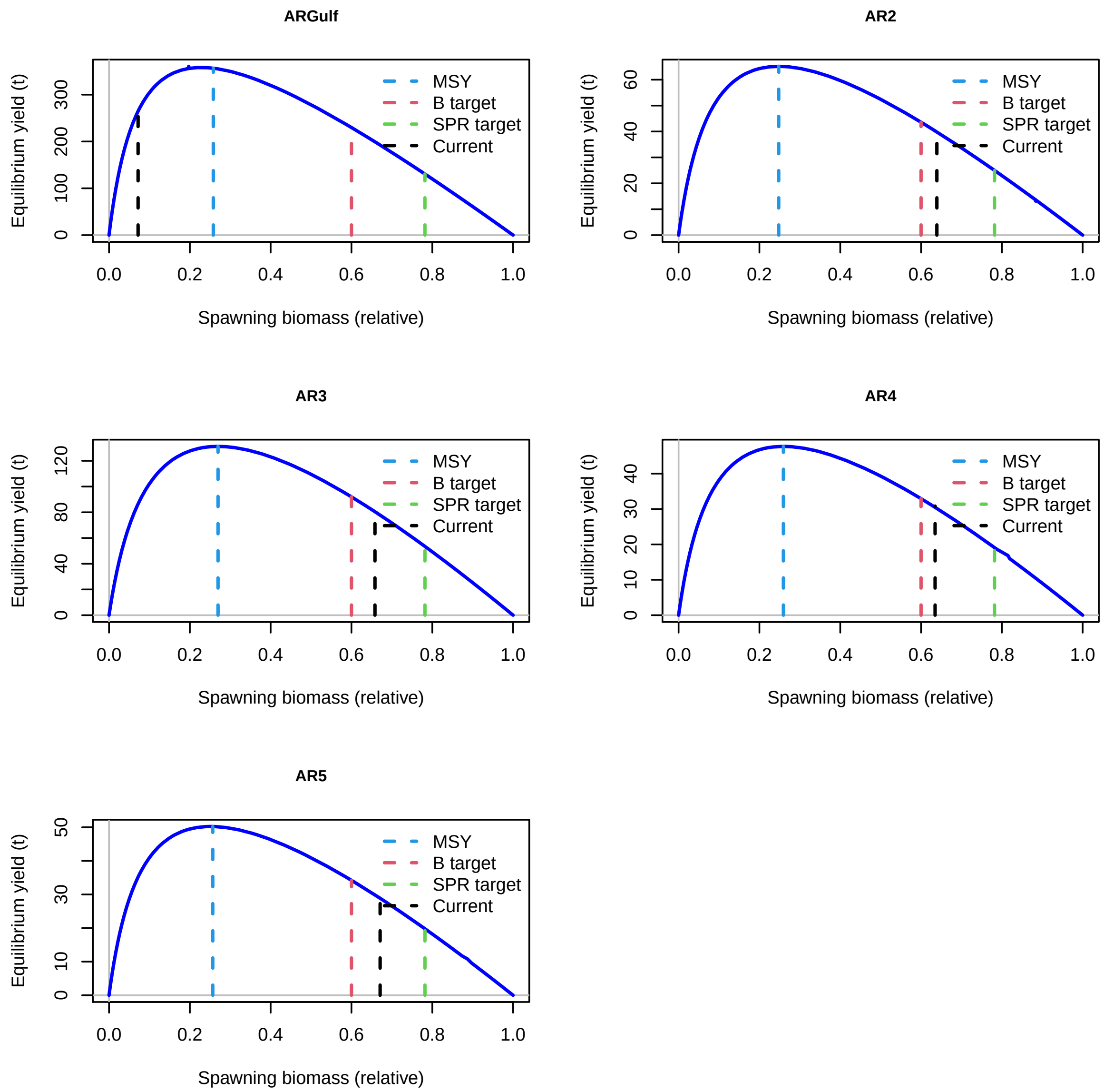

Figure 3.28: Equilibrium yield curve for king threadfin in each region

3.2.5 Harvest targets

Recommended biological harvests to move the stocks to the desired level B_{60} are shown in Table 3.6. The only Assessment Region in which the recommended harvests are less than current harvests is ARGulf. There, annual harvests in the last few years have been between 150 t and 250 t. Because the current biomass is less than B_{20}, the recommended limit is zero for the first three years of rebuilding, gradually rising to 124 t in the eighth year of rebuilding and 220 t in the fourteenth year.

Table 3.6: Estimated total harvests and relative biomass levels of king threadfin
Future recruitment is assumed to be deterministic, with no random recruitment deviations.

Region	Year	Harvest (t)	Biomass ratio
ARGulf	2020	0	0.07
	2021	0	0.13
	2022	0	0.2
	2023	40	0.26
	2024	71	0.31
	2025	97	0.35
	2026	124	0.4
	2027	147	0.44
AR2	2020	45	0.64
	2021	44	0.62
	2022	43	0.6
	2023	43	0.59
	2024	43	0.58
	2025	43	0.58
	2026	43	0.59
	2027	43	0.59
AR3	2020	91	0.66
	2021	90	0.66
	2022	89	0.66
	2023	88	0.65
	2024	87	0.64
	2025	87	0.63
	2026	86	0.63
	2027	86	0.63
AR4	2020	35	0.63
	2021	35	0.66
	2022	34	0.66
	2023	34	0.65
	2024	34	0.64
	2025	33	0.63
	2026	33	0.62
	2027	33	0.62
AR5	2020	34	0.67
	2021	34	0.64
	2022	33	0.63
	2023	33	0.62
	2024	33	0.62
	2025	33	0.62
	2026	33	0.62
	2027	33	0.62

Model results indicate that AR4 would also have required rebuilding if the Net Free Zone had not been introduced in 2015. With the Net Free Zone in place, no further management action is required at present.

The harvest limit for AR3 is uncertain. The indicated sustainable, equilibrium annual harvest is 89 t, which is higher than any historical harvest. The model estimates that this Assessment Region has never gone below B_{60}. We have no reason to doubt that result, but it implies lack of contrast in the data and consequent uncertainty in the level of sustainable harvest. This Region does not draw nutrients from drainage basins reaching far inland, such as the Fitzroy and Normanby River basins (see Figure 1.1). It does, however, contain many muddy bays which constitute suitable habitat for king threadfin, and it has a high tidal range with strong tidal currents which may circulate nutrients effectively and make the region productive.

3.2.6 Model fits

Plots of fit for the model to abundance indices, length compositions and conditional age-at-length are provided in Appendix B, Section B.2. The fits to abundance indices are shown for the original indices input to the model, without correction for increasing catchability: they represent the catch-rate index rather than the estimated abundance. As noted in Section 2.7.1, fits to abundance indices were achieved by means of recruitment deviations, whereas in reality these indices would be driven more by environmental effects such as floods and droughts on catchability, natural mortality and growth rates.

3.2.7 Sensitivity

Sensitivity results (Tables 3.7–3.11) indicate that, in general, the model results are not greatly sensitive to the parameter values that were fixed. A higher value of the q_{inc} parameter produces a greater effect of fishing, and hence a lower biomass ratio. For our base cases we avoided q_{inc} settings that produced very high biomass, on which fishing had hardly any effect. Some of these cases are presented in the tables, such as $q_{\text{inc}} = 0.02$ yr^{-1} in Table 3.8.

Lower steepness values generally produce higher biomass ratios but only because such steepness values mean that the population is more sensitive to fishing and will not recover as quickly in response to management action.

Table 3.7: Summary of the king threadfin results from the base case and the sensitivity tests in ARGulf "Base case" is defined as medium harvest scenario with steepness = 0.75 and natural mortality = 0.325 yr^{-1}. Log-likelihood ($-\ln L$) values that are comparable contain a "*"; lower values indicate better fit. Biomass and annual harvest values are in tonnes.

Model	$-\ln L$	SB_0	SB_{2019}	SB_{2019}/SB_0	Harvest at SB_{60}
Base case*	425.454	2045	105	0.051	229
High harvest	426.028	2188	108	0.049	246
Low harvest	425.028	1947	101	0.052	218
Natural mortality 0.35*	426.198	1860	112	0.06	228
Natural mortality 0.30*	425.037	2257	99	0.044	230
Steepness 0.55*	430.272	2933	95	0.033	264
Steepness 0.65*	426.995	2388	101	0.042	244
Steepness 0.85*	426.592	1781	118	0.066	215

Table 3.8: Summary of the king threadfin results from the base case and the sensitivity tests in AR2 "Base case" is defined as steepness = 0.75 and q_{inc} = 0.035 yr^{-1}. Log-likelihood ($-\ln L$) values that are comparable contain a "*"; lower values indicate better fit. Biomass and annual harvest values are in tonnes.

Model	$-\ln L$	SB_0	SB_{2019}	SB_{2019}/SB_0	**Harvest at SB_{60}**
Base case*	109.157	481	290	0.602	44
q_{inc} 0.050*	112.198	411	149	0.363	25
q_{inc} 0.020*	106.4	1.7×10^8	1.5×10^8	0.914	2×10^7
Steepness 0.55*	108.823	505	288	0.571	37
Steepness 0.65*	109.015	489	287	0.588	41
Steepness 0.85*	109.264	478	293	0.613	46

Table 3.9: Summary of the king threadfin results from the base case and the sensitivity tests in AR3 "Base case" is defined as steepness = 0.75 and q_{inc} = 0.0625 yr^{-1}. Log-likelihood ($-\ln L$) values that are comparable contain a "*"; lower values indicate better fit. Biomass and annual harvest values are in tonnes.

Model	$-\ln L$	SB_0	SB_{2019}	SB_{2019}/SB_0	**Harvest at SB_{60}**
Base case*	-23.5171	1228	792	0.645	89
q_{inc} 0.070*	-23.0986	753	319	0.424	43
q_{inc} 0.050*	-24.0784	3.5×10^8	3.1×10^8	0.879	2.7×10^7
Steepness 0.55*	-23.5222	1328	835	0.629	76
Steepness 0.65*	-23.2901	2.8×10^8	2.3×10^8	0.806	2.1×10^7
Steepness 0.85*	-23.5224	1212	790	0.652	95

Table 3.10: Summary of the king threadfin results from the base case and the sensitivity tests in AR4 "Base case" is defined as: steepness = 0.75; and q_{inc} = 0.030 yr^{-1}. Log-likelihood ($-\ln L$) values that are comparable contain a "*"; lower values indicate better fit. Biomass and annual harvest values are in tonnes.

Model	$-\ln L$	SB_0	SB_{2019}	SB_{2019}/SB_0	**Harvest at SB_{60}**
Base case*	486.472	415	237	0.571	33
q_{inc} 0.050*	477.875	408	141	0.345	30
q_{inc} 0.020*	491.985	431	314	0.728	36
Steepness 0.55*	490.716	500	331	0.661	36
Steepness 0.65*	488.522	447	276	0.617	35
Steepness 0.85*	484.457	393	205	0.521	31

Table 3.11: Summary of the king threadfin results from the base case and the sensitivity tests in AR5 "Base case" is defined as: steepness = 0.75; and q_{inc} = 0.020 yr^{-1}. Log-likelihood ($-\ln L$) values that are comparable contain a "*"; lower values indicate better fit. Biomass and annual harvest values are in tonnes.

Model	$-\ln L$	SB_0	SB_{2019}	SB_{2019}/SB_0	**Harvest at SB_{60}**
Base case*	355.138	457	327	0.716	34
q_{inc} 0.050*	371.989	305	100	0.328	19
q_{inc} 0.010*	351.643	1217	1164	0.956	101
Steepness 0.55*	356.294	575	423	0.735	36
Steepness 0.65*	355.652	505	366	0.726	35
Steepness 0.85*	354.714	422	298	0.706	33

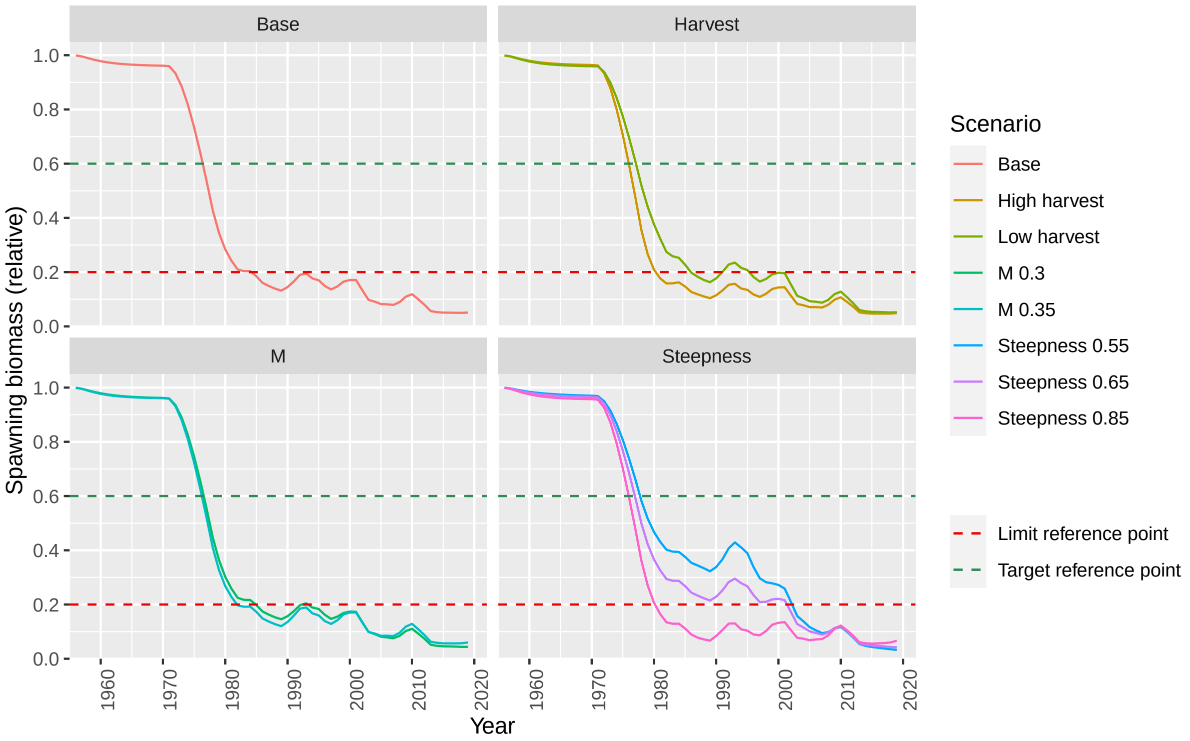

Figure 3.29: Predicted spawning biomass trajectory relative to unfished for king threadfin in ARGulf under different model settings

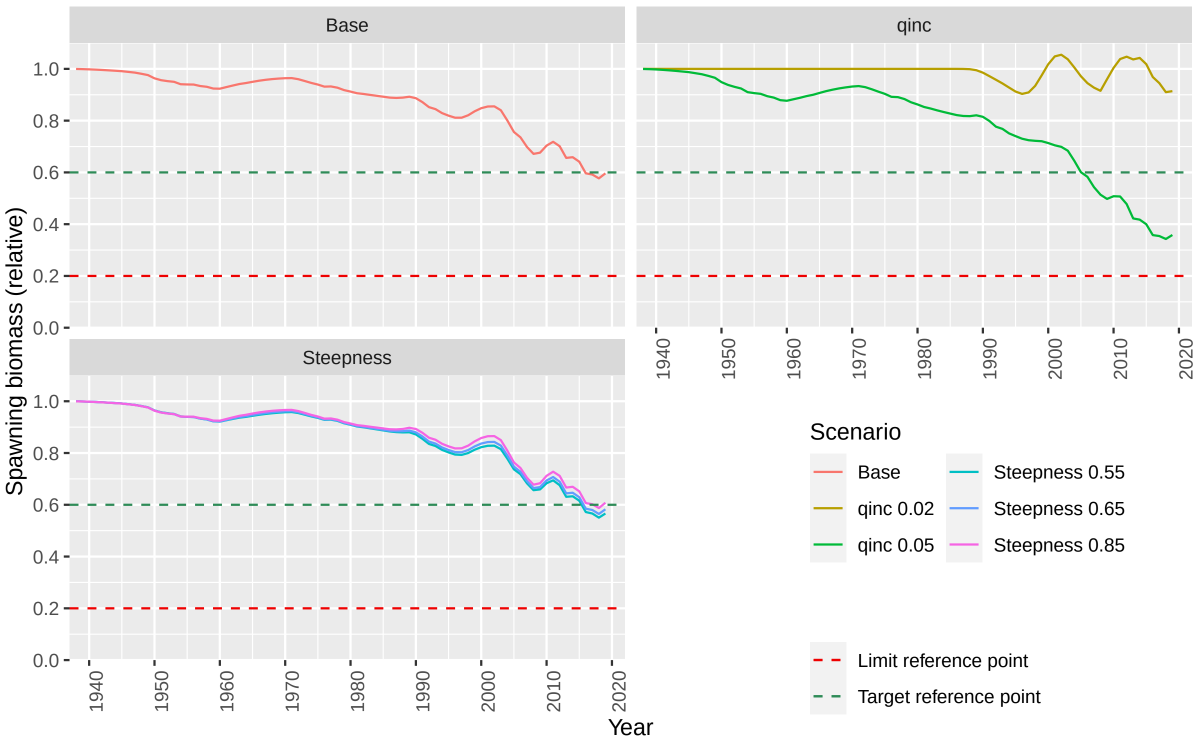

Figure 3.30: Predicted spawning biomass trajectory relative to unfished for king threadfin in AR2 under different model settings

Figure 3.31: Predicted spawning biomass trajectory relative to unfished for king threadfin in AR3 under different model settings

Figure 3.32: Predicted spawning biomass trajectory relative to unfished for king threadfin in AR4 under different model settings

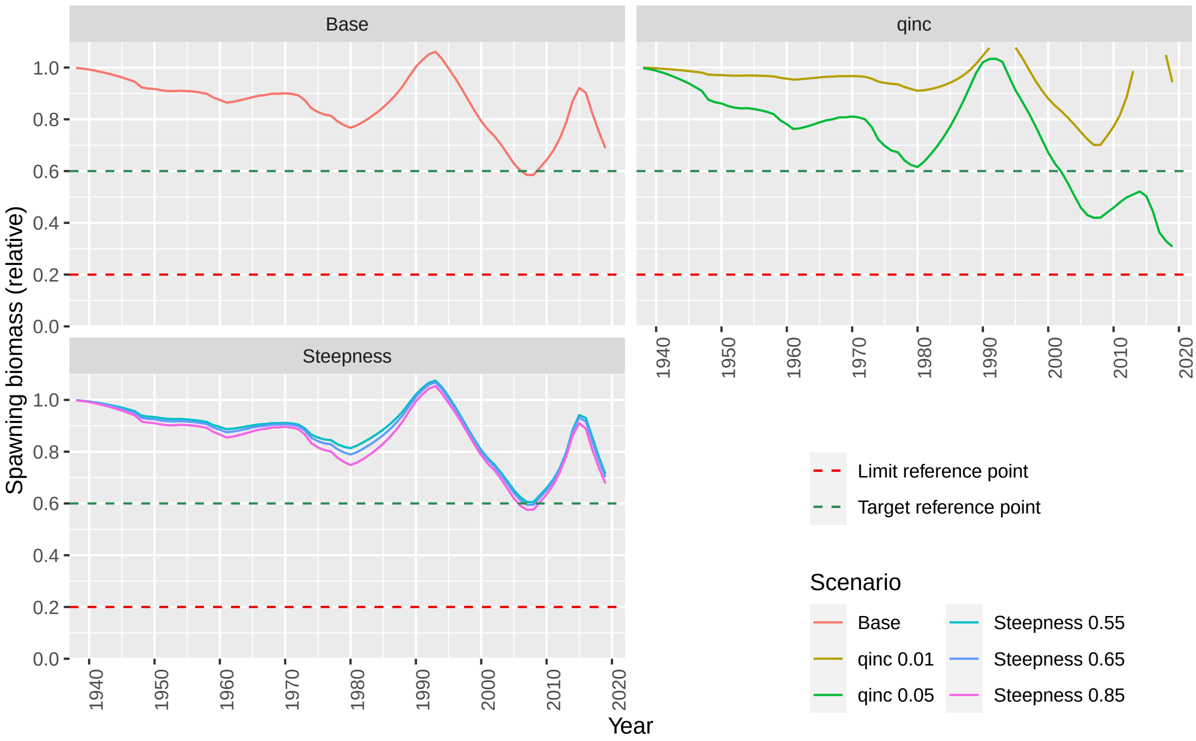

Figure 3.33: Predicted spawning biomass trajectory relative to unfished for king threadfin in AR5 under different model settings

4 Discussion

4.1 Population status

The results of this assessment are fairly definitive that the Gulf of Carpentaria requires management intervention to rebuild stocks of king threadfin, but the East Coast currently does not require rebuilding.

There will be a long term benefit to rebuilding the Gulf stock. After rebuilding, the future annual harvest in the Gulf will be approximately the same as the current harvest, but will be taken with much less fishing effort. Commercial fishing will be more profitable and fishing in the Gulf will be sustainable. The ability of a king threadfin stock to recover quickly has been observed in East Coast Region AR4 (see Appendix D). Management intervention may have been necessary in AR4 if the Net Free Zone had not been introduced, but with the Net Free Zone further measures are currently not needed.

4.2 Stock structure

This assessment has assumed that the spatial scale of king threadfin stocks is about the same as that of the Management Regions. There appear to be nursery areas around Karumba (ARGulf), Tully (AR2), Rockhampton (AR4) and Fraser Inshore (AR5), from which king threadfin may move hundreds of kilometres as they grow larger. Princess Charlotte Bay (AR1) may be another nursery area; this is uncertain due to lack of length and age data from this region. The hypothesis of numerous, highly localised stocks of king threadfin (see, e.g., Welch et al. 2010) is not supported by either the length and age data used for this assessment, or available tagging data (Infofish 2014a; Infofish 2014b).

The ability to move long distances would confer a biological advantage to king threadfin, in that they could explore new habitat areas that may become productive following a flood or other favourable environmental event. They appear able to do this, judging by, for example, their appearance in the Moreton Bay Catch Rate Region following the 2011 flood.

The stocks of king threadfin that we have identified can be distinguished by different asymptotic lengths to which the fish grow. Most notably, the asymptotic length is largest in AR4 and smallest in the neighbouring region AR3. The populations in AR3 and AR4 appear to mix very little. We caution, however, that it was difficult for the Fishery Monitoring program to sample AR3, so the estimate there is based on a relatively small sample.

4.3 Performance of the population model

The population model used was adequate, although not ideal, for assessment of king threadfin. A multi-regional model, in which population parameters such as natural mortality rate M and steepness h could be made common to all regions, but recruits could be restricted to the region in which they were born, may perform better and provide more precision about those population parameters. Stock Synthesis currently does not have the latter capability. It always mixes the recruits from all regions, thereby allowing a depleted region to gain recruits from spawning stock in regions with higher biomass ratios. Such mixing over the large distances between Assessment Regions is not compatible with current theory about biology of king threadfin.

The performance of the methods of weighting length and age data was poor. We did our best to manually weight the data to match the Francis (2011) indicators, but the indicators were often implausibly large or small. Our attempts to use the Dirichlet–multinomial procedure of Stock Synthesis also didn't work well. That method consistently estimated effective sample sizes that were around 50% of the actual sample sizes, even though the fit of predictions to observed data was often poor and obviously should have produced much smaller effective sample sizes. For length-frequency data, typical effective sample sizes from simpler but efficient methodology developed within DAF (Leigh et al. 2017; Leigh et al. 2019) are between 1% and 20% of the actual sample size.

We do not believe that either of these problems compromised the assessment itself to any appreciable degree; the major impact was that subjective human intervention that was necessary in the modelling. A bigger problem was constituted by variation in abundance and catch rates of this species over time, due to environmental influences and fishers' continual improvements to gillnetting practices to target king threadfin. Another problem was inability to distinguish between catches from foreshores and rivers, as this information is not recorded in fishery logbooks.

Environmental influences on king threadfin populations are complex, and it is currently not realistic to expect any model to deal adequately with the precise mechanisms. Models can fit recruitment deviations to partly deal with environmental effects, and Stock Synthesis does this well.

Better modelling of lengths of fish would improve the assessment only slightly. The model's handling of the effects of catchability increases and environmental influences on standardised catch rates is more important.

4.4 Environmental influences

Analysis of fishery logbook data indicates that the most noticeable environmental influences on king threadfin are floods and droughts. Floods tend to produce high abundance, and droughts low abundance, perhaps by way of the effect of these events on prey availability. It is unclear whether king threadfin are genuinely absent from whole regions in drought years and enter quickly after floods, or they are present all the time and simply have a low metabolic rate and are not encountered during droughts.

It may be possible in future to model the environmental effects. It would require many large data sets, such as time series of river flows. It would also require the mechanism of the effect of the environmental variable on king threadfin, and its time lag, to be decided. Possible mechanisms are

- Change in the natural mortality rate
- Change in recruitment
- Stimulus to fish to move into or away from a region
- Change in individuals' metabolic rate, which may affect the rate at which fishing or other detection equipment encounters the fish, and thereby give the impression that fish have moved in or out when in fact they have stayed in the same region.

4.5 Recommendations

4.5.1 Data

Historical data on length and age of fish from the Gulf in the 1980s and 1990s would be valuable. Electronic entry of these data is in progress, and they should be available for the next assessment.

Even more valuable would be length and especially age data from the Gulf in the early 1970s, before the peak of the fishery. Such data would provide contrast in the data and resolve the question of what the life span was before this stock was heavily fished. As far as we know, no such data exist.

4.5.2 Monitoring

Age data from the Fitzroy estuary (AR4) in future years would be very informative about the status of that stock. Due to the Net Free Zone, these data would have to come from either the recreational fishery or fishery-independent sampling.

The current Fishery Monitoring of length and age in commercial catches is valuable, and we recommend that it be continued.

Monitoring is currently fishery-dependent, relying on sampling of commercial and recreational catches by monitoring staff. If future management changes and catch restrictions make it difficult to conduct temporally and spatially representative sampling, alternative strategies including fishery-independent sampling may be required.

4.5.3 Research

Results from this assessment imply that major increases in gillnet catchability of king threadfin have taken place over time. Research is needed into the factors that have brought about these increases, and when they took effect. In the absence of data, the assessment has assumed that catchability increased at a constant annual rate between 1988 and the present. The actual pattern of increase is unknown.

Such a research project could also investigate environmental causes of variability in catch rates. It is unknown whether, in times of drought, king threadfin relocate to a less drought-affected locality, or stay in the same place and slow down their metabolism. Such knowledge will be important to future assessments, as it is highly desirable to know the level of exposure to fishing during times of drought. A third possibility, that natural mortality of king threadfin increases greatly during droughts, was discounted by the assessment, because the fish reappear quickly in times of flood.

Research to improve knowledge of stock structure would also be beneficial to future stock assessments of king threadfin.

4.5.4 Management

Action needs to be taken to limit the harvest in the Gulf to a sustainable level, as this assessment has found that the stock there is below both its target and limit reference points.

No urgent action is required on the East Coast but we still recommend that either a biological harvest or fishing effort be set in the East Coast Management Regions. This would ensure that fishing remains sustainable, given that active targeting of king threadfin has increased in recent years.

4.5.5 Assessment

A different population model could be considered which may overcome the limitations mentioned in Section 4.3. A multi-regional model, in which recruits are produced only by spawning stock in the same region, could estimate population parameters such as M and h more precisely and with less subjectivity.

A model with accurate automatic weighting of length and age data is also desirable, again to remove subjectivity. Such a model can estimate an effective sample size for each length and age sample, directly from the multinomial distribution (Leigh et al. 2017; Leigh et al. 2019). Francis (2011) points out that a method based on the multinomial distribution can in theory overestimate effective sample sizes when the sample distributions are smooth but biased. In practice, sample distributions are rarely smooth and this is not a major problem.

Better modelling of fish length, by incorporating it directly into the model, would offer a small extra improvement. This may be more important in Queensland than in many other jurisdictions in the world, as minimum legal sizes for many species in Queensland have changed quite often. Fishery management may benefit if the effect of a change in MLS can be estimated more accurately.

Harvest taken by Indigenous coastal communities should be included in future assessments.

Wind data could be considered in the catch rate analysis in future. Care would have to be taken to (a) use data from the most appropriate available weather station for each fishing location on each day, and (b) select the most appropriate explanatory variables to include, from the available wind speed and direction data at various times of day.

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A Model inputs

A.1 Harvest

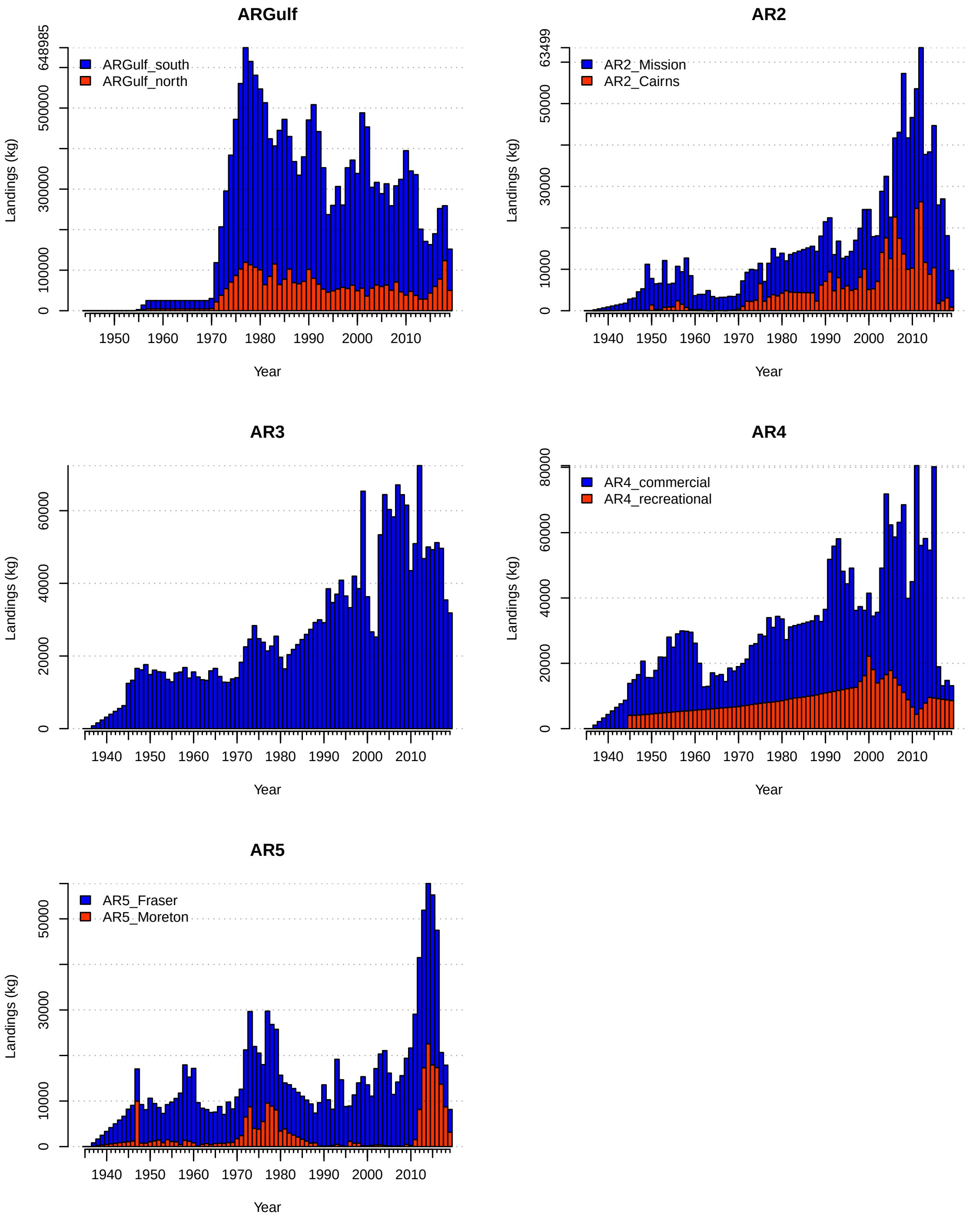


Figure A.1: Total harvest of king threadfin, using base case for ARGulf

A.2 Lunar terms in catch-rate analysis

When lunar-phase term was included in the catch-rate generalised linear models, it consisted of four continuous variables: two for sinusoidal dependence with a period of one month (equivalent to an amplitude and a phase offset), and another two for sinusoidal dependence with a period of half a month. The half-month period can account for high catch rates during neap tides, which occur twice per month. The half-month period was highly significant in the two GLMs in which lunar data were used. The lunar data began with the luminance, denoted `Lunar` and ranging from 0 at new moon to 1 at full moon. For input to the GLMs, the four lunar variables, denoted `LunarSin` and `LunarCos` for the one-month period and `Lunar2Sin` and `Lunar2Cos` for the half-month period, were defined by the following code in the statistical software R (R Core Team 2020):

```
LunarSin = 2 * Lunar - 1 # Expand to range [-1, 1] for sine function
LunarDeriv = rep(0, length(LunarSin)) # Derivative; only want the sign.
nLunar = length(LunarSin)
Ind = 2:(nLunar - 1)
LunarDeriv[Ind] = LunarSin[Ind + 1] - LunarSin[Ind - 1]
LunarDeriv[1] = 2 * (LunarSin[2] - LunarSin[1])
LunarDeriv[nLunar] = 2 * (LunarSin[nLunar] - LunarSin[nLunar - 1])
LunarCos = sign(LunarDeriv) * sqrt(1 - LunarSin^2) # Cosine function
Lunar2Sin = 2 * LunarSin * LunarCos # Half-period sine function
Lunar2Cos = 1 - 2 * LunarSin^2 # Half-period cosine function
```

A.3 Length-frequency sample sizes

These actual sample sizes for length frequencies are input to the model and form a starting point for data set weighting. This weighting reduces the actual sample size to an effective sample size which takes account of the lack of statistical independence of the measured fish.

Table A.1: Actual sample sizes for length-frequency inputs

Year	ARGulf south	ARGulf north	AR2 Mission	AR2 Cairns	AR3	AR4 Commercial	AR4 Recreational	AR5 Fraser	AR5 Moreton
2000						47			
2001					114	208			
2002						492			
2003						49			
2004						91			
2005						110			
2008	262								
2009	223								
2010	205								
2011	238								
2015						39		33	109
2016	462	99	268				76	284	268
2017	878	164	314	109			126	26	58
2018	565	148	182	98			155	28	83
2019	496	277	92		364	38			39

A.4 Conditional age-at-length

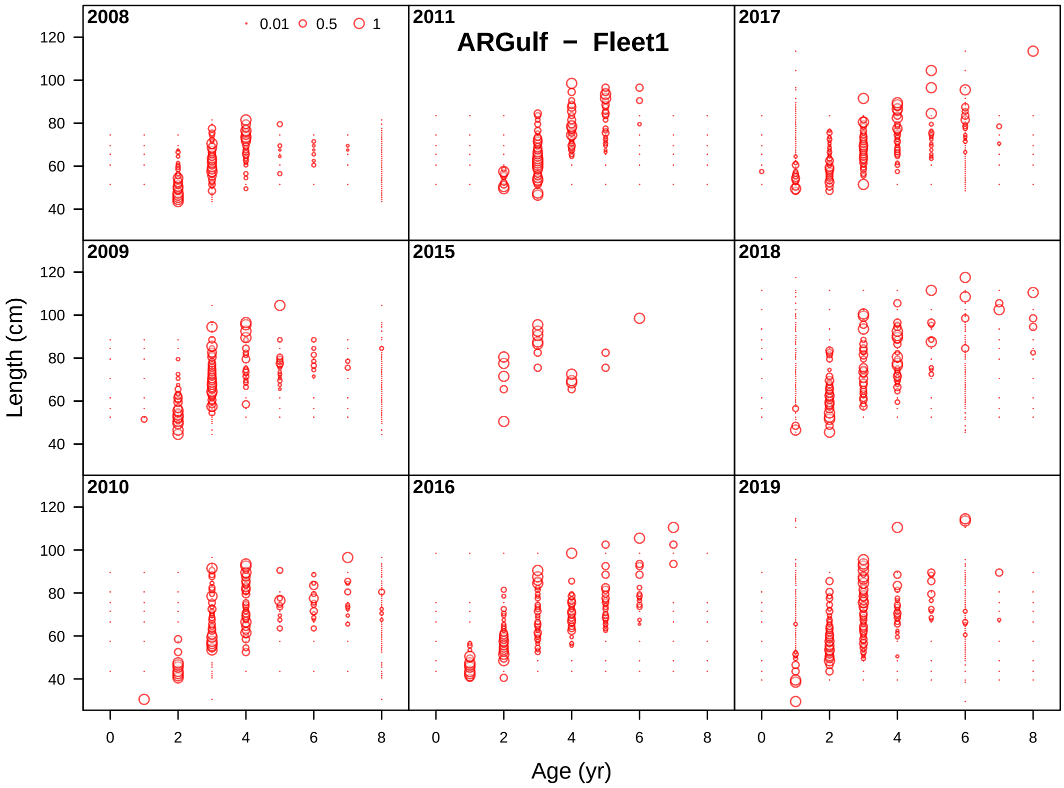


Figure A.2: Conditional age-at-length compositions for king threadfin in ARGulf south
Circle size is proportional to relative sample size in each bin across rows (i.e. for a given length bin).

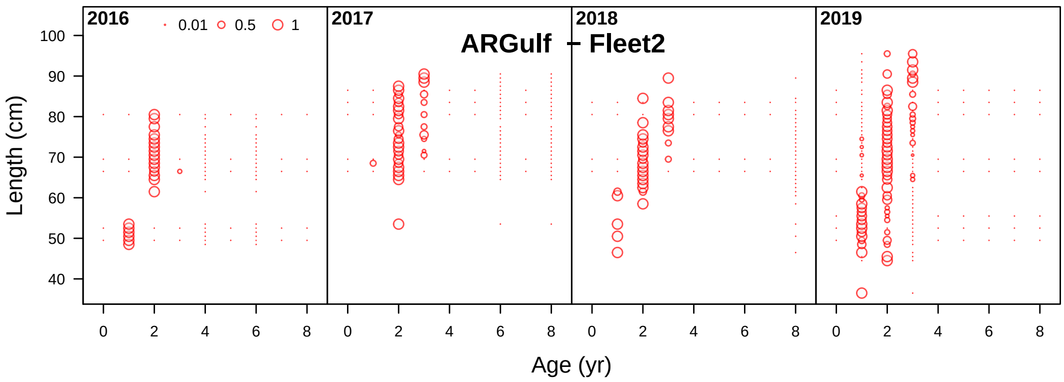


Figure A.3: Conditional age-at-length compositions for king threadfin in ARGulf north
Circle size is proportional to relative sample size in each bin across rows (i.e. for a given length bin).

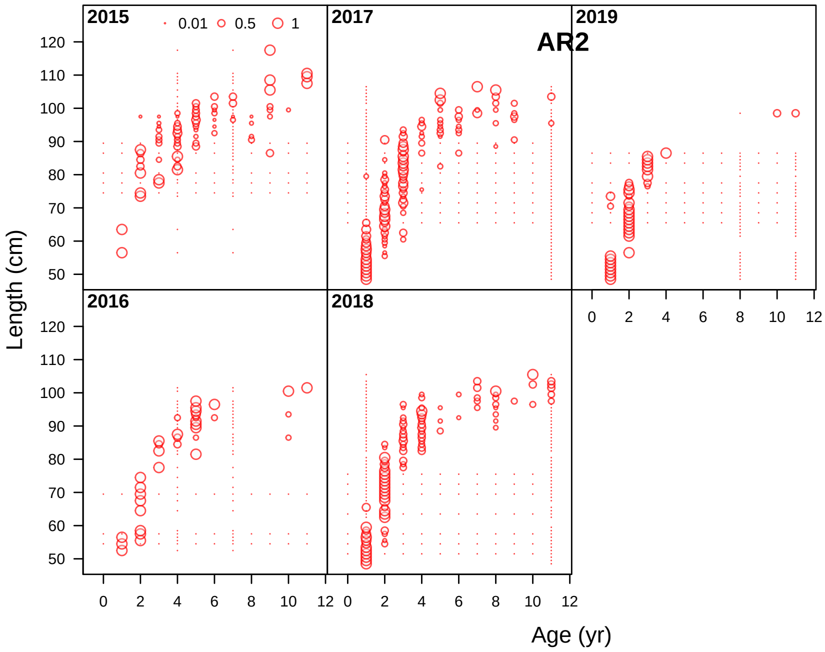


Figure A.4: Conditional age-at-length compositions for king threadfin in AR2
Circle size is proportional to relative sample size in each bin across rows (i.e. for a given length bin).

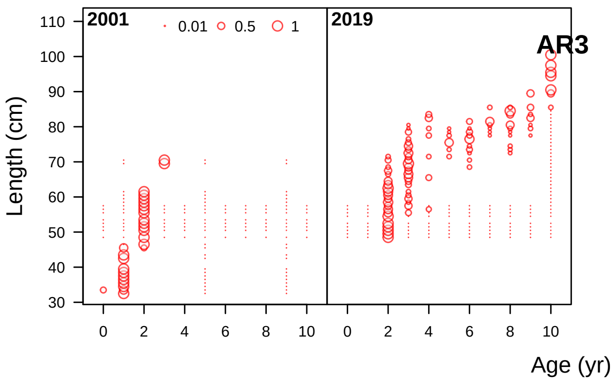


Figure A.5: Conditional age-at-length compositions for king threadfin in AR3
Circle size is proportional to relative sample size in each bin across rows (i.e. for a given length bin).

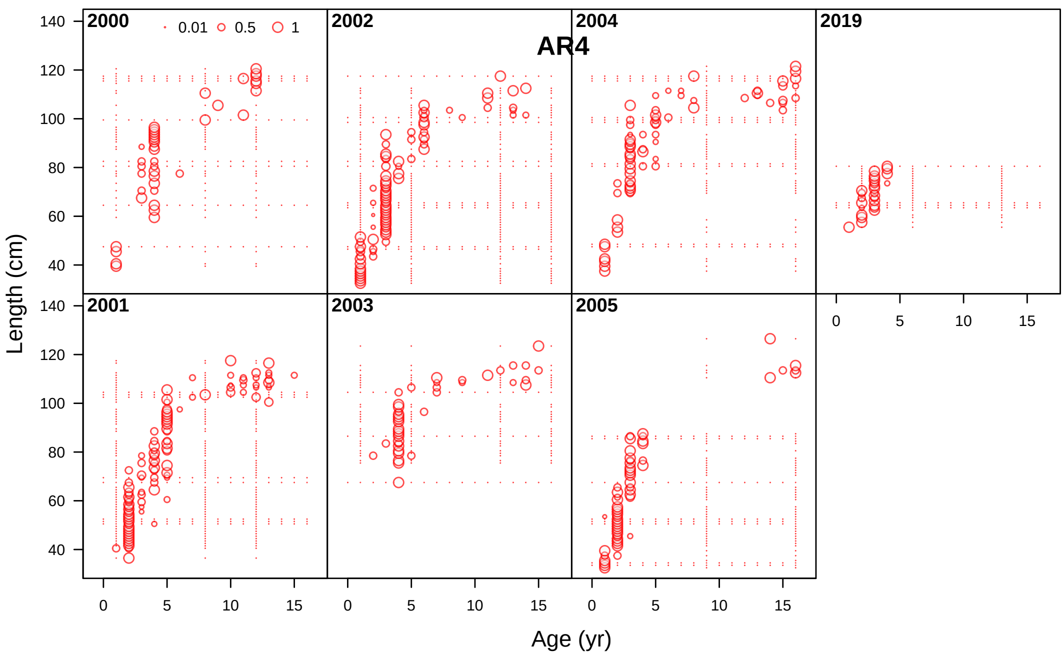


Figure A.6: Conditional age-at-length compositions for king threadfin in AR4
Circle size is proportional to relative sample size in each bin across rows (i.e. for a given length bin).

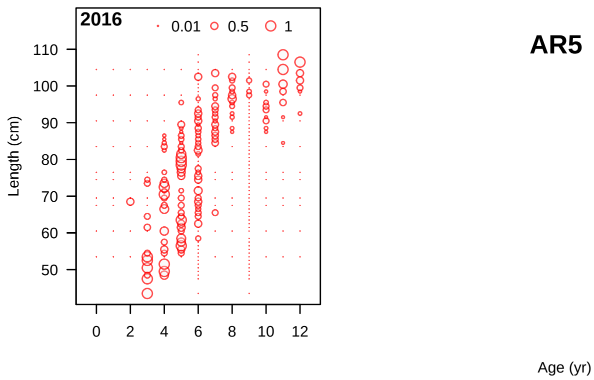


Figure A.7: Conditional age-at-length compositions for king threadfin in AR5
Circle size is proportional to relative sample size in each bin across rows (i.e. for a given length bin).

A.5 Biological data

A.5.1 Fecundity and maturity

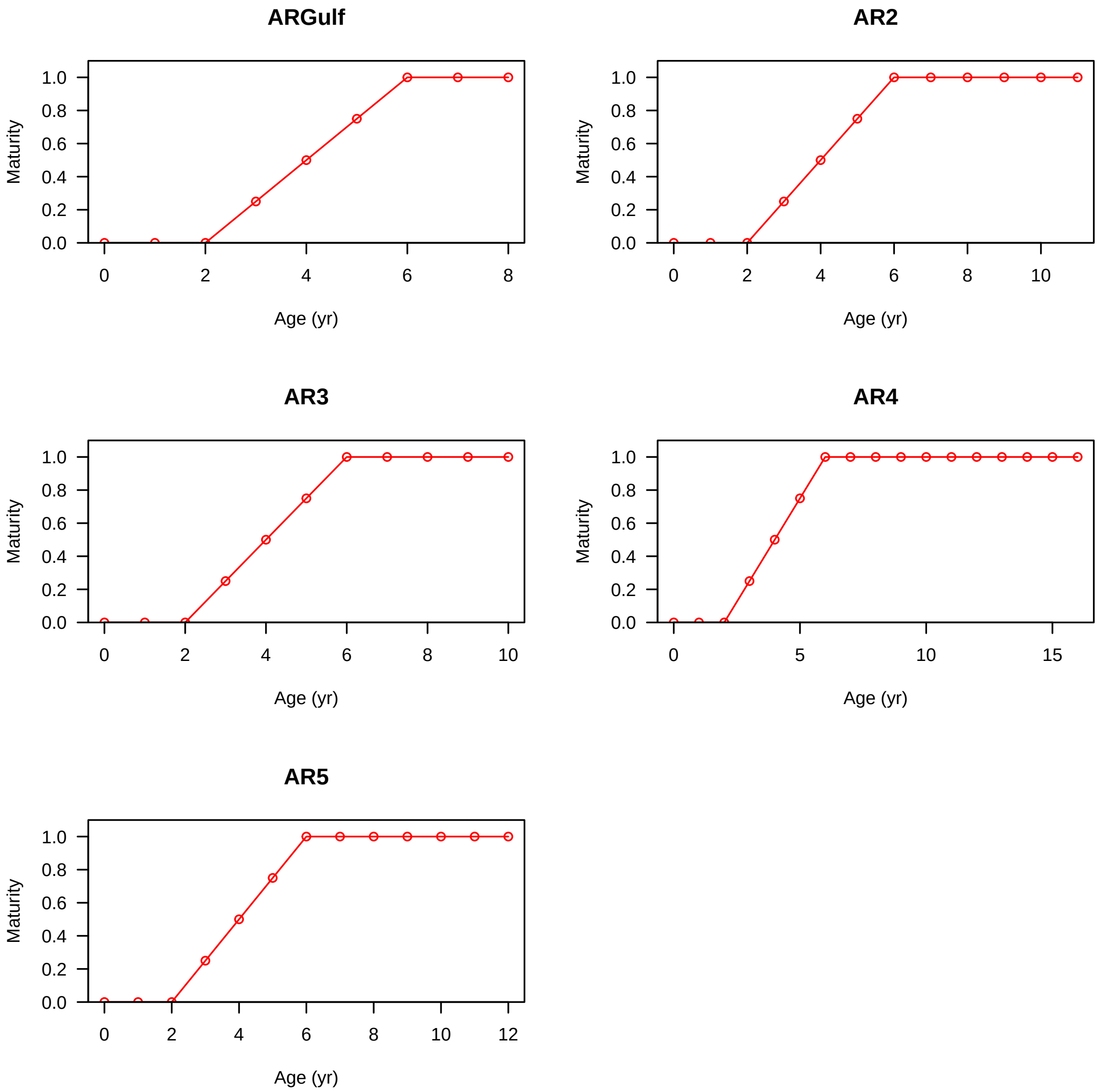


Figure A.8: Maturity at age for king threadfin
Source: Moore et al. (2011)

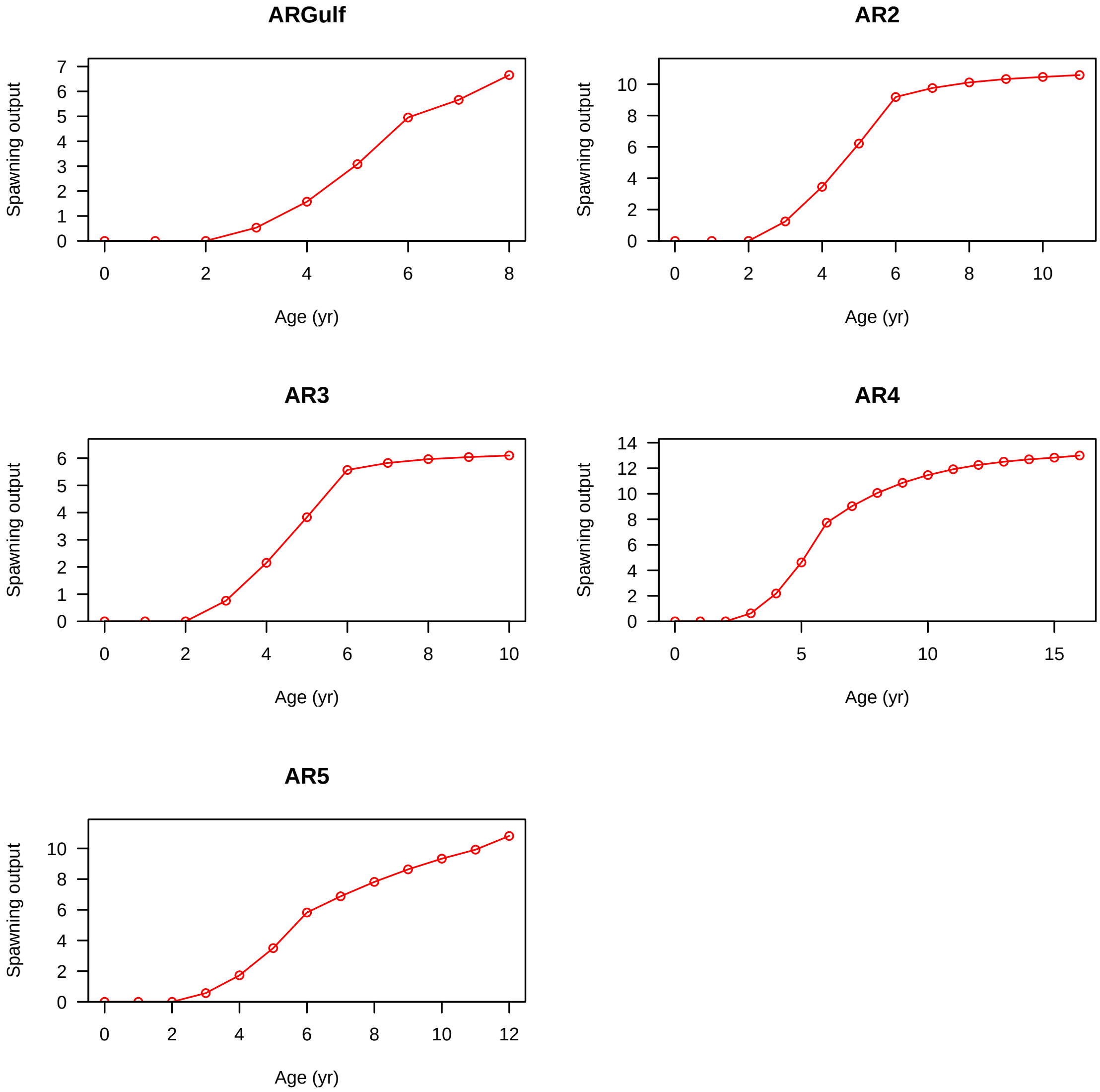


Figure A.9: Spawning output (maturity multiplied by fecundity) at age for king threadfin

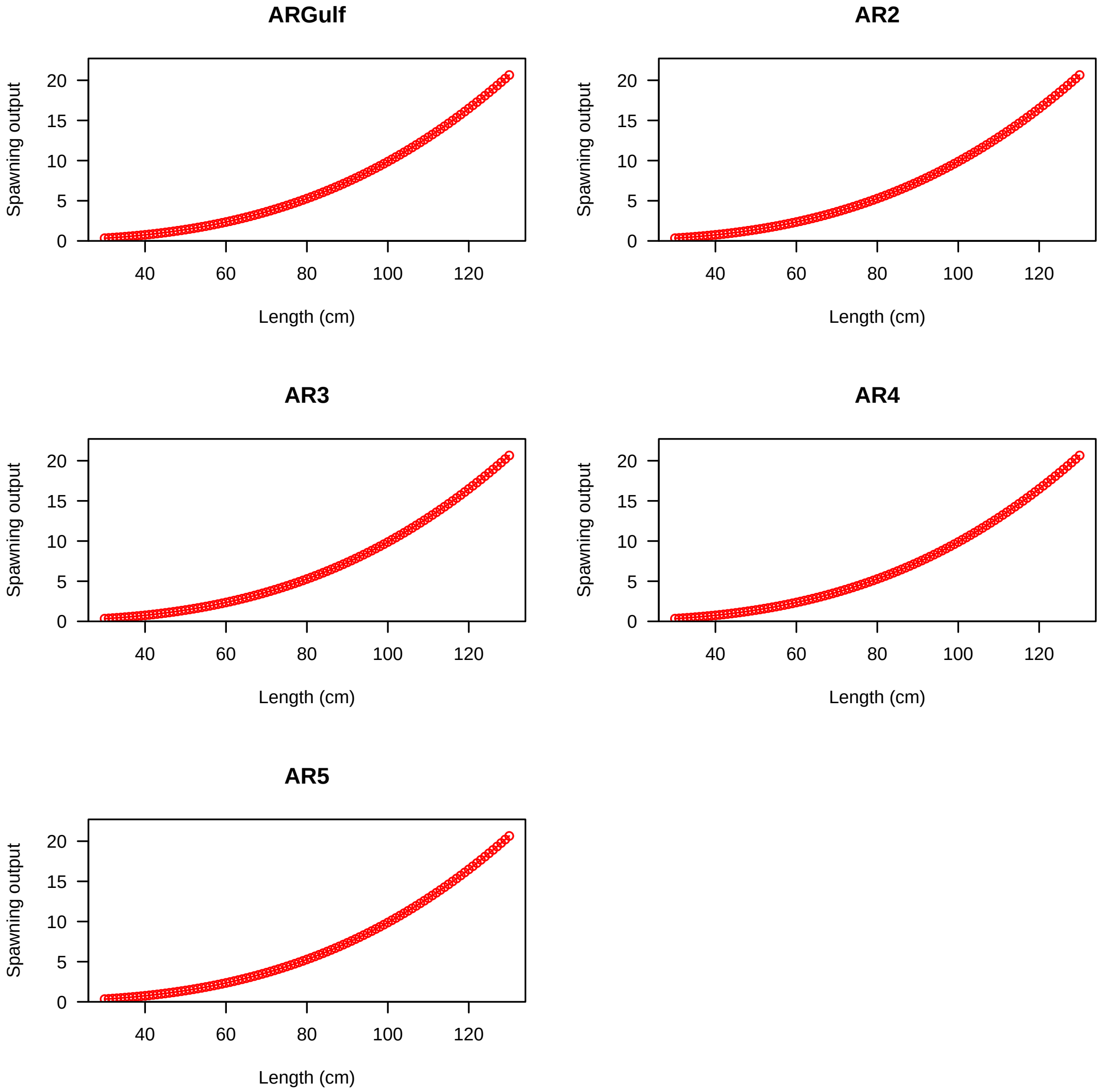


Figure A.10: Spawning output (maturity multiplied by fecundity) at length for king threadfin

A.5.2 Weight and length

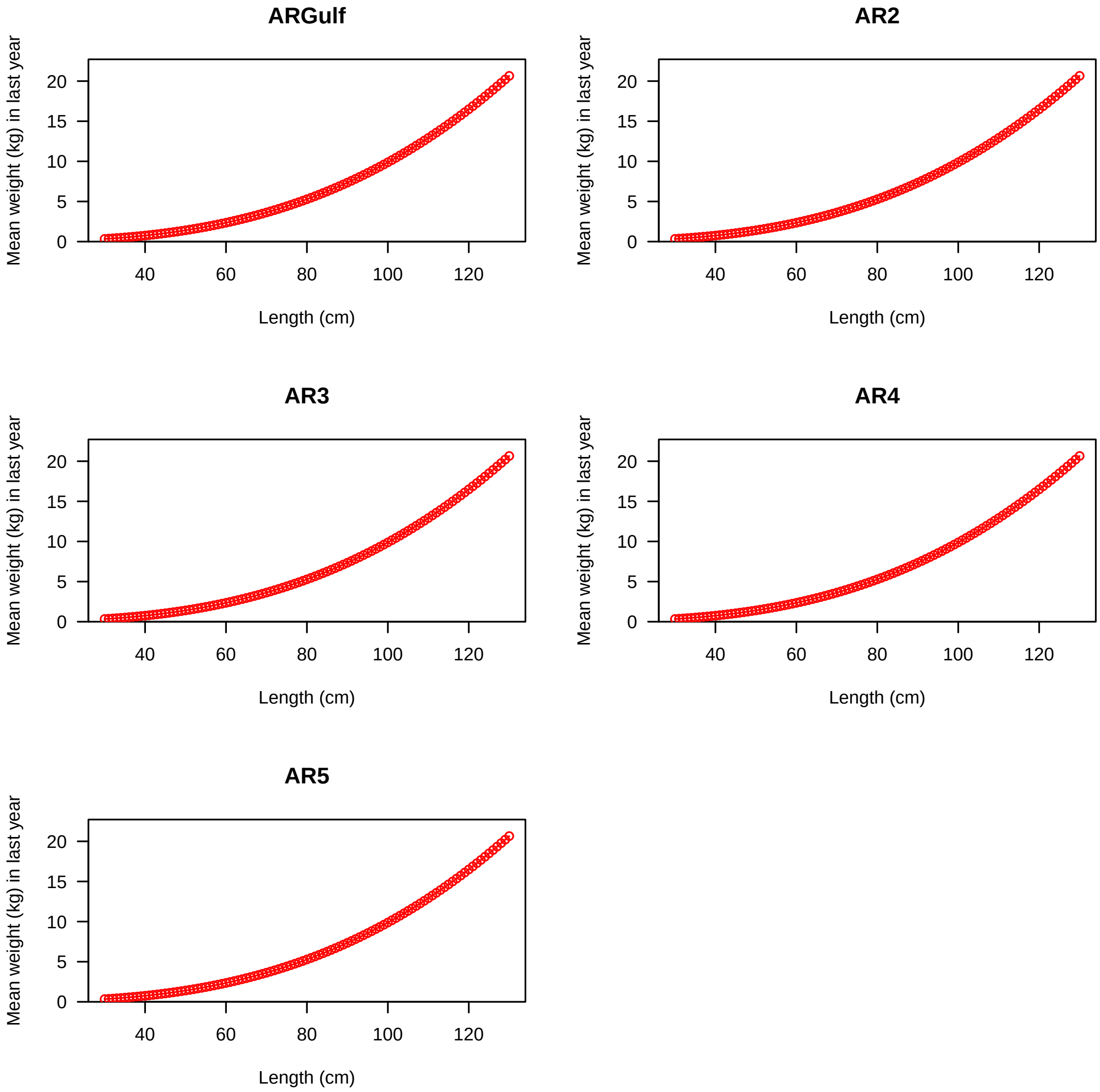


Figure A.11: Weight-length relationship for king threadfin

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 king threadfin

Stock Synthesis Parameter Label	Explanation
NatM_p_1	Natural mortality (M)
L_at_Amin	Total length at age (cm FL)
L_at_Amax	Total length at maximum observed age (cm FL)
VonBert_K	von Bertalanffy growth parameter, K (yr^{-1})
SD_young	Standard deviation of length at age 1 (cm)
SD_old	Standard deviation of length at max. obs. age (cm)
SR_LN(R0)	Logarithm of the number of recruits in unfished stock
SR_sigmaR	Standard deviation of log recruitment deviations
LnQ_base_Region_Fleet	Intercept parameter for catchability
LnQ_base_Region_Fleet_ENV_add	Annual increase parameter for catchability (yr^{-1})
Size_inflection_Region_Fleet	Length at 50% selectivity, L_{50} (cm FL), for Region_Fleet
Size_95%width_Region_Fleet	Amount by which length at 95% selectivity is greater than L_{50} (cm), for Region_Fleet

Table B.2: Stock Synthesis parameter estimates for king threadfin in ARGulf

Parameter	Estimate	Phase	Min	Max	Initial value	Standard deviation	Gradient
L_at_Amin_Fem_GP_1	37.55	3	0	80	52.34	1.59	-1.7×10^{-4}
VonBert_K_Fem_GP_1	0.2723	3	0.05	0.7	0.39	0.0626	-1.3×10^{-4}
SD_young_Fem_GP_1	9.04	3	2	20	9.29	0.7	-7.8×10^{-5}
SD_old_Fem_GP_1	19.56	3	2	25	9.29	2.95	-9.2×10^{-5}
SR_LN(R0)	13.07	1	5	25	14	0.03	-0.0046
SR_sigmaR	0.35	5	0.2	1	0.3	0.06	2.1×10^{-5}
LnQ_base_ARGulf_south(1)	-7.34	1	-30	1	-6	0.22	-1.4×10^{-5}
LnQ_base_ARGulf_north(2)	-6.61	1	-30	1	-6	0.29	-4.3×10^{-6}
LnQ_base_ARGulf_south(1)_ENV_add	0.0291	1	0	0.08	0.05	0.0097	5.5×10^{-7}
LnQ_base_ARGulf_north(2)_ENV_add	0.0499	1	0	0.08	0.05	0.0065	-1.6×10^{-7}
Size_inflection_ARGulf_south(1)	61.08	5	20	120	45	1.97	-3.1×10^{-4}
Size_95%width_ARGulf_south(1)	12.75	5	2	50	7	2.45	4.6×10^{-5}
Size_inflection_ARGulf_north(2)	70.96	5	20	120	45	3.29	-7.3×10^{-5}
Size_95%width_ARGulf_north(2)	16.03	5	2	50	7	3.01	3.1×10^{-5}

Table B.3: Stock Synthesis parameter estimates for king threadfin in AR2

Parameter	Estimate	Phase	Min	Max	Initial value	Standard deviation	Gradient
NatM_p_1_Fem_GP_1	0.3106	3	0.05	0.5	0.3	0.0677	-7.9×10^{-8}
L_at_Amin_Fem_GP_1	49.58	3	0	80	50.7	1.35	-1.9×10^{-8}
L_at_Amax_Fem_GP_1	102.17	3	60	140	103.69	1.6	-3×10^{-8}
VonBert_K_Fem_GP_1	0.5086	3	0.05	0.7	0.36	0.0419	-6.6×10^{-10}
SD_young_Fem_GP_1	7.28	3	2	20	8.57	0.58	-1.1×10^{-8}
SD_old_Fem_GP_1	5.46	3	2	25	8.57	0.57	-8.5×10^{-9}
SR_LN(R0)	10.94	1	5	25	14	0.76	5.8×10^{-7}
LnQ_base_AR2_Mission(1)	-8.57	1	-30	1	-6	0.58	5.5×10^{-7}
LnQ_base_AR2_Cairns(2)	-7.92	1	-30	1	-6	0.61	1.5×10^{-7}
Size_inflection_AR2_Mission(1)	49.42	5	20	100	45	2.86	-2×10^{-9}
Size_inflection_AR2_Cairns(2)	86.66	5	20	100	45	7.9	-2×10^{-9}
Size_95%width_AR2_Cairns(2)	19.57	5	2	40	7	9.15	-3.5×10^{-9}

Table B.4: Stock Synthesis parameter estimates for king threadfin in AR3

Parameter	Estimate	Phase	Min	Max	Initial value	Standard deviation	Gradient
NatM_p_1_Fem_GP_1	0.2956	3	0.05	0.5	0.3	0.1103	-5.9×10^{-9}
L_at_Amin_Fem_GP_1	36.21	3	0	80	42.09	1.44	3.3×10^{-8}
L_at_Amax_Fem_GP_1	83.76	3	60	140	85.39	3.01	2.6×10^{-7}
VonBert_K_Fem_GP_1	0.6287	3	0.05	0.7	0.41	0.0948	2.2×10^{-8}
SD_young_Fem_GP_1	3.26	3	2	20	2	0.79	-1.8×10^{-8}
SD_old_Fem_GP_1	6.37	3	2	25	7.74	0.95	-1.7×10^{-8}
SR_LN(R0)	12.29	1	5	25	14	1.64	3×10^{-7}
LnQ_base_AR3_Commercial(1)	-10.14	1	-30	1	-6	1.39	4.2×10^{-7}
Size_inflection_AR3_Commercial(1)	32.23	5	20	100	45	6.31	2.9×10^{-9}

Table B.5: Stock Synthesis parameter estimates for king threadfin in AR4

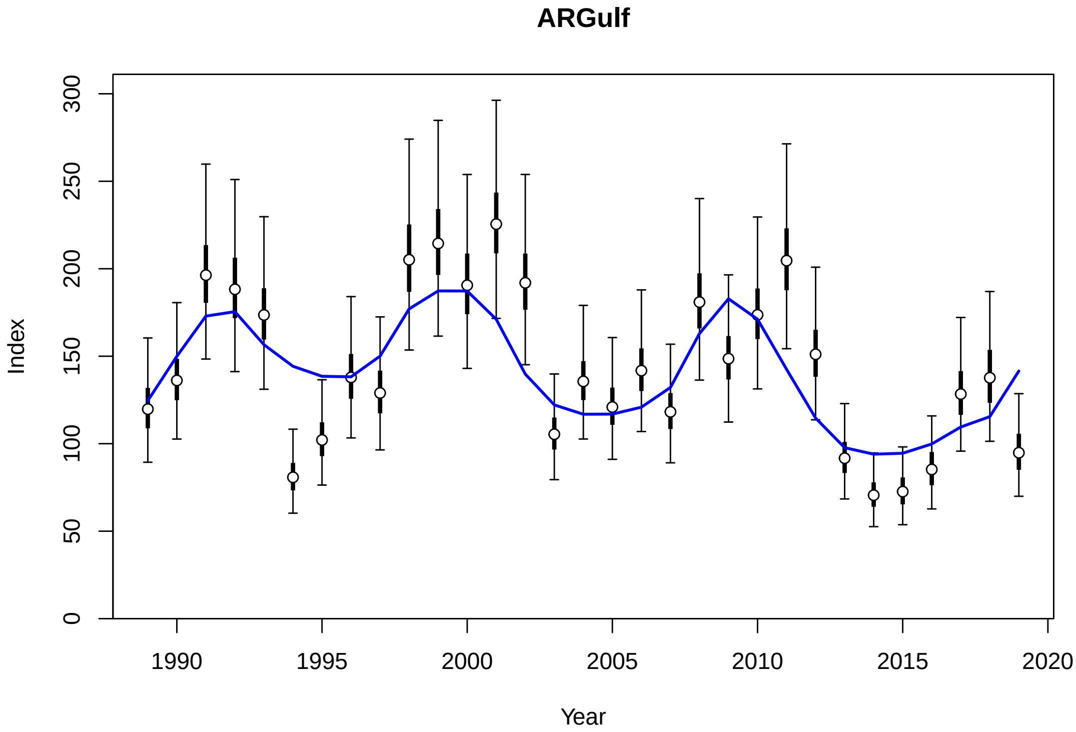
Parameter	Estimate	Phase	Min	Max	Initial value	Standard deviation	Gradient
NatM_p_1_Fem_GP_1	0.3191	3	0.05	0.5	0.3	0.0316	3.9×10^{-6}
L_at_Amin_Fem_GP_1	29.95	3	0	80	35.71	1.89	-3.3×10^{-6}
L_at_Amax_Fem_GP_1	109.64	3	60	140	114.05	1.94	-4.6×10^{-6}
VonBert_K_Fem_GP_1	0.3156	3	0.05	0.7	0.29	0.0188	-4.3×10^{-6}
SD_young_Fem_GP_1	9.64	3	2	20	7.84	1.17	3×10^{-6}
SD_old_Fem_GP_1	8.24	3	2	25	7.84	1.2	1.1×10^{-6}
SR_LN(R0)	11.03	1	5	25	14	0.21	-2.1×10^{-5}
LnQ_base_AR4_Commercial(1)	-8.11	1	-30	1	-6	0.18	-1.3×10^{-5}
Size_inflection_AR4_Commercial(1)	49	5	20	100	45	2.96	-3×10^{-6}
Size_95%width_AR2_Commercial(1)	12.63	5	2	40	7	3.71	9.5×10^{-7}
Size_inflection_AR4_Recreational(2)	60.98	5	20	100	45	1.17	3.1×10^{-6}
Size_95%width_AR4_Recreational(2)	7.23	5	2	40	7	1.49	3×10^{-8}

Table B.6: Stock Synthesis parameter estimates for king threadfin in AR5

Parameter	Estimate	Phase	Min	Max	Initial value	Standard deviation	Gradient
NatM_p_1_Fem_GP_1	0.2952	3	0.05	0.5	0.3	0.0424	4.1×10^{-5}
SR_LN(R0)	11.14	1	5	25	14	0.72	-5.2×10^{-5}
LnQ_base_AR5_Fraser(1)	-8.45	1	-30	1	-6	0.58	1.3×10^{-5}
Size_inflection_AR5_Fraser(1)	53.6	5	20	100	45	3.51	-1.5×10^{-5}
Size_95%width_AR5_Fraser(1)	14.12	5	2	40	7	9.21	6.1×10^{-6}
Size_inflection_AR5_Moreton(2)	71.62	5	20	100	45	1.66	-3.7×10^{-5}
Size_95%width_AR5_Moreton(2)	14.95	5	2	40	7	1.89	3.7×10^{-6}

B.2 Plots of model fit

B.2.1 Abundance indices



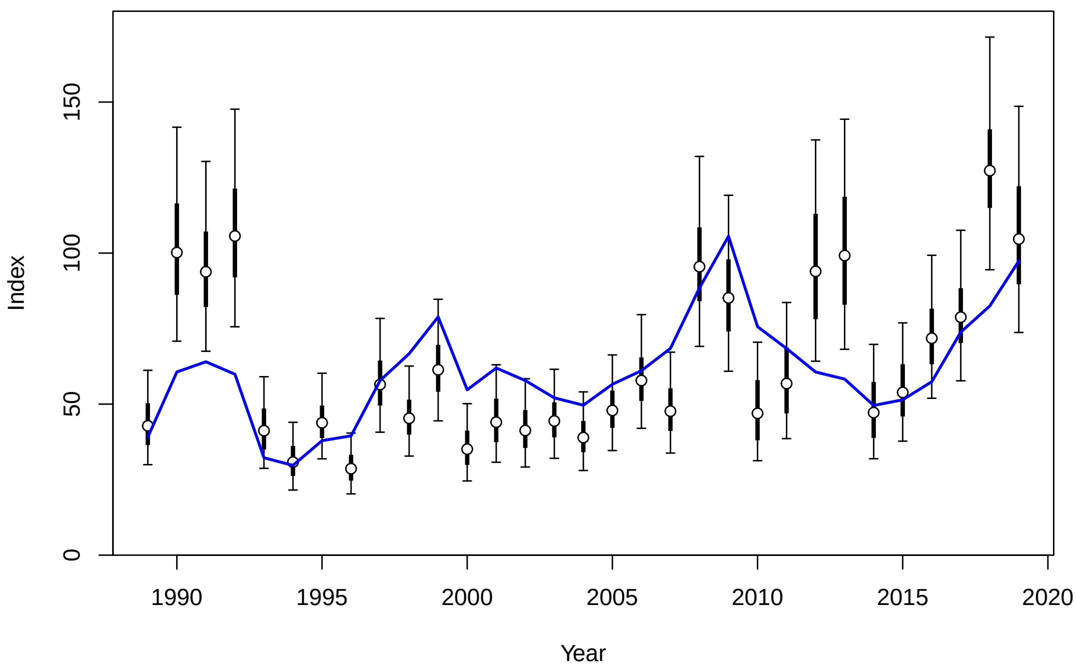


Figure B.1: Model predictions (blue line) of standardised gillnet catch rates (circles) in ARGulf south (upper plot) and north (lower)

Thick black bars represent the standard error input into the model, while the thin error bars represent additional error estimated by the model.

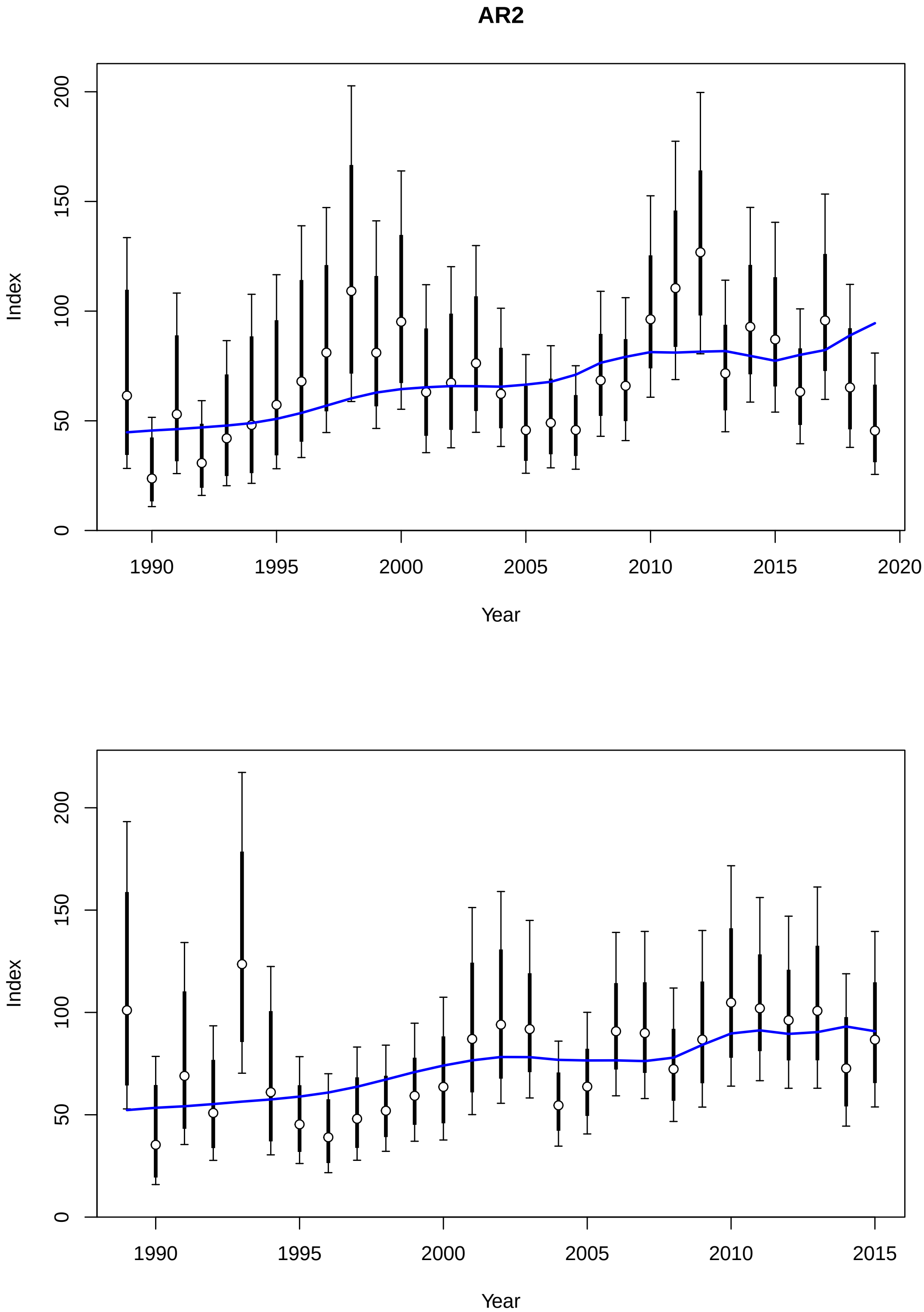


Figure B.2: Model predictions (blue line) to standardised gillnet catch rates (circles) in AR2 Mission (upper plot) and Cairns (lower)
Thick black bars represent the standard error input into the model, while the thin error bars represent additional error estimated by the model.

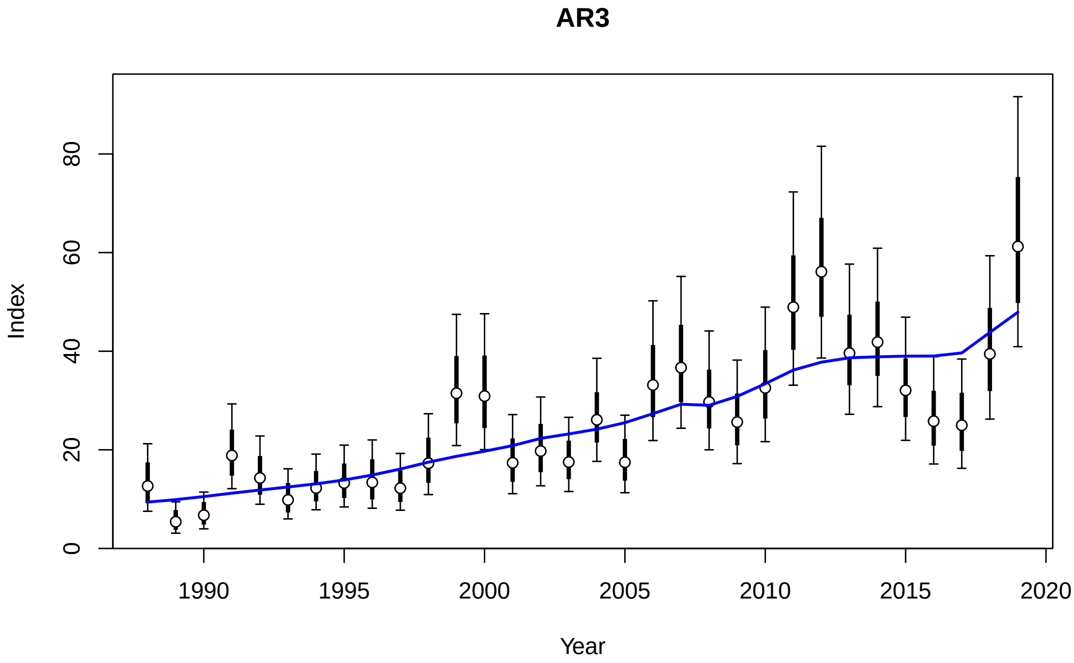


Figure B.3: Model predictions (blue line) to standardised gillnet catch rates (circles) in AR3
Thick black bars represent the standard error input into the model, while the thin error bars represent additional error estimated by the model.

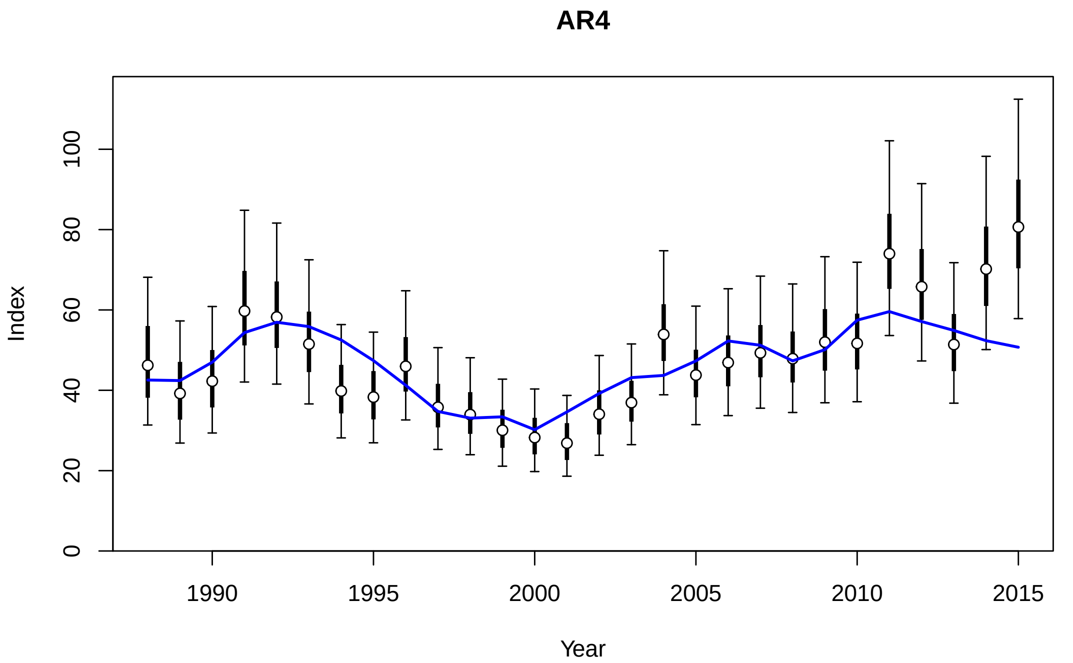


Figure B.4: Model predictions (blue line) to standardised catch rates (circles) for AR4 commercial gillnet fleet (upper plot) and recreational line-fishing fleet (lower)
Thick black bars represent the standard error input into the model, while the thin error bars represent additional error estimated by the model.

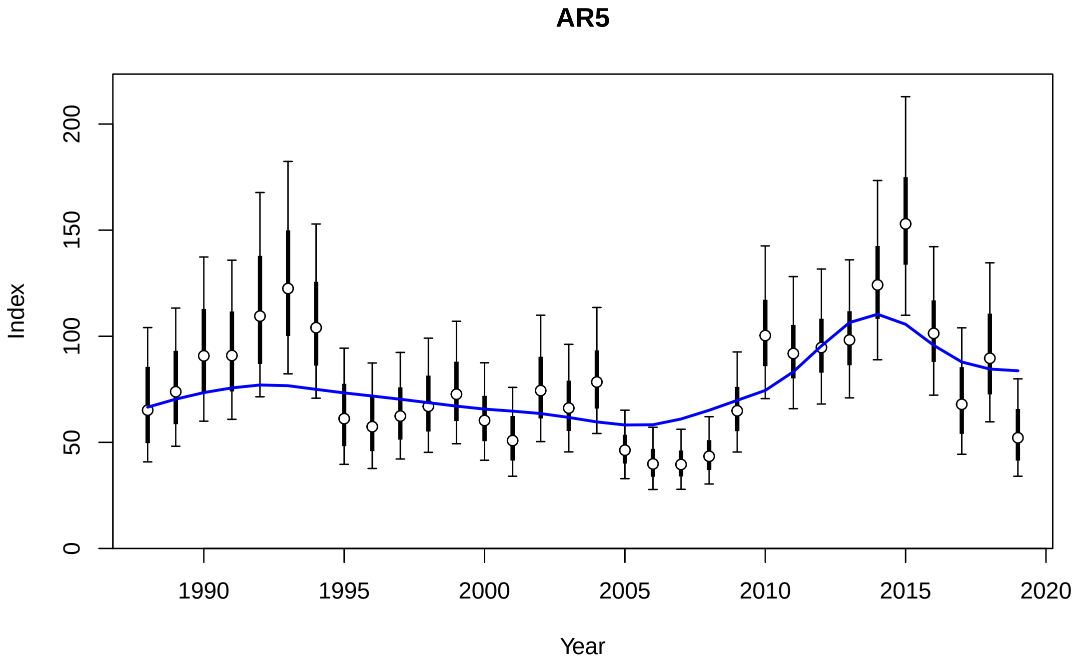


Figure B.5: Model predictions (blue line) to standardised gillnet catch rates (circles) in AR5 Fraser (upper plot) and Moreton (lower)

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 composition

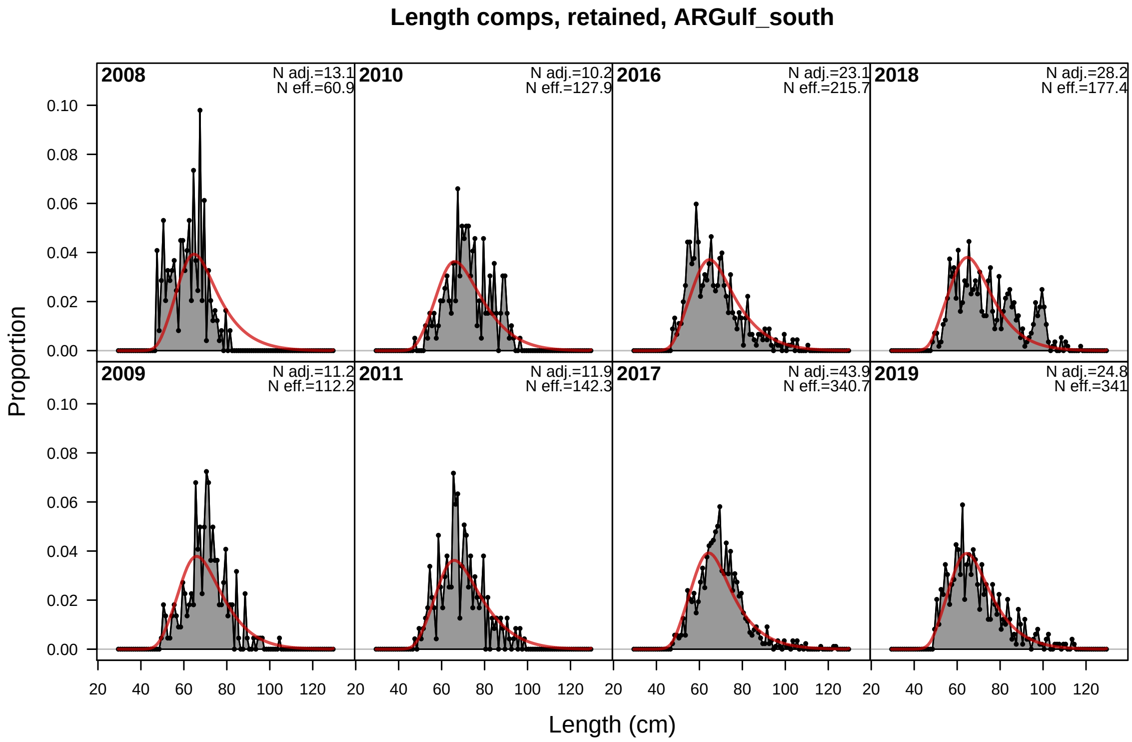


Figure B.6: Length structure for king threadfin in ARGulf south
"N adj." is the input sample size after data-weighting adjustment. N eff. is the calculated effective sample size used in the Francis tuning method.

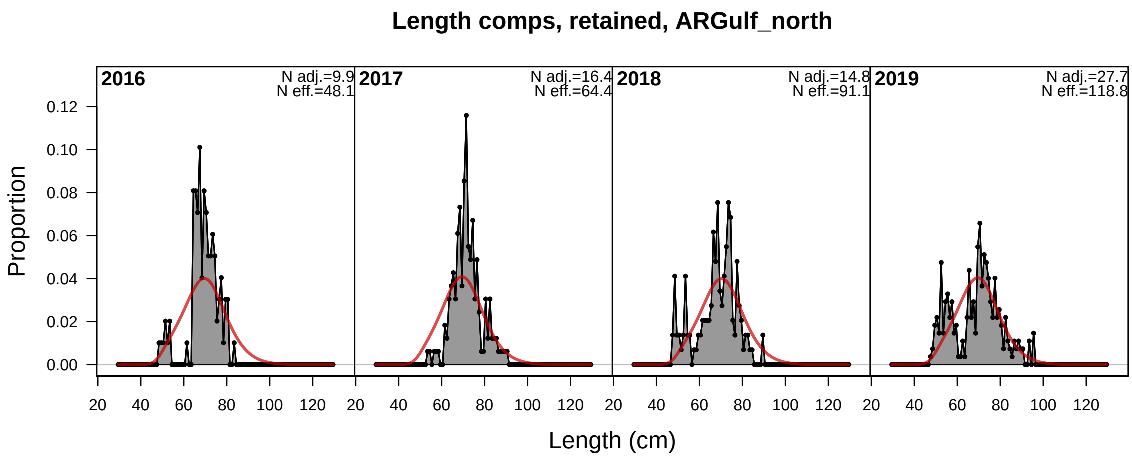


Figure B.7: Length structure for king threadfin in ARGulf north
"N adj." is the input sample size after data-weighting adjustment. N eff. is the calculated effective sample size used in the Francis tuning method.

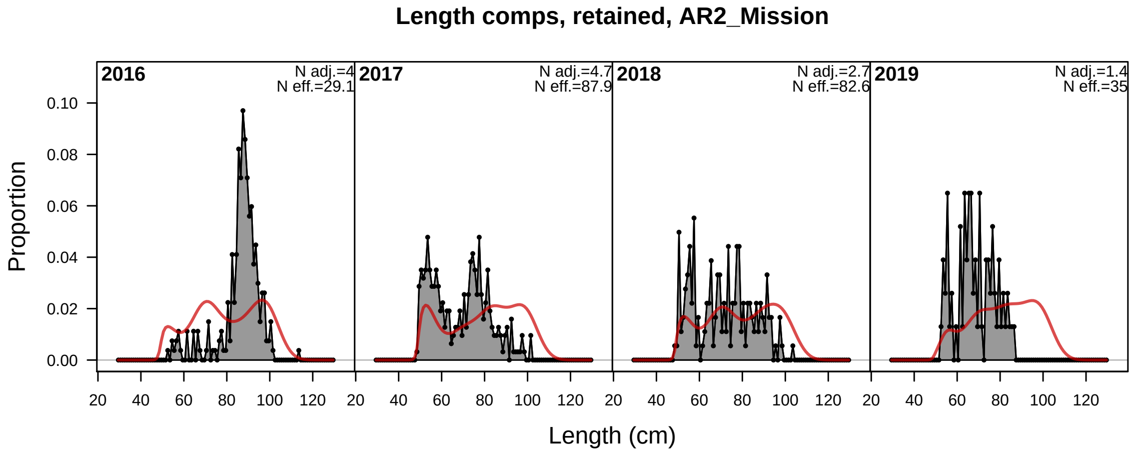


Figure B.8: Length structure for king threadfin in AR2 (Mission)
"N adj." is the input sample size after data-weighting adjustment. N eff. is the calculated effective sample size used in the Francis tuning method.

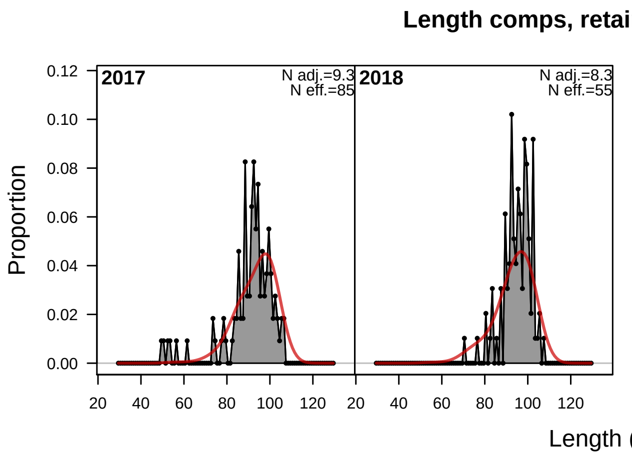


Figure B.9: Length structure for king threadfin in AR2 (Cairns)
"N adj." is the input sample size after data-weighting adjustment. N eff. is the calculated effective sample size used in the Francis tuning method.

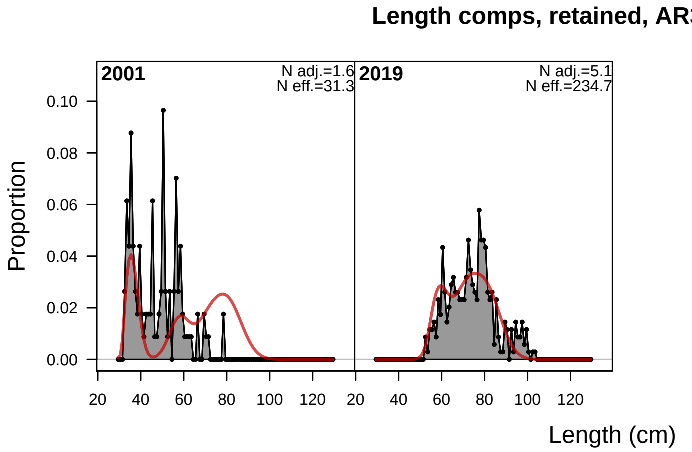


Figure B.10: Length structure for king threadfin in AR3
"N adj." is the input sample size after data-weighting adjustment. N eff. is the calculated effective sample size used in the Francis tuning method.

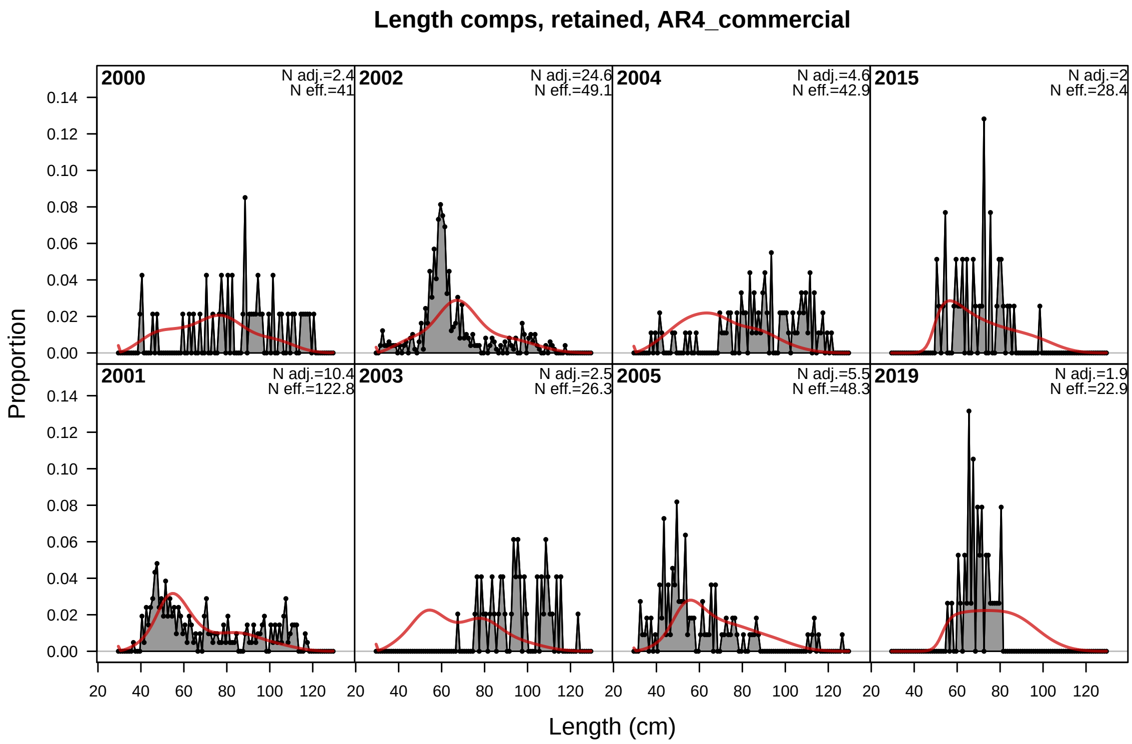


Figure B.11: Length structure for king threadfin in AR4 (commercial)
"N adj." is the input sample size after data-weighting adjustment. N eff. is the calculated effective sample size used in the Francis tuning method.

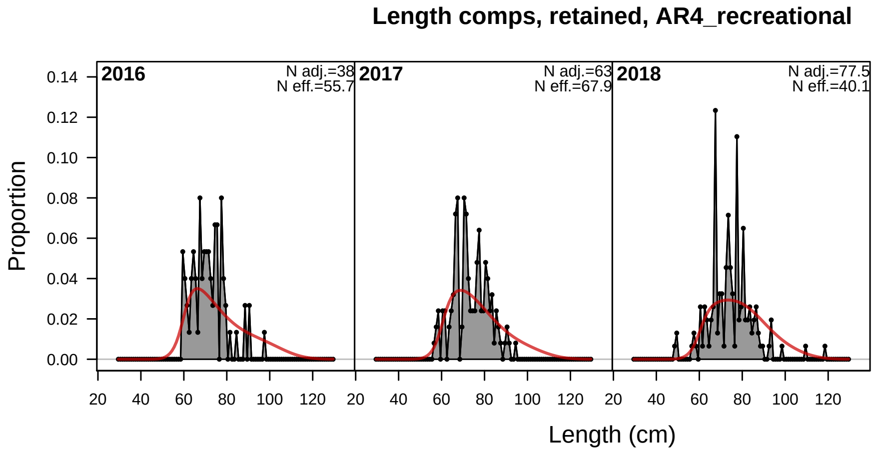


Figure B.12: Length structure for king threadfin in AR4 (recreational)
"N adj." is the input sample size after data-weighting adjustment. N eff. is the calculated effective sample size used in the Francis tuning method.

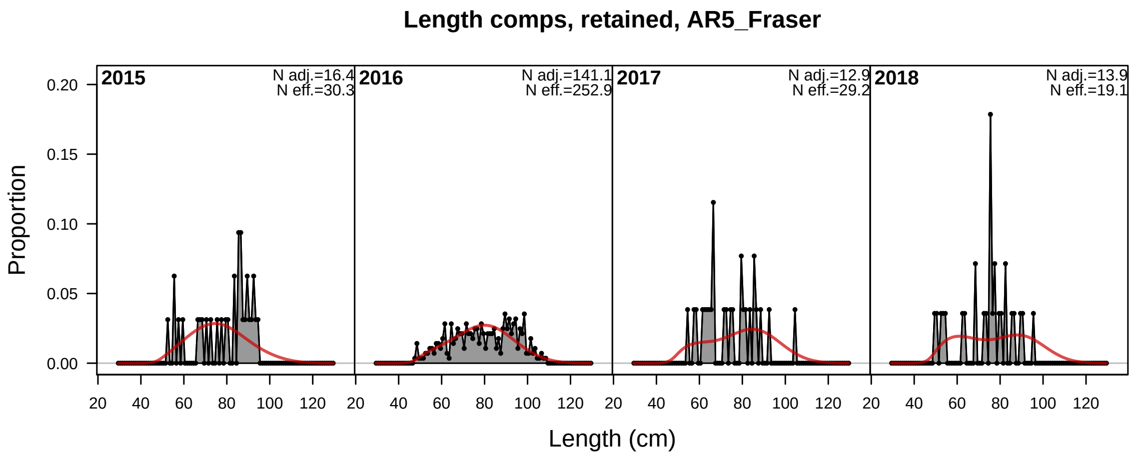


Figure B.13: Length structure for king threadfin in AR5 (Fraser)
"N adj." is the input sample size after data-weighting adjustment. N eff. is the calculated effective sample size used in the Francis tuning method.

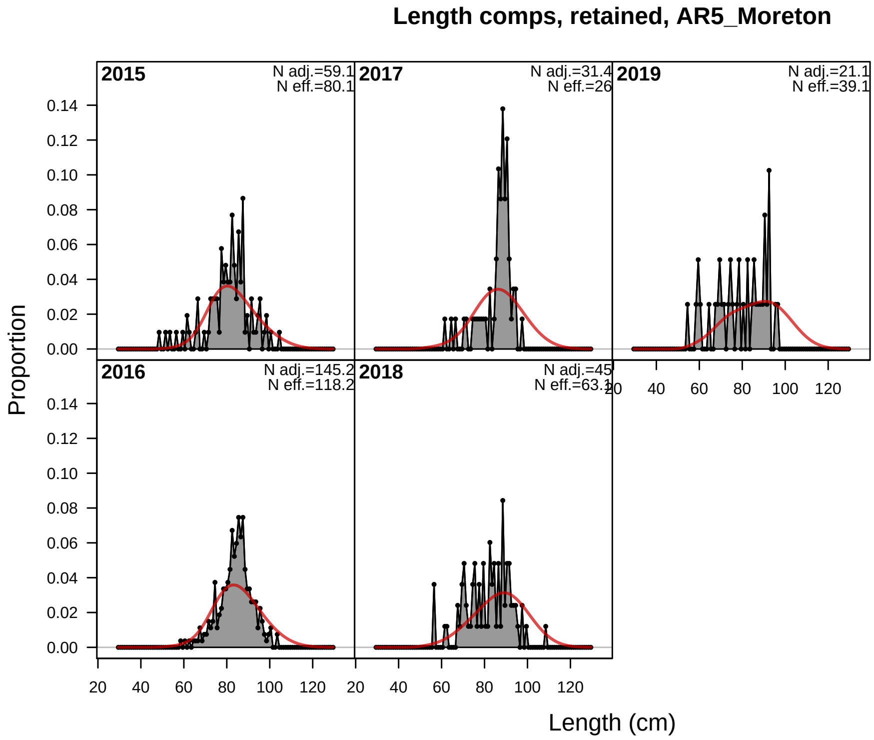


Figure B.14: Length structure for king threadfin in AR5 (Moreton)
"N adj." is the input sample size after data-weighting adjustment. N eff. is the calculated effective sample size used in the Francis tuning method.

B.2.3 Conditional age-at-length compositions

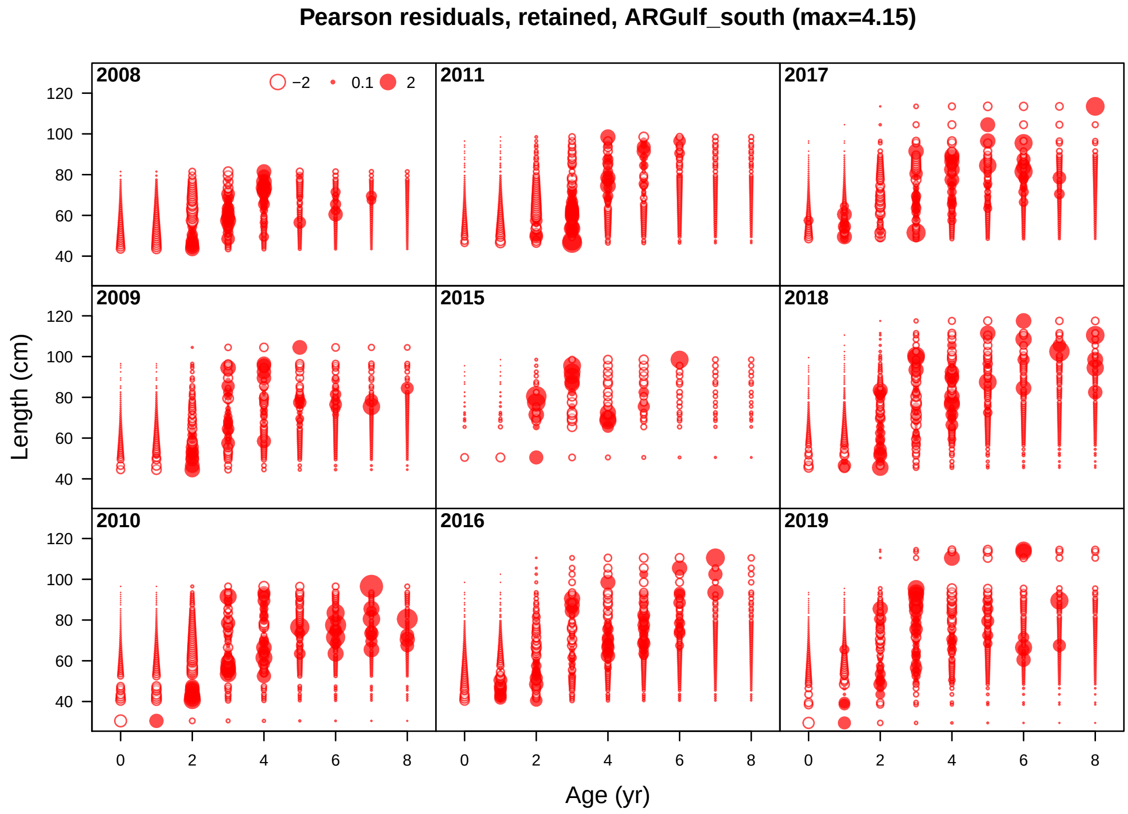


Figure B.15: Pearson residuals for age-at-length compositions for ARGulf south

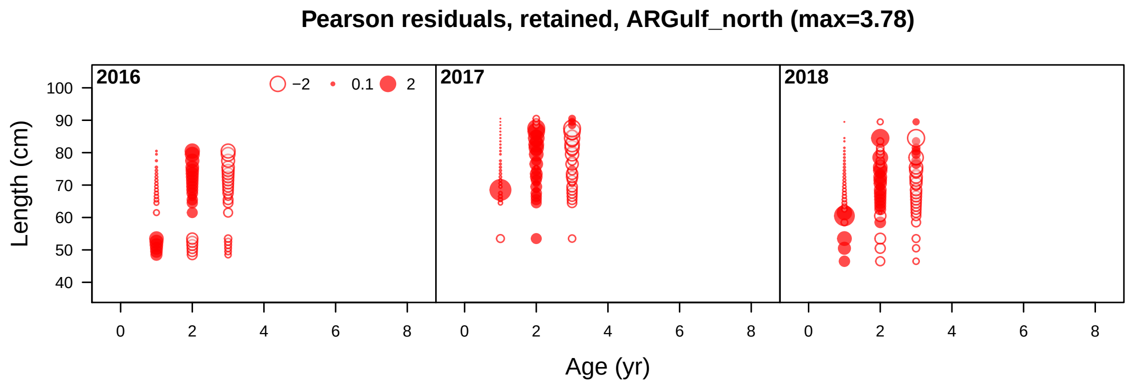


Figure B.16: Pearson residuals for age-at-length compositions for ARGulf north

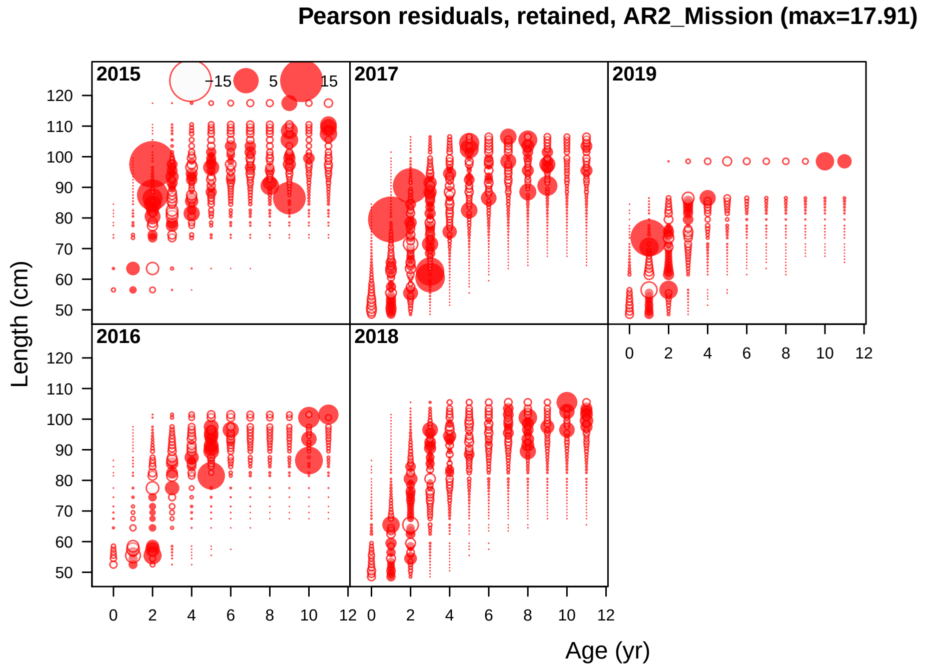


Figure B.17: Pearson residuals for age-at-length compositions for AR2

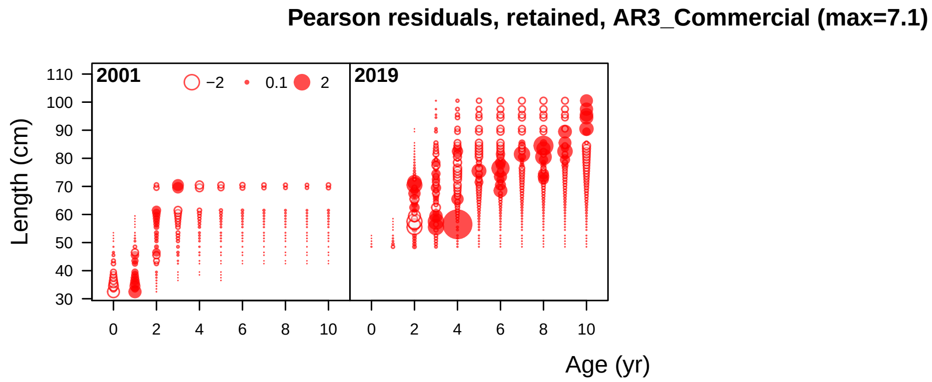


Figure B.18: Pearson residuals for age-at-length compositions for AR3

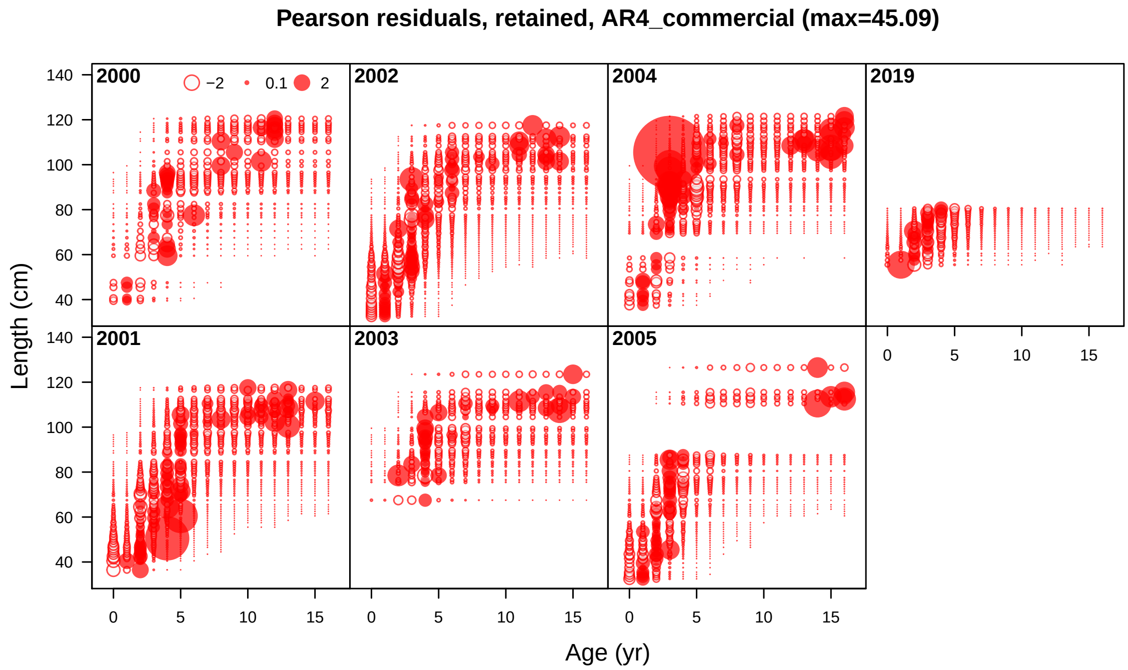


Figure B.19: Pearson residuals for age-at-length compositions for AR4

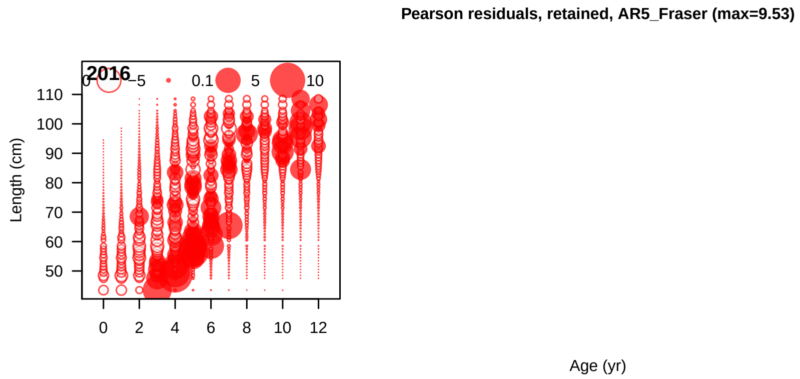


Figure B.20: Pearson residuals for age-at-length compositions for AR5

B.3 Other outputs

B.3.1 Phase plots

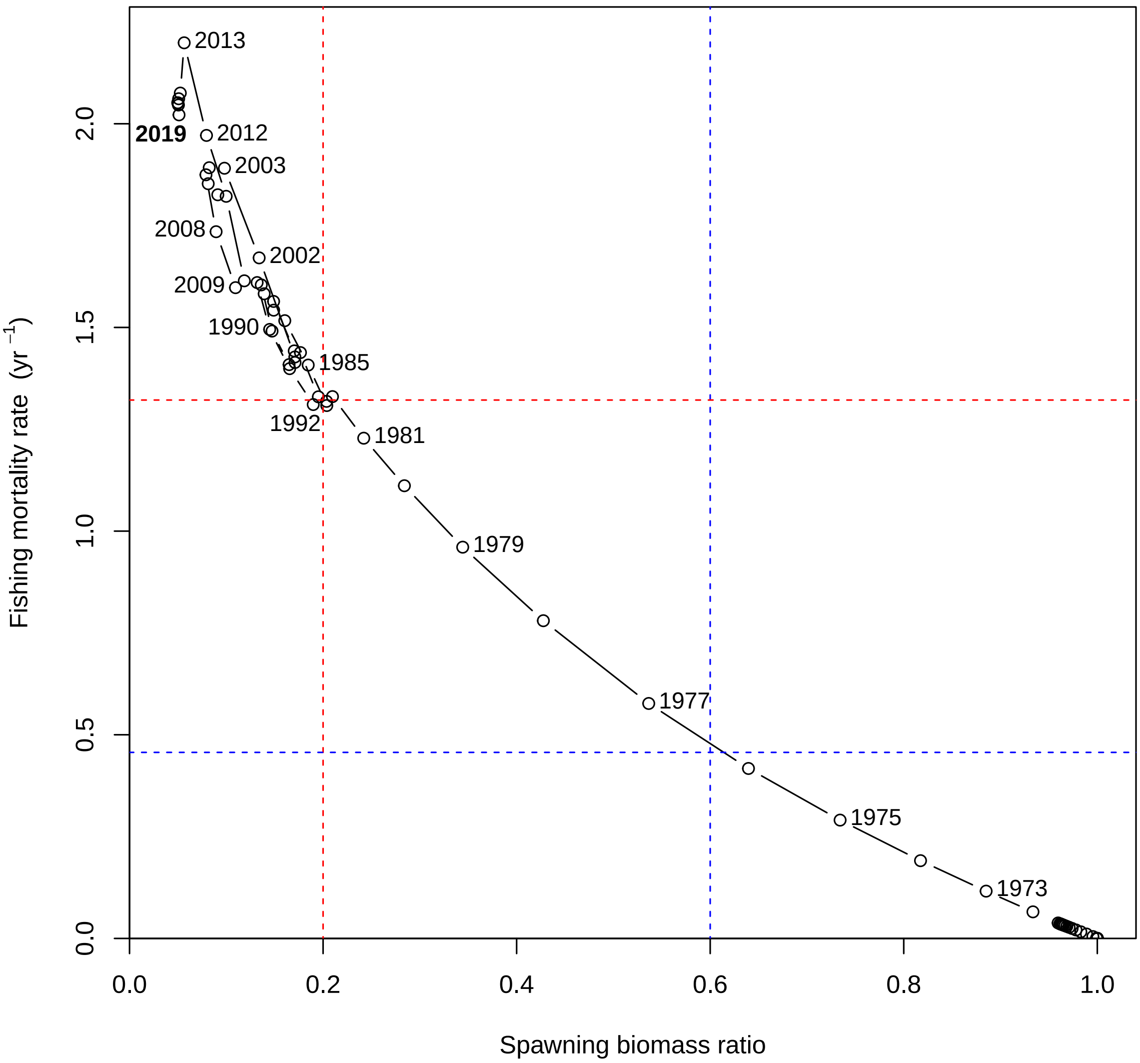


Figure B.21: Phase plot of fishing mortality ratio against biomass ratio for ARGulf
Blue dashed lines are at B_{60} and the corresponding steady-state fishing mortality rate F_{60}, the targets for the Sustainable Fisheries Strategy. Red dashed lines are at B_{20} and F_{20}, levels that would lead the harvest control rule to close the fishery.

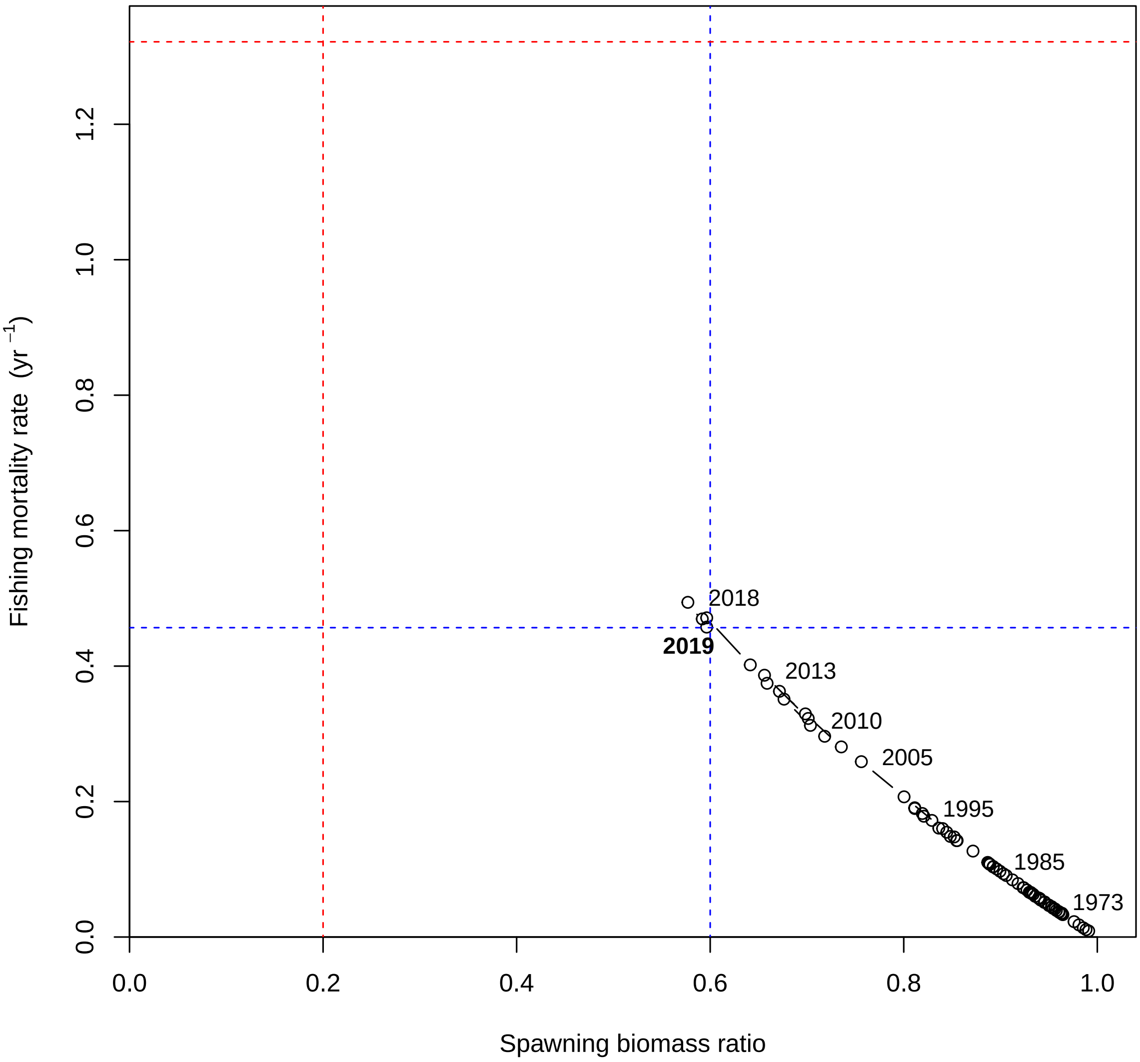


Figure B.22: Phase plot of fishing mortality ratio against biomass ratio for AR2
Blue dashed lines are at B_{60} and the corresponding steady-state fishing mortality rate F_{60}, the targets for the Sustainable Fisheries Strategy. Red dashed lines are at B_{20} and F_{20}, levels that would lead the harvest control rule to close the fishery.

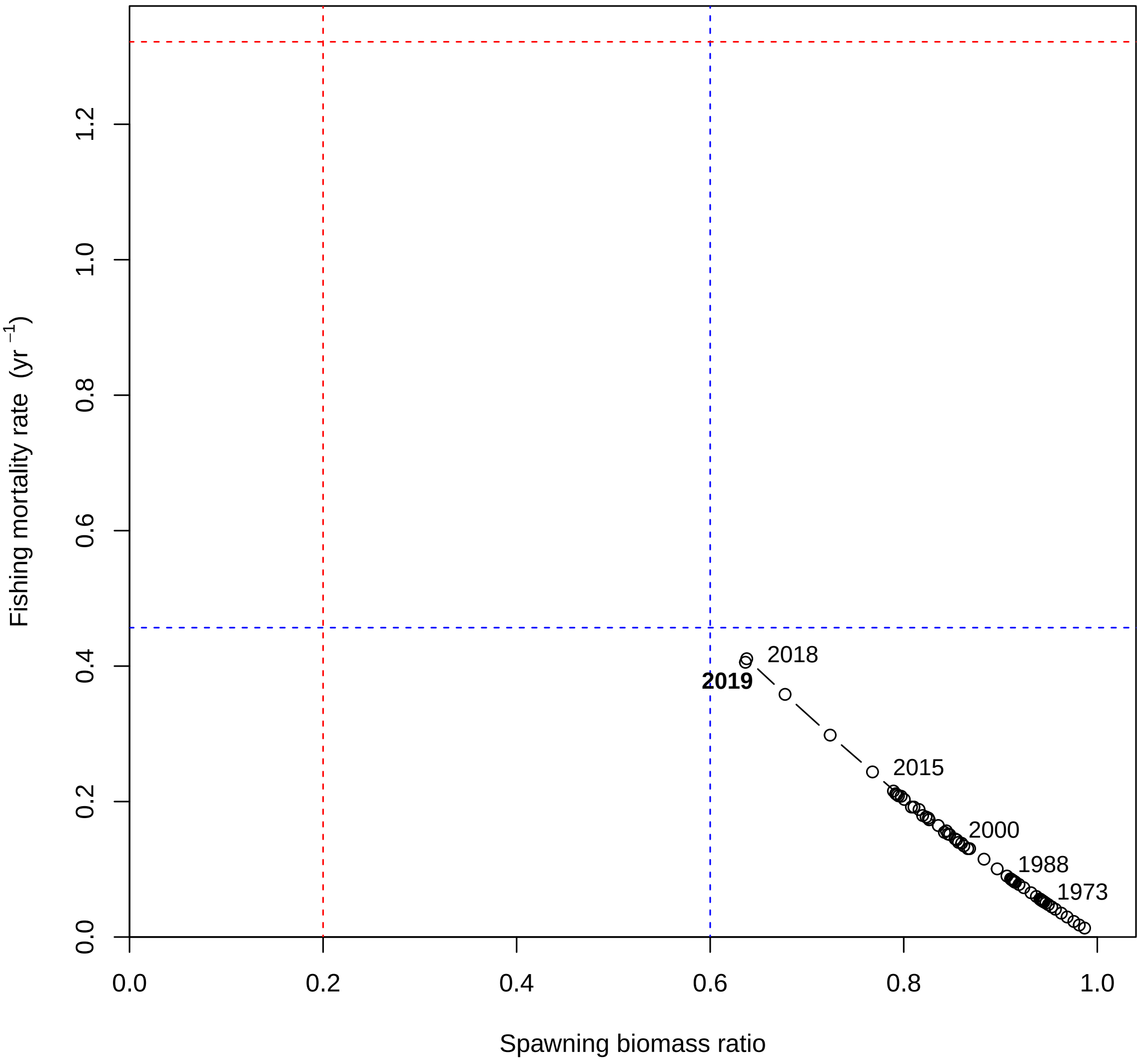


Figure B.23: Phase plot of fishing mortality ratio against biomass ratio for AR3
Blue dashed lines are at B_{60} and the corresponding steady-state fishing mortality rate F_{60}, the targets for the Sustainable Fisheries Strategy. Red dashed lines are at B_{20} and F_{20}, levels that would lead the harvest control rule to close the fishery.

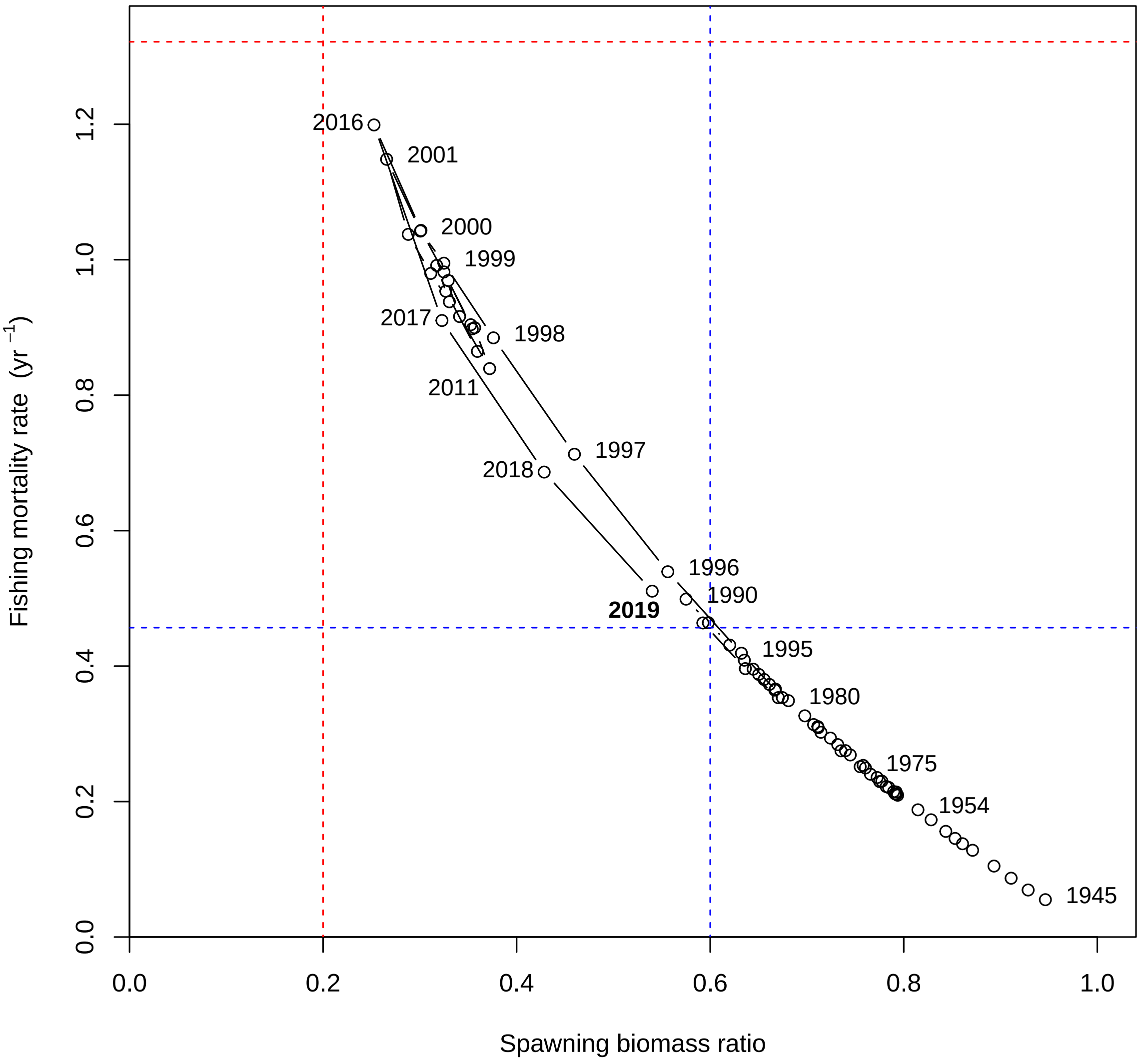


Figure B.24: Phase plot of fishing mortality ratio against biomass ratio for AR4
Blue dashed lines are at B_{60} and the corresponding steady-state fishing mortality rate F_{60}, the targets for the Sustainable Fisheries Strategy. Red dashed lines are at B_{20} and F_{20}, levels that would lead the harvest control rule to close the fishery.

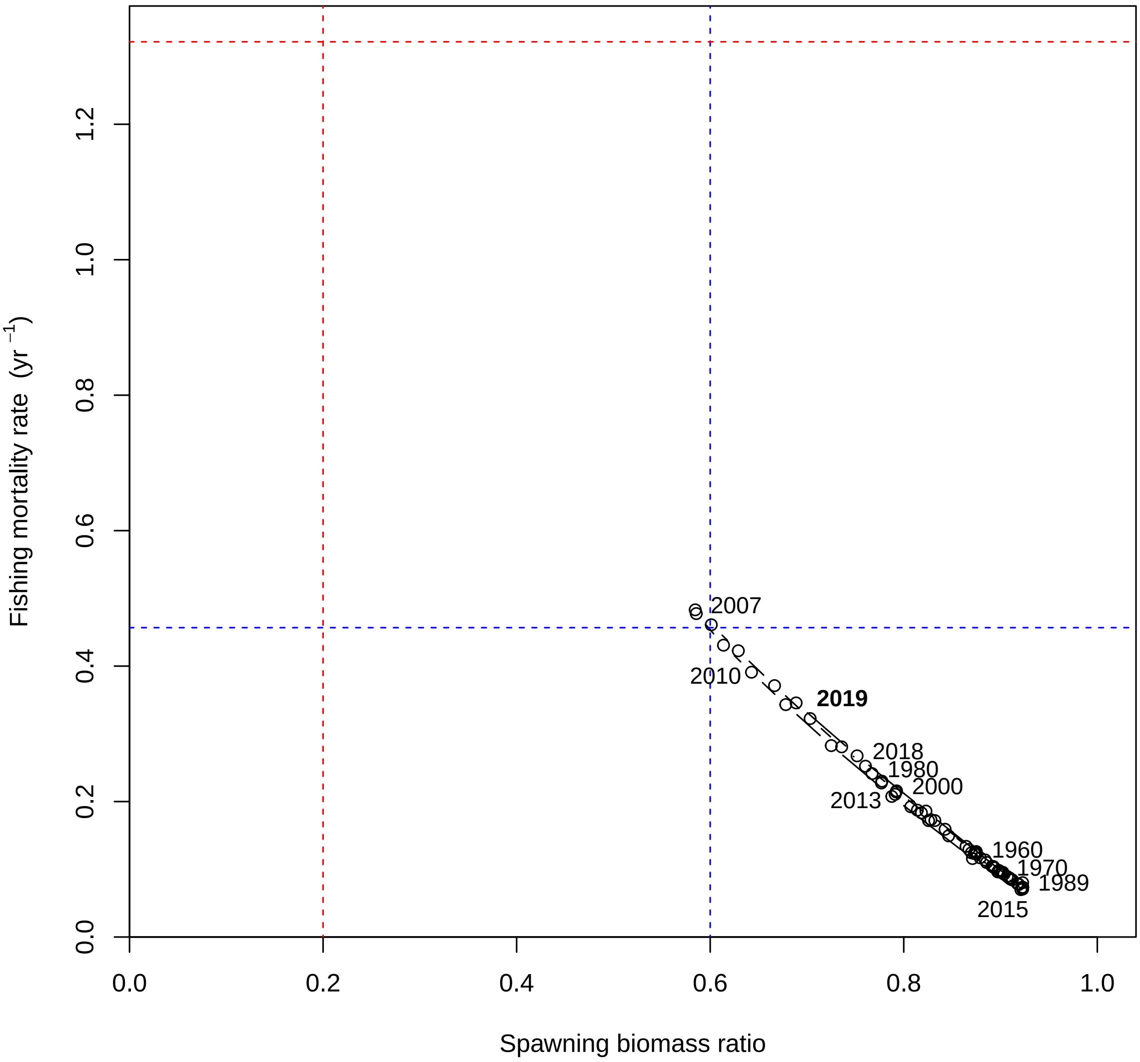


Figure B.25: Phase plot of fishing mortality ratio against biomass ratio for AR5

Blue dashed lines are at B_{60} and the corresponding steady-state fishing mortality rate F_{60}, the targets for the Sustainable Fisheries Strategy. Red dashed lines are at B_{20} and F_{20}, levels that would lead the harvest control rule to close the fishery.

B.3.2 Sensitivity harvest targets

Table B.7: Estimated total harvests and relative biomass levels of king threadfin in ARGulf to rebuild the stock to the target reference point of 60% unfished spawning biomass, following a 20:60:60 control rule with no buffer
"Low" and "High" values are obtained from the most pesimistic and optimistic sensitivity runs, respectively. Sensitivity runs that failed to produce realistic outputs are not presented.

Year	Harvest base (t)	Biomass ratio base	Harvest low (t)	Biomass ratio low	Harvest high (t)	Biomass ratio high
2020	0	0.07	0	0.04	0	0.1
2021	0	0.13	0	0.07	0	0.19
2022	0	0.2	0	0.11	53	0.29
2023	40	0.26	0	0.13	95	0.37
2024	71	0.31	0	0.15	122	0.43
2025	97	0.35	0	0.17	142	0.46
2026	124	0.4	7	0.21	160	0.5
2027	147	0.44	39	0.25	172	0.53

Table B.8: Estimated total harvests and relative biomass levels of king threadfin in AR2 to rebuild the stock to the target reference point of 60% unfished spawning biomass, following a 20:60:60 control rule with no buffer
"Low" and "High" values are obtained from the most pesimistic and optimistic sensitivity runs, respectively. Sensitivity runs that failed to produce realistic outputs are not presented.

Year	Harvest base (t)	Biomass ratio base	Harvest low (t)	Biomass ratio low	Harvest high (t)	Biomass ratio high
2020	45	0.64	14	0.4	49	0.65
2021	44	0.62	15	0.42	47	0.63
2022	43	0.6	17	0.45	46	0.61
2023	43	0.59	18	0.47	46	0.59
2024	43	0.58	20	0.49	46	0.58
2025	43	0.58	21	0.52	46	0.58
2026	43	0.59	22	0.54	46	0.59
2027	43	0.59	23	0.55	46	0.59

Table B.9: Estimated total harvests and relative biomass levels of king threadfin in AR3 to rebuild the stock at the target reference point of 60% unfished spawning biomass, following a 20:60:60 control rule with no buffer
"Low" and "High" values are obtained from the most pesimistic and optimistic sensitivity runs, respectively. Sensitivity runs that failed to produce realistic outputs are not presented.

Year	Harvest base (t)	Biomass ratio base	Harvest low (t)	Biomass ratio low	Harvest high (t)	Biomass ratio high
2020	91	0.66	27	0.43	98	0.67
2021	90	0.66	30	0.47	96	0.66
2022	89	0.66	33	0.5	95	0.66
2023	88	0.65	35	0.52	93	0.65
2024	87	0.64	36	0.54	92	0.64
2025	87	0.63	38	0.55	92	0.63
2026	86	0.63	39	0.57	91	0.63
2027	86	0.63	39	0.58	91	0.62

Table B.10: Estimated total harvests and relative biomass levels of king threadfin in AR4 to rebuild the stock at the target reference point of 60% unfished spawning biomass, following a 20:60:60 control rule with no buffer
"Low" and "High" values are obtained from the most pesimistic and optimistic sensitivity runs, respectively. Sensitivity runs that failed to produce realistic outputs are not presented.

Year	Harvest base (t)	Biomass ratio base	Harvest low (t)	Biomass ratio low	Harvest high (t)	Biomass ratio high
2020	35	0.63	17	0.4	46	0.79
2021	35	0.66	21	0.46	44	0.79
2022	34	0.66	23	0.49	42	0.76
2023	34	0.65	24	0.52	40	0.73
2024	34	0.64	26	0.53	39	0.7
2025	33	0.63	27	0.55	38	0.67
2026	33	0.62	27	0.56	38	0.65
2027	33	0.62	28	0.57	37	0.64

Table B.11: Estimated total harvests and relative biomass levels of king threadfin in AR5 to rebuild the stock at the target reference point of 60% unfished spawning biomass, following a 20:60:60 control rule with no buffer

"Low" and "High" values are obtained from the most pesimistic and optimistic sensitivity runs, respectively. Sensitivity runs that failed to produce realistic outputs are not presented.

Year	Harvest base (t)	Biomass ratio base	Harvest low (t)	Biomass ratio low	Harvest high (t)	Biomass ratio high
2020	35	0.63	6	0.33	125	0.88
2021	35	0.66	8	0.37	116	0.8
2022	34	0.66	10	0.41	110	0.74
2023	34	0.65	12	0.45	107	0.71
2024	34	0.64	13	0.48	104	0.69
2025	33	0.63	14	0.5	102	0.67
2026	33	0.62	15	0.52	101	0.66
2027	33	0.62	15	0.54	100	0.65

B.3.3 Likelihood profile

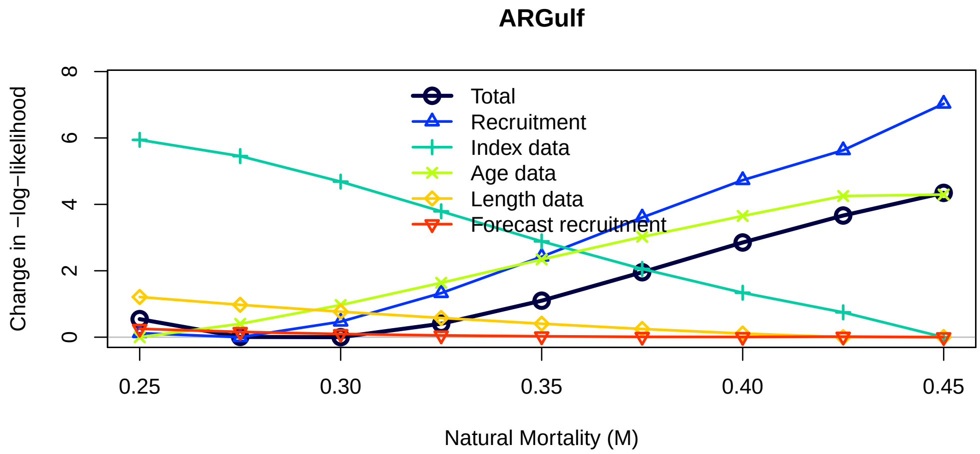


Figure B.26: Likelihood profile for natural mortality rate (M), ranging from 0.25 to 0.45 yr^{-1} for king threadfin in ARGulf

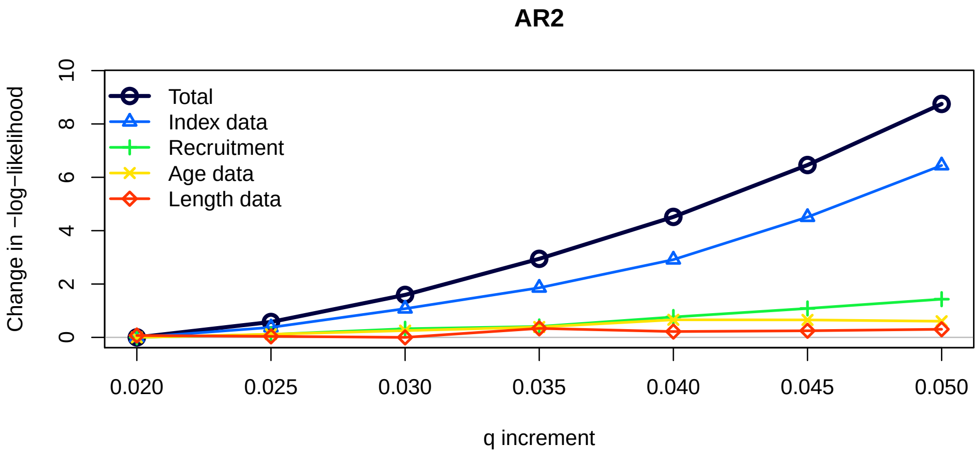


Figure B.27: Likelihood profile for catchability coefficent (q_{inc}), ranging from 0.025 to 0.050 yr^{-1} for king threadfin in AR2

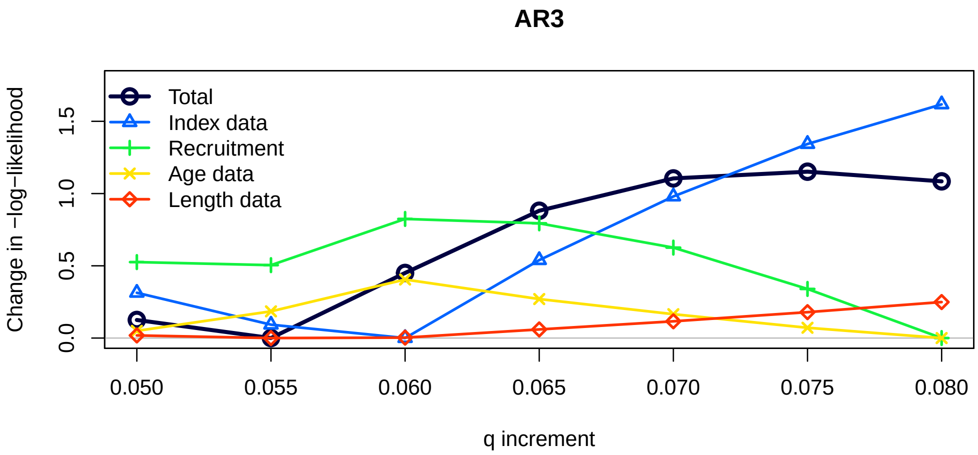


Figure B.28: Likelihood profile for catchability coefficent (q_{inc}), ranging from 0.050 to 0.080 for king threadfin in AR3

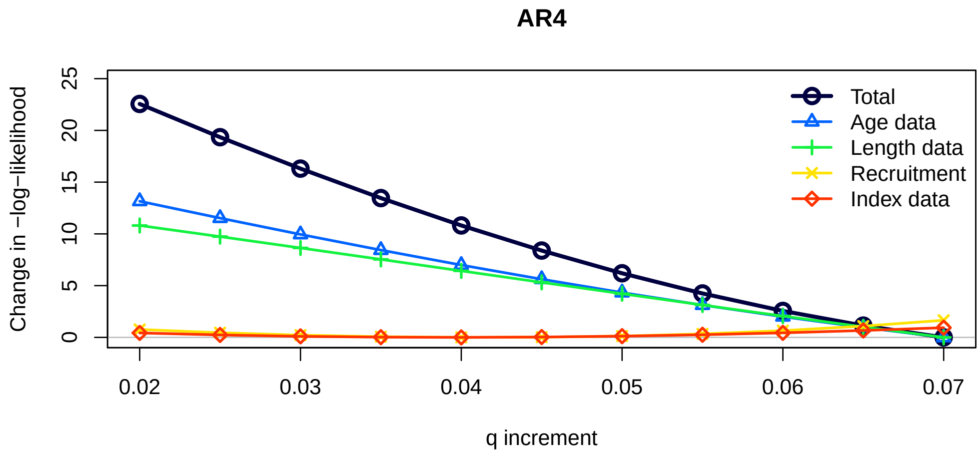


Figure B.29: Likelihood profile for catchability coefficent (q_{inc}), ranging from 0.03 to 0.07 yr^{-1} for king threadfin in AR4

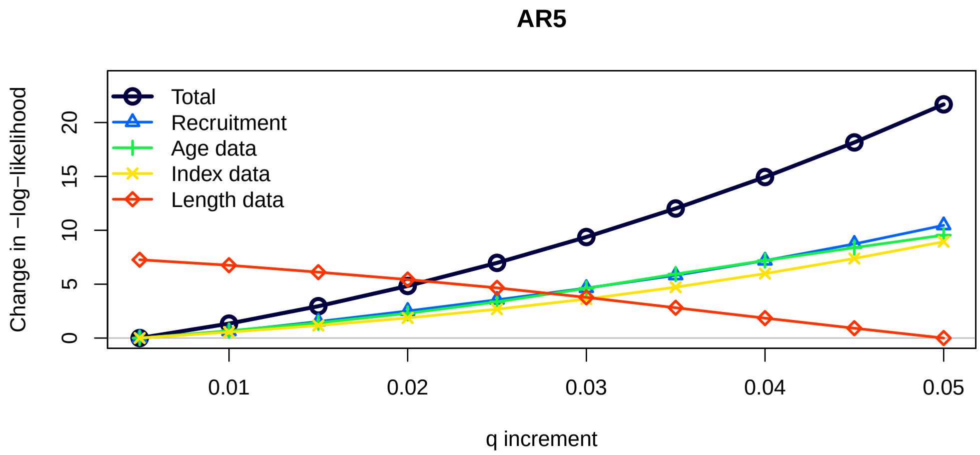


Figure B.30: Likelihood profile for catchability coefficent (q_{inc}), ranging from 0.020 to 0.050 yr^{-1} for king threadfin in AR5

B.3.4 Mortality due to discarding

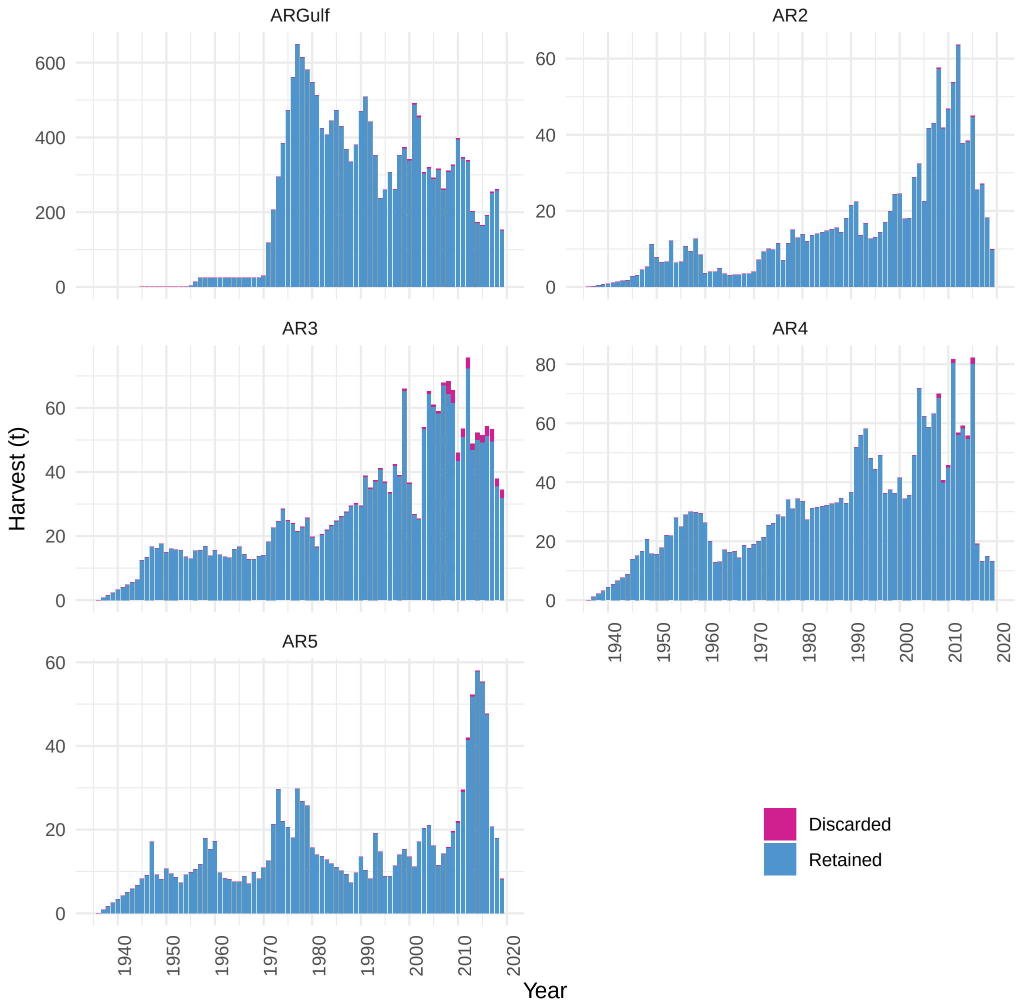


Figure B.31: Estimated total dead biomass, categorised by whether it was retained or discarded, from 1936 to 2019
This is calculated under the model assumption that only fish below minimum legal size were discarded, so the discard fraction changes when the MLS does.

C CPUE time series not used in the model

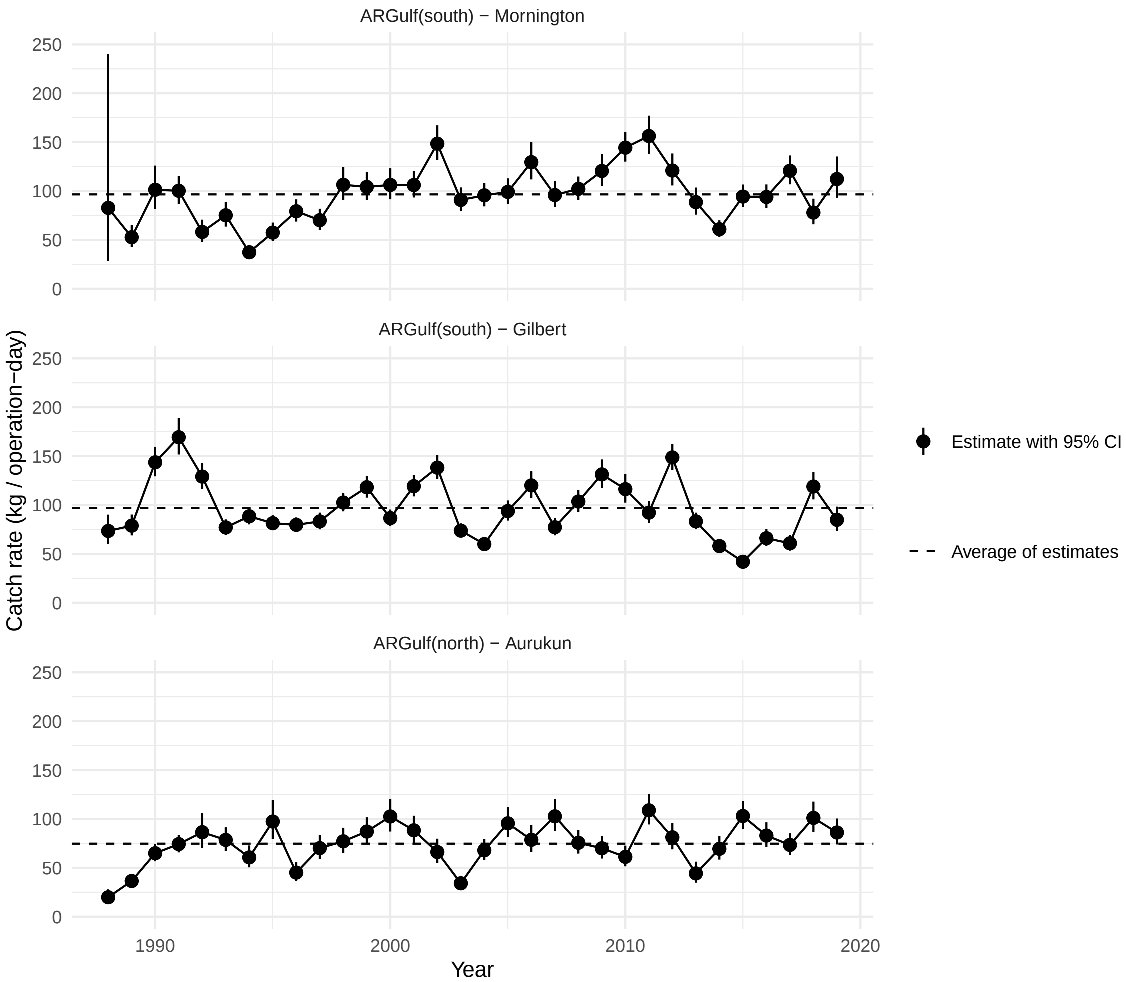


Figure C.1: Other annual standardised catch rates (95% confidence intervals) for king threadfin in ARGulf (not used in the analyses)

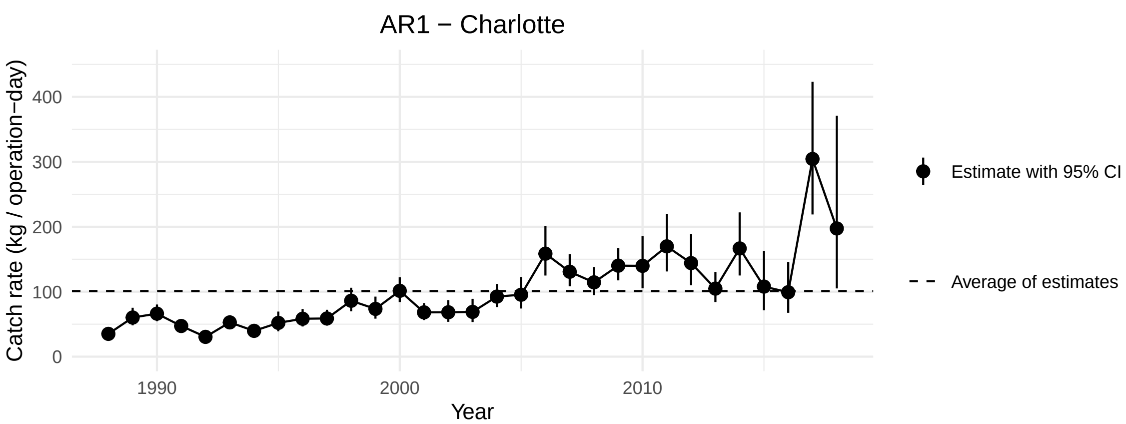


Figure C.2: Annual standardised catch rates (95% confidence intervals) for king threadfin in AR1

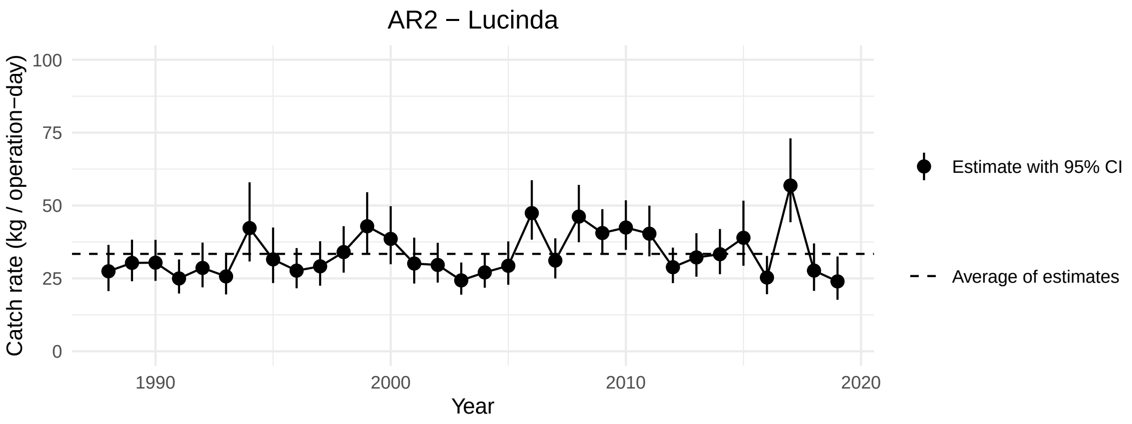


Figure C.3: Other annual standardised catch rates (95% confidence intervals) for king threadfin in AR2 (not used in the analyses)

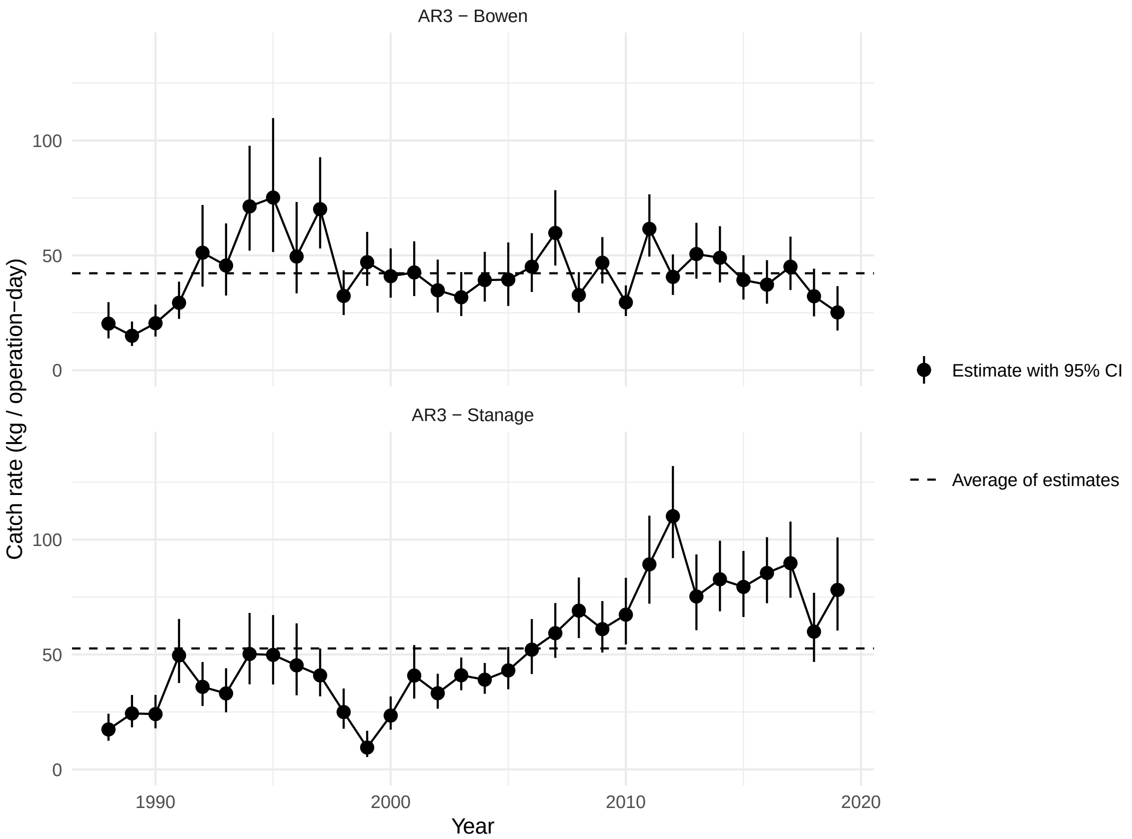


Figure C.4: Other annual standardised catch rates (95% confidence intervals) for king threadfin in AR3 (not used in the analyses)

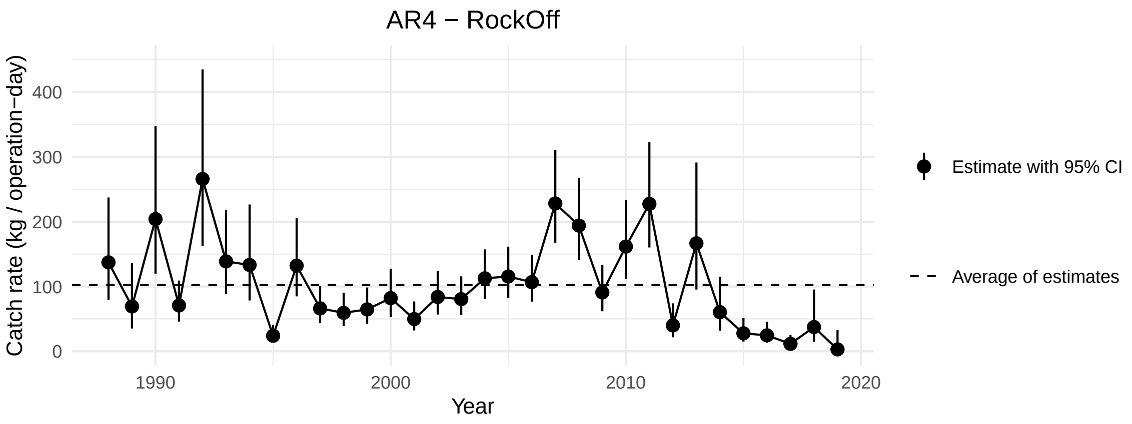


Figure C.5: Other annual standardised catch rates (95% confidence intervals) for king threadfin in AR4 (not used in the analyses)

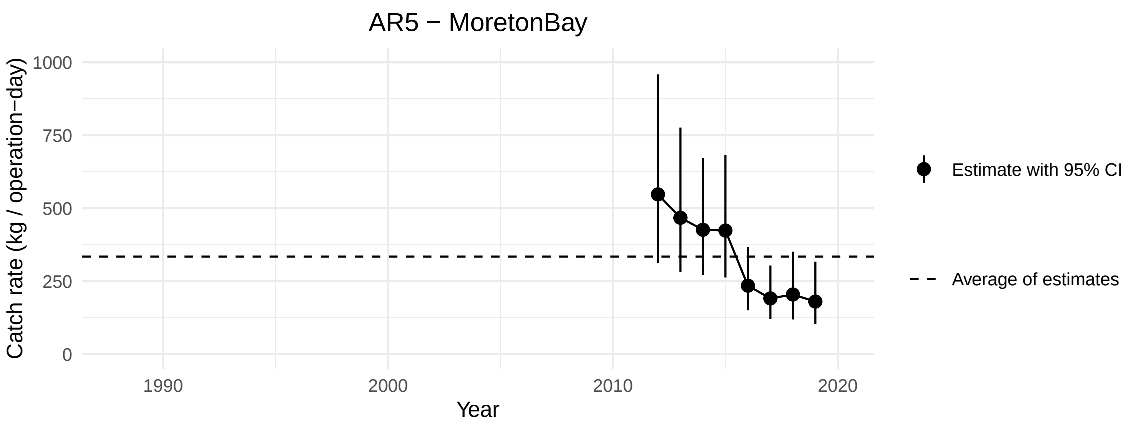


Figure C.6: Other annual standardised catch rates (95% confidence intervals) for king threadfin in AR5 (not used in the analyses)

D Preliminary analysis of Boat Ramp Survey catch rates

D.1 Methods

As in the commercial catch-rate analysis, Boat Ramp Survey data were collated to one record per fisher-day. Records were included in the analysis when either king threadfin or blue threadfin were caught. Some of these records provided zero catches of king threadfin.

The analysis used the quasi-Poisson generalised linear model with log link. This model is simpler than the quasi-negative-binomial model and its residual plots showed no need for any extra variance scaling.

Explanatory variables included in the GLM were year, calendar month and fishing location, all as factors. The recorded effort measures, comprising the number of fishers in the boat and the number of hours fished, were not statistically significant, so were excluded. Year was specified as financial year (July to June) because this better matched the availability of the data, which ran from November 2015 to June 2019.

Only retained catches were analysed. The surveys also recorded numbers of released fish but these were not validated by Fisheries Queensland staff, as releases occurred before the boat returned to the boat ramp.

This analysis can be revisited in the next assessment of king threadfin, when more years of data will be available and extra potential associated species can be included in addition to blue threadfin.

D.2 Results

The standardised Boat Ramp Survey catch rate for AR4 is plotted in Figure D.1. It shows a steep increase in catch rate from 0.87 fish per trip in 2015–16 to 2.29 fish per trip in 2017–18, a factor of more than 2.6. The catch rate fell back to 1.49 fish per trip in 2018–19, for unknown reasons. The surveyed number of king threadfin was very low in that year, only 9 fish versus 152 in 2017–18.

This result provides support to the biomass results for AR4 (Section 3.2.4 and Figure 3.27), which show a sharp rise in biomass after the introduction of the Net Free Zone in this Region.

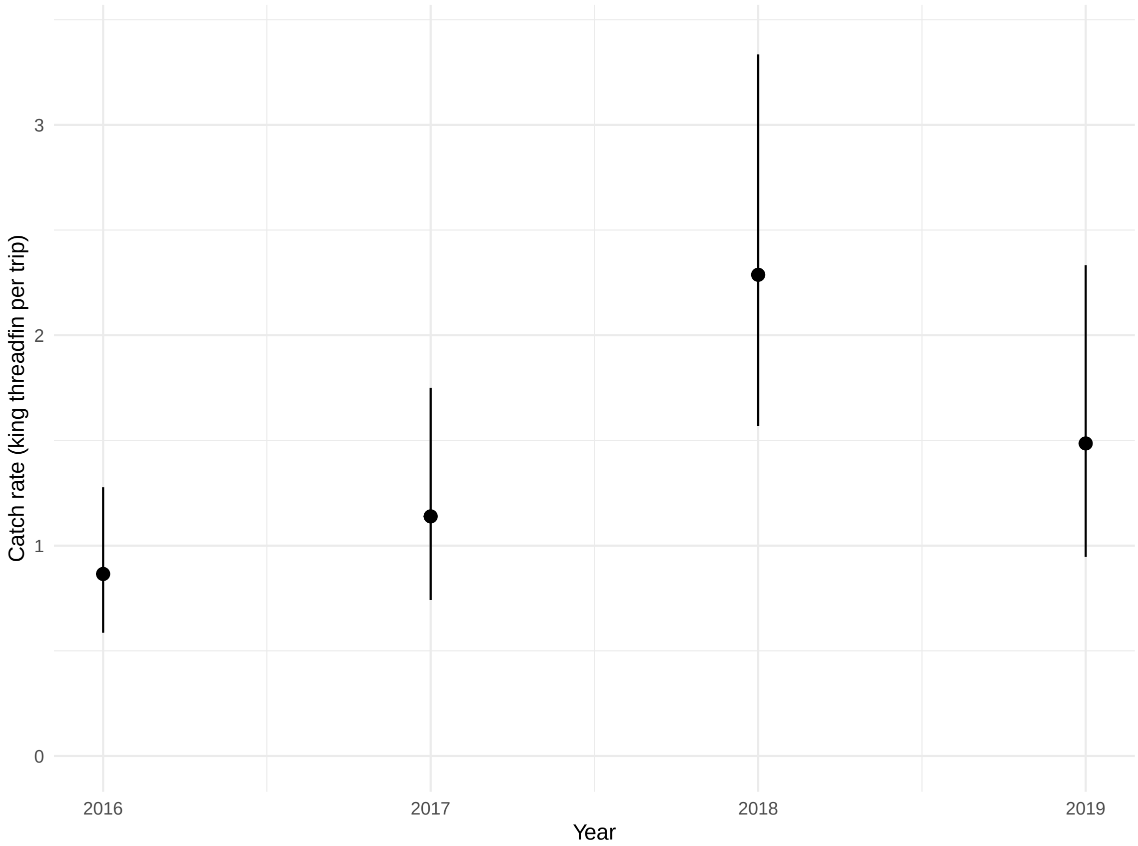


Figure D.1: Annual standardised Boat Ramp Survey catch rates for king threadfin from Assessment Region AR4, financial years 2015–16 to 2018–19, with 95% confidence intervals