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Status of inshore demersal scalefish stocks on the south coast of Western Australia

NRM Project 12034 Final Report

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Executive Summary

Inshore demersal scalefish in waters of 20-250 m depth in the South Coast Bioregion (SCB) are an important resource targeted by commercial, recreational and charter fishing sectors. The SCB, from east of Cape Leeuwin to the South Australian border (115°30' to 129°00 E) is the last remaining region in WA where commercial open access line and net fishing activities may occur, i.e., no specific legislative management arrangements (Notice or Management Plan) have been developed for that activity/method, so that any person holding a Commercial Fishing License and an unrestricted Fishing Boat Licence can fish. Knowledge of the status of these fish stocks will inform a current review of this fishery, with the purpose of developing new and formal access and management arrangements.

This stock assessment of South Coast Bioregion demersal scalefish stocks will inform a current review of management arrangements in the "open access" commercial wetline sector.

Because many inshore demersal scalefish species are caught, indicator species that dominate the catch have been chosen to represent the status of the entire inshore demersal ecological suite in the SCB: snapper (*Chrysophrys auratus*), Bight redfish (*Centroberyx gerrardi*), blue morwong (*Nemadactylus valenciennesi*) and western blue groper (*Achoerodus gouldii*). This report presents the first higher level stock assessment of these indicator species.

The status of the four inshore demersal indicator species was assessed: snapper, Bight redfish, blue morwong and western blue groper.

All available lines of evidence were used to conduct a risk based, weight of evidence assessment. This included gathering representative samples of the catch of the commercial wetline and gillnets sectors in 2013 and 2014 by collecting fish frames (filleted skeletons with head and usually guts intact) from recreational and commercial fishers and commercial processors. Recreational samples were collected through the Department of Fisheries (DoF) *Send Us Your Skeletons* citizen science program, and the catch of a charter operator was also sampled. Fish ages were determined for 2,683 snapper, 5,672 Bight redfish, 2,621 blue morwong and 682 western blue groper by counting the annual growth rings deposited in the fish's otoliths (ear stones). The age composition of catches was analysed using up to eight different catch curve models that integrated a wide range of information on each species' biology (e.g., growth, size and age at maturity) and fishery operations (e.g., gear selectivity). The best model was chosen for each species based on a range of criteria including biology, fishery practices, goodness of fit to raw data and the validity of the model's underlying statistical assumptions. Estimates of fishing mortality and spawning potential ratio (i.e. the ratio of spawning biomass at the current level of fishing relative to the unfished state) from the best model were compared to internationally recognised reference points for fisheries management to assess the risk to sustainability for each of the four species.

Stock assessments were underpinned by age estimates for 11,613 fish from counts of annual growth rings on their otoliths. This age data was analysed by up to eight statistical models that also incorporated information on biology and fishery practices.

Other lines of evidence were also investigated: biology and inherent vulnerability, temporal changes in catches, catch rates, length distributions and the geographic distribution of the catch. All lines of evidence were used to determine the risk profile of each of the four species, i.e. the combinations of consequence (depletion level) and likelihood. Evidence from the age based assessments was given greatest weight.

Each species' risk profile was compared to the ISO 31000 based, risk assessment matrix used by DoF to determine the overall current risk status of the stocks, and the resultant scientific advice for fisheries management and monitoring and reporting requirements.

Overall, the status (risk to sustainability) of each indicator species was classified as:

- Bight redfish – Medium Risk (acceptable); while it is possible there was some localised depletion, the extent was considered acceptable at the whole of stock level
- Snapper – Medium Risk (acceptable); unlikely to be unacceptably depleted at stock level
- Blue morwong – Medium Risk (acceptable); unlikely to be unacceptably depleted at stock level
- Western blue groper – Low Risk (acceptable); unlikely to be unacceptably depleted at stock level

After considering all lines of evidence, all species/stocks were considered to be at an acceptable level of depletion and with acceptable risk profiles.

The risk levels for all species are acceptable and stock levels of all four species were unlikely to have been, or to be depleted to unacceptable levels in the next five years. Snapper and Bight redfish were assessed as fully exploited and any significant increase to their total catch beyond recent historical levels would increase the risk for those stocks to unacceptable levels. There is slightly higher capacity for increased total catches of blue morwong and western blue groper before risk levels become unacceptable. Being the first assessments for these stocks by the Dept. of Fisheries, they form a baseline for comparison with future assessments to determine stock trajectories.

Catch levels for snapper and Bight redfish should not be increased beyond recent historical levels. For blue morwong and western blue groper, only modest catch increases can be sustained.

For future monitoring, the current status suggests an updated assessment be completed within approximately five years. For snapper and bight redfish this requires a representative age sample from the commercial wetline catch in the west sub-region only, in 2018 and/or 2019. For blue morwong and western blue groper, a single year's age sample could be collected around the same time from the commercial gillnet catch in the east sub-region, or alternatively their status could be inferred from the other two indicator species and a Level 1 (catch based) assessment. An updated assessment could then be provided in 2020/21.

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1 Introduction

1.1 Background

Demersal scalefish species (excludes sharks and rays) on the south coast of Western Australia (WA) are important marine resources and support a range of recreational and commercial (State and Commonwealth) fisheries. The Western Australian Department of Fisheries (DoF) defines the South Coast Demersal Scalefish Resource (SCDSR) as all demersal scalefish species inhabiting oceanic waters of 20 m depth and greater between 115° 30’ E (~40 km east of Cape Leeuwin) and the South Australian border at 129° 00’ E.

While many species make up the SCDSR, recreational and commercial catches in oceanic waters off the south coast are dominated by only a few species. The species chosen as indicators for the inshore demersal ecological suite, i.e., demersal species taken predominantly in depths from 20 to 250 meters, were snapper (*Chrysophrys auratus*), Bight redfish (*Centroberyx gerrardi*) blue morwong (*Nemadactylus valenciennesi*) and western blue groper (*Achoerodus gouldii*) (see 1.3 Resource Assessment Framework). Prior to the work reported here the SCDSR had been assessed by DoF as medium-high risk, due to limited knowledge of the stock structure and biology of the main indicator species (see below).

These oceanic waters on the south coast are the last in WA where some open access commercial fishing activities occur, i.e., fishing activities where no specific legislative management arrangements (Notice or Management Plan) have been developed for that method/area whereby any person that holds a Commercial Fishing License and an unrestricted Fishing Boat Licence can fish in the area but only using those methods. The total annual open access catch taken by line-fishing methods ranged from 100-168 tonnes between 2000 and 2014 (Norriss and Walters 2015). More than 70% of this was comprised of four species: Bight redfish, snapper, hapuku and Samson fish. Blue morwong and western blue groper are taken mainly by the fully managed Joint Authority Southern Demersal Gillnet and Demersal Longline Managed Fishery (JASDGDLMF), which predominantly targets sharks but also retain scalefish as a legitimate part of their catch.

1.2 Need

To date, the SCDSR has received minimal attention from DoF, as resources have been focused on the larger demersal scalefish fisheries in the West Coast, Gascoyne Coast and North Coast Bioregions. As those fisheries have been brought under more effective management, focus was shifted to assessing the status of the SCDSR.

In September 2015 DoF published a discussion paper on the review of ‘open access’ commercial line, trap, net and squid fisheries on the South Coast, with the purpose of developing formal management arrangements for these fisheries (Department of Fisheries 2015a). The marine resources on the south coast have also received recent attention with regard to the Commonwealth Marine Bioregional Planning Process (CMBPP).

The purpose of the research reported here was to assess the stock status of the demersal scalefish indicator species (snapper, Bight redfish, blue morwong and western blue groper) and develop a future monitoring and assessment framework for the SCDSR. The assessment will also inform the review of the South Coast open access fisheries, management arrangements for the JASDGDLMF, and assist in understanding the potential impacts of the CMBPP in the south coast.

1.3 Resource Assessment Framework for Finfish Resources

WA's fish and aquatics resources are managed by the DoF at a bioregional level using an Ecosystem Based Fisheries Management approach (Fletcher *et al.* 2010). A key component of this integrated approach is the Resource Assessment Framework for Finfish Resources, which divides the state into four coastal bioregions and classifies finfish species into five ecological suites within each of these bioregions (Department of Fisheries 2011).

Given the large number of finfish species captured along approximately 12,800 km of coastline, several of the fished species have been designated as indicators of sustainability for the entire suite within each bioregion. The inshore demersal suite includes bottom dwelling species for which the largest share of the catch was taken between depths of 20 and 250 m. The SCB stretches from 115°30' (just east of Cape Leeuwin) to 129°00' (South Australian border), and 200 nautical miles out to the edge of the Exclusive Economic Zone (Figure 1.1).

This report describes the stock status of the four indicator species for the inshore demersal suite in the SCB: snapper (*Chrysophrys auratus*), Bight redfish (*Centroberyx gerrardi*), blue morwong (*Nemadactylus valenciennesi*) and western blue groper (*Achoerodus gouldii*).

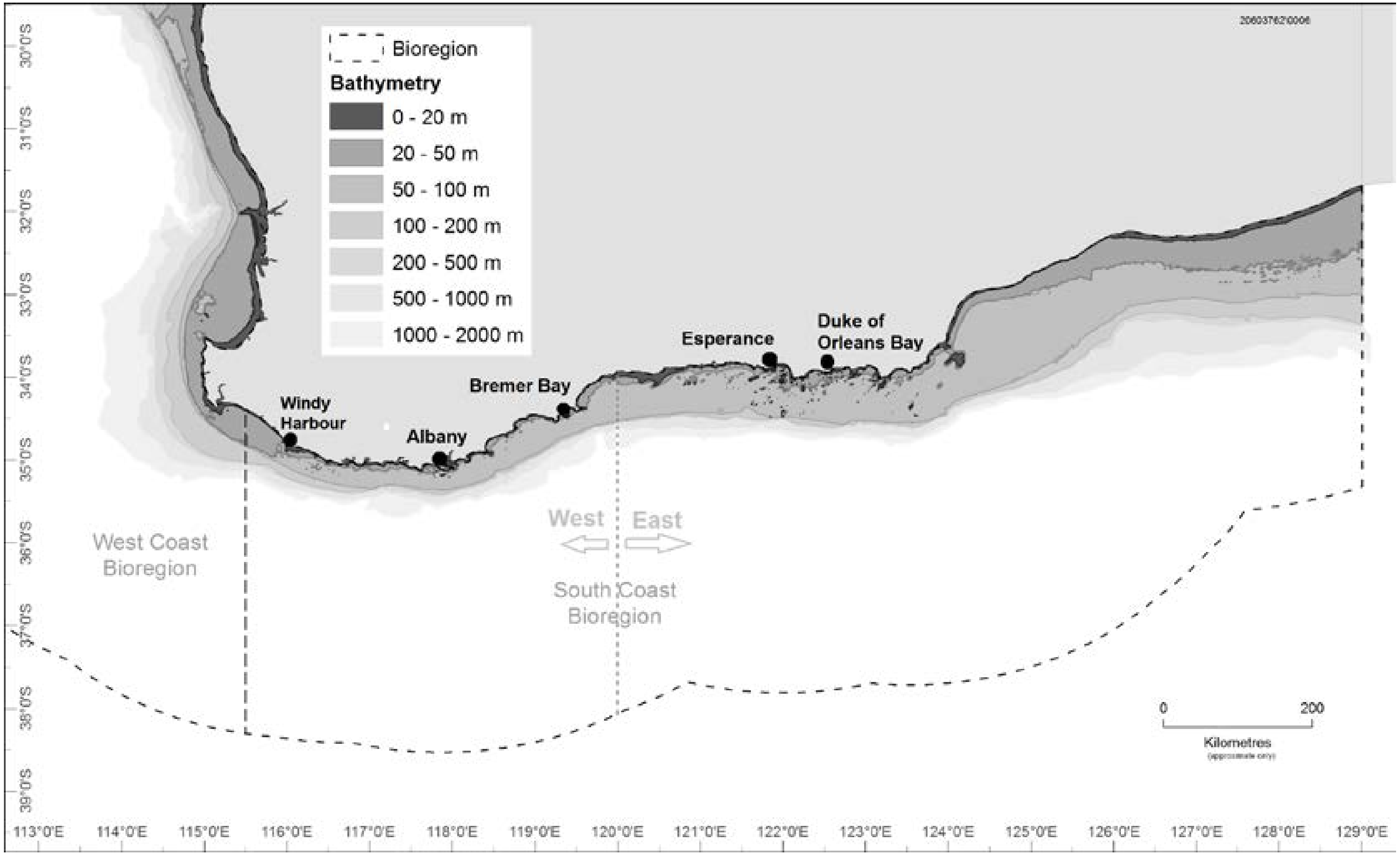


Figure 1.1 The SCB ranges from 115°30' to the South Australian border at 129°, and out 200 nautical miles to the edge of the Exclusive Economic Zone. For fishery stock assessment purposes in this report, it has been split into two sub-regions west and east of 120° E. Note the wider continental shelf in the east sub-region.

1.4 Risk based assessment using weight of evidence

To assess stock status, all available lines of evidence were examined to determine the risk profile of each of the four inshore demersal species (Wise *et al.*, 2007; Department of Fisheries 2015a, Fletcher 2015; Wise *et al.*, in prep). Such evidence includes information on biology and inherent vulnerability, catch and catch rate trends, geographic distribution of the catch, age and length distribution information, and model estimates of fishing mortality and spawning potential ratio.

This updated WoE approach has been developed by Wise et al., (in prep) based on Fletcher (2015) such that each of the lines of evidence are both individually and collectively assessed. This clearly identifies how consistent they are in describing the current status of the stock. The collective assessment is made by appropriately weighting each of these lines of evidence to determine the overall likelihood of a range of possible depletion (consequence) levels, from minimal to catastrophic for each stock (Appendix 1).

This flexible approach to risk-based stock assessment complies with International Standards (ISO 31000, 2009) and can include lines of evidence from quantitative methods and qualitative sources. Thus, while the various age-based assessments were generally considered the strongest lines of evidence because they integrate biological and fishery data, by also having each of these inputs individually assessed provided greater transparency and robustness to the assessments (Fletcher 2015; Bellchambers *et al.*, in press).

1.5 Objectives

This research project, funded by the State Natural Resource Management Office of Western Australia (SNRMO), was conducted between November 2012 and December 2015. The principle objective was to assess the status of inshore demersal scalefish stocks in the SCB. Collaboration with key commercial and recreational stakeholders and the broader south coast community was essential if this objective was to be achieved. This report presents the first risk-based, 'weight-of-evidence' assessments of the four inshore demersal indicator species for the SCB – snapper, Bight redfish, blue morwong and western blue groper.

Specific objectives were:

1. Collect representative biological samples of the four inshore demersal indicator species from catches taken by recreational and commercial sectors over a two consecutive year period.
2. Determine stock status of these species using a risk-based 'weight-of-evidence' approach.
3. Provide a succinct report on stock status of south coast inshore demersal species that will inform fisheries managers, stakeholder groups and the broader south coast community (herein). A more comprehensive analysis is available in the DoF's Resource Assessment Report (RAR) for the SCDSR, a living document that is updated as new information, data and analyses emerge.

4. Make recommendations for future monitoring and assessment of south coast inshore demersal species.

5. Engage and consult with south coast community and stakeholder groups throughout the project.

An additional objective was to investigate stock structure of Bight redfish using otolith chemistry and genetic techniques. This work was undertaken and completed, and while not reported here, has been integrated into the stock assessment and recommendations. A scientific paper is in preparation for submission to an international journal (Bertram *et al.* in prep).

1.6 Overview of fisheries taking inshore demersal scalefish in the South Coast Bioregion

A consequence of the low productivity of WA's marine eco-systems is the low scalefish catch levels that can be sustained compared to other Australian regions and internationally (Molony *et al.* 2011). Primary productivity is particularly low along the south coast due to a general absence of nutrient rich upwellings, few wetlands and coastal embayments, and limited terrestrial runoff from infertile landscapes. This helps explain why the overall catch of inshore demersal species has been much lower in the SCB compared to the other three coastal bioregions in WA (Fletcher and Santoro 2014). Thus, only low sustainable catches should be expected from this relatively small, unproductive resource.

The indicator species for inshore demersal stocks in the SCB are exploited by several fishery sectors. These include the commercial Joint Authority Southern Demersal Gillnet and Demersal Longline Managed Fishery (JASDGDLMF) and the "open access" wetline fishery, as well as charter and recreational sectors, all managed by the DoF. The federally managed Great Australia Bight Trawl Sector (GABTS) also takes a significant catch of Bight redfish from the SCB.

The JASDGDLMF is a limited entry fishery using predominantly demersal gillnets to target sharks, with scalefish also being a legitimate component of the catch (Simpfendorfer and Donohue 1998, Braccini *et al.* 2014). It is managed via input controls in the form of transferable time/gear effort units, with additional restrictions on mesh and hook sizes, net height and maximum net length. The JASDGDLMF was formally established in 1988 following rapidly increasing catches of sharks in the 1980s.

The commercial wetline sector in the SCB fishes primarily with droplines and handlines with multiple hooks, although minor quantities were taken by trapping and in nearshore waters by haul nets and set nets (Norriss and Walers 2015, Department of Fisheries 2015a). In general terms, the sector is not part of an officially managed fishery, has no dedicated management plan, and no separate authority is required to fish beyond holding a commercial fishing licence and a fishing boat license. This wetline sector has therefore been referred to as "open access", but a management plan review is underway (Department of Fisheries 2015a) with the aim of bringing this resource under formal management. The information presented in this stock status report will provide managers with advice on risks to sustainability and sustainable catch levels.

Bight redfish are an important component of the catch of the GABTS, part of a Commonwealth (Australian Fisheries Management Authority) managed fishery operating across southern Australia as far west as Cape Leeuwin (Moore and Curtotti 2014). Off the WA coast (i.e. west of 129º E) it operates outside State fishery shelf waters (in waters deeper than 200 metres), except for east of 125º E (approximately 250 km east of Esperance) where shelf waters are also able to be fished. In the 2013-14 fishing season, 196 t of Bight redfish were taken by the GABTS, mostly from waters off South Australia.

Fishing tour operators (charter fishing) in WA must be licensed by the DoF and since 2006 have been required to lodge daily trip return sheets with information on location, fishing effort and catch composition. Since 2006, six to eleven operators have reported taking the four inshore demersal indicator species in the SCB each year.

Almost all of the SCB recreational catch of inshore demersal species is by boat. A Recreational Fishing from Boat Licence is required to recreationally fish from a boat in WA. The sector is also managed using bag and size limits (Table 2.3).

Table 2.3 History of minimum legal lengths and recreational bag limits per person in the South Coast Bioregion since the implementation of the *Fish Resources Management Act 1994.* MLL = minimum legal length, na = not applicable.

Species	Date	MLL, mm	Bag limit	Mixed species bag limit
Snapper 	01-Oct-95	410	8	8[1]
	01-Jan-06	410	4	8[2]
	01-Feb-13	410	3	5[3]
Bight redfish 	01-Oct-95	230	20	na
	01-Jan-06	300	8	16[4]
	01-Feb-13	300	8	na
Blue morwong 	01-Oct-95	410	8	8[5]
	01-Jan-06	410	4	8[6]
	01-Feb-13	410	3	5[7]
Western blue groper 	01-Oct-95	400	1	na
	01-Oct-03	500	1	na
	01-Jan-06	500	1	7[8]
	01-Feb-13	500	1	5[9]

1: included blue morwong.

2: included “high risk species” such as blue morwong, mulloway, Samson fish, most cods (family Serranidae) and western blue groper, but ***not*** Bight redfish.

3: incudes demersal species such as dhufish, western blue groper, blue morwong and hapuka, but ***not*** Bight redfish.

4: included tailor, King George whiting, silver trevally, salmon, leatherjackets, banded and sea sweep, flathead and swallowtail, but ***not*** snapper, blue morwong or western blue groper.

5: included snapper.

6: included “high risk species” such as snapper, mulloway, Samson fish, most cods (family Serranidae) and western blue groper, but ***not*** Bight redfish.

7: incudes demersal species such as dhufish, western blue groper, snapper and hapuka, but ***not*** Bight redfish.

8: included snapper, blue morwong, mulloway and Samson fish, but ***not*** Bight redfish.

9: incudes demersal species such as blue morwong, dhufish, snapper and hapuka, but ***not*** Bight redfish.

2 Stock status based on a risk-based weight of evidence

Below is the stock status advice and risk to sustainability for snapper, Bight redfish, blue morwong and western blue groper from the SCB. The Level 3 (catch, fishing effort and age based) assessments summarised here were the first higher level assessments undertaken for these species/stocks in the SCB from samples collected in 2013 and 2014. As these are the first higher level stock assessments for these species/stocks, they form a baseline for comparison with future assessments.

2.1 Snapper – Lines of evidence

Category	Lines of evidence (Consequence/Status)
Catch	Around 57% of the current total catch of snapper in the SCB is taken by the commercial wetline sector, 25% by the commercial gillnet fishery, 3% by the estuarine net fishery, and 15% by the recreational and charter sector. Wetline catches were low from 1975 to 1995 before increasing to 30-50 t between 2000 and 2011. Catches have declined since then but remained within the historical range. Historical recreational catches prior to the recent estimates for boat based catches were unknown but are likely to have been restricted to similar or lower levels by the oceanic conditions and remoteness of this region. **There was no indication within the catch data of unacceptable stock depletion**.
Catch distribution	Most of the commercial wetline, recreational and charter catches were taken in the western sub-region. The spatial distribution of commercial wetline catches (noting the coarseness of these data due to 60’ x 60’ reporting blocks) has expanded slightly over the past 25 years but has been stable over the last decade. **There was no indication that catch levels have been maintained by a progressive shifting of the areas fished that would be indicative of unacceptable stock depletion**.
Catch rates	The coarseness and multi-species nature of the commercial data makes it uncertain how accurately and responsively the catch rates represent an index of abundance for this species. Standardised catch rates for both gillnet and wetline sectors have, however, remained stable since mid-1990s. **There were no indications from catch rates of unacceptable stock depletion during this period**.

Vulnerability (Productivity Susceptibility Analysis [PSA])	Snapper are long-lived (maximum recorded age 41 years). Individuals typically mature on the south coast at around 543 mm (TL) and 4.6 years of age and are selected by line fishing (the dominant fishing method for commercial and recreational sectors) at around 410-450 mm. With a productivity score of 1.86 and susceptibility score of 2.33, the derived PSA score was 2.98 (60<MSC SGA score<80). **This level of vulnerability would indicate that unacceptable stock depletion would be possible if there was no management of the relevant fisheries across the region. However, as there is formal management of one sector, partial management of the other sectors and processes already in place to complete these arrangements, the calculated likelihood is not accurate.**
Length and/or age composition	Length composition of the commercial gillnet catch in 2013 and 2014 was slightly larger compared to observer data from 1994 to 1999 when a similar gillnet mesh size was used. This result was not consistent with unacceptable stock depletion having occurred over this period. The age composition considered the most representative for this stock (commercial wetline samples - western sub-region) had individuals of more than 20 years or age, which was also not consistent with unacceptable stock depletion having occurred. Furthermore, the distribution of the ages in these samples in general suggests there have been regular and consistent levels of annual recruitment into this stock over the last two decades. There were indications of strong year classes in 1996 and 1998. **Length and age composition data provide evidence that an unacceptable stock depletion has not occurred over the last two decades, and the consistency of recruitment suggests robust spawning stock levels are being maintained.**
Fishing mortality (F)	Based on the age composition data considered the most representative of the snapper stock (commercial wetline, western sub-region), estimates of total mortality (Z) were 0.23-0.24. The associated estimates of fishing mortality (F) varied depending upon whether the estimate of natural mortality (M) was derived using Hoenig (1983) or the recently developed method of Then et al. (2015). Using simulated values of M uniformly distributed between the Hoenig and Then estimates, there was only a 25% chance of F estimates breaching the threshold while the limit level was never breached. **This indicates that an unacceptable level of stock depletion is unlikely to occur if historic levels of fishing are maintained.**

Index of spawning stock biomass (Spawning Potential Ratio [SPR])	Estimates of female SPR based on the most representative age sample and *F* estimates derived using values of *M* uniformly distributed between the Hoenig and Then estimates indicate a 21-43% chance of the breaching the threshold and a 0-9% chance of falling below the limit level. **This indicates that unacceptable stock depletion is unlikely if historic levels of fishing are maintained.**

All of the lines of evidence outlined above were combined within the Department's ISO 31000 based risk assessment framework (Fletcher 2005; Department of Fisheries 2015b; Fletcher 2015; Appendix 1) to determine the most appropriate combinations of consequence and likelihood to determine the overall current risk status to the sustainability of the stock.

Snapper risk matrix

Consequence (stock depletion) Level	Likelihood					Risk Score
	L1 Remote (<5%)	L2 Unlikely (5-30%)	L3 Possible (30-50%)	L4 Likely (50-90%)	L5 Certain (90-100%)	
C1 Minimal		X				2
C2 Moderate				X		8
C3 High		X				6
C4 Major	X					4
C5 Catastrophic						na

C1 (Minimal Depletion – above target): **L2** – Based on the catch history, catch distribution time series, current age structure and fishing mortality estimates, there is an Unlikely likelihood (L2) that the current level of stock depletion is above the target level. Only the length composition line of evidence was consistent with minimal depletion.

C2 (Maximum Acceptable Depletion - above threshold): **L4** – The catch distribution time series, age structure, F and SPR lines of evidence are consistent with a Likely (L4) likelihood that the snapper stock is now between the threshold and target levels and therefore at an acceptable level. The lines of evidence also suggest that if the current total levels of annual capture are maintained, the stock level is likely to remain within this band during the next five years. However the level of fishing as measured by F and SPR suggest this is currently close to the maximum level to maintain the stock within this acceptable range.

C3 (Unacceptable Depletion – below threshold): **L2** – The catch, catch rates, catch distribution, current age structure, F and SPR lines of evidence were all consistent with an Unlikely (L2) likelihood that at the current (historic) levels of fishing that stock depletion has or will breach the threshold level to become unacceptably High within the next five years. While the range of SPRs did suggest a 21-43 % chance of breaching the threshold, all the other lines of evidence suggested this was unlikely, hence the lower end of this range was considered more appropriate.

C4 (Unacceptable - below limit): **L1** – While the SPR analysis suggests a Remote (L1) likelihood that the stock has breached the limit level (C4), or will do so within 5 years, there were no other lines of evidence consistent with this scenario, including that recruitment levels have not been affected at any point over the past 20 years.

C5 (Catastrophic) – Not plausible under current circumstances.

2.2 Snapper - Current Risk Status of the Stock

The maximum risk score for snapper is 8, based on a combination of C2 and L4. **This constitutes a Medium Risk, the maximum acceptable risk level** (see Appendix 1).

This score assumes the total catch will be maintained at near current levels which could require the development and implementation of a suitable set of management arrangements for all sectors to ensure this is maintained. Stock status will also need to be monitored at regular intervals into the future.

It should also be noted that the information in the lines of evidence for F and SPR presented in the above analyses indicate that a significant increase in annual catch levels would increase the likelihood of the stock declining below the threshold level.

2.3 Bight redfish – Lines of evidence

Category	**Lines of evidence (Consequence/Status)**
Catch	Around 60% of the current total catch of Bight redfish in the SCB was taken by the commercial wetline sector, compared with around 30% by the recreational and charter sector and around 10% by the commercial gillnet fishery. Following a period of low catches from 1975-1980, the wetline catch steadily increased to around 30 t by 1987 and then ranged between 10-40 t over the next three decades. Although commercial catches in 2013 and 2014 were the lowest since 2000, they remained within the historical range. Historical recreational catches were unknown but were likely to have been restricted by the oceanic conditions and remoteness of this region. **There was no indication within the catch data of unacceptable stock depletion**.
Catch distribution	Most of the commercial wetline and recreational (and charter) catch was taken close to the major population centres, in particular around Albany. The spatial distribution of commercial wetline catches (noting the coarseness of these data due to 60’ x 60’ reporting blocks) has expanded only slightly over the past 25 years but has been stable for the last decade. **There was no indication that catch levels have been maintained by a progressive shifting of the areas fished that would be indicative of unacceptable stock depletion**.

Catch rates	The coarseness and multi-species nature of the commercial data makes it uncertain how accurately and responsively the catch rates represent an index of abundance for this species. Standardised catch rates for both gillnet and wetline sectors have, however, remained stable since the mid-1990s. **There were no indications from catch rates of unacceptable stock depletion during this period**.
Vulnerability (Productivity Susceptibility Analysis [PSA])	Bight redfish are long-lived (maximum recorded age 84 years). Individuals typically mature at around 430 mm (TL) and between 5-14 years of age. They become selected by line fishing (dominant fishing method for commercial and recreational sectors) at around 300-350 mm. With a productivity score of 1.86 and susceptibility score of 2.33, the derived PSA score was 2.98 (60<MSC SGA score<80). **This level of vulnerability would indicate that unacceptable stock depletion would be possible if there was no management of the relevant fisheries across the region**. **However, as there is formal management of one sector, partial management of the other sectors and processes already in place to complete these arrangements, the calculated likelihood is not accurate.**
Length and/or age composition	The age composition varied among samples collected from the various sectors and sub-regions in 2013 and 2014. The commercial wetline sample (western sub-region), considered the most representative of the entire stock, contained individuals of more than 40 years of age, which is not consistent with unacceptable stock depletion having occurred. Age samples from the recreational and charter catches in the eastern sub-region suggest either localised depletion may be occurring within the restricted inshore areas where they operate or this pattern may be explained by ontogenetic movements (young [smaller] individuals located inshore moving offshore as they age). Furthermore, the distribution of the ages in these samples also suggests there have been regular and consistent levels of annual recruitment into this stock over the last two decades. **Length and age composition data provide further evidence that an unacceptable stock depletion has not occurred over the last two decades, and the consistency of recruitment suggests robust spawning stock levels are being maintained.**

Fishing mortality (*F*)	Based on the age composition samples considered the most representative of the stock, estimates of total mortality (*Z*) were 0.10-0.11. The associated estimates of fishing mortality (*F*) varied depending upon whether the estimate of natural mortality (*M*) was derived using the method of Hoenig (1983) or the recently developed Then et al. (2015) method. Using simulated values of *M* uniformly distributed between the Hoenig and Then estimates, there was only a 20% chance of *F* estimates breaching the threshold while the limit level was never breached. **This indicates that an unacceptable level of stock depletion is unlikely to occur if historic levels of fishing are maintained.**
Index of spawning stock biomass (Spawning Potential Ratio [SPR])	Estimates of female SPR (i.e. the ratio of spawning biomass at the current level of fishing relative to the unfished state) based on the most representative age sample and *F* estimates derived using values of *M* uniformly distributed between the Hoenig and Then estimates indicated a 7-25% chance of breaching the threshold and <1% chance of falling below the limit level. **This indicates that unacceptable stock depletion is unlikely if historic levels of fishing are maintained.**

All of the lines of evidence outlined above were combined within the Department's ISO 31000 based risk assessment framework (Department of Fisheries 2015b; Fletcher 2015; Appendix 1) to determine the most appropriate combinations of consequence and likelihood to determine the overall current risk status of the stock.

Bight redfish risk matrix

Consequence (stock depletion) Level	Likelihood					**Risk Score**
	L1 Remote (<5%)	L2 Unlikely (5-30%)	L3 Possible (30-50%)	L4 Likely (50-90%)	L5 Certain (90-100%)	
C1 Minimal		X				2
C2 Moderate				X		8
C3 High		X				6
C4 Major	X					4
C5 Catastrophic						na

C1 (Minimal Depletion – above target): **L2** – Based on the catch history, current age structure and fishing mortality estimates, it is Unlikely (L2) that the level of current stock depletion is above the target level. This option was only supported by the distribution of catches still being relatively concentrated closer to main fishing ports rather than covering the entire stock.

C2 (Maximum Acceptable Depletion - above threshold): **L4** – All of the lines of evidence were consistent with a Likely (L4) likelihood that the Bight redfish stock is now between the threshold and target levels and therefore at an acceptable level. Based on the age structure, F and SPR lines of evidence, these were all consistent with the level of depletion currently being somewhere near the threshold level, and that if the current total catch levels are maintained the stock level is likely to remain within this band during the next five years. This is not inconsistent with the other lines of evidence.

C3 (Unacceptable Depletion – below threshold): **L2** – The catch, catch rates and catch distribution, current age structure, F and SPR lines of evidence were all consistent with an Unlikely (L2) likelihood that at the current (historic) levels of fishing that stock depletion has or will breach the threshold the level within the next five years.

C4 (Unacceptable - below limit): **L1** – Given there was no evidence that recruitment levels have been affected at any point over the past 40 years it is not plausible that the stock has breached the limit and experienced a Major depletion (C4). There remains a Remote (L1) likelihood of this occurring within 5 years based on the potential for unknown factors.

C5 (Catastrophic) – Not plausible under current circumstances.

2.4 Bight redfish – Current Risk Status of the Stock

The maximum risk score for Bight Redfish is 8 is generated by the combination of C2 and L4. **This constitutes a Medium Risk which is the maximum acceptable risk level** (See Appendix 1). This score assumes the total catch will be maintained at or near current levels which could require the development and implementation of a suitable set of management arrangements for all sectors to ensure this is maintained. Stock status will also need to be monitored at regular intervals into the future.

It should also be noted that the information in the lines of evidence for F and SPR presented in the above analyses indicate that a significant increase in annual catch levels would increase the likelihood of the stock declining to below the threshold level.

2.5 Blue morwong – Lines of evidence

Category	Lines of evidence (Consequence/Status)
Catch	Around 70% of the total catch of blue morwong in the SCB was taken by the commercial gillnet fishery, compared with 21% taken by the recreational and charter sector and 9% by the commercial wetline sector. Commercial gillnet catches, which were dominated by male fish due to the net mesh selecting for their larger size, increased steadily from 5-11 t in the mid-1970s to a peak of 64 t in 1990, then declined with reduced fishing effort to fluctuate between 20-56 t. Catches have been in decline since 2009 but remain within the historical range. Historical recreational catches prior to the recent estimates for boat based catches were unknown but are likely to have been restricted to similar or lower levels by the oceanic conditions and remoteness of this region. **There was no indication within the catch data of unacceptable stock depletion**.
Catch distribution	Catches of blue morwong by the dominant commercial gillnet sector have been widely distributed throughout the SCB over the past 25 years. **There was no indication that catch levels have been maintained by a progressive shifting of the areas fished that would be indicative of unacceptable stock depletion**.
Catch rates	While standardised catch rates for blue morwong were not calculated for the dominant gillnet sector, catches since 1991/92 have been maintained while effort has declined. **There were no indications from catch rates of unacceptable stock depletion during this period**.

Vulnerability (Productivity Susceptibility Analysis [PSA])	Blue morwong are moderately long-lived (maximum recorded age 24 years). Individuals typically mature on the south coast at around 520 mm (TL). Males grow substantially larger than females and, because of their larger size, are more susceptible to capture. With a productivity score of 1.71 and susceptibility score of 2.80, the derived PSA score was 3.28 (MSC SG score<60). **This level of vulnerability indicates that unacceptable stock depletion is likely if there was no management of the relevant fisheries across the region. However, as there is formal management of one sector, partial management of the other sectors and processes already in place to complete these arrangements, the calculated likelihood is not accurate.**
Length and/or age composition	Length composition of the commercial gillnet catch in 2013 and 2014 was similar to both observer data from 1994 to 1999 and catch sampling from 2004 to 2007, when a similar gillnet mesh size was used. This was not consistent with unacceptable stock depletion having occurred over this period. The age composition considered the most representative for this stock (commercial gillnet sector, eastern sub-region) still had individuals of more than 15 years or age, and a new longevity record was set. This was not consistent with unacceptable stock depletion having occurred. Furthermore, age distributions suggest there have been regular and consistent levels of annual recruitment into this stock over the last two decades. **Length and age composition evidence suggest that it is unlikely that an unacceptable stock depletion has occurred over the last two decades, and consistent recruitment suggests robust spawning stock levels are being maintained.**
Fishing mortality (*F*)	Males comprise 70% of the catch of the dominant gillnet sector by number of fish. Catch curve analyses showed that blue morwong do not become fully selected by gillnet and line fishing gears until they attain a relatively large size. Estimates of fishing mortality *F* for fully-selected females in the age sample considered the most representative never breached the threshold level, regardless of the assumed value(s) for natural mortality (*M*) (Hoenig, Then or between these *M* estimates). In contrast, the chance of the estimated *F* values for males breaching the threshold level was 97% when a Hoenig *M* was assumed, zero when a Then value of *M* was applied, but only 25% when using values of *M* uniformly distributed between the Hoenig and Then estimates. *F* estimates for males never breached the limit level. **This indicates that the likelihood of unacceptable stock depletion is remote for females and unlikely for males, and is unlikely to occur if historic levels of fishing are maintained.**

Index of spawning stock biomass (Spawning Potential Ratio [SPR])	Estimates of female SPR based on the most representative sample never breached the threshold level. For males, estimates based on applying values of *M* between the Hoenig and Then estimates indicated a 19-31% chance of breaching the threshold while the limit level was never breached. However, the high proportion of males in the catch of both the commercial gillnet and recreational sectors suggest recruitment was not constrained by sperm limitation. **The overall SPR for the stock suggests that the likelihood of unacceptable stock depletion is remote if recent (historic) total catch levels are maintained.**

All of the lines of evidence outlined above were combined within the Department's ISO 31000 based risk assessment framework (Department of Fisheries 2015b; Fletcher 2015; Appendix 1) to determine the most appropriate combinations of consequence and likelihood to determine the overall current risk status of the stock.

Blue morwong risk matrix

Consequence (stock depletion) Level	Likelihood					Risk Score
	L1 Remote (<5%)	L2 Unlikely (5-30%)	L3 Possible (30-50%)	L4 Likely (50-90%)	L5 Certain (90-100%)	
C1 Minimal			X			3
C2 Moderate				X		8
C3 High	X					3
C4 Major						na
C5 Catastrophic						na

C1 (Minimal Depletion – above target): **L3** – The catch history, catch distribution time series, current age and length composition, and fishing mortality and SPR estimates were consistent with a Possible (L3) likelihood that the current level of stock depletion is above the target level. Only the vulnerability (PSA) line of evidence suggests a higher level of depletion may have occurred.

C2 (Maximum Acceptable Depletion - above threshold): **L4** – All lines of evidence were consistent with a Likely (L4) likelihood that the blue morwong stock is now between the threshold and target levels and therefore at an acceptable level. The lines of evidence also suggest that if the current total levels of annual capture are maintained, the stock level is likely to remain within this band during the next five years. Fishing mortality is currently near the maximum acceptable level for males but at a lower level for females.

C3 (Unacceptable Depletion – below threshold): **L1** – Evidence from estimates of *F* and SPR and suggest only a Remote (L1) likelihood that stock depletion has or will breach the threshold within the next five years with current (historic) catch levels. With the exception of the vulnerability (PSA) analysis, which inaccurately assumes no appropriate fishery management, all other lines of evidence were inconsistent with a breach of the threshold level.

C4 (Unacceptable - below limit) – Not plausible under current circumstances.

C5 (Catastrophic) – Not plausible under current circumstances.

2.6 Blue morwong - Current Risk Status of the Stock

The maximum risk score for blue morwong is 8, based on a combination of C2 and L4. **This constitutes a Medium Risk, the maximum acceptable risk level** (See Appendix 1). Recent (historic) catches are at sustainable levels and management arrangements for all sectors should ensure that any increase remains modest. Larger increases of the total catch would increase the likelihood of the stock declining below threshold levels. The stock status should be monitored at regular intervals into the future.

2.7 Western blue groper – Lines of evidence

Category	Lines of evidence (Consequence/Status)
Catch	Almost all of catch (around 94%) of western blue groper was taken by the commercial gillnet fishery which had very low catches until 1990 but since then has increased and fluctuated between 20-50 t annually while fishing effort declined. **There was no indication within the catch data of unacceptable stock depletion**.
Catch distribution	Catches by the gillnet sector have been widely distributed throughout the SCB over the past 25 years. **There was no indication that catch levels have been maintained by a progressive shifting of the areas fished that would be indicative of unacceptable stock depletion**.
Catch rates	While standardised catch rates were not calculated, catches since 1991/92 have been maintained while effort has declined. **There were no indications from catch rates of unacceptable stock depletion during this period**.

Vulnerability (Productivity Susceptibility Analysis [PSA])	Western blue groper are long-lived (maximum recorded age 71 years), exhibit high variability in annual recruitment, mature at around 600 mm (TL) and 17 years of age, and change sex from female to male at around 35 years of age. They become selected by gillnet gear at around 500 mm (TL). Males accounted for only 12% of the catch for which the sex could be determined. With a productivity score of 2.14 and susceptibility score of 2.96, the derived PSA score was 3.65 (MSC SG score <60). **This level of vulnerability indicates that unacceptable stock depletion is likely if there was no management of the relevant fisheries across the region. However, as there is formal management of one sector, partial management of the other sectors and processes already in place to complete these arrangements, the calculated likelihood is not accurate.**
Length and/or age composition	Length composition of the commercial gillnet catch in 2013 and 2014 was similar to both observer data from 1994 to 1999 and catch sampling from 2004 to 2007, when a similar gillnet mesh size was used. This was not consistent with unacceptable stock depletion having occurred. The only age sample (gillnet catch, eastern sub-region) still had individuals of more than 35 years or age, and a new longevity record was set. This was not consistent with unacceptable stock depletion having occurred. Furthermore, the distribution of the ages in these samples suggests that, although inter-annual recruitment is naturally highly variable, longer term levels of recruitment into this stock have been consistent over the last three decades. **Length and age composition evidence suggest that it is highly unlikely that an unacceptable stock depletion has occurred over the last three decades, and consistent recruitment suggests robust spawning stock levels are being maintained.**
Fishing mortality (F)	Estimates of F derived from a catch curve model that accounts for the high level of recruitment variability almost never breached the threshold level and never breached the limit, regardless of the method for estimating natural mortality (M) (Hoenig or Then mortality equations). There was only a 1% chance of the F estimates calculated using the Hoenig value for M breaching the threshold. **Fishing mortality evidence indicates that the likelihood of an unacceptable level of stock depletion is remote if historic levels of fishing are maintained.**

Index of spawning stock biomass (Spawning Potential Ratio [SPR])	Estimates of female SPR (based on *F* derived from a catch curve accounting for variable annual recruitment) never breached the threshold level. For males, applying values of *M* uniformly distributed between the Hoenig and Then estimates indicated that SPR values had only a 14-18% chance of breaching the threshold and only 1-2% chance of falling below the limit level. Although the proportion of males in the gillnet catch was low (~11%), it was similar to results from catch sampling in 2004-2007, and facultative sex change may occur in this species, suggesting recruitment was not constrained by sperm limitation. **The overall SPR for the stock suggests that the likelihood of unacceptable stock depletion is remote if recent (historic) total catch levels are maintained.**

All of the lines of evidence outlined above were combined within the Department's ISO 31000 based risk assessment framework (Department of Fisheries 2015b; Fletcher 2015; Appendix 1) to determine the most appropriate combinations of consequence and likelihood to determine the overall current risk status of the stock.

Western blue groper risk matrix

Consequence (stock depletion) Level	Likelihood					**Risk Score**
	L1 Remote (<5%)	L2 Unlikely (5-30%)	L3 Possible (30-50%)	L4 Likely (50-90%)	L5 Certain (90-100%)	
C1 Minimal				X		4
C2 Moderate			X			6
C3 High	X					3
C4 Major						na
C5 Catastrophic						na

C1 (Minimal Depletion – above target): **L4** – The catch history, catch distribution time series, current age and length composition, and fishing mortality and SPR estimates were consistent with a Likely (L4) likelihood that the current level of western blue groper stock depletion is above the target level. Only the vulnerability (PSA) line of evidence suggests a higher level of depletion may have occurred but this assumed no fishing effort management which is incorrect. The evidence suggests that if the current total catch level is maintained, the stock is likely to remain above target levels for the next five years.

C2 (Maximum Acceptable Depletion - above threshold): **L3** – All lines of evidence were consistent with the stock only Possibly (L3) now being between threshold and target levels. The SPR indicates no concerns for female stock levels.

C3 (Unacceptable Depletion – below threshold): **L1** – Evidence from the SPR analysis, when considering both sexes, suggest only a Remote (L1) possibility that the stock has depleted to between threshold and limit levels, or will do so within the next five years if current (historic) catch levels continue. Only the vulnerability (PSA) evidence suggests such depletion likely, but only in the absence of appropriate management of fishing effort which is not accurate.

C4 (Unacceptable - below limit) – Not plausible under current circumstances.

C5 (Catastrophic) – Not plausible under current circumstances.

2.8 Western blue groper - Current Risk Status of the Stock

The maximum risk score for western blue groper is 6, based on a combination of C2 and L3. **This constitutes a Low Risk level, which is acceptable** (See Appendix 1). Recent (historic) catches are at sustainable levels and the greatest likelihood is that the stock remains above the target level. Although there is scope for some increase in total catch, management arrangements for all sectors should ensure that any increase in catches does not reduce the stock to below the threshold level.

2.9 Future monitoring

Future assessments should be designed to detect any change in the age composition of Bight redfish, snapper, blue morwong and western blue groper. Such analyses would not only enable an update to the stock status but also provide information that may reduce the uncertainties in determining which method of estimating *M* is more appropriate.

To monitor the age structure of the respective stocks into the future, based on the current analyses, a representative age sample for each of the four species could be obtained as follows:

- Bight redfish & snapper - from sampling the commercial wetline catch in the western sub-region (Albany);

- Blue morwong & western blue groper - from sampling the commercial gillnet catch in the eastern sub-region (Esperance).

Given the longevity of these species and current status of the respective stocks, an updated assessment could be completed in 5 years (2020/21) which would require age samples to be collected in one or more years during the period 2018-2019.

Alternatively the status of blue morwong and western blue groper could be inferred from a Level 1 (catch-based) assessment in conjunction with the status of other inshore demersal indicator species (Bight redfish and snapper).

Finally, if new management arrangements with improved catch and effort reporting (daily/trip logbooks) are implemented, more informative catch rates may also become available for future assessments.

3 Methods

3.1 General Methods

3.1.1 Sampling

Catches of snapper, Bight redfish, blue morwong and western blue groper from the SCB were sampled in 2013 and 2014 by collecting fish frames (filleted skeletons with head and usually guts intact) from commercial, recreational and charter catches. To best ensure samples were representative of the total catch of each species in each fishery sector, catches were sampled from multiple fishers operating over a wide area and throughout the year. The minimum legal total length for capture and retention during sampling was 410 mm for snapper and blue morwong, 300 mm for Bight redfish and 500 mm for western blue groper. Sampling was stratified by fishery sector: recreational, commercial wetline, commercial gillnet (JASDGDLF), and charter, and by sub-region: west or east of 120^0 E longitude (Table 3.1, Figure 1.1). The samples years are henceforth referred to as 2013 and 2014, although the two year sampling period was brought forward by two months for blue morwong taken by the commercial gillnet in the east sub-region, and by up to two months in the wetline sector (Table 3.1), because valuable samples became available at that time. Snapper samples were also collected in October and November 2012 from wetline catches of spawning aggregations in the western area of the west sub-region. The Bight redfish catch of a seasonal (summer - autumn) charter tour operator running single day fishing trips out of Duke of Orleans Bay, about 60 km east of Esperance, was also sampled. Those two sample periods were December 2012 to April 2013 (13 catches sampled), and December 2013 to March 2014 (6 catches sampled).

Table 3.1: Sample stratification by fishery sector and sub-region, and date in 2014 of completion of two year sampling period. JASDGDLF = Joint Authority Southern Demersal Gillnet and Demersal Longline Managed Fishery. NS = not sampled or insufficient samples.

Sector	**Sub-region**	**Snapper** 	**Bight redfish** 	**Blue morwong** 	**Western blue groper** 
Recreational	west	31-Dec	31-Dec	31-Dec	NS
	east	NS	31-Dec	31-Dec	NS
Wetline	west	30-Nov	31-Oct	NS	NS
	east	NS	30-Nov	NS	NS
JASDGDLF	west	31-Dec	NS	31-Dec	NS
	east	31-Dec	31-Dec	31-Oct	31-Dec
Charter	east	NS	30-Jun	NS	NS

Commercial catch sampling was undertaken by sourcing frames of all four species from commercial fishers and processors.

Recreational fishers were encouraged to donate frames of snapper, Bight redfish and blue morwong (but not western blue groper which has a very small recreational catch – see section 4.4.2) through a citizen science program promoted as *Send Us Your Skeletons* (Fairclough *et al.* 2014a). This involved making freezers available to receive frame donations at advertised locations such as caravan parks and fishing tackle stores across the SCB. Recreational fishers were also directly engaged at boat ramps, and frames were collected from fish waste bins at public filleting tables. Intense sampling of recreationally caught Bight redfish at Esperance was possible over a short period encompassing an annual recreational fishing tournament run by the Esperance Deep Sea Angling Club: from 4 to 10 March 2013 and from 9 to 11 March 2014. These samples accounted for 28.1% and 49.3% of the total recreational Bight redfish sample for the east sub-region in 2013 and 2014 respectively.

3.1.2 **Processing and age estimation**

All fish were measured to the nearest 1 mm (total length TL and length to caudal fork FL for snapper, Bight redfish and blue morwong, TL only for blue groper). Sagittal otoliths were extracted and the sex of each fish was recorded where it could be determined by macroscopically examining it gonads. Snapper gonads were removed, weighed and the developmental stage recorded to assess length and age at maturity and spawning times (see Appendix 2).

Fish ages were estimated by interpreting growth rings (alternating opaque and translucent increments) deposited annually on otoliths, with regard to the nominal birthdate based on the estimated mid-point of the spawning period, and adjusted for the category assigned to the increment observed at the otolith periphery (opaque or narrow or wide translucent) having regard to month of capture and known timing of increment delineation. Otoliths were embedded in polyester resin, transversely sectioned through the primordium, and mounted on a glass microscope slide using casting resin for examination (Jenke 2002). The methods and validation of the annual periodicity of increment formation have been described for SCB snapper (Wakefield 2006), Bight redfish (Coulson *et al.* in prep.b), blue morwong (Coulson *et al.* 2010) and western blue groper (Coulson *et al.* 2009).

The precision of age estimates was assessed using inter- and intra-reader age-bias plots (Campana *et al.* 1995) and an index of average percent error (IAPE) (Campana 2001). Acceptable precision was achieved for all species, with all IAPE scores < 3.9% except for blue morwong where the IAPE for two readers ranged between 4.6% and 6.7%.

A sub-sample of Bight redfish otoliths collected from wetline and recreational catches in 2014 were randomly selected for ageing because the large number collected in that year could not all could be aged. A Kolmogorov-Smirnov two sample test failed to detect any significant difference between the length distributions for all fish and for only those that were aged (wetline D= 0.015, $p \gg 0.05$; recreational D= 0.014, $p \gg 0.05$).

3.1.3 **Inherent Vulnerability**

The biology and inherent vulnerability of each species were investigated by examining various biological parameters relevant to fishing resilience, and by using Productivity Susceptibility Analysis (PSA) (Marine Stewardship Council 2014) to generate productivity and fishery susceptibility scores, culminating in an overall vulnerability score. The productivity score was the mean of scores assigned to seven attributes: average age at maturity, average maximum age, fecundity, average maximum size, average size at maturity, reproductive strategy and trophic level. The susceptibility score was the weighted mean (by catch share among fishery sectors) of scores assigned to four attributes: availability (combined geographical overlap of all fisheries impacting the stock), encounterability (combined vertical overlap of all fisheries impacting the stock), selectivity and post-capture mortality (both determined individually for each fishery). The overall PSA score is comparable to sustainability standards set out by the Marine Stewardship Council (MSC).

In its current form, the MSC PSA has no capacity to incorporate additional information that may be directly relevant to the risk assessment process including the effectiveness of management strategies within the 'fished area' (Penney et al. 2013, Fletcher 2015). Combined with the PSA being extremely sensitive to changes in the scoring of a single category, this may often result in an overly precautionary approach (Fletcher 2015; Bellchambers et al., in press) which has therefore been taken into consideration within each of the assessments.

3.1.4 **Fishery catch and effort assessment**

Commercial

Data from the DoF's Catch and Effort Statistics (CAES) databases, compiled from statutory catch and effort returns lodged by commercial fishers, provide a time series of catches, their spatial distribution (by 1° x 1° block) and the level of fishing effort expended since 1975. The catch of Bight redfish by the federally managed Great Australia Bight Trawl Sector is mainly from east of 129°E, i.e. off the South Australian coast. The WA component is taken from the western area of the Bight and is not recorded in this report. From the DoF's CAES database a time series of catch and catch rates (catch per unit effort) can be generated that might be useful as an index of abundance. Interpreting catch rates of one species in a multi-species fishery can be confounded by temporal and spatial variation in the intensity of targeting by fishers and the non-comparable measures of effort when multiple gear types were used, such as in the SCB commercial wetline sector.

To enhance confidence in the use of catch rates as an index of abundance, an analysis and filtering of CAES data was undertaken to generate standardised catch rates for snapper and Bight redfish in both the commercial wetline and commercial gillnet sectors. For both species, the two catch rate time series therefore constituted independent datasets that can be compared to increase confidence in their interpretation. Catch rates were not assessed for blue morwong or western blue groper because of very low catches by wetliners that resulted in a single catch rate series only, i.e. from the commercial gillnet sector.

The model selected to describe catch rates was: ln(U) = $Y + M + V + Z$, where U was the nominal rate for factors financial year Y (1996-97, 1997-98,…,2013-14), month M (Jan, Feb,…Dec), fishing vessel V ("primary" vessels, see below) and fishing sub-region Z (east or west). Catch rates were calculated as the least squares mean of monthly effects for each financial year.

To reduce the influence of variation in targeting intensity on catch rates, only fishing records explaining 90% of the total annual catch of the species of interest were included in the model, i.e. starting with the catch with the lowest non-zero catch proportion, records with progressively increasing proportions were excluded until 10% of the annual catch was excluded. Of the records remaining, only those from primary vessels were included, i.e. those vessels comprising the minimum number necessary to account for 80% of the annual catch. Nominal catch rates of primary vessels were also generated for comparison.

In the commercial wetline sector, catches of snapper and bight redfish have been taken primarily by handline and dropline, so only these catches were included in the model. The number of hooks used could not be reliably determined, so fishing effort reported was the total number of hours fished, i.e. number of block days x total hours fished per day. Thus catch rates for snapper and Bight redfish were expressed as kilograms per fishing hour.

In the JASDGDLMF gillnetting was the primary fishing method used for taking snapper and Bight redfish, so only gillnet catches were included in the model. The catch rate reported here was kilograms per kilometre gillnet hour^{-1}. Importantly, in 2006-07 the fishery transitioned from monthly to hourly effort entitlements, and daily CAES returns were introduced, providing a more accurate estimate of the time nets actually spent fishing (Bracini *et al.* 2014). Catch rates before and after 2006-07 were therefore not directly comparable, and the latter were considered likely to provide a more accurate index of abundance.

Charter

The catch of the charter fishing sector was recorded through the compulsory monthly lodgement by tour operators (since 2006) of daily trip returns with the DoF. Information recorded includes the number of each species kept and released, location (GPS latitude and longitude or 5' x 5' block) and daily fishing effort (e.g. number of fishing lines/pots/divers).

Recreational

The boat-based recreational catch of SCB snapper, Bight redfish and blue morwong was estimated by two state-wide surveys for the 12 month periods to 29 February 2012 (Ryan *et al.* 2013) and to 30 April 2014 (Ryan *et al.* 2015).

3.1.5 Age-based assessment

Catch curve analysis

For each of the four species, estimates of the instantaneous rate of total mortality (Z, year^{-1}) and associated 95% confidence intervals (i.e. measure of uncertainty in mortality estimates) were derived using catch curve analyses based on data collected in 2013 and 2014. These estimates were used to generate associated estimates of the instantaneous rate of fishing mortality (F, year^{-1}) using the equation $F = Z - M$, where M is the instantaneous rate of natural (unfished) mortality (M; year^{-1}) (see below for M estimate methods). Up to eight catch curve models were fitted to each data set to explore the extent to which model uncertainty (i.e., alternative modelling assumptions) impacted on the assessment results. The catch curves considered in this assessment included models that were fitted solely to age or length composition data, or simultaneously to length and age composition data. They were fitted to data for each sub-region (west/east) and fishing sector (commercial wetline, commercial gillnet and recreational line) where each sample was sufficiently large (n> ~250). The catch curve models were implemented in AD Model Builder and the model outputs were analysed using the R software package.

The various catch curves differed widely with respect to model complexity and assumptions. The age-based mortality estimators ranged from simple models assuming constant recruitment and knife-edge selectivity, including linear regression (see Ricker 1975) and a method based on the mean age (Chapman and Robson 1960), to multi-year models assuming age-based (logistic) selection and either constant or variable annual recruitment. Length-based methods included a model assuming length-based selection, with constant recruitment, and another that was fitted simultaneously to age and length composition data to estimate growth, (length-based) selectivity and mortality.

The eight catch curve methods considered in this assessment, which are described in more detail in Appendix 4, along with all results, were:

1. Linear regression catch curve
2. Chapman & Robson estimator
3. Multinomial catch curve with age-based, knife-edge selectivity
4. Multinomial catch curve with age-based, logistic selectivity
5. Multi-year catch curve with constant recruitment and age-based, logistic selectivity
6. Multi-year catch curve with variable recruitment and age-based, logistic selectivity
7. Catch curve fitted to age and length data, with length-based, logistic selectivity
8. Length-based catch curve

A judgement was then made on a species by species basis as to which model was most suitable based on a range of criteria including: features of the biology of the species (e.g. level of inter-annual recruitment variation, growth characteristics), information from diagnostic plots detailing how well the various models fitted to the data, degree of model complexity (i.e. a model should only be as complex as it needs to be to account for important factors influencing reliability of results), the likely validity of statistical assumptions made by the various models, and information from the published literature regarding the reliability of alternative approaches as determined from simulation studies. For this assessment, it was important to recognise that although a particular catch curve model was selected for the purpose of providing a single “answer” (on which to assess stock status) and thereby help inform management of the fishery, each of the alternative catch curve models explored had some merit in explaining the trends in the data to which these models were fitted. Moreover, comparisons of the various models provided valuable insights into the various factors that, for a given species, were likely to impact most on the reliability of estimates of mortality, and allowed an assessment of the extent to which model uncertainty (alternative modelling assumptions) impacted on results.

The catch curve model considered most appropriate for the assessment of snapper, Bight redfish, and western blue groper was a multi-year catch curve that accounted for inter-annual variability in recruitment (Method 6), a common biological characteristic for many demersal scalefish species (e.g. Coulson *et al.* 2009, Fairclough *et al.* 2014). For blue morwong, where individuals only become fully selected by the fishery at relatively large sizes, a catch curve model that was simultaneously fitted to age and length composition data and assumed length-based selectivity (Method 7) was selected.

Focusing only on the age (and length if appropriate) composition sample considered most representative, and the preferred catch curve method, a sensitivity analysis was then undertaken to explore the effect of assuming different values for natural (unfished) mortality (M; year^{-1}) on the outputs of this assessment. The analysis involved generating 5,000 values of Z (using catch curve estimates and associated measures of uncertainty for each species) and 5,000 values of M for each of three "scenarios". The first scenario was based on a constant value of M for each species, estimated using Hoenig's (1983) life history equation relating the estimates of mortality for lightly-exploited stocks to their maximum recorded ages A (i.e. $\ln M = 1.46 - 1.01 \ln A$), which is the same approach previously employed for catch curve-based assessments in WA (e.g. Wise *et al.* 2007, Fairclough *et al.* 2014) (Table 3.2). A second scenario assumed a constant M for each species, calculated using an "updated" equation by Then *et al.* (2015), i.e. $M = 4.899\ A^{-0.916}$, which was based on a larger dataset than that used by Hoenig (1983) (Table 3.2). The Then *et al.* (2015) equation, while potentially more reliable due to a larger and more refined dataset, tends to yield higher values of natural mortality, resulting in a more optimistic stock assessment. However the equation and its impact on assessment results have yet to be fully evaluated by the international scientific community. A third scenario was therefore evaluated, where values of M were drawn from a uniform probability distribution ranging between the Hoenig and Then estimates of M which were considered to bound the likely feasible range.

Table 3.2: Estimates of natural mortality (M, year-1) calculated for each species using two alternative methods described by Hoenig (1983) and Then et al. (2015).

	Hoenig method	Then method
Snapper	0.104	0.167
Bight redfish	0.049	0.085
Blue morwong	0.174	0.267
Western blue groper	0.058	0.099

For each set of associated Z, M and F estimates, the relative F (as a proportion of M) was calculated and compared to F-based target, threshold and limit reference points to assess the current status of each stock (see Performance measures below). The probabilities of *F* breaching the threshold and limit reference levels were also determined.

Per-recruit analyses

Per-recruit analyses were undertaken for each species to provide estimates of spawning potential ratio (SPR, i.e. the reproductive potential of the stock at the current level of fishing compared to that at an unfished level). SPR estimates, and associated 95% confidence intervals, were based on estimates of spawning stock biomass per recruit (i.e. the average lifetime contribution of individual fish to overall population reproductive potential) from the above *Z* estimates derived from the catch curve analysis (and alternative values for *M*). Values of SPR are often considered to represent more reliable indicators of stock status compared to *F* estimates due to the inclusion in per-recruit models of other known biological information for the species, such as growth and maturity (Goodyear 1993). The two alternative methods that were considered in these analyses were a traditional per-recruit model and an extended model that accounts for the effect of fishing on the annual recruitment to the population (Appendix 5). The SPR values (calculated based on the 5000 values of *Z*, *M* and *F* resulting from the catch curve analysis) for each species were compared to target, threshold and limit reference levels to assess the current stock status (see Performance measures below). The probabilities of SPR breaching threshold and limit reference levels were also determined.

Performance measures

Stock performance for the four species in this report was assessed by comparing *F* and SPR with reference levels that were based on the species biology, and were consistent with other age-based assessments of WA scalefish stocks and international best practice for longer lived finfish species (Caddy and Mahon 1995; Gabriel and Mace 1999; Wise *et al.* 2007, Department of Fisheries 2015b). Reference levels are based on the principle of maintaining spawning stocks above a level where future recruitment should not be materially affected, so that environmental conditions become the main driver of recruitment variation. Stock performance relative to reference levels shape advice for ongoing fisheries research, monitoring and management. Note that robust stocks are associated with *lower F* and *higher* SPR values.

The reference levels for all four species in this report were:

Target: $F = \frac{2}{3} M$, SPR = 0.4. (Where *F* and SPR should be).

Threshold: $F = M$, SPR = 0.3. (Trigger for additional management and research actions).

Limit: $F = 1.5\ M$, SPR = 0.2. (Fishing must cease or be heavily restricted).

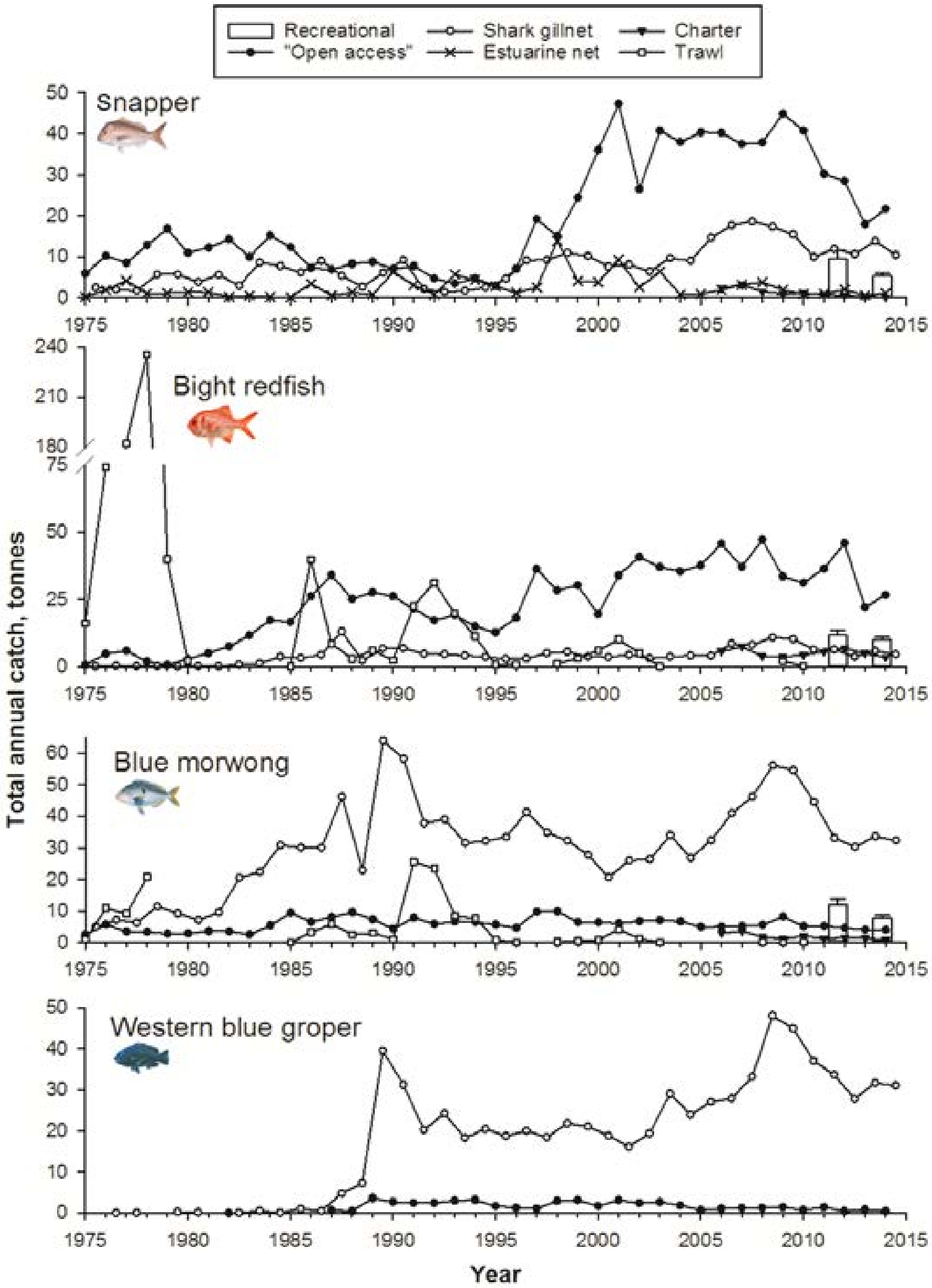


Figure 3.1: Time series of the total annual catches of the four inshore demersal indicator species by sector in the SCB. Bight redfish catch by federally managed GABTS is excluded. Wetline and charter catches are for calendar years. Shark gillnet is for financial years, and includes catches in the JASDGDLMF, and prior to its inception in 1988 all gillnet and longline catches in oceanic waters. All catches in blocks straddling the West Coast Bioregion boundary at 115.30°E (i.e. between 115.00°E and 116.00°E) have been included if they could not be allocated between bioregions. The two available boat-based recreational catch estimates (+ standard error) were for years ended 29 February 2012 and 30 April 2014. For western blue groper the recreational catch estimates were low and weights unavailable (see text), and the low charter catch from 2006 to 2014 has been omitted for clarity (annual mean = 150 kg, range 44 to 264 kg).

4 Biology and assessment of indicator species

4.1 Snapper (*Chrysophrys auratus*)

4.1.1 Biology and inherent vulnerability

Stock assessments and management interventions for snapper in the Gascoyne and West Coast Bioregions of Western Australia have demonstrated the species' inherent vulnerability to over fishing (Wise *et al.* 2007, Marriott *et al.* 2012, Fairclough *et al.* 2014b). Biological factors contributing to this vulnerability include:

- a high maximum age of 41 years (Norriss and Crisafulli 2010, this study)
- sexual maturity at around 543 mm TL and 4.6 years of age on the south coast (Appendix 2)
- variable inter-annual recruitment (Lenanton *et al.* 2009)
- high post-release mortality from gut-hooking and barotrauma at capture depths >30 m (St John *et al.* 2009)
- formation of spawning aggregations at predictable times and places (Wakefield 2010, Jackson 2012). However, limited data on the recreational catch of spawning snapper near Windy Harbour on the south coast did not indicate a particularly high vulnerability to overfishing in that area (Appendix 3).

Snapper in the open oceanic waters off the WA coast are considered to comprise three separate management units (i.e. Shark Bay oceanic, west coast and south coast) based on research indicating low levels of genetic differentiation over large spatial scales (Gardner and Chaplin 2011), high levels of adult residency and limited recruitment sources/nursery areas (Moran *et al.* 2003; Wakefield *et al*. 2011; Fairclough *et al.* 2013).

Productivity Susceptibility Analysis (PSA) for snapper generated a productivity score of 1.86 and susceptibility score of 2.33, resulting in an overall score of 2.98. The analysis indicates that an unacceptable stock decline would be possible without appropriate fisheries management.

4.1.2 Catch and effort

The commercial wetline sector has dominated the catch of snapper since CAES records commenced in 1975 (Figure 3.1). Annual wetline catches increased substantially after 1995 to peak at 30-50 t between 2000 and 2010, followed by a decline but remaining within the historical range. In comparison, the commercial gillnet sector (JASDGDLMF) had much lower catches since 1975. Since 2006 around 57% of the total snapper catch has been taken by the commercial wetline sector, around 25% by commercial gillnet, and 15% by the recreational and charter sectors combined, although historical recreational catches are unknown. The two annual recreational catch estimates (± standard error) were 9.4 (±2.2) and 5.3 (±0.7) tonnes in the years ended 29 February 2012 and 30 April 2014, respectively (Ryan *et al.* 2013, 2015). The estuarine net fishery takes around 3% of the total catch as well as causing an unknown level of mortality from discarded juvenile (undersize) bycatch. Overall, catch history provides no indication of significant stock depletion.

Analysis of the spatial distribution of the commercial wetline catch since 1990 shows that most of the snapper catch was from the west sub-region (Figure 4.1). There was a slight expansion of the spatial distribution of commercial wetline catches since 1990, such as in the far west where seasonal spawning aggregations are targeted, and in the far east near Eucla. But there was no indication that catch levels have been maintained by a progressive shifting of the areas fished that would be indicative of serial spatial stock depletion.

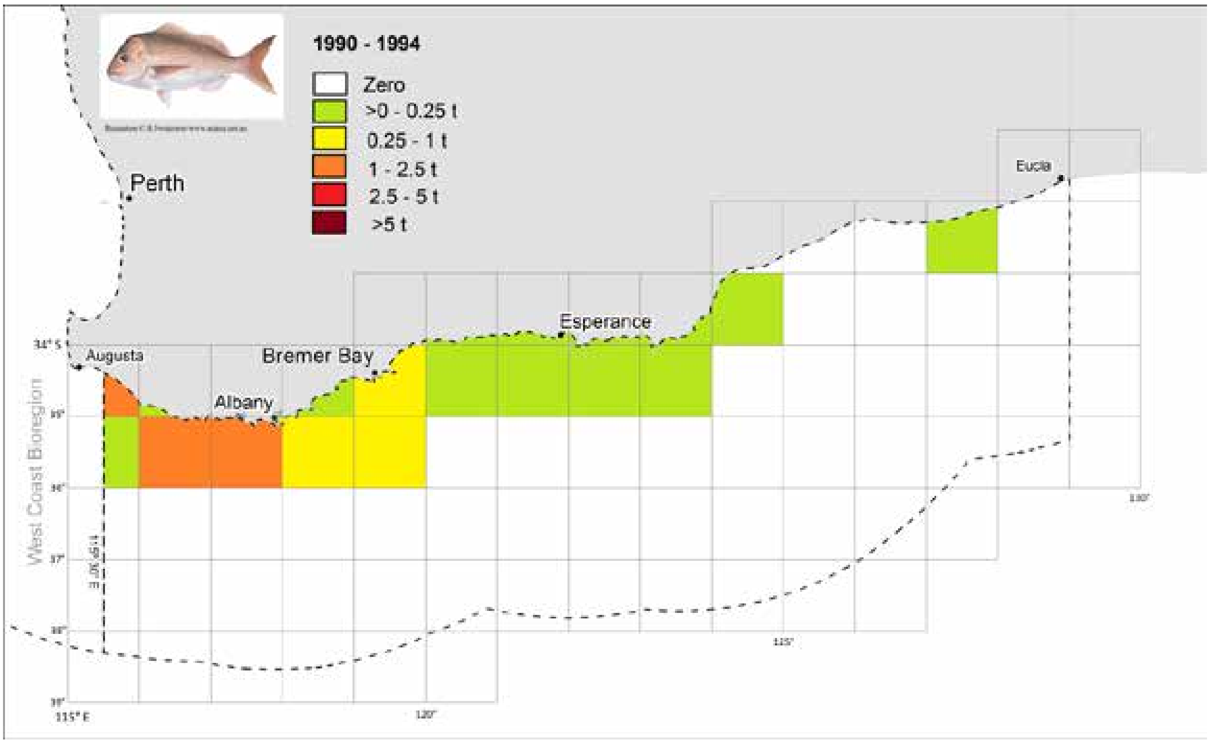
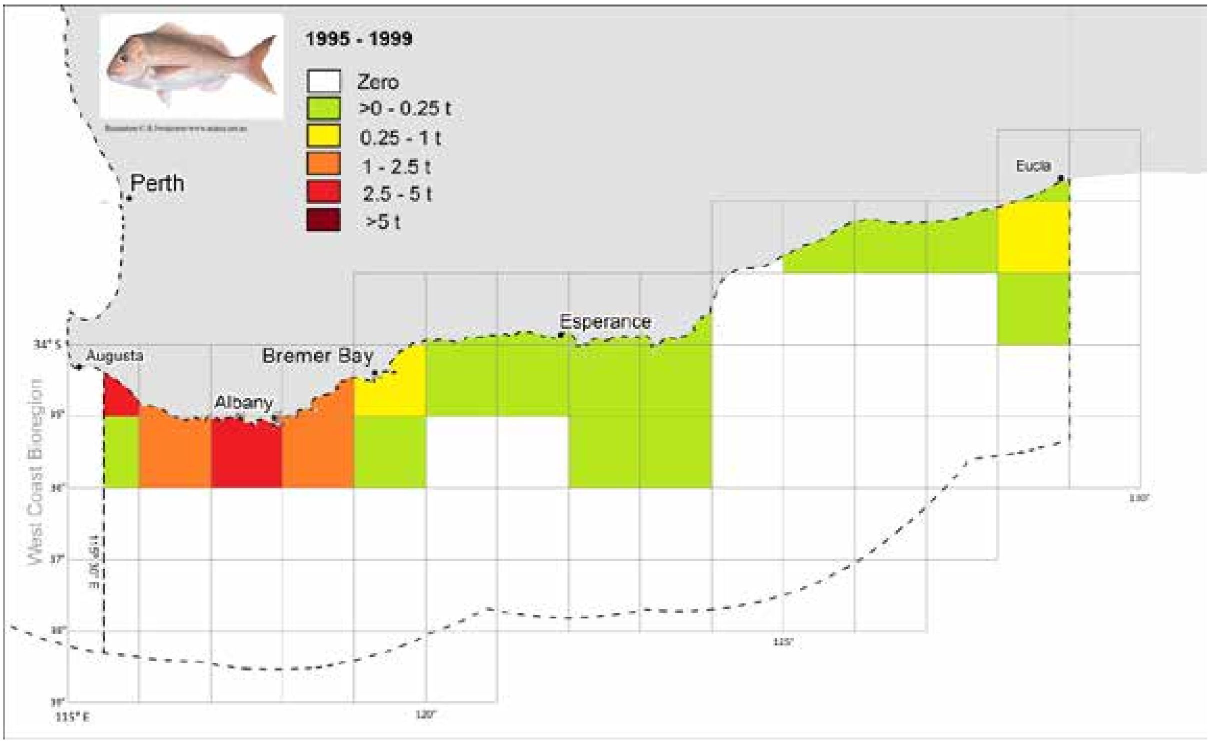
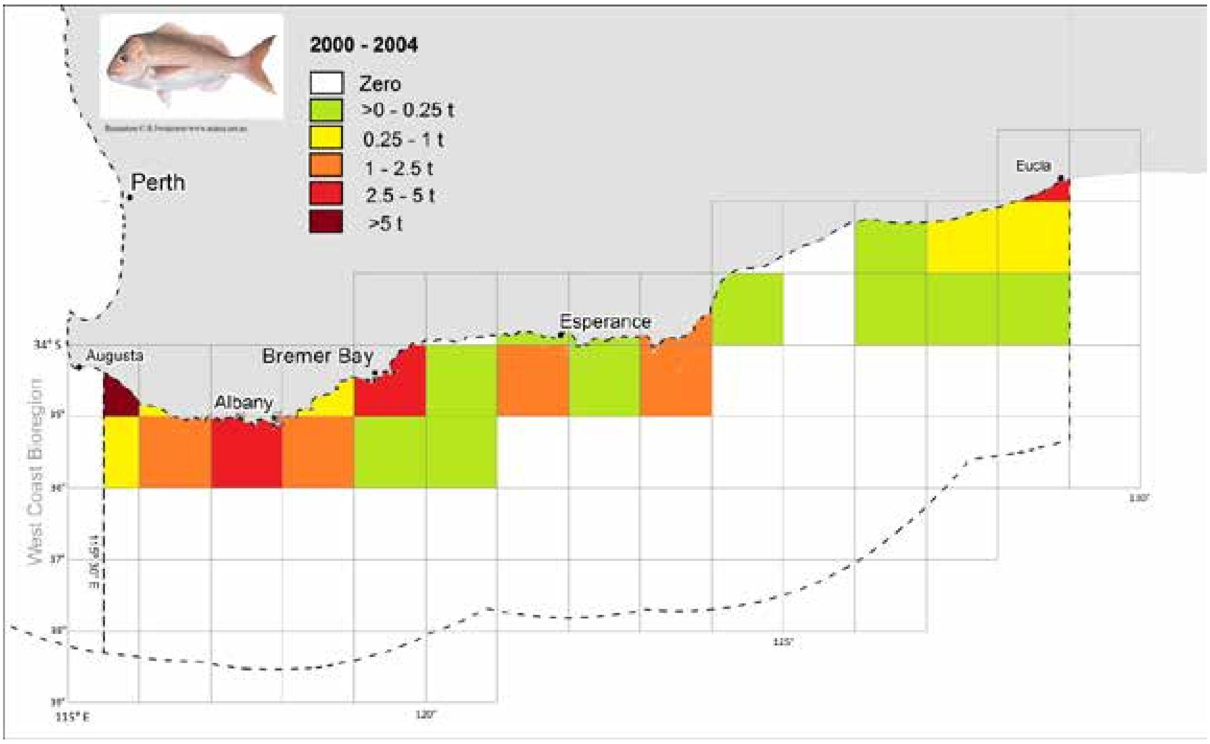


Figure 4.1: Time series of the spatial distribution of average annual wetline catch of snapper in each 1° x 1° block in the South Coast Bioregion, from 1990 to 2014.





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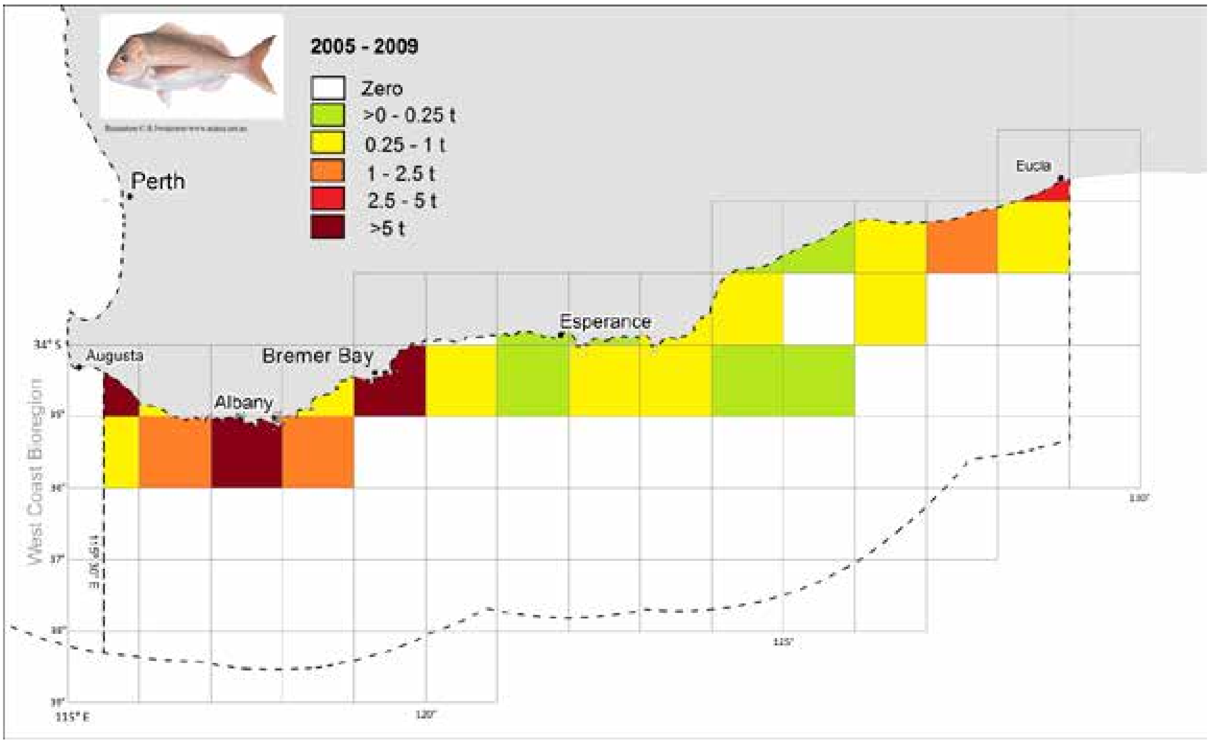


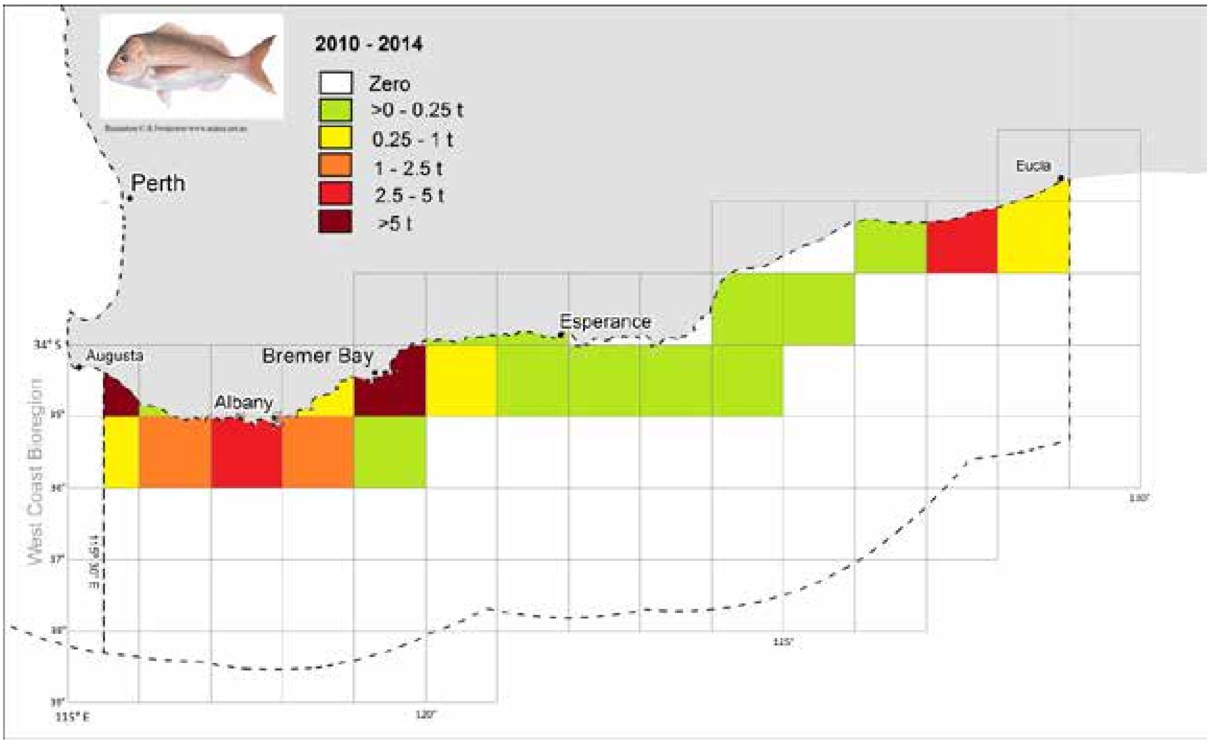


Figure 4.1: Continued.

Standardized wetline catch rates of snapper gradually increased from historically low levels in 1997/98 and 1998/99, to a peak around 2006 to 2008 and then returned to historic levels (Figure 4.2). Commercial gillnet catch rates were stable up to 2006, although these catch rates were less reliable as an index of abundance than post 2006 catch rates due to transitioning to daily CAES returns. From 2007, commercial gillnet catch rate declined, but cannot be directly compared to earlier catch rates due to the transitioning. Any influence on catch rates from new technology such as the Global Positioning System, colour sounders and hydraulic reels likely to have occurred around 1989 to 1991 (i.e., before the start of this time series), based on an analysis of the snapper catch rates in the West Coast Bioregion demersal wetline sector (Marriott *et al.* 2011). In conclusion, catch rates provide no evidence of changing abundance of snapper in the SCB.

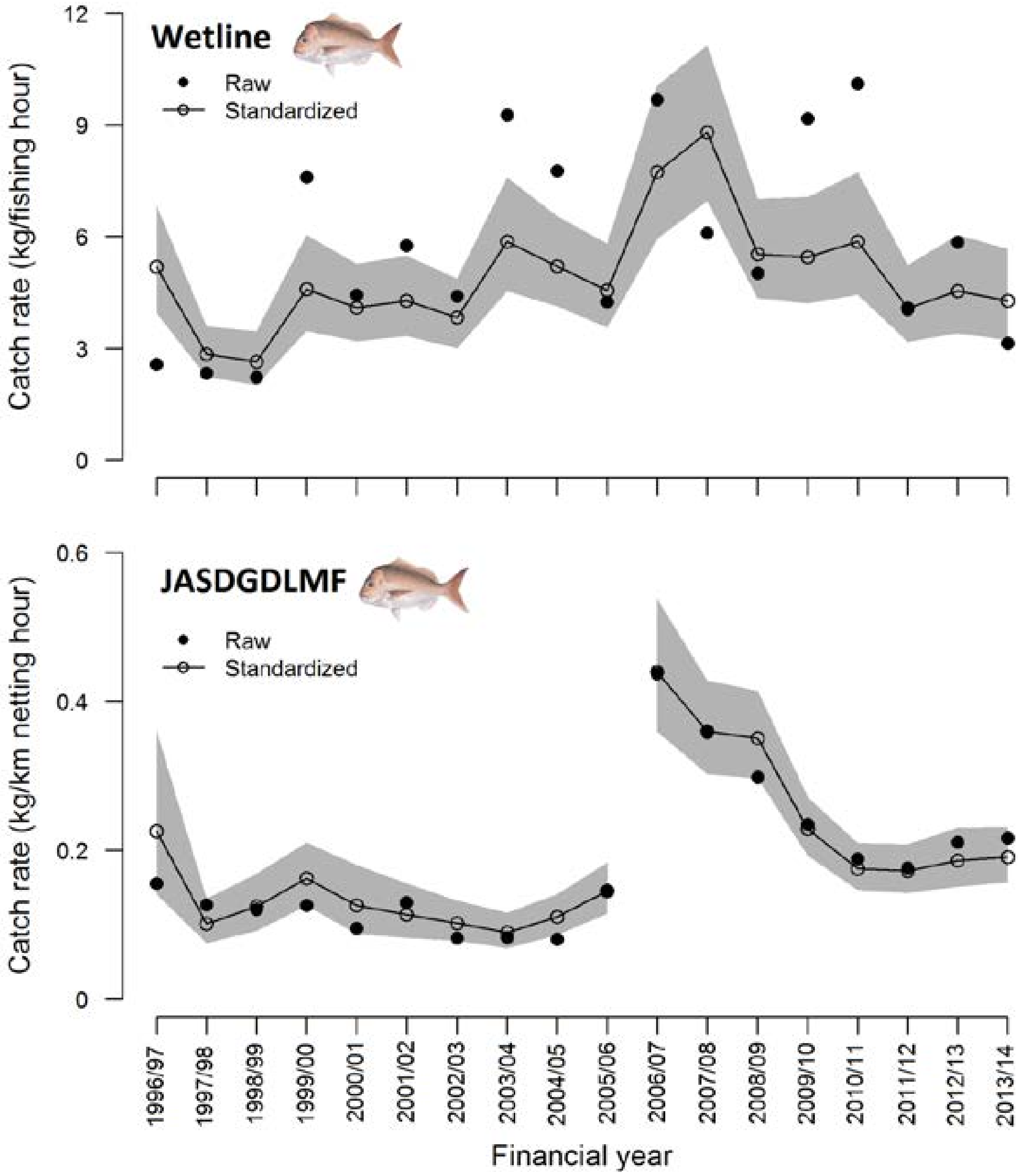


Figure 4.2: Time series of snapper nomial and standardized catch rates (± 95% confidence intervals, grey shading) in the wetline sector and the JASDGDLMF (commercial gillnet). Catch rates from 2006/07 in the JASDGDLMF were not comparable with earlier years due to transitioning to daily CAES returns.

The lengths of snapper from the commercial gillnet sector had a lower proportion of small (<50 cm TL) and very large (>90 cm TL) fish compared to the other sectors (Figure 4.3), a result of the selectivity of the gill net mesh sizes. The mean (± standard deviation) length of snapper from the commercial gillnet sector was 64.9cm TL (±9.8, n= 622), slightly higher than that recorded by observers on board commercial gillnet vessels fishing on the south and lower west coasts from 1994 to 1999, i.e. 61 cm TL (±10, n= 767) (McAuley and Simpfendorfer 2003), providing no evidence of a stock decline since then.

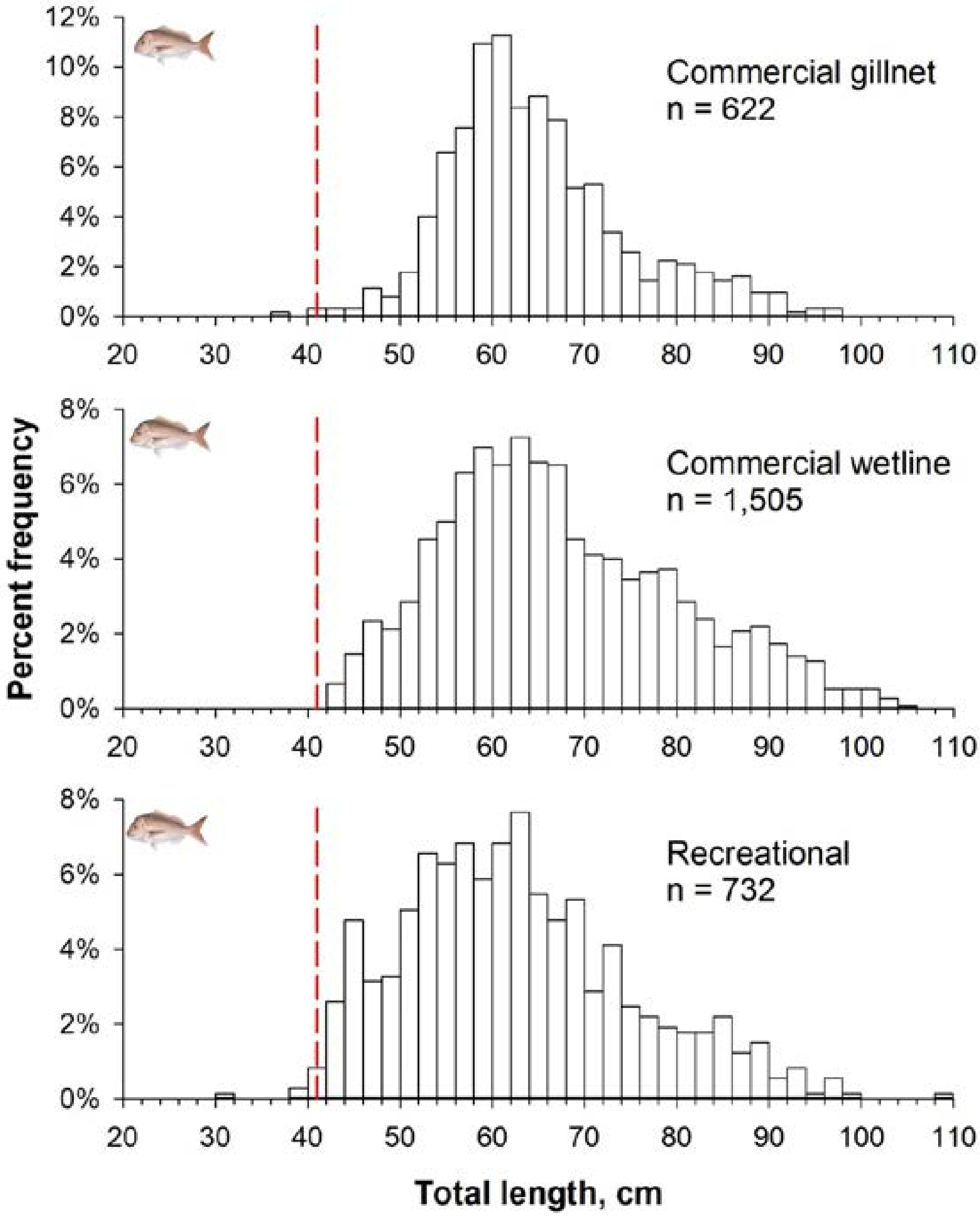


Figure 4.3: Length-frequency distribution of the catch of snapper sampled by fishery sector. Dashed red line represents minimum legal length of 410 mm TL. n = sample size.

4.1.3 **Age-based assessment**

The age-frequency distribution of the snapper catches varied among fishery sectors and sub-regions (Figure 4.4). Relatively old fish (>20 years) we recorded in the west sub-region, and the oldest fish encountered in the study (41 years) equalled the oldest recorded snapper in Australia (Norriss and Crisafulli 2010). The absence of old fish in the only sample from the east sub-region (commercial gillnet) may be explained by a relatively small and potentially non-representative sample. In the west sub-region, the age distributions indicate some inter-annual variability, but the long term pattern shows a consistent level of recruitment into this stock over the last two decades. With the persistence of at least some some old snapper, age data suggest that stock depletion is at an acceptable level.

The commercial wetline catch from the west sub-region sample was thought to provide the most representative age sample of snapper in the SCB, and therefore the most suitable sample for estimating fishing mortality and spawning potential ratio. This was because:

- A large majority of the catch was from the west sub-region, and the largest catch share was taken by commercial wetliners.
- The recreational sector was comprised of smaller vessels fishing predominantly in relatively shallow water and nearer to access points in the main population centres, whereas commercial wetliners were thought to fish across a wider area and depth range of the stock.
- Snapper was a key target species of the commercial wetline fishery whilst the commercial gillnet fishers retained snapper as by-product when targeting sharks and thus may not operate in areas where snapper are most abundant. The gillnets are also size selective.
- The commercial wetline sample from west sub-region was easily the largest (n = 1,356) of all sectors in either sub-region, twice the size of the next largest sample.

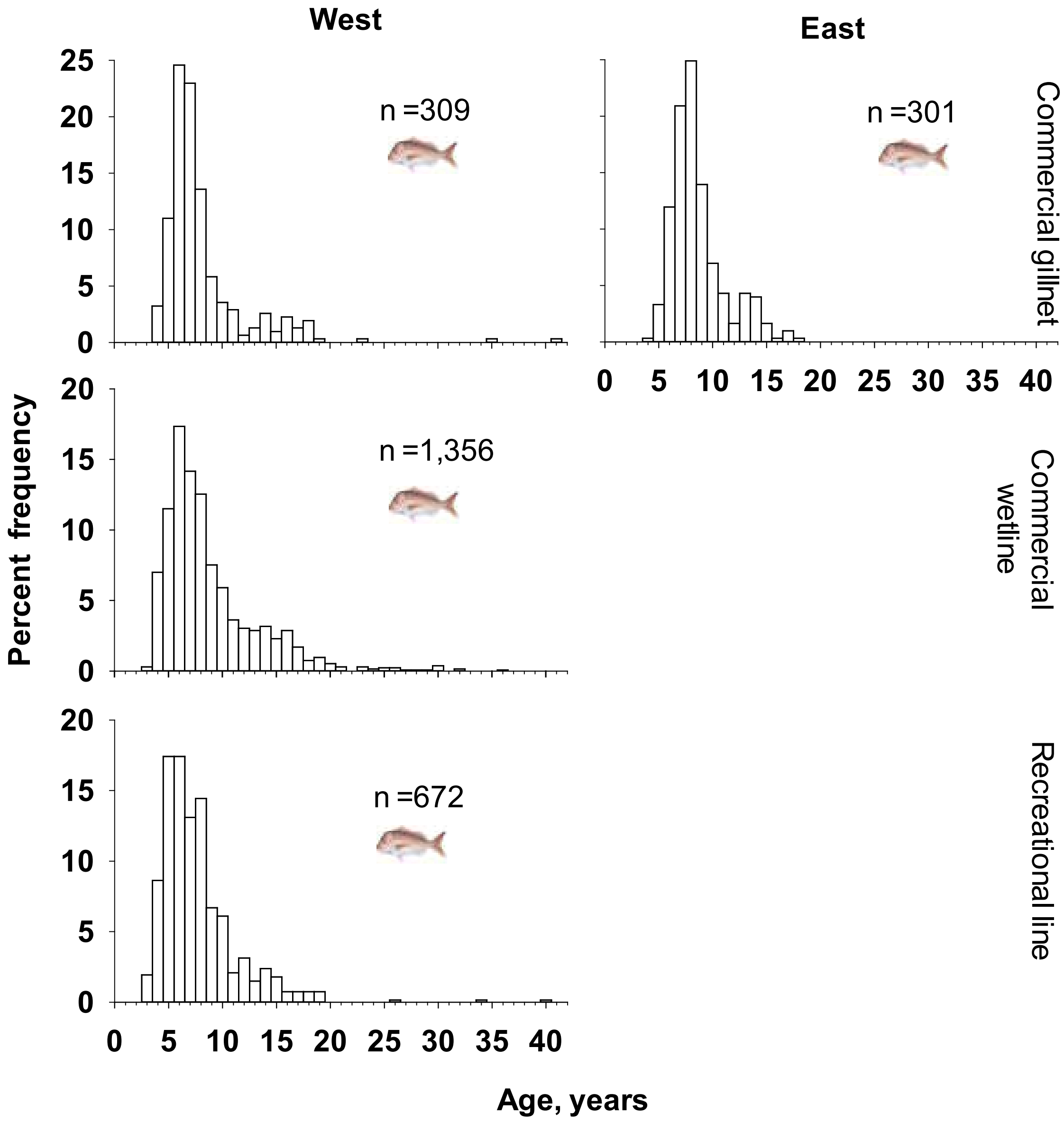


Figure 4.4: Age-frequency distribution of the catch of snapper sampled by sub-region and fishery sector from 2012 to 2014. n = sample size.

The median estimates of total mortality (*Z*) from the sample considered most representative of the SCB snapper stock (commercial wetline catch from the west sub-region) were very similar among the eight catch curve analyses, ranging from 0.23 to 0.25 year^{-1} (see Appendix 4 for all *Z* estimates). The preferred catch curve model (see methods section 3.1.5) for this species, i.e., the multi-year catch curve accounting for variable annual recruitment and assuming age-based, logistic selectivity, generated a median *Z* estimate (± 95% confidence intervals) of 0.24 (0.22 to 0.26) year^{-1}. Based on the two estimates of natural mortality (*M*) for snapper of 0.104 year^{-1} (Hoenig 1983) and 0.167 year^{-1} (Then *et al.* 2015), median fishing mortality (*F*) estimates for snapper were 0.134 (0.115 to 0.154) year^{-1} and 0.071 (0.051 to 0.091) year^{-1}, respectively.

The F estimates taken to be most accurate (see methods section 3.1.5) were those based on resampling analysis assuming a uniform distribution of M values ranging between the point estimates of Hoenig (1983) and Then *et al.* (2015), resulting in:

- M = 0.135 (0.105 to 0.165) year^{-1} and
- F = 0.103 (0.065 to 0.141) year^{-1}.

Based on these values, the point estimate of F/M = 0.76 does not breach the threshold reference level of $F = M$ (i.e. F/M = 1). Considering the uncertainty around these estimates, there was a 25% chance of F beaching that threshold and an almost zero chance of breaching the limit level of $F = 1.5M$ (Figure 4.5a). Thus, the level of fishing mortality for snapper was likely to be at an acceptable level.

Estimates (± 95% confidence intervals) of the median female traditional (SPR1) and extended (SPR2) spawning potential ratios for snapper were SPR1 = 0.25 (0.21 to 0.29) and SPR2 = 0.18 (0.14 to 0.22) based on the Hoenig (1983) estimate of M, and SPR1 = 0.55 (0.47 to 0.63) and SPR2 = 0.51 (0.43 to 0.60) when using the Then *et al.* (2015) estimate of M. The SPR estimates taken to be most accurate were based on simulated values of M uniformly distributed between the two above M estimates:

- SPR1 = 0.39 (0.25 to 0.56) and
- SPR2 = 0.33 (0.32 to 0.18).

Although median estimates from the two per-recruit models were similar, the slightly lower estimate from the extended model (SPR2) reflected the more pessimistic and realistic assumption that juvenile recruitment can be impacted by fishing pressure. The SPR1 model does not assume this. There was a 21% (SPR1) and 43% (SPR2) chance of this indicator breaching the threshold reference point of SPR = 0.30, and an almost zero (SPR1) and 9% (SPR2) chance of breaching the limit level of SPR = 0.20 (Figure 4.5b). The female SPR was therefore likely to be at an acceptable level.

4.1.4 **Conclusion: Snapper stock status**

All lines of evidence were consistent with the level of depletion of the SCB snapper stock at an acceptable level in 2013-14. Neither the time series of total catches, catch rates nor catch distributions offer evidence of unacceptable depletion. While Productivity and Susceptibility Analysis indicates the stock is vulnerable in the future without appropriate fisheries management, this risk is mitigated if appropriate management actions are taken, as are currently proposed (Department of Fisheries 2015a). The persistence of old fish in age samples, and the similarity of the commercial gillnet length distribution to historical observer data suggest that the stock remains at an acceptable level. The strongest lines of evidence however, were from the age-based estimates of fishing mortality and SPR because they incorporate a wide range of information on age, growth and reproduction. Both indicate that depletion remains at an acceptable level, and is likely to remain so for the next five years if the total catch remains within recent historical levels.

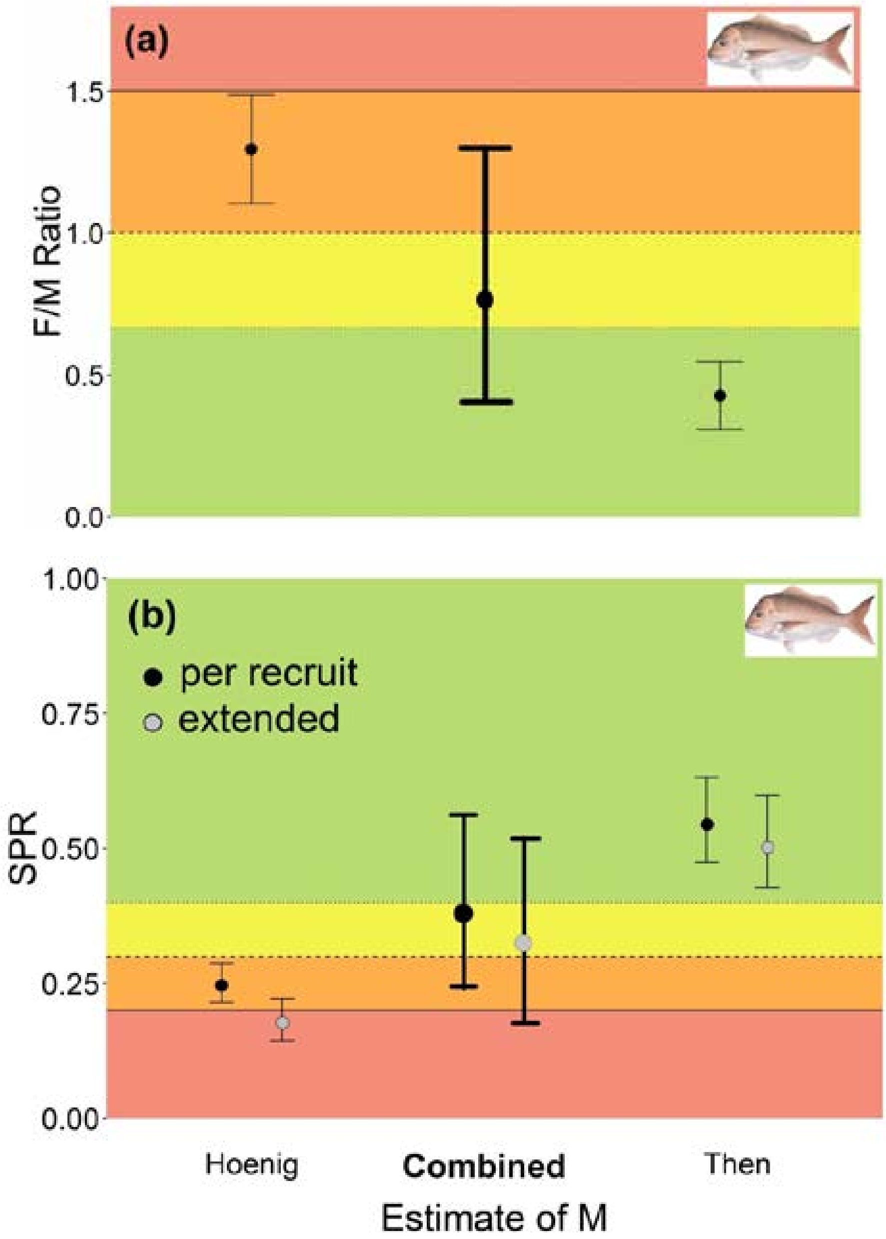


Figure 4.5: Snapper: estimates (±95% confidence intervals) of (a) ratio of fishing mortality to natural mortality (*F/M)* (b) female spawning potential ratio (SPR), both derived from a catch curve model fitted to age composition data collected from the commercial wetline fishery in the west sub-region. In (b) SPR estimates were from traditional per recruit analysis and an extended model accounting for impacts of fishing on recruitment. The best estimates of *F* and SPR, denoted by bold error bars, were obtained assuming distribution of *M* values ranging between those estimated by the equations of Hoenig (1983) and Then *et al.* (2015). The dotted, dashed and solid horizontal lines denote the target, threshold and limit reference levels, respectively, for fisheries management purposes, as applied to the management of other, similar demersal scalefish resources in WA.

4.2 Bight redfish (*Centroberyx gerrardi*)

4.2.1 Biology and inherent vulnerability

Bight redfish have a high inherent vulnerability to overfishing due to their biology. Contributing factors include:

- an exceptionally high maximum age of 84 years (this study)
- late onset of sexual maturity (at least 6 years of age) and slow growth rate (Coulson *et al.* in prep. a, b)
- the formation of seasonal spawning aggregations, known to be targeted by fishers in the Cape Naturaliste area (Mackie *et al.* 2009b)

Bight redfish are likely to be strongly resistant to barotrauma based on a tagging study of the closely related *Centroberyx affinis* that recorded many recaptures of fish caught by trawling in depths from 73 to 360 m on Australia's east coast (Rowling 1990). Moreover, many line fishers report that immediately after release Bight redfish typically swim strongly downwards, even in capture depths of around 100 m.

Research undertaken as part of this SNRMO funded project indicated genetic homogeneity across WA and GAB waters but some separation based on otolith chemistry between WA and the GAB locations. Bight redfish caught in WA State waters and those taken by the Commonwealth GAB fishery should continue to be monitored and assessed as separate management units (Bertram *et al.* in prep).

Productivity Susceptibility Analysis (PSA) for Bight redfish generated a productivity score of 1.86 and susceptibility score of 2.33, resulting in an overall score of 2.98. The analysis indicates that an unacceptable stock decline would be possible without appropriate fisheries management.

4.2.2 Catch and effort

Early attempts to commercially fish Bight redfish in the Great Australian Bight date back to trawling in the 1930s that took small mixed species catches including Bight redfish, suggesting a small fishery resource (Maxwell 1981). CAES records kept by the DoF since 1975 (Figure 3.1) show some relatively high catches from exploratory trawls between 1976 and 1980 in an attempt to establish the resource size (Walker *et al*. 1982, Walker and Clarke 1989). In the early 1980s commercial wetline catches started to increase, and since ~1995 have far exceeded the other sectors, landing around 60% of the total catch. The two most recent years have seen a decline in the wetline catch to levels last seen in the late 1990s. The recreational sector took the second highest catch share in the two years it was estimated: 11.8 (±1.7 se) and 9.9 (±1.1 se) tonnes in the years ended 29 February 2012 and 30 April 2014, respectively (Ryan *et al.* 2013, 2015). Bight redfish have been less important to the commercial gillnet sector than any of the other three species presented in this report, in terms of both catch share and tonnes caught. For the charter sector, however, Bight redfish have been the most important, with more taken than any of the other three indicator species (snapper, blue morwong or western blue groper). Overall, catch history provides no indication of significant stock depletion.

Since 1990 the large majority of the wetline Bight redfish catch came from the west sub-region close to the major human population centres, particularly Albany (Figure 4.6). Some expansion occurred into the far west after 2000, and catches declined near Esperance since 2010. However, there was no indication that catch levels have been maintained by a progressive expansion of the areas fished that would be indicative of serial spatial stock depletion.

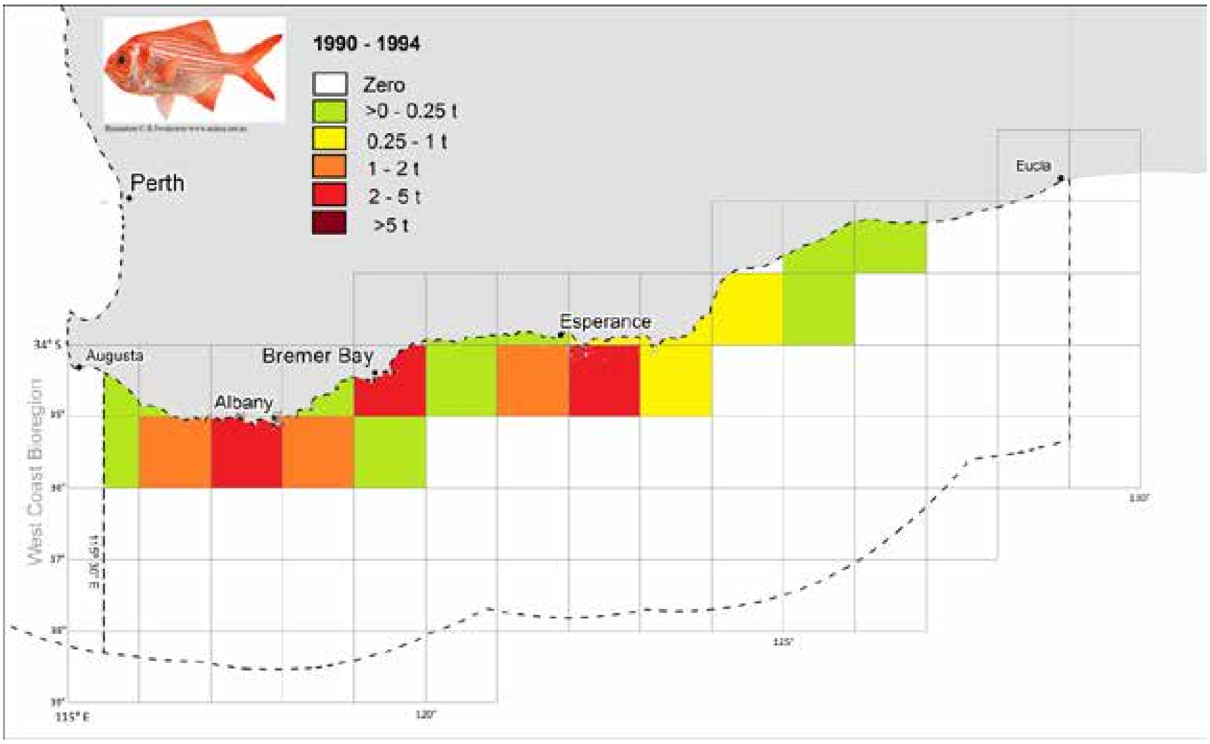
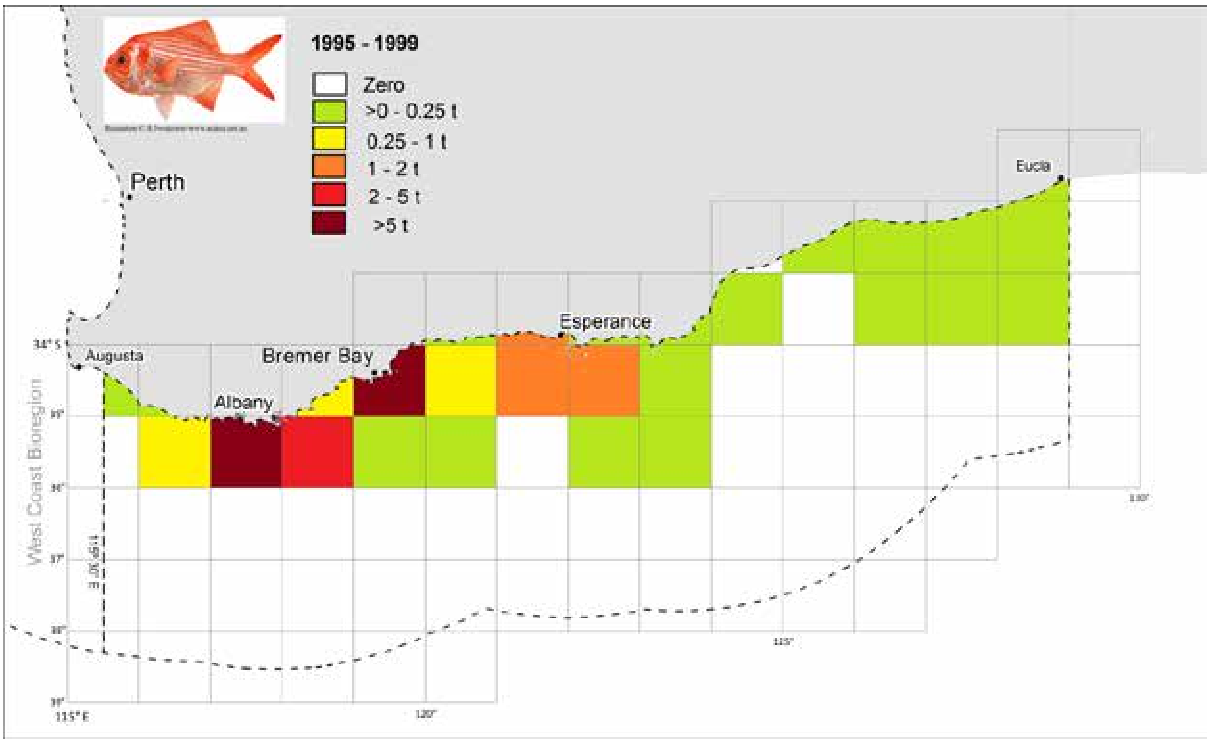
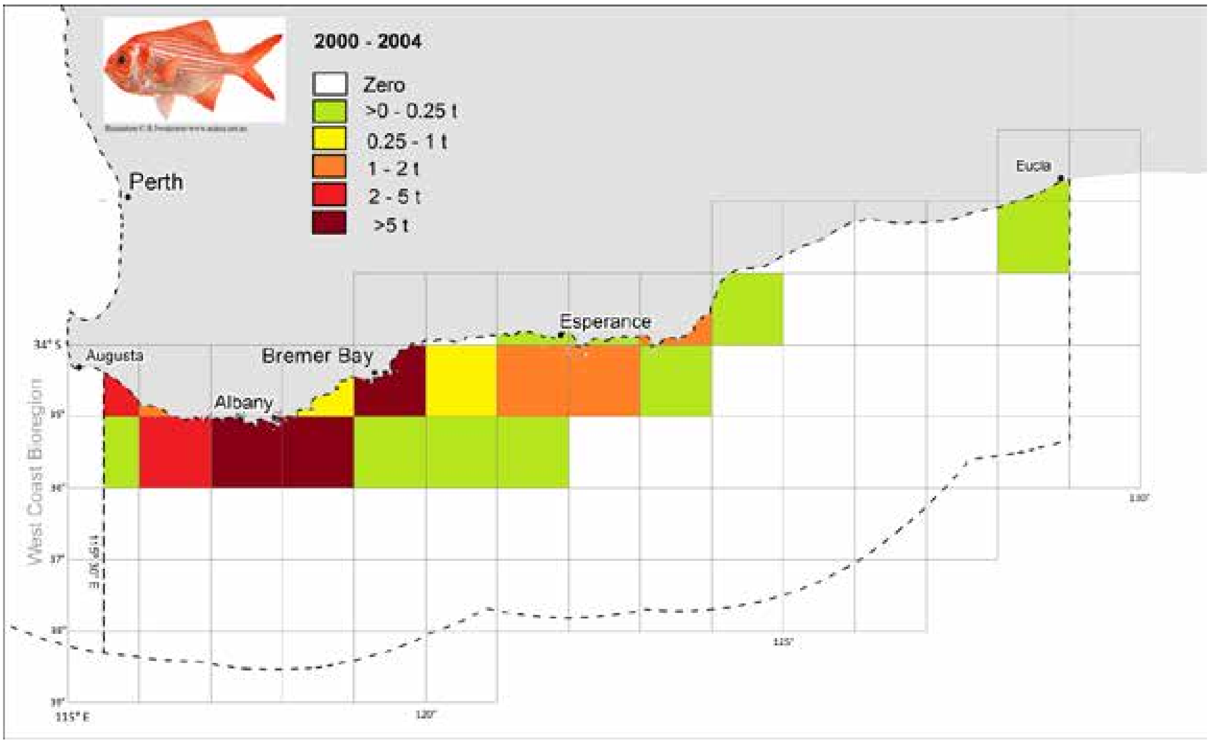


Figure 4.6: Time series of the spatial distribution of average annual commercial wetline catch of Bight redfish in each 1° x 1° block in the South Coast Bioregion, from 1990 to 2014.





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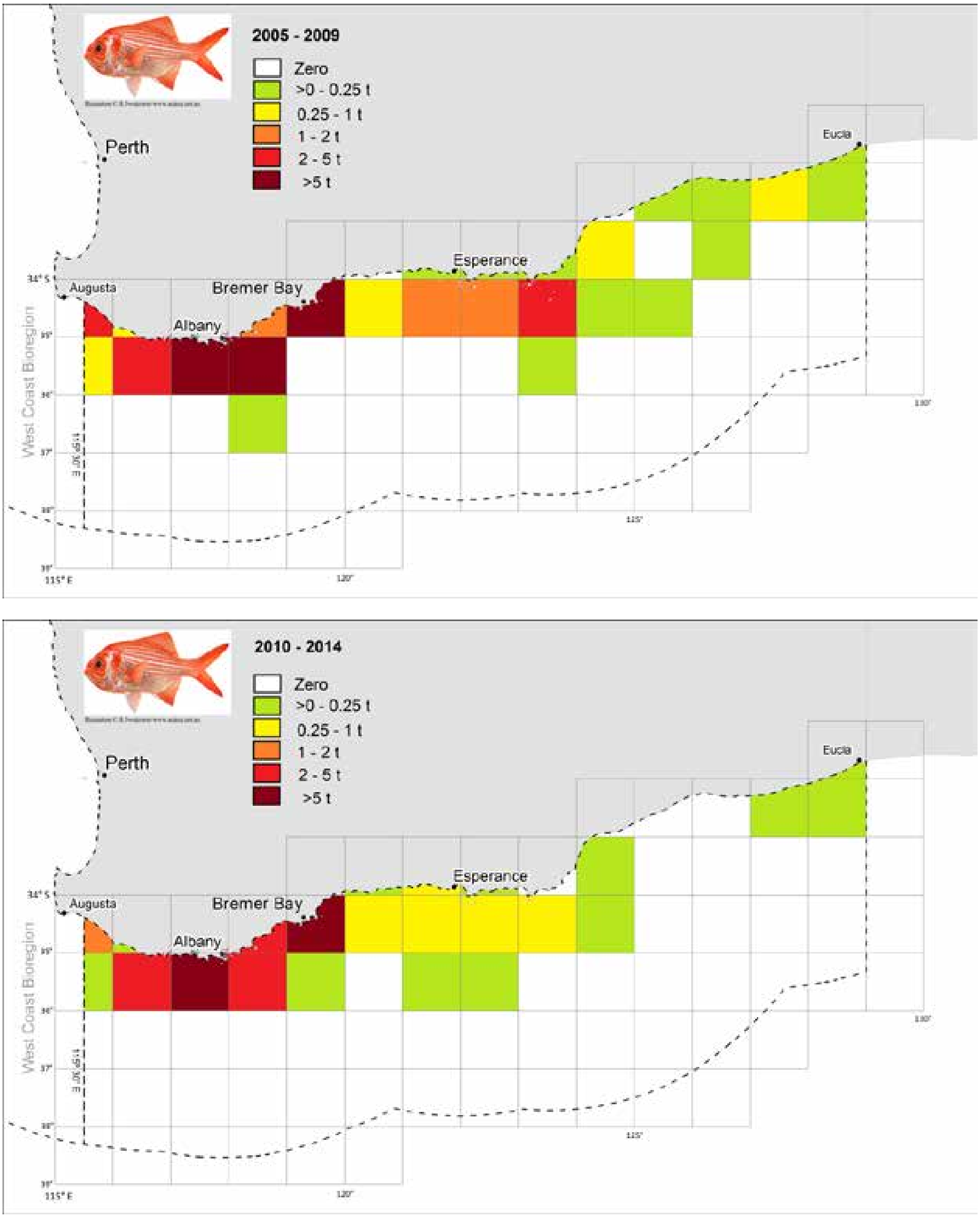


Figure 4.6: Continued.

Standardised Bight redfish catch rates in the dominant wetline sector have been steady since 1996/97 (Figure 4.7). Similarly, the catch rates for the commercial gillnet sector (JASDGDLMF) from 1988/89 until to transitioning to daily CAES returns in 2006 remained relatively stable. The catch rate for the first year of the new daily CAES returns (2006/07) was easily the highest and is likely an artefact of transitioning, as catch rates declined markedly in the following year and remained steady thereafter. Commercial gillnet catch rates for Bight redfish were considered the least informative of the four indicator species as this sector takes a lower share of the total Bight redfish catch. In conclusion, multi-sector catch rates for Bight redfish provide no evidence of changing abundance in the SCB.

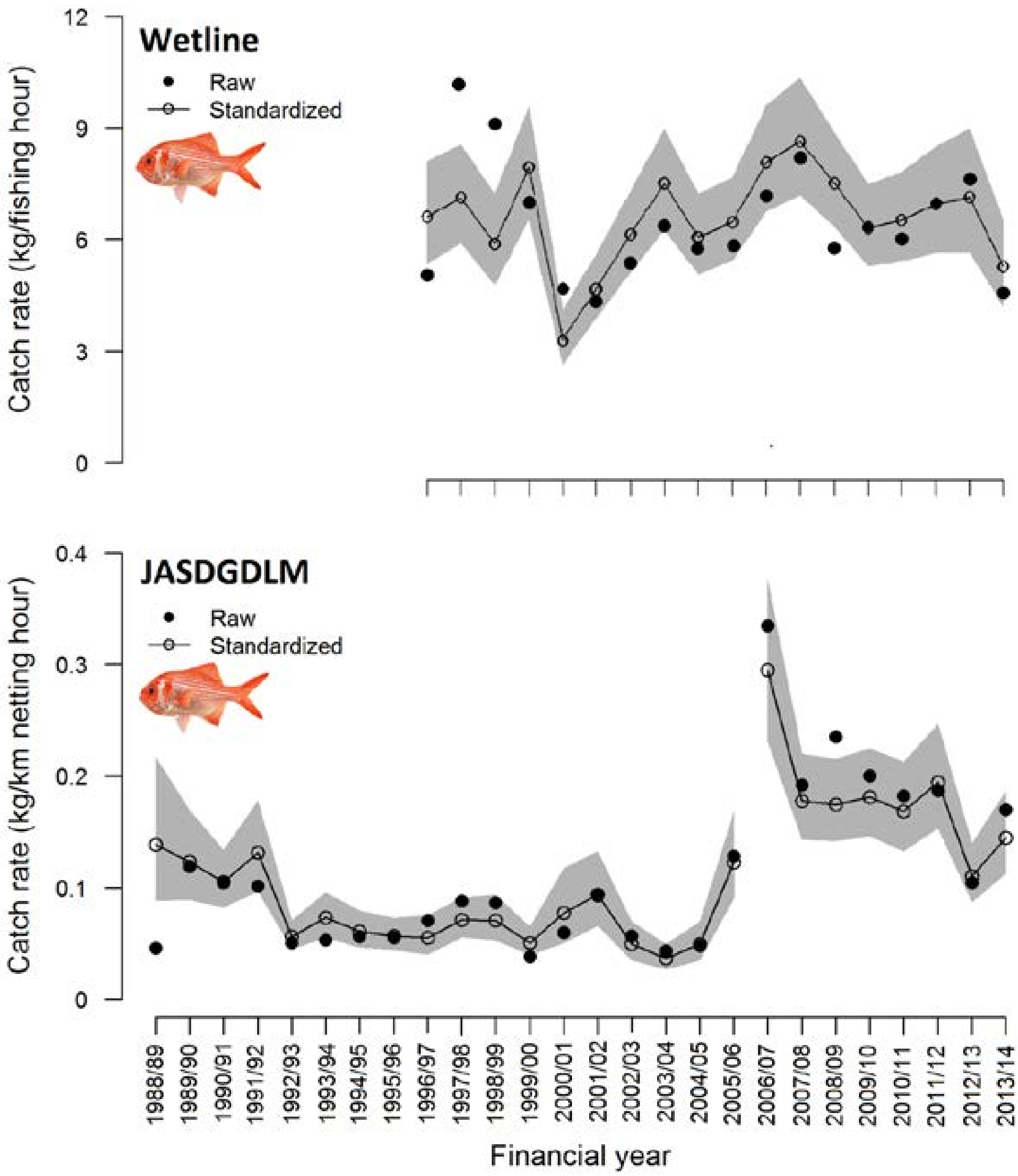


Figure 4.7: Time series of Bight redfish nominal and standardized (± 95% confidence intervals, grey shading) catch rates in the commercial wetline and JASDGDLMF (commercial gillnet) sectors. Catch rates from 2006/07 in the JASDGDLMF were not comparable with earlier years due to transitioning to daily CAES returns.

Length-frequency distributions show the commercial sectors tended to catch larger Bight redfish than the recreational or charter sectors (Figure 4.8), probably due to the use of larger vessels that stay at sea longer and fish in deeper waters where larger/older fish are likely to be

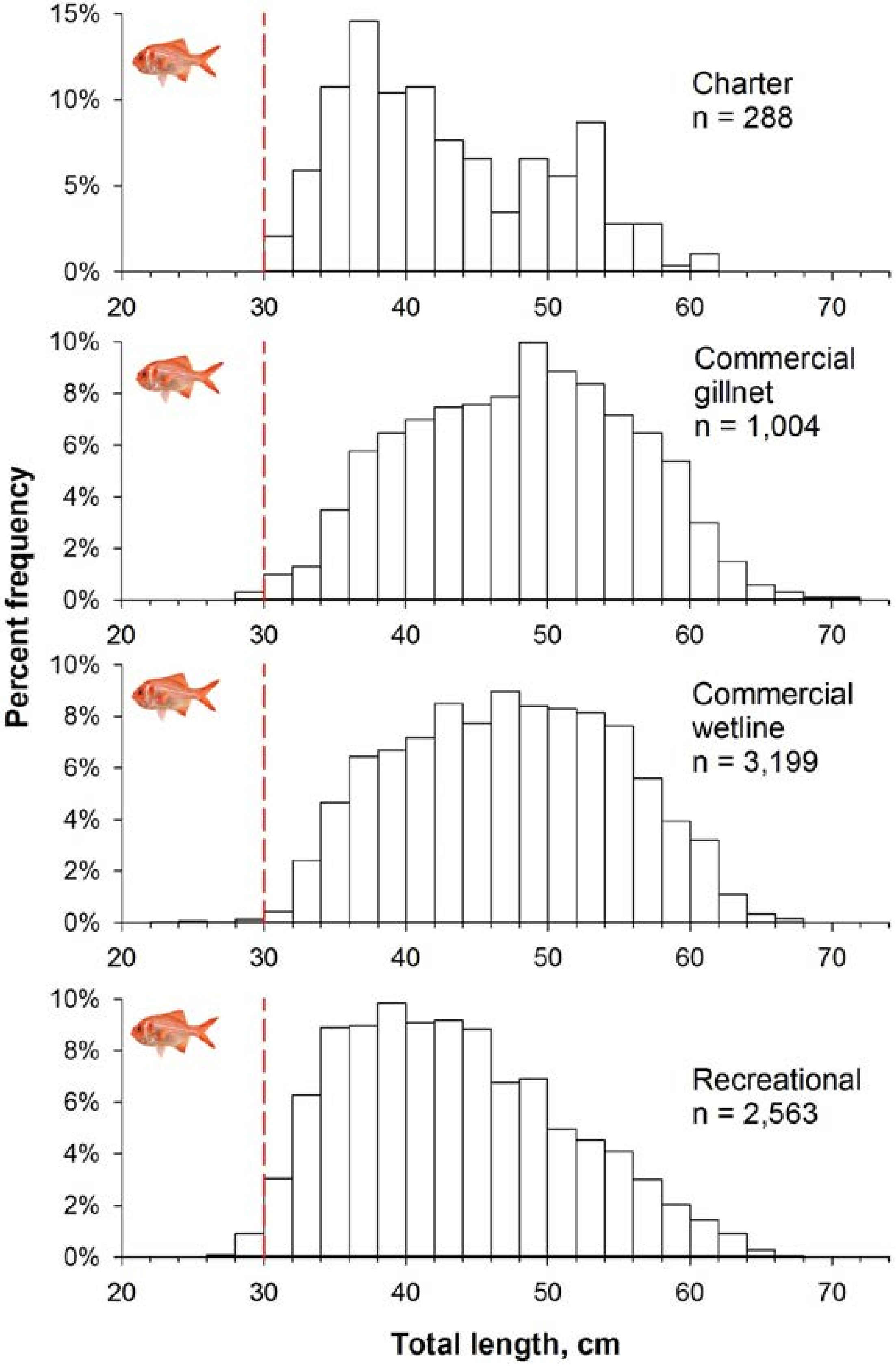


Figure 4.8: Length-frequency distributions of Bight redfish catch samples for each fishery sector from 2012 to 2014. Dashed red line represents minimum legal length of 300 mm TL. n = sample size.

more abundant, as well as the length selectivity of gillnets used by the JASDGDLMF. This conclusion was supported by intra-sector comparisons showing larger fish tended to be caught in the west sub-region compared to the east, for both the wetline and recreational

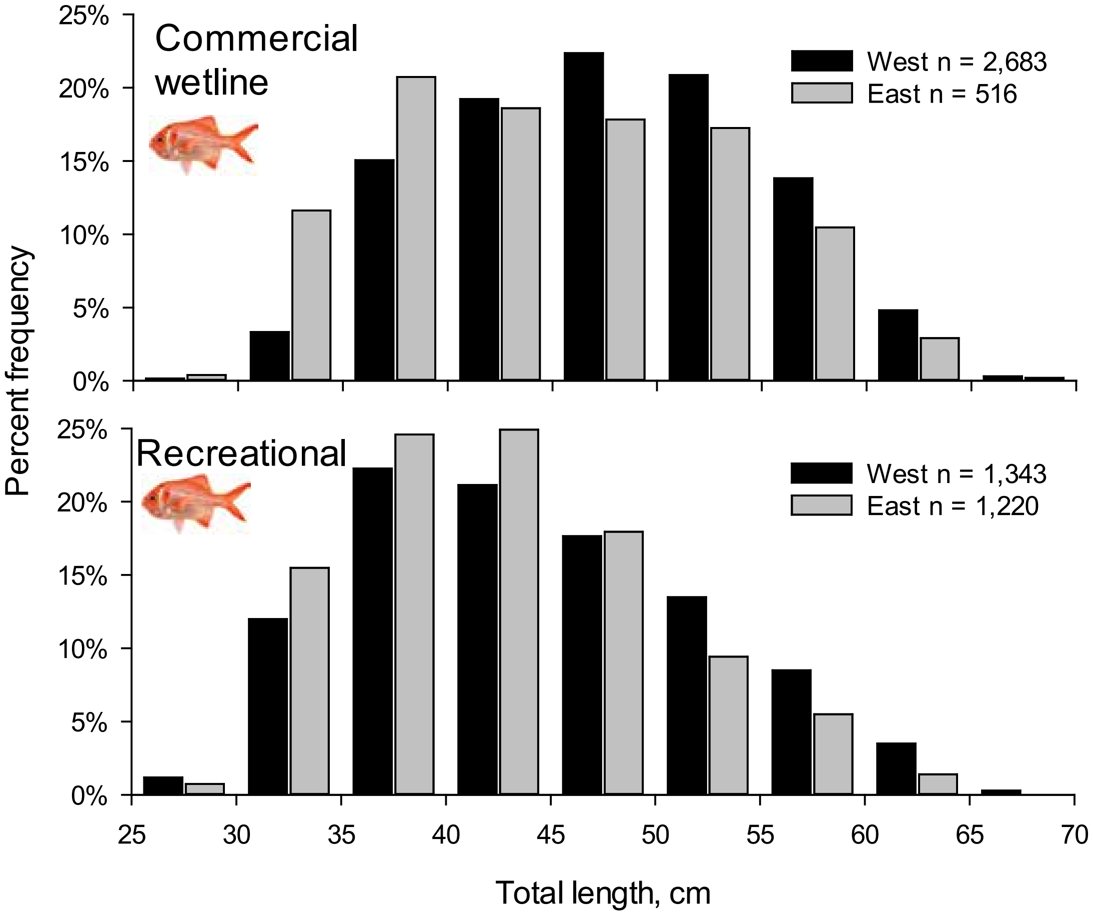


Figure 4.9: Length-frequency distributions from wetline and recreational catch samples between 2012 and 2014 show the west sub-region yielded larger Bight redfish compared to the east, probably due to the narrower width of the continental shelf in the west (shorter distance to deeper waters where larger fish are more common).

sectors (Figure 4.9), where deeper waters (>100 m) are closer to shore due to a narrower continental shelf (Figure 1.1).

Although the commercial gillnet mean of 48.0 cm TL (standard deviation = 7.9, n= 1,004) was 5 cm smaller than that recorded between 1994 and 1999 by observers on board commercial gillnet vessels fishing on the south and lower west coasts, i.e. 53 TL (std dev = 7, n= 399) (McAuley and Simpfendorfer 2003), the current study only included commercial gillnet caught fish from the east sub-region, confounding any comparison due to the length differences between sub-regions described above. Thus the length distribution data provide no evidence of changed abundance of Bight redfish in the SCB.

4.2.3 **Age-based assessment**

Bight redfish can live up to 84 years. The age-frequency distribution of the Bight redfish catches varied among fishery sectors and sub-regions (Figure 4.10). Old fish (>40 years) were present in age samples from all fishing sectors except the charter catch landed at Duke of Orleans Bay, located 60 km to the east of Esperance, and the recreational catch in the east sub-region, much of which was caught in the vicinity of Esperance.

Two possible causes for the young age composition of the east sub-region recreational catch were:

- localised depletion in the vicinity of Esperance caused by fishing.
- size/age based movement from inshore to deeper waters. Given the continental shelf is wider in the east sub-region (Figure 1.1), the recreational sample may have included a greater inshore (depth <100 m) component compared to the recreational sample from the west sub-region, due to the greater distance to deeper waters. Assuming Bight redfish tend to move offshore with increasing size/age, the recreational fishing effort in the east would therefore have been targeted more at the younger, inshore Bight redfish compared to the west-subregion.

While both causes may have contributed to the result, the latter is supported by the even younger age composition of the charter sample from Duke of Orleans Bay (only one of 282 fish >30 years), but where local fishing pressure is likely to be lower than Esperance.

Age frequency distributions of samples from catches taken across the major areas of the stock, including in deeper waters, suggest there have been regular and consistent levels of annual recruitment into this stock over the last two decades. These lines of evidence suggest the overall stock depletion is likely to be at an acceptable level.

The commercial wetline catch from the west sub-region sample provides the most representative age sample of Bight redfish in the SCB, and therefore the most suitable sample for estimating fishing mortality and SPR, due to:

- Intra-sector comparisons of age and length distributions show that a wider, more representative age and length distribution was caught in the west sub-region in both the wetline and recreational sectors. This was probably due to size/age related movement to deeper water and a narrower continental shelf in the west, resulting in a more even distribution of fishing effort in that sub-region.
- A large majority of the catch was from the west sub-region, and the largest catch share was taken by commercial wetliners.
- The commercial gillnet catch share of Bight redfish was the lowest of the four indicator species, and the only age sample available from this sector was from the east

sub-region. As with snapper, gillnet fishers retain this species as a by-product whilst targeting sharks, and thus may not have fished key areas where this species occurs.

- The recreational sector was comprised of smaller vessels fishing predominantly in relatively shallow water and nearer to access points in the main population centres, whereas commercial wetliners were thought to fish across a wider area and depth range of the stock.
- The commercial wetline sample from the west sub-region was easily the largest (n = 2,011) of all sectors in either sub-region, almost twice the size of the next largest sample.

Median estimates of *Z* obtained from the most representative Bight redfish sample (wetline catch from the west sub-region) were similar among the seven catch curve models fitted, ranging from 0.100 to 0.112 year^{-1} (see Appendix 4). The catch curve model considered the most suitable for Bight redfish was the multi-year catch curve with variable recruitment and age-based, logistic selectivity, producing a median *Z* estimate (± 95% confidence intervals) of 0.112 (0.103 to 0.121) year^{-1}. Based on estimates for *M* of 0.049 year^{-1} (Hoenig 1983) and 0.085 year^{-1} (Then *et al.* 2015), *F* was estimated as 0.063 (0.054 to 0.073) year^{-1} and 0.027 (0.018 to 0.037) year^{-1}, respectively. The estimates taken to be most accurate for the current assessment, given the level of uncertainty that exists in relation to the true value of *M*, were those based on simulated values of *M* uniformly distributed between the two estimates:

- $M = 0.067$ (0.050 to 0.084) year^{-1} and
- $F = 0.045$ (0.025 to 0.065) year^{-1}.

Based on these values, the point estimate for F/M of 0.67 was at the target reference level of $F = 2/3M$. Considering the uncertainty around the estimates, there was a 20% chance of *F* breaching the threshold level of $F = M$ and a zero probability of breaching the limit level of $F = 1.5M$ (Figure 4.11a). Thus, the level of fishing mortality for Bight redfish was likely to be at an acceptable level.

Median estimates of the female Bight redfish traditional (SPR1) and extended (SPR2) SPRs were SPR1 = 0.28 (0.25 to 0.33) and SPR2 = 0.22 (0.18 to 0.26) when assuming a Hoenig (1983) estimate of *M*, and SPR1 = 0.64 (0.56 to 0.74) and SPR2 = 0.61 (0.52 to 0.71) when assuming the Then *et al.* (2015) estimate of *M*. The SPR estimates considered most accurate, as it accounts for the substantial uncertainty that exists with respect to the true value for *M*, were based on simulated values of *M* uniformly distributed between the two above *M* estimates:

- SPR1 = 0.45 (0.28 to 0.66) and
- SPR2 = 0.40 (0.22 to 0.63).

As with snapper, the median estimates for SPR produced for Bight redfish by the two methods were similar and neither breached the threshold level of SPR = 0.30. Considering the uncertainty around the estimates, there was a 7% (SPR1) and 25% (SPR2) chance of breaching that threshold, and a <1% chance of breaching the limit (SPR = 0.20) (Figure 4.11b). The SPR for Bight redfish was therefore likely to be at an acceptable level.

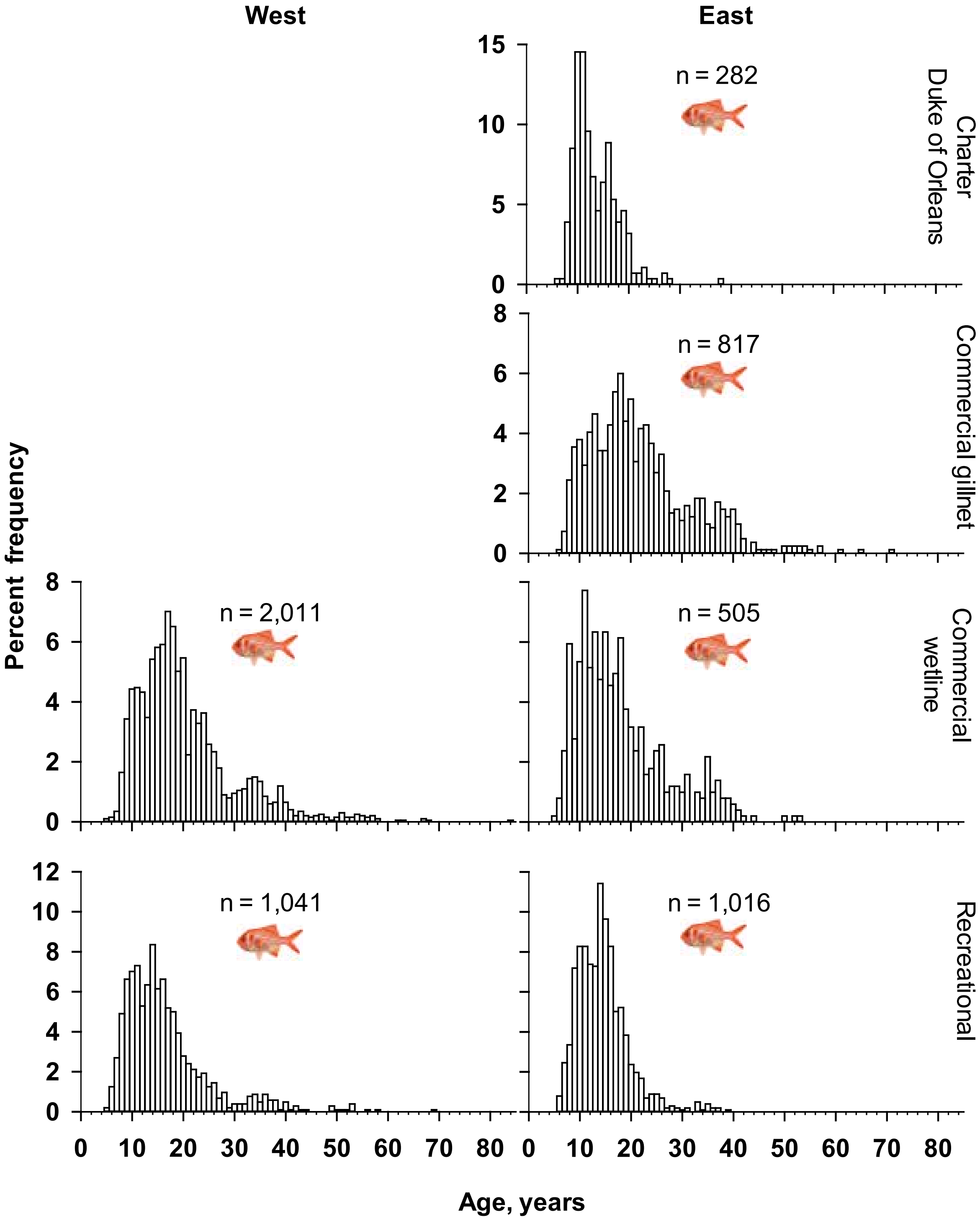


Figure 4.10: Age-frequency distribution of the catch of Bight redfish sampled by sub-region and fishery sector from 2012 to 2014. n = sample size.

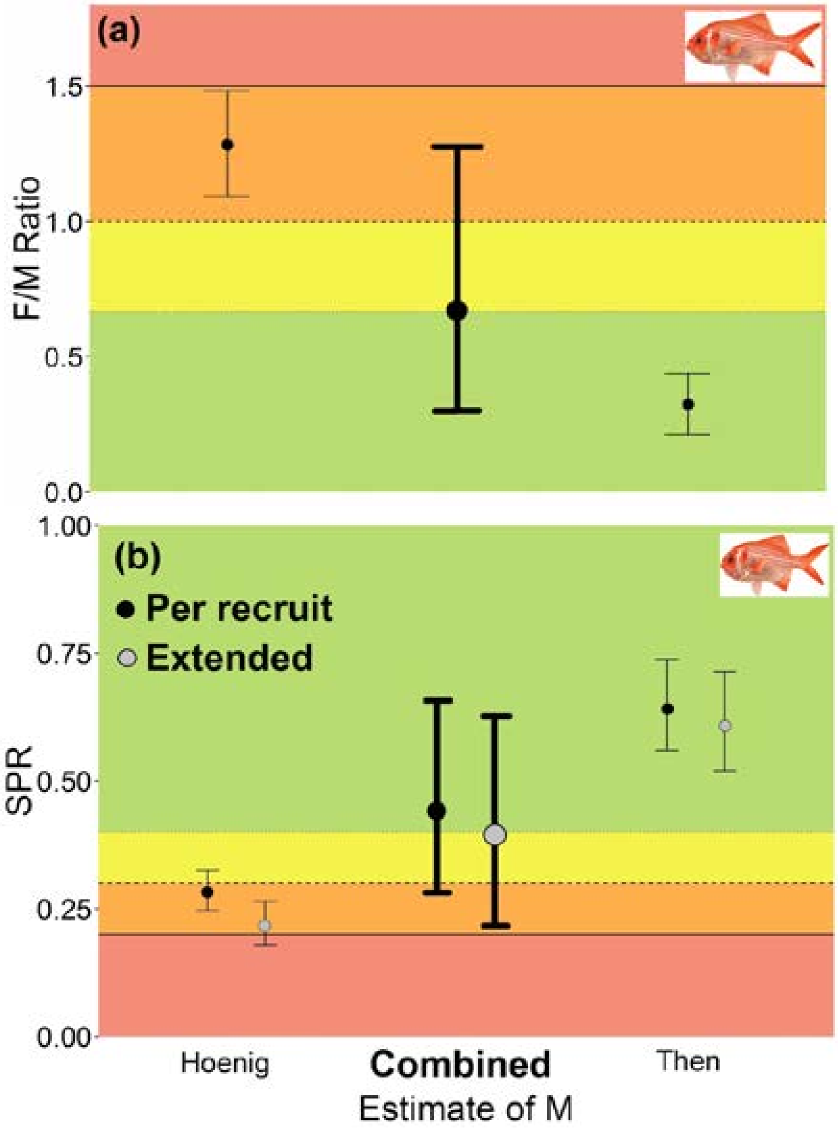


Figure 4.11: Bight redfish: estimates (±95% confidence intervals) of (a) ratio of fishing mortality to natural mortality (*F/M*) (b) female spawning potential ratio (SPR), both derived from a catch curve model fitted to age composition data collected from the commercial wetline fishery in the west sub-region. In (b) SPR estimates were from traditional per recruit analysis and an extended model accounting for impacts of fishing on recruitment. The best estimates of *F* and SPR, denoted by bold error bars, were obtained assuming distribution of *M* values ranging between those estimated by the equations of Hoenig (1983) and Then *et al.* (2015). The dotted, dashed and solid horizontal lines denote the target, threshold and limit reference levels, respectively, for fisheries management purposes, as applied to the management of other, similar demersal scalefish resources in WA.

4.2.4 Conclusion: Bight redfish stock status

The lines of evidence were consistent with the level of depletion of the Bight redfish stock being at an acceptable level in 2013 and 2014. Neither the time series of total catches, catch rates nor the time series of catch distributions offer evidence of unacceptable depletion. While PSA indicates the stock is vulnerable to unacceptable depletion in the future without appropriate fisheries management, this risk is mitigated if appropriate actions are taken (e.g.

Department of Fisheries 2015a). The persistence of old fish in age samples suggests overall depletion has been at an acceptable level, although their absence in some east sub-region samples suggests possible localised depletion and/or age based movement to offshore waters. The strongest lines of evidence were from the age-based estimates of fishing mortality and SPR, because they incorporate a wide range of information on age, growth and reproduction. Both indicate that depletion was at an acceptable level, and is likely to remain so for the next five years if the total catch remains within recent historical levels.

4.3 Blue morwong (*Nemadactylus valenciennesi*)

4.3.1 Biology and inherent vulnerability

Blue morwong in the SCB reach a maximum age of 24 years (this study), are gonochorists (do not functionally change sex) with late onset of sexual maturity typically at about 70 to 75 cm TL and age 7 to 8 years, have moderately fast growth (at age 5 years average total length was 55 cm for females and 58 cm for males) (Coulson *et al.* 2010).

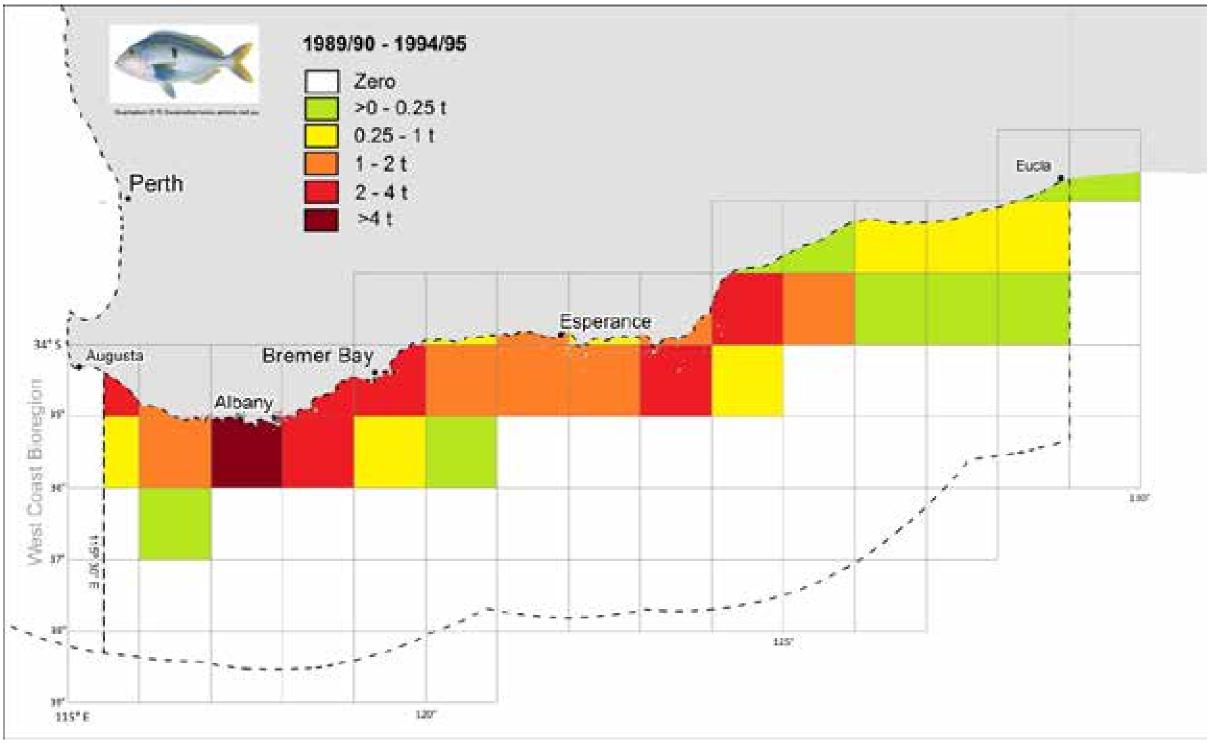
While stock structure with this species remains to be investigated, Coulson *et al.* (2010) suggested connectivity between populations along the lower west coast and south coast of WA. Blue morwong in the WCB and SCB are currently managed as separate management units.

Productivity Susceptibility Analysis (PSA) for blue morwong generated a productivity score of 1.71 and susceptibility score of 2.80, resulting in an overall score of 3.28. The analysis indicates that an unacceptable stock decline is likely without appropriate fisheries management.

4.3.2 Catch and effort

In the 1970s approximately 41 tonnes of blue morwong were taken by exploratory trawling in the GAB (Walker and Clarke 1989), but since then the catch has been dominated by the commercial gillnet sector, taking 20 to 64 t annually since 1990 (Figure 3.1). In comparison the commercial wetline annual catch has fluctuated between 4 and 10 t over the same period. The two annual recreational catch estimates (± standadard error) were also small in comparison at 12.0 (± 1.8) and 7.8 (±0.8) t in the years ended 29 February 2012 and 30 April 2014, respectively (Ryan *et al.* 2013, 2015). The charter sector had the lowest catch share.

The spatial distribution of the commercial gillnet catch of blue morwong has been consistently widespread across the SCB since 1989/90 (Figure 4.12). There was no indication that catch levels have been maintained by a progressive shifting in the areas fished that would be indicative of unacceptable stock depletion.



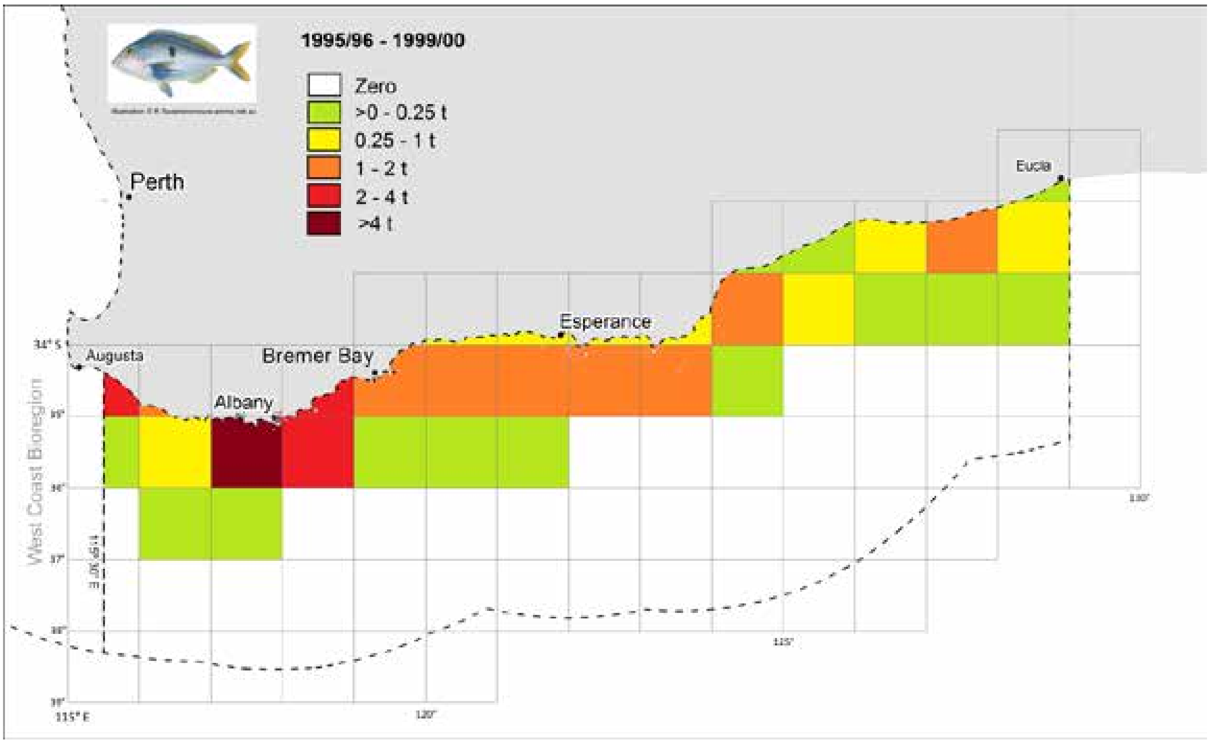
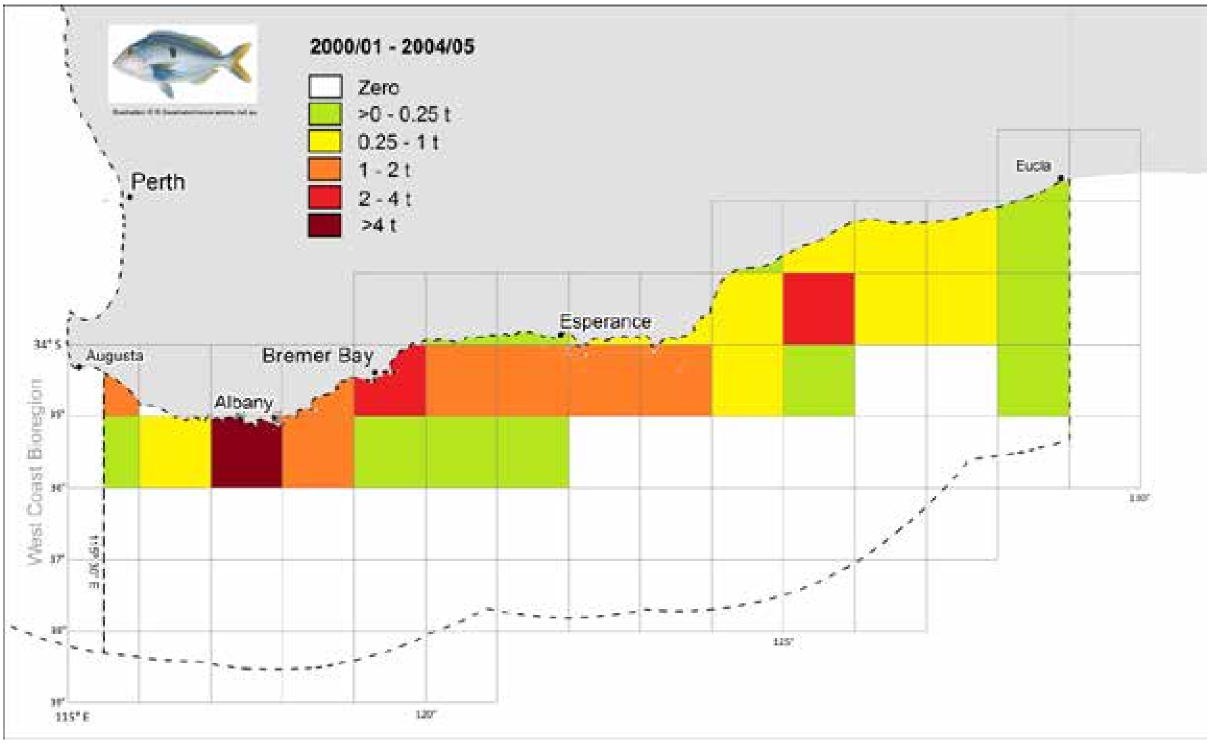


Figure 4.12: Time series of the spatial distribution of average annual commercial gillnet catches of blue morwong in each 1° x 1° block in the South Coast Bioregion, from 1989/90 to 2014/15.



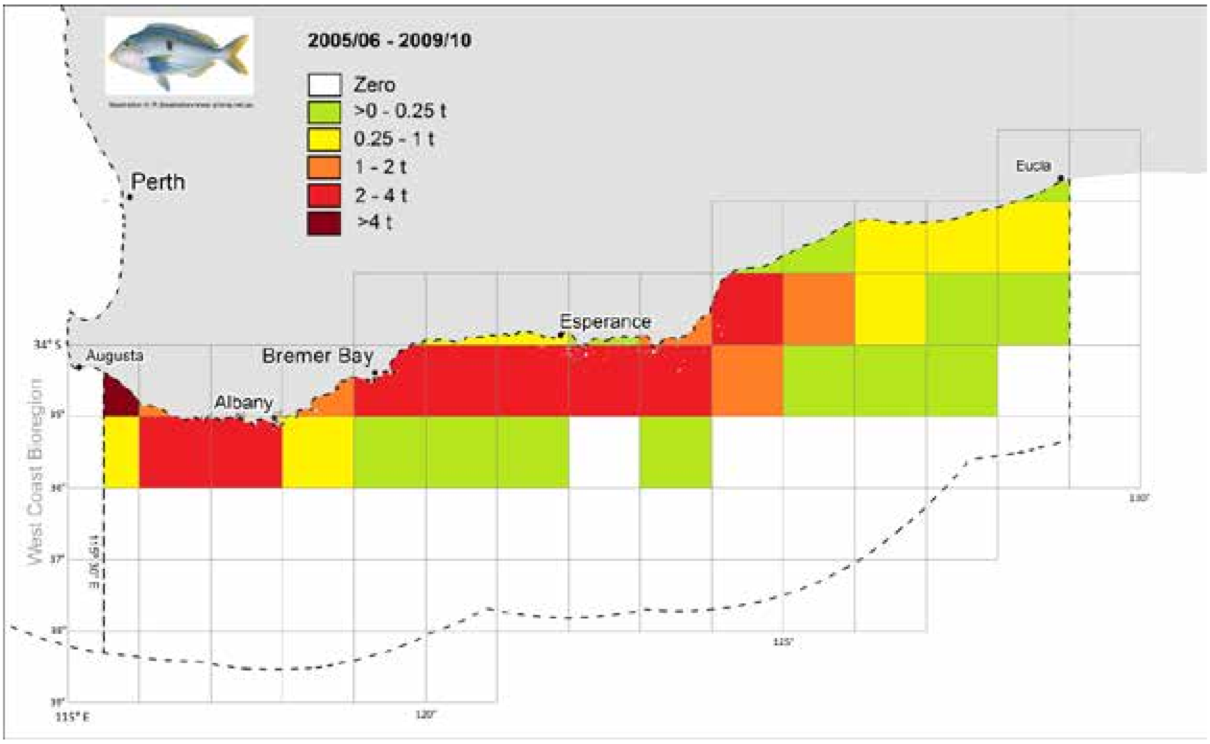


Figure 4.12: Continued.

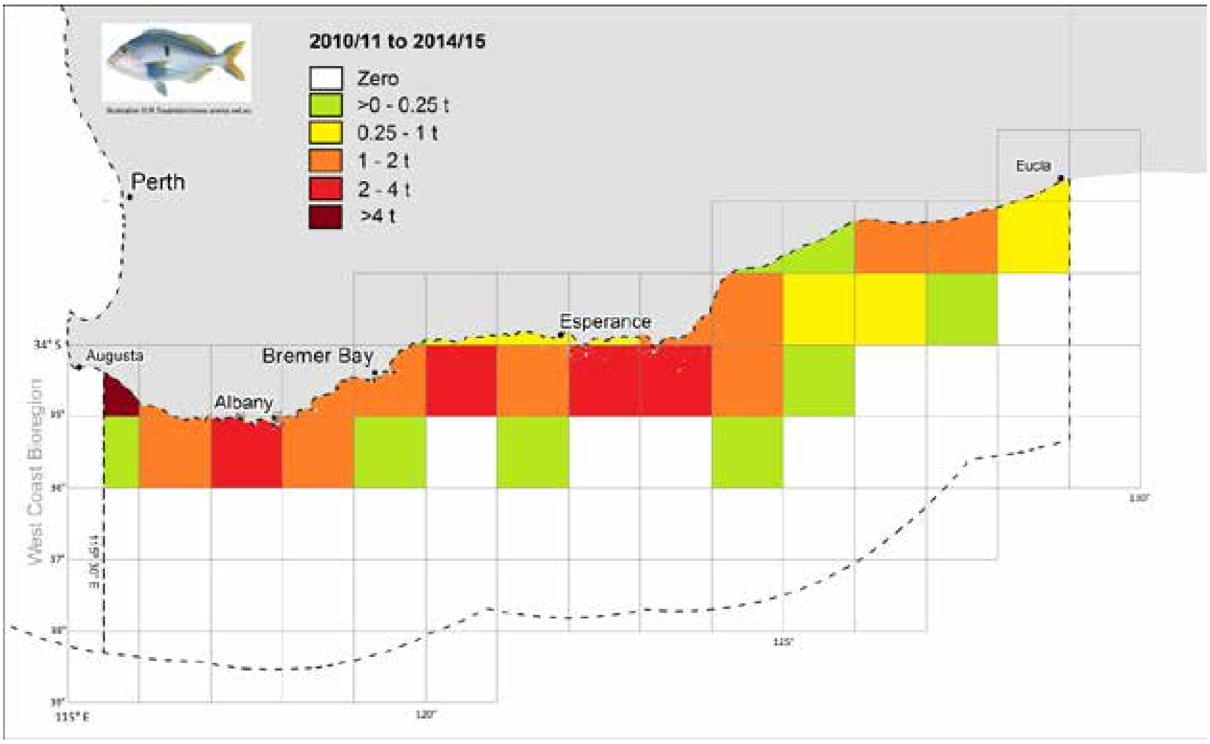


Figure 4.12: Continued.

The length-frequency distribution of the blue morwong sample from the commercial gillnet catch showed 'knife-edge' recruitment to the fishery with respect to length (Figure 4.13). Although the legal minimum length was 410 mm during the sampling period, only 1% of sample were <50 cm TL. The proportion between 55 and 60 cm TL increased rapidly, resulting in the overall catch being dominated by larger fish. This pattern is similar to the length frequency distribution of blue morwong sampled from the commercial gillnet catch on the south and lower west coasts between 1994 and 1999 when a similar gillnet mesh size was used (McAuley and Simpfendorfer 2003). The commercial gillnet length frequency distribution was influenced by the selectivity of the gill net mesh. In comparison the recreational sector, which used hook and line took a greater proportion of smaller fish (<55 cm TL), demonstrating a more gradual recruitment to that sector's catch.

The mean (± standard deviation) length of blue morwong sampled from the commercial gillnet sector between 2012 and 2014 was 68.6 cm TL (± 8.8, n= 1,790), and was similar to:

- 1994 to 1999 length measurements by observers on board commercial gillnet vessels fishing on the south and lower west coasts: mean 66 cm TL (± 8, n= 2,513; McAuley and Simpfendorfer 2003).
- 2004 to 2007 length measurements from commercial gillnet catch sampling from the lower west and south coasts: mean 68.2 cm TL (± 8.5, n= 1,121; Coulson *et al.* 2010).

These consistent length frequency distributions suggest there has been no unacceptable decline of the blue morwong stock in the SCB over the previous two decades.

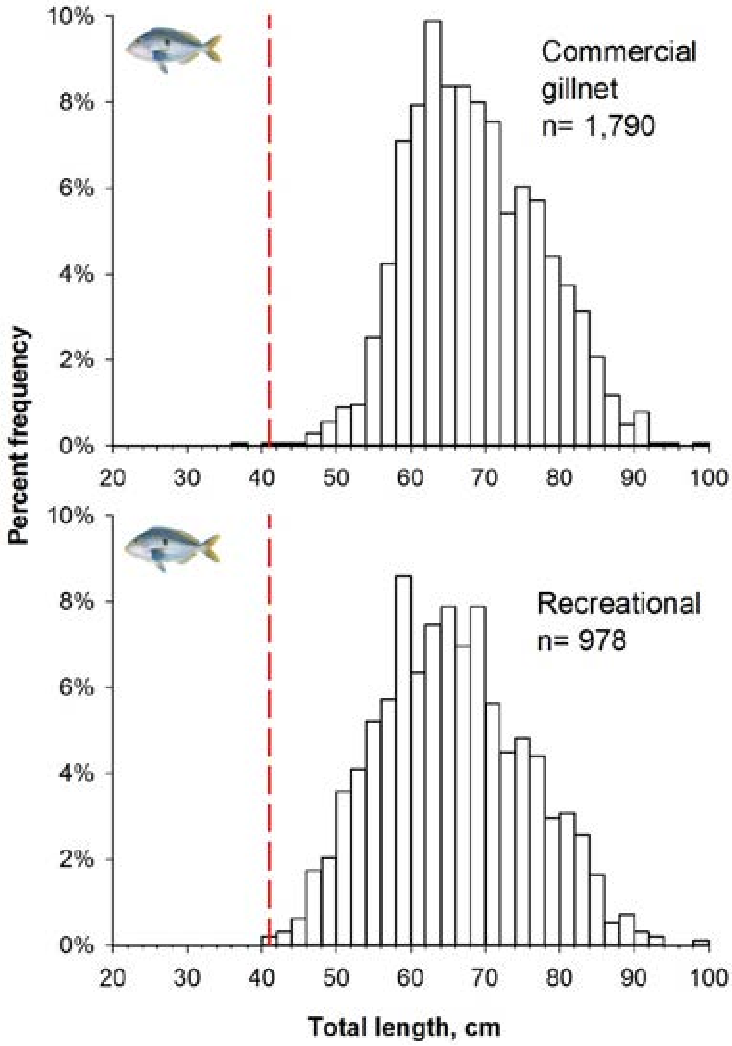


Figure 4.13: Length-frequency distributions for blue morwong sampled from the commercial gillnet and recreational sectors, 2012 to 2014. Dashed red line was the minimum legal length of 410 mm TL.

Although blue morwong are gonochoristic (do not change sex; Coulson *et al.* 2010) catches were dominated by males, whether taken by net or hook and line (Figure 4.14). For fish that could be sexed in the current study, males comprised 70.5% and 61.7% of the catch by the commercial gillnet and recreational sectors respectively. Males attain a larger size (Coulson *et al.* 2010) and because of the exponential relationship between length and weight (Coulson *et al.* 2007) they constituted an estimated 77% and 68% of the total respective catch weights. Assuming the overall reproductive output does not become sperm limited, the male catch bias helps to preserve the blue morwong spawning potential which is set by females, and facilitates a higher sustainable catch level (see also the SPRs given below).

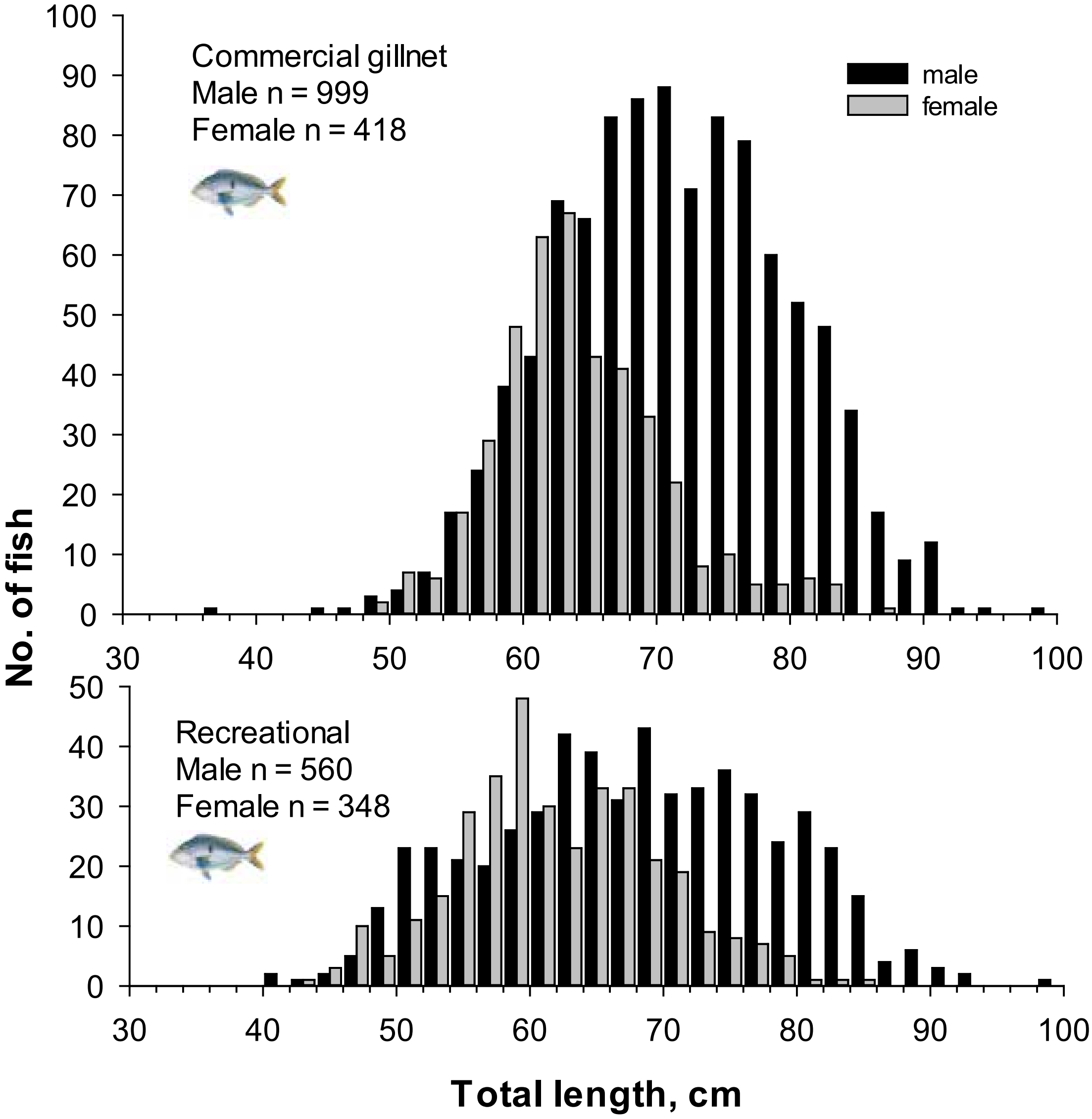


Figure 4.14: Length-frequency distributions of samples collected between 2012 and 2014 show males grow larger and dominate the catch of both the commercial gillnet and recreational sectors.

4.3.3 **Age-based assessment**

Commercial gillnet catches had a younger age-frequency distribution compared to recreational catches with respect to the proportion of fish <6 years (Figure 4.15). This was likely due to the selectivity of the gill net mesh. Age distributions suggest there have been regular and consistent levels of annual recruitment into this stock over the last two decades. Old fish (>13 years) were present in all samples, and the oldest fish encountered (24 years) was three years older than the previously recorded maximum age (Coulson *et al.* 2010). The age data suggest that the stock remains at an acceptable level.

The east sub-region of the commercial gillnet catch was assessed to be the most suitable sample for estimating fishing mortality and SPR due to its large sample size (n = 1,243).

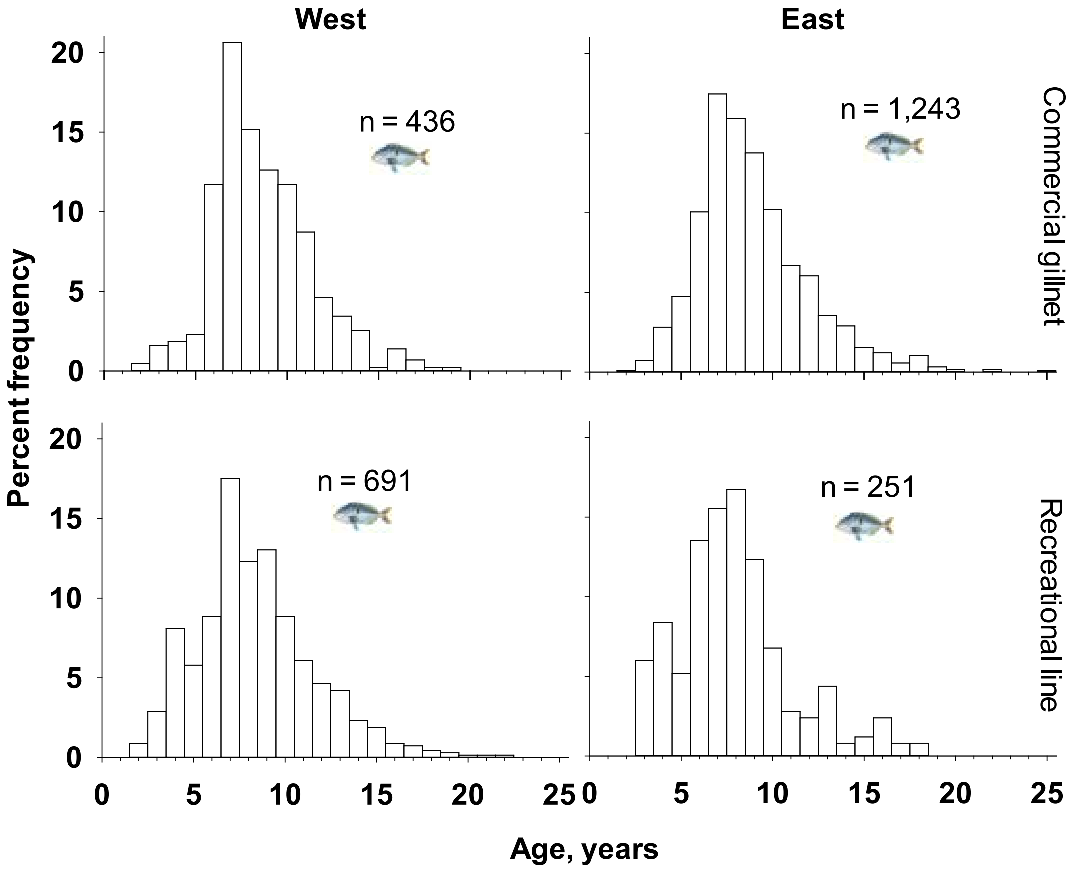


Figure 4.15: Age-frequency distribution of the catch of blue morwong sampled by sub-region and fishery sector from 2012 to 2014. n= sample size.

Interpretation of the commercial gillnet catch curve results for blue morwong was not straightforward. This was because, in contrast to snapper and Bight redfish, the individuals of this species, and particularly its females, which attain a smaller maximum length than males (Coulson *et al.* 2010) do not become fully selected to fishing until they attain a relatively large size. In the gillnet fishery it was >64 cm TL for females and >70 cm TL for males (see Appendix 4). As a result, estimates of (fully-selected) Z produced by the eight catch curve models ranged widely, from 0.25 to 0.48 year^{-1} (see Appendix 4).

The catch curve considered most suitable for blue morwong was the model fitted simultaneously to both age and length data. Despite producing the highest median estimate of Z of all catch curve methods (fully-selected Z = 0.48 (0.40 to 0.56) year^{-1}), this was the only model that assumed a length-based, logistic selectivity. As individuals of this species are not selected by gillnets until they reach a relatively large size, the value for the fully-selected Z was not representative of the mortality experienced, on average, by individuals throughout the entire stock. A more useful measure of mortality was derived by weighting Z according to the estimated spawning stock biomass at age of female and male blue morwong (as estimated in per-recruit analysis). Weighted Z estimates (± 95% confidence intervals) were $Z_{females}$ =

0.30 (0.27 to 0.32) $year^{-1}$ and Z_{males} = 0.38 (0.34 to 0.42) $year^{-1}$. Based on *M* estimates of 0.174 $year^{-1}$ (Hoenig 1983) and 0.267 $year^{-1}$ (Then *et al.* 2015), estimates of $F_{females}$ were 0.13 (0.11 to 0.15) $year^{-1}$ and F_{males} = 0.21 (0.17 to 0.25) $year^{-1}$, and $F_{females}$ = 0.08 (0.06 to 0.10) $year^{-1}$ and F_{males} = 0.15 (0.10 to 0.18) $year^{-1}$, respectively. The estimates taken to be most accurate for the current assessment, given the level of uncertainty that exists in relation to the true value of *M*, were those based on simulated values of *M* uniformly distributed between the Hoenig (1983) and Then *et al.* (2014) estimates:

- M = 0.22 (0.18 to 0.26) $year^{-1}$ and
- $F_{females}$ = 0.106 (0.072 to 0.137) $year^{-1}$ and F_{males} = 0.180 (0.123 to 0.231) $year^{-1}$.

Neither of the resulting point estimates of $F/M_{females}$ = 0.49 (0.28 to 0.76) and F/M_{males} = 0.84 (0.49 to 1.26) breached the threshold reference level of $F = M$ (i.e. $F/M = 1$) (Figure 4.16a). Considering the uncertainty around these estimates, the probability of breaching the threshold level was zero for females and 25% for males, with a zero probability of either sex breaching the limit level of $F = 1.5M$. Thus, the level of fishing mortality for blue morwong was likely to be at an acceptable level.

Due to the marked differences in growth of female and male blue morwong, estimates of both female and male SPR were calculated for this species. Median estimates of female and male traditional (SPR1) and extended (SPR2) SPRs varied depending on whether the Hoenig (1983) or Then *et al.* (2015) estimate of *M* was used (Figure 4.16b). The estimates considered most accurate were based on unweighted *Z* estimates and simulated values of *M* uniformly distributed between the two above *M* estimates, resulting in:

- Females: SPR1 = 0.58 (0.46 to 0.71), SPR2 = 0.54 (0.41 to 0.68) and
- Males: SPR1 = 0.36 (0.25 to 0.51), SPR2 = 0.34 (0.23 to 0.50).

The median estimates for female and male SPR never breached the threshold reference level of SPR = 0.30. Considering the uncertainty around these estimates, there was an almost zero chance of the female SPR breaching the threshold, while there was a 19% (SPR1) and 31% (SPR2) chance of the male SPR breaching that threshold. There was an almost zero chance of the SPR of either sex breaching the limit reference level of SPR = 0.20 (Figure 4.16b). The female SPR was therefore likely to be at an acceptable level. The whole of stock SPR was also likely to be at an acceptable level, as the male SPR estimates and the high frequency of males in the catch indicate sperm limitation was unlikely.

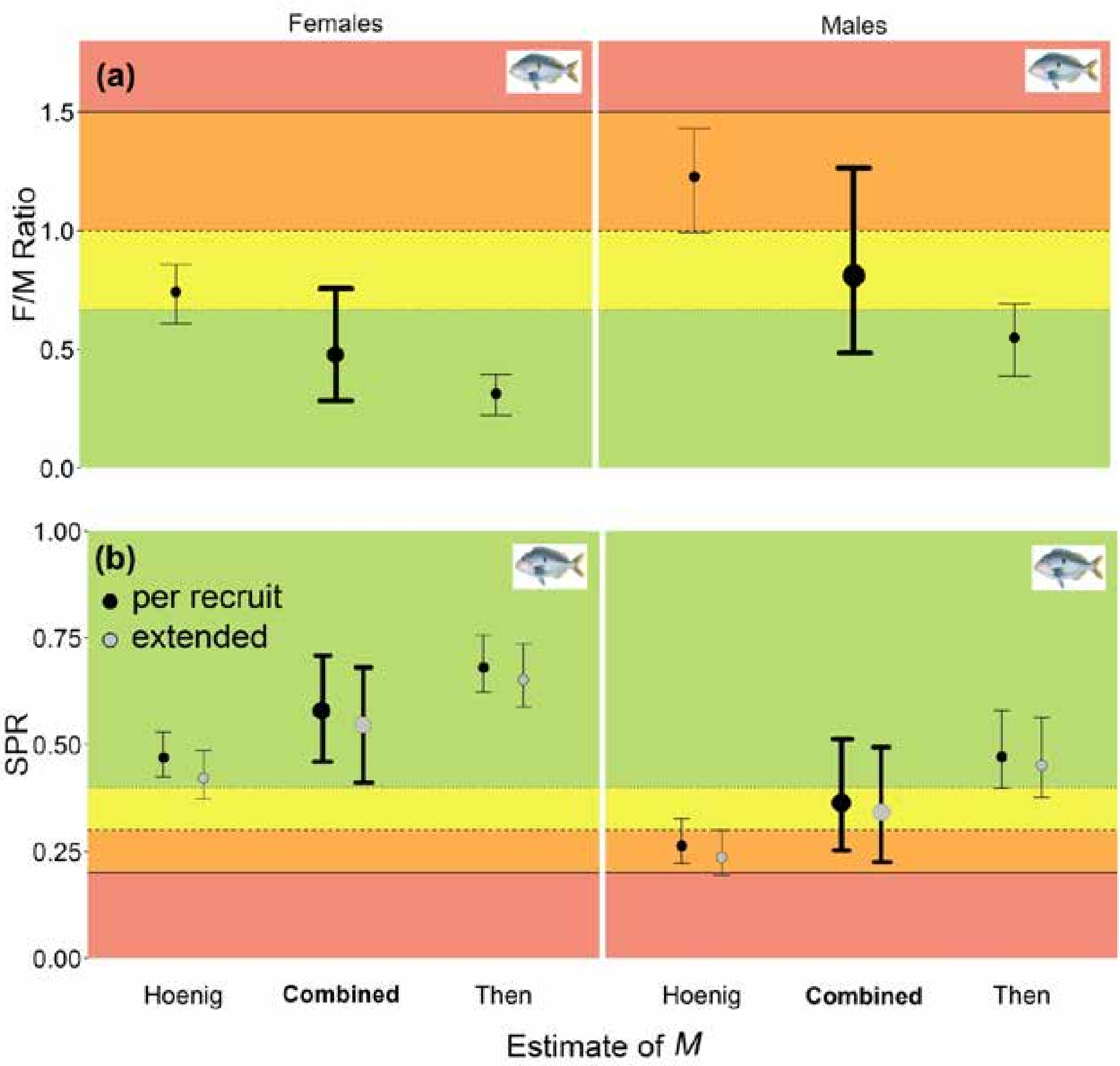


Figure 4.16: Blue morwong: estimates (±95% confidence intervals) of (a) ratio of fishing mortality to natural mortality (*F/M)* (b) spawning potential ratio (SPR), both derived from a catch curve model fitted to age composition data collected from the commercial gillnet fishery in the east sub-region. In (b) SPR estimates were from traditional per recruit analysis and an extended model accounting for impacts of fishing on recruitment. The best estimates of *F* and SPR, denoted by bold error bars, were obtained assuming distribution of *M* values ranging between those estimated by the equations of Hoenig (1983) and Then *et al.* (2015). The dotted, dashed and solid horizontal lines denote the target, threshold and limit reference levels, respectively, for fisheries management purposes, as applied to the management of other, similar demersal scalefish resources in WA.

4.3.4 **Conclusion: Blue morwong stock status**

The lines of evidence were consistent with the level of depletion of the blue morwong stock being an acceptable level. Neither the time series of total catches, catch rates nor the time series of catch distributions offer evidence of unacceptable depletion. While PSA indicated that an unacceptable stock decline is likely without appropriate fisheries management, this risk is mitigated if appropriate actions are taken. The presence of old fish in age samples, and the consistent length distributions in commercial gillnet catches over the last two decades suggest that the stock remains was at an acceptable level in 2013 and 2014. The strongest lines of evidence were from the age-based estimates of fishing mortality and SPR, because they incorporate a wide range of information on age, growth, reproduction and fishery operations. Both indicate that depletion remains at an acceptable level and is likely to remain so for the next five years if the total catch remains within recent historical levels.

4.4 Western blue groper (*Achoerodus gouldii*)

4.4.1 Biology and inherent vulnerability

The western blue groper is a protogynous hermaphrodite (some change sex from female to male) that can reach ~40 kg, with exceptional longevity (70 years), slow growth rate, late onset of sexual maturity (~17 years) at a large total length (~65 cm), very late sex change (age ~35 years) at a very large total length (~82 cm), and highly variable inter-annual recruitment (Coulson *et al.* 2009). During sub-adulthood there is a migration from inshore protected habitats to deeper (up to 20 m) waters with increasing bottom relief, but they otherwise maintain small home ranges (Shepherd and Brook 2007, Bryars *et al.* 2012), making them vulnerable to localised depletion from overfishing. In South Australia there was an negative correlation between an index of local fishing intensity and the abundance of sub-adults and adults, and sub-adult length (Shepherd and Brook 2007). Western blue groper are reportedly indifferent to the presence of spear fishers, or even inquisitive, enabling highly size selective fishing by that sector. Coulson *et al.* (2009) assessed western blue groper in southwestern Australian waters to be close to or at full exploitation based on samples collected between 2004 and 2007.

Western blue groper in the SCB are currently treated as a discrete management unit.

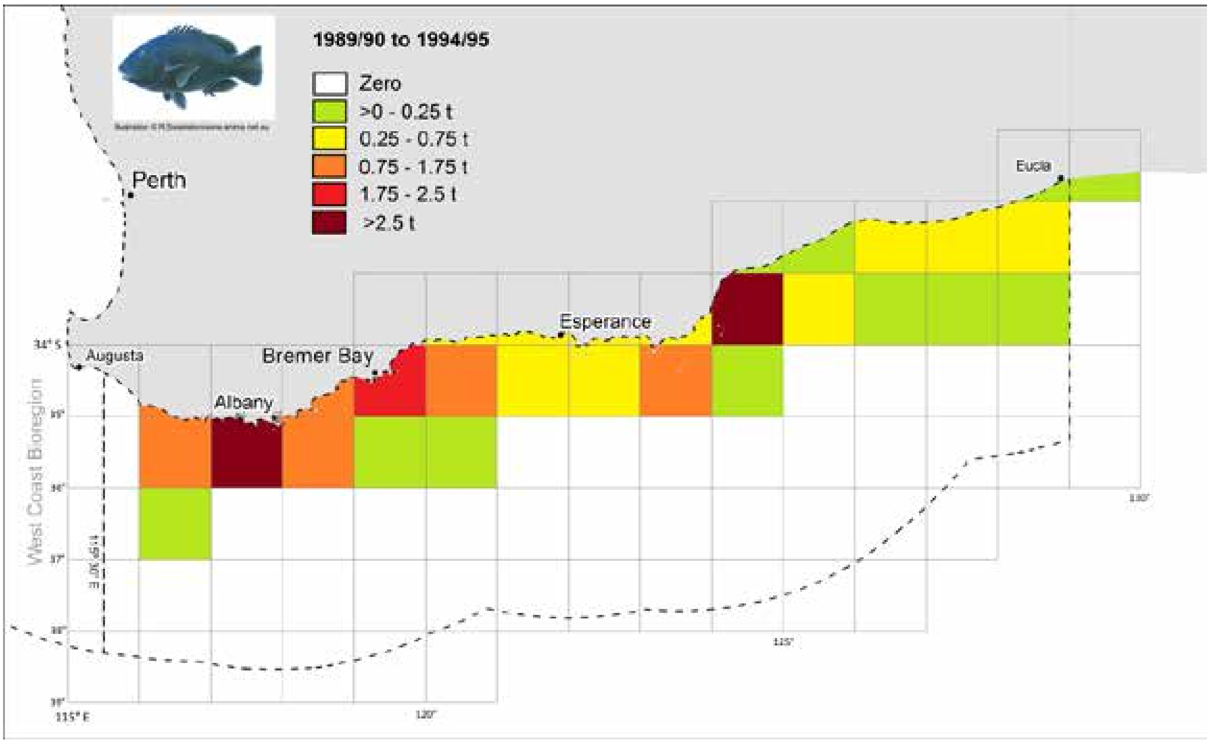
Western blue groper therefore has a very high inherent vulnerability to overfishing. Productivity Susceptibility Analysis (PSA) generated a productivity score of 2.14 and susceptibility score of 2.96, resulting in an overall score of 3.65, suggesting an unacceptable stock decline would be likely without appropriate fisheries management.

4.4.2 Catch and effort

Since commercial catch records commenced in 1975, over 90% of the western blue groper catch has been taken by the commercial gillnet sector (Figure 3.1). Initially, annual catches in this sector were <1 tonne until an increase to 5 t in 1987/88 and then 39 t in 1989/90. Catches then ranged between 16 and 33 t until a peak of 48 t in 2008/09. Over the last four years they have been within the historical range at 28 to 37 t. Wetline catches have always been relatively minor. The estimated (±standard error) boat based recreational catch, in number of fish (weights estimates are unavailable), was also low at 393 (±136) for the year ended 29 Feb 2012 (Ryan *et al*. 2013), and 104 (±34) for the year ended 30 Apr 2014 (Ryan *et al.*

2015). Western blue groper are also targeted by spear fishers (Figure 4.17). Charter catches were also relatively low from 2006 to 2014: annual mean = 150 kg, range 44 to 264 kg. Catch history provides no indication of an unacceptable stock decline.

There has been a somewhat even spatial distribution of the commercial gillnet catch since 1989/90, with the exception of relatively low catches east of 125° E (Figure 4.17). There was no indication that catch levels have been maintained by a progressive shifting of the areas fished that would be indicative of unacceptable stock depletion.



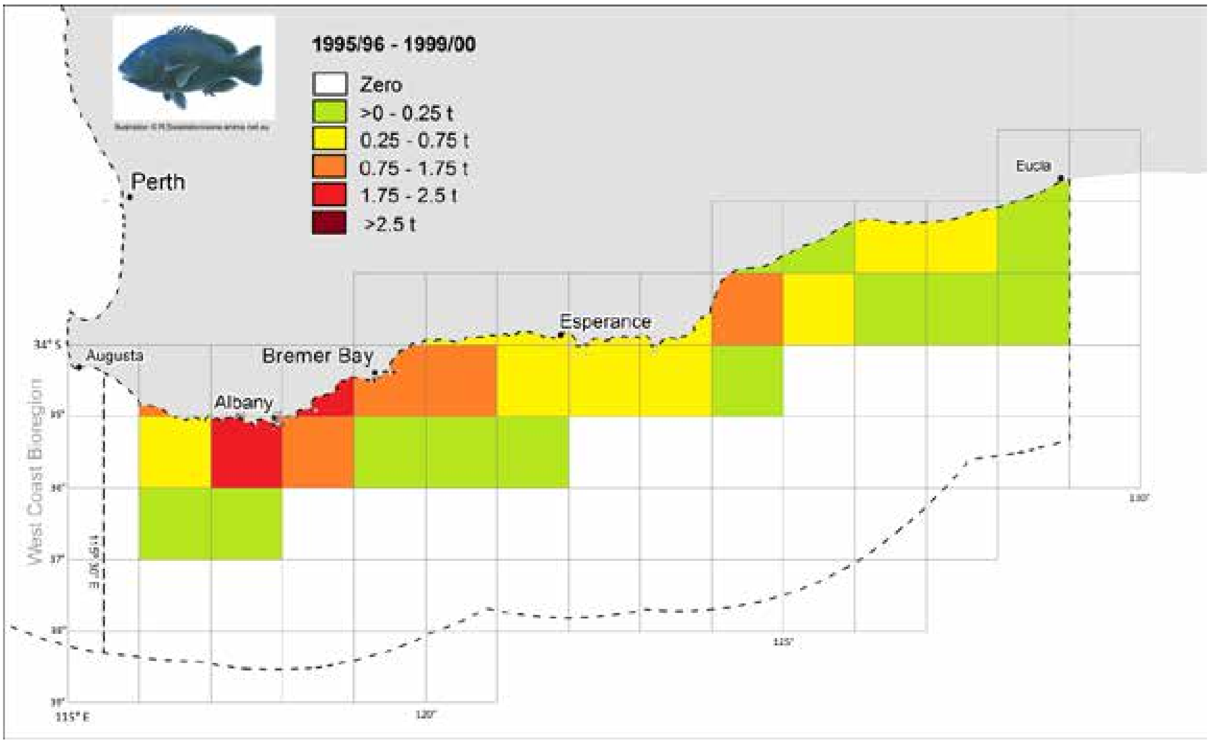
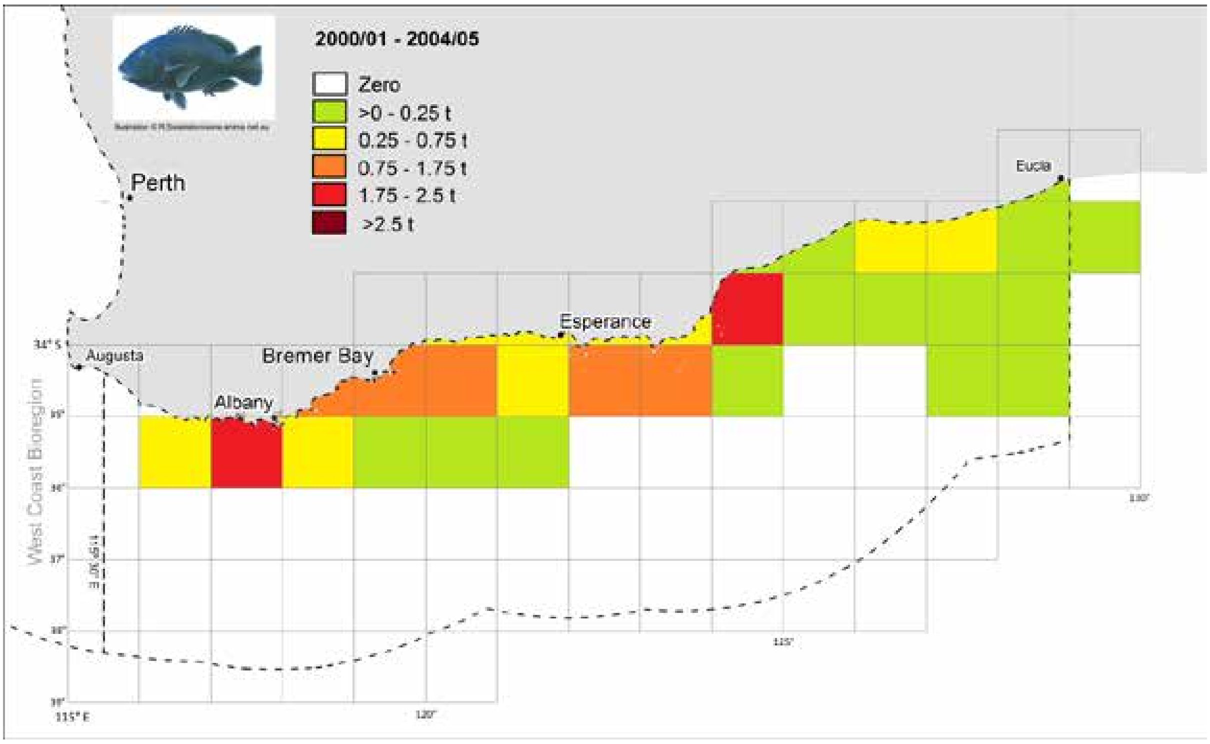
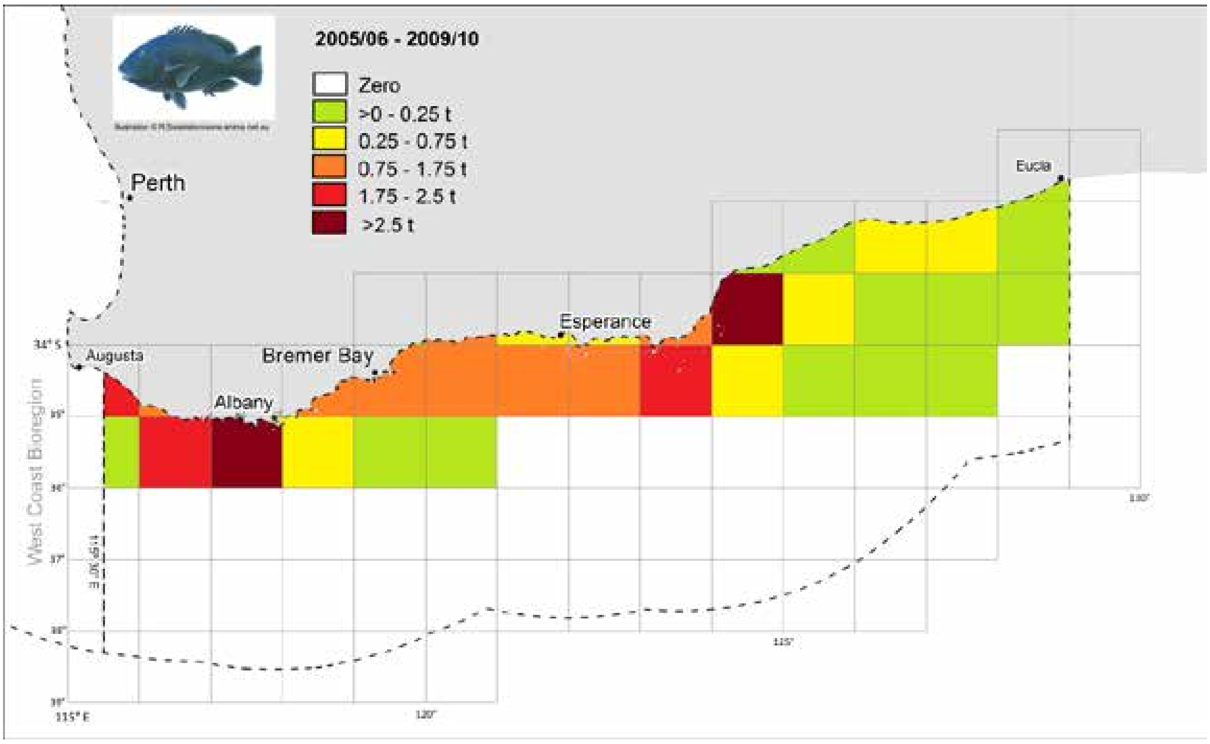


Figure 4.17: Time series of the spatial distribution of average annual commercial gillnet catch of western blue groper in each 1° x 1° block in the South Coast Bioregion, from 1989/90 to 2014/15.





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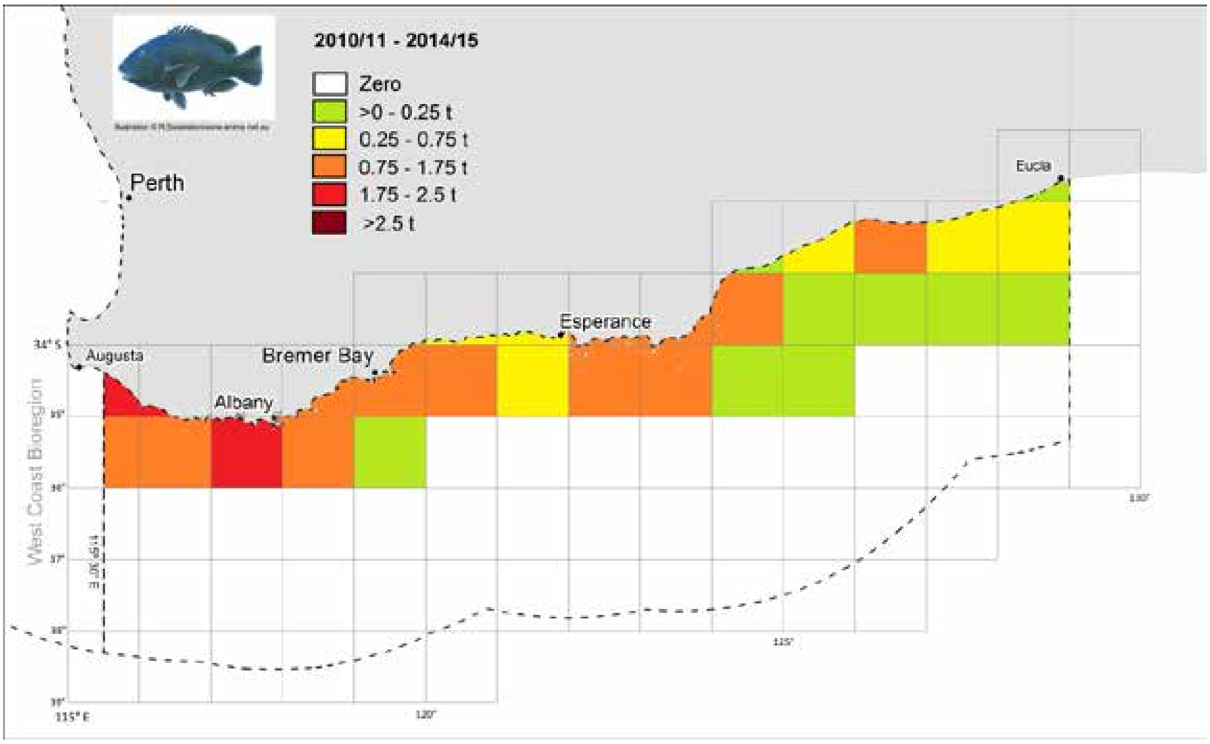

Figure 4.17: Continued.

The western blue groper sample in the current study was entirely from the east sub-region, and was dominated by females (81% female, 10% male and 9% unknown or transitional). Lengths ranged from 436 to 1,119 mm TL, with 94% between 500 and 900 mm TL (Figure 4.18). The mean (± standard deviation) TL of western blue groper from the commercial gillnet sector was 65.1 cm (±10.8, n= 736), similar to:

- 1994 to 1999 length measurements by observers on board commercial gillnet vessels fishing on the south and lower west coasts: mean 65 cm TL (± 9, n= 895; McAuley and Simpfendorfer 2003); and

- 2004 to 2007 length measurements from commercial gillnet catch sampling predominantly (~97%) from the south coast: mean 67.1 cm TL (± 12.1, n= 1,106; Coulson *et al.* 2009).

These consistent length frequency distributions suggest there has been no unacceptable decline of the east sub-region stock of western blue groper over the previous two decades.

4.4.3 **Age-based assessment**

The age-based stock assessment of western blue groper was based on the only sample available for this species, from the commercial gillnet catch in the east sub-region (Figure 4.19). Older fish (>35 years) were present and the oldest fish (71 years) surpassed the previously known maximum age (70 years, Coulson *et al.* 2009), suggesting that stock depletion was at an acceptable level.

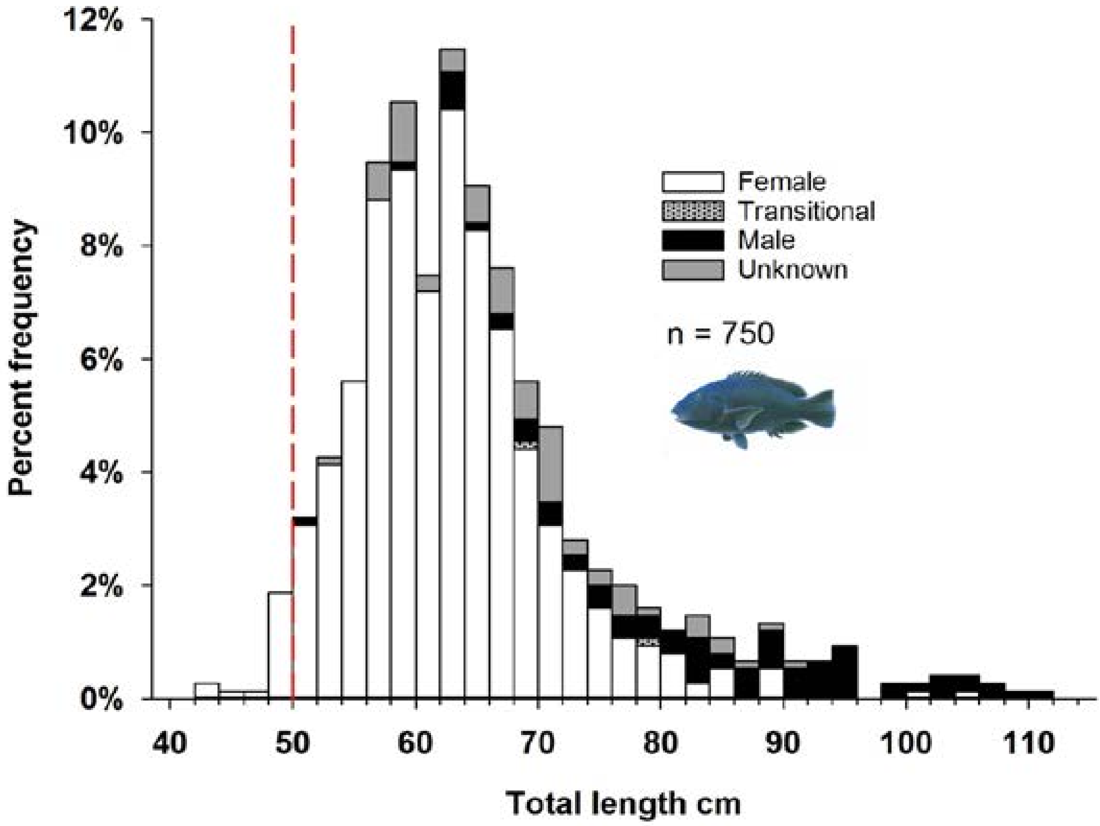

Figure 4.18: Length-frequency distribution of western blue groper sampled from the commercial gillnet sector from the east sub-region. Dashed red line was the minimum legal length of 500 mm TL.

The median estimates of Z for western blue groper from the eight catch curve analyses used ranged from 0.058 to 0.104 year^{-1} (see Appendix 4). The multi-year catch curve model that accounts for recruitment variability was considered the most appropriate for this species and produced a median Z estimate (± 95% confidence intervals) of 0.101 (0.088 to 0.114) year^{-1}, similar to Coulson *et al.*'s (2009) estimate of Z = 0.093 year^{-1} from catch sampling between 2004 and 2007 and using relative abundance analysis and assuming variable recruitment. Based on estimates for M of 0.058 year^{-1} (Hoenig 1983) and 0.099 year^{-1} (Then *et al.* 2015), F was estimated as 0.043 (0.029 to 0.057) year^{-1} and 0.006 (0 to 0.017) year^{-1}, respectively. The estimates taken to be most representative of the stock, given the level of uncertainty that exists in relation to the true value of M, were those based on simulated values of M uniformly distributed between the Hoenig (1983) and Then et al. (2014) estimates, resulting in:

- M = 0.077 (0.059 to 0.097) year^{-1} and
- F = 0.023 (0.002 to 0.047) year^{-1}.

Based on these value, the point estimate of F/M of 0.30 was well below the target reference levels of $F = 2/3M$ (i.e. F/M = 0.67), with an almost zero probability of beaching the threshold level of $F = M$ (Figure 4.20 a). Thus, the level of fishing mortality for western blue groper was likely to be at an acceptable level.

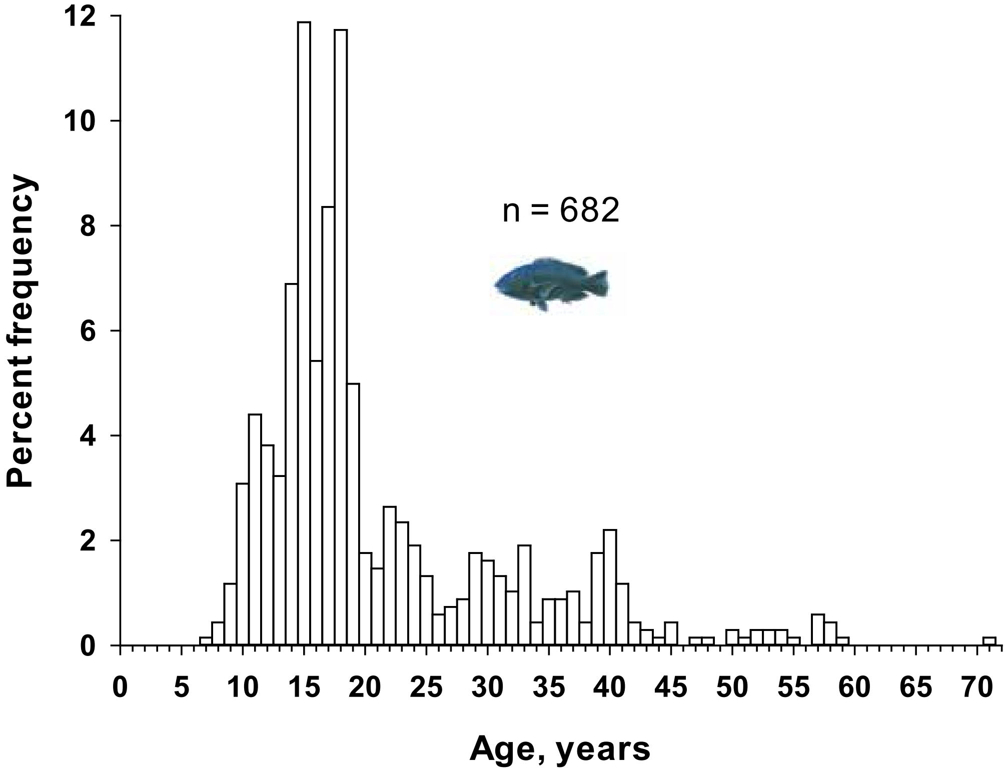

Figure 4.19: Age-frequency distribution of western blue groper taken by the commercial gillnet sector from the east sub-region in 2013 and 2014. N=sample size.

As some western blue groper change sex from females to males, estimates of female and male SPR were calculated separately for this species. Median estimates of female traditional (SPR1) and extended (SPR2) SPRs for western blue groper were SPR1 = 0.54 (0.46 to 0.64) and SPR2 = 0.50 (0.41 to 0.61) when assuming a Hoenig (1983) estimate of *M*, and SPR1 = 0.94 (0.82 to 1.00) and SPR2 = 0.93 (0.81 to 1.00) when assuming the Then *et al.* (2015) estimate of *M* (Figure 4.3.5b). Median estimates of male SPRs were much lower compared to females; SPR1 = 0.25 (0.17 to 0.38) and SPR2 = 0.23 (0.15 to 0.36) when assuming a Hoenig (1983) estimate of *M*, and SPR1 = 0.86 (0.63 to 0.99) and SPR2 = 0.85 (0.61 to 0.99) when assuming the Then *et al.* (2015) estimate of *M* (Figure 4.20 b). The estimates considered most accurate were based on simulated values of *M* uniformly distributed between the two above *M* estimates, resulting in:

- Females: SPR1 = 0.74 (0.52 to 0.97), SPR2 = 0.71 (0.48 to 0.97) and
- Males: SPR1 = 0.49 (0.23 to 0.94), SPR2 = 0.48 (0.21 to 0.93).

While the point estimates for female SPR for western blue groper never breached the threshold reference level of SPR = 0.30, there was a 14% (SPR1) and 18% (SPR2) probability of the male SPR breaching that threshold, and a low (1-2%) probability of breaching the limit level of SPR = 0.20 (Figure 4.20 b). Although the proportion of males in the gillnet catch was low (~11%), it was similar to results from catch sampling in 2004-2007, (Coulson *et al.* 2009) and facultative sex change may occur in this species, suggesting recruitment was not constrained by sperm limitation. The SPR for female and male western blue groper were therefore likely to be at an acceptable level.

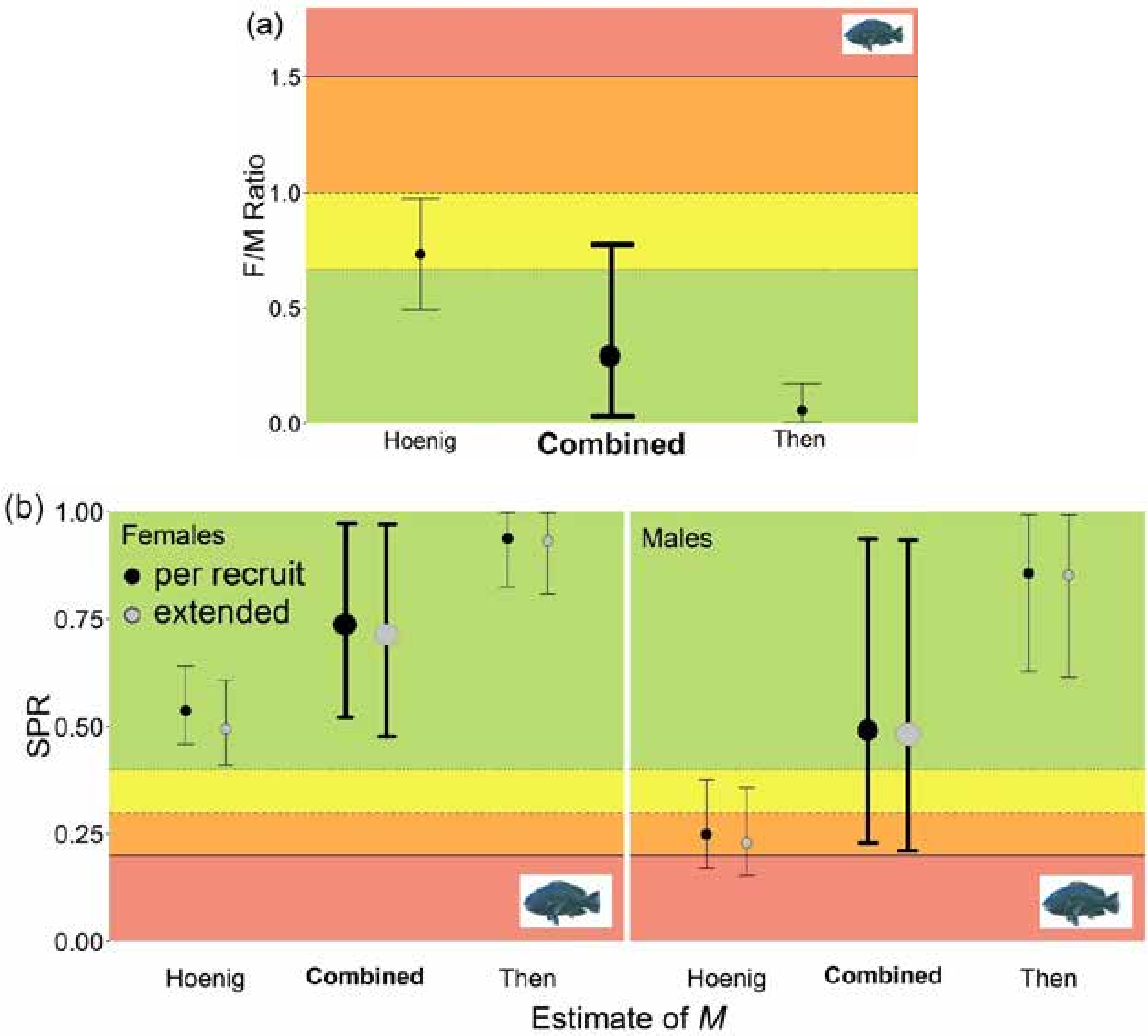

Figure 4.20: Western blue groper: estimates (±95% confidence intervals) of (a) ratio of fishing mortality to natural mortality (*F/M*) (b) spawning potential ratio (SPR), both derived from a catch curve model fitted to age composition data collected from the commercial gillnet fishery in the east sub-region. In (b) SPR estimates were from traditional per recruit analysis and an extended model accounting for impacts of fishing on recruitment. The best estimates of *F* and SPR, denoted by bold error bars, were obtained assuming distribution of *M* values ranging between those estimated by the equations of Hoenig (1983) and Then *et al.* (2015). The dotted, dashed and solid horizontal lines denote the target, threshold and limit reference levels, respectively, for fisheries management purposes, as applied to the management of other, similar demersal scalefish resources in WA.

4.4.4 **Conclusion: Western blue groper stock status**

The lines of evidence were consistent with the level of depletion of the western blue groper stock being at an acceptable level. Neither the time series of total catches, catch rates nor the time series of catch distributions offer evidence of unacceptable depletion. While PSA indicated the stock is vulnerable without appropriate fisheries management, this risk is mitigated if appropriate actions are taken. The persistence of old fish in the age sample, and the consistent length distributions in the commercial gillnet catch over the last two decades suggests that the stock remains at an acceptable level. The strongest lines of evidence were from the age-based estimates of fishing mortality and SPR because they incorporate a wide range of information on age, growth, and fishery operations. Both indicate that depletion remains at an acceptable level and is likely to remain so for the next five years if the total catch remains within recent historical levels.

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Appendix 1

Consequence, Likelihood and Risk Levels (based on AS 4360 / ISO 31000) considered in the Department's Risk Assessment Framework

Adapted from Fletcher (2005, 2015).

CONSEQUENCE LEVELS

1. Minimal – Measurable but minor levels of depletion of fish stock
2. Moderate – Maximum acceptable level of depletion of stock
3. High – Level of depletion of stock unacceptable but still not affecting recruitment level of the stock
4. Major – Level of depletion of stock are already, or will definitely, affect future recruitment potential level of the stock
5. Catastrophic – Permanent or widespread and long-term depletion of key fish stock, close to extinction levels

LIKELIHOOD LEVELS

1. Remote – Never heard of but not impossible here (< 5 % probability)
2. Unlikely – May occur here but only in exceptional circumstances (> 5 %)
3. Possible – Clear evidence to suggest this is possible in this situation (> 30 %)
4. Likely – It is likely, but not certain, to occur here (> 50 %)
5. Certain – It is almost certain to occur here (> 90 %)

Consequence × Likelihood Risk Matrix		Likelihood				
		Remote (1)	Unlikely (2)	Possible (3)	Likely (4)	Certain (5)
Consequence	Minimal (1)	1	2	3	4	5
	Moderate (2)	2	4	6	8	10
	High (3)	3	6	9	12	15
	Major (4)	4	8	12	16	20
	Catastrophic (5)	5	10	15	20	25

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; Major changes required to management in immediate future	Recovery strategy and detailed monitoring	Increased management activities needed urgently

Appendix 2

Snapper (*Chrysophrys auratus*) length and age at maturity and spawning season

Introduction

The reproductive biology of snapper on the south coast of Western Australia, including the age and length at which sexual maturity is attained and spawning times, has been investigated by Wakefield *et al.* (2015) from samples collected between 2002 and 2006. The estimated total lengths (TL) and ages at which 50% of south coast snapper reach sexual maturity (L_{50} and A_{50}, respectively) was 600 mm and 7.0 years for females, and 586 mm and 6.5 years for males. The precision of these estimates was limited, however, by small sample sizes in key length and age ranges over which individuals of this species start to become mature (30 to 50 cm TL, ages 5 for females and 4 for males).

Spawning on the south coast occurs predominantly in October and November, which is similar to mid-spring to early summer spawning on the lower west coast (31°00' S to 33°00' S), including the Perth metropolitan area (Wakefield *et al.* 2015).

The current study seeks to improve the precision of estimates of length and age at sexual maturity for south coast snapper by collecting additional data and pooling it with data from Wakefield *et al.* (2015). It also attempts to confirm the time of spawning.

Methods

Length and age at sexual maturity was assessed by examining snapper gonads during the reported spawning months of October and November. Gonads were classified by developmental stages based on macroscopic assessment criteria: I (immature), II (resting), III (developing), IV (developed), V (spawning) and VI (spent) (Wakefield 2006, Mackie *et al.* 2009a). Sexual maturity was defined as the possession of stages III to VI, which was equivalent and comparable to stages II to V in the staging key used by Wakefield *et al.* (2015).

The data for estimating length and age at maturity were collected during spawning seasons 2002 to 2006 (Wakefield *et al.* 2015) combined with those from 2012 to 2014 (see general methods in section 4.1). The recent dataset excluded fish from waters off Bremer Bay and eastwards due to lack of spawning in that area: only one of 14 females (7%) and three of 19 males (16%) above the L_{50} estimated by Wakefield *et al.* (2015) possessed gonads at any developmental stage from III to VI during October and November. This may be related to generally cooler sea temperatures in that eastern area, noting that very restricted spawning along the entire south coast in 2005 was associated with low temperatures (Wakefield *et al.* 2015). The recent dataset therefore only included fish from west of Bremer Bay, where the above parameter did not fall below 66% for either sex in any of the 3 years sampled. Although the sex of the vast majority of fish could be determined from macroscopic inspection of gonads, the lengths of 6 and the ages of 5 immature (stage I) fish of indeterminate sex were randomly assigned in equal number as female or male.

A logistical relationship between the proportion of snapper sexually mature and total length/age was used to assess onset of sexual maturity (Wakefield *et al.* 2015):

$P_L = \{1+\exp[-\log_e(19)(L-L_{50})/(L_{95}-L_{50})]\}^{-1}$

where P_L was the probability of maturity at a particular length L, and L_{50} and L_{95} were the estimated lengths at which 50% and 95% of snapper mature, respectively. The same form of equation was used to describe the relationship between probability of maturity and age, substituting age (A) for length. The L_{50}, L_{95}, A_{50} and A_{95} and corresponding 95% confidence intervals were estimated from the pooled dataset by bootstrapping 500 estimates of the equation parameters from random re-sampling with replacement (Wakefield *et al.* 2015). The point estimates and upper and lower 95% confidence limits for these parameters were taken as the median, 97.5 and 2.5 percentiles of the 500 parameter estimates. To determine whether the maturity relationships differed between the sexes, and thus whether the data sets for the sexes could be pooled, comparisons of fitted length and age at maturity curves were made using a likelihood-ratio test (Cerrato 1990).

To ascertain spawning time, a gonadosomatic index (GSI) was calculated for all fish greater than the L_{50} estimated in this study that were sampled from October 2012 to December 2014. GSI = (100 x GW)/(WW-GW), where GW was gonad weight (g) and WW was wet whole weight (g), estimated as 0.00006439 x $FL^{2.8076}$, where FL = length to caudal fork (mm) (Wakefield *et al.* 2015). A mean monthly GSI for each sex was generated by pooling across sample years. Spawning time was also investigated by observing monthly trends in the percent frequencies of gonads at different developmental stages for females $>L_{50}$ from samples collected over the same period. Snapper from Bremer Bay and eastwards were excluded from spawning time analysis due to lack of spawning in that area (see above).

Results

The length-maturity and age-maturity relationships did not differ significantly between the sexes (all $P > 0.05$), so the data were pooled to produce a single set of parameter estimates for each relationship. The smallest and youngest mature fish encountered were 366 mm TL and 3 years, respectively. The observed proportion that were sexually mature increased with increasing length, ranging from ~40% to 60 % between 40 and 65 cm TL, and over 77% for all larger fish (Figure 1). Sexual maturity also increased with age, from 48% for age 3 years to over 80% for all fish age 9 years or older (Figure 1). All individuals above 850 mm TL and age 15 years or older were sexually mature. L_{50} was estimated to be 543 mm TL and the A_{50} was 4.6 years (Table 1).

The mean monthly GSI for females remained low at ≤ 0.5 from January to August, and then progressively increased to a peak of 2.5 in November followed by a rapid decline through December (Figure 2). This pattern was closely paralleled by male GSIs. The proportion of females with developed (stage IV) or spawning (stage V) ovaries was between zero and 5% from February to July, and then progressively increased to a peak of 82% in November, followed by a rapid decline to 15% by January (Figure 3). November was by far the month with the largest proportion of females with spawning ovaries (63%), followed by October (30%) and December (20%).

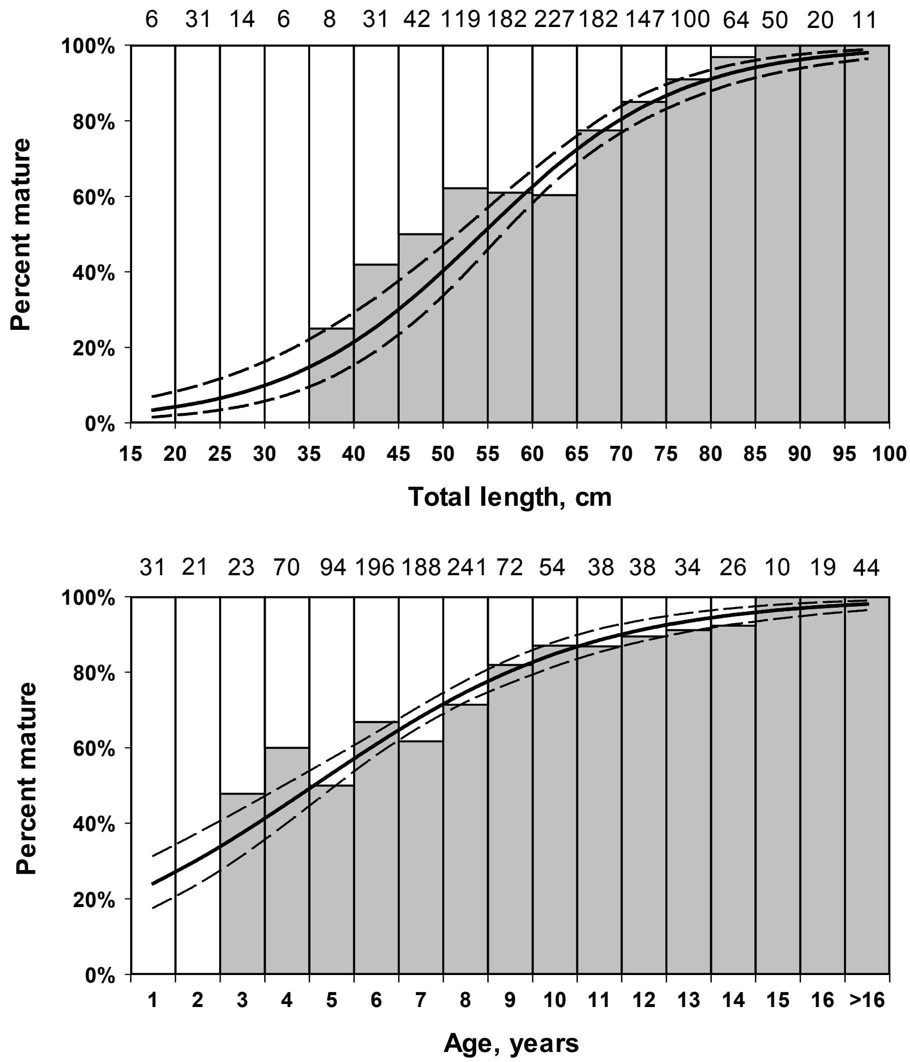

Figure 1: Proportion of mature snapper in sequential length and age classes. Curve represents best fit derived from logistic regression. Dashed lines represent upper and lower 95% confidence limits. Numbers above bars denote samples sizes.

Table 1: Total lengths (mm) and ages (years) at which an estimated 50% and 95% (L_{50}, L_{95}, A_{50} and A_{95}, respectively) of snapper attain sexual maturity, with 95% confidence intervals (CL).

	L_{50}	L_{95}	A_{50}	A_{95}
Point estimate	543	868	4.6	13.8
Lower 95% CL	515	825	3.9	12.5
Upper 95% CL	566	926	5.1	15.5

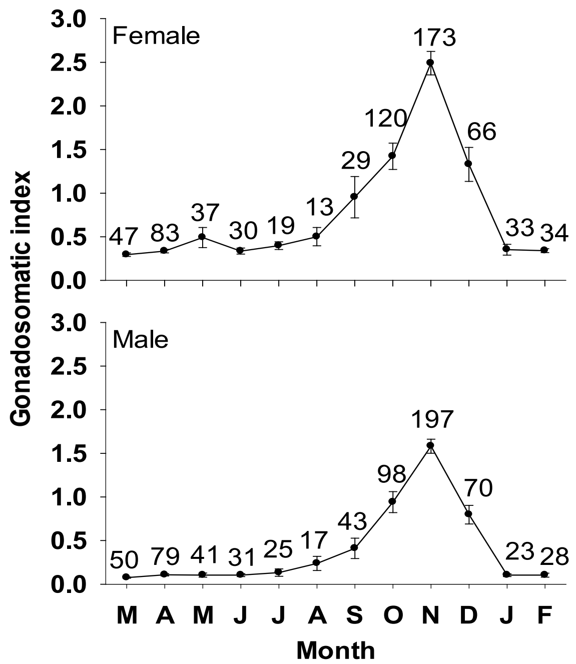

Figure 2: Mean monthly GSIs ± standard error. Numbers above are samples sizes.

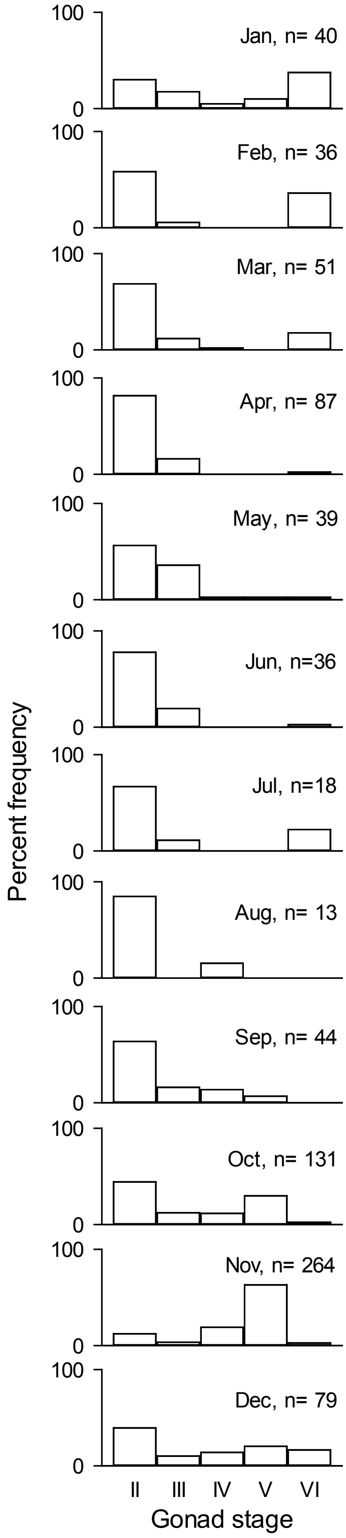

Figure 3: Percent frequency of occurrences of each gonad developmental stage for female snapper ≥ L_{50}.

Conclusion

The updated estimates of L_{50}, (543 mm) and A_{50} (4.6 years) for snapper on the south coast were smaller and younger than the previous estimates from Wakefield *et al.* (2015) of 600 mm and 7.0 years (females), and 586 mm and 6.5 years (males). This may be partly due to including only snapper from west of Bremer Bay in the recent dataset, where the spawning fraction was higher. The L_{50} estimate was considerably higher than the current legal minimum length of 410 mm TL, a length at which snapper are typically aged about 3.7 years (Wakefield 2006). The updated south coast estimates were smaller and younger than for the lower west coast, but larger and older than for the Gascoyne coast (Wakefield *et al.* 2015).

The month of peak spawning for south coast snapper was November, based on maximum values for both the GSI and percentage frequency of developed or spawning ovaries occurring in that month. Spawning also occurred in October and to a lesser extent December based on relatively high values for these parameters. The results were broadly consistent with the finding of October and November spawning for the whole of the south coast by Wakefield *et al.* (2015), and confirm the appropriate use of 1 November as the nominal birthdate for age estimation purposes in this report and by Wakefield (2006). The mean female GSI for the spawning months was much higher in the current study compared to results from Wakefield *et al.* (2015), however. For example the peak GSI November was 2.5 compared to ~1.2. This was probably due to a spawning omission in 2005 detected by Wakefield *et al.* (2015), and by excluding snapper from Bremer Bay and eastwards in the current study. Together the studies demonstrate spawning can be spatially and temporally restricted on the south coast. However, anecdotal reports of small juvenile snapper in Bandy Creek boat harbour, Esperance, suggest spawning was not totally absent in that region.

Appendix 3

Survey of boat-based recreational catch rates of snapper at Windy Harbour during spawning season

Introduction

Snapper are known to form spawning aggregations in Western Australia at predictable times and locations that make them vulnerable to overfishing, such as in Shark Bay (Jackson 2012) and Cockburn Sound (Wise *et al.* 2007), requiring specially tailored fishing regulations. Snapper in the South Coast Bioregion spawn around October and November (Appendix 1, Wakefield *et al.* 2015), but there was no information on their vulnerability to capture at this time. There is a moratorium on the recreational take of demersal scalefish, including snapper, in the neighbouring West Coast Bioregion around the same time (15 October to 15 December). If south coast snapper were highly vulnerable to capture during the spawning season, and if there was a substantial shift of fishing effort from the west to the south coast at this time, it would constitute a serious risk of overfishing.

High vulnerability to capture is expected to result in a high proportion of recreational catches at, or close to, the legal minimum bag limit. The high catch rates would be facilitated by spawning snapper repeatedly and predictably aggregating at known locations, resulting in a high proportion of the catch taken from a small area. We tested the hypothesis of high vulnerability to capture by surveying recreational snapper catches and their geographical spread during their south coast spawning season.

Methods

The recreational boat catch of snapper landed at Windy Harbour (Figure 1.1 in main report) was surveyed on eight separate days during the 2014 spawning season (October and November). Windy Harbour has been identified as a snapper spawning area, and its boat ramp, upgraded in 2011/12, was the closest to the West Coast Bioregion boundary which was at 115°30’ E longitude. Windy Harbour was therefore a likely recipient of any redirected fishing effort from the West Coast Bioregion during that region’s seasonal closure. The boat ramp survey was conducted opportunistically while frames of demersal species were collected for stock assessment purposes.

Upon return from a fishing trip, Windy Harbour boat fishers were asked how many snapper they were landing, the depth of capture, the number of licensed fishers on board, and the location of the catch by identifying the 5’ x 5’ block(s) (latitude x longitude) on a grid map. Capture locations were provided on a confidential basis so the actual grids were not identified here. Only vessels that had caught at least one snapper were included in the survey. The legal daily bag limit for snapper was 3 per licensed fisher on board, subject to a demersal finfish mixed species daily bag limit of 5 per licensed fisher. The upper legal boat limit for snapper was therefore the number of licensed fishers multiplied by three, so boat catches here were expressed as a proportion of this upper limit.

Results

The number of snapper taken was recorded for 34 boat catches, of which 16 (47%) had just one snapper (Figure 1). The next most common number caught was four, occurring in five catches. The most snapper in any catch was eight, occurring in just one catch.

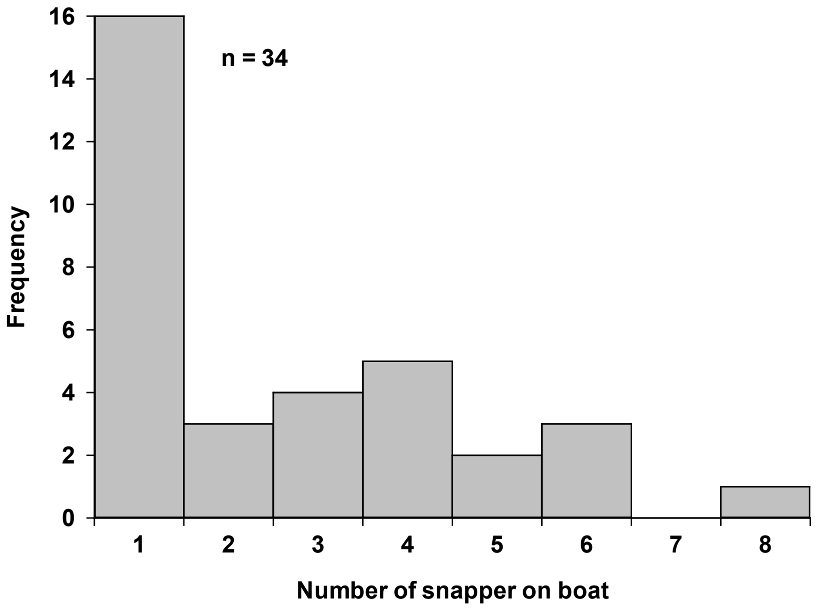

Figure 1: Frequency distribution of the number of snapper in 34 boat-based recreational catches landed at Windy Harbour during October and November 2014.

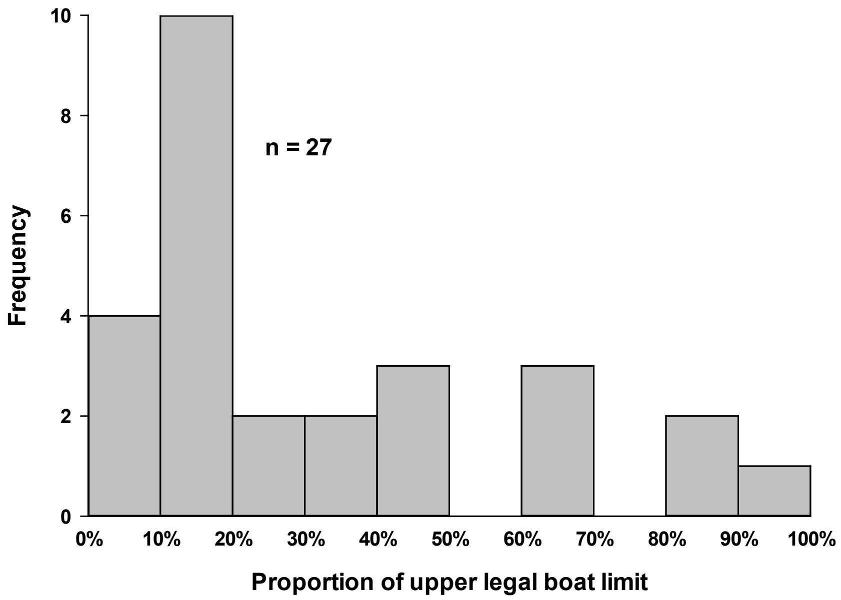

Figure 2: Frequency distribution of the proportion of the upper legal boat limit for snapper achieved.

Catch depth was provided for 17 catches. The mean was 42 m (standard deviation 8.9 m) and ranged from 27 to 60 metres.

Of the 27 boat catches where the number of licensed fishers on board was recorded, 14 had achieved less than 20% of the upper legal boat limit and three had caught over 70% including one that had caught 100% (Figure 2).

Spatial distribution, recorded for 28 catches, was spread widely over 14 separate 5’ x 5’ blocks. The most catches from a single block was eight, with eight blocks providing a just single catch.

Discussion

The limited data available did not suggest the spawning snapper were highly vulnerable to overfishing as almost half of the catches had only one snapper, and over half were less than 20% of the upper boat limit. The wide spatial distribution in fishing effort, and the range of capture depths, suggested that effort was not focussed on a single spawning aggregation that was easily found. Compared to spawning snapper in Cockburn Sound and Shark Bay, Windy Harbour spawning snapper appear to be less vulnerable. However, further surveys are required to more precisely establish the level of vulnerability.

Appendix 4

Details of catch curve methods and results from age-based assessments

Methods

Up to eight different catch curve methods were fitted to age and/or length composition samples for each species. For the first three of the catch curve methods considered in this assessment (i.e. linear regression, Chapman & Robson and multinomial catch curve with knife-edge selectivity), the age at full recruitment for fish in each sample was determined as one year older than the peak in the age frequency distribution. Note that all methods were dependent on the assumption that the age and/or length compositions represent a random sample from the overall population.

Model descriptions

1. Linear regression catch curve

Linear catch curve analysis (e.g. Ricker 1975), may be described by the following equation

$$\log_e N_a = \log_e N_{a_r} - Z(a - a_r)$$

where N_a was the number of fish of integer age a, a_r was the assumed age at full recruitment of fish into the fishery and Z is the total mortality (year^{-1}). For all analyses using this method, a_r was taken as one age above that at which the number of fish was greatest in each sample. The catch curve was fitted to the natural logarithms of the frequencies at age of fish in the sample, from ages i to that prior to the first age for which the frequency was zero. The estimate of Z was taken as the negative of the slope of the regression equation.

2. Chapman & Robson estimator

Chapman and Robson (1960) devised an equation that provides an unbiased estimate of survival, based on the assumption that the age distribution in a population has a geometric distribution. They advised that, with the geometric distribution, an unbiased estimator of the instantaneous rate of mortality does not exist, but that a "nearly unbiased" estimate may be calculated as

$$Z = \log_e[1 + \bar{X} - 1/n] - \log_e\bar{X} - [(n-1)(n-2)/n(t+1)(n+t-1)],$$

where Z is the instantaneous rate of total mortality (year^{-1}). In the above equation, $\bar{X}$ corresponds the mean of the values of the integer ages for fish above the assumed age at which fish become fully-recruited into the fishery, n refers to the sample size at or above this age and $t = n\bar{X}$. Recruitment into the fishery was assumed to be "knife-edged". For this assessment, the recruitment age was taken as that corresponding to one above the age with the greatest number of fish in each sample.

3. Multinomial catch curve with age-based, knife-edge selectivity

For fish at or above the age at recruitment, a_r, the per-recruit survival of fish to integer age a, S_a , may be calculated as

$$S_a = e^{-Z(a-a_r)}$$

$\hat{P}_a$, the expected proportion of fully-recruited fish at age a was

$$\hat{P}_a = \frac{S_a}{\sum_{a=a_r}^{A} S_a},$$

where A refers to the maximum age assumed in the analysis (i.e. greater than the observed maximum age). Assuming "knife-edge" selectivity, the age at recruitment into the fishery was taken as one age above the age with the largest number of fish in the sample. The catch curve was fitted by maximising the multinomial log-likelihood, λ, associated with the observed and expected proportions at age, i.e.

$$\lambda = \sum_{a=a_r}^{A} f_a \log_e \hat{P}_a,$$

where f_a refers to the observed frequency at age a (see also Fairclough *et al.* 2014b).

<u>4. Multinomial catch curve with age-based, logistic selectivity</u>

This catch curve uses a logistic curve to describing the vulnerability of fish (to capture by the fishing gear) at age. V_a, the vulnerability of fish to capture at age a, was calculated as

$$V_a = 1/\{1 + e^{-\log_e(19)(a-A_{50})/(A_{95}-A_{50})}\},$$

where A_{50} and A_{95} refer to the ages at which 50 and 95% of fish become selected into the fishery. The fishing mortality at age a, F_a, was calculated as

$$F_a = V_a F,$$

and the total mortality at age a, Z_a, was determined as

$$Z_a = F_a + M.$$

M was the assumed value for natural mortality, estimated from an empirical life history equations relating the natural logarithms of mortality estimates for 84 unfished or lightly-fished stocks to their respective maximum recorded ages (Hoenig's 1983; Then *et al.* 2015). Setting the survival at age zero, $S_{a=0}$, to 1, the per-recruit survival for all ages above zero was calculated as

$$S_a = S_{a-1}\, e^{-Z_a}.$$

$\hat{C}_a$, the estimated catch at age a, was calculated using the Baranov catch equation, i.e.

$$\hat{C}_a = S_a(F_a/Z_a)(1 - e^{-Z_a a}).$$

$\hat{P}_a$, the expected catch proportion at age a, was calculated as

$$\hat{P}_a = \frac{\hat{C}_a}{\sum_{a=0}^{A} \hat{C}_a},$$

where A was the value of maximum age assumed for the analysis (greater than the observed maximum recorded age in samples).

The multinomial log-likelihood λ was calculated as

$$\lambda = \sum_{a=0}^{A} f_a \log_e \hat{P}_a.$$

5. Multi-year catch curve with constant recruitment and age-based, logistic selectivity

Full details of this catch curve method, including all mathematical equations, were provided by Fairclough *et al.* (2014b). In brief, this method was an extension to the previous method, with separate curves being fitted simultaneously to age composition data for different years. The analysis was based on "biological years" of data, i.e. a year was considered to start from the estimated mean birth date (based on reproductive indices) rather than from January 1, with the result that any age was only represented by a single cohort. Selectivity was considered to be age-based and was represented by an (asymptotic) logistic curve.

6. Multi-year catch curve with variable recruitment and age-based, logistic selectivity

Full details of this catch curve method, including all mathematical equations, were provided by Fairclough *et al.* (2014b). In brief, this method extends the previous multi-year catch curve method further by allowing for inter-annual variation in recruitment. This was the only catch curve, of the eight approaches used in this assessment, to allow for variation in annual recruitment. Note that the model assumes a prior for the natural logarithm of the standard deviation of recruitment (i.e. level of recruitment variability) of 0.6.

7. Catch curve fitted to age and length data, with length-based, logistic selectivity

This model simultaneously estimates growth, size-based selectivity and fishing mortality. It is similar in concept to the model of Taylor et al. (2005), but was fitted to length and age data, rather than tagging data. A point of interest about this model may be that, because it accounts for effects of both selectivity and fishing mortality on size at age data, the pattern of growth estimated by this model, in theory, is that which would be expected for a fish species under conditions of zero harvesting, i.e. the "true" patterns of growth of individuals in the population, rather than just a description of sample size at age data. A key point, however, is that unlike most catch curve models which are fitted solely to age composition or size composition data, this model makes use of both age and size compositions, as is typically available from biological sampling of fish. The age composition data were likely to contain the most information regarding mortality, whereas the length composition data contain the most information on selectivity (i.e. as this process is typically related more to length than to age). Correctly accounting for selectivity in catch curve analysis has been shown by simulation studies to improve estimates of mortality (Thorson and Prager 2011).

The growth of individuals of a fish species was assumed to follow a pattern that may be described by the von Bertalanffy growth equation. $\overline{L}_t$, the mean length of fish at age a (years), *was* determined as

$$\overline{L}_a = L_\infty \, e^{-k(a-t_0)},$$

where L_∞ was the asymptotic length of the fish (mm), k was the growth coefficient (year^{-1}) and t_0 was the hypothetical age (years) at which fish were expected to have zero length.

The vulnerability of a fish of length L, V_L, may be calculated as

$$V_L = 1/\{1 + e^{-\delta(L-L_{50})}\},$$

where δ and L_{50} are the slope of the logistic function and the length at which 50% of individuals were selected to the fishing gear, respectively.

F_L, the instantaneous rate of fishing mortality (year^{-1}) for fish of length L was calculated as

$$F_L = V_L F.$$

Z_L, the instantaneous rate of total mortality (year^{-1}) for fish of length L was determined as

$$Z_L = F_L + M,$$

where M was the instantaneous rate of natural mortality (year^{-1}). M, which was assumed to be constant for all individuals in the catch, was specified as a fixed parameter.

Using i to denote the number of each 1-mm length class between a specified minimum and maximum size (that should extend well beyond the minimum and maximum sizes of the observed size and age range), and using j for each age class, the expected proportion of fish within each length and age class, $\psi_{i,j}$, was calculated as

$$\psi_{i,j} \int_{L_i}^{L_{i+1}} f_j\,(L) dL,$$

where L_i was the lower bound of length class i and $f_j(L)$ was the value of the normal probability density function for a fish of length L in age class j, calculated using a constant standard deviation σ over all ages. Note that, by using 1 mm length classes, which is the resolution for which most fish length data are recorded, the estimated proportions of catch within each length class can, if desired, be applied directly to “ungrouped data” (see Hall 2009). The value of σ was a parameter estimated when fitting the model.

Denoting the value of the age step for that age class as Δa, the numbers of fish of length class i that survive to the end of that age class, $s_{i,j,}$, was calculated as

$$s_{i,j} = e^{-Z_j \, \Delta a}.$$

Note that use of a small age step (e.g. 0.1 years) when a fitting catch curve to length data was recommended by Taylor et al. (2005) particularly for short-lived species (<10 years) to increase the precision with which the model can account for effects of length-based selectivity on the data. $C_{i,j}$, the expected catch from fish of length class i in age class j, was calculated using the Baranov catch equation, i.e.

$$C_{i,j} = s_{i,j}\left(F_j/Z_j\right)\left(1 - s_{i,j}\right).$$

$C_{i,a}$, the catch of fish of integer age a was determined by summing the catches over all of the age classes within that integer age. Denoting the maximum integer age as A, and the maximum length class number as I, the total catch, C, was determined as

$$C = \sum_{i=1}^{I}\sum_{a=1}^{A} C_{i,a}.$$

The estimated proportion of fish within integer age a in the overall catch, $\hat{p}_a$, was determined as

$$\hat{p}_a = \frac{\sum_{i=1}^{I} C_{i,a}}{C}, \text{ and}$$

$\hat{p}_{i,a}$, the proportion of fish of belonging to length class i within integer age a, was estimated as

$$\hat{p}_{i,a} = \frac{C_{i,a}}{\sum_{i=1}^{I} C_{i,a}}.$$

Denoting the observed frequency of fish of integer age a as f_a, the log-likelihood associated with the age composition, λ_1, was

$$\lambda_1 = \sum_{a=1}^{A} f_a \log_e(\hat{p}_a)$$

The log-likelihood associated with the length-at-age data, λ_2, was determined from the values of $\hat{p}_{i,a}$ and the observed frequencies of fish within each length and age class, $f_{i,a}$, *i.e.*

$$\lambda_2 = f_{i,a} \log_e\left(\hat{p}_{i,a}\right)$$

When fitting the model to a set of length and age data, the overall log-likelihood was calculated as

$$\lambda = \lambda_1 + \lambda_2$$

9. Length-based catch curve

The above-described length- and age-based model was modified slightly so that it could be fitted solely to length composition data. For this length-based version of the model, the growth parameters (i.e. L_∞, k, t_0 and σ) must be specified rather than estimated (as there is insufficient information in the length data alone to calculate growth). This model a value fishing mortality, F, and the two parameters of the logistic selectivity function, δ and L_{50} (see description for model 7).

It is appropriate, when using this model, to estimate the growth parameters using a different data set (and thereby not use the same data set twice). For three of the four species (snapper, blue morwong and western blue groper) considered in this assessment, von Bertalanffy growth curves had been derived in previous biological studies (on the same stocks). For modelling in this study, von Bertalanffy growth curves were re-fitted to the length-at-age data produced in those former studies to also provide an estimate, for each species, of the standard deviation for the mean lengths at age (σ). After the growth curves had been re-fitted, σ was calculated based on the residuals between the observed and estimated lengths-at-age for fish above the minimum legal length (MLL), i.e. as the fish in the current study were collected from recreational and commercial fishers and thus all above this MLL. Note that this length-based catch curve was not fitted to data for Bight redfish, as growth had not previously been estimated for the stock of this species in WA, and growth of this species in South Australia was known to differ (i.e. it grows larger in WA).

The length-based model has a single log-likelihood component to the objective function. As described for the above model, the estimated proportion of fish within length class i in the overall catch, $\widehat{p}_i$, was calculated as

$$\widehat{p}_i = \frac{\sum_{a=1}^{A} C_{i,a}}{C}.$$

Denoting the observed frequency of fish in length class i as f_i, the log-likelihood associated with the length composition, λ, was calculated as

$$\lambda = \sum_{i=1}^{I} f_i \log_e(\hat{p}_i).$$

Estimation of uncertainty

With the exception of the Chapman and Robson (1960) approach, all catch curves were fitted in AD Model Builder. Approximate 95% confidence limits for Z estimated by each of these catch curve models were calculated from the standard errors associated with this parameter, Z_e,as estimated by AD Model Builder. The lower and upper asymptotic confidence limits were determined as $Z \pm (1.96\, Z_e)$.

The Chapman and Robson mortality estimator was implemented in R. Similar to above, the 95% confidence limits were calculated based on the standard error for Z (i.e., which in this case was equivalent to the standard deviation), taken as the square root of the variance σ^2, which was approximated (see Smith *et al.* 2012) as

$$\sigma^2 \approx \frac{(1 - e^{-Z})^2}{n\, e^{-Z}}$$

where n refers to the sample size.

Results and Discussion

Snapper

In the west sub-region, point estimates of Z for the commercial gillnet and recreational line sectors were similar and slightly higher than the values based on samples from the commercial line fishery (Table 1). Despite the similarity of Z estimates for the commercial gillnet and recreational line fisheries, it was considered that the samples derived from the commercial line fishery in the western sub-region may be the most representative of the overall snapper population. The reasons for this were that 1) recreational fishing for snapper was likely to be occurring closer to shore and nearer to access points in the main population centre, 2) commercial gillnet fishers along the south coast catch fish as by-product whilst mainly targeting sharks and thus may not operate in areas where snapper were most abundant, and 3) the commercial gillnets contain only a single mesh size and thus, potentially, fish of certain sizes above the length at which this species can legally be retained on the south coast (410 mm) were not fully-vulnerable to this gear type. In contrast, snapper was a key target species of the commercial line fishery. The preferred catch curve model (see methods section 3.1.5) for this species, i.e., the multi-year variable recruitment catch curve, provided a relatively good fit to the age composition data for snapper in the commercial wetline fishery in the west sub-region, with the exception of the final sample year (2014/15) for which sample was very low (Figure 1).

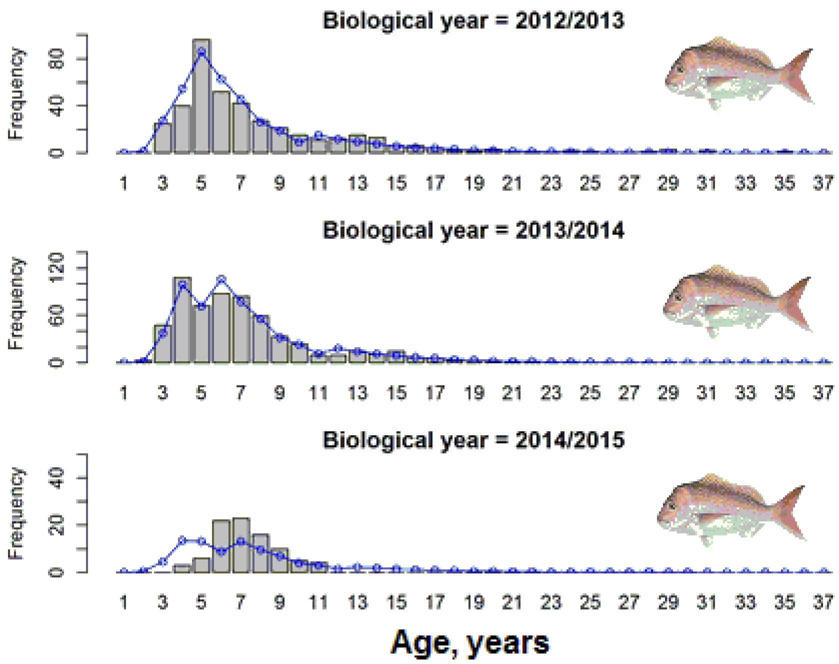

Figure 1: Multi-year, variable recruitment catch curve model (blue line) fitted to the age composition sample for snapper collected from the commercial line fishery in the west sub-region.

For snapper in the east sub-region, the overall sample size for the age composition was relatively low (~ 300 fish over the sampling period), with a limited number of sampling events in the latter part of study, and thus may not be representative of the snapper population.

For these reasons, the estimates of Z for the eastern sub-region based on samples for the commercial gillnet sector were not considered very reliable and should thus be viewed with caution. They do, however, raise the possibility that overfishing of snapper in this area was occurring.

Table 1: Estimates of the instantaneous rate of total mortality (Z year^{-1}) for each age sample collected for snapper, produced by eight methods of catch curve analysis. Results in bold were those for the dataset and catch curve model reported for this species in the "weight-of-evidence" summary table, and used in subsequent analyses for estimating fishing mortality and spawning potential ratio.

 Catch curve method	West Commercial Gillnet	West Commercial Line	West Recreational Line	East Commercial Gillnet
1. Linear catch curve	0.22 (0.12-0.32)	0.23 (0.20-0.26)	0.29 (0.25-0.33)	0.29 (0.14-0.44)
2. Chapman & Robson	0.30 (0.27-0.33)	0.24 (0.22-0.26)	0.29 (0.27-0.31)	0.39 (0.34-0.44)
3. Multinomial catch curve	0.30 (0.26-0.34)	0.24 (0.22-0.26)	0.29 (0.26-0.32)	0.39 (0.32-0.46)
4. Multinomial + selectivity	0.31 (0.28-0.34)	0.23 (0.21-0.25)	0.28 (0.26-0.30)	0.39 (0.35-0.43)
5. Multi-year, constant recruitment	0.31 (0.27-0.35)	0.25 (0.24-0.26)	0.30 (0.27-0.33)	0.42 (0.36-0.48)
6. Multi-year, variable recruitment	0.25 (0.21-0.29)	**0.24 (0.22-0.26)**	0.26 (0.23-0.29)	0.66 (0.28-1.04)
7. Length and age catch curve	0.33 (0.30-0.36)	0.24 (0.23-0.25)	0.29 (0.27-0.31)	0.47 (0.41-0.53)
8. Length-based catch curve	0.38 (0.30-0.46)	0.23 (0.22-0.24)	0.28 (0.25-0.31)	0.48 (0.38-0.58)

Bight redfish

In the west sub-region, point estimates of Z for the recreational line fishery were typically higher than those for the commercial line fishery (Table 2). As the fishing gears used by these sectors were very similar, it was likely that the differences reflected dissimilar spatial fishing patterns. The most likely explanation was that, as with snapper, the recreational fishing effort directed towards Bight redfish was concentrated in waters further inshore and closer the access points around the main population centre (Albany) compared with commercial line fishers. The differing age structures (and associated mortality estimates) may reflect localised depletion in the more accessible inshore areas and/or an age-related offshore movement of this species. Unfortunately, the movement patterns of this species are largely unknown (Smallwood et al. 2013).

Although the Z estimates for the east sub-region were relatively similar among the various catch curve methods and across the two commercial fishing sectors, the point estimates for the recreational line fishery were all much higher (Table 2). As the vast majority of the age samples from the recreational line fishery in the eastern sub-region were collected on two occasions (at annual fishing competitions in Esperance), these data were considered less likely to constitute a representative sample of the Bight redfish in this sub-region. In contrast, the samples for the commercial gillnet and line sectors in the eastern sub-region had been collected on many occasions and at regular intervals throughout the year, and thus were considered far more representative.

Table 2: Estimates of the instantaneous rate of total mortality (Z year^{-1}) for each age sample collected for Bight redfish, produced by seven methods of catch curve analysis. Results in bold were those for the dataset and catch curve model reported for this species in the "weight-of-evidence" summary table, and used in subsequent analyses for estimating fishing mortality and spawning potential ratio. NF = not fitted.

 **Catch curve method**	**West Commercial Line**	**West Recreational Line**	**East Commercial Gillnet**	**East Commercial Line**	**East Recreational Line**
Linear catch curve	0.108 (0.095-0.121)	0.133 (0.113-0.153)	0.073 (0.056-0.090)	0.083 (0.064-0.102)	0.267 (0.243-0.291)
Chapman & Robson	0.110 (0.104-0.116)	0.120 (0.113-0.127)	0.102 (0.093-0.111)	0.112 (0.101-0.123)	0.236 (0.217-0.255)
Multinomial catch curve	0.110 (0.104-0.116)	0.121 (0.112-0.130)	0.102 (0.092-0.112)	0.112 (0.100-0.124)	0.236 (0.213-0.259)
Multinomial + selectivity	0.100 (0.094-0.106)	0.119 (0.111-0.127)	0.091 (0.083-0.099)	0.106 (0.094-0.118)	0.201 (0.189-0.213)
Multi-year, constant recruitment	0.104 (0.097-0.111)	0.126 (0.116-0.136)	0.103 (0.091-0.115)	0.113 (0.099-0.127)	0.229 (0.204-0.254)
Multi-year, variable recruitment	**0.112 (0.103-0.121)**	0.118 (0.107-0.129)	0.123 (0.104-0.142)	0.148 (0.120-0.176)	0.229 (0.181-0.277)
Length and age catch curve	0.100 (0.095-0.105)	0.125 (0.116-0.134)	0.092 (0.083-0.101)	0.107 (0.097-0.117)	0.209 (0.190-0.228)
Length-based catch curve	NF	NF	NF	NF	NF

Estimates of Z for Bight redfish were relatively similar among the majority of catch curve methods used (Table 2). The differences in the assumptions of these alternative models (i.e. model uncertainty) thus had only limited influence on the assessment results. The most prominent differences in point estimates of Z among the alternative catch curve models were between the linear regression model and the other methods. As the Z values produced by the linear catch curve for a particular area and sector were sometimes well above and at other times well below those produced by all of the other methods, this suggests that the method may not be robust. That is, although certain assumptions were violated by each of the catch curve methods (e.g. the equilibrium assumption that all fish in the population had experienced the same fishing mortality throughout their full lives), violation of certain assumptions required for the linear catch curve method had a large influence on the reliability of results.

The similarity of Z estimates for Bight redfish produced by the catch curve methods that assumed constant vs variable annual recruitment (Table 2) suggests, as also indicated by the data, that inter-annual recruitment variability in this species was relatively low. Thus, for this species, catch curve analysis was not particularly sensitive to this assumption, particularly if models were fitted to multiple years of data. The preferred catch curve model (see methods section 3.1.5) for this species was the multi-year catch curve that allowed for variable recruitment to be estimated, providing a very good fit to the age composition data for Bight redfish in the commercial wetline fishery in the west sub-region (Figure 2).

Note that the length-based catch curve, which was fitted solely to length composition data and requires growth information derived from length-at-age data, was not fitted to data for Bight redfish. This was because (1) it would be inappropriate to construct a growth curve based on length-at-age data collected in this study in a separate analysis and then use the same length data to fit the catch curve, and (2) this species is known to grow to a larger size on the south coast of WA compared with in South Australian waters where it has been studied previously (Wise and Tilzey 2000, Stokie 2004).

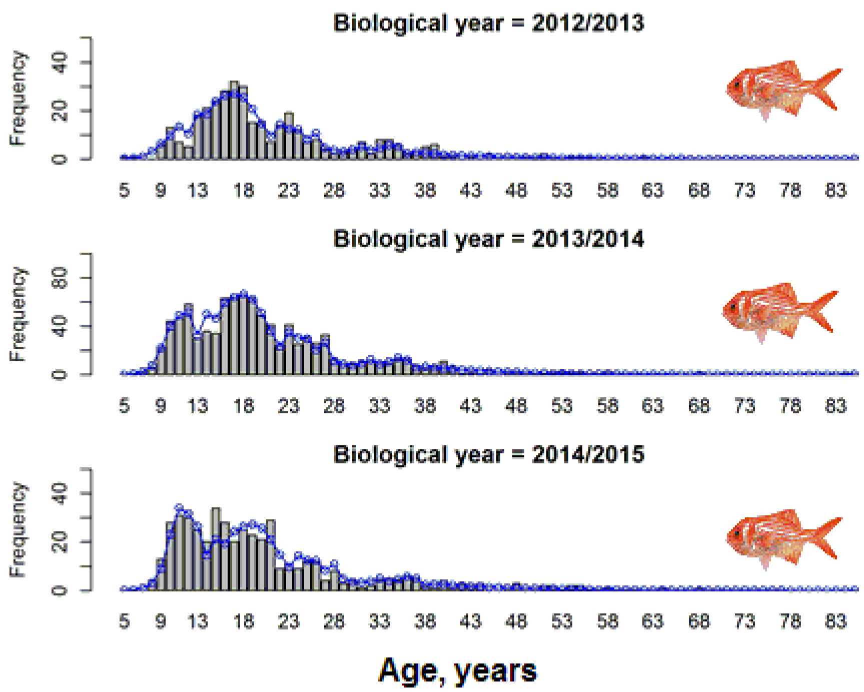

Figure 2: Multi-year, variable recruitment catch curve model (blue line) fitted to the age composition sample for Bight redfish collected from the commercial line fishery in the west sub-region.

Blue morwong

Interpretation of the catch curve results for blue morwong was complicated due to individuals of this species not becoming fully vulnerable to the fishing gears used by the various fishing sectors until they attain a relatively large size. As the estimates of total mortality outputted by catch curve analyses typically relate to the mortality individuals experience once they become fully vulnerable to fishing (i.e. the estimates were often referred to as "fully-selected Z values"), these results can be misleading for a species such as blue morwong (i.e. may suggest the stock was more heavily exploited than in reality). Compounding interpretation of the catch curve results further was that selectivity was a process which often relates more to the length of the animal than to its age. Thus, potentially, the results from catch curve methods assuming age-based selectivity can be biased.

A number of steps were undertaken in this analysis to help overcome these issues. Firstly, a range of catch curve approaches have been adopted, enabling comparisons of the results of models with alternative selectivity assumptions, i.e. age- vs length-based selectivity. Secondly, as some data were for blue morwong were collected from recreational line anglers, this allowed comparisons of catch curve results based on fish caught by different fishing gears. Thirdly, per-recruit analyses have been undertaken that explicitly account for different levels of vulnerability, and thus fishing mortality, for fish of different sizes. Finally, from the outputs of the model identified as being the most appropriate for the data, a "weighted Z" was calculated, which represented the value of total mortality to which, on average, individuals in the population had been subjected.

Results from models assuming age-based selectivity

The point estimates of (fully-selected) Z produced by the first four age-based catch curve analyses, fitted to pooled data for different sampling years, were typically higher for the commercial gillnet sector in the west sub-region compared to other sectors (Table 3). The point estimates produced by the multi-year catch curves were slightly higher than those produced by the first four catch curve methods. Note that as the annual samples collected from the commercial gillnet sector in the west sub-region, and from the recreational line sector in the east sub-region, were relatively small, multi-year catch curves were not fitted to these data.

The above age-based catch curve results were based on models fitted to data composition data, after pooling for the two sexes. Given that male and female blue morwong exhibit different growth patterns, it may be expected that the age-based selectivity of individuals to the fishing gears also differ between the sexes. Catch curves were thus also fitted separately to the data for females and males for this species (results not shown). Unexpectedly, the estimates of fully-selected total mortality differed between the two sexes, i.e. with the values for males being substantially higher than for females (and the estimates of selectivity not differing markedly between the two sexes). This result was unexpected as 1) the two sexes have a similar maximum age (Coulson *et al.* 2010) implying that natural mortality was about the same and 2) as they occur together and were caught by the same gears, this implies that the fully-selected fishing mortality should be the same. It was concluded from these analyses that the different Z estimates for the two sexes were due to model misspecification, i.e. the assumption of age-based selectivity was not appropriate for this species. Note also that combining the data for the two sexes was not ideal as the age-based selectivity may differ between the sexes due to differences in their growth. In summary, the estimates of Z for blue morwong derived from catch curve models assuming age-based selectivity, particularly for the gillnet data, should be treated with caution.

Table 3: Estimates of the instantaneous rate of total mortality (Z year^{-1}) for each age sample collected for blue morwong, produced by up to eight methods of catch curve analysis. Results in bold were those for the dataset and catch curve model reported for this species in the "weight-of-evidence" summary table, and used in subsequent analyses for estimating fishing mortality. SPR was estimated using the unweighted length- and age-based catch curve. NF = not fitted.

 **Catch curve method**	**West Commercial Gillnet**	**West Recreational Line**	**East Commercial Gillnet**	**East Recreational Line**
Linear catch curve	0.42 (0.35-0.49)	0.37 (0.33-0.41)	0.37 (0.32-0.42)	0.23 (0.18-0.28)
Chapman & Robson	0.39 (0.36-0.42)	0.33 (0.31-0.35)	0.35 (0.33-0.37)	0.35 (0.29-0.41)
Multinomial catch curve	0.39 (0.34-0.44)	0.33 (0.30-0.36)	0.35 (0.33-0.37)	0.35 (0.27-0.43)
Multinomial + selectivity	0.38 (0.34-0.42)	0.34 (0.31-0.37)	0.35 (0.33-0.37)	0.35 (0.30-0.40)
Multi-year, constant recruitment	NF	0.38 (0.32-0.44)	0.38 (0.34-0.42)	NF
Multi-year, variable recruitment	NF	0.38 (0.34-0.42)	0.44 (0.40-0.48)	NF
Length and age catch curve	0.70 (0.48-0.92)	0.51 (0.29-0.73)	0.48 (0.40-0.56)	NF
Weighted* (females)	*0.31 (0.27-0.34)*	*0.30 (0.23-0.36)*	***0.30 (0.27-0.32)***	NF
Weighted* (males)	*0.43 (0.36-0.48)*	*0.38 (0.26-0.47)*	***0.38 (0.34-0.42)***	NF
Length-based catch curve	0.39 (0.27-0.51)	0.24 (0.20-0.28)	0.25 (0.21-0.29)	NF

*The estimates represents the average fishing mortality experienced by mature individuals in the population, rather than the fully-selected fishing mortality

Results from models assuming length-based selectivity

For the commercial gillnet sector, the results obtained when fitting the length- and age-based catch curve, which assumes selectivity was length- rather than age-related, indicated 1) higher values for fully-selected total mortality than estimated by the age-based catch curves (Table 3) and that 2) individuals of this species do not begin to become vulnerable to commercial gillnet fishing until they attain about 600 mm, and are not fully-vulnerable until they grow to about 800 mm. As the mean asymptotic length for females was well below this size, this analysis suggests that females, because of their smaller size, never become fully vulnerable to this fishing gear. Thus, the value for the fully-selected Z was *not* representative of the total mortality experienced, on average, by individuals in the population. A more useful measure of Z may be derived by weighting this according to the estimated spawning stock biomass at age (from the per-recruit analysis) (see Table 3 for weighted estimates).

Note that when assuming length-based selectivity, the vulnerability of individuals of a given length to the fishing gear would not be expected to differ among the two sexes (given that they have essentially the same body shape). Likewise, the fully-selected fishing mortality would not be expected to differ among the two sexes (as, for this species, there was no evidence that individuals of the two sexes interact differently with fishing gear). Thus, it was considered appropriate, in the length- and age-based catch curve model to assume common selectivity and mortality among the two sexes.

The estimates of mortality derived from the length-based catch curve provided much lower values of Z compared with all other methods. It was not clear why this was the case, except to note that the length-based catch curve model has essentially the same structure as the length- and age-based model, but the former model only has length data, and that growth must be imposed based on results obtained from another study (i.e. as estimated by Coulson *et al.* 2010). Given that this species does not become fully-selected into the fishery until a relatively large size, there would be very limited information in the catch size data from which to estimate mortality (i.e. as there was no growth signal in the data). In addition, it was also possible that the growth of blue morwong has changed over time, or that it differs among the sampling areas covered in the study of Coulson *et al.* (2010) which were not all the same as in the current study.

In summary, the length- and age-based catch curve model provided very good fits to both the length and age data for female and male blue morwong in the commercial gillnet fishery in the east sub-region (Figure 3), and provided the most reliable (weighted) estimates of Z. Although the estimates derived from the age-based catch curves were considered less reliable, they were similar to these weighted Z values. Note that the multi-year catch curve analysis did reveal that this species does not exhibit a high level of inter-annual recruitment variability, and thus this assumption was not likely to have impacted on the results obtained from the “preferred” length- and age-based model.

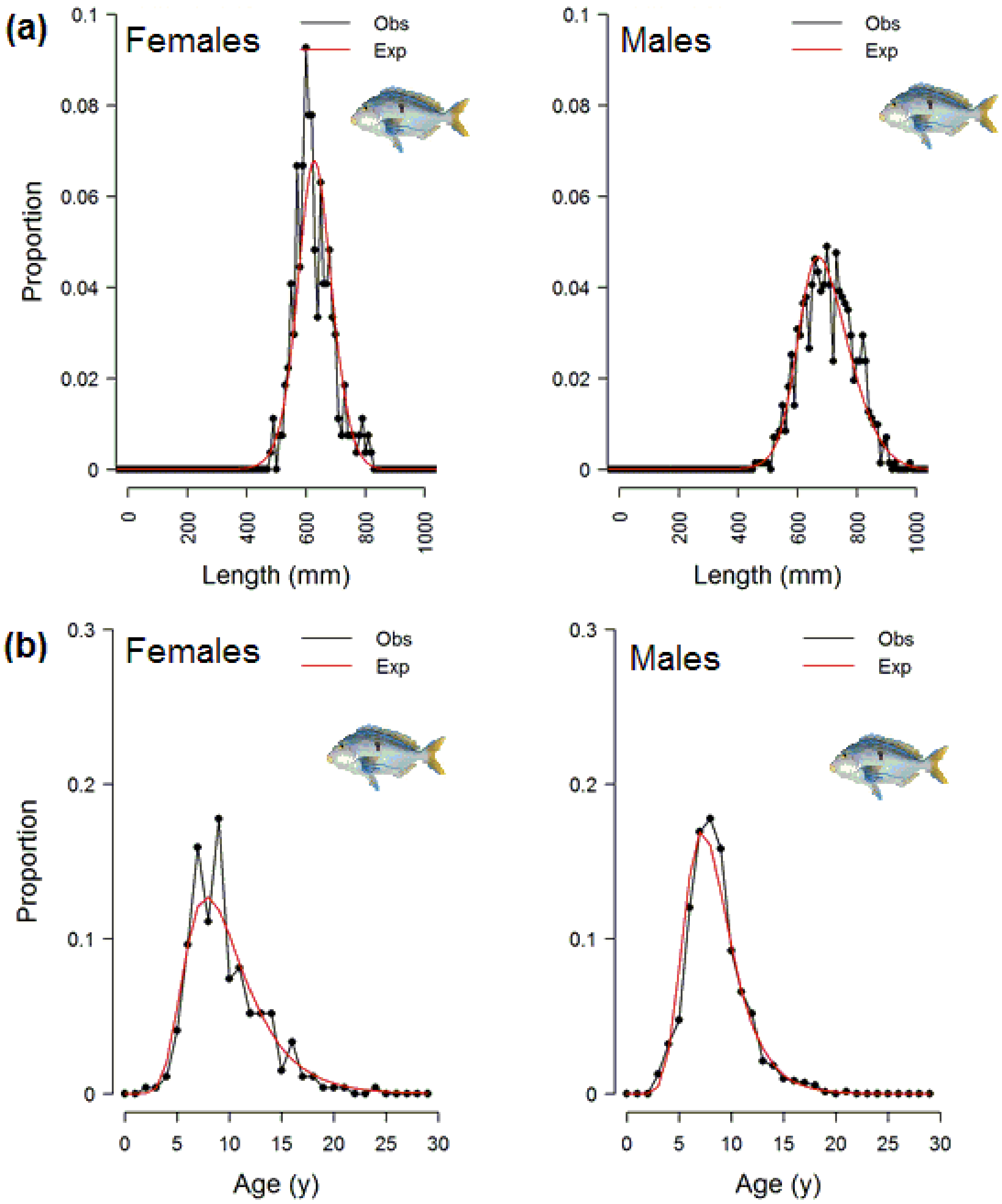

Figure 3: Length- and age-based catch curve model (red line) fitted to the (a) length composition and (b) age composition samples for female and male blue morwong collected from the commercial gillnet fishery in the east sub-region.

Western blue groper

Consistent with the results from a former study of western blue groper (Coulson *et al.* 2009), the age composition data reveal that this species exhibits substantial inter-annual recruitment variability. Even when the data were pooled across sampling years, the large variations in inter-annual recruitment resulted in an age composition that was far from smooth (see Section 4.4.3). Thus, the multi-year catch curve allowing for recruitment variability was considered most appropriate for western blue groper. The point estimate of Z of 0.101 year^{-1} produced by this method was very similar to that provided by Coulson *et al.* (2009; 0.093 year^{-1}) for western blue groper caught in 2004-2007 by commercial gillnetting, using a catch curve model accounting for variable recruitment.

Table 4: Estimates of the instantaneous rate of total mortality (Z year^{-1}) for each age sample collected for western blue groper, produced by eight methods of catch curve analysis. Results in bold were those for the dataset and catch curve model reported for this species in the "weight-of-evidence" summary table, and used in subsequent analyses for estimating fishing mortality and spawning potential ratio.

 **Catch curve method**	**East Commercial Gillnet**
Linear catch curve	0.058 (0.058-0.081)
Chapman & Robson	0.080 (0.071-0.089)
Multinomial catch curve	0.080 (0.071-0.089)
Multinomial + selectivity	0.103 (0.094-0.112)
Multi-year, constant recruitment	0.104 (0.094-0.114)
Multi-year, variable recruitment	**0.101 (0.088-0.114)**
Length and age catch curve	0.099 (0.087-0.111)
Length-based catch curve	0.095 (0.077-0.113)

The study by Coulson *et al.* (2009), which sampled western blue groper from across the entire South Coast Bioregion, highlighted four strong year classes, namely the cohorts born in 1972, 1980, 1983 and 1990. The current study highlighted that 1996 and 1999 cohorts were relatively strong and the 1993 and 1994 years classes were relatively weak. This analysis was not, however, able to distinguish the earlier strong year classes detected in the study by Coulson *et al.* (2009), reflecting that the abundances of fish in cohorts born prior to 1990 are now heavily reduced, and thus there was limited information content relating to recruitment variation in the data for these cohorts. This comparison highlights that estimates of recruitment strength produced by catch curve analysis were only likely to be reliable for the younger and relatively abundant year classes.

Recruitment variability appeared to impact, in particular, on the reliability of the linear catch curve method, which produced a value for Z that differed markedly from those produced by the other approaches (Table 3). In addition, a characteristic of the linear catch curve was that, as it was fitted in log space, it was necessary to truncate the age distribution (on the right-hand limb of the age distribution) at least to the age below that at which a frequency of zero was recorded. As in this study, others have also found that linear catch curve analysis tends to underestimate mortality (e.g. Dunn *et al.* 2002; Fisher 2012). Murphy (1997) suggests this was because it violates the assumption of linear regression analysis that the variance is equal throughout the range of values for the independent variable, *i.e.* age groups. However, when considering logged abundances of fish, the variances were positively correlated with age until the distribution was truncated when zero frequencies appear in samples for older age groups. Although the effects of violating the linear regression assumption of constant variance can be reduced by truncating age frequency distributions and employing a minimum threshold abundance rule for fitting the linear regression, e.g. five individuals per age class (Chapman and Robson 1960), this does not fully eliminate the bias (Murphy 1997; Fisher 2012). Note that the approach of adopting a threshold abundance rule was not universally accepted as being appropriate. From the above, the estimates of Z produced by linear regression (as for the other three species) should be treated with caution. In contrast to linear regression, the multinomial catch curves and the Chapman and Robson approach considers all of the older fish in the sample, which for longer-lived species, appears to result in more robust Z estimates.

For western blue groper, it was not possible to simultaneously estimate selectivity, growth and mortality based on the length and age composition data collected in this study. Although a substantial sample was able to be collected during the study of this species, very few of the fish were males. This reflects the fact that this species is a protogynous hermaphrodite (changes sex from female to male) and that the overall sex ratio is highly skewed towards females. Note also that following sex change, the growth patterns for the two sexes increasingly diverges, with males growing to a larger size (Coulson *et al.* 2009). Thus, it was necessary, when fitting to length and age data, to impose growth (based on the parameters estimated by Coulson *et al.* 2009). Despite this, the estimate of Z lay in the same "ballpark" as those produced by the other catch curve approaches. Notably, the growth curves fitted well the lengths at age for western blue groper collected in this study, thereby providing an indication that the growth of this species was relatively stable (and that the previous growth estimates were reliable). In the case of the length-based catch curve, the resultant estimate of Z was very similar to that produced by the length- and age-based catch curve, except that the precision was less (as would be expected given that this curve was fitted to length composition data alone). The preferred catch curve model for this species, i.e., the multi-year catch curve that simultaneously estimates fishing mortality and recruitment variability, provided a very good fit to the age composition data from the commercial gillnet fishery in the east sub-region, accounting for the substantial recruitment variability (Figure 4).

Note, however, that by necessity (i.e. sample size), the catch curve analyses were fitted to pooled data for the two sexes, and thus do not account for possible differential impacts of fishing on male and female western blue groper. Such impacts were accounted for in the per-recruit analyses (see Appendix 5).

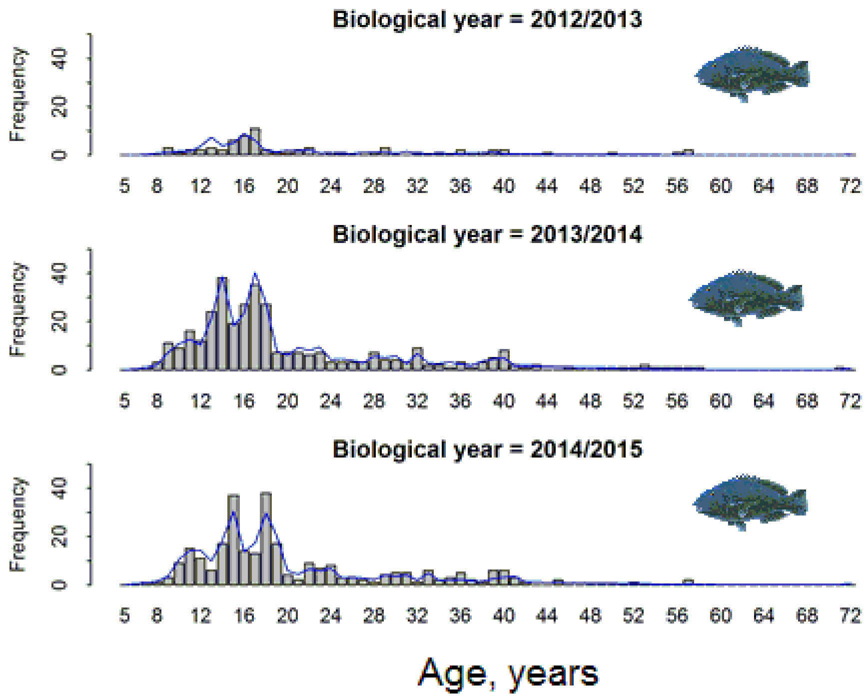

Figure 4: Multi-year, variable recruitment catch curve model (blue line) fitted to the age composition sample for western blue groper collected from the commercial gillnet fishery in the east sub-region.

Appendix 5

Details of per-recruit methods and results from age-based assessments

Methods

Two alternative per-recruit analyses were undertaken to explore the influence of estimated levels of fishing mortality on the reproductive potential of each of the four species assessed. The first model was a traditional per-recruit analysis, based on all available biological information for the species (e.g. growth, maturity and, where relevant, sex change in hermaphroditic species) and assuming constant recruitment. The second model accounts for the effect of fishing on recruitment, by extending the conventional per recruit model to include a Beverton and Holt stock-recruitment relationship.

Model descriptions

<u>1. Traditional per-recruit model</u>

Values of female and male spawning biomass at age were calculated for fish from age zero, assuming constant natural mortality (for all ages) and constant (specified) fishing mortality for fully-recruited animals. The model applied an annual time step and assumed deterministic growth, but allowed for sex-specific differences in growth.

$V_{t,s}$, the vulnerability of fish of age a and sex s (where females were denoted as 1 and males were denoted as 2) to capture by the fishing gear was calculated as

$$V_{a,s} = 1/\left\{1 + e^{-\delta\left(L_{a,s} - L_{50}\right)}\right\}$$

where $L_{a,s}$ was the mean length at age a for sex s, calculated from the respective von Bertalanffy growth curve for each species (see Tables 1 to 4 below). The δ and L_{50} were the slope of the logistic function and the length at which 50% of individuals were selected to the fishing gear, respectively. Both these parameters were assumed to be common to both sexes.

The values of the length-based selectivity parameters employed for per-recruit analyses (see Tables 1-4) were those estimated using the catch curve model fitted to length- and age-composition data (Method 7), fitted to the sample most representative for each species (i.e. western commercial wetline sector for snapper and Bight redfish, and eastern commercial gillnet data for blue morwong and western blue groper). Selectivity estimates from this catch curve method was chosen as they were considered more reliable than the age-based selectivity parameters estimated by the other catch curve models (i.e. as selectivity is often considered related more to length than to age, and also as this was the only model fitted to both length and age data).

The fishing mortality age a, $F_{a,s}$, was calculated as the $S_{a,s}F$ for sex s, where F was the fully-selected fishing mortality determined from catch curve analysis (assumed to be the same for both sexes). $Z_{a,s}$, the total mortality at age a for sex s, was calculated as $F_{a,s} + M$, where M was rate of natural mortality (year^{-1}), assumed to be common to both sexes.

For the non-hermaphroditic species, the initial sex ratio was assumed to be 0.5. Thus, the initial number of each sex at age zero was 0.5 for snapper, Bight redfish and blue morwong. For western blue groper, which is a protogynous hermaphrodite (female to male sex change), all individuals at age zero were assumed to be female, i.e. the initial number of females and males at age zero was 1 and 0, respectively.

For the non-hermaphroditic species, $N_{a,s}$, the number of fish of sex s which survive to age a for ages 1 to A, the maximum age used for the analysis (set to 100 years, which was well above the maximum recorded ages for each of the four species), was calculated as

$$N_{a,s} = N_{a-1,s}\, e^{-Z_{a,s}}.$$

For western blue groper, which undergoes a sex change from female to male, the respective numbers of females (s = 1) and males (s = 1) which survive to age a was calculated as

$$N_{a,1} = e^{-Z_a}\,(1-\xi_a)\textstyle\sum_{s=1}^{2} N_{a-1,s}\text{ , and}$$

$$N_{a,2} = e^{-Z_a}\,(\xi_a)\textstyle\sum_{s=1}^{2} N_{a-1,s}$$

ξ_a was the probability that a fish at age a has changed sex from female to male, which was calculated as

$$\xi_a = 1/\left\{1 + e^{-\log_e(19)(a-A_{50})/(A_{95}-A_{50})}\right\}$$

where A_{50} and A_{95} were the ages at which 50% and 95% of individuals fish were male.

For each species, the weight of fish of sex s at age a, $W_{a,s}$, was calculated as

$$W_{a,s} = a^{\mathrm{W}}\, {L_{a,s}}^{b^{\mathrm{W}}}$$

where a^{W} and b^{W} were the parameters of this power relationship.

For Bight redfish, snapper and western blue groper, the maturity of fish of age a and sex s, $\psi_{a,s}$, was calculated as

$$\psi_{a,s} = 1/\left\{1 + e^{-\log_e(19)\left(L_{a,s}-L_{50,s}\right)/\left(L_{95,s}-L_{50,s}\right)}\right\}$$

where $L_{50,s}$ and $L_{95,s}$, were the lengths at which 50% and 95% of individuals fish of sex s were mature. For blue morwong, an asymmetrical, four parameter logistic curve (modified from the curve by Richards 1959) was found to provide the best fit to available length data (i.e. those collected for this assessment, pooled with data from Coulson et al. 2007). This function allows for the possibility that maturity was not attained by all fish of the largest length classes, which was evident in female blue morwong. $\psi_{a,s}$ for this species was thus calculated as

$$\psi_{a,s} = P/\left\{1 + Q\, e^{-\log_e(B\, L_{a,s})^{\frac{1}{v}}}\right\}$$

where P was the maximum probability of fish of that length attaining maturity, and where Q, B and v were each constants.

For fish of each sex s, the spawning stock biomass per recruit, SSBR_s, was calculated as

$$\mathrm{SSBR}_s = \sum_{a=0}^{A} N_{a,s}\, \psi_{a,s}\, W_{a,s}\,.$$

Denoting the estimate of F resulting from the catch curve analysis as $\hat{F}$, the spawning potential ratio for fish of sex s, SPR_s, was calculated as

$$\mathrm{SPR}_s = \mathrm{SSBR}_s^{F=\hat{F}} / \mathrm{SSBR}_s^{F=0}$$

2. Extended model

An important consideration for per-recruit analyses is that they assume constant recruitment (e.g. Punt et al. 1993). It was thus considered important to explore the extent to which accounting for the effect, on recruitment, of fishing, altered estimates of YPR and SPR. Thus, the per-recruit analysis described above was extended to include a Beverton and Holt stock-recruitment relationship.

Setting the level of initial recruitment for (i.e. R^*) to 0.5 (i.e. for females), the unfished level of female spawning biomass as considered in the stock recruitment equation, S^*, is equivalent to X, the unfished level of female spawning stock biomass per recruit (i.e. $\mathrm{SSBR}_{F=0}$).

Specifying a value (0.75 for all analyses in this study) for the Beverton and Holt stock-recruitment steepness parameter, h, the two parameters of this relationship, a_{SRR} and b_{SRR} of the relationship may be calculated as

$$a_{\mathrm{SRR}} = \frac{S^*}{R^*}\left(\frac{1-h}{4h}\right), \text{ and}$$

$$b_{\mathrm{SRR}} = \frac{h-0.2}{0.8h\, R^*}.$$

Having defined the stock-recruitment relationship, the equilibrium recruitment, R_e, for a fished stock for a given level of fishing mortality was

$$R_e = \frac{X - a_{\mathrm{SRR}}}{b_{\mathrm{SRR}} X}$$

The expected yield, Y, and spawning stock biomass, B, given the level of R_e was thus

$$Y = R_e\, \mathrm{YPR}_{F=\hat{F}}, \text{ and}$$

$$B = R_e\, \mathrm{SSBR}_{F=\hat{F}}.$$

Input parameters

The per-recruit analysis was based on all available biological information for the four species (see Tables 1-4).

Table 1: Snapper parameters used in per-recruit analysis.

Variable / Parameter	Value	Source
Max age (A_{max} years)	40	Data from this project
Natural mortality (M year^{-1})	0.104	Hoenig's (1983) mortality equation for fish, substituting M for Z: $\ln M = 1.46\text{-}1.01 \ln A_{max}$
	0.167	Then *et al.*'s (2015) A_{max} based estimator $M = 4.899\ A_{max}^{-0.916}$
	0.135	Random resampling assuming uniform distribution between Hoenig (1983) and Then *et al.* (2015) estimates
Growth		Wakefield (2006) – estimated using the von Bertalanffy growth curve, fitted to south coast data
L_∞ (mm TL)	876 (both sexes)	
K (year^{-1})	0.109 (both sexes)	
t_0 (years)	-1.15 (both sexes)	
Fork-total length (mm)		Wakefield (2006) – estimated as FL = aTL – b, fitted to south-west and south coast data
a	0.897 (fem), 0.892 (mal)	
b	23.058 (fem), 23.797 (mal)	
Weight-length (g, mm FL)		Wakefield (2006) – estimated as $W = aFL^b$, fitted to south-west and south coast data
a	0.00005611 (both sexes)	
b	2.827 (both sexes)	
Maturity (logistic)		Wakefield et al. (2015, see Appendix 2), fitted to combined data from Wakefield (2006) and this project
L_{50} (mm TL)	543 (females)	
L_{95} (mm TL)	850 (females)	
Selectivity (logistic)		Estimated using length- and age-based catch curve, fitted to western commercial line data from this project
L_{50} (mm TL)	470 (both sexes)	
Slope, δ	0.04 (both sexes)	

Table 2: Bight redfish parameters used in per-recruit analysis.

Variable / Parameter	Value	Source
Max age (A_{max} years)	84	Data from this project
Natural mortality (M year^{-1})	0.049	Hoenig's (1983) mortality equation for fish, substituting M for Z: $\ln M = 1.46 - 1.01 \ln A_{max}$
	0.085	Then *et al.*'s (2015) A_{max} based estimator $M = 4.899\ A_{max}^{-0.916}$
	0.067	Random resampling assuming uniform distribution between Hoenig (1983) and Then *et al.* (2015) estimates
Growth		Estimated using the von Bertalanffy growth curve, fitted to data from this project
L_∞ (mm TL)	582 (both sexes)	
K (year^{-1})	0.09 (both sexes)	
t_0 (years)	-0.96 (both sexes)	
Weight-length (g, mm TL)		Estimated using equation $W = aTL^b$, fitted to data from this project
a	0.00001299 (both sexes)	
b	3.000 (both sexes)	
Maturity (logistic)		Estimated using data from this project
L_{50} (mm TL)	426 (females, west), 561 (females, east)	
L_{95} (mm TL)	667 (females, west), 767 (females, east)	
Selectivity (logistic)		Estimated using length- and age-based catch curve, fitted to western commercial line data from this project
L_{50} (mm TL)	351 (both sexes)	
Slope, δ	0.07 (both sexes)	

Table 3: Blue morwong parameters used in per-recruit analysis.

Variable / Parameter	Value	Source
Max age (A_{max} years)	24	Data from this project
Natural mortality (M year^{-1})	0.174	Hoenig's (1983) mortality equation for fish, substituting M for Z: $\ln M = 1.46\text{-}1.01 \ln A_{\max}$
	0.267	Then *et al.*'s (2015) A_{max} based estimator $M = 4.899\ A_{max}^{-0.916}$
	0.220	Random resampling assuming uniform distribution between Hoenig (1983) and Then *et al.* (2015) estimates
Growth		Coulson et al. (2010) – estimated using the von Bertalanffy growth curve
L_∞ (mm TL)	696 (females), 839 (males)	
K (year^{-1})	0.29 (females), 0.22 (males)	
t_0 (years)	-0.36 (females), -0.52 (males)	
Weight-length (g, mm TL)		Coulson et al. (2007) – estimated using the equation lnW = a lnTL – b
a	2.969 (both sexes)	
b	11.154 (both sexes)	
Maturity (asymmetric logistic)		Estimated by fitting, to combined data from Coulson et al. (2007) and this project, an (asymmetrical) four parameter logistic curve allowing for the possibility that maturity was not obtained by all fish of the largest length classes.
$P_{\max}$	0.9 (females), 1 (males)	
Q	1.4E-4 (females), 0.22 (males)	
B	0.01 (females), 0.005 (males)	
v	1.2E-6 (females), 0.01 (males)	
Selectivity (logistic)		Estimated using length- and age-based catch curve, fitted to eastern commercial gillnet data from this project
L50 (mm TL)	622 (both sexes)	
Slope, δ	0.029 (both sexes)	

Table 4: Western blue groper parameters used in per-recruit analysis.

Variable / Parameter	Value	Source
Max age (A_{max} years)	71	Data from this project
Natural mortality (M year^{-1})	0.058	Hoenig's (1983) mortality equation for fish, substituting M for Z: $\ln M = 1.46\text{-}1.01 \ln A_{\max}$
	0.099	Then *et al.*'s (2015) A_{max} based estimator $M = 4.899\ A_{max}^{-0.916}$
	0.077	Random resampling assuming uniform distribution between Hoenig (1983) and Then *et al.* (2015) estimates
Growth		Coulson et al. (2009) – estimated using the von Bertalanffy growth curve
L_∞ (mm TL)	682 (fem), 982 (mal)	
K (year^{-1})	0.14 (fem), 0.08 (mal)	
t_0 (years)	0.06 (fem), -0.48 (mal)	
Weight-length (g, mm TL)		Coulson et al. (2009) – estimated using equation lnW = a lnTL – b
a	3.041 (both sexes)	
b	11.017 (both sexes)	
Maturity (logistic)		Coulson et al. (2009)
L_{50} (mm TL)	653 (both sexes)	
L_{95} (mm TL)	926 (both sexes)	
Sex change (logistic)		Estimated using data from Coulson et al. (2009) (sex identified from gonadal examination or colour)
A_{50} (years)	32.7	
A_{95} (years)	48.0	
$P_{\max}$	0.52	($P_{\max}$ was the maximum proportion of fish at any age which were male)
Selectivity (logistic)		Estimated using length- and age-based catch curve, fitted to eastern commercial gillnet data from this project
L_{50} (mm TL)	519.6 (both sexes)	
Slope, δ	0.052 (both sexes)	

Per-recruit analyses diagnostic plots

Per-recruit analysis revealed the relationship between yield per recruit (YPR, kg) and SPR, and the level of fishing mortality (*F*, year^{-1}) for the four inshore demersal indicator species. The plots (Figure 1-4) show results from conventional per-recruit analysis and from extended analysis that accounts for reduced recruitment when *F* increases (i.e. includes a stock-recruitment relationship).

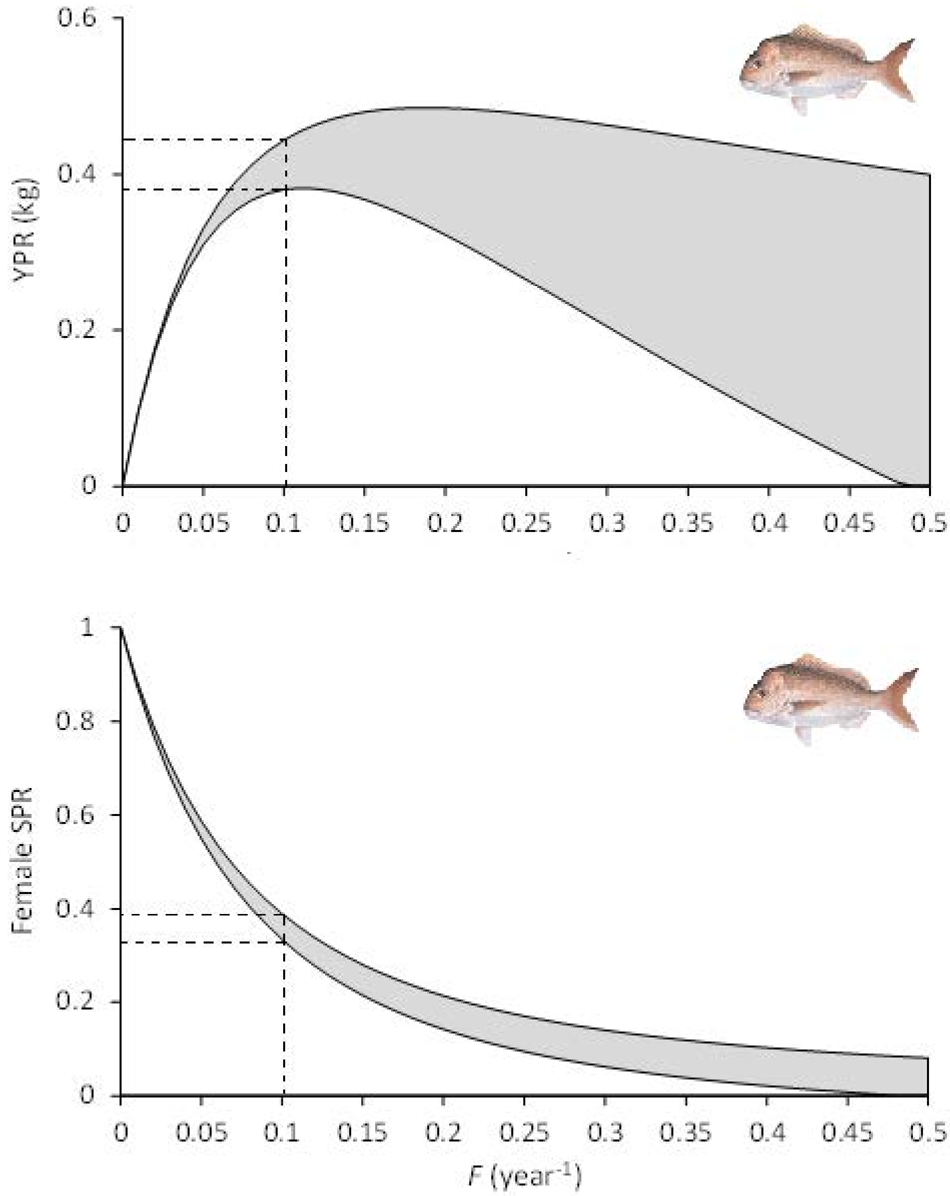

Figure 1: Snapper YPR and female SPR for different levels of fishing mortality (*F*, year^{-1}), using conventional (upper curve) and extended (lower curve) per-recruit analysis, estimated from samples collected in the SCB between 2012 and 2014. The dashed line corresponds to the *F* estimate reported in section 4.1.3. Grey area thus reflects some of the uncertainty in the results, dependent on the inherent assumptions of the analyses used.

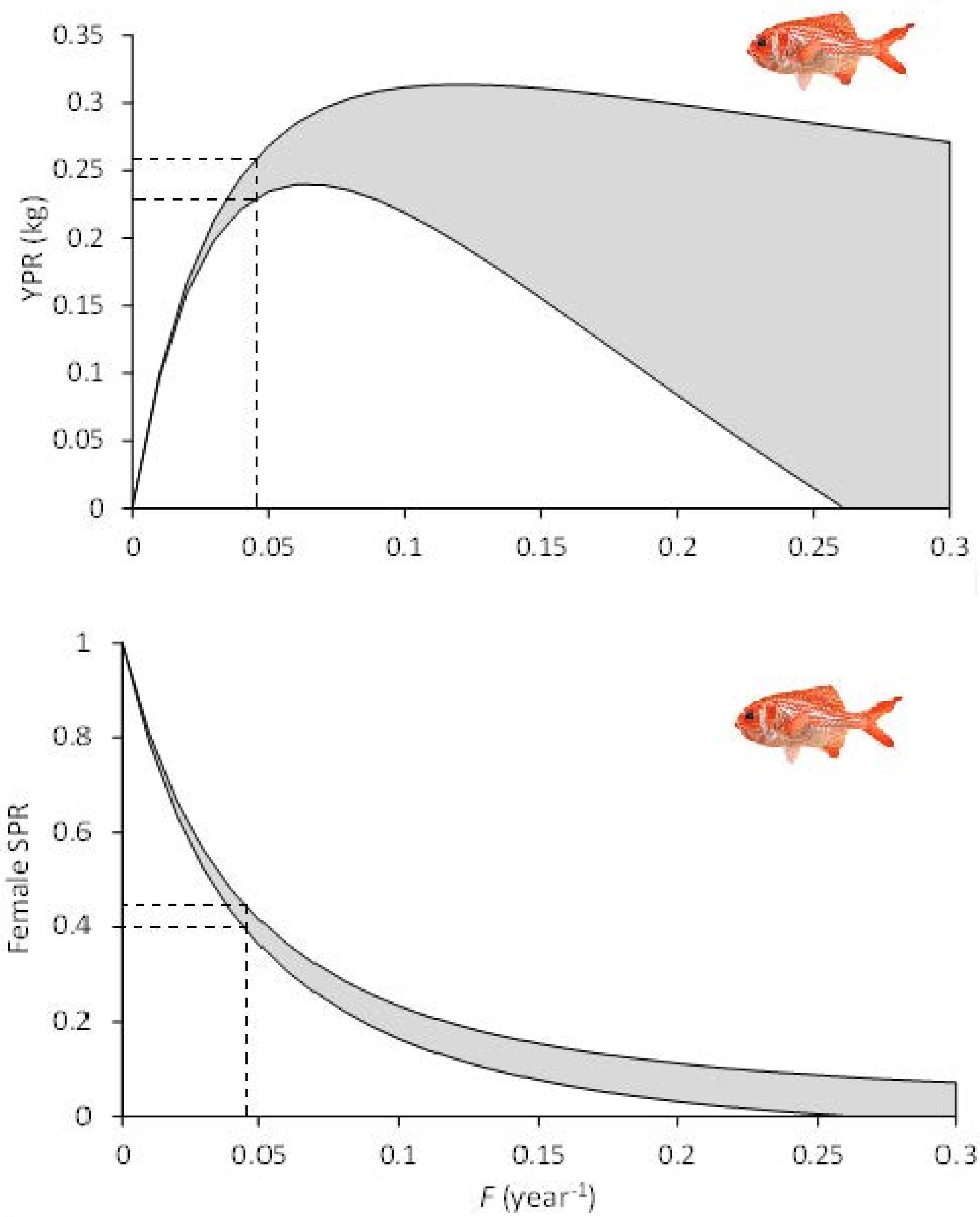

Figure 2: Bight redfish YPR and female SPR for different levels of fishing mortality (F, year^{-1}), using conventional (upper curve) and extended (lower curve) per-recruit analysis, estimated from samples collected in the west sub-region of the SCB between 2012 and 2014. The dashed line corresponds to the F estimate reported in section 4.2.3. Grey area thus reflects some of the uncertainty in the results, dependent on the inherent assumptions of the analyses used.

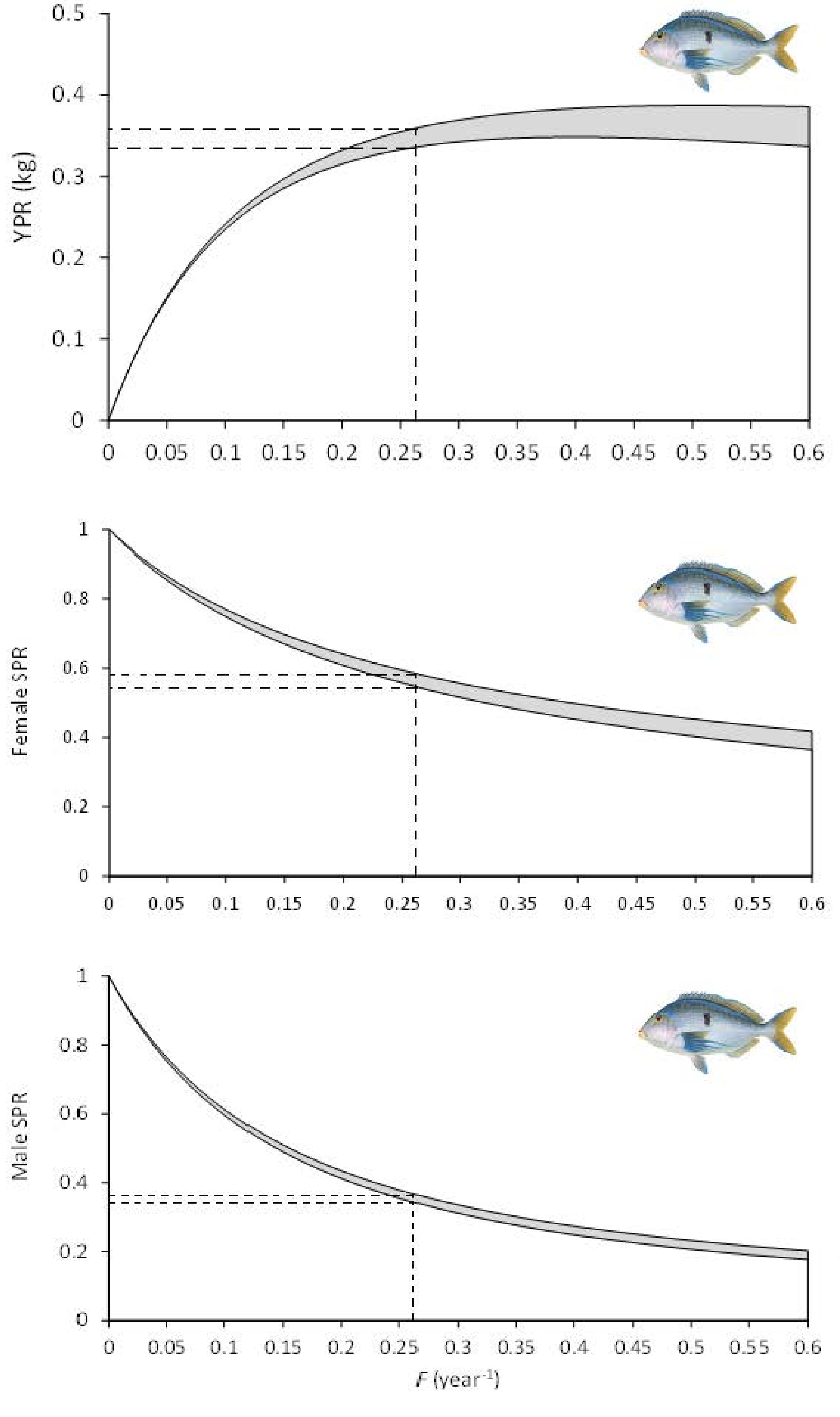

Figure 3: Blue morwong YPR and female and male SPR for different levels of fishing mortality (*F*, year^{-1}), using conventional (upper curve) and extended (lower curve) per-recruit analysis, estimated from samples collected in the SCB between 2012 and 2014. Note the dashed line corresponds to the unweighted *F* estimate used for the per-recruit analysis, rather than the weighted *F* estimate reported in section 4.3.3. Grey area reflects some of the uncertainty in the results, dependent on the inherent assumptions of the analyses used.

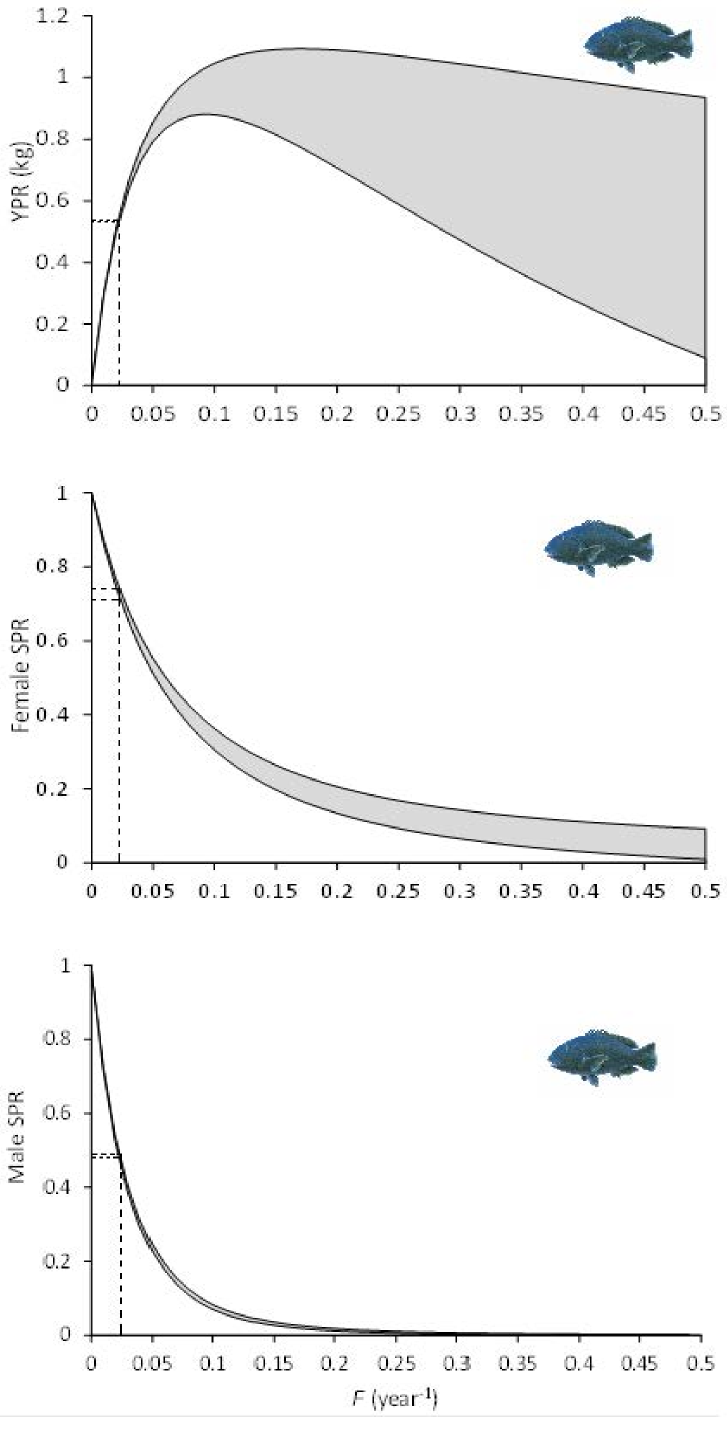

Figure 4: Western blue groper YPR and female and male SPR for different levels of fishing mortality (F, year-1), using conventional (upper curve) and extended (lower curve) per-recruit analysis, estimated from samples collected in the SCB between 2012 and 2014. The dashed line represents the F estimate reported in section 4.4.3. Grey area reflects some of the uncertainty in the results, dependent on the inherent assumptions of the analyses used.