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Resource Assessment Report for Australian Herring in Western Australia

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Executive Summary

Australian herring, *Arripis georgianus* (Valenciennes 1831) is distributed from Shark Bay in Western Australia, and as far east as Victoria. The majority of the adult spawning biomass resides on the west coast of Western Australia. These fish spawn in autumn and the eggs and larvae are transported eastward via currents and wind action. Larvae and juveniles settle in the east where they grow. When maturing in their second or third year, herring migrate back to Western Australia to spawn. Multiple methods have been used to confirm herring are a single stock, although there are spatial differences in some biological parameters.

Herring have a long history of commercial exploitation, and in Western Australia, have been taken in very large quantities, near to 1500 t in the early 1990's. The vast majority of the catch has occurred on the south coast, facilitated by the highly efficient herring trap net method that captures mature and maturing fish migrating west for spawning. Since the closure of the herring trap net fishery in 2015, the average catch has been about 75 t (commercial), of which the majority has been taken by five fisheries: South West Beach Net (~28%), Cockburn Sound Fish net (~27%), Open Access Fishing on the South Coast (~18%), South Coast Estuarine managed fishery (~18%), and West Coast Estuarine Managed Fishery (~7%). Herring is also an important recreational species; it has consistently been the top caught shore-based species by recreational anglers in the metropolitan region (~9 t in 2021) and is the 3rd most caught species by boat in the South and West (~13 t in 2019).

Three contemporary stock assessments of herring have been undertaken, the outcomes of which indicated the catch was sustainable in 2000, a high/severe risk in 2013, and a medium risk and recovering in 2018. The current assessment follows the Department's risk-based *Weight of Evidence* approach, which considered catch (including catch-MSY (maximum sustainable yield) analyses), effort, catch distribution, catch rates (raw and standardised), vulnerability and susceptibility to fishing (PSA), age and length composition data, catch curve estimates of (long-term) fishing mortality, age and length-based spawner potential ratio (SPR) estimates, stock-recruitment-environment relationships, and a dynamic, age-structured model.

Herring is a short-lived and productive species that has experienced more than a decade of low catch, well below that of estimates of MSY derived from different methods (Catch-MSY analysis produced an estimate for MSY of 1199 t (95% CLs = 960 -1431 t) for Australia, 218 t (95% CLs = 175 – 253) for the west coast, and 667 t (95% CLs = 525 – 807) for the south coast). Length composition data showed no truncation in recent years that could be considered indicative of overfishing. The increasing catch rates (until closure in 2015) for the trap net fishery on the south coast (which is composed largely of recent recruits), the South Australian catch rate which has remained within an acceptable range over a long period, and age structure data, all demonstrate that recruitment failure/overfishing has not occurred. Recent SPR estimates further support an adequate level of spawning stock. Preliminary analyses investigating the influence of environment on recruitment (empirical and model-based) showed contrasting results and more work is required. Overall, the lines of evidence indicate the stock is not experiencing overfishing and is not overfished, therefore risk assessment indicates that minor stock depletion is considered likely.

Based on the information available, the current risk level for herring is estimated to be LOW. The low risk reflects acceptable levels of fishing mortality, recruitment, and spawning stock biomass. Therefore, the overall Weight of Evidence assessment indicates the stock has recovered to a level at or around the target and the status of the stock is considered adequate

The current herring risk score of low allows for a moderate increase in catch, which would result in a medium risk status. An appropriate way to test the response of the herring fishery is within an adaptive management framework that reviews the stock status after the increase in catch has occurred.

To reduce uncertainties in subsequent assessments, the following areas should be examined: further investigation of the role of environment on recruitment dynamics; development of a sample collection program that is considered to provide representative age and length data for the stock; a detailed investigation into the ability of the fishery-independent recruitment index to provide information on stock status; and further consideration given to estimates of natural mortality, including the influence of salmon predation.

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List of Abbreviations

CLs	Confidence Limits
CSFNMF	Cockburn Sound Fish Net Managed Fishery
DoF	Department of Fisheries (Western Australia)
DPIRD	Department of Primary Industries and Regional Development (Western Australia)
EBFM	Ecosystem-Based Fisheries Management
ESD	Ecologically Sustainable Development
EPBC	Environment Protection and Biodiversity Conservation (Act)
FBL	Fishing Boat Licence
FRMA	Fish Resources Management Act
GCB	Gascoyne Coast Bioregion
LBSPR	Length Based Spawning Potential Ratio
LML	Legal Minimum Length
MSC	Marine Stewardship Council
RAP	Research Angler Program
RFBL	Recreational fishing from boat licence
SA	South Australia
SCB	South Coast Bioregion
SCEMCF	South Coast Estuarine Managed Commercial Fishery
SCEMF	South Coast Estuarine Managed Fishery
SCTNF	South Coast Trap Net Fishery
SAFS	Status of Australian Fish Stocks
SWBS	South West Beach Seine
SWBSF	South West Beach Seine Fishery
VFAS	Voluntary Fishery Adjustment Scheme
WOE	Weight of Evidence

WA	Western Australia
WCB	West Coast Bioregion

1 Scope

This document provides a cumulative description and assessment of the Australian herring (referred to as herring throughout this document), *Arripis georgianus* (Valenciennes 1831), resource and all of the fishing activities (i.e., fisheries / fishing sectors) affecting this resource in Western Australia (WA). The resource comprises a single species, herring, caught within WA, primarily the West Coast and South Coast bioregions, but considers all factors affecting the stock including catch from other States.

Herring are primarily captured by i) commercial netting (gill/haul/seine/trap net) fisheries on ocean beaches and in estuaries, and ii) recreational line fishing by shore- and boat-based fishers in estuaries and coastal waters.

2 How the Department Operates

Fisheries management in WA has evolved over the last 40-50 years from a focus on managing catch of target species by commercial fishers to a fully integrated Ecosystem-Based Fisheries Management (EBFM) approach, which ensures that fishing impacts on the overall ecosystems are appropriately assessed and managed (Fletcher et al. 2010). In line with the principles of Ecologically Sustainable Development (ESD; Fletcher 2002), the EBFM approach also recognises that the economic and social benefits of fishing to all users must be considered.

Implementation of EBFM involves a risk-based approach to monitoring and assessing the cumulative impacts on WA's aquatic resources from all fishing activities (commercial, recreational, customary), operating at a bioregional or ecosystem level. The level of risk to each resource is used as a key input to the Department of Primary Industries and Regional Development (DPIRD) Risk Register, which is an integral component of the annual planning cycle for assigning activity priorities (research, management, compliance, education etc.) across each bioregion. A summary of the Department's risk-based planning annual cycle that is delivering EBFM in the long-term is provided in Figure 2.1.

To ensure that management is effective in achieving the relevant ecological, economic and social objectives, formal harvest strategies are being developed for each resource. These harvest strategies outline the performance indicators used to measure how well objectives are being met and set out control rules that specify the management actions to be taken in situations when objectives are not being met. The WA harvest strategy policy (DoF 2015) has been designed to ensure that the harvest strategies cover the broader scope EBFM and thus considers not only fishing impacts of target species but also other retained species, bycatch, endangered, threatened and protected (ETP) species, habitats and other ecological components (Fletcher et al. 2016).

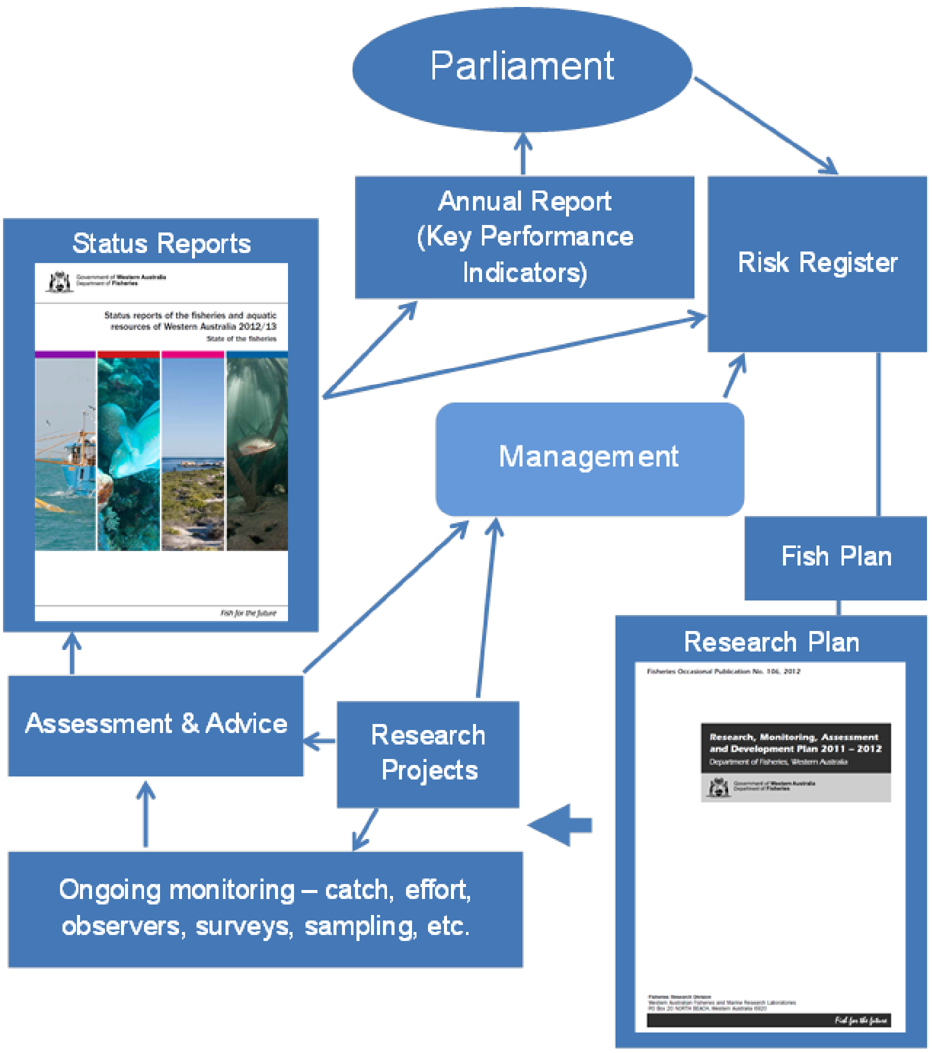

Figure 2.1. An outline of the risk-based planning cycle used for determining Departmental priorities and activities

3 Aquatic Environment

3.1 West Coast Bioregion

The marine environment of the West Coast Bioregion between 27°00'S (north of Kalbarri) and 115°30' E (west of Augusta) is predominantly a temperate oceanic zone, but it is heavily influenced by the Leeuwin Current, which transports warm tropical water southward along the edge of the continental shelf. The Integrated Marine and Coastal Regionalisation for Australia (IMCRA V 4.0) scheme identifies four meso-scale regions, or parts thereof, within this bioregion: Zuytdorp, Abrolhos Islands, Central West Coast and Leeuwin Naturaliste (Figure 3.1).

Most of the fish stocks of the region are temperate, in keeping with the coastal water temperatures that range from 18° C to about 24° C. The Leeuwin Current is also responsible for the existence of the unusual Abrolhos Islands coral reefs at latitude 29° S and the extended southward distribution of many tropical species along the West Coast and even into the South Coast.

The Leeuwin Current system, which can be up to several hundred kilometres wide along the West Coast, flows most strongly in autumn/winter (April to August) and has its origins in ocean flows from the Pacific through the Indonesian archipelago. The current is variable in strength from year-to-year, flowing at speeds typically around 1 knot, but has been recorded at 3 knots on occasions. The annual variability in current strength is reflected in variations in Fremantle sea levels and is related to El Niño or Southern Oscillation events in the Pacific Ocean.

Weaker counter currents on the continental shelf (shoreward of the Leeuwin Current), such as the Capes Current that flows northward from Cape Leeuwin as far as Shark Bay, occur during summer and influence the distribution of many of the coastal finfish species.

The most significant impact of the clear, warm, low-nutrient waters of the Leeuwin Current is on the growth and distribution of the temperate seagrasses. These form extensive meadows in protected coastal waters of the West Coast Bioregion, generally in depths of 20 m (but up to 30 m), and act as major nursery areas for many fish species and particularly for the western rock lobster stock.

The West Coast is characterised by exposed sandy beaches and a limestone reef system that creates surface reef lines, often about 5 kilometres off the coast. Further offshore, the continental shelf habitats are typically composed of coarse sand interspersed with low limestone reef associated with old shorelines. There are few areas of protected water along the west coast, the exceptions being within the Abrolhos Islands, the leeward sides of some small islands off the Midwest Coast, plus behind Rottnest and Garden Islands in the Perth metropolitan area.

The two significant marine embayments in the West Coast are Cockburn Sound and Geographe Bay. Along the West Coast, there are four significant estuarine systems – the Swan/Canning, Peel/Harvey, and Leschenault estuaries, and Hardy Inlet (Blackwood estuary). All of these are permanently open to the sea and form an extension of the marine environment except when freshwater run-off displaces the oceanic water for a short period in winter and spring.

Southward of Cape Naturaliste, the coastline changes from limestone to predominantly granite and becomes more exposed to the influences of the Southern Ocean.

3.2 South Coast Bioregion

The continental shelf waters of the South Coast Bioregion (Figure 3.1) are generally temperate but low in nutrients, due to the seasonal winter presence of the tropical Leeuwin Current and limited terrestrial run-off. Sea surface temperatures typically range from approximately 15°C to 21°C, which is warmer than would normally be expected in these latitudes due to the influence of the Leeuwin Current. The effect of the Leeuwin Current, particularly west of Albany, limits winter minimum temperatures (away from terrestrial effects along the beaches) to about 16 to 17°C. Summer water temperatures in 2012/13 were at a record high, which may have affected the recruitment of some species.

Fish stocks in this region are predominantly temperate, with many species' distributions extending right across southern Australia. Tropical species are occasionally found, which are thought to be brought into the area as larvae.

The South Coast is a high-energy environment, heavily influenced by large swells generated in the Southern Ocean. The coastline from Cape Leeuwin to Israelite Bay is characterised by white sand beaches separated by high granite headlands. East of Israelite Bay, there are long sandy beaches backed by large sand dunes, an extensive length (160 km) of high limestone cliffs and mixed arid coastline to the South Australian border. There are few large areas of protected water along the South Coast, the exceptions being around Albany and in the Recherche Archipelago off Esperance.

Along the western section of the coastline that receives significant winter rainfall, there are numerous estuaries fed by winter-flowing rivers. Several of these, such as Walpole/Nornalup Inlet and Oyster Harbour, are permanently open, but most are closed by sandbars and open only seasonally after heavy winter rains. The number of rivers and estuaries decreases to the east as the coastline becomes more arid. While these estuaries, influenced by terrestrial run-off, have higher nutrient levels, their outflow to the ocean does not significantly influence the low nutrient status of coastal waters.

The marine geography of the South Coast is similar to the coastline, having fine, clear sand sea floors interspersed with occasional granite outcrops and limestone shoreline platforms and sub-surface reefs.

A mixture of seagrass and kelp habitats occurs along the South Coast, with seagrass more abundant in protected waters and some of the more marine estuaries. The kelp habitats are diverse but dominated by the relatively small *Ecklonia radiata*, rather than the larger kelps expected in these latitudes where waters are typically colder and have higher nutrient levels.

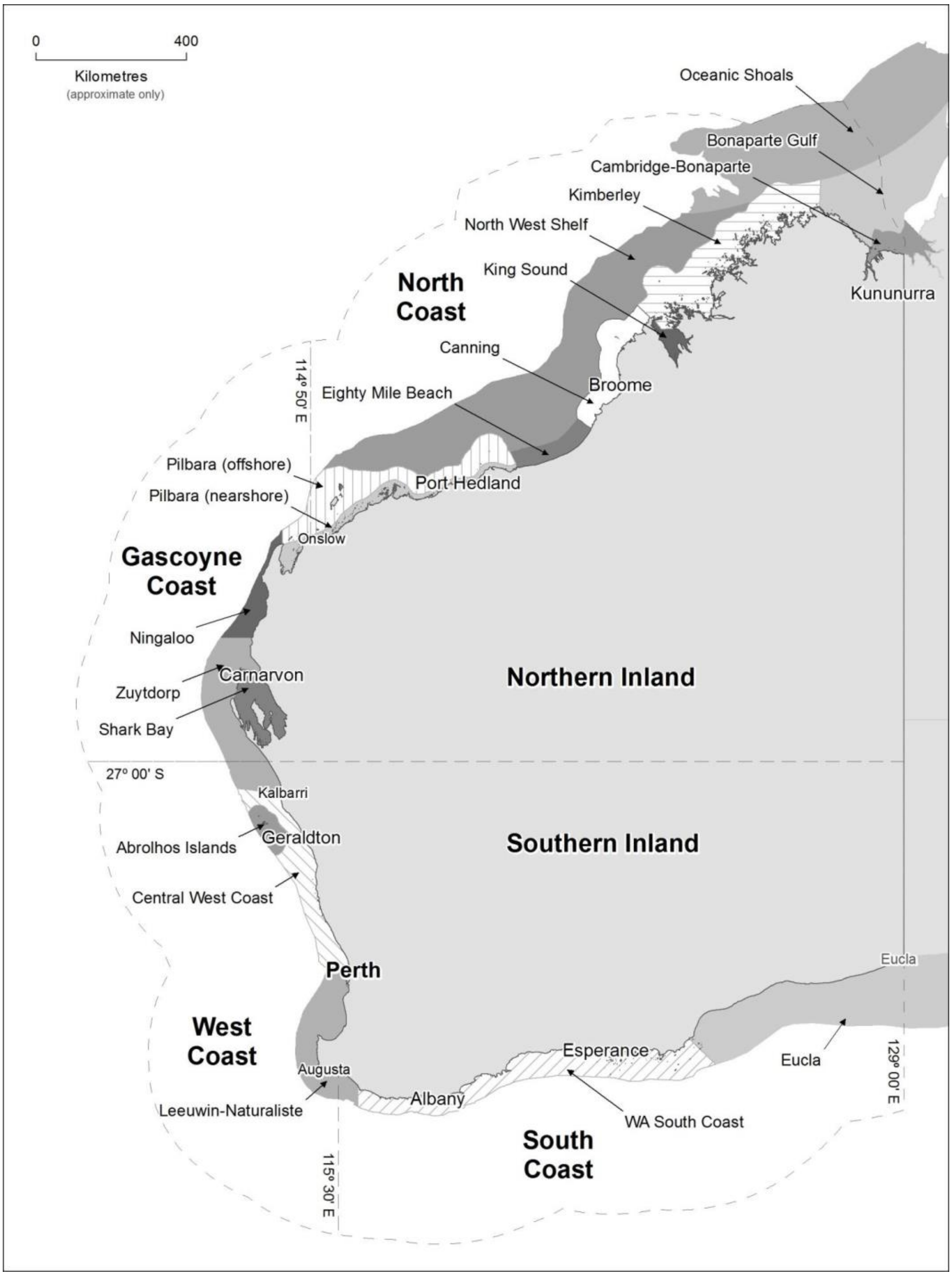

Figure 3.1. Location of bioregions within WA

4 Resource Description

The herring resource covers the entire herring stock, including all fish in WA waters and take of immature fish from other State waters

5 Species Description

Species description of Australian Herring has been comprehensively covered by Smith and Brown (2014) and references therein. The following information is largely a summary of that information.

5.1 Australian herring (*Arripis georgianus*)

Figure 5.1. The Australian herring, *Arripis georgianus*. Illustration © R. Swainston (www.anima.net.au)

5.1.1 Taxonomy and Distribution

Herring (Figure 5.1) are members of the family Arripidae, which contains a single genus with four species. Herring have a silvery head and body, with slightly oblique rows of yellow-brown spots forming faint bars, transparent fins and the caudal fin lobes are tipped with black (Paulin 1993). Herring are distinguished from other members in the family by their smaller size, they appear similar to juvenile salmon, but can be differentiated by their larger eye and more rounded head and scales that are noticeably rough to touch (Gomon et al. 1994).

Herring is endemic to southern Australia and occur from Shark Bay in Western Australia (WA) south and eastwards to Victoria (Figure 5.2).

Figure 5.2. Distribution map of Australian herring (https://fishesofaustralia.net.au/home/species/405)

5.1.2 Stock Structure

The herring population is composed of a single genetic stock across its range (Ayvazian et al. 2000). This has been demonstrated by three stock delineation methods: tag-recapture (Ayvazian et al. 2004, Malcolm 1973), analysis of otolith chemistry (Ayvazian et al. 2004) and genetic studies (Ayvazian et al. 2004, Moore and Chaplin 2013).

Several tagging studies have been conducted to examine movement patterns, with consensus that the movements of recaptured fish indicated a net westward (along the south coast) and northward (along the west coast) movement of the stock (Ayvazian *et al*. 2004, Malcolm 1973, Smith and Brown, 2014).

Stable oxygen isotope ratios in otolith carbonate were determined for *A. georgianus* collected from sites located between Dongara (WA) and Port Adelaide (SA) (Ayvazian et al. 2004). The study found that at south-western sites, the oxygen isotope values of otolith carbonate did not have the same signature as the water from which they were captured, indicating that prior movement had occurred and suggested a highly migratory species with a small proportion of individuals showing partial residency.

Allozyme electrophoresis on fish collected from 11 sites between Jurien Bay (WA) to Port Philip Bay (Victoria) was conducted and no evidence of population genetic subdivision was found (Ayvazian et al. 2004). Moore and Chaplin (2013) provided stronger evidence of genetic homogeneity in *A. georgianus*. They used fragment length polymorphisms at two to four nDNA intron loci in samples of *A. georgianus* collected from across their entire range; this study also found no evidence of genetic subdivision. WCB, west coast bioregion; SCB, south coast bioregion.

5.1.3 Life History

Table 5.1. Summary of biological parameters for herring

Parameter	Value(s)	Comments / Source(s)
Growth parameters		Smith et al. (2013)
L_∞ (mm)	Females 272, Males 232 (WCB) Females 296, Males 246 (SCB)	
K (year^{-1})	Females 0.57, Males 0.86 (WCB) Females 0.48, Males 0.79 (SCB)	
t_0 (years)	Females -0.30, Males -0.08 (WCB) Females -0.20, Males -0.02 (SCB)	
Maximum age (years)	10.5 (WCB)	
Maximum size (mm)	41cm	Hutchins and Swainston (1986) However, most caught at 20-30cm
Natural mortality, M (year^{-1})	0.57	Then et al. (2015) t_{max} = 10.5 y
Length-weight parameters	W = (1.0829 x 10^{-5}) x TL$^{2.9990}$	Smith and Brown (2014)
Reproduction	Gonochoristic Broadcast spawner	Smith and Brown (2014)
Maturity parameters		
A_{50} (years)	Females 2.19, Males 1.76 (WCB) Females 2.77, Males 1.90 (SCB)	Smith et al. (2013)
A_{95} (years)	Females 3.97, Males 2.27 (WCB) Females 3.81, Males 3.47 (SCB)	
L_{50} (mm)	Females 194.1, Males 174.4 (WCB) Females 219.6, Males 196.4 (SCB)	
L_{95} (mm)	Females 250.8, Males 188.8 (WCB) Females 265.3, Males 231.1 (SCB)	
Annual fecundity	F = 498.9W – 4501.3 (Wgt in g) F = 18519A + 13640 (Age in yr) F = 4619.3 x e$^{(0.0114 \times TL)}$ (TL in mm)	Fairclough et al. (2000b)

5.1.3.1 Life Cycle

Herring undergo an annual spawning event in coastal waters south of *c*. 28°40’S and eastwards to *c*.119°25’E in WA - mainly during late May to early June (Fairclough et al. 2000a). The transformation from larva to juvenile occurs between 12-27 mm standard length (Fahlbusch 1995). The pelagic eggs and larvae are transported southwards and then eastwards via the

Leeuwin Current and wind-driven easterly movements of coastal waters, dispersing into WA, SA and Victorian nursery areas from June to November (Fairclough et al. 2000b, Jones et al. 1990, Ayvazian et al. 2000). The timing, length and age at recruitment to coastal nurseries appear to vary between regions, increasing with distance from the spawning area on the lower west coast (Ayvazian et al. 2000, Smith et al. 2013).

Juveniles typically remain in shallow inshore nursery sites for at least the first year of their life and typically emigrate from shallow waters at the start of their second year (Smith et al. 2013). After approximately two years, most herring individuals undertake a migration back to the western part of the south coast and lower west coast of Western Australia where they spawn (Fairclough et al. 2000b). There is no evidence of a post-spawning migration, therefore adult *A. georgianus* are assumed to remain within south-western Australia, with most of the spawning stock concentrated in the West Coast Bioregion (WCB) (Ayvazian et al. 2004).

5.1.3.2 Habitats and Movements

Herring are an inshore marine species and mainly occur in nearshore coastal waters, around offshore islands and in the lower reaches of estuaries (Smith and Brown 2014). Adults and juveniles form pelagic schools over a range of habitats (reef/sand/weed) (Smith et al. 2013).

During years of strong Leeuwin Current flow, such as in a *La Niña* year, higher levels of recruitment tend to occur in nurseries in the eastern region of the WA and SA and during years of weak Leeuwin Current flow, such as in a *El* Niño year, higher levels of recruitment tend to occur in WA nurseries (Ayvazian et al. 2000, Smith et al. 2013). Year class abundance may be linked to juvenile recruitment success to South Australian nursery areas (Ayvazian et al. 2000).

Juveniles grow to maturity in shallow nursery areas, often near seagrass beds in protected embayments along the southern coast of WA (typically from Perth southwards), SA and Victoria (Smith and Brown 2014) (Figure 5.3). At coastal sites along the west coast, the abundance of juvenile herring is positively correlated with the level of detached macrophytes, which appear to be an important source of shelter and food (Lenanton et al. 1982).

Herring approaching maturity for the first time, embark on a migration towards their spawning grounds in south-western Australia during summer (Ayvazian et al. 2000) (Figure 5.3).

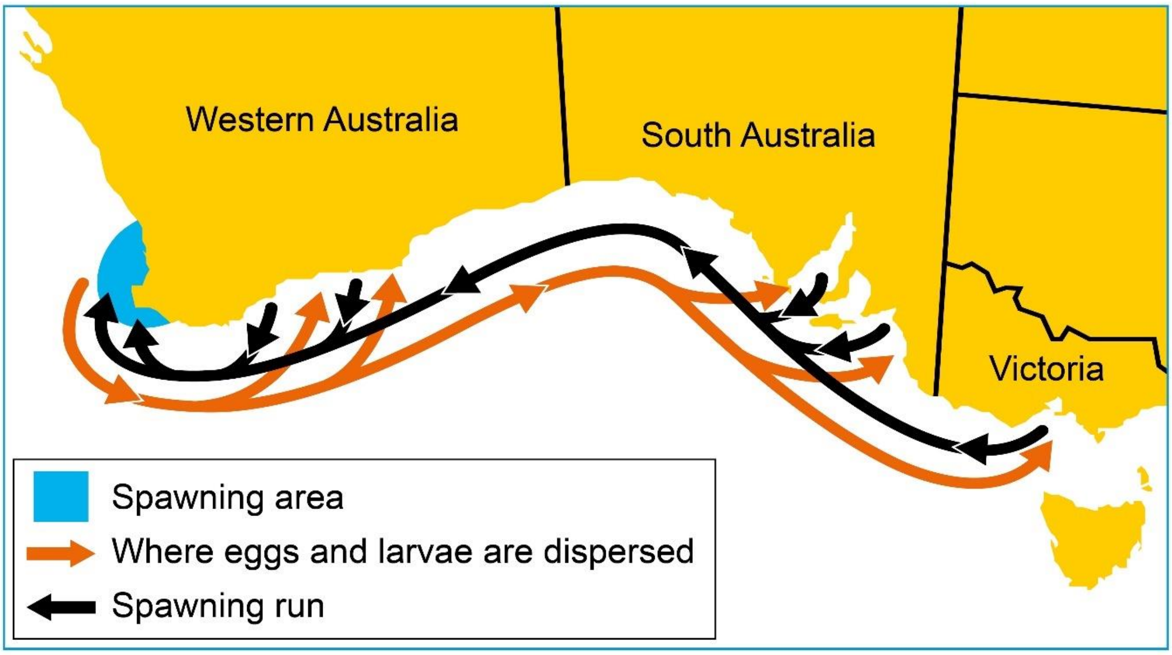

Figure 5.3. Australian Herring migration, spawning and larvae dispersal. http://www.fish.wa.gov.au/Documents/recreational_fishing/fact_sheets/fact_sheet_australian_herring.pdf

5.1.3.3 Age and Growth

The maximum reported total length of Australian is 41 cm (Hutchins and Swainston 1986), however they are more frequently caught under 30 cm (Smith et al. 2013) (Table 5.1).

The growth of herring is rapid in the first two to three years of life and slow when maturity is attained around this age. The von Bertalanffy growth models were fitted for the length-at-age of each sex in each Bioregion (Figure 5.4) (Smith et al. 2013).

5.1.3.3.1 Maximum Age (t_{max})

Longevity in fish, as measured by the maximum age of a fish (t_{max}) is an important parameter that can be used to provide estimates for natural mortality, which are then applied in stock assessments.

The oldest herring recorded was a 12 year old female caught in Wilson Inlet (SCB) and the oldest ocean caught female was 10.5 years caught in Jurien Bay (WCB) (Smith et al. 2013). The oldest ocean caught male recorded was 9.1 years, caught in the ocean at Cockburn Sound (WCB) (Smith et al. 2013). The oldest male recorded was 11.4 years caught in Wilson Inlet (SCB) (Potter et al. 2011).

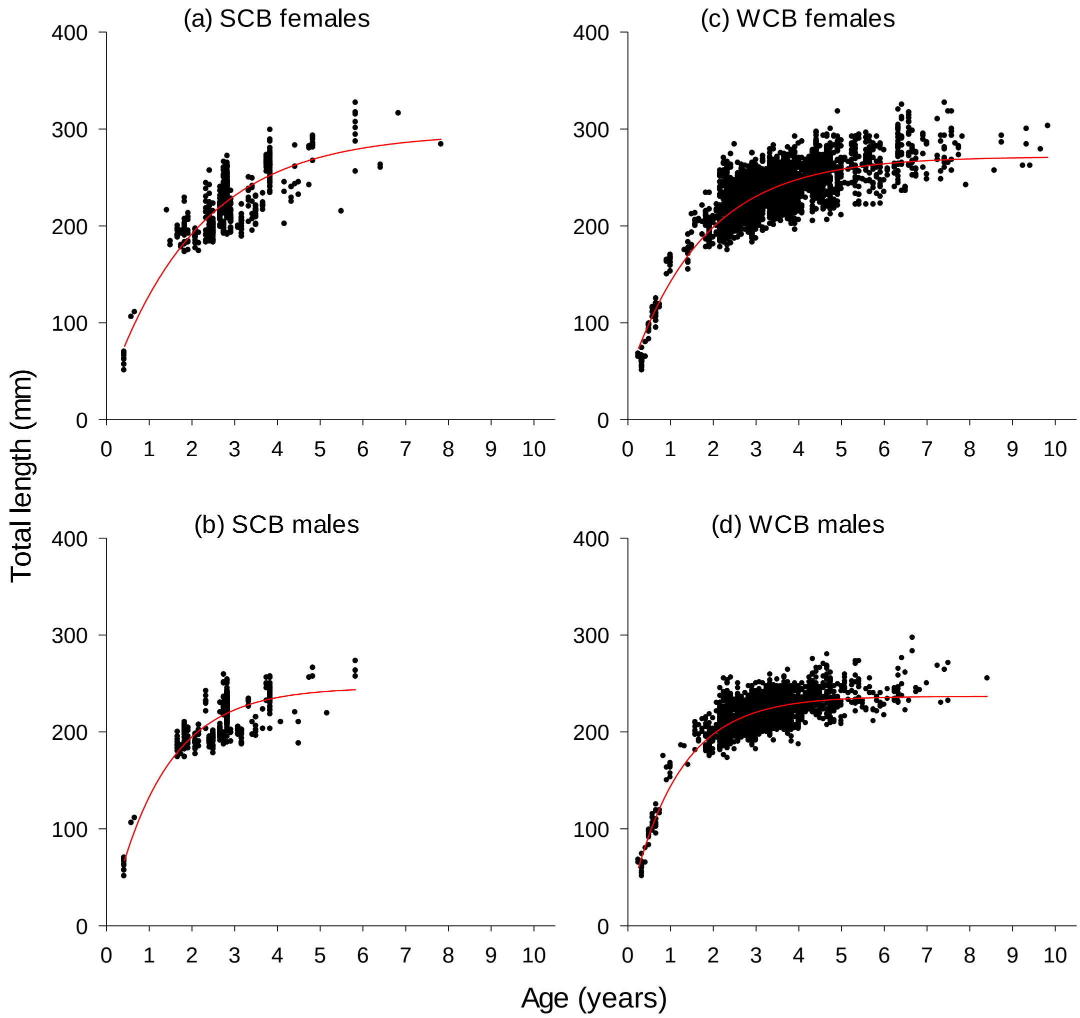

Figure 5.4. von Bertalanffy growth curves fitted to length-at-age data collected in 2009-2011 for female and male herring by Bioregion. Reproduced from Smith et al. 2013

5.1.3.4 Natural Mortality and intrinsic rate of increase (*r*)

Natural mortality is one of the most important, yet most difficult to estimate, parameters used in stock assessment (Then et al. 2015). For herring, a natural mortality estimate of approximately $M = 0.4\ y^{-1}$ has been used in previous assessments. It has also been used in this assessment so that trends in outcomes from analyses undertaken in each assessment can be examined. Based on more recent research (Then et al. 2015), an alternative value of $M = 0.57\ y^{-1}$ is estimated for herring. The higher estimate will yield a more positive stock status. Acknowledging the importance of *M*, and the difficulty in empirically estimating it, both $M = 0.4\ y^{-1}$ and $M = 0.57\ y^{-1}$ have been used where appropriate. The integrated model presented in section 9.3.15 provides some support for the use of a higher *M*.

Two factors that are hypothesized to have resulted in increased natural mortality of herring are the pilchard herpes virus (Smith et al. 2013) and an increase in Western Australian salmon, *Arripis truttaceus*, abundance (Wise & Molony 2018). The herpes virus impacted pilchard populations, and anecdotal evidence suggests salmon may have switched to a greater reliance of herring in the diet (Smith et al. 2013). Whilst the salmon population is thought to have increased due to little fishing effort over many years (wise & Molony 2018), the increased abundance, therefore, may be consuming a larger quantity of herring than in the past.

Natural mortality is closely linked with another key population parameter, the intrinsic rate of increase (*r*). Based on a meta-analysis, a formula derived for producing an estimate of r from M teleosts is $r = 1.73M$ (Zhou et al. 2016). Using the results of that meta-analysis, an M of 0.57 y^{-1} may be expected to equate to an r of 0.99. These parameters give an indication of the general productivity dynamics of a species, and in data poor situations, can be used to assist in assessment and management.

5.1.3.5 Reproduction

Herring are gonochoristic broadcast spawners (Smith and Brown 2014). Egg fertilisation is external. The simultaneous presence of post-ovulatory follicles and hydrated and yok-granule oocytes in some ovaries during the spawning period indicates that *A. georgiana* is a multiple spawner i.e., females spawn more than once in a breeding season (Fairclough et al. 2000a). Spawning occurs between April and late June (Fairclough et al. 2000b, Smith et al. 2013) (Figure 5.5). However, if females present within estuary are prevented from migrating to oceanic waters by the closure of the estuary mouth, those individuals do not spawn in those estuaries and mature oocytes are resorbed (Potter et al. 1983). Herring spawn in south-western Australia (Fairclough et al. 2000, Smith et al. 2013), with the majority of spawning activity occurring on the west coast and only limited spawning on the south coast (Smith et al. 2013, Wise & Molony 2018).

Fairclough et al. (2000b) estimated potential annual fecundity of individual females by counting the number of large vitellogenic oocytes in the pre-spawning ovaries (as appropriate for species with determinate fecundity) of 37 fish in mid-May. Total lengths of sampled fish were 197–335 mm (mean 247 mm) and weights were 94–439 g (mean 179 g). The number of large oocytes ranged from ~32,000 to 207,000 (mean 84,700) per fish.

The relationships between these estimates of fecundity (F), total length in millimetres (TL), wet weight in grams (W) and age in years (A) of fish, are expressed by

$F = 4619.3\ e^{(0.0114\ TL)}$ ($r^2 = 0.84$, n = 37),

$F = 498.9\ W – 4501.3$ ($r^2 = 0.88$, n = 37) and

$F = 18519\ A + 13640$ ($r^2 = 0.71$, n = 33). (Fairclough et al. 2000b).

Smith *et* al. (2013) found that females attain maturity at a greater size and age than males. The mean length-at-maturity (L_{50}) was lower in the WCB than the SCB for both sexes – the L_{50} for females was 194.1 mm (± 11.4) in the WCB and 219.6 mm (±2.2) in the SCB. The L_{50} for males was 174.4 mm (±1.8) in the WCB and 196.4 mm (±4.3) in the SCB.

Limited evidence suggests that preflexion stage *Arripis* spp. larvae are typically dispersed throughout the water column, whereas post-flexion larvae and early juveniles are concentrated in surface waters so wind-driven surface currents would be a dispersal factor (Smith and Brown, 2014).

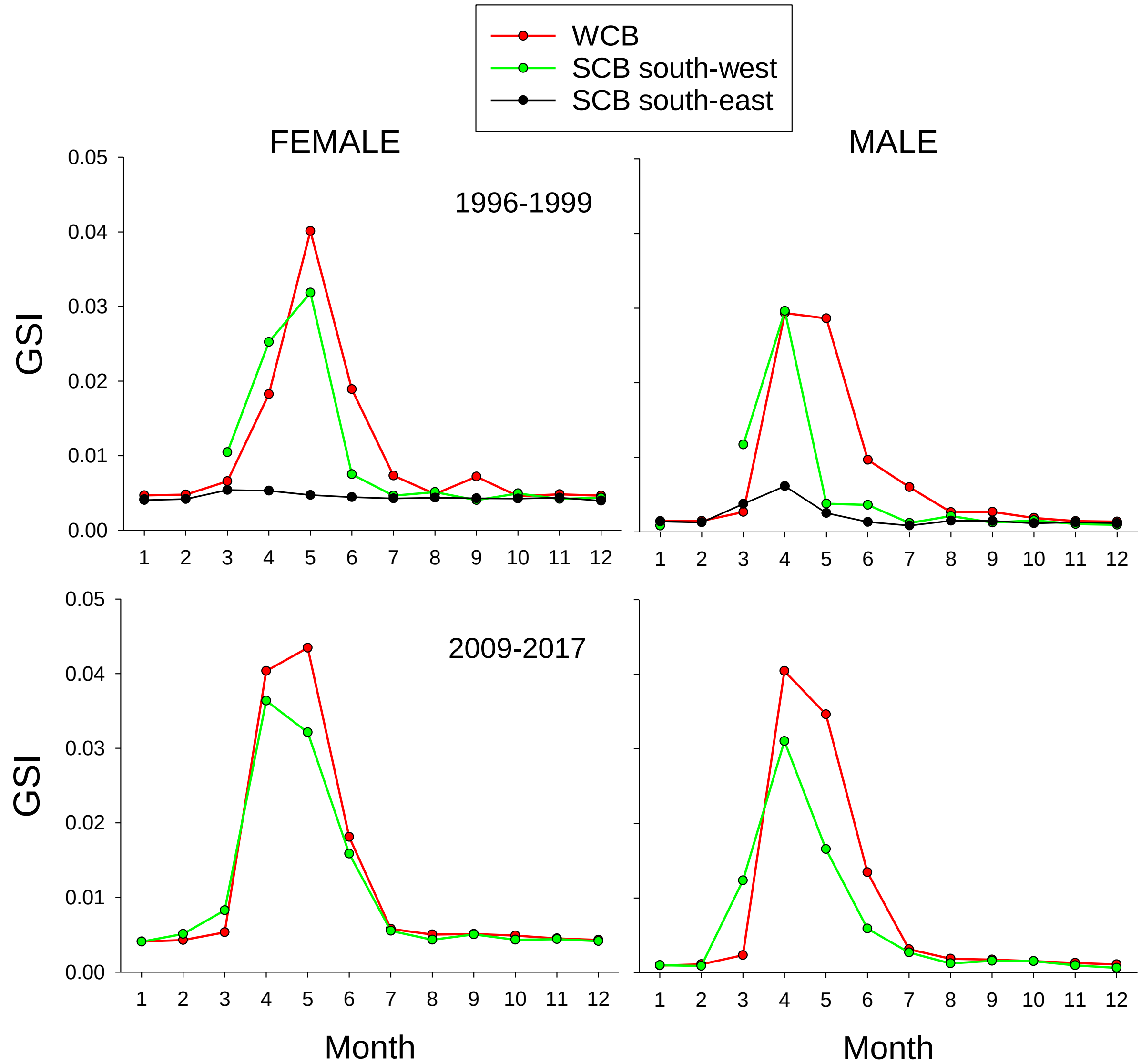

Figure 5.5. A comparison of average monthly GSI in WA regions – the top two graphs are from Fairclough et al. (2000a) data and the bottom two graphs are from Department of Fisheries data (Wise and Molony 2018).

5.1.3.6 Factors Affecting Year Class Strength and Other Biological Parameters

Herring has been identified as having a high sensitivity to climate change (Caputi et al. 2015). A weakening of the Leeuwin Current may occur due to climate change which would reduce recruitment eastwards (Caputi et al. 2015). The fluctuations in the strength of the Leeuwin Current affect herring; spawning coincides with the annual peak in flow by the Leeuwin Current, therefore the strength of the current greatly affects larval dispersal (Ayvazian et al. 2000). Recruitment on the west coast was higher in weak or average Leeuwin Current years, and higher on the south coast in strong Leeuwin current years (Smith et al. 2013).

5.1.3.7 Diet and Predators

Juveniles and adults are opportunistic carnivores and feed on a wide range of invertebrates and fish (Lenanton et al. 1982, Greenwell 2001). Larvae appear to feed mainly at night (Fahlbusch 1995).

Herring are consumed by predators such as dolphins, seabirds, sharks, seals, Western Australian salmon, tailor, yellowtail kingfish and mulloway (Kaiola *et al*. 1993). Bool *et al*. (2007) found that herring were consumed by little penguins (*Eudyptula minor*) and made up between 2-8% of their diet depending on location. They have been found in the stomachs of southern Bluefin tuna (*Thunnus maccoyii*) (Itoh et al. 2011).

The trophic level of this species is estimated to be 4.3 (±0.76 se) (Froese and Pauly 2021).

5.1.3.8 Parasites and Diseases

Seventeen parasite species have been identified from *A. georgianus* (Hutson et al. 2011), and there are no known issues with parasites or diseases.

5.1.4 Inherent Vulnerability

Herring are early maturing and not long lived. They are opportunistic feeders with a highly variable diet (Greenwell 2001, Lenanton et al. 1982). This may provide resilience to varied environmental conditions due to ability to alter prey intake.

Herring are a schooling species and migrate to spawn each year. The majority of commercial landings are taken in autumn (February – April) during the pre-spawning period when migrating schools are targeted (Smith and Brown 2014). They are easily caught on the south coast through the use of passive east facing nets, that capture entire schools on their westward migration. In addition, fishers are able to actively target schools when sighted off the beach. The species has a relatively high catchability and there are uncertainties in the total recreational catch level (Smith et al. 2013). This combination of factors could make the species vulnerable to hyper-stability in catch rates.

6 Fishery Information

6.1 Fisheries / Sectors Capturing Resource

Herring are mainly caught in the South Coast and West Coast bioregions, with occasional smaller catches from the Gascoyne bioregion. Commercial and recreational take of herring has a long history. Since compulsory commercial catch records system that began in 1975, catch of herring has been recorded in CAES as occurring in 23 different fisheries with 19 different gears.

The majority of the herring catch has historically occurred on the South Coast, with most of this taken using herring trap until that method was prohibited in 2015 to reduce commercial catch in response to the 2013 assessment. Since cessation of herring trap net fishing, the following fisheries have accounted for more than 95% of the catch of Australian herring: South West Coast Beach Net Fishery (Prohibition Order 2010), Cockburn Sound (Fish Net) Managed Fishery, Open Access South Coast (transitioned to the South Coast Nearshore Net Managed Fishery as of 2021/22), South Coast Estuarine Managed Fishery, and the West Coast Estuarine Managed Fishery. Sections below provide more detailed information about the main fisheries that currently target herring, or have significant historical catch, i.e., Condition 42.

6.2 South West Beach Seine (SWBS) Commercial Fishery

6.2.1 History of Development

Historically, 40–75% of annual landings of herring in the WCB were reported from the Geographe Bay/Bunbury area, where it was retained by beach fishers who also targeted salmon in this region (Smith et al. 2013). Ninety percent of annual herring landings from the Geographe Bay/Bunbury area have been taken using beach seine and haul nets, by what is hereafter collectively referred to as the South West Beach Seine Fishery (SWBSF).

In October 1989, the WA Minister for Fisheries announced a prohibition on commercial beach seining between Tim’s Thicket (south of Mandurah) and Point D’Entrecasteaux (DoF 2005 (Figure 6.1). The following year, the South West Beach Seine Fishery Notice 1990 (No. 416) was gazetted to give effect to this freeze (DoF 2005). A small number of FBL holders that could demonstrate they had historically fished in this fishery were excepted from the prohibition (by way of a permission placed on their FBL). This decision therefore limited entry to the SWBSF by placing a freeze on the number of commercial fishers permitted to fish using beach seine nets from south-west beaches.

In 2010, the South West Beach Seine Fishery Notice 1990 was revoked and replaced by *Prohibition on Commercial Fishing (South-West Coast Beach Net) Order 2010*. As the previous Notice had permitted fishing with a beach seine net as far south as Point D’Entrecasteaux, a large section of southern Geographe Bay was effectively closed to commercial fishing (Smith et al. 2013). This closure was intended to reduce conflict with recreational fishers and other beach users in this region (Smith et al. 2013).

6.2.2 Current Management

The *Prohibition on Commercial Fishing (South-West Coast Beach Net) Order 2010* permits nine fishing units to operate in the SWBSF. Historical FBL holders listed as excepted from this prohibition in Schedule 3 of the Order are permitted to fish with a beach seine net to take scalefish within 800 m of the high-water mark between Tim’s Thicket (32°39.08’S) and Port Geographe Marina (33°37.71’S, 115°23.625’S) (Figure 6.1).

Input controls are utilised to contain effort in the fishery. In particular, all nets must be hand-hauled from the shore and only one beach seine net is allowed per licensed fishing boat unit. A net must not exceed 250 m in length and the mesh size may be no less than 7 mm. Minimum legal sizes limits apply to some species caught in the SWBSF, however, this does not include whitebait.

6.2.3 Fishing Methods and Gear

Although beach seine nets in this fishery are typically set using small dinghies, all nets must be hand-hauled from the shore. A single net is allowed per licensed fishing boat unit. Fishers look for schools of fish before deploying nets to encircle fish and haul the catch to shore.

6.2.4 Current Fishing Activities

The fishers operate mainly during the warmer months of the year (November to April) and catch of herring varies between 10 and 30 tonnes each year (20 to 50% of the total catch from this fishery). Over the last 10 years, approximately 90% of herring caught by the SWBSF was taken between December and March each year. Constraints on catch within this time may relate to many of the fishers also fishing for salmon, which are targeted from March to May. A summary of the key attributes of the fishery are shown in Table 6.1.

Table 6.1. Summary of key attributes of the commercial SWBS commercial fishery in 2020

Attribute	
Fishing methods	Beach seine
Fishing capacity (net length)	250 m per Fishing Unit
Number of licences	9 Fishing Unit (= 27 FBLs)
Number of vessels	n/a
Size of vessels	n/a
Number of people employed	~29
Value of fishery	Level 1(< $1million)

Figure 6.1. Locations and restrictions for South West Beach Seine fishers permitted under the Prohibition on Commercial Fishing (South-West Coast Beach Net) order 2010

6.3 Cockburn Sound (Fish Net) Managed Fishery

6.3.1 History of Development

Commercial fishers in Cockburn Sound have historically operated throughout the year using set and haul nets to target blue swimmer crabs (*Portunus armatus*), as well as herring and southern garfish (*Hyporhamphus melanchir*) (Smith et al. 2013). Since the early 1990s, when crab fishers in this area shifted to trapping as a method for catching crabs, herring and southern garfish have been the primary target species of net fishers in Cockburn Sound. The fishery operates all year round. Catches are typically highest in summer and autumn, due to the availability of certain fish species and more favourable weather. The catch is sold locally in Perth.

The Cockburn Sound (Fish Net) Managed Fishery (CSFNMF) was recognised in legislation in 1995. Initial entry to the fishery in 1995 was based on catch history during the late 1980s.

6.3.2 Current Management

The *Cockburn Sound (Fish Net) Managed Fishery Management Plan 1995* permits the use of haul nets, set nets and garfish nets with the following controls:

- a haul net must be hauled by hand, with maximum length of 300 m and maximum depth of 6 m, permitted mesh sizes 48-114 mm.
- a set net has a maximum length of 1000 m and a maximum depth of 3 m, permitted mesh sizes 48-114 mm
- a garfish net is a surface set net (25-76 mm mesh size) with a maximum depth of 18 m.

A licenced boat must not use more than 1000 m of haul net or set net, or 260 m of garfish net, at any time. All nets used in the fishery must have a float line and may not contain a bunt or pocket. The boat length must be no more than 5.5 m.

Take of Southern Garfish has been prohibited in Metro waters incl Cockburn Sound since 2017 (*Prohibition on Taking Southern Garfish (Perth Metropolitan Waters) Order 2017*). Operators are not allowed to take crustaceans unless they hold has a separate authorisation to do so. Minimum legal sizes limits apply to some species caught in the CSFNMF, but this does not include herring.

The fishery encompasses the inner waters of Cockburn Sound from South Mole at Fremantle Harbour to Stragglers Rocks, through Mewstone to Carnac Island and Garden Island, along the eastern shore of Garden Island, and back to John Point on the mainland (Figure 6.2). There are a number of permanently closed areas in the CSFNMF, with no fishing permitted (Figure 6.2).

6.3.3 Fishing Methods and Gear

The majority (70-100%) of annual herring catches in Cockburn Sound have typically been taken by set nets, except for during a 9-year period from 1986 to 1994 when landings by haul/seine nets contributed 35-65% of total annual landings in this region (Smith et al. 2013). Although set net landings prior to 1990 were recorded as taken by gillnets, more recent landings are known to have been mainly taken by garfish nets (set nets of a smaller mesh size. There have been no haul net catches of herring in Cockburn Sound recorded since 2001. Fishing occurs throughout Cockburn Sound (excluding closed areas).

6.3.4 Current Fishing Activities

The majority of herring landed in this embayment since 1990 have been taken by set nets. Commercial catch has been reported by only a single vessel since 2002. There has been a single licensee in this fishery since 2003. The fisher targets specific schools of fish depending on what is marketable at that time. Once a school is sighted, the net is deployed to encircle the school. The boat is then anchored, and the net hauled onto the boat. Fish are removed from the net as it is collected. Any unwanted catch is discarded back into the water immediately upon landing. The main target species were traditionally herring and southern garfish. Take of Southern garfish was banned in June 2017 due to concerns over stock sustainability (*Prohibition on Taking Southern Garfish (Perth Metropolitan Waters) Order 2017*). The proportion of herring has continued to increase and is now close to 90% of the entire catch. A summary of the key attributes of the fishery are shown in Table 6.2.

Table 6.2. Summary of key attributes of the CSFN commercial fishery in 2020

Attribute	
Fishing methods	Haul net, garfish net, set net
Fishing capacity (net length)	1000 m of haul or set net, 260 m of garfish net
Number of licences	1
Number of vessels	1
Size of vessels	<5.5 m
Number of people employed	2
Value of fishery	Level 1(< $1million)

Figure 6.2. Cockburn Sound Fish Net Managed fishery and areas prohibited to fishing.

6.4 South Coast Estuarine Managed Commercial Fishery (SCEMCF)

6.4.1 History of Development

The South Coast Estuarine Managed Fishery (SCEMF) is one of the oldest fisheries in WA and has been operating in much the same way since the mid-1800s (Wright 1989). Although aluminium dinghies with outboard motors have now replaced the wooden boats that were sailed in the early days of the fishery, fishers still use gillnets and haul nets to target the same fish species in the same way as their predecessors did (Wright 1989).

Historically, the majority of herring catches in the SCEMF were taken in Princess Royal Harbour and Oyster Harbour near Albany (76% of total landings during 1976-1990), although this contribution has gradually declined over the past two decades (Smith et al. 2013).

Minor annual catches of herring are also taken primarily by gillnetting in Wilson Inlet (3-24 t), Broke Inlet (< 12 t), and Irwin Inlet (< 4 t) (Smith et al. 2013). Landings in Broke and Irwin Inlets occur from May to October, when these estuaries are open to commercial fishing. In Wilson Inlet, which is open to fishing all year, landings mainly occur in the warmer months (Smith et al. 2013). The other south coast estuaries have collectively contributed < 600 kg herring per year since 1976 (Smith et al. 2013).

Fishing effort targeting herring in the estuaries of southern WA is likely to have declined since 1990 as a consequence of a decline in total fishery effort (Smith et al. 2013). The number of licences in the SCEMF was substantially reduced via a Voluntary Fishery Adjustment Scheme (VFAS, i.e. licence buy-backs), thus eliminating a significant amount of latent effort (inactive licences) that previously existed in this fishery. The number of licensees declined from a peak of 66 in 1987 to 25 in 2002 (Smith et al. 2013).

6.4.2 Current Management

As outlined in the *South Coast Estuarine Fishery Management Plan 2005*, the SCEMF includes all estuaries on the south coast of WA between Cape Beaufort and 129ºE, including all river, streams and tributaries that flow into those estuaries (Figure 6.3). Since 2005, 13 south coast estuaries have been open to commercial fishing; Broke Inlet, Irwin Inlet, Wilson Inlet, Princess Royal Harbour; Oyster Harbour, Waychinicup Inlet, Beaufort Inlet, Gordon Inlet, Hamersley Inlet, Culham Inlet, Jerdacuttup Inlet, Oldfield Inlet and Stokes Inlet. Some estuaries are fished year-round (e.g., Wilson Inlet, Princess Royal Harbour and Oyster Harbour), whilst others, in particular the smaller estuaries in the east, are open on seasonal basis (Wright 1989). At present, there remains 25 licensees in the SCEMF.

6.4.3 Fishing Methods and Gear

Gillnets are set overnight, with no gillnetting permitted in the estuaries on weekends and public holidays. As the estuaries are popular with recreational boat users this restriction not only reduces the potential for conflict between commercial fishermen and recreational users but reduces the potential for fishing gear to be damaged.

The primary commercial method used to catch herring in Princess Royal Harbour and Oyster Harbour is seine/haul nets, whilst in Wilson Inlet it is gillnetting.

6.4.4 Current Fishing Activities

Over the last 10 years the take of herring by this fishery has ranged between 10 and 20 t, nearly 80% of which comes from two estuaries (Wilson Inlet – 54%, Princess Royal Harbour – 25%), while Oyster Harbour now only accounts for approximately 6%. A summary of the key attributes of the fishery are shown in Table 6.3.

Table 6.3. Summary of key attributes of the SCEMF in 2020

Attribute	
Fishing methods	Haul/set/seine/throw/ring nets, crab pot, fish trap, hand gathering
Fishing capacity	1500 m of fishing net (1000 m of fishing net in Beaufort Inlet), 25 crab pots, 10 fish traps, 4 shellfish collectors (and other restrictions in Management Plan)
Number of licences	25 (23 active)
Number of vessels	59
Number of people employed	~40
Value of fishery	Level 2 ($1-5million)

Figure 6.3. South Coast Estuarine Managed Fishery

6.5 West Coast Estuarine Managed Commercial Fishery

6.5.1 History of Development

There are four main (i.e., relatively large) estuaries in the WCB (Swan-Canning, Peel-Harvey and Leschenault estuaries, and Hardy Inlet). Catch and effort records are available from the Swan-Canning Estuary since 1912, and from the other three estuaries since 1941 (Lenanton 1984).

The Leschenault Estuary was closed to commercially fishing in 2001. In 2003, the *West Coast Estuary Interim Managed Fishery Management Plan* was implemented, incorporating the Swan-Canning (Area 1 of the fishery) and Peel-Harvey (Area 2) estuaries.

The Peel-Harvey Estuary is the area of the fishery with the highest finfish production. The number of vessels operating in this estuary declined substantially from about 45 to about 10 between 1980 and 2000, resulting in a decline in annual finfish landings from ~700 t to ~150 t over the same period. In addition to this major reduction in vessels, commercial effort and finfish landings in this estuary have also been affected by several other major events: i) major environmental changes (eutrophication leading to algal blooms in 1980s and 1990s, then implementation of Dawesville Cut in 1994 leading to increased marine influence) which affected catchability and species composition; ii) change from gill nets to pots to target crabs in the period 1996-1999 which eliminated the finfish by-product that had previously been taken while targeting crabs; iii) implementation of the first formal Harvest Strategy for finfish in 2015.

6.5.2 Current Management

In 2014, the West Coast Estuarine Managed Fishery Management Plan was implemented, which also included the Hardy Inlet (Area 3) (Figure 6.4). A VFAS was established in 2018 to reduce the number of commercial licenses in the Peel-Harvey Estuary (Fisher et al. 2020). This initiative aimed to enhance and protect the recreational fishing experience in the estuary by re-allocating a component of the resource to recreational fishers and the ecosystem, with four of the original 11 licenses recently bought out as part of this process (Fisher et al. 2020).

6.5.3 Fishing Methods and Gear

Haul nets and gill nets are used to capture finfish in the Peel-Harvey Estuary, although it is generally the same net, it is method of deployment that differs (Fisher et al. 2020). Haul netting is used when fishers visually target a school of fish by deploying a net in a circular manner around a school of fish (Fisher et al. 2020). The net is then hauled onto the boat and sorted. Gill netting is primarily undertaken in winter to avoid entanglement of crabs (Fisher et al. 2020). Nets are set overnight and hauled the next day. Herring generally composes less than 5% of the total catch.

6.5.4 Current Fishing Activities

The finfish component of the fishery operates year-round. The finfish catch is sold on domestic markets. The Peel-Harvey Estuary commercial fishery operates in accordance with a formal Harvest Strategy and sea mullet landings in this estuary received Marine Stewardship Council (MSC) certification in June 2016 (DoF 2015, Johnston et al. 2015).

Since 1999, a single licencee has operated in Hardy Inlet, targeting finfish. Since 2009, a single licencee has operated in the Swan-Canning Estuary, primarily targeted blue swimmer crabs. This fisher has mainly caught crabs since 2013. A summary of the key attributes of the fishery are shown in Table 6.4.

Table 6.4. Summary of key attributes of the WCEMF in 2020

Attribute	
Fishing methods	Haul net, set net, prawn net, beam trawl net, crab pot
Fishing capacity	Area 1: 500 m of haul net, or 500 m of set net (mesh size <63mm or >127mm) or 1000 m of set net (mesh size >127mm) Area 2:1000 m of set and haul nets, 96 m of beam trawl, 42 crab pots. Area 3: 1000 m of net (haul or set)
Number of licences	1 (Area 1); 8 (Area 2); 1 (Area 3)
Number of vessels	1 (Area 1); 8 (Area 2); 1 (Area 3)
Number of people employed	3 (Area 1); ~12 (Area 2); 2 (Area 3)
Value of fishery	Level 1 (< $1million)

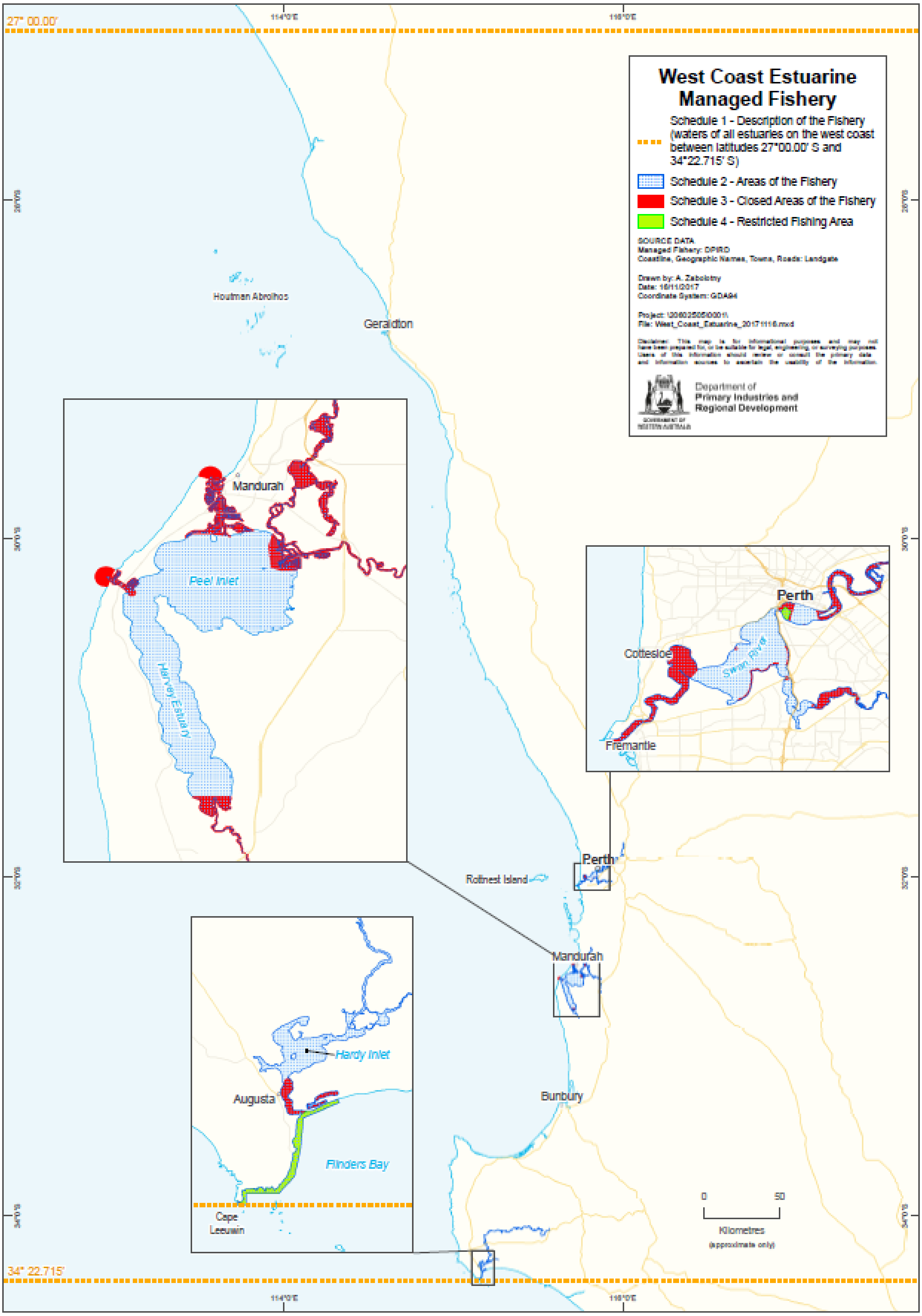

Figure 6.4. Areas covered by the West Coast Estuarine Managed Fishery

6.6 FBL Condition 42 - Herring trap net fishery

6.6.1 History of Development

The herring trap net fishery originated as a secondary activity for fishers in the South Coast Salmon Fishery, which commenced operation in the 1940s (Wright 1989). The first herring trap net was used at Cheynes Beach in 1953 (Wright 1989). As demand and price for herring as rock lobster bait increased during the late 1970s and early 1980s, this led to a shift in effort by salmon fishers towards herring and the entry of new fishers that exclusively targeted herring (Wright 1989). Although the herring trap net fishing season typically only lasts around one to two months per year, this fishery has historically been the major commercial fishery for herring in WA, landing between 60 and 90% of the total annual commercial catch of this species (Ayvazian et al. 2000).

Management of the method trap net method began in November 1983, when the use of trap nets was prohibited unless authorized by a Licensing Officer (Government Gazette 1983, Notice No.91(7)). Subsequently the *Herring Trap Net Notice 1991*, restricted take of herring by a herring trap net to licenced professional fisherman with a Fishing Boat Licence (FBL) with the *Herring Trap Net notice 1991* endorsement (Condition 42). This endorsement restricts the licensee to a beach (Figure 6.5), restricts setting times to between 16:00 and 09:00, and excludes use of the nets between 09:00 February 10 to 16:00 March 25 in any year.

Catches of herring increased from over 400 t in 1976 to a peak of 1,383 t in 1991. In 1995/96, there was a significant drop in the average price of herring, mainly due to the decreased demand for herring as bait in the rock lobster fishery.

There was an adjustment scheme in 1998 to buy out some licences. Again in 2000 (South Coast Herring Trap Fishery and Related Fisheries Voluntary Fisheries Adjustment Scheme Notice 2000.) Use of herring trap nets was prohibited on the 1st of March 2015 (*Prohibition on Herring Trap Nets Order 2015*) and a buyback scheme was implemented in June 2015 to reduce the number of people and boats.

6.6.2 Current Management

The fishery is currently closed.

6.6.3 Fishing Methods and Gear

Herring trap nets target schools of maturing/mature herring as they migrate from nursery areas on the south coast of Australia to the spawning areas on the lower west coast (Smith et al. 2013). The trap net is set in the afternoon, perpendicular to the beach, extending from the shore out to sea, approximately 150 m, in the shape of a ‘6’ or ‘g’ shape, with the opening of the ‘g’ facing the migrating school of fish (Ayvazian et al. 2000). The herring swimming along the shore hit the net, which forms a barrier, and follow it out to sea where the net turns on right angles three times (forming a g). The herring swim in a circular pattern in this section of the net, thus, most fish are not entangled by the net but ‘trapped’. The following morning, the net is closed by operators, typically a team of between 4 and 6 people, and hauled to the beach where the fish are removed.

Fishing units in the South Coast Trap Net Fishery (SCTNF) target herring for only a few months each year (end of March-June). The trap nets are only operated in favourable weather conditions, with about 10-20 settings occurring per fishing unit and season (Ayvazian et al. 2000). Historically, it was reported that fishers will only beach a trap net once they have established that all fish in the net can be sold and that the processing factories can pick up and manage the tonnage captured (Wright 1989). However, fishers currently suggest that they take a proportion of the catch that can be used, and the rest of the catch is released by lifting the lead line and allowing the fish to swim out to continue their spawning migration.

6.6.4 Current Fishing Activities

Use of herring trap nets is currently not permitted, therefore no catch is taken.

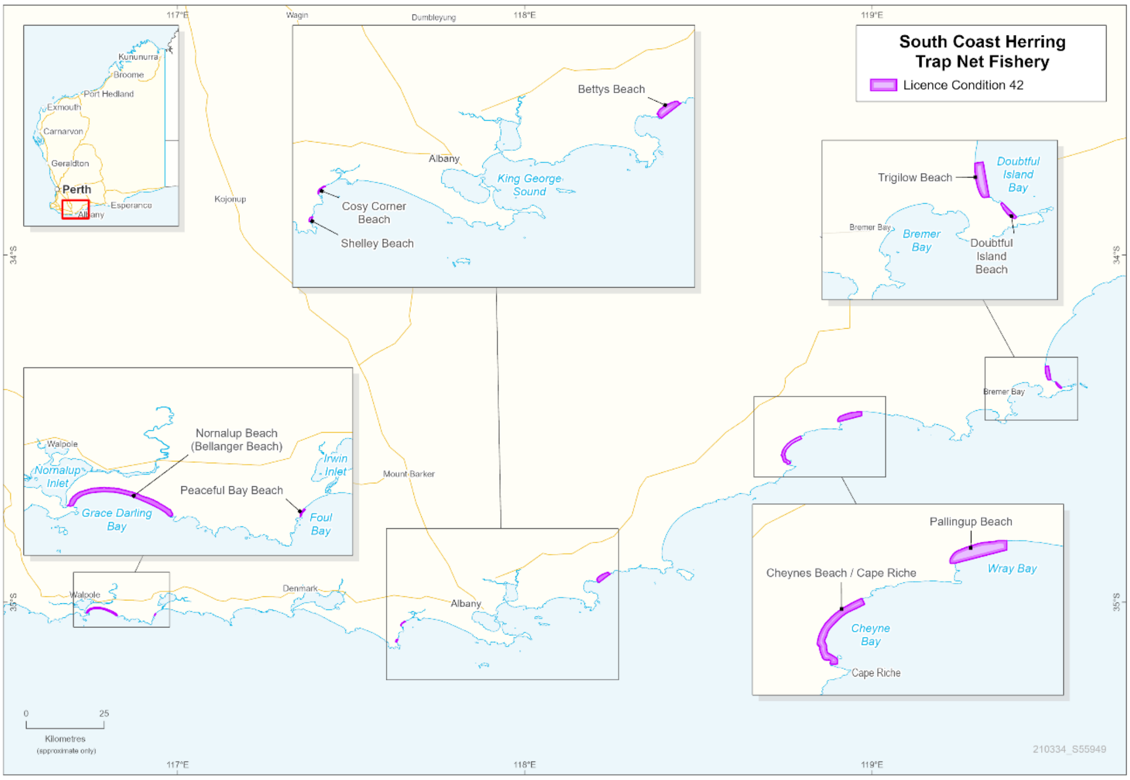

Figure 6.5. Location where herring fish trap nets are permitted for FBL holders with Condition 42.

6.7 Recreational / Charter Fishery

6.7.1 History of Development

Due to its accessibility and ease of capture, herring is the most common finfish species retained by recreational fishers in WA (Henry and Lyle 2003, Tate and Smallwood in press). It is targeted primarily by line-fishing from the shore and from boats in coastal and estuarine waters of the west coast and south coast of WA. A recent recreational survey of boat-based recreational fishing in WA estimated approximately 85% of herring are caught in the West coast bioregion, with approximately 15% of catches taken in the South Coast Bioregion (SCB) (Ryan et al. 2019). The same survey showed that herring are harvested throughout the year, with higher catches observed in summer and autumn (approximately 30% each).

Shore-based line fishing does not require a licence. Lack of a suitable licence database has prohibited any comprehensive surveys of shore-based fishing from being undertaken in recent years. There have been some partial surveys of this sector, but no state-wide estimates of annual catch or effort by this sector are currently available.

A major review of recreational fishing management arrangements was completed in February 2013. At this time, a single state-wide system of rules replaced the previous bioregion-based rules. The new rules were 'resource-based'. For nearshore finfish, a mixed species total possession limit of 16 fish was implemented. In 2015, the recreational bag limit for herring was reduced from 30 to 12 in response to concerns over stock status (Smith et al. 2013).

6.7.2 Current Management

Shore-based fishers do not require a licence to fish for herring. A legal minimum length (LML) has applied to herring since at least 1913, with variations as follows: 6 inches (implemented in 1913), 7 inches (1937), 7.875 inches/ 177.8 mm (1973) and 180 mm (1975). These limits applied to both commercial and recreational fishers until 1991 when the LML for recreationally caught herring was removed. There is currently no size limit on herring. In June 1991 herring were placed in a 'low risk' finfish category. A mixed species recreational bag limit of 40 applied to this group until October 2009. On 15 October 2009, the daily bag limit for this group was reduced to 30 fish in the WCB, while remaining at 40 fish in the SCB. In February 2013, a state-wide mixed species daily bag limit of 30 'other finfish' (including herring) was implemented in all bioregions. In March 2015, the specific bag limit for herring was reduced to 12, whilst remaining within the state-wide mixed species daily bag limit of 30 'other finfish'. See http://www.fish.wa.gov.au/Fishing-and-Aquaculture/Recreational-Fishing/Recreational-Fishing-Rules/Bag_And_Size_Limits/Pages/default.aspx for current rules.

Since 2 March 2010, all persons fishing from a powered boat anywhere in WA have been required to hold a RFBL or fish in the company of a licence holder. The RFBL provides a State-wide database of recreational boat fishers that can be used for survey purposes. State-wide boat-based fishing surveys now provide regular estimates of the boat-based catch of nearshore finfish in each Bioregion effort.

Since 1992, a recreational fishing licence have been required for all recreational net fishing using set (gill) nets, haul nets or throw nets. Recreational net fishing is only permitted in WA's marine and estuarine waters, not in freshwater. Further, most of WA's estuarine waters are closed to protect juvenile fish stocks. Set netting is now prohibited in all ocean waters of WA except for in the Gascoyne Coast Bioregion.

Recreational netting regulations are complex. Full details are given in the current edition of the '*Recreational Net Fishing Guide'* (*https://www.fish.wa.gov.au/Documents/recreational_fishing/licences/rec_licence_netting.pdf*.). Licenced fishers must comply with the numerous spatial closures to netting, especially in close proximity to towns, cities and closed areas such as marine parks. In general, netters must lift and clean their nets of the fish at least once an hour. Fishers must stay within 100 m of their net at all times whilst fishing. There are gear restrictions with respect to the types of permitted net, mesh size, length and depth/drop:

- Set nets, ocean: 60 m max. length, 75-114 mm mesh size, 25 mesh cells max. depth;
- Set nets, inland: 60 m max. length, 63-87 mm mesh size, 25 mesh cells max. depth;
- Haul nets: 60 m max. length, 51-114 mm mesh size; 25 mesh cells max. depth;
- Throw nets: max. radius 3 m, max. mesh size 25 mm.

6.7.3 Current Fishing Activities

Recreational fishing for herring is undertaken in coastal waters and the lower parts of estuaries, by shore- and boat-based fishers. It is an accessible activity with relatively high participation rates and has high social value in WA. The majority of the recreational catch of herring is thought to be taken by shore-based fishers, however, catch levels are uncertain due an absence of data. Metropolitan shore-based surveys over the last decade have begun to better inform catch level, at least at the local scale.

6.7.4 Fishing Methods and Gear

Recreational fishers predominantly target herring using rod and line, from the shore or a boat. Both bait and lures are used to target the species. Minor quantities are also harvested by other methods such as netting.

6.8 Customary Fishing

The Wardandi Aboriginal people of the Cape Naturaliste region in south-western WA historically used fish traps to catch predominantly whiting, mullet, bream, pilchards, small tailor and herring (Gaynor et al. 2008). In the present day, however, the customary catch of estuarine and nearshore species in this region is likely to be negligible.

6.9 Illegal, Unreported or Unregulated Fishing

Illegal activities (possession and size limit breaches) by recreational fishers are regularly detected by compliance officers. The proportion of the total recreational catch/effort represented by illegal activity is unquantified, but likely to be a minor part of total catch.

6.10 Susceptibility to commercial and recreational fishing

Table 6.5 below provide a brief outline of susceptibility of herring to the commercial (all fisheries combined) and recreational fishing sectors, using the following 4 criteria:

1. What is the area overlap (i.e., spatial distribution of fishing effort compared to the distribution of the exploited stock)?
2. What is the encounterability of the stock within the water column relative to the fishing gear (typically high for target species)?
3. What is the selectivity of the gear type used (i.e., individuals < size at maturity are rarely/regularly/frequently caught)?
4. Is there evidence for survival following capture and release, or is this species always retained?

Table 6.5. Susceptibility of herring to the commercial and recreational fishing sector

Commercial	1. very high overlap of spatial distribution of fishing effort with stock distribution. 2. high encounterability with the fishing gear during pre-spawning period (lower since closure of trap net fishery) 3. low selectivity of immature fish; net mesh sizes limit retention of small fish 4. post-release survival of netted fish is believed to be relatively high; fishers sometimes pen schools for short periods (hours), then release them.
Recreational	1. high (almost 100%) overlap of spatial distribution of fishing effort with stock distribution. 2. high encounterability with the fishing gear throughout the year. 3. low selectivity of immature fish; juveniles make up a low proportion of the catch. 4. post-release survival of line-caught fish is believed to be relatively high.

7 Fishery Management

7.1 Management System

A formal harvest strategy was drafted for herring; however, an updated version is proposed in (see section 7.2). A full harvest strategy will be developed for herring and West Australian salmon (*Arripis truttaceus*), the range of which extends across multiple jurisdictions herring are also caught within the Peel-Harvey Estuary MSC certified sea mullet fishery. Within this fishery, their status is considered under an Ecological Risk Assessment process (Fisher et al. 2020).

The *Fish Resources Management Act 1994* (FRMA) provides the overarching legislative framework to implement the management arrangements for the fisheries in south-western WA. Management arrangements for each fishery are described in detail in management plans and other legislation. Generally, measures to regulate effort/catch include:

- Limited entry, Gear restrictions, Species restrictions, Minimum legal sizes limits for some species, Seasonal and time closures, and Spatial closures.

7.2 Harvest Strategy

The herring Resource Harvest Strategy has evolved over the development of the fishery. It makes explicit the management objectives, performance indicators, reference levels and harvest control rules for this resource, which are taken into consideration by the Department when preparing advice for the Minister for Fisheries. The harvest strategy has been developed in line with the Department's over-arching Harvest Strategy Policy (DoF 2015) and relevant national policies / strategies (ESD Steering Committee 1992) and guidelines (e.g., Sloan et al. 2014).

Smith et al. (2013) proposed a harvest strategy based on Fishing Mortality as a proxy for spawning biomass. The harvest strategy was then adapted to be based on SPR in a draft strategy in 2016 (DoF 2016). Whilst SPR is retained as the performance indicator in the proposed strategy below, additional work could be undertaken to determine whether empirical performance indicators based on stock-recruitment-environment relationships can be developed.

The main objectives, performance indicators, reference levels and control rules that are proposed as a result of the current assessment of the herring fishery are defined in Table 7.1.

Table 7.1. Summary of the performance indicators, reference levels and control rules for the Australian herring resource in Western Australia

Management Objective	Performance Indicator(s)	Reference Levels*	Control Rules
To maintain spawning stock biomass of each retained species above B_{MSY} to maintain high productivity and ensure the main factor affecting recruitment is the environment.	Periodic estimates of SPR.	**Target:** SPR_{40}	No management action required
		Threshold: SPR_{30}	If the Threshold is breached, a review is triggered to investigate the reasons for the variation. If sustainability is considered to be at risk, appropriate management action will be taken to reduce the total catch by up to 50%.

Management Objective	Performance Indicator(s)	Reference Levels*	Control Rules
		Limit: SPR_{20}	If the Limit is breached, management strategies to further protect the breeding stock will be implemented (50 – 100 % reduction of total catch).

7.3 External Influences

External influences include other activities and factors that occur within the aquatic environment that may or may not impact on the productivity and sustainability of fisheries resources and their ecosystems. The main external influences included here are environmental factors, introduced pest species, market influences, non-WA managed fisheries, and other activities.

7.3.1 Environmental Factors

It is likely that annual variation in coastal currents (particularly the Leeuwin and Capes Currents) influences the patterns of larval dispersal of herring, and thus their subsequent recruitment into fisheries (Lenanton et al. 2009, Smith et al. 2013). Coastal currents may also influence the distribution and catchability of adult fish. Water temperature may also influence herring growth and age at maturity as demonstrated by the earlier age at maturity of fish in the WCB compared to the SCB. Recent work shows that the environmental factors related to the Leeuwin Current, such as the Fremantle Sea level during the May spawning period, and the sea surface temperature during the annual westward pre-spawning migration (February) may be key determinants of recruitment strength (section 9.3.14).

7.3.1.1 Climate Change

A risk assessment of WA’s key commercial and recreational finfish and invertebrate species has demonstrated that climate change is having a major impact on some exploited stocks (Caputi et al. 2015). This is primarily occurring through changes in the frequency and intensity of El Niño Southern Oscillation (ENSO) events, decadal variability in the Leeuwin Current, increase in water temperature and salinity, and change in frequency and intensity of storms and tropical cyclones affecting the state (Caputi et al. 2015). In 2010/11, a very strong Leeuwin Current resulted in unusually warm ocean temperatures in coastal waters of south-western WA (Pearce et al. 2011). This “marine heatwave” altered the distribution and behaviour (e.g., spawning activity and migration) of some species and caused widespread mortalities of others.

7.3.2 Introduced Pest Species

No known issues directly affecting target species.

Anecdotal evidence suggests the mass mortality of pilchards in the 1990s, due to herpes virus, caused Australian salmon to shift from consuming pilchards (formerly an important prey item) to other species, e.g., herring, southern garfish. Thus, the event may have affected growth, condition, natural mortality, etc. of various nearshore species., including herring.

7.3.3 Market Influences

Fluctuating market demand is a significant factor affecting the annual commercial catch level of many nearshore finfish species. Since the mid-1990s, there has been a significant decline in the price of herring due to the increased importation of relatively low-priced North Sea herring for use as rock lobster bait (Ayvazian et al. 2000). By purchasing only a limited quantity of herring each year, fish processors effectively restrict catch levels. Commercial fishers sometimes elect not to capture a school of fish, or release part of their catch, when a market is not available. COVID-19 and reductions in bait demand due to changes in market demand for Western rock lobster have impacted herring catch.

7.3.4 Non-WA Managed Fisheries

Herring are targeted by commercial and recreational fishers in SA; minor quantities are taken in Victoria and Tasmania. Catch of herring in other States are immature fish, that migrate towards WA and are also produced from the spawning stock that resides in Western Australia.

7.3.5 Other Activities

Historical and current industrial and urban activities have various impacts on habitats in Cockburn Sound (dredging, groundwater contamination, effluent discharges/spills, vessel movements, etc). Most south-western estuaries are affected to some extent by anthropogenic factors such as eutrophication, altered river flow and habitat loss.

8 Information and Monitoring

8.1 Range of Information

There is a range of information available to support the assessment and harvest strategy for the herring resource (see Table 8.1).

8.2 Monitoring

8.2.1 Commercial Catch and Effort

Commercial catches and fishing effort are monitored via compulsory monthly returns (‘Netting’ version) for each commercial fishery. Each licenced fisher records the monthly catch totals (to the nearest kilogram) for each retained species, monthly effort (total days fished), estimates of daily effort (e.g., average hours fished per day, average length of net deployed per day) and spatial information (CAES block(s) fished, per method. These data are collected and collated by the DPIRD and stored in the Catch and Effort Statistics (CAES) database.

8.2.2 Recreational / Charter Catch and Effort

The recreational catch level is uncertain due to lack of information about shore-based fishers, who are believed to harvest a larger quantity of nearshore finfish than boat-based fishers. The boat-based catch has been estimated every 2 years (Ryan et al. 2013, 2015, 2017, 2019) and partial shore-based catch for the metropolitan region occurs every 3 years.

A state-wide survey was implemented in 2011 to collect information on private (non-charter), boat-based recreational fishing in WA (Ryan et al. 2013, 2015). This survey uses three complementary components, off-site phone diary surveys, on-site boat ramp surveys and remote camera monitoring, to collect information on fishing catch, effort, location and other demographic information every two years.

Since 2001, it has been a statutory requirement for boat-based charter fishing operators to submit monthly returns detailing catches and effort.

Table 8.1. Summary of information available for assessing herring.

Data type	Fishery-dependent or independent	Purpose / Use	Area of collection	Frequency of collection	History of collection
Commercial catch	Dependent	Monitoring of commercial catch	State	Annual	1951-52 to 1974-75
Commercial catch and effort statistics (CAES returns)	Dependent	Monitoring of commercial catch and effort trends, calculation of catch rates and the area fished	CAES block	Monthly	Since 1975, or earlier.
Recreational catch and effort estimates	Dependent	Monitoring of recreational catch and effort trends	State-wide, boat-based Metropolitan shore-based survey	Biennial Annual	Since 2011 2010, & 2014 onwards
Catch at age data	Dependent	Age structure, estimation of total mortality	WCB, SCB	Every 1-5 years	Since ~2000
Biological information	Dependent and independent	Patterns of growth and reproduction, stock structure	WCB, SCB, GCB	Intermittent	Since 1970s
Recreational voluntary daily logbook	Dependent	Monitoring abundance trends & size composition	WCB, SCB	Monthly	Since 2005
Environmental data	NA (External to DPIRD)	Identify environmental influences on abundance	Various	Various	Various

A voluntary recreational daily logbook scheme (Research Angler Program, RAP) commenced in 2004/05. This collecting catch (no. of fish), effort (hours) and catch composition (sizes, discards) data. The majority of participants are in the WCB, including shore- and boat-based recreational fishers. RAP provides some data not currently available from other sources.

8.2.3 Fishery-Dependent Monitoring

In addition to catch and effort data, fishery-dependent data have also been collected from a biological monitoring program of age and length composition in fishery landings is for herring.

Age is estimated by counting the number of opaque and translucent zones in otoliths, following documented quality control protocols for each species (DoF unpublished). The annual periodicity of opaque zones has been validated for herring by Fairclough et al. (2000b).

8.2.4 Fishery-Independent Monitoring

Fishery-independent seine netting was conducted by DoF annually from 1995 to 2001 (Gaughan et al. 2006) and 2005 to 2015 and recommenced in 2020. Netting occurred at multiple beaches in the WCB and SCB. A wide range of species were captured, including juveniles of key fishery species. The main aim of the project was to capture juvenile fish and monitor annual recruitment trends for key species. The project provided important biological information (growth, reproduction, recruitment, distribution) used in stock assessments.

8.2.5 Environmental Monitoring

Databases with environmental variables (e.g., water temperature, wind and sea level) are continuously updated and extended as new data becomes available from collections by the Department, internet sources and from other agencies (see Caputi et al. 2015). The environmental variables from these databases have been used in analyses of correlations with biological parameters of species and allow for the examination of long-term trends.

8.2.6 Other Information

Biological parameters and other information (e.g., selectivity curves for gill nets) used in assessments are available from numerous fishery-independent studies in WA conducted by universities.

9 Stock Assessment

9.1 Assessment Principles

The different methods used by the Department to assess the status of aquatic resources in WA have been categorised into five broad levels, ranging from relatively simple analysis of catch levels and standardised catch rates, through to the application of more sophisticated analyses and models that involve estimation of fishing mortality and biomass (Fletcher and Santoro 2015). The level of assessment varies among resources and is determined based on the level of ecological risk, the biology and population dynamics of the relevant species, the characteristics of the fisheries exploiting the species, data availability and historical level of monitoring.

Irrespective of the types of assessment methodologies used, all stock assessments undertaken by the Department take a risk-based, weight of evidence approach (Fletcher 2015). This requires specifically the consideration of each available line of evidence, both individually and collectively, to generate the most appropriate overall assessment conclusion. The lines of evidence include the outputs that are generated from each available quantitative method, plus any qualitative lines of evidence such as biological and fishery information that describe the inherent vulnerability of the species to fishing and information from fishers, stakeholders and other sources. The strength of the WOE risk-based approach is that it explicitly shows which lines of evidence are consistent or inconsistent with a specific consequence level and therefore where there are uncertainties which assist in determining the overall risk level. For each species, all of the lines of evidence are then combined within the Department's ISO 31000 based risk assessment framework (see Fletcher 2015; section 12) to determine the most appropriate combinations of consequence and likelihood to determine the overall current risk status.

9.2 Assessment Overview

The specific methods used for monitoring and assessment vary among resources and indicator species which is affected by many factors including the level of ecological risk, the biology and the population dynamics of the relevant species; the type, size and value of the fishery exploiting the species; data availability and historical level of monitoring. There are five levels of assessment:

Level	Description
Level 1	Catch data and biological/fishing vulnerability.
Level 2	Level 1 plus fishery-dependent effort.
Level 3	Levels 1 and/or 2 plus fishery-dependent biological sampling of landed catch (e.g., average size; fishing mortality, etc. estimated from representative samples).
Level 4	Levels 1, 2 or 3 plus fishery-independent surveys of relative abundance, exploitation rate, recruitment; or standardised fishery-dependent relative abundance data.
Level 5	Levels 1 to 3 and/or 4 plus outputs from integrated simulation, stock assessment model.

There have been four major herring stock assessments since 1999, that have culminated in an assessment of the risk to the sustainability of the stocks (Table 9.1). The findings on stock status varied from sustainable in 2000, to high risk in 2013, to medium risk in 2018, and low risk in 2021 (Table 9.1).

Table 9.1. Summary of contemporary herring stock assessment outcomes 2000 to 2020

Year	Assessment outcome	Key assessment details
2000[a]	Sustainable (p212)	• Assessment made after large and sustained catches (mean ~ 1590 t for 1980-2000, whole of Australia, recreational and commercial) • Future development needed for recruitment monitoring • Natural mortality assumed to be 0.4
2013[b]	High/Severe risk to sustainability	• Made after reduced harvest (mean catch ~ 790 t for 2000-2013, whole of Australia, recreational and commercial) • Main risk factors: High F (fishing mortality), high % of immature fish, declining mean length and age of catch, low recruitment, truncated age structure. • Natural mortality assumed to be 0.42
2018[c]	Medium risk to sustainability	• Made after further reductions in harvest (mean catch ~520 t for 2013-2016, whole of Australia, recreational and commercial) • Increasing biomass detected, and supported by 2015 management changes • Natural mortality assumed to be 0.4

[a] Avayzian et al. 2000

[b] Smith et al. 2013

[c] Wise and Molony 2018

9.2.1 Peer Review of Assessment

The weight-of-evidence approach, incorporating a Level 3 age-based assessment, has been applied by the Department to numerous finfish stocks (e.g., Wise et al. 2007, Marriot et al. 2012, Smith et al. 2013, Brown et al. 2013) and the approach has been published in peer-reviewed journals (e.g., Braccini et al. 2021, Marriot et al. 2010).

External, expert reviews were conducted for recent Level 3 assessments of herring (Jones 2013, Haddon 2014, Wise and Molony 2018). The methods used in the current Level 5 assessment are standard techniques, used globally and consistent with previous assessments. Additional analyses examining stock-recruitment-environment relationships has been included. Peer-review of this assessment, therefore, was conducted internally within the Department.

9.3 Analyses and Assessments

9.3.1 Data Used in Assessment

Commercial catch Commercial catch and effort statistics (CAES returns) Recreational catch and effort estimates Catch at age data Recruitment index Biological information

Recreational voluntary daily logbook
Environmental data

9.3.2 Catch

9.3.2.1 Commercial Catch Western Australia

Annual commercial catch of herring in Western Australia increased from the 1950s to a peak around 1990, after which the catch declined to 2015, where it has since stabilized (Figure 9.1). Management changes, i.e., closure of herring trap net fishery have contributed to this decline. In recent years, commercial fishers suggest the declining catch reflects declining market demand (Wise and Molony 2018), similar to the opinion of fishers from the pre-1970’s who indicated that markets were driving catch (Department of Fisheries and Fauna 1973, Department of Fisheries and Wildlife 1975). Such a situation, however, does not preclude changes in abundance. A characteristic of the times series is the frequent punctuation of underlying trends with large peaks in catches, which suggests strong recruitment pulses.

The majority of the catch has historically occurred on the south coast via herring trap nets described in section 6.6. The trap net fishery was closed in 2015, which explains the drop in catch post-2015. Since the closure of the trap net fishery, catches have remained around 100 t, most of which now comes from the west coast. When caught in trap nets, fish are not entangled, therefore, only the quantity required is harvested, and the rest released. Data on the quantity released are not captured in Departmental records, however commercial fishers indicate this can be substantial and could confound interpretation of catch and catch rate trends.

Since the closure of the trap net fishery in 2015, approximately 97% of the catch has been taken by five fisheries: South West Beach Net (~28%), Cockburn Sound Fish Net (~27%), Open Access Fishing on the South Coast (transitioned to the South Coast Nearshore Net Managed Fishery) (~18%), South Coast Estuarine Managed fishery (~18%), and West Coast Estuarine Managed Fishery (~7%).

9.3.2.2 Commercial Catch South Australia

The catch of herring in South Australia is composed entirely of immature fish and trends in catch are similar to Western Australia. The peak in SA catch occurred in the late 1980’s at over 400 t, a few years earlier than in Western Australia (Figure 3-32A in Steer et al. (2020)). It declined to the early 2000s and has since fluctuated between approximately 75 to 150 t. As with WA catch trends, the SA catch is also punctuated with peaks and troughs, most likely a result of variable recruitment.

9.3.2.3 Seasonal trends in commercial catch

Catch of herring showed distinct seasonal trends between each bioregion, as demonstrated previously (Smith et al. 2013). In the SCB, more than 60% of the catch is taken in a single month, April (Figure 9.2a). In the WCB peak catch occurs from January to April, then declines markedly in winter, before beginning to increase through to the following January (Figure 9.2b). The difference in timing of peak catch is considered to be associated with maturing fish that have settled in the east migrating back to the west coast for spawning. This spawning migration, on the south coast, occurs over a short period of a March and April. Catch of fish in the WCB however, consist largely of the adult spawning stock. For SA trends, refer to Figure 3-33C of Steer et al. (2020).

9.3.2.4 Recreational Catch

A detailed investigation of recreational catch records for herring from a variety of data streams, some short and broken, some longer but from single fishers or clubs has been previously completed (Smith et al. 2013). Patterns in the data are as equally variable as the data streams themselves, refer to Smith et al. (2013) for a full description. At that time, limited data was available through standardized methods (Smith et al. 2013). This new assessment in 2021 is focused on more recent data collected through standardized sampling protocols, which are beginning to form an informative time series, i.e., surveys of boat-based fishers (Ryan et al. 2019) and shore based metropolitan fishers (Tate and Smallwood in press).

The estimate of shore-based, metropolitan catch of herring in 2021 was 9 t (95%CI 5 – 13 t) and has been steady since 2018 (Figure 9.3) (Tate and Smallwood in press). It was lower than the peak harvest in 2017 of 32 t (95%CI 20 – 44) and a similar peak of 31 t (95%CI 20 – 42) in 2010 (over a shorter, 3-month survey period) (Tate and Smallwood in press). The peaks and troughs in catch may be associated with effects on abundance due to recruitment variability.

Surveys of catch from boat-based fishers within WA have occurred biennially since 2011/12. These surveys have shown a decline in herring catch from around 200 000 fish (retained) in 2011/12 to just under 100 000 fish (retained) in 2017/18 (Figure 9.4, Ryan et al. 2019). The number of fish released, is much lower than that retained, under 50 000, and relatively similar over the duration of the surveys (Ryan et al. 2019). Part of the decline in catch trend might also be attributed the reduced bag limits from 2015 onwards.

9.3.2.5 Conclusion

There are strong declines in commercial catch from historical highs in the 1990s, and indications of contemporary declines in recreational catch since 2010. A pattern consistent among data streams is the punctuation of trends with peaks and troughs indicating variable recruitment. Interpretation of trends is confounded by the impact of market demand on commercial catch, and management changes aimed at reducing both commercial and recreational catch. Overall, these external factors are considered to have had a greater impact on catch than potential change in abundance.

Catch data is considered to provide no indication of unacceptable stock depletion.

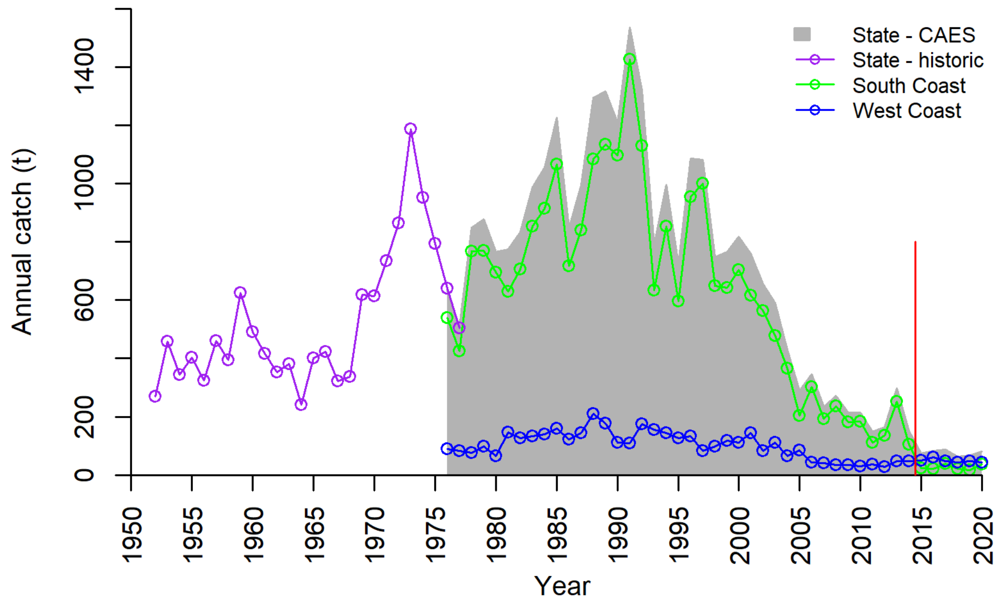

Figure 9.1. Total annual commercial catch of herring, by region. Red vertical line indicates closure of herring trap net fishery. State – CAES = commercial catch data collected and recorded by the Department (1975 onwards), State – historic = catch data collected by the state but reported by the Australian Bureau of Statistics. South Coast and West Coast are presented only for CAES data as data reported by the Australian Bureau of Statistic is not broken down by bioregion.

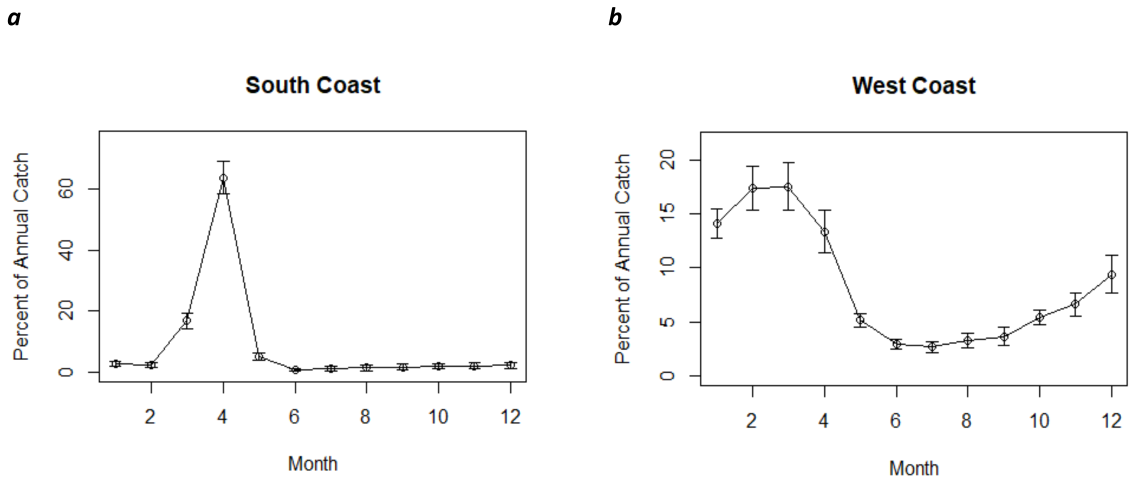

Figure 9.2 Percentage of commercial herring catch by month (±95% CI) since 1975 split by a) South Coast and b) West Coast bioregion.

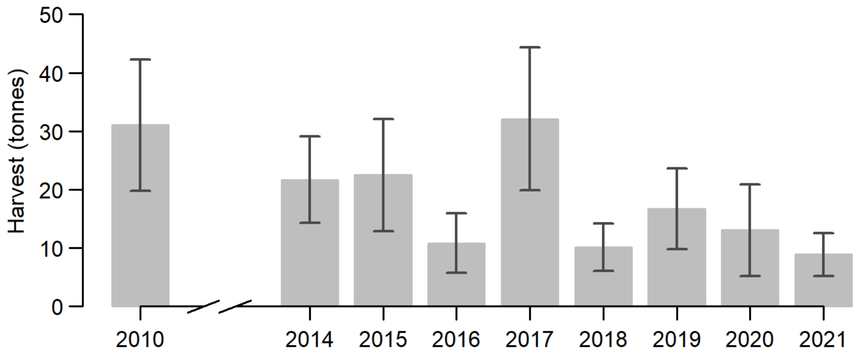

Figure 9.3. Estimated harvest (95%CI) for herring caught by recreational shore-based fishers in the Perth Metropolitan area, calculated from the roving creel surveys. Note: 3-month survey duration in 2010 (Tate and Smallwood in press).

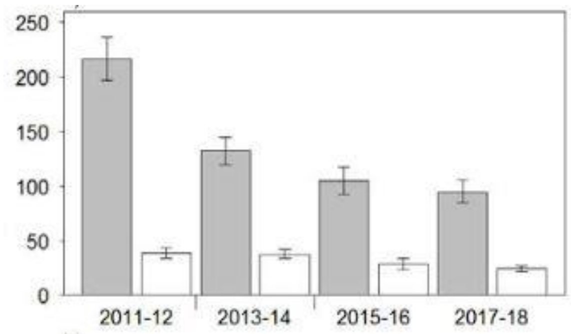

Figure 9.4. Boat-based kept (grey bars) and released (white bars) recreational catch (numbers x 1000 with standard error bars) of Australian Herring from the last four state-wide boat-based recreational fishing survey in WA (Ryan et al. 2019)

9.3.3 Catch Distribution

Catch grouped by 60 x 60 NM blocks show the spatial extent of the herring catch within Western Australia has changed very little from 1999- 2001 (Figure 9.5) to 2019-2021 (Figure 9.6). Where reductions have occurred, i.e., the Capes Region, this is a result of management changes restricting commercial fishers' access. Although the magnitude of catch within some blocks has decreased over time, this also is a result of either management, i.e., closure of the herring trap net fisher, and/or reduced market demand leading to reduced catch. As a migratory species, if the stock was in decline, this may not be evident in changes to the overall spatial distribution.

There has been little change in distribution of herring catch through time, and where changes have occurred, it is related to management rather than abundance. **Catch distribution provides no indication of unacceptable stock decline**

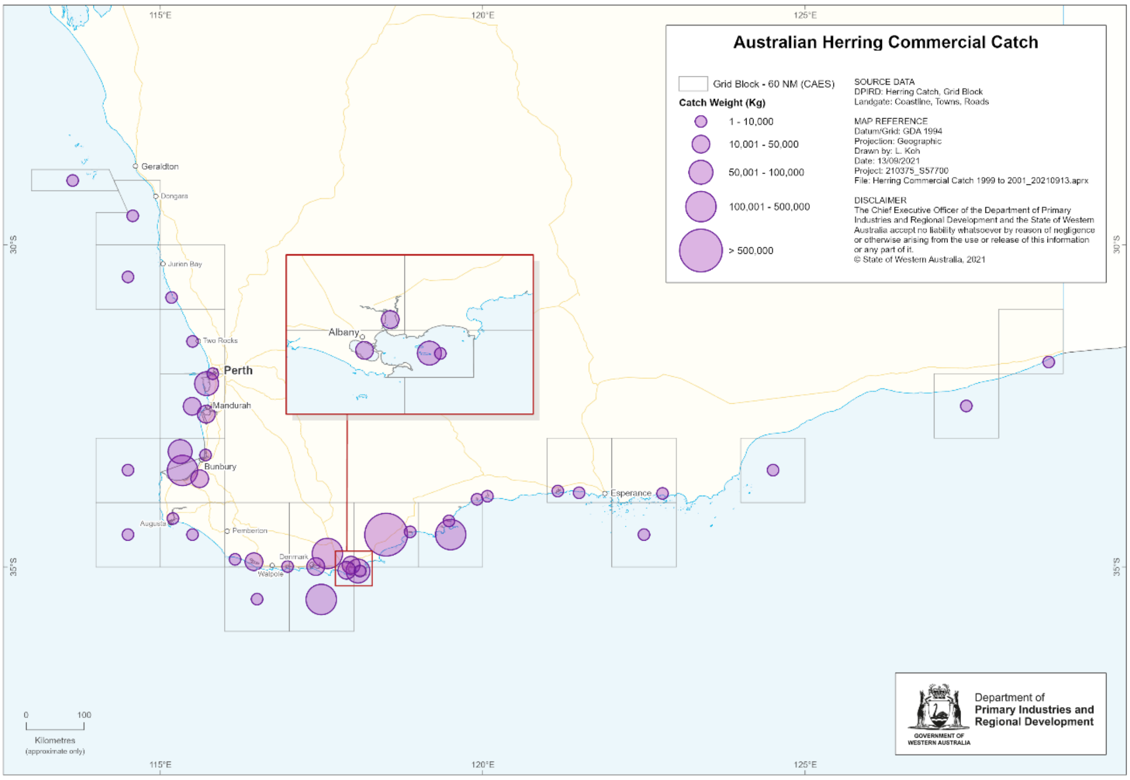

Figure 9.5. Location and magnitude of herring catch for years 1999 and 2000.

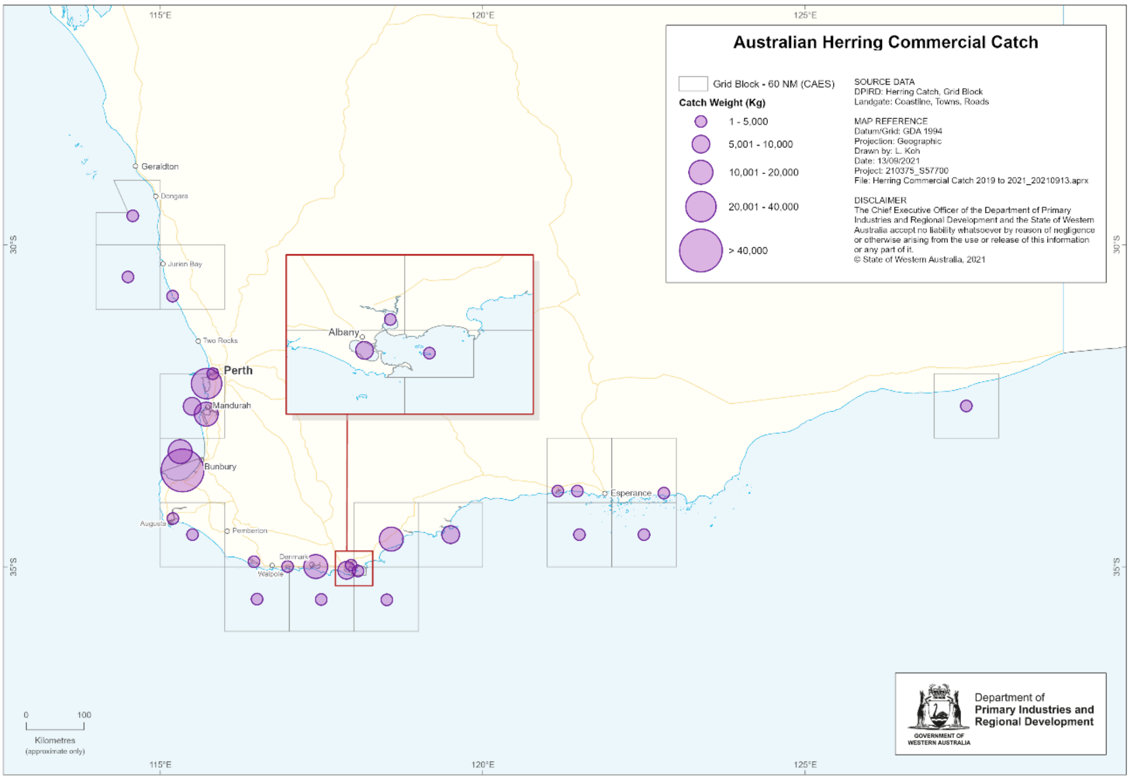

Figure 9.6. Location and magnitude of herring catch for years 2019 and 2020.

9.3.4 Effort Trends

9.3.4.1 Commercial Effort

All the five main fisheries that currently take herring, are multispecies and multigear fisheries that report catch and effort as monthly summaries. Effort measures recorded in monthly summaries are ‘number of days fished’, ‘block days’ (the no. of days that a particular gear type was deployed within a block), ‘mesh size’, ‘net length’, ‘hours fished per day’, and ‘number of shots per day’. Aggregation of this data within the monthly return does not allow for analysis of daily variations, and at the resolution provided, potentially the most reliable measure of effort is ‘*block days’*. The following section explores block days as the measure of effort for herring fishers. Data was extracted by species, as a result fishing days of months with zero catch are absent. Therefore, it may underestimate effort, as months when herring could have been caught by a vessel, but weren’t, will be absent from the data extraction.

Contrary to the fisheries that currently take herring, the now closed herring trap net fishery used a single method, trap nets, and was permitted to only take herring. As such, this fishery was an important source of data for effort, and subsequently catch per unit effort.

Total effort (block days where herring were caught by all gears) for herring trended slightly upwards through the 1980s, and then trended slightly downwards since. Overall effort is now the lowest level recorded. This pattern was similar at the state and bioregion level (Figure 9.7). The introduction of herring trap nets is hypothesized to have increased efficiency and may explain some of the decline in effort in the 1990s and 2000s, however trap nets were used to catch herring for many more years prior to the actual recording of the method in CAES data. Closure of the herring trap net fishery in 2015 may explain the increase in effort on the south coast at this time. Over the course of the time series, many different management changes directed at reducing effort have occurred, including buybacks of licences.

Four fisheries that take herring, were previously identified for further investigation into effort due to limited management changes: Herring trap net fishery, Geographe Bay Bunbury Seine Net Fishery, Cockburn Sound Fishery, and the South Australian Hauling Section, Marine Scalefish Fishery (Wise and Molony 2018).

9.3.4.1.1 **Herring Trap Net Fishery**

The majority of the catch of herring in the herring trap net fishery occurs in April, and block days recorded as using trap nets in April were examined for effort trends. Trend in effort was stable until 1995, followed by a decline in effort to 2000, a subsequent peak occurred a few years later, before a continued decline to the closure of the fishery in 2014 (Figure 9.8). Overall, the trend was largely one of decline. The declining trend indicates less time spent targeting herring, which supports statements by fishers that their fishing activities are influenced by market demand.

9.3.4.1.2 **Geographe Bay Bunbury Seine Net Fishery**

Fishers in the Geographe Bay/Bunbury area (CAES blocks 96010, 33150 and 33151) that utilise beach seine or beach haul (South West Beach Seine Fishery - SWBSF) showed an increasing trend in effort (total block days during peak herring season - January to April) to approximately 1200 block days around 2000 (Figure 9.9). A decline followed, which reached a low of approximately 200 block days in 2010. The low was followed by a slight increase to around 300 block days, where effort has remained stable over the last 8 years.

9.3.4.1.3 **Cockburn Sound Fishery – Gillnet fishery**

Overall, effort in the Cockburn Sound by fishers using gillnets to catch herring has declined from a peak in the early 1980s. During the period between 1980 and 2000, there was interannual variation. From 2000 onwards, effort was consistent between years. Recently, between 2012 and 2020, effort was relatively stable at around 200 days per year. Data is not presented due to confidentiality regarding data when less than 3 vessels are operating in a fishery.

9.3.4.1.4 **South Australian Hauling Sector, Marine Scalefish Fishery**

Effort in the hauling sector of the Marine Scalefish Fishery in SA, measured as targeted fisher days) has declined substantially since the early 1980s. Since the mid-2000s it has been below 100 targeted fisher days (Steer et al. 2020, Figure 3-32b).

9.3.4.2 Conclusion

The fisheries examined all show declines in effort to recent times. Only the herring trap net fishers specifically targeted herring, all other fisheries capture other species and effort in these fisheries can change based on market demand and the abundance and price of species.

Effort trends have declined through time; however, they have been strongly affected by management changes and market demand. Therefore, effort is not considered to provide evidence of unacceptable stock depletion.

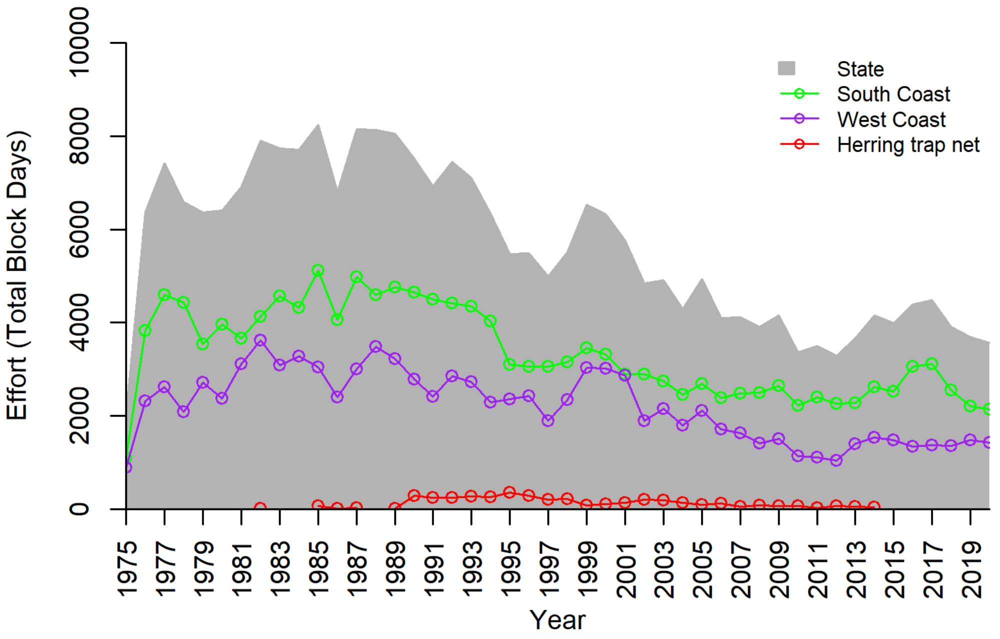

Figure 9.7. Combined number of Block days for all gears which caught herring since 1975.

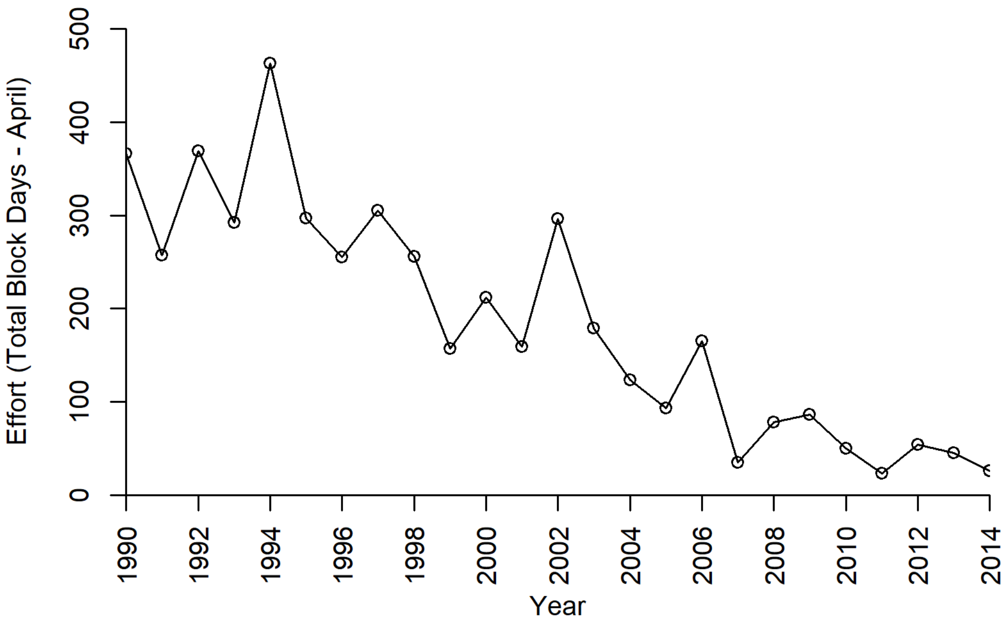

Figure 9.8. Total block days of herring trap net in April each year since 1990 and up to its closure in 2014.

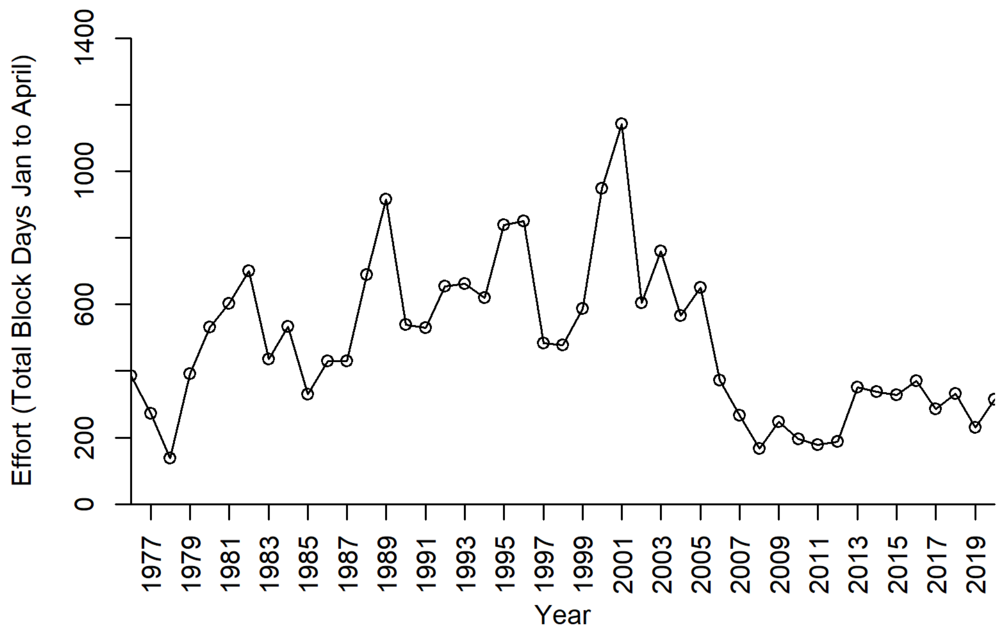

Figure 9.9. Total block days where herring was caught by beach-based haul netting during peak herring season, January to April, each year.

9.3.5 Fishery-Dependent Catch Rate Analyses

Herring are caught by a variety of multi-species, multi-gear fisheries and catch rates are reported monthly. Nominal catch rate analysis was undertaken on herring catch from peak months and methods, such as the trap net fishery on the south coast, and the Geographe Bay Seine Net Fishery.

To address the complexity of factors influencing catch rates, data were standardised with generalised linear model to produce indices of abundance (Section 9.3.6). These were used as independent lines of evidence, and to examine stock-recruit-environment relationships (Section 9.3.14).

The limitations and biases of fishery catch rate data have been examined in detail by many authors (Li et al., 2015; Ye and Denis, 2009; Maunder and Punt, 2004). They include changing vessel efficiency, poorly defined effort, and non-linear relationships between catch and effort (hyper stability or hyper depletion; Roa-Ureta, 2012), However, they are often the only available time series of abundance that span the history of the fishery, and regularly contain environmental signals within them (Feenstra et al., 2014; Leitão, 2015; Heerman et al., 2013). The decision to include fishery catch rate data as a line of evidence in the stock assessment of the herring fishery is based on two justifications. First, the longevity of the time series, and second, the appropriately standardised catch rates were used in a model to test an important biological hypothesis about the population dynamics of the fishery, that had not previously been examined in a quantitative manner. This hypothesis, known as the stock-recruitment-environment (SRE) relationship, required a spawning stock index (south-west fishery catch rates), a recruitment index (south coast fishery catch rates), and appropriate environmental information. Further details found in section 9.3.14. Finally, testing this hypothesis also provided an opportunity to validate the usefulness of the fishery catch rate data as an abundance index.

9.3.5.1 Nominal commercial catch rate trends

9.3.5.1.1 **Trap net fishery**

Overall, monthly catch rate in April (peak month of herring catch) of fishers using herring trap nets has had a sideways trend, with a possible increase in the last four years of the fishery, 2011-2014 (Figure 9.10). The sideways trend is punctuated with peaks and troughs, however there is significant overlap of 95% CL. There appears to be a decline in the catch rate from 1991 to 1994, followed by an increase to 2000. The decline occurs after the peak catch and suggests that this level of catch impacted abundance. However, an equally valid explanation is that this was a period of low recruitment due to weak Leeuwin Current (during El Niño events in the early 1990s) which is demonstrated to impact recruitment (section 9.3.14). Increase of catch rates from the low in 1994 was rapid, supporting literature that indicates the species is highly productive and has variable recruitment.

The recovery to 2000, occurred as catches declined, but no further increase in catch rate occurred with further declines in catch. Peaks and troughs may reflect inter-annual variations in recruitment strength as the trap net fishery catches a large proportion of fish on their first westward spawning migration. The combination of schooling and migratory behaviour of herring, may result in hyper stability of catch rates, considered further in section 9.3.6.2.

9.3.5.1.2 **Geographe Bay Bunbury Seine Net Fishery**

Catch rate of fishers has varied over time, it peaked in the early 1980s and declined to a low in the mid to late 2000’s (Figure 9.11). Since then, catch rates have improved with essentially no trend, and have remained at approximately 50% of the catch rate in the 1980s.

9.3.5.1.3 **Cockburn Sound Fishery**

Catch rates in the Cockburn Sound using gillnets have shown an increasing trend. There is a dramatic peak in catch rate in 1991, which remained for a few years, before catch rates declined, but continued an increasing trend. Data is not presented due to confidentiality regarding catch when less than 3 vessels are operating in a fishery.

9.3.5.1.4 **South Australia**

South Australian catch is composed of juveniles and catch rate trends are punctuated by strong dips and peaks. which are likely to reflect variations in recruitment (Steer et al. 2020, Figure 3-32c). Since 1984, there is no evidence of a decline in catch rate.

9.3.5.2 Recreational catch rate trends

The standardised catch rate for herring from the metropolitan region in 2021 was 0.76 ± 0.05 fish per fishing party per day (Tate and Smallwood in press). Catch rates for this species showed a downward trend between 2010 (1.71 ± 0.15) and 2016 (1.01 ± 0.06) and catch rates have remained steady since 2016 (Tate and Smallwood in press) (Figure 9.12).

9.3.5.3 Conclusion

Catch rate trends between fisheries and sectors are not consistent. Catch rates for the fishery with the largest take of herring, the trap net fishery, show a stable sideways trend, punctuated with peaks and troughs representing variable recruitment. These trends are similar to those seen in SA. Catch rates from Geographe Bay-Bunbury and Cockburn Sound show conflicting trends. As these are multispecies fisheries, dynamics impacting herring catch rates are more complex than the single species herring trap net fishery, therefore nominal catch rate trends may not be a reliable index of abundance and require consideration of other factors that may affect CPUE. Recreational catch rates have been stable since 2016.

Nominal catch rate trends provide evidence that stock depletion is possible, however catch rates have been stable in most indices since approximately 2013 and were potentially increasing in the trap net fishery until its closure.

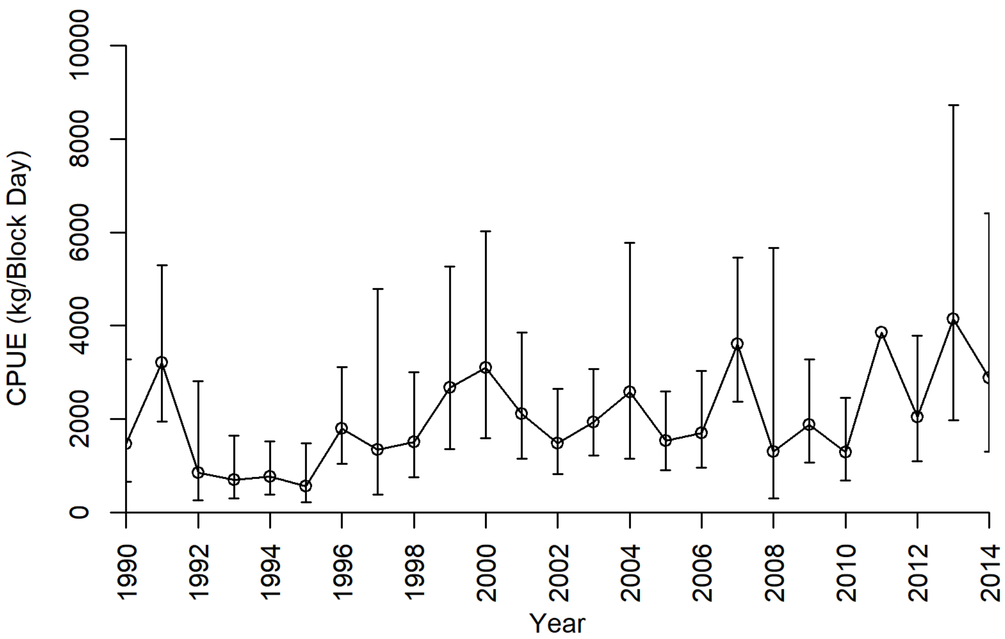

Figure 9.10. Nominal Catch rate (kg/block day) plus 95%CL of herring from trap nets in the peak month (April) each year from 1990 when the method was recognised in CAES until closure in 2015.

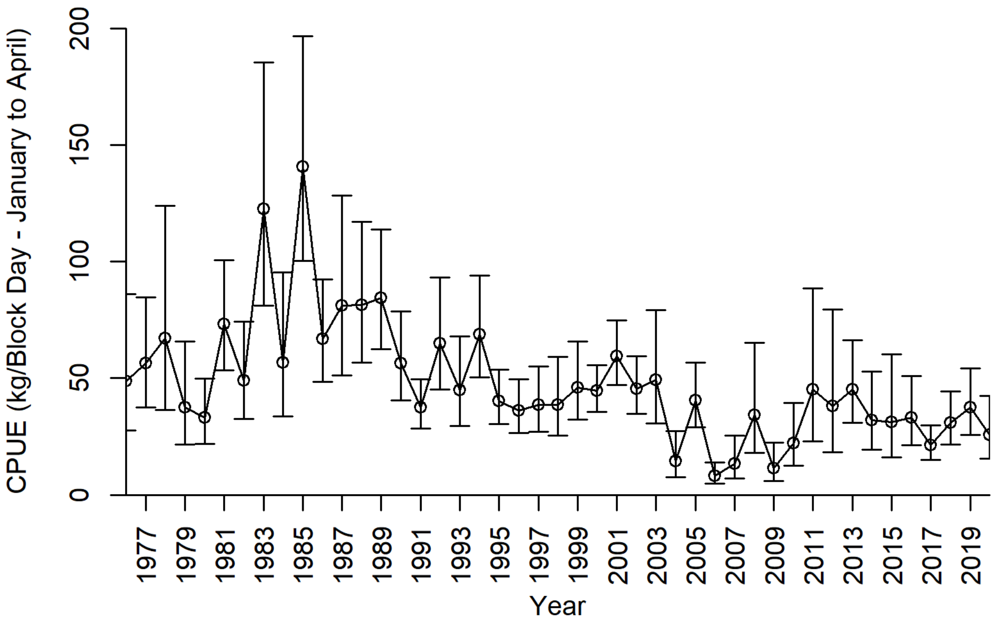

Figure 9.11 Nominal catch rate (kg/block day) with 95%CL of herring from Geographe Bay Bunbury Seine Net Fishery.

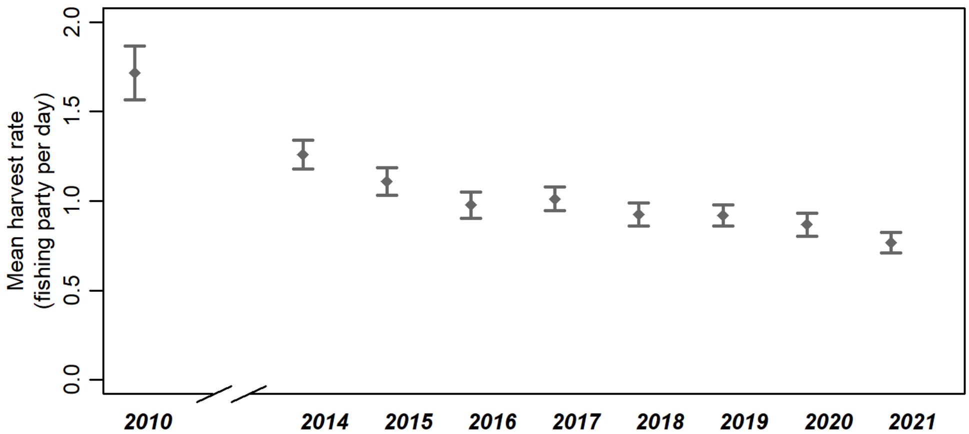

Figure 9.12. Standardised harvest rates (±SE) (fishing party per day) (using selected Tweedie model and variables survey year, targeted and time of day) for herring based on data from the roving creel survey (Tate and Smallwood in press).

9.3.6 Standardised catch per unit effort (SCPUE) analysis

9.3.6.1 Spawning stock index

Preliminary exploration of a spawning stock index was based on a standardised catch rate analysis of fishery data from the South-West Coast. The fishery uses two main methods (seine net and gill net) and herring have been observed to spawn in this region, Fishery data from the mid-1970's were available to construct an abundance index. After examining various models, the Geographe Bay data (Block 3115) were chosen to represent the spawning stock index. This block is well within the spawning region, experienced the majority of the fishing and had the most consistent vessel dataset over the years. Monthly logbook data were standardised using a GLM model that accounted for the effects of year, month, vessel, and days fished (per month) on the monthly catch rate. The model chosen was as follows:

$$log_e(U_{i,j,k,l}) = \alpha_i + \beta_j + \gamma_k + \delta_l + \varepsilon$$

where

$U_{i,j,k,l}$ is the CPUE (kg / month) for year *i*, month *j*, vessel *k*, and days fished *l*.

α_i is fishing year; *i* (1976-2021); fishing year is Nov – May, so catch reported in Nov/Dec of 1995 would be included in 1996 spawning index.

β_j is month; *j* (Nov, Dec, Jan, Feb, Mar, April, May)

γ_k is vessel; *k* (10 vessels produced the majority of the catch during 1976 to 2021 in the Geographe Bay fishing bock – 3115)

δ_l is days fished per month; *m* (5 categories; <5, 5-9, 10-14, 15-19, 20-24, >24)

ε is the normally distributed error around a mean of zero

Year, month, vessel, and days fished significantly influenced the West Coast SCPUE, which is a proxy for the spawning stock abundance (Table 9.2). Overall, the three most important factors influencing catch rates were vessel, days fished, and year, as indicated by the SS and MS scores (Table 9.2).

Spawning stock abundance increased through the 1980’s, reaching a peak in the early 1990’s, declined between 1990 and 2009 to levels similar to the 1970s, and has shown a slight increase since then (Figure 9.13). The influence of market demand as a driver of catch adds some uncertainty to the reliability of these data as an abundance index.

9.3.6.2 Recruitment stock index

The following analysis attempted to develop a recruitment index based on a standardised catch rate of herring trap net data from the South Coast, which although not a pure index of recruitment, occurs at a time when 2+ fish are first recruiting into the fishery. Only the data arising from the herring trap net fishery was used, as this accounted for 95% of the harvest, and was specifically focused on the months during the spawning run, a time when 2+ fish first recruit into the fishery, i.e., March and April. The monthly logbook data were standardised using GLM models to account for the effects of year, month and vessel on daily catch rates (kg/day).

$$log_e(U_{i,j} + 1) = \alpha_i + \beta_j + \varepsilon$$

where

$U_{i,j}$ is the CPUE (kg / month) for year i, and vessel j.

α_i is recruitment year; i (1990-2014); note that the herring trap net fishery has been closed since 2015, hence data are only available up to 2014.

β_j is vessel; j (12 vessels that produced 95% of the catch)

ε is the normally distributed error around a mean of zero

Year and vessel significantly influenced the south coast recruitment index (trap net SCPUE), which is a proxy for the annual recruitment to the fishery (Table 9.3, Figure 9.15). The index shows substantial peaks and troughs, with peak recruitment occurring in 2000. A low was recorded in 2005, and it has been increasing since.

9.3.6.3 Conclusion

Preliminary investigations suggest spawning stock abundance has shown substantial changes since 1975, however levels since the mid-2000s are similar to the levels in the late 1970s, which were prior to the largest catches. The recruitment index indicates strong annual fluctuations but does not indicate any decline. It does indicate a contemporary increase since 2005. As recruitment has not declined to an unacceptable level, it indicates the spawning stock is at a level where environment is the main factor impacting recruitment. Further work is required to explore uncertainties in the preliminary indices, e.g., associated with older age classes in the recruitment index, and external influences on CPUE, e.g., markets.

The preliminary recruitment index provides no evidence of recruitment failure. The long-term declining trend in the preliminary spawning index indicates possible stock depletion, although the trends in this index may also be impacted by external factors, e.g., markets.

Table 9.2 GLM results for the effect of Year, Month, Vessel, and days fished on catch rates (kg month^{-1}) of *Arripis georgianus*. On the South-West Coast (Spawning area – see Figure 5.3) Data has been log (x) transformed. Type III SS.

Source of variability	d.f.	SS	MS	F	*P*
Year	45	416	9.2	7.9	<0.001
Month	6	233	38.8	33.2	<0.001
Vessel	9	143	15.8	13.5	<0.001
Days fished	5	282	56.3	48.1	<0.001
Residual	1552	1818	1.17		

Table 9.3 GLM results for the effect of Year and Vessel on catch rates (kg month^{-1}) of *Arripis georgianus* on the South Coast (Albany area) Data has been log (x+1) transformed. Type III SS.

Source of variability	d.f.	SS	MS	F	*P*
Year	24	51.9	2.16	2.39	<0.001
Vessel	11	22.86	35.06	33.5	<0.001
Residual	2725	2854.3	1.05		

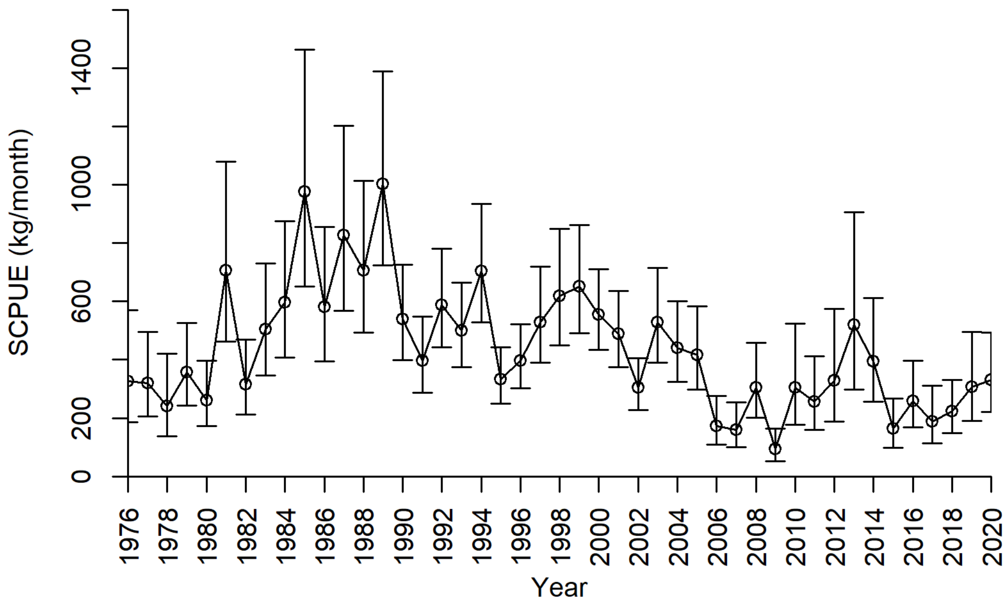

Figure 9.13 Spawning stock index (SCPUE-West Coast) (95% CL) of herring between 1976 and 2020.

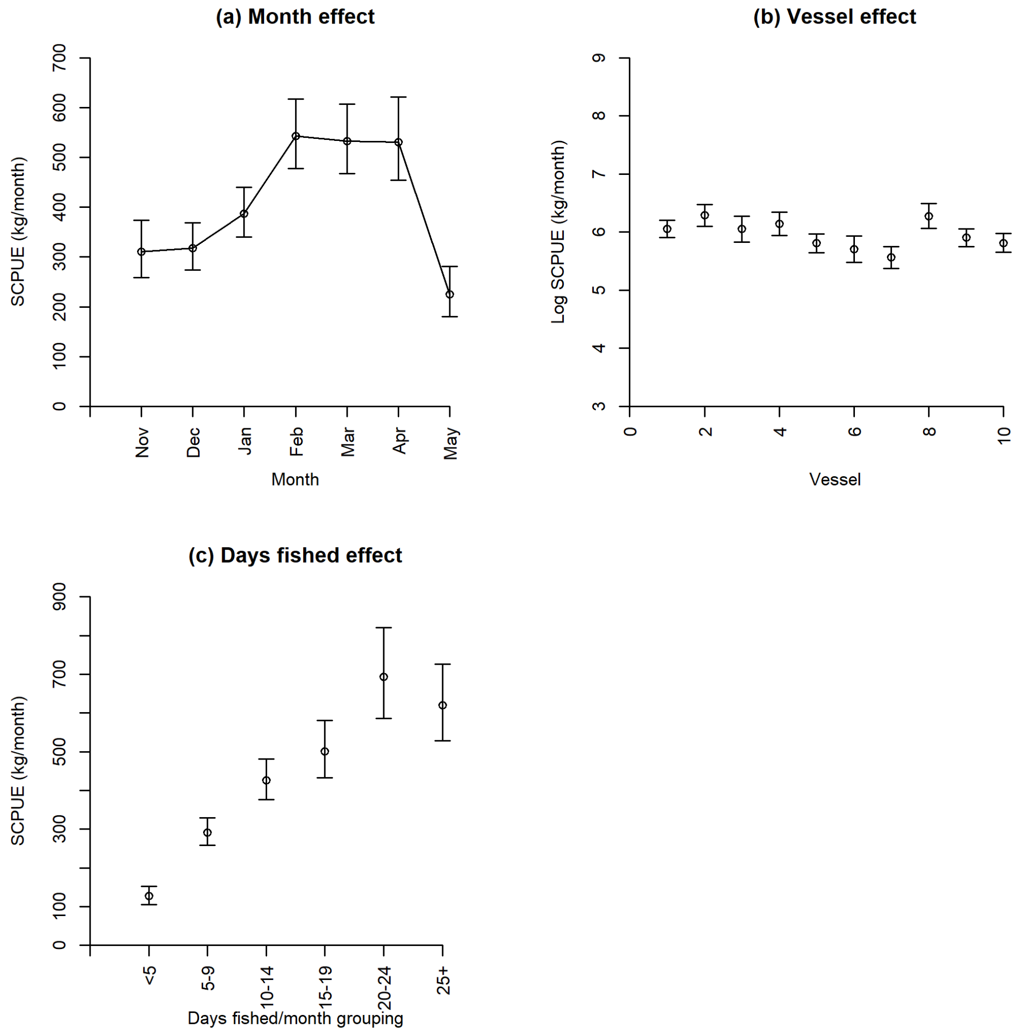

Figure 9.14 Effect of (a) Month, (b) Vessel, and (c)) Days fished (per month) on the spawning stock abundance index (SCPUE-West Coast) of herring. Including 95% CL for all figures.

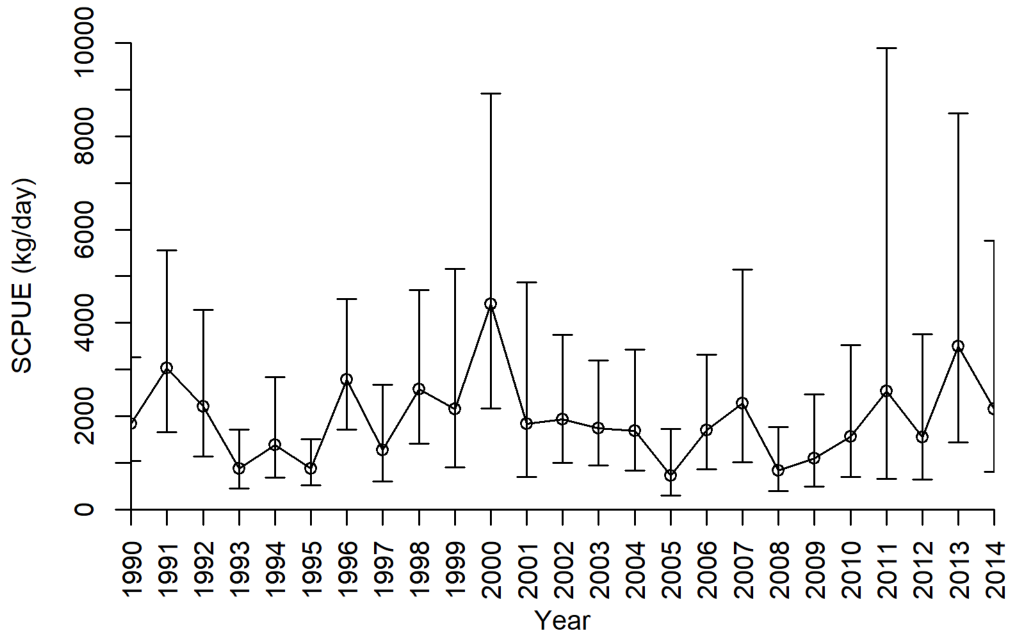

Figure 9.15 Recruitment index for herring (SCPUE-South Coast) (95% CL) of herring between 1990 and 2014

9.3.7 Vulnerability – Productivity Susceptibility Analysis (PSA)

Productivity Susceptibility Analysis (PSA) is a semi-quantitative risk analysis originally developed for use in Marine Stewardship Council (MSC) assessments to score data-deficient stocks, i.e., where it is not possible to determine status relative to reference points from available information (Hobday et al. 2011, MSC 2014). The PSA approach is based on the assumption that the risk to a stock depends on two characteristics: (1) the productivity of the species, which will determine the capacity of the stock to recover if the population is depleted, and (2) the extent of the impact on the stock due to fishing, which will be determined by the susceptibility of the species to fishing activities (refer to section 13 for PSA scoring criteria).

Although a valuable tool for determining the overall inherent vulnerability of a stock to fishing, the PSA is limited in its usefulness for providing stock status advice. This is because of the simplicity and prescriptiveness of the approach, which means that risk scores are very sensitive to input data and there is no ability to consider management measures implemented in fisheries to reduce the risk to a stock. Consequently, the PSA is used by the Department to produce a measure of the vulnerability of a stock to fishing, which is then considered within the overall weight of evidence assessment of stock status.

The sections below outline the PSA scores for herring.

9.3.7.1 Productivity

Values for productivity scoring are provided in the species description section of this document (Section 5) and the resulting scores for these values are provided in Table 9.4 (refer to section 13 for PSA scoring criteria). All criteria received a score of 1 (low risk) except maximum age (scored a 2, based on maximum observed age of 12 years) and trophic level scored a 3, based on the trophic level value of 4.3 accessed in FishBase (Froese and Pauly 2021). The average productivity score for herring based on these values is 1.43, which is a low risk, indicating the species is highly productive.

9.3.7.2 Susceptibility

Susceptibility scores are provided for the main herring fisheries (Table 9.5). All fisheries have high risk score for encounterability and post-capture mortality as the species can be caught through the water column with commercial and recreational methods, and it is targeted and retained by all fisheries. Selectivity score, reflected by the relative portion of captured fish that are immature, was scored 2, a medium risk for all fisheries.

The south and west coast estuarine fisheries, South west beach net, and Cockburn Sound fish net fisheries all received an aerial overlap score of 1, low risk, as they are restricted to a small portion of the herring's range. The trap net fishery scored a 3, high risk, because a large proportion of all maturing fish must pass through the grounds of this fishery on their first spawning migration. The recreational fishery got the same score as recreational fishers can fish for herring across much of their range from both shore and boat.

9.3.7.3 Conclusion

Based on the productivity and susceptibility scores, the overall weighted (by fishery / sector catches) PSA score for herring was 83, which equates to a low risk.

The low PSA score indicates that under current management arrangements, unacceptable stock depletion is unlikely.

Table 9.4. PSA productivity scores (1-3, where 1 reflects low vulnerability/risk)

Productivity attribute	Aust. herring
Average maximum age	2
Average age at maturity	1
Average maximum size	1
Average size at maturity	1
Reproductive strategy	1
Fecundity	1
Trophic level	3
Total productivity (average)	1.43

Table 9.5. PSA susceptibility scores for each fishery / sector that impact on herring.

Susceptibility attribute	South Coast Trap Net Fishery	South Coast Estuarine Fishery	West Coast Estuarine Fishery	South West Beach Net Fishery	Cockburn Sound Fishnet Fishery	Recreational Fishery (SC & WC combined)
Areal overlap (availability)	3	1	1	1	1	3
Vertical overlap (encounterability)	3	3	3	3	3	3
Selectivity	2	2	2	2	2	2
Post-capture mortality	3	3	3	3	3	3
Approximate catch(tons)	0	20	5	15	20	41
PSA score = 83 (low risk)						

9.3.8 Length Composition

Length distributions from the 1990's (Figure 9.16) differ from latter years as they contain a higher proportion of smaller animals. Wise and Molony (2018) attributed this to the retention of smaller animals by the commercial sector for research purposes, and so this data is not directly comparable to latter years. Data from 2009 onwards suggest similar length composition between years, as well as within and between sectors (Figure 9.17, Figure 9.18, Figure 9.19). However, recreational data does tend to contain some larger fish absent from commercial data. Larger size achieved by females than males are shown in the plots, reflecting the different growth patterns between sexes.

There are relatively high k values estimated for the growth curves (i.e., rate at which fish approach asymptotic length) indicating limited growth beyond relatively young ages (2-3 y). Therefore, a length composition plots may not reflect changes in the underlying age structure.

9.3.8.1 Conclusion

There is no evidence of a change in length composition overtime that could reflect overfishing.

Length composition data provides no evidence of unacceptable stock depletion.

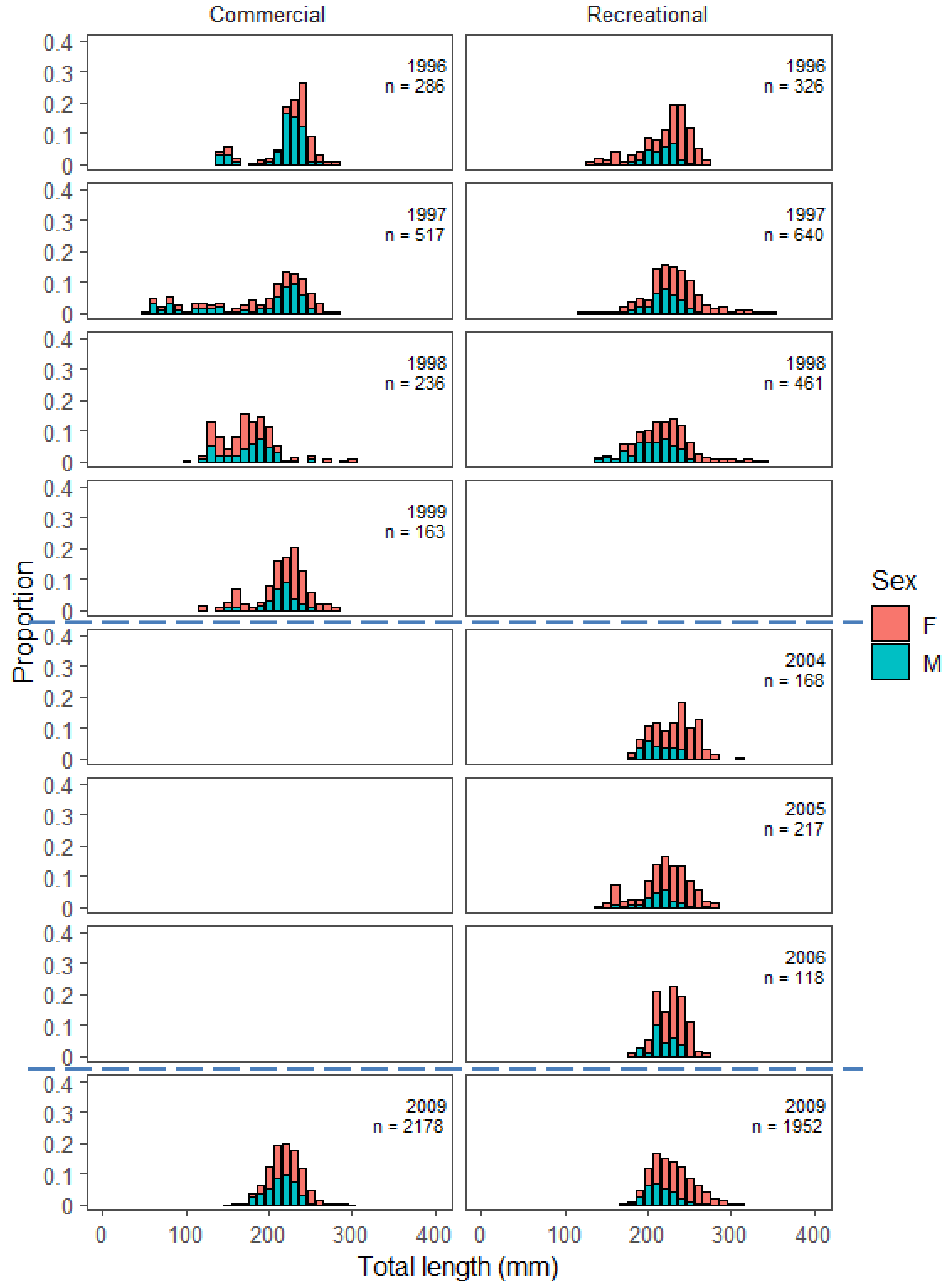

Figure 9.16 Length frequency of recreational and commercial herring samples (both sexes) in the west coast bioregion (1996 – 2009). Dashed blue line indicates break in continuity of years between charts.

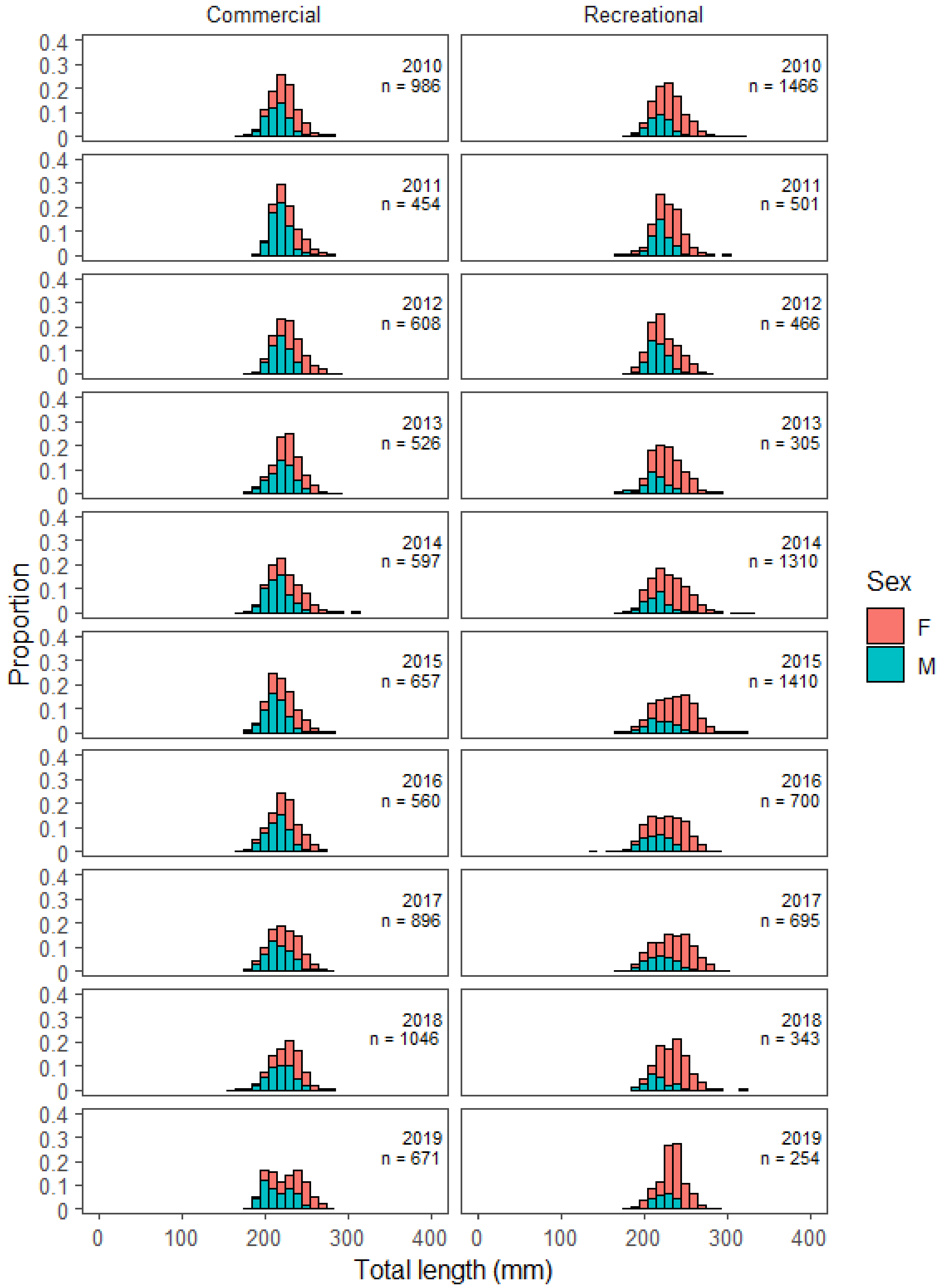

Figure 9.17 Length frequency of recreational and commercial herring samples (both sexes) in the west coast bioregion (2010 – 2019).

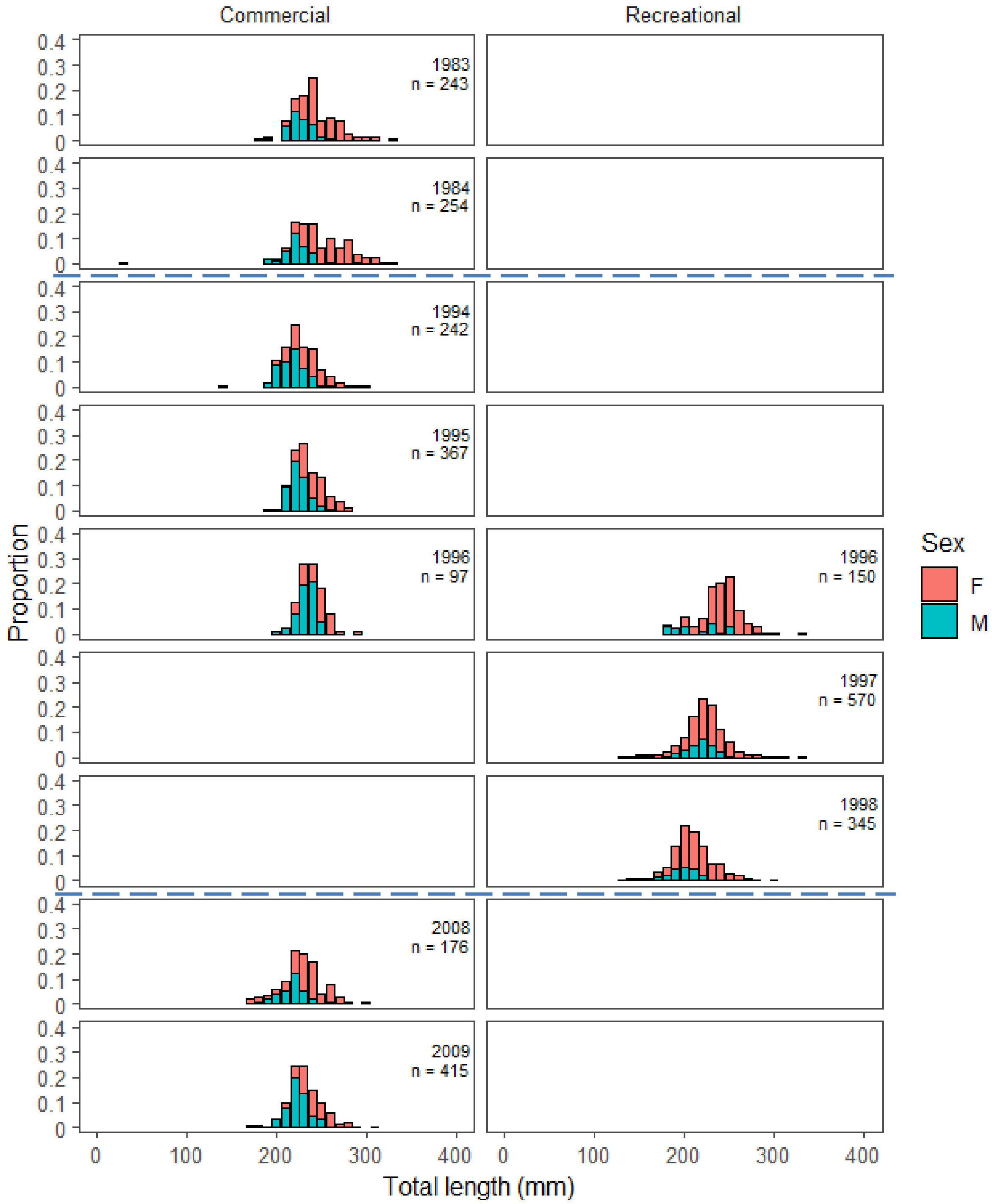

Figure 9.18 Length frequency of recreational and commercial herring samples (both sexes) in the south coast bioregion (1983 – 2009). Dashed blue line indicates break in continuity of years between charts.

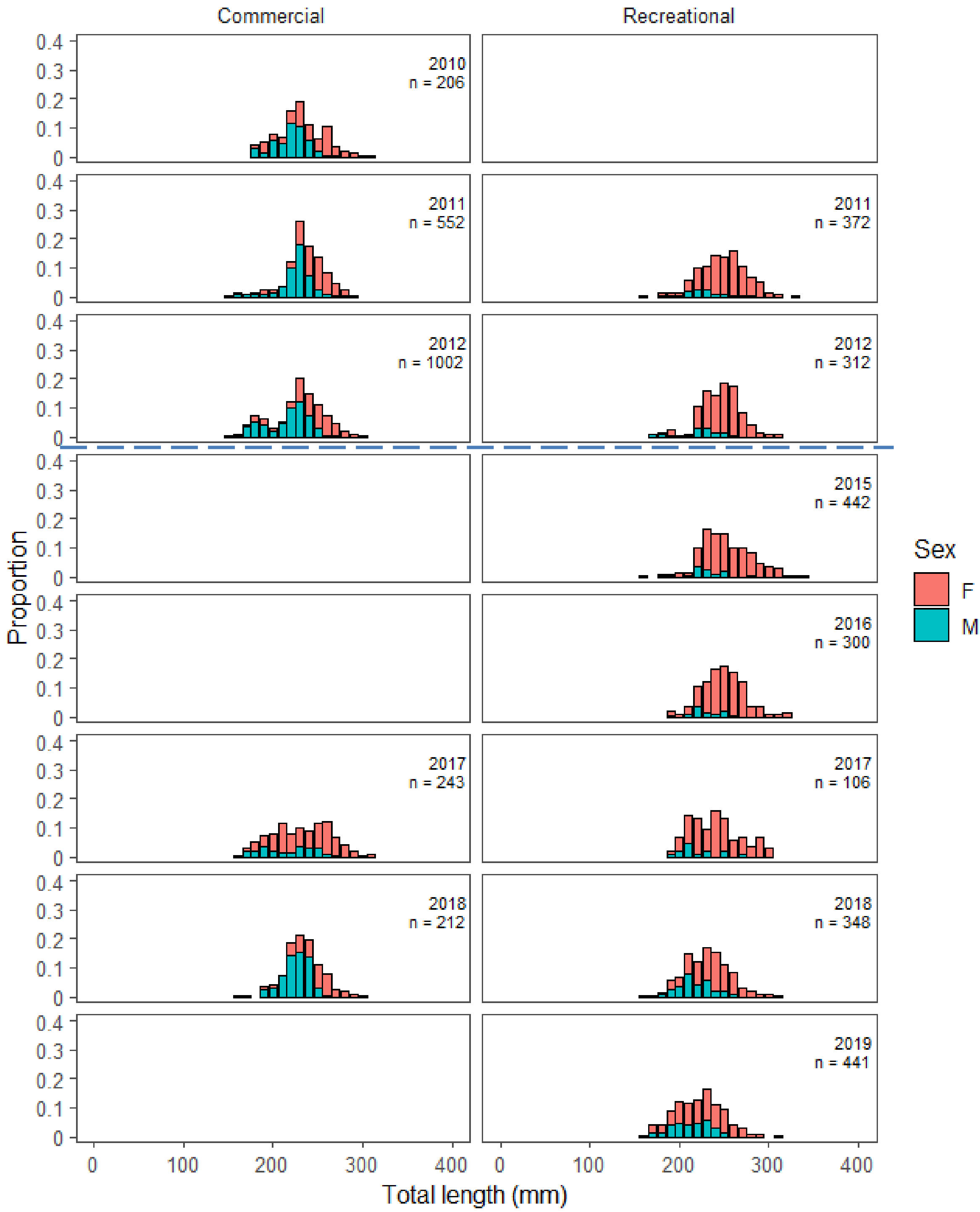

Figure 9.19 Length frequency of recreational and commercial herring samples (both sexes) in the south coast bioregion (2010 – 2019). Dashed blue line indicates break in continuity of years between charts.

9.3.9 Age Composition

Age structure data for herring differs between sectors (recreational vs commercial) in both the west coast and south coast (west coast - Figure 9.20 & Figure 9.21, south coast - Figure 9.22 & Figure 9.23). The differences can occur as differences between the dominant year class, e.g., west coast 2012 & 2013 (Figure 9.21) and south coast 2012 (Figure 9.23); the relative strength of a dominant year class, e.g. west coast 3+ 2016 (Figure 9.20), south coast 2+ 2011 (Figure 9.23); and a difference in abundance of older cohorts e.g. west coast 2015 (Figure 9.21), south coast 2011 (Figure 9.23). Furthermore, these differences are not always consistent and indicate the possibility that samples collected from one or both sectors are not representative of the population.

The previous two assessments considered sample representativeness. Smith et al. (2013) indicated that samples from the west coast bioregion are likely to be more representative of the breeding stock, and that recreational samples have better temporal and spatial distribution. Wise and Molony (2018) indicated commercial fishers may preferentially retain larger fish, and south coast recreational fishes may high-grade their catches. Until further work on the representativeness of sample collection , we have continued with the assumption that the west coast recreational samples better represent the entire stock and have much better spatial and temporal distribution. However, Wise & Molony (2018) indicate that these samples are female biased.

Examination of the west coast recreational female samples shows that the dominant cohort varies between 2+ and 3+, indicating variable recruitment strength between years, and year classes from strong recruitment events in 2009/10 and 2014/15 can been seen in subsequent years. Variable recruitment makes it difficult to differentiate age truncation due to strong recruitment, from age truncation caused by increased mortality.

9.3.9.1 Conclusion

Age data shows variation between sectors and regions, indicating that the sampled age structure from all regions/sectors, may not be representative of the entire stock. However, it does provide evidence of variable recruitment between years, with strong year classes able to be tracked through recent years.

Strong recruitment events in recent years provide no evidence of recruitment impairment that would indicate unacceptable stock depletion.

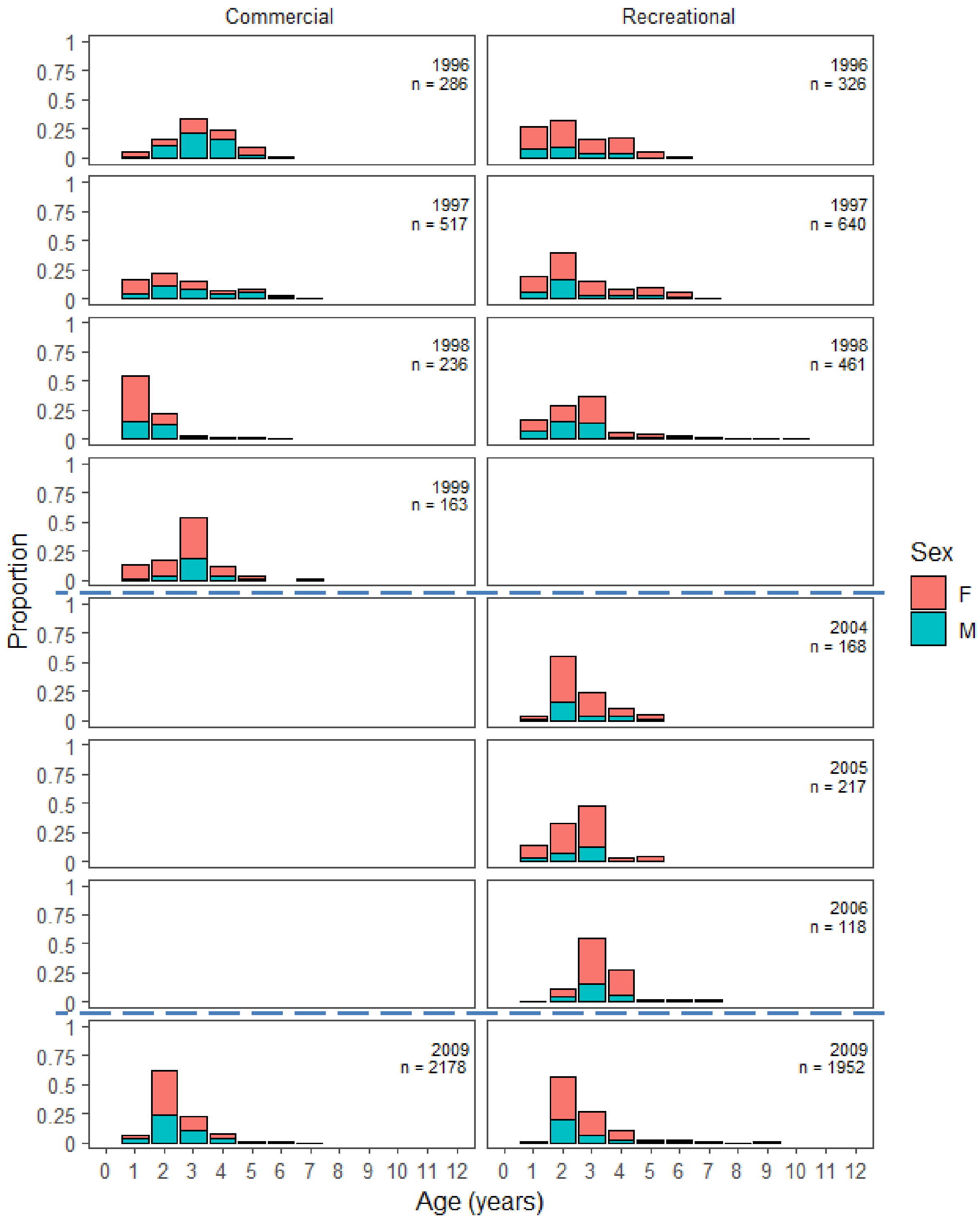

Figure 9.20 Age structure of recreational and commercial herring samples (both sexes) in the west coast bioregion (1996 – 2009). Dashed blue line indicates break in continuity of years between charts.

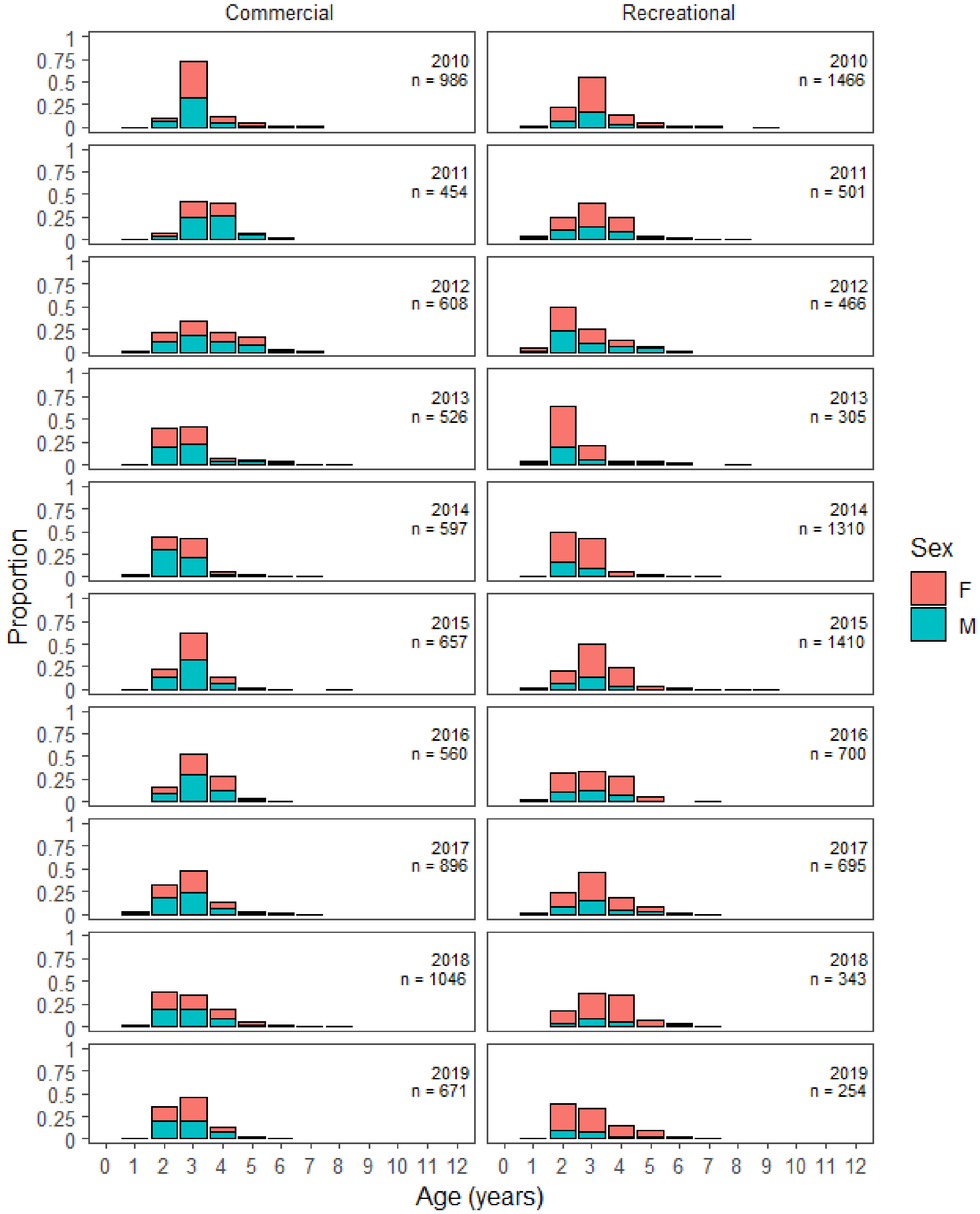

Figure 9.21 Age structure of recreational and commercial herring samples (both sexes) in the west coast bioregion (2010 – 2019).

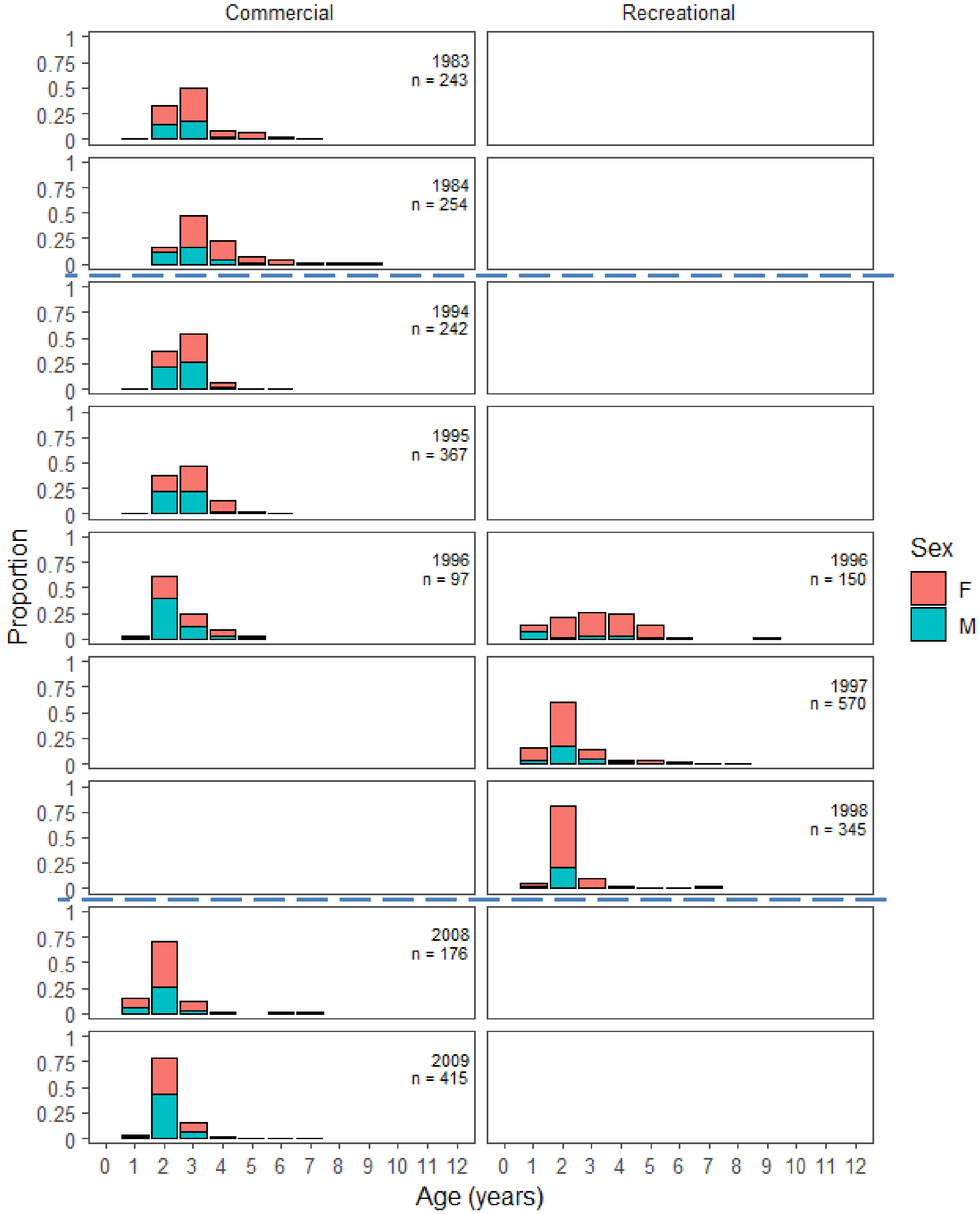

Figure 9.22 Age structure of recreational and commercial herring samples (both sexes) in the south coast bioregion (1983 – 2009). Dashed blue line indicates break in continuity of years between charts.

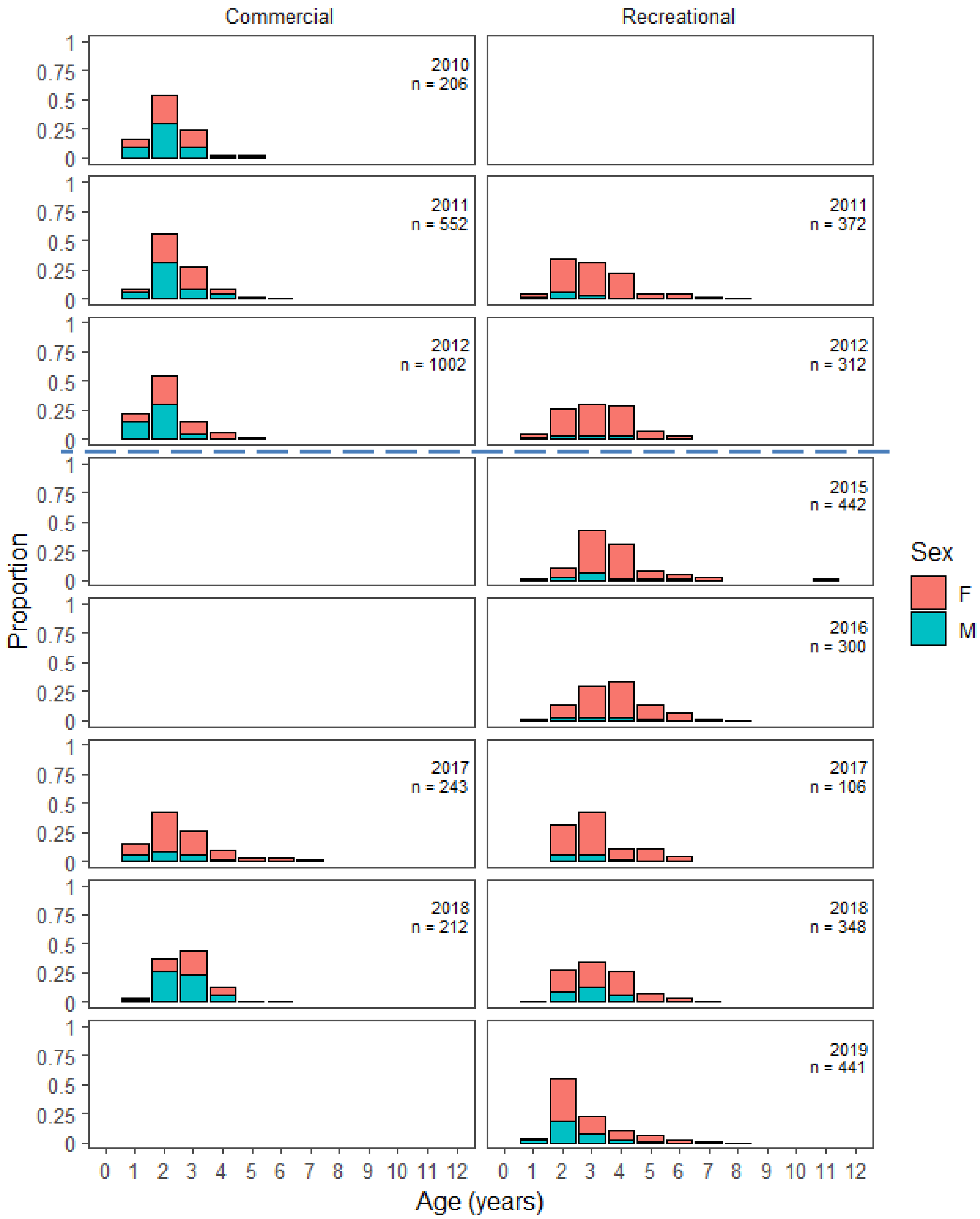

Figure 9.23 Age structure of recreational and commercial herring samples (both sexes) in the south coast bioregion (2010 – 2019). Dashed blue line indicates break in continuity of years between charts.

9.3.10 Fishing Mortality - Catch curve analysis

Estimates of the instantaneous rate of total mortality (Z, y^{-1}) for female herring were derived by fitting a multi-year catch curve model (accounting for recruitment variation) to recent (2017/18 - 2019/20) biological years (*i.e.*, 1 June - 30 May, where 1 June is taken to represent the 'peak' spawning time) of age composition data. Although additional analyses were undertaken, those utilising the age data assumed as most representative, female samples collected from the west coast by recreational fishers, are presented in the main body of this document. For details regarding the model and additional analyses of sector/region, refer to Appendix D.

Estimates of F for fully-selected fish are calculated by subtracting a specified value for natural mortality (M) from each catch curve estimate of Z, i.e., $F = Z - M$. Following the recommendation of Then et al. (2015) for best practice estimation of M, the estimate of M=0.57 y^{-1} was used to determine the current F and F to M ratio for the stock. This approach yielded a current estimate of F= 0.44 y^{-1} and provides an F/M ratio of 0.77, well below the acceptable level of $F = M$, indicating an acceptable level of fishing mortality has recently occurred (Table 9.6). However, use of M = 0.4 y^{-1} yields an F/M ratio of 1.53, which is near the limit of F=1.5M. Trends in F since the last assessment (Wise and Molony 2018), using a natural mortality estimate of 0.4 y^{-1}, show fishing mortality in recent years was slightly lower (Table 9.7). The decline in estimate of F from the previous assessment is consistent with fishing pressure being reduced in recent years, associated with low catches.

9.3.10.1 Conclusion

Fishing mortality has declined from the previous assessment; however, the actual value of *F* is highly dependent on the value assumed for *M*. Based on the most recent evidence for estimating *M* (Then et al. 2015), the current *F/M* ratio is well less than *F = M*, however using methods from the previous assessment F/M ratio is close to F=1.5*M*.

Declining *F* compared to the previous assessment, and the current *F/M* ratio of well less than *F = M* suggest no evidence of unacceptable stock depletion; however, it is possible if *M* is assumed to be 0.4 y^{-1}.

Table 9.6 Point estimates of ratio of fishing mortality (F) to natural mortality (F/M) for female herring (biological years 2017/18 to 2019/20) caught by recreational fishers on the west coast of Western Australia from catch curve analysis.

Region	Sector	Sex	Natural Mortality	Fishing mortality	*F/M* ratio
WC	Recreational	F	0.57	0.44	0.77
WC	Recreational	F	0.4	0.61	1.53

Table 9.7. Comparison of fishing mortality estimates (*F*) between current assessment and previous assessment using *M* = 0.4 y^{-1}.

Region	Sector	Sex	*F* (Wise & Molony 2018)	*F* Current assessment
WC	Recreational	Female	0.66 y^{-1}	0.61 y^{-1}

9.3.11 Per recruit analysis - SPR

Per recruit analyses were undertaken using catch curve estimates of *F*, calculated with a value of $M = 0.4$ y^{-1} for comparability with the previous assessment (Wise and Molony 2018), and the selectivity parameters A_{50} and A_{95} for female herring were applied together with other available biological information (growth, maturity, weight-length relationship, natural mortality estimate (see section 5)) for herring on the west coast of Western Australia. The analysis reported here is for west coast samples as this was considered to more appropriately represent the majority of the spawning stock biomass (Smith et al. 2013, Wise & Molony 2018). Additionally, *F* estimates from this stock are considered more reliable due to the migratory nature of spawning fish on the south coast, particularly the 2+ age class. For analyses based on other sectors/regions, refer to Appendix D.

These analyses provided estimates of (i) female spawning potential ratio (SPR), based on traditional per recruit analysis, which assumes constant recruitment, and (ii) relative female spawning biomass (B_{rel}), from an extended model incorporating a Beverton-Holt stock recruitment relationship to account for potential effects of fishing on recruitment, i.e. associated with impacts of fishing of female spawning biomass (Table 9.8). Further details of these per recruit models, full results and additional analyses are provided in section 14.3.

The values of SPR and B_{rel} are taken as proxies for female spawning biomass. For this analysis, the target, threshold and limit reference points for SPR and B_{rel} were considered as 0.4, 0.3 and 0.2, respectively and are based on internationally accepted benchmarks (Mace 1994; Caddy and Mahon 1995; Gabriel and Mace 1999; Wise et al. 2007). Point estimates of SPR were at the target, or above the target, for recreational and commercial data respectively (Table 9.8). As expected, after accounting for possible effects of fishing on recruitment, the estimate of B_{rel} was slightly lower than for SPR. The point estimate for B_{rel} was close to the target.

9.3.11.1 Conclusion

Point estimates of B_{rel} and *SPR* for the west coast spawning stock are at or above the Target, respectively.

***SPR* and B_{rel} provide no evidence of unacceptable stock depletion.**

Table 9.8. Estimates of female spawning potential ratio (SPR) from traditional per recruit analysis and female relative biomass (Brel) from extended per recruit analysis (with stock-recruitment relationship, with steepness=0.75) for herring on the west coast of Western Australia. Key input parameters used are also listed, including the growth and maturity parameters and estimates of fishing mortality and selectivity parameters from catch curve analysis.

Region / Sex	Sector	Maturity (mm, TL)	Selectivity (y)	Growth	F^* (±1SE)	SPR (±95% CL)	B_{rel} (±95% CL)
West coast (Female)	Rec.	L_{50}=194.1 L_{95}=250.8	A_{50}=2.64 A_{95}=3.36	L_∞=271.5 mm k=0.57 y^{-1} t_0=-0.3 y	0.612 (0.051)	0.446 (0.416-0.484)	0.396 (0.363-0.437)

* *F* estimates calculated with assumed value of $M = 0.4$ y^{-1}

9.3.12 Length-based spawning potential ratio (LBSPR)

Length-based spawning potential ratio analyses were undertaken with length composition data from recreational and commercial fishers. Analyses of data collected from the catch by recreational fishers on the west coast are presented as the majority of the spawning activity occurs in this region and recreational catch data is thought to better represent the stock due to better temporal and spatial coverage (Smith et al. 2013), although subject to much debate in the herring assessment workshop (Wise & Molony 2018)). Analyses for other regions and sectors are presented in Appendix D.

The analysis utilised the length-based spawning potential ratio method, available as an R package (version 0.1.5), using the default model type (length-structured growth-type-growth model, or GTG-LBSPR model) described by Hordyk et al. (2016). It utilised similar values for input parameters as Wise and Molony (2018), including a value for M = 0.4 y^{-1} (Table 9.9). Refer to Appendix D for further details and additional analyses.

The estimated ratios of fishing mortality to natural mortality, were highly variable from year to year (Table 9.10), which may reflect, in part, some sensitivity of this type of analysis to the effects of annual recruitment variation. LBSPR estimates were more consistent and were above the target (0.4) in all years (Table 9.10). Analyses using the higher M estimate from Then et al. (2015) were not undertaken as LBSPR estimates were already above the target using the conservative value of 0.4y^{-1}.

9.3.12.1 Conclusion

Estimates of SPR produced by the LBSPR analysis using length composition data for herring caught by recreational fishers on the west coast are above the target reference point (0.4). This is assumed to better represent the stock than samples from other regions or sectors.

LBSPR estimates provide no evidence of unacceptable stock depletion.

Table 9.9 Values of input parameter used in the length-based spawning potential ratio (LBSPR) analysis for recreationally caught female herring on the west coast of Western Australia.

Region / Sex	Sector	Maturity (mm, TL)	Natural mortality (M, y^{-1})	Growth coefficient (k y^{-1})	M/K ratio	Asymptotic length (L_∞, mm)	Bin width (mm)
West coast (Female)	Rec.	L_{50}=194.1 L_{95}=250.8	0.4	0.57	0.702	L_∞=271.5 mm	10

Table 9.10 Results from the length-based spawning potential ratio (LBSPR) analysis for recreationally caught female herring on the west coast of Western Australia using *M* = 0.4 y^{-1}, rawSL50 and rawSL95 are non-smoothed estimates for selectivity parameters. rawFM are non-smoothed estimates of the F:M ratio. rawSPR are non-smoothed estimates for spawning potential ratio.

Source	Biol. Year	rawSL50	rawSL95	rawFM	rawSPR
WC-rec	2015/16	242.63	285.27	2.03	0.55
WC-rec	2016/17	246.25	295.61	4.08	0.43
WC-rec	2017/18	253.28	302.09	3.15	0.53
WC-rec	2018/19	233.04	261.14	2.69	0.47
WC-rec	2019/20	245.53	277.39	6.90	0.42

9.3.13 Catch-MSY

The Catch-MSY model is a “data-poor” stock assessment method with population dynamics described according to the same production function as applied in the Schaefer surplus production model. It requires input data in the form or a time series of total catch from a stock where the population is closed to immigration and emigration (Martell and Froese 2013). The Catch-MSY model produces a range of outputs relevant to stock assessment, including distributions for population carrying capacity (*K*), maximum intrinsic population growth rate (*r*), maximum sustainable yield (MSY), and annual trends in biomass (B) and fishing mortality (F) and stock depletion. It is one of many methods used to estimate potential for increased commercial fisheries production in Australia (Smith et al. 2021).

The analysis is based on the entire catch of herring from Australia; as it is a single stock and this fulfils the requirements of Martell and Froese (2013) that the population is closed to immigration and emigration. Separate analyses for the west coast and south coast are also presented for consistency with past assessments.

The catch-MSY model was run assuming an initial depletion range of 0.5-0.975 (program default based on recent and maximum catch levels), and resilience set to “low” (corresponding to *r* = 0.1-0.6), and program default range for *K* (i.e., *K* = maximum annual catch to 60 x maximum catch). The final depletion range was changed from the calculated program default (0.05-0.5), to recognise that low catches for the last several years have been sustained due to management and is expected to have allowed stock to rebuild.

The assumption of “low resilience” (*r*=0.1-0.6) was consistent with the previous assessment (Wise and Molony 2018). Model sensitivity runs using a resilience level (*r*=0.3-0.8), tended to result in fewer “successful r-K pairs”, indicating this assumption was not consistent with other modelling assumptions and the catch data.

The Catch-MSY analysis produced an estimate for MSY of 1199 t (95% CLs = 960 -1431 t) (Table 9.11, Figure 9.24) for Australia, 218 t (95% CLs = 175 – 253) for the west coast (Table 9.12, Figure 9.25), and 667 t (95% CLs = 525 – 807) for the south coast (Table 9.13, Figure 9.26). Although catches in the early 1970s, and the mid-1980s to mid-1990s were well above the estimate of MSY in all regions, they declined to well below MSY in the mid-2000s where they have remained (Figure 9.24, Figure 9.25, Figure 9.26).

The point estimates of current depletion for 2020 (i.e. relative biomass, the ratio of current biomass to unfished biomass) of 0.51, 0.51 and 0.5, for the entire stock, west coast, and south coast respectively, corresponds to the B_{MSY} (0.5) for the Schaefer model, indicating that stock biomass has now recovered to the threshold level (Table 9.11,Table 9.12, Table 9.13), thus well above the limit level ($0.5B_{\mathrm{MSY}}$), the level at which the stock would be considered at increased risk of recruitment failure.

The values for current harvest rate (0.03, 0.03 & 0.01 for the entire stock, west coast, and south coast respectively) (fishing pressure) in 2020, relative to the threshold reference point is low, indicating recent fishing pressure has been low (Table 9.11,Table 9.12, Table 9.13). The phase plots, showing the annual relative stock biomass levels and harvest rate, indicate increasing levels of stock biomass in recent years to around B_{MSY}, with sustained, low harvest rate levels over this period (Figure 9.27, Figure 9.28, Figure 9.29).

9.3.13.1 Conclusion

Catch-MSY analysis, applied to catch series at various spatial stock levels consistently indicated increasing levels of stock biomass in recent years to around B_{MSY}, and low harvest rate levels over this period consistent with low recent catches relative to MSY. The Catch-MSY analysis produced an estimate for MSY of 1199 t (95% CLs = 960 -1431 t) for Australia, 218 t (95% CLs = 175 – 253) for the west coast, and 667 t (95% CLs = 525 – 807) for the south coast.

Catch-MSY analysis provide no evidence of current unacceptable stock depletion.

Table 9.11 Catch-MSY model estimates (±95% CLs) of *MSY* (maximum sustainable yield), *r* (intrinsic increase) *K* (carrying capacity), and *d* (final depletion, i.e. current biomass relative to the unfished level), *B* (current biomass), *H* (harvest rate), B_{MSY} (stock biomass at *MSY*) and F_{MSY} (fishing mortality at *MSY*), for herring catches from all of Australia.

Parameter	Mean	Lower	Upper
MSY	1,199	960	1,431
r	0.19	0.12	0.39
K	25,166	14,592	33,808
d	0.51	0.18	0.69
B	14344	5001	22351
H	0.03	0.02	0.07
B_{MSY}	12583	7296	16904
H_{MSY}	0.1	0.06	0.2

Table 9.12. Catch-MSY model estimates (±95% CLs) of *MSY* (maximum sustainable yield), *r* (intrinsic increase) *K* (carrying capacity), and *d* (final depletion, i.e., current biomass relative to the unfished level), *B* (current biomass), *H* (harvest rate), B_{MSY} (stock biomass at *MSY*) and F_{MSY} (fishing mortality at *MSY*), for herring catches from the west coast of Western Australia.

Parameter	Mean	Lower	Upper
MSY	218	175	253
r	0.19	0.12	0.36
K	4,533	2,710	6,088
d	0.51	0.18	0.69
B	2588	916	4022
H	0.03	0.02	0.08
B_{MSY}	2266	1355	3044
H_{MSY}	0.1	0.06	0.18

Table 9.13. Catch-MSY model estimates (±95% CLs) of *MSY* (maximum sustainable yield), *r* (intrinsic increase) *K* (carrying capacity), and *d* (final depletion, i.e., current biomass relative to the unfished level), *B* (current biomass), *H* (harvest rate), B_{MSY} (stock biomass at *MSY*) and F_{MSY} (fishing mortality at *MSY*), for herring catches from the south coast of Western Australia.

Parameter	Mean	Lower	Upper
MSY	667	525	807
r	0.19	0.12	0.35
K	14,289	9,262	18,354
d	0.50	0.18	0.69
B	7816	2767	12136
H	0.01	0	0.02
B_{MSY}	7145	4631	9177
H_{MSY}	0.1	0.06	0.17

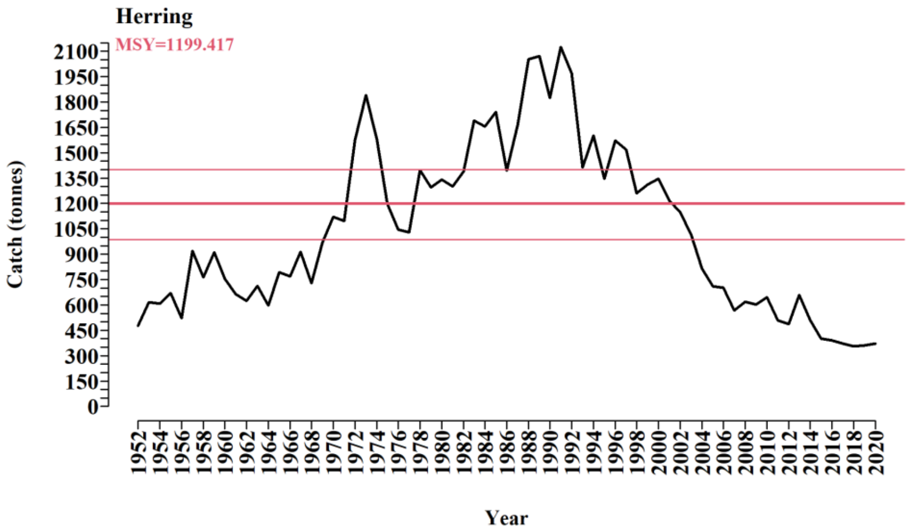

Figure 9.24. **Annual time series of catches for herring relative to the estimated Maximum Sustainable Yield (MSY) (thick red line) and associated 95% CLs (thin red lines), estimated from Catch-MSY analysis for Australia.**

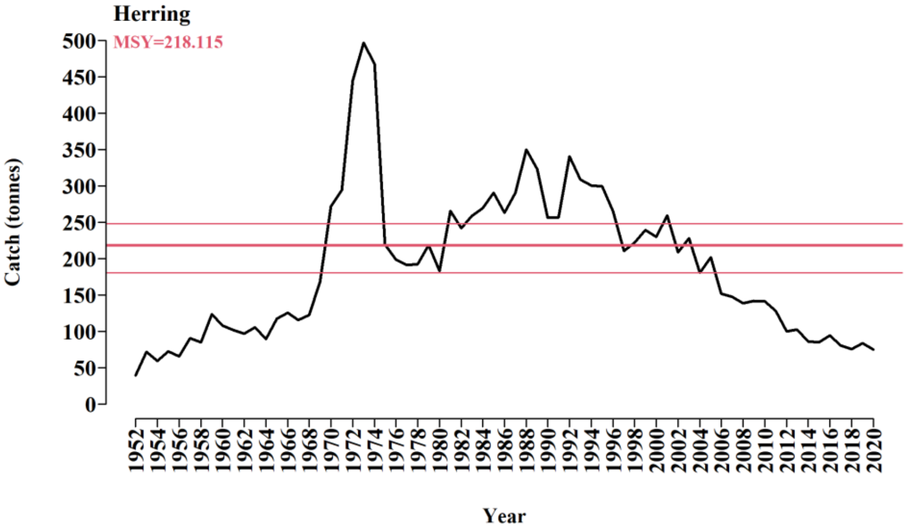

Figure 9.25. Annual time series of catches for Australian Herring on the west coast of Western Australia relative to the estimated Maximum Sustainable Yield (MSY) (thick red line) and associated 95% CLs (thin red lines), estimated from Catch-MSY analysis for this region.

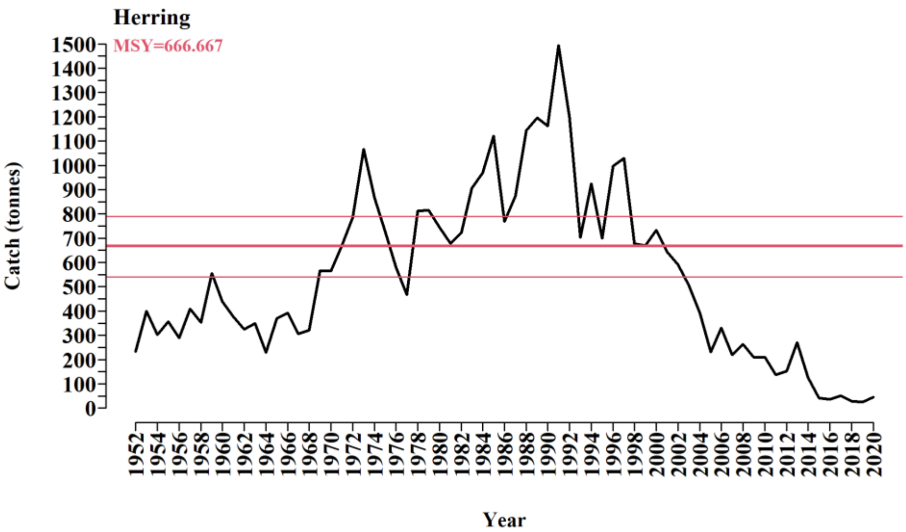

Figure 9.26. Annual time series of catches for Australian Herring on the south coast of Western Australia relative to the estimated Maximum Sustainable Yield (MSY) (thick red line) and associated 95% CLs (thin red lines), estimated from Catch-MSY analysis for this region.

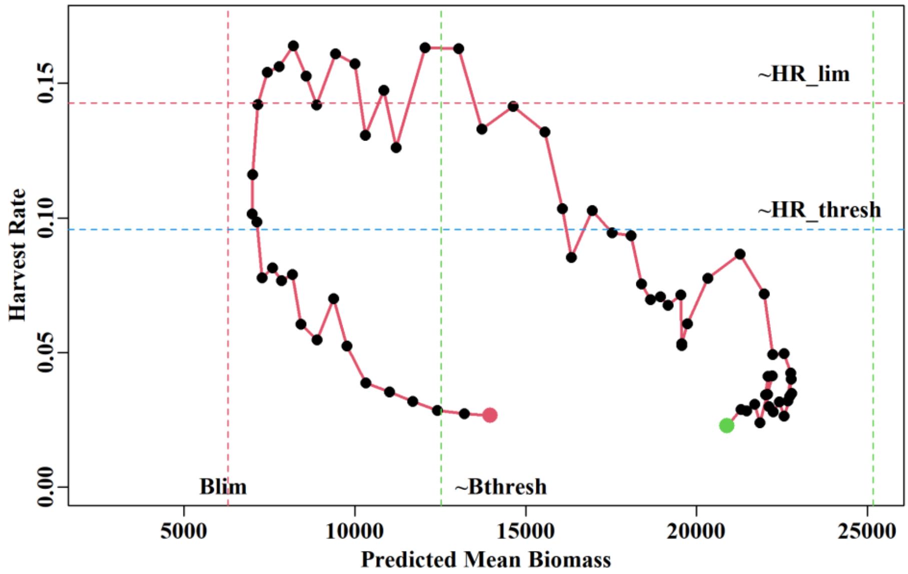

Figure 9.27. Phase plot showing annual estimates biomass and harvest rate values for herring relative to associated threshold and limit reference points, from a Catch-MSY model for Australia. The green and red dots represent the beginning and end of the time series, respectively

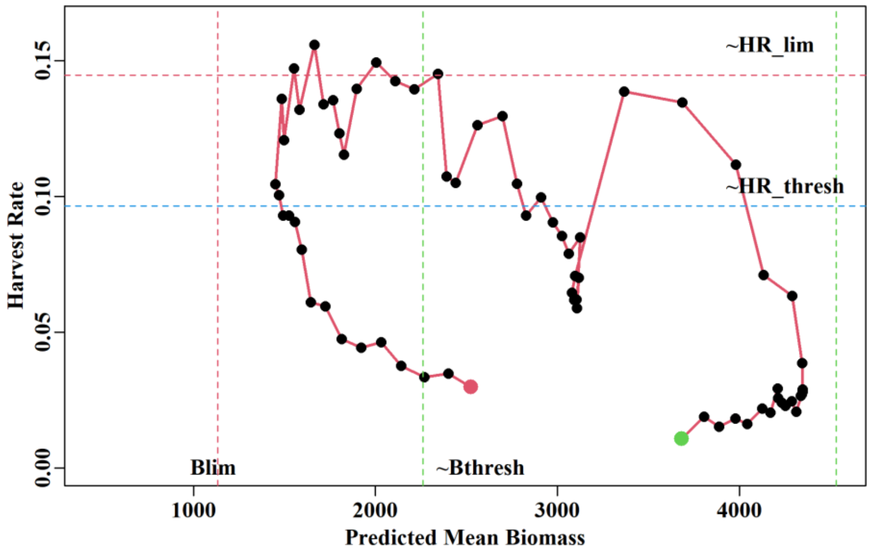

Figure 9.28. Phase plot showing annual estimates biomass and harvest rate values for Australian Herring on the west coast of Western Australia relative to associated threshold and limit reference points, from a Catch-MSY model. The green and red dots represent the beginning and end of the time series, respectively.

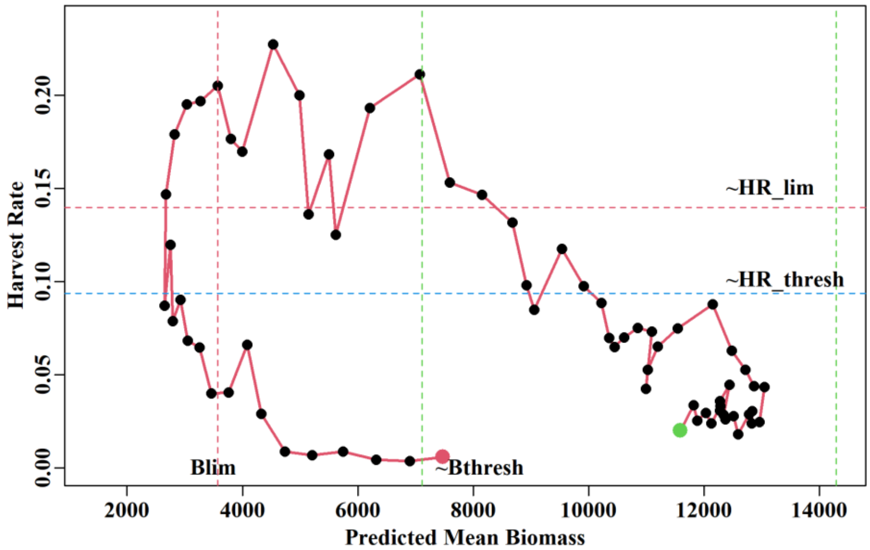

Figure 9.29. Phase plot showing annual estimates biomass and harvest rate values for Australian Herring on the south coast of Western Australia relative to associated threshold and limit reference points, from a Catch-MSY model. The green and red dots represent the beginning and end of the time series, respectively.

9.3.14 Preliminary Stock-Recruitment-Environment Relationships (SRER)

9.3.14.1 Empirical

The population cycle of herring is assumed to involve a biological adaptation to spawning during the peak strength of the Leeuwin Current (May) in south-west Western Australia, dispersal of eggs and larvae to southern areas of Western and South Australia, and Victoria, and migration back two years later (section 5.1.3.5). This large-scale dispersal and movement mean that the herring stock may be influenced by dynamic oceanographic processes, independent of the size of the spawning stock. To investigate this, a preliminary empirical stock-recruitment-environment (SRE) relationship was developed. A preliminary annual recruitment index (South-coast SCPUE – see Figure 9.15) was developed to see whether fluctuations in spawning stock and environmental conditions could explain the variations in catch rates. This recruitment index is based on the commercial catch rate on the south coast, which mostly consists of catch data from the herring net trap method. Therefore, “recruitment” refers predominantly to those fish undertaking the westward annual spawning migration. Although this index is a measure of the recruitment to the spawning stock the fish are at or close to maturity when caught.

The contribution of stock size and environmental factors to recruitment variability was examined using multivariate regression. Exploratory correlation analyses were conducted between recruitment and various indices to established which factors were likely to be most influential. After examining a range of possible models, the chosen model was as follows:

$$\log(R_n) = a + b \log S_{n-2} + c\,\mathrm{FSL}_{n-2} + d\,\mathrm{SST}_n \qquad (1)$$

where R_n was the recruitment in year n, S_{n-2} was the spawning stock in year n-2, FSL was Fremantle Sea Level (an index of the Leeuwin Current) in May during the year of spawning (n-2), and SST was February SST on the South Coast (GPS: 32.875 S, 115.125 E) during the pre-spawning migration of recruits (year n). The b parameter provides an indication of the level of density-dependence and a, c and d are other regression parameters. If $b = 1$, it indicates no evidence of density dependence with the changes in recruitment and spawning stock being proportional to each other. If $b < 1$ it is evidence of compensatory density dependence with the changes in recruitment occurring slower than the decline in the spawning stock.

Stock density and the environmental parameters of Fremantle Sea Level (FSL) and Albany Sea Surface temperature (SST) were found to significantly influence recruitment in herring during the years 1990 to 2014 (Table 9.14). The parameter estimate for stock was 0.35, which was significantly less than 1, and indicates that density dependence exists in this species.

Looking first at the observed and predicted diagnostic fits, the SRE model predicted well the three major peaks in recruitment, which were 1991, 2000, and 2013 (Figure 9.30). It was less accurate with the 1996 increase and did not predict the 2011 increase, or lowest ever recruitment in 2005 (Figure 9.30).

The SRE model shows that Fremantle Sea Level in May, which influences spawning, and Albany Sea Surface Temperature in February, which influences migration, had a compounding influence on recruitment (Figure 9.31). This meant that a good stock year with unfavourable environmental conditions (weak Leeuwin Current and cool SST) could produce less recruitment than a poor stock year with good environmental conditions. This feature is seen by contrasting the 1150 spawning index in 1992 with the 250 spawning index in 2009 (Figure 9.31). These stock levels produced recruitments of 1100 in 1994 (1:1), and 2500 in 2013 (1:10) respectively. These S/R ratios represent a ten-fold difference in productivity between the poor environmental conditions experienced in 92/94 and the good conditions during 09/11. They point to the necessity of understanding environmental influences on stock dynamics to ensure a realistic assessment of stock status can be made.

9.3.14.1.1 **Predictions of missing years recruitment (2016-2020)**

The development of the SRER model allows for prediction of what recruitment would have been during the years for which stock estimates were available (2015 to 2020), but no recruitment data was received due to the closure of the herring trap net fishery.

Predictions reveal that recruitment would have been between 1000 and 2000 kg/month for 2016 to 2020, and all were above the five lowest recruitment years (Figure 9.31). There are, however, considerable uncertainty around these predictions, as shown by the error bars for the 2015 and 2020 predictions (Figure 9.31).

9.3.14.2 Model based

A preliminary, model-based stock-recruitment environment relationship was constructed for Australian herring based on outputs from a slightly modified version of the (L5) age-based integrated model (Figure 9.32) used in this assessment, i.e., incorporating an environmental effect on recruitment, and fitting to a preliminary spawning stock CPUE index. The model was applied to annual catch (WA, SA and Vic), age composition (west coast recreational), standardized annual CPUE (west coast commercial; Geographe Bay) and environmental (mean Fremantle sea level anomaly, FSL, considered as a proxy for Leeuwin Current strength e.g. Feng et al. 2003, see Fig. 2).

In this analysis, it was assumed that expected recruitment is related to Leeuwin Current strength (indicated by annual FSL anomalies, see Figure 11 in Feng et al. 2003, Figure 2 in Feng et al. 2004 and Figure 6.1 in Berthot et al. 2007). Calculation of the FSL anomaly index involves calculating (1) monthly deviations from overall mean of time series, (2) a 3-month, centered and weighted (1-2-1) moving average, (3) average annual cycle of the smoothed deviations, which is subtracted from the monthly smoothed deviations, (4) annual index of the average monthly deviations, (5) fitting a smoother (LOESS curve in this study, Hanning filter in Berthot et al. 2007) through the annual index, and subtracting the trend from the annual data to produce the annual FSL anomalies. The detrended sea level anomaly values (Figure 9.33) calculated closely match the time series presented in the above cited papers.

Recruitment was modelled according to a Beverton-Holt stock recruitment relationship (steepness = 0.75), linked (i.e., assuming a power relationship) to the annual FSL environmental index, with a parameter that is estimated, describing the strength and direction of the relationship. In the model, recruitment occurs at age 1 y. As is typical when incorporating environmental data in stock-assessment models, the environmental anomaly index was rescaled to have a mean of zero and standard deviation of 1.0 (i.e., the data were normalised). The first year of data in the model is 1930, including ~20 y burn in period from 1930-1951. The analysis included FSL data from 1929-2020, allowing for a one-year lag as in the model the fish recruit at age 1 y (obtained from https://www.psmsl.org/data/obtaining/stations/111.php). This model run assumed a value for natural mortality of 0.6 y^{-1}, noting this is less conservative than that used in the previous assessment (0.4 y^{-1}), and multiple values should be explored for further work.

Although the point estimate for the value of the environmental parameter, linking the FSL index to expected recruitment, was marginally positive (0.054), the associated standard error was large (0.090) indicating that the parameter is not significantly different from zero (95% CI -0.123 – 0.231), i.e., no environmental effect on recruitment was able to be detected.

As indicated above, other environmental variables such as sea surface temperature may also influence recruitment strength. Further work could involve considering other variables using this model-based framework, if considered appropriate.

9.3.14.3 Conclusion

Preliminary empirical analyses suggest that recruitment of herring is correlated with both spawning stock and environmental conditions (Leeuwin Current strength and sea surface temperature), such that the lowest stock level of 2009 produced twice as much recruits as the highest stock level of 1992. However, a preliminary model-based stock-recruitment analysis did not detect a significant effect of mean sea level anomaly data (as a proxy for Leeuwin Current strength) on recruitment. Further investigation is required to confirm preliminary recruitment-environment relationships, and better account for various uncertainties in the data.

There is no evidence of unacceptable stock depletion from the preliminary stock-recruitment-environment relationships.

Table 9.14 Multiple regression results for the importance of spawning stock and environmental variables (Fremantle sea level during spawning; Albany SST during migration) in recruitment on the South Coast (Albany area). Multiple R^2 = 0.41; F = 4.8; df = 3, 21; p = 0.01. * denotes statistical significance

Variable	Parameter	Estimate (± SE)	t-value	p-value
Intercept	a	-3.9 (3.3)	-1.42	0.168
Stock (Year n)	S_{n-2}	0.35 (0.16)	2.22	0.037*
Fremantle Sea Level (May – Year n)	FSL_{n-2}	2.69 (1.0)	2.75	0.012*
Albany SST (February – Year n+2)	SST_n	0.36 (0.13)	2.71	0.013*

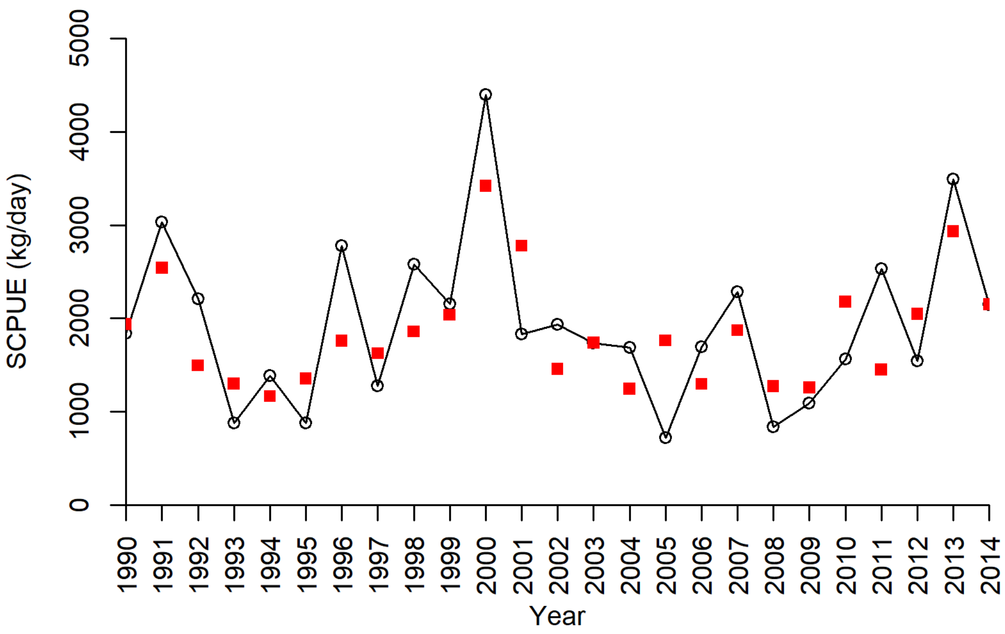

Figure 9.30 Diagnostic plot comparing the predicted (red squares) and observed (lines and circles) recruitment index for herring.

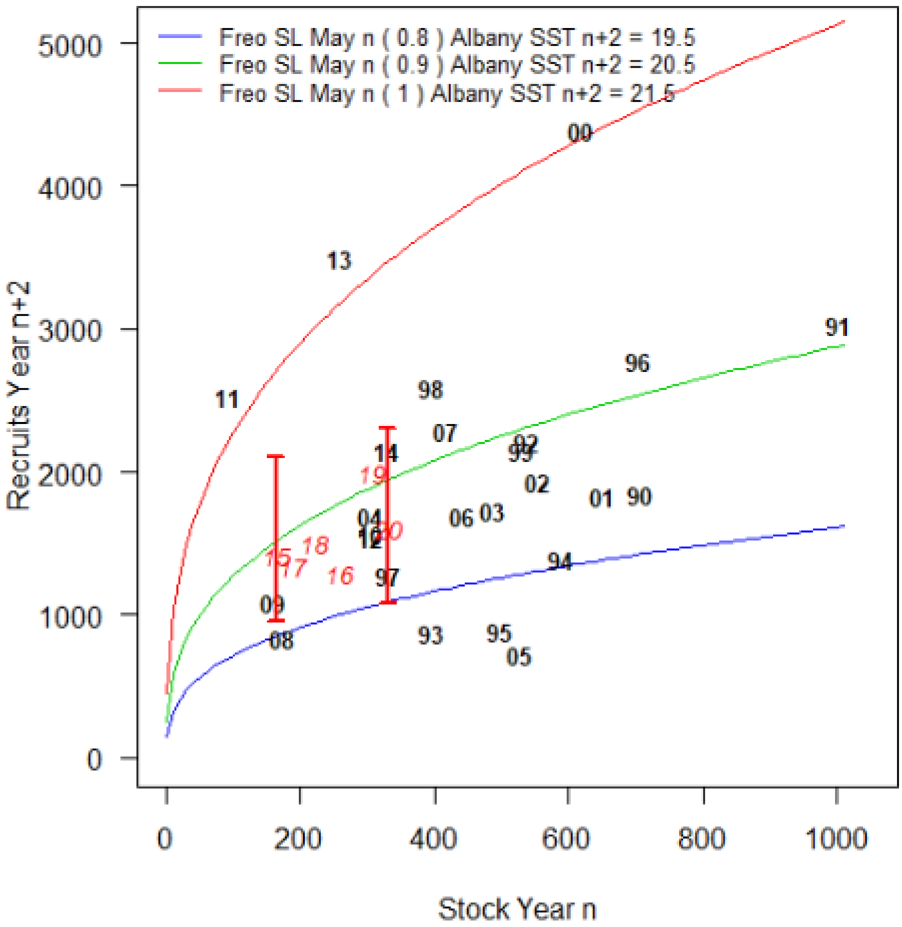

Figure 9.31 Preliminary stock-recruitment-environment relationship (SRER) for herring in Western Australia, based on spawning stock abundance (Year *n*) and recruitment two years later (Year *n*+2). The three coloured lines are predictions for good (red), average (green), and poor (blue) environment conditions. Legend shows value of environmental factors for each line, e.g., a Fremantle Sea Level of 1.0 m in May during spawning (Year *n*), and an Albany SST of 21.5ºC in February during recruitment (Year *n*+2) for the red line. Black numbers (e.g., 14) represent year *n*+2 of recruitment from year *n* of stock. Red numbers (15-20) are predictions of recruitment using the Fremantle Sea level for the spawning years of 2014-2018, and the Albany SST (February) for the recruitment years of 2016–2020. Error bars (±SE) relate to predicted recruitment in 2015 and 2020.

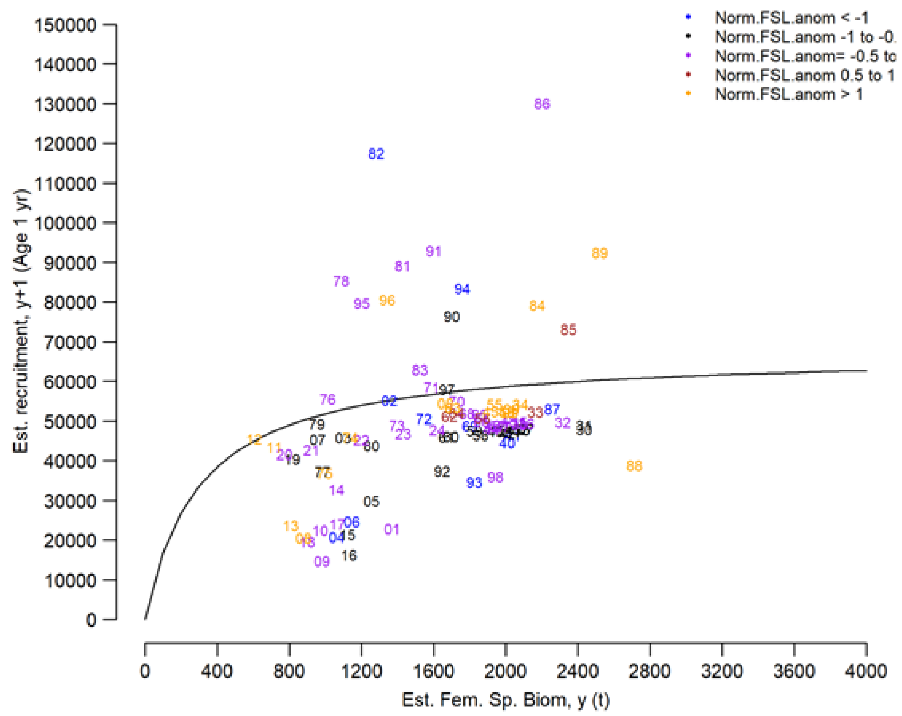

Figure 9.32 Preliminary estimated stock-recruitment environment relationship. The spawning year (y) is indicated above each point on plot by the last 2 digits of the year i.e., "95" means 1995. Note that values shown for years 2021-2024 are based on prediction with normalised FSL anomaly set to the average environmental condition i.e., FSL anomaly = 0.

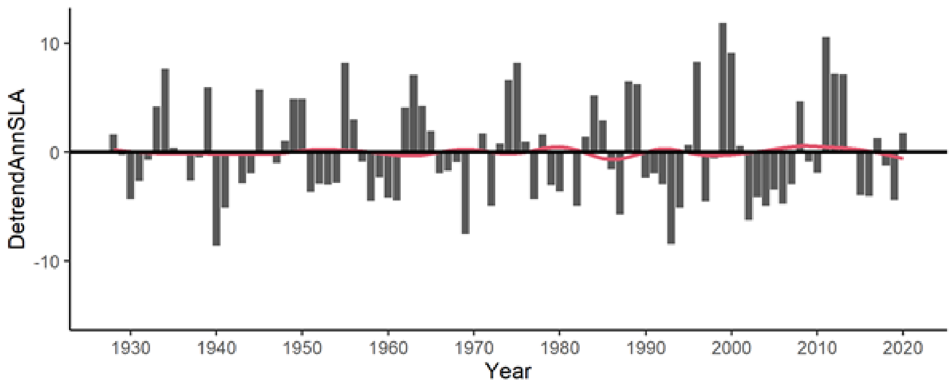

Figure 9.33 Fremantle mean sea level data (corrected, detrended and normalised anomalies).

9.3.15 Integrated Model

A dynamic, single area, sex- and age-structured statistical catch at age model was fitted to age composition and catch data for herring. The structure of the model used is similar to that of Wise and Molony (2018). The model used a time series of total catches for herring (1952-2020). Using this time series, the model was fitted to recreational age composition data on the west coast of Western Australia as this data is assumed most representative of the spawning stock due to better spatial and temporal coverage (Smith et al. 2013) although noting it is biased towards females (Wise & Molony 2018). Additional model runs were undertaken for other sectors/regions, and to undertake model sensitivity analyses, and details of these are reported in Appendix D, along with a full description of the method.

The model also incorporates biological parameters that have been separately estimated and pre-specified, e.g., for describing growth, weight-at-length relationships, and size at maturity (see section 5.0 Species Description).

There were small, but consistent improvements in model fits (lower objective function values) as M was increased from 0.4 to 0.6 y^{-1} indicating that a higher value for M may be appropriate. Therefore, all analyses conducting using M = 0.4 may represent conservative results.

The results, based on M=0.6 y^{-1}, indicate that by 2020, B_{rel} has recovered to above the target level, and that if current catch levels are maintained, B_{rel} will continue to increase, albeit with high uncertainty. Results based on lower M values (M=0.5 or 0.4 y^{-1}) were less optimistic. For all scenarios, catches in recent years have been well below the model estimates for *MSY* of approximately 1500 t. Results from the integrated model should be treated with caution, due to high uncertainty in model outputs, associated with limited data.

9.3.15.1 Conclusion

The integrated model analyses, based on M=0.6 yr^{-1} and using recreational age composition data for the west coast, indicate that B_{rel} has recovered to at least the threshold and will continue to increase at current catch levels. Catch in recent years has been well below the model estimate for MSY.

The dynamic catch-age modelling results (using age composition data for the west coast, applying M=0.6 y^{-1}), provide no evidence of unacceptable stock depletion.

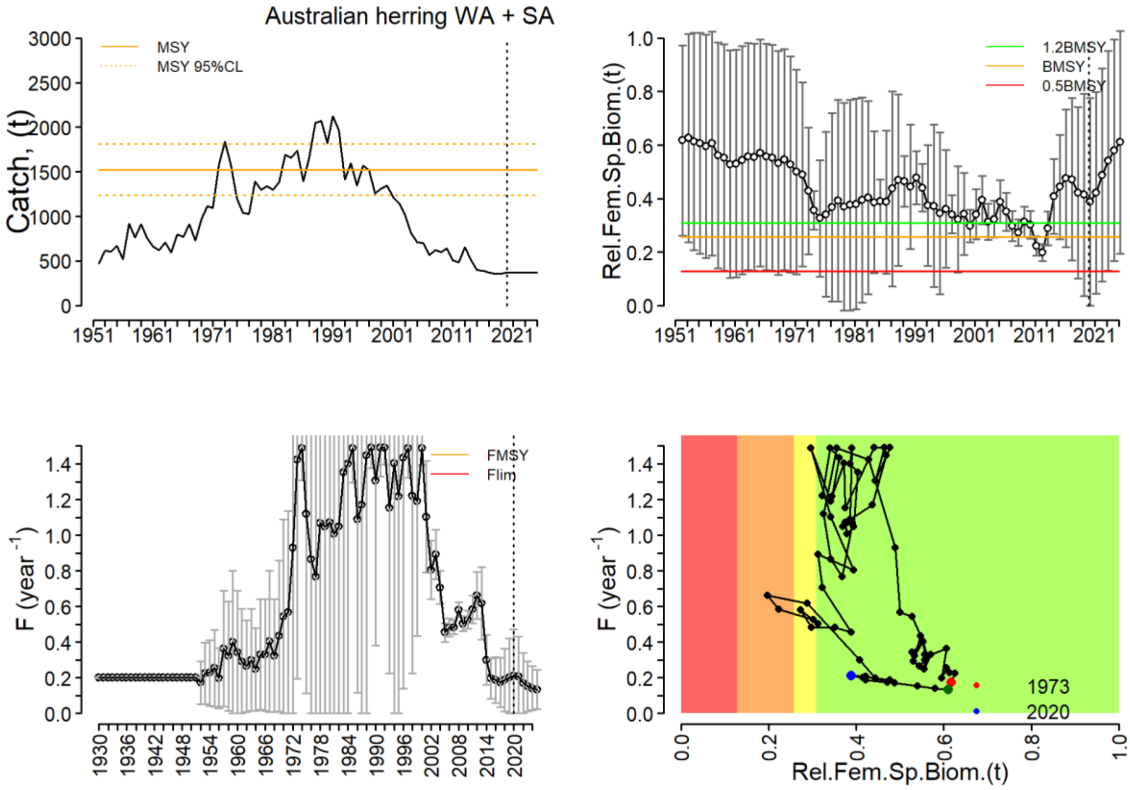

Figure 9.34 ***Top left*, Annual catches of herring (Western Australia and South Australia) vs estimated maximum sustainable yield, MSY (± 95% CLs); *top right*, estimates of relative female spawning biomass and associated values at BMSY (threshold) and 0.5MSY (limit); *bottom left*, estimates of fishing mortality, *F* (year^{-1}) vs FMSY; *bottom right*, phase plot, showing progression of female spawning biomass and fishing mortality. Results for model fitted to recreational data from the west coast of Western Australia, with *M* set to 0.6 y^{-1}.**

9.4 Stock Status Summary

Presented below is a summary of each line of evidence considered in the overall weight of evidence assessment for herring, followed by the management advice and recommendations for future monitoring of the species.

9.4.1 Weight of Evidence Risk Assessment

Category	Lines of evidence (Consequence / Status)
Catch	There are strong declines in commercial catch from historical highs in the 1990s, and indications of contemporary declines in recreational catch since 2010. A pattern consistent among data streams is the punctuation of trends with peaks and troughs indicating variable recruitment. Interpretation of trends is confounded by the impact of market demand on commercial catch, and management changes aimed at reducing both commercial and recreational catch. Overall, these external factors are considered to have had a greater impact on catch than potential change in abundance. **Catch data is considered to provide no indication of unacceptable stock depletion.**
Catch distribution	There has been little change in distribution of herring catch through time, and where changes have occurred, it is related to management rather than abundance. **Catch distribution provides no indication of unacceptable stock decline**
Effort	The fisheries examined all show declines in effort to recent times. Only the herring trap net fishers specifically targeted herring, all other fisheries capture other species and effort in these fisheries can change based on market demand and the abundance and price of species. **Effort trends have declined through time; however, they have been strongly affected by management changes and market demand. Therefore, effort is not considered to provide evidence of unacceptable stock depletion**.
Fishery-dependent catch rate - Nominal	Catch rate trends between fisheries and sectors are not consistent. Catch rates for the fishery with the largest take of herring, the trap net fishery, show a stable sideways trend, punctuated with peaks and troughs representing variable recruitment. These trends are similar to those seen in SA. Catch rates from Geographe Bay-Bunbury and Cockburn Sound show conflicting trends. As these are multispecies fisheries, dynamics impacting herring catch rates are more complex than the single species herring trap net fishery, therefore nominal catch rate trends may not be a reliable index of abundance and require consideration of other factors that may affect CPUE. Recreational catch rates have been stable since 2016. **Nominal catch rate trends provide evidence that stock depletion is possible, however catch rates have been stable in most indices since approximately 2013 and were potentially increasing in the trap net fishery until its closure.**

Fishery-dependent standardised catch rate	Preliminary investigations suggest spawning stock abundance has shown substantial changes since 1975, however levels since the mid-2000s are similar to the levels in the late 1970s, which were prior to the largest catches. The recruitment index indicates strong annual fluctuations but does not indicate any decline. It does indicate a contemporary increase since 2005. As recruitment has not declined to an unacceptable level, it indicates the spawning stock is at a level where environment is the main factor impacting recruitment. Further work is required to explore uncertainties in the preliminary indices, e.g., associated with older age classes in the recruitment index, and external influences on CPUE, e.g., markets. **The preliminary recruitment index provides no evidence of recruitment failure. The long-term declining trend in the preliminary spawning index indicates possible stock depletion, although the trends in this index may also be impacted by external factors, e.g., markets.**
Vulnerability (PSA)	Based on the productivity and susceptibility scores, the overall weighted (by fishery / sector catches) PSA score for herring was 83, which equates to a low risk. **The low PSA score indicates that under current management arrangements, unacceptable stock depletion is unlikely.**
Length composition	There is no evidence of a change in length composition overtime that could reflect overfishing. **Length composition data provides no evidence of unacceptable stock depletion.**
Age composition	Age data shows variation between sectors and regions, indicating that the sampled age structure from all regions/sectors, may not be representative of the entire stock. However, it does provide evidence of variable recruitment between years, with strong year classes able to be tracked through recent years. **Strong recruitment events in recent years provide no evidence of recruitment impairment that would indicate unacceptable stock depletion.**
Fishing mortality (F)	Fishing mortality has declined from the previous assessment; however, the actual value of F is highly dependent on the value assumed for M. Based on the most recent evidence for estimating M (Then et al. 2015), the current F/M ratio is well less than $F = M$, however using methods from the previous assessment F/M ratio is close to $F=1.5M$. **Declining F compared to the previous assessment, and the current F/M ratio of well less than $F = M$ suggest no evidence of unacceptable stock depletion; however, it is possible if M is assumed to be 0.4 y^{-1}.**
Per recruit analysis - SPR	Point estimates of B_{rel} and *SPR* for the west coast spawning stock are at or above the Target, respectively. ***SPR* and B_{rel} provide no evidence of unacceptable stock depletion.**

Length-based spawning potential ratio (LBSPR)	Estimates of SPR produced by the LBSPR analysis using length composition data for herring caught by recreational fishers on the west coast are above the target reference point (0.4). This is assumed to better represent the stock than samples from other regions or sectors. **LBSPR estimates provide no evidence of unacceptable stock depletion.**
Catch-MSY	Catch-MSY analysis, applied to catch series at various spatial stock levels consistently indicated increasing levels of stock biomass in recent years to around B_{MSY}, and low harvest rate levels over this period consistent with low recent catches relative to MSY. The Catch-MSY analysis produced an estimate for MSY of 1199 t (95% CLs = 960 -1431 t) for Australia, 218 t (95% CLs = 175 – 253) for the west coast, and 667 t (95% CLs = 525 – 807) for the south coast. **Catch-MSY analysis provide no evidence of current unacceptable stock depletion.**
Preliminary Stock-Recruitment-Environment Analysis	Preliminary empirical analyses suggest that recruitment of herring is correlated with both spawning stock and environmental conditions (Leeuwin Current strength and sea surface temperature), such that the lowest stock level of 2009 produced twice as much recruits as the highest stock level of 1992. However, a preliminary model-based stock-recruitment analysis did not detect a significant effect of mean sea level anomaly data (as a proxy for Leeuwin Current strength) on recruitment. Further investigation is required to confirm preliminary recruitment-environment relationships, and better account for various uncertainties in the data. **There is no evidence of unacceptable stock depletion from the preliminary stock-recruitment-environment relationships.**
Integrated Model	The integrated model analyses, based on M=0.6 yr^{-1} and using recreational age composition data for the west coast, indicate that B_{rel} has recovered to at least the threshold and will continue to increase at current catch levels. Catch in recent years has been well below the model estimate for MSY. **The dynamic catch-age modelling results (using age composition data for the west coast, applying *M*=0.6 y^{-1}), provide no evidence of unacceptable stock depletion.**

Consequence (Stock Depletion) Level	Likelihood				Risk Score
	L1 Remote (<5%)	L2 Unlikely (5- <20%)	L3 Possible (20- <50%)	L4 Likely (≥50%)	
C1 Minor (above Target)				X	4
C2 Moderate (below Target, above Threshold)		X			**4**
C3 High (below	X				3

Threshold, above Limit)					
C4 Major (below Limit)	NA				NA

C1 (Minor Depletion): **Likely L4 –** Herring is a short-lived and productive species that has experienced a prolonged period of low catch, well below that of the estimated MSY from different methods. In addition, the most recent length and age composition data showed no truncation that could be considered indicative of overfishing. The increasing catch rates for the trap net fishery on the south coast (which is composed largely of recruits), the SA catch rate which has trended sideways over a long period, and age structure data, all demonstrate that recruitment failure/overfishing has not occurred. SPR further supports an adequate level of spawning stock. Although the stock-recruitment-environment relationship showed recruitment was heavily dependent on environment, increased recruitment occurred under warming conditions, suggesting that this may be a species that benefits from climate change. Therefore, the lines of evidence indicate the stock is not experiencing overfishing and is not overfished, therefore MINOR stock depletion is considered LIKELY.

C2 (Moderate Depletion): **Unlikely L2 –** Some nominal fishery dependent catch rates indicate depletion is possible, however these have been stable or increasing since 2016. No other lines of evidence indicate moderate depletion is possible, however all results have a level of uncertainty attached. Additionally, an unknown factor in this analysis is the impact of the large biomass of salmon, that is predicted to have occurred due to prolonged low salmon catches, and its potential for consuming herring.

Acute events related to climate change can have major impacts on the marine ecosystem. Given the strong relationship between herring recruitment and environmental factors, acute climate change events may impact herring stocks, although evidence suggest warming events may have a positive impact, currents are complex and the impact of alterations to these is unknown. Overall, we consider a moderate level of depletion of the herring stock still to be unlikely.

C3 (High Depletion): **Remote L1 –** Based on the reasons already discussed, high depletion is considered a remote likelihood.

C4 (Major Depletion): **NA –** No analyses, or data streams provide evidence of major depletion occurring. Therefore, this consequence is rated as Not Applicable.

9.4.2 Current Risk Status

Based on the information available, the current risk level for herring is estimated to be LOW (C1 x L4 or C2 x L2). The low risk reflects acceptable levels of fishing mortality, recruitment, and spawning stock biomass. Therefore, the overall Weight of Evidence assessment indicates the stock has recovered to a level at or around the target and the status of the stock is considered adequate, as conceptualised in Figure 9.35.

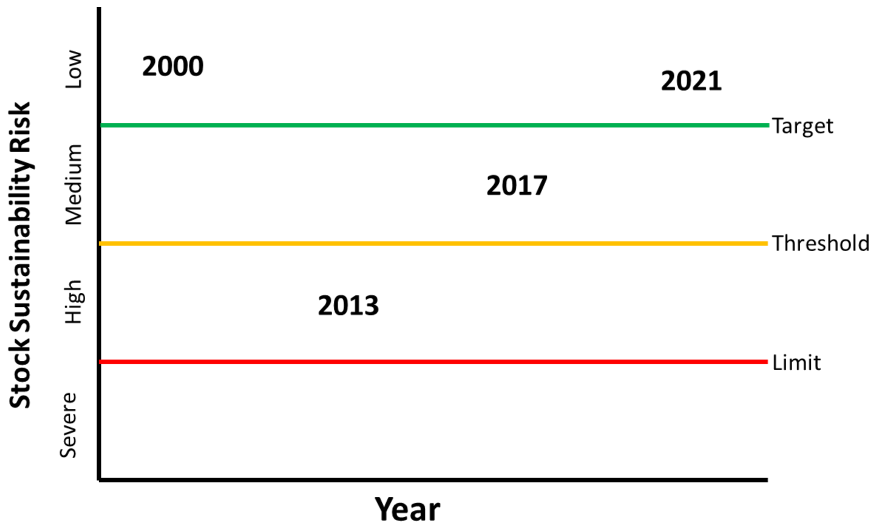

Figure 9.35 Graphical representation of changes in stock sustainability risk status from contemporary stock assessments.

9.4.3 Future Catch scenarios

In general, sustainably managed fisheries in Western Australia which harvest the full production available from a given population are ranked at a medium risk. From a sustainability perspective the current herring risk score of low allows for a potential increase in catch. An appropriate way to test the response of the herring fishery is within an adaptive management framework.

9.4.4 Future Monitoring

To reduce uncertainties in subsequent assessments, the following areas should be examined:

- Further development of preliminary analyses investigating the role of environment on recruitment dynamics.
- Development of a sample collection program that is considered to provide representative age and length data for the stock.
- A detailed investigation into fishery-independent recruitment index sampling to determine the value of this data to stock assessments (including herring), and potential for improved or modified design.
- The assumed value for natural mortality had substantial influence on the risk status, further consideration of the choice of value used is warranted.
- Investigation into diet of Western Australia salmon and the change in salmon abundance in recent years would provide insight into predator-prey relationships that may impact herring stock.

Whether these suggestions are examined further depends on resources, as well as the resolution of management actions.

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11 Appendix A - Justification for Harvest Strategy Reference Levels

The performance indicator used to evaluate the stock status of herring in Western Australia is spawning biomass (*B*), or an appropriate proxy such as spawning potential ratio (SPR) (see Table 11.1). The performance indicator is estimated periodically (at least every 5 years) and compared to associated reference levels (Table 11.1). The reference levels are consistent with those used by the Department in other similar assessments and are based on internationally accepted benchmarks (Mace 1994, Caddy and Mahon 1995, Gabriel and Mace 1999, Wise et al. 2007). Note that the threshold level of B_{30} (and SPR_{30}) corresponds to B_{MSY} (Table 11.1).

Table 11.1. Performance indicators and associated reference levels used to evaluate the status of indicator species and secondary indicator species in the Pilbara and Kimberley

Performance Indicator	Reference Levels		
	Target	**Threshold (B_{MSY})**	**Limit**
Spawning biomass (*B*)	B_{40}	B_{30}	B_{20}
Spawning potential ratio (SPR)	SPR_{40}	SPR_{30}	SPR_{20}

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12 Appendix B - Consequence, Likelihood and Risk Levels (based on AS 4360 / ISO 31000) modified from Fletcher et al. (2011) and Fletcher (2015)

CONSEQUENCE LEVELS

As defined for major target species

1. Minor – Fishing impacts either not detectable against background variability for this population; or if detectable, minimal impact on population size and none on dynamics

   Spawning biomass > Target level (B_{MEY})

2. Moderate – Fishery operating at maximum acceptable level of depletion

   Spawning biomass < Target level (B_{MEY}) but > Threshold level (B_{MSY})

3. High – Level of depletion unacceptable but still not affecting recruitment levels of stock

   Spawning biomass < Threshold level (B_{MSY}) but >Limit level (B_{REC})

4. Major – Level of depletion is already affecting (or will definitely affect) future recruitment potential/ levels of the stock

   Spawning biomass < Limit level (B_{REC})

LIKELIHOOD LEVELS

These are defined as the likelihood of a particular consequence level actually occurring within the assessment period (5 years was used)

1. Remote – The consequence has never been heard of in these circumstances, but it is not impossible within the time frame (Probability of <5%)
2. Unlikely – The consequence is not expected to occur in the timeframe but it has been known to occur elsewhere under special circumstances (Probability of 5 - <20%)
3. Possible – Evidence to suggest this consequence level is possible and may occur in some circumstances within the timeframe. (Probability of 20 - <50%)
4. Likely – A particular consequence level is expected to occur in the timeframe (Probability of ≥50%)

Consequence × Likelihood Risk Matrix		Likelihood			
		Remote (1)	Unlikely (2)	Possible (3)	Likely (4)
Consequence	Minor (1)	Negligible	Negligible	Low	Low
	Moderate (2)	Negligible	Low	Medium	Medium
	High (3)	Low	Medium	High	High
	Major (4)	Low	Medium	Severe	Severe

Risk Levels	Description	Likely Reporting & Monitoring Requirements	Likely Management Action
1 Negligible	Acceptable; Not an issue	Brief justification – no monitoring	Nil
2 Low	Acceptable; No specific control measures needed	Full justification needed – periodic monitoring	None specific
3 Medium	Acceptable; With current risk control measures in place (no new management required)	Full Performance Report – regular monitoring	Specific management and/or monitoring required
4 High	Not desirable; Continue strong management actions OR new / further risk control measures to be introduced in the near future	Full Performance Report – regular monitoring	Increased management activities needed
5 Severe	Unacceptable; If not already introduced, major changes required to management in immediate future	Recovery strategy and detailed monitoring	Increased management activities needed urgently

References

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13 Appendix C - Productivity Susceptibility Analysis (PSA) Scoring Tables

Productivity attribute	**High productivity** **Low risk** **Score = 1**	**Medium productivity** **Medium risk** **Score = 2**	**Low productivity** **High risk** **Score = 3)**
Average maximum age	<10 years	10-25 years	>25 years
Average age at maturity	<5 years	5-15 years	>15 years
Average maximum size (not to be used when scoring invertebrates)	<1000 mm	1000-3000 mm	>3000 mm
Average size at maturity (not to be used when scoring invertebrates)	<400 mm	400-2000 mm	>2000 mm
Reproductive strategy	Broadcast spawner	Demersal egg layer	Live bearer
Fecundity	>20,000 eggs per year	100-20,000 eggs per year	<100 eggs per year
Trophic level	<2.75	2.75-3.25	>3.25
Density dependence (only to be used when scoring invertebrates)	Compensatory dynamics at low population size demonstrated or likely	No depensatory or compensatory dynamics demonstrated or likely	Depensatory dynamics at low population sizes (Allele effects) demonstrated or likely

Susceptibility attribute	**Low susceptibility** **Low risk** **Score = 1**	**Medium susceptibility** **Medium risk** **Score = 2**	**High susceptibility** **High risk** **Score = 3)**
Areal overlap (availability) i.e. overlap of fishing effort with stock distribution	<10% overlap	10-30% overlap	>30% overlap
Encounterability i.e. the position of the species / stock within the water column / habitat relative to the position of the fishing gear	Low encounterability / overlap with fishing gear	Medium overlap with fishing gear	High encounterability / overlap with fishing gear (Default score for target species in a fishery)
Selectivity of gear type i.e. potential of gear to retain species	a) Individual < size at maturity are rarely caught	a) Individual < size at maturity are regularly caught	a) Individual < size at maturity are frequently caught
	b) Individual < size can escape or avoid gear	b) Individual < half the size can escape or avoid gear	b) Individual < half the size are retained by gear
Post-capture mortality i.e. the chance that, if captured, a species would be released and that it would be in a condition permitting subsequent survival	Evidence of majority released post-capture and survival	Evidence of some released post-capture and survival	Retained species or majority dead when released

14 Appendix D - Additional Analyses

14.1 Catch-MSY

14.1.1 Description of analysis

Using the datalowSA R package, a Catch-MSY model (see Haddon et al. 2018) was fitted using catch data for herring on the west coast (WC), south coast (SC) of Western Australia, *i.e.* treating these as separate management stocks, state level, and entire stock. The Catch-MSY model is a "data-poor" stock assessment method with population dynamics described according to the same production function as applied in the Schaefer surplus production model. The Catch-MSY model produces a range of outputs relevant to stock assessment, including distributions for population carrying capacity (K), maximum intrinsic population growth rate (r), maximum sustainable yield (MSY), and annual trends in biomass (B) and fishing mortality (F) and stock depletion. Input data include a time series of total catch removals, specified level of population "resilience" (i.e. range for r), and specified prior distribution ranges for K, and initial and final stock depletion levels.

Broadly, the Catch-MSY model works by drawing many (e.g. 20,000) random pairs of r and K from their specified prior distributions, and then applying the discrete form of the Schaefer population dynamics equation and annual catches to simulate population biomass trajectories. Only those population trajectories (and associated results) that are consistent with the ranges specified for initial and final depletion are retained.

14.1.2 Impacts of model assumptions

As discussed above, results of Catch-MSY can be sensitive to input assumptions. The catch-MSY model was run using catch data for herring from 1952 for each coast, assuming an initial depletion range of 0.5-0.975 (program default based on recent and maximum catch levels), a final depletion range of 0.15-0.7, and resilience set to "low" (corresponding to r = 0.1-0.6), and program default range for K (i.e. K = maximum annual catch to 60 x maximum catch). The final depletion range was changed from the calculated program default (0.05-0.5), to recognise that low catches have been sustained, due to management, for several years, expected to allow stock rebuilding. The assumption of "low resilience" (r=0.1-0.6) may be a conservative estimate of stock productivity, as this species is not particularly longer-lived (maximum age ~10.5-12 years). Model sensitivity runs allowing for a higher resilience level (r=0.3-0.8), however, tended to result in fewer "successful r-K pairs", indicating this assumption was not consistent with other modelling assumptions and the catch data. For consistency with the previous assessment (Wise and Molony 2018) the Catch-MSY analyses were run separately using data for the WC and SC, i.e. for the two 'management' stocks.

14.2 Catch curve analysis

Estimates of the instantaneous rate of total mortality (Z, y^{-1}) and associated 95% confidence intervals for female herring were derived by fitting a catch curve model to recent biological years (*i.e.* June 1-May 30, where June 1 is taken to represent the 'peak' spawning time) years of age composition data, collected in the 2017/18 - 2019/20 for each sector on the west coast (WC), 2018/19 - 2020/21 for the recreational sector on the south coast (SC) and 2017/18 – 2018-19 for the commercial sector on the SC. The age composition samples were limited to fish caught in ocean waters.

The catch curve model, as described in Fairclough et al. (2014) (see also Coulson et al. 2009) provides estimates of fishing mortality (F, y^{-1}), logistic age-based selectivity parameters (A_{50} and A_{95}) and annual recruitment deviations for specified year cohorts. The catch curve model must be fitted simultaneously to at least two consecutive years of age composition data. Consistent with the previous assessment (Wise and Molony 2018), estimates of F for fully-selected fish are calculated by subtracting a specified value for natural mortality (M) from each catch curve estimate of Z, i.e. $F = Z – M$. The model assumes constant mortality over the lifespans of the fish in samples collected. Natural mortality was set to 0.4 $year^{-1}$, consistent with the previous assessment (Wise & Molony 2018), based on an observed maximum age of 10.5 y for ocean waters, and according to the equation of Hewitt and Hoenig (2005), similar to that provided by Hoenig (1983).

The estimated value for selectivity parameter estimates were similar for the two sectors operating on both coasts. One each coast, the estimates for fishing mortality were slightly lower for the recreational sector than for the commercial sector, and the values estimated for the west coast were slightly higher than for the south coast. Compared to the previous assessment, when the same method of catch curve analysis (referred to as model 5 in Wise & Molony (2018)) was fitted to 2015/16-2016/17 age sample data, the point estimates of fishing mortality were slightly lower for a given sector and region, i.e. F=0.66 down to 0.61 y^{-1} for female herring caught by recreational fishers on the west coast, F=0.88 down to 0.716 y^{-1} for females caught by commercial fishers on the west coast, and F=0.54 down to 0.50 y^{-1} for females caught by recreational fishers on the south coast (see Wise and Molony 2018).

One of the least certain parameters required by many model-based assessment methods, and most difficult to estimate, is the level of natural mortality. If the ‘true’ value of M for herring were higher than the specified value of 0.4 y^{-1} applied for this analysis, estimates for F would be lower, indicating a lower level of fishing pressure than estimated. Additional support for a higher M estimate comes from improved fit in integrate models with increasing M (section 14.5). Note also that the analysis assumed constant mortality over the lifespans of the fish in collected samples, which may be unlikely.

Table 14.1. Estimates of selectivity parameters and fishing mortality for female Australian Herring caught by commercial and recreational fishers on the west and south coasts of Western Australia from catch curve analysis. ±1SE denotes standard error estimates.

Region / Sex	Sector	Selectivity (±1SE)	Fishing mortality (±1SE)	Biological years

West coast (Female)	Recreational	A_{50}=2.64 (0.05) A_{95}=3.36 (0.11)	0.612 (0.051)	2017/18-2019/20
West coast (Female)	Commercial	A_{50}=2.75 (0.06) A_{95}=3.59 (0.13)	0.716 (0.062)	2017/18-2019/20
South coast (Female)	Recreational	A_{50}=2.50 (0.07) A_{95}=3.21 (0.11)	0.504 (0.063)	2018/19-2020/21
South coast (Female)	Commercial	A_{50}=2.61 (0.29) A_{95}=4.25 (0.58)	0.532 (0.138)	2017/18-2018/19

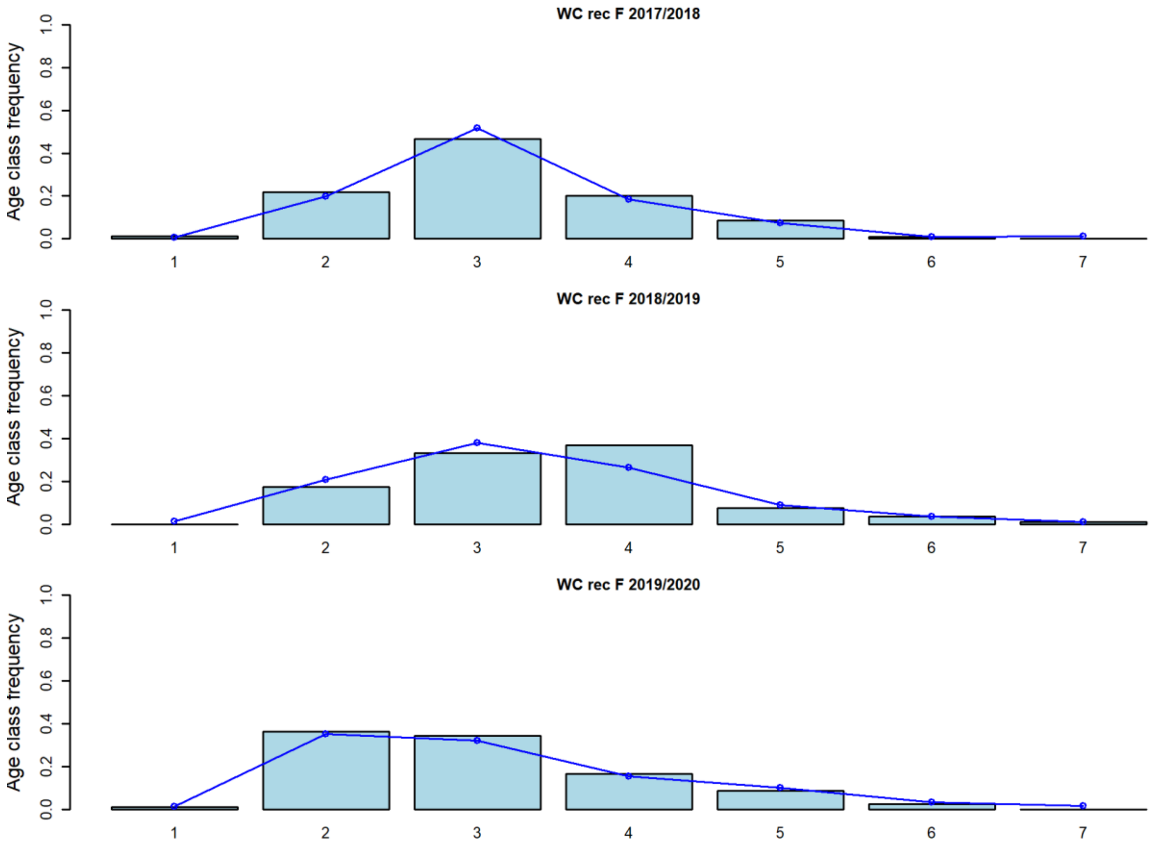

Figure 14.1. Fit of the catch curve model, allowing for variable annual recruitment to age composition data for female herring caught in 2017/18-2019/20 by recreational fishers on the west coast of Western Australia.

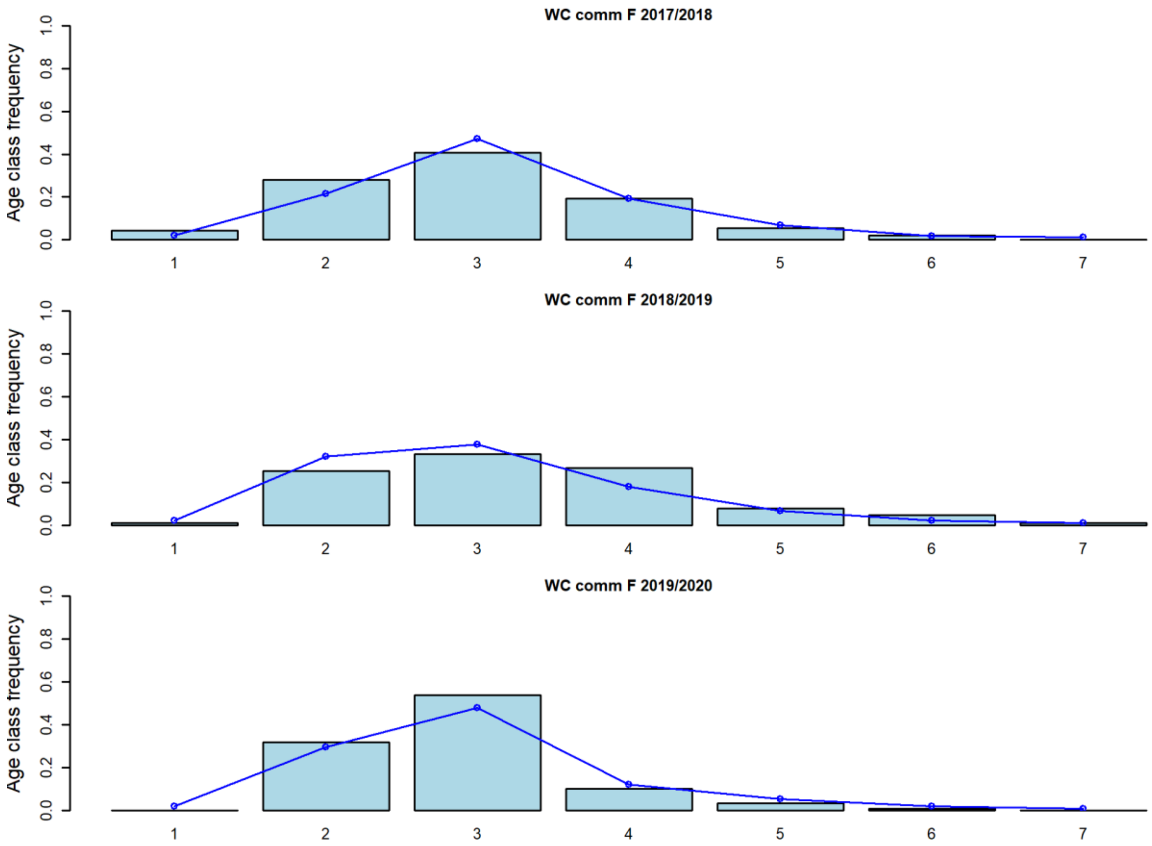

Figure 14.2. Fit of the catch curve model, allowing for variable annual recruitment to age composition data for female herring caught in 2017/18-2019/20 by commercial fishers on the west coast of Western Australia.

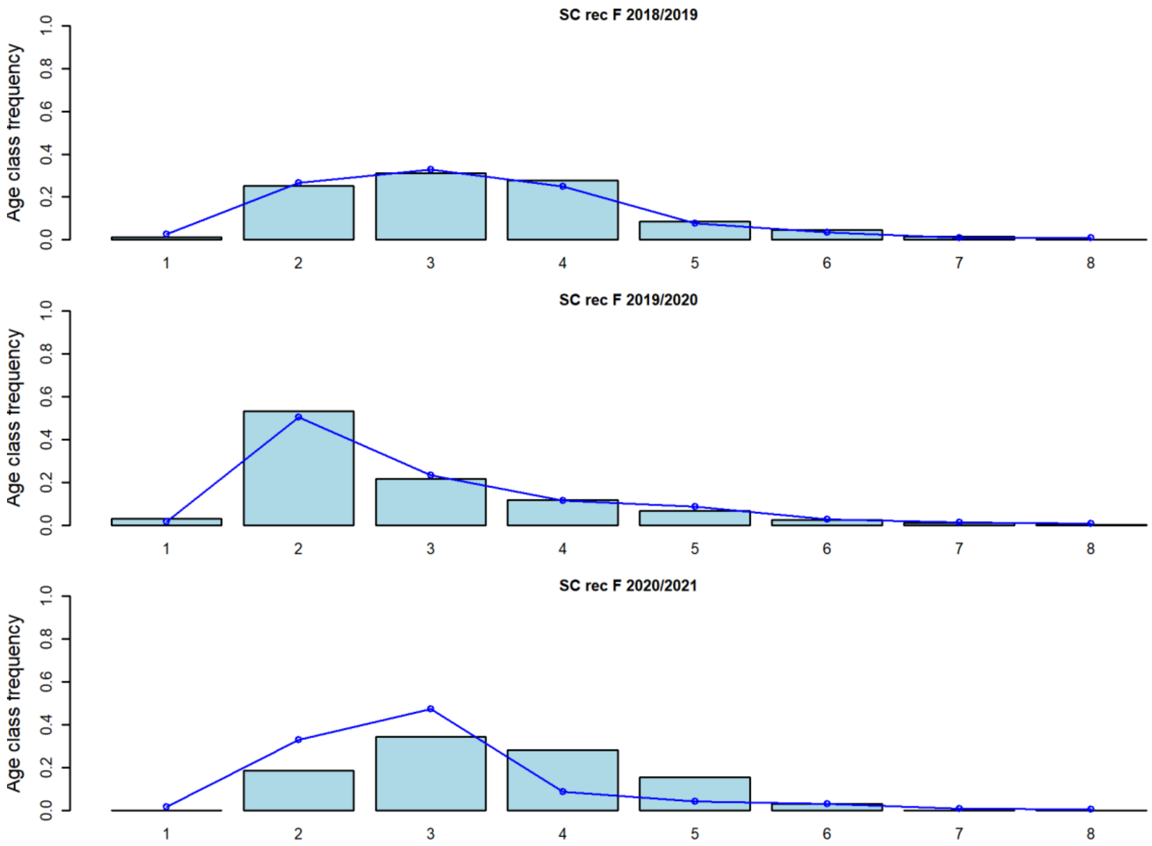

Figure 14.3. Fit of the catch curve model, allowing for variable annual recruitment to age composition data for female herring caught in 2017/18-2019/20 by recreational fishers on the south coast of Western Australia.

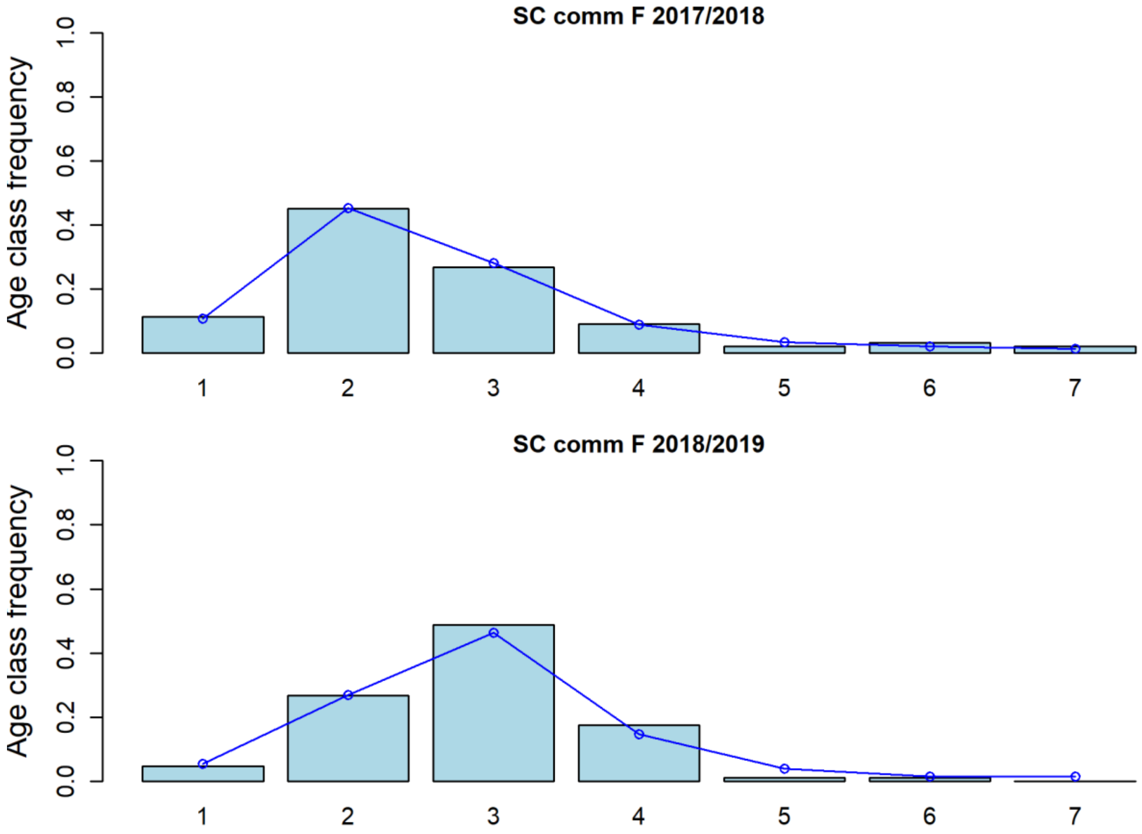

Figure 14.4. Fit of the catch curve model, allowing for variable annual recruitment to age composition data for female herring caught in 2017/18-2019/20 by commercial fishers on the south coast of Western Australia.

14.3 Per recruit analysis

Catch curve estimates of F and the selectivity parameters A_{50} and A_{95} for female herring were applied together with other available biological information (growth, maturity, weight-length relationship, natural mortality estimate) for herring on the west and south coasts of Western Australia (see Smith et al. 2013), in per recruit analyses. These analyses provided estimates of (i) female spawning potential ratio (SPR), based on traditional per recruit analysis, which assumes constant recruitment, and (ii) relative female spawning biomass (B_{rel}), from an extended model incorporating a Beverton-Holt stock recruitment relationship to account for potential effects of fishing on recruitment, i.e. associated with impacts of fishing of female spawning biomass (Table 14.2, Figure 14.5 to Figure 14.8). Further details of these per recruit models can be found in Norriss et al. (2016) and Wakefield et al. (2020). For this analysis, the target, threshold and limit reference points for SPR and B_{rel} were considered as 0.4, 0.3 and 0.2, respectively. The values of SPR and B_{rel} are taken as proxies for female spawning biomass.

Depending on whether fishing mortality was calculated (from catch curve analyses) using recreational or commercial age data, the point estimates of SPR were at and above the target reference point (0.4), respectively, for herring on the west coast (Table 14.2). On the south coast, the estimates were between the threshold and target reference points, based on the age data for both sectors. As expected, after accounting for possible effects of fishing on recruitment, the estimates of B_{rel} were always slightly lower than for SPR. On the west coast, the point estimate for B_{rel} was close to the target, based recreational age data and midway between the threshold and target based commercial data. On the south coast, the point estimates for B_{rel} were just below the threshold, based on either recreational or commercial data. The lower estimates for the south coast, despite slightly lower estimates for *F* and similar estimates for the selectivity parameters, likely relate mainly to differences in maturity parameters (maturity attained, on average, at a larger size on the south coast) (Table 14.2). Note that the analysis applied estimates of fishing mortality derived from catch curve analysis, a method assuming constant mortality over the lifespans of the fish in collected samples, which would not be true for a rebuilding stock.

Table 14.2. Estimates of female spawning potential ratio (SPR) from traditional per recruit analysis and female relative biomass (B_{rel}) from extended per recruit analysis (with stock-recruitment relationship, with steepness=0.75) for herring on the west and south coasts of Western Australia. Key input parameters used are also listed, including the growth and maturity parameters and estimates of fishing mortality and selectivity parameters from catch curve analysis. ±1SE denotes standard error estimates and ±95% CL denotes 95% confidence limits. The analysis assumed a common value for natural mortality (M = 0.4 y^{-1}), and common weight-length relationship for both sexes in both regions, and a model time step of 0.1 y.

Region / Sex	Sector	Maturity (mm, TL)	Selectivity (y)	Growth	*F* (±1SE)	SPR (±95% CL)	B_{rel} (±95% CL)
West coast (Female)	Rec.	L_{50}=194.1 L_{95}=250.8	A_{50}=2.64 A_{95}=3.36	L_∞=271.5 mm k=0.57 y^{-1} t_0=-0.3 y	0.612 (0.051)	0.446 (0.416-0.484)	0.396 (0.363-0.437)
West coast (Female)	Comm.	L_{50}=194.1 L_{95}=250.8	A_{50}=2.75 A_{95}=3.59	L_∞=271.5 mm k=0.57 y^{-1} t_0=-0.3 y	0.716 (0.062)	0.409 (0.379-0.447)	0.355 (0.322-0.396)

South coast (Female)	Rec.	L_{50}=219.6 L_{95}=265.3	A_{50}=2.50 A_{95}=3.21	L_{∞}=295.8 mm k=0.48 y^{-1} t_0=-0.2 y	0.504 (0.063)	0.355 (0.303-0.427)	0.296 (0.239-0.375)
South coast (Female)	Comm.	L_{50}=219.6 L_{95}=265.3	A_{50}=2.61 A_{95}=4.25	L_{∞}=295.8 mm k=0.48 y^{-1} t_0=-0.2 y	0.532 (0.138)	0.342 (0.249-0.527)	0.282 (0.181-0.484)

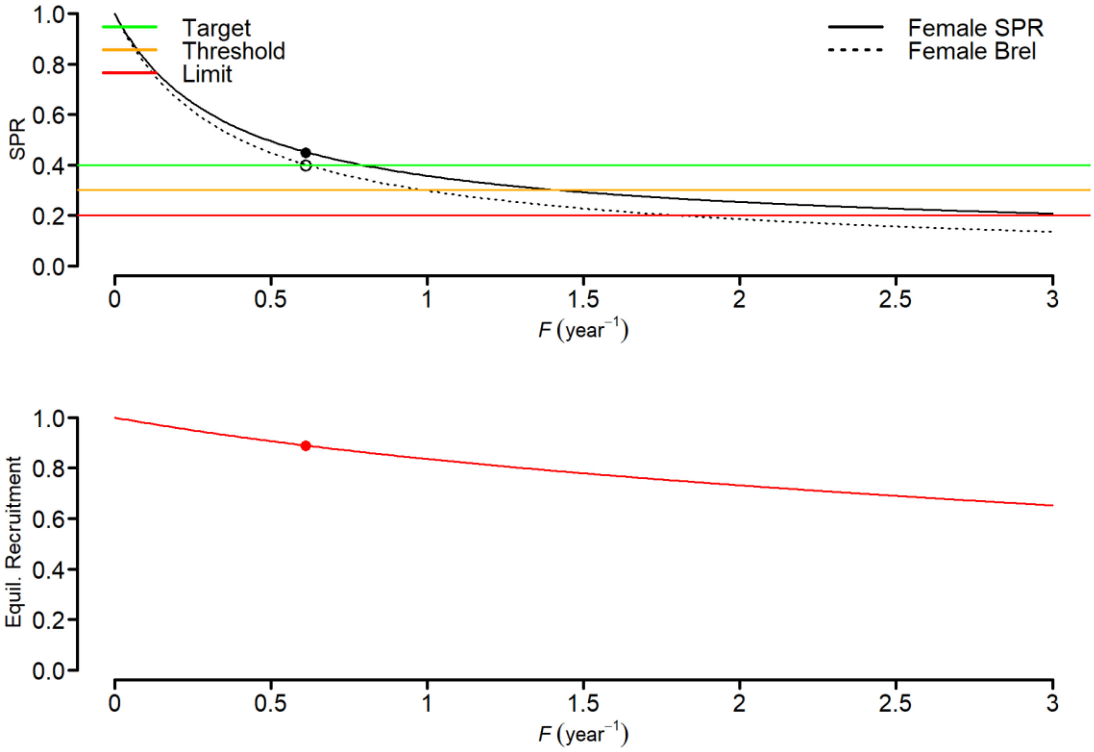

Figure 14.5. (top). Effect of different levels of fishing mortality (F) on female spawning potential ratio (SPR, solid black line) and relative biomass (Brel, dotted black line) for herring on the west coast of Western Australia. Estimates of SPR (close circle) and Brel (open circle), applying the catch curve estimate for F for this coast using recreational age data are shown, together with the target (0.4), threshold (0.3) and limit (0.2) reference points. (bottom). Effect of fishing mortality on recruitment, used when calculating Brel.

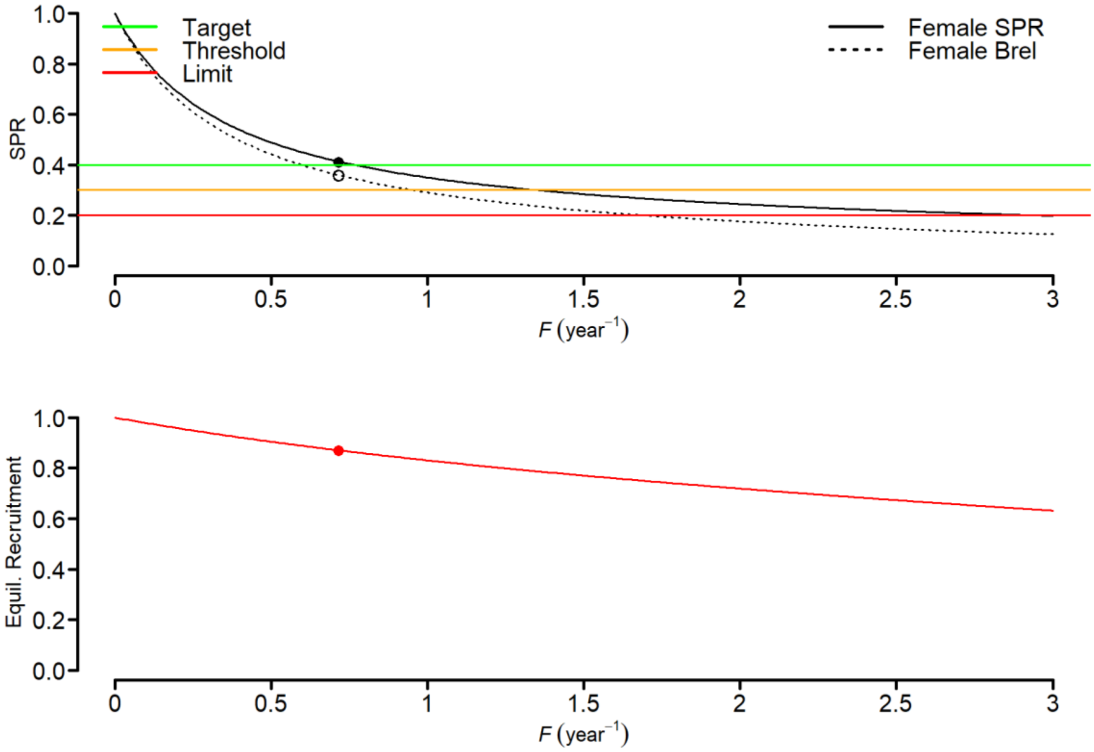

Figure 14.6. (top). Effect of different levels of fishing mortality (F) on female spawning potential ratio (SPR, solid black line) and relative biomass (Brel, dotted black line) for herring on the west coast of Western Australia. Estimates of SPR (close circle) and Brel (open circle), applying the catch curve estimate for F for this coast using commercial age data are shown, together with the target (0.4), threshold (0.3) and limit (0.2) reference points. (bottom). Effect of fishing mortality on recruitment, used when calculating Brel.

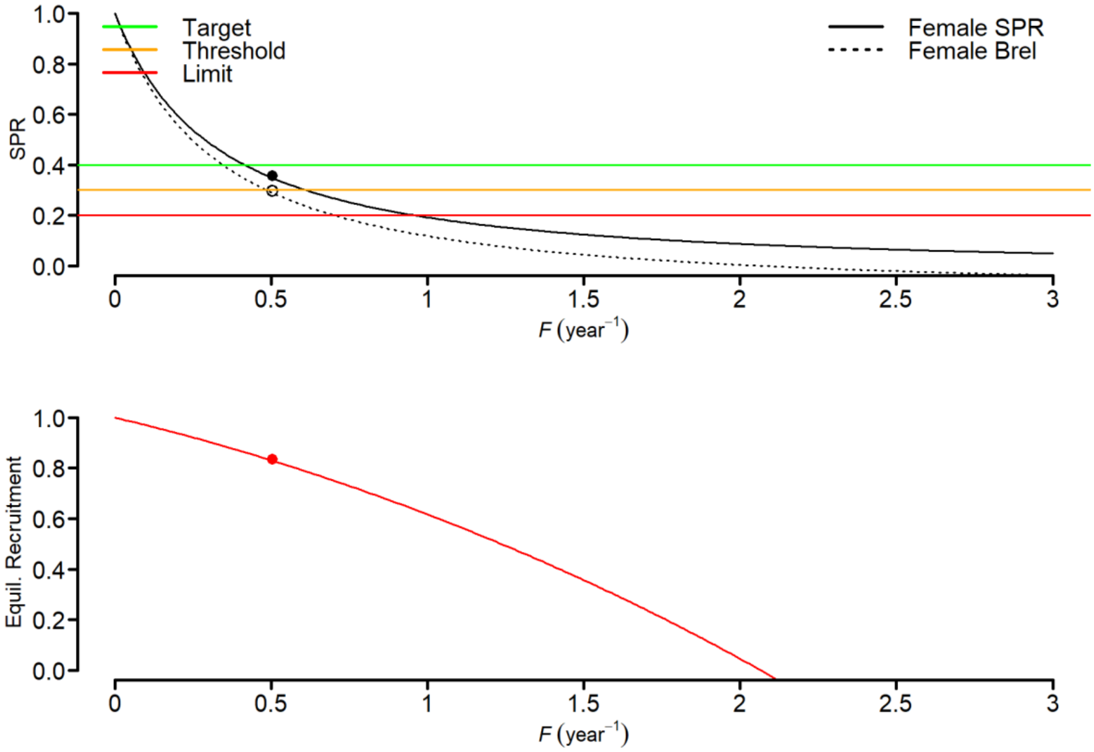

Figure 14.7. (top). Effect of different levels of fishing mortality (F) on female spawning potential ratio (SPR, solid black line) and relative biomass (Brel, dotted black line) for herring on the south coast of Western Australia. Estimates of SPR (close circle) and Brel (open circle), applying the catch curve estimate for F for this coast using recreational age data are shown, together with the target (0.4), threshold (0.3) and limit (0.2) reference points. (bottom). Effect of fishing mortality on recruitment, used when calculating Brel.

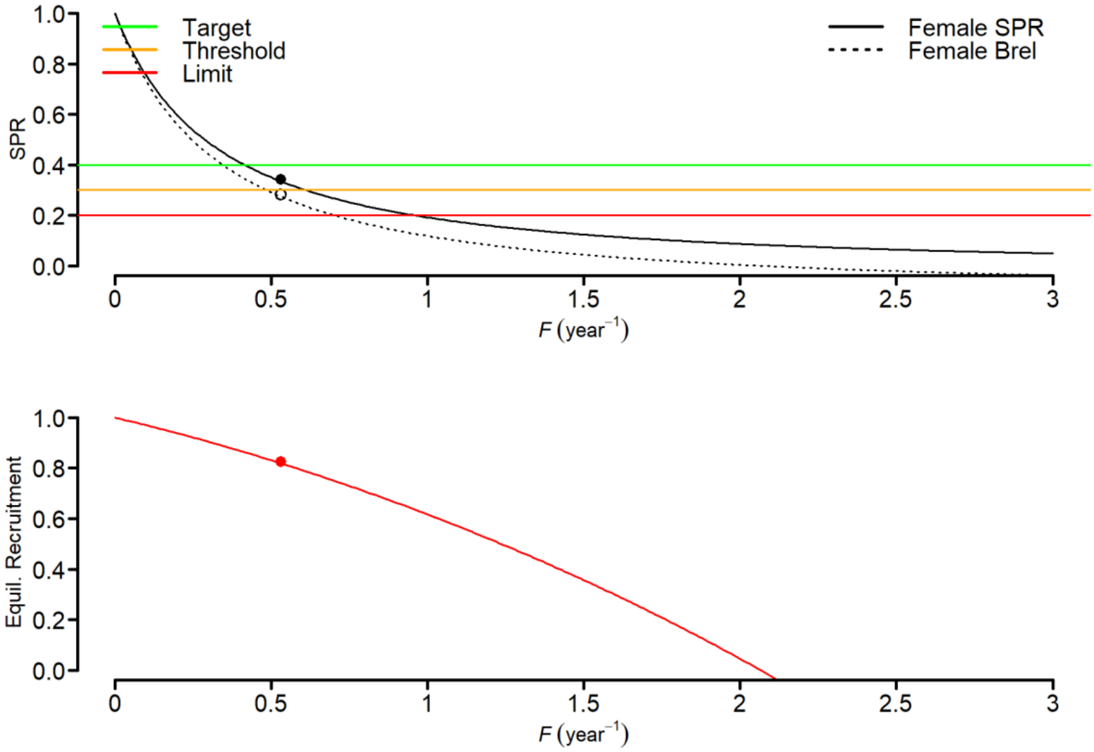

Figure 14.8. (top). Effect of different levels of fishing mortality (F) on female spawning potential ratio (SPR, solid black line) and relative biomass (Brel, dotted black line) for herring on the south coast of Western Australia. Estimates of SPR (close circle) and Brel (open circle), applying the catch curve estimate for F for this coast using commercial age data are shown, together with the target (0.4), threshold (0.3) and limit (0.2) reference points. (bottom). Effect of fishing mortality on recruitment, used when calculating Brel.

14.4 Length-based spawning potential ratio (LBSPR) method

Available length composition data caught by recreational and commercial fishers on the west and south coasts of Western Australia were used to provide further estimates of spawning potential ratio (as with the previous assessment, Wise and Molony 2018), applying the length-based spawning potential ratio method, available as an R package (version 0.1.5), using the default model type (length-structured growth-type-growth model, or GTG-LBSPR model) described by Hordyk et al. (2016).

Analyses assumed similar values for input parameters as used in the previous assessment (Wise & Molony 2018) for consistency (Table 14.3). The natural mortality rate applied of 0.4 y^{-1} is midway between the two values (0.38 and 0.42 y^{-1}) considered in the previous assessment. For each coast, the analysis applied the same values for the asymptotic size parameter (L_∞), maturity parameters, and almost the same values for the growth coefficient (0.52 in previous assessment vs 0.57 for this assessment, selected to match the value for females in table 5.1 in

Smith et al. (2013) and table 3 of Smith and Brown (2014)). For this assessment, a bin width of 10 mm was specified (Table 14.3).

For all but one case (i.e. recreational data for the south coast for 2019/20), the SPR estimates were at or above the threshold of 0.3, and the majority were above the target (0.4) (Table 14.4). The estimated ratios of fishing mortality to natural mortality, for a given sector and region, were often highly variable from year to year, which may reflect, in part, some sensitivity of this type of analysis to effects of annual recruitment variation. The estimates for spawning potential ratio (SPR), however, were more consistent from year-to-year. On the south coast, the SPR estimates followed downward trends (Table 14.4), which likewise could be influenced by recruitment variability. Note that, as with the above analyses, this approach is an equilibrium method assuming constant mortality over the lifespans of the fish in collected in each annual sample, which would not be true for a rebuilding stock.

Table 14.3. Values of input parameter used in the length-based spawning potential ratio (LBSPR) analysis for female herring on the west and south coasts of Western Australia.

Region / Sex	Sector	Maturity (mm, TL)	Natural mortality (M, y^{-1})	Growth coefficient (k y^{-1})	M/K ratio	Asymptotic length (L_∞, mm)	Bin width (mm)
West coast (Female)	Rec.	L_{50}=194.1 L_{95}=250.8	0.4	0.57	0.702	L_∞=271.5 mm	10
West coast (Female)	Comm.	L_{50}=194.1 L_{95}=250.8	0.4	0.57	0.702	L_∞=271.5 mm	10
South coast (Female)	Rec.	L_{50}=219.6 L_{95}=265.3	0.4	0.48	0.833	L_∞=295.8 mm	10
South coast (Female)	Comm.	L_{50}=219.6 L_{95}=265.3	0.4	0.48	0.833	L_∞=295.8 mm	10

Table 14.4. Results from the length-based spawning potential ratio (LBSPR) analysis for female herring on the west and south coasts of Western Australia. WC-rec and WC-comm, recreational and commercial length data, respectively for the west coast; SC-rec and SC-comm, recreational and commercial length data, respectively for the south coast; rawSL50 and rawSL96, non-smoothed estimates for selectivity parameters, far FM, non-smoothed estimate of the F:M ratio, raw SPR, non-smoothed estimates for spawning potential ratio.

Source	Biol. Year	rawSL50	rawSL95	rawFM	rawSPR
WC-rec	2015/16	242.63	285.27	2.03	0.55
WC-rec	2016/17	246.25	295.61	4.08	0.43
WC-rec	2017/18	253.28	302.09	3.15	0.53
WC-rec	2018/19	233.04	261.14	2.69	0.47
WC-rec	2019/20	245.53	277.39	6.90	0.42
WC-comm	2015/16	217.75	242.98	2.91	0.35
WC-comm	2016/17	236.38	268.86	5.14	0.38
WC-comm	2017/18	225.03	259.30	2.71	0.40
WC-comm	2018/19	236.06	268.33	5.27	0.38
WC-comm	2019/20	201.17	211.23	0.92	0.50
SC-rec	2015/16	231.75	264.52	0.76	0.59
SC-rec	2016/17	240.01	273.83	1.85	0.44
SC-rec	2017/18	216.51	242.59	0.98	0.46
SC-rec	2018/19	228.66	267.39	2.64	0.30
SC-rec	2019/20	212.80	255.27	2.34	0.24
SC-comm	2017/18	196.79	226.41	0.61	0.52
SC-comm	2018/19	251.31	295.75	3.99	0.35

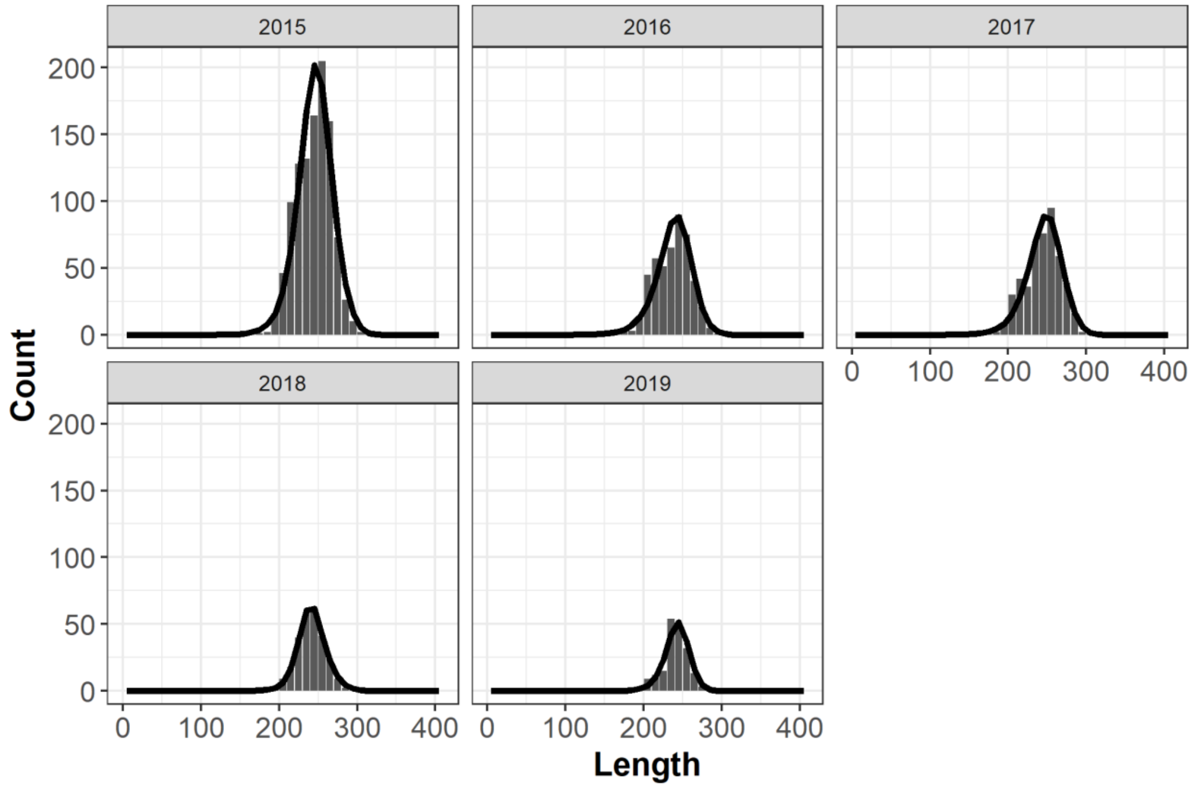

Figure 14.9. Fits (solid black lines) of the LB-SPR model to length-frequency data for female herring caught by recreational fishers on the west coast of Western Australia in 2015-2019.

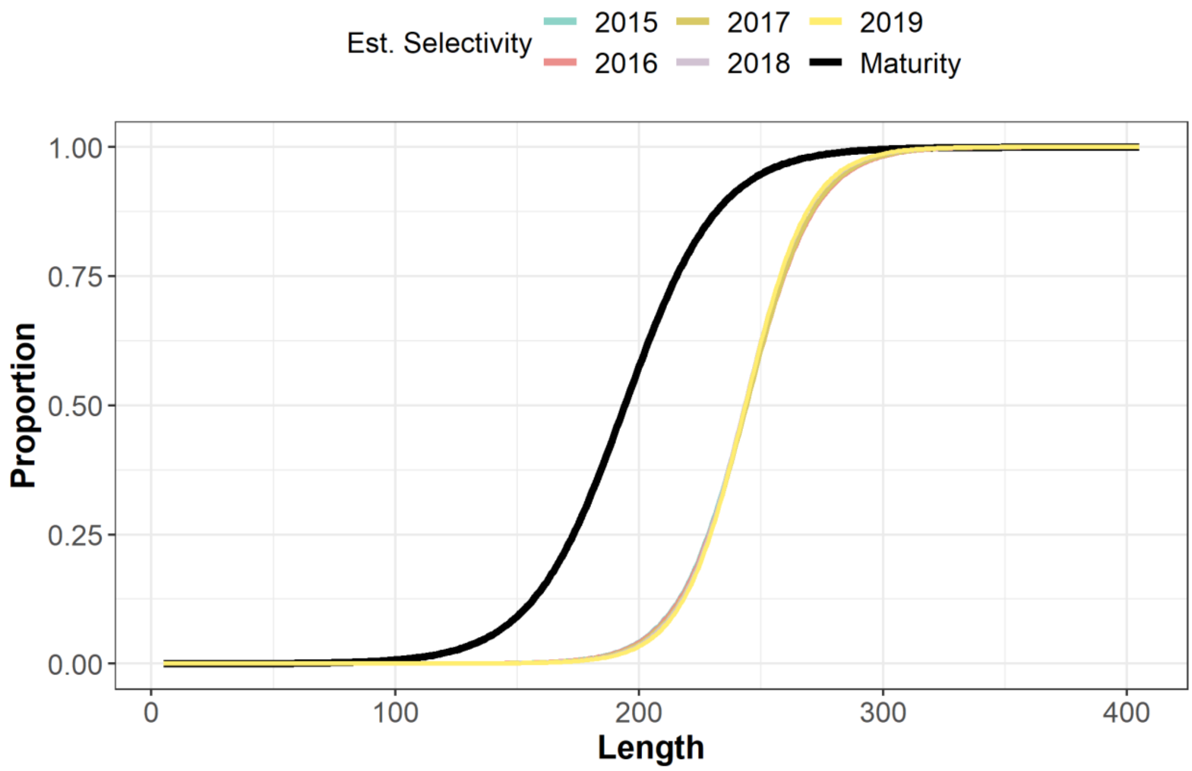

Figure 14.10. Estimated selectivity-length relationships for female herring caught by recreational fishers on the west coast of Western Australia in 2015-2019, and specified maturity-length relationship.

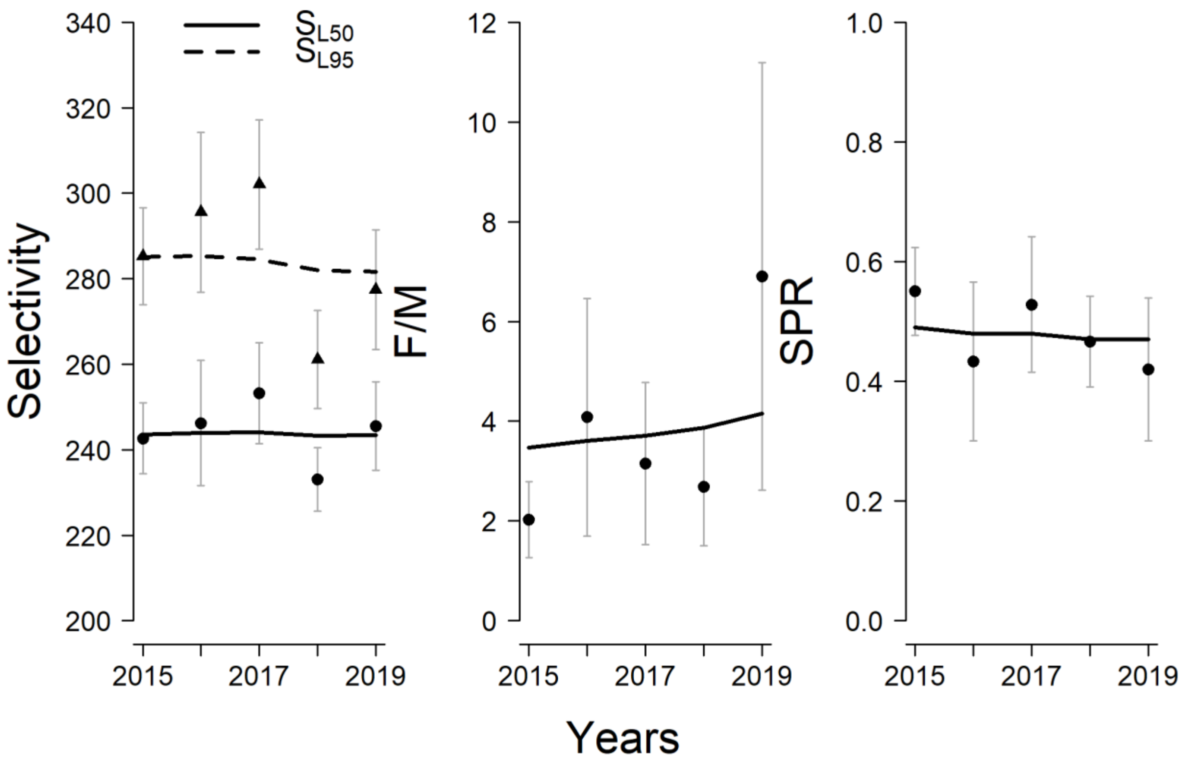

Figure 14.11. Raw and smoothed estimates for selectivity parameters, ratio of fishing mortality to natural mortality (F/M) and spawning potential ratio (SPR) for female herring caught by recreational fishers on the west coast of Western Australia in 2015-2019.

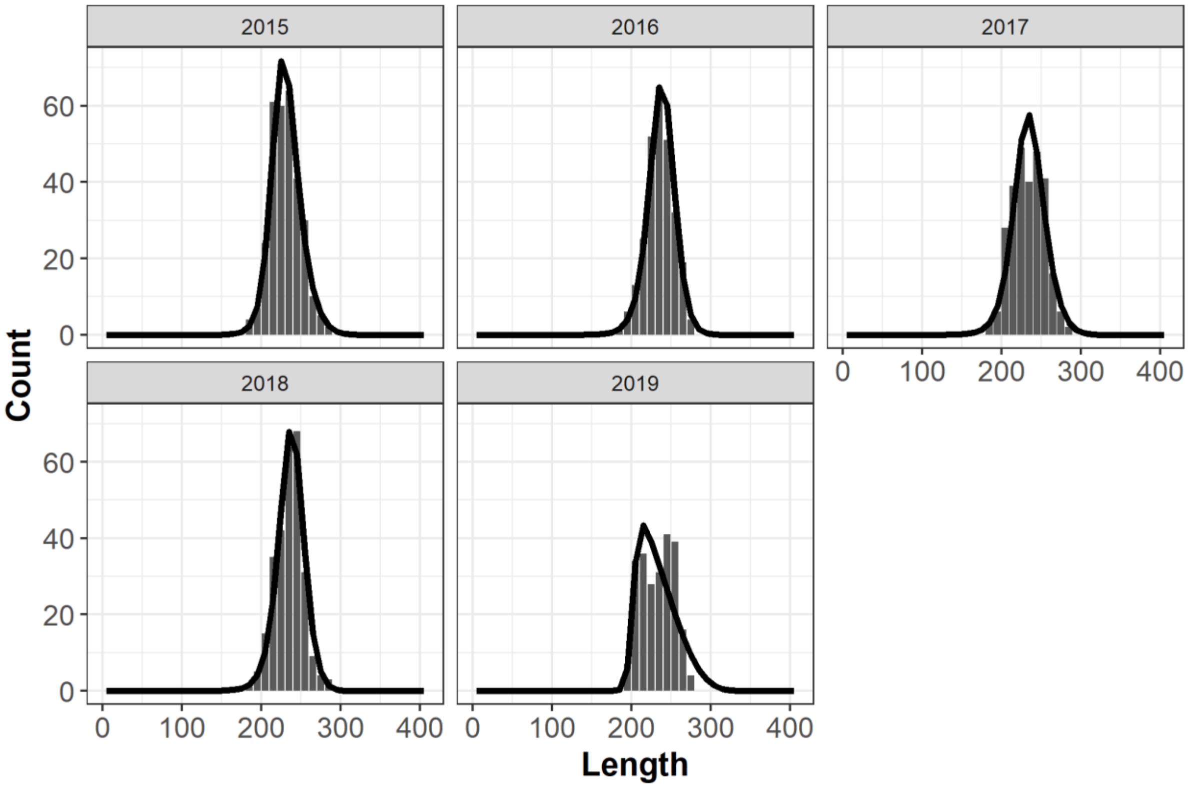

Figure 14.12. Fits (solid black lines) of the LB-SPR model to length-frequency data for female herring caught by commercial fishers on the west coast of Western Australia in 2015-2019.

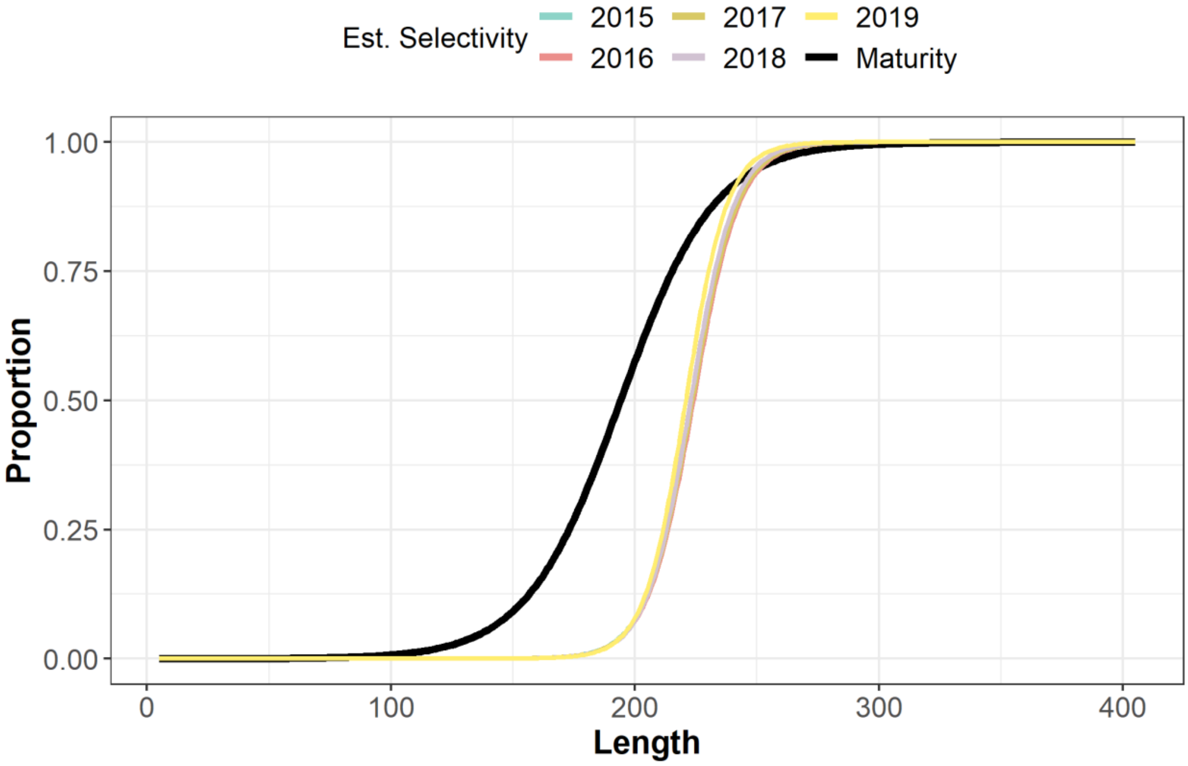

Figure 14.13. Estimated selectivity-length relationships for female herring caught by commercial fishers on the west coast of Western Australia in 2015-2019, and specified maturity-length relationship.

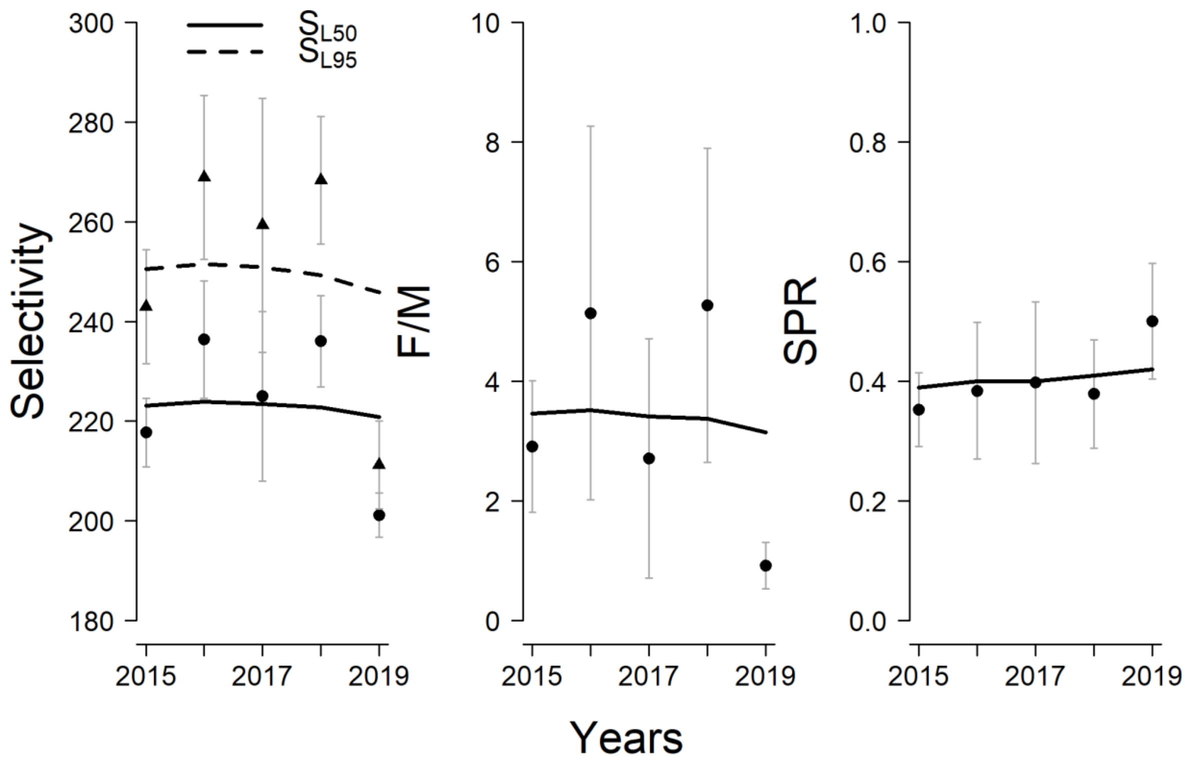

Figure 14.14. Raw and smoothed estimates for selectivity parameters, ratio of fishing mortality to natural mortality (F/M) and spawning potential ratio (SPR) for female herring caught by commercial fishers on the west coast of Western Australia in 2015-2019.

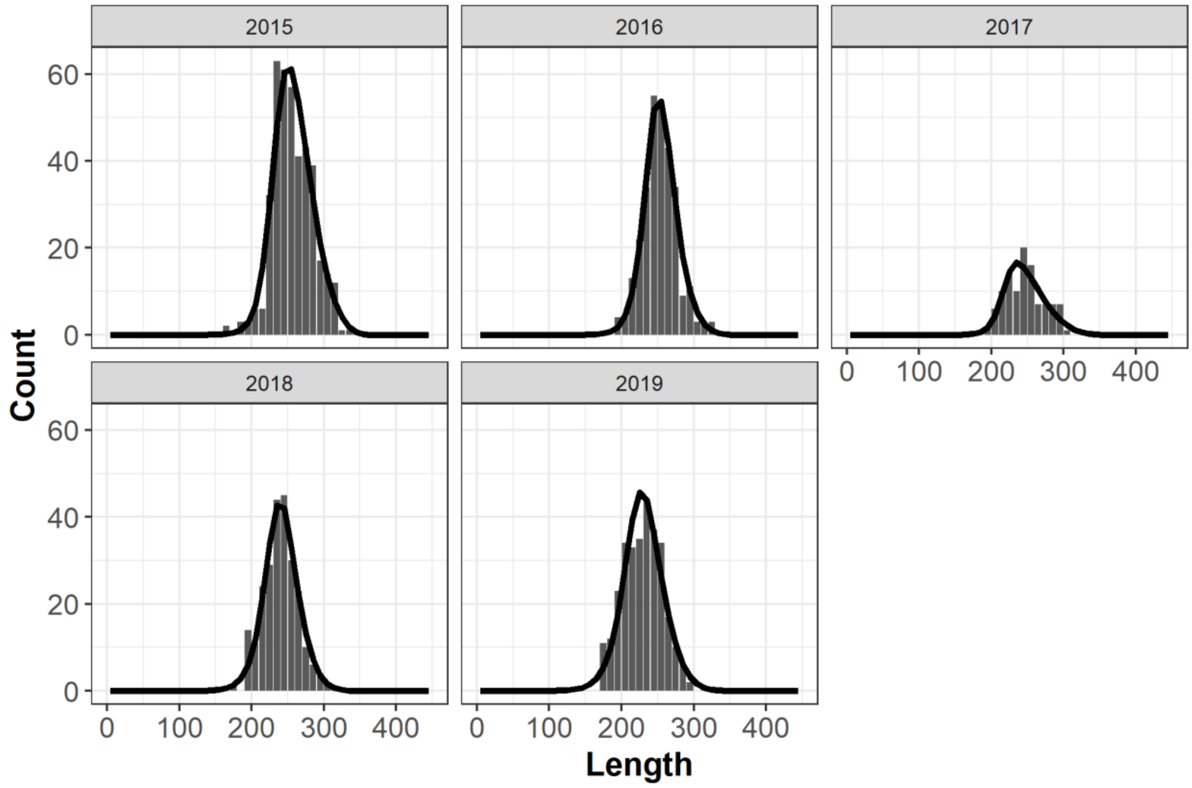

Figure 14.15. Fits (solid black lines) of the LB-SPR model to length-frequency data for female herring caught by recreational fishers on the south coast of Western Australia in 2015-2019.

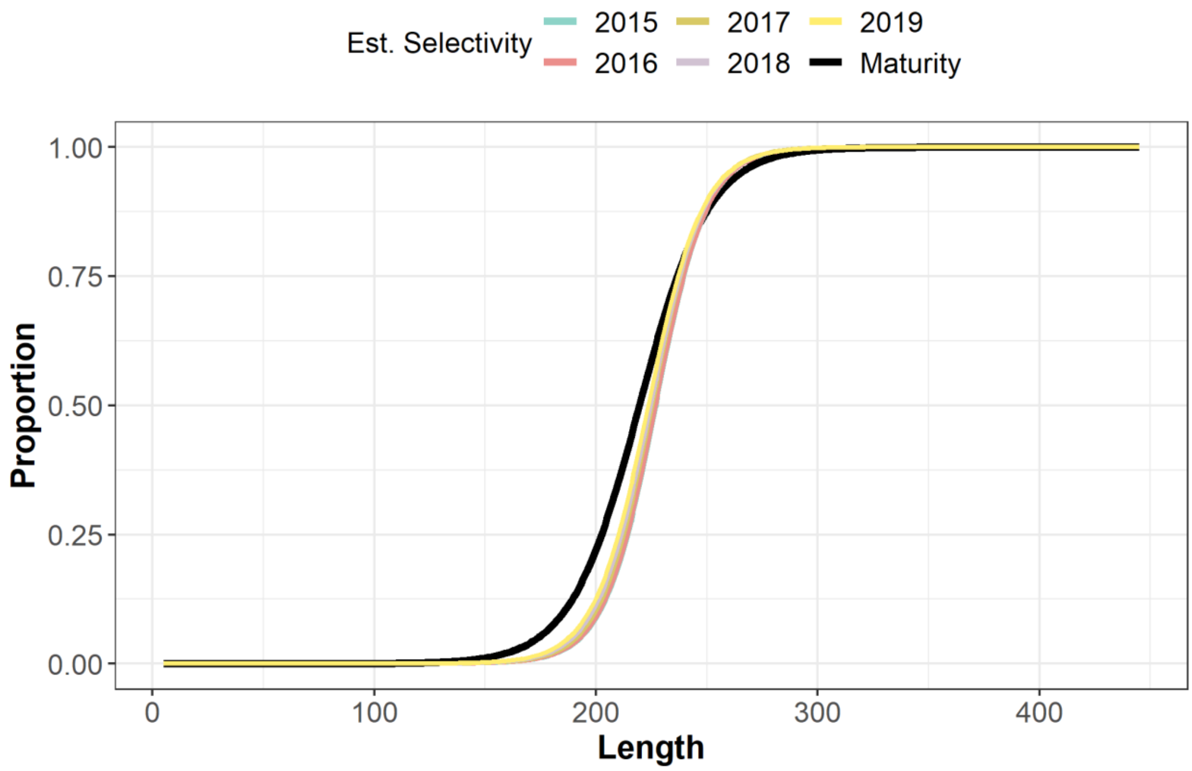

Figure 14.16. Estimated selectivity-length relationships for female herring caught by recreational fishers on the south coast of Western Australia in 2015-2019, and specified maturity-length relationship.

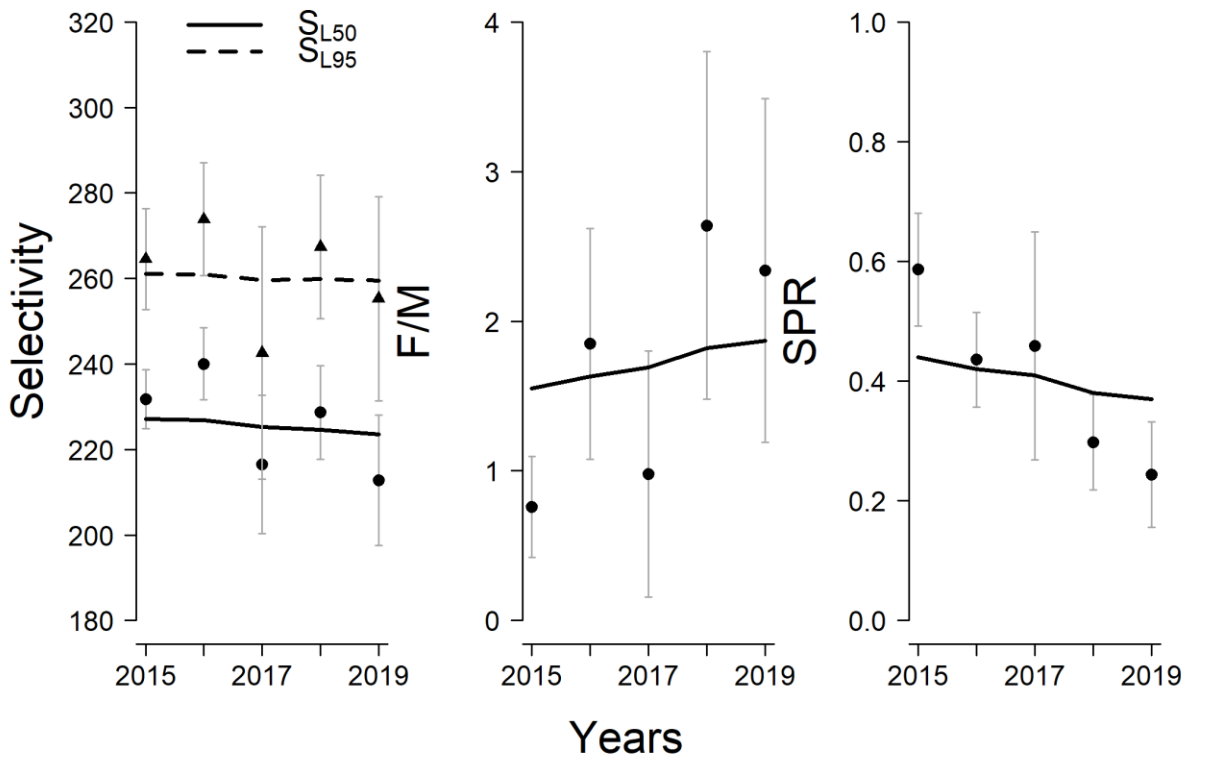

Figure 14.17. Raw and smoothed estimates for selectivity parameters, ratio of fishing mortality to natural mortality (F/M) and spawning potential ratio (SPR) for female herring caught by recreational fishers on the south coast of Western Australia in 2015-2019.

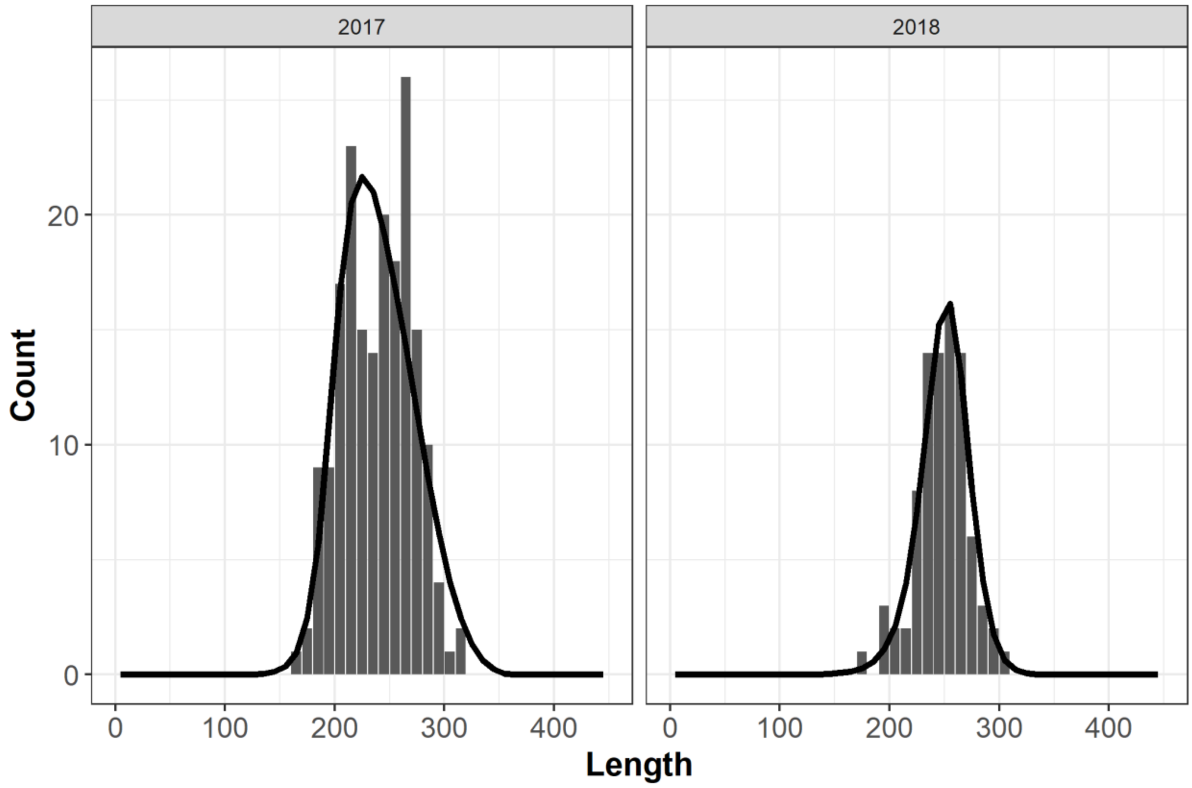

Figure 14.18. Fits (solid black lines) of the LB-SPR model to length-frequency data for female herring caught by commercial fishers on the south coast of Western Australia in 2015-2019.

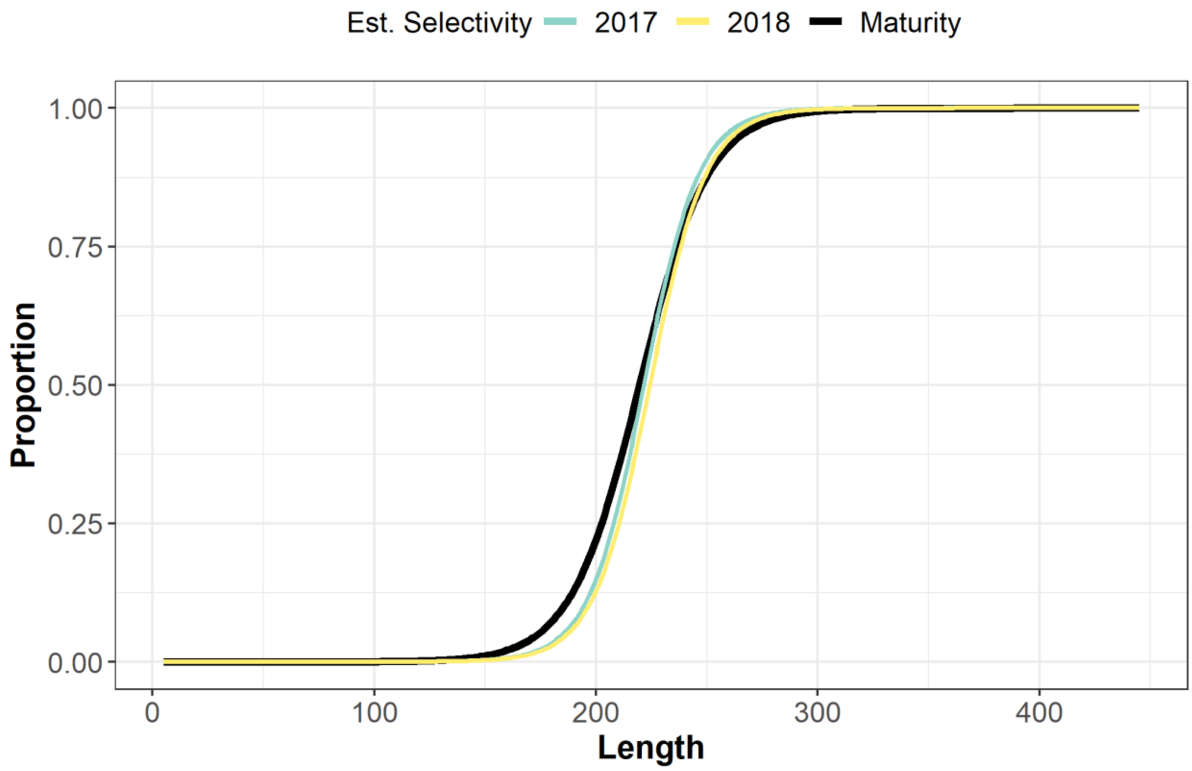

Figure 14.19. Estimated selectivity-length relationships for female herring caught by commercial fishers on the south coast of Western Australia in 2015-2019, and specified maturity-length relationship.

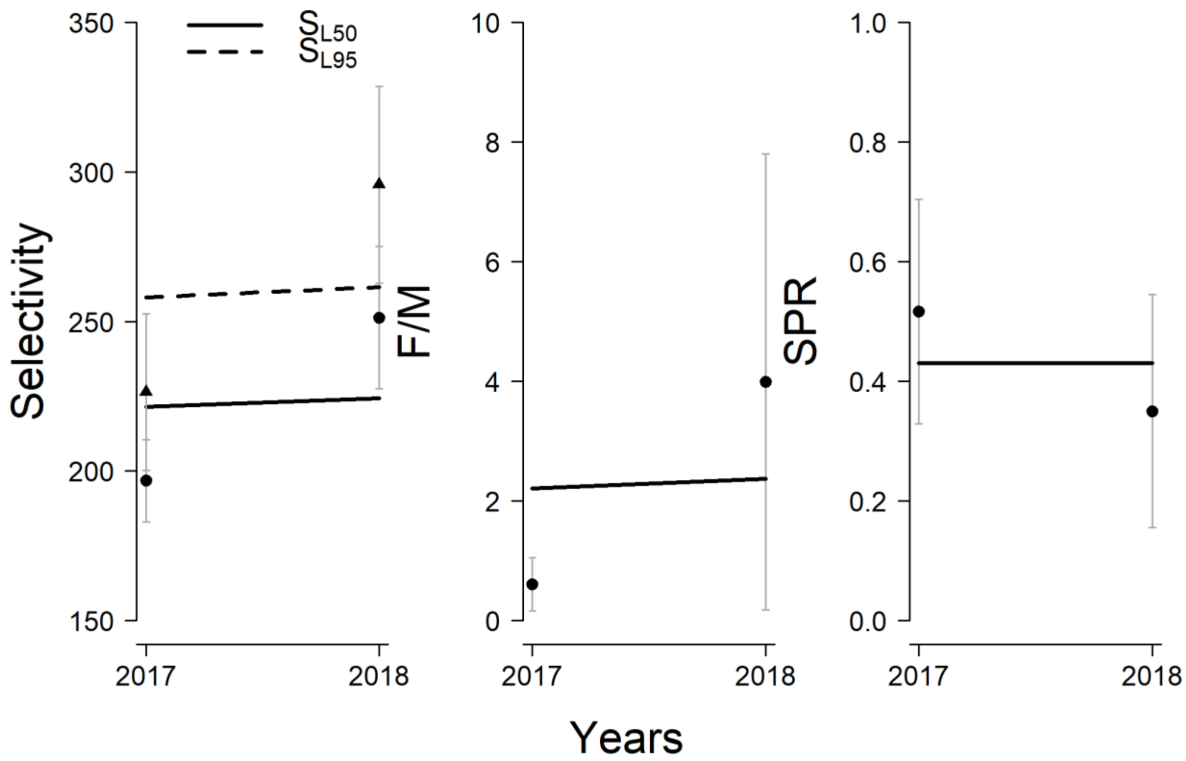

Figure 14.20. Raw and smoothed estimates for selectivity parameters, ratio of fishing mortality to natural mortality (F/M) and spawning potential ratio (SPR) for female herring caught by commercial fishers on the south coast of Western Australia in 2015-2019.

14.5 Integrated Model

14.5.1 Generic description of model

As with the previous assessment (Wise and Molony 2018), a dynamic, single area, sex- and age-structured statistical catch at age model was fitted to age composition and catch data for herring. The structure of model used is similar to that applied for the previous assessment. Model sensitivity analyses were run to explore the effects of applying alternative values for natural mortality, age composition from different sectors/regions, using a preliminary spawning stock abundance index (based on commercial CPUE data from the west coast), and linking recruitment to environmental data.

For this assessment, the time series of total catches for herring used for modelling were the combined catches for southern Australia (1952-2020). Using this time series, the model was fitted separately to recreational age composition data on the west and south coasts of Western Australia and commercial data on each coast. Note that the model requires a full time series of total stock removals. Although commercial catches are available for all years, information on recreational catches is limited to data from recreational surveys conducted in several years. As with the previous assessment, the full time series of recreational catches was "constructed" based on estimates from these surveys and linear interpolation where data were missing.

The model also incorporates biological parameters that have been separately estimated and pre-specified, e.g. for describing growth, weight-at-length relationships and size at maturity (see Smith et al. 2013 and Smith and Brown 2014).

The age-structured population model, starts with an assumed, stable age distribution of fish based on the numbers of fish reducing in each age class as a result of an initial specified fishing mortality $F0$. The population dynamic model consists of:

- A Beverton and Holt stock-recruitment relationship with a fixed value for steepness (default = 0.75). Log-normal recruitment deviations with a mean of zero are estimated to account for annual variation in recruitment around the value predicted by the stock-recruitment relationship.
- A deterministic sexual maturity vector for females, derived from parameters of a logistic function fitted to maturity data for females, calculated external to the assessment model.
- A deterministic weight-at-age vector, determined from parameters of a von Bertalanffy growth curve and weight-length relationship, calculated external to the assessment model.
- A logistic function with median age and slope at the inflection point estimated in the model, used to calculate the vector of vulnerability at age.
- A pre-specified value for natural mortality M (0.4, 0.5 or 0.6), i.e. where the lowest value is similar to that based on an observed maximum age of 10.5 y using the equation

of Hoenig (1983), and the largest value similar to that when using the equation of Then et al. (2015).

- The annual age composition data, which were observed for each species, were assumed to be drawn from a multinomial distribution. The “effective” sample size of the age composition data was not estimated, noting that as the model was not fitted to a catch rate time series, scaling between likelihoods associated with catch rate and age data was not required.
- Annual fishing mortalities are calculated based on the Baranov catch equation, applying Newton’s algorithm to iteratively calculate, for each year, the fishing mortality that produces an expected catch (i.e. from the model) that matches the observed annual catch.
- The overall log-likelihood has contributions associated with age composition data and recruitment deviations. The natural logarithms of the recruitment deviations are assumed to be normally distributed, with a mean of zero and a standard deviation of 0.6.
- The model contains a penalty function that constrains the fishing mortality in any year to below a maximum of F=1.5 y^{-1}.
- The model estimates, as parameters, the initial recruitment, the parameters of a logistic retention curve, and recruitment deviations for all years for which there are catch data, a 20 year ‘burn-in’ period of specified initial mortality, and a five-year projection period of specified constant catch (set equal to the catch in 2020).

The stock assessment model was run using the software package AD Model Builder (ADMB) with point estimates and their associated upper and lower 95% confidence limits determined for various quantities of interest based on estimates of the asymptotic standard errors (i.e. using sd_report variables). The key quantities of interest were current fishing mortality and current relative female spawning biomass (B_{rel}), i.e. estimated female spawning biomass as a percentage of unfished female biomass, and associated BMSY-based reference points calculated by the model, i.e. 1.2B_{MSY} (target), B_{MSY} (threshold), 0.5B_{MSY} (limit), and F_{MSY}.

14.5.2 Results and discussion

Applying the same biological parameters as used for the per recruit analyses, when fitting the model to age composition data from recreational fishers operating on the west coast, yielded estimates of recent B_{rel} that were unexpectedly low (i.e. around the limit), together with an unusual pattern in the estimated recruitment deviations (declining trend from late 1990s, rather than being centered around zero, when in log space). Such a pattern in residual structure can be indictive of ‘tension’ between the various data sources and/or an issue with model structure, which may occur if an important parameter is mis-specified. One of the parameters in the model that is influential, and uncertain, is natural mortality.

Increasing the value of M to from 0.4 y^{-1} to 0.5 y^{-1} and 0.6 y^{-1} led to less structural patterns for recruitment deviations (i.e. no obvious downward trends at M=0.6 y^{-1}). In addition, increasing the value of M led to slightly improved model fits to the west coast recreational age composition data, as indicated by lower values of the negative log-likelihood (NLL = 13673 at M=0.4 y^{-1}, NLL=13672 at M=0.5 y^{-1} and NLL= 13668 at M=0.6 y^{-1}), noting that a statistically significant difference in model fit typically corresponds approximately to a reduction in NLL by value of about 2. Fitting the model with M set to 0.6 y^{-1} also led to a higher estimate for current B_{rel}, around the threshold level (B_{MSY}) (Fig. 1), consistent with overall catches of herring having remained at historically low levels since around the mid-2000s. These results, i.e. small improvements in model fits, were repeated when applying the model to recreational age composition data from the south coast (NLL = 3882 at M=0.4 y^{-1}, NLL=3881 at M=0.5 y^{-1} and NLL= 3876 at M=0.6 y^{-1}), and commercial data from the west coast (NLL = 10049 at M=0.4 y^{-1}, NLL=10048 at M=0.5 y^{-1} and NLL= 10047 at M=0.6 y^{-1}). Using commercial data for the south coast, the model did not converge when setting M=0.4 y^{-1}. The NLL was slightly lower when setting M=0.5 y^{-1} (3753) vs M=0.6 y^{-1} (3756).

In all cases where M was set to 0.6 y^{-1} (except when using commercial data for the west coast), the results indicate that by 2020, B_{rel} has recovered to the target level, and that if current catch levels are maintained, B_{rel} will continue to increase. For all scenarios, catches in recent years have been well below the model estimates for *MSY*.

As noted above, results of this assessment are affected by uncertainty regarding the 'true' value of natural mortality (also noting that this can vary over time, which could occur for example if the population of a predator increases). Some other important specified model parameters included initial fishing mortality, for the stock at its initial fished equilibrium (F_{init}=0.2 y^{-1}), the steepness parameter for the Beverton-Holt stock recruitment curve (set to h=0.75), and level of recruitment variation (standard deviation of the natural logarithms of recruitment deviations, or sigmaR=0.6). As the value for F_{init}, applied over the initial model 'burn in' period is consistent with estimates for fishing mortality in early years (e.g. see Figure 14.21), and low-moderate catch levels at this time, this value was deemed appropriate. The values for h (e.g. Myers et al. 1999, Francis 2009, Punt et al. 2014) and sigmaR (e.g. Smith and Punt, citing Beddington and Cook 1983) are consistent with those used widely in stock assessments for fish species throughout the world.

The small, but consistent improvements in model fits as M was increased from 0.4 to 0.6 y^{-1} suggests that a higher value for M than used previously may be appropriate for herring, although this result is not definitive. The results of the analyses that utilised a lower value in this assessment may represent conservative estimates of stock status.

Fitting the model to commercial CPUE data from the west coast (Geographe Bay), i.e. used as a preliminary spawning biomass index, with M=0.6 y^{-1}, produces less optimistic results than when CPUE are not used, with current female spawning biomass (2020) estimated at about the threshold level (Figure 14.35 and Figure 14.36). Allowing for a potential effect of Leeuwin current strength (using Fremantle, detrended mean sea level anomaly data as a proxy), on recruitment, produced essentially the same results to when no environmental effect was considered (Figure 14.37 and Figure 14.38). The model was unable to detect a significant environmental effect on recruitment, as indicated by the broad confidence limits for the 'environmental parameter', overlapping zero. It should be noted, however, that other environmental variables, e.g. sea surface temperature, could potentially impact on recruitment success, and should be explored for future work. The estimated stock-recruitment relationship from the model is presented in section 9.3.14.2. The results produced by the dynamic catch-age model, for scenarios of natural mortality considered most consistent with the catch, age data and other modelling assumptions, using age composition data from either the west coast or south coast, indicate that the stock has now recovered to the target.

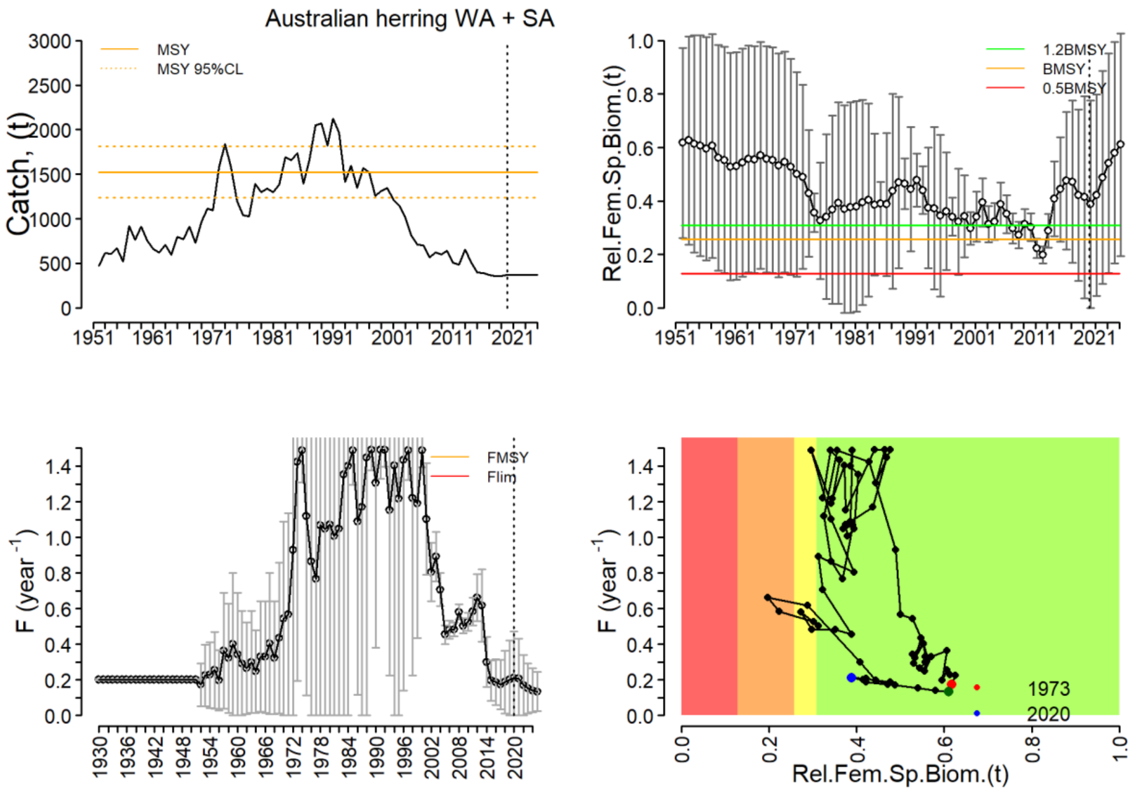

Figure 14.21. ***Top left*, Annual catches of herring (Western Australia and South Australia) vs estimated maximum sustainable yield, MSY (± 95% CLs); *top right*, estimates of relative female spawning biomass and associated values at BMSY (threshold) and 0.5MSY (limit); *bottom left*, estimates of fishing mortality, *F* (year^{-1}) vs FMSY; *bottom right*, phase plot, showing progression of female spawning biomass and fishing mortality. Results for model fitted to recreational data from the west coast of Western Australia, with *M* set to 0.6 y^{-1}.**

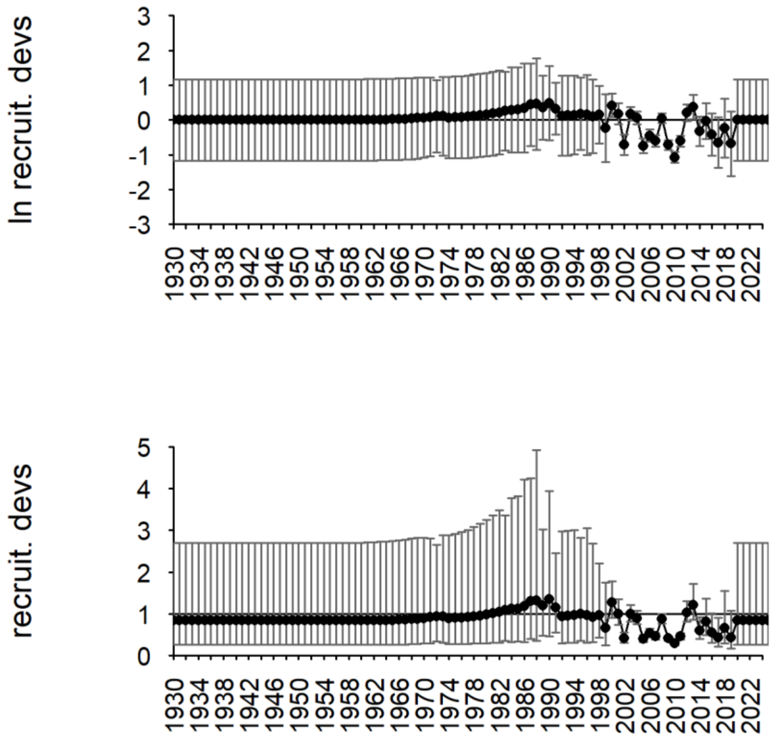

Figure 14.22. Estimated recruitment deviations in log space (*top*) normal space (*bottom*). Results for model fitted to recreational data from the west coast of Western Australia, with *M* set to 0.6 y^{-1}.

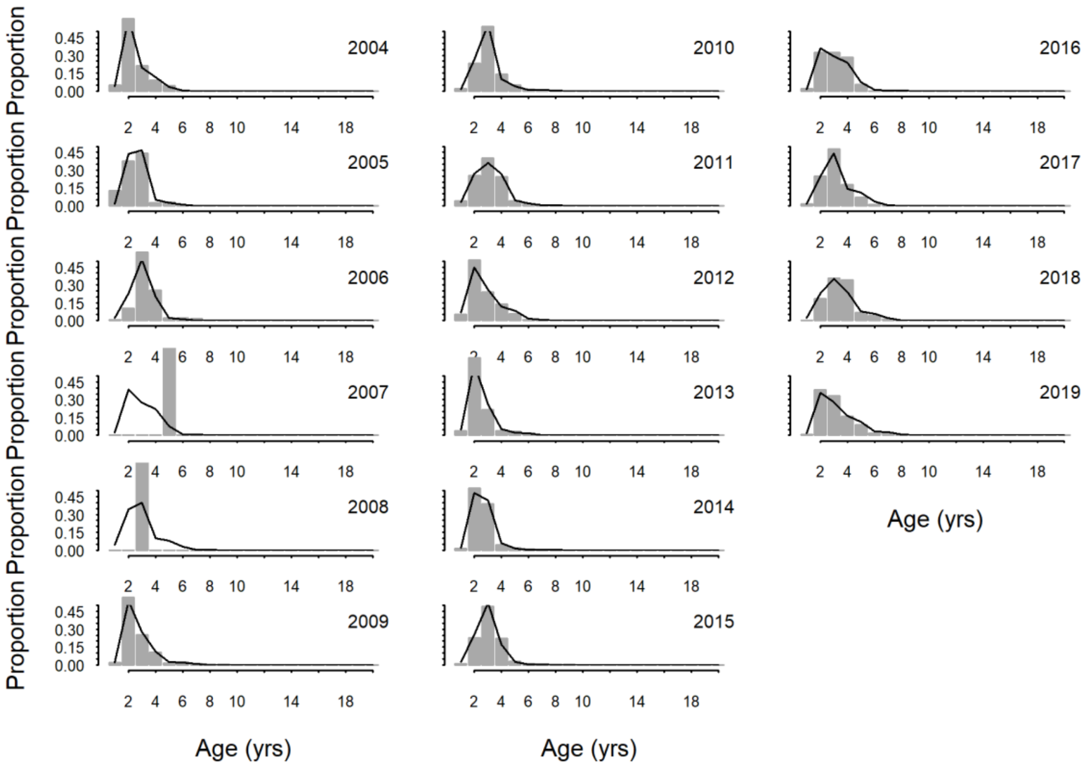

Figure 14.23. Observed (grey bars) vs expected (black lines) age compositions for herring. Results for model fitted to recreational data from the west coast of Western Australia, with *M* set to 0.6 y^{-1}.

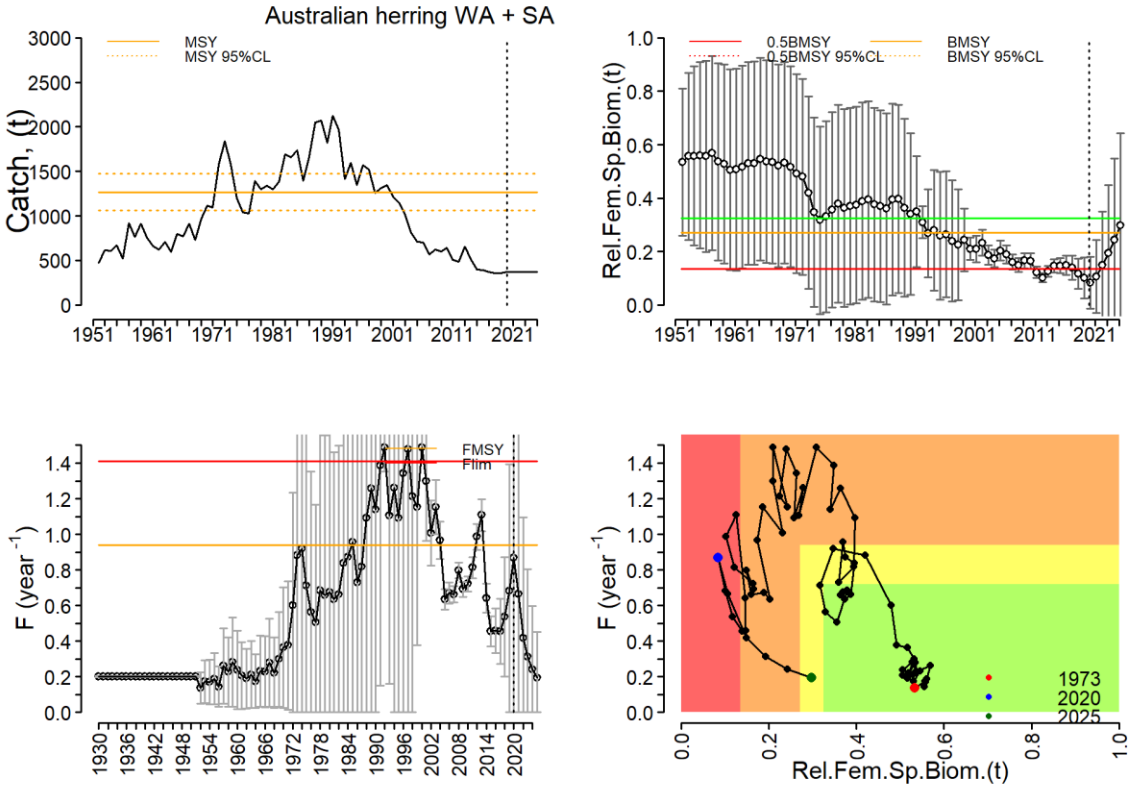

Figure 14.24. ***Top left***, **Annual catches of herring (Western Australia and South Australia) vs estimated maximum sustainable yield, MSY (± 95% CLs);** ***top right***, **estimates of relative female spawning biomass and associated values at BMSY (threshold) and 0.5MSY (limit);** ***bottom left***, **estimates of fishing mortality,** $\boldsymbol{F}$ **(year^{-1}) vs FMSY;** ***bottom right***, **phase plot, showing progression of female spawning biomass and fishing mortality. Results for model fitted to recreational data from the west coast of Western Australia, with** $\boldsymbol{M}$ **set to 0.4 y^{-1}.**

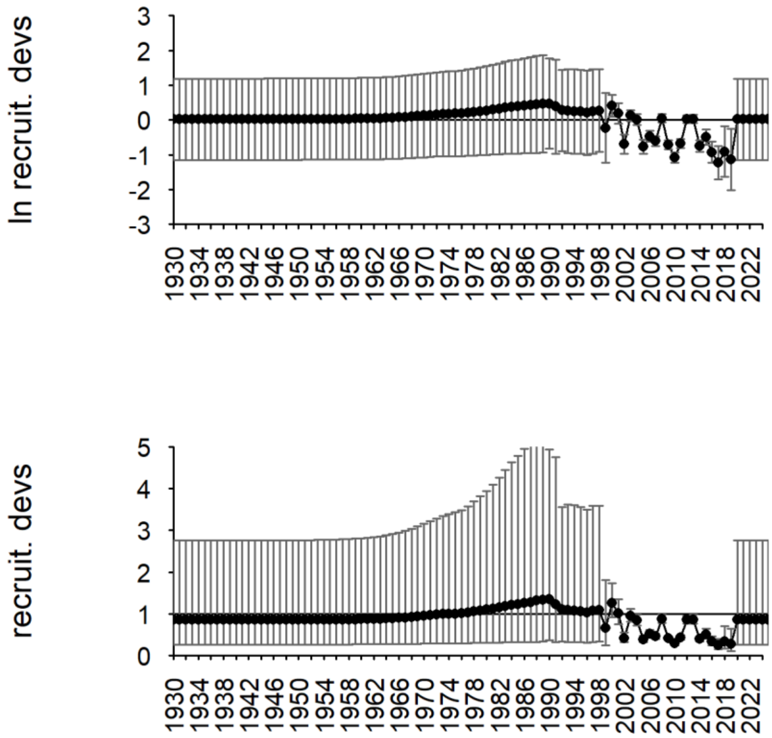

Figure 14.25. Estimated recruitment deviations in log space (*top*) normal space (*bottom*). Results for model fitted to recreational data from the west coast of Western Australia, with *M* set to 0.4 y^{-1}.

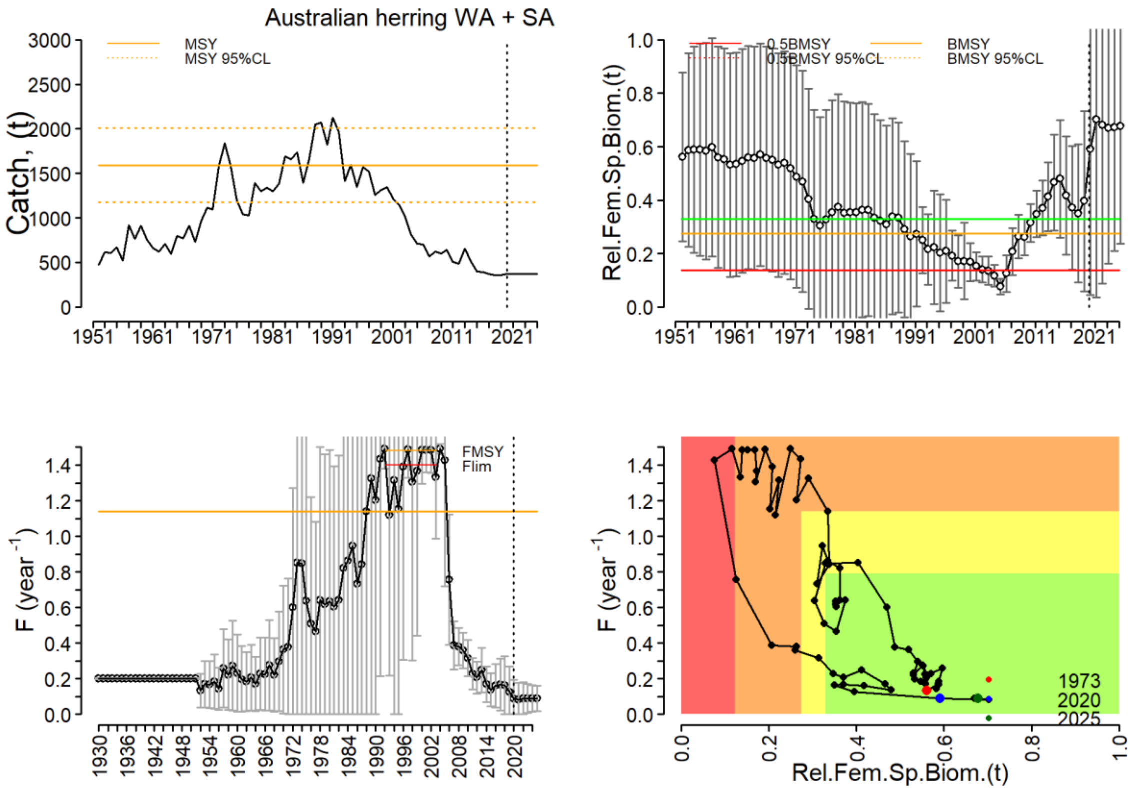

Figure 14.26. ***Top left***, **Annual catches of herring (Western Australia and South Australia) vs estimated maximum sustainable yield, MSY (± 95% CLs);** ***top right***, **estimates of relative female spawning biomass and associated values at BMSY (threshold) and 0.5MSY (limit);** ***bottom left***, **estimates of fishing mortality,** ***F*** **(year^{-1}) vs FMSY;** ***bottom right***, **phase plot, showing progression of female spawning biomass and fishing mortality. Results for model fitted to recreational data from the south coast of Western Australia, with** ***M*** **set to 0.6 y^{-1}.**

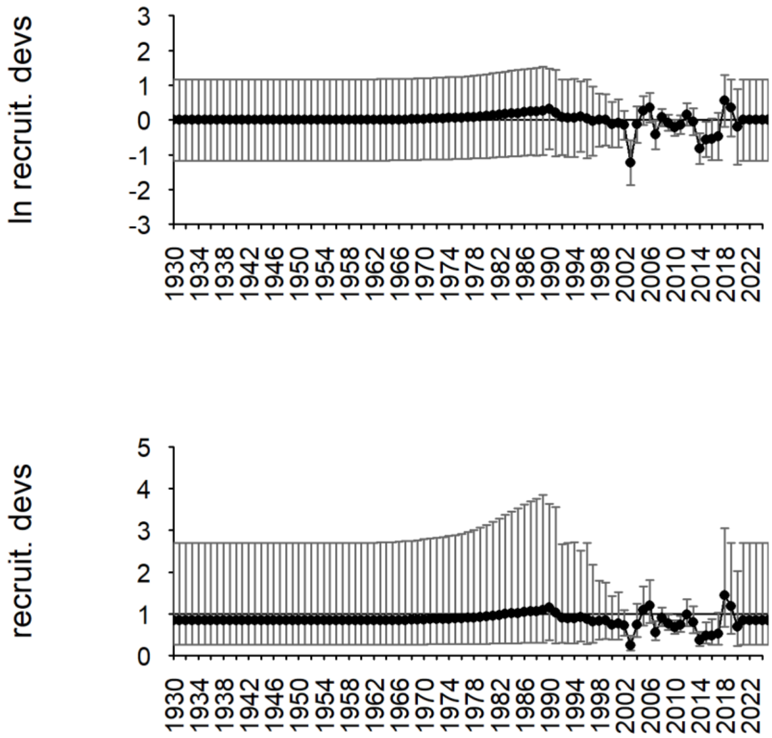

Figure 14.27. Estimated recruitment deviations in log space (*top*) normal space (*bottom*). Results for model fitted to recreational data from the south coast of Western Australia, with *M* set to 0.6 y^{-1}.

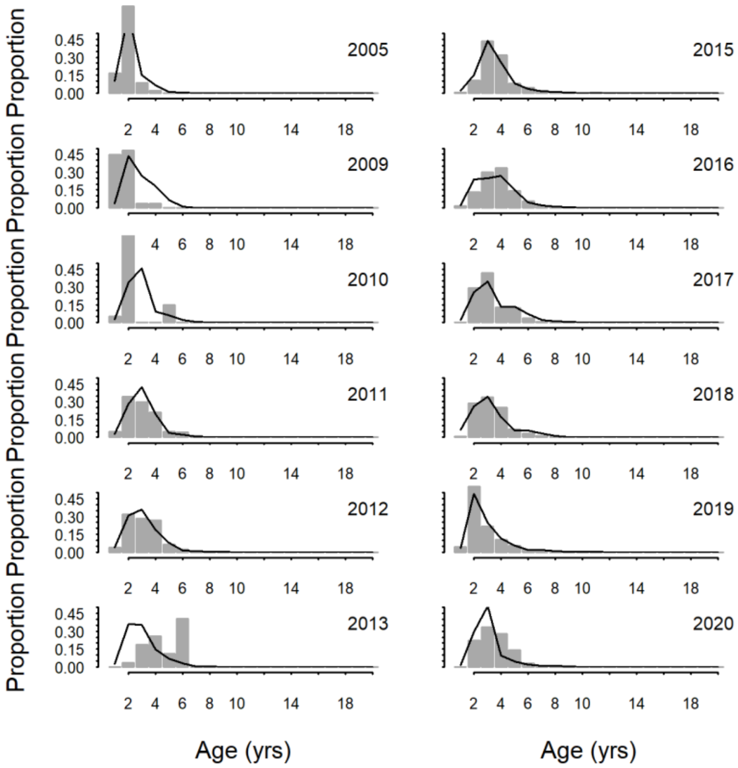

Figure 14.28. Observed (grey bars) vs expected (black lines) age compositions for herring. Results for model fitted to recreational data from the south coast of Western Australia, with *M* set to 0.6 y^{-1}.

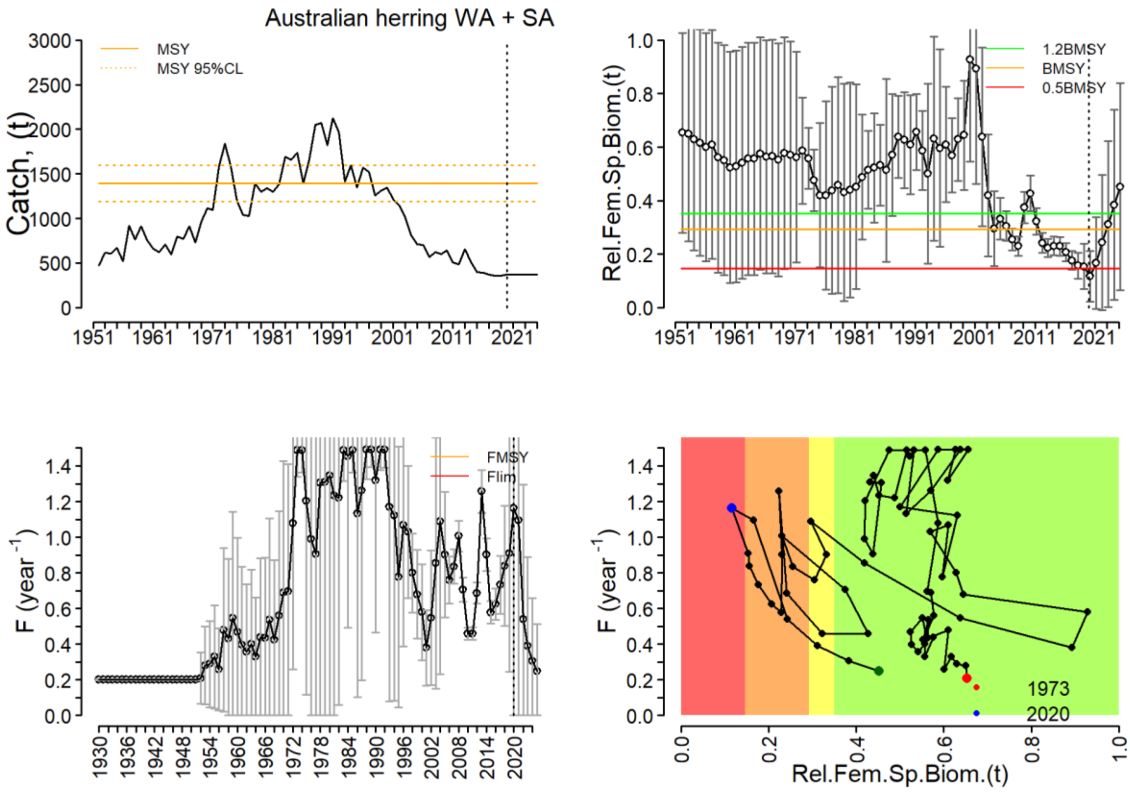

Figure 14.29. ***Top left*, Annual catches of herring (Western Australia and South Australia) vs estimated maximum sustainable yield, MSY (± 95% CLs); *top right*, estimates of relative female spawning biomass and associated values at BMSY (threshold) and 0.5MSY (limit); *bottom left*, estimates of fishing mortality, *F* (year^{-1}) vs FMSY; *bottom right*, phase plot, showing progression of female spawning biomass and fishing mortality. Results for model fitted to commercial data from the west coast of Western Australia, with *M* set to 0.6 y^{-1}.**

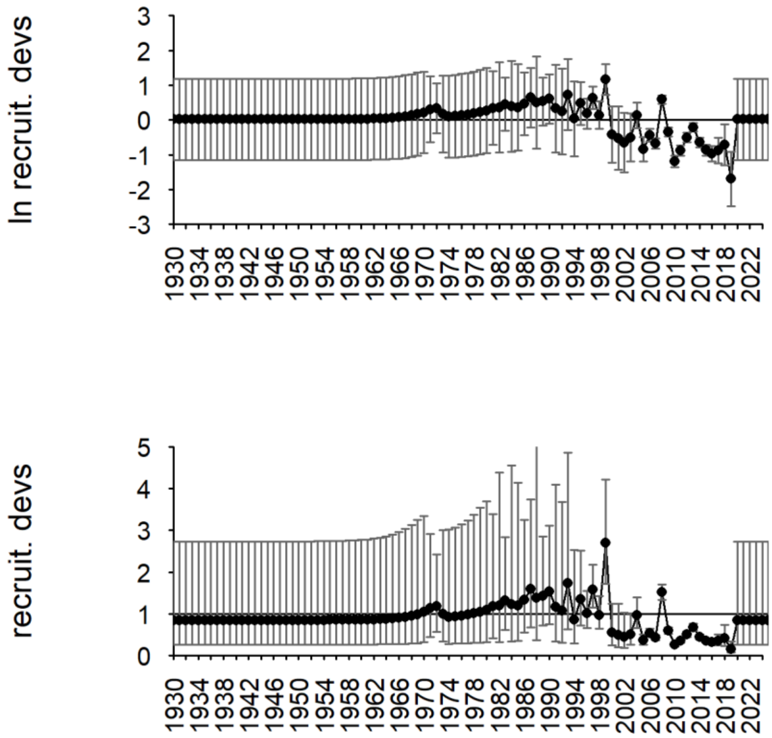

Figure 14.30. Estimated recruitment deviations in log space (*top*) normal space (*bottom*). Results for model fitted to commercial data from the west coast of Western Australia, with *M* set to 0.6 y^{-1}.

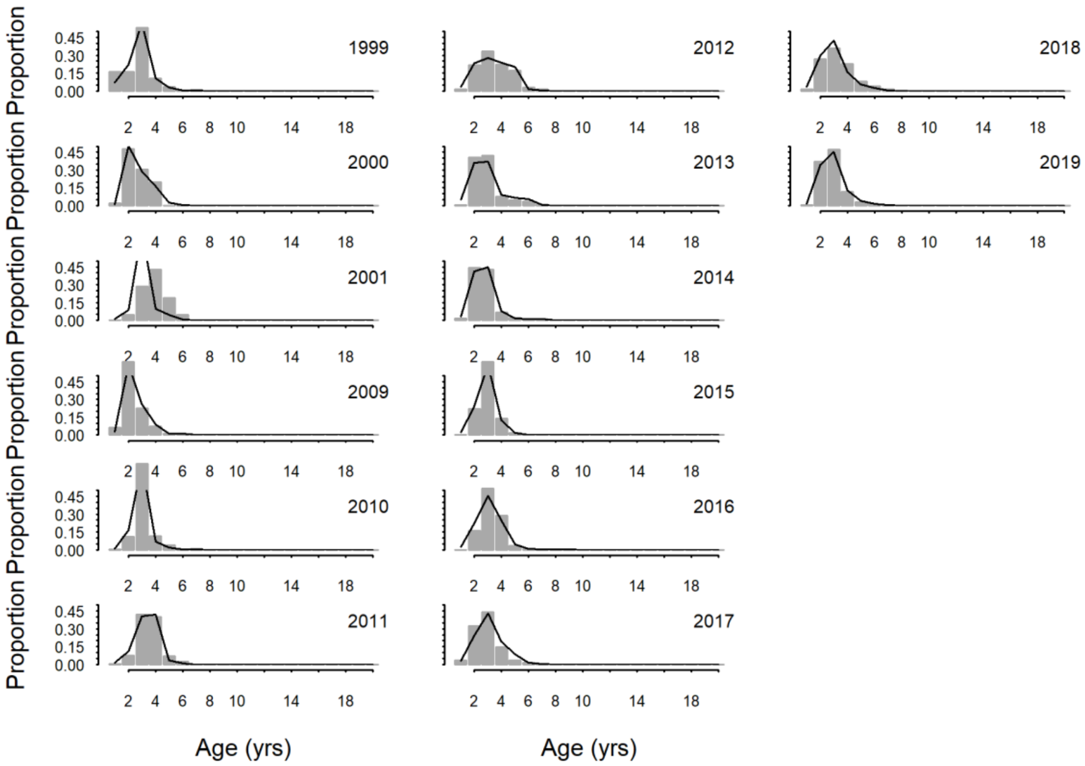

Figure 14.31. Observed (grey bars) vs expected (black lines) age compositions for herring. Results for model fitted to commercial data from the west coast of Western Australia, with *M* set to 0.6 y^{-1}.

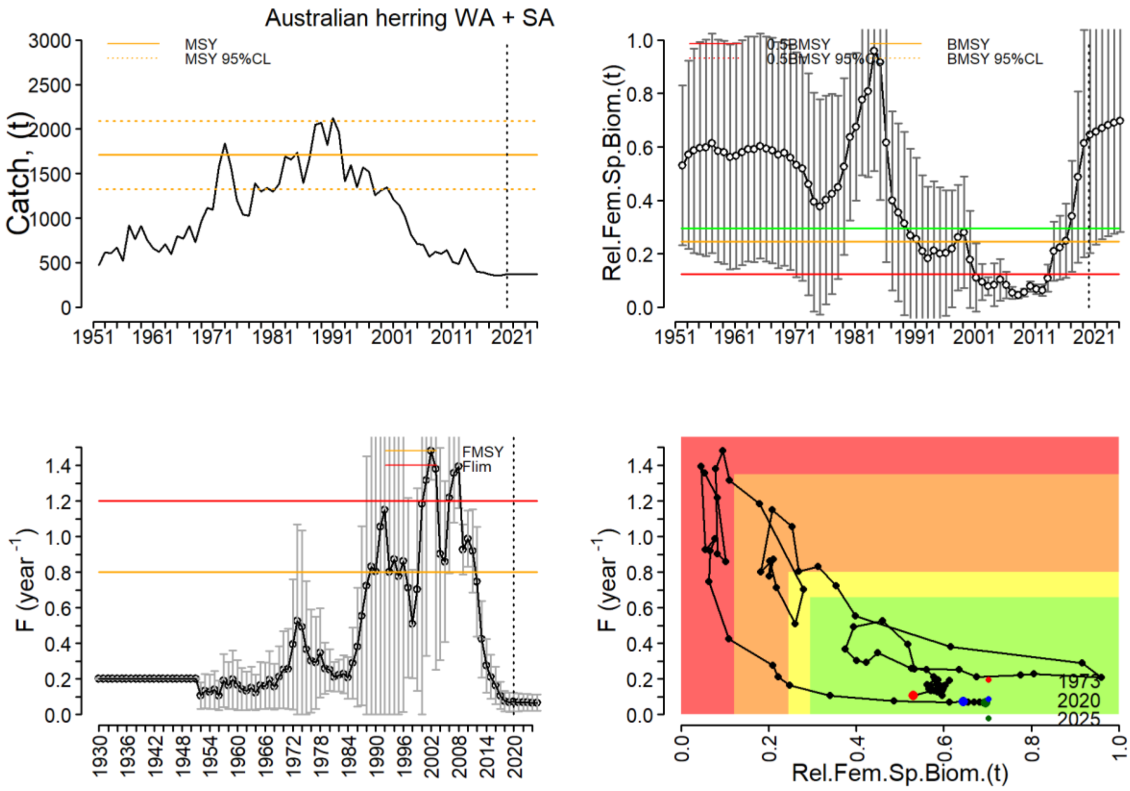

Figure 14.32. ***Top left*, Annual catches of herring (Western Australia and South Australia) vs estimated maximum sustainable yield, MSY (± 95% CLs); *top right*, estimates of relative female spawning biomass and associated values at BMSY (threshold) and 0.5MSY (limit); *bottom left*, estimates of fishing mortality, *F* (year^{-1}) vs FMSY; *bottom right*, phase plot, showing progression of female spawning biomass and fishing mortality. Results for model fitted to commercial data from the south coast of Western Australia, with *M* set to 0.6 y^{-1}.**

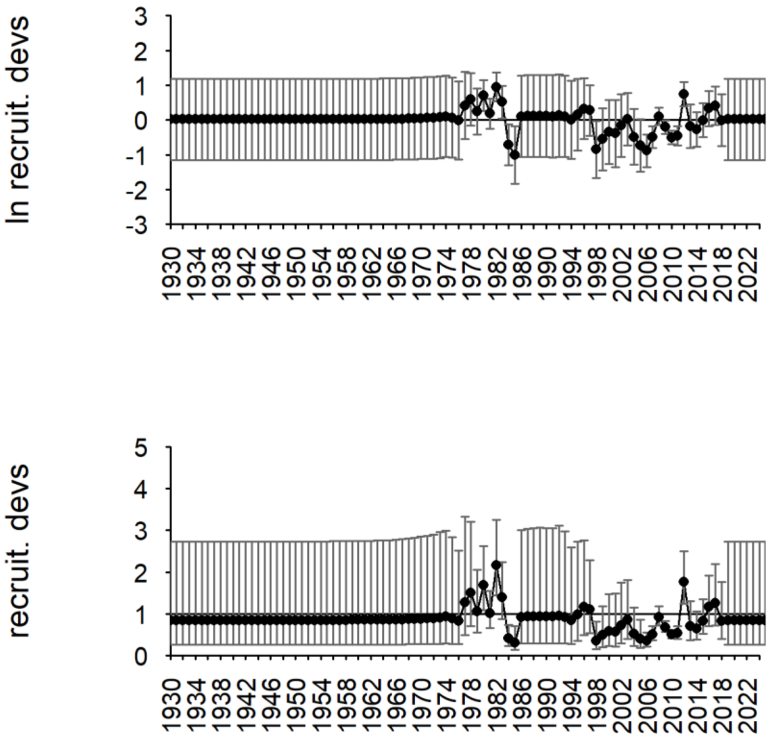

Figure 14.33. Estimated recruitment deviations in log space (*top*) normal space (*bottom*). Results for model fitted to commercial data from the south coast of Western Australia, with *M* set to 0.6 y^{-1}.

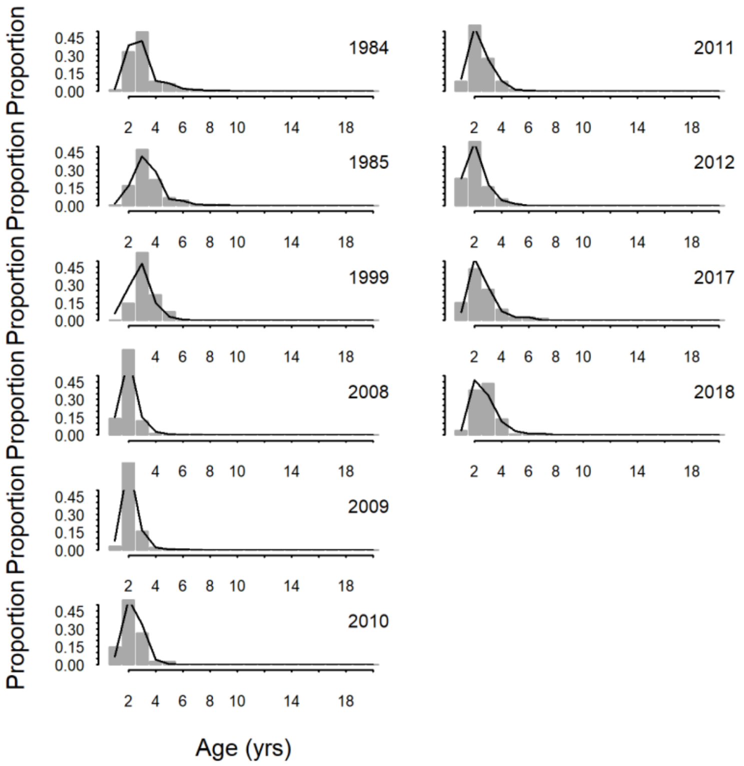

Figure 14.34. Observed (grey bars) vs expected (black lines) age compositions for herring. Results for model fitted to commercial data from the south coast of Western Australia, with *M* set to 0.6 y^{-1}.

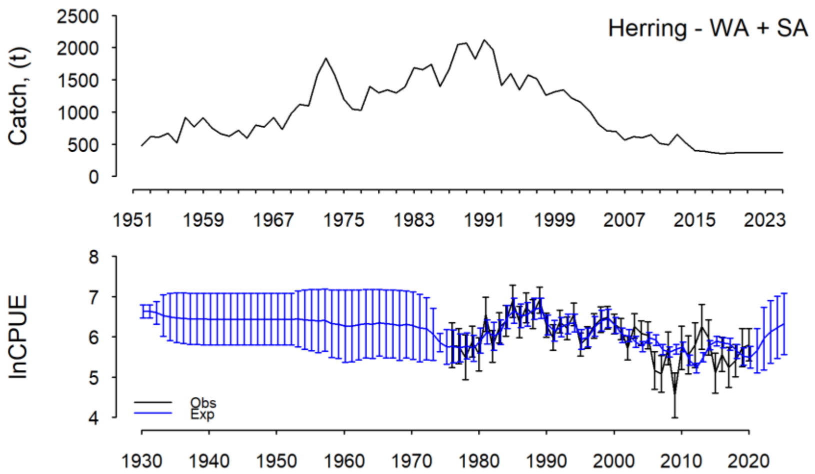

Figure 14.35 Annual catches and observed and expected catch per unit effort (CPUE). The observed CPUE data are those from the commercial (Geographe Bay) fishery on the west coast.

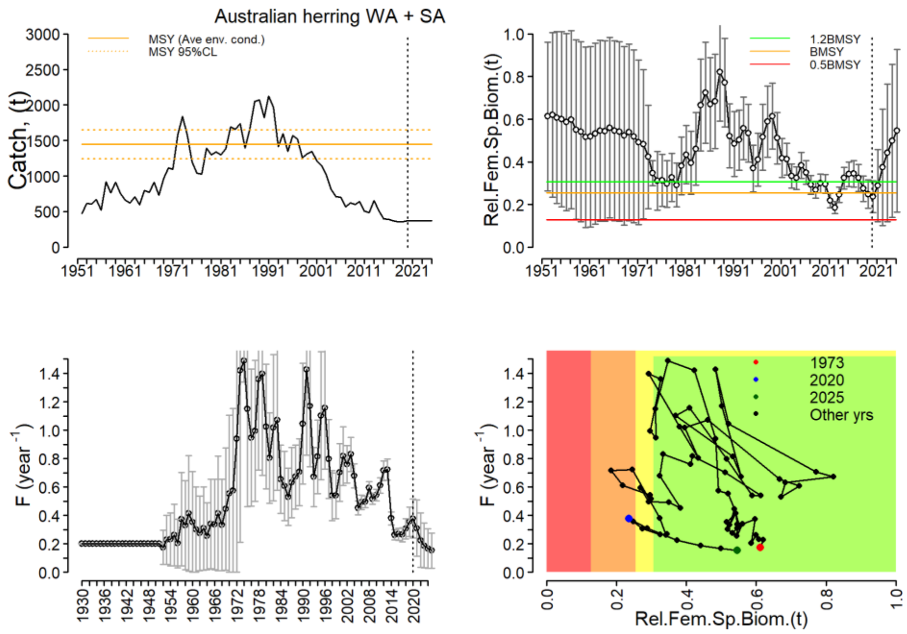

Figure 14.36 ***Top left*****, Annual catches of herring (Western Australia and South Australia) vs estimated maximum sustainable yield, MSY (± 95% CLs);** ***top right*****, estimates of relative female spawning biomass and associated values at BMSY (threshold) and 0.5MSY (limit);** ***bottom left*****, estimates of fishing mortality, F (year-1) vs FMSY;** ***bottom right*****, phase plot, showing progression of female spawning biomass and fishing mortality. Results for model fitted to commercial catch and CPUE data from the west coast of Western Australia, with M set to 0.6 y-1.**

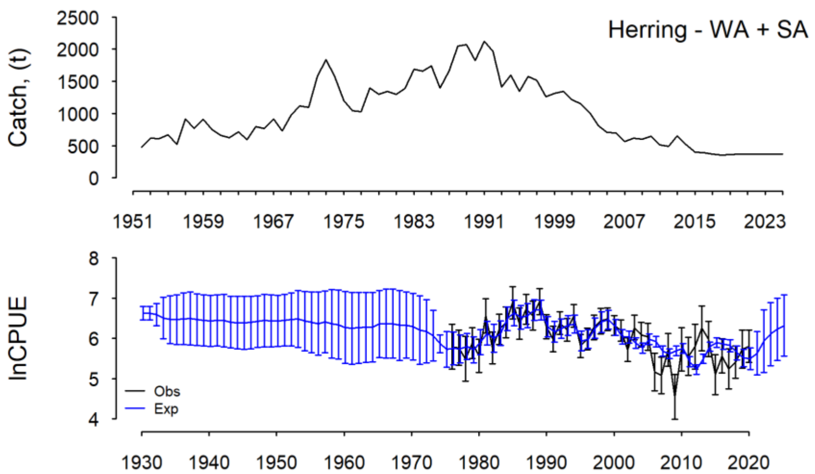

Figure 14.37 Annual catches and observed and expected catch per unit effort (CPUE). The observed CPUE data are those from the commercial (Geographe Bay) fishery on the west coast. Recruitment has been linked to an environmental index (Fremantle, detrended mean sea level anomaly data), to assess whether there is evidence of an environmental effect on recruitment.

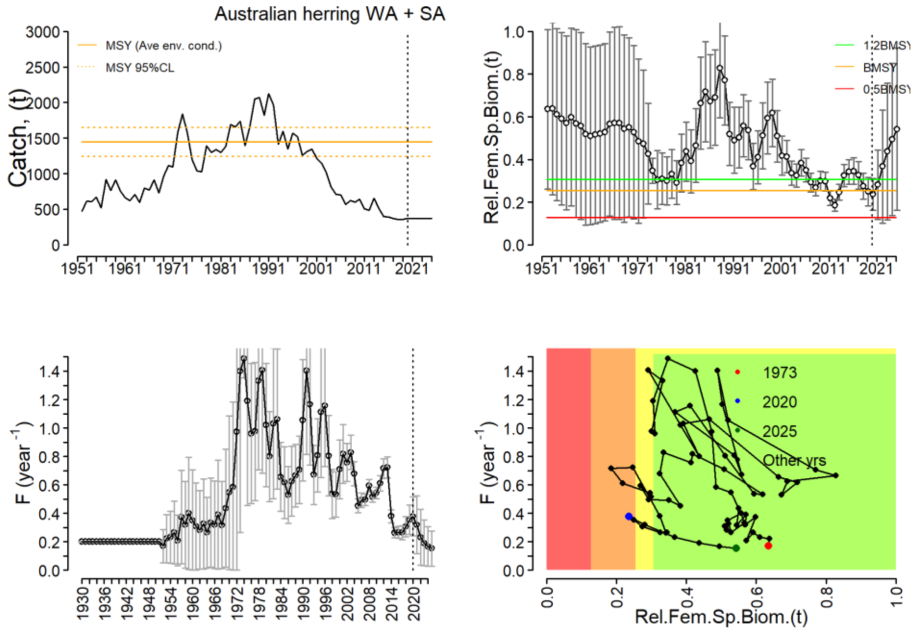

Figure 14.38 *Top left*, Annual catches of herring (Western Australia and South Australia) vs estimated maximum sustainable yield, MSY (± 95% CLs); *top right*, estimates of relative female spawning biomass and associated values at BMSY (threshold) and 0.5MSY (limit); *bottom left*, estimates of fishing mortality, F (year-1) vs FMSY; *bottom right*, phase plot, showing progression of female spawning biomass and fishing mortality. Results for model fitted to commercial catch and CPUE data from the west coast of Western Australia, with M set to 0.6 y-1. Recruitment has been linked to an environmental index (Fremantle, detrended mean sea level anomaly data), to assess whether there is evidence of an environmental effect on recruitment.

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